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
$W \to e\nu$	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

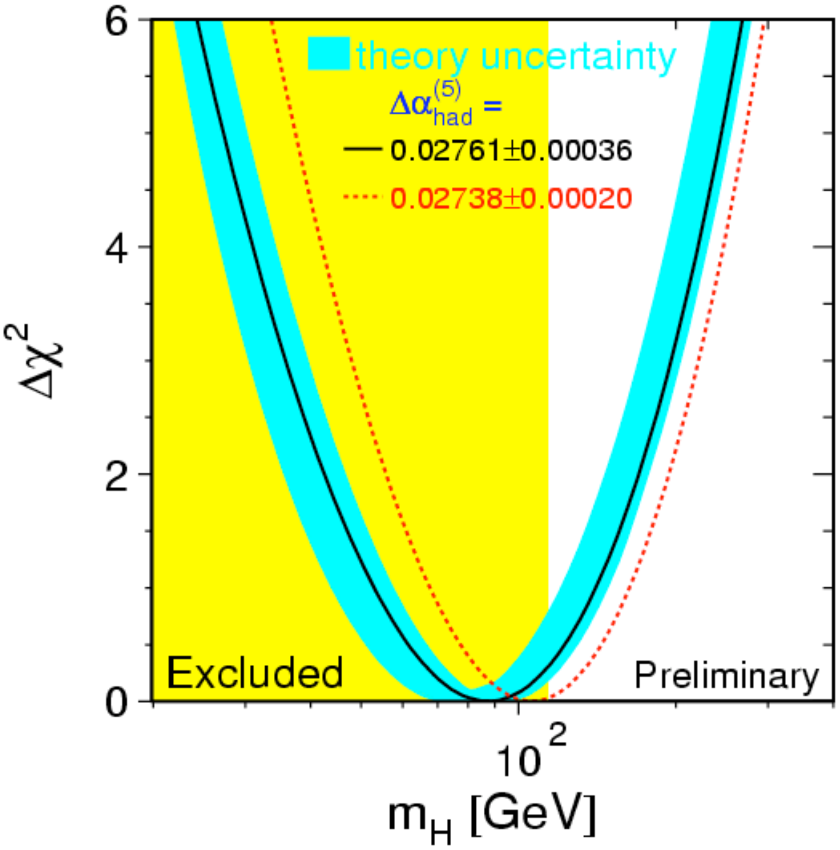
→ LHC is a B-factory, top factory, W/Z factory Higgs factory, SUSY factory, etc.

Search for the Standard Model Higgs boson

What do we know today about m_H ?

Not predicted by theory (but production and decays versus m_H predicted).
Experimental limits /indications:

- $m_H > 114$ GeV from 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



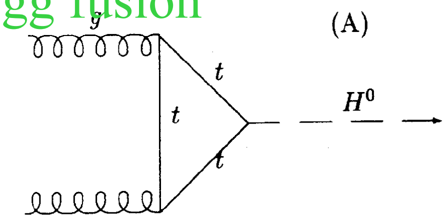
Best fit of SM to data (minimum χ^2) found for $m_H = 88^{+35}_{-45}$ GeV

$m_H < 196$ GeV 95% C.L.

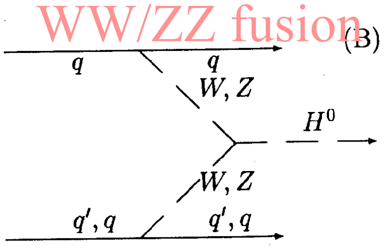
-- ≈ 2σ excess from LEP for $m_H \sim 115.6$ GeV

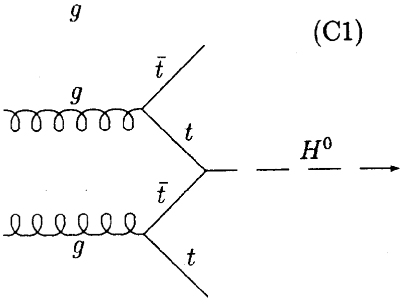
Higgs production at LHC

gg fusion

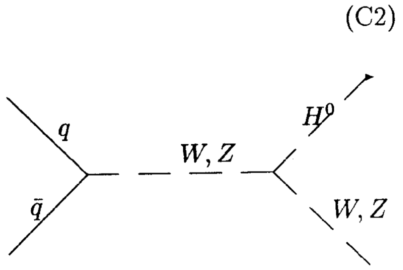


WW/ZZ fusion



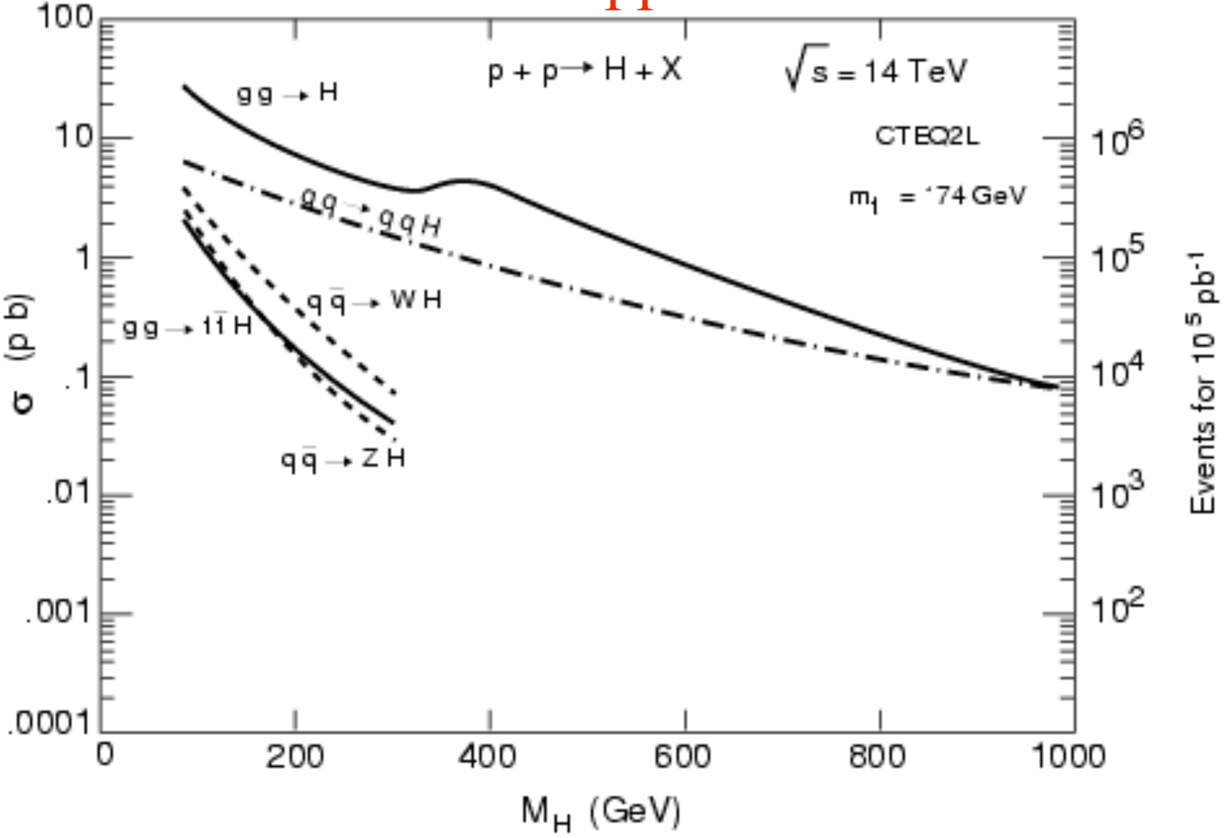


associated $t\bar{t}H$

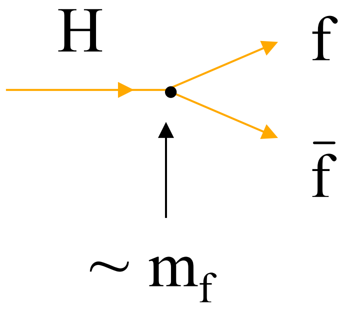


associated WH, ZH

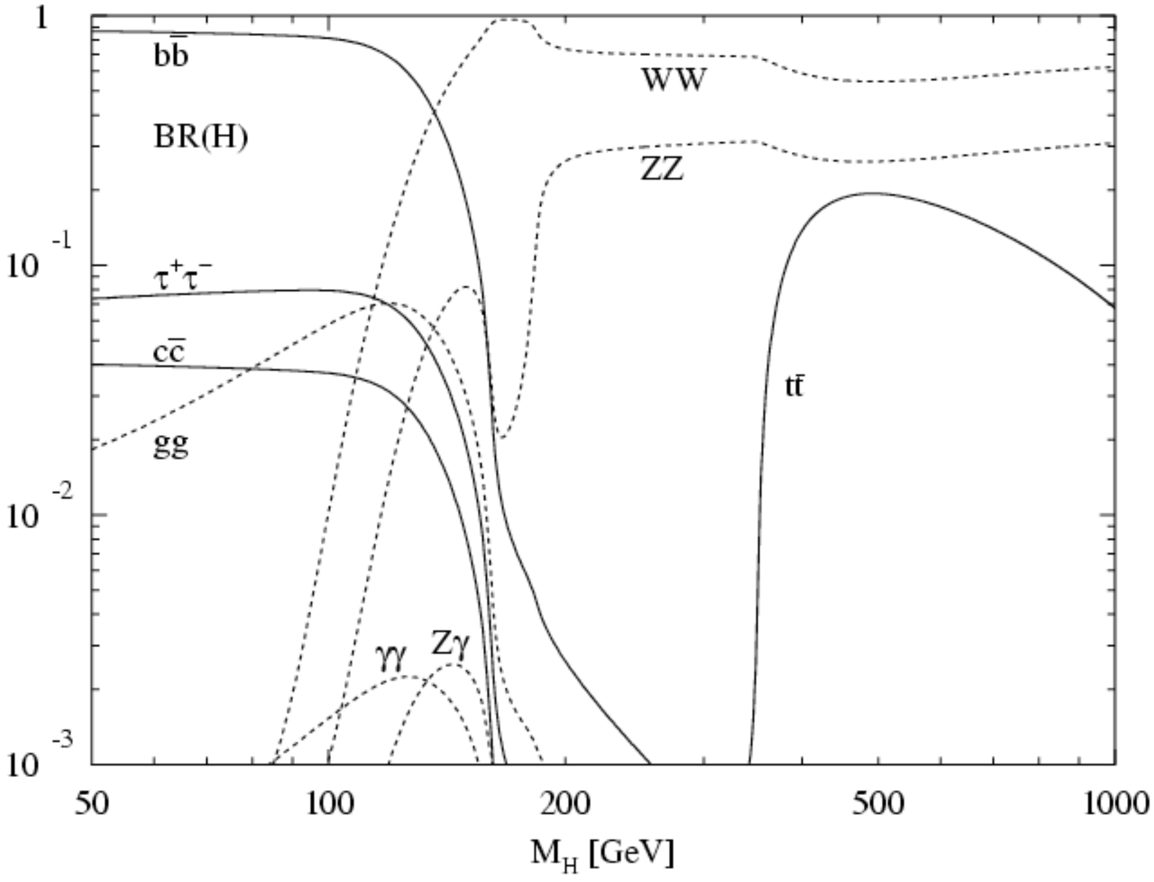
Cross-section for pp → H + X



Higgs decays



Decay branching ratios (BR)



