SM Measurements with Photons

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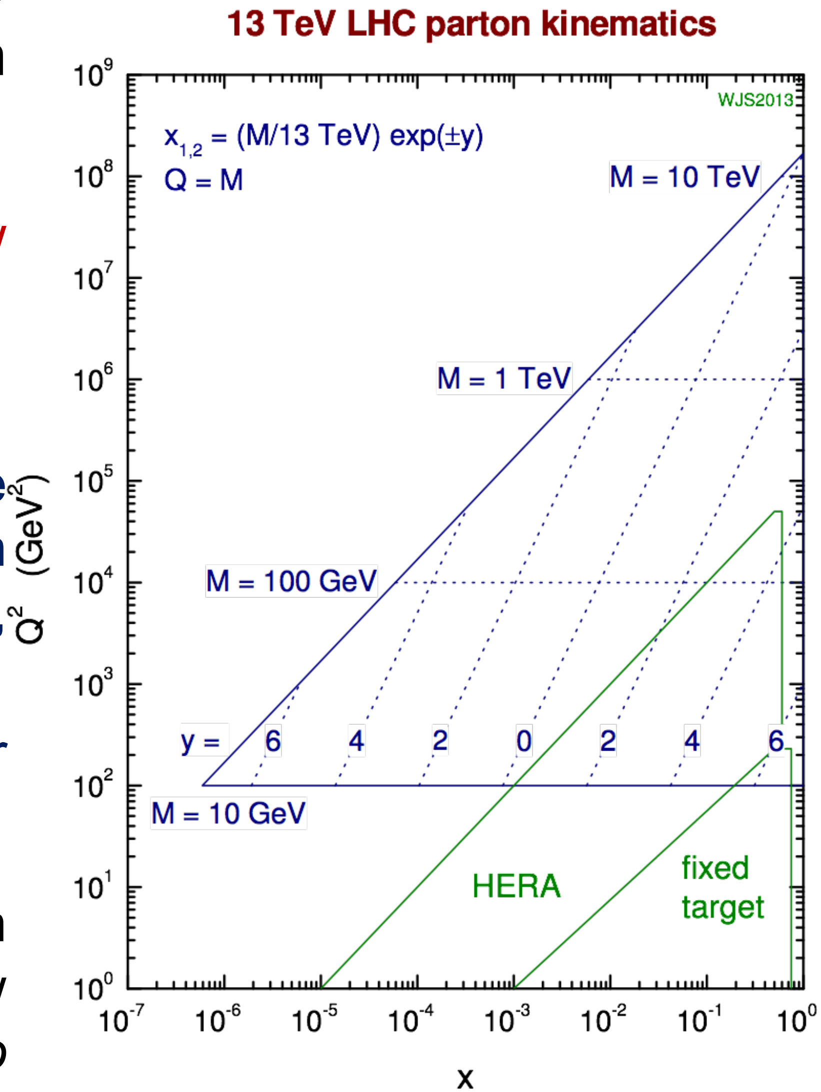
Will focus mostly on LHC results

A small selection of results, cannot show everything!!

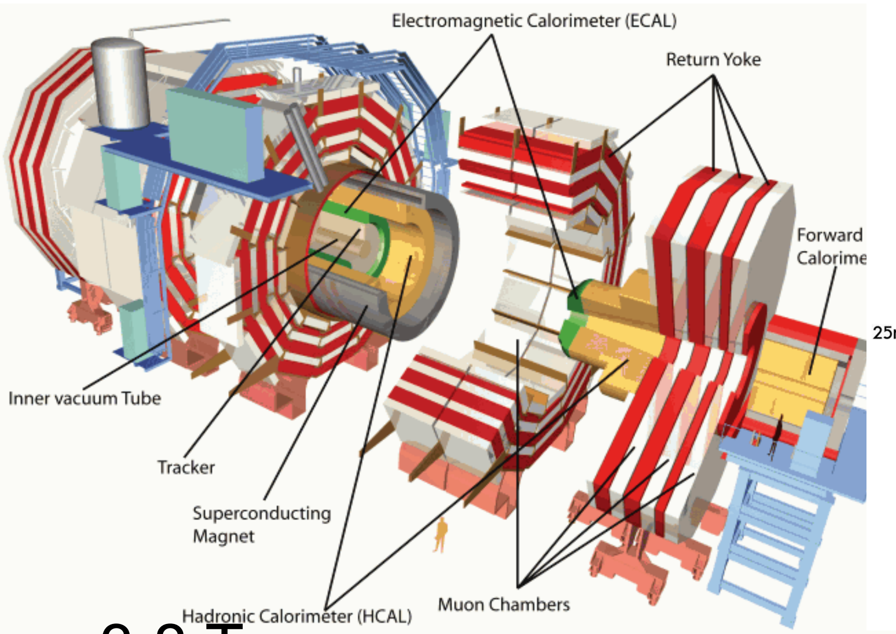
- Introduction **: [Why]**
- Photon reconstruction and Identification **: [How]**
- Photons and : **[What]**
  - Tests of pQCD & Tunning of PDFs
  - "Completion" of the SM
  - Test of EW SM sector and perform **SM Measurements for the discovery of new physics**
- Summary and Future

