Photon physics at the LHC with the ATLAS detector

Marco Delmastro

ATLAS

CERN

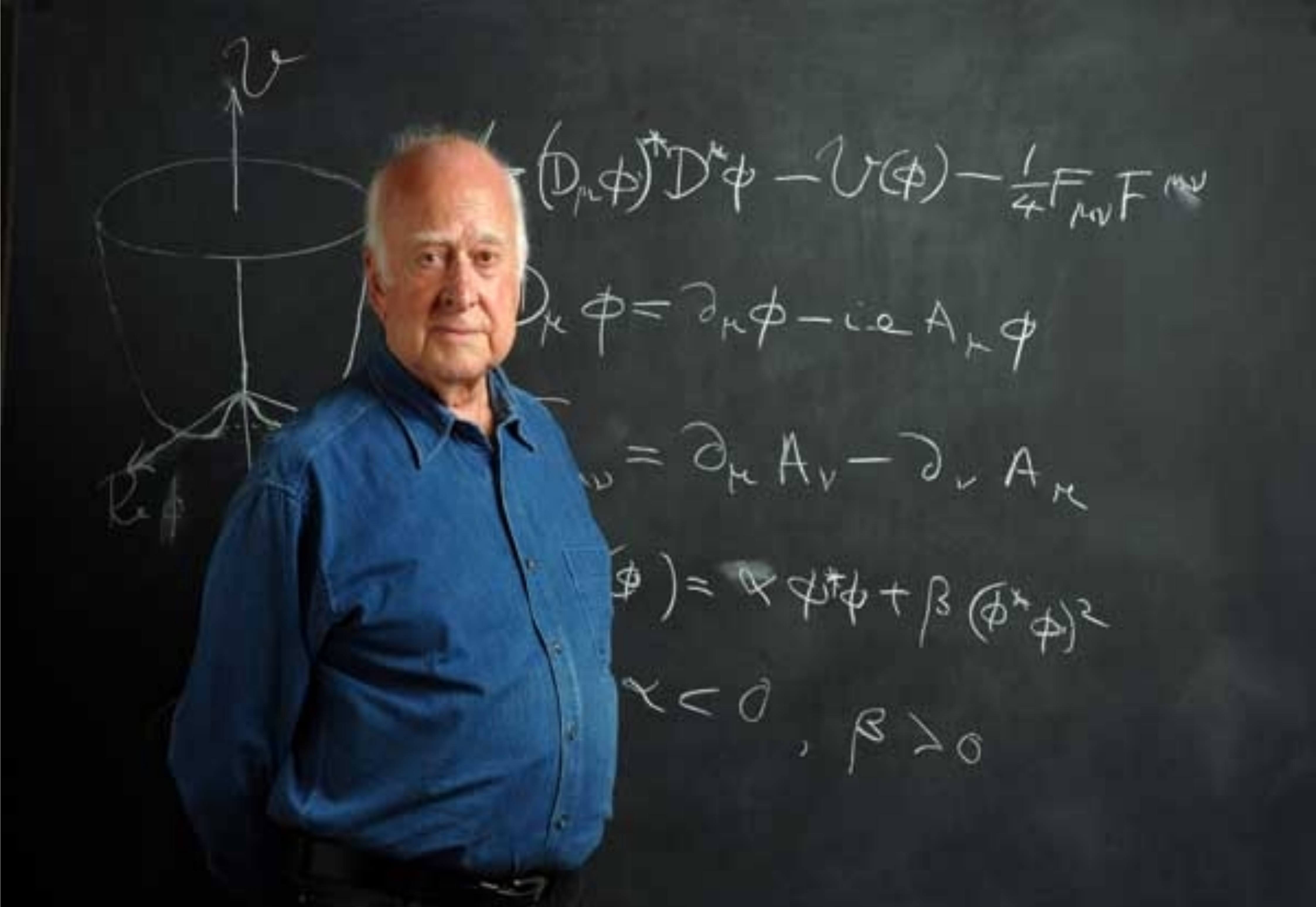

already
yawning?

How ATLAS will discover the SM Higgs boson* ** (or prove it does not exist)

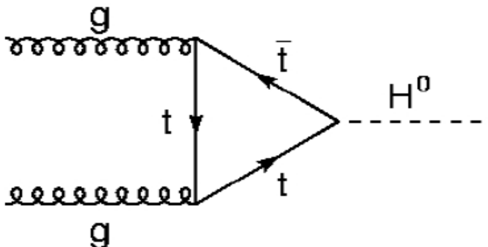
Marco Delmastro

* using photons!

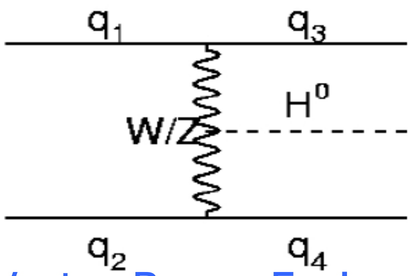
** and learning a lot of physics!


$(D_\mu \phi)^* D^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$D_\mu \phi = \partial_\mu \phi - ie A_\mu \phi$
$= \partial_\mu A_\nu - \partial_\nu A_\mu$
$) = \alpha \phi^* \phi + \beta (\phi^* \phi)^2$
$\alpha < 0 , \beta > 0$

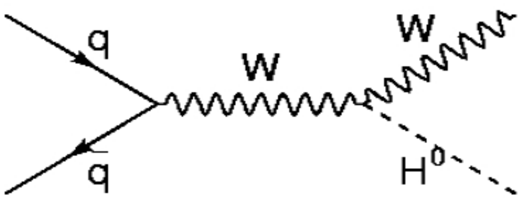
How *would* the SM Higgs be produced at LHC?



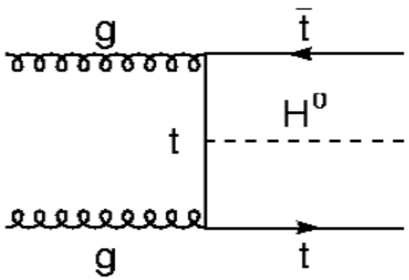
gluon fusion



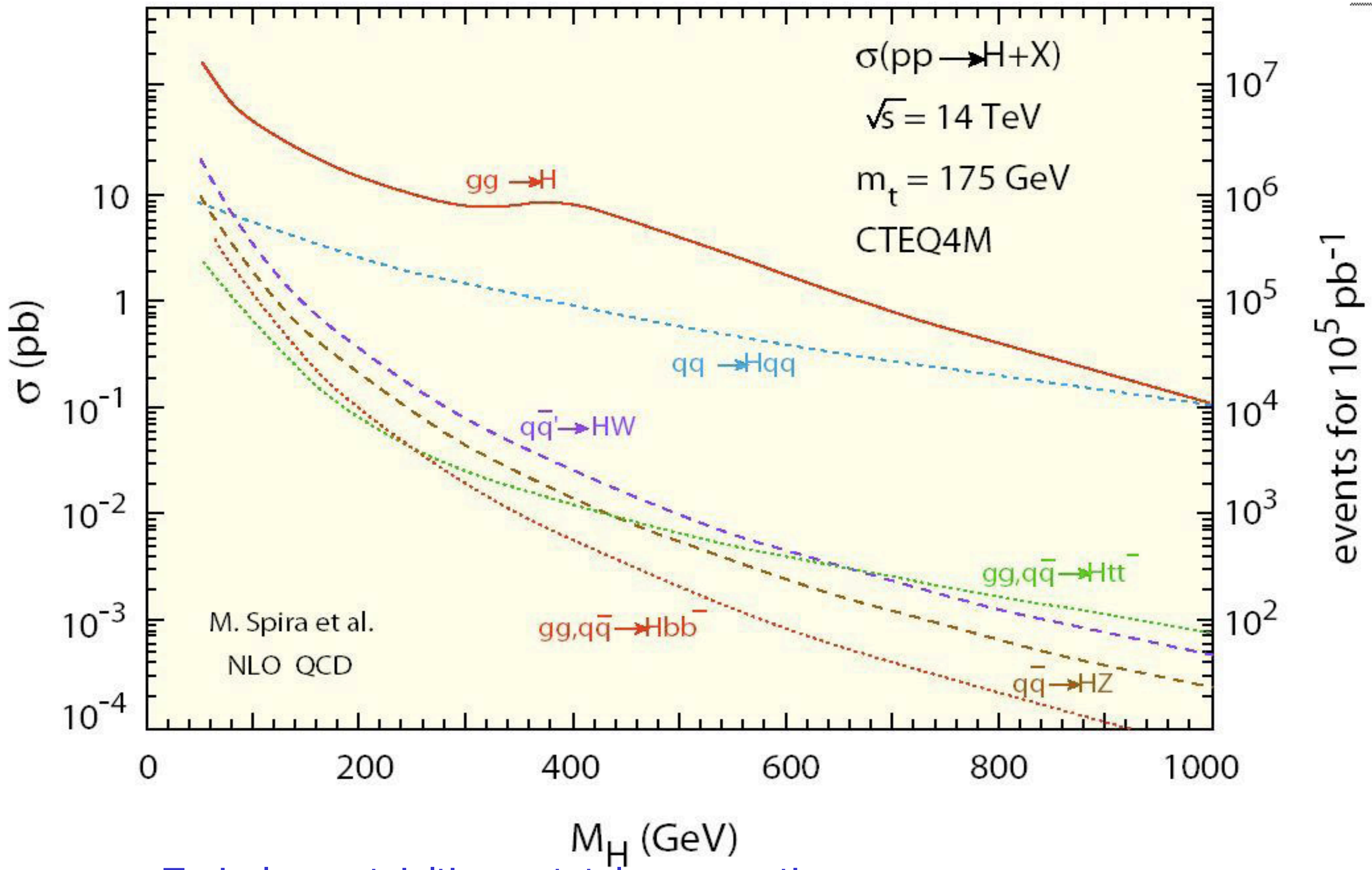
Vector-Boson-Fusion (VBF)



associated production (W, Z)



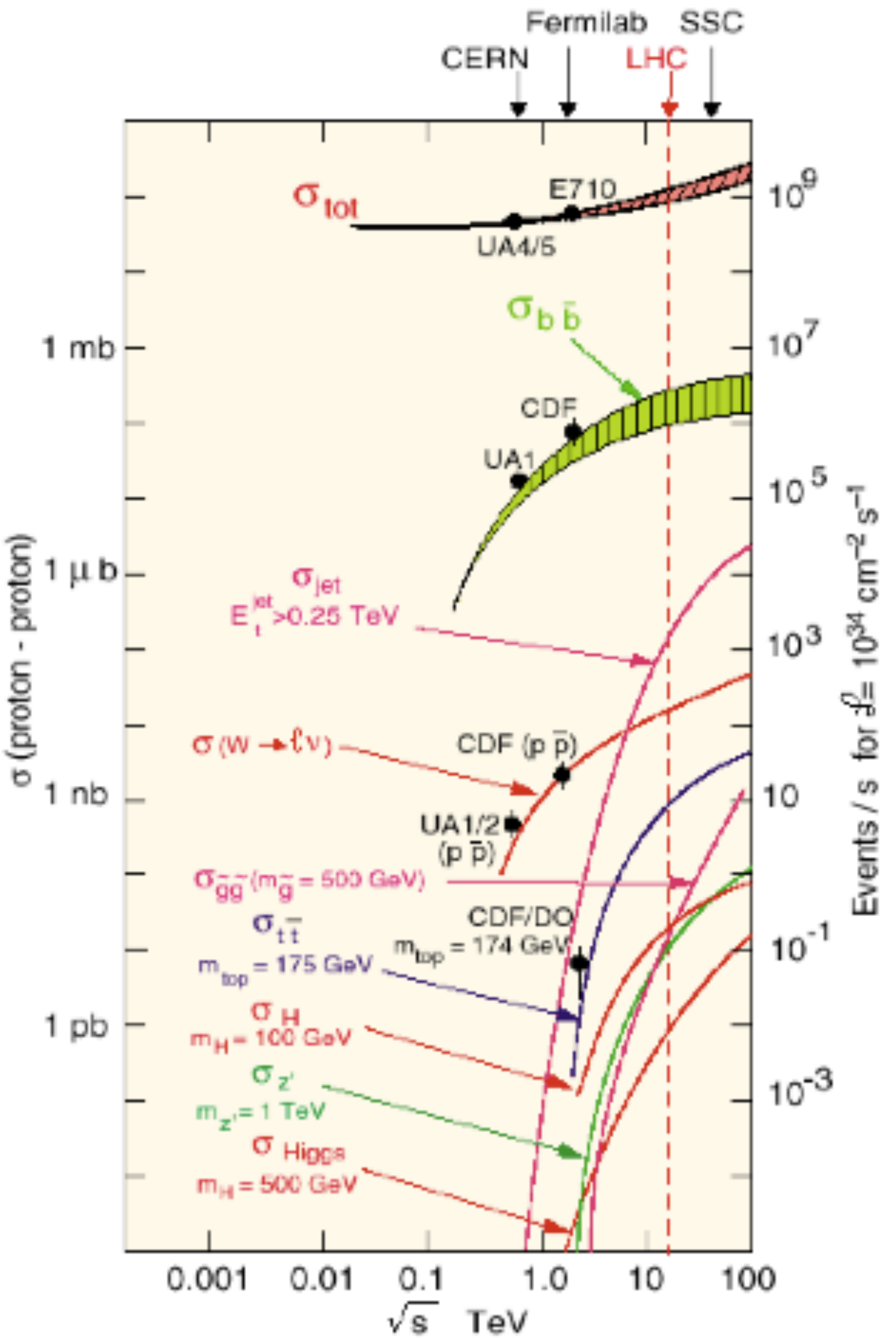
associated production (ttbar)



Typical uncertainlties on total cross-sections

gg	10%	NNLO + NNLL + NLO EW
VBF	5%	NNLO + NLO EW
WH, ZH	5%	NNLO + NLO EW
ttH	15%	NLO

Cross sections and rates (at 14 TeV)



Total inelastic cross-section: $\sigma \sim 100$ mb

bb production cross-section: $\sigma \sim 100\ \mu$b

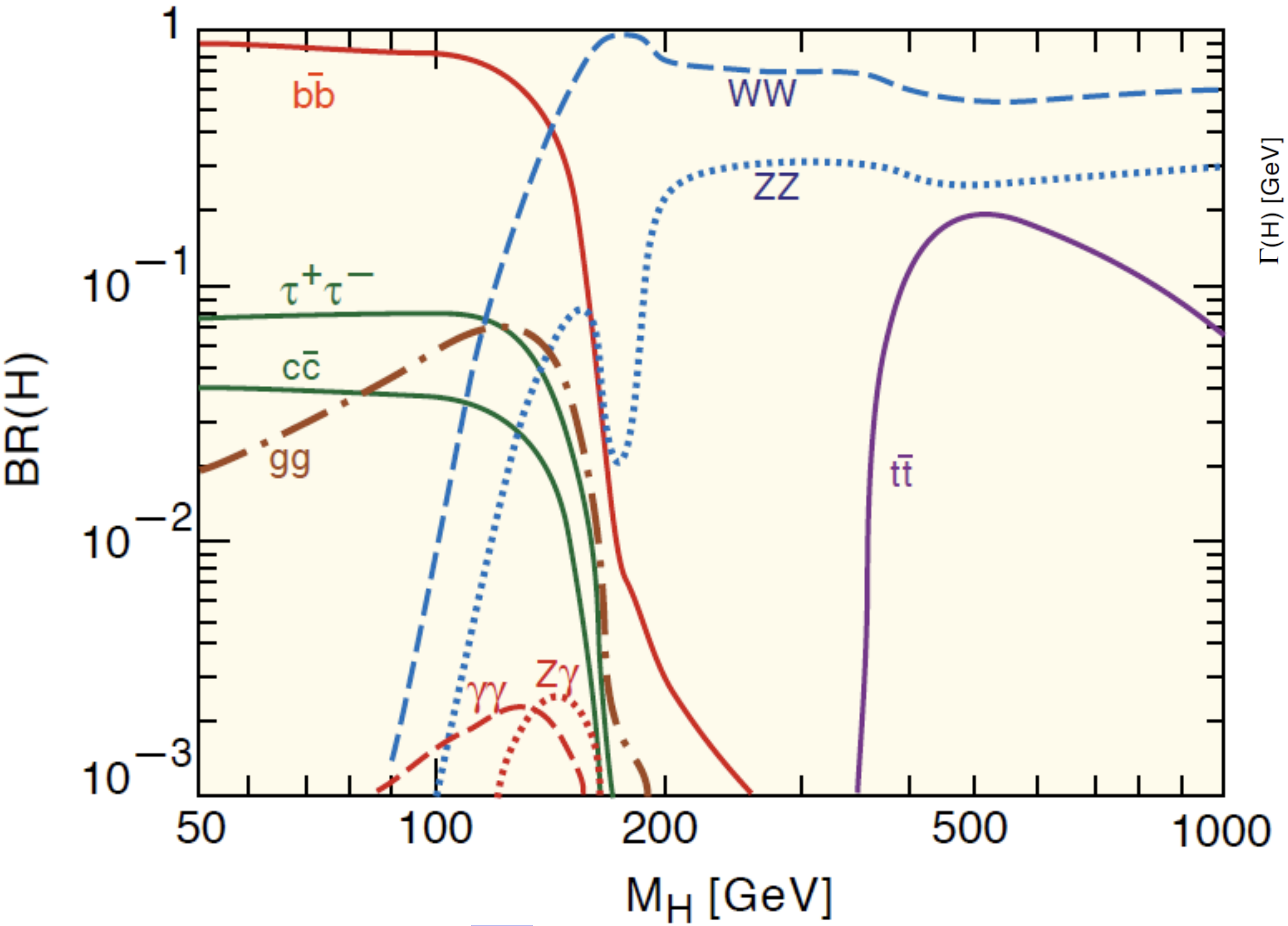
W ($\rightarrow l\nu$) production cross-section: $\sigma \sim 10$ nb

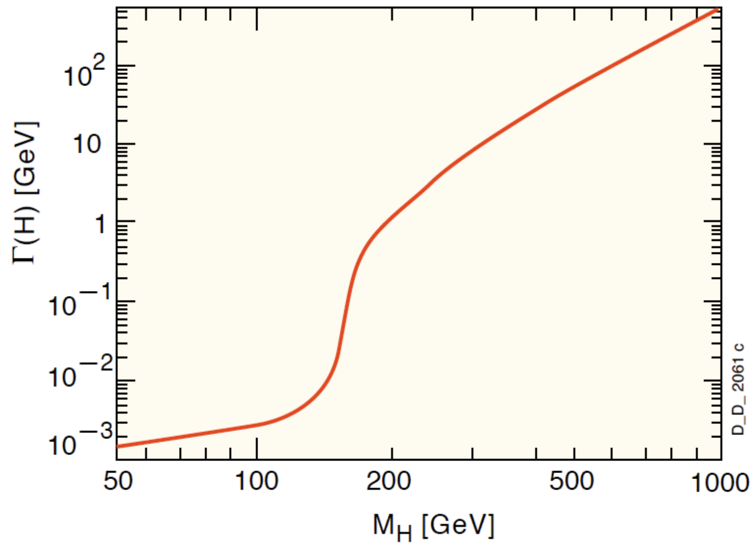
Higgs (m_H=150 GeV) cross-section: $\sigma \sim 10$ pb

Total σ / Higgs σ > 10^{10}

Why do we want to measure photons at LHC ?

How *would* the SM Higgs decay?





$bb \rightarrow m_H < 130$ GeV

$\gamma\gamma \rightarrow m_H < 140$ GeV

$\tau\tau \rightarrow m_H < 150$ GeV

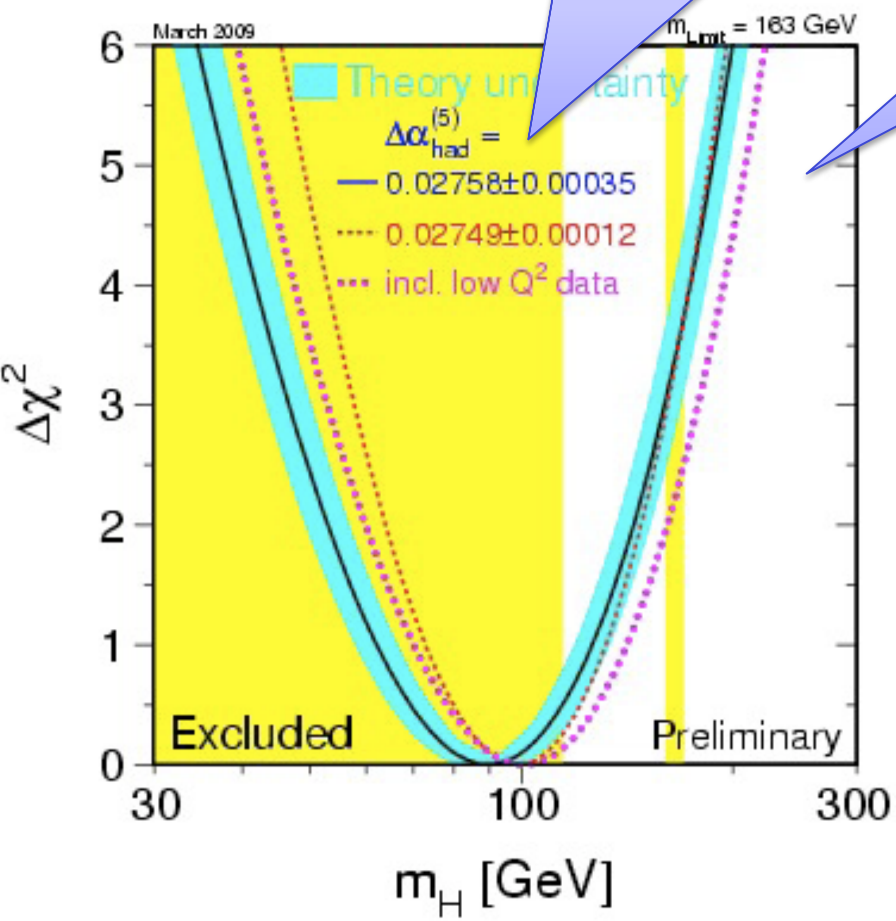
$WW \rightarrow 2m_W < m_H < 2m_Z$

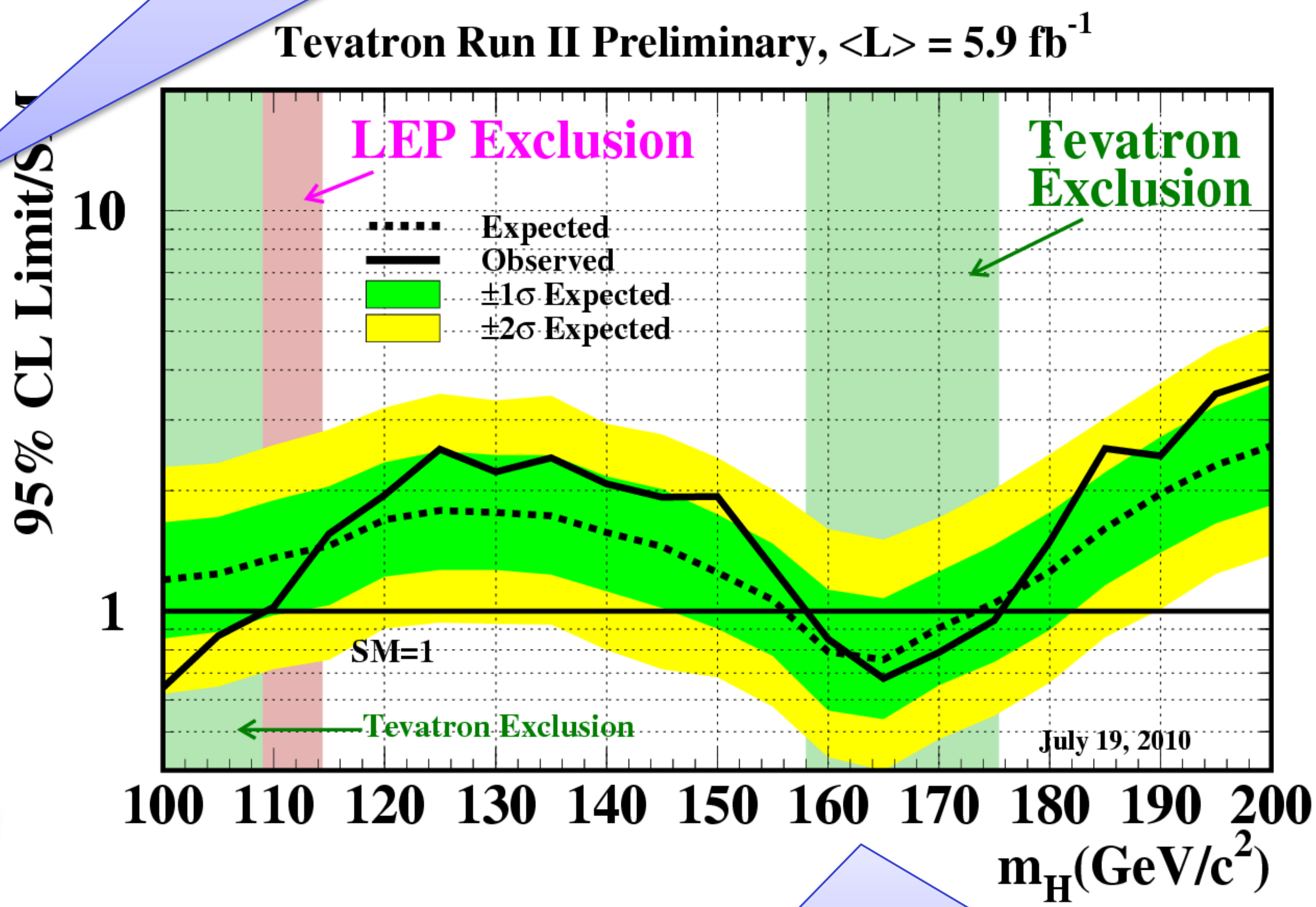
$ZZ \rightarrow m_H > 130$ GeV

Where is the Higgs boson hiding?

