Photon physics at the LHC with the ATLAS detector

Marco Delmastro


already
yawning?

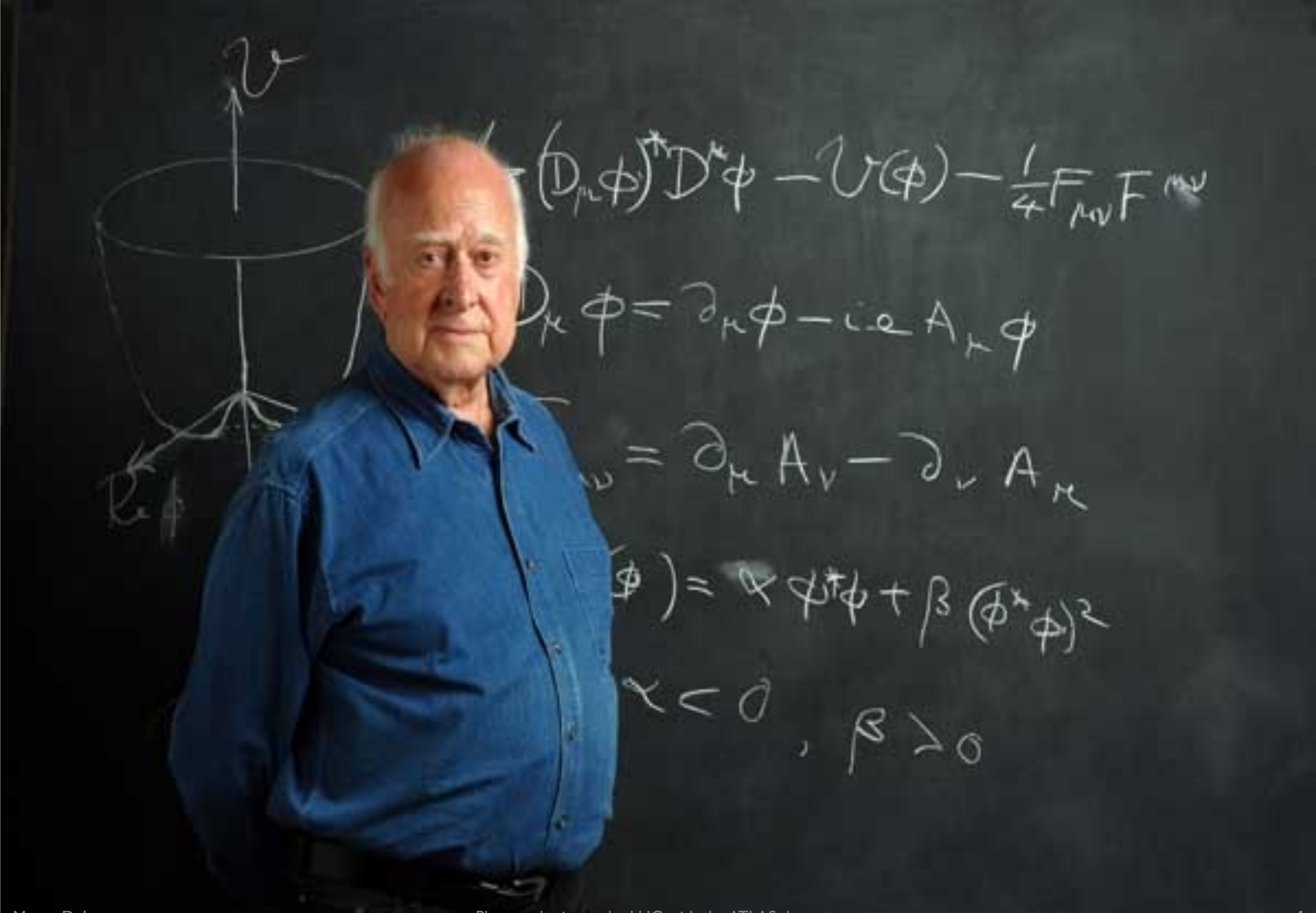
How ATLAS will discover the SM Higgs boson* **

(or prove it does not exist)

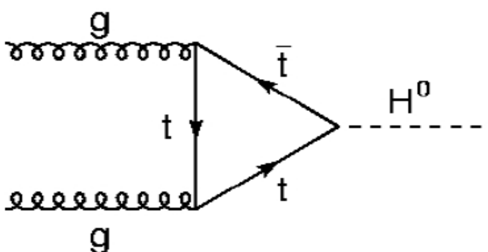
Marco Delmastro

* using photons!

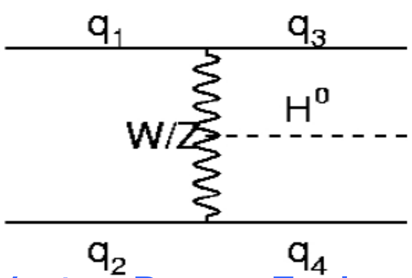
** and learning a lot of physics!



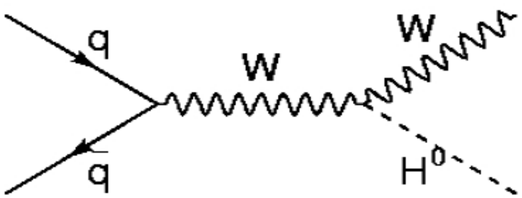
How *would* the SM Higgs be produced at LHC?



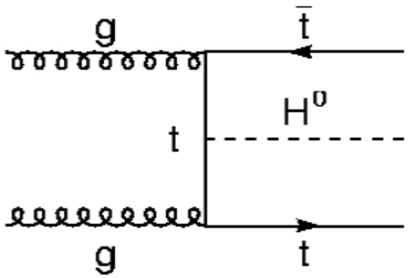
gluon fusion



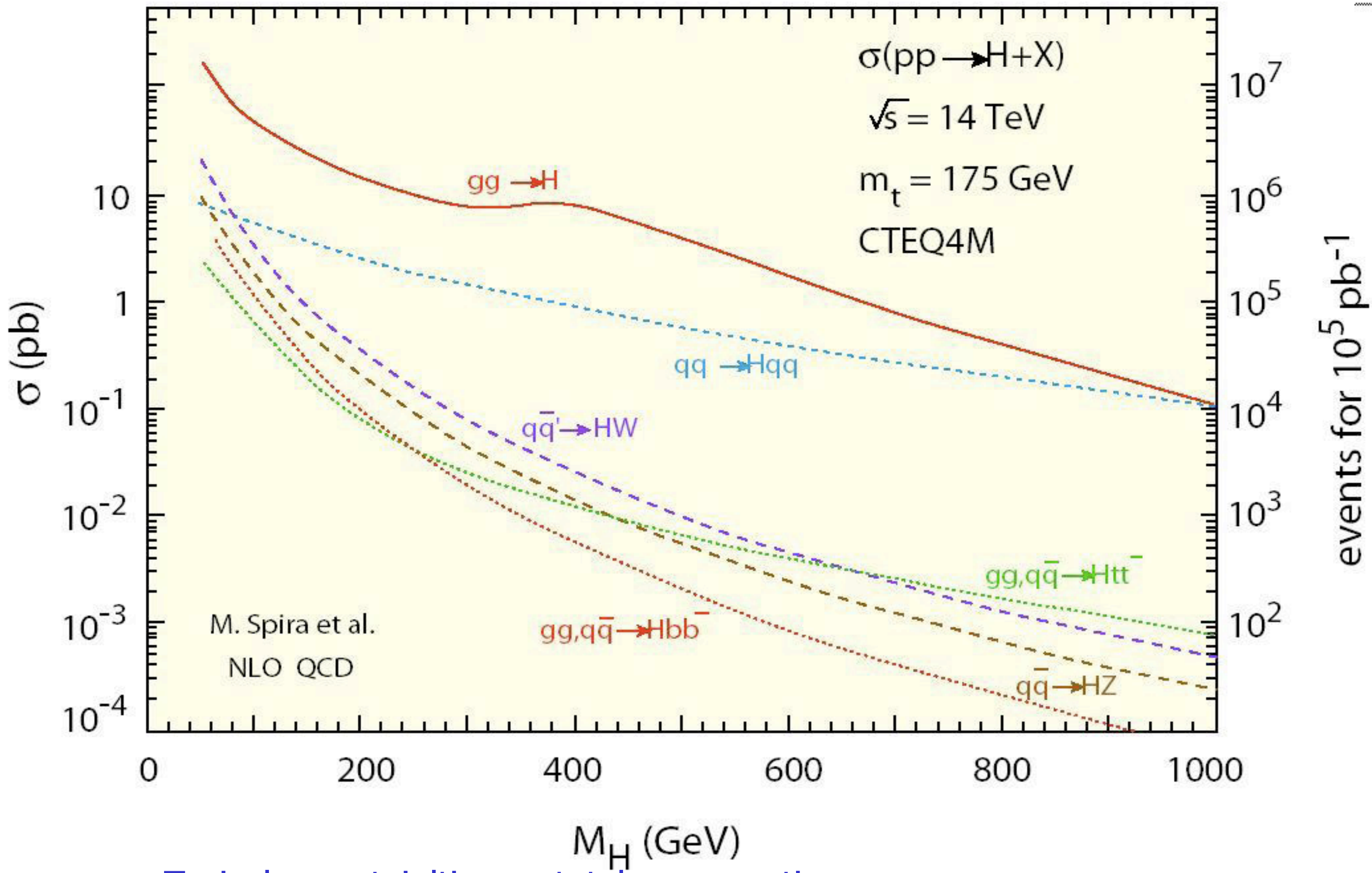
Vector-Boson-Fusion (VBF)



associated production (W, Z)



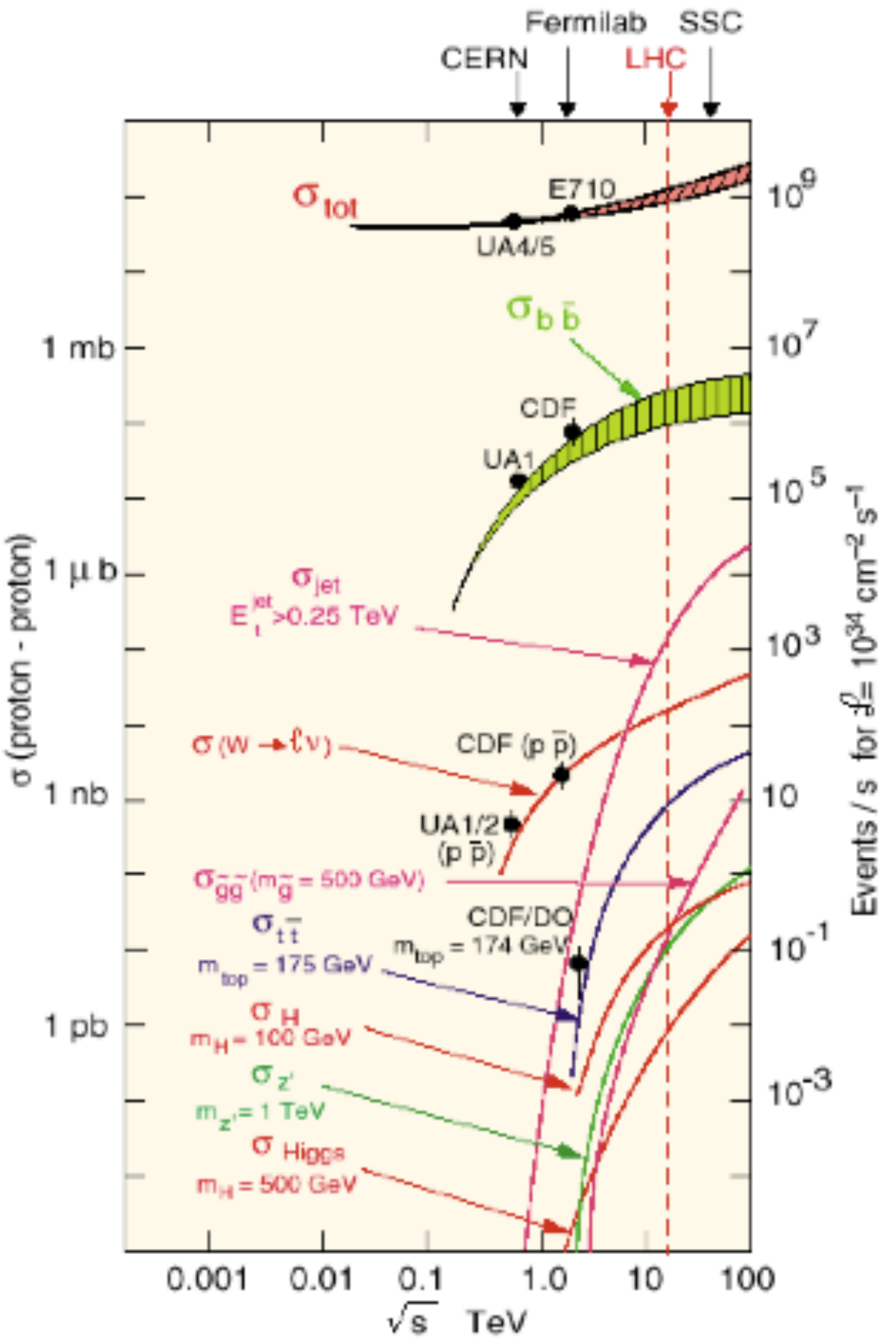
associated production (ttbar)



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

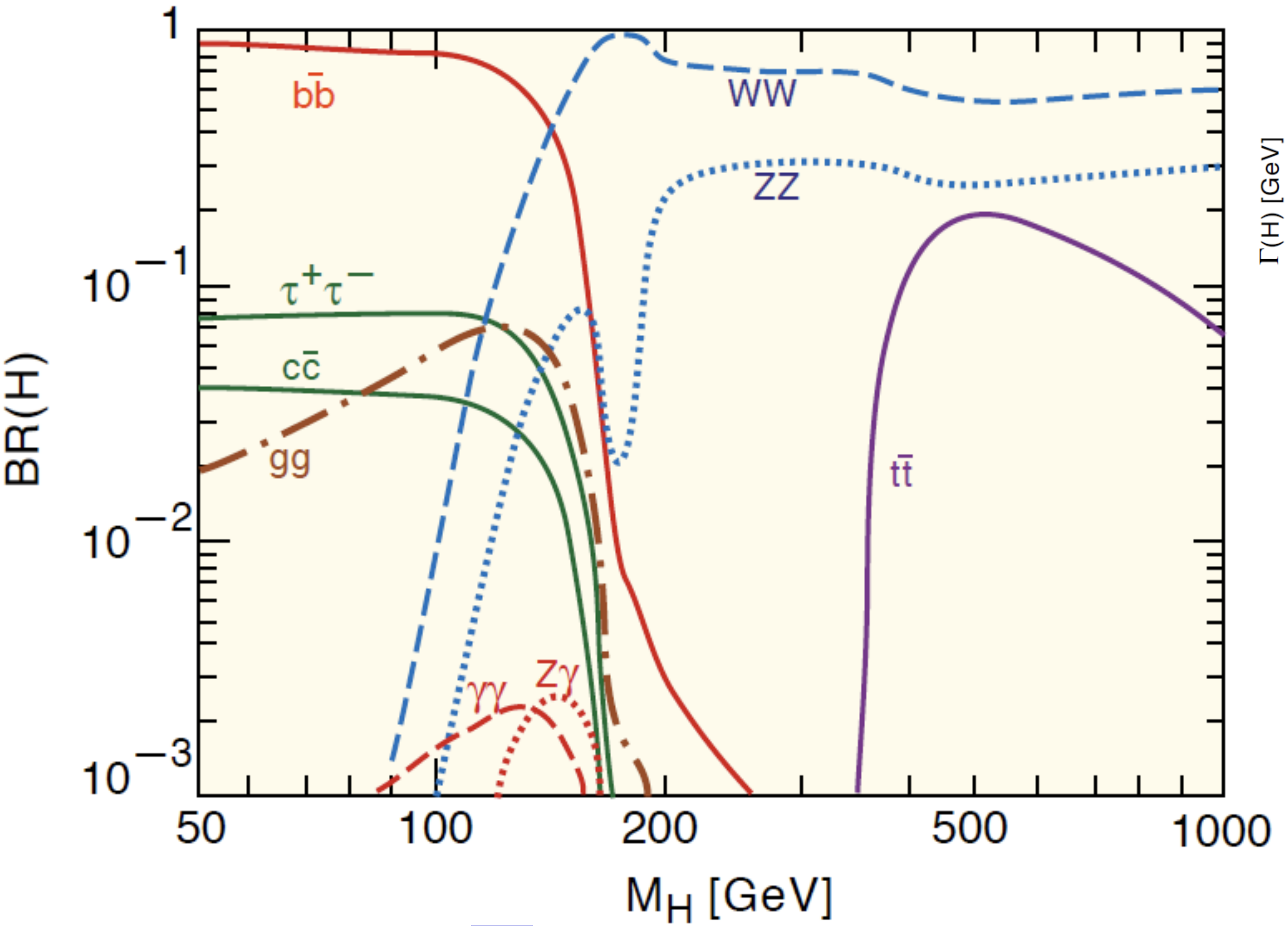
W ($\rightarrow l\nu$) production cross-section: $\sigma \sim 10$ nb

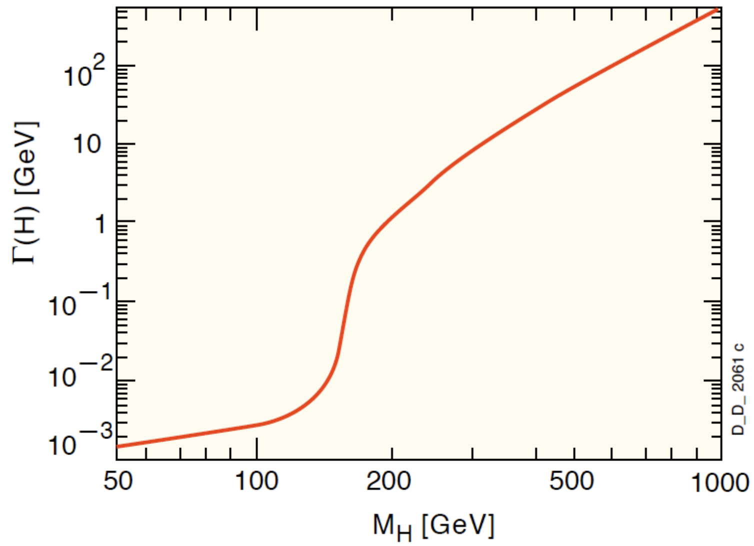
Higgs (m_H=150 GeV) cross-section: $\sigma \sim 10$ pb

Total σ / Higgs σ > 10^{10}

Why do we want to measure photons at LHC?