- $m_H < 120$ GeV: $H \rightarrow b\bar{b}$ dominates
- $130 \text{ GeV} < m_H < 2\, m_Z$: $H \rightarrow WW^{(*)}, ZZ^{(*)}$ dominate
- $m_H > 2\, m_Z$: 1/3 $H \rightarrow ZZ$
  2/3 $H \rightarrow WW$
- important rare decays : $H \rightarrow \gamma\gamma$

Search strategy

Fully hadronic final states dominate but cannot be extracted from large QCD background → look for final states with leptons and photons (despite smaller BR).

Main channels:

- Low mass region ($m_H < 150$ GeV):

-- $H \rightarrow b\bar{b}$: BR ~ 100% → $\sigma \approx 20$ pb

however: huge QCD background ($N_S/N_B < 10^{-5}$)

→ can only be used with additional leptons:

$WH \rightarrow \ell\nu\, b\bar{b}$ $\quad t\bar{t}H \rightarrow \ell\nu X\ b\bar{b}$ associated production

($\sigma \approx 1$ pb)

-- $H \rightarrow \gamma\gamma$: BR ~ 10^{-3} → $\sigma \approx 50$ fb

however: clean channel ($N_S/N_B \approx 10^{-2}$)

- Intermediate mass region (120 GeV $\leq m_H \leq 2\ m_Z$):

-- $H \rightarrow WW^* \rightarrow \ell\nu\ \ \ell\nu$
-- $H \rightarrow ZZ^* \rightarrow \ell\ell\ \ \ell\ell$

~ only two channels which can be extracted from background

- High mass region ($m_H > 2\ m_Z$):

-- $H \rightarrow ZZ \rightarrow \ell\ell\ \ \ell\ell$
gold-plated channel (~ no background) !

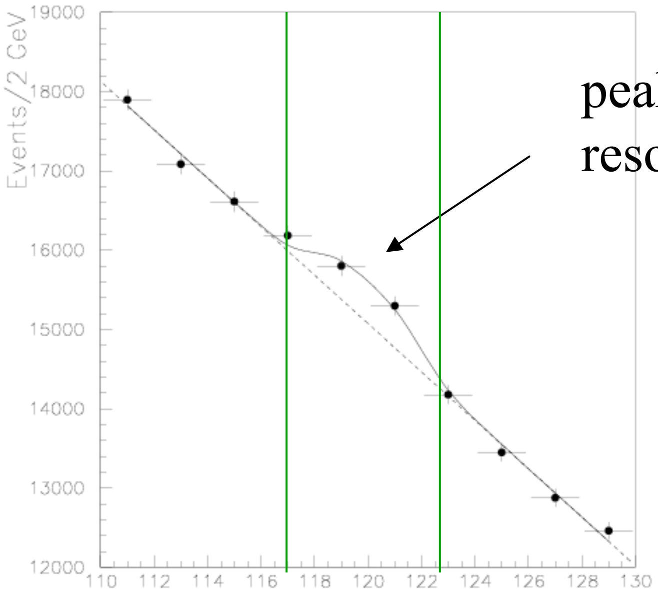
$$\left.\begin{array}{l} \text{-- } H \rightarrow ZZ \rightarrow \ell\ell\ \nu\nu,\ \ell\nu\,\text{jet jet} \\ \text{-- } H \rightarrow WW \rightarrow \ell\nu\ \ \text{jet jet} \end{array}\right\}$$

larger BR
→ increase
rate for
$m_H > 500$ GeV

Only a few examples discussed here

How can one claim a discovery ?

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



peak width due to detector resolution

$m_{\gamma\gamma}$

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} → 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.

$\rightarrow$ N_B increases by ~ 2
(assuming background flat)

N_S unchanged

$\Rightarrow S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$

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

detector with better resolution has larger probability to find a signal

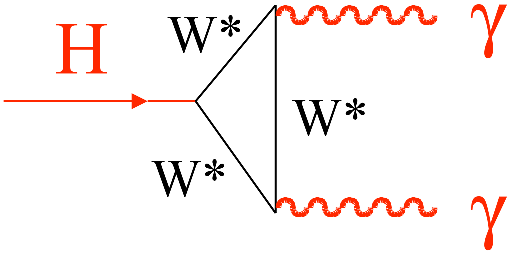
Note: only valid if $\Gamma_H << \sigma_m$. If Higgs is broad detector resolution is not relevant.

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

- integrated luminosity :

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

$\boxed{H \to \gamma\gamma}$ $80 < m_H < 150$ 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

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

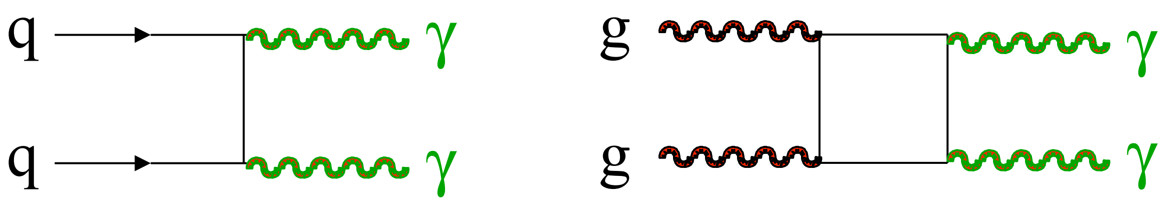
- Plot distribution of $m_{\gamma\gamma} \to$ Higgs should appear as a peak at m_H

Most challenging channel for LHC electromagnetic calorimeters

Main backgrounds:

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

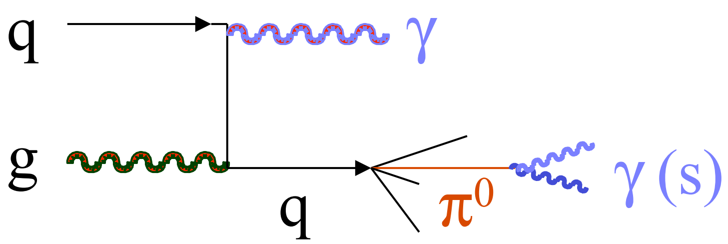
e.g. :



$$\frac{\sigma\ (\gamma\gamma)}{\sigma\ (H \rightarrow \gamma\gamma)} \approx 60 \qquad m_{\gamma\gamma} = 100 \text{ GeV}$$

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

e.g. :



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

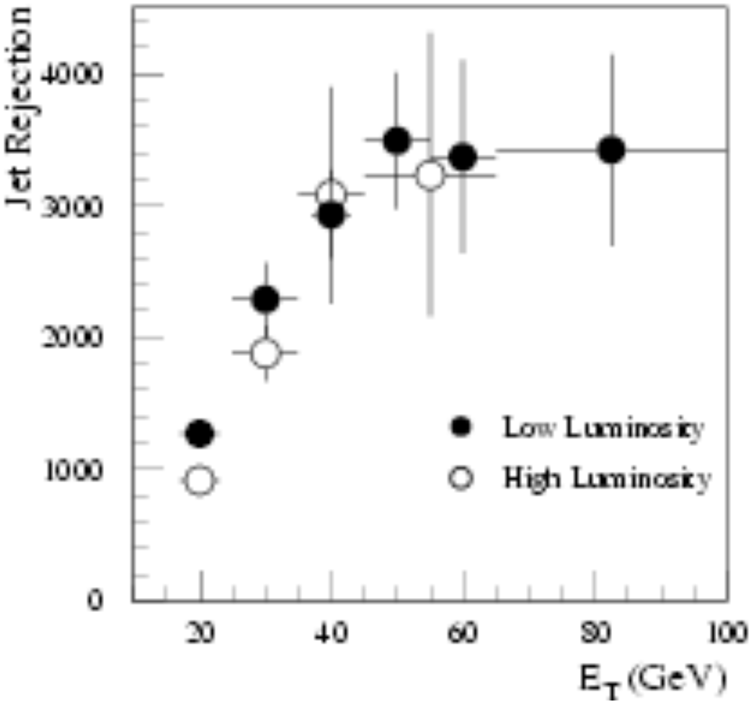
How can one fight these backgrounds ?