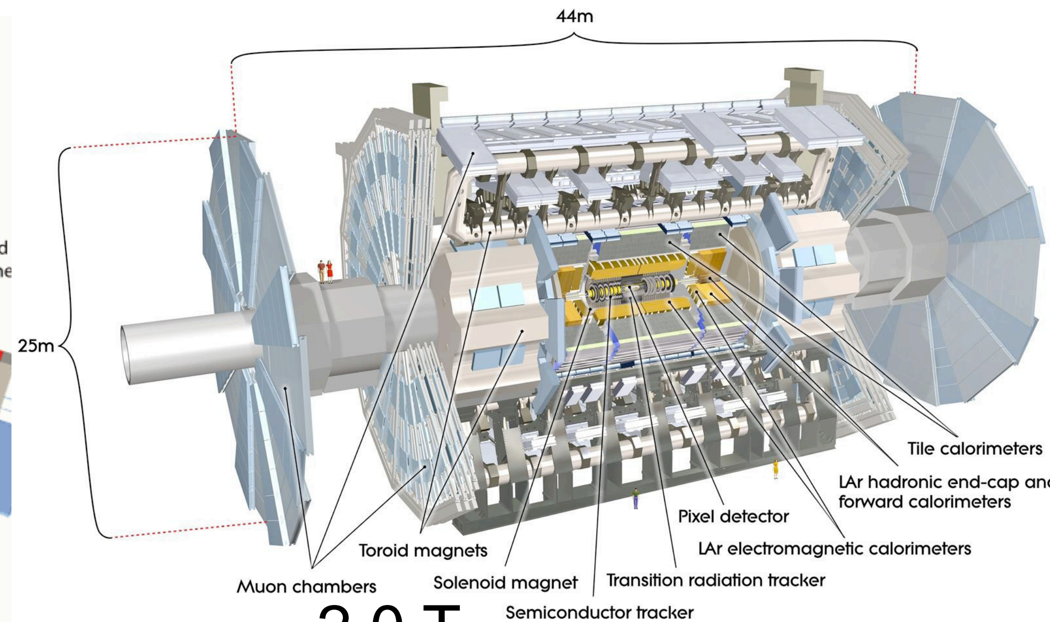
Introduction

- Measurements with photons in the final state are of great important in order to:
  - Test pQCD in ever-growing and new energy regime
  - Test the EW sector of the SM
  - Provide constraints on PDFs, whose uncertainties often dominate both Standard Model (SM) measurements, and beyond the SM searches
  - Tune Monte Carlo generators in order to better describe the data.
  - Measure and understand the main background to a variety of new physics searches, *or get a chance to have a first glimpse of something new and unexpected*.