How *would* the SM Higgs decay?





bb → m_H < 130 GeV

$\gamma\gamma$ → m_H < 140 GeV

$\tau\tau$ → m_H < 150 GeV

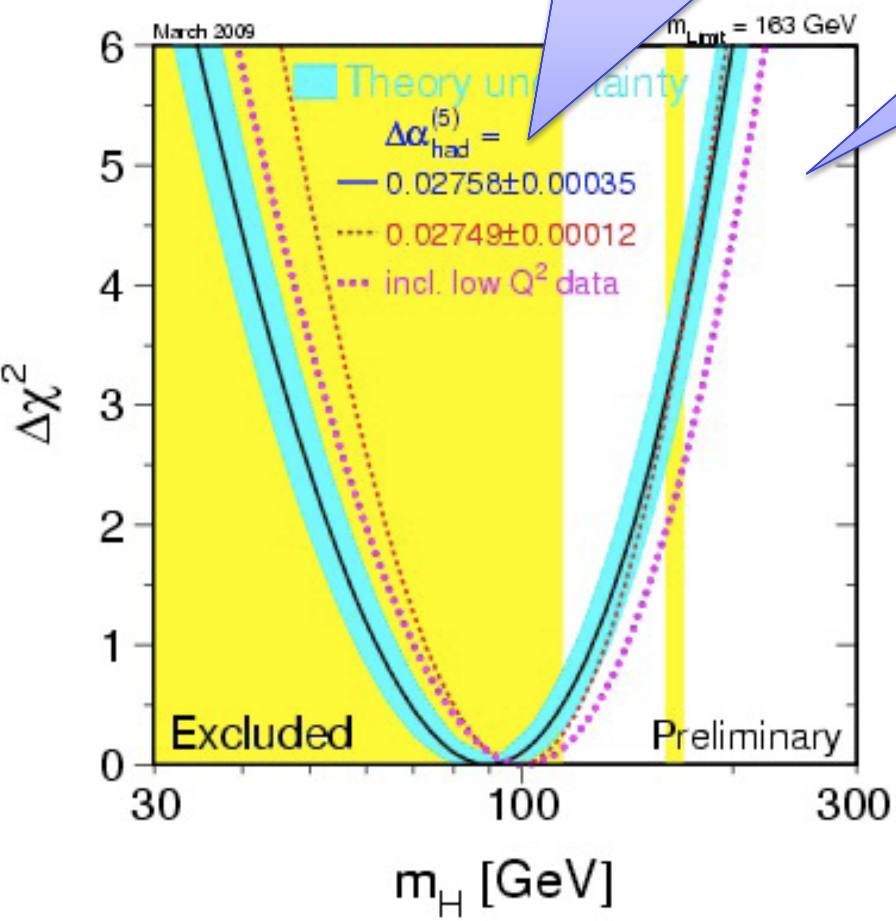
WW → $2m_W < m_H < 2m_Z$

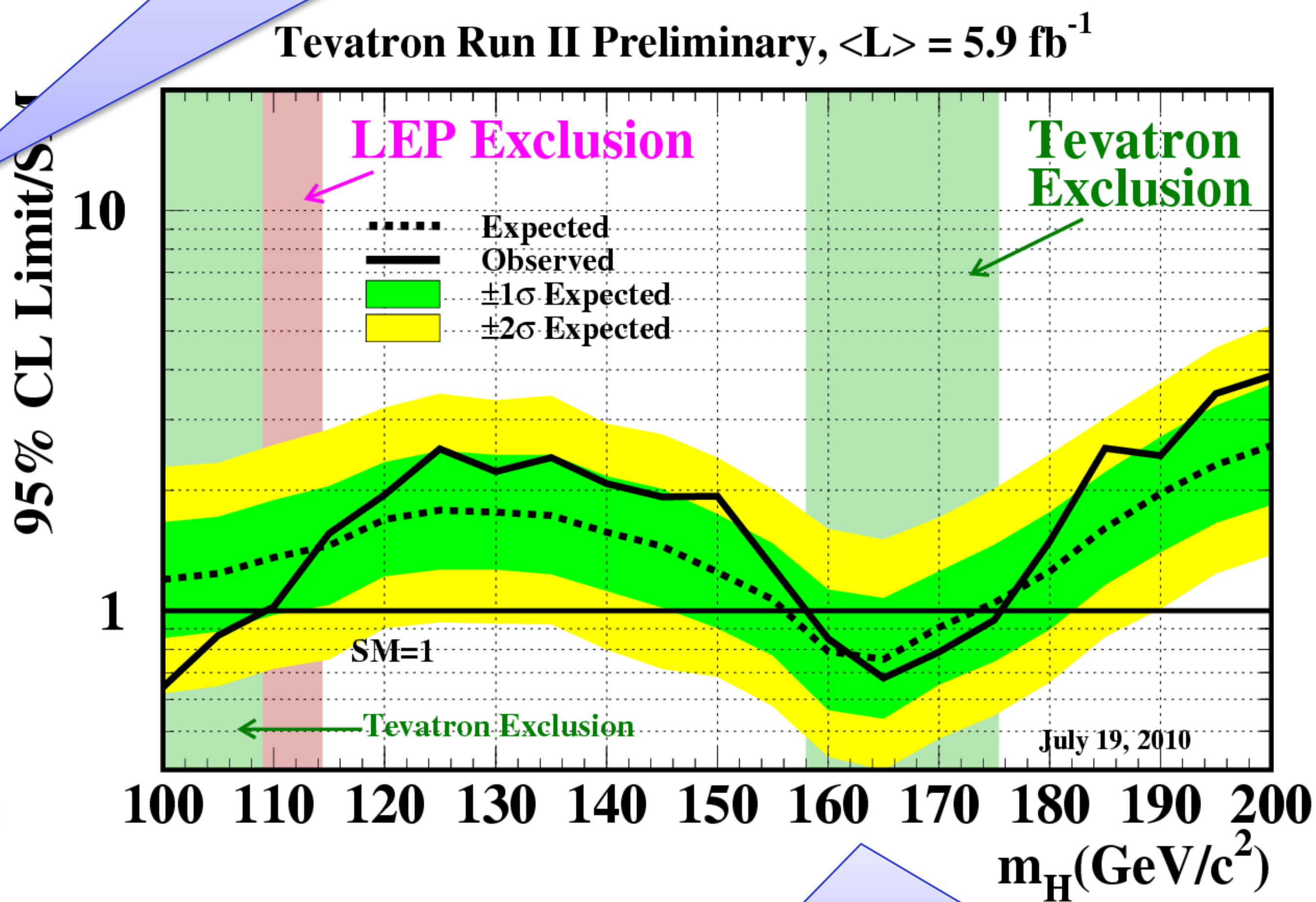
ZZ → m_H > 130 GeV

Where is the Higgs boson hiding?

LEP direct search: m_H > 114.4 GeV

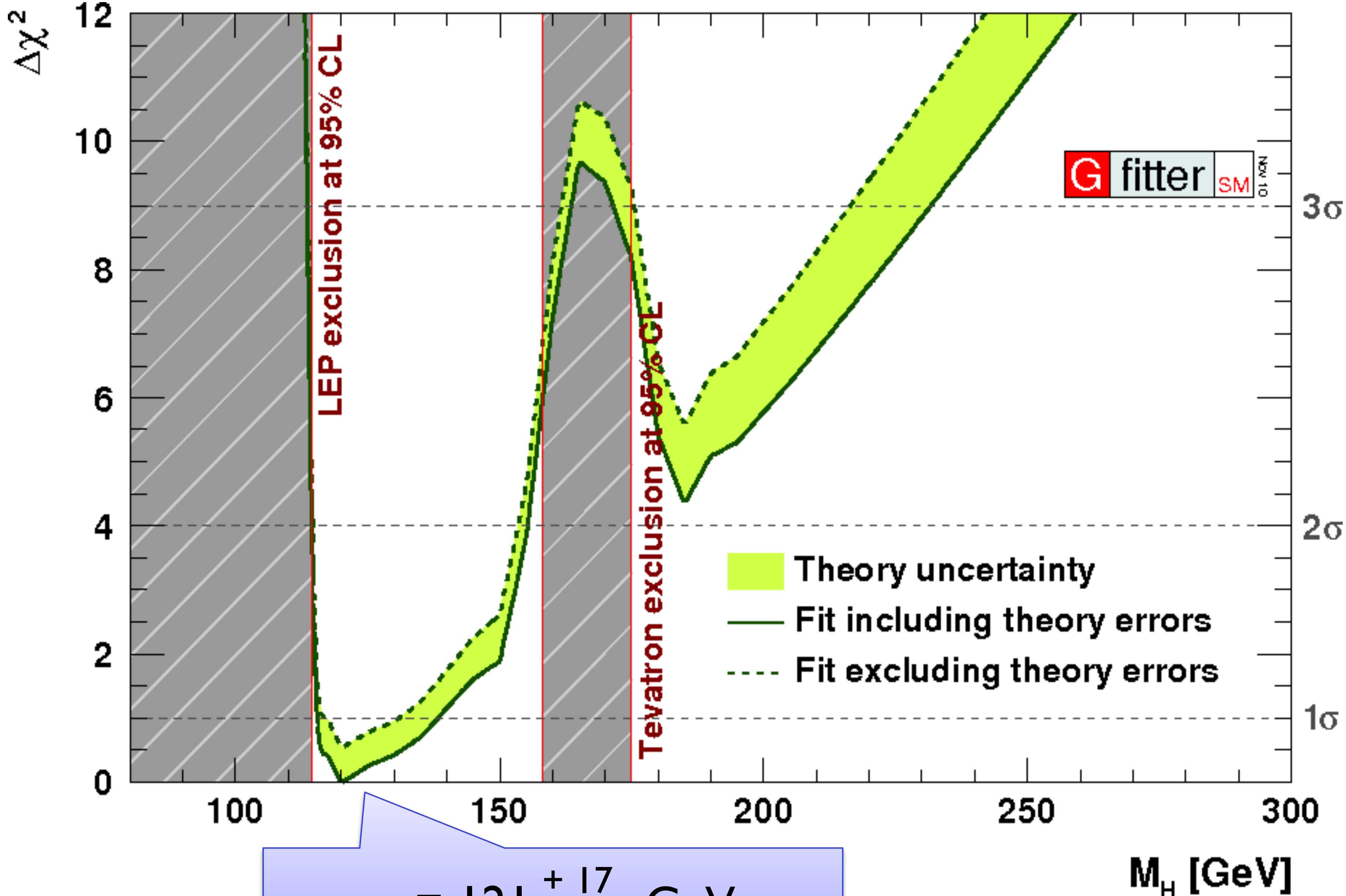
EW fit favors m_H < 163 GeV





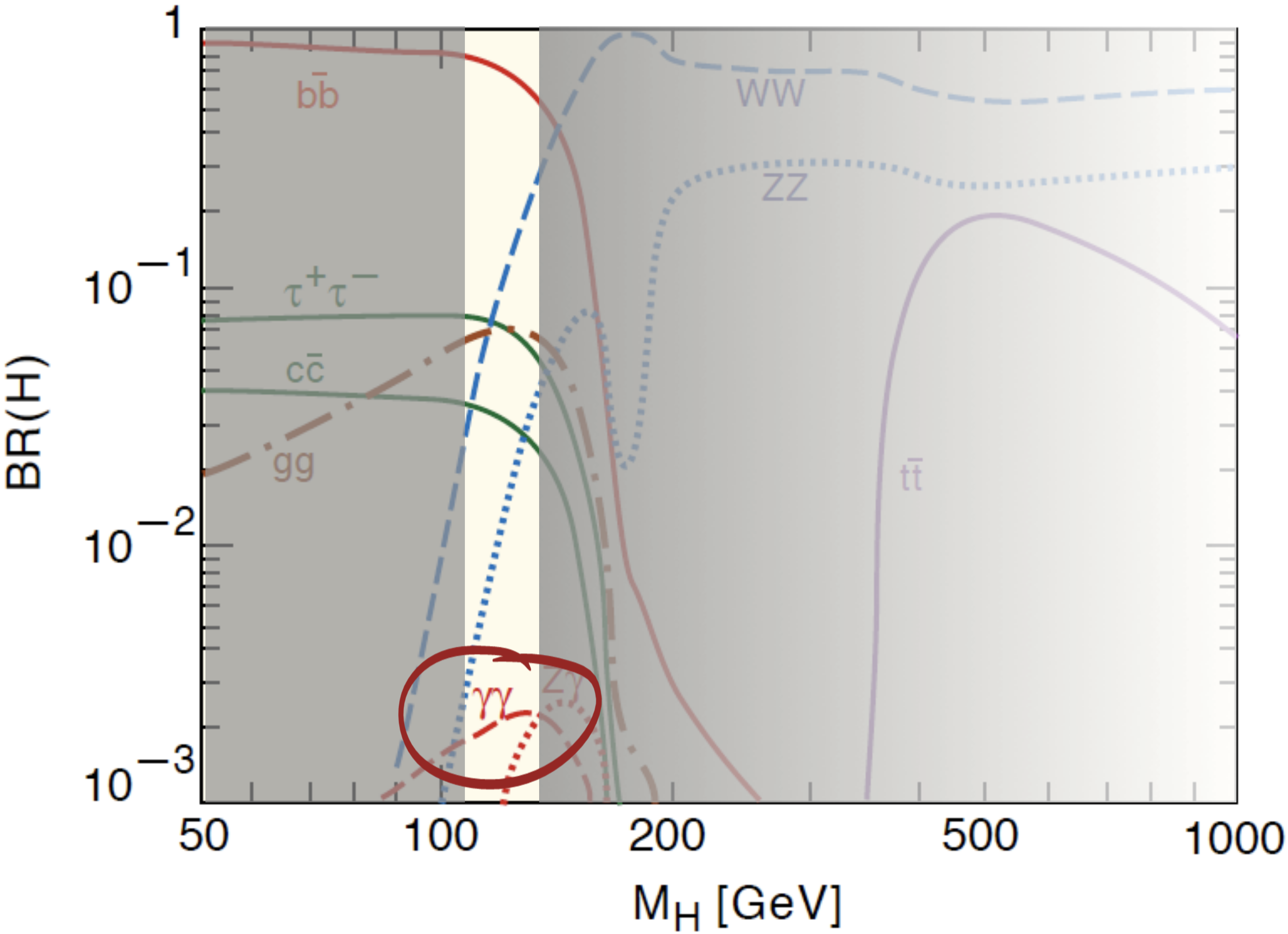
CDF+D0 direct search combination (~6 fb^{-1})
excludes ranges 100-109 GeV and 158-175 GeV

Where is the Higgs boson?

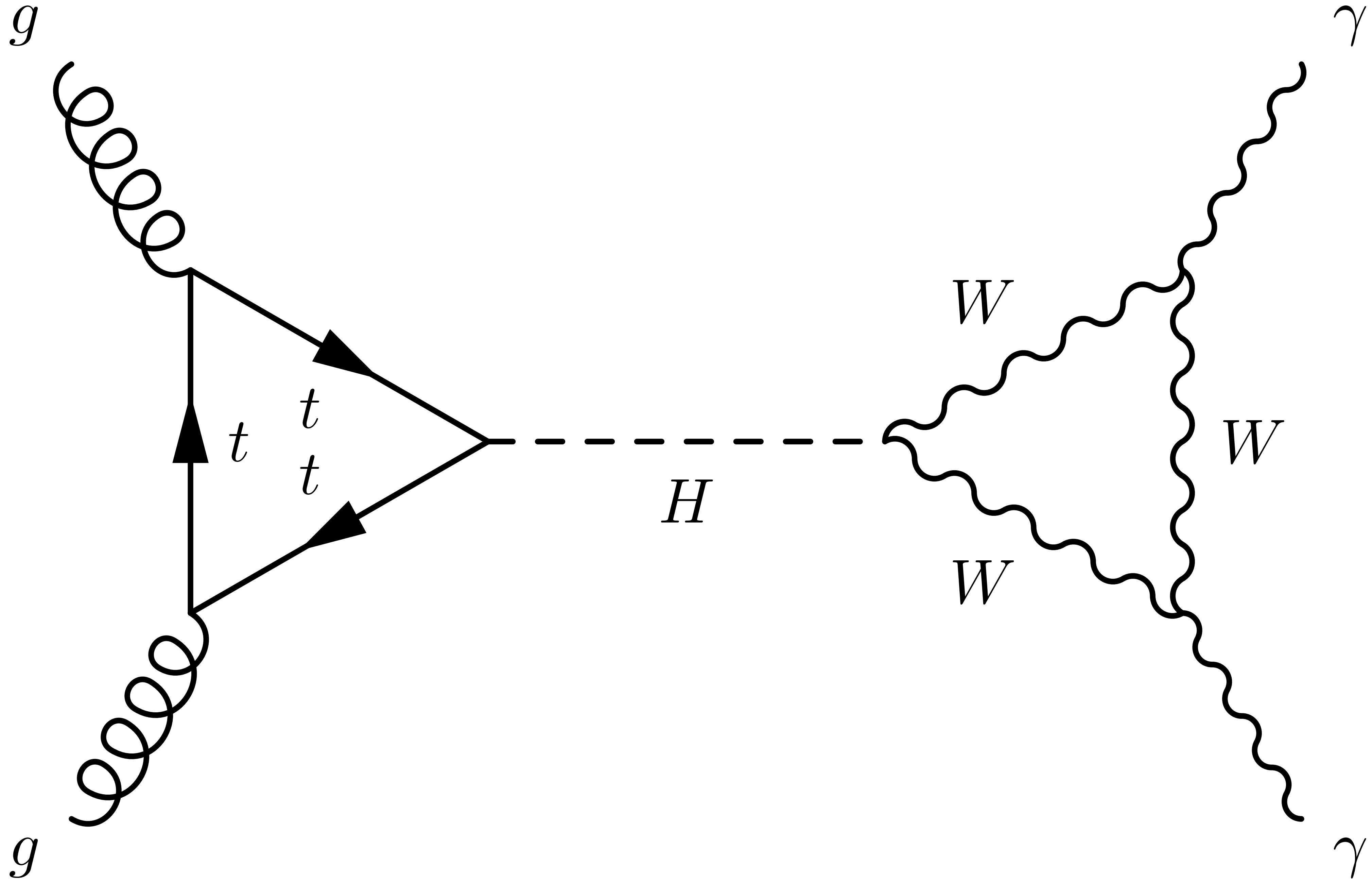


$$m_H = 121^{+17}_{-6}\ \text{GeV}$$

Why photons?



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


g
g
t
t
t
H
W
W
W
γ
γ

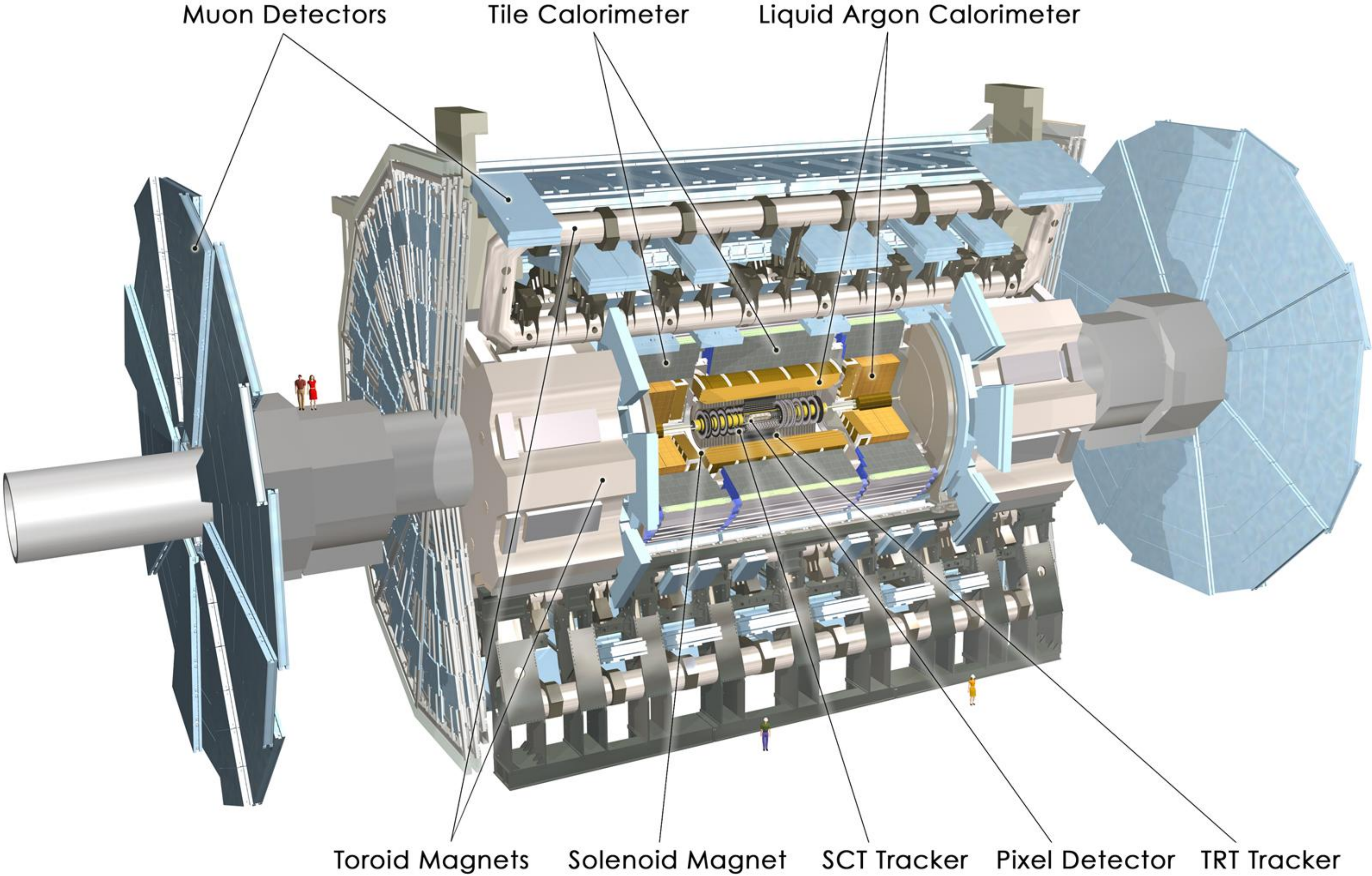
What ?