LEP direct search: m_H > 114.4 GeV

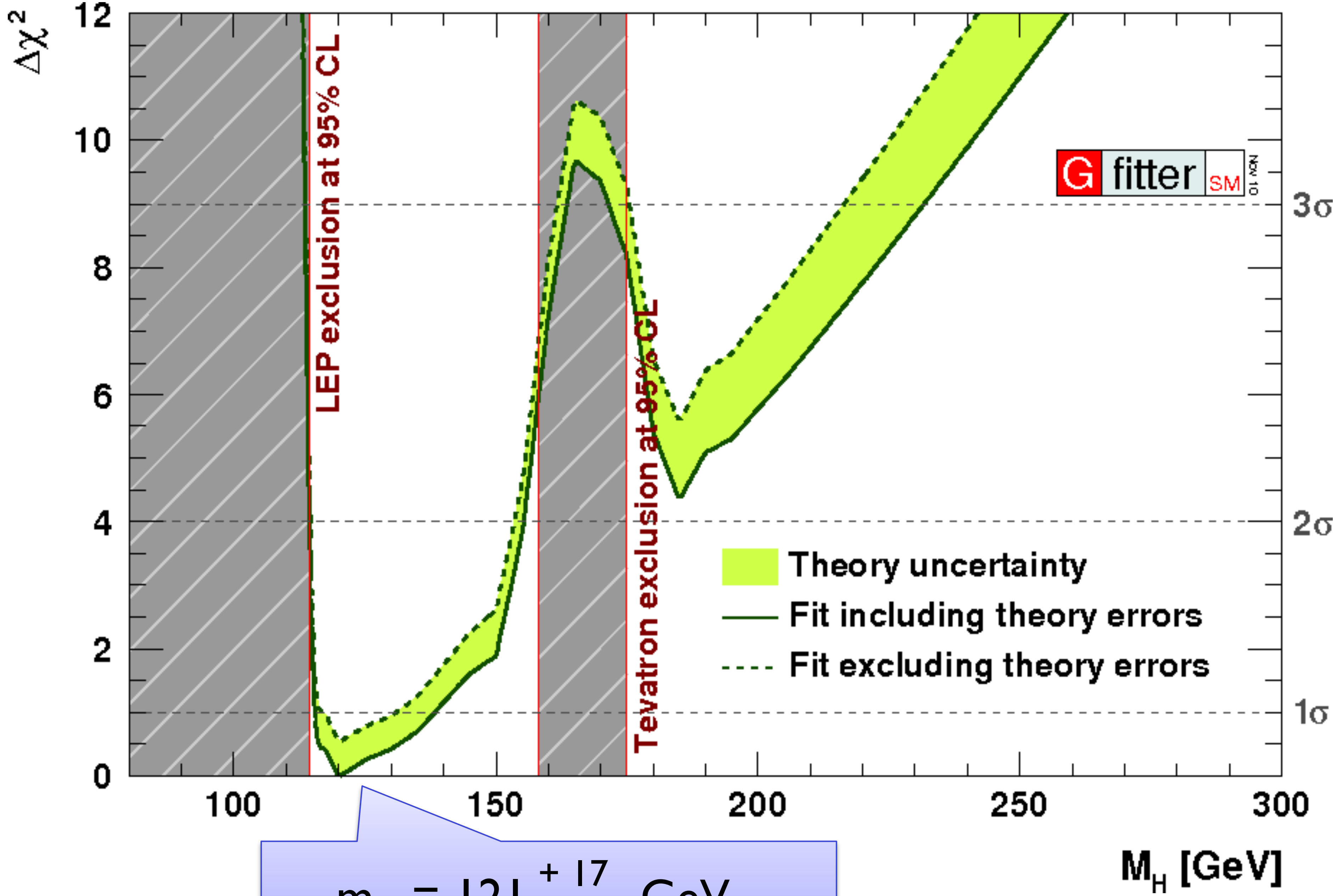
EW fit favors m_H < 163 GeV





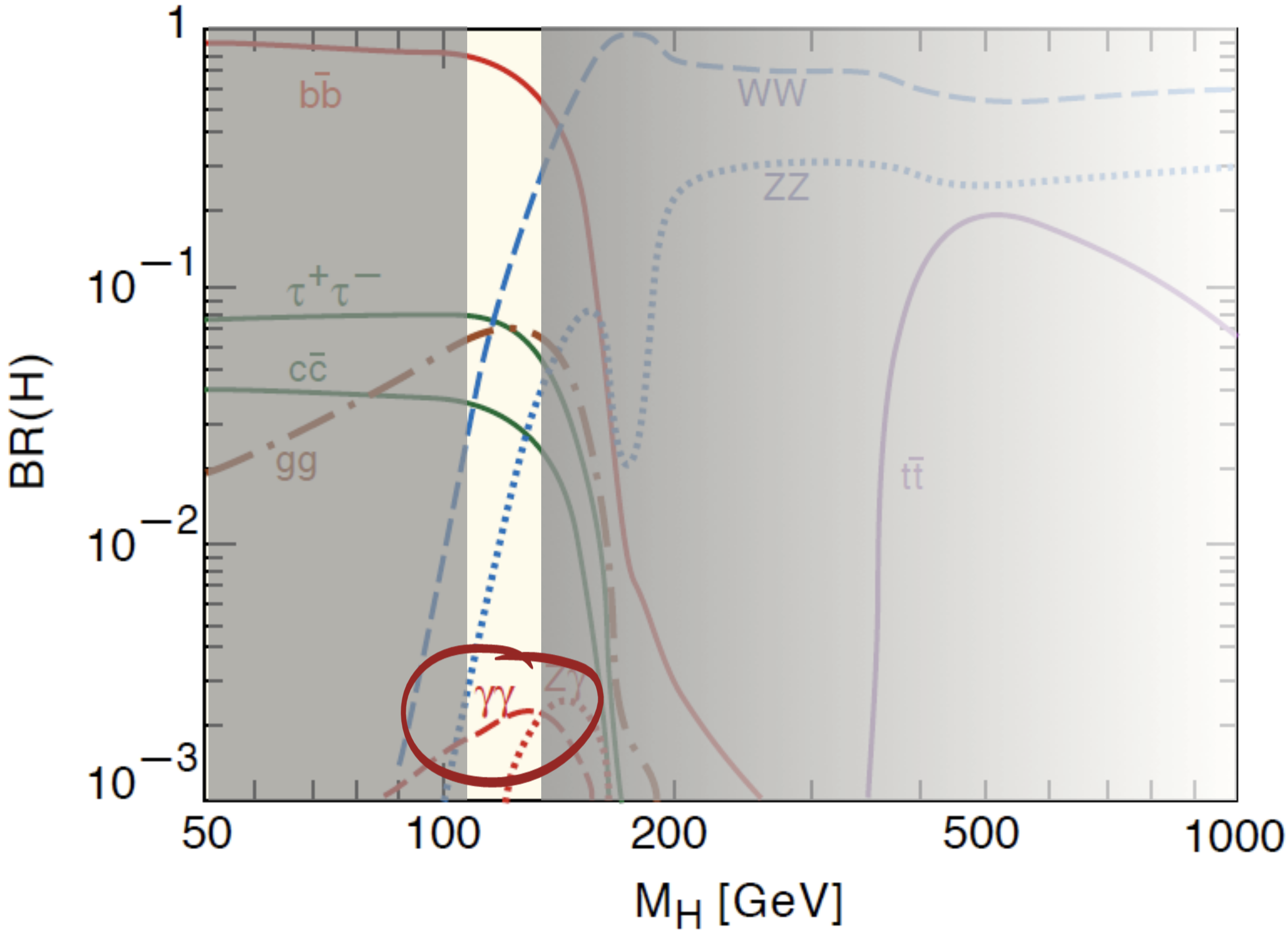
CDF+D0 direct search combination (~6 fb^{-1}) excludes ranges 100-109 GeV and 158-175 GeV

Where is the Higgs boson?

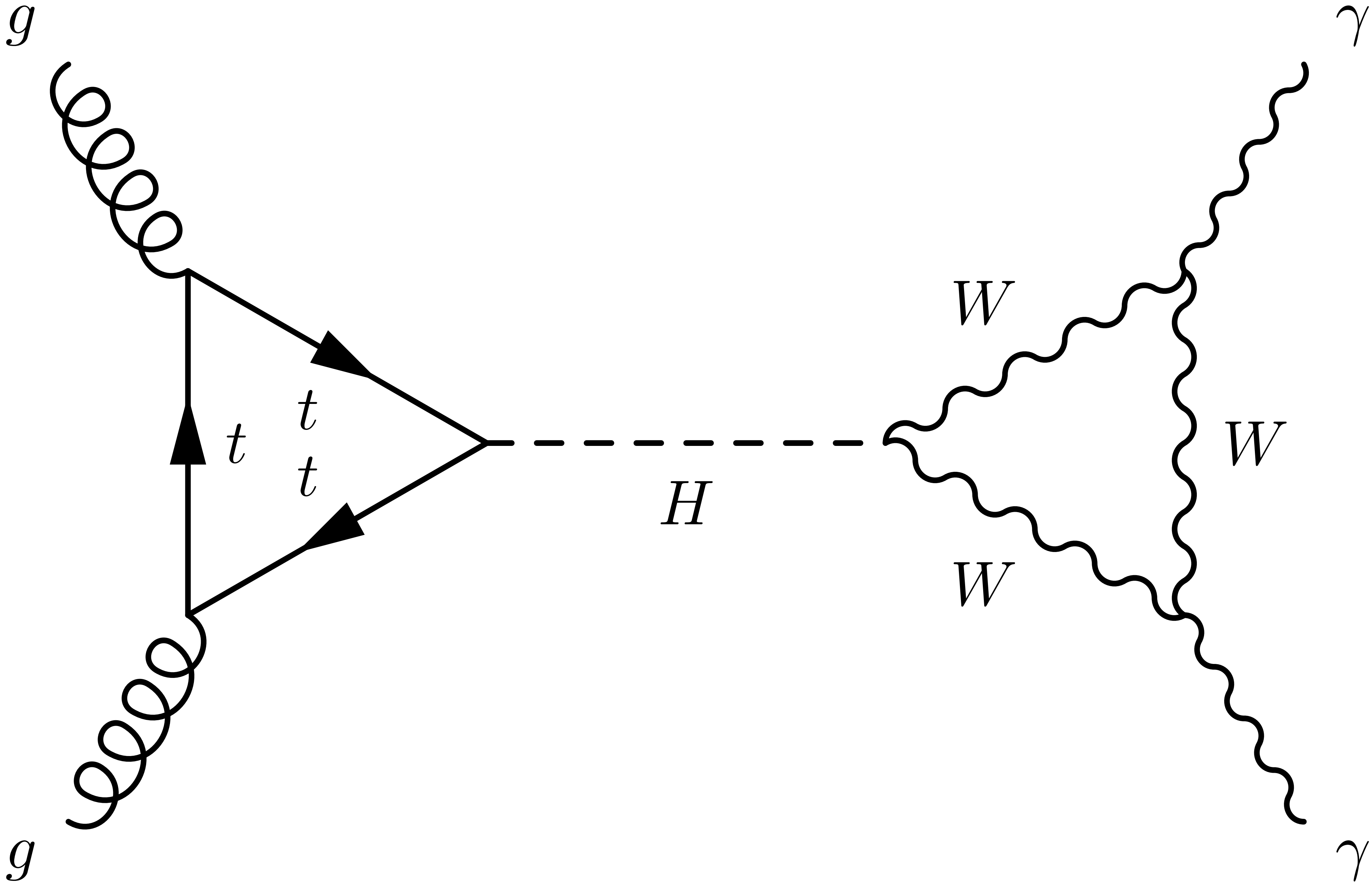


$m_H = 121^{+17}_{-6}$ GeV

Why photons?



1
10^{-1}
10^{-2}
10^{-3}
BR(H)
$b\bar{b}$
$\tau^+\tau^-$
$c\bar{c}$
gg
$\gamma\gamma$
$Z\gamma$
WW
ZZ
$t\bar{t}$
50
100
200
500
1000
M_H [GeV]



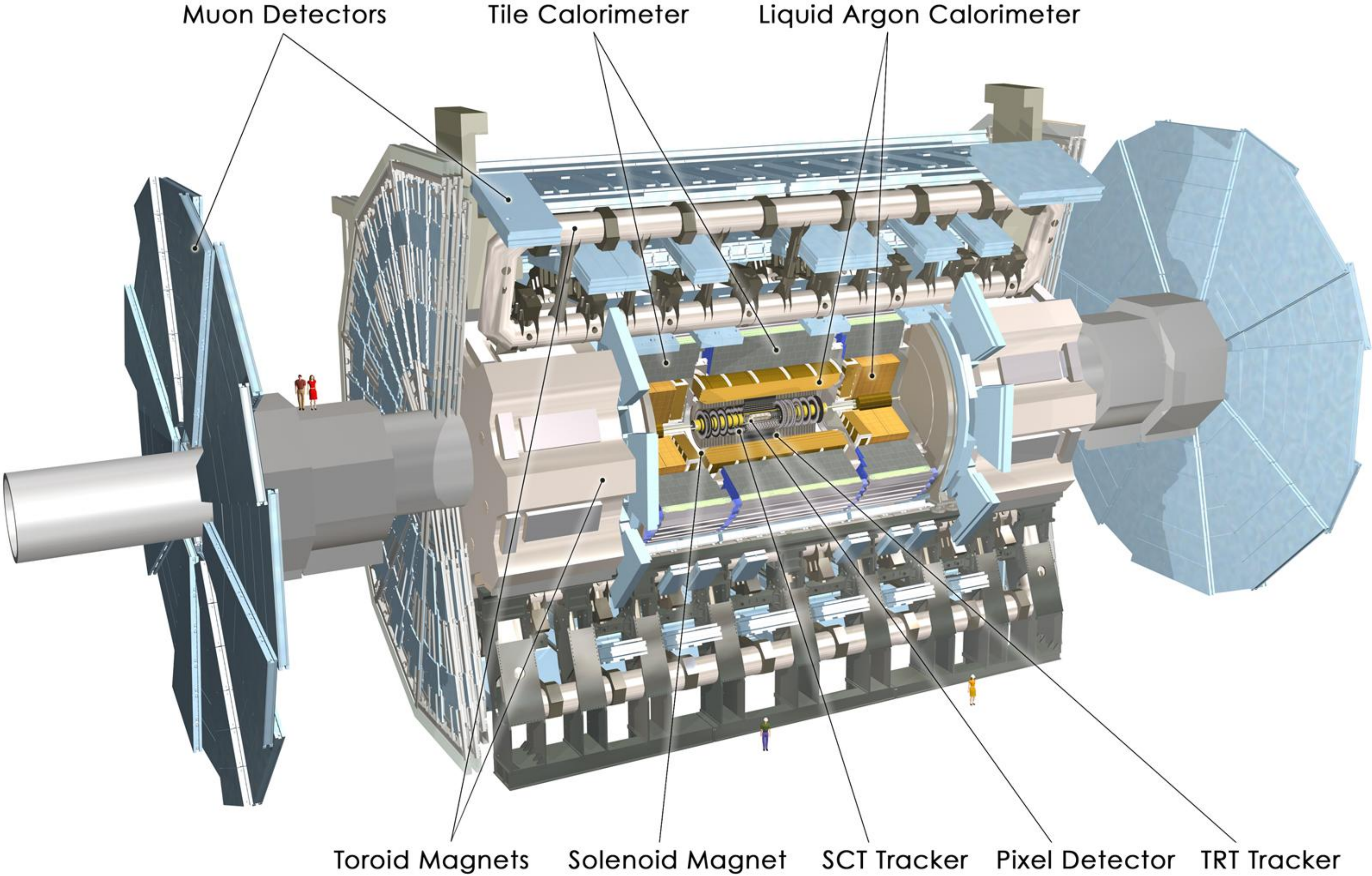
g
g
t
t
t
H
W
W
W
γ
γ

What photons ?