ATLAS and CMS Experiments





3.8 T

Pixels

σ/pT~ $1.5\cdot10^{-4}$pT(GeV)⊕0.005

Electromagnetic Calorimeter

σE/E ≈ 2.9%/√E(GeV) ⊕ 0.5%⊕0.13GeV/E

Hadronic Calorimeter

σE/E ≈ 120%/√E(GeV) ⊕ 6.9%

Muon Spectrometer

σpT/pT ≈ 1% for low pT muons

σpT/pT ≈ 5% for 1 TeV muons

2.0 T

Pixels,Si strips & Straw tubes

σ/pT~ $3.8\cdot10^{-4}$pT(GeV)⊕0.015

Electromagnetic Calorimeter

σE/E ≈ 10%/√E(GeV)⊕0.7%⊕0.2GeV/E

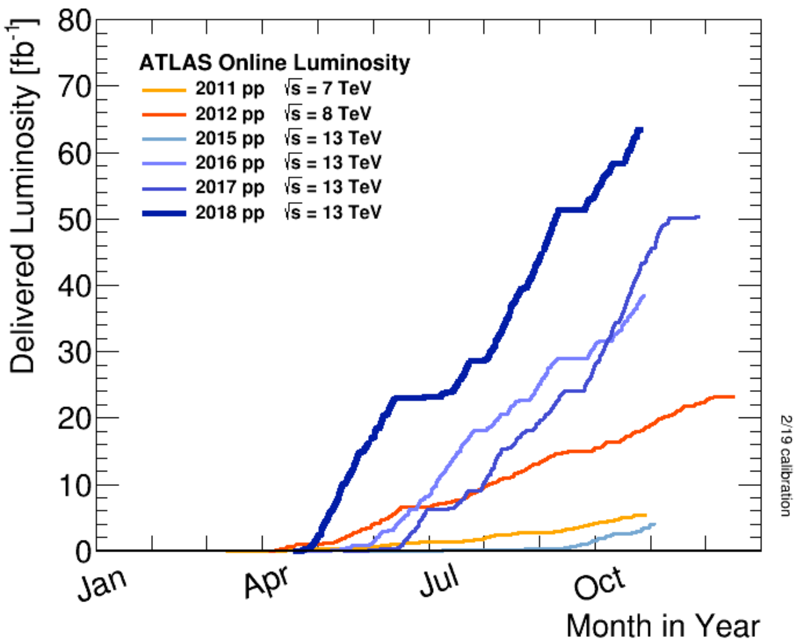
Hadronic Calorimeter

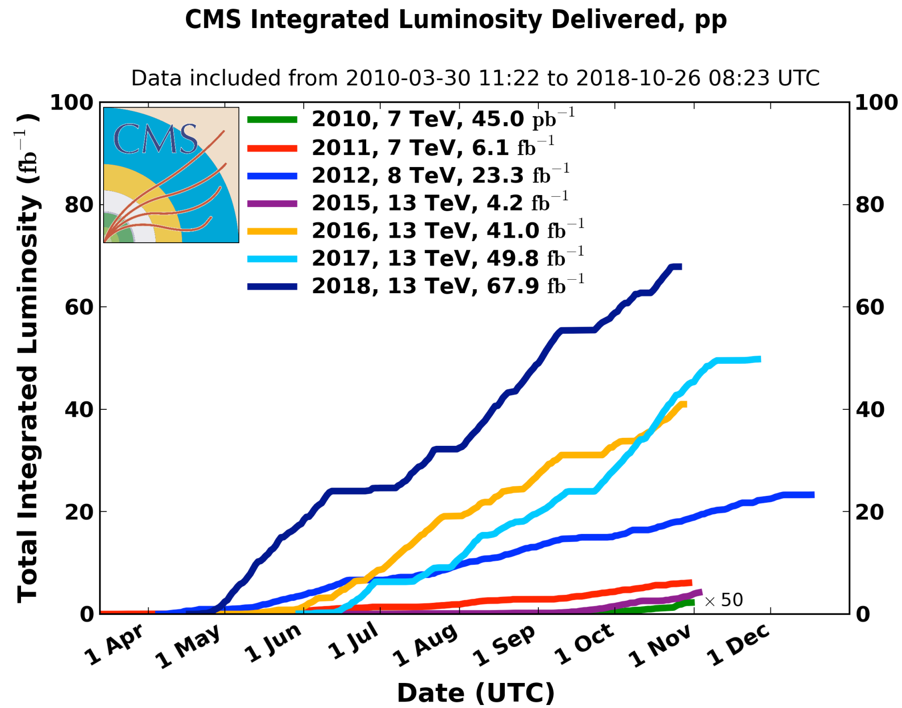
σE/E ≈ 60-100%/√E(GeV) ⊕ 3%

Muon Spectrometer

σpT/pT <10 % up to 1 TeV muons

Data Collection





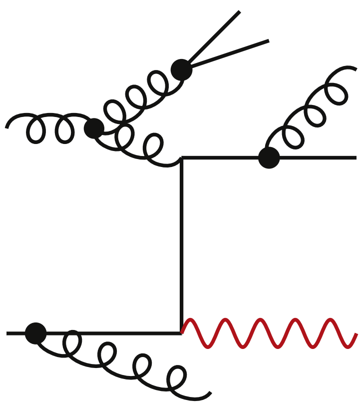
All of the ATLAS and CMS results shown can be found at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Prompt Photons and Backgrounds

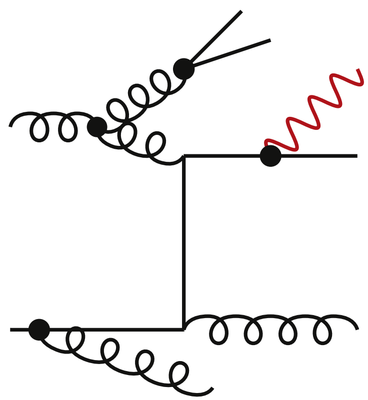
- **Prompt photons** are **isolated energy deposits** in the experiments electromagnetic calorimeter (ECAL), with no charged track pointing to them, and with a **shape compatible with a photon electromagnetic shower** : they can be converted or unconverted.

- **Non prompt photons** (main background) are $\boldsymbol{\pi^0}$ **from hadronic jets**, discrimination in this case based on isolation and different shower shape characteristics.