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

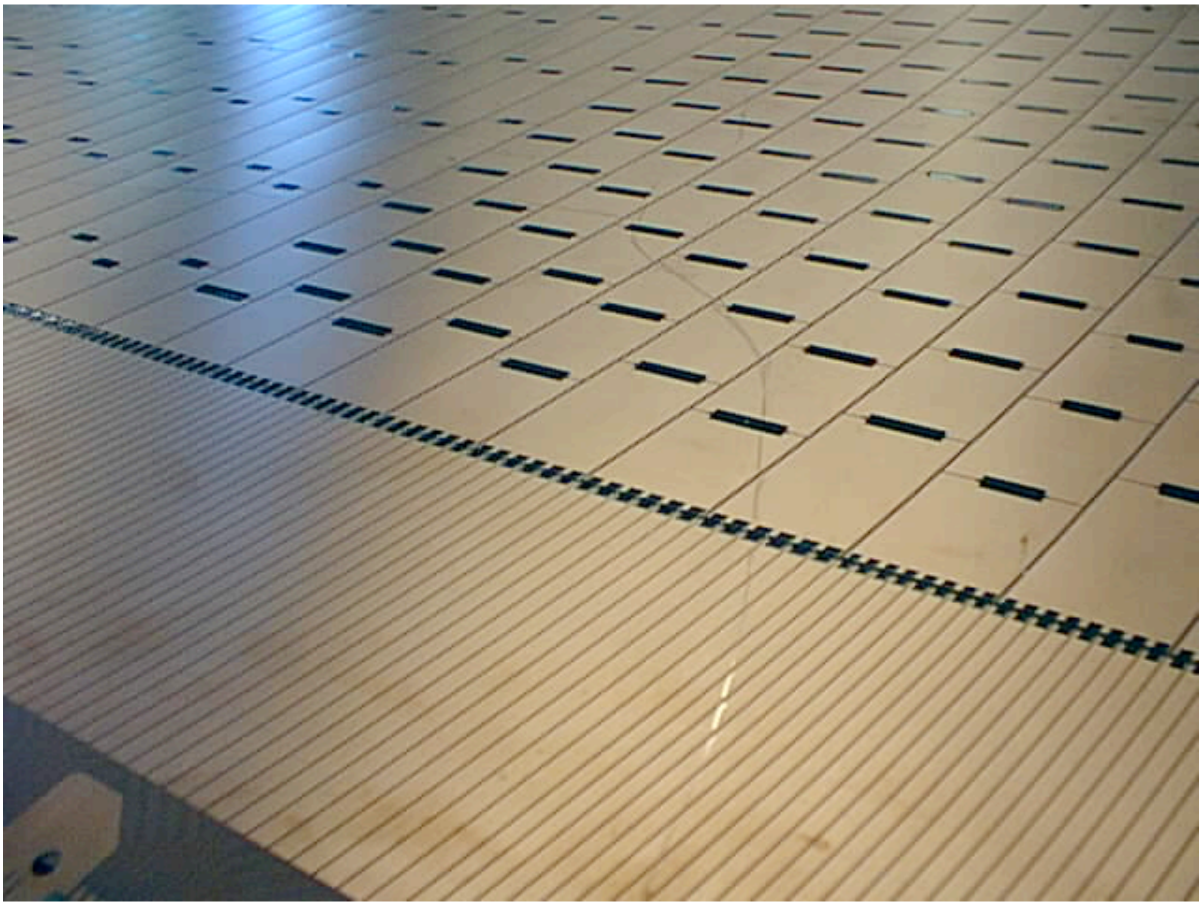
$R_{jet} \approx 10^3$ needed for $\varepsilon_\gamma \approx 80\%$

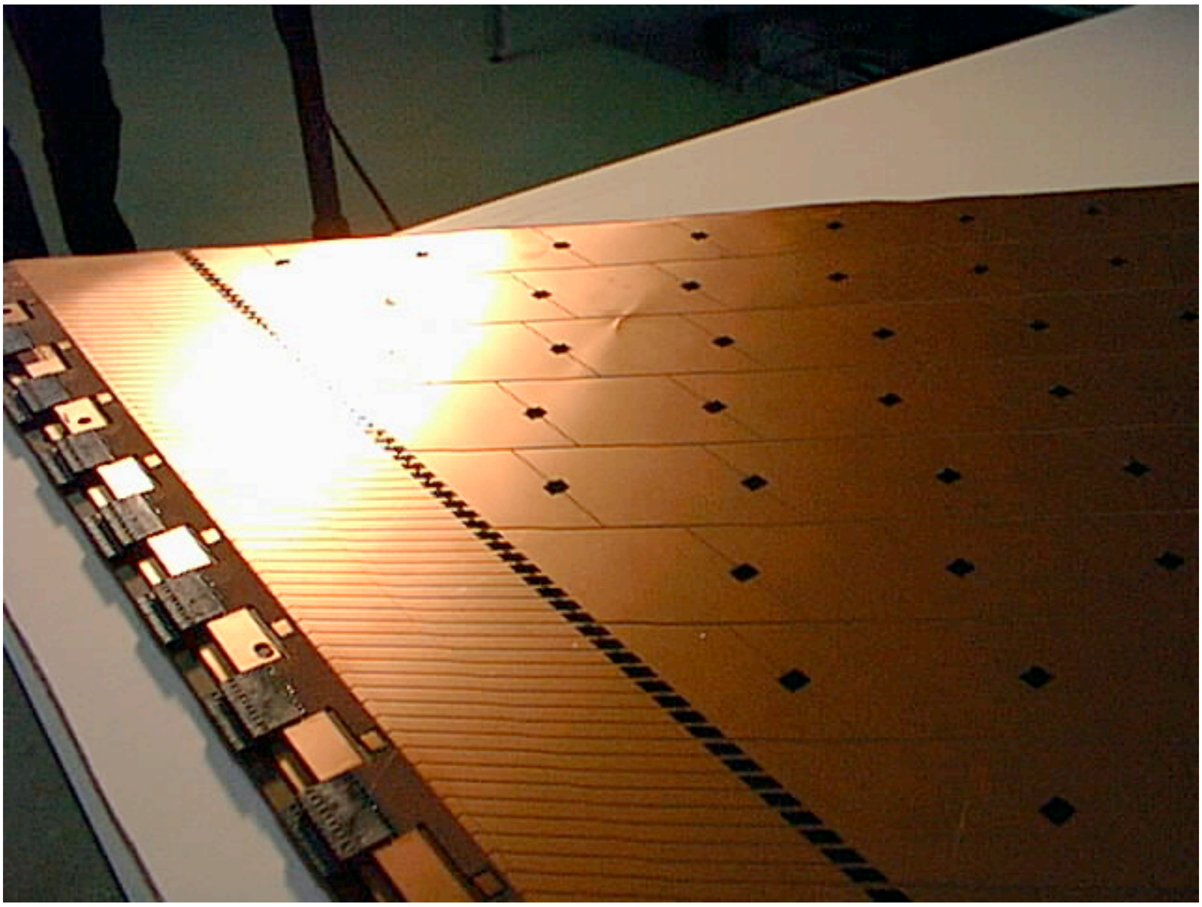
ATLAS and CMS have calorimeters with good granularity to separate single γ from jets or from $\pi^0 \rightarrow \gamma\gamma$.

Simulation of ATLAS calorimeter



With this performance : (γjet + jet-jet) $\leq$ 30% $\gamma\gamma$ → small





- Irreducible γγ : 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

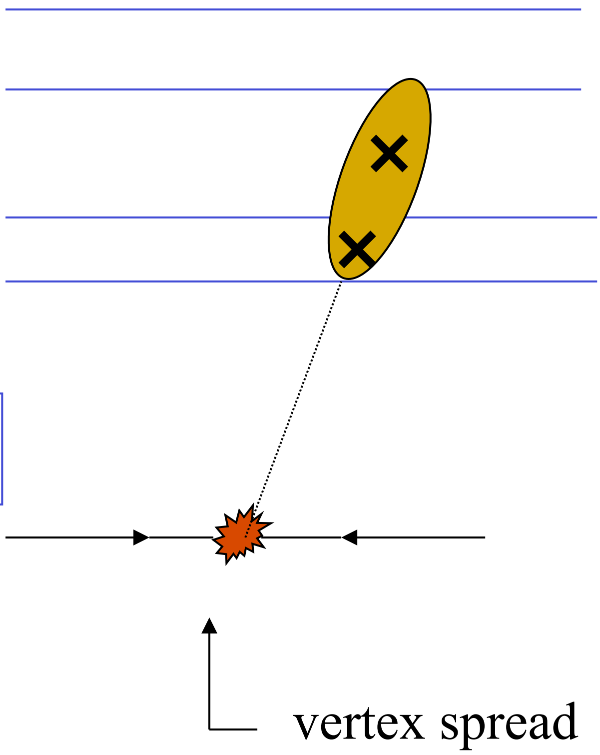
ATLAS EM calorimeter:

- liquid-argon/lead sampling calorimeter $\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}}$