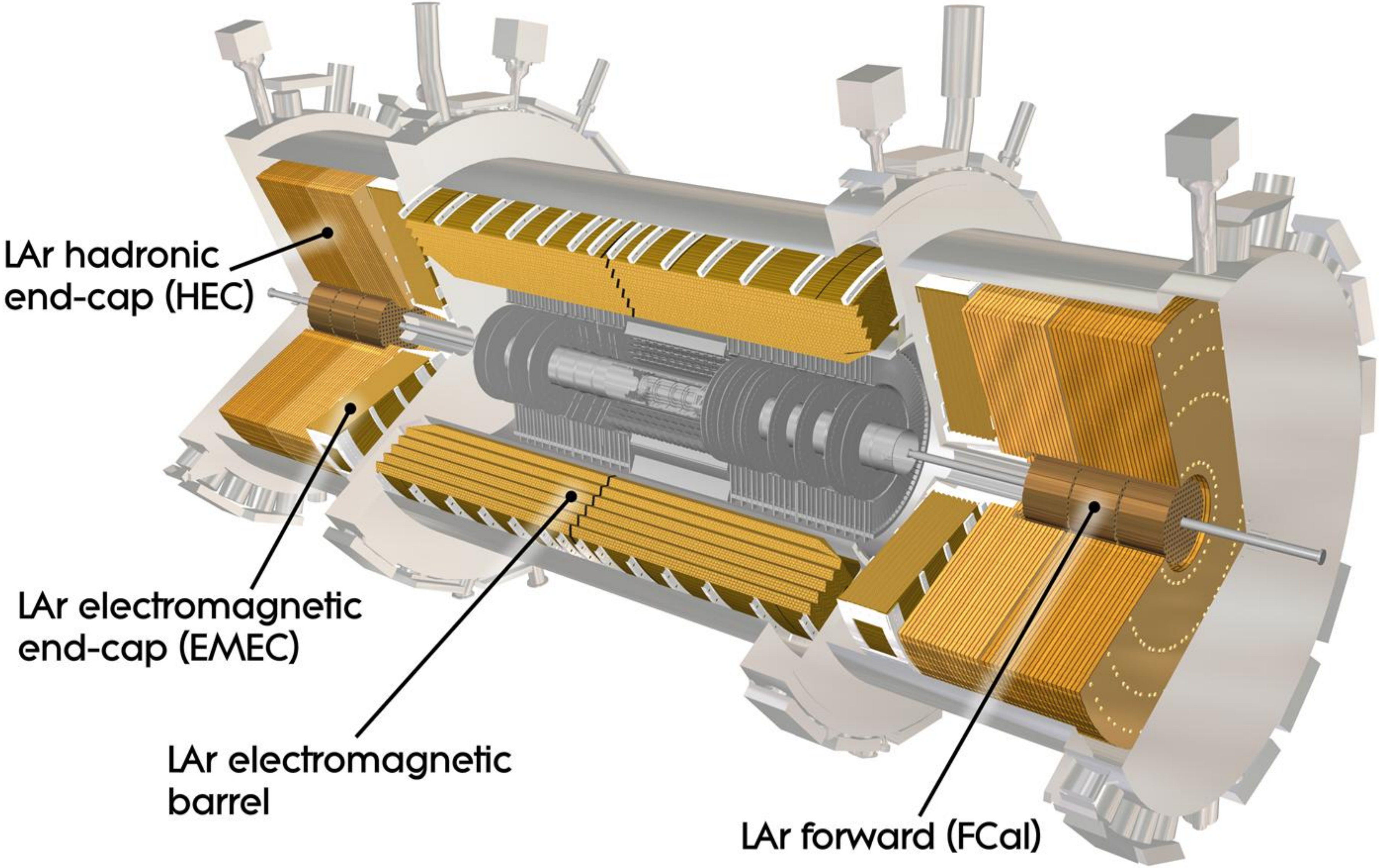
do we use to measure

from the Higgs boson decay

ATLAS

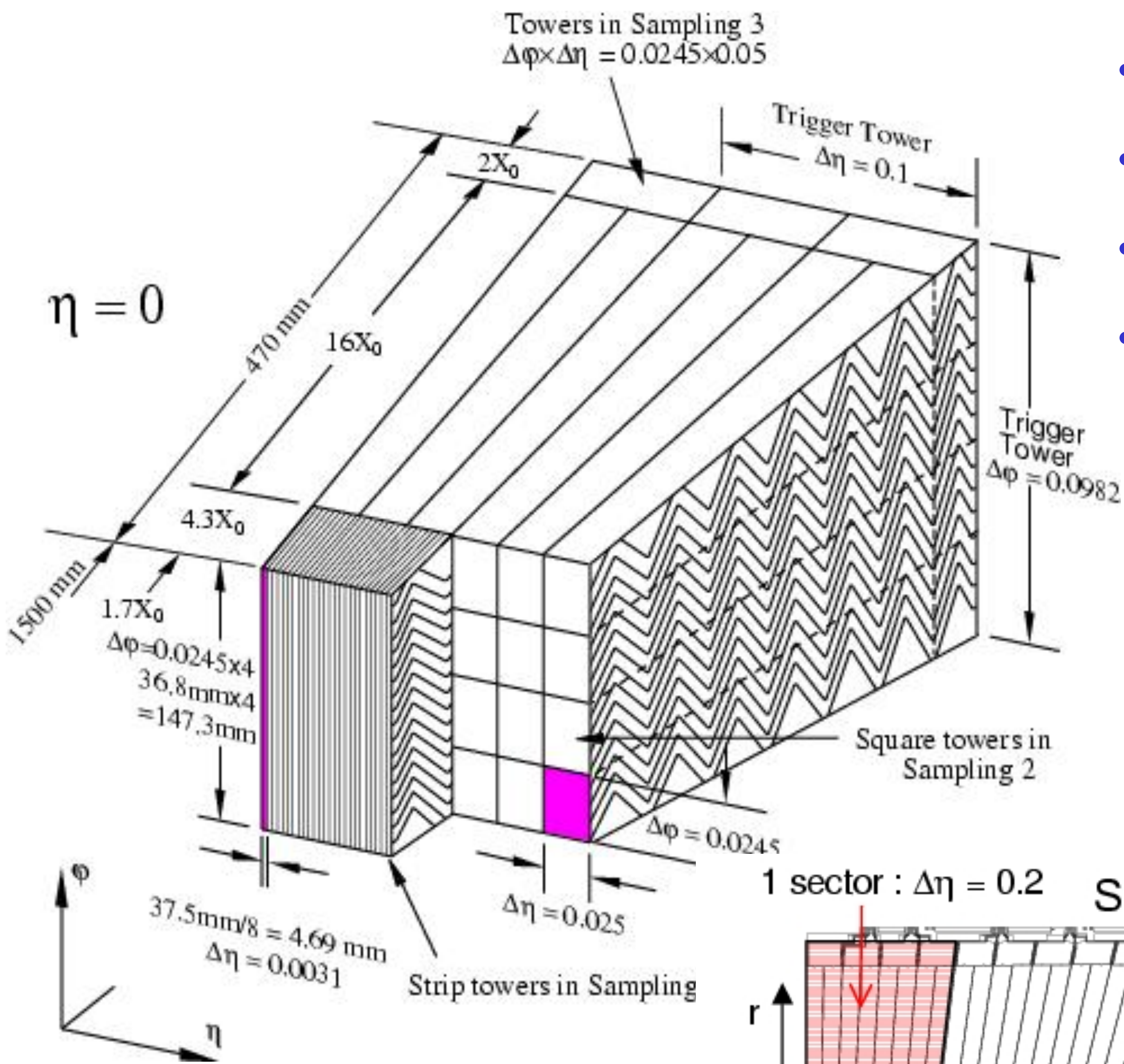

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

ATLAS liquid argon calorimeters



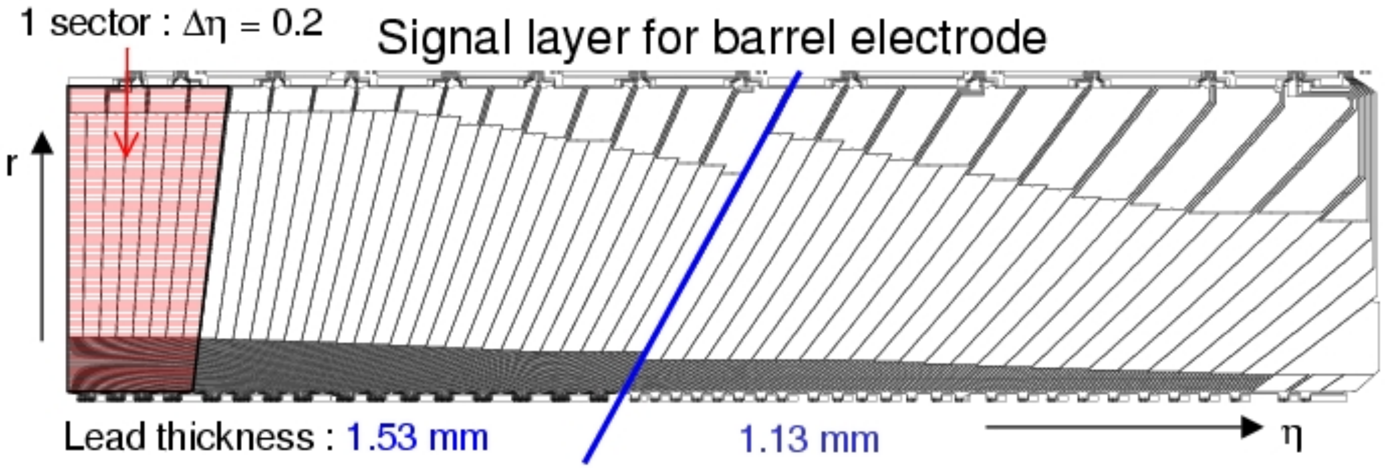
- ✓ EM Barrel : ($|\eta|<1.475$) [Pb-LAr]
- ✓ EM End-caps : $1.4<|\eta|<3.2$ [Pb-LAr]
- ✓ Hadronic End-cap: $1.5<|\eta|<3.2$ [Cu-LAr]
- ✓ Forward Calorimeter: $3.2<|\eta|<4.9$ [Cu,W-Lar]

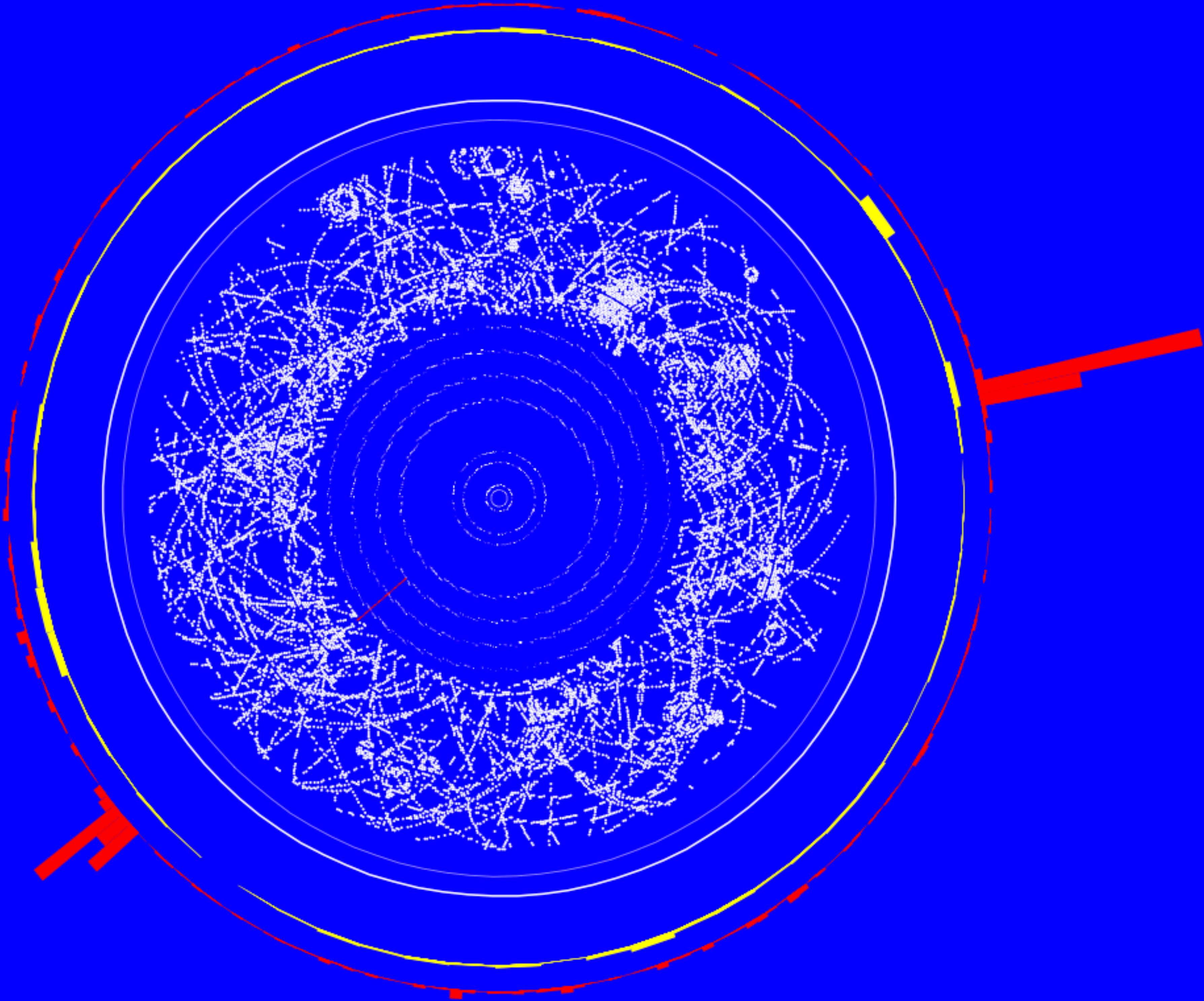
ATLAS EM calorimeter



- S0 (Presampler) — Energy loss correction
- S1 (Strips) — γ/π^0 separation
- S2 (Middle) — Main energy deposit
- S3 (Back) — High energy showers, hadr/em separation

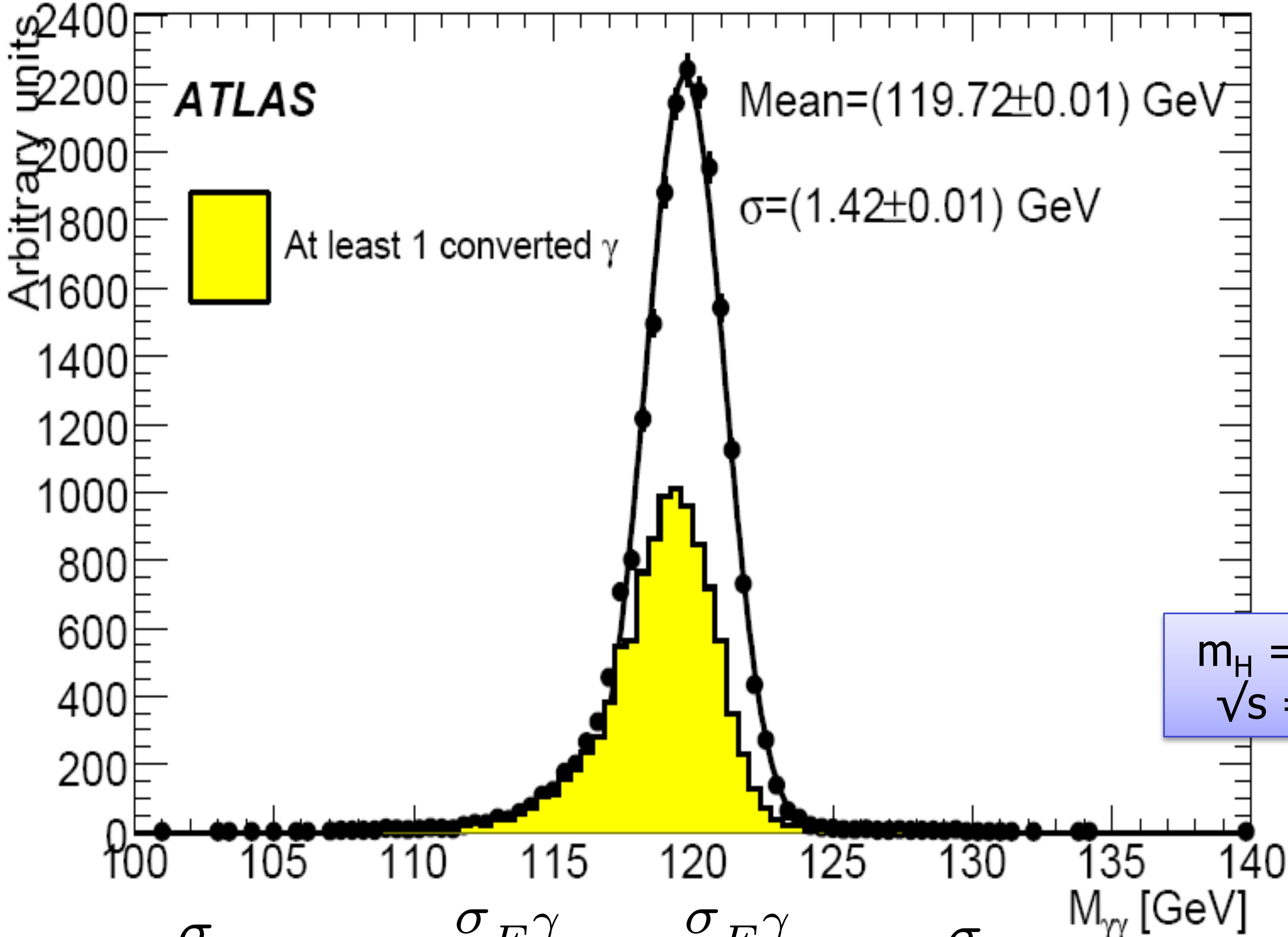
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$





A narrow mass peak…

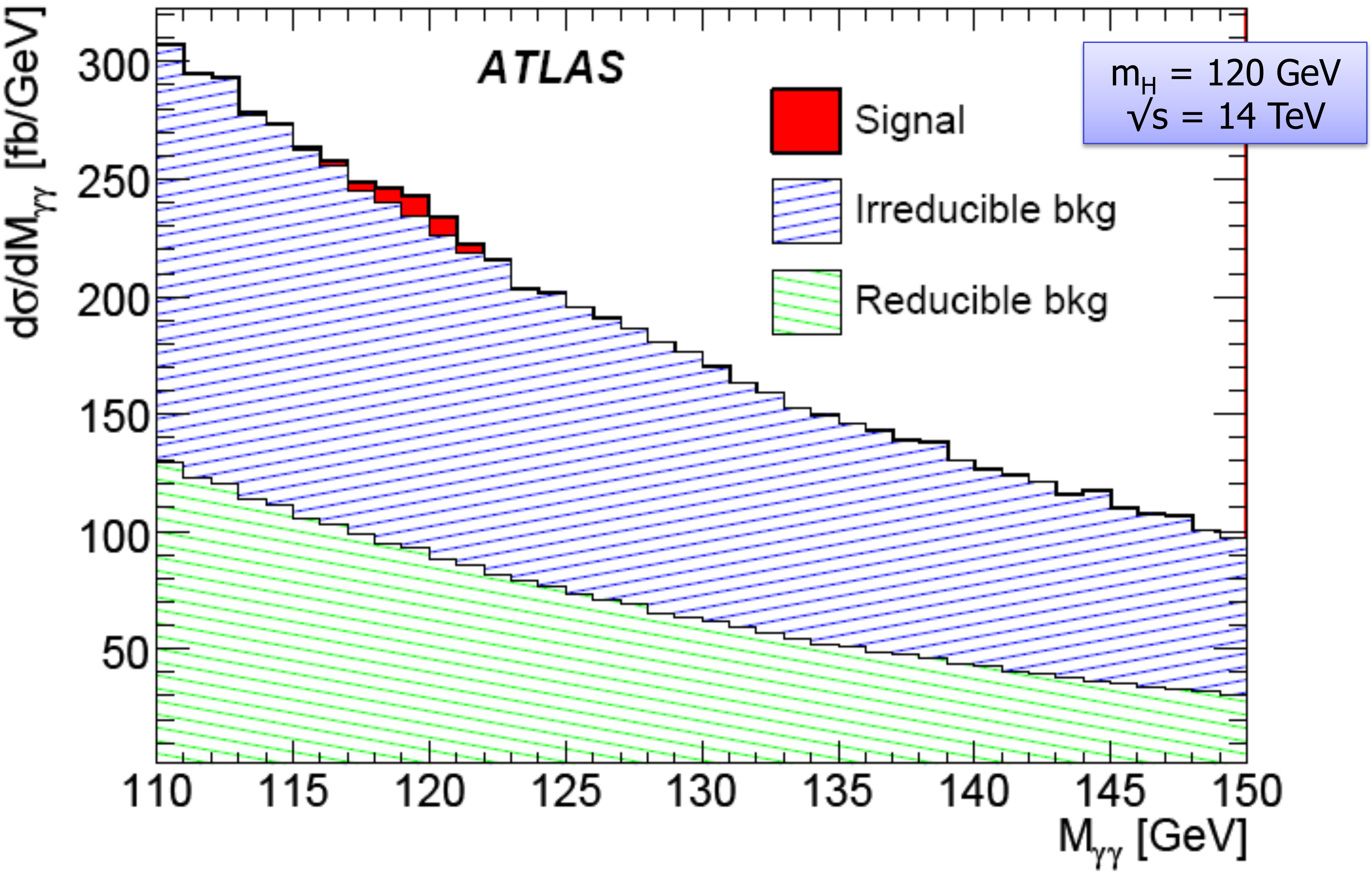
$$m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$$



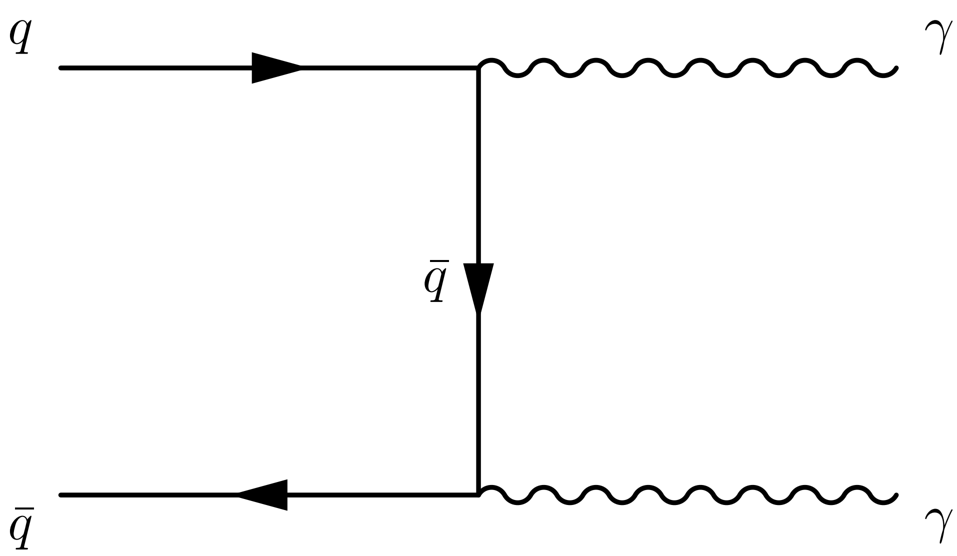
m_H = 120 GeV
$\sqrt{s}$ = 14 TeV

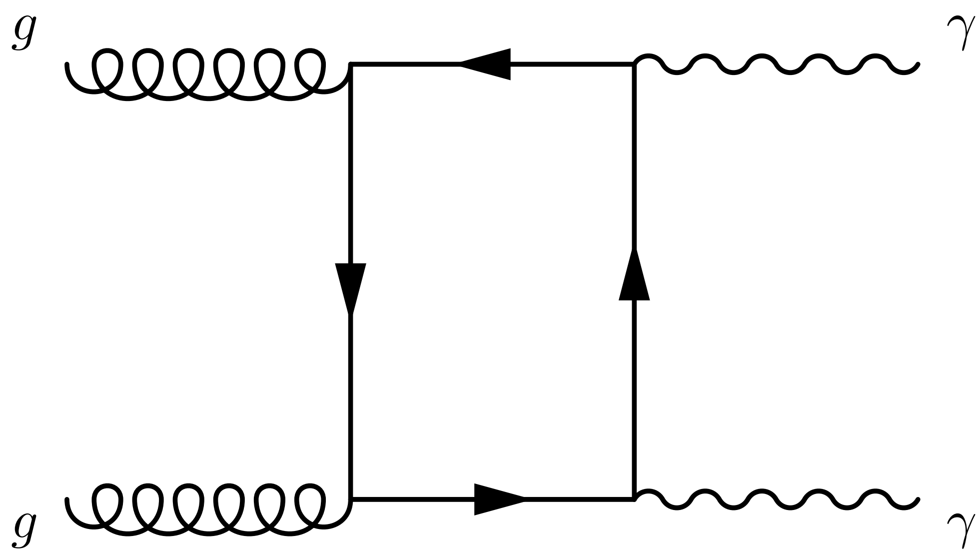
$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{\sigma_{E_1^\gamma}}{E_1^\gamma} \oplus \frac{\sigma_{E_2^\gamma}}{E_2^\gamma} \oplus \frac{\sigma_{\alpha_{12}}}{\tan\alpha_{12}}$$

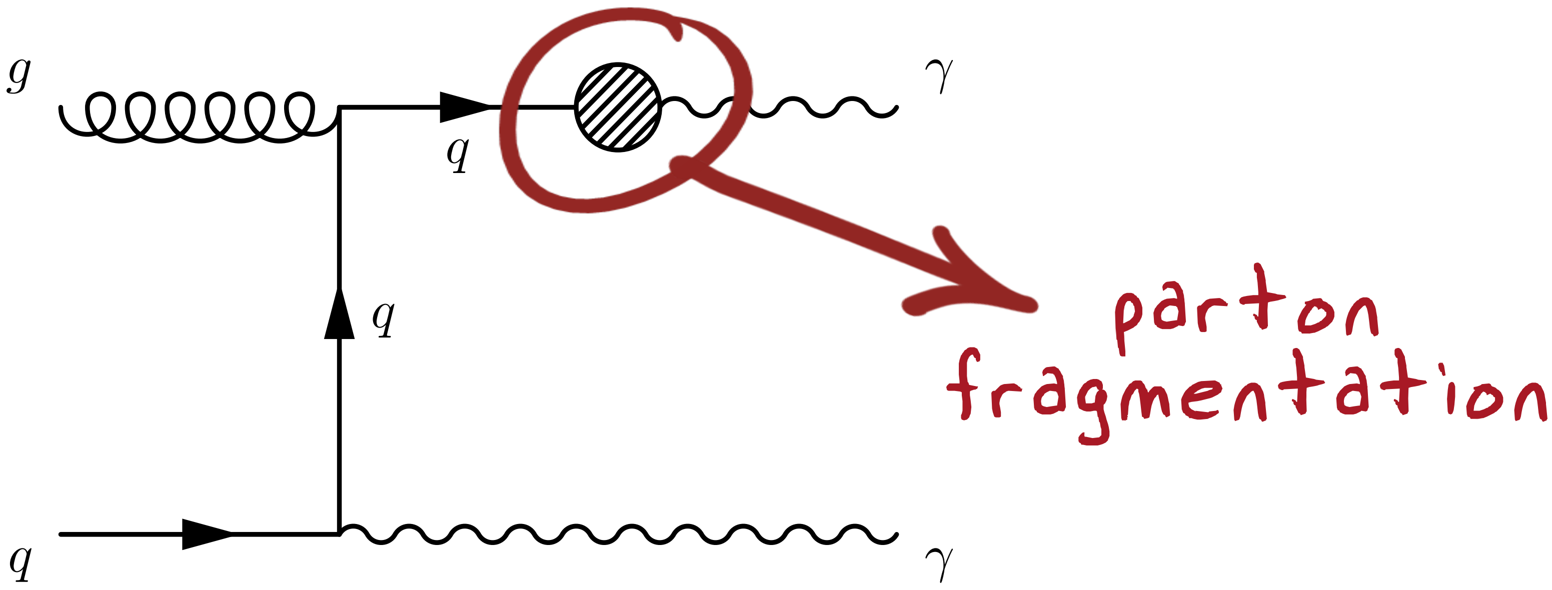
… on a large background!



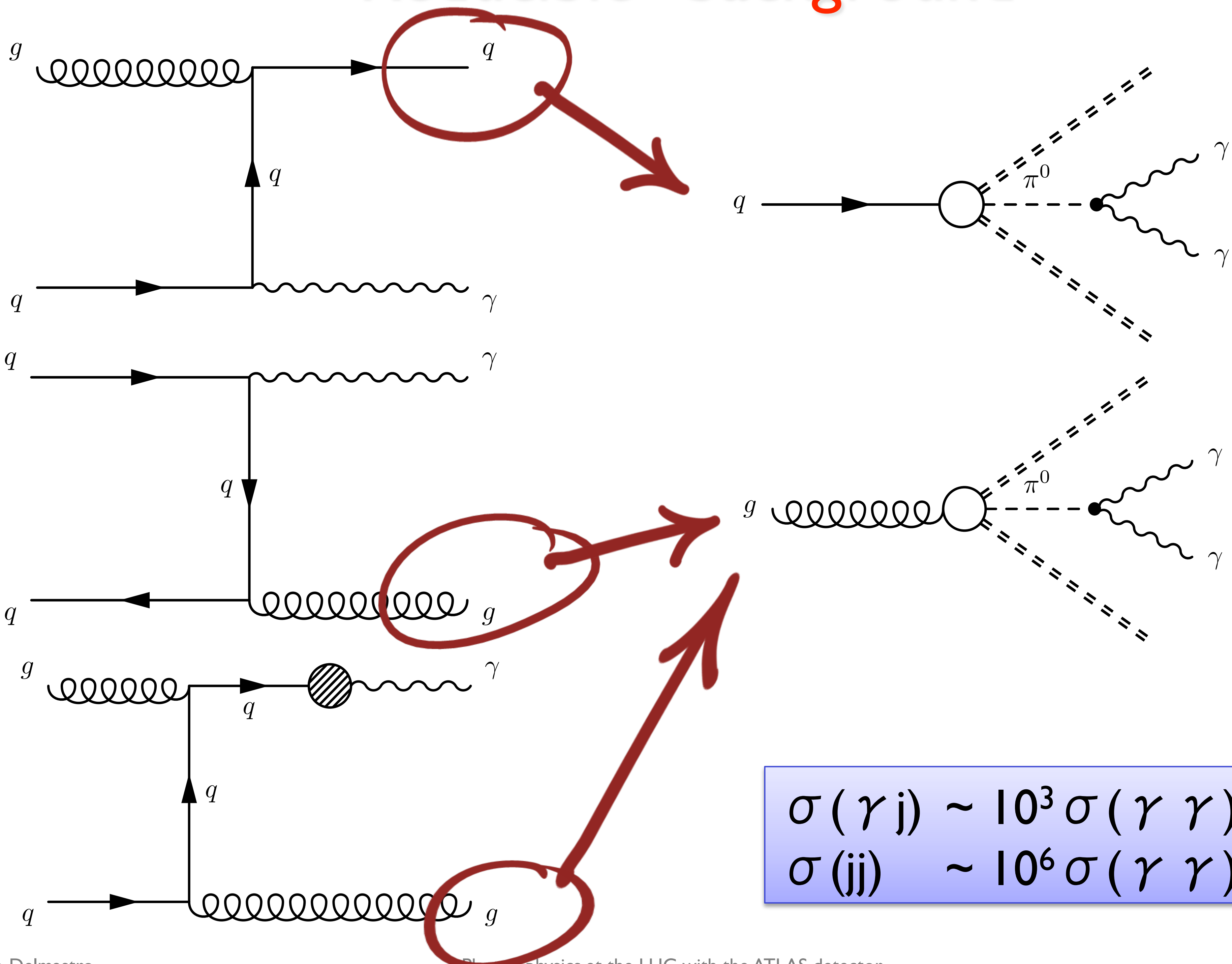
“Irreducible” background







“Reducible” background

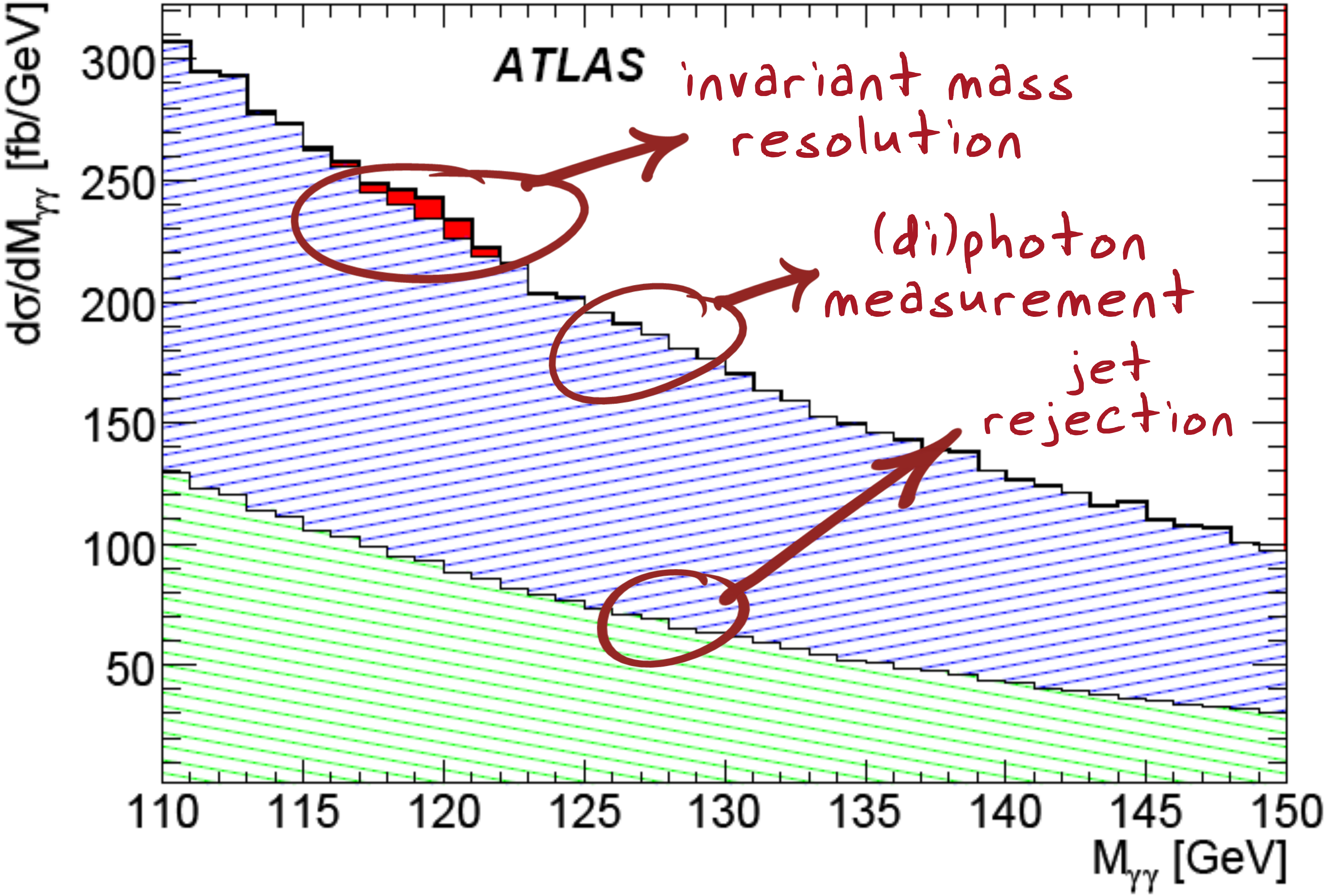


$$\sigma(\gamma j) \sim 10^3 \sigma(\gamma\gamma)$$
$$\sigma(jj) \sim 10^6 \sigma(\gamma\gamma)$$

How large is the “large” background?

M_H (GeV)	110	115	120	130	140
Signal	20.1	20.4	20.7	18.5	14.1
$\gamma\gamma$			5540		
γj			2500		
jj			360		
Drell Yan			90		
Total background			8490		

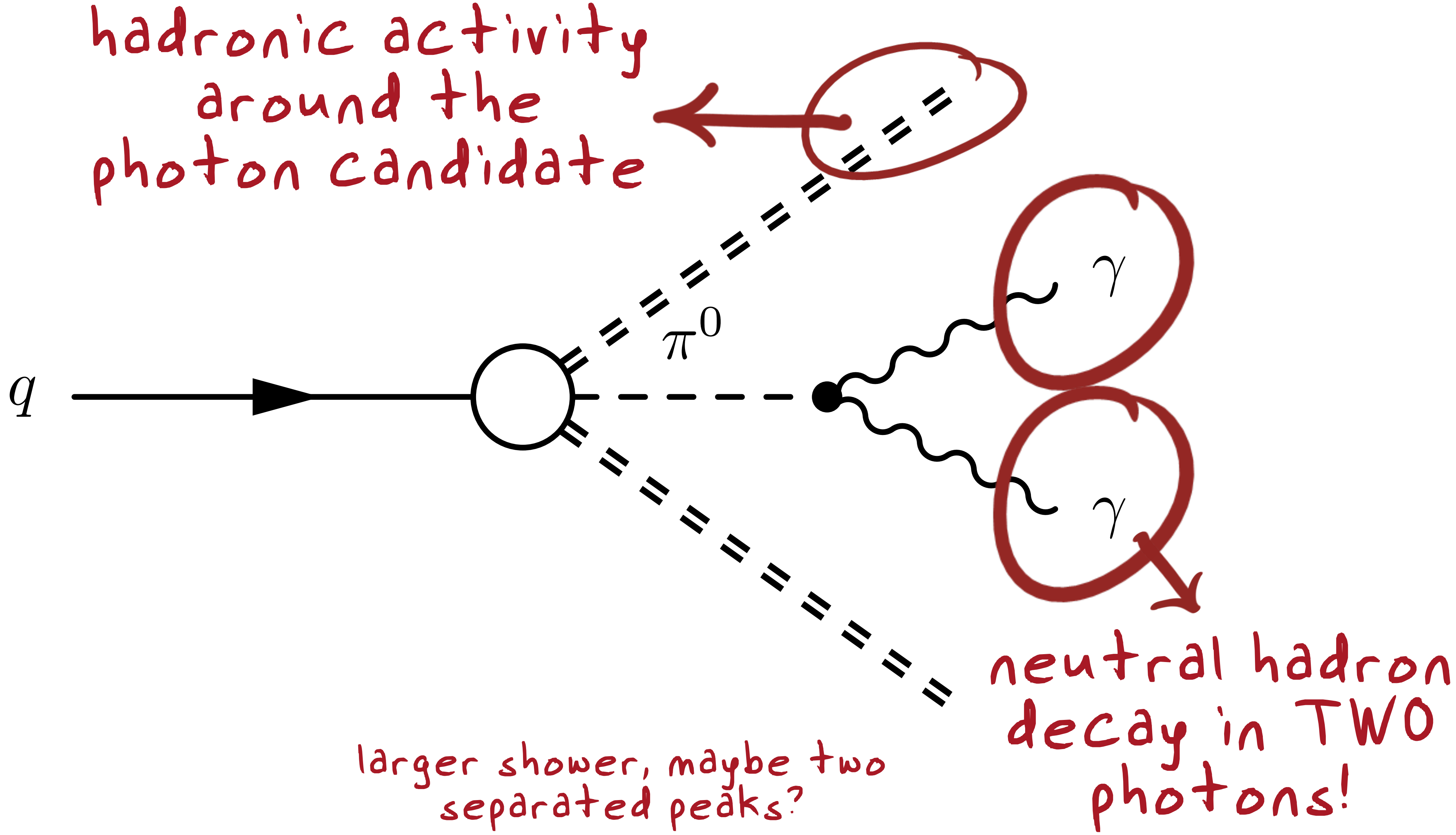
Table 12: Numbers of signal ($H \to \gamma\gamma$) and background events expected at an integrated luminosity of 1 fb^{-1} for $\sqrt{s}$ = 7 TeV. For the backgrounds, the number of events is estimated in the mass window of [100 – 150] GeV.

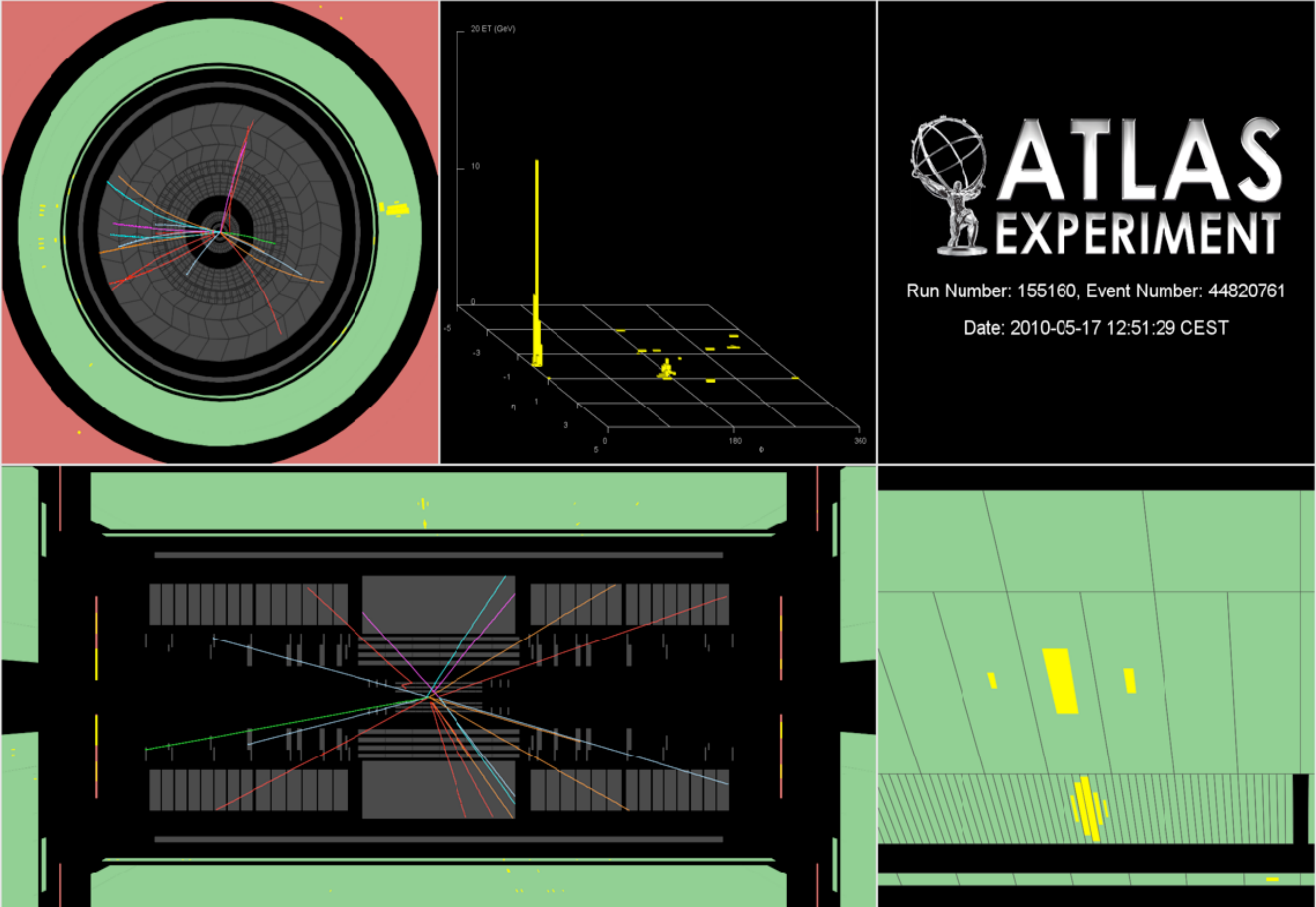


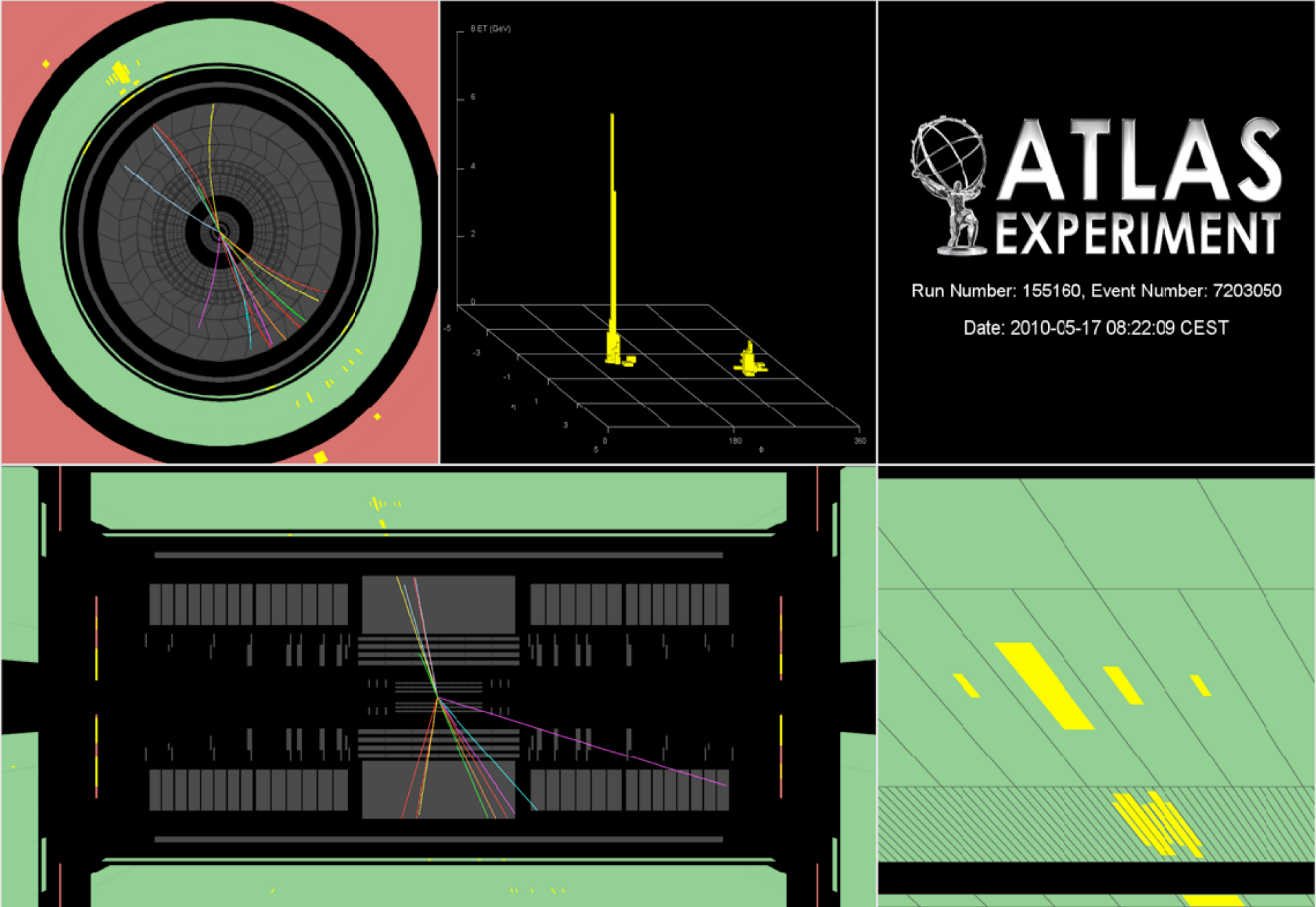
ATLAS
invariant mass
resolution
(di)photon
measurement
jet
rejection
$d\sigma/dM_{\gamma\gamma}$ [fb/GeV]
300
250
200
150
100
50
110
115
120
125
130
135
140
145
150
$M_{\gamma\gamma}$ [GeV]

How can we distinguish direct photons from jets?

How does a jet faking a direct photon look like?