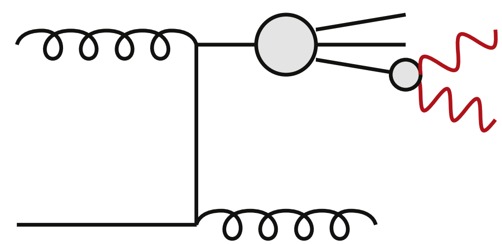
Prompt Photons **Non-prompt Photons**



Annihilation & Compton Scattering



Fragmentation

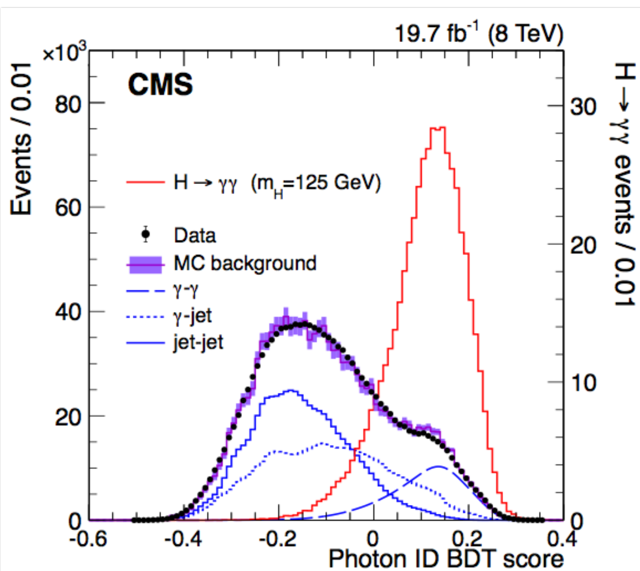


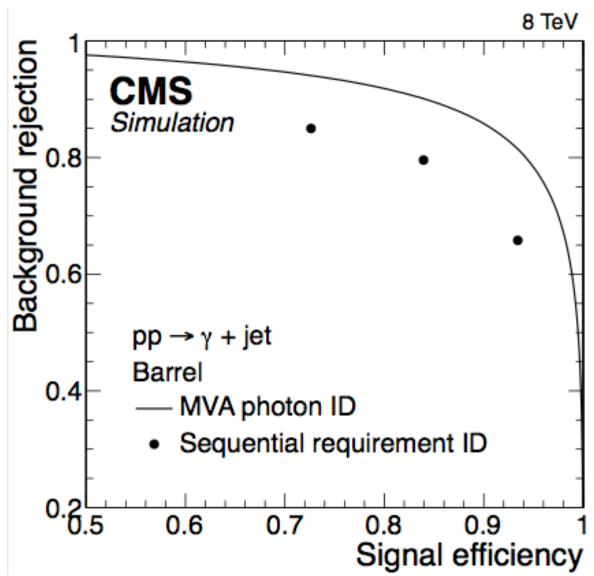
$\boldsymbol{\pi^0}$ **η in jets**

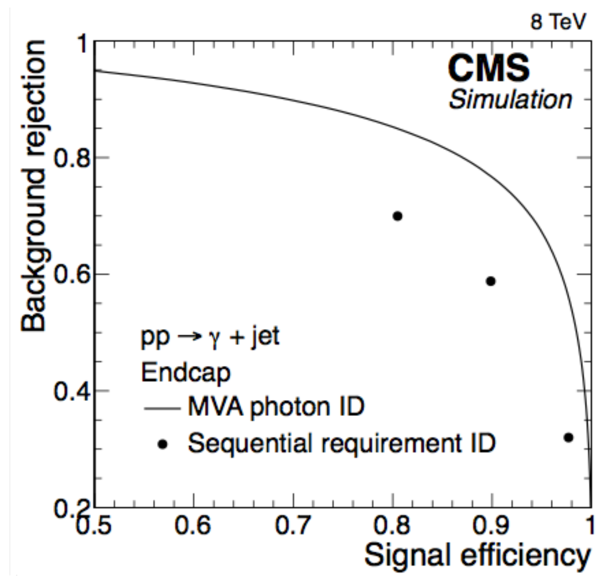
Photon Identification in CMS

- **Several shower shape and isolation variables**, used as sequential cuts, or combined in a multivariate analyzer (BDT).
- Selection efficiencies estimated in a data-driven way using Z → llγ and Z → ee data-drive methods.

