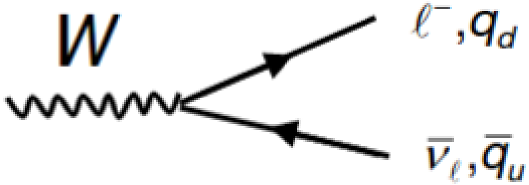
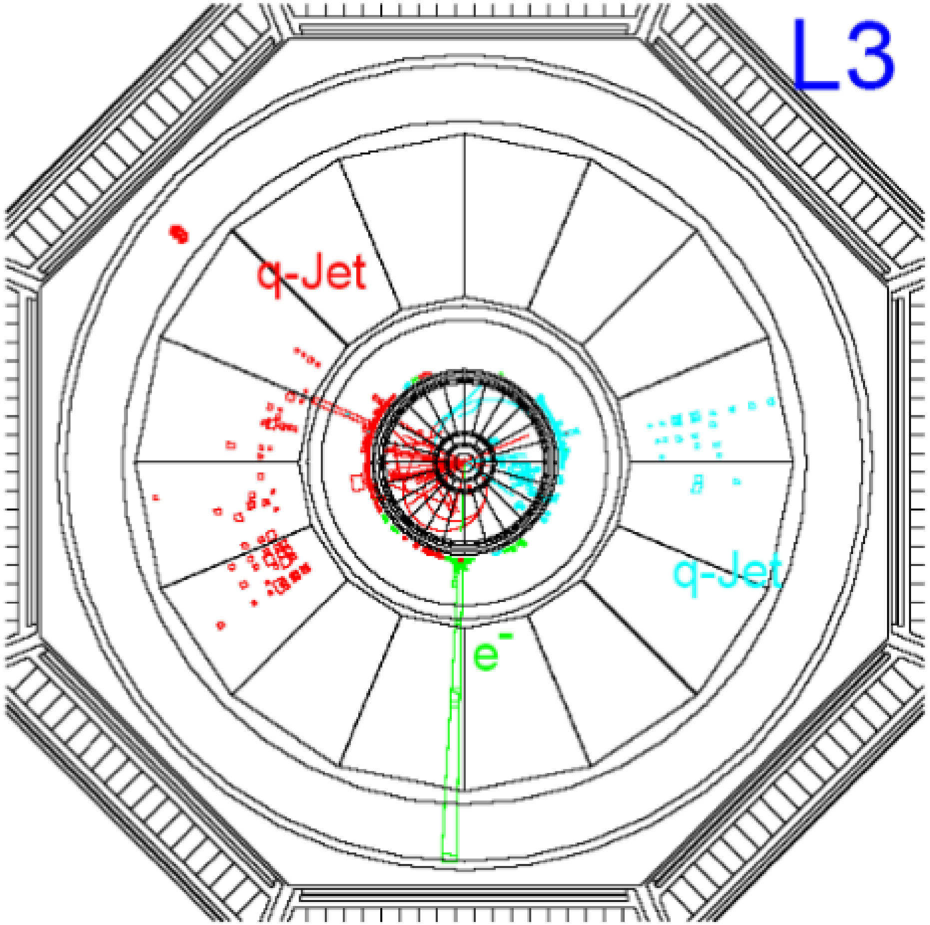
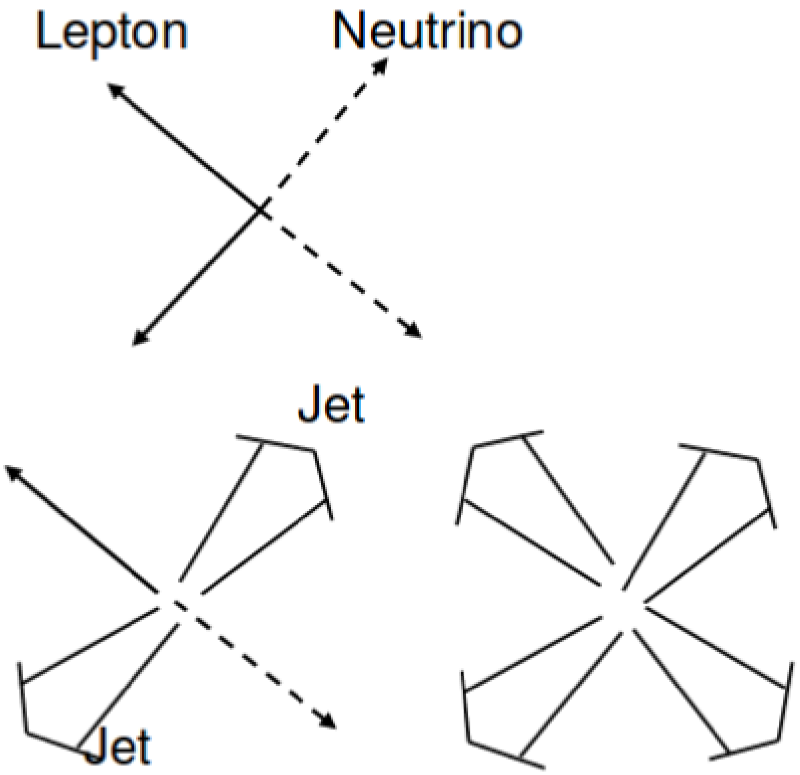
W decays





Run # 945004 Event # 4035 DAQ Time : 02.11.2000 4:25.34 h

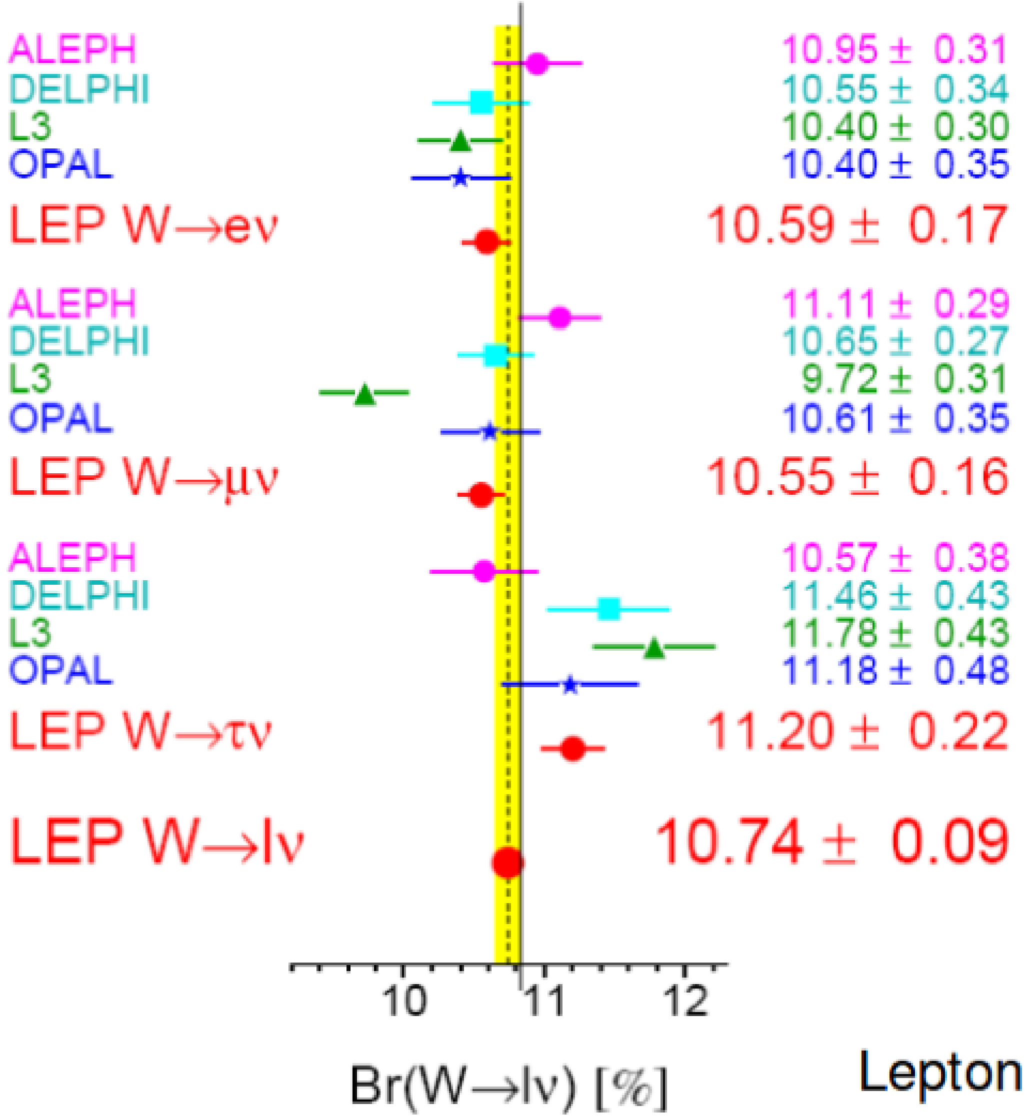
$$WW \rightarrow \begin{cases} qq\ell\nu & 44\% \\ qqqq & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$



Easiest signature for a mass measurement:

$W_1 \rightarrow l\nu$ $W_2 \rightarrow$ JetJet: use JetJet invariant mass

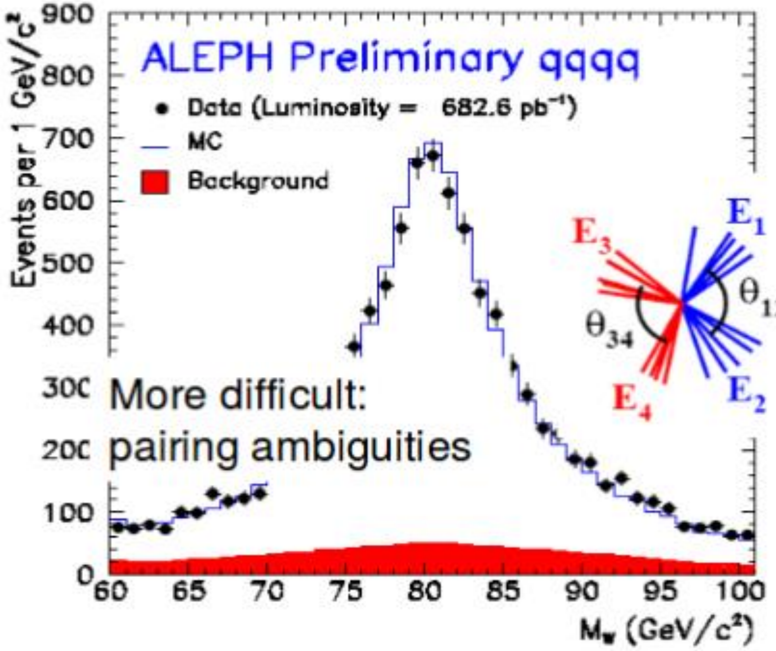
W leptonic branching fractions



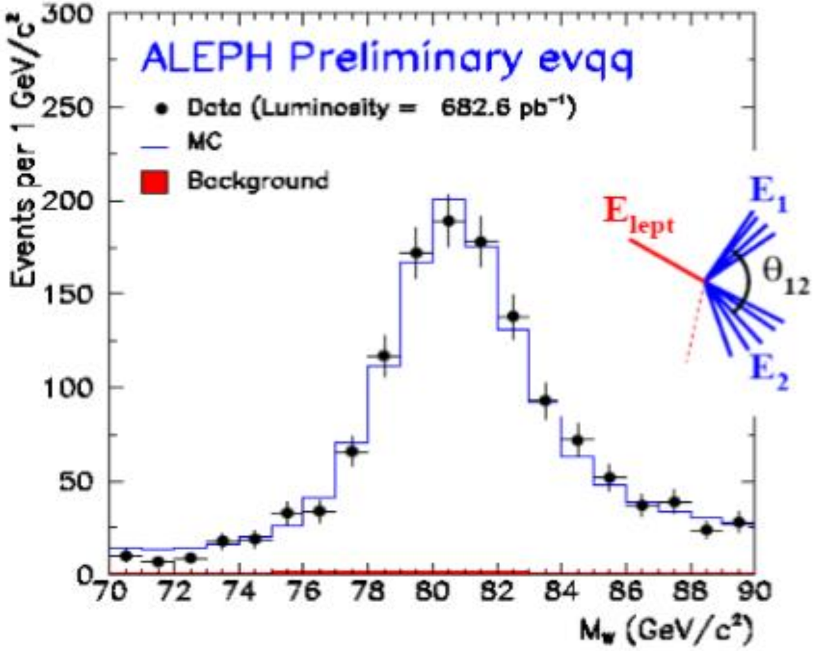
$$Br(W \rightarrow q\bar{q}) = (67.77 \pm 0.28)\%$$

Lepton universality tested to 2%

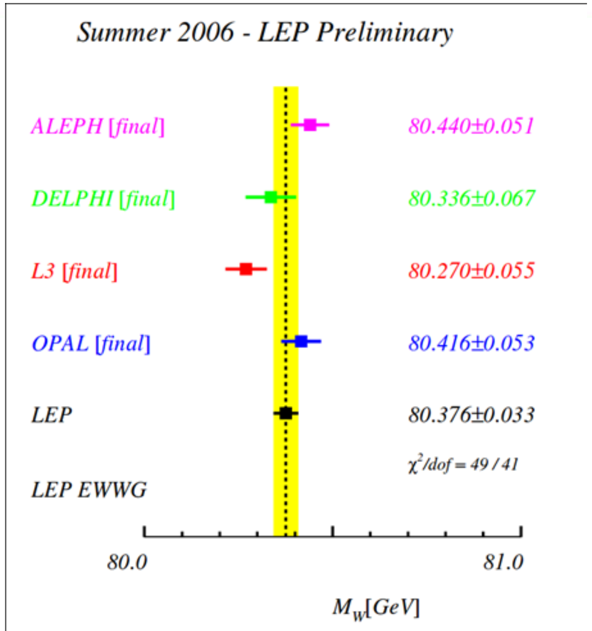
Invariant W mass recontruction



More difficult:
pairing ambiguities



Final LEP result:



Higher order corrections and the Higgs mass

$$\sin^2\theta_w = 1 - \frac{M_W^2}{M_Z^2} \qquad \sin\theta_w = \frac{e}{g}$$

Lowest order SM predictions:

$$\rho = \frac{m_W^2}{m_Z^2\cos^2\theta_W} = 1 \quad \Longrightarrow \quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{eff} = (1 + \Delta\kappa)\sin^2\theta_W$$

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

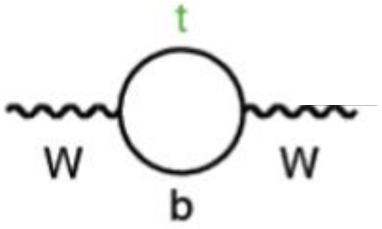
$$\alpha(0) \quad \Longrightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

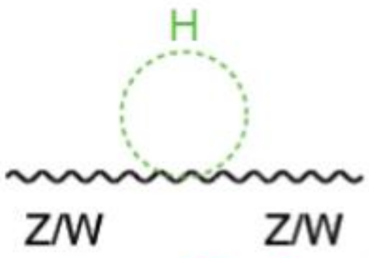
Including radiative corrections

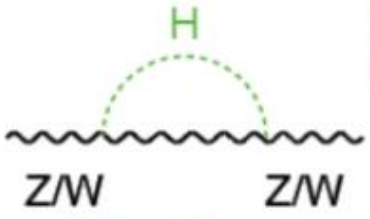
with : $\Delta\alpha = \Delta\alpha_{lept} + \Delta\alpha_{top} + \Delta\alpha_{had}^{(5)}$

$$\Delta\rho, \Delta\kappa, \Delta r = f\,(m_t^2, \log(m_H), \dots)$$

$\sin^2\theta_w$, g_A, g_V ⇒ $\sin^2\theta_{eff}$, $\bar{g}_A, \bar{g}_V$







$$\bar{g}_A = \sqrt{\bar{\rho}}\,T^3 \qquad \bar{g}_V = \sqrt{\bar{\rho}}\,(T^3 - 2Q\sin^2\theta_{eff})$$

Top mass prediction from radiative corrections

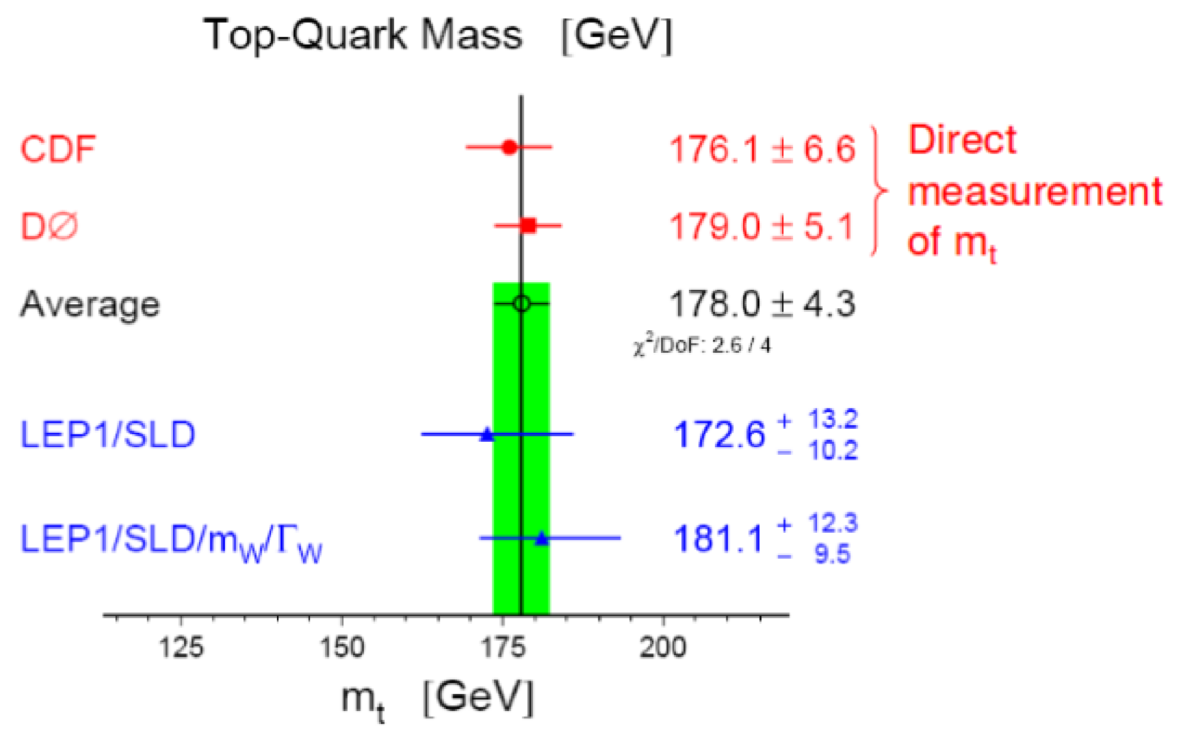
e.g.: $$\Delta r(m_t, M_H) = -\frac{3\alpha \cos^2\theta_w}{16\pi \sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi \sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \ldots$$

The measurement of the radiative corrections:

$$\sin^2\theta_{eff} \equiv \frac{1}{4}(1 - \bar{g}_V / \bar{g}_A)$$

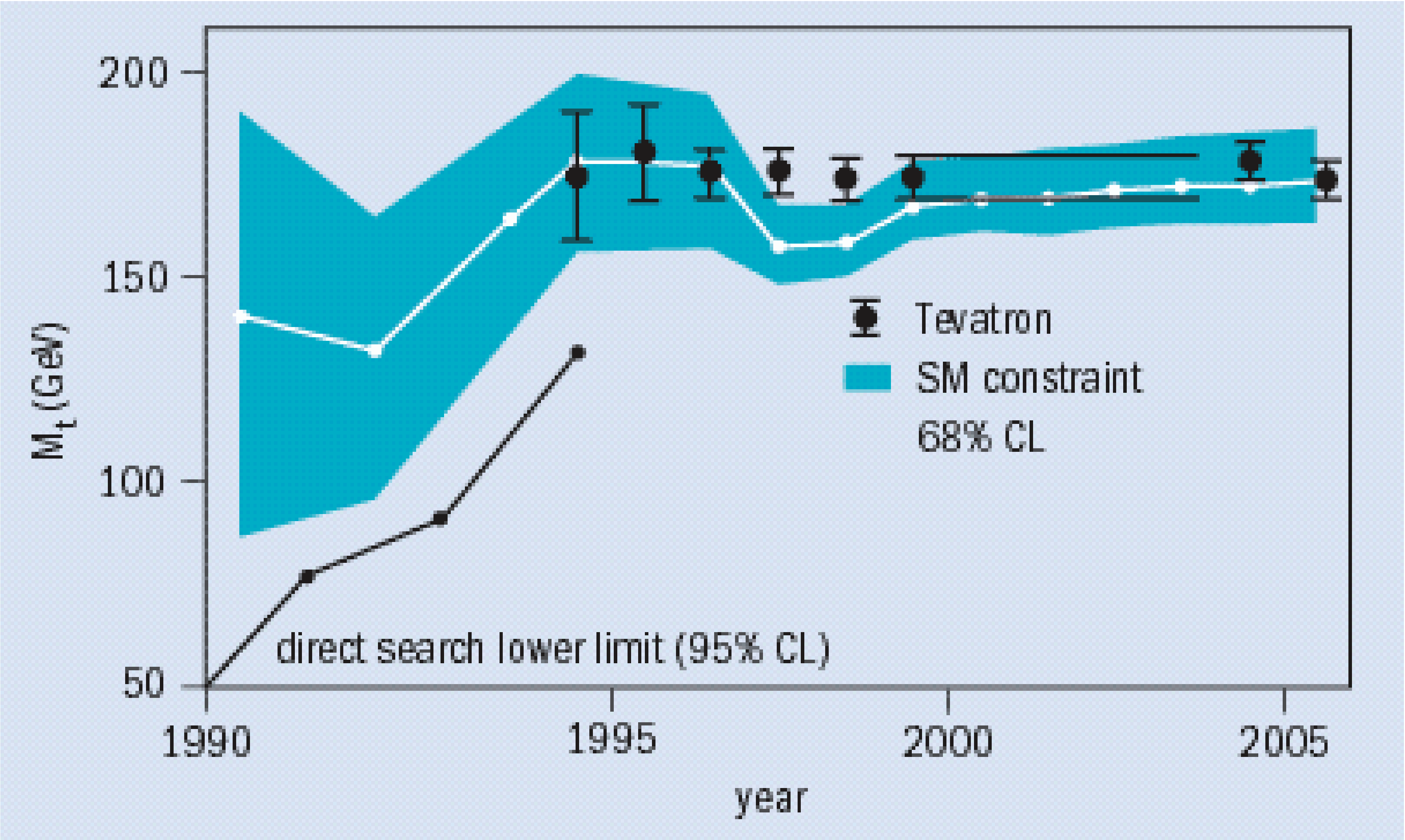
$$\sin^2\theta_{eff} = (1+\Delta\kappa)\sin^2\theta_w$$

Allows the indirect determination of the unknown parameters m_t and M_H.



Good agreement between the indirect prediction of m_t and the value obtained in direct measurements confirm the radiative corrections of the SM

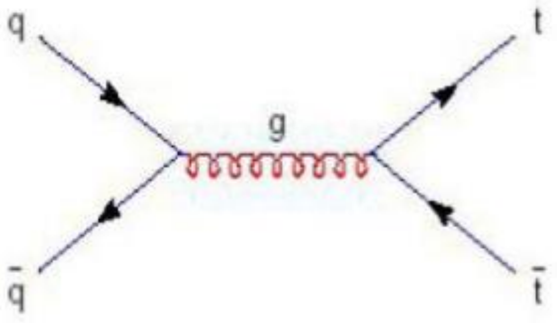
Prediction of m_t by LEP before the discovery of the top at TEVATRON.



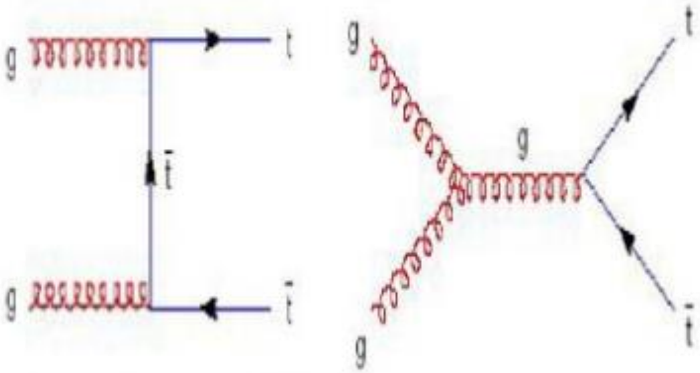
200
150
100
50
M_t (GeV)
1990
1995
2000
2005
year
Tevatron
SM constraint
68% CL
direct search lower limit (95% CL)

Observation of the top quark at TEVATRON (1995)

$p\bar{p}$ @ 2 TeV

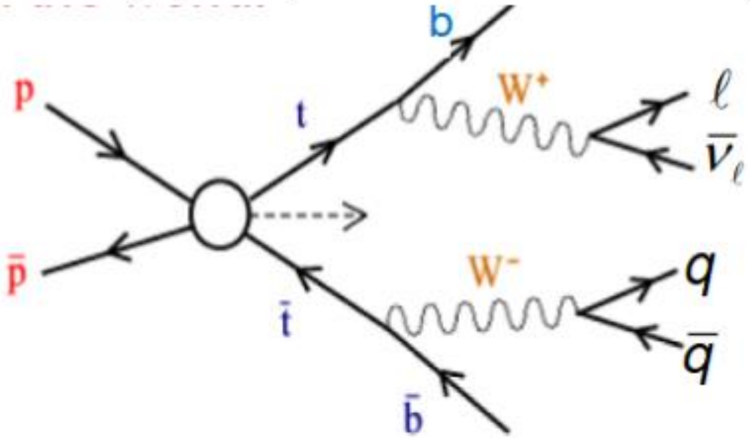


$q\bar{q}$ annihilation (85%)



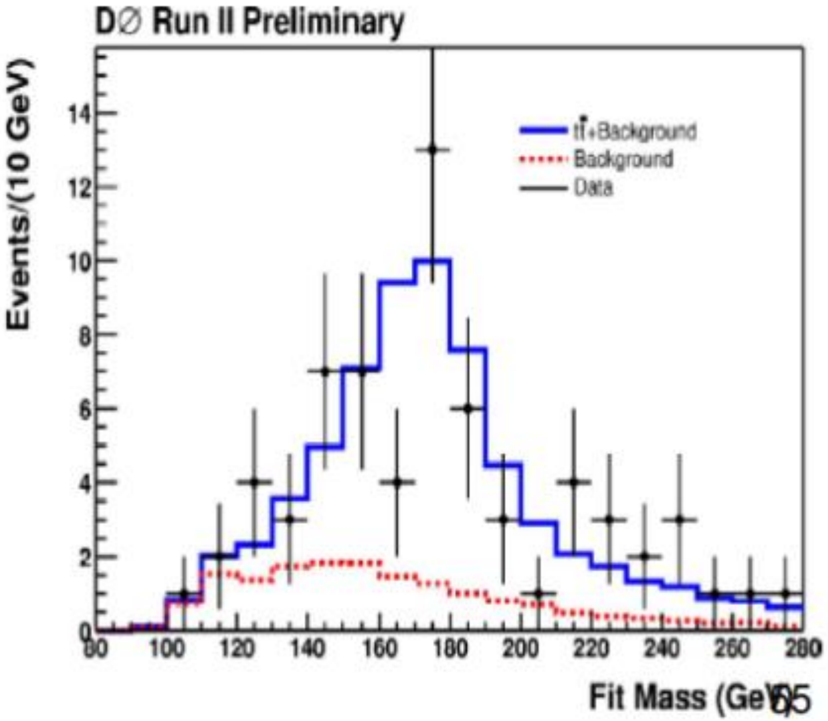
gluon fusion (15%)

Top decay (decays before hadronization)