do we use to measure

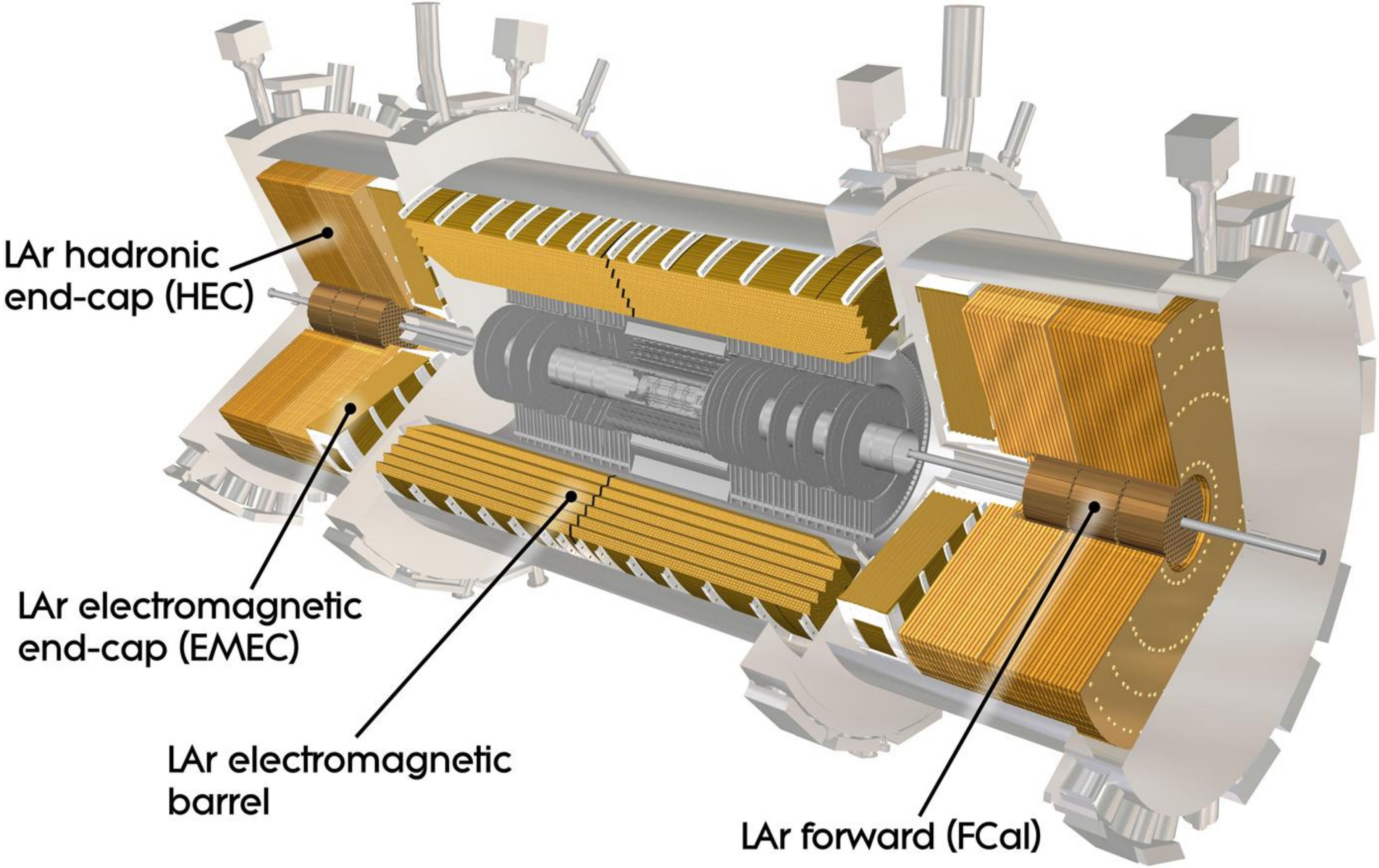
photons

from the Higgs boson decay

ATLAS

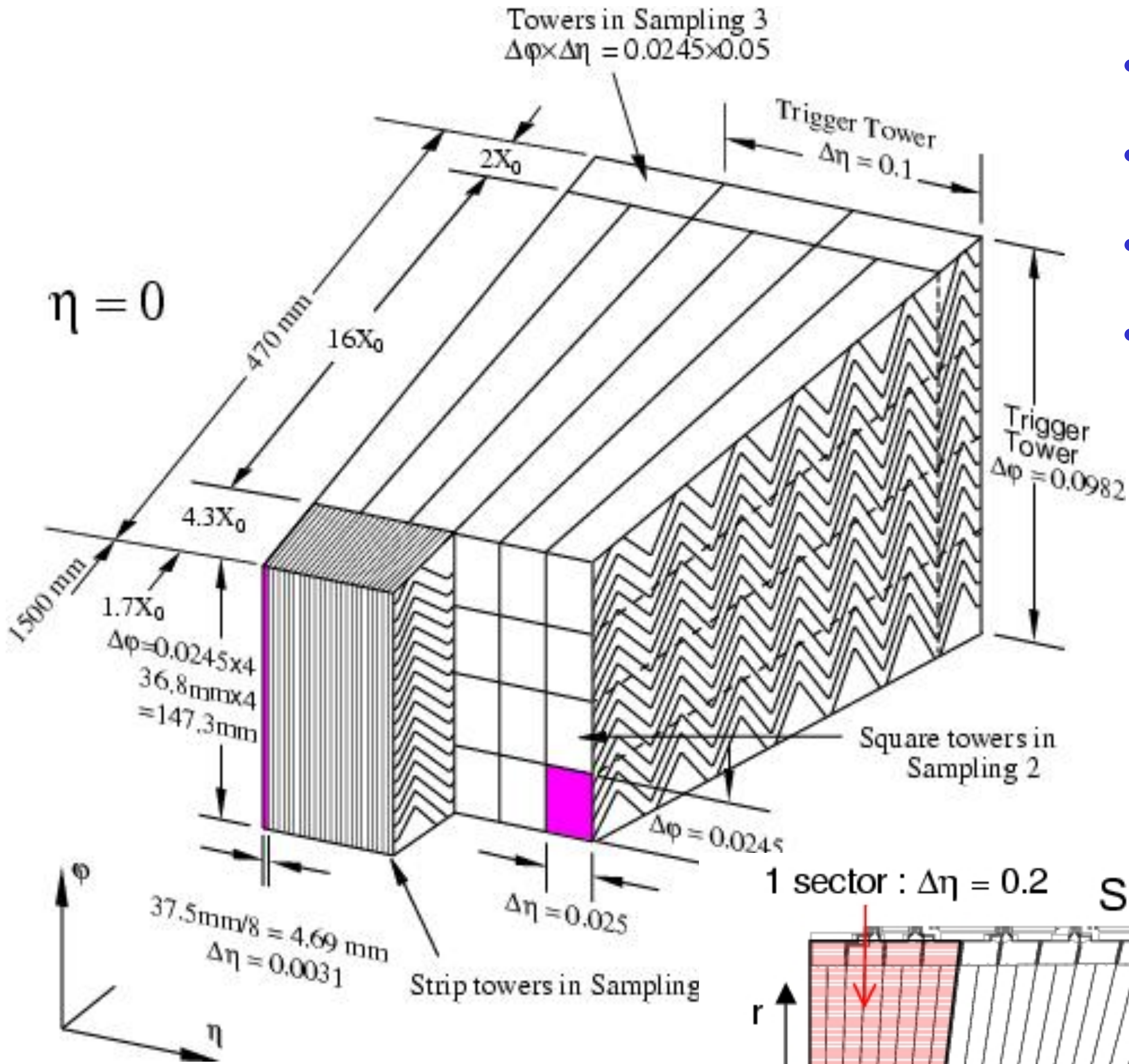

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

ATLAS liquid argon calorimeters



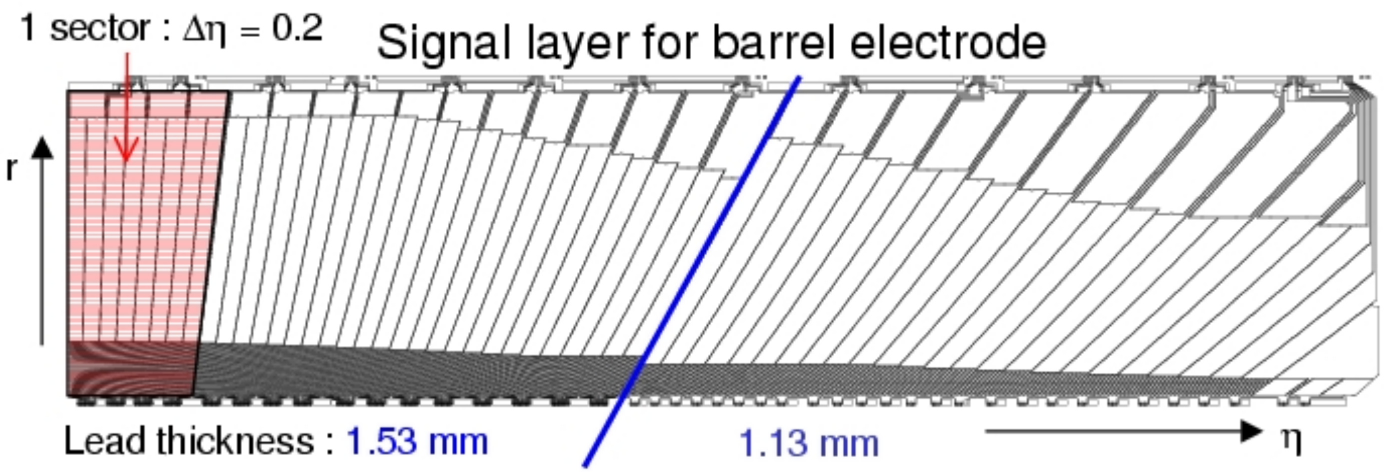
- ✓ EM Barrel : ($|\eta|<1.475$) [Pb-LAr]
- ✓ EM End-caps : $1.4<|\eta|<3.2$ [Pb-LAr]
- ✓ Hadronic End-cap: $1.5<|\eta|<3.2$ [Cu-LAr]
- ✓ Forward Calorimeter: $3.2<|\eta|<4.9$ [Cu,W-Lar]

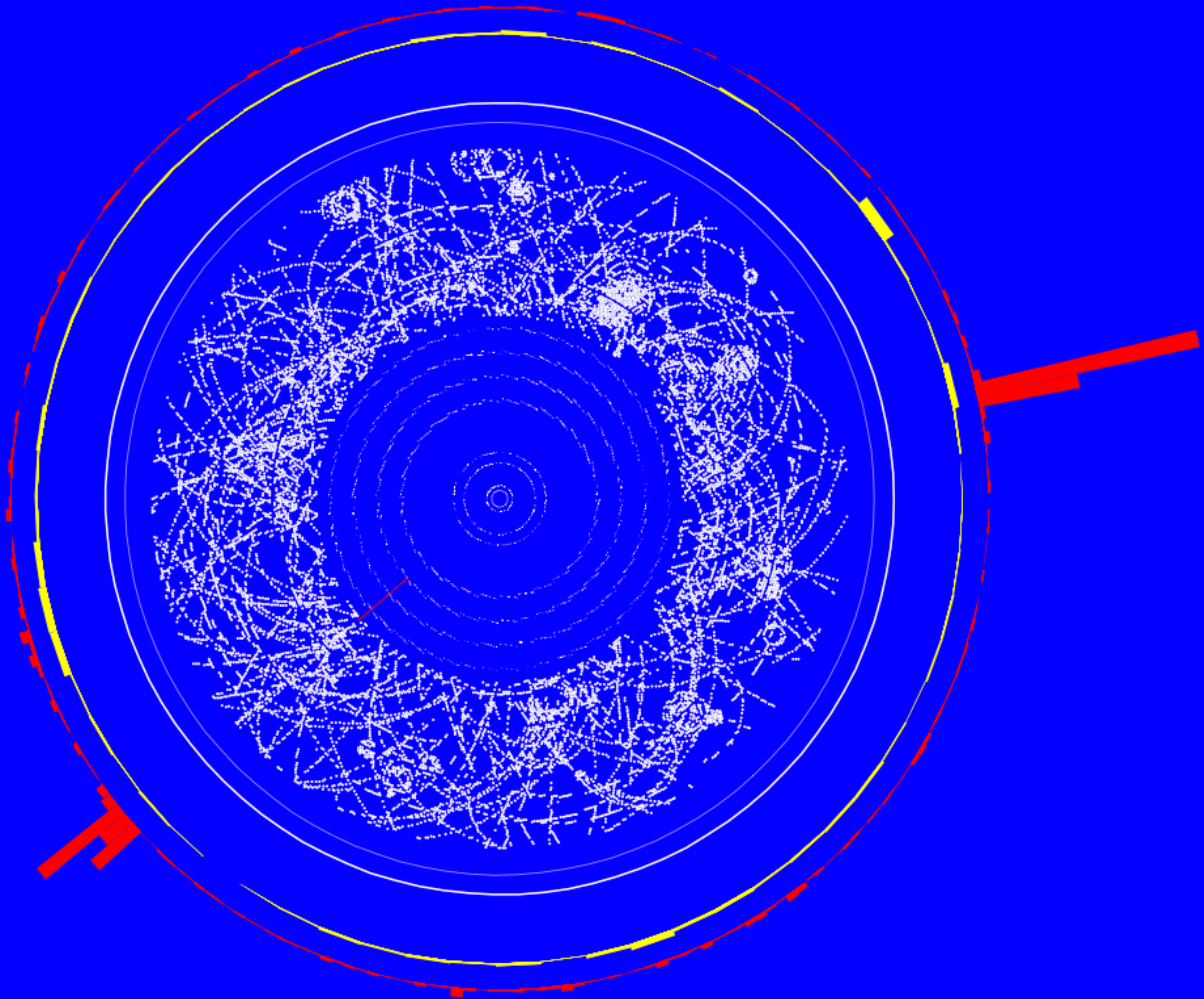
ATLAS EM calorimeter



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

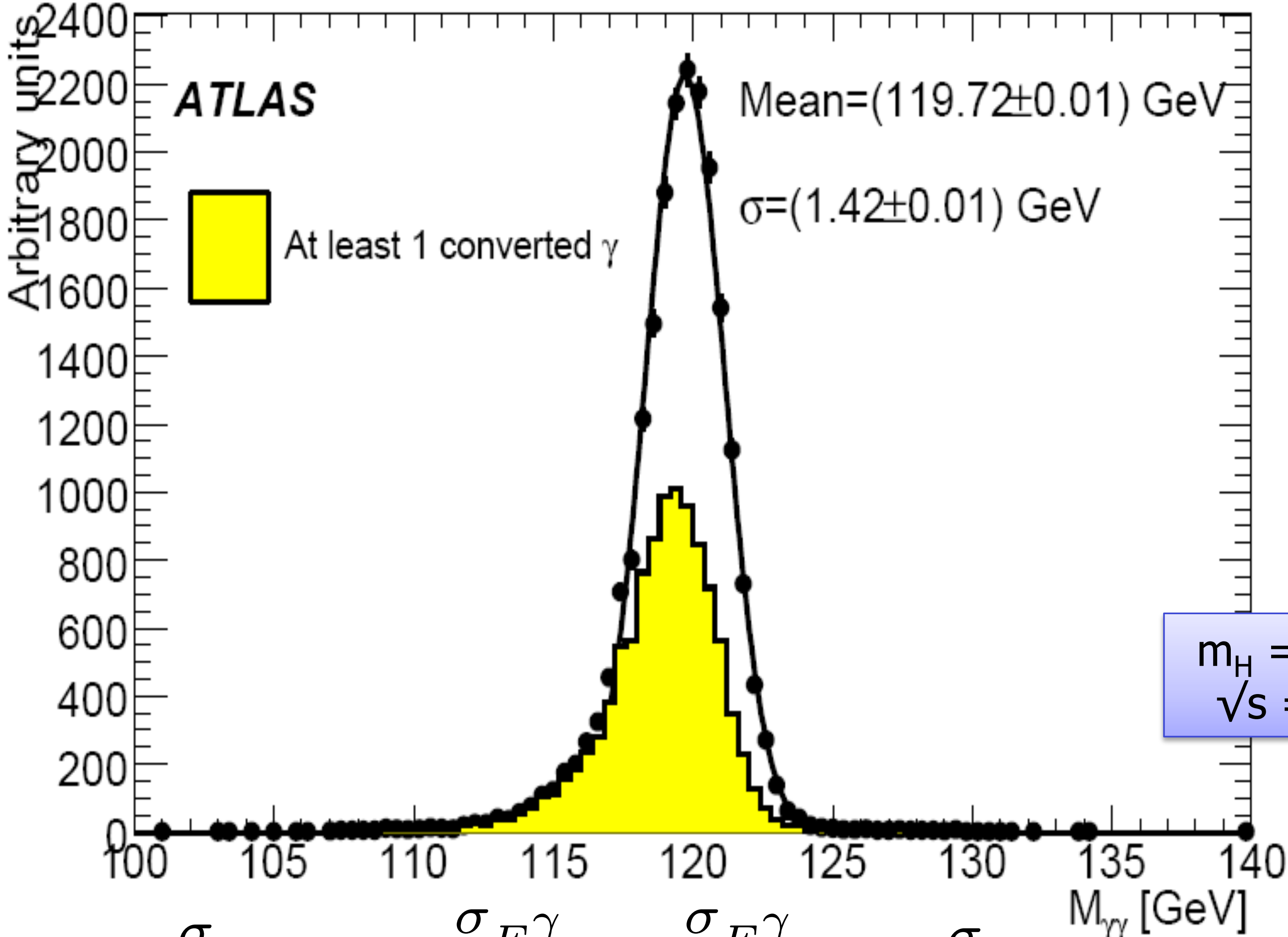
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$





A narrow mass peak...

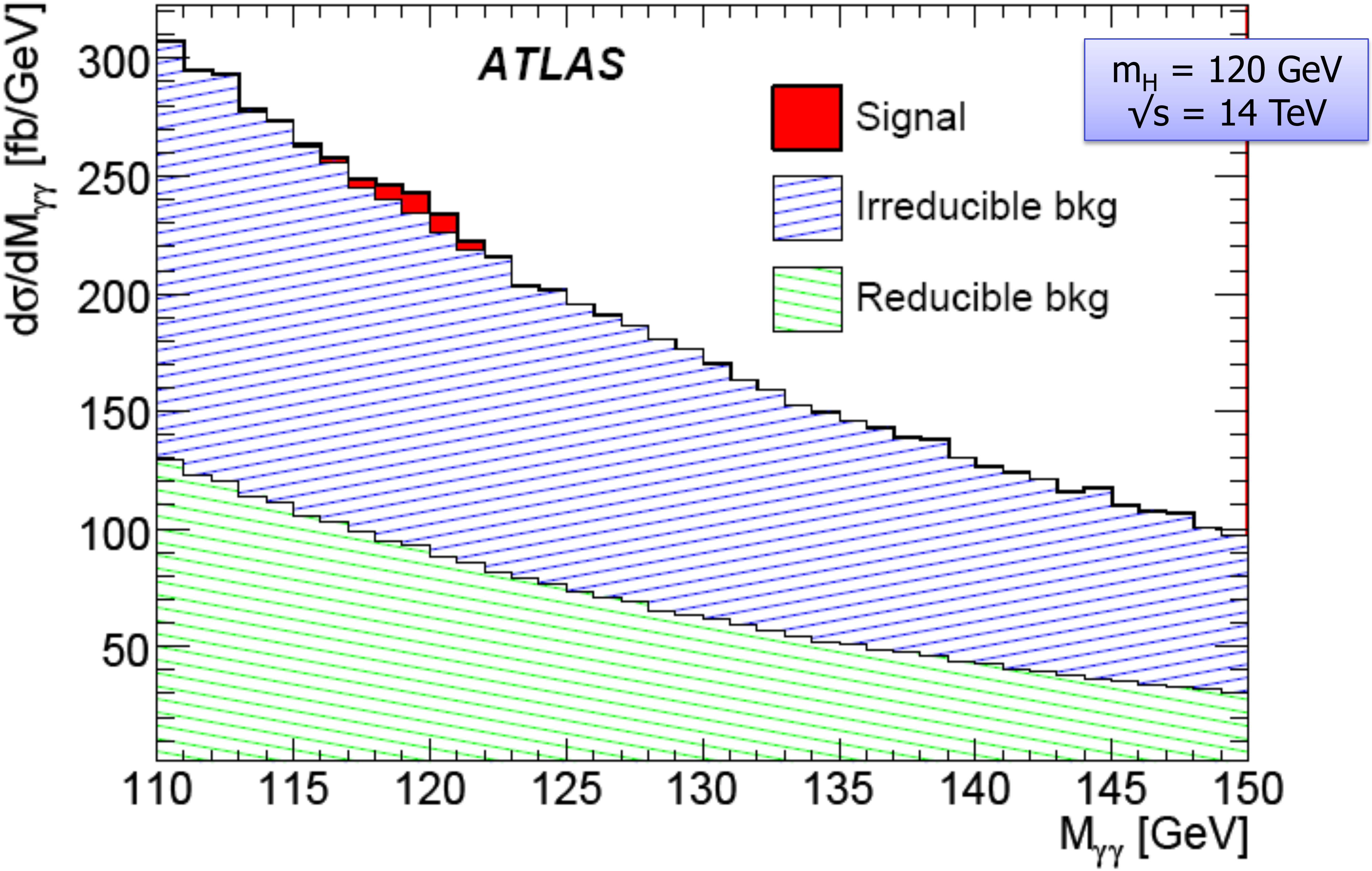
$$m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$$