- longitudinal segmentation

$\rightarrow$ can measure γ direction

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



vertex spread
~ 5.6 cm

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

$\varepsilon \approx 25\ \%$

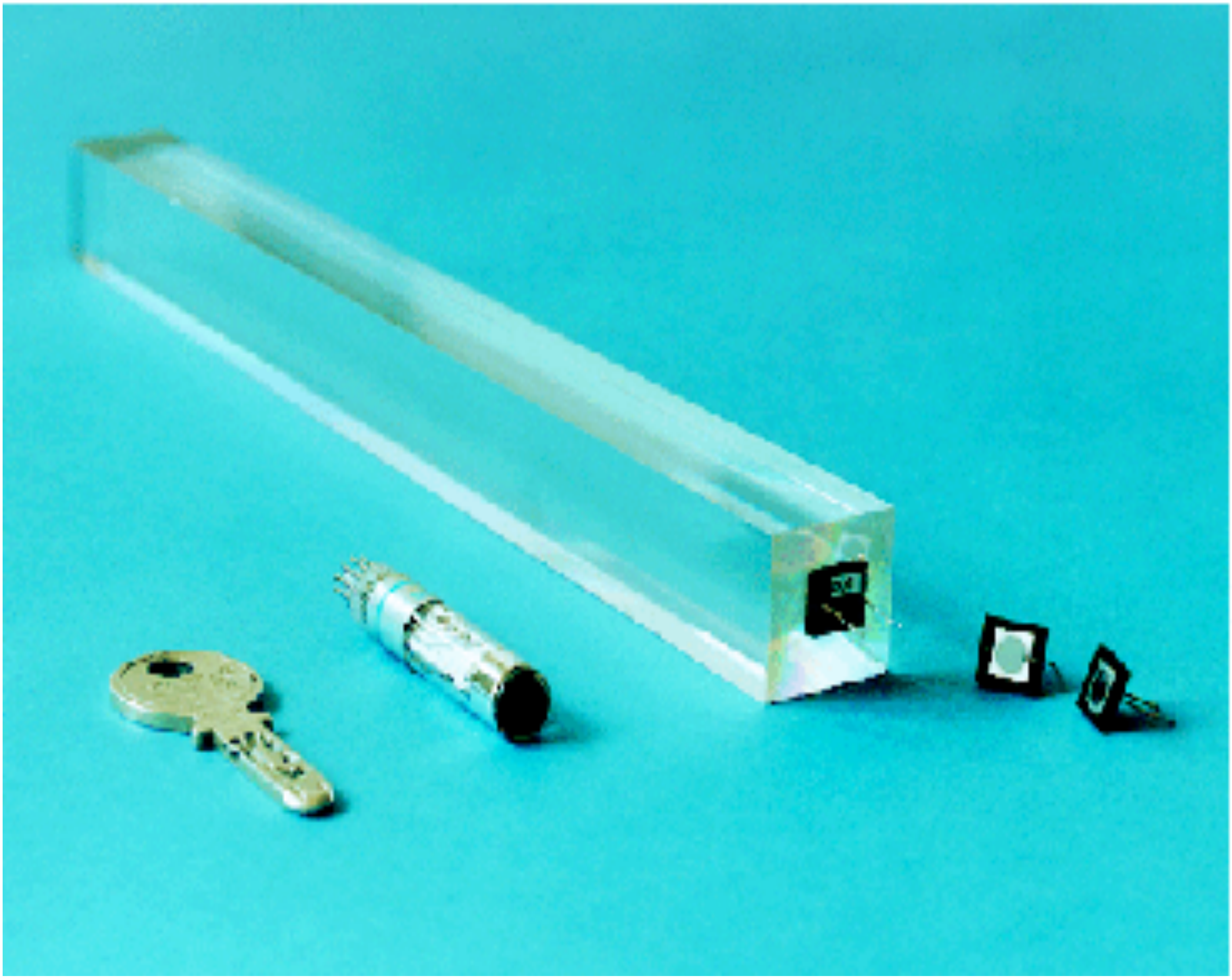
CMS EM calorimeter:

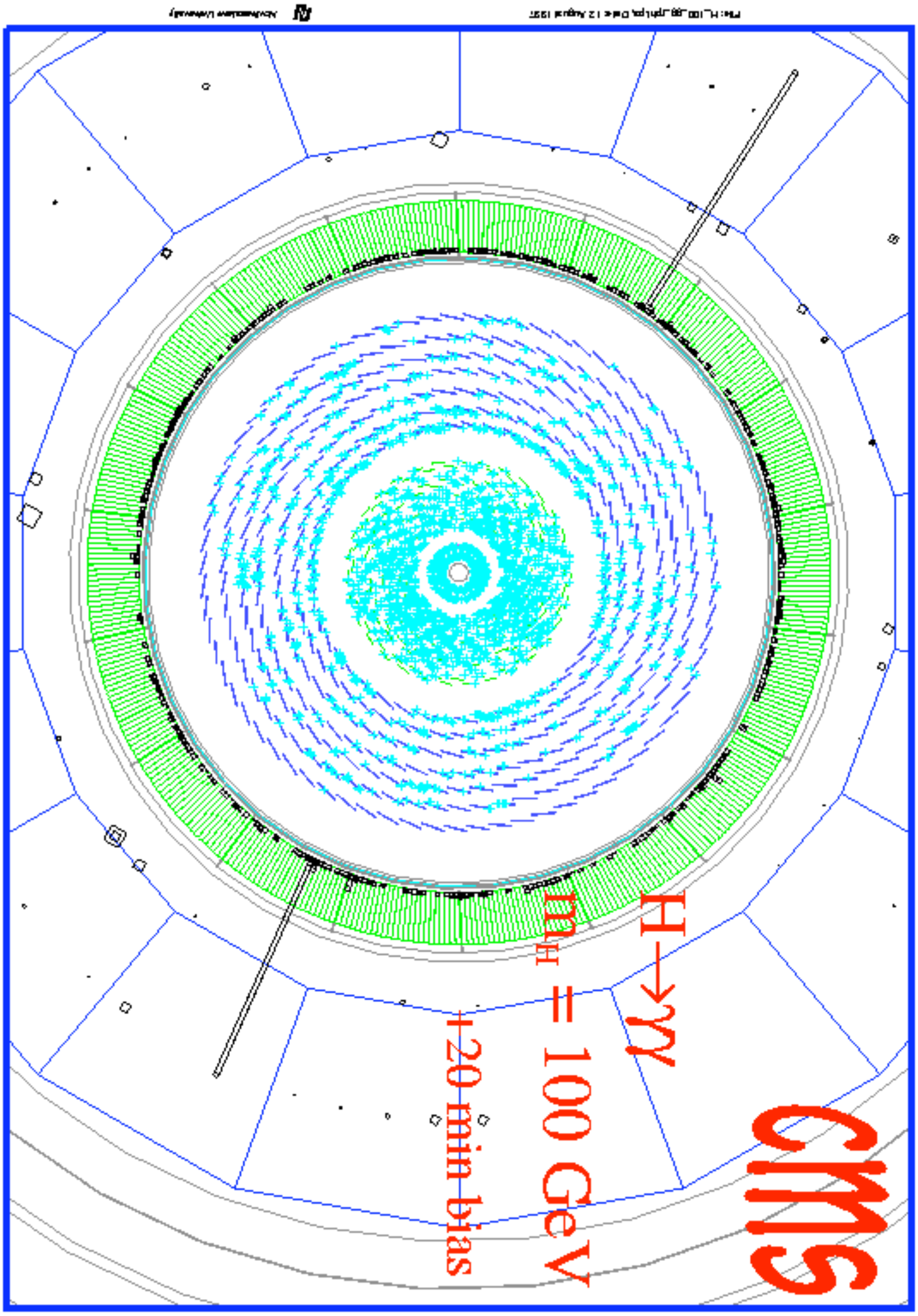
- homogeneous crystal calorimeter $\frac{\sigma(E)}{E} \approx \frac{3-5\%}{\sqrt{E}}$

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

$\boxed{\sigma_m \approx 0.7\text{ GeV} \quad m_H = 100\text{ GeV}}$ $\varepsilon \approx 20\%$