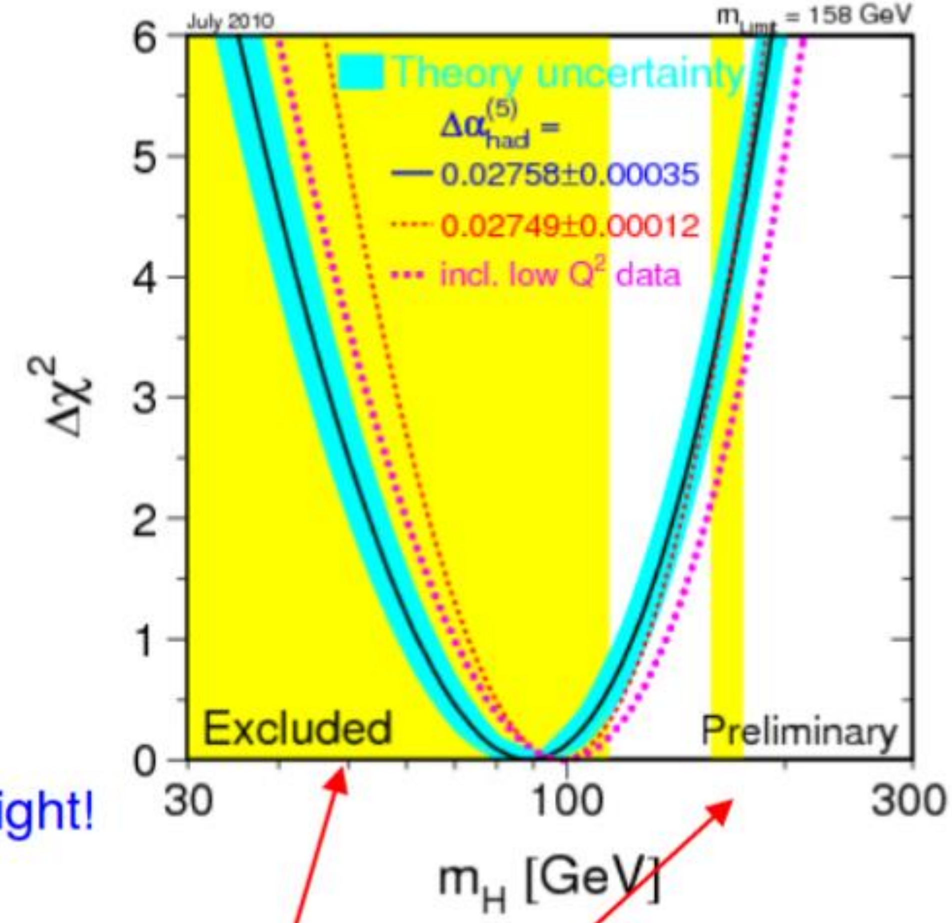
Channel used for mass reconstruction:

$$m_t = m_{inv}(b - jet, W \rightarrow jet + jet)$$



Status before the start of the LHC:

http://lepewwg.web.cern.ch/LEPEWWG/



Fits to electro-weak data:

$m_H = 89^{+35}_{-26}$ GeV

$m_H < 158$ GeV (95% CL)

Assumption for fit:

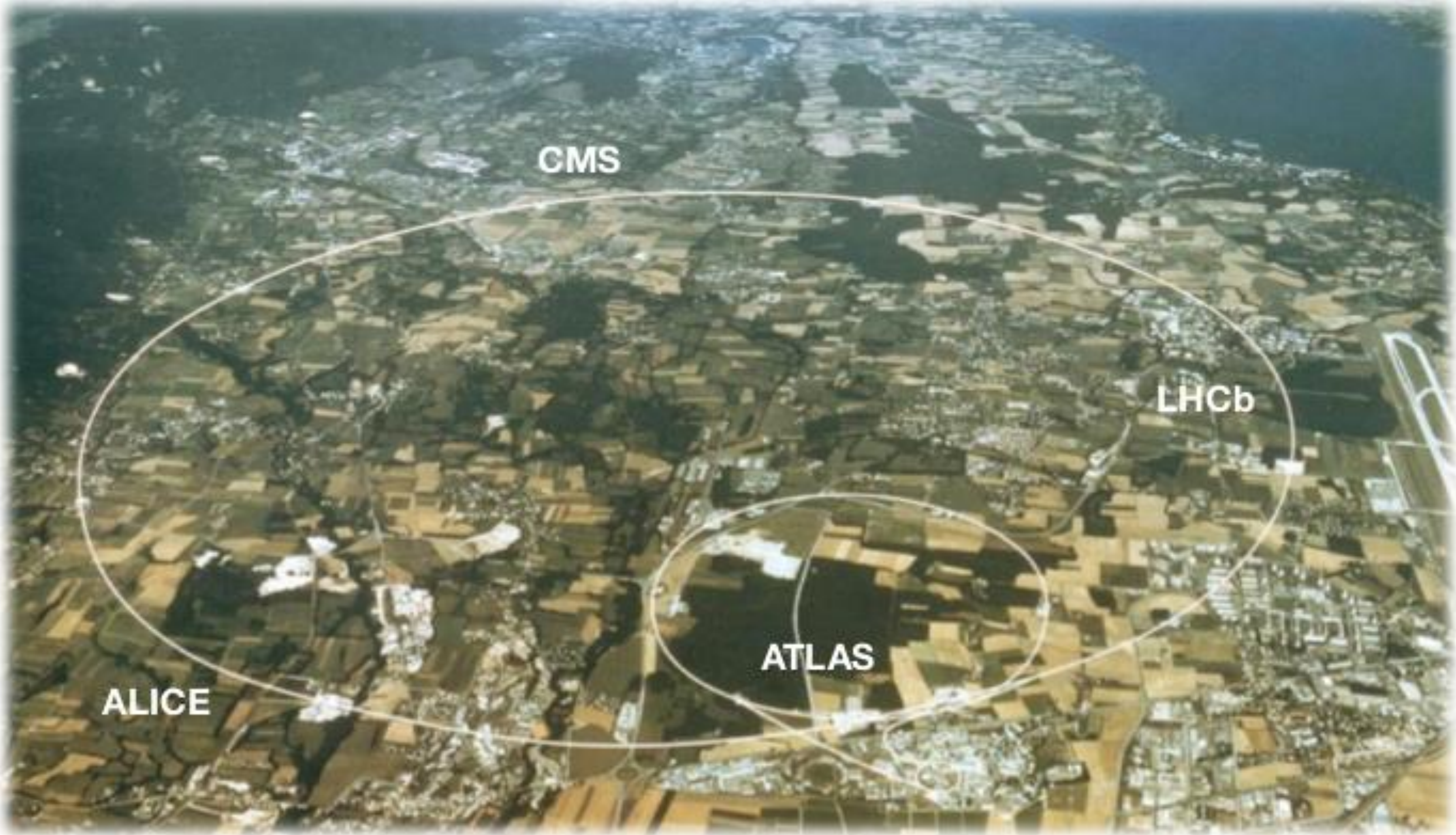
- SM including Higgs

If existing, Higgs seems to be light!

- Direct searches at LEP:
  $m_H > 114.4$ GeV @ 95 % CL
- Direct searches at Tevatron

Unfortunately this mass region is the most difficult to explore!

The LHC
A New Dimension in Particle Physics



LHC Cross Sections

10^9 Events/sec

[1 Mbyte/Event]

10^{10}

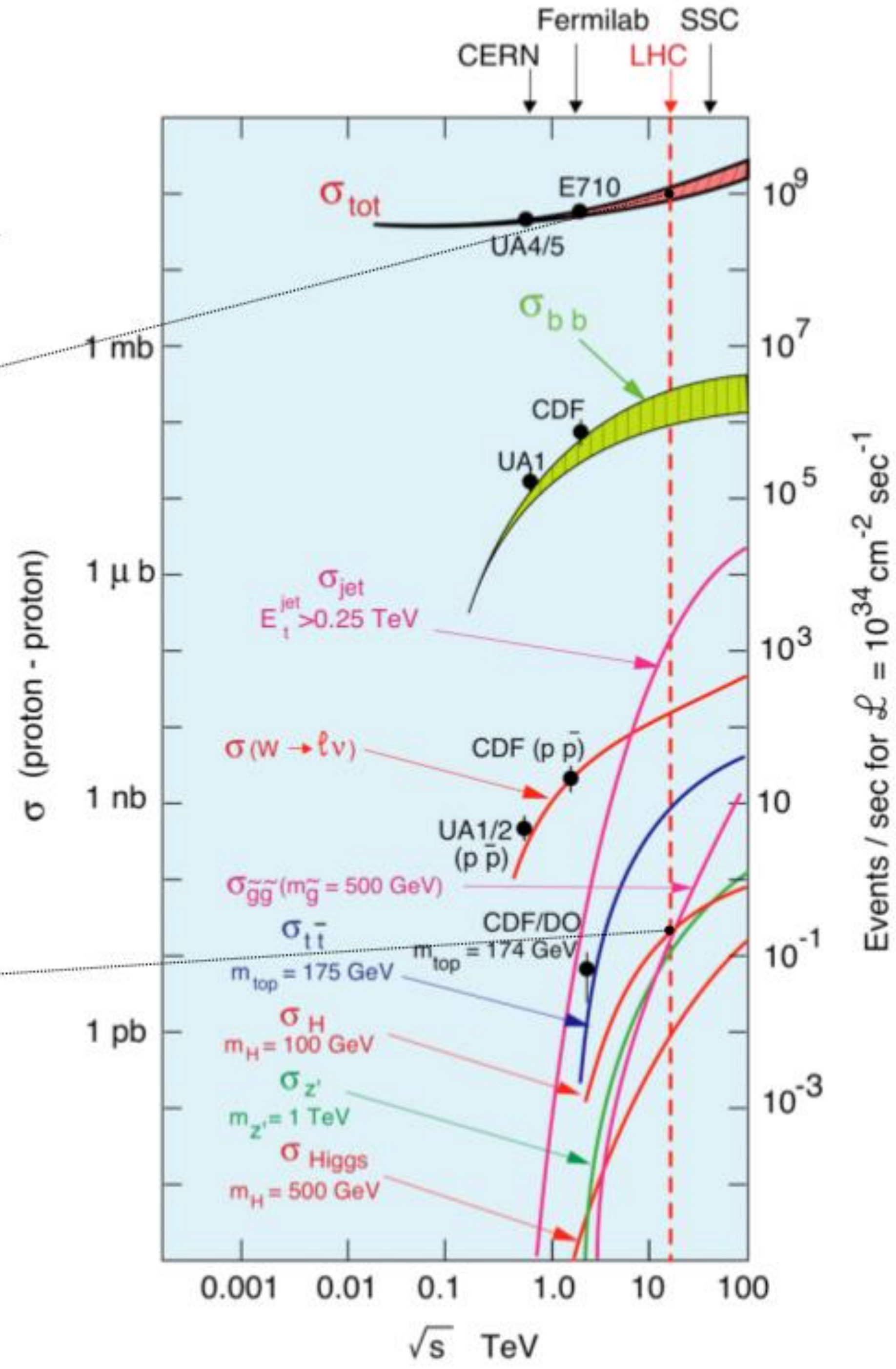
Efficient
rate reduction needed

[Storage rate: 100 Hz]

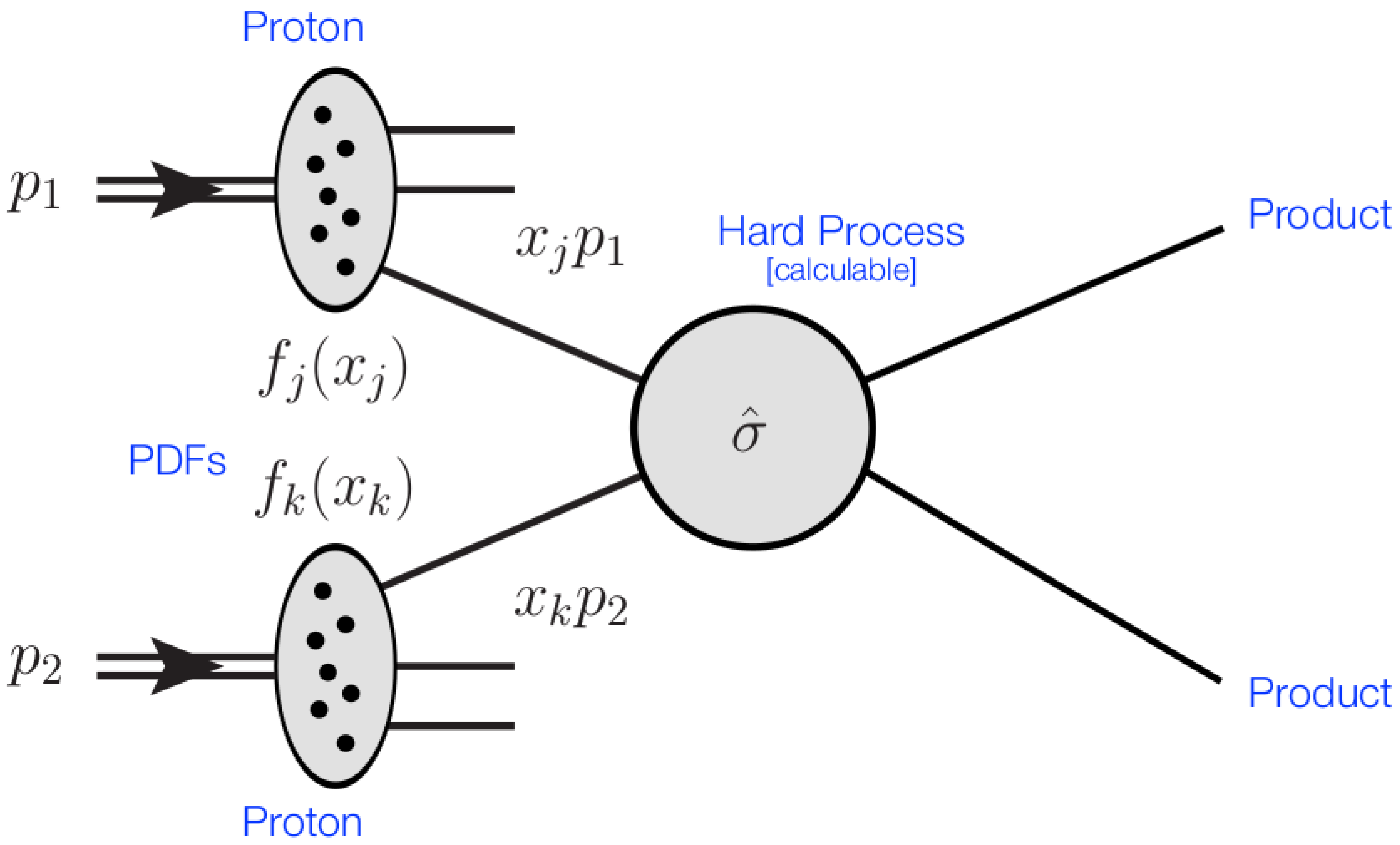
10 Events/min

[$m_H \approx$ 100 GeV]

with 0.2% $H \rightarrow \gamma\gamma$
1.5% $H \rightarrow ZZ$

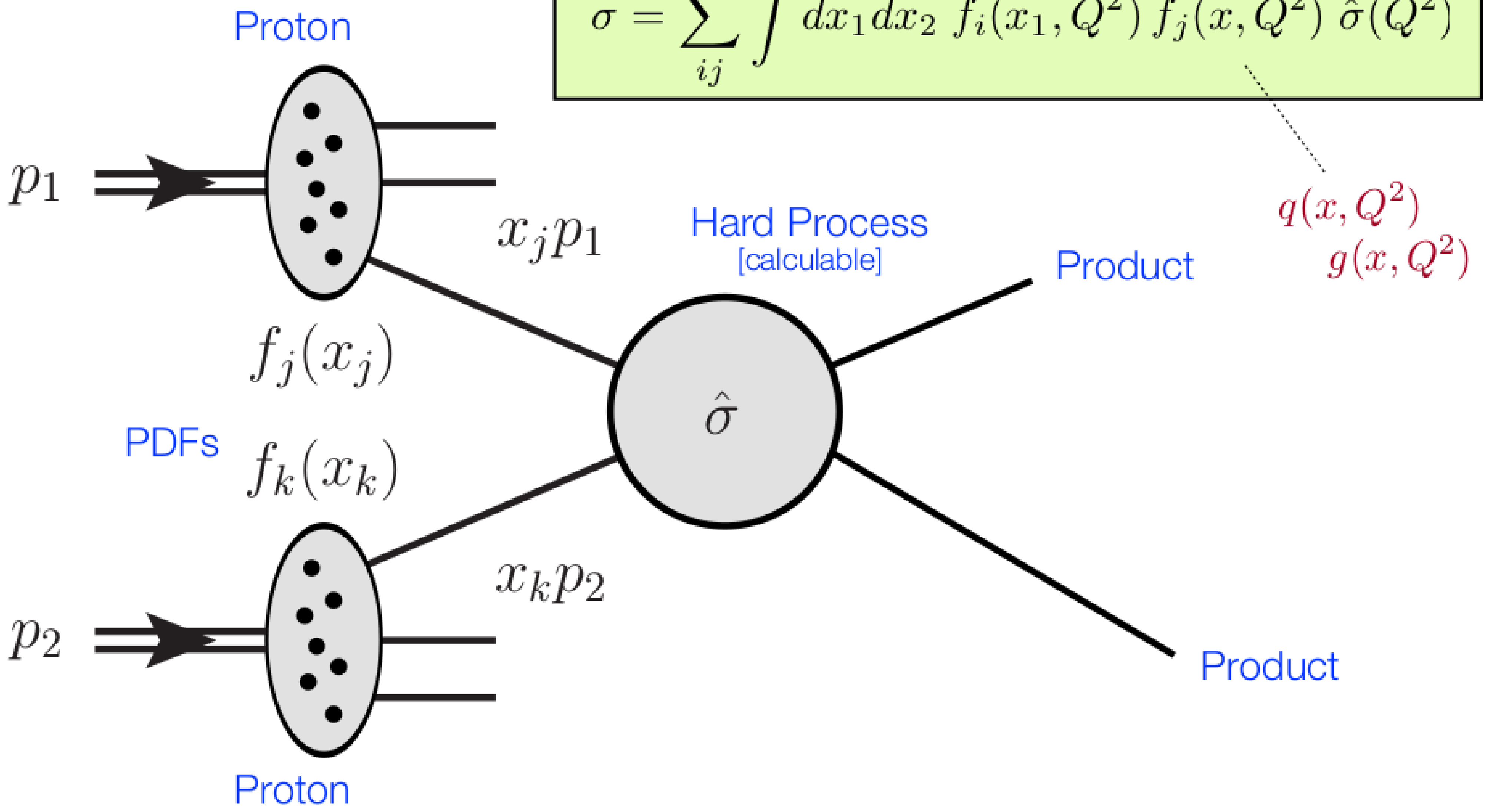


Proton-Proton Scattering @ LHC



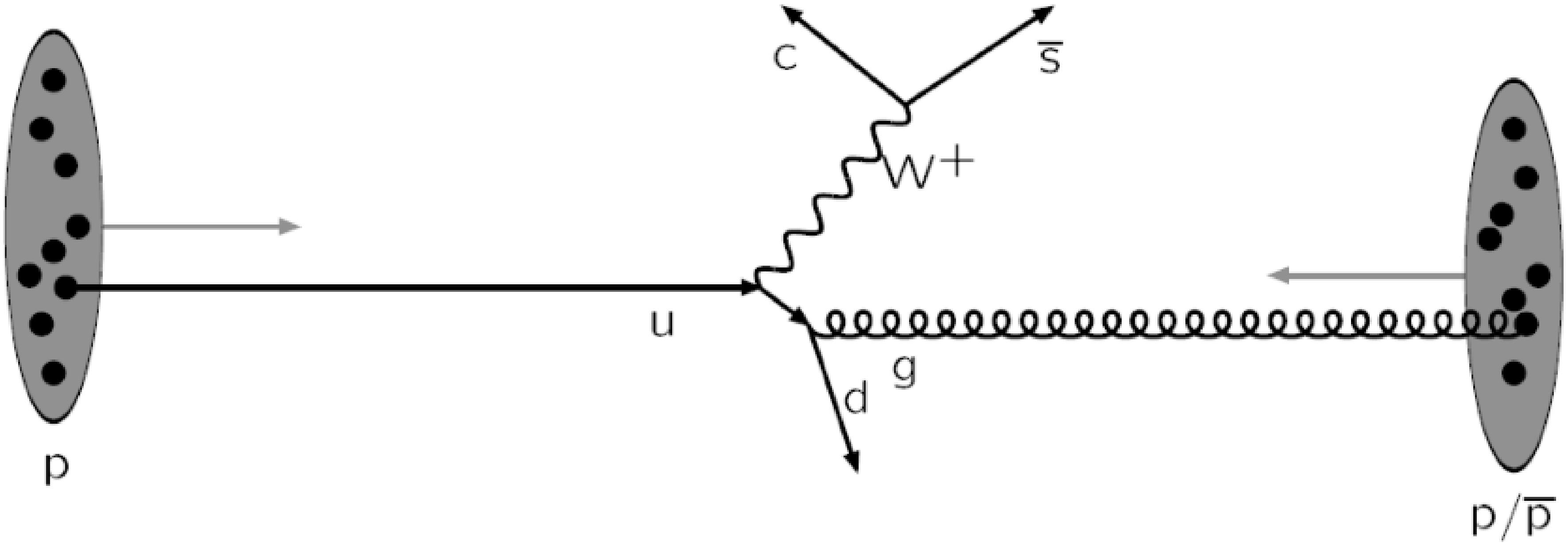
Proton-Proton Scattering @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \, f_i(x_1, Q^2) \, f_j(x, Q^2) \, \hat{\sigma}(Q^2)$$



Proton-Proton Scattering @ LHC

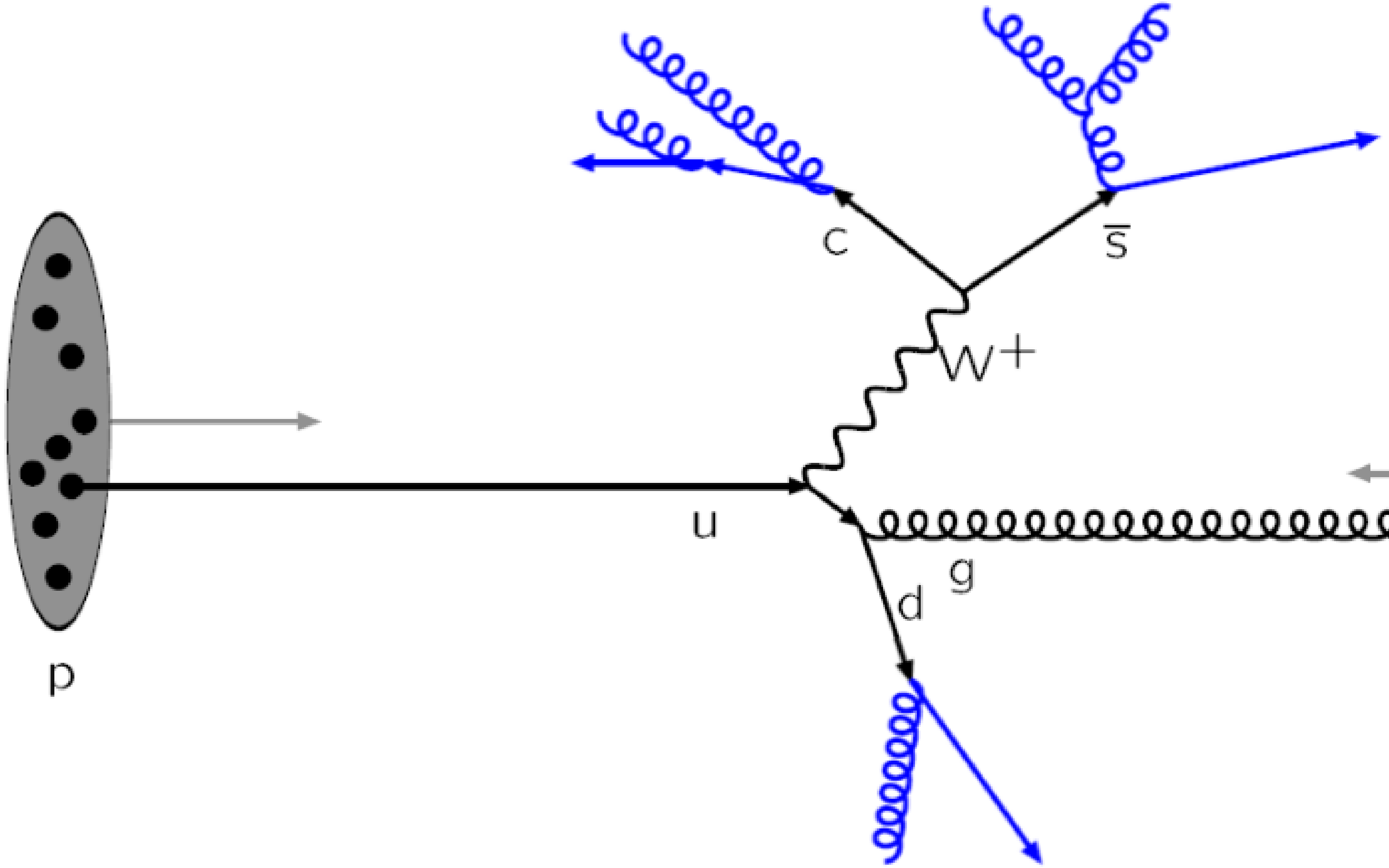
- Hard interaction: qq, gg, qg fusion



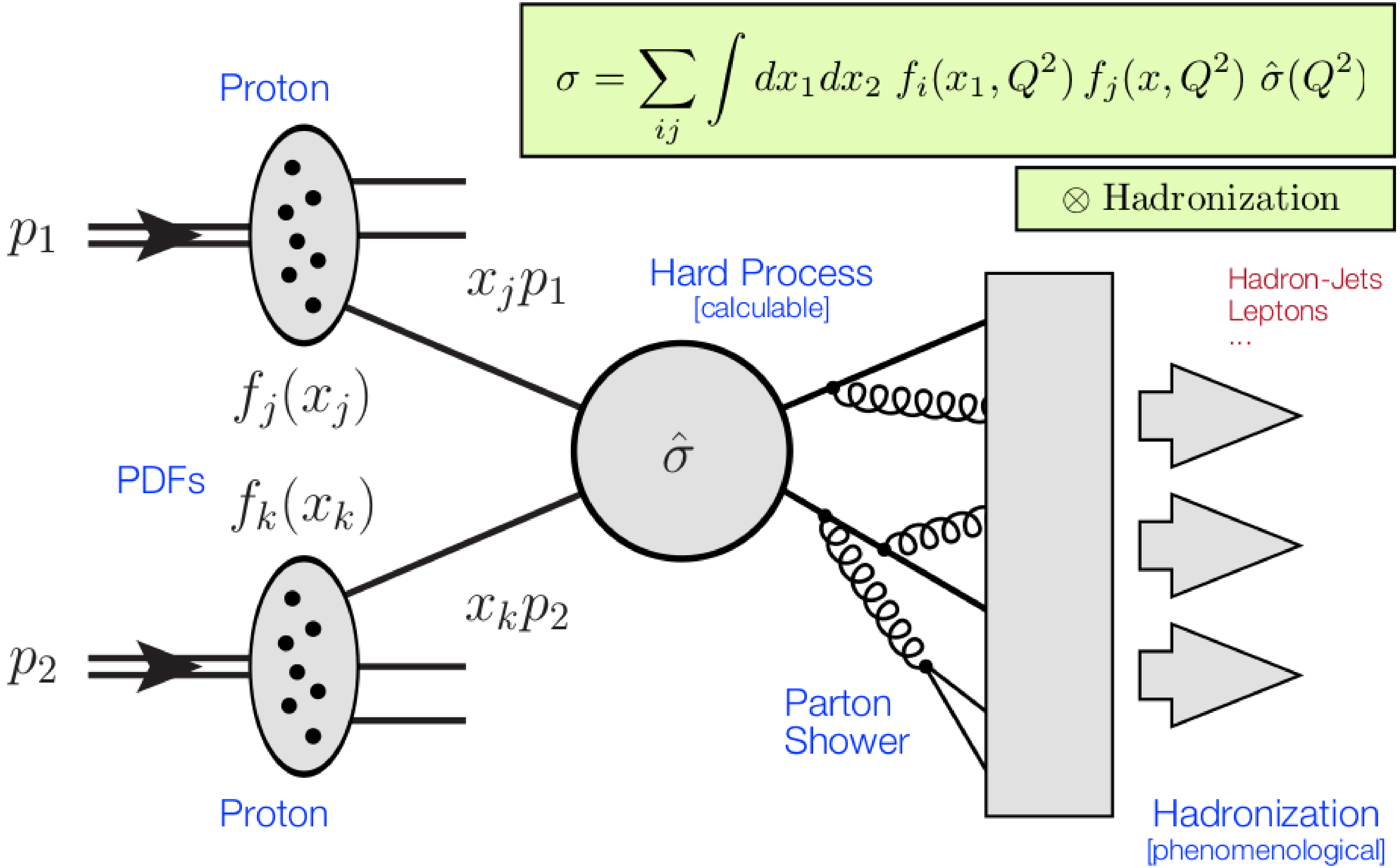
Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion

parton shower

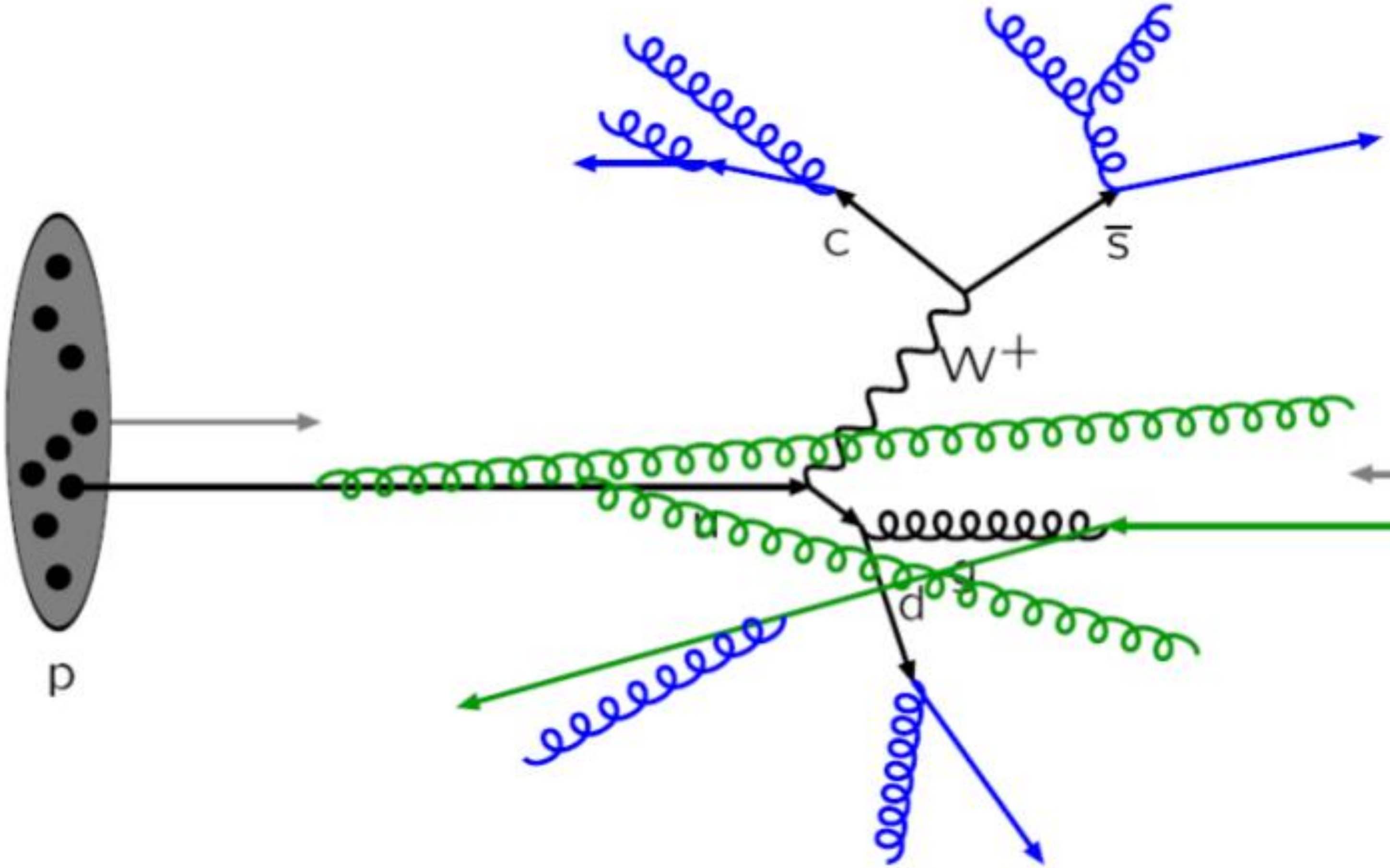


Proton-Proton Scattering @ LHC



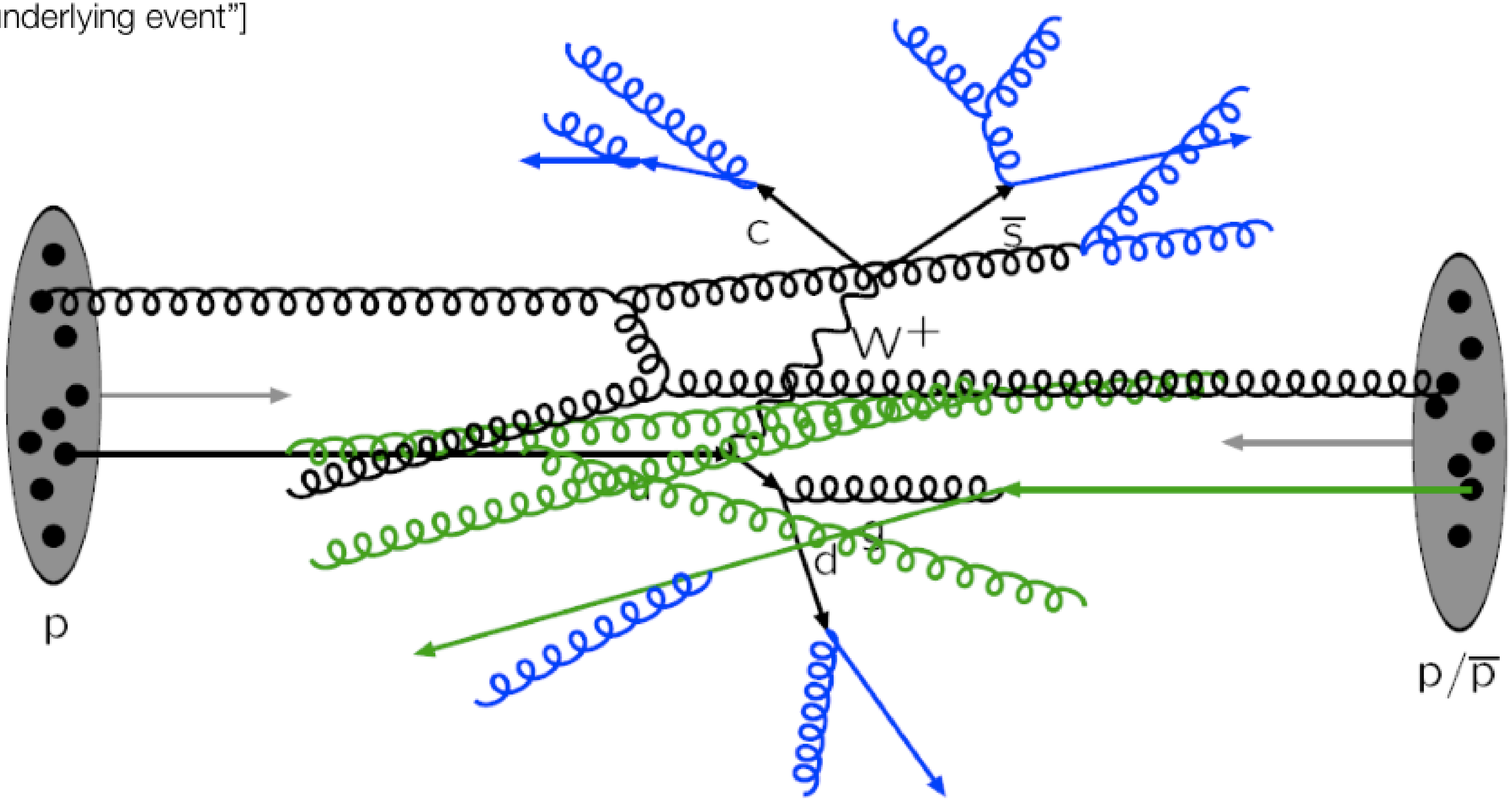
Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion
- Initial State Radiation (ISR)



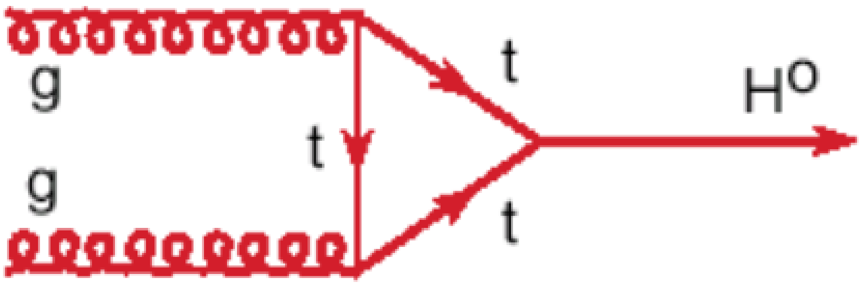
Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion
- Initial State Radiation (ISR)
- Secondary Interaction
  [“underlying event”]

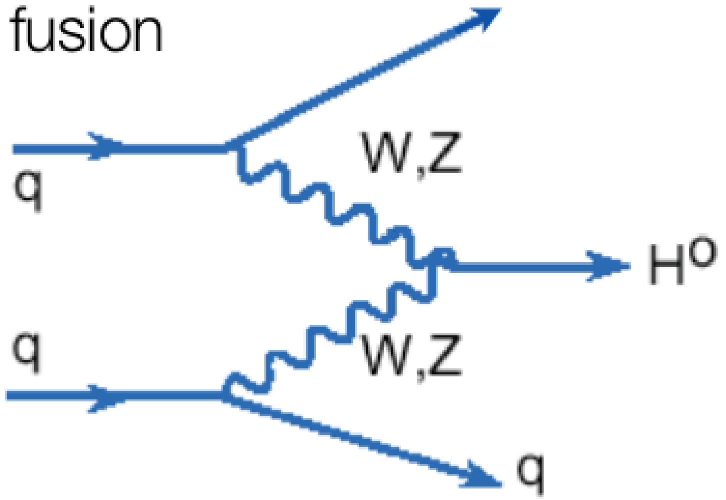


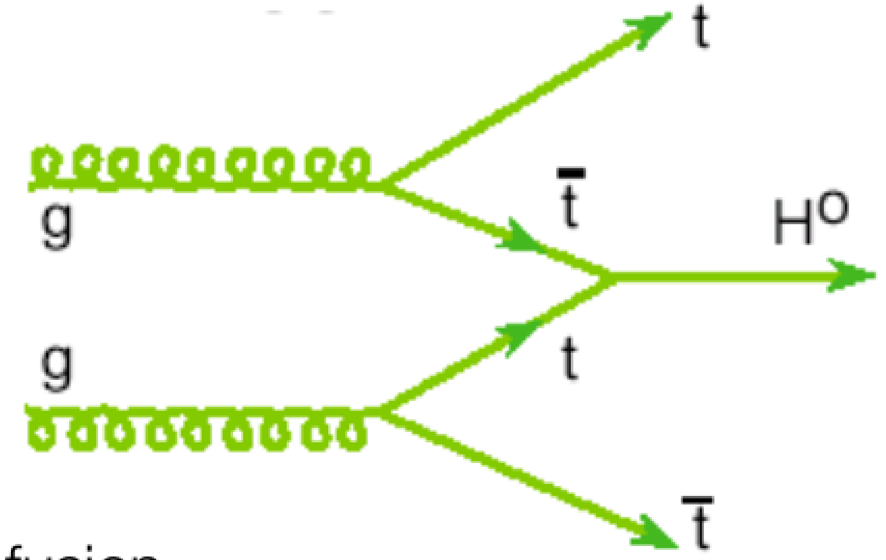
Higgs Production Mechanisms

Gluon fusion

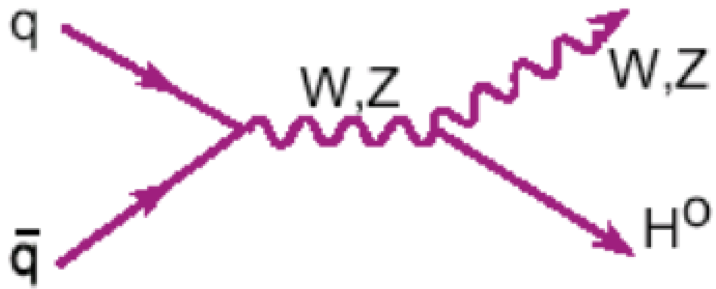


Vector boson fusion



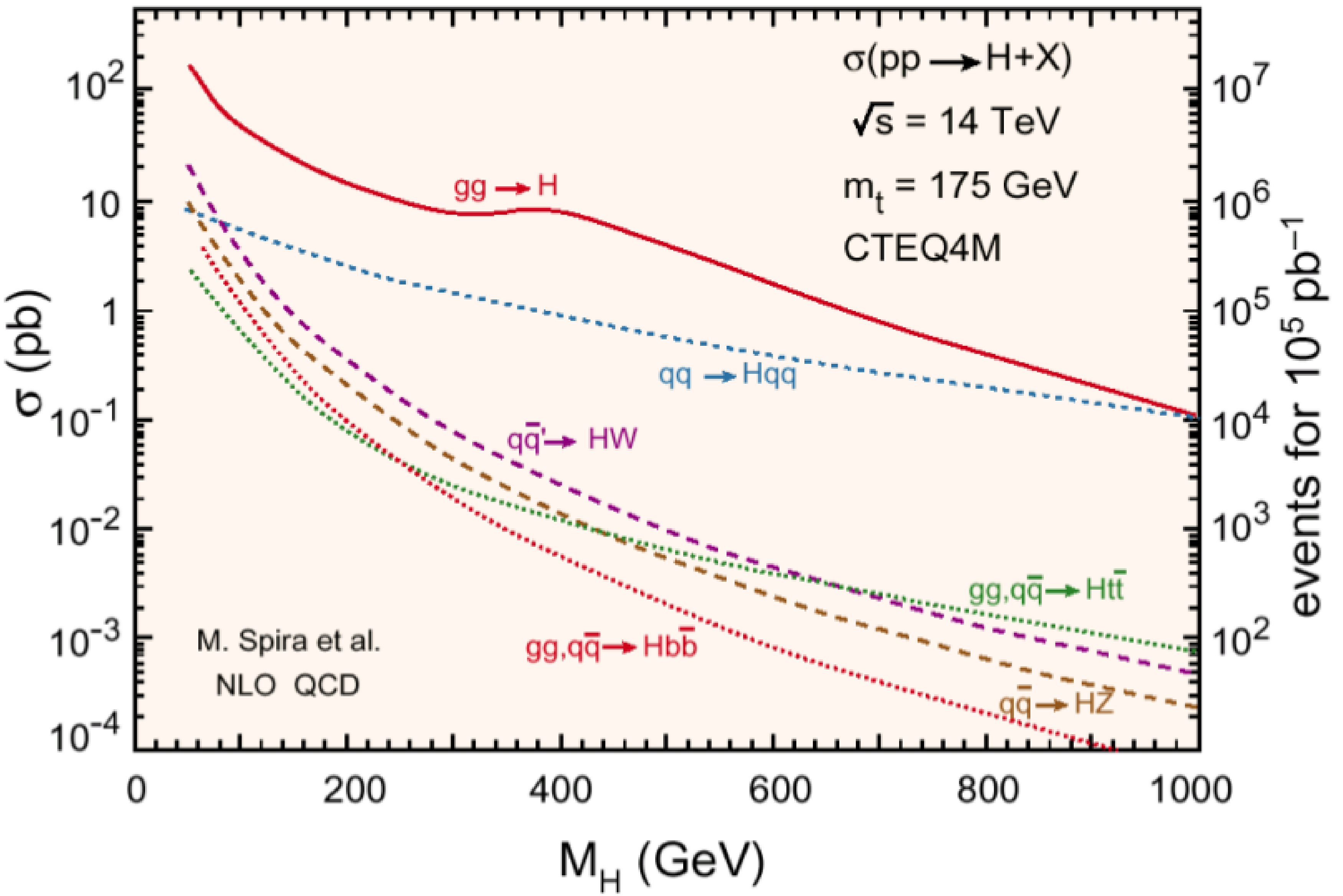


tt̄-fusion

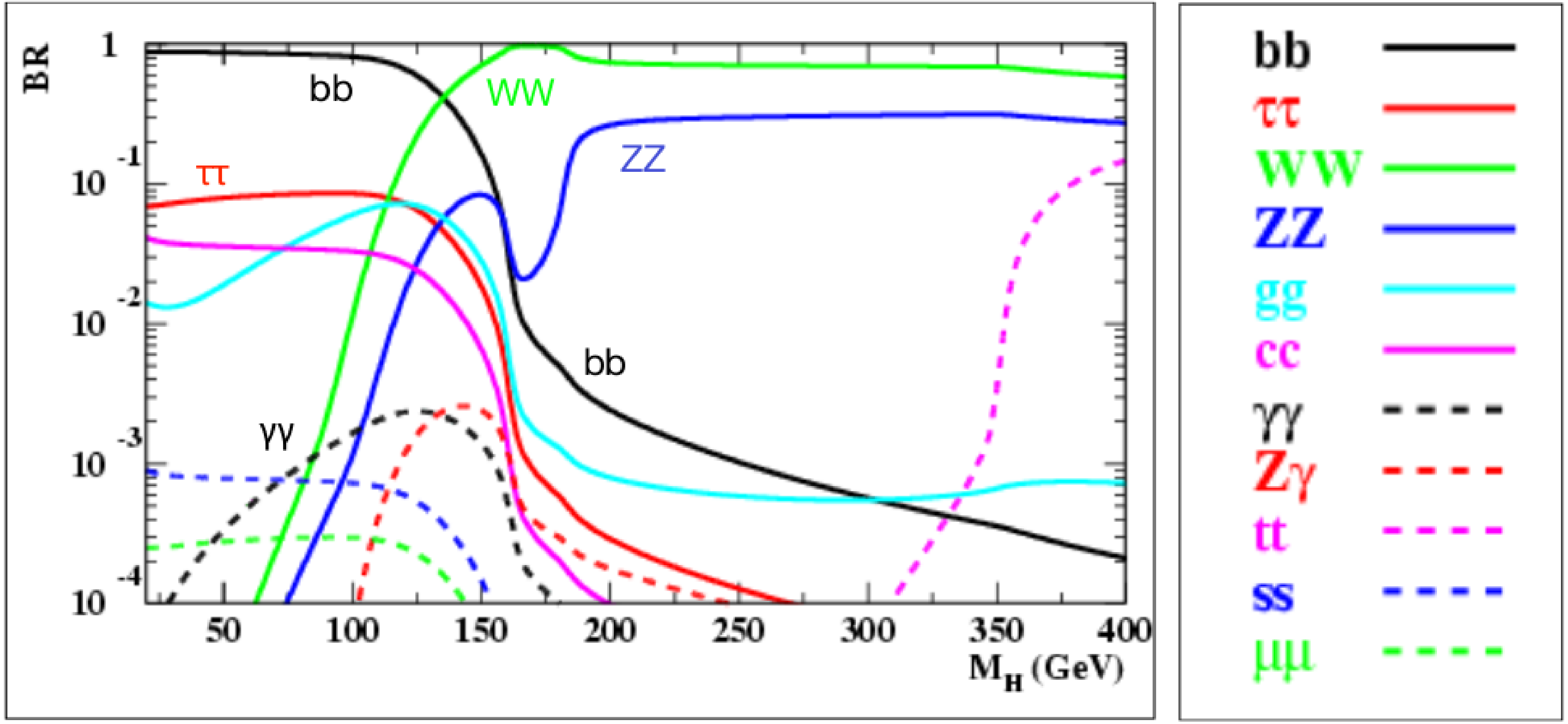


Associated production

Higgs Production Cross Sections



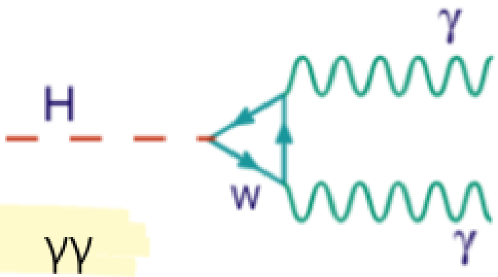
Higgs Boson Decays



For M < 135 GeV: H ➛ bb, ττ dominant

For M > 135 GeV: H ➛ WW, ZZ dominant

Tiny but also important: H ➛ γγ

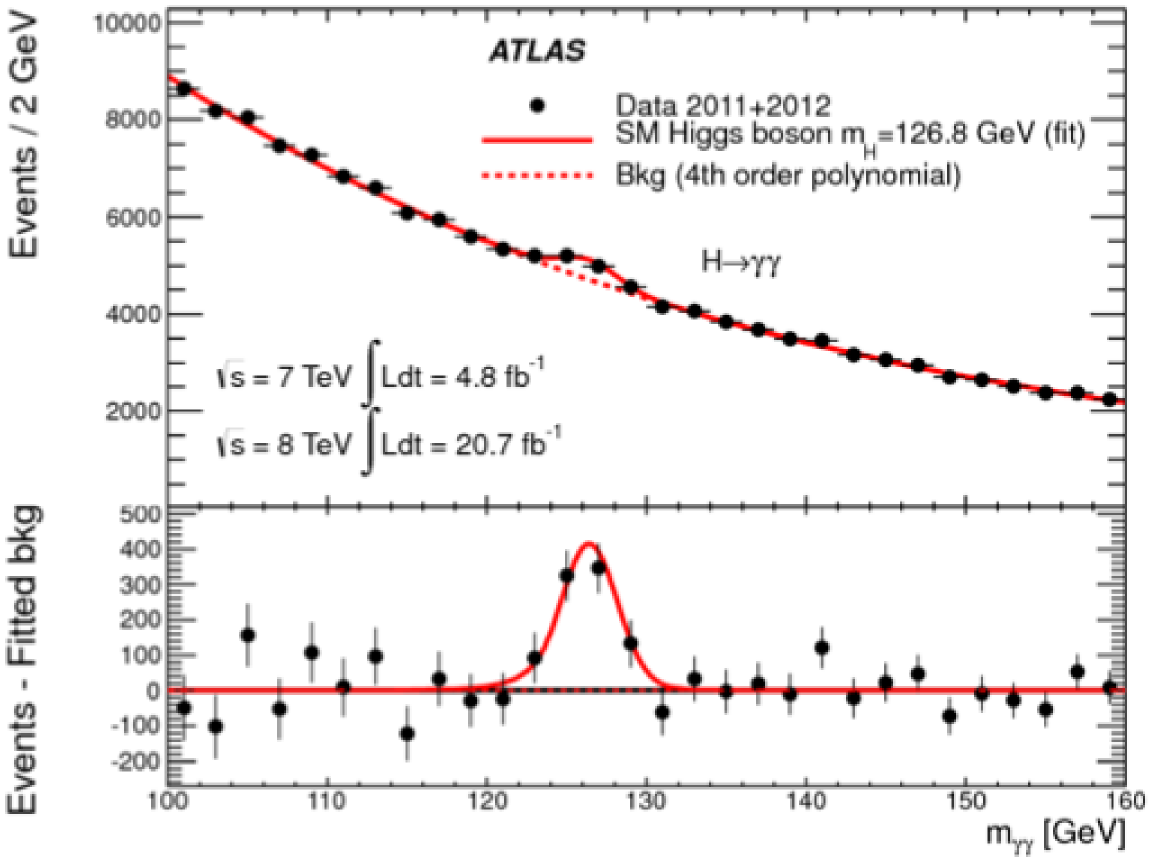


What is needed for discovery

- Signal significance:

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

- If S > 5
    - N_S is 5 times larger than the statistical uncertainty
    - Gaussian probability that this is an upward fluctuation is 10^{-7}



Maximizing S

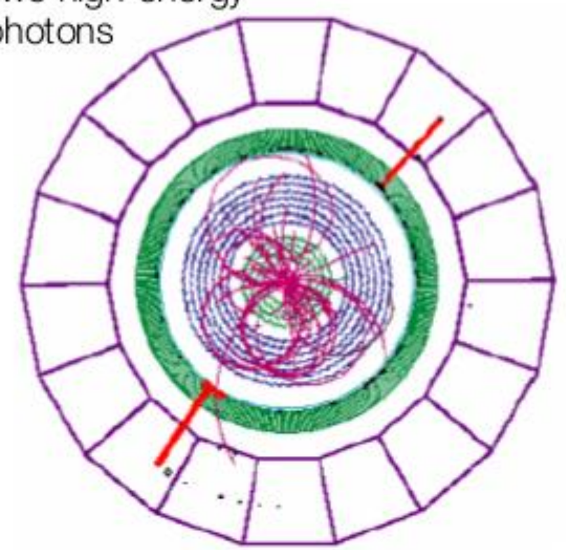
$$S = \frac{N_S}{\sqrt{N_B + N_S}}$$

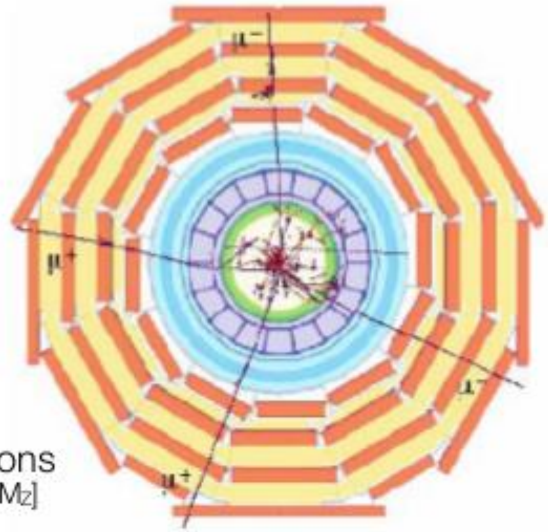
- Option 1: More signal
  - Channel with highest cross section
  - Optimize event selection to keep more events
  - N_S ~ Luminosity (get more data)
- Option 2: Choose channels with low backgrounds
- Option 3: Improve detector resolution
  - If the measured mass resolution increases, the peak is wider, wider peak means more background

Option 1 and 2 are often in conflict

Higgs Searches @ LHC: Examples

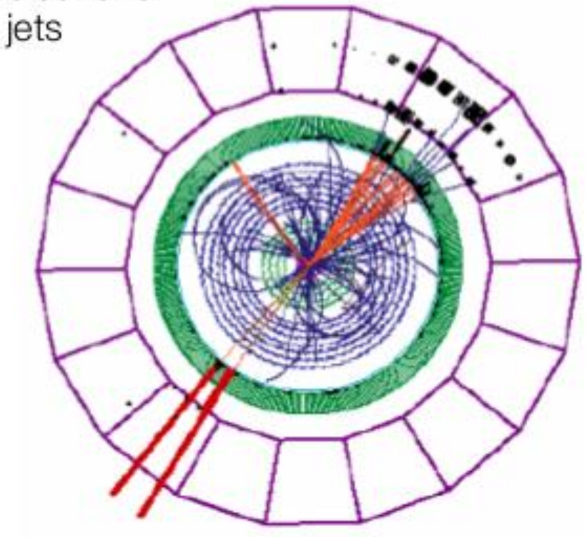
Two high-energy photons

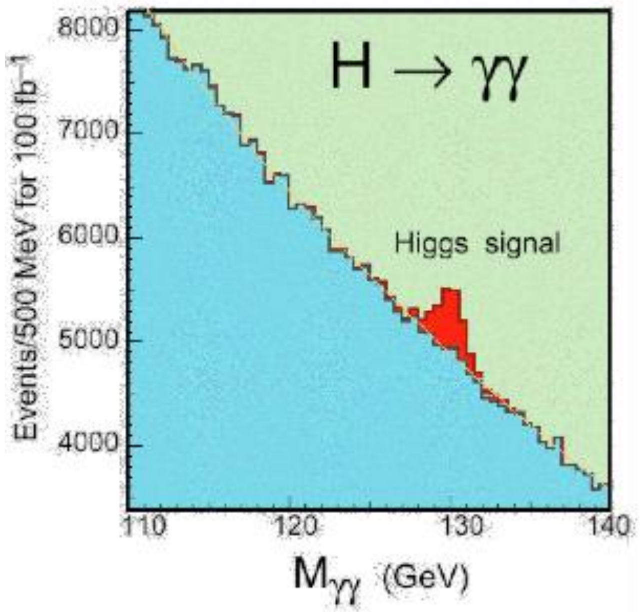


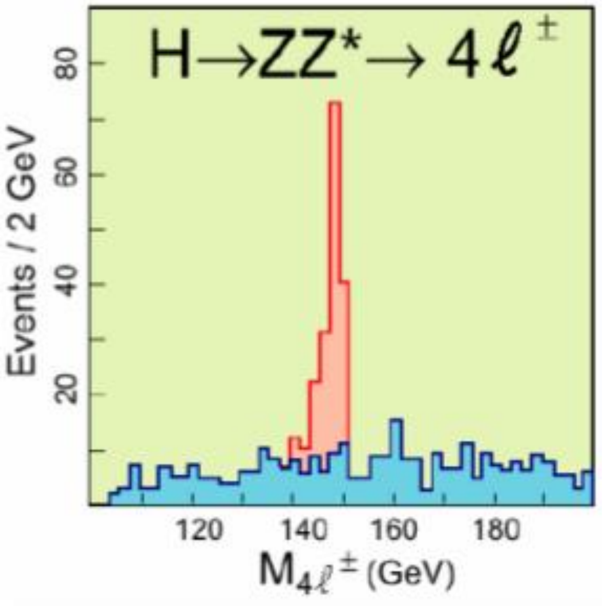


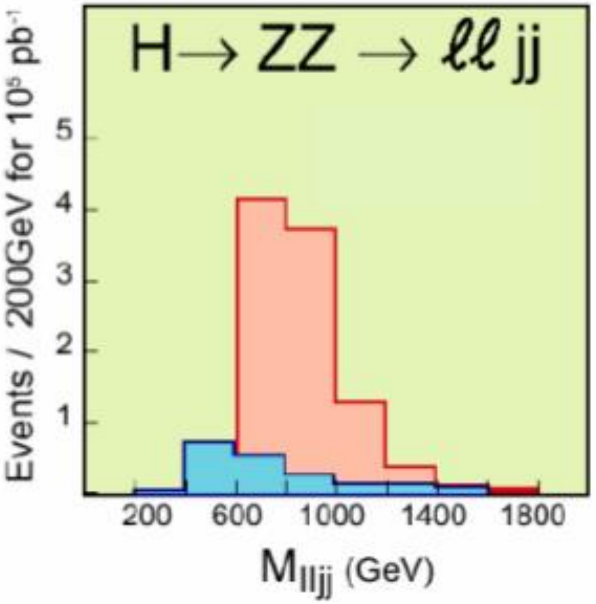
4 muons
$[M_{\mu\mu} = M_Z]$

2 electrons
2 jets

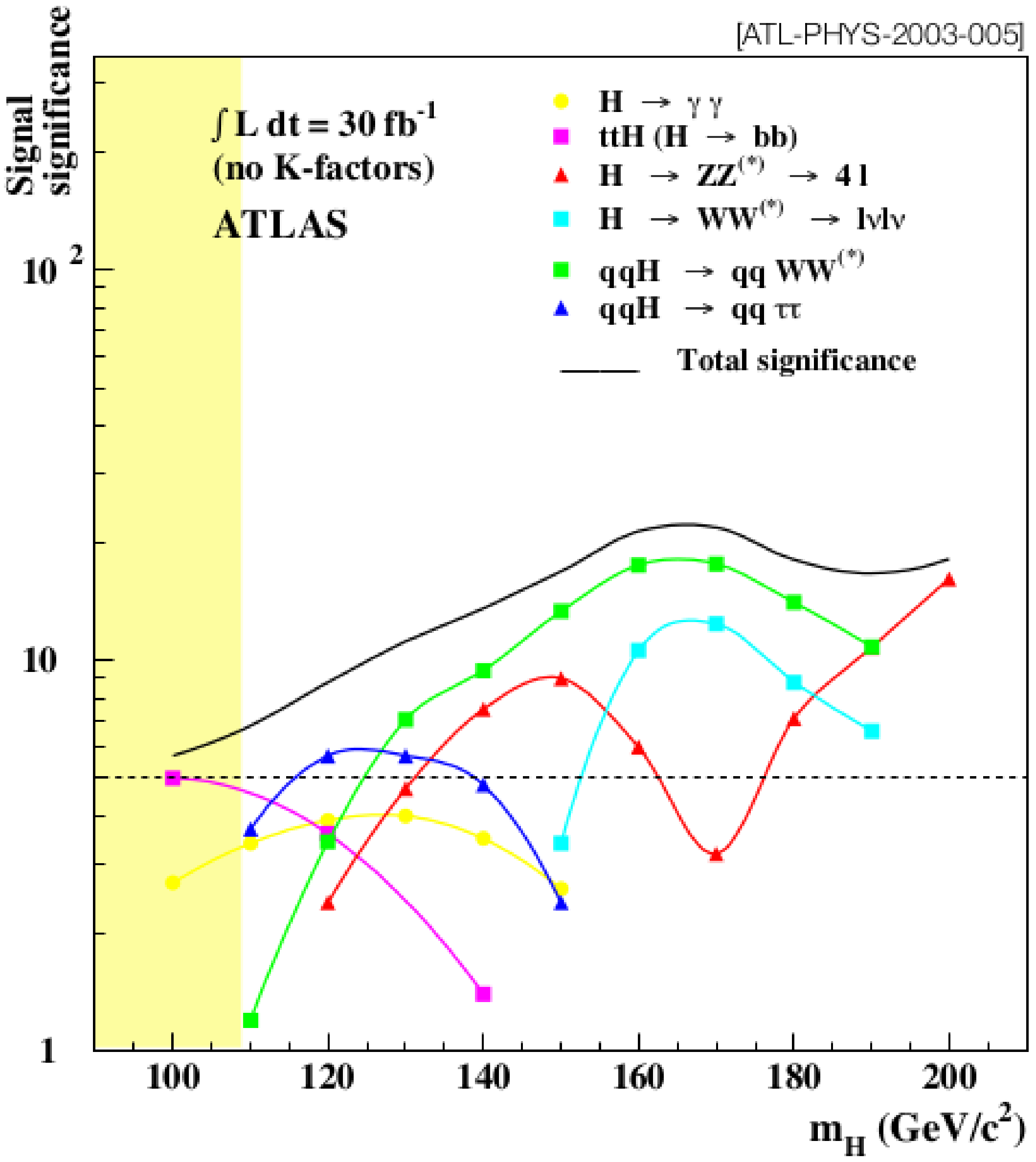








LHC: Higgs Discovery Potential



ATLAS
estimates 2005:

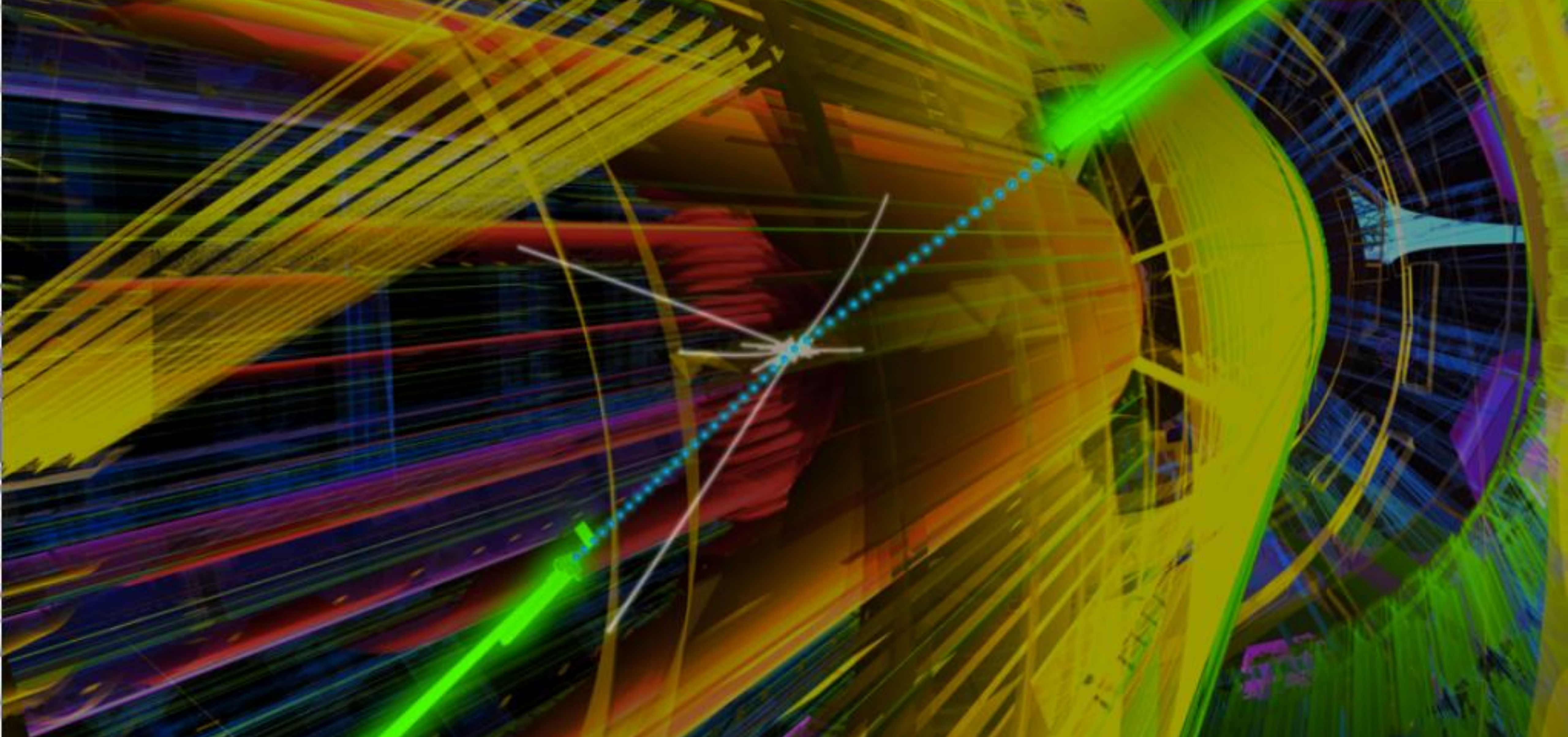
Full mass range can already be covered after a few years at low luminosity

Several channels available over a large range of masses

Low mass discovery requires combination of three of the most demanding channels

Comparable situation for the CMS experiment

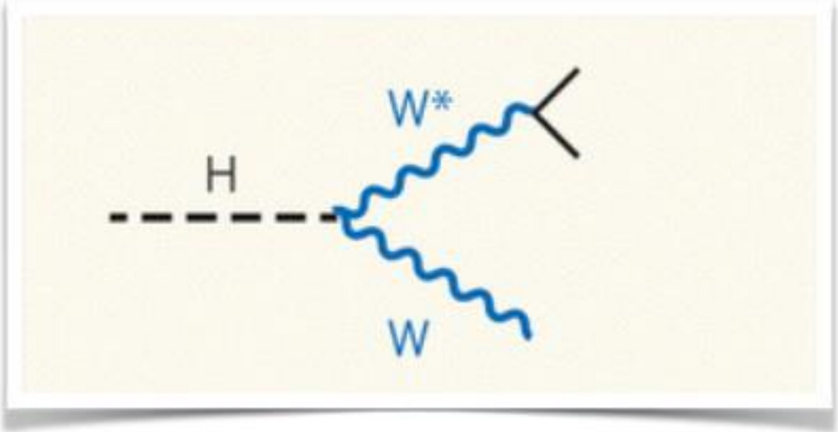
The Discovery Channels



A tale of two channels

- H to WW:
  - High cross section, high backgrounds
  - Focus on background estimates
- H to $\gamma\gamma$:
  - Low cross section, clean signal
  - Focus on photon reconstruction

H→WW Experimental Signature

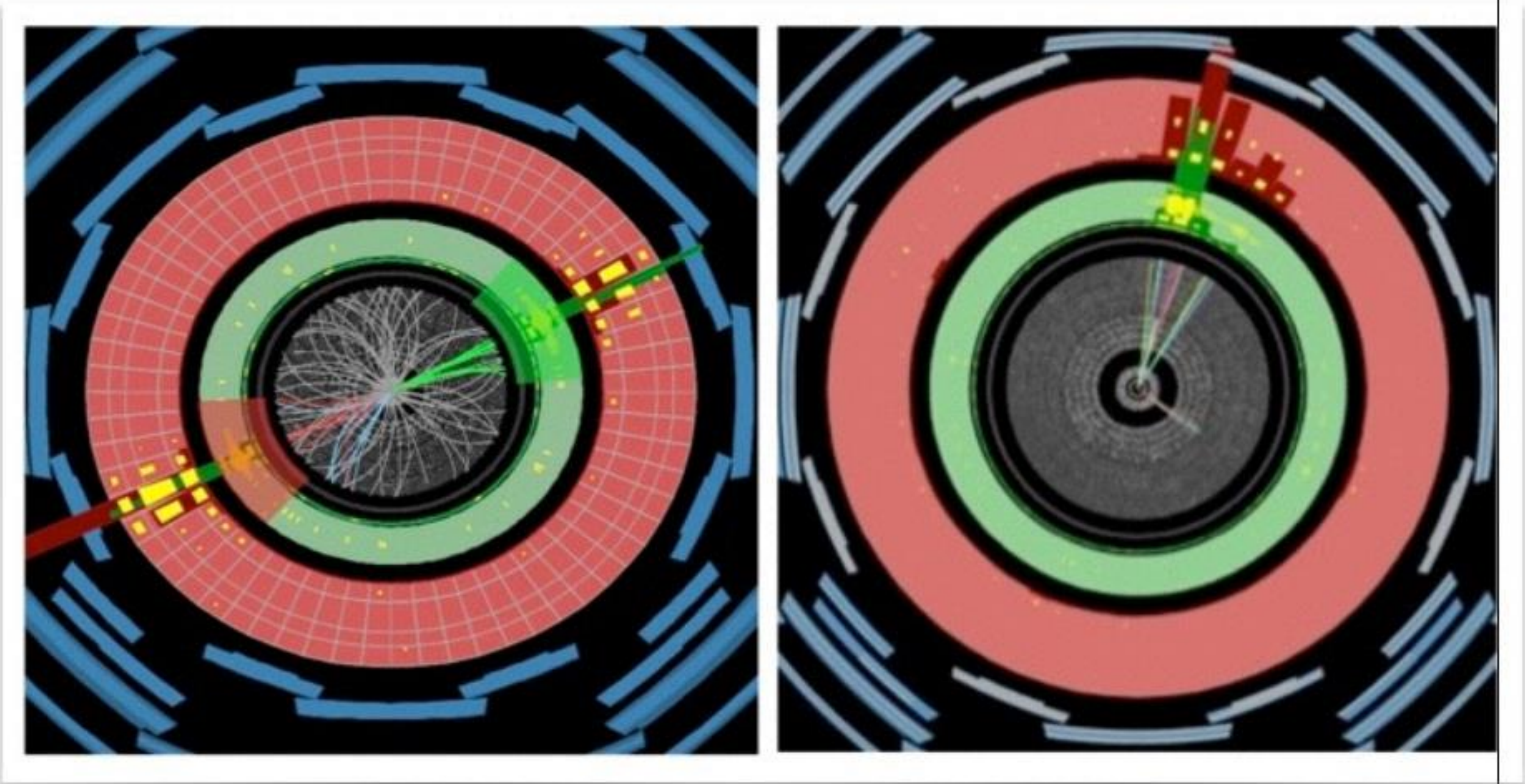


Basic Selection
- ee events
- μμ events
- e+μ events
- Missing energy

- For this diagram, possibilities are
  - 0-lepton, 4-jets
    - Huge gg→qq background
  - 1-lepton, 2-jets
    - Huge W+jet background
  - 2-leptons, 0-jets
    - Best option but only a fraction of the events

Reconstructing the mass

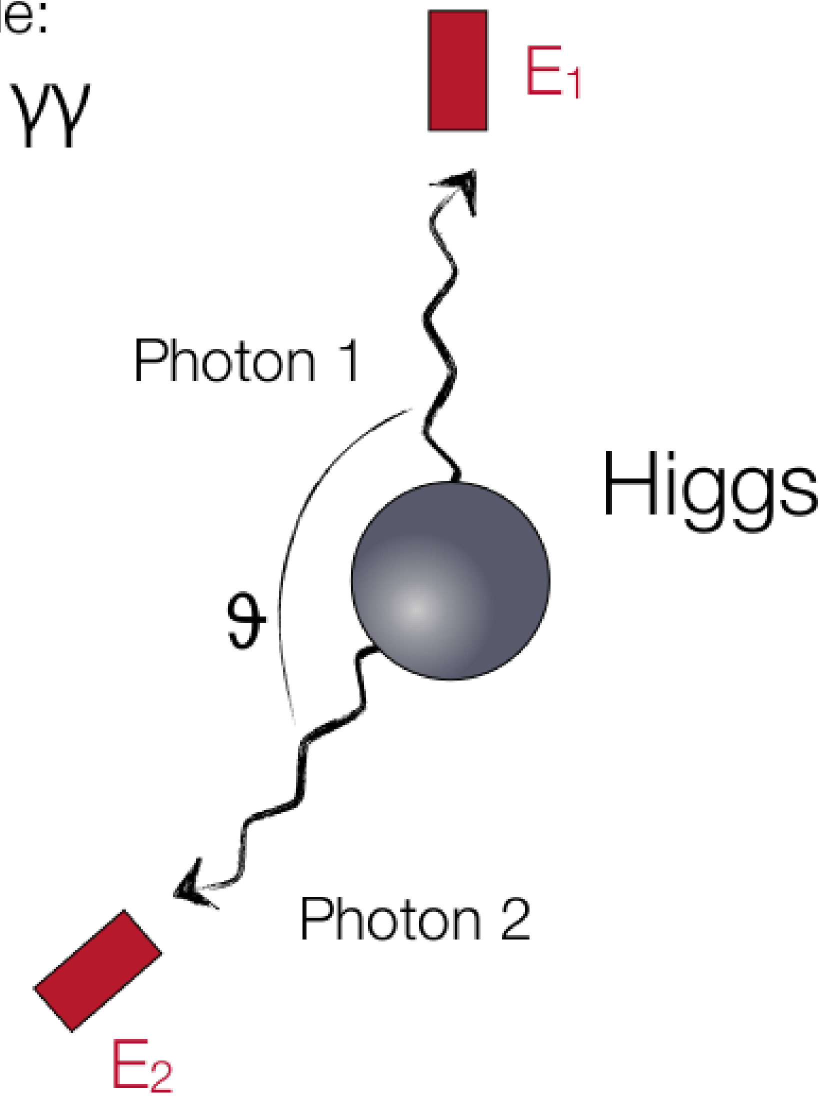
- Neutrino are not measured, only inferred by energy conservation in the transverse plane

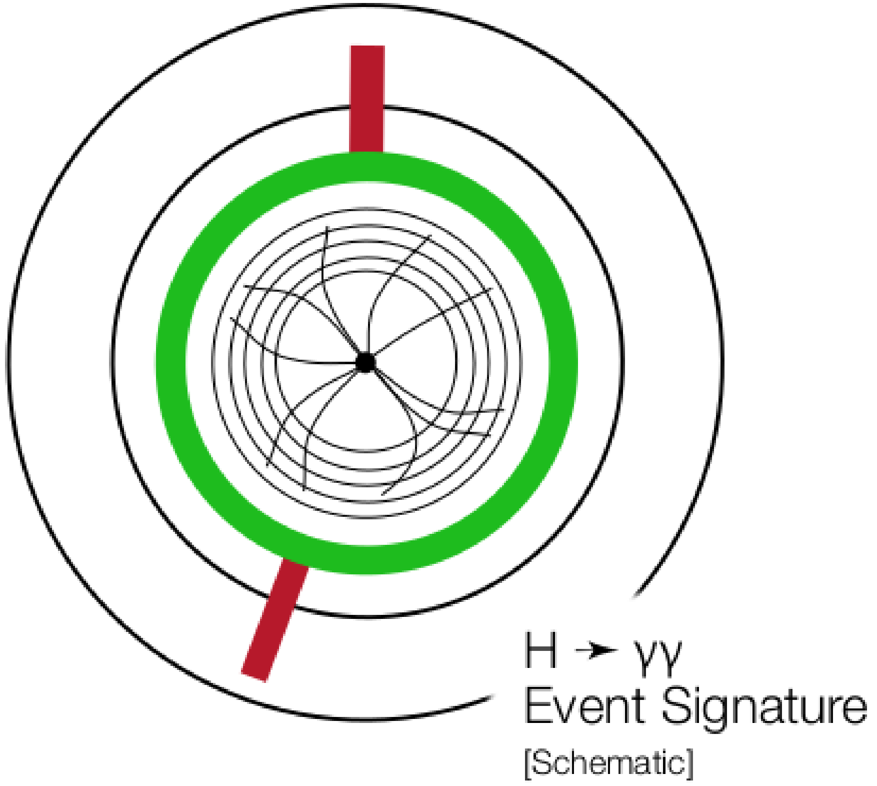


Mass reconstruction example

Example:

$H \rightarrow \gamma\gamma$





Invariant Mass:

$$m_{\gamma\gamma}^2 = 2E_1E_2\,(1-\cos\vartheta)$$

Reconstructing the mass

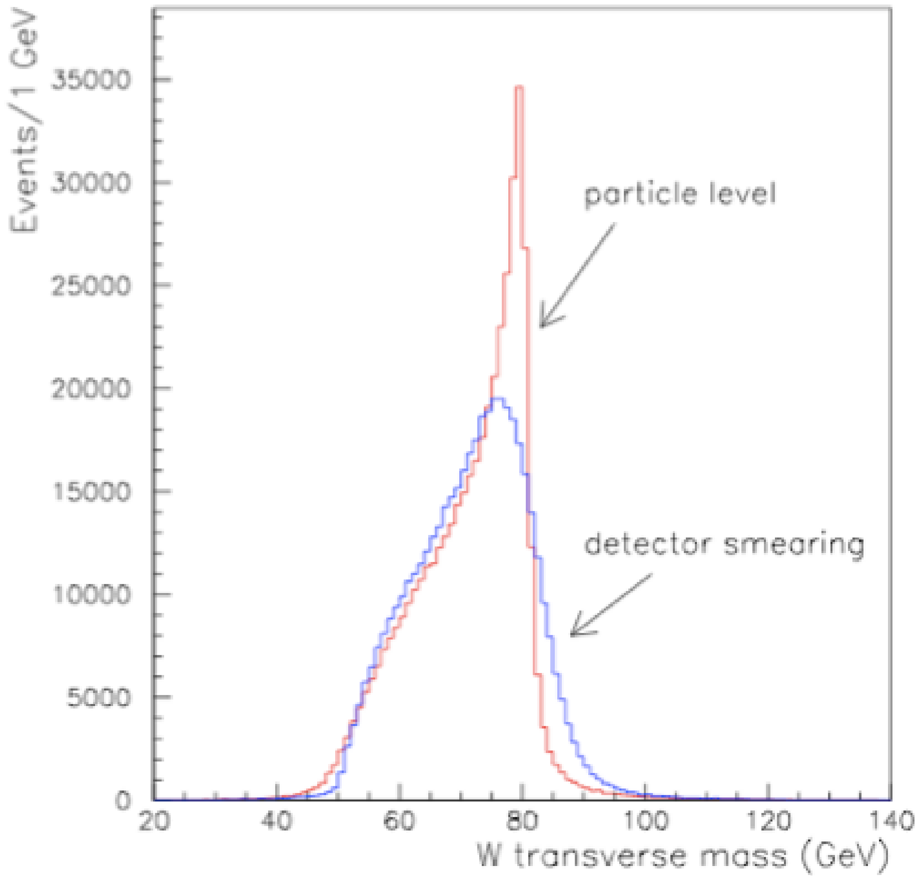
- Only know the x- and y-components of the missing energy (called MET)
- Can not reconstruct a mass peak

$$M_T^2(W) = 2\,p_T(l)\,p_T(\nu)[1-\cos(\Delta\phi)]$$

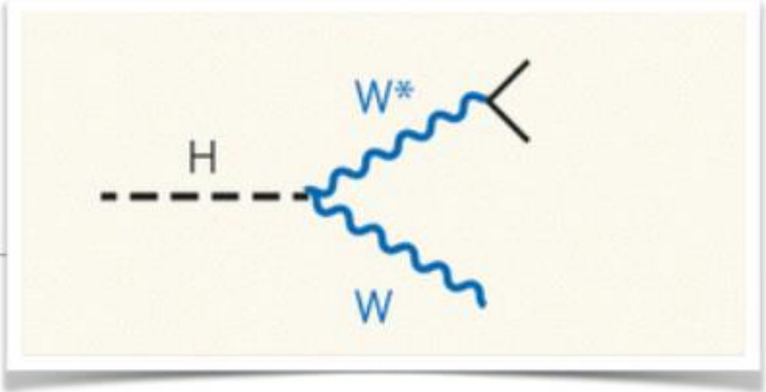
Lepton transverse momentum

Missing E_t

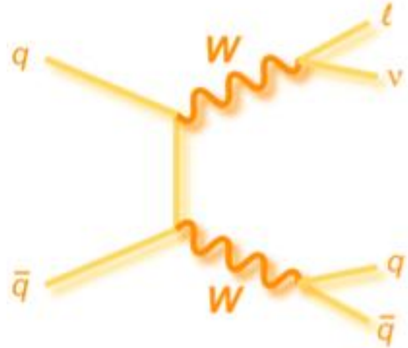
Angle between lepton and missing E_t in the transverse plane

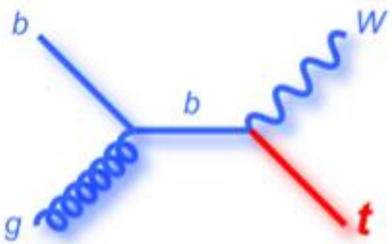


The Backgrounds

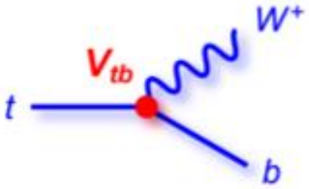


A prefect detector



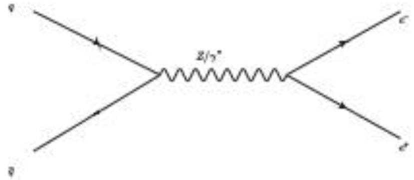


All have two Ws in the event

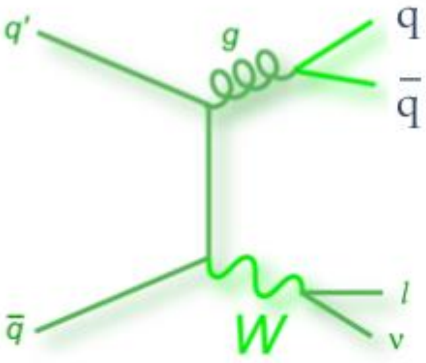


A real detector

2 leptons, but no 'real' missing Et



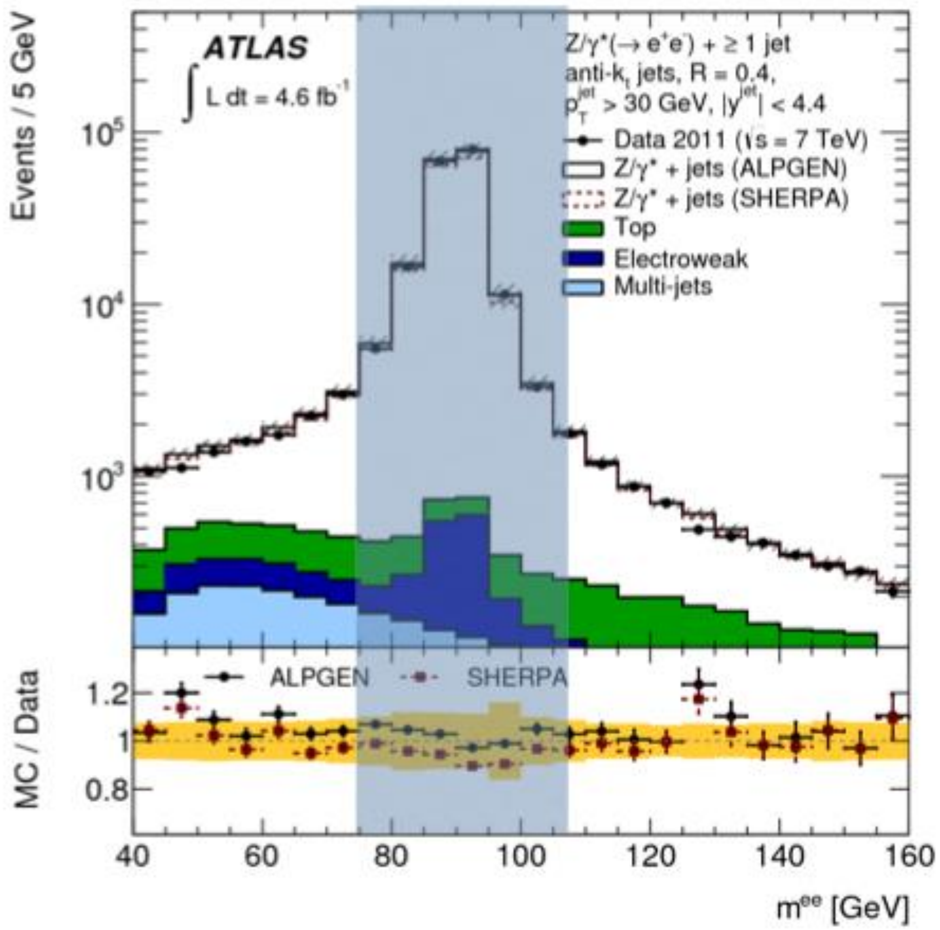
Only 1 W, but other objects like jets



Others: ZZ, WZ, Wγ, single top

H→WW Event Selection

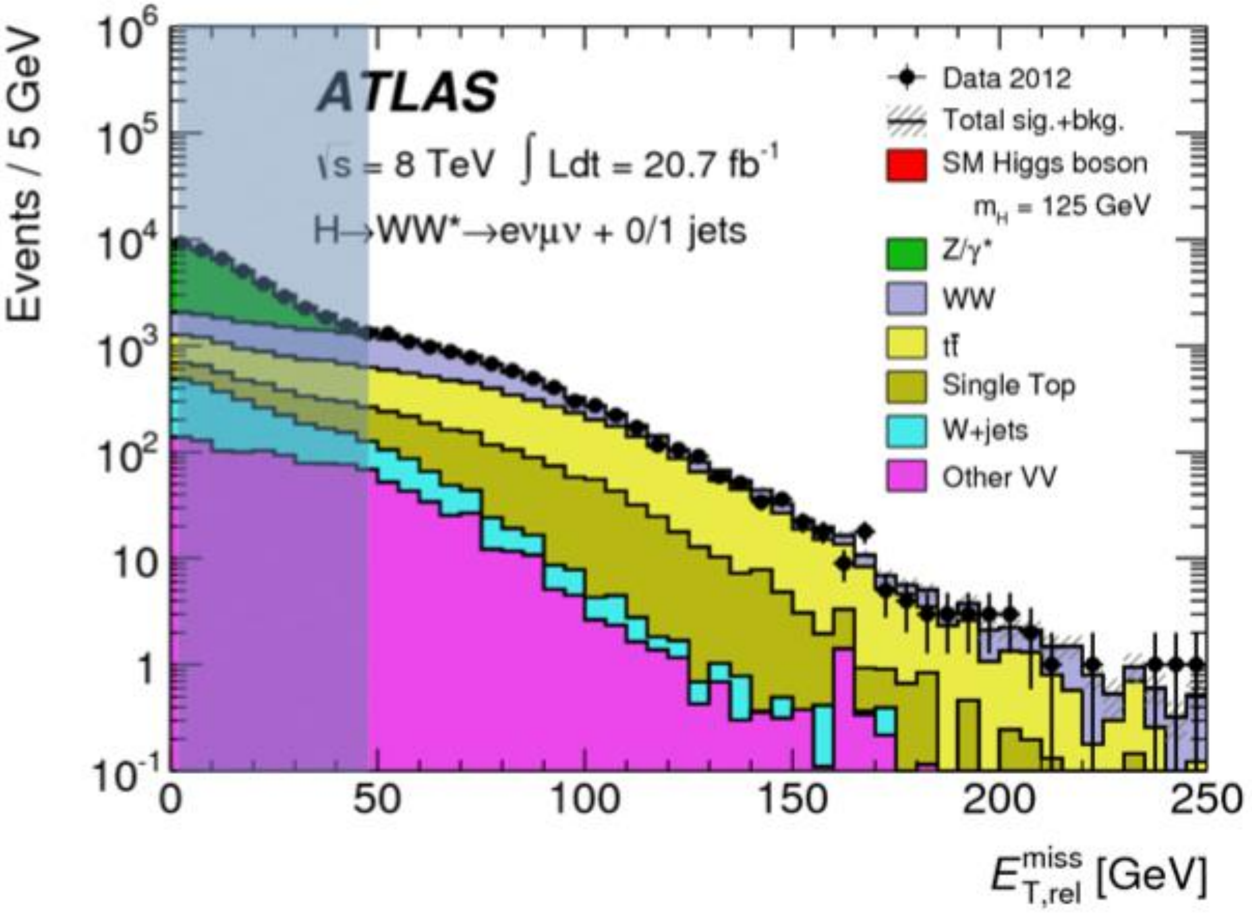
Cut on…
M_{ll} around Z-peak



Removes Z+jet background

H→WW Event Selection

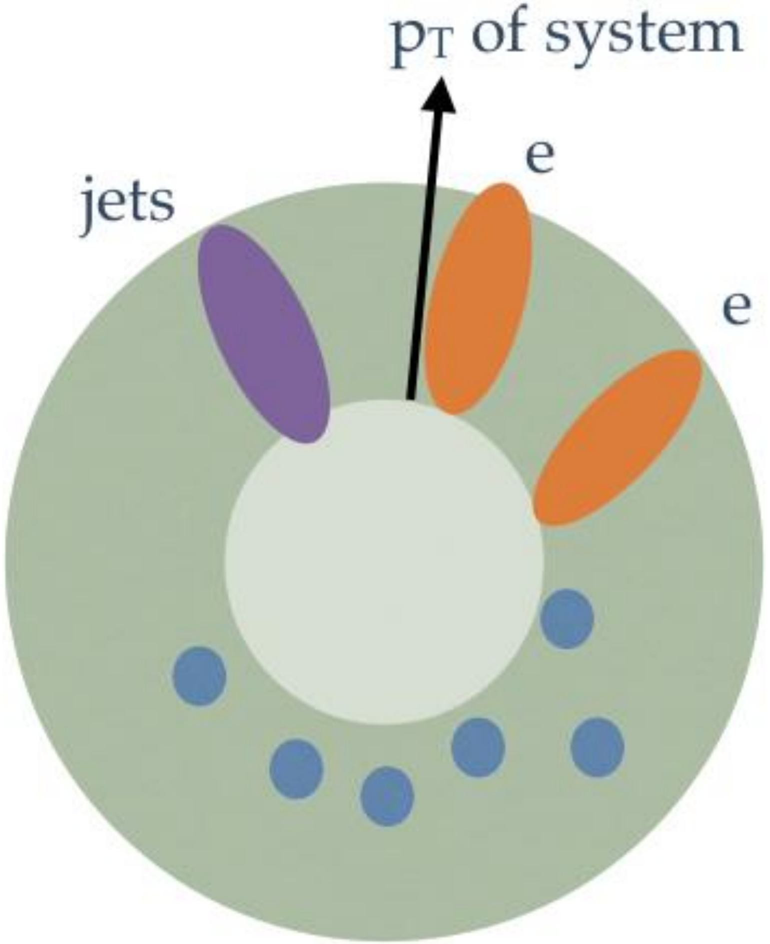
Cut on…
M_{ll} around Z-peak
MET-like variable