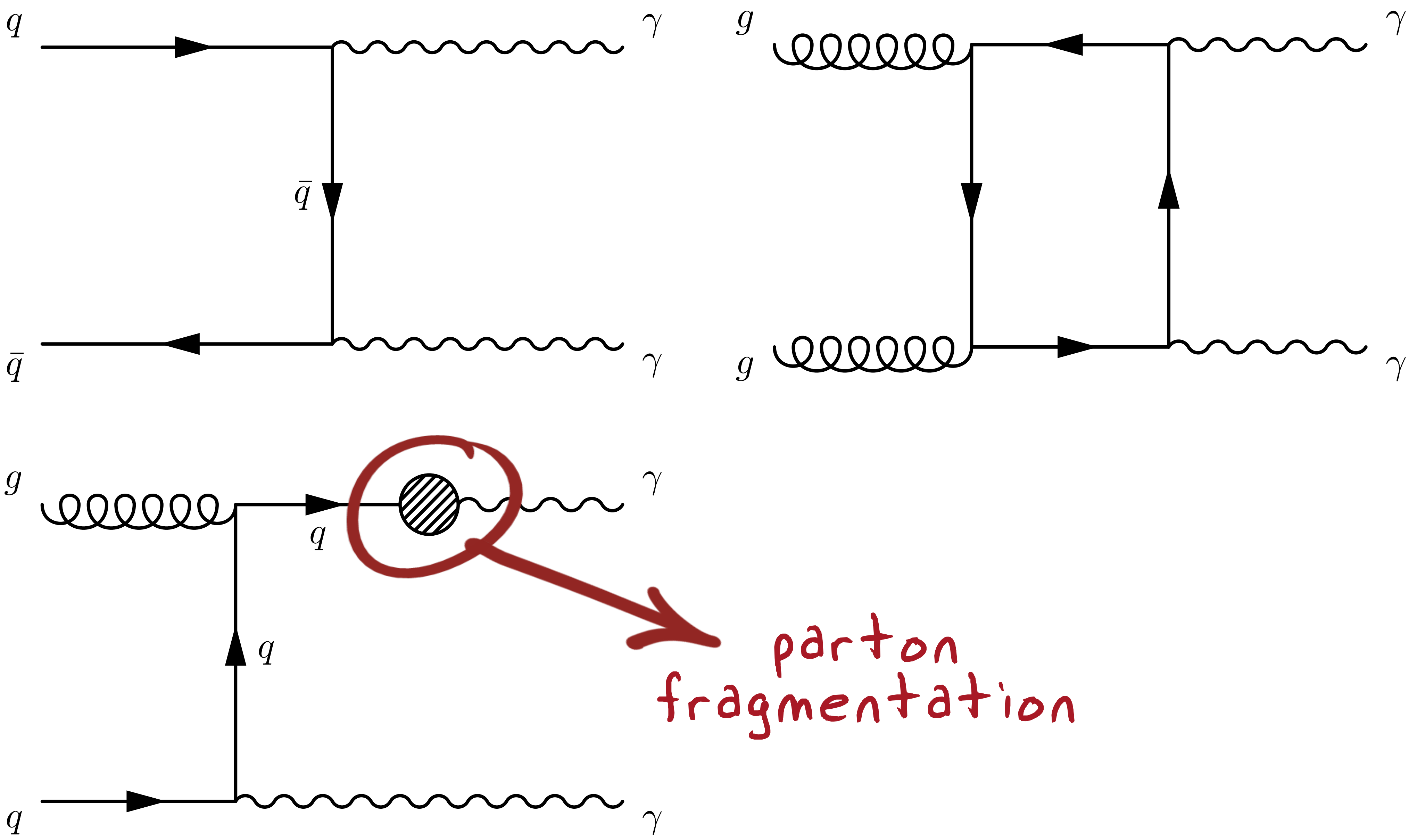
m_H = 120 GeV
$\sqrt{s}$ = 14 TeV

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

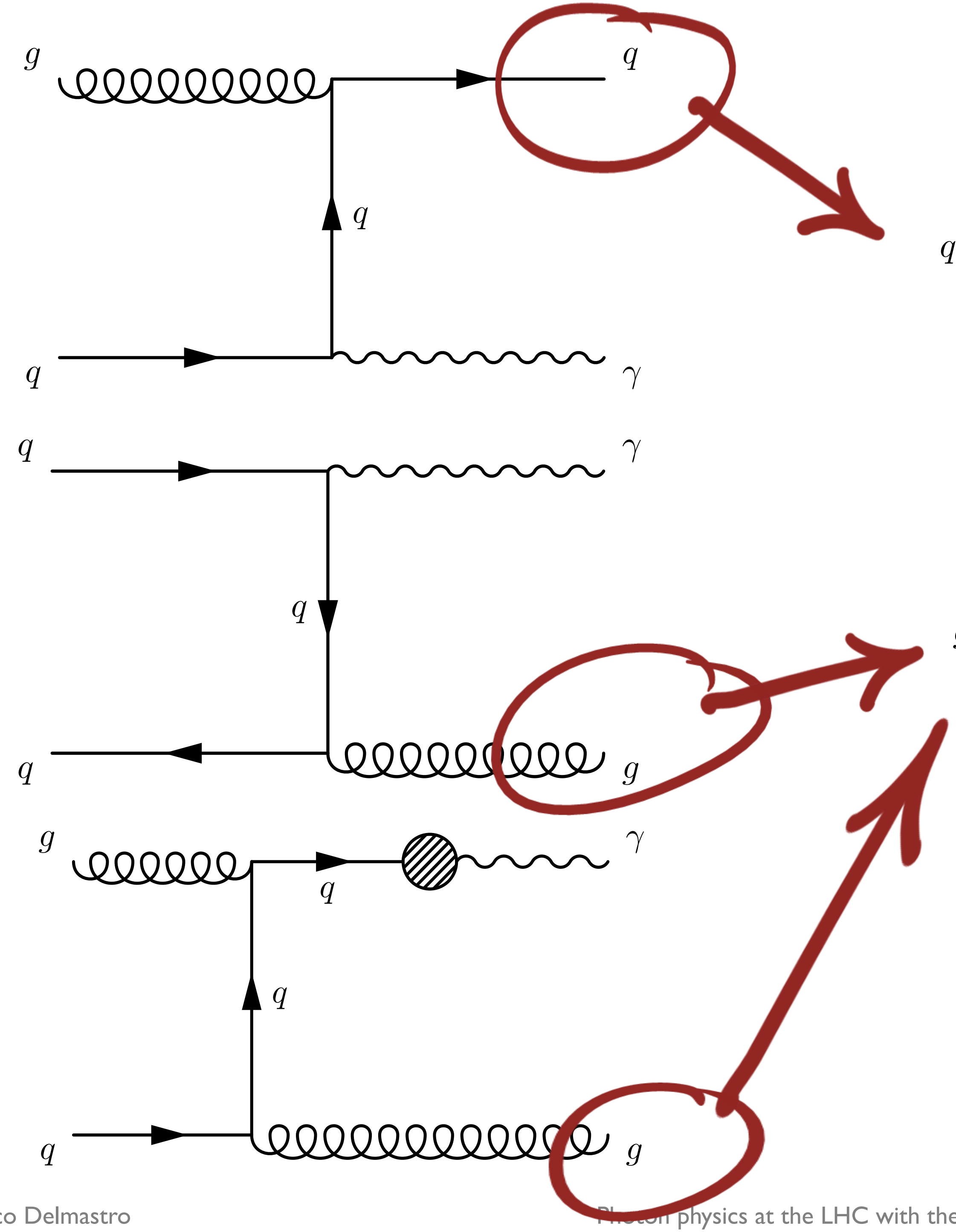
… on a large background!

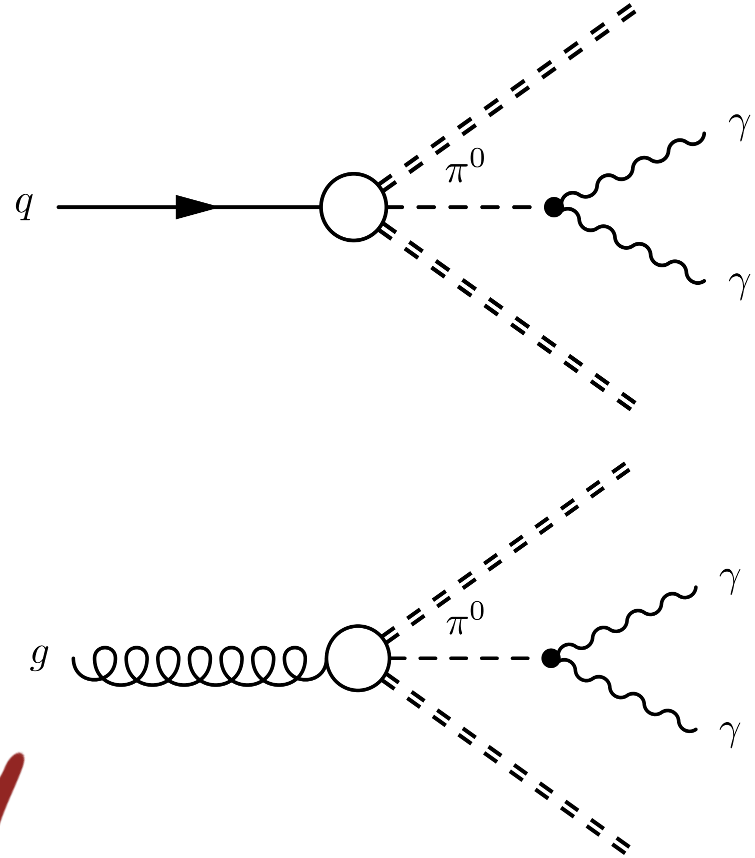


“Irreducible” background



“Reducible” background





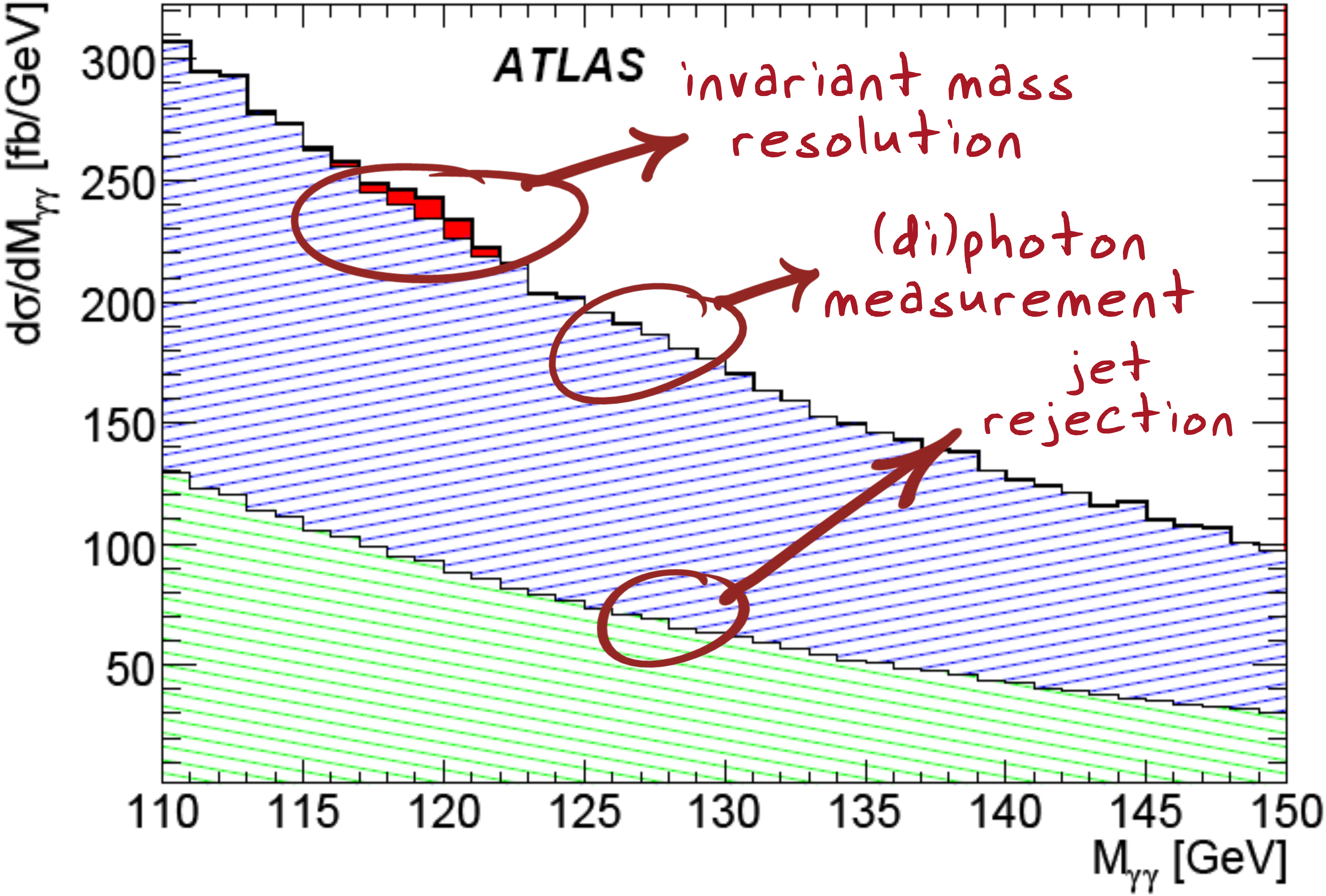
$\sigma(\gamma j) \sim 10^3 \sigma(\gamma\gamma)$

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

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
dσ/dM$_{\gamma\gamma}$ [fb/GeV]
300
250
200
150
100
50
110
115
120
125
130
135
140
145
150
M$_{\gamma\gamma}$ [GeV]

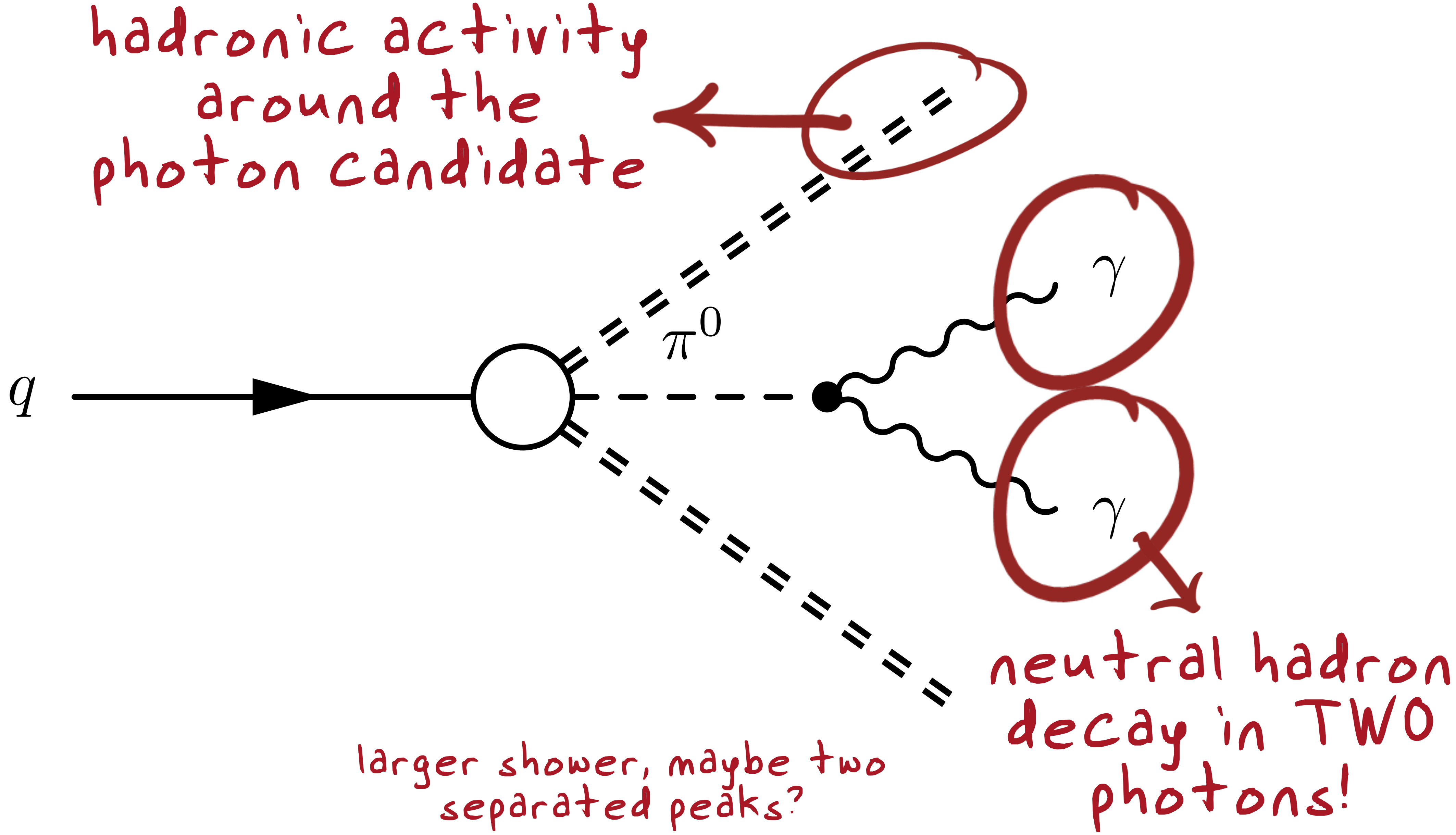
How ?