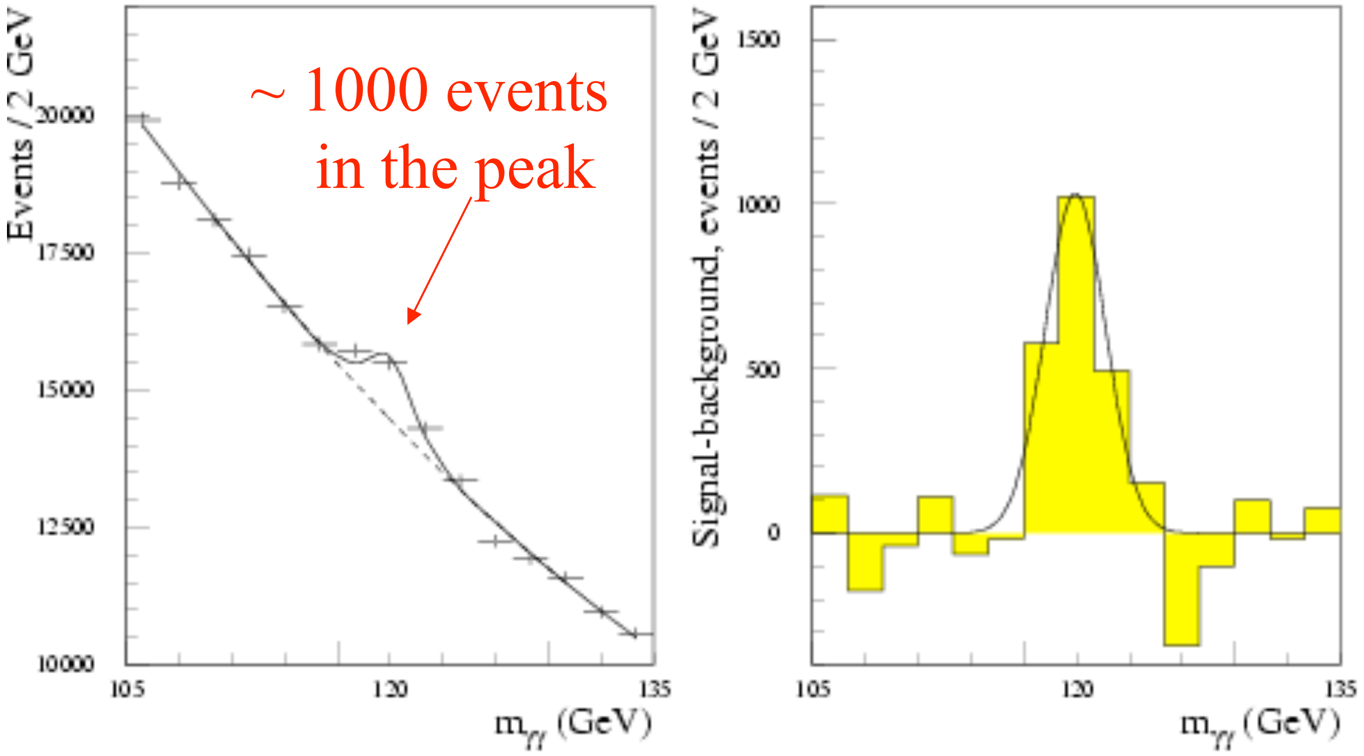
CMS crystal calorimeter




CMS
H→γγ
m_H = 100 GeV
+20 min bias

Expected performance

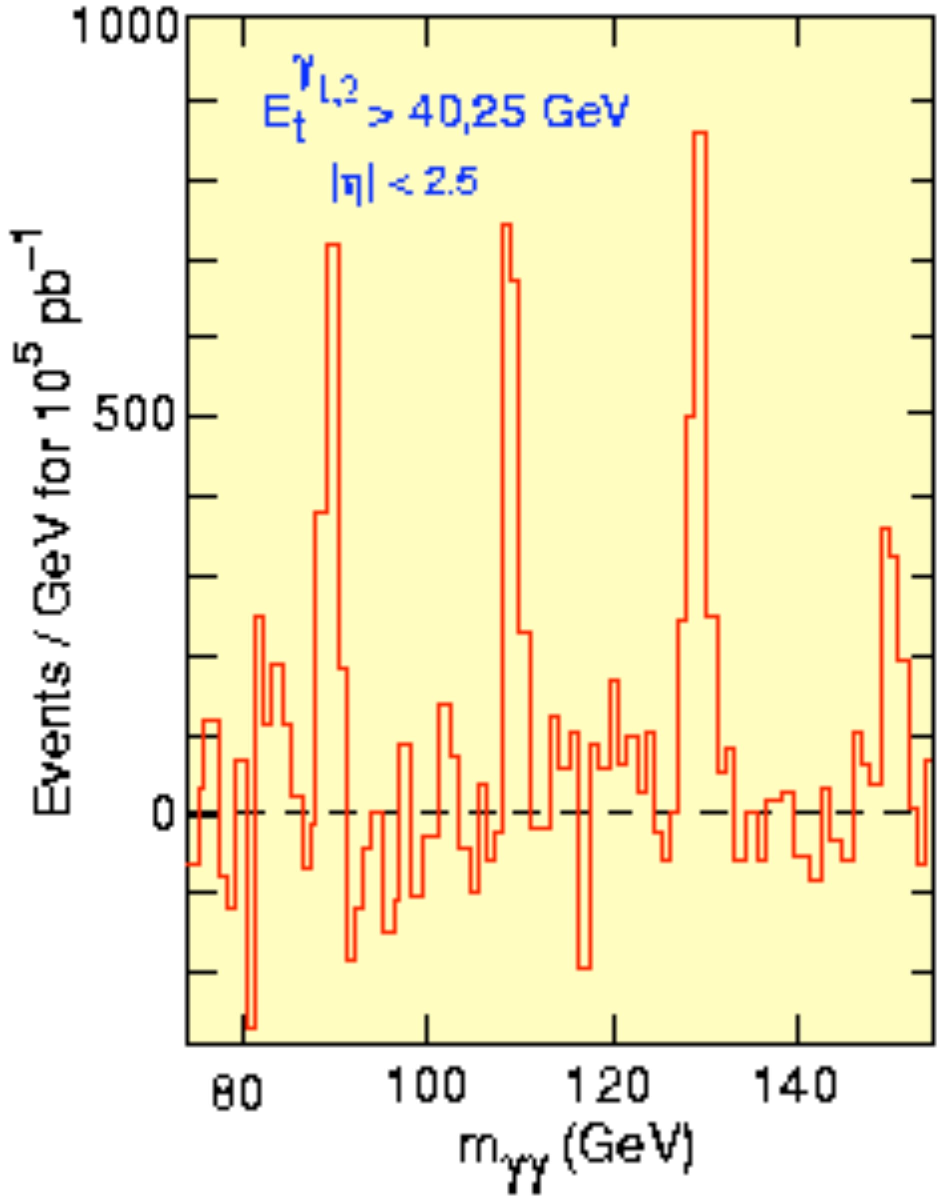
ATLAS : 100 fb^{-1}



~ 1000 events in the peak

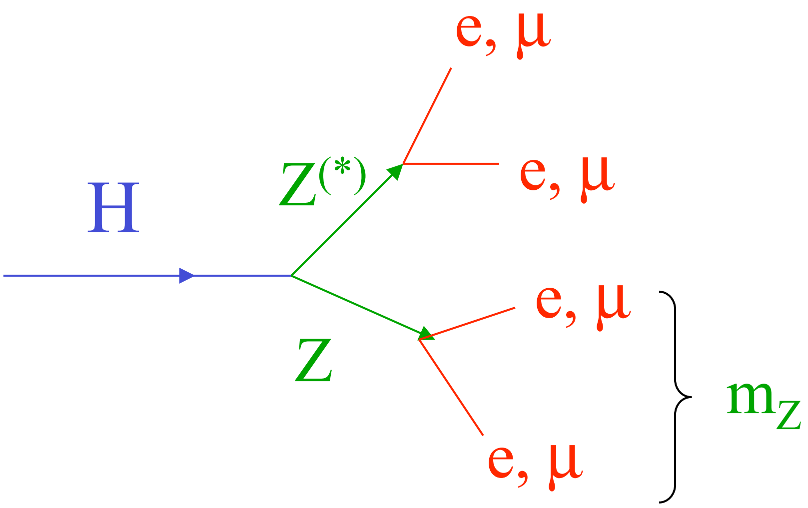
m_H (GeV)	100	120	150
Significance ATLAS, 100 fb^{-1}	4.4	6.5	4.3

CMS : significance is 15% better thanks to better EM calorimeter resolution



100 fb^{-1}

$\boxed{H \rightarrow ZZ^{(*)} \rightarrow 4\,\ell}$ $130 \leq m_H < 700$ 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 :

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

⇒ Higgs signal should appear as peak in the mass distribution

- $\underline{m_H > 180\ \text{GeV: both Z are real}}$

  -- $\sigma \times \text{BR} \approx 10$ fb   BR ($H \rightarrow ZZ$) ≈ 30 %
  -- leptons have $p_T >> 10$ GeV
  -- $\Gamma_H > 1$ GeV, $\Gamma_H \sim m_H^3 \rightarrow$ detector resolution not relevant
  -- background is small (require Z have high-p_T since H is heavy)

- $\underline{m_H < 180\ \text{GeV: one Z is virtual}}$

  -- $\sigma \times \text{BR} \approx$ fb   BR ($H \rightarrow ZZ^*$) < 10 %
  -- leptons from Z* can have $p_T \sim$ 5-10 GeV
  -- $\Gamma_H << 1$ GeV → detector resolution important for good S
  -- background is large (only one Z-mass constraint, etc.)

Backgrounds:

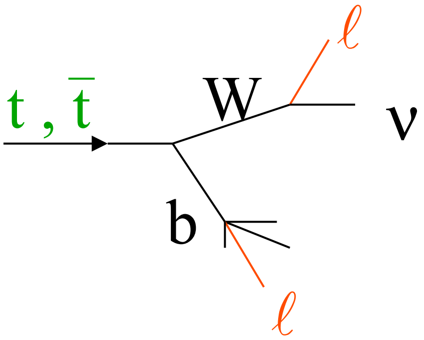
-- irreducible : $pp \rightarrow ZZ^{(*)} \rightarrow 4\ell$

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

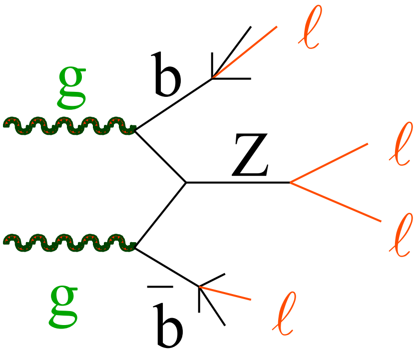
For $m_H > 300$ GeV $\Gamma_H > \sigma_m$

-- 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)

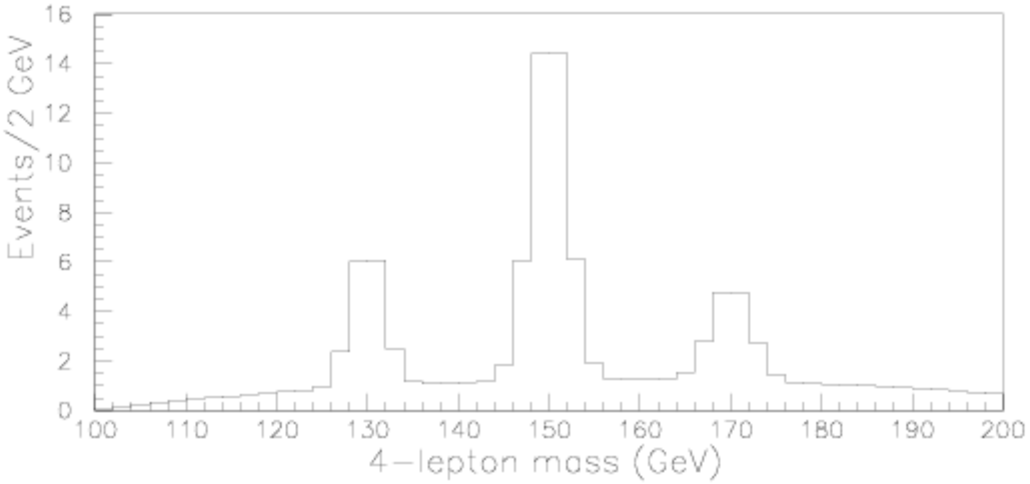
Distance of muon tracks from vertex (divided by resolution)