JINST 10 (2015) no.08, P08010





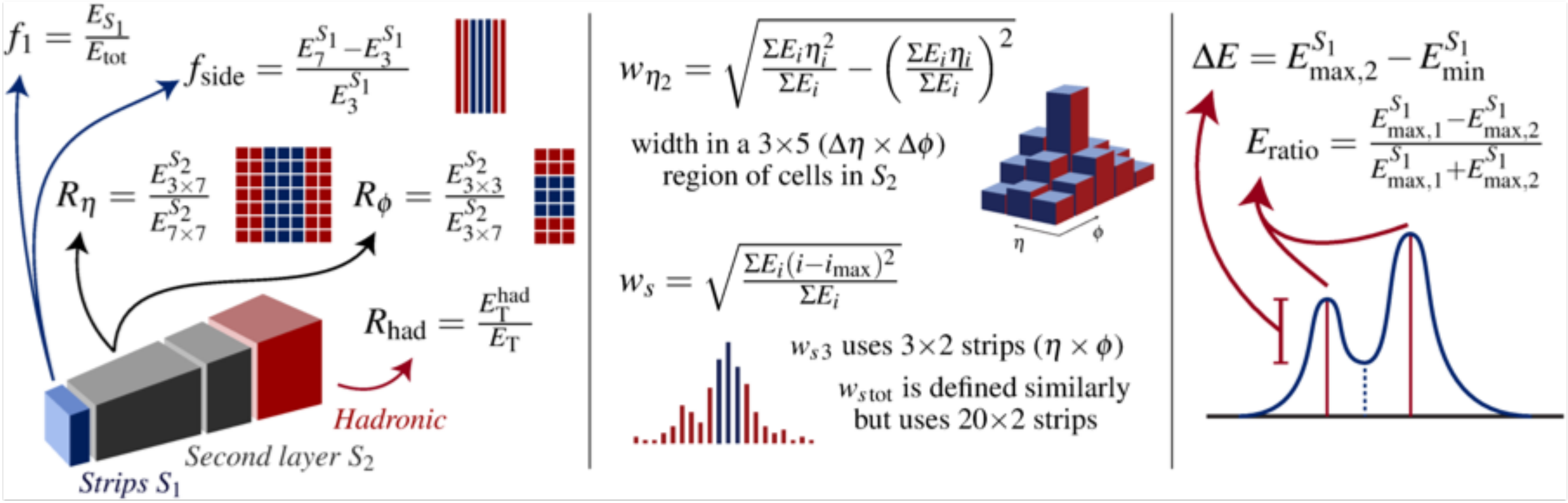


Photon Identification in ATLAS

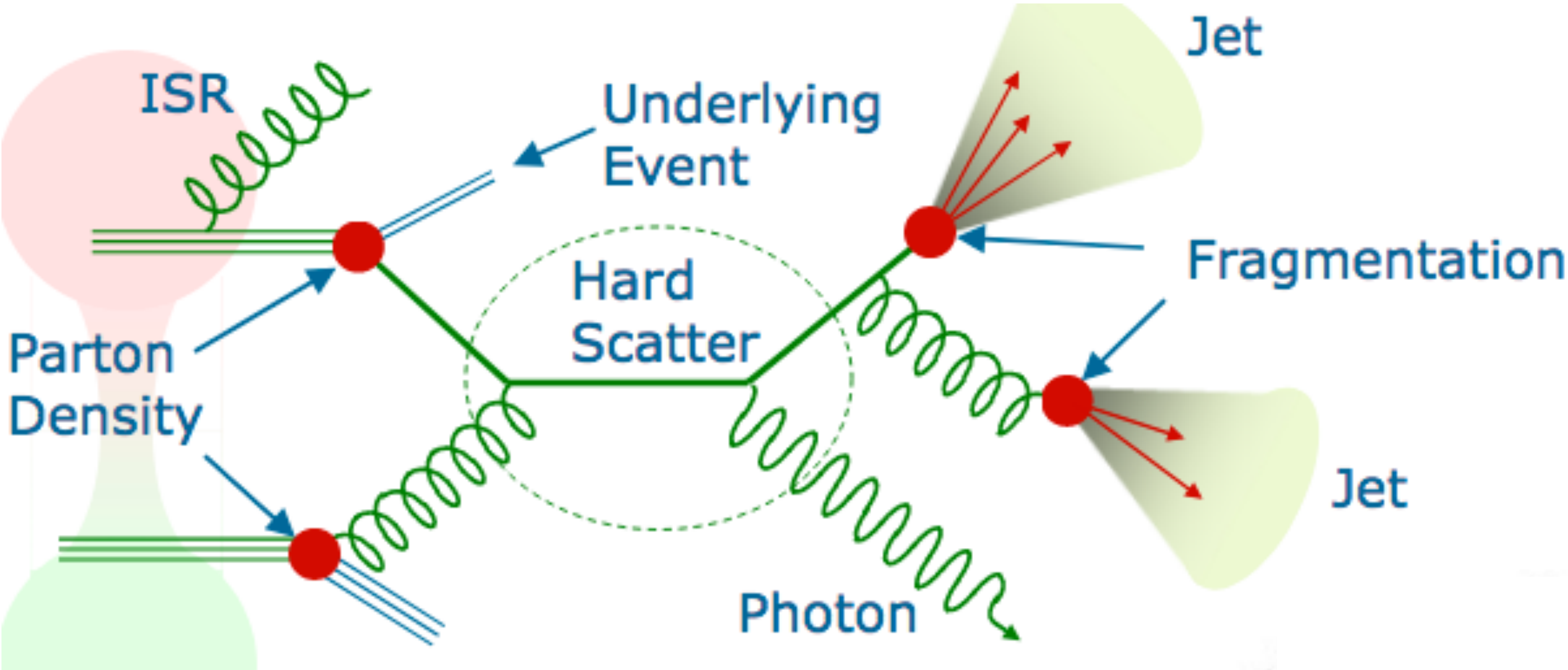
- **Several shower shape and isolation** variables utilized and combined with sequential cuts.

- Detailed **data-driven methods** deployed **to measure efficiencies** in data and simulation, using **Z→llγ , Z→ee and isolation measurements using the tracker in an inclusive photon sample**