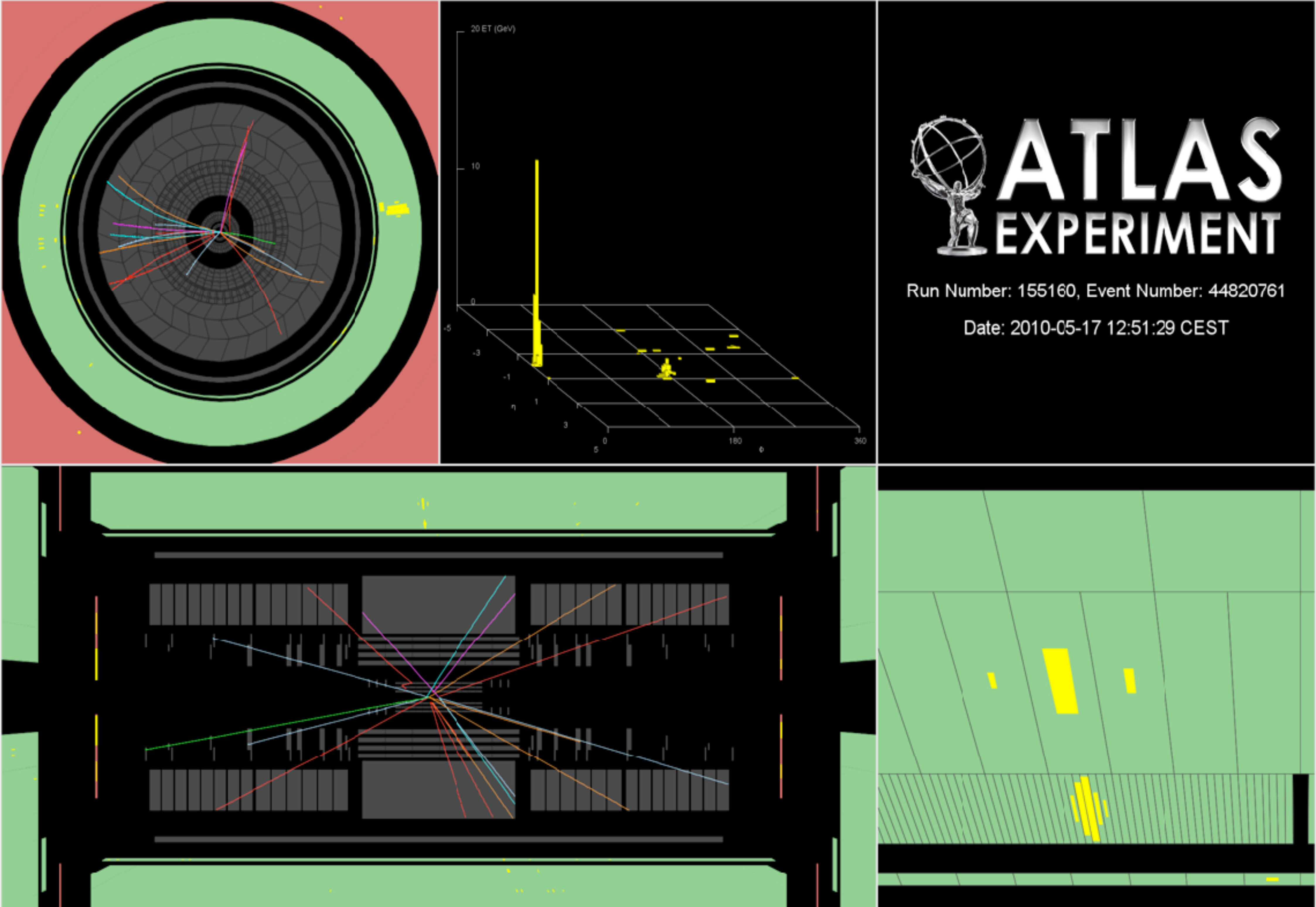
can we distinguish

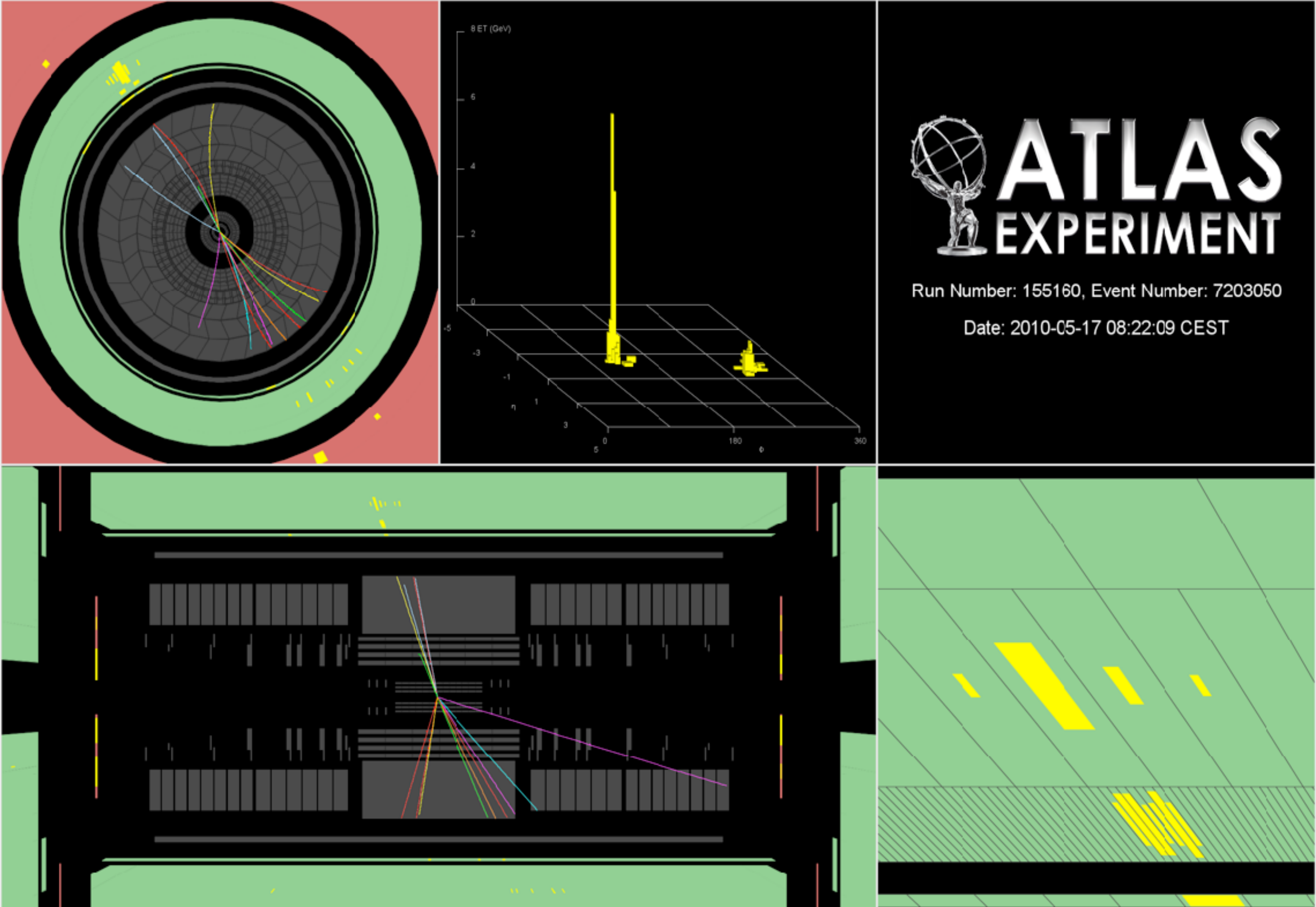
direct **photons**

from jets

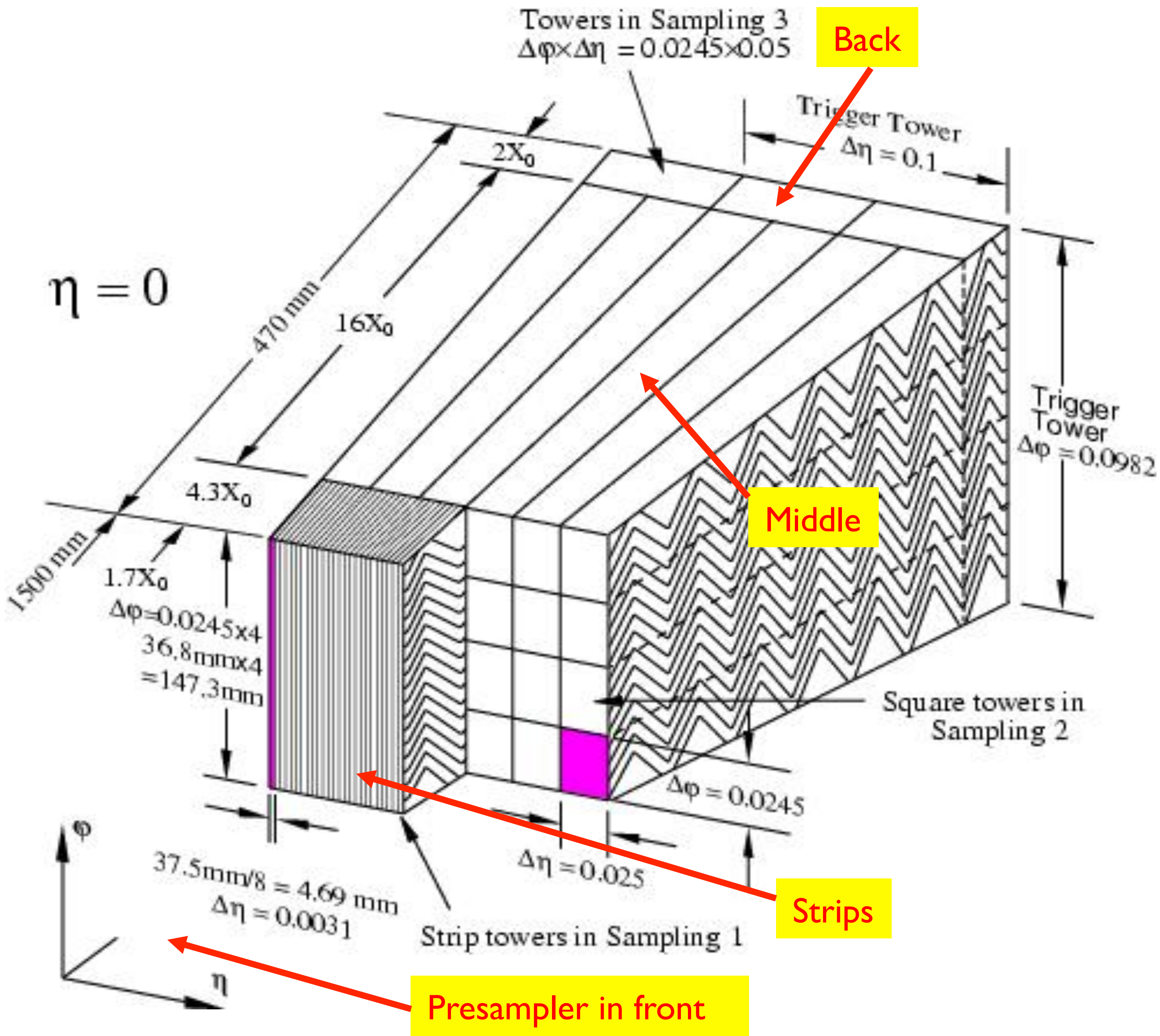
How does a jet faking a direct photon look like?




20 ET (GeV)
10
0
-5
-3
-1
1
3
5
η
0
180
360
φ
ATLAS
EXPERIMENT
Run Number: 155160, Event Number: 44820761
Date: 2010-05-17 12:51:29 CEST


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

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

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

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

Middle layer (S2) variables

containment in η

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

containment in ϕ

$$R_\phi = \frac{E^{S2}_{3\times 3}}{E^{S2}_{3\times 7}}$$

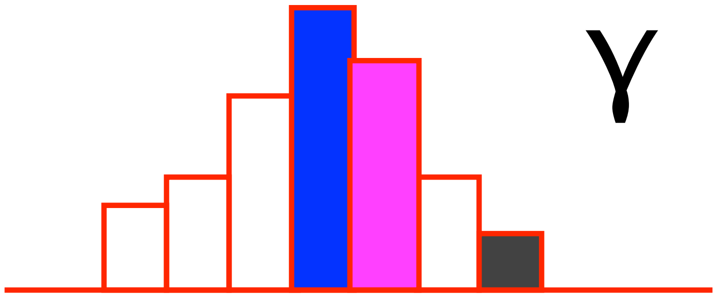
E^{S2}_{XY} is the summed energy of S2 cells in a window of size X×Y ($\eta \times \phi$ units)

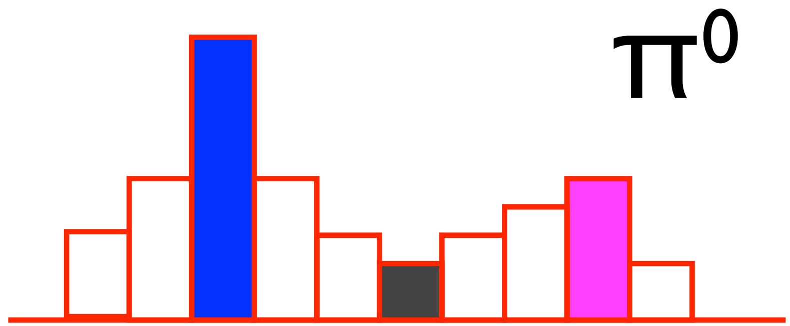
$$w_2 = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2}$$

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^{st} and 2^{nd} maxima

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

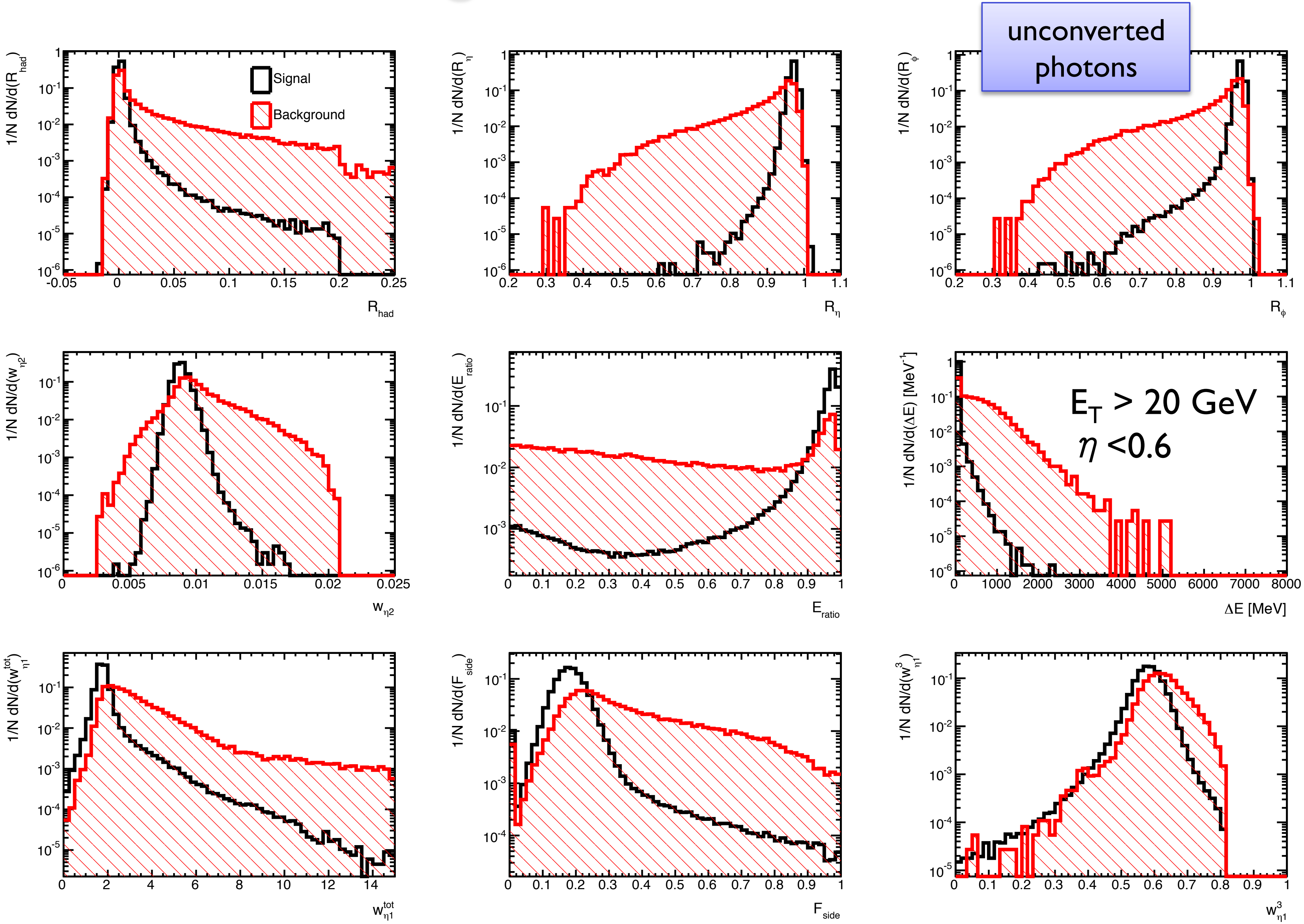
E^{S1}_{min} is the energy of the strip cell with least energy between the 1^{st} and and 2^{nd} maxima

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

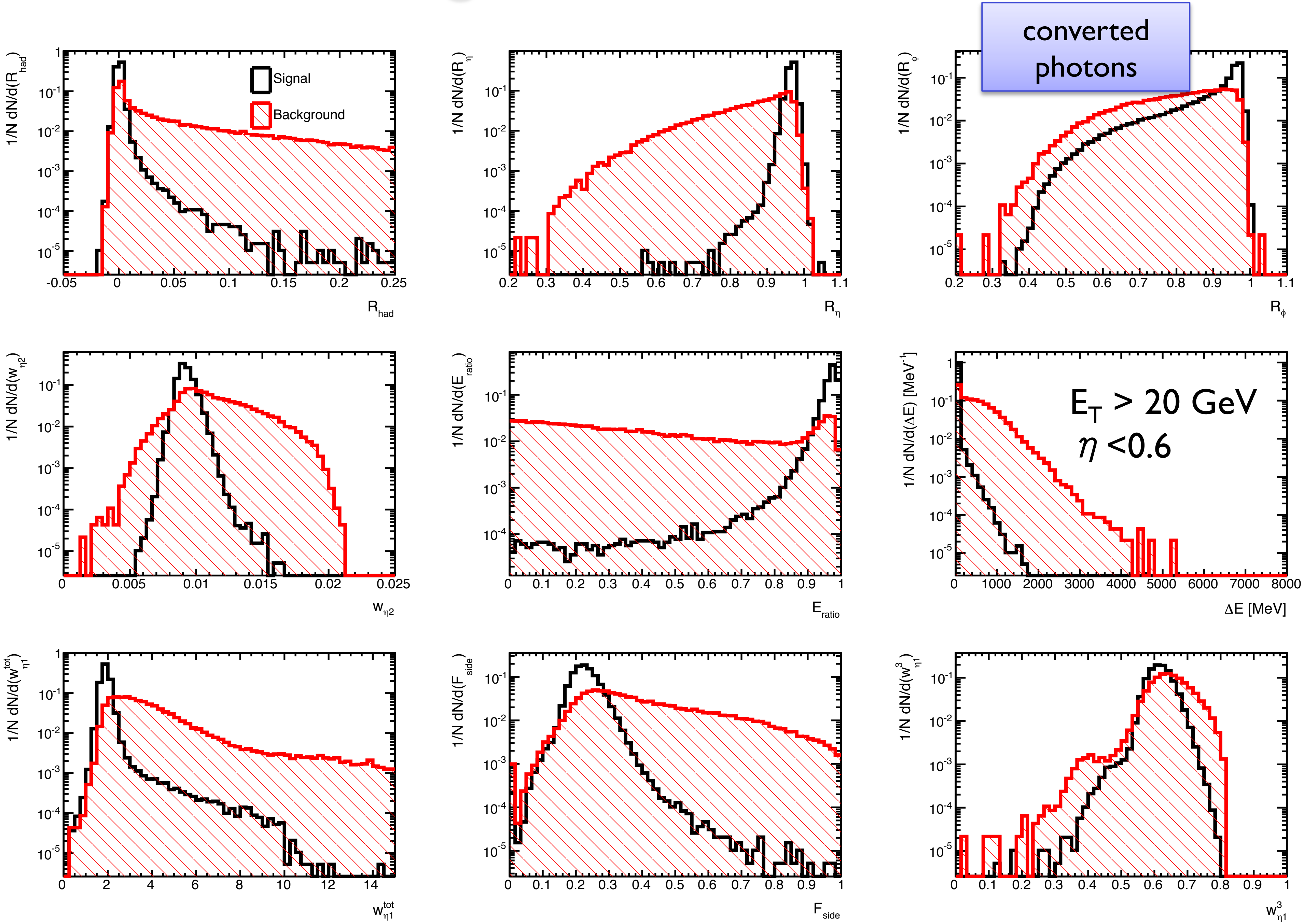
Width (cell units) using 2 strips about max.

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

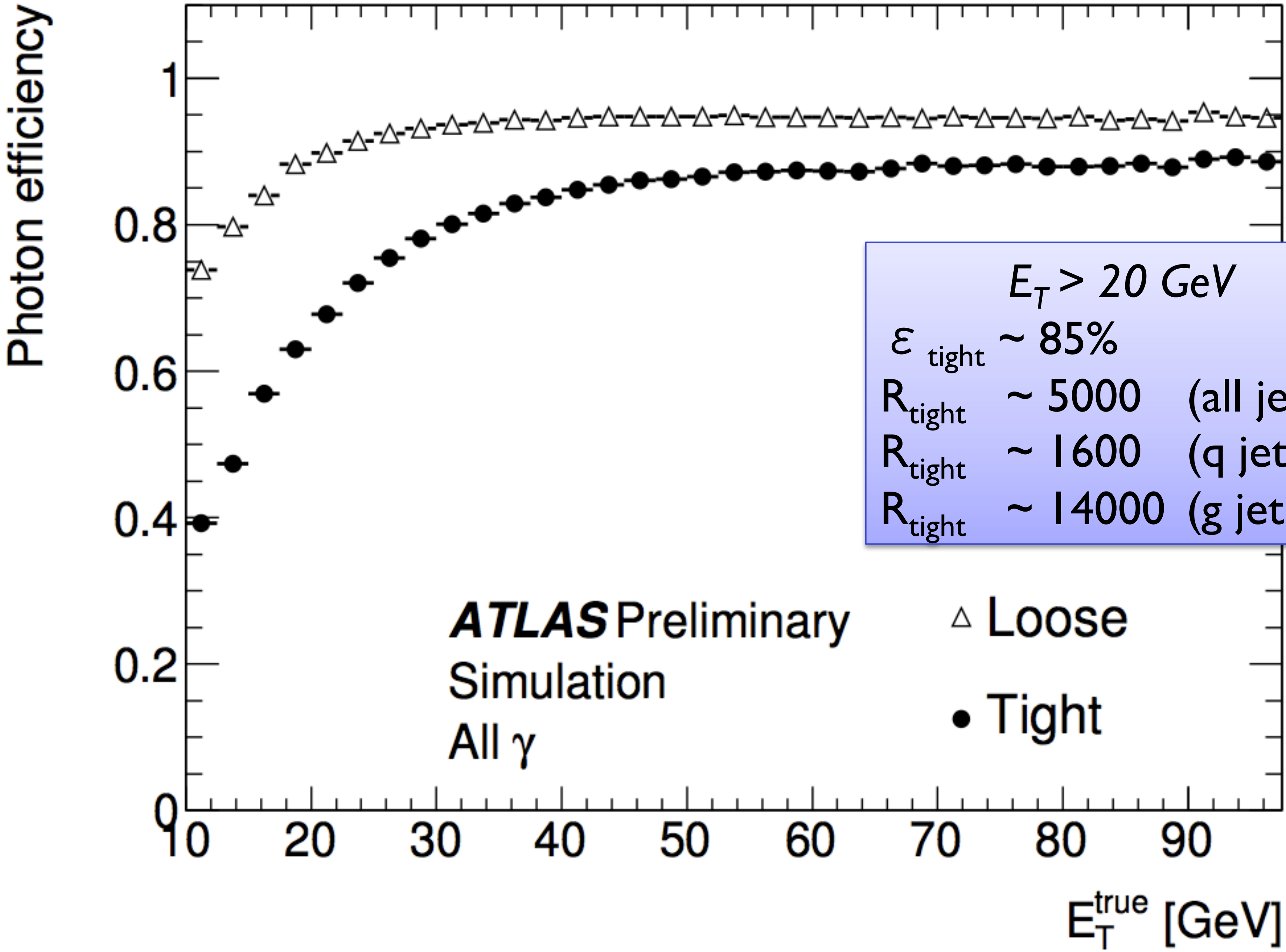
Discriminating variables in simulated data



Discriminating variables in simulated data



Photon identification efficiency in simulated data



$E_T > 20$ GeV

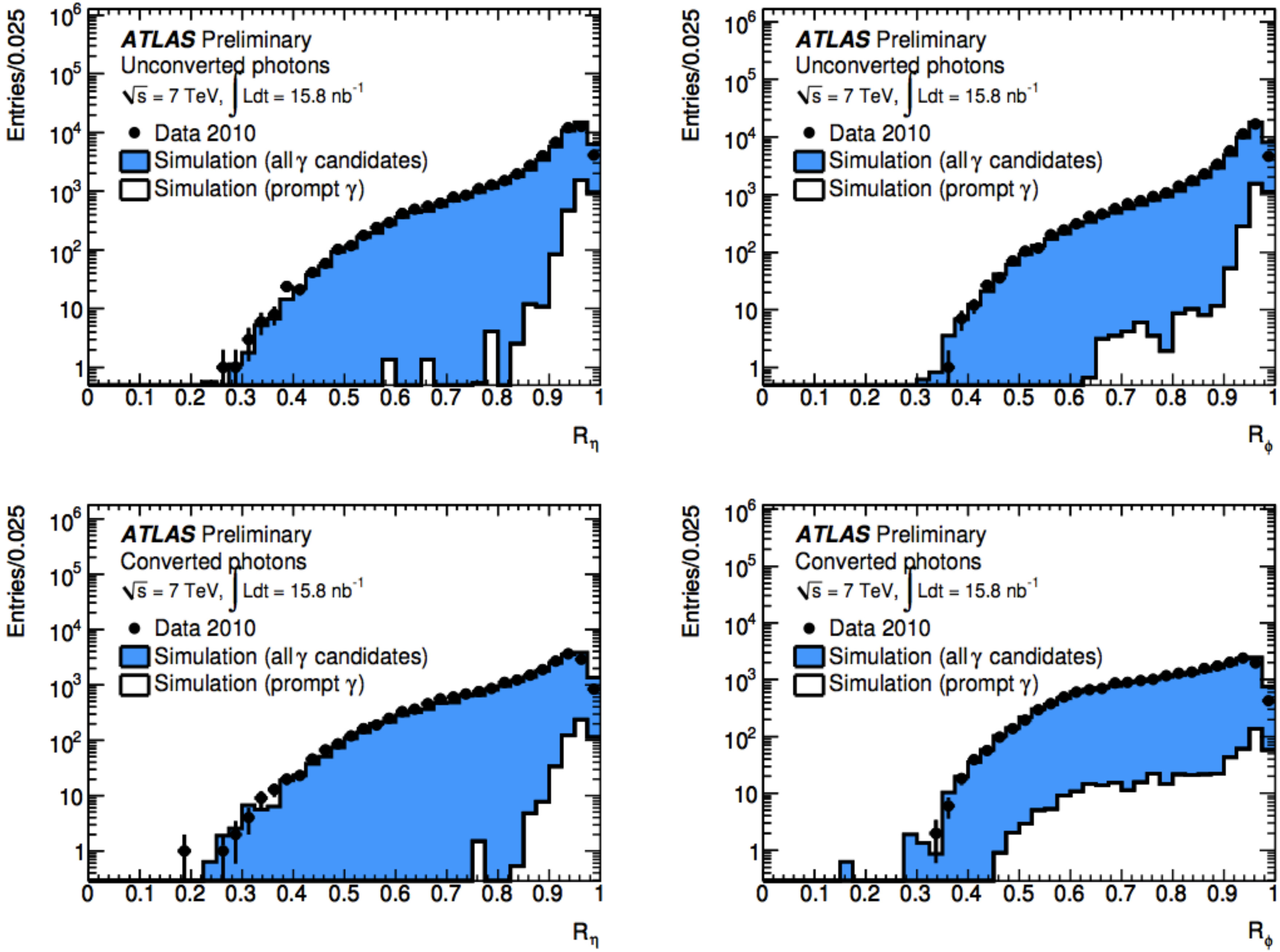
$\varepsilon_{tight} \sim 85\%$

$R_{tight} \sim 5000$ (all jets)

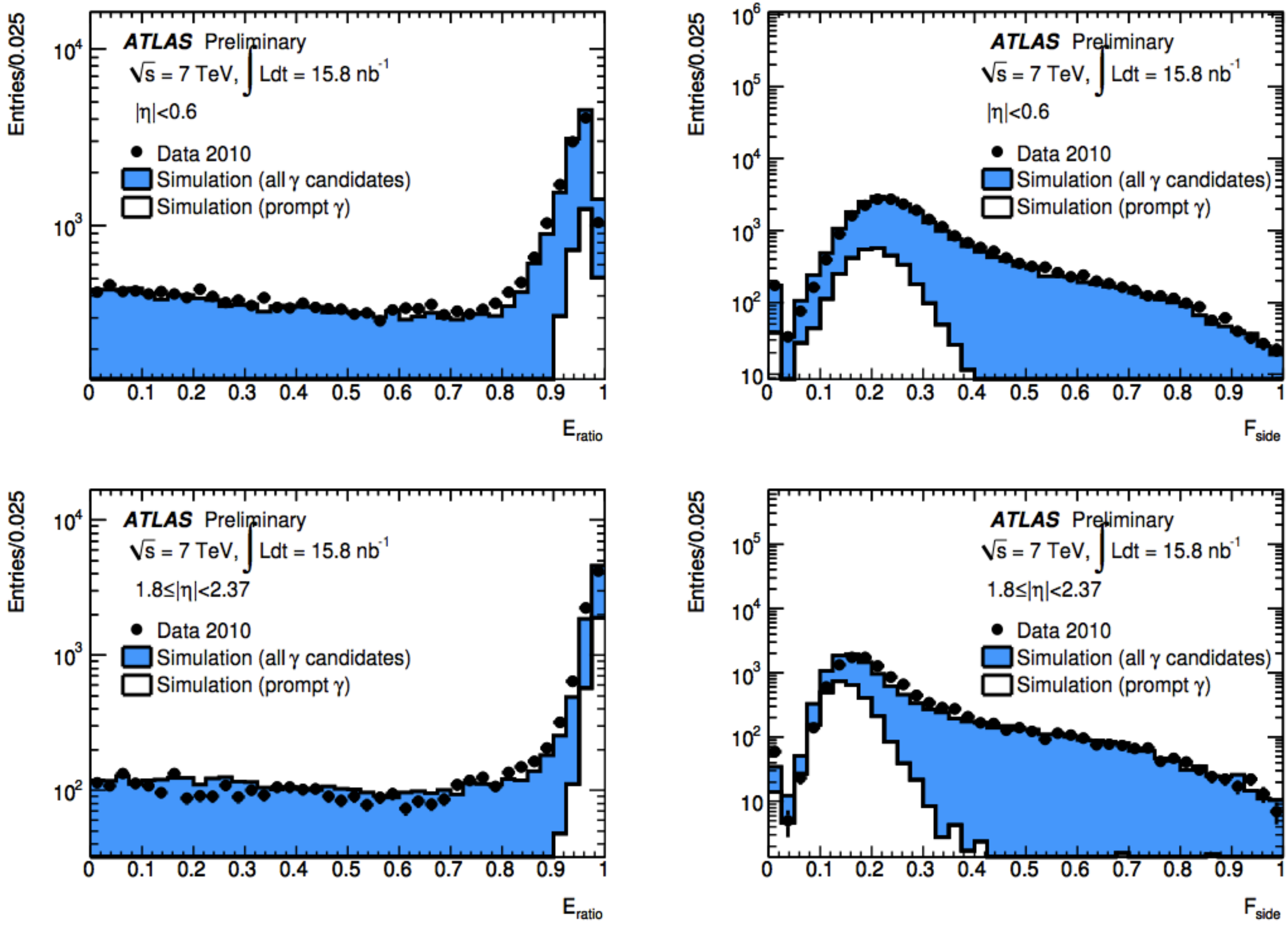
$R_{tight} \sim 1600$ (q jets)

$R_{tight} \sim 14000$ (g jets)

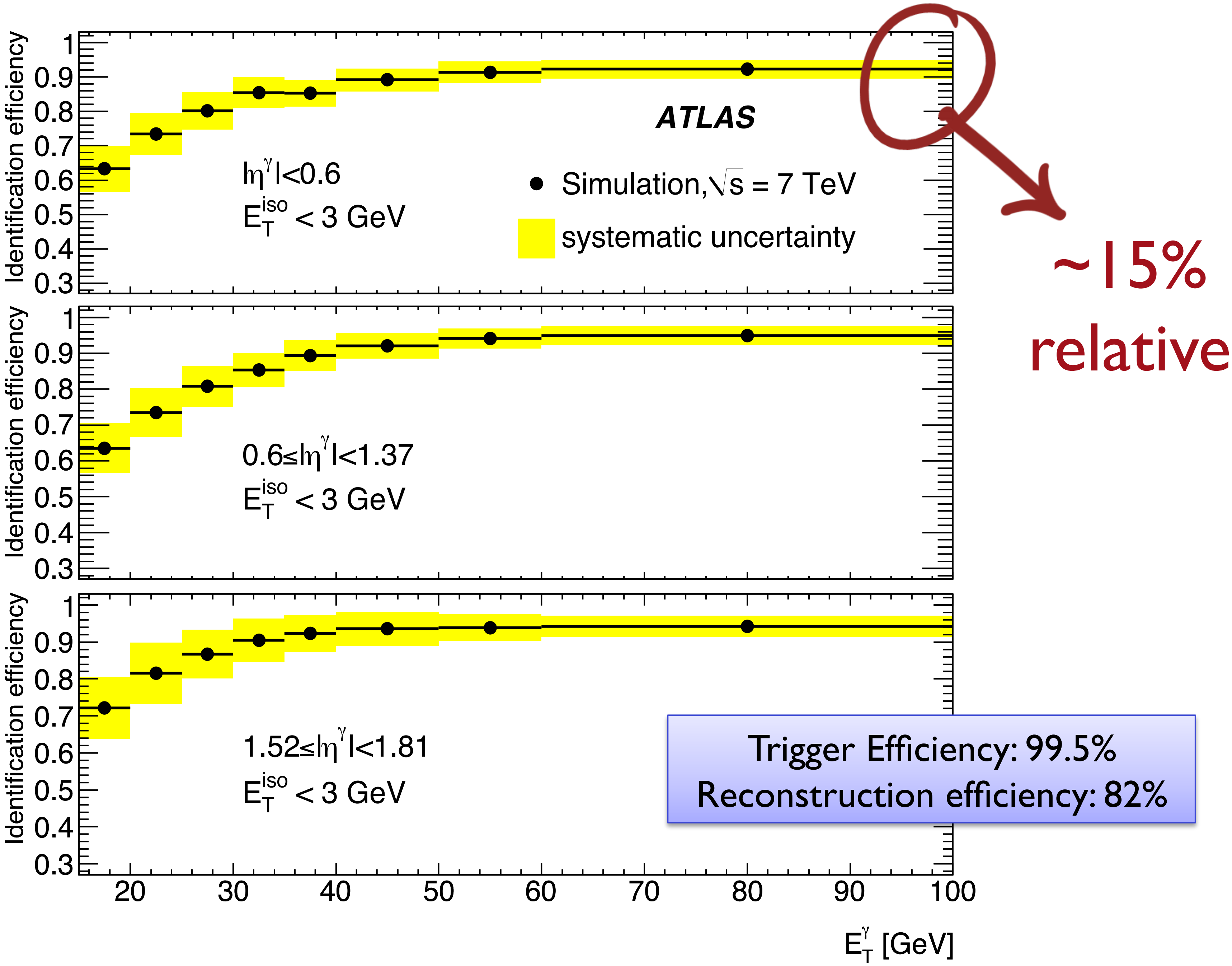
Discriminating variables in real data



Discriminating variables in real data

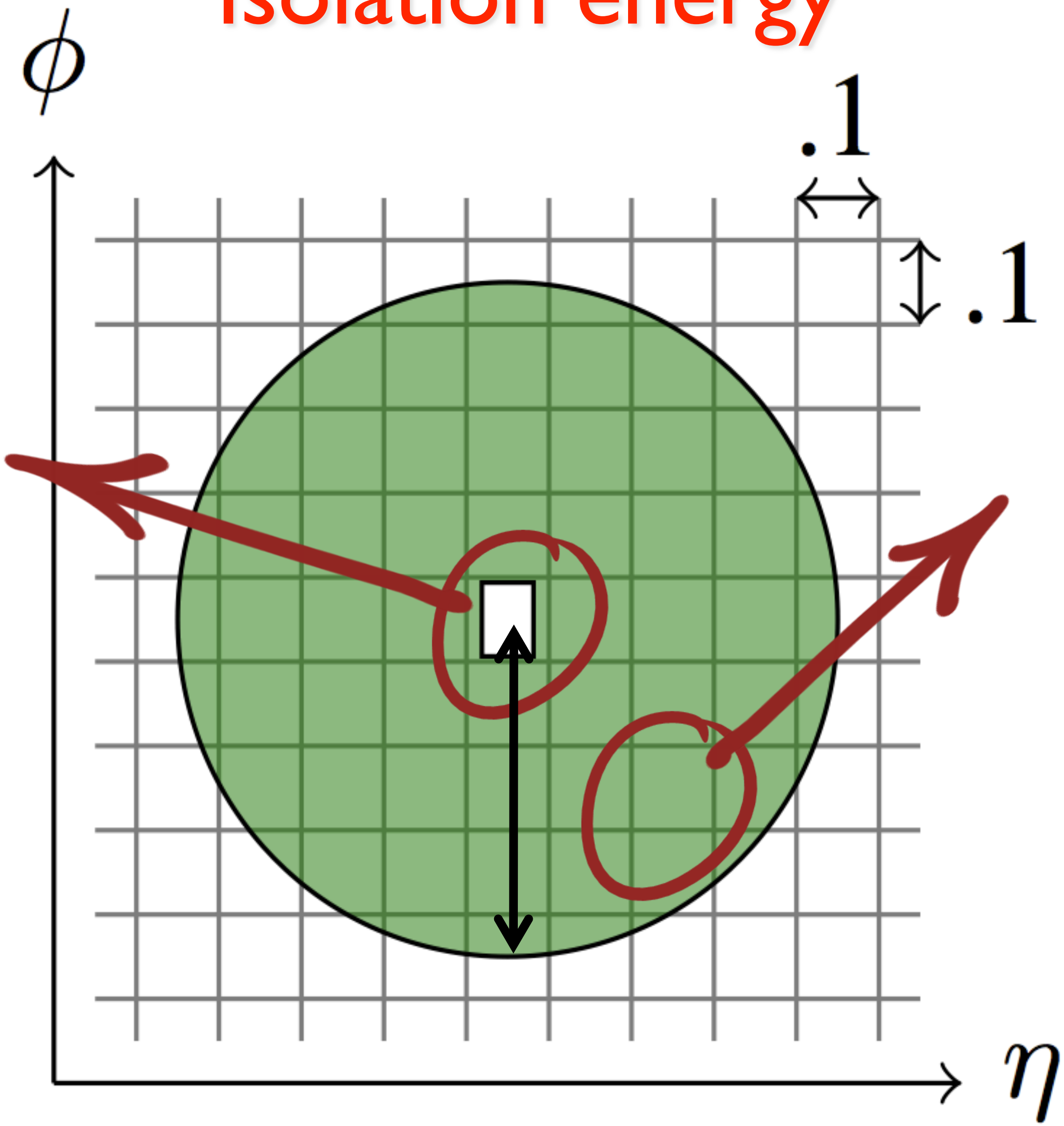


Photon identification efficiency from real data



Trigger Efficiency: 99.5%
Reconstruction efficiency: 82%

Isolation energy



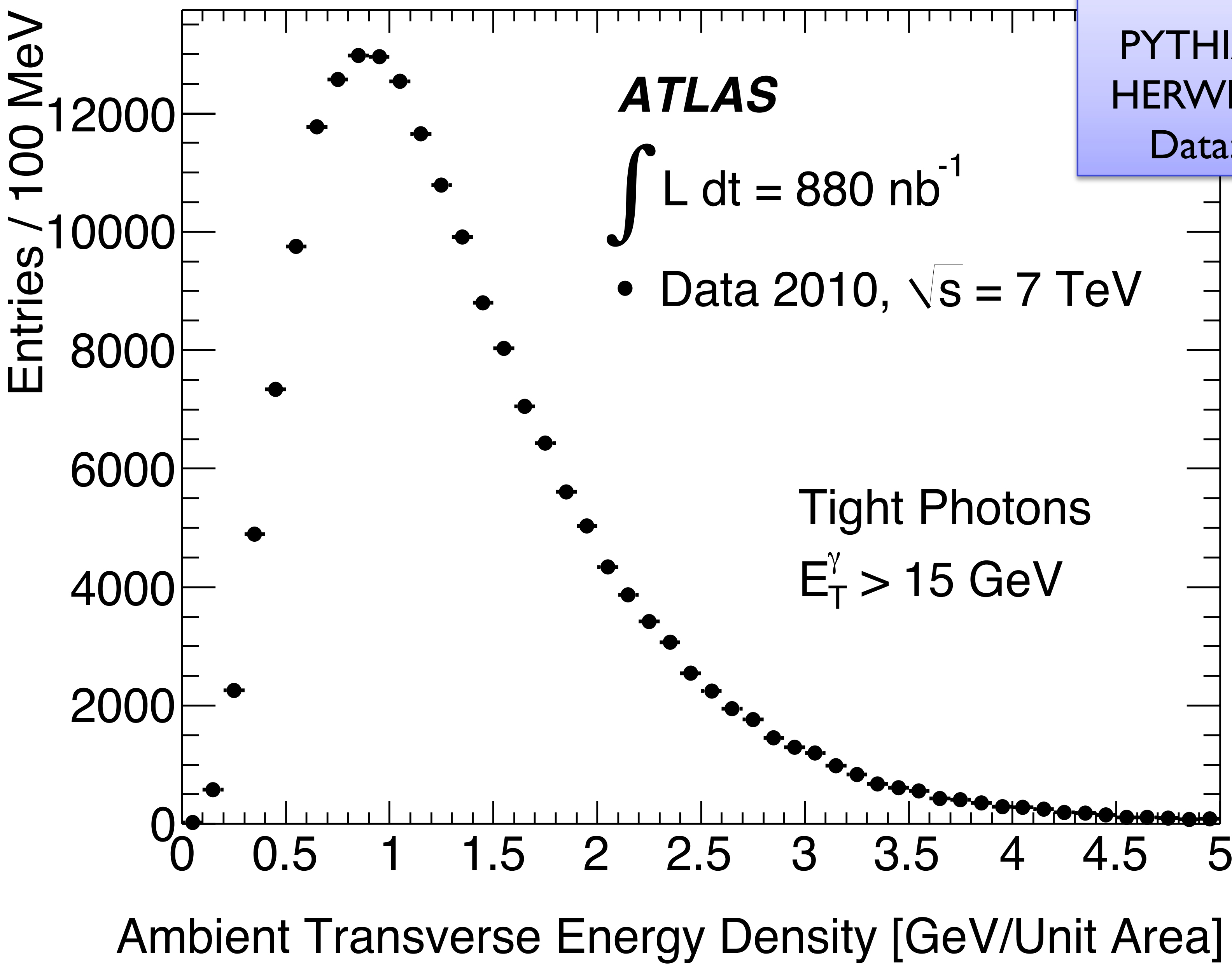
Corrected for the photon energy leaking outside the cluster

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

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

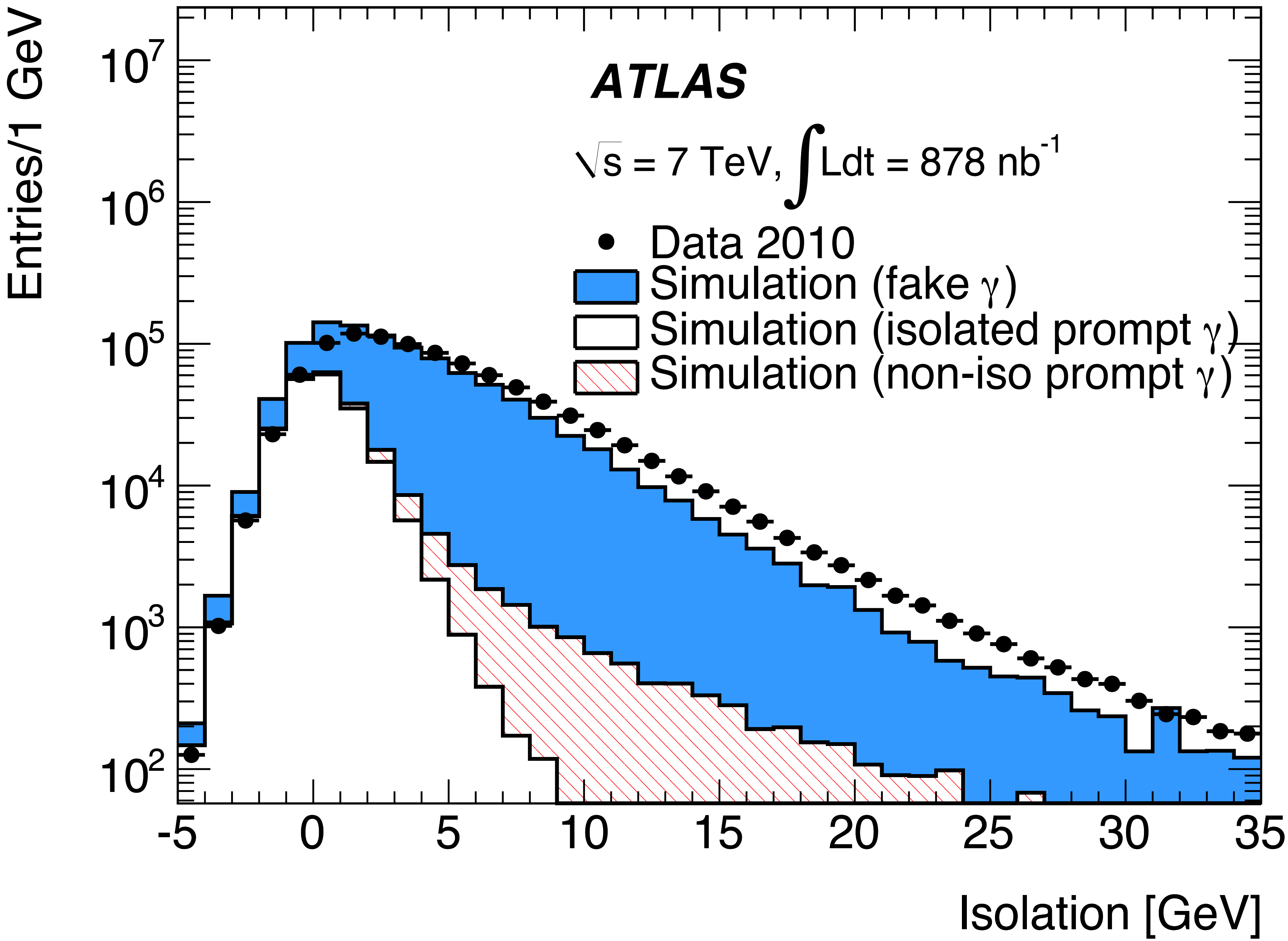
Cacciari, Salam and Sapeta, JHEP 04 (2010) 065

Ambient energy density



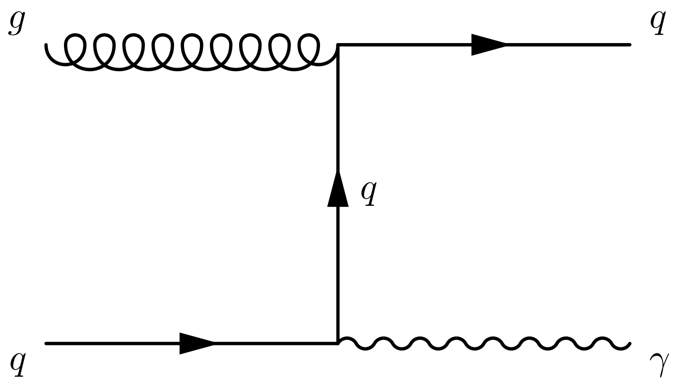
1 PV
PYTHIA: 440 MeV
HERWIG: 550 MeV
Data: 540 MeV

Isolation energy (all photon candidates)

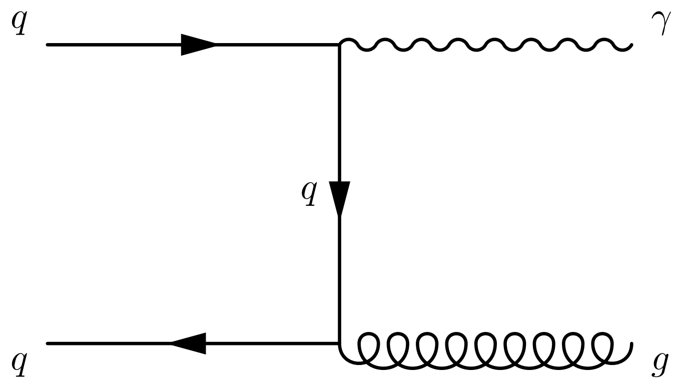


What can we learn from direct photons production?

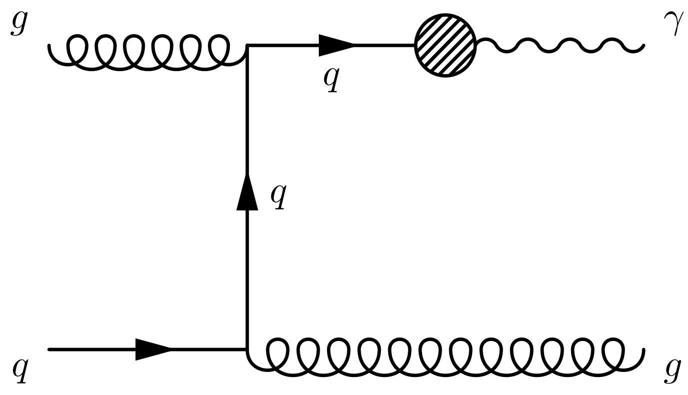
A lot of interesting physics!



Compton scattering



annihilation



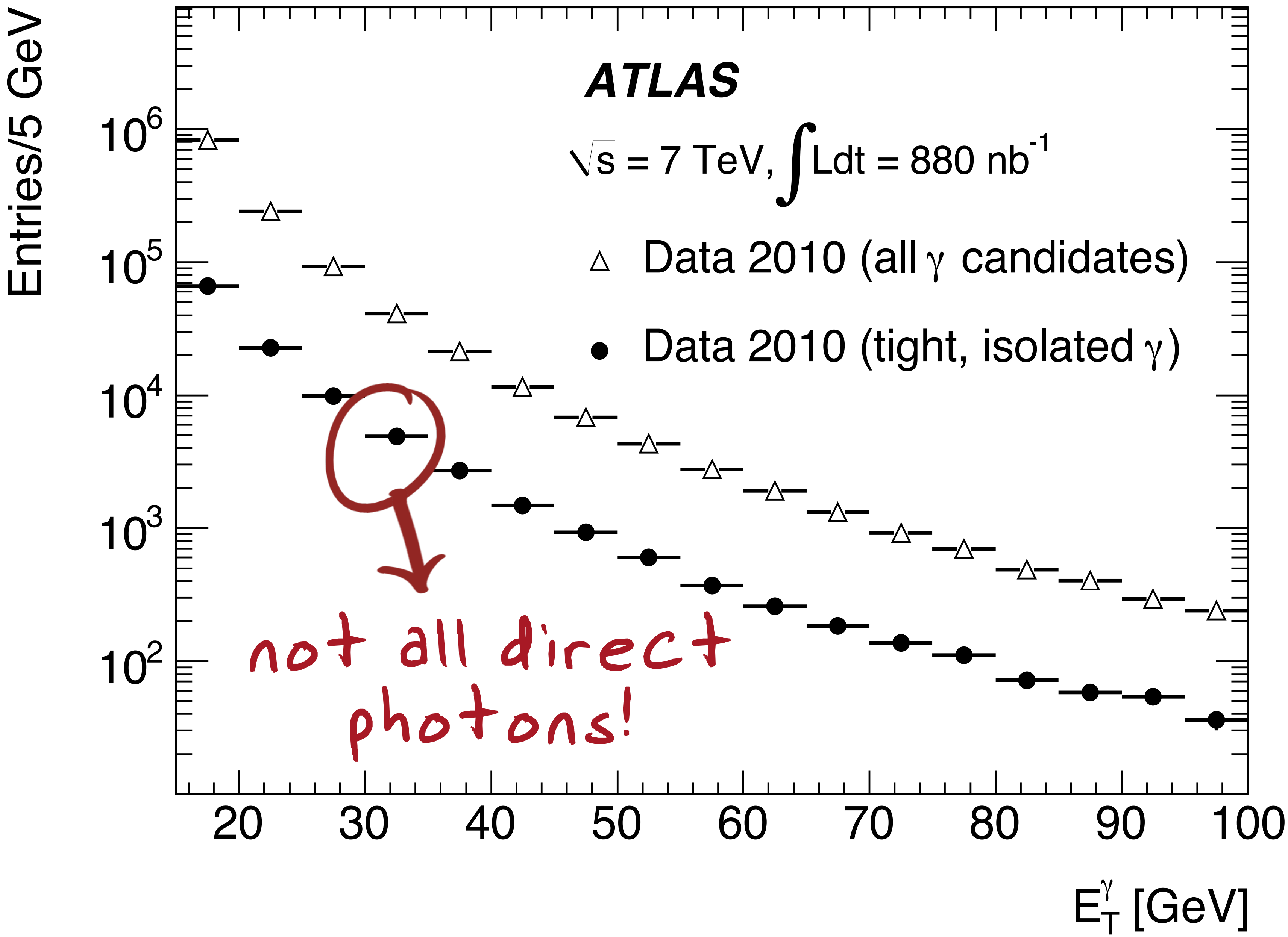
fragmentation

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

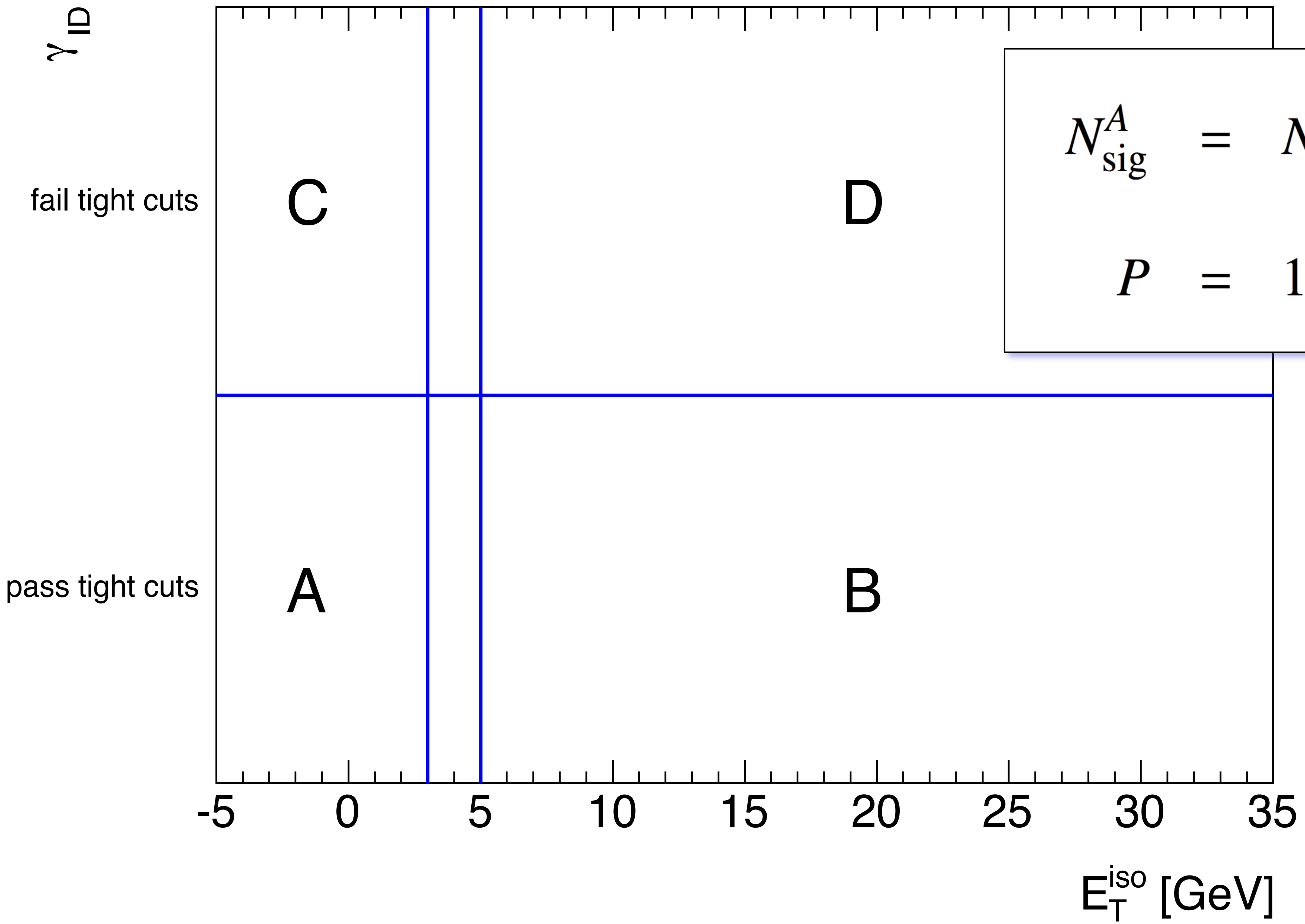
probe the gluon content of the proton

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

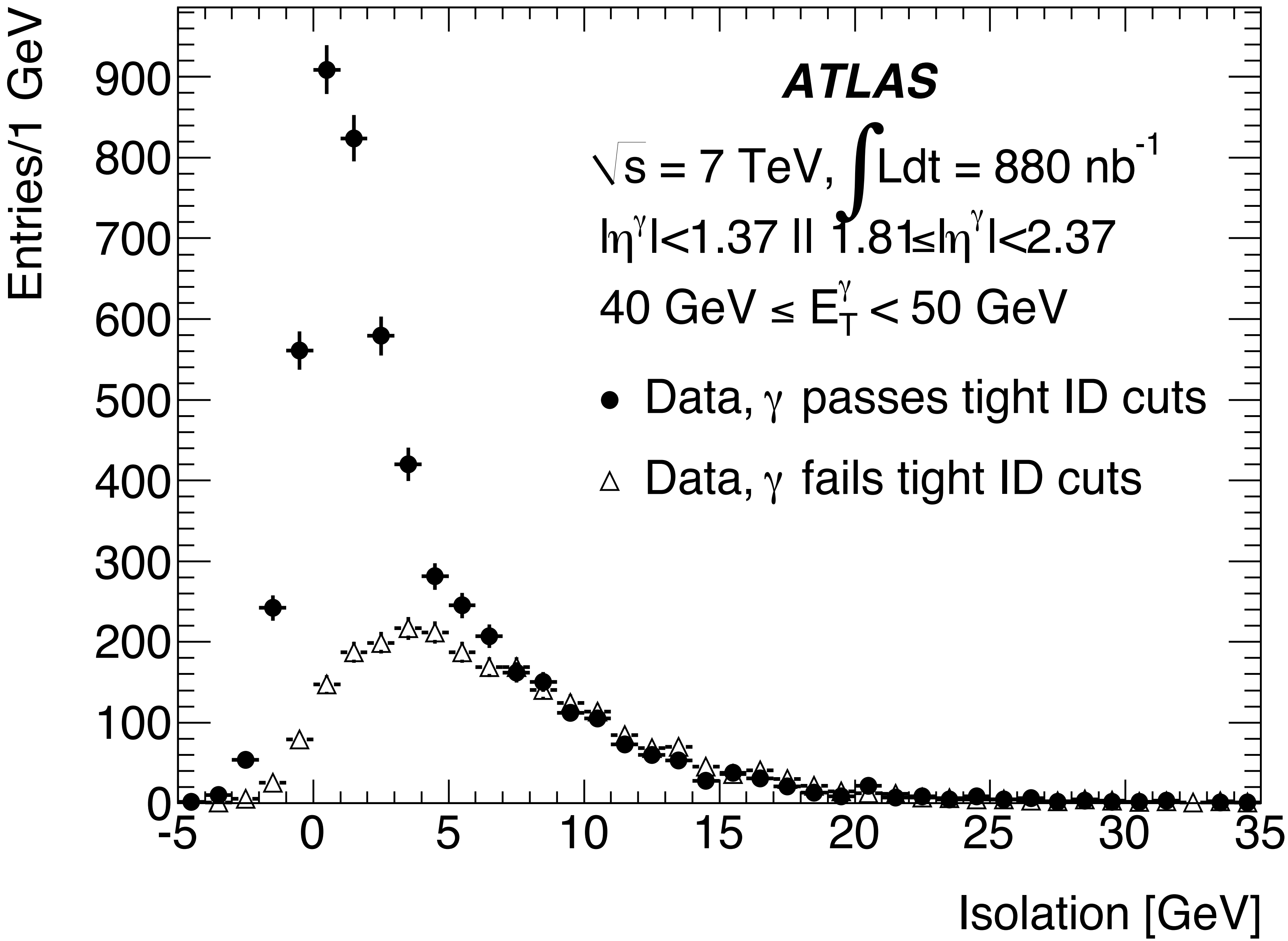
$$N^A_{\text{sig}} = N^A - \left[(N^B - c_1 N^A_{\text{sig}}) \frac{M^A - c_2 N^A_{\text{sig}}}{M^B - c_3 N^A_{\text{sig}}} \right] \left(\frac{N^A_{\text{bkg}}}{N^B_{\text{bkg}}} \frac{M^B_{\text{bkg}}}{M^A_{\text{bkg}}} \right)$$

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

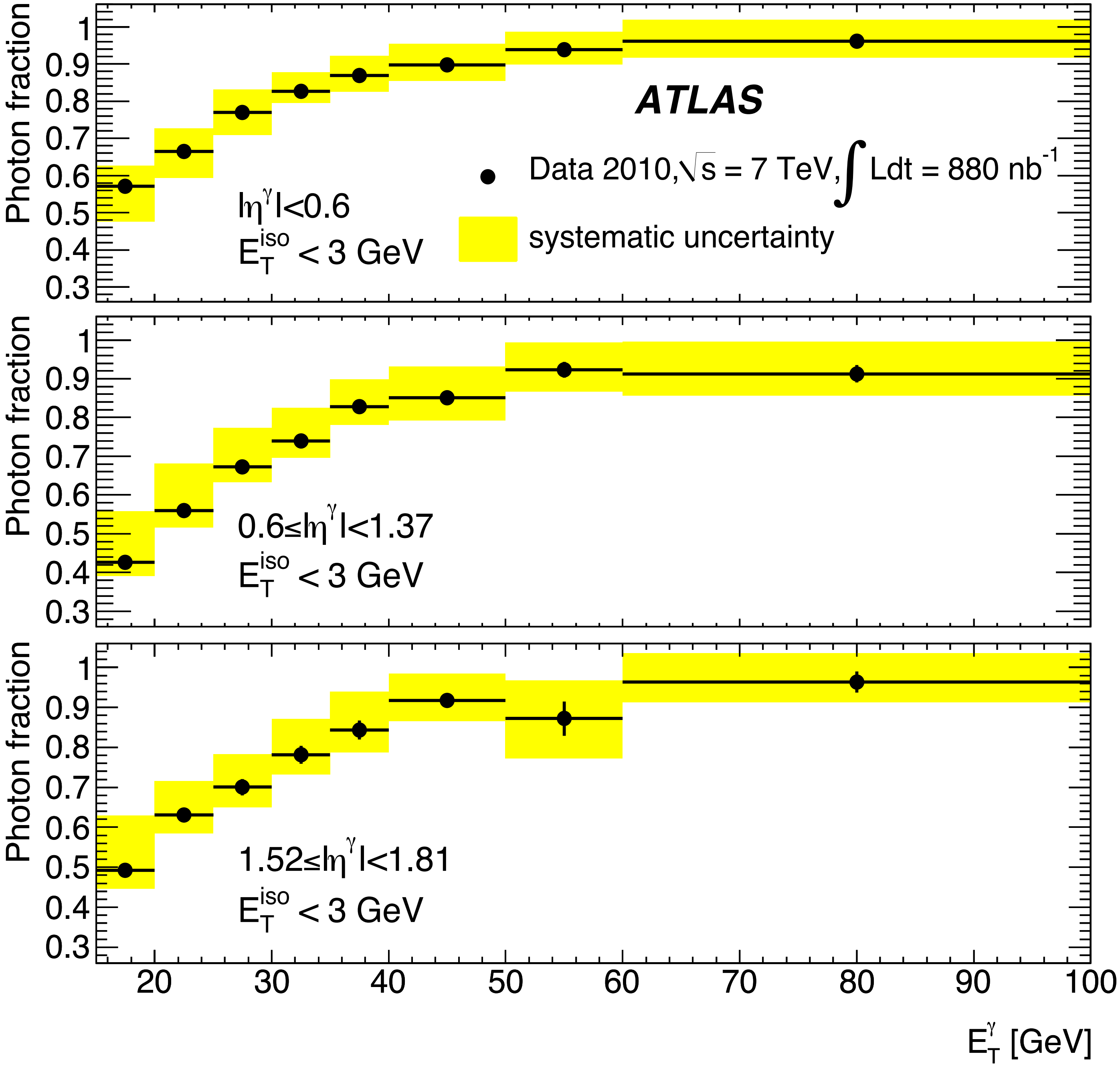
Corrections for signal leakage

Corrections for correlation

Direct photons!

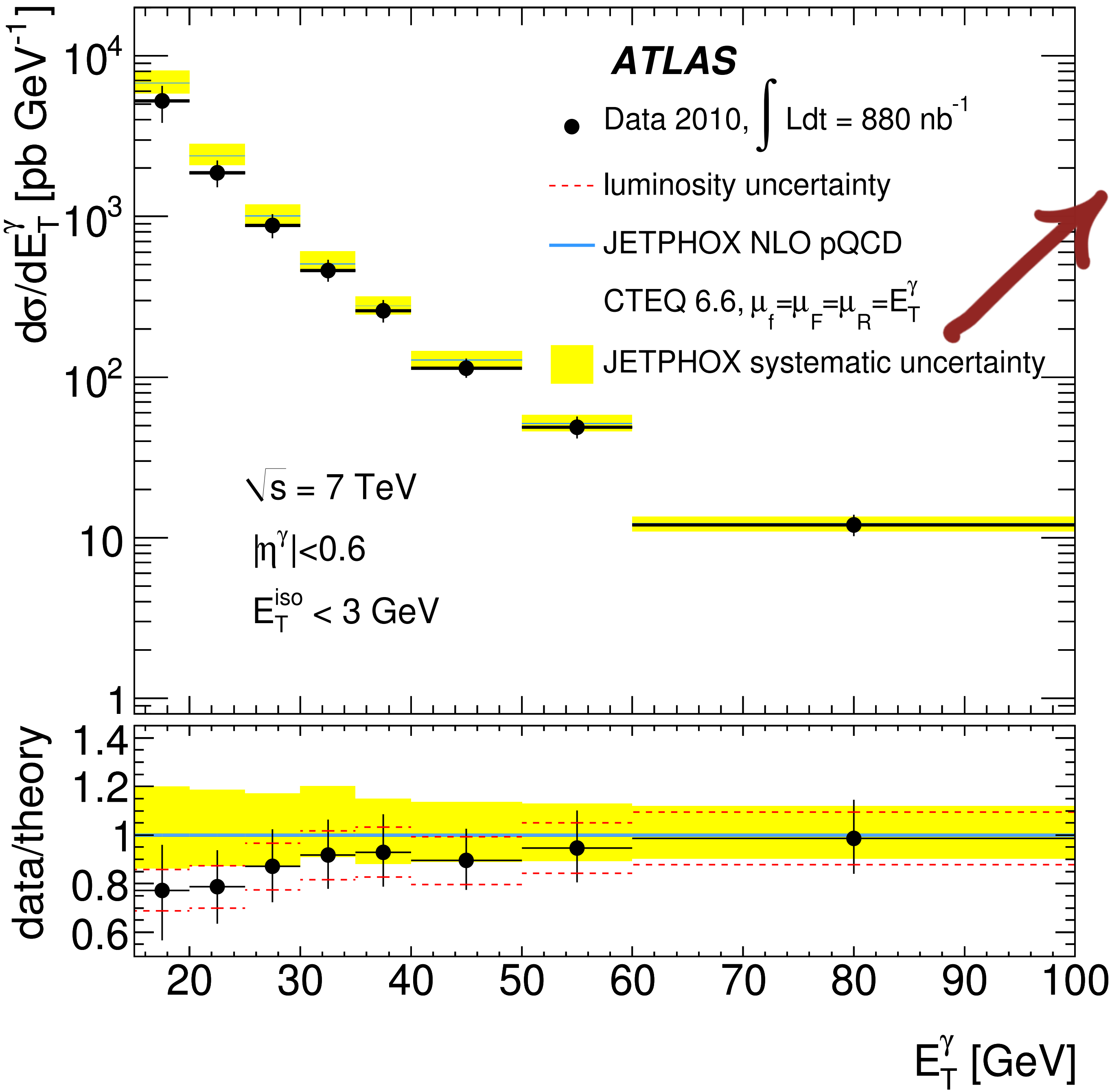


Data-driven photon purity



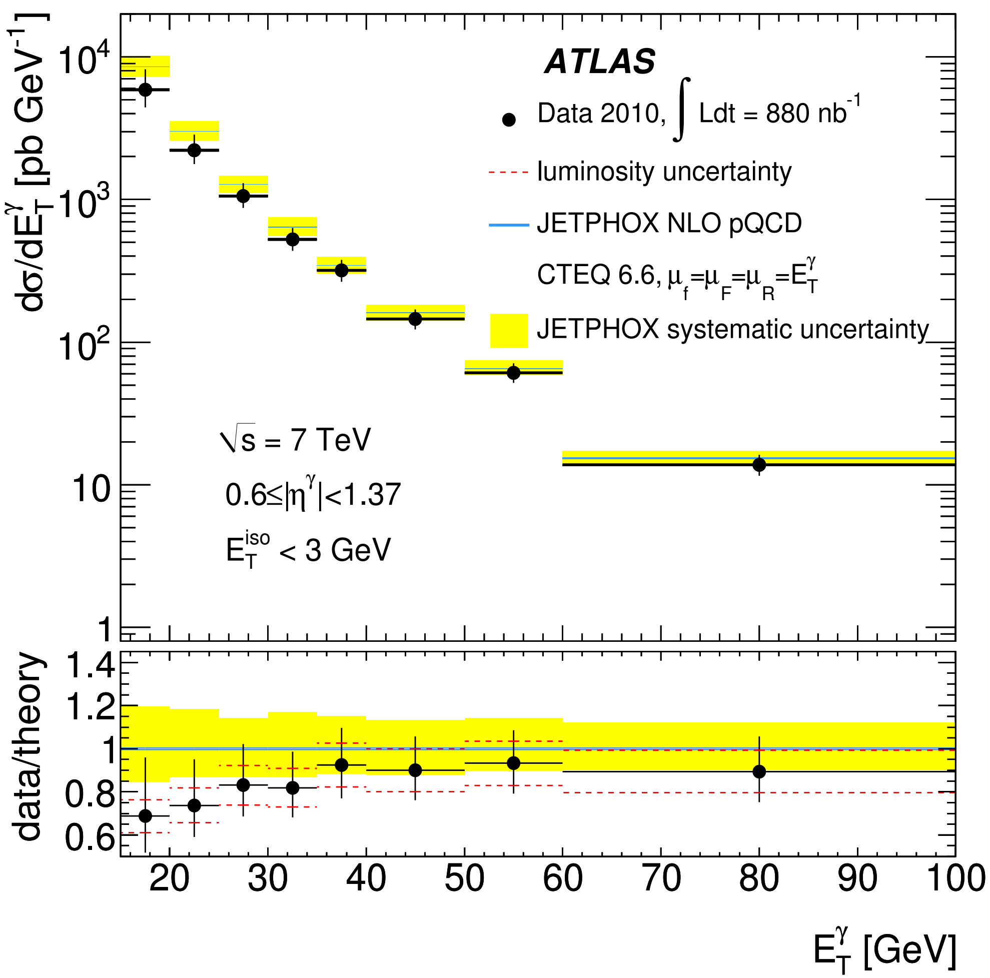
Inclusive direct photon cross section

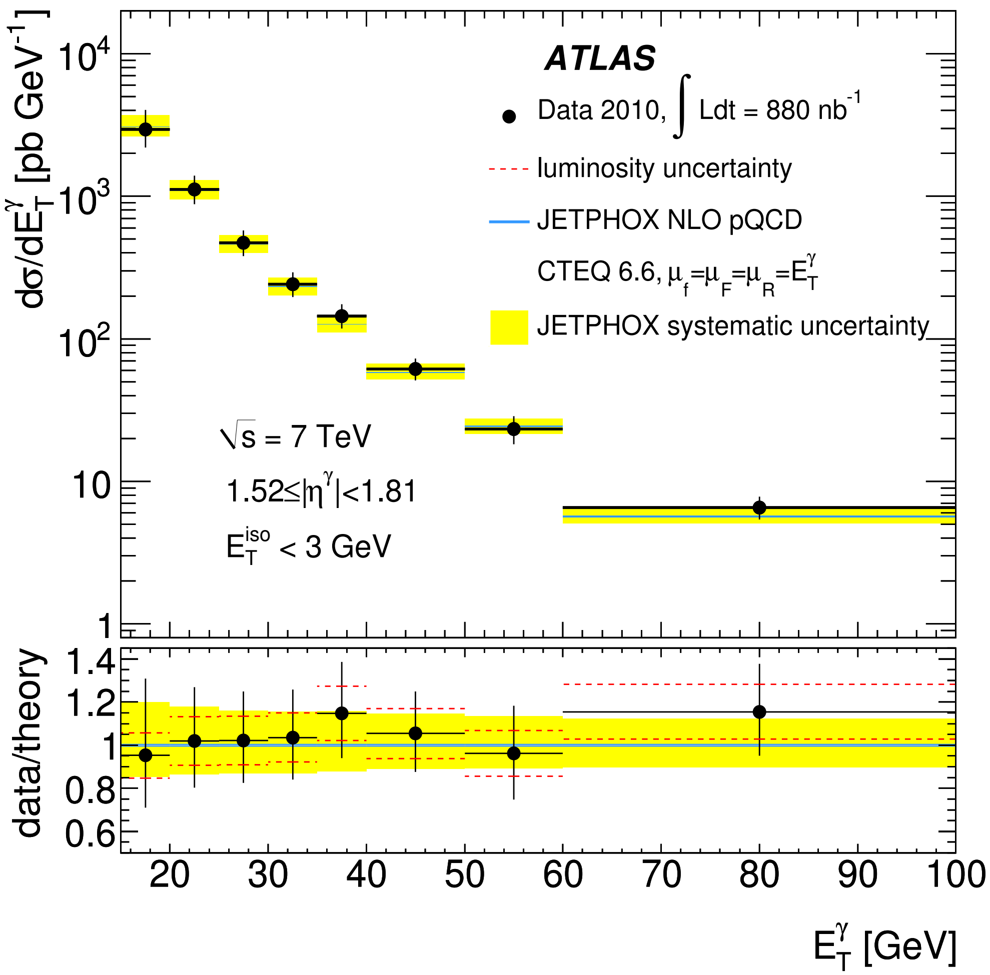
Isolation < 4 GeV in cone $\Delta R = 0.4$ (vary isolation from 2 to 6 GeV)



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

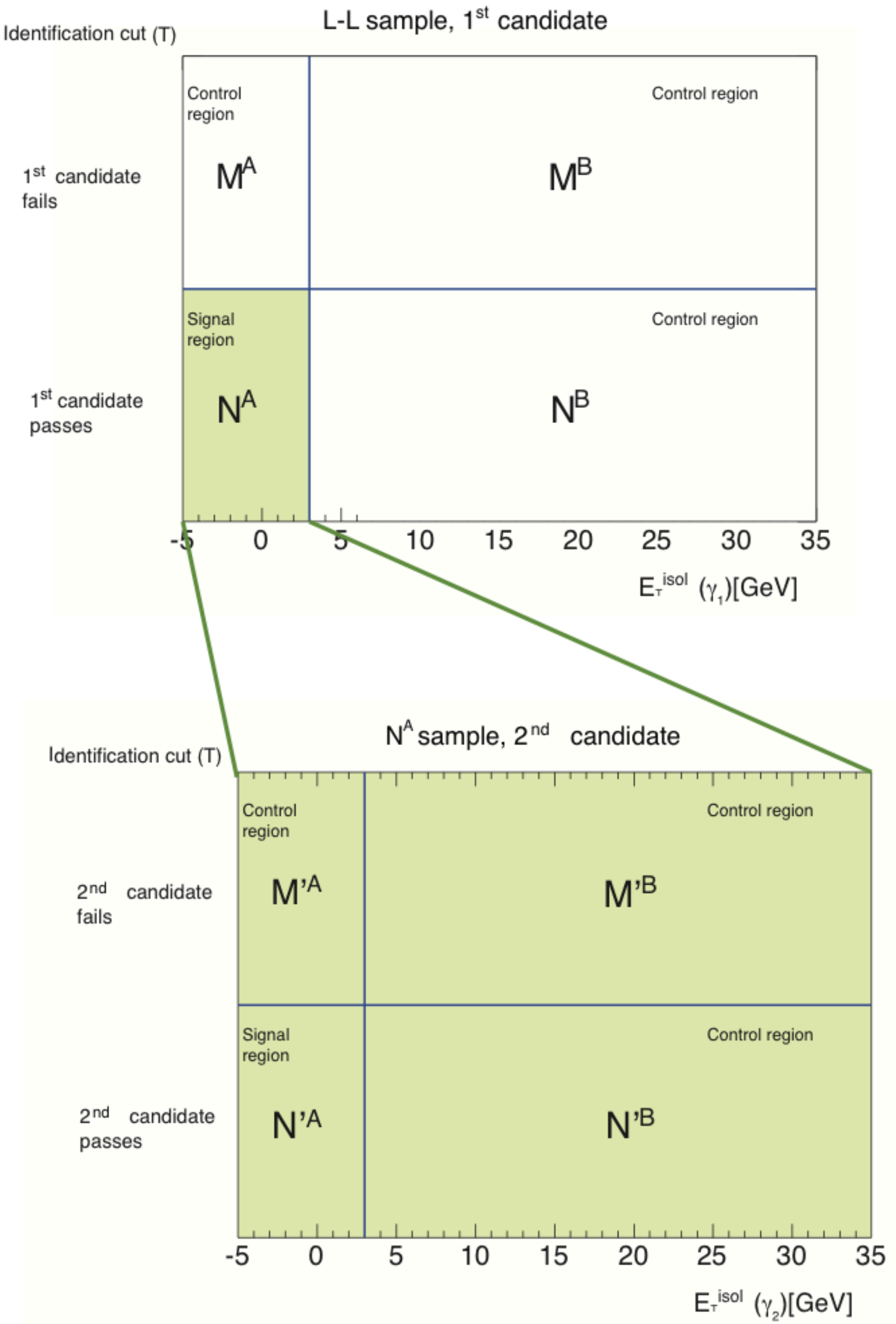
Inclusive direct photon cross section





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 ($M^B = M^B_{\rm bkg}$).

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

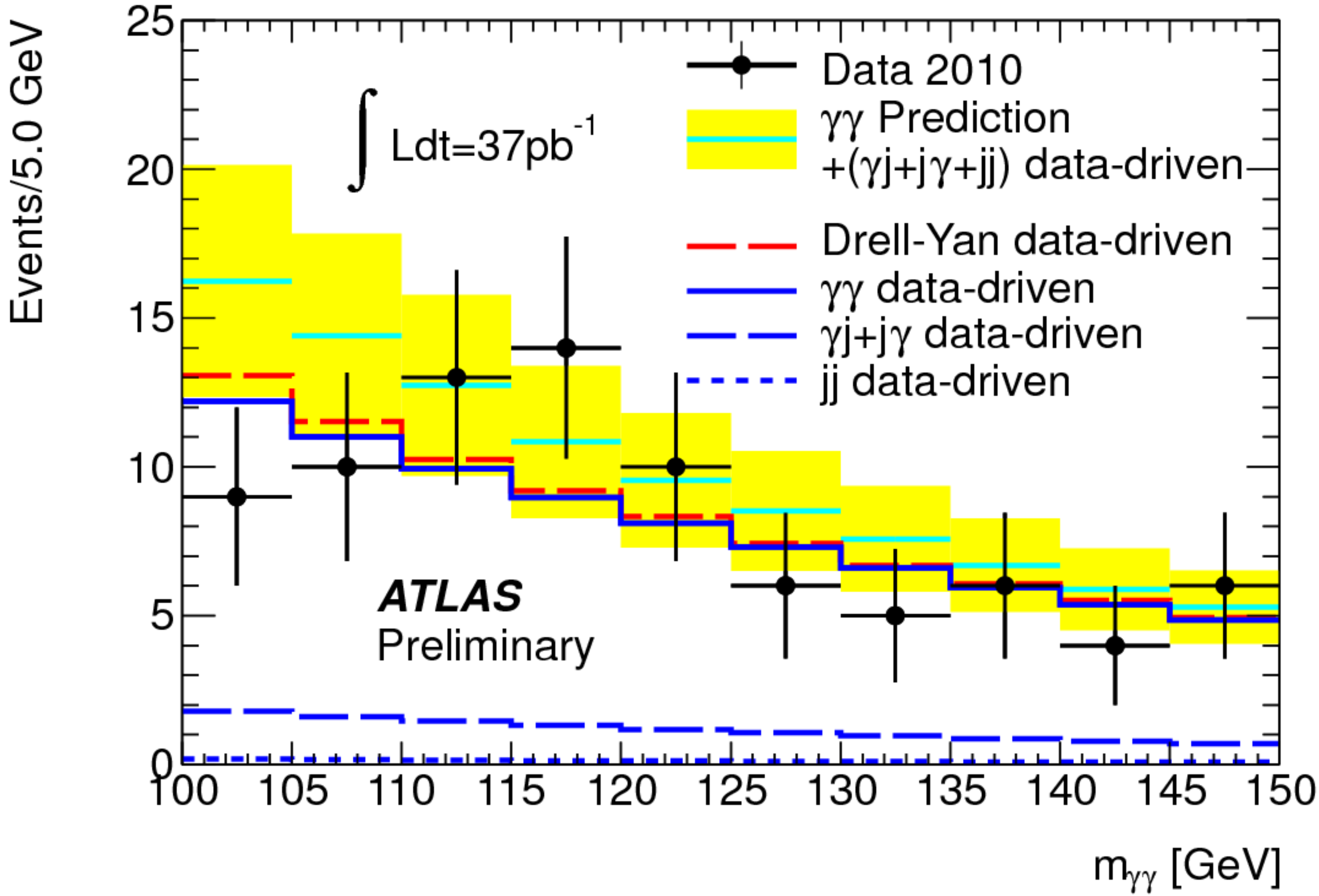
leading candidate is a photon, i.e. $\gamma\gamma$ and γ-jet

- 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 ($M'^B = M'^B_{\rm bkg}$).

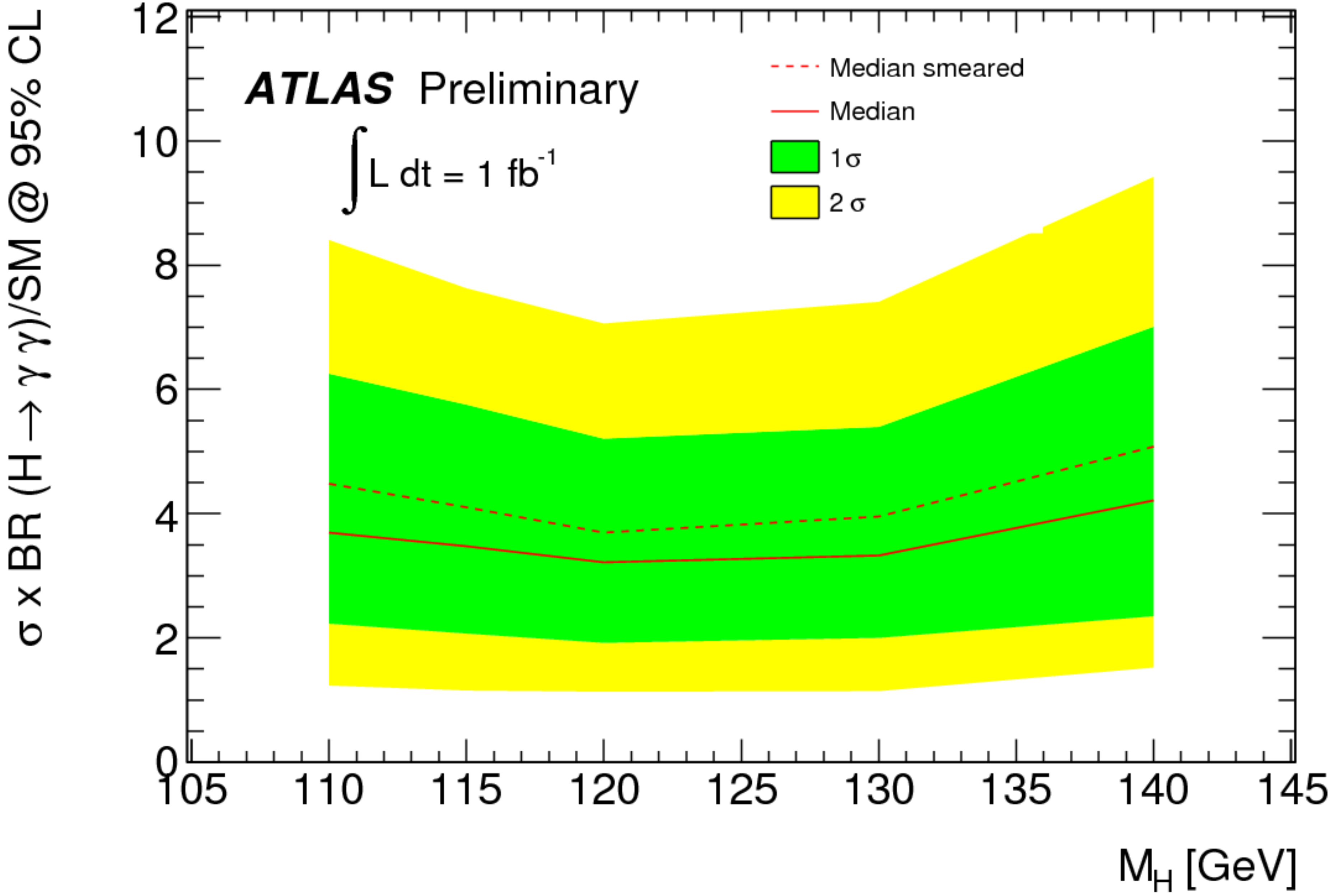
$$N'^A_{\rm sig} = N'^A - N'^A_{\rm bkg} = N'^A - N'^B \frac{M'^A}{M'^B}$$

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

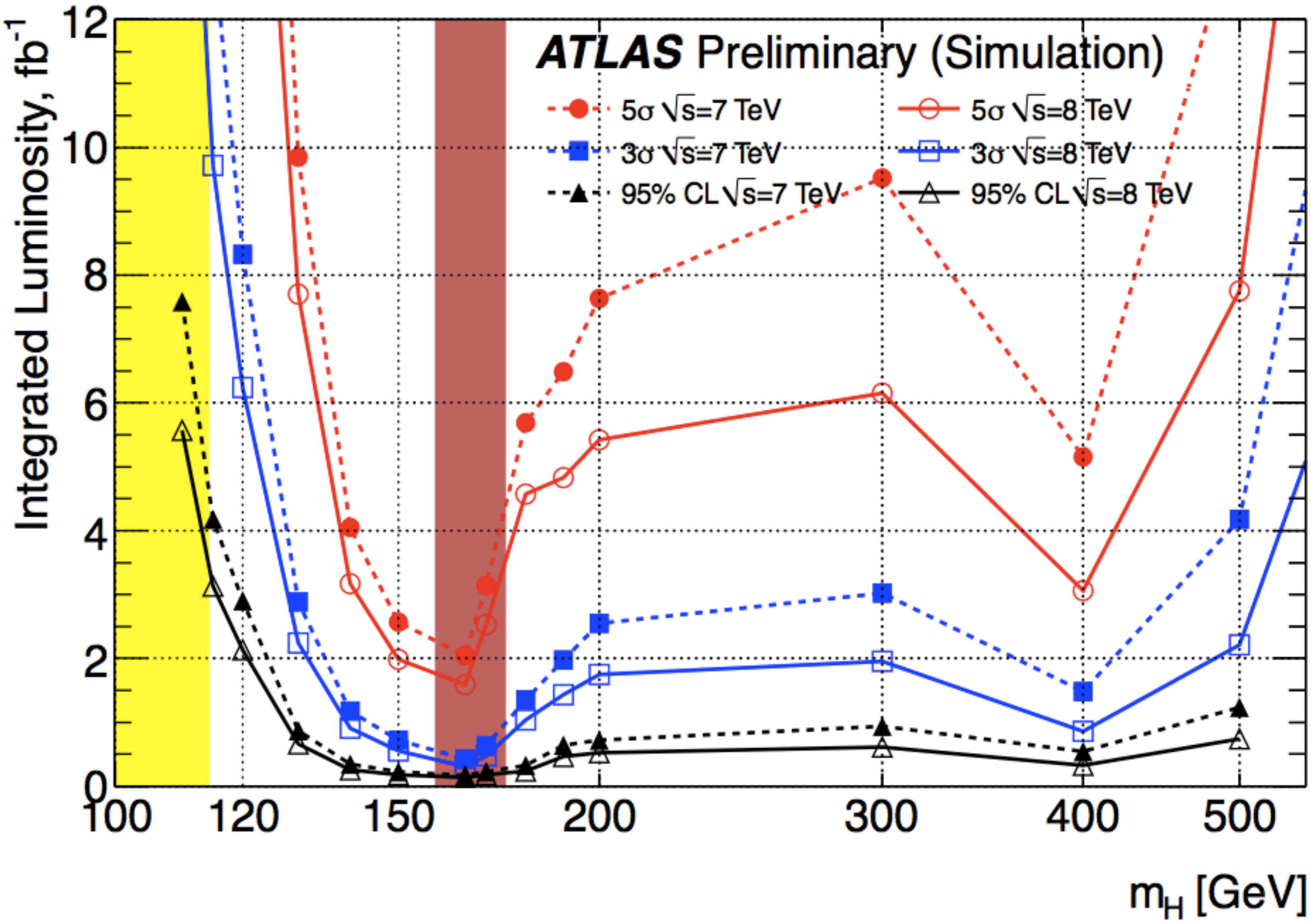
Diphoton spectrum vs $m_{\gamma\gamma}$



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.
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  - ✓ 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
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  - ✓ ATL-PHYS-PUB-2011-001, 2011