Removes Z+jet background

H→WW Event Selection

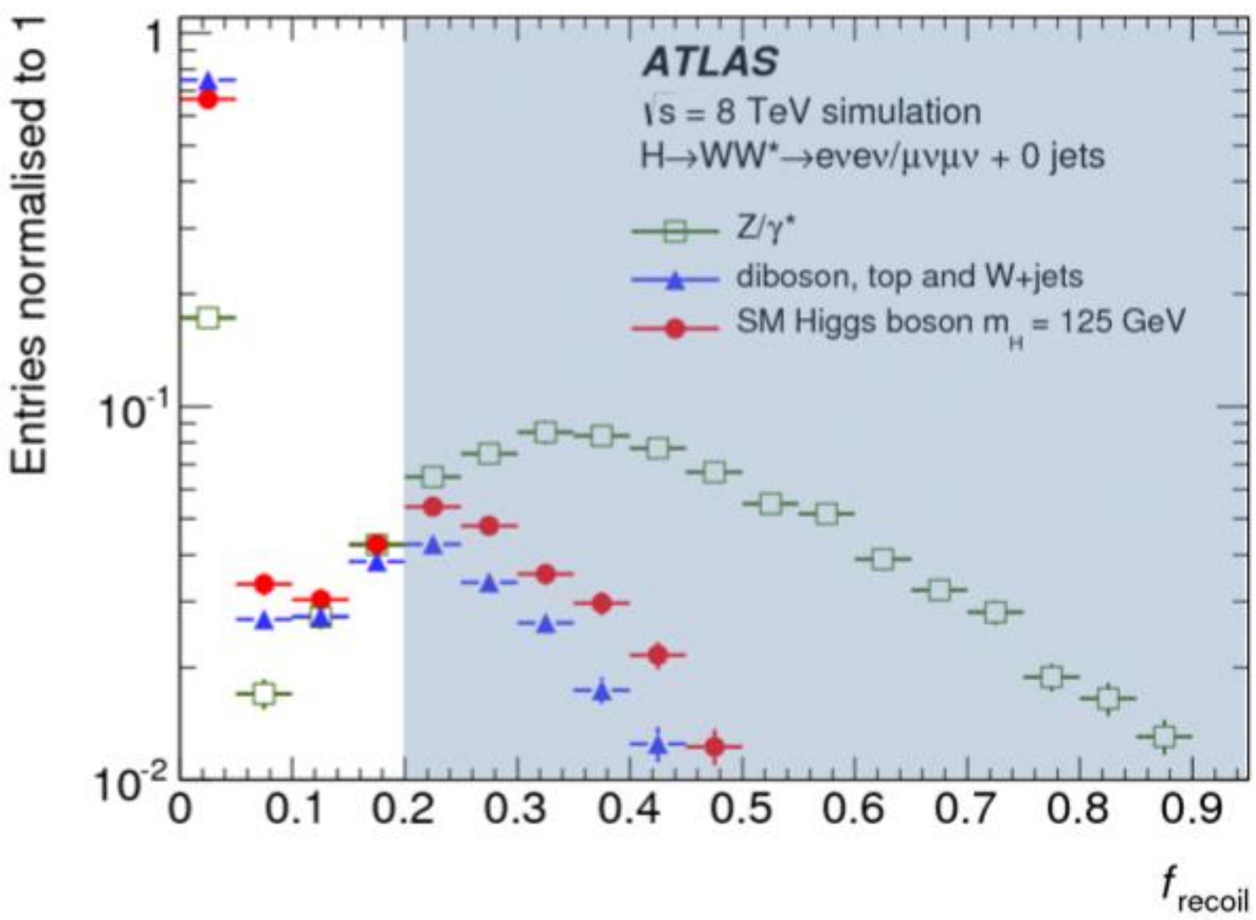
Cut on…
M_{ll} around Z-peak
MET-like variable
Recoil fraction



Look at the fraction of soft energy opposite the system p_T

H→WW Event Selection

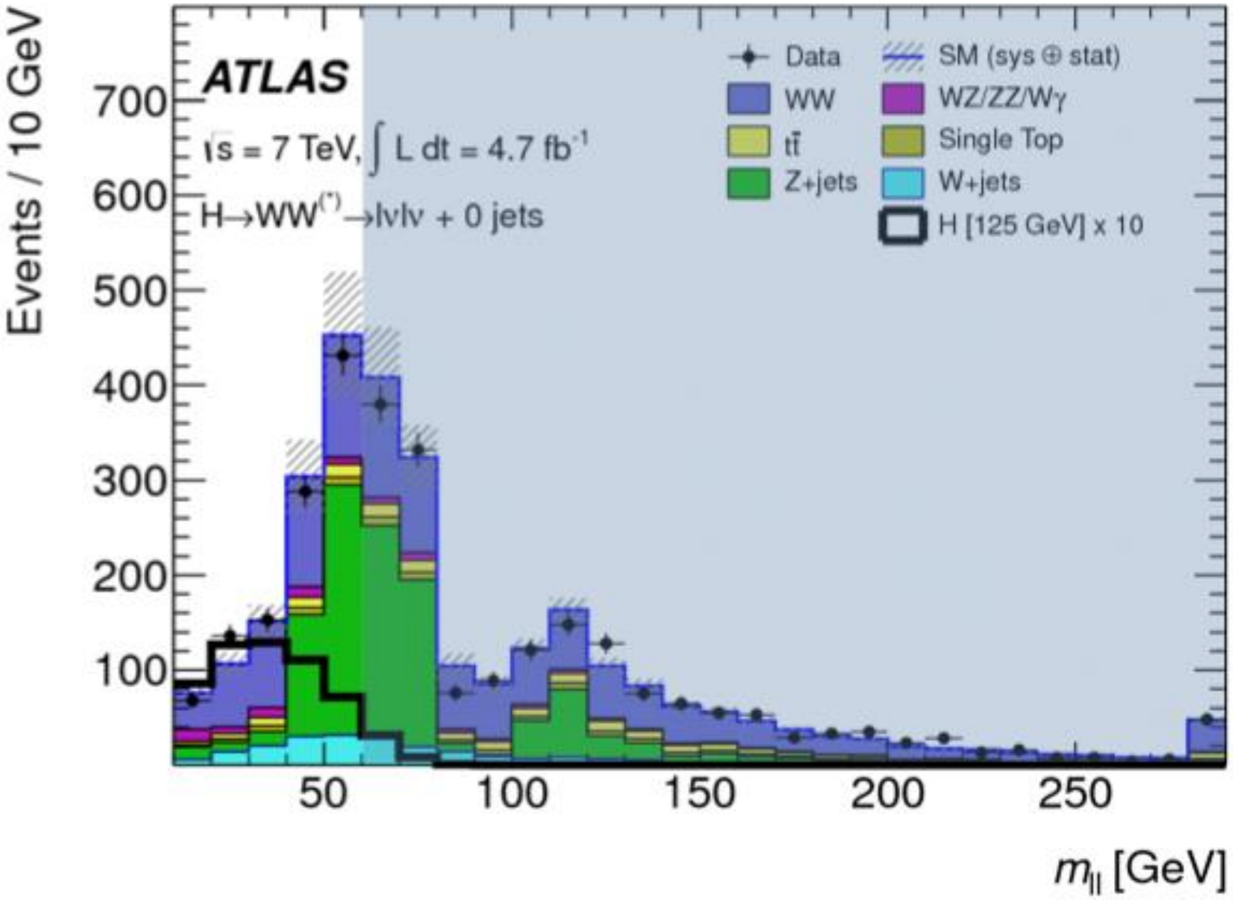
Cut on…
M_{ll} around Z-peak
MET-like variable
Recoil fraction



Removes Z+jet background

H→WW Event Selection

Cut on…
M_{ll} around Z-peak
MET-like variable
Recoil fraction
Tighter on M_{ll}

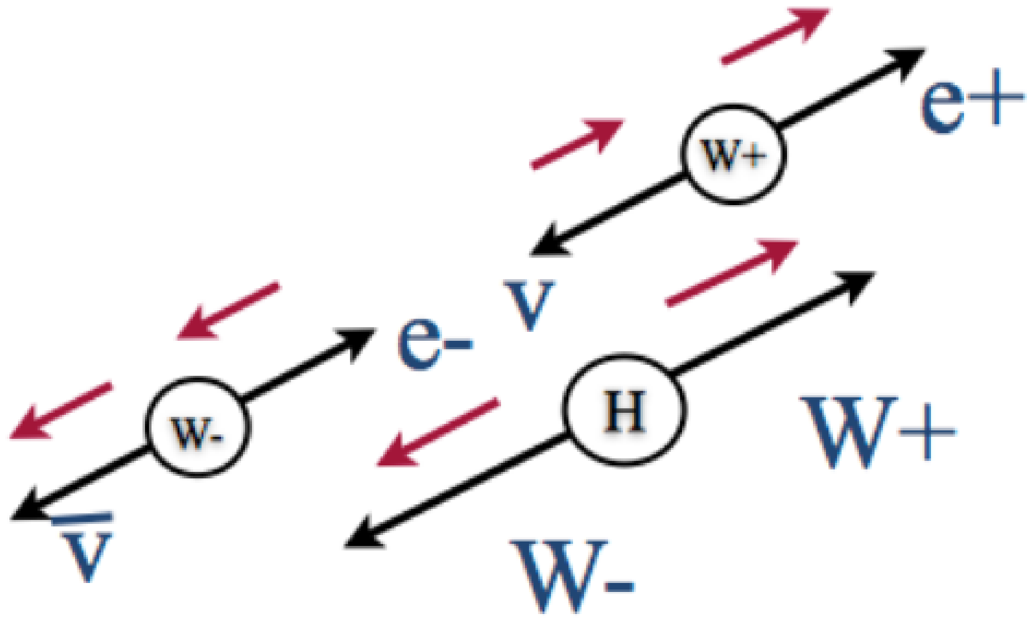


Removes WW background

H→WW Event Selection

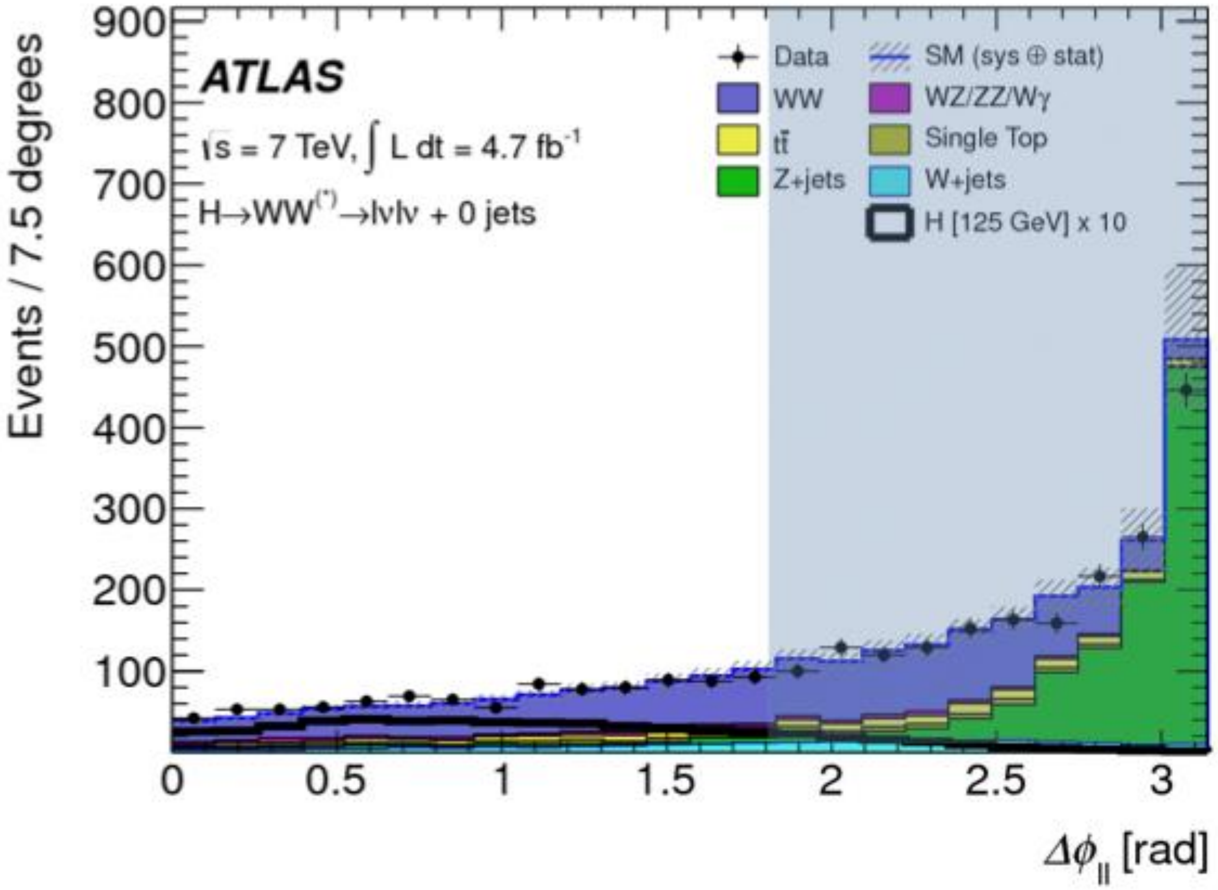
Cut on…
M_{ll} around Z-peak
MET-like variable
Recoil fraction
Tighter on M_{ll}
ϕ angle between lep.

Can use that Higgs is a spin-0 particle



H→WW Event Selection

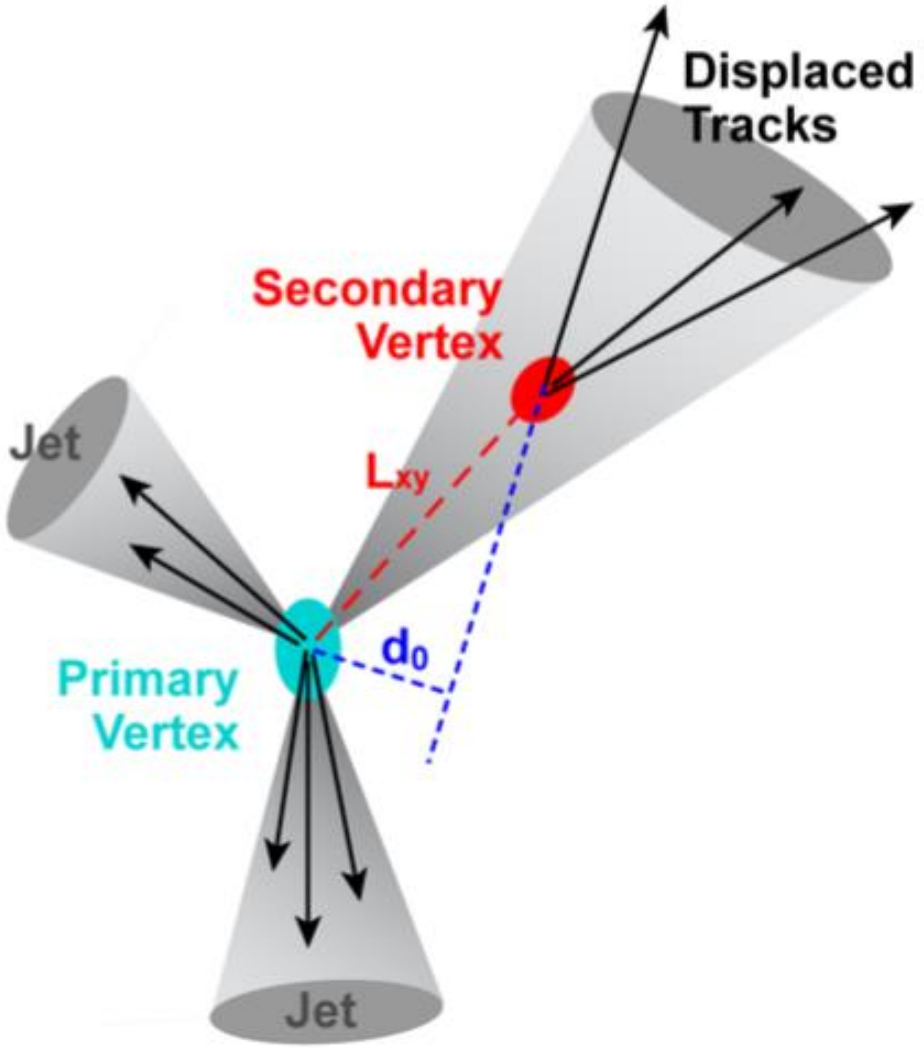
Cut on…
M_{ll} around Z-peak
MET-like variable
Recoil fraction
Tighter on M_{ll}
φ angle between lep.



Removes WW background

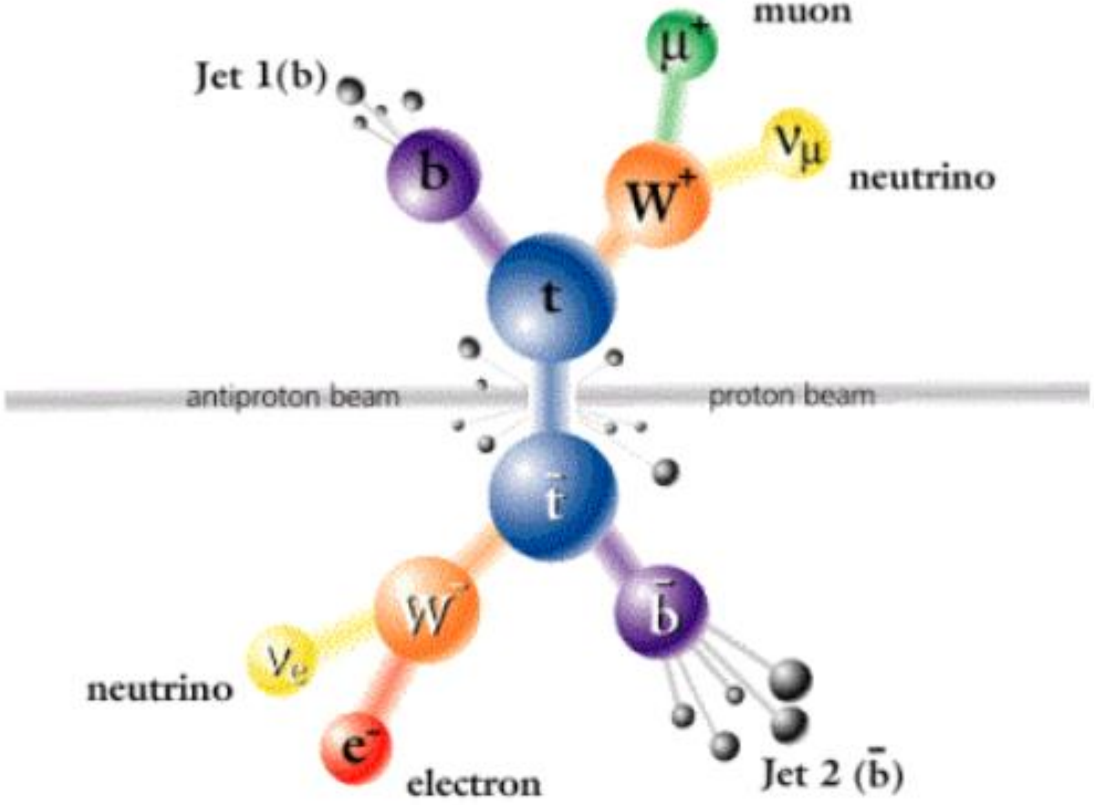
H→WW Event Selection

Cut on…
M_{ll} around Z-peak
MET-like variable
Recoil fraction
Tighter on M_{ll}
ϕ angle between lep.
Veto on b-jets



H→WW Event Selection

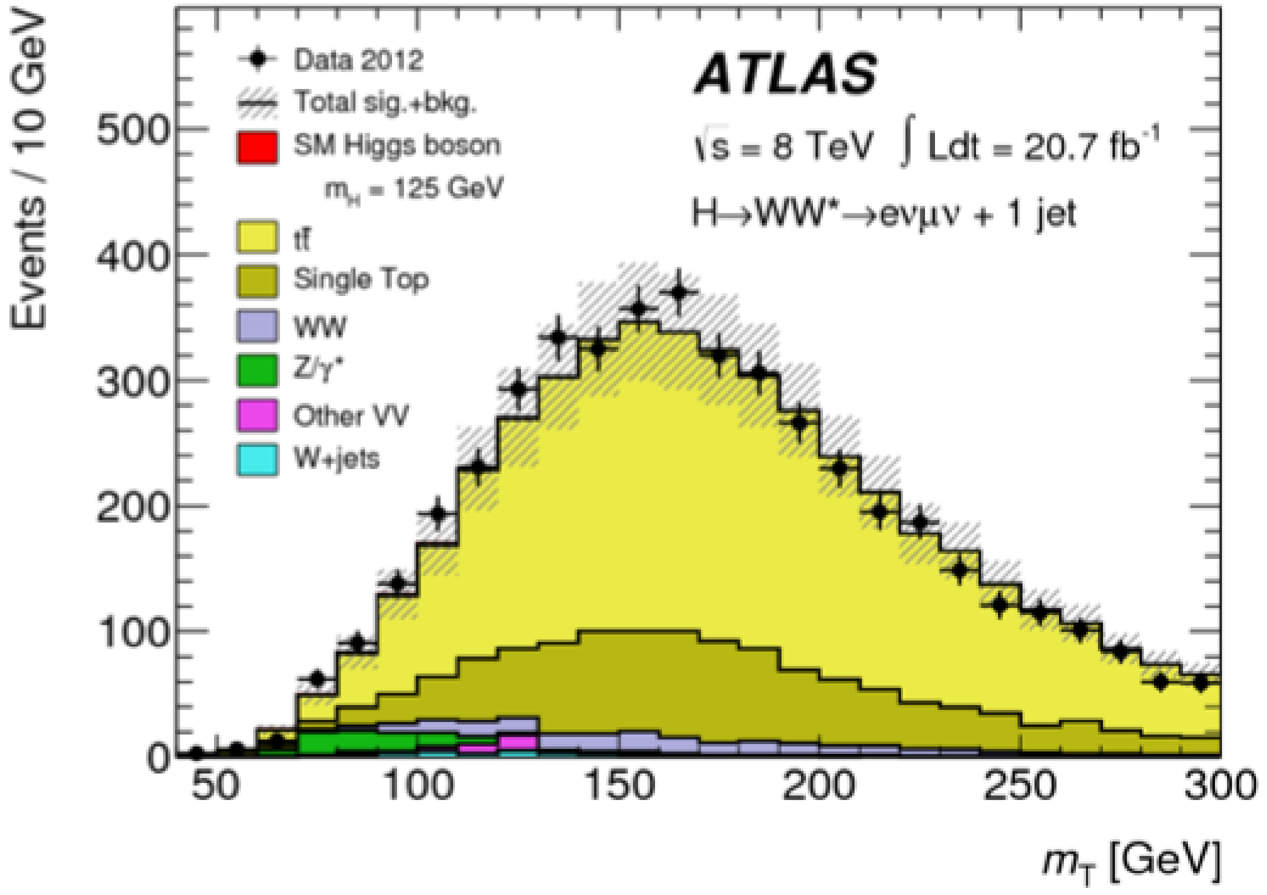
Cut on…
M_{ll} around Z-peak
MET-like variable
Recoil fraction
Tighter on M_{ll}
ϕ angle between lep.
Veto on b-jets



Removes top background

Top Estimates

- Define a control region
  - Exactly 1-bjet
  - Remove the M_{ll} and $\Delta\phi$ cuts
- Use Monte Carlo as the model to estimate the number of events in the signal region