ATLAS

Thanks to Pixel/Silicon layers σ ~ 15 μ

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

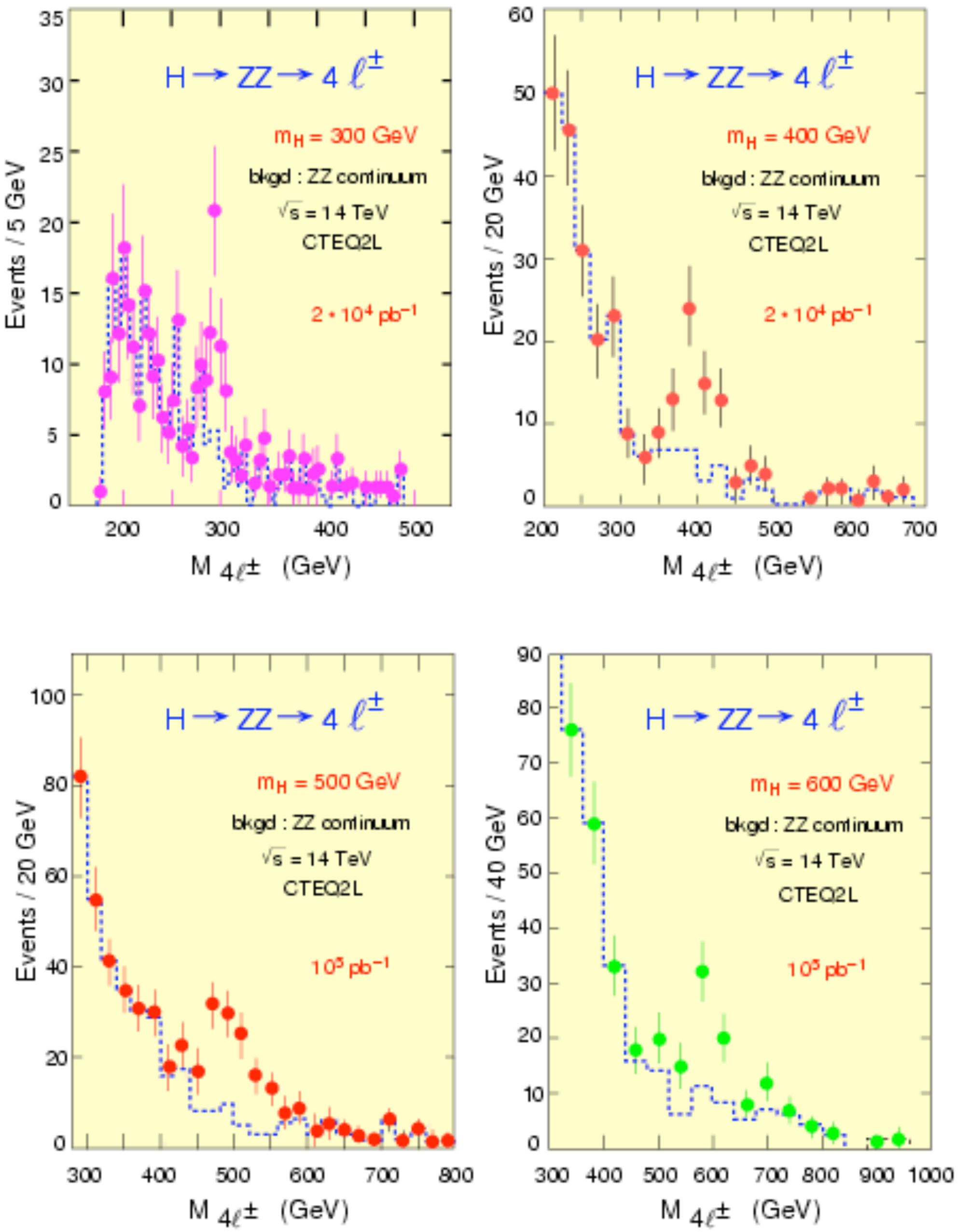


$H \rightarrow ZZ^* \rightarrow 4\ell$

ATLAS, 30 fb^{-1}

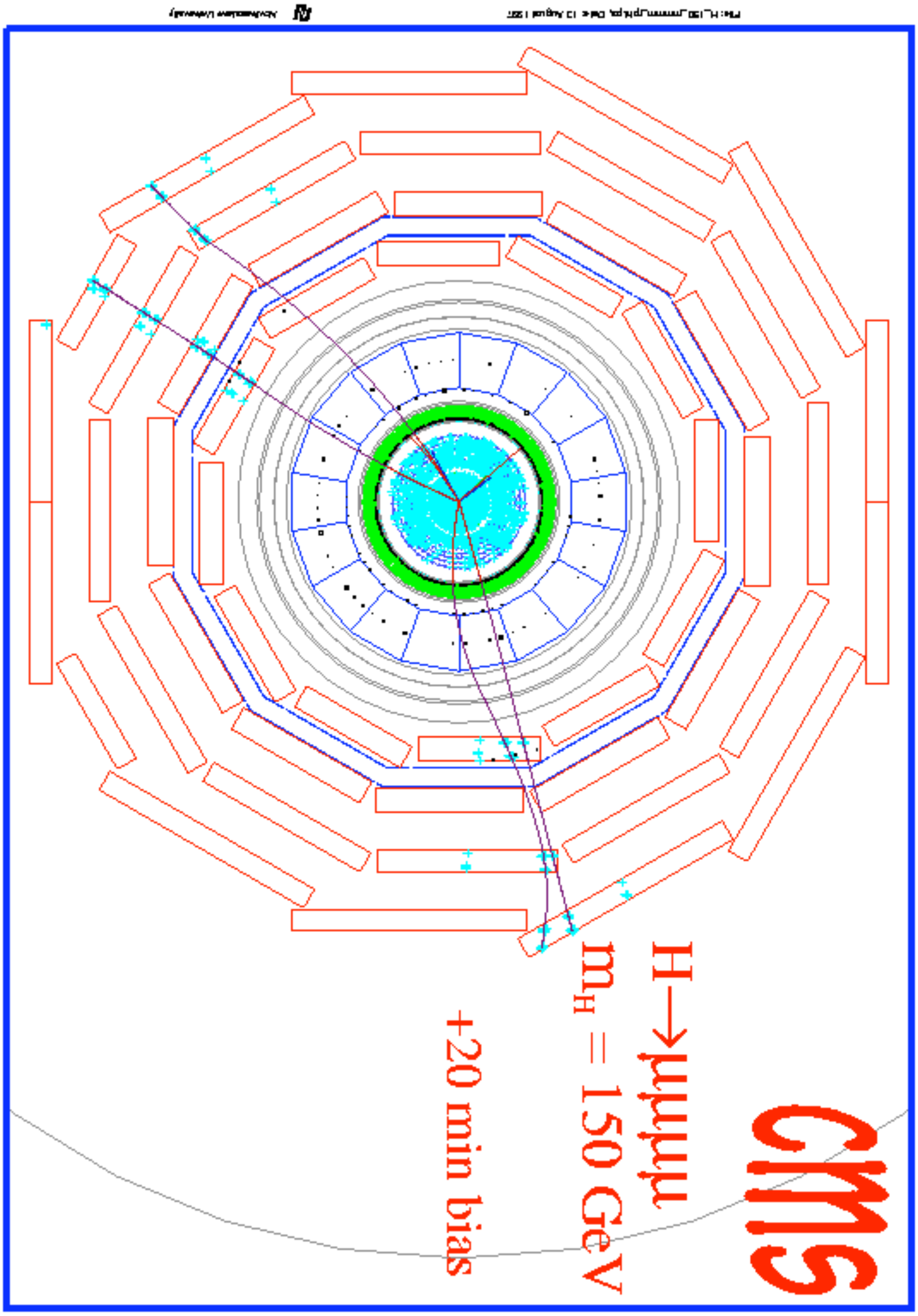
$H \to ZZ \to 4\ell^{\pm}$

in CMS



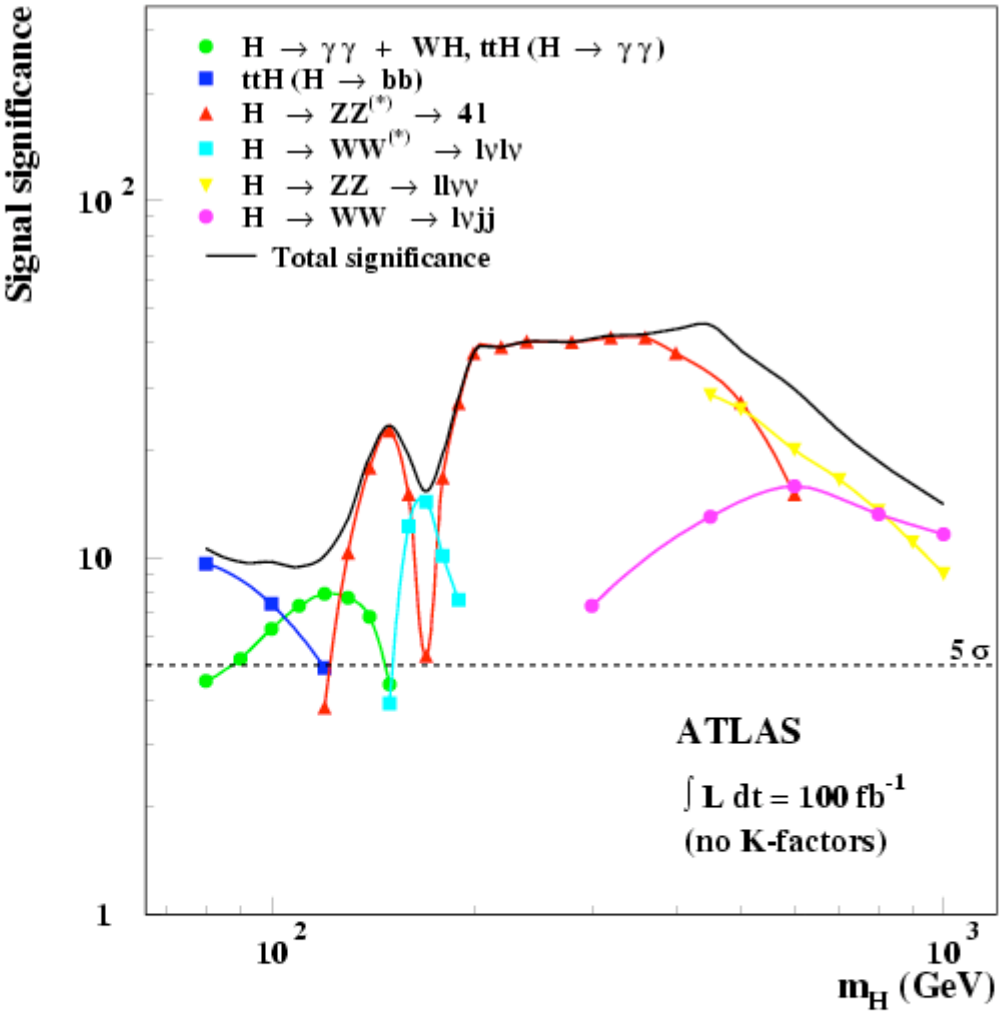
20 fb^{-1}

100 fb^{-1}

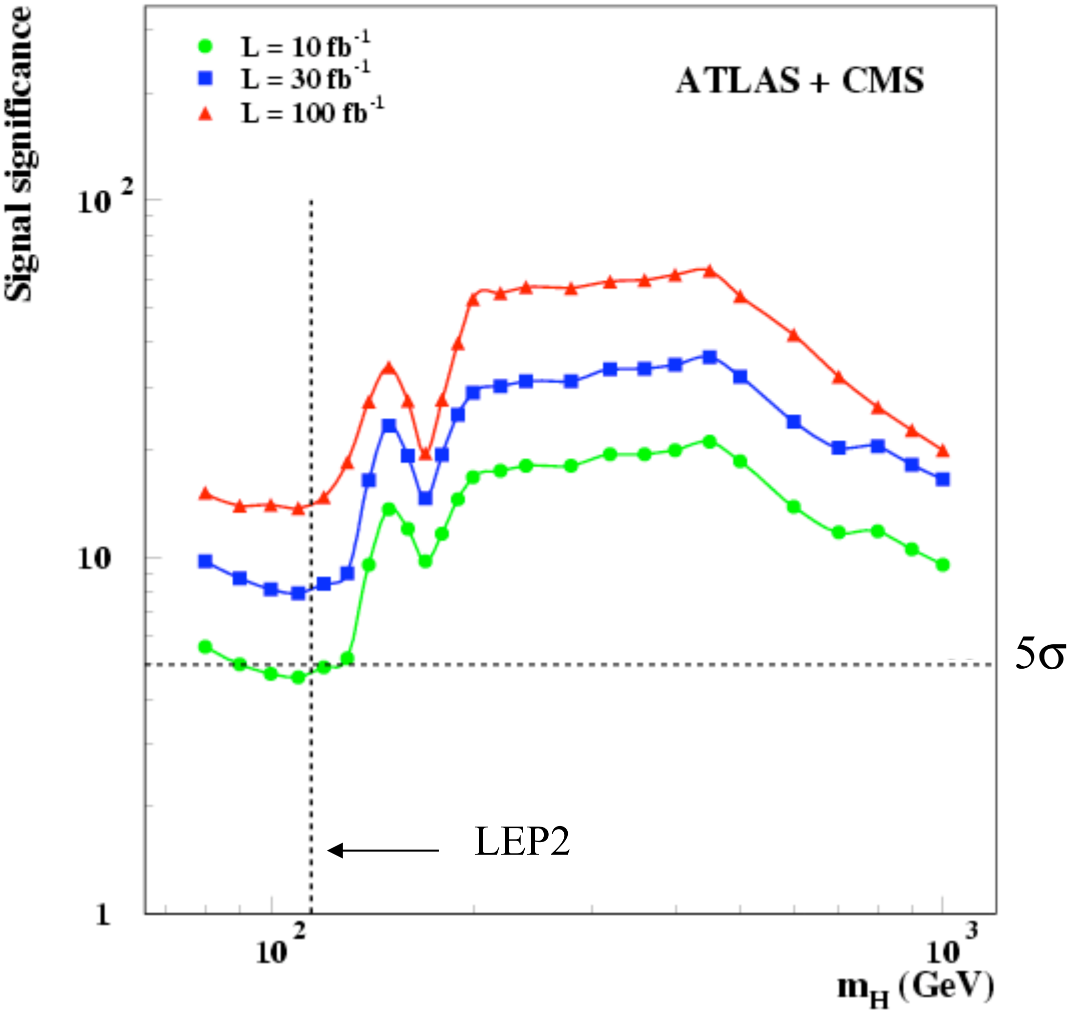

CMS
H→μμμμ
m_H = 150 GeV
+20 min bias

Summary of Standard Model Higgs

Expected significance for one experiment over mass range 80 GeV → 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



L is per experiment

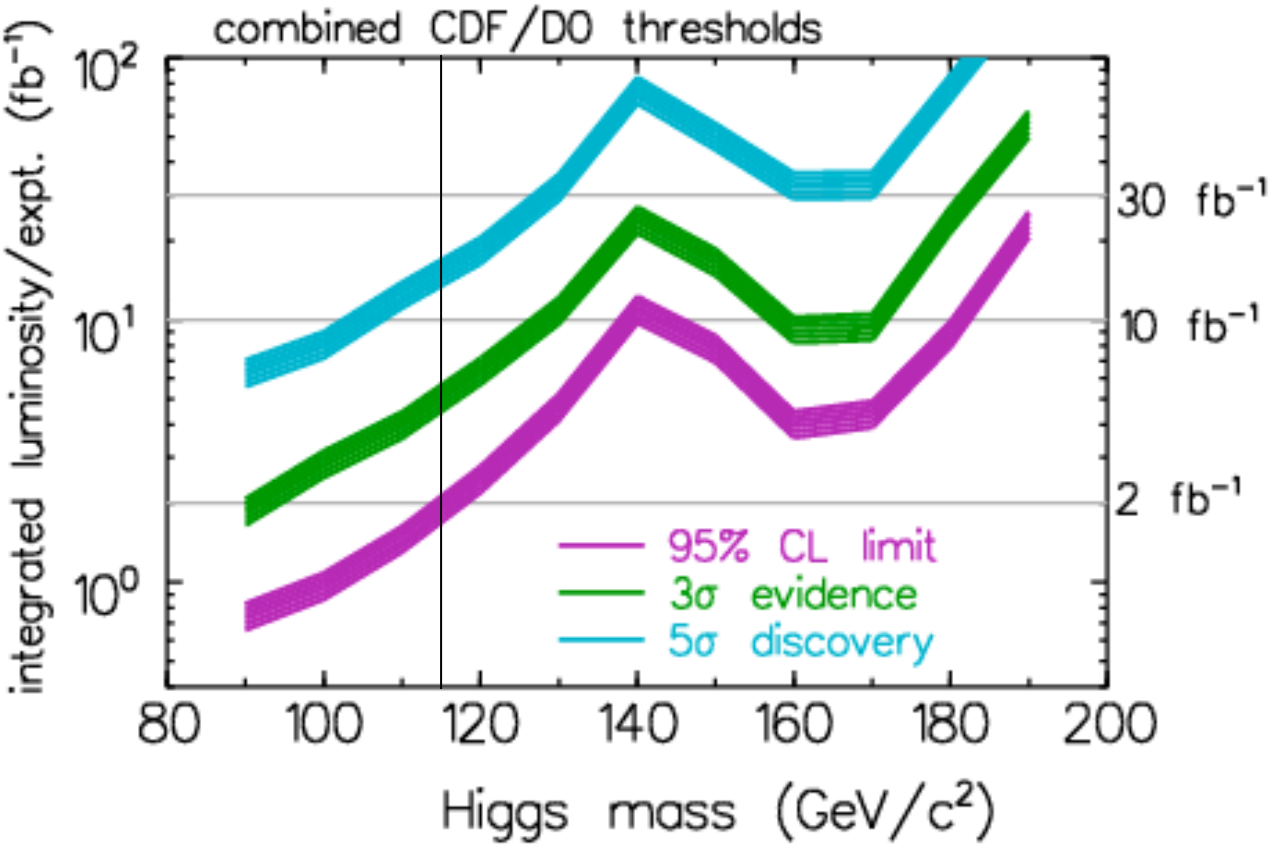