Eur. Phys. J. C 79 (2019) 205

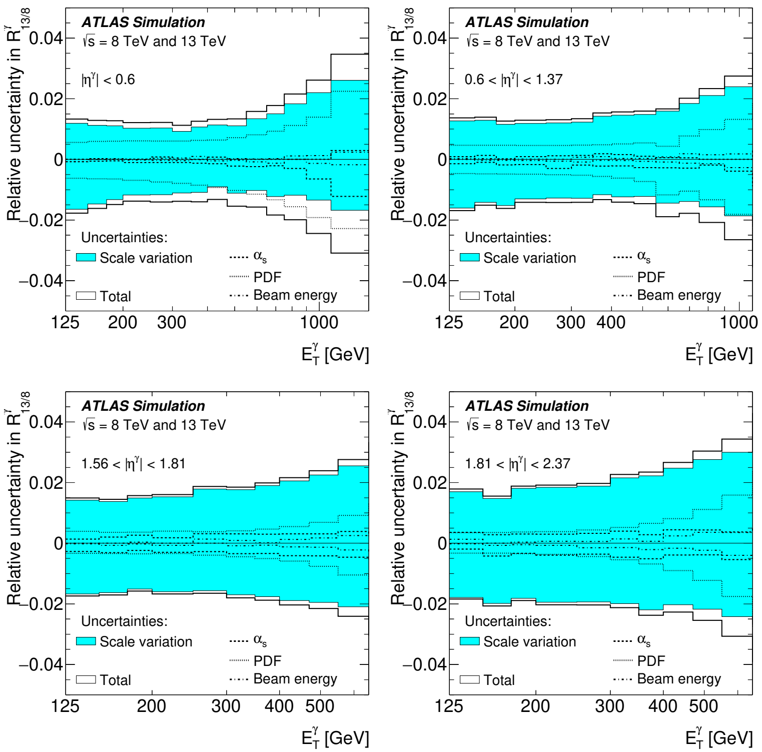


Isolated prompt Photon and Photon + jets measurements

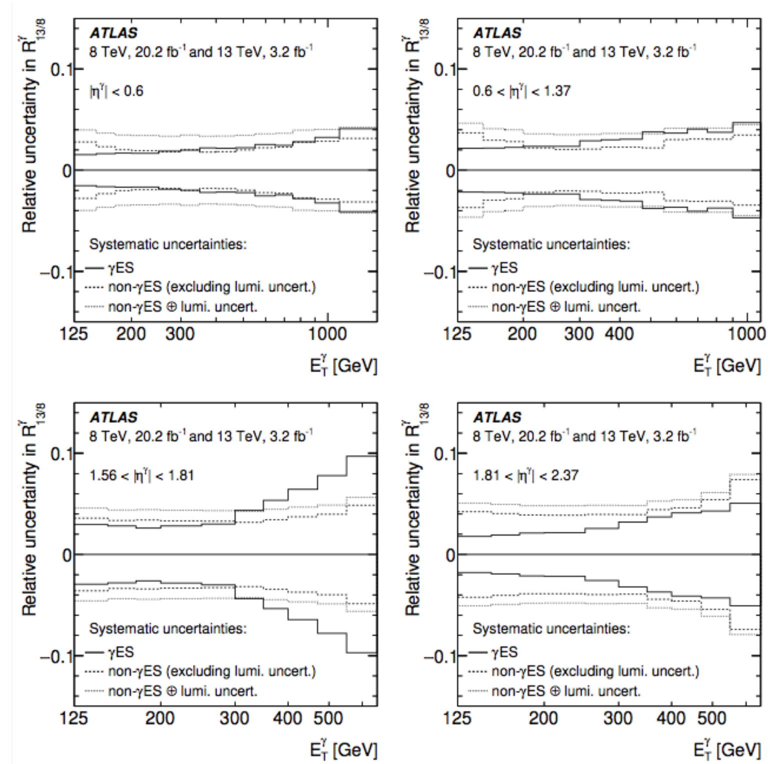


- **Direct photons are a direct (colorouless) probe of the hard scattering**
- **Sensitive in the gluon PDF**
- **Can be used to tune MC Models**

Inclusive Photon Cross Section at 8 and 13 TeV and their ratio : ATLAS (1)



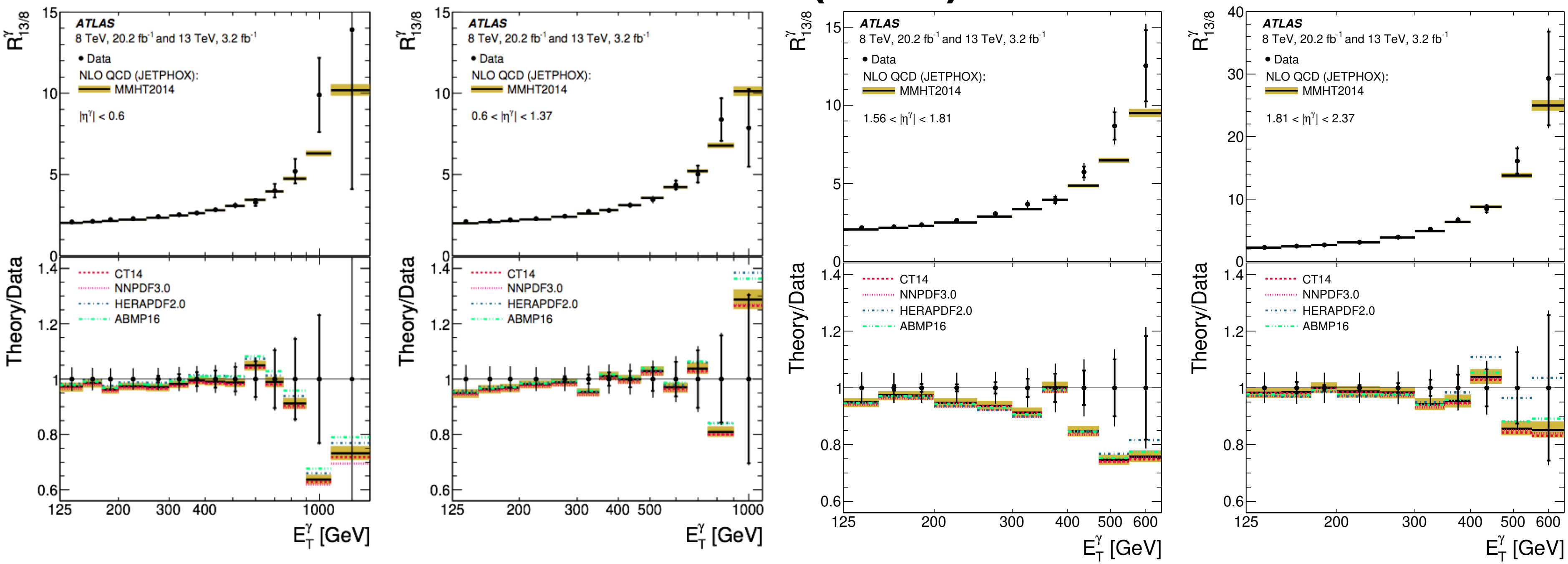
JHEP 1904 (2019) 093



- Utilizing **ratios of photon cross section measurements at 8 TeV and 13 TeV** achieve, through **cancelation, smaller experimental and theoretical systematics!**
- Main theoretical uncertainty coming from scale, and PDFs and main experimental uncertainty from photon energy scale.
- Theoretical uncertainties now smaller than experimental ones