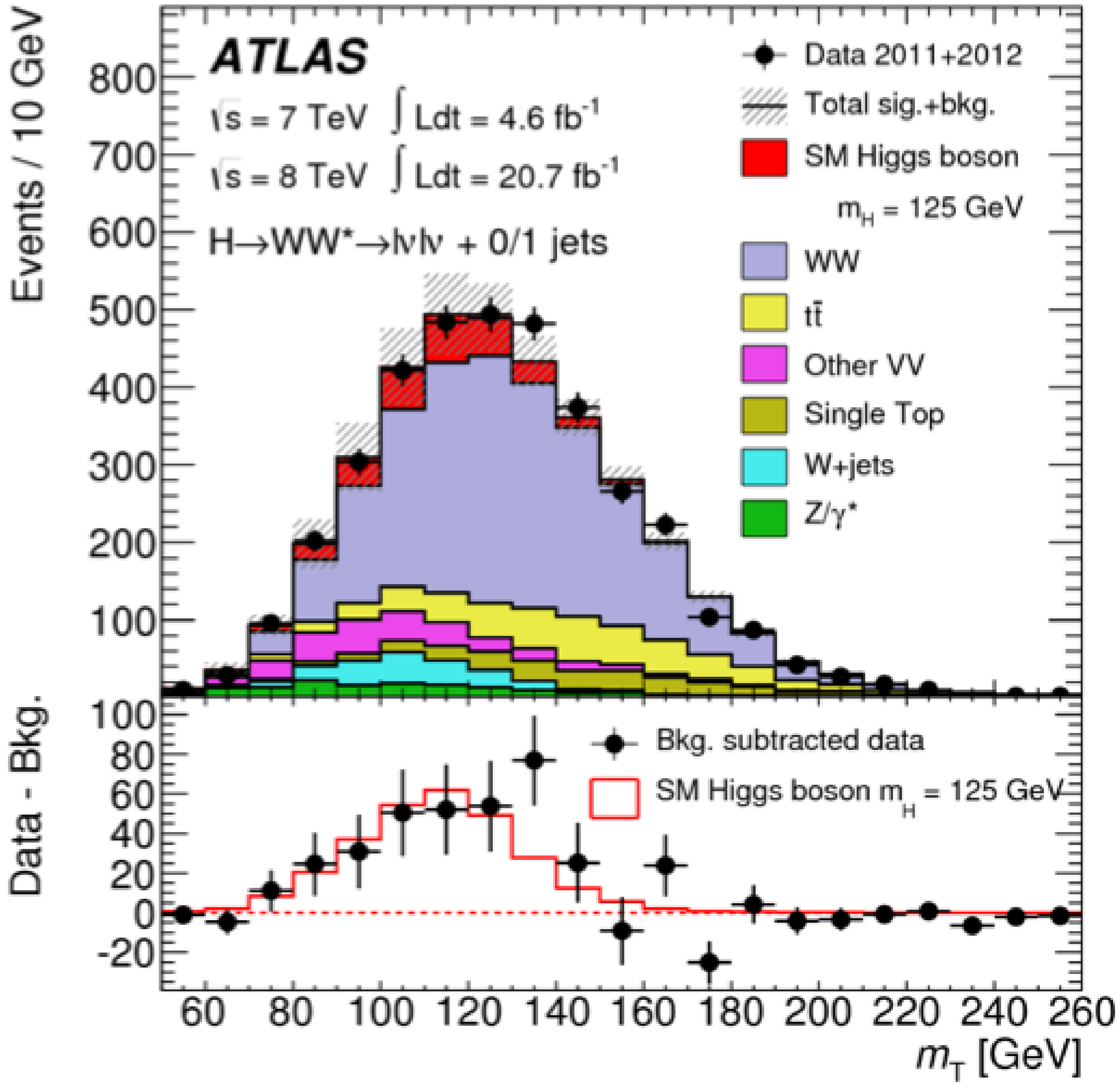
The Results

- MT is defined here as

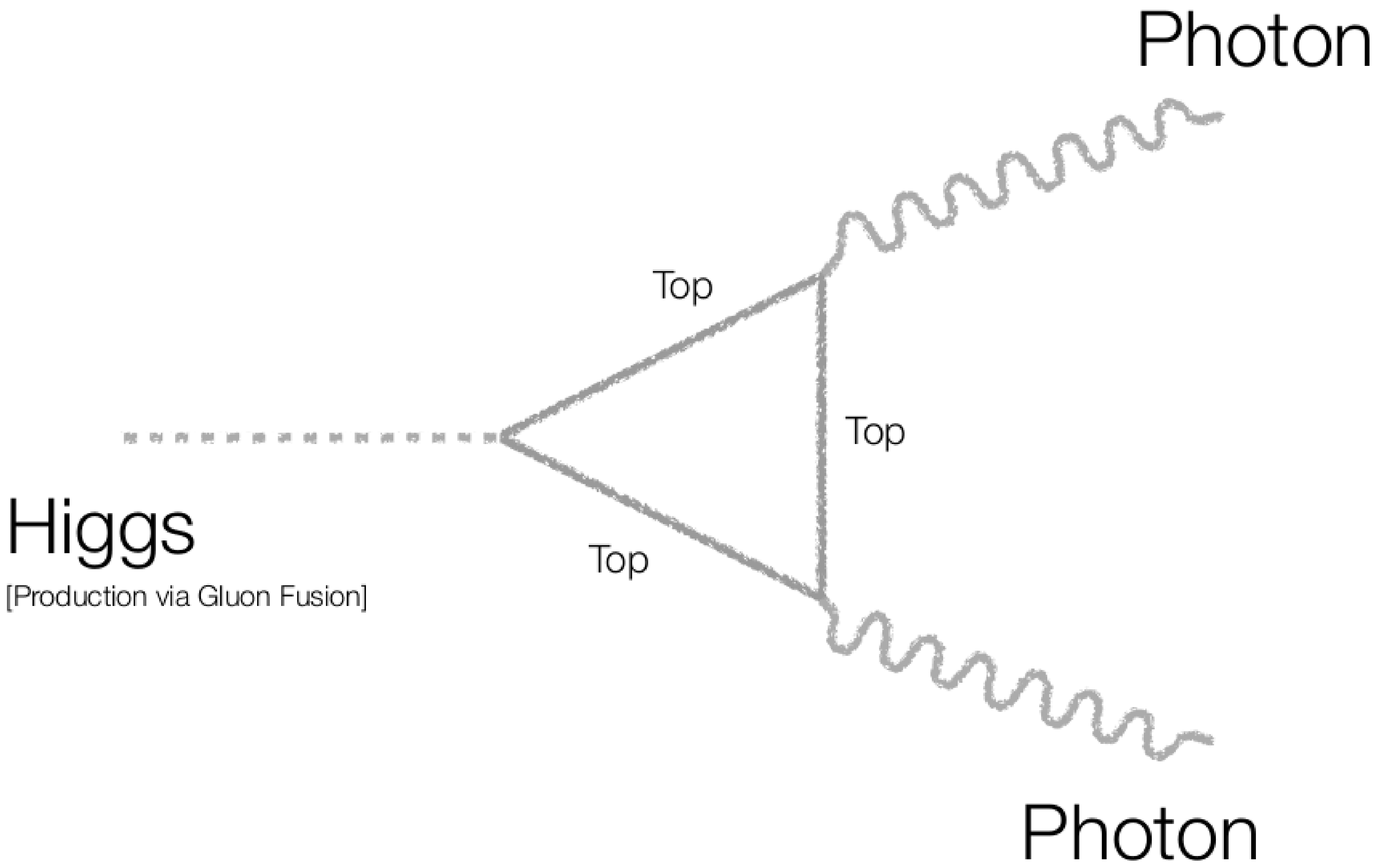
$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |\vec{p}_T^{ll} + \vec{E}_T^{miss}|^2}$$

- No clear mass peak

- Clear excess over background

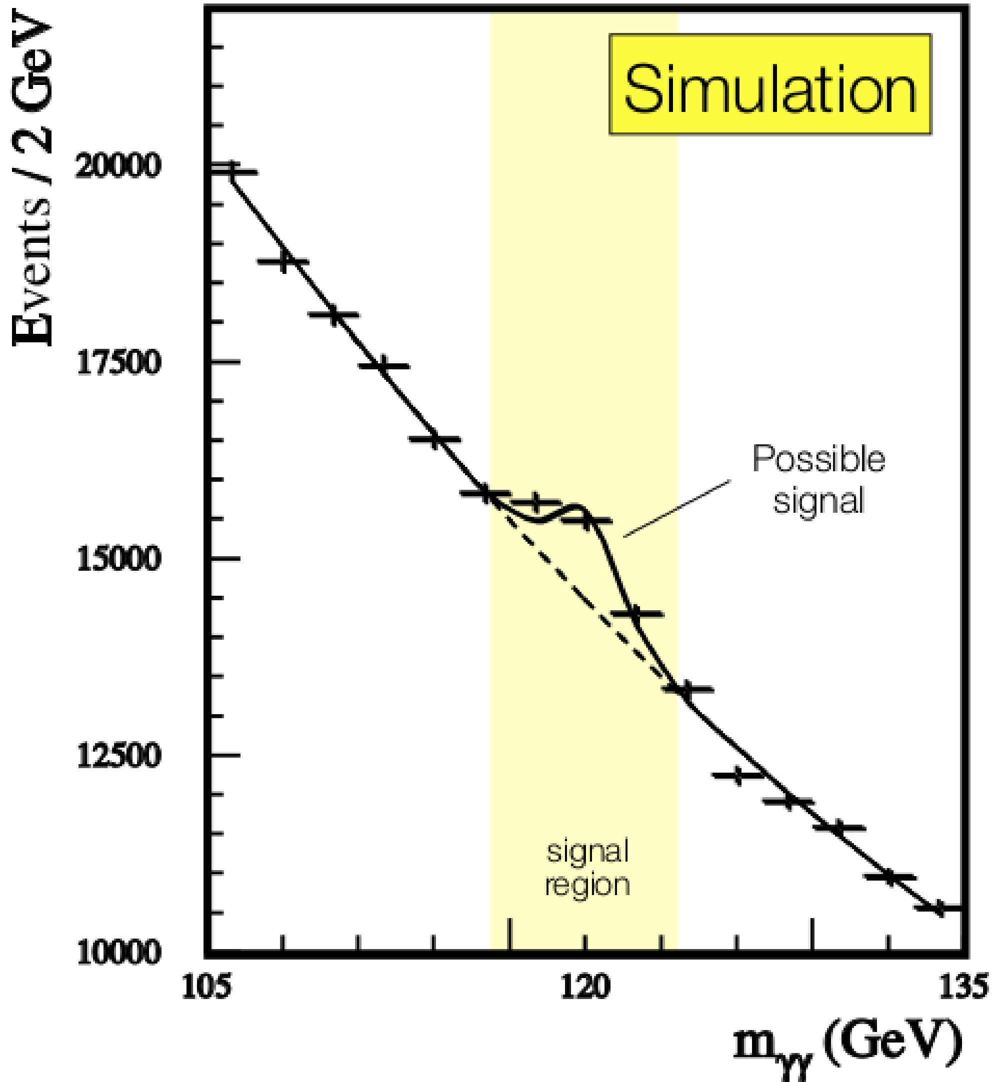


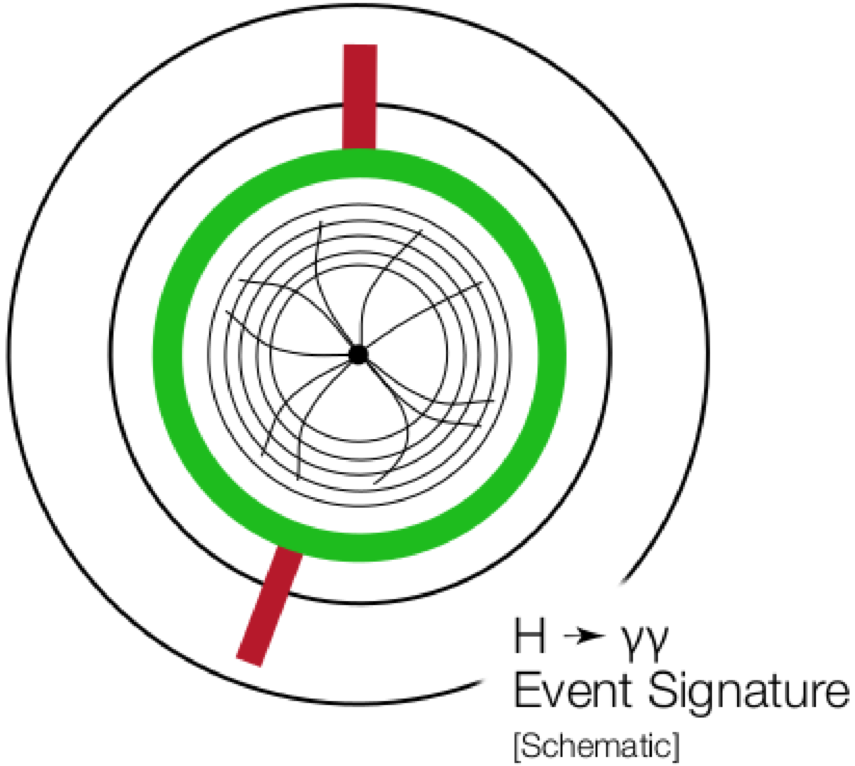
H to γγ



Photon
Top
Top
Higgs
[Production via Gluon Fusion]
Top
Photon

Basic Analysis Principle





Invariant Mass:

$$m_{\gamma\gamma}^2 = 2E_1E_2\,(1-\cos\vartheta)$$

Analysis Necessities & Steps …

Photon reconstruction

Photon identification

Photon isolation

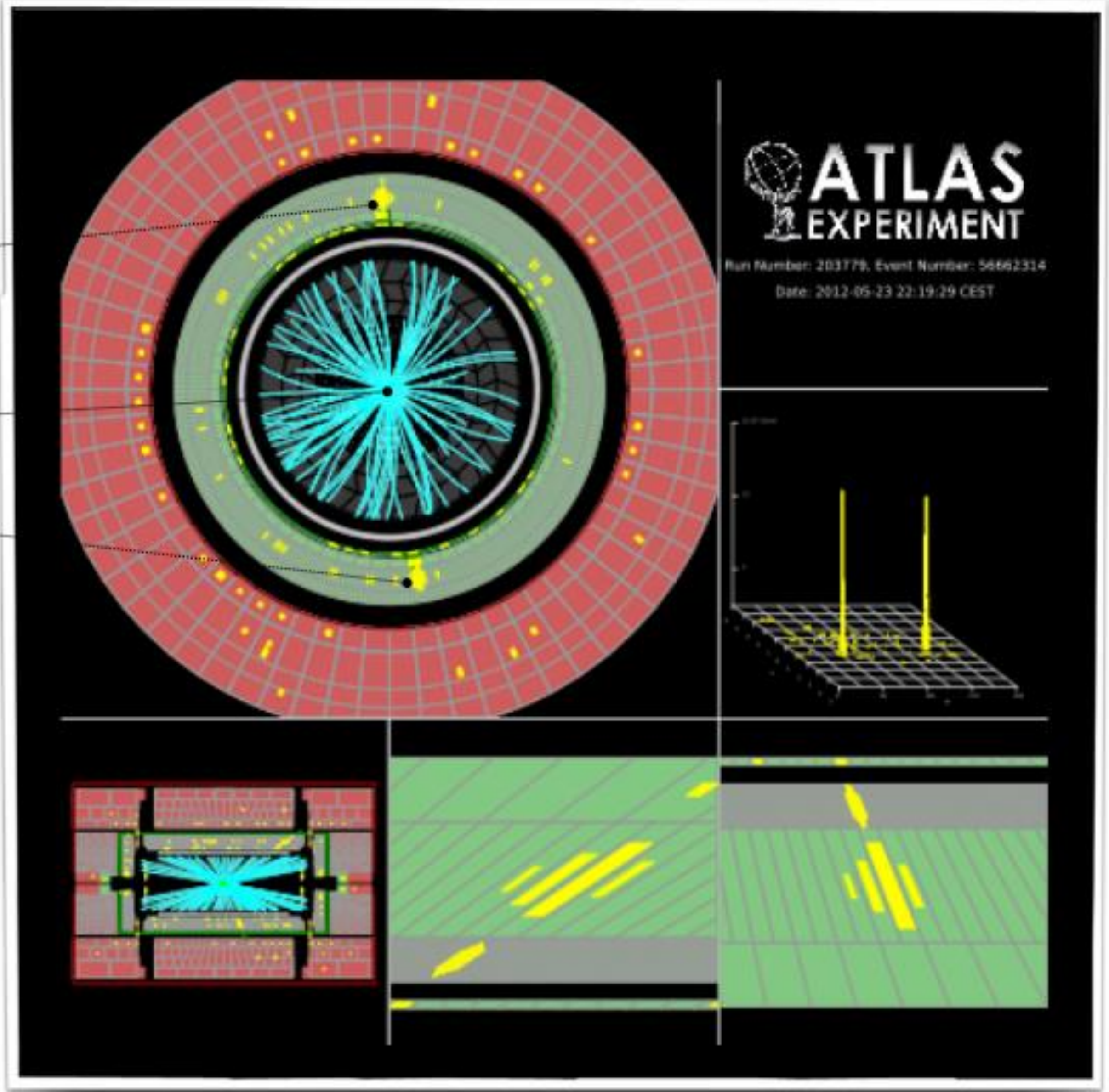
Primary vertex

Energy calibration

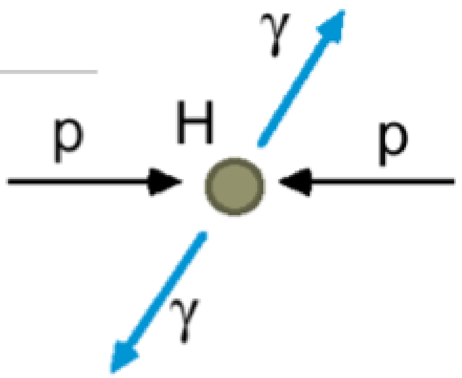
Background modeling

Event categories

Limits & signal strength



2γ-Channel – Signal and Background

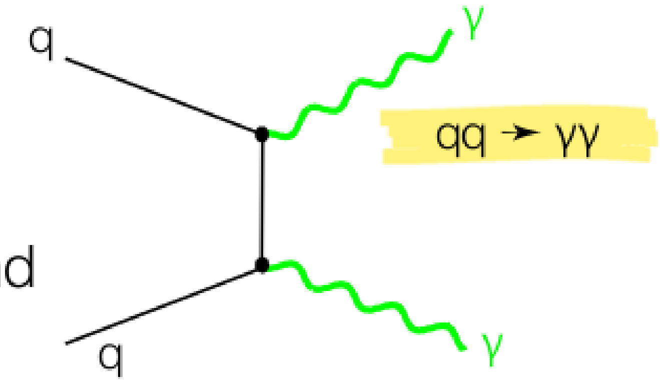


Signal: $\sigma \cdot BR = 50$ fb [$m_H = 100$ GeV]

very demanding channel due to huge irreducible background ...

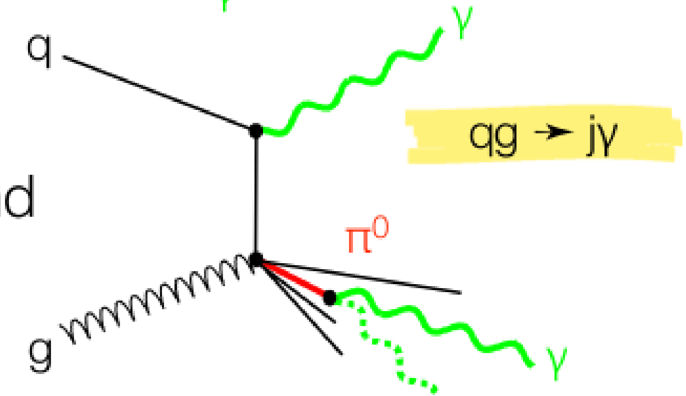
very harsh requirements on calorimeter performance
[acceptance, E and θ-resolution, separation of γ from jets and π^0]

Two main background sources:



2γ-production: irreducible background

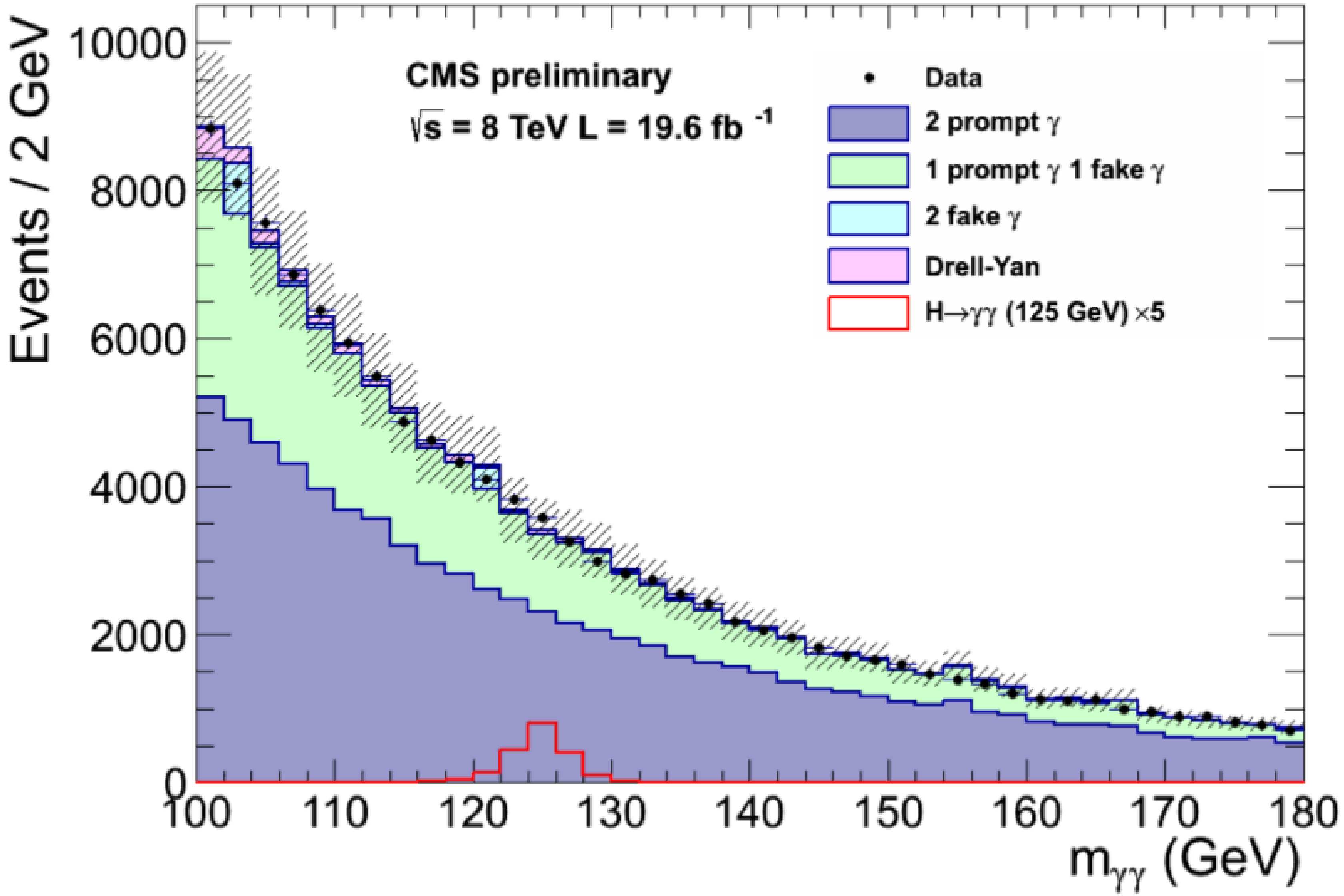
$\sigma_{\gamma\gamma}$ ~ 2 pb/GeV and Γ_H ~ MeV



γ-jet and di-jet production: reducible background

$\sigma_{\gamma j+jj}$ ~ 10^6 $\sigma_{\gamma\gamma}$; jet rejection of > 10^3 needed

Di-Photon Invariant Mass Distribution

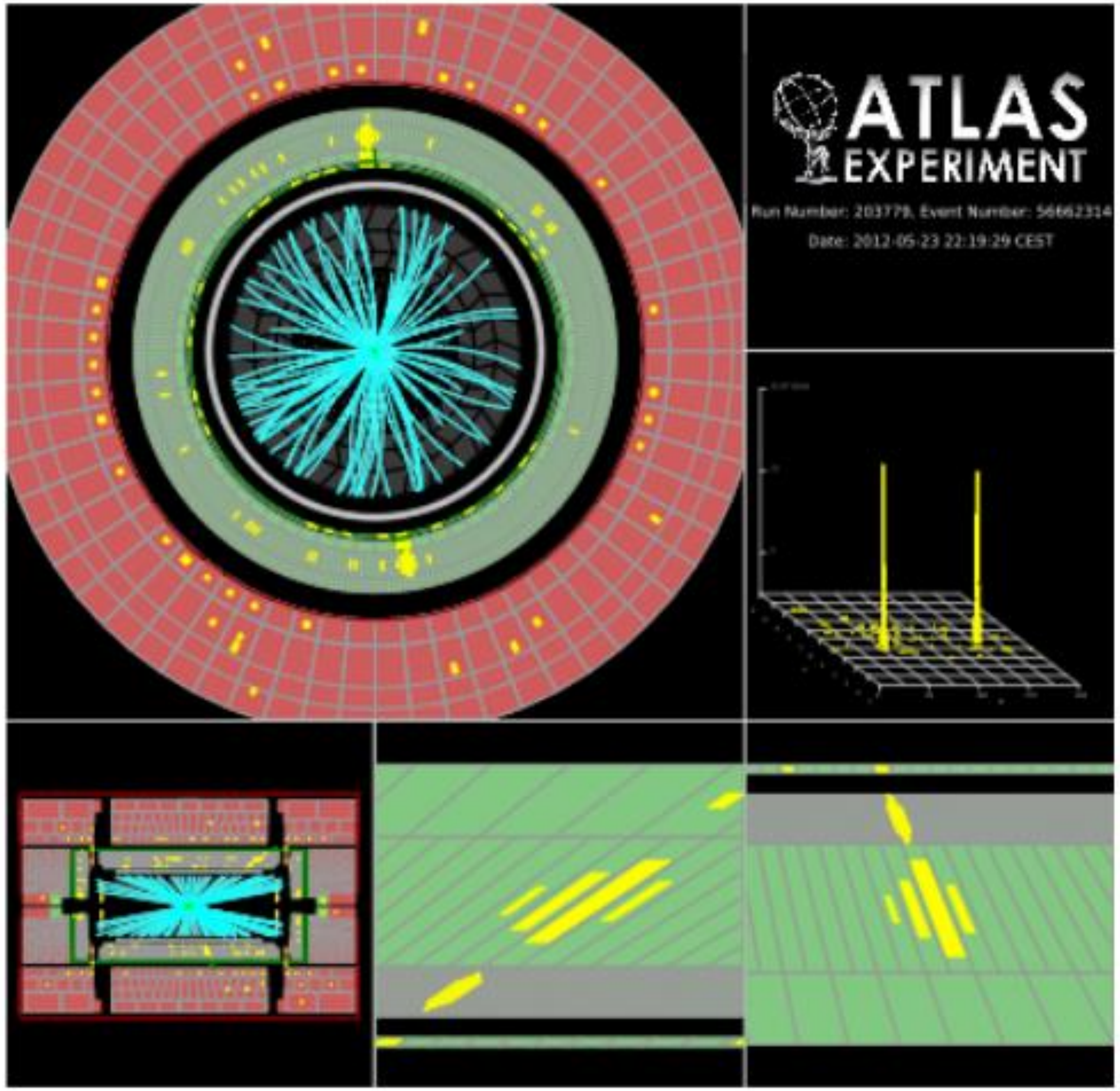


Photon & Object Reconstruction

Photons

isolated EM clusters, identified using shower shape variables
[use track or calorimeter isolation cone $\Delta R < 0.2$ or 0.4]

converted (two matched tracks, or single with no inner layer hit) and un-converted photon categories utilized



Shower Comparison …

Electromagnetic shower

consists of visible electromagnetic energy only

is very compact ($X_0 \approx 2$ cm)

can be simulated with high precision since mostly electromagnetic processes need to be calculated

allows high accuracy calibration

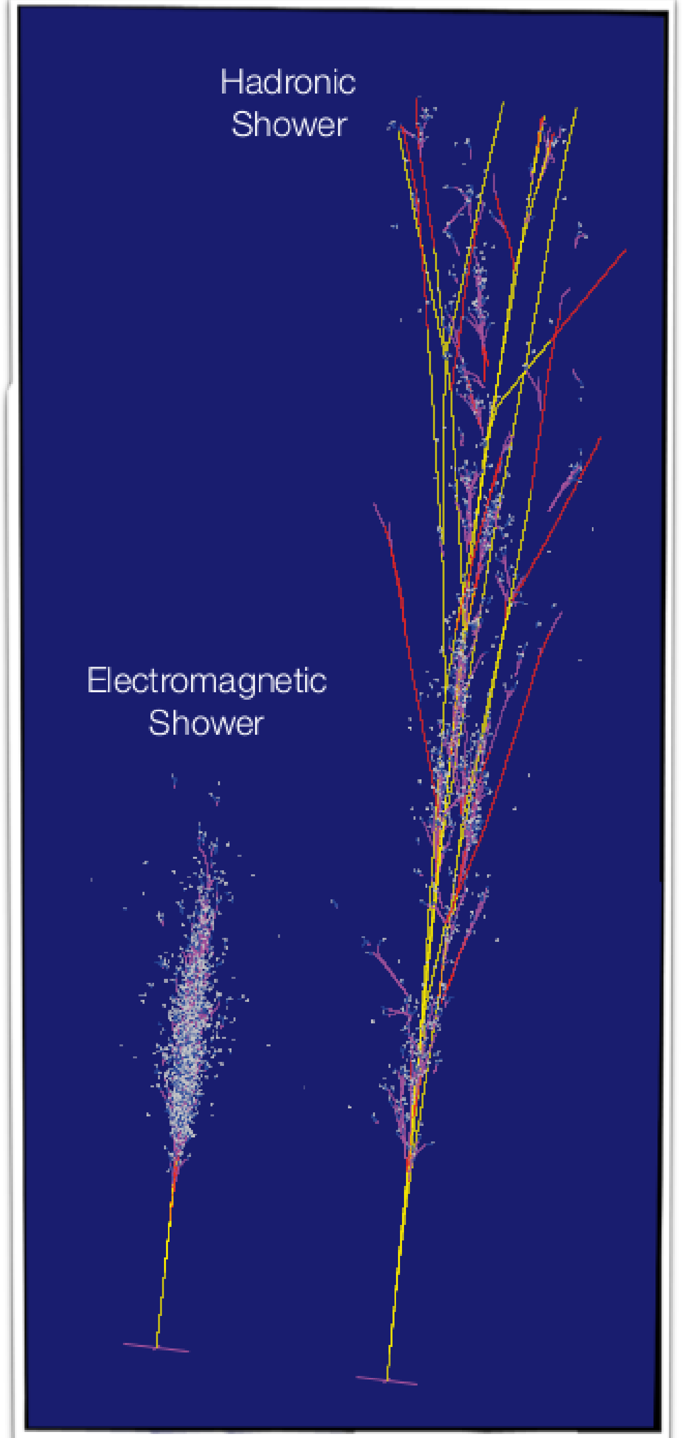
Hadronic shower

consists of EM and hadronic energy (some invisible)
is very large ($\lambda_0 \approx 20$ cm)

is difficult to simulate since it involves QCD

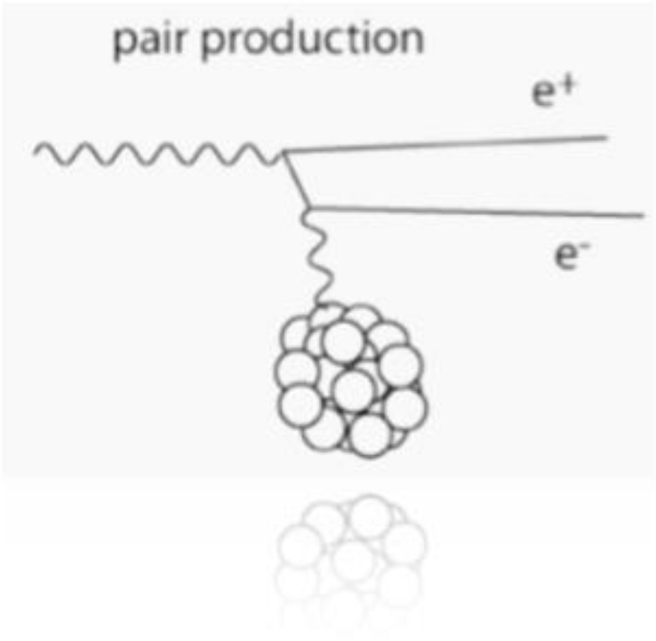
limits the accuracy for calibration
(mostly due to large fluctuations)