- -- SM Higgs boson can be discovered at ≈ 5 σ with 10 fb^{-1}/ experiment (nominally one year at 10^{33} cm^{-2} s^{-1}) for $m_H \leq 130$ GeV
- -- Discovery faster for larger masses
- -- Whole mass range can be excluded at 95% CL after ~1 month of running at 10^{33} cm^{-2} s^{-1}.

However, it will take time to operate, understand, calibrate ATLAS and CMS → Higgs physics will not be done before 2007 given present machine schedule

TEVATRON

Present Tevatron schedule :

-- Run 2A : March 2001-end 2003 : ~ 2 fb^{-1} /expt.
-- Run 2B : middle 2004 → ? : ~ 15 fb^{-1} /expt by 2007



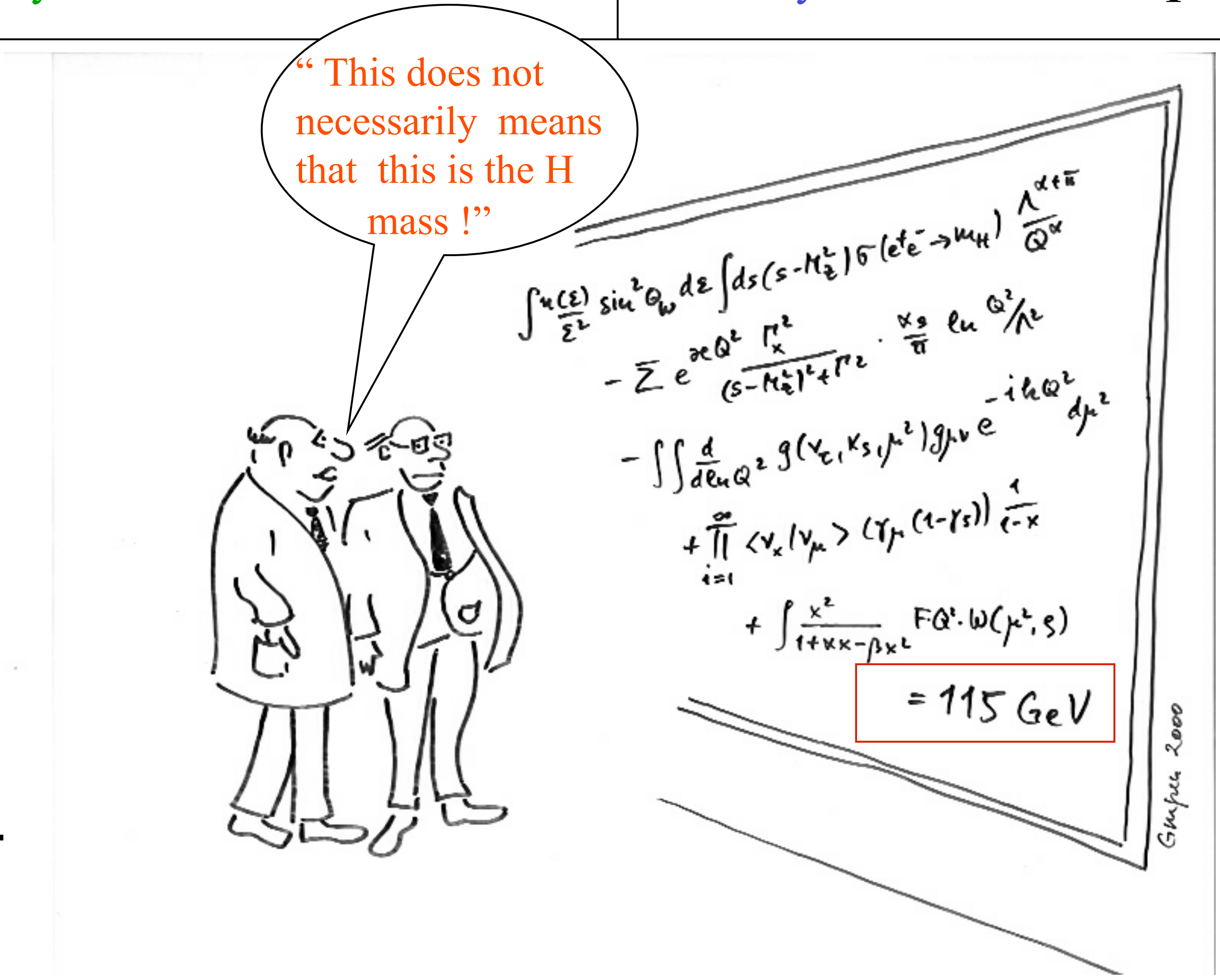
For m_H ~ 115 GeV Tevatron needs (optimistic analysis):