Inclusive Photon Cross Section at 8 and 13 TeV and their ratio : ATLAS

JHEP 1904 (2019) 093

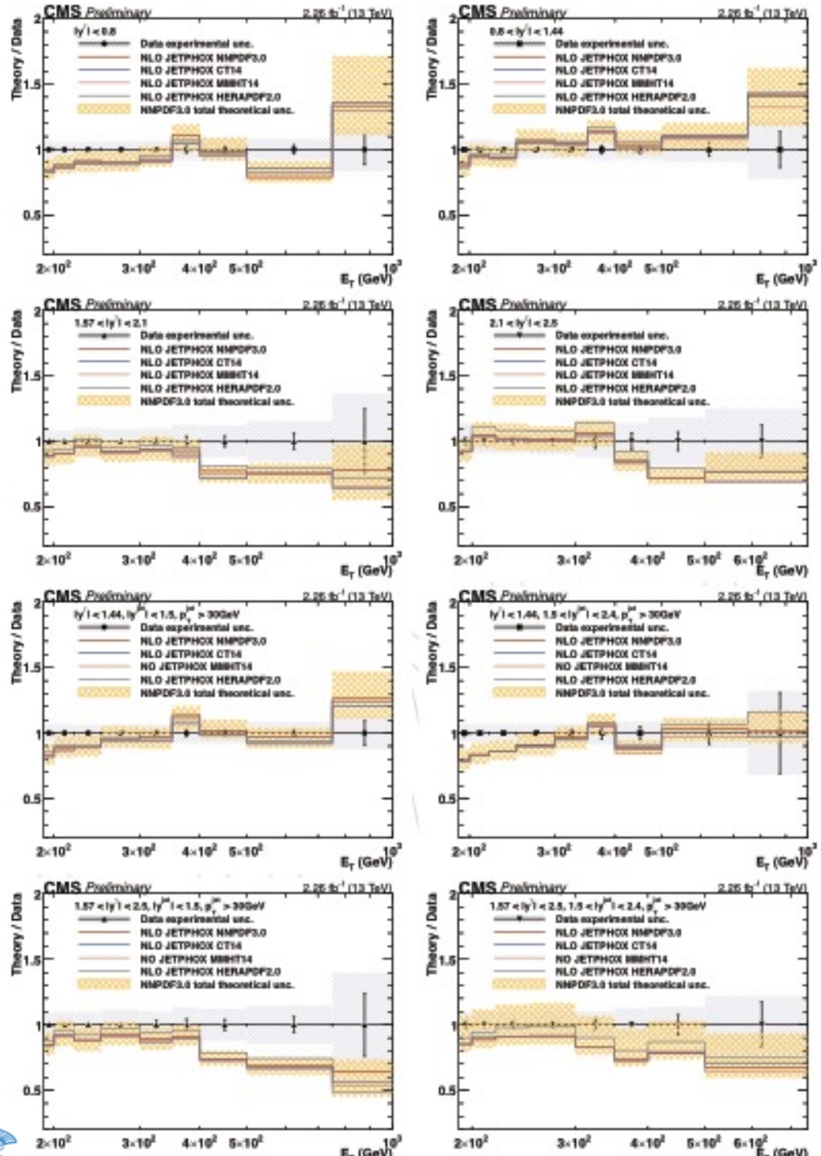


Photon isolation in a cone of ΔR = 0.4 **I <** $4.8 + 4.2 \cdot 10^{-3} \cdot E_T^{\gamma}$ [GeV]

- The **significant reduction** of the experimental and theoretical **uncertainties** allows for a **more stringent test of NLO QCD.**

- **NLO pQCD predictions and data agree** given uncertainties. **This validates the description of the evolution of isolated-photon production in pp collisions with the centre-of-mass energy.**

Inclusive photon and Photon plus jet cross section at 13 TeV : CMS



EPJC 79 (2019) 20

- **Measurements compared with theoretical predictions** produced using JETPHOX NLO calculations and several different PDF sets, **and found to be in agreement.**

- For **low to middle range in photon energies**, where the experimental uncertainties are smaller or comparable to theoretical uncertainties, **these measurements provide the potential to further constrain the proton gluon PDFs.**

Ratio of photon + jet / Z+jet cross differential sections at 8 TeV : CMS (1)

J. High Energy Phys. 10 (2015) 128

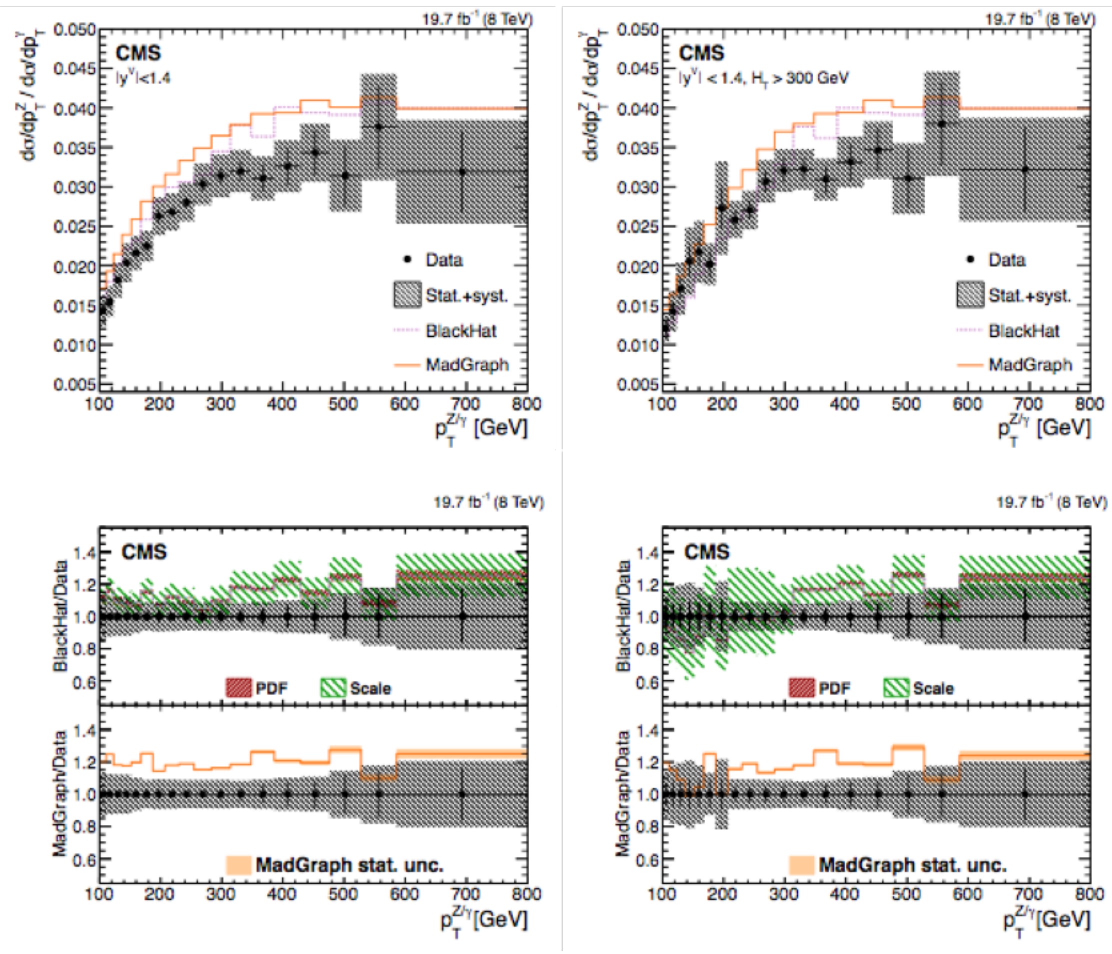
- **At high vector boson pT and at LO** effects due to the mass of the Z boson are small : **cross section ratio of Z + jets to γ + jets as a function of pT is expected to become constant,** reaching a plateau.

- A **precise measurement of the (pp→Z+jets)/(pp→ γ + jets) cross section ratio** provides important information about **the higher-order effects of large logarithmic corrections [ln(pT_Z /m_Z)] at higher pT**

- **Searches for NP characterized by the presence of large missing ET and hard jets, use the γ + jets process to model the invisible Z decays, Z → νν.** Measurements of the **(pp→Z+jets)/(pp→ γ + jets) can help reduce uncertainties related to the Z → νν background estimation in these searches.**

Ratio of photon + jet / Z+jet cross differential sections at 8 TeV : CMS (2)

J. High Energy Phys. 10 (2015) 128

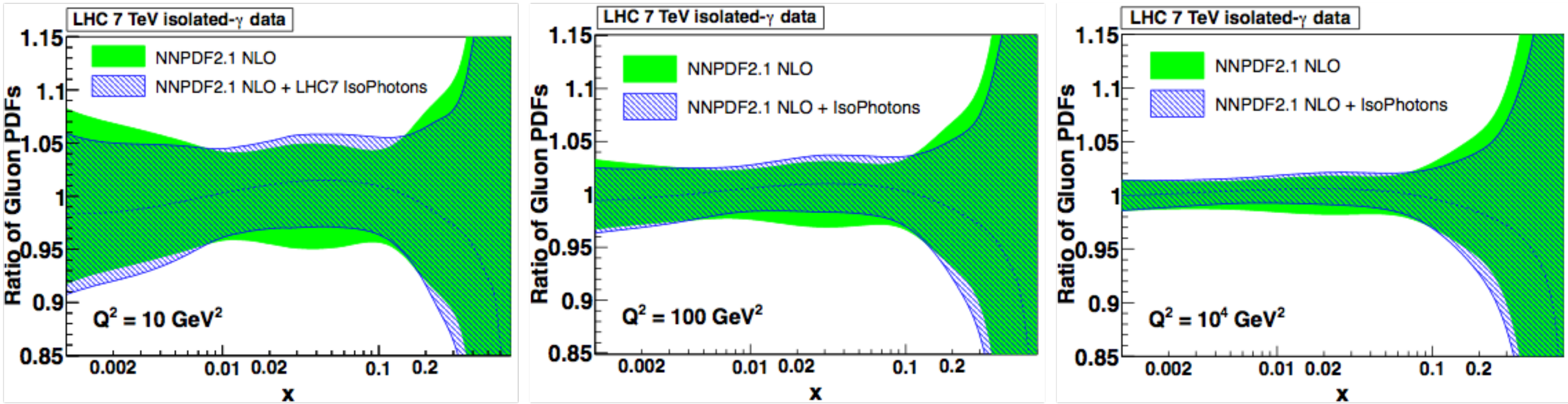