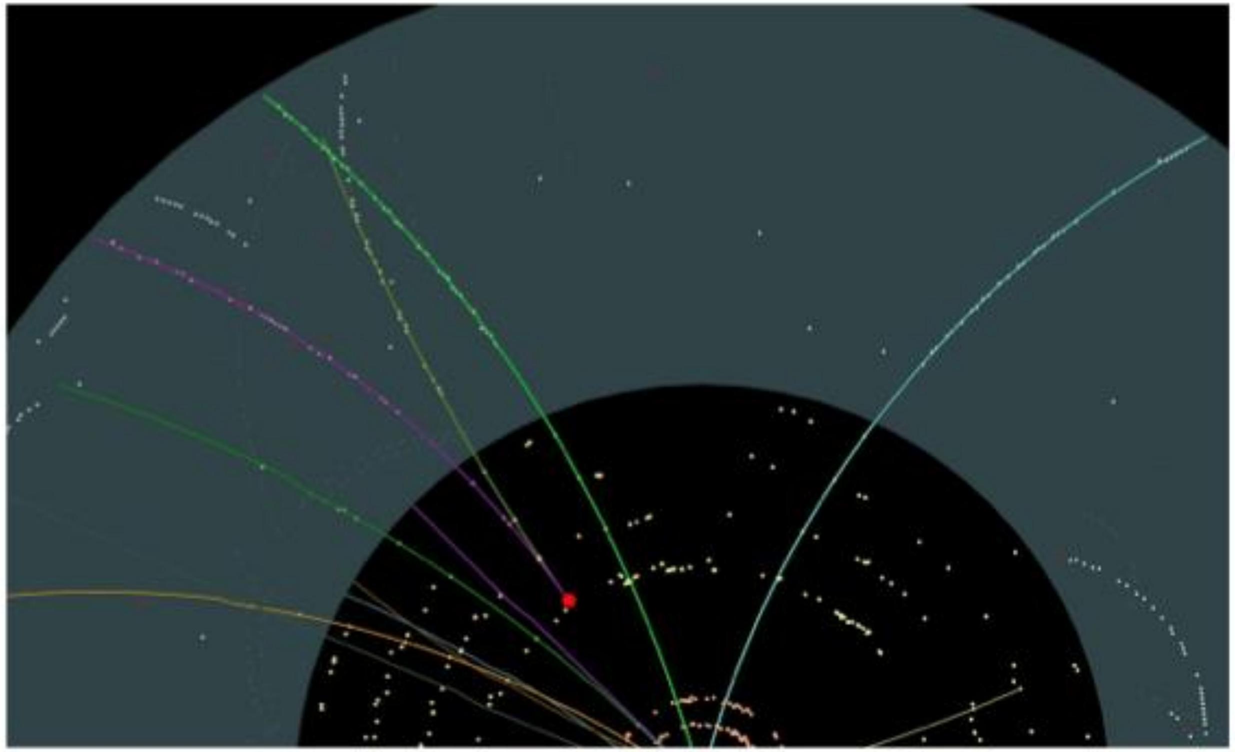
Examples show 50 GeV showers
of an electron and a pion in iron …



Photon conversions

Have to be careful!
Photons can pair-produce when passing through material
Results in tracks – but also a secondary vertex

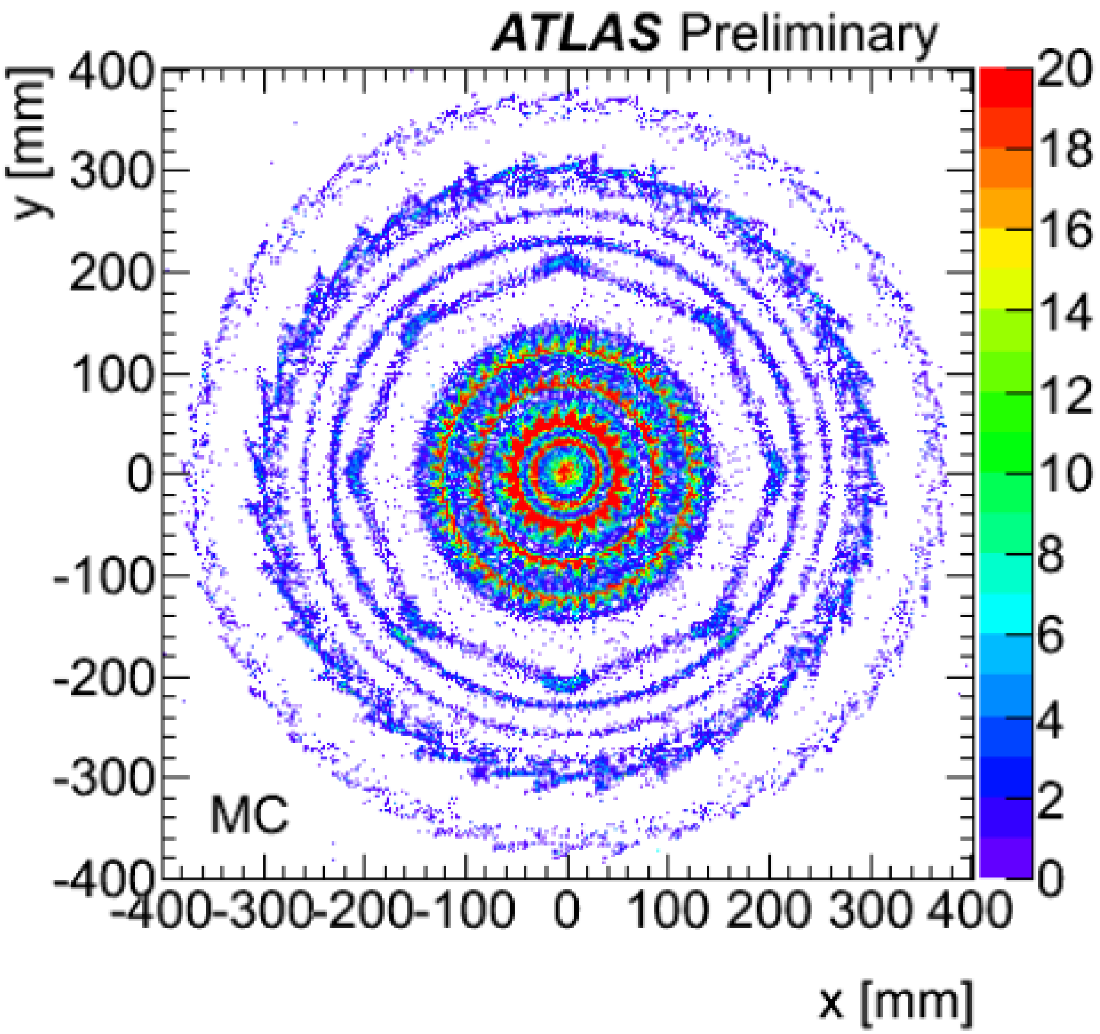


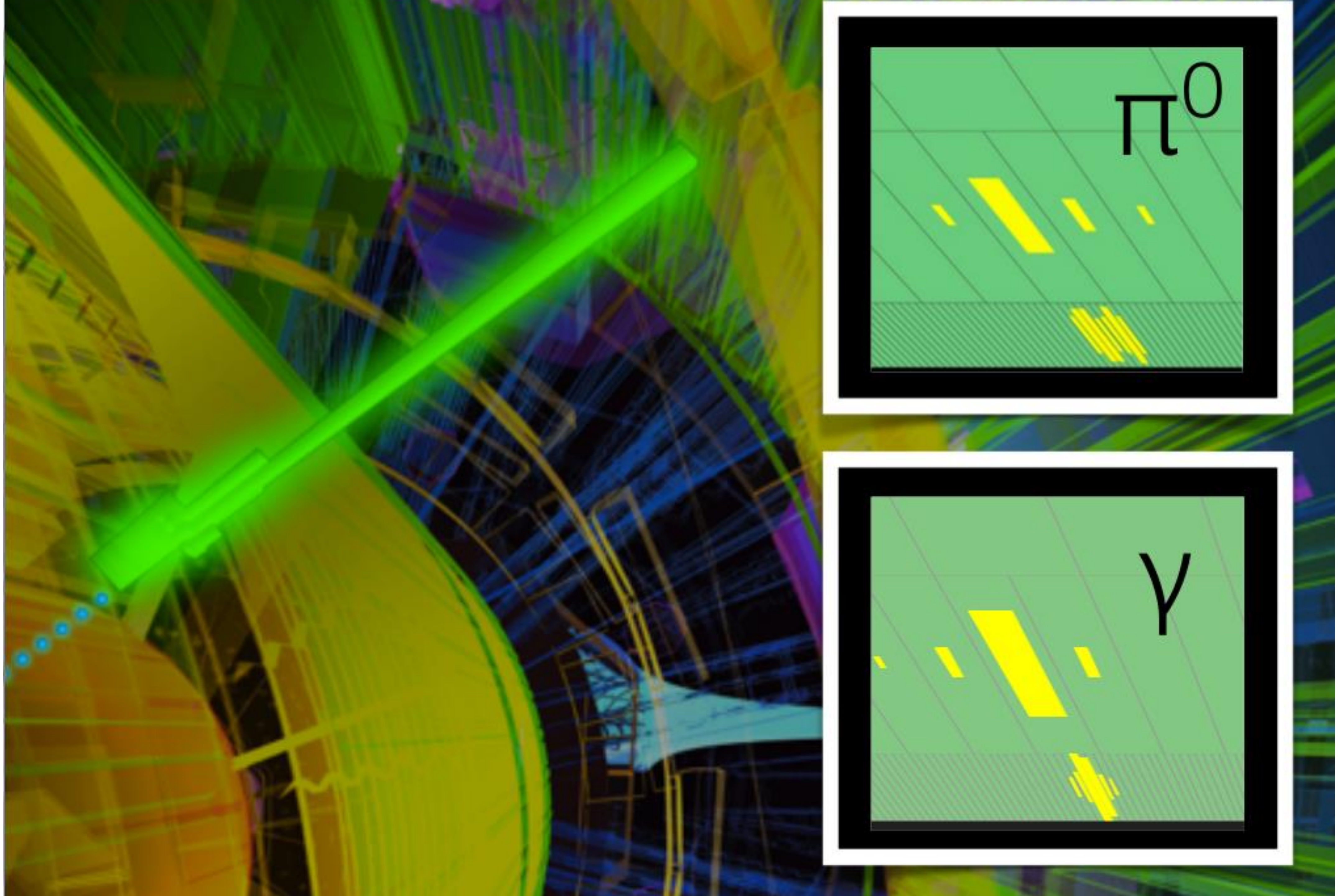


Photon conversions

The more material, the more photon conversions

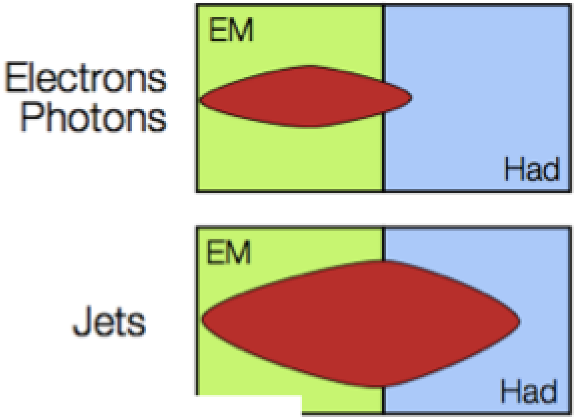
Here: Location of photon conversions
→ The structure of the material is clear

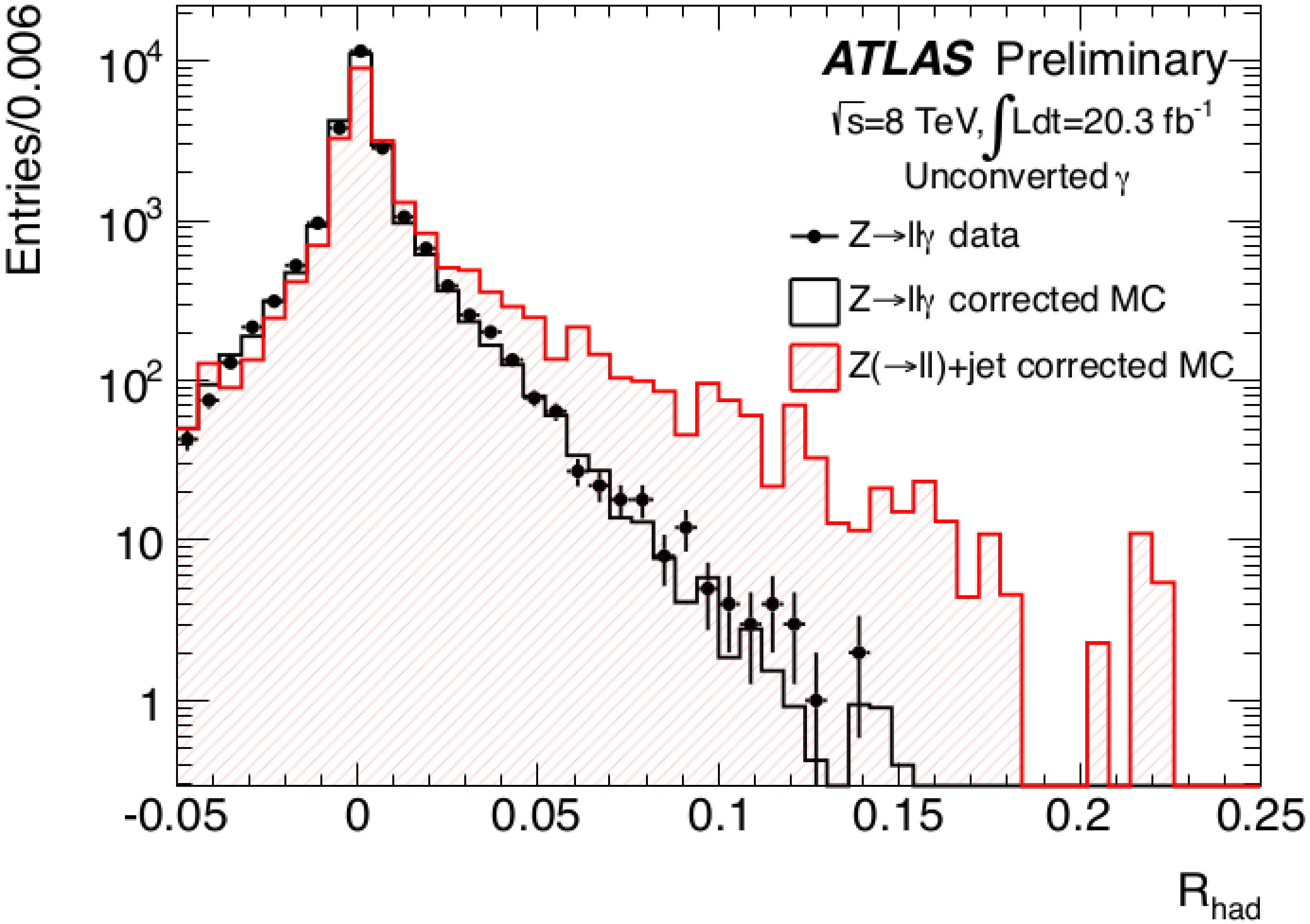




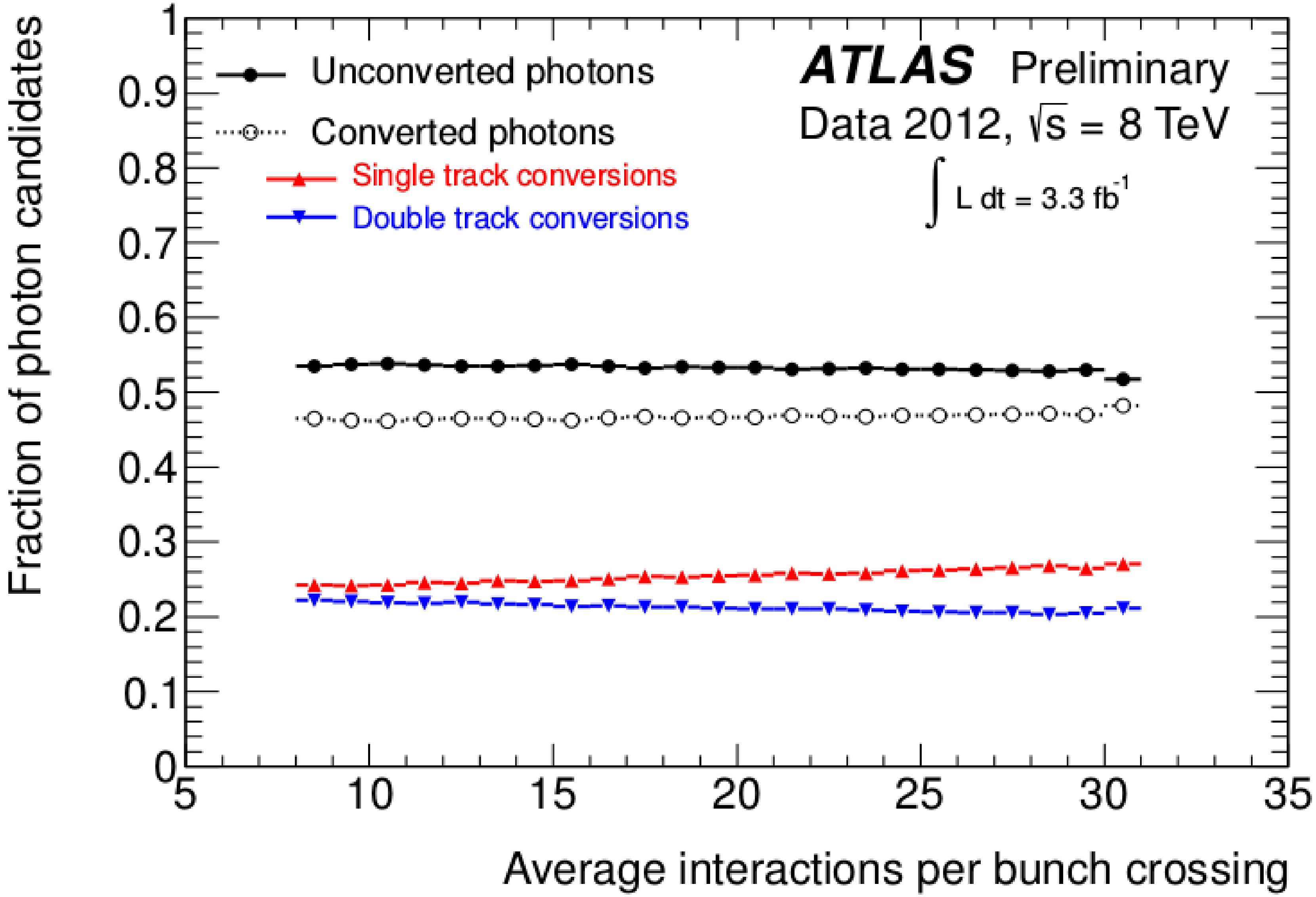
π^0
γ

Hadronic Leakage

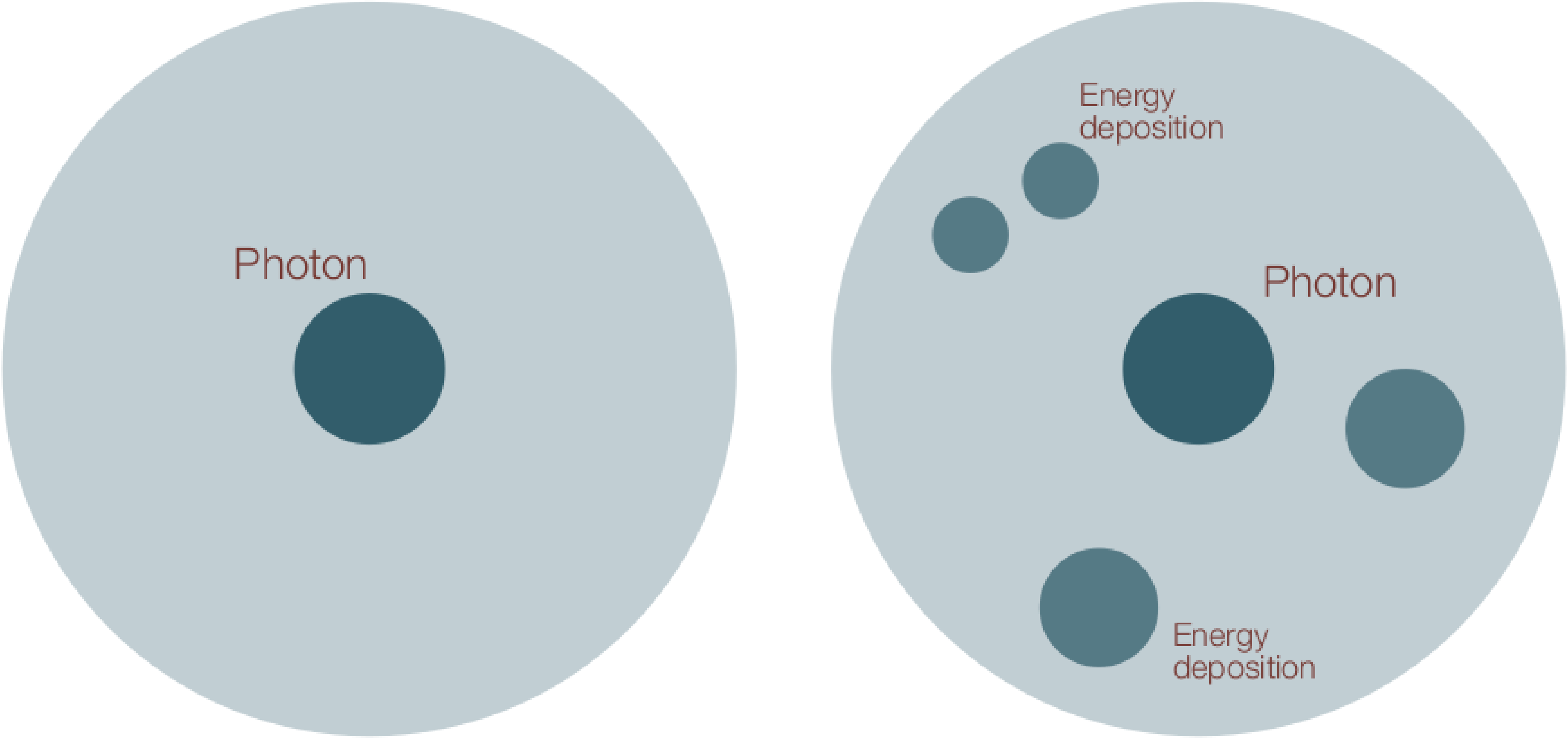




Pile-Up Robustness



Finding Isolated Photons …

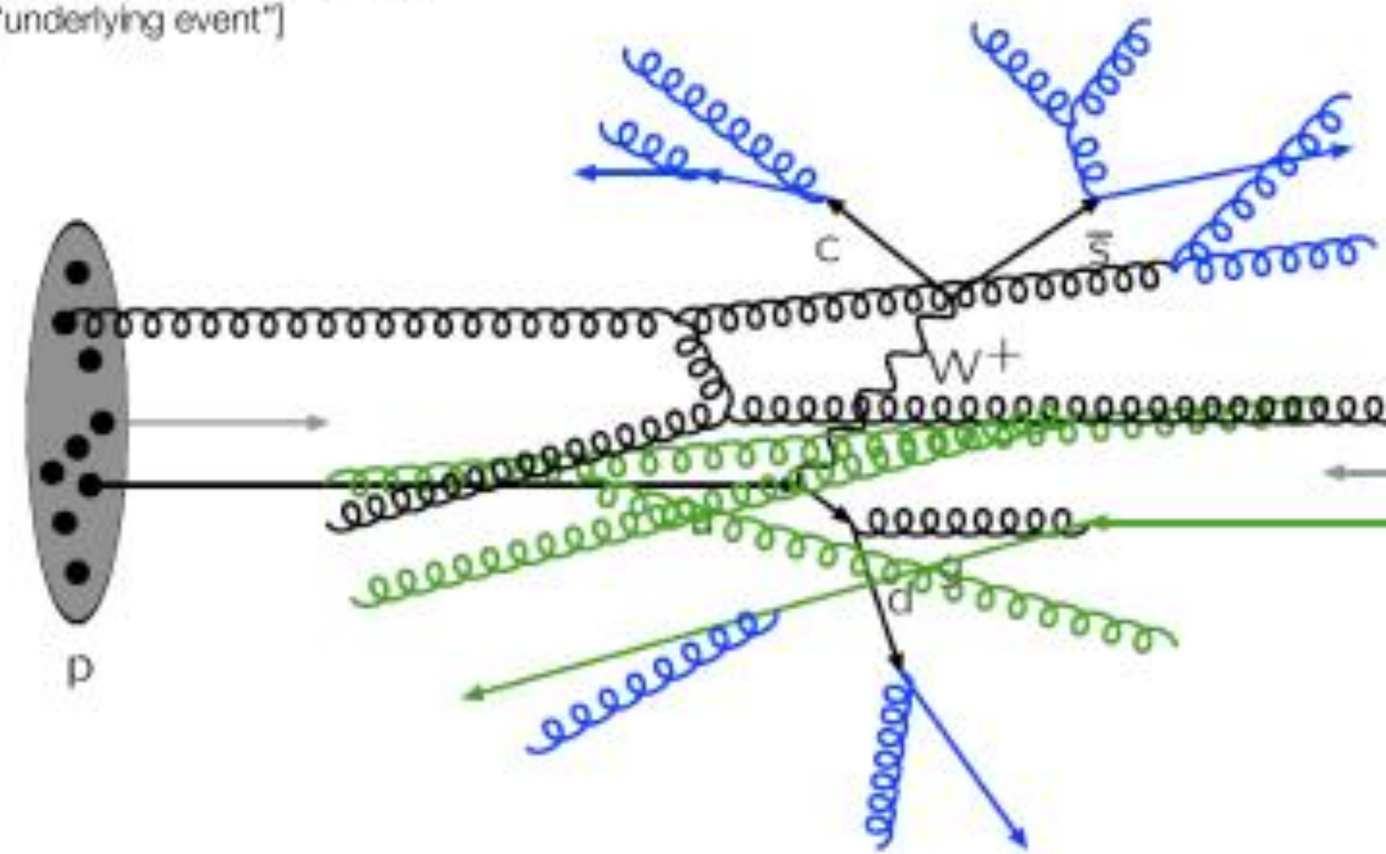


Isolated

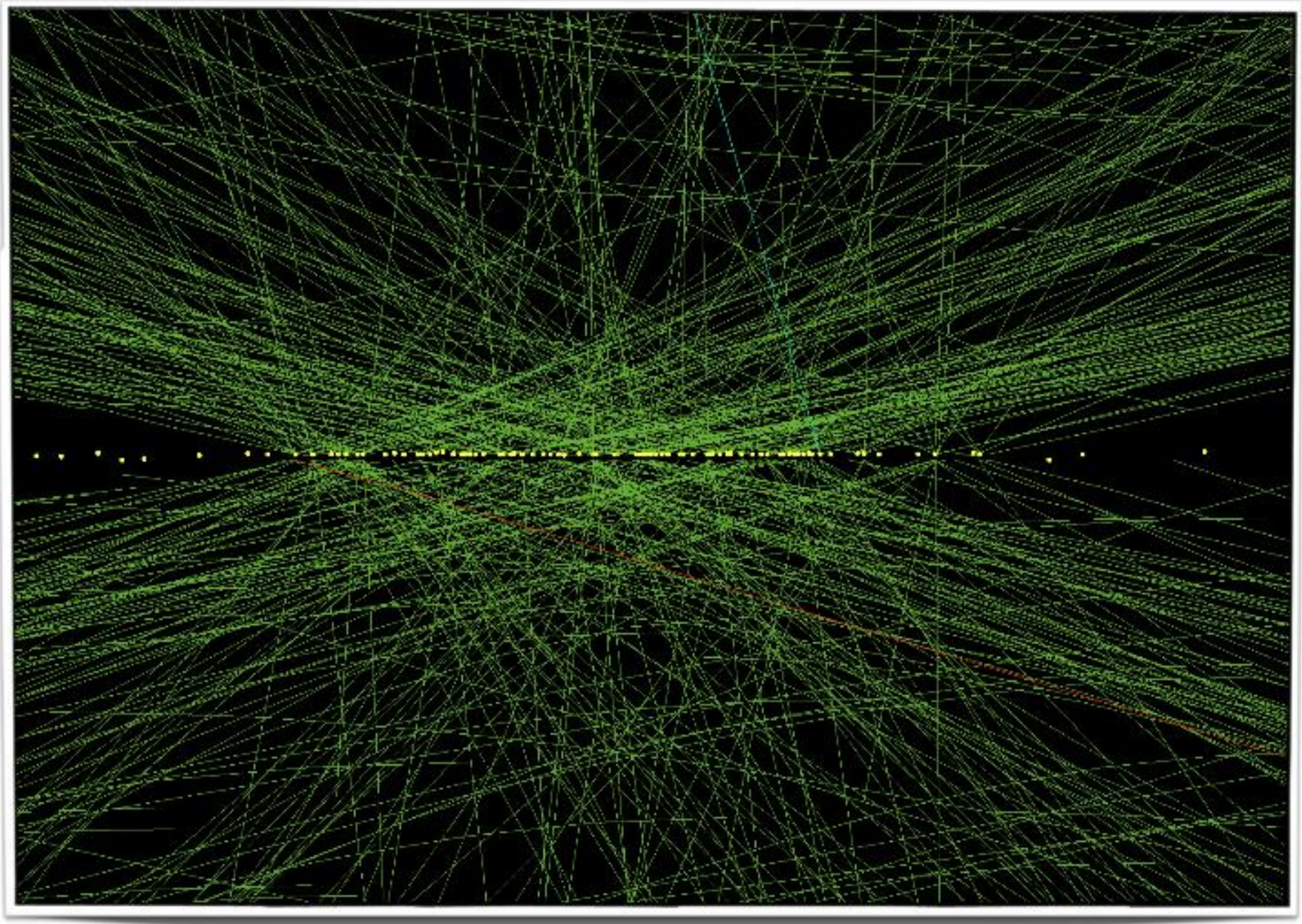
Non-isolated

Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion
- Initial State Radiation (ISR)
- Secondary Interaction
  ["underlying event"]