~ 2 fb^{-1} for 95% CL exclusion → end 2003 ?
~ 5 fb^{-1} for 3σ obervation → end 2004 ?
~ 15 fb^{-1} for 5σ discovery → end 2007 ?

2007

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

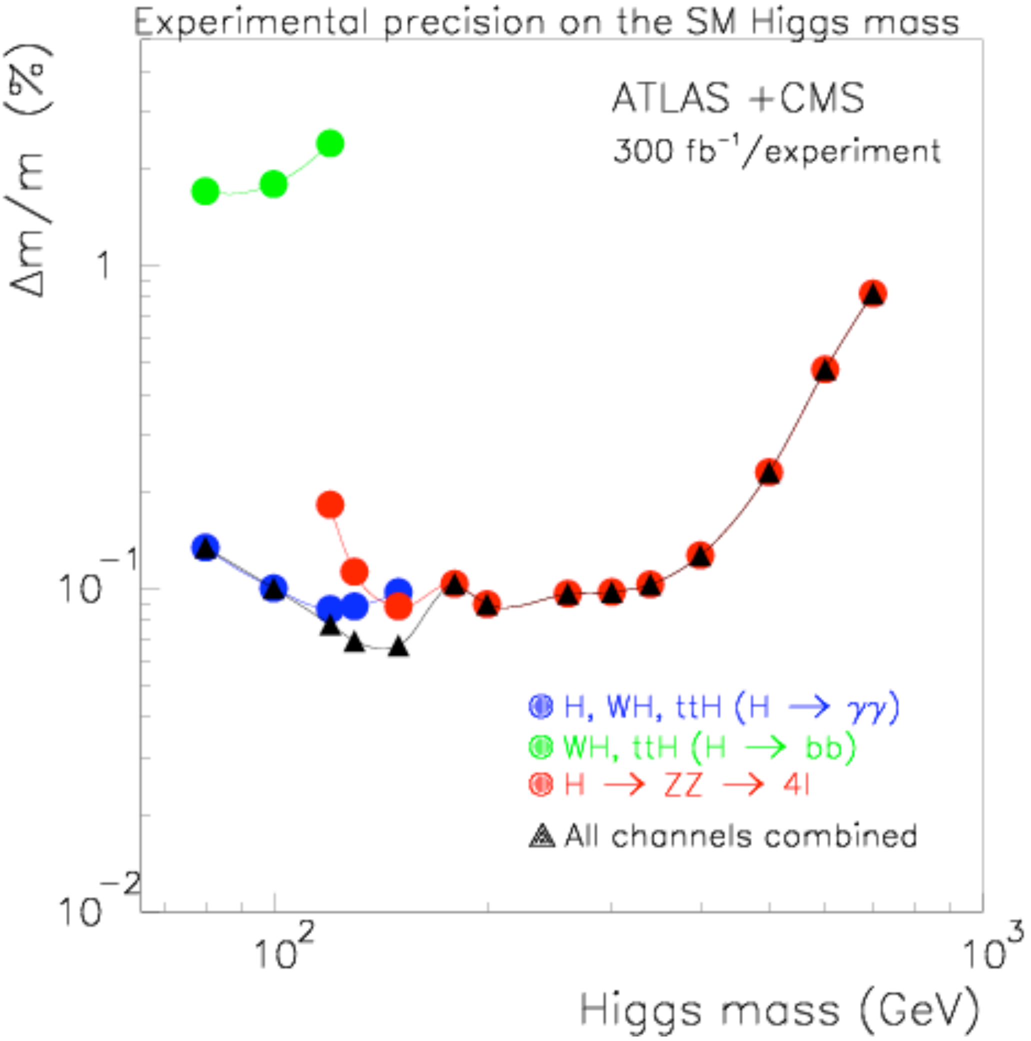
LHC versus	TEVATRON
Higgs cross-section ~10-100 higher	S/B ~ 5 higher
Conservative estimates (cross-sections, cut analyis, etc.) m_H=115 GeV 10 fb^{-1} $S/\sqrt{B} \approx 4.7$ 4.7 → 7 using Tevatron approach	Less conservative predictions (e.g. NN analysis) m_H=115 GeV 10 fb^{-1} $S/\sqrt{B} \approx 5.3$
Will take lot of time to understand detector and physics	Has lot of time to understand detector and physics
Ready in 2006 ?	15 fb^{-1} by 2007 ? Need 3 * $\bar{p}$



Let's assume the Higgs is found; what do we do now ?

Want to measure the Higgs properties, e.g.

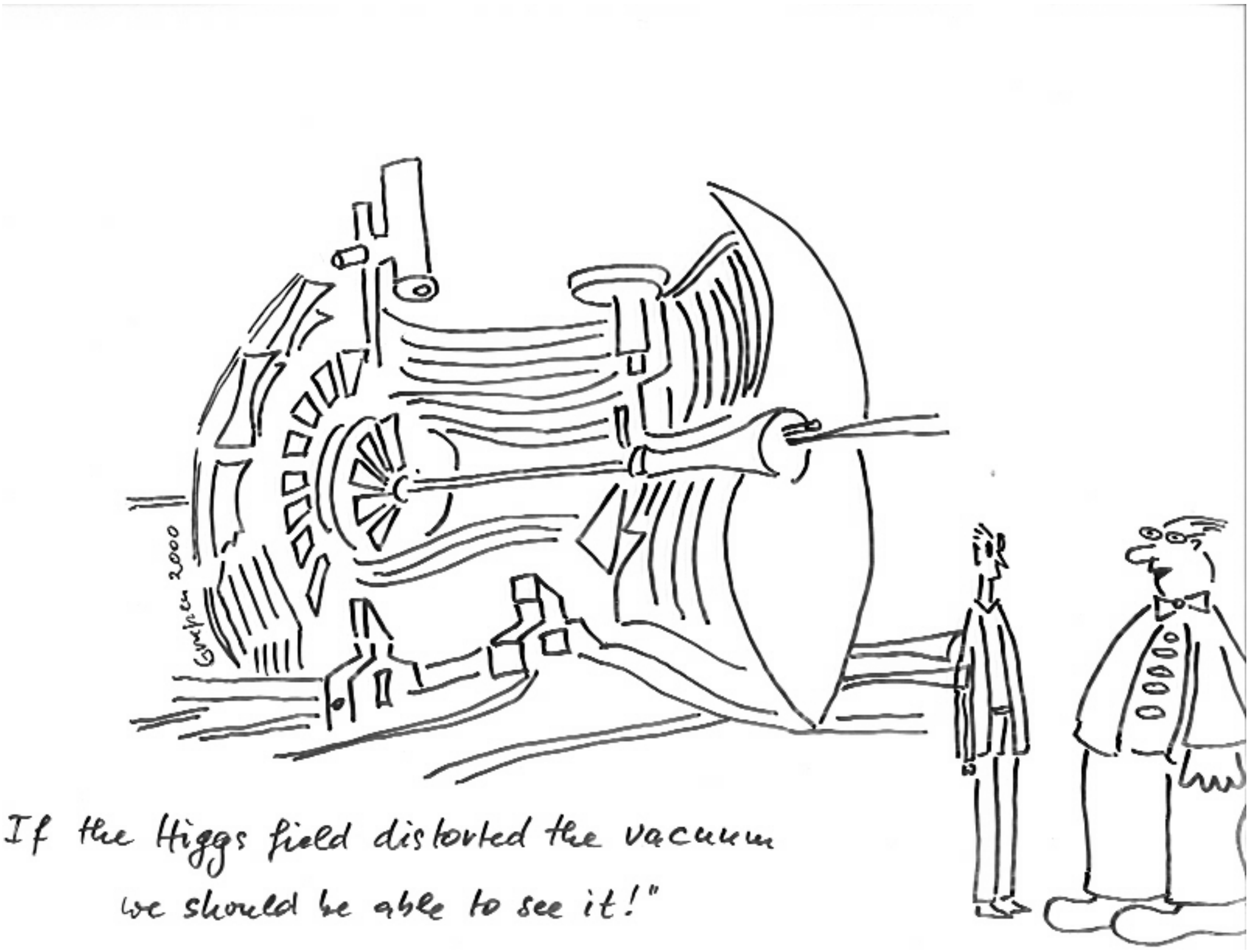
m_H



→ m_H can be measured to 0.1% using precise calorimeter and muon systems of ATLAS and CMS

Summary of Part 2

- At LHC Standard Model Higgs boson can be discovered over the full mass region up to 1 TeV (upper limit from theory).
- Excellent detector performance required:
  → Higgs searches have driven the LHC detector design.
- Main channels : $H \rightarrow \gamma\gamma$, $H \rightarrow 4\ell$
- If SM Higgs not found at LHC, then alternative methods for electroweak symmetry breaking will have to be found



If the Higgs field distorted the vacuum we should be able to see it!"