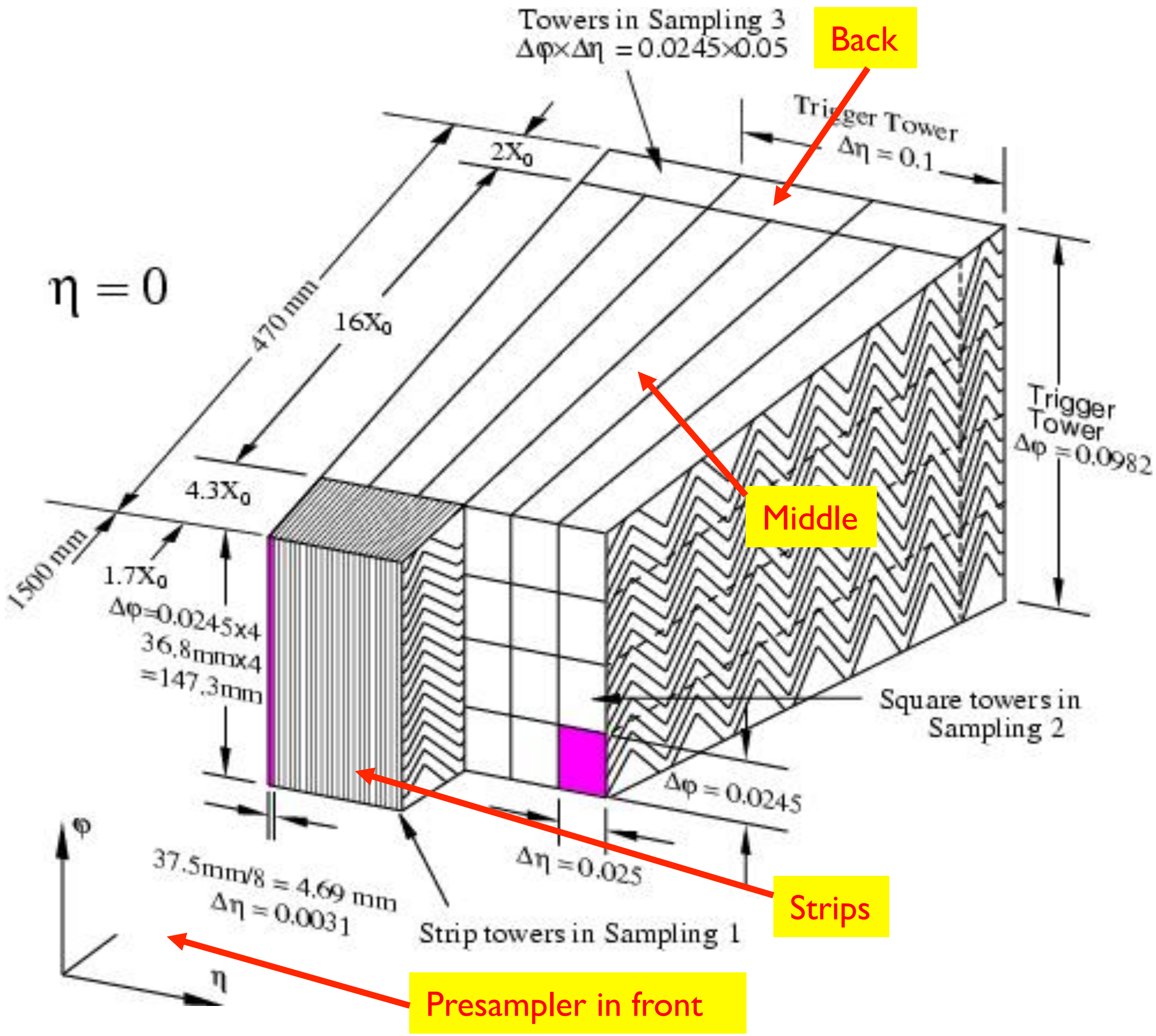



20 ET (GeV)
10
ATLAS EXPERIMENT
Run Number: 155160, Event Number: 44820761
Date: 2010-05-17 12:51:29 CEST



ET (GeV)
η
φ
ATLAS
EXPERIMENT
Run Number: 155160, Event Number: 7203050
Date: 2010-05-17 08:22:09 CEST

A well-segmented EM calorimeter comes at hand!



γ candidate

↓

Cut on HAD leakage, 2^{nd} sampling of EM

Rejects jets with high energy pions and wide showers

↓

Cuts on 1^{st} sampling of EM calo

Rejects jets with one or more π^0, η, …

↓

Isolation cuts (ID or EM calo)

Rejects low multiplicity π^0 jets

Discriminating variables for photon ID

Hadronic leakage

$$R_{\mathrm{had}_1} = \frac{E_T^{\mathrm{had}\,1}}{E_T}$$

$E_t^{had\ 1}$ is the energy in the first layer of the hadronic calorimeter behind EM cluster

Middle layer (S2) variables

containment in η

$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}}$$

containment in ϕ

$$R_\phi = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$$

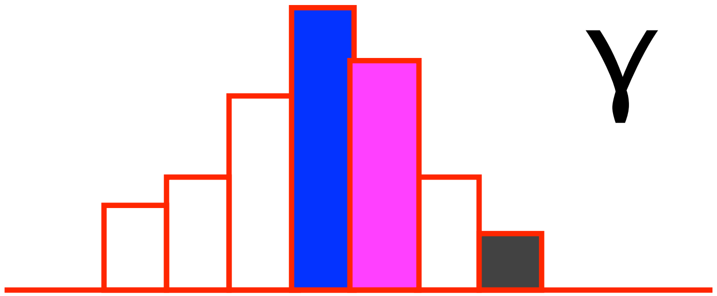
E^{S2}_{XY} is the summed energy of S2 cells in a window of size X×Y ($\eta \times \phi$ units)

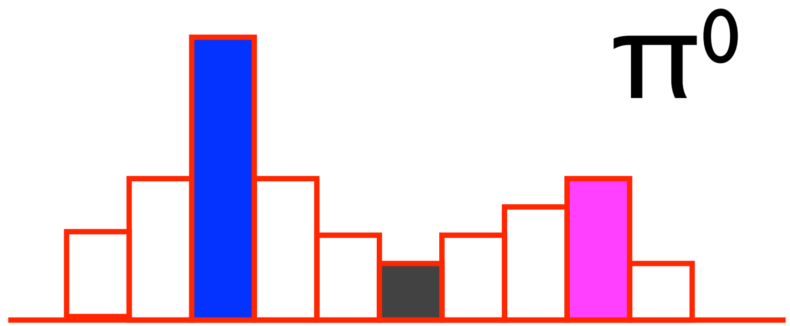
$$w_2 = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

Lateral width (physical units) calculated in a window of size 3×5 ($\eta \times \phi$ units)

Discriminating variables for photon ID

Front Layer (Strip, S1) Variables





$$F_{\text{side}} = \frac{E(\pm 3) - E(\pm 1)}{E(\pm 1)}$$

Containment in η
E(±n) is the sum of E in ±n strips about max

$$E_{\text{ratio}} = \frac{E^{S1}_{1^{\text{st}}\,\text{max}} - E^{S1}_{2^{\text{nd}}\,\text{max}}}{E^{S1}_{1^{\text{st}}\,\text{max}} + E^{S1}_{2^{\text{nd}}\,\text{max}}}$$

Asymmetry between 1$^{\text{st}}$ and 2$^{\text{nd}}$ maxima

$$\Delta E = \left[E^{S1}_{2^{\text{nd}}\text{max}} - E^{S1}_{\text{min}}\right] / \text{ MeV}$$

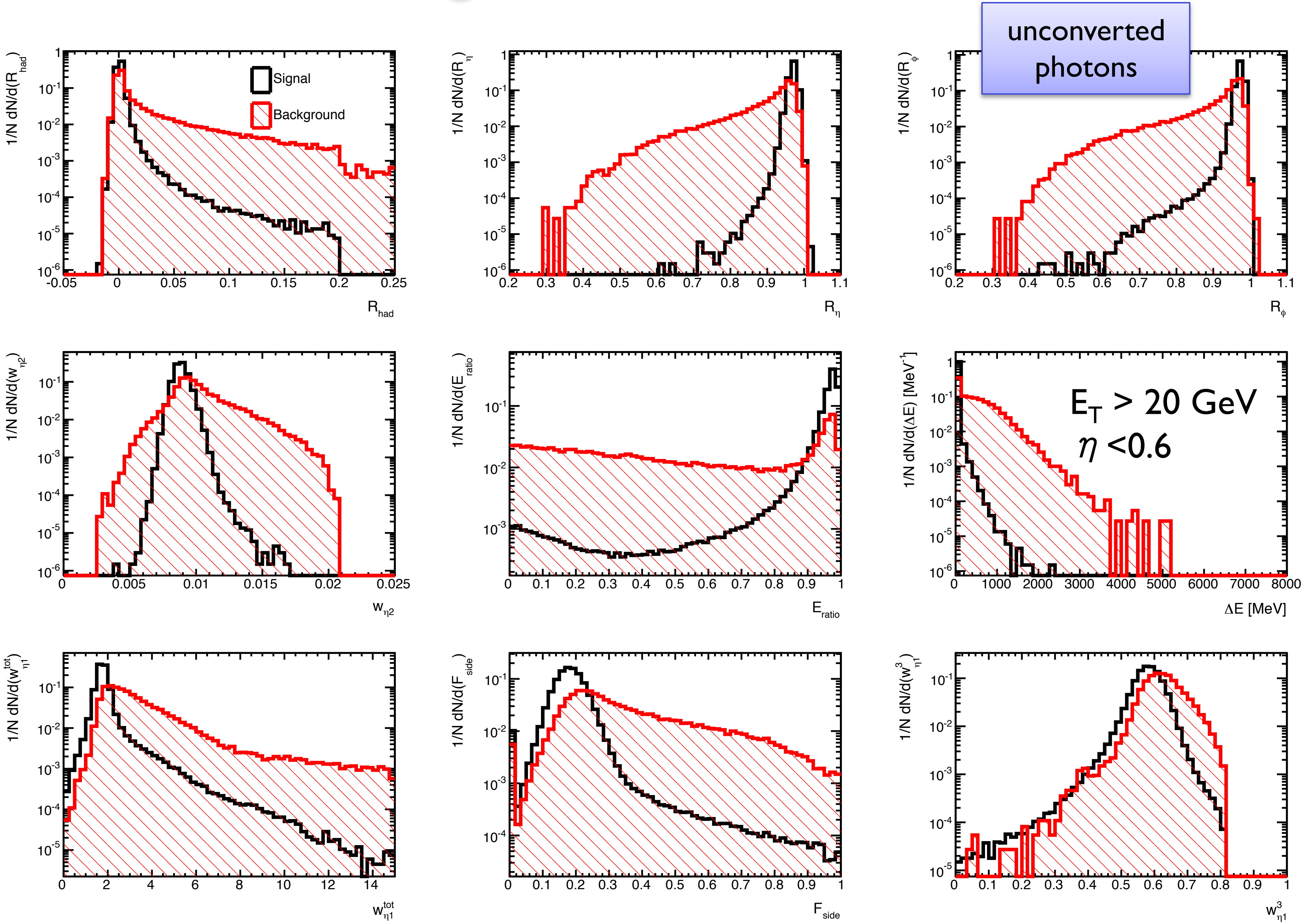
E^{S1}_{min} is the energy of the strip cell with least energy between the 1$^{\text{st}}$ and and 2$^{\text{nd}}$ maxima

$$w_{s\,3} = \sqrt{\frac{\sum E_i (i - i_{\text{max}})^2}{\sum E_i}}$$

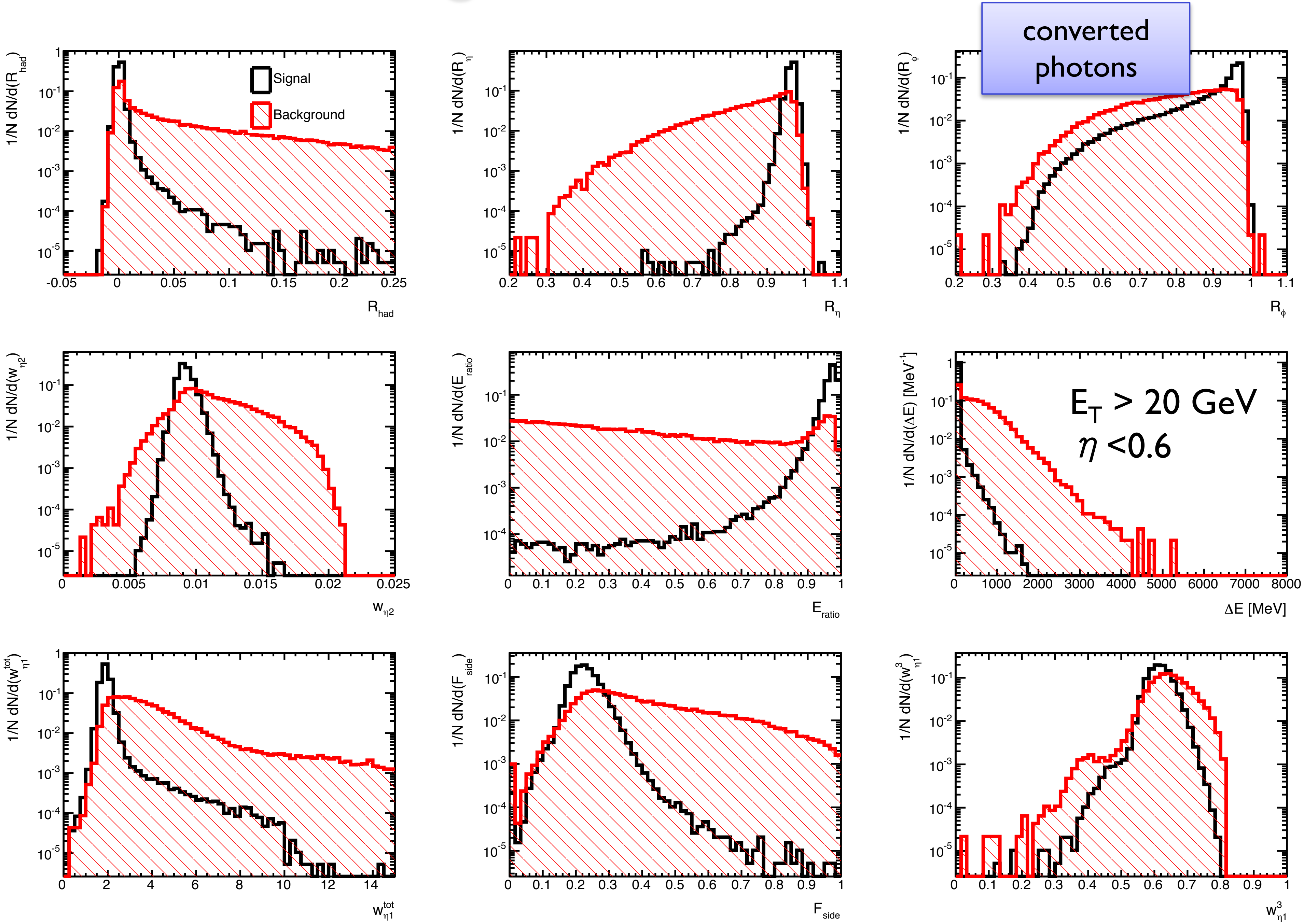
Width (cell units) using 2 strips about max.

$w_{s\,\text{tot}}$ Width (cell units) using ~ 40 strip cells, 20 in η and 2 in ϕ.

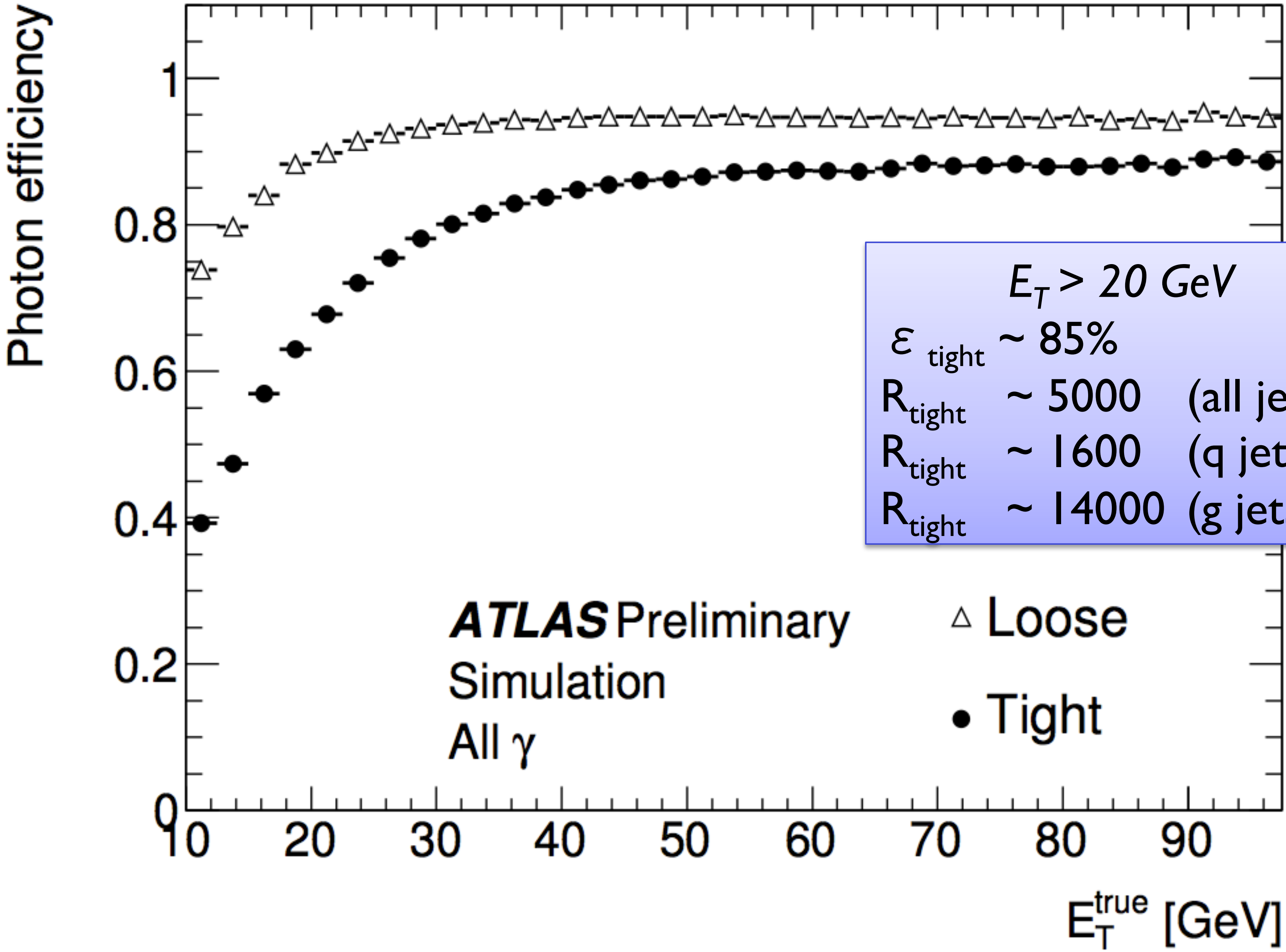
Discriminating variables in simulated data



Discriminating variables in simulated data

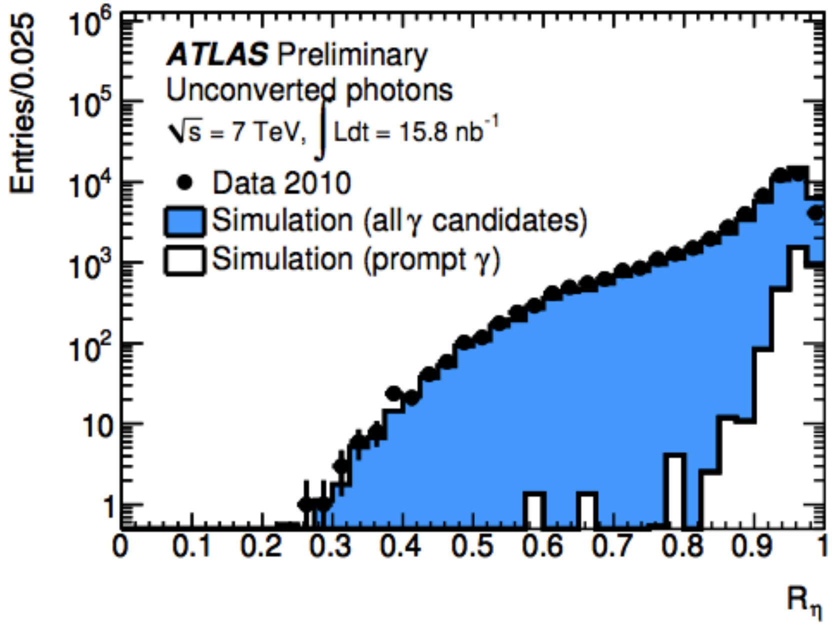


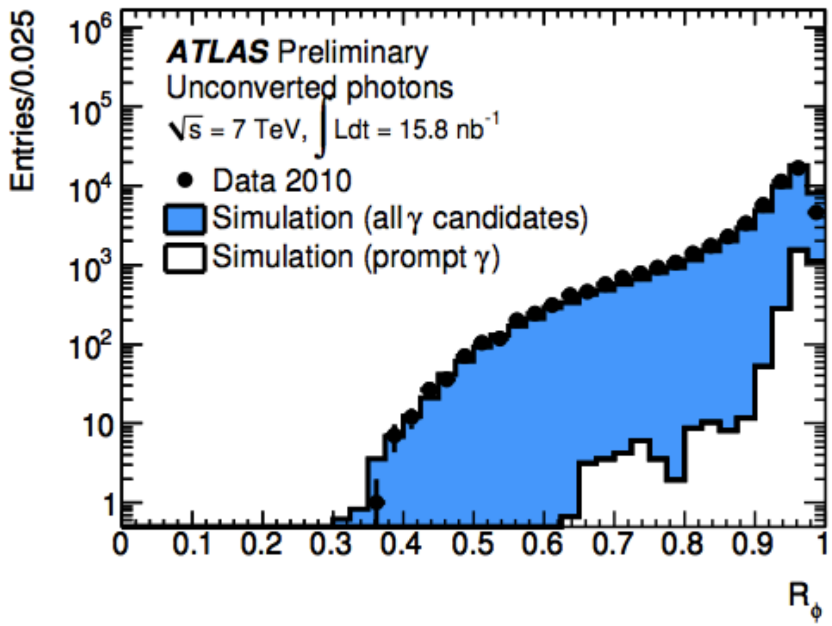
Photon identification efficiency in simulated data

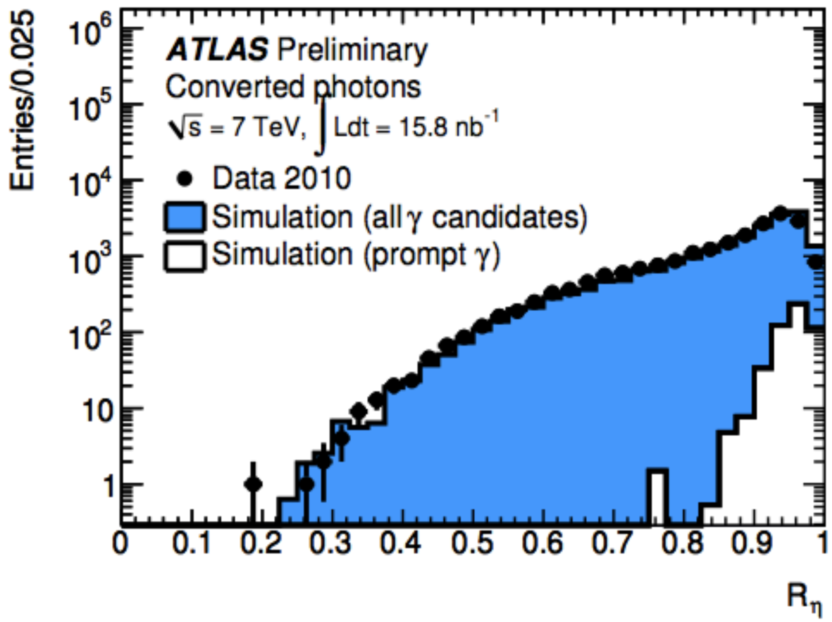


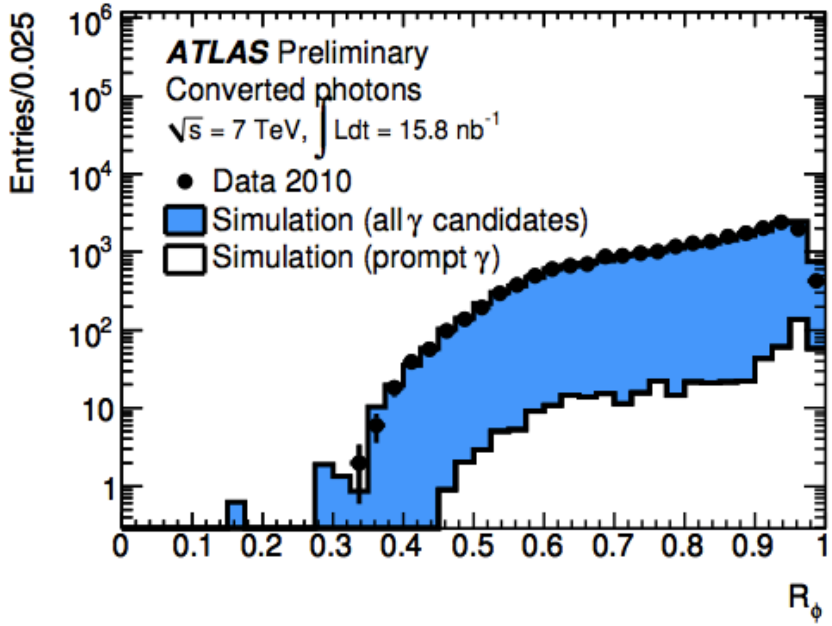
$E_T > 20$ GeV
ε_{tight} ~ 85%
R_{tight} ~ 5000 (all jets)
R_{tight} ~ 1600 (q jets)
R_{tight} ~ 14000 (g jets)

Discriminating variables in real data

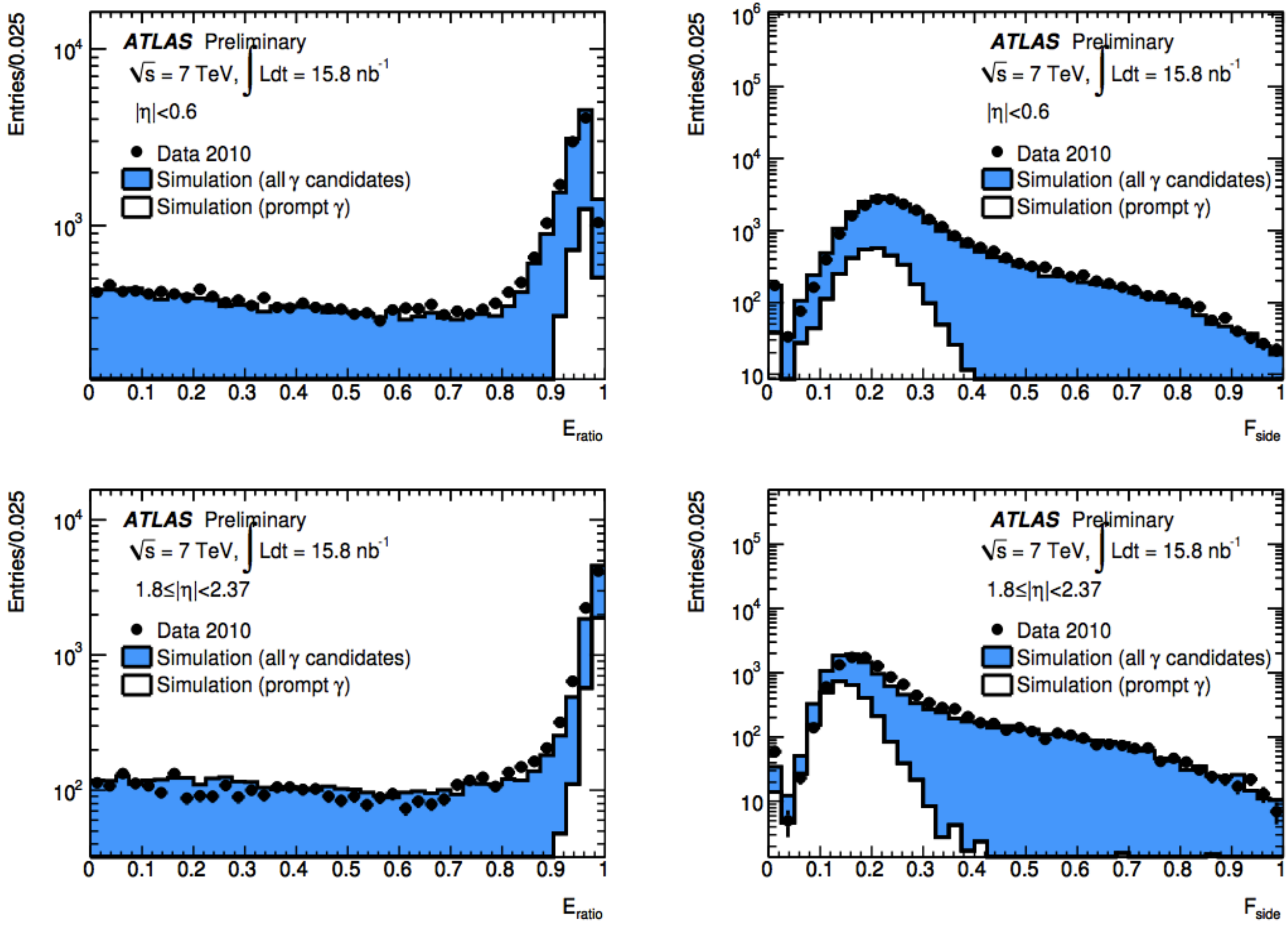




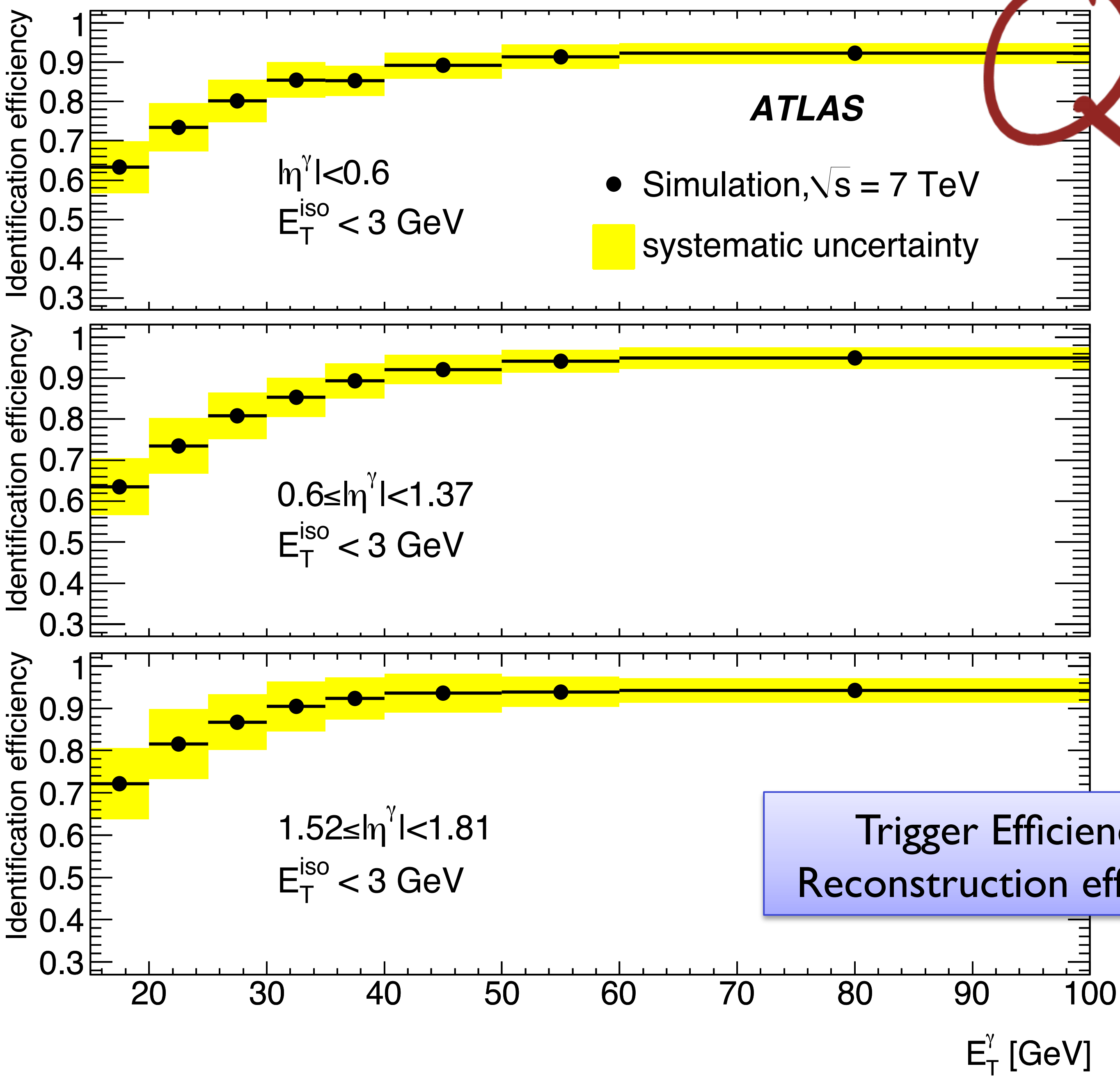




Discriminating variables in real data



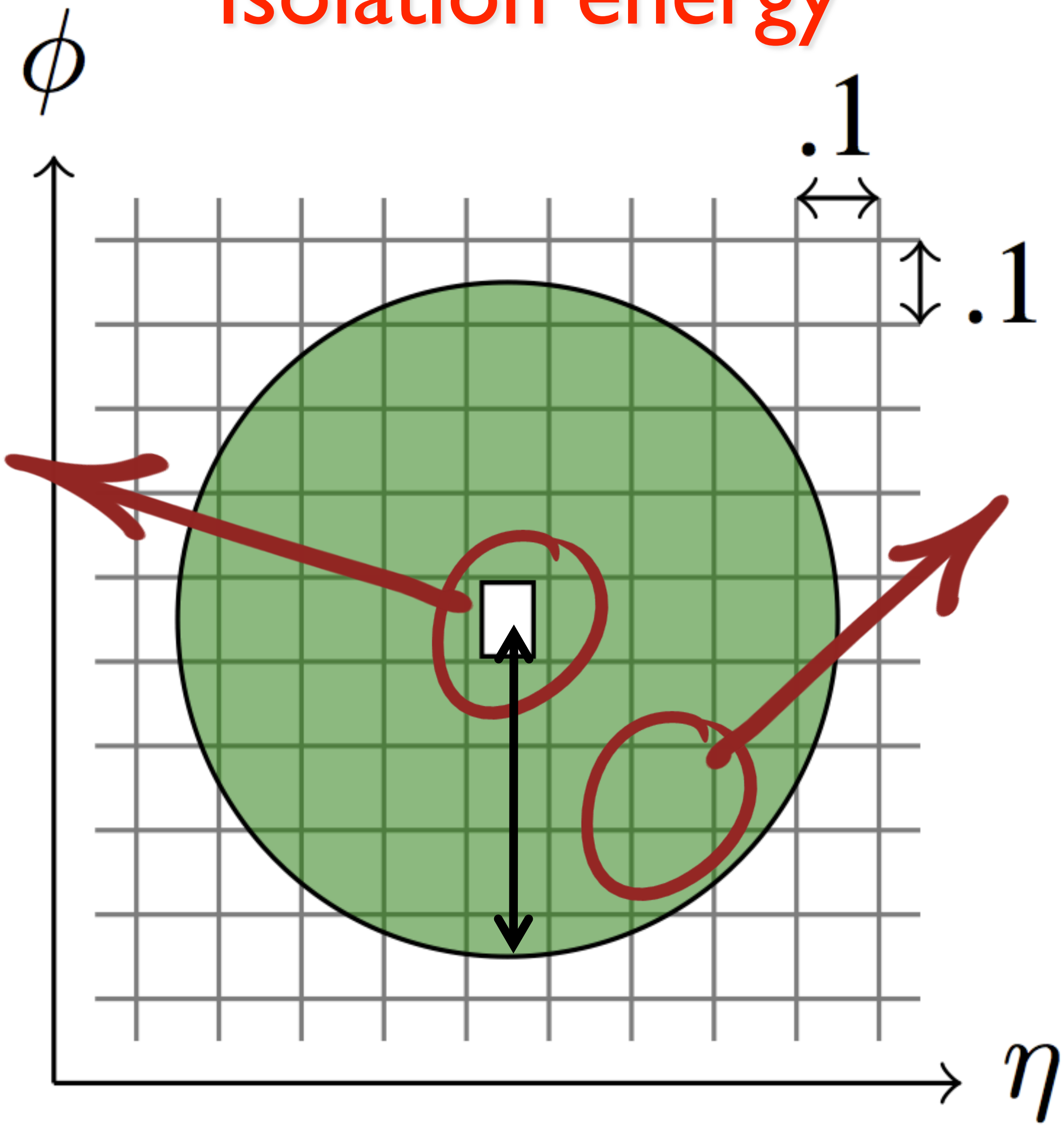
Photon identification efficiency from real data



~15% relative

Trigger Efficiency: 99.5%
Reconstruction efficiency: 82%

Isolation energy



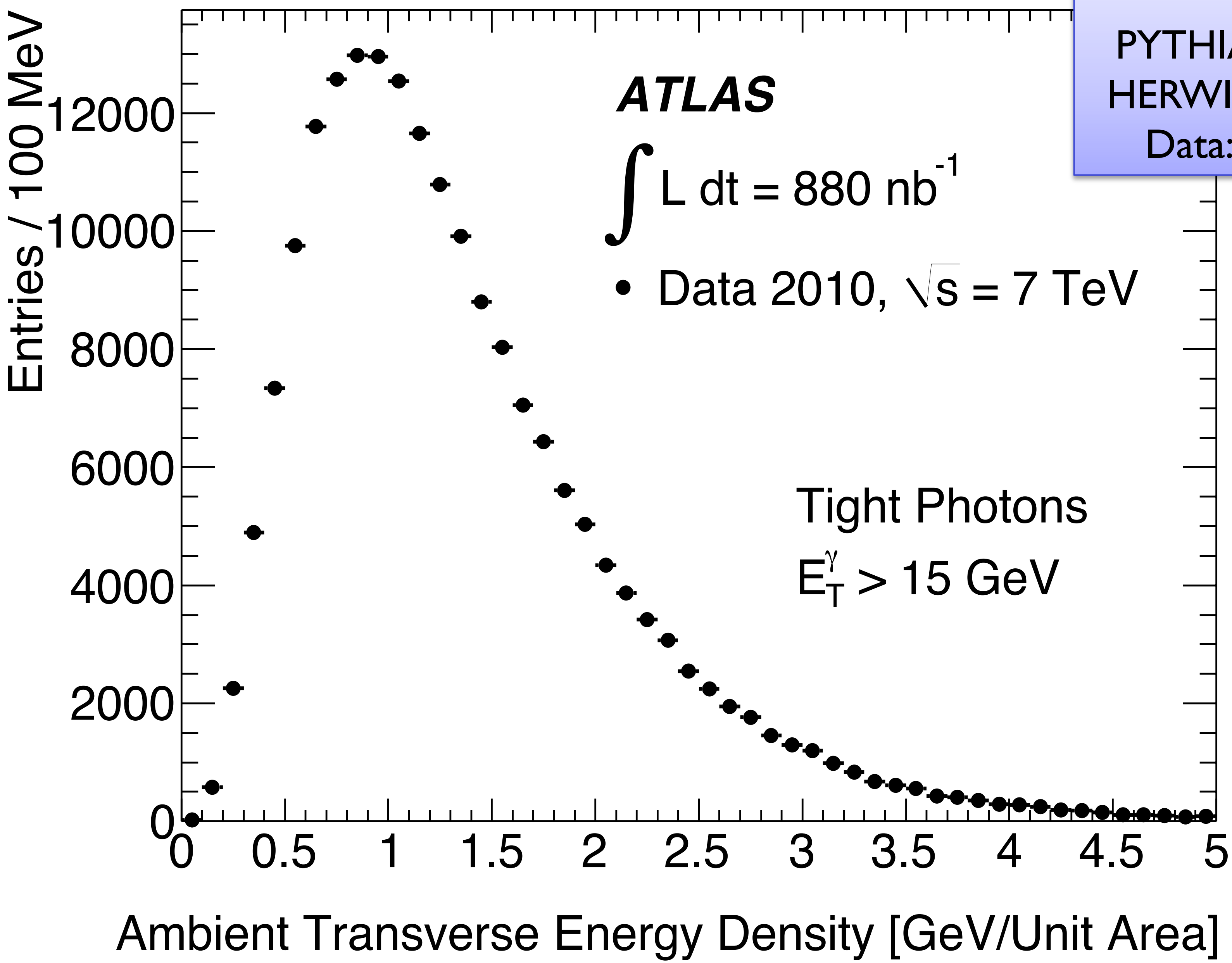
Corrected for the photon energy leaking outside the cluster

Corrected for contributions from soft-jet activity, pileup and underlying event, estimated event-by-event by using low-p_T jets and their areas

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < .4$$

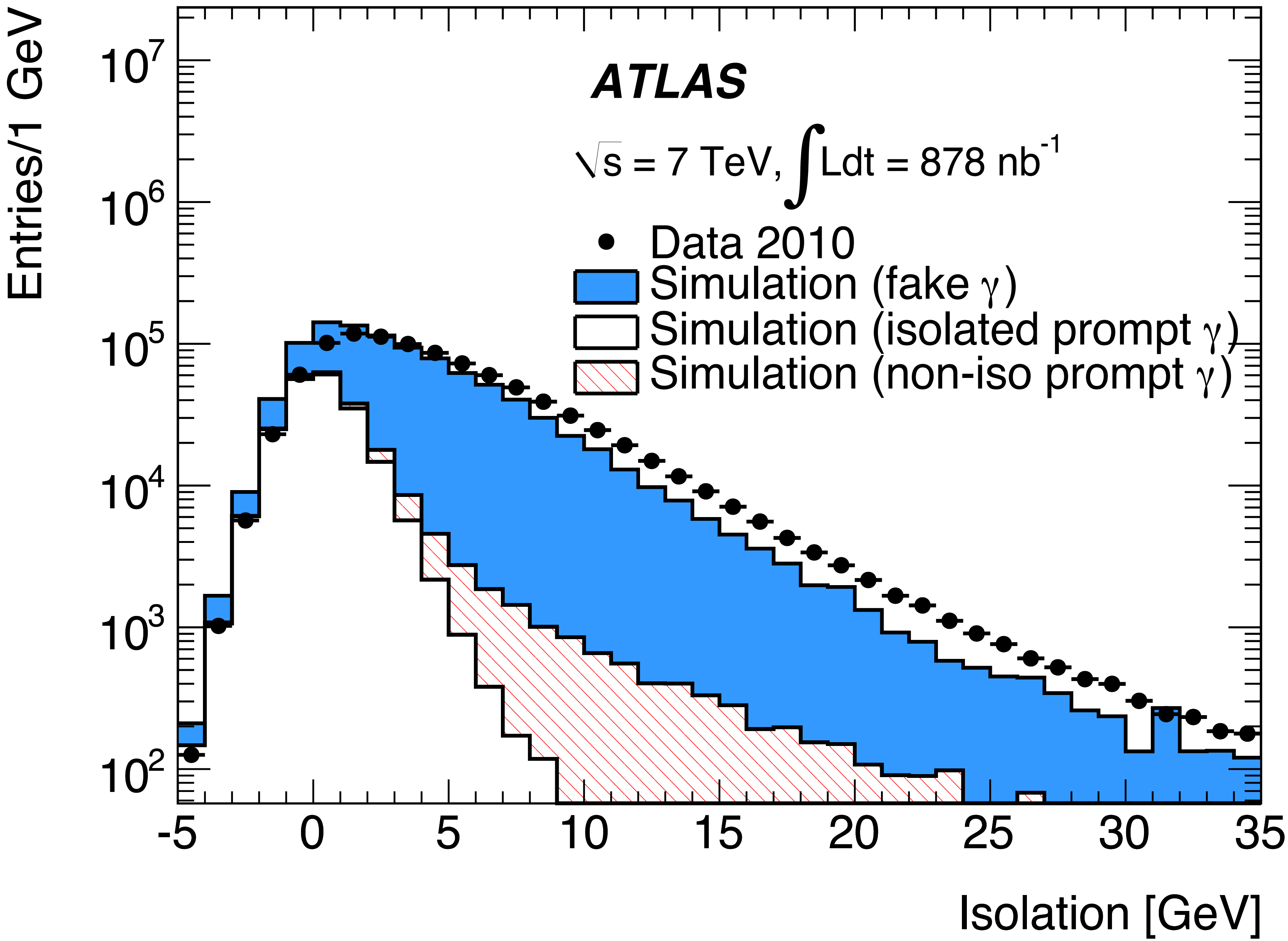
Cacciari, Salam and Soyez, JHEP 04, 005 (2008)
Cacciari, Salam and Sapeta, JHEP 04, 065 (2010)

Ambient energy density



1 PV
PYTHIA: 440 MeV
HERWIG: 550 MeV
Data: 540 MeV

Isolation energy (all photon candidates)



What

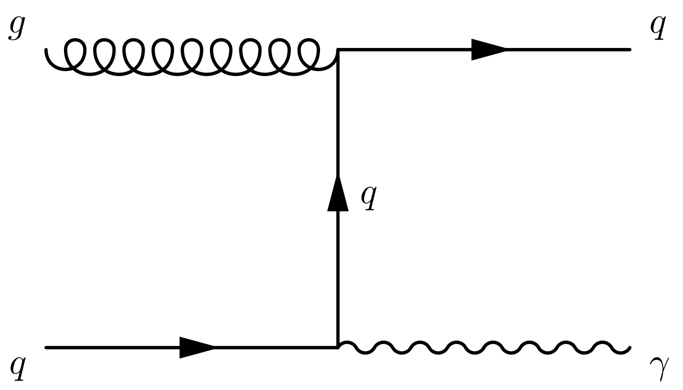
can we learn from

direct **photons**

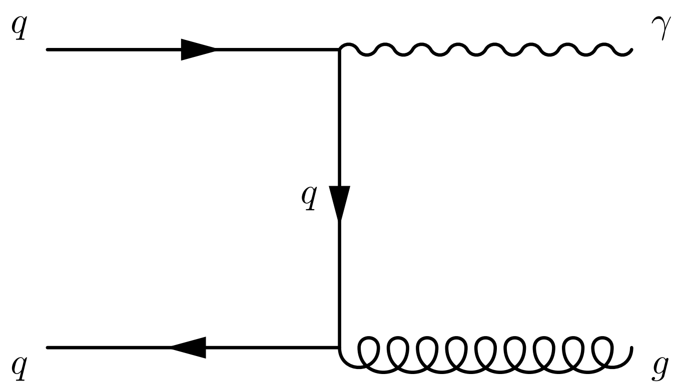
production

?

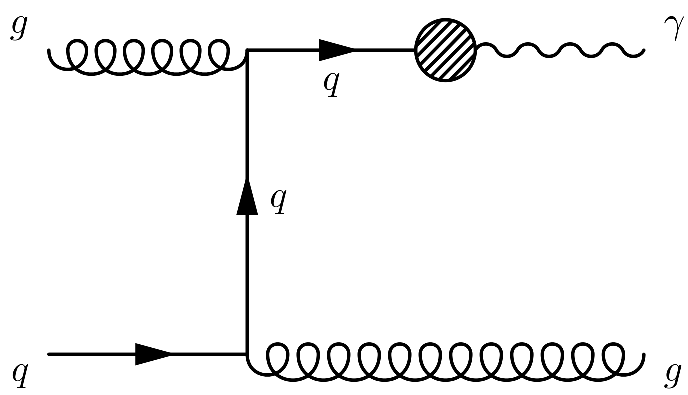
A lot of interesting physics!



Compton scattering



annihilation



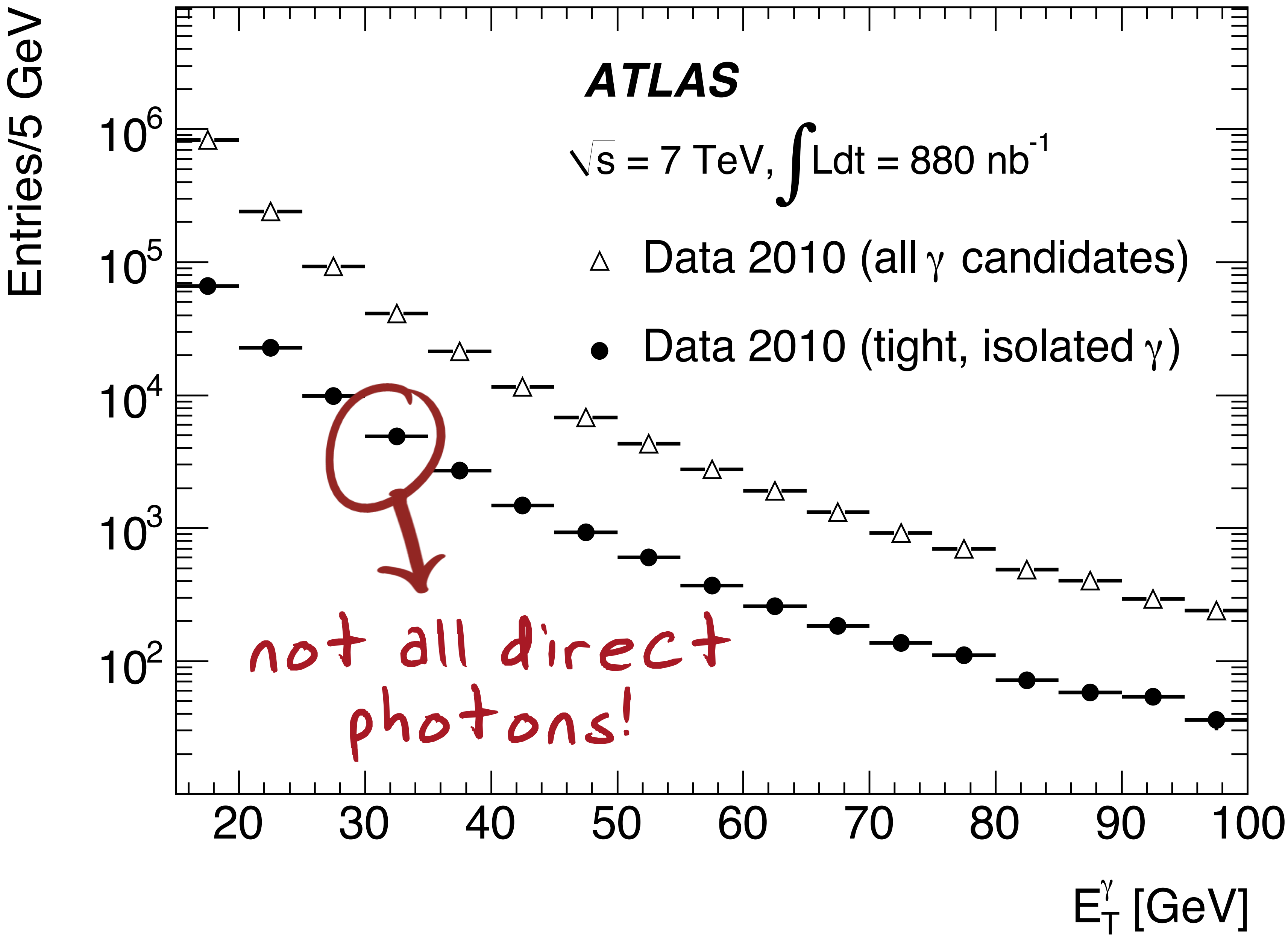
fragmentation

test of *p*QCD predictions using a measurement without jets

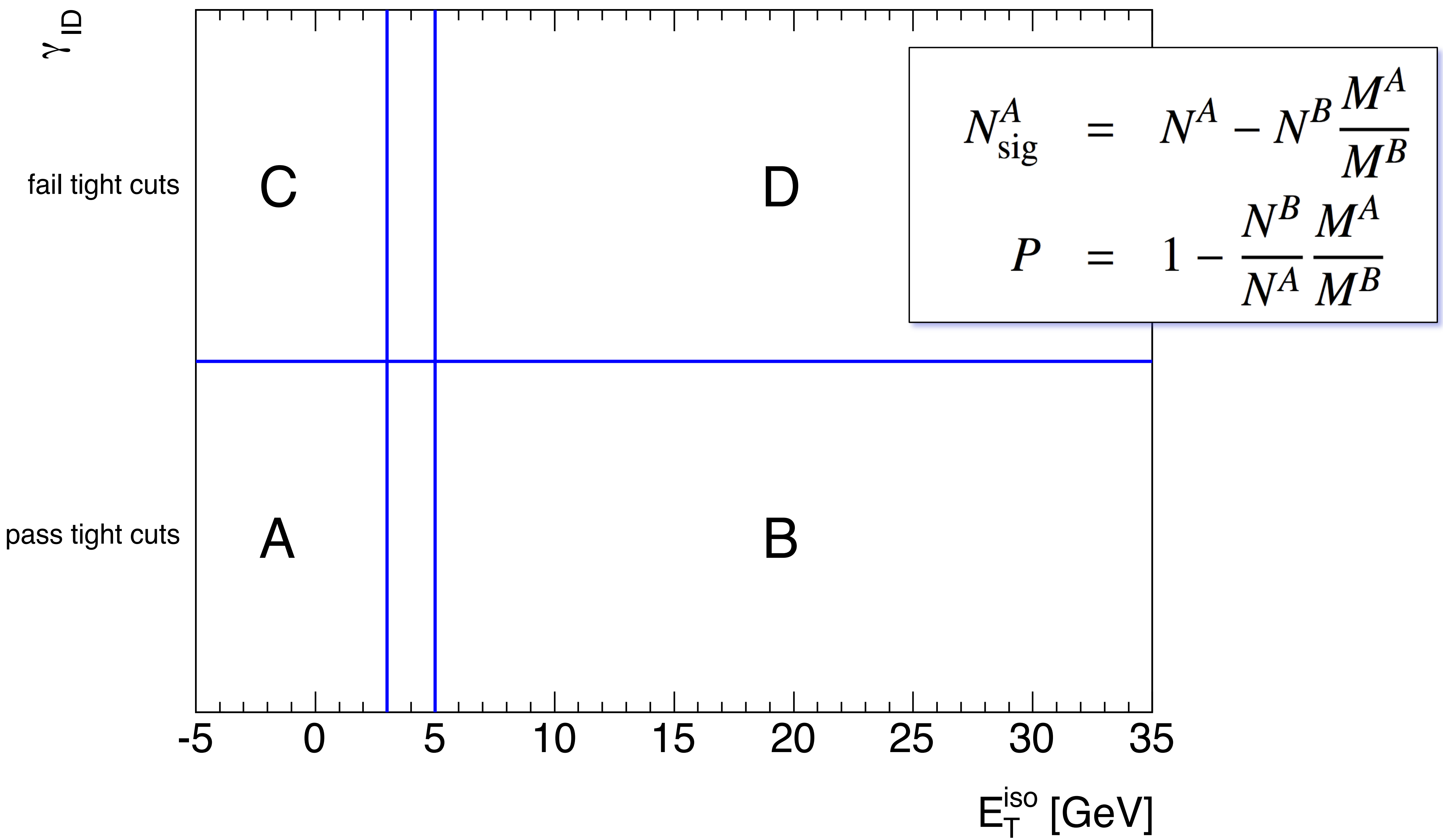
probe the gluon content of the proton

more important at low E_T
suppressed (but not not completely killed!) by isolation cut

Photon candidates in inclusive sample after cuts



"2D-sidebands" purity estimation method



$$N^A_{\mathrm{sig}} = N^A - N^B \frac{M^A}{M^B}$$

$$P = 1 - \frac{N^B}{N^A}\frac{M^A}{M^B}$$

Purity estimation: two (small!) corrections

$$N^A_{\text{sig}} = N^A - N^B \frac{M^A}{M^B}$$

$$P = 1 - \frac{N^B}{N^A}\frac{M^A}{M^B}$$

- No signal in control regions
- No correlation between isolation energy and discriminating variables in background

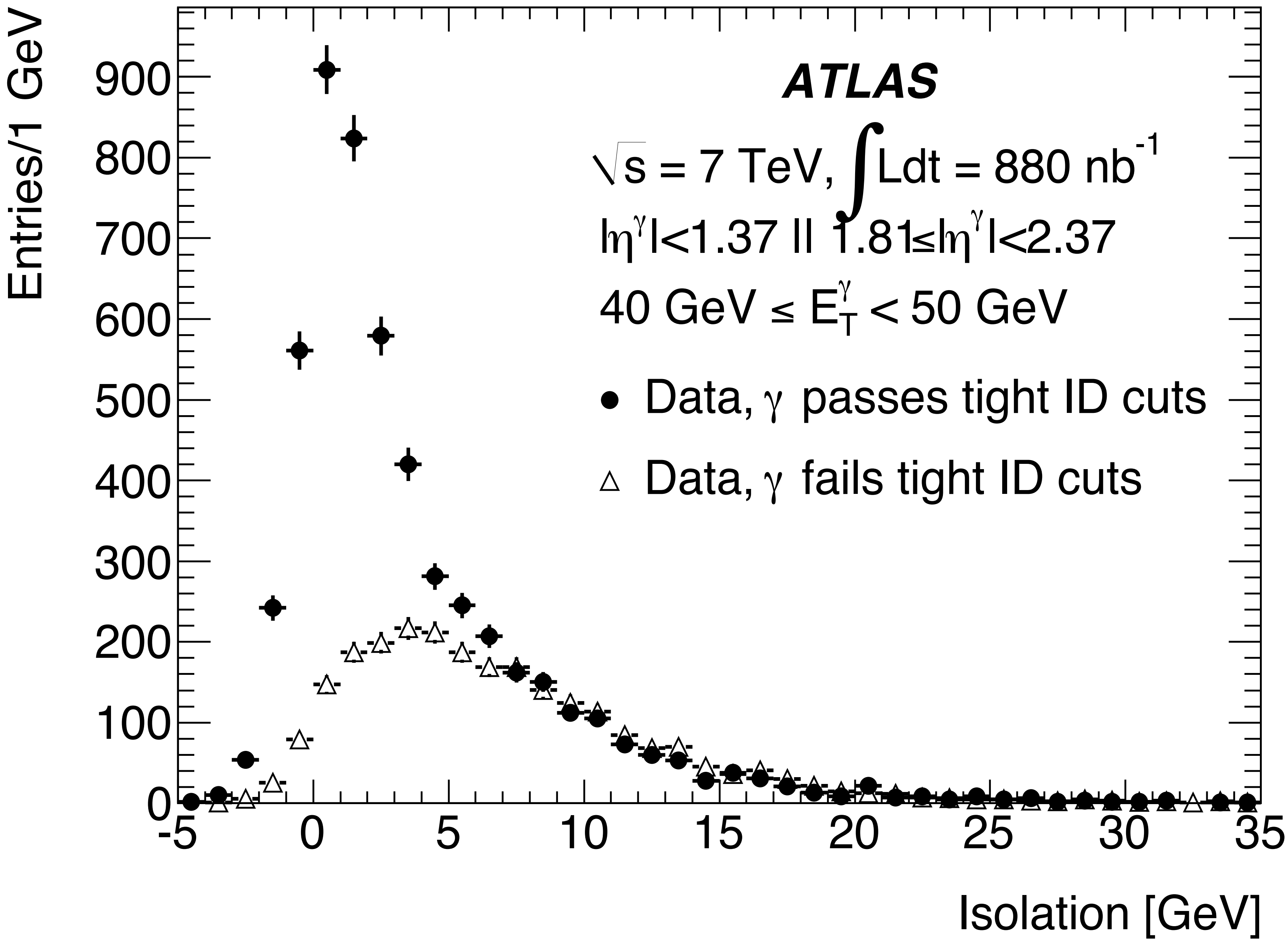
$$N^A_{\text{sig}} = N^A - \left[(N^B - c_1 N^A_{\text{sig}}) \frac{M^A - c_2 N^A_{\text{sig}}}{M^B - c_3 N^A_{\text{sig}}} \right] \left(\frac{N^A_{\text{bkg}}}{N^B_{\text{bkg}}} \frac{M^B_{\text{bkg}}}{M^A_{\text{bkg}}} \right)$$

$$P = \frac{N^A_{\text{sig}}}{N^A}$$

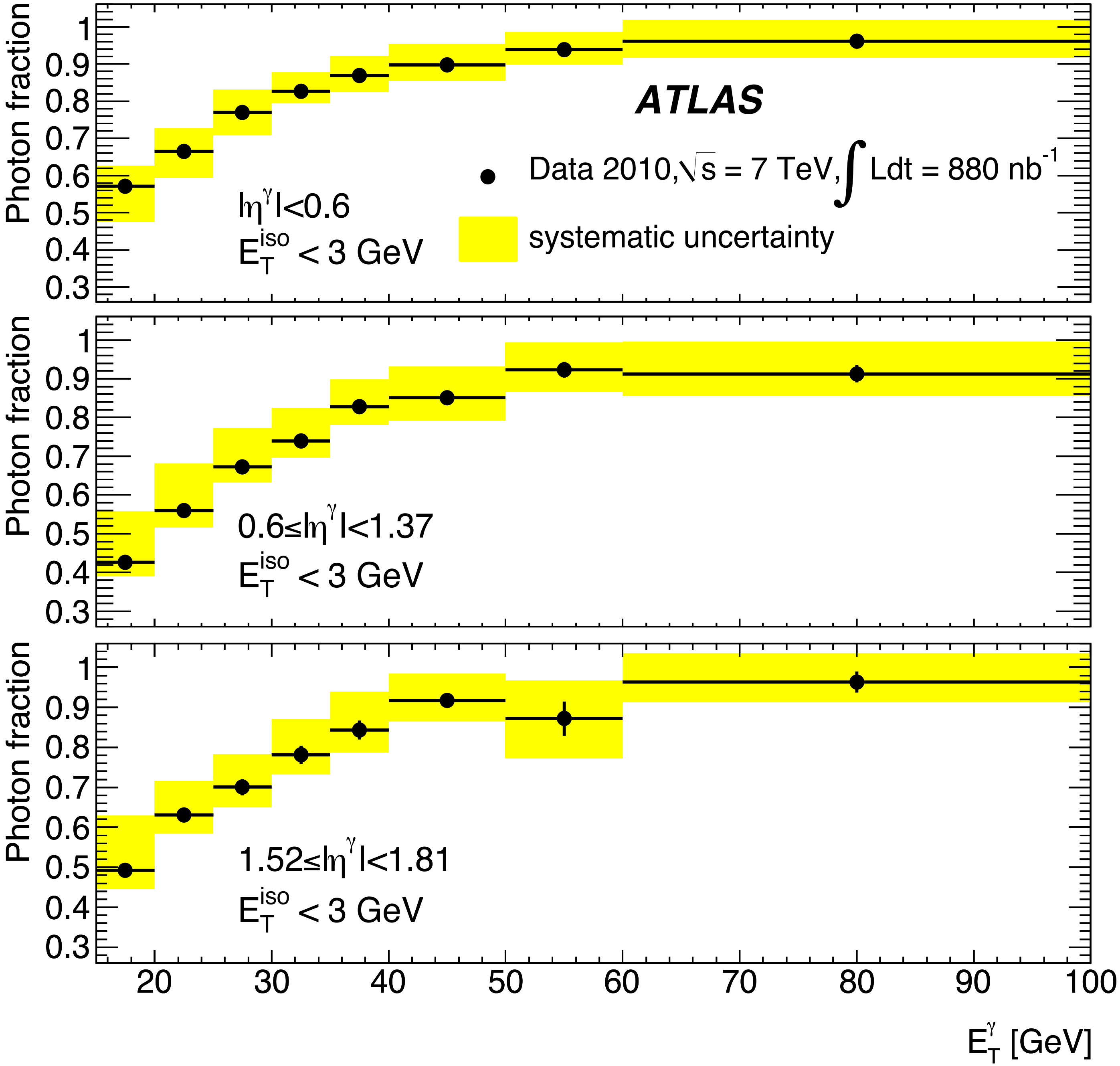
Corrections for signal leakage

Corrections for correlation

Direct photons!

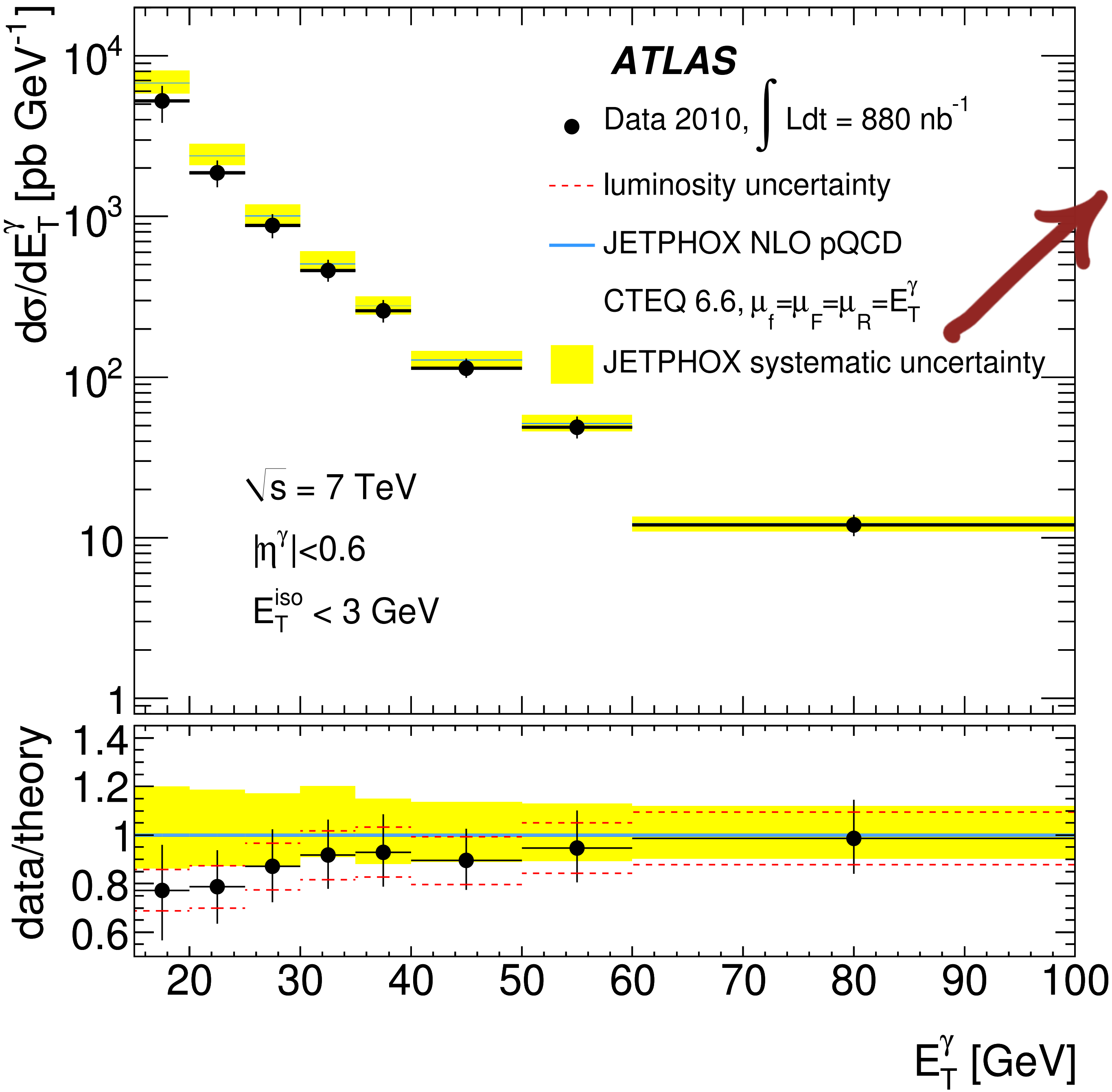


Data-driven photon purity



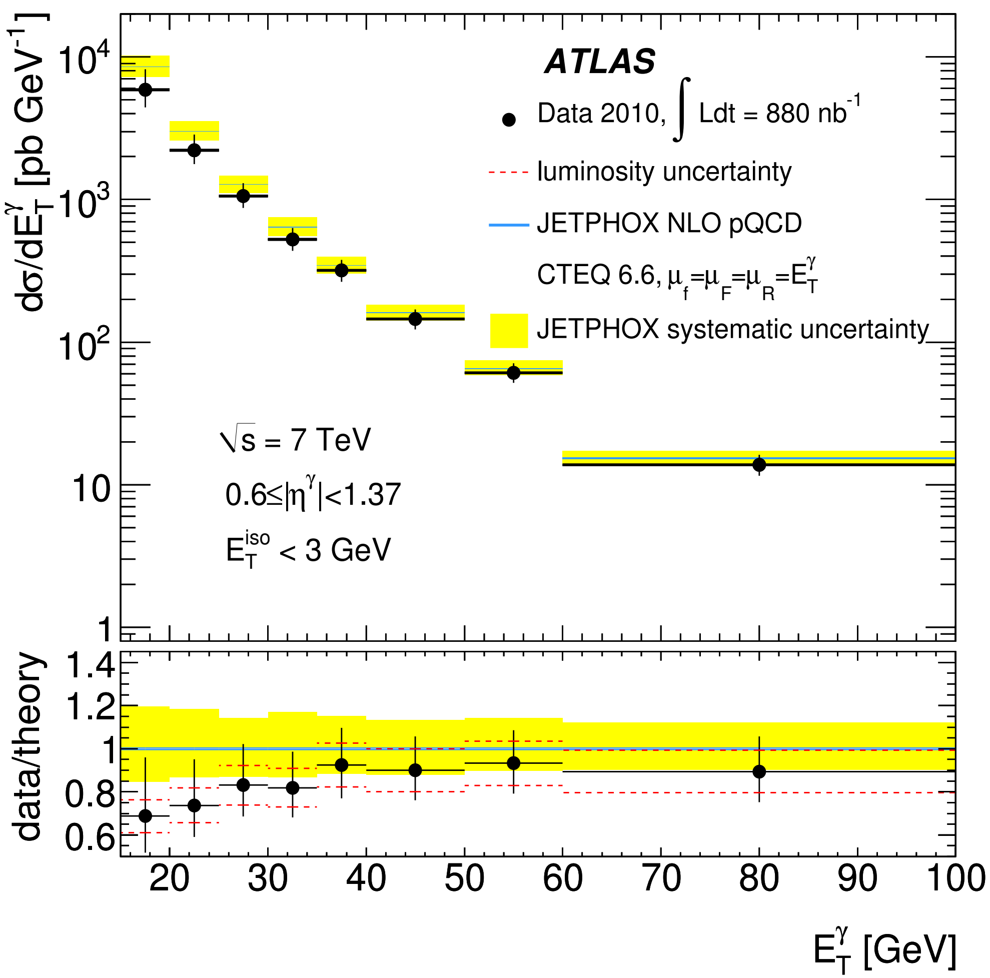
Inclusive direct photon cross section

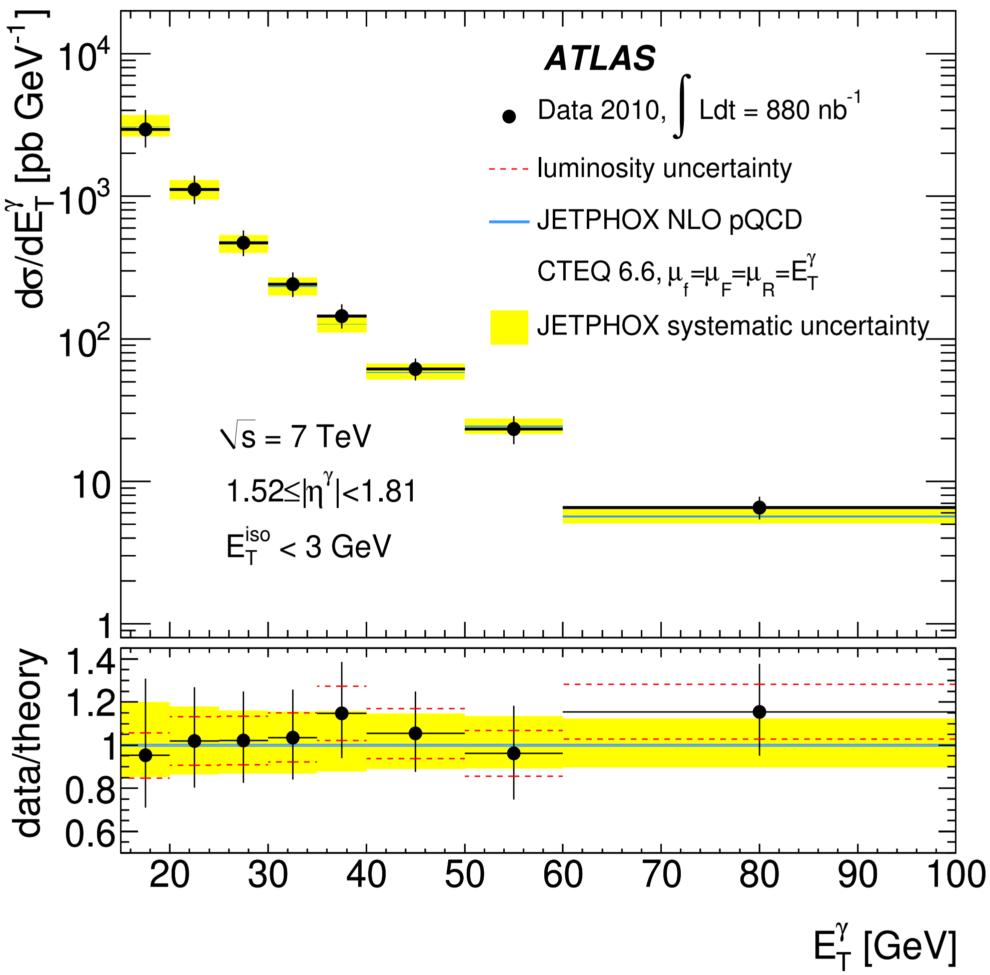
Isolation < 4 GeV in cone $\Delta R = 0.4$ (vary isolation from 2 to 6 GeV)



Scale variation (independently from μ = 0.5 $E_T\gamma$ to μ = $2E_T\gamma$)

Inclusive direct photon cross section





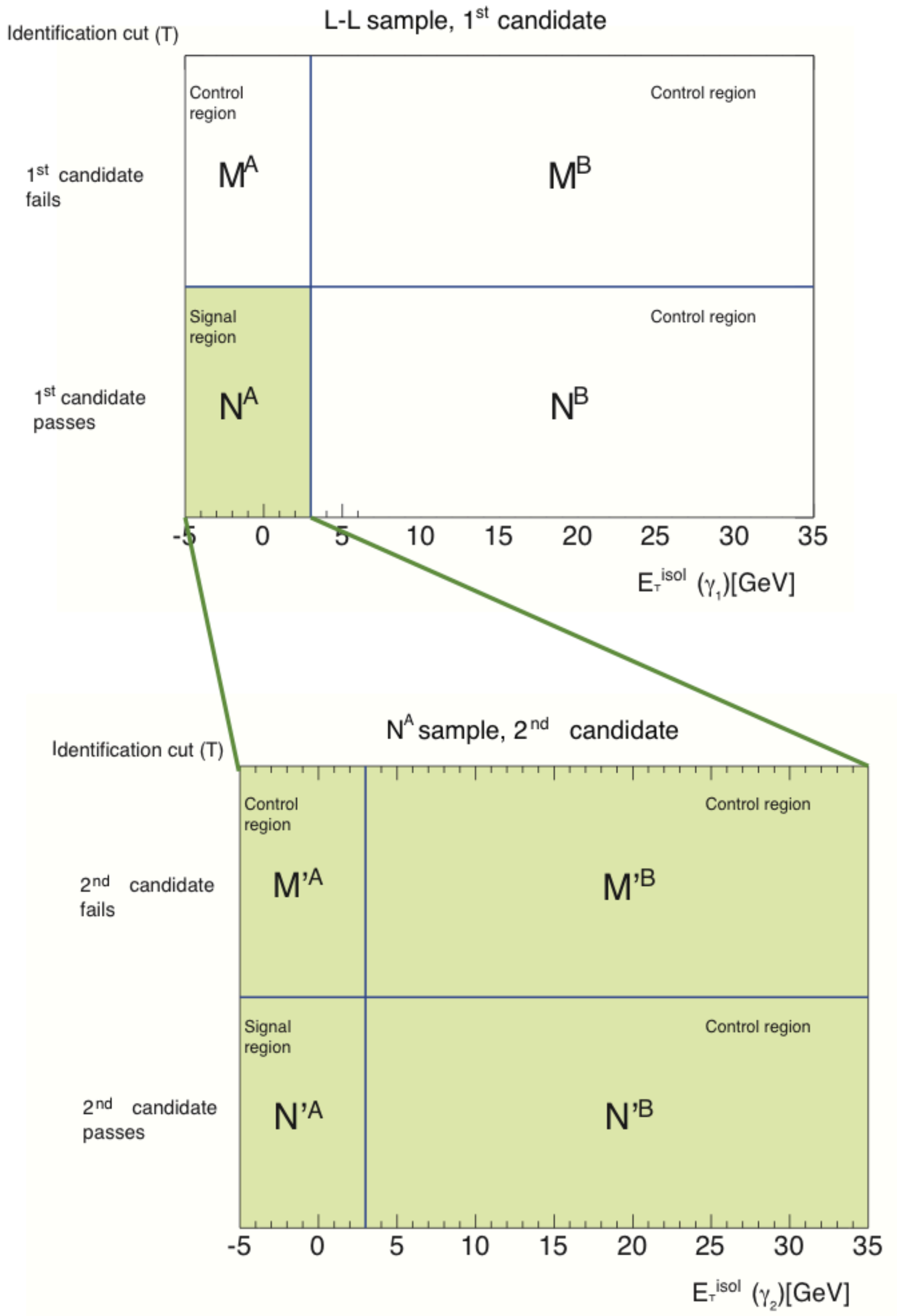
What ?

can we say about the

Higgs boson

with the photon measurements
already done at LHC

Twice the 2D-sidebands method



- N^A: signal and background ($N^A = N^A_{\rm sig} + N^A_{\rm bkg}$),
- N^B: only background ($N^B = N^B_{\rm bkg}$),
- M^A: only background ($M^A = M^A_{\rm bkg}$),
- M^B: only background ($M^B = M^B_{\rm bkg}$).

$$N^A_{\rm sig} = N^A - N^A_{\rm bkg} = N^A - N^B \frac{M^A}{M^B}$$

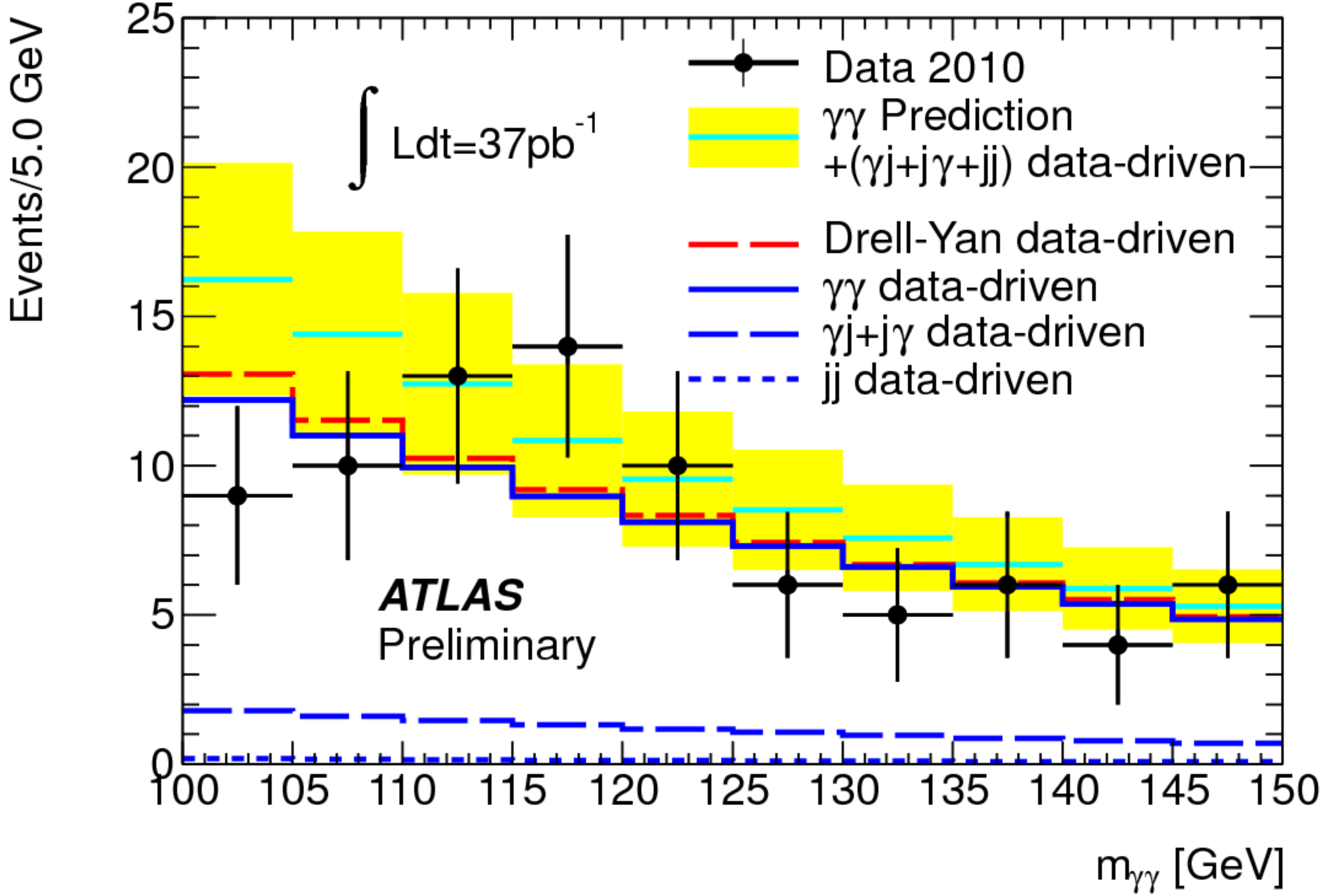
leading candidate is a photon, i.e. $\gamma\gamma$ and γ-jet

- N'^A: signal and background ($N'^A = N'^A_{\rm sig} + N'^A_{\rm bkg}$),
- N'^B: only background ($N'^B = N'^B_{\rm bkg}$),
- M'^A: only background ($M'^A = M'^A_{\rm bkg}$),
- M'^B: only background ($M'^B = M'^B_{\rm bkg}$).

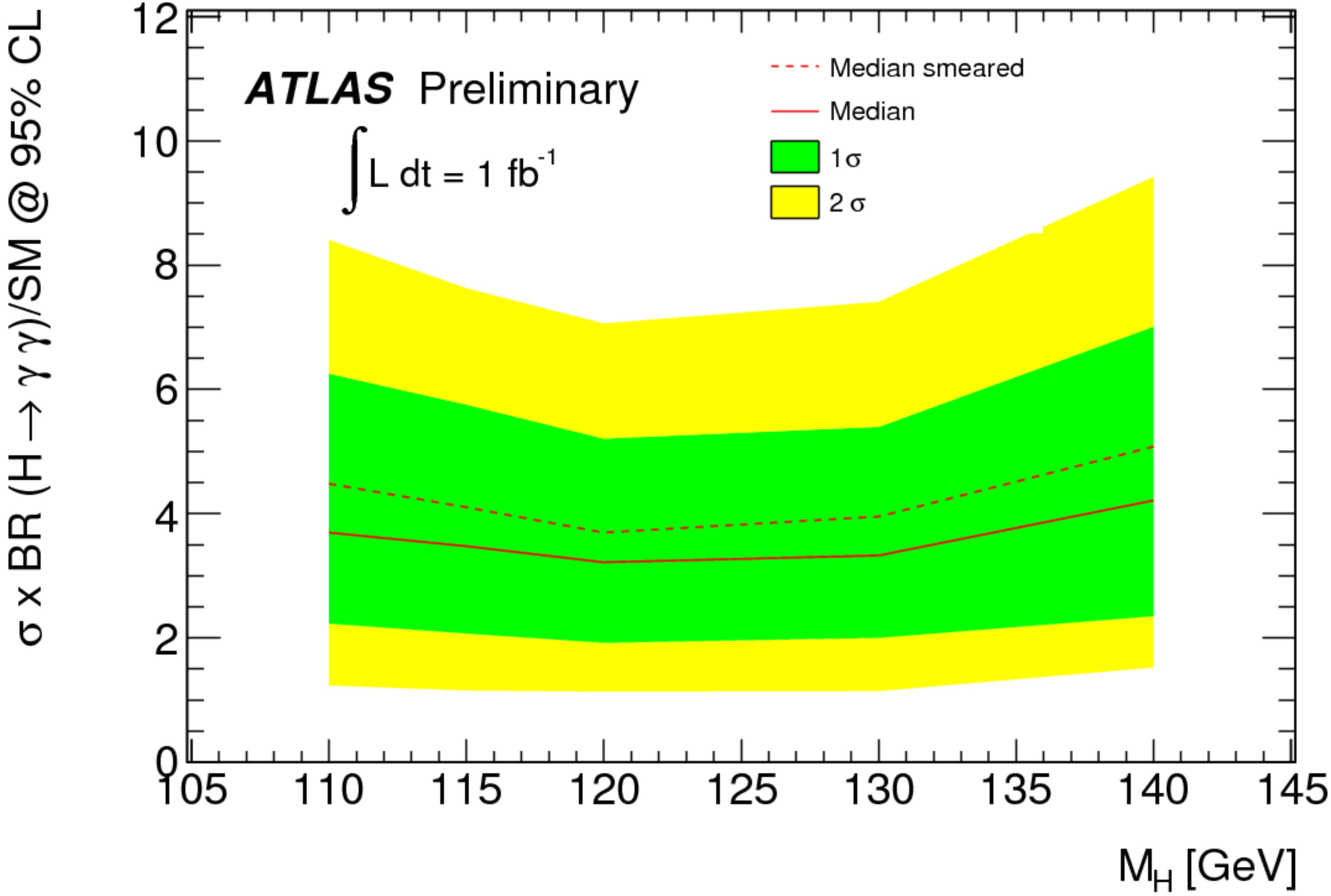
$$N'^A_{\rm sig} = N'^A - N'^A_{\rm bkg} = N'^A - N'^B \frac{M'^A}{M'^B}$$

leading candidate is tight and isolated, and sub-leading candidate is a photon, i.e. $\gamma\gamma$ and jet-γ !

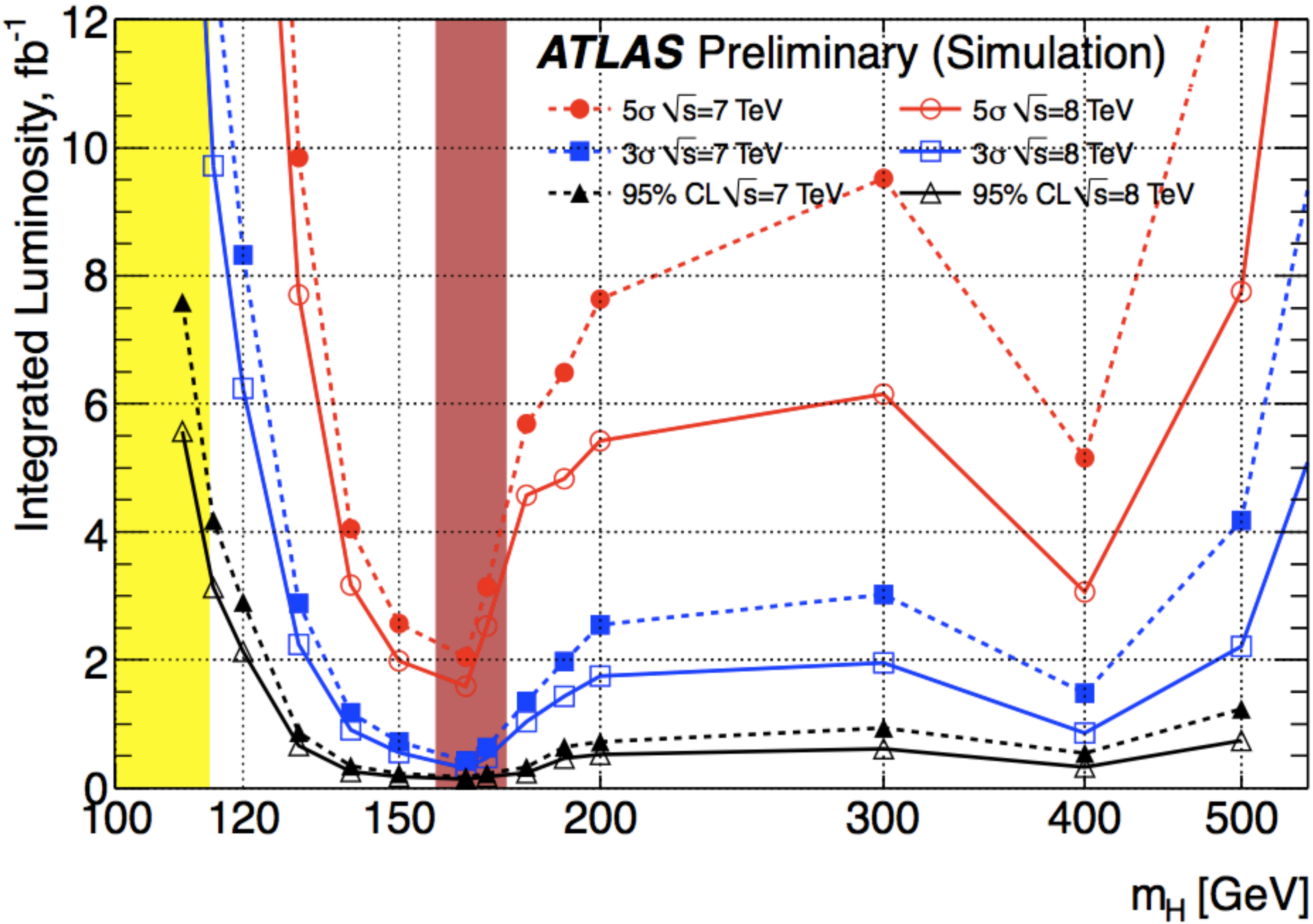
Diphoton spectrum vs $m_{\gamma\gamma}$



Projected sensitivity with 1 fb^{-1} at 7 TeV



How much data for a discovery (or exclusion?)



the first Higgs seen by ATLAS

References

- The ATLAS Collaboration. *Prospects for the Discovery of the Standard Model Higgs Boson Using the $H \rightarrow \gamma\gamma$ Decay.*
  - ✓ ATL-PHYS-PUB-2009-053, 2009.
- The ATLAS Collaboration. *Evidence for prompt photon production in pp collisions at $\sqrt{s}$ = 7 GeV with the ATLAS detector.*
  - ✓ ATLAS-CONF- 2010-077, 2010.
- The ATLAS Collaboration. *Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s}$= 7 TeV with the ATLAS detector.*
  - ✓ Accepted for publication by Phys. Rev. D, 2010. arXiv:1012.4389.
- The ATLAS Collaboration. *Measurement of the backgrounds to the $H \rightarrow \gamma\gamma$ search and reappraisal of its sensitivity with 37 pb^{-1} of data recorded by the ATLAS detector.*
  - ✓ ATLAS-CONF-2011-004
- The ATLAS Collaboration. *Further investigations of ATLAS Sensitivity to Higgs Boson Production in different assumed LHC scenarios.*
  - ✓ ATL-PHYS-PUB-2011-001, 2011