Extreme Pile-up Event



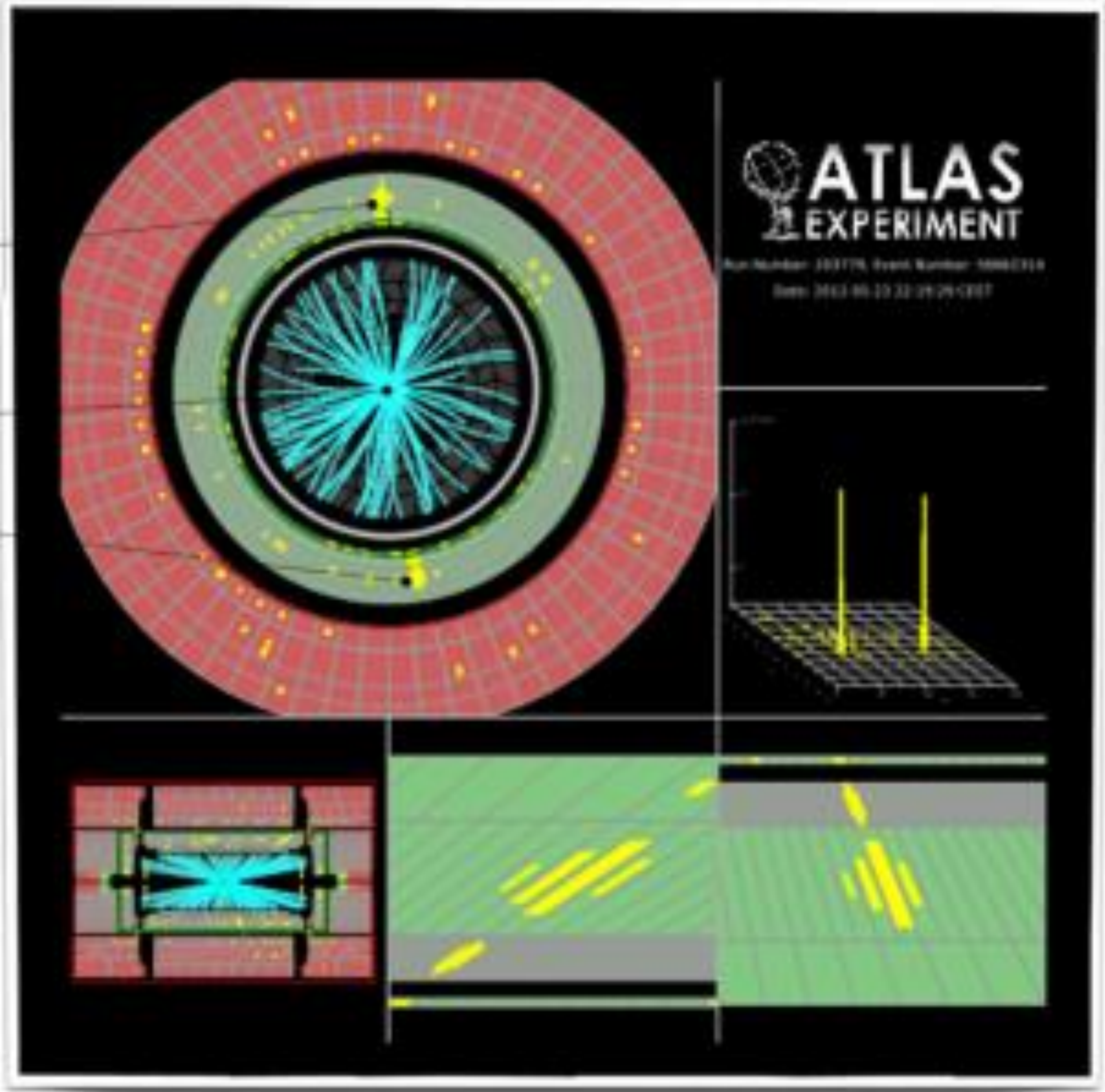
CMS

Analysis Necessities & Steps …

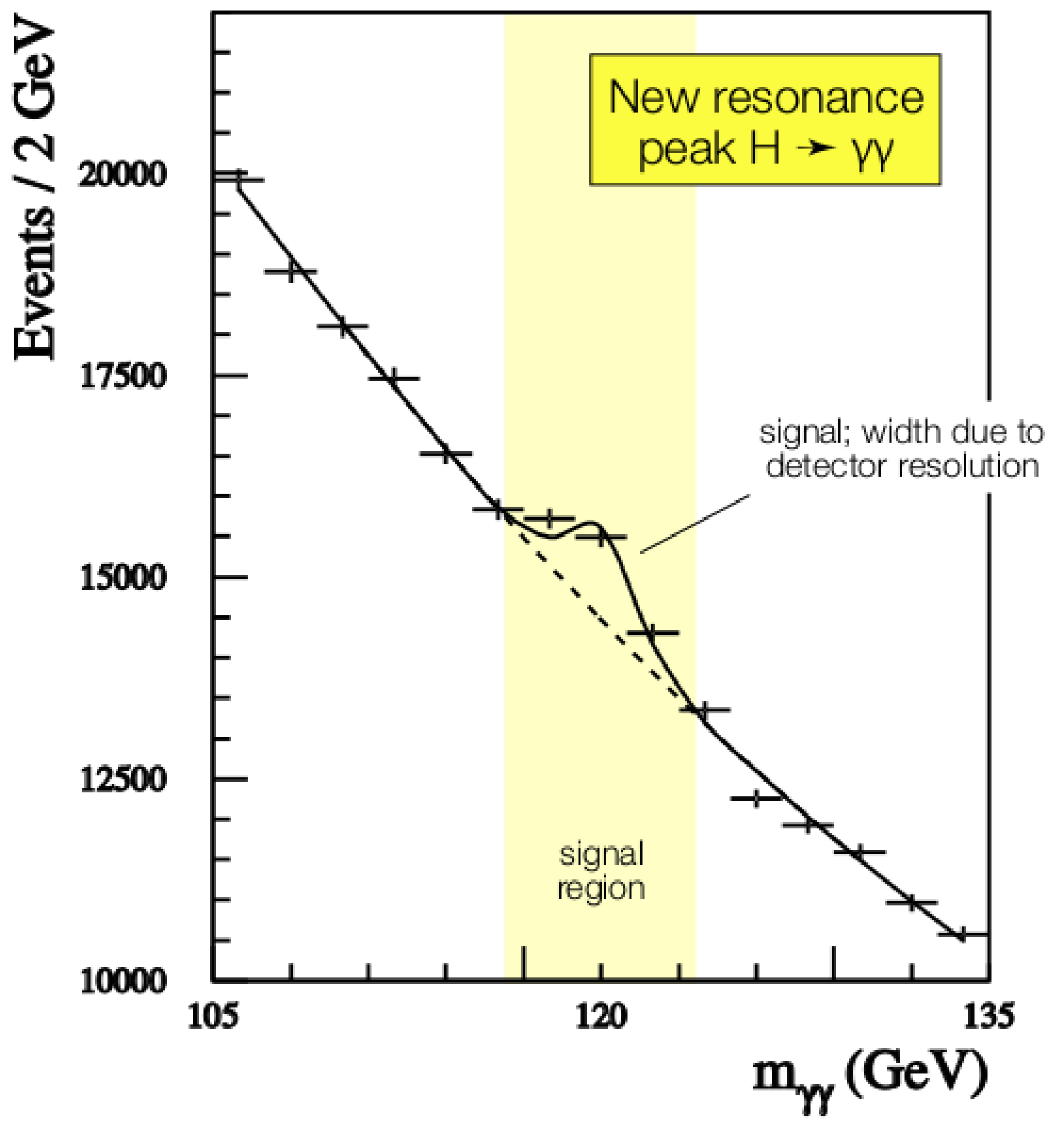
Photon reconstruction
Photon identification
Photon isolation
Primary vertex
Energy calibration
Background modeling

Event categories

Limits & signal strength



Energy Resolution



Signal significance:

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

N_S: # signal events
N_B: # background events
... in peak region

Estimate

[assuming 1-2% resolution; $M_H \approx 120$ GeV]

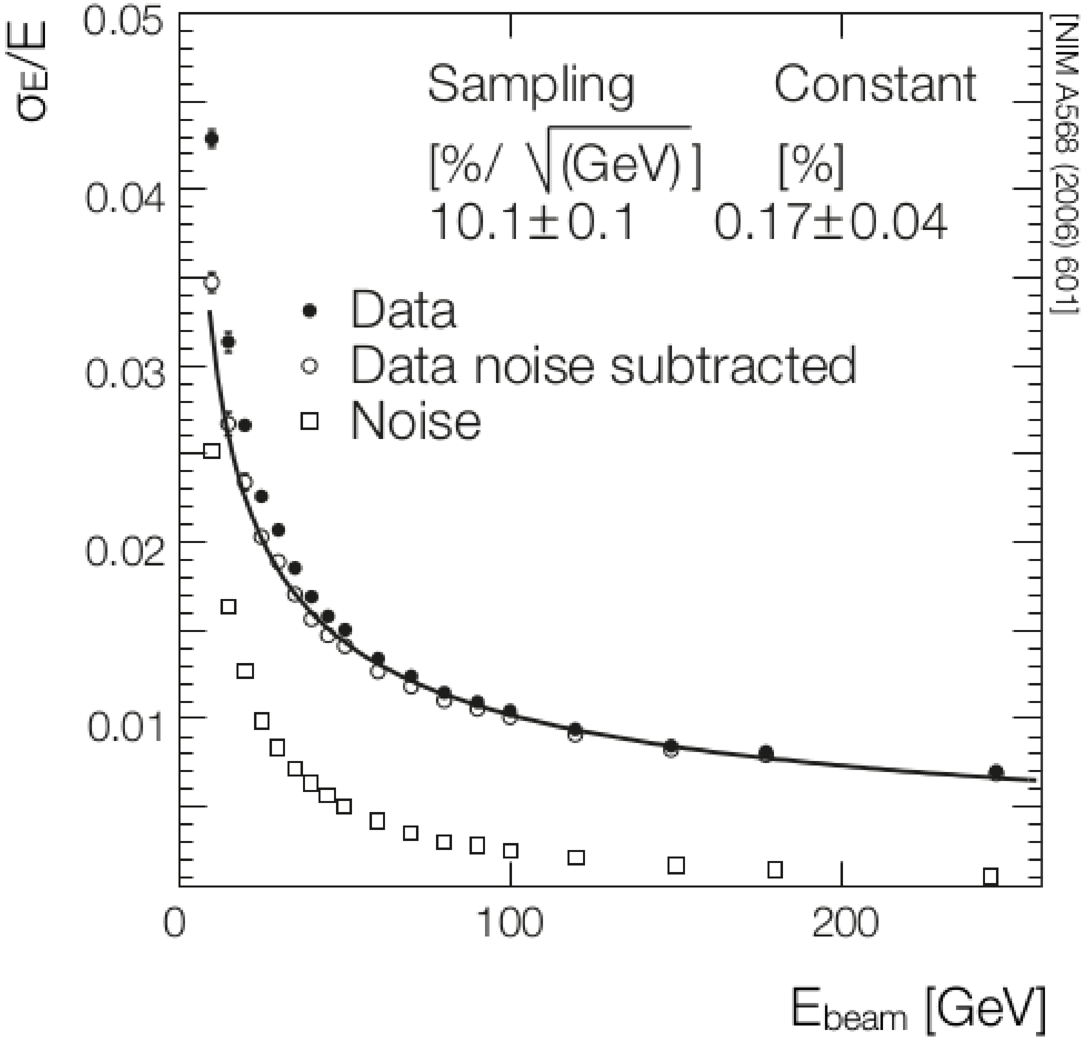
$\sigma_{H\gamma\gamma}$ ~ 50 fb
$\sigma_{\gamma\gamma}$ ~ 2 pb/GeV [Γ_H ~ negligible ...]

$L = 20\ fb^{-1}$
$N_s = 50\ fb \times 20\ fb^{-1} = 1000$
$N_b = 4\ pb \times 20\ fb^{-1} = 80.000$

$S = 3.5$

Energy Resolution

Test Beam Result
Fractional Energy Resolution



Resolution @ 60 GeV:

$\sigma_E \approx 0.014$ [FWHM = 3.3 %]

Event numbers and mass resolution for the H ➛ γγ ATLAS analysis …

[Mass range: 100 - 160]

$\sqrt{s}$	7 TeV		8 TeV		
$\sigma \times B(H \to \gamma\gamma)$ [fb]		39		50	FWHM
Category	N_D	N_S	N_D	N_S	[GeV]
Unconv. central, low p_{Tt}	2054	10.5	2945	14.2	3.4
Unconv. central, high p_{Tt}	97	1.5	173	2.5	3.2
Unconv. rest, low p_{Tt}	7129	21.6	12136	30.9	3.7
Unconv. rest, high p_{Tt}	444	2.8	785	5.2	3.6
Conv. central, low p_{Tt}	1493	6.7	2015	8.9	3.9
Conv. central, high p_{Tt}	77	1.0	113	1.6	3.5
Conv. rest, low p_{Tt}	8313	21.1	11099	26.9	4.5
Conv. rest, high p_{Tt}	501	2.7	706	4.5	3.9
Conv. transition	3591	9.5	5140	12.8	6.1
2-jet	89	2.2	139	3.0	3.7
All categories (inclusive)	23788	79.6	35251	110.5	3.9

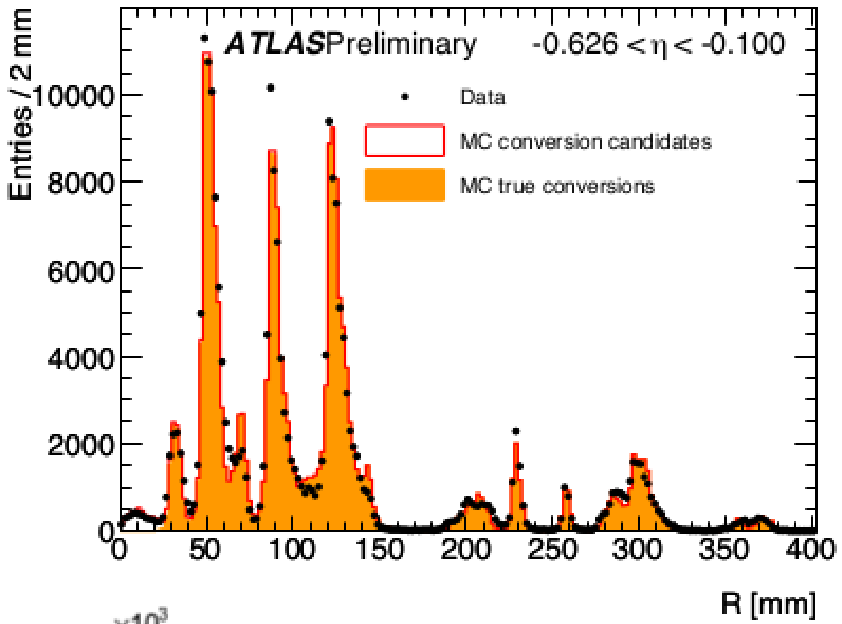
[ATLAS, Phys. Lett. B 716 (2012) 1]

Energy Calibration

Monte Carlo based calibration

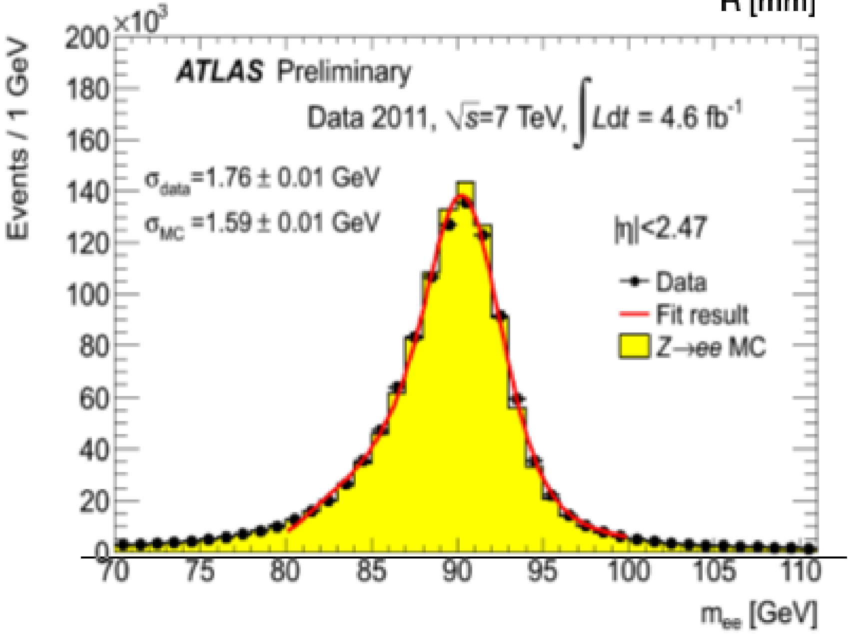
Monte Carlo simulation tuned with test beam data.

Accurate description of materials is confirmed by measurements in data.



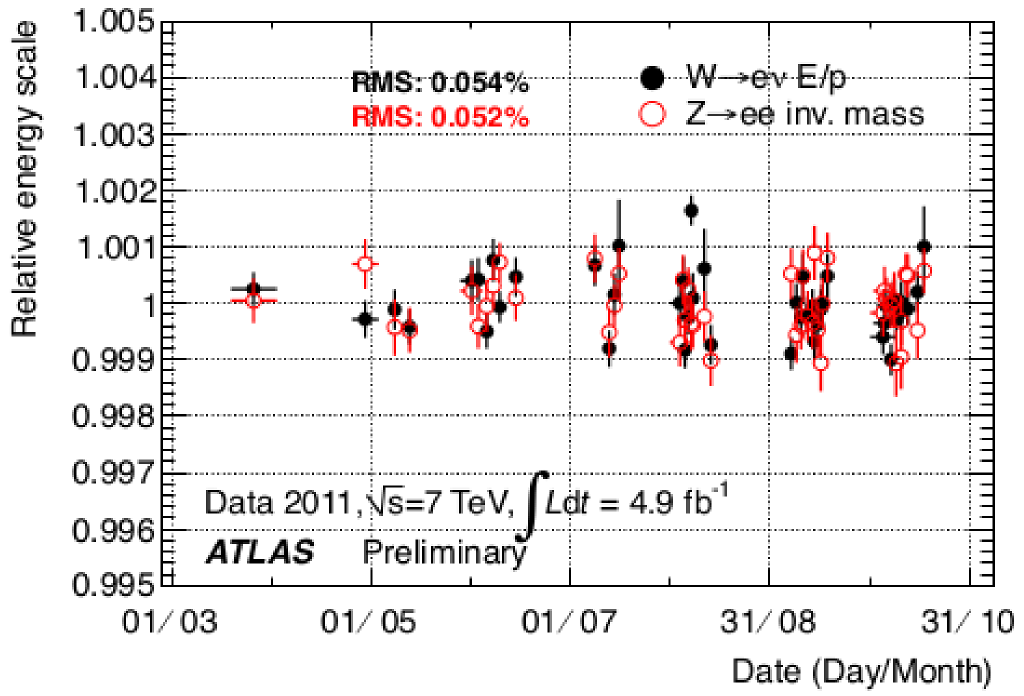
Energy scale corrections using Z ➛ ee decay data …

- Energy scale correction applied to data …
- Correction from a fit to the 2010 Z ➛ ee data …
- Extrapolation of energy scale correction from electron to photon is treated as uncertainty …
- MC energy is smeared to match the energy resolution determined from data …

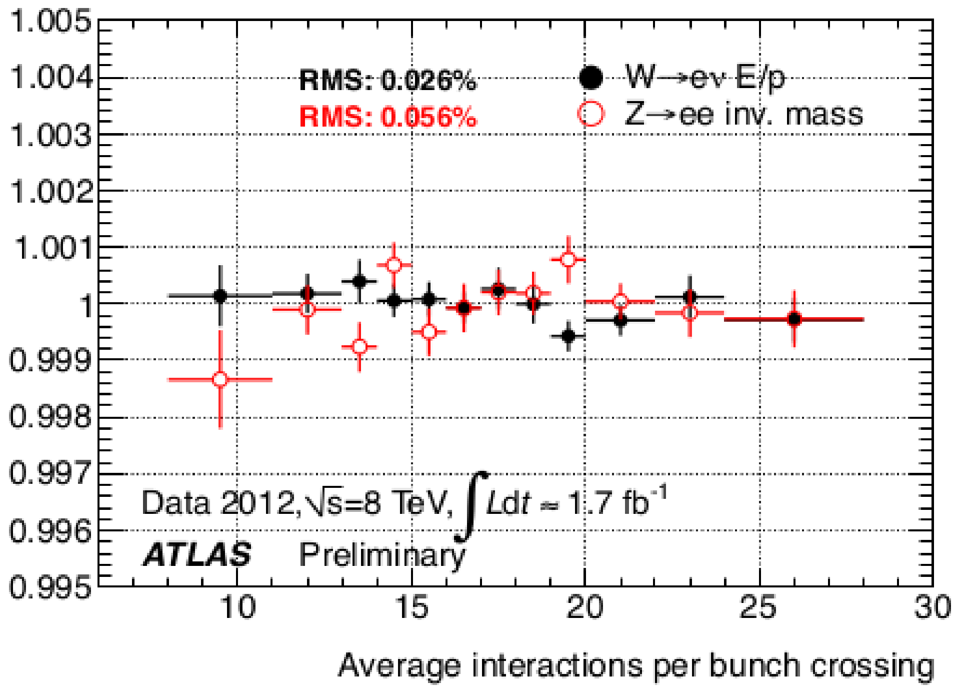


Energy Calibration

Relative Energy Scale
as function of time



Relative Energy Scale
as function of interactions



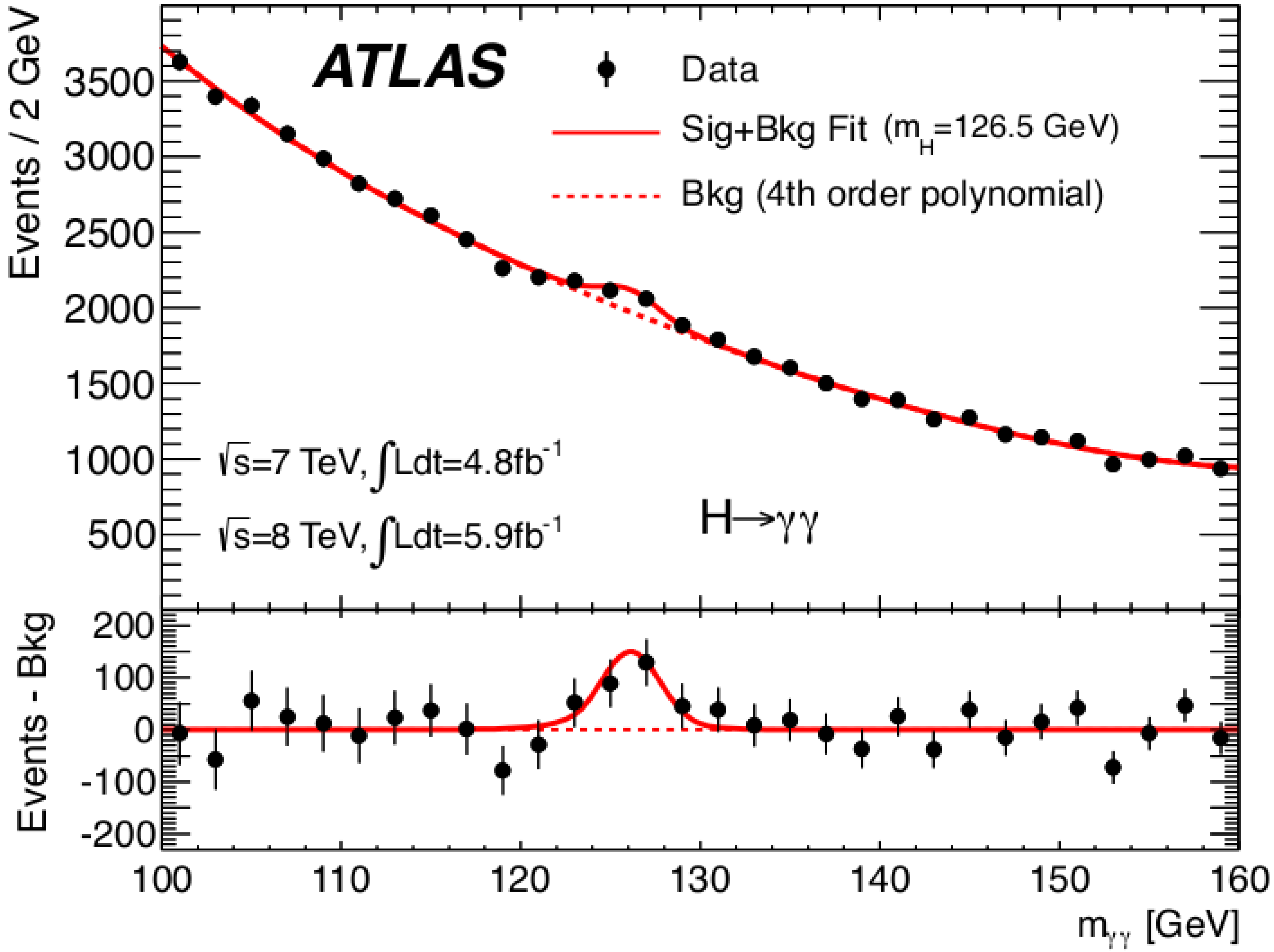
Excellent stability with time and pileup !

Photon energy resolution around 1%

ATLAS Result

Observation of a New Particle [H ➛ γγ]

[Summer 2012]



ATLAS Result

Observation of a New Particle [H ➝ γγ]

[Spring 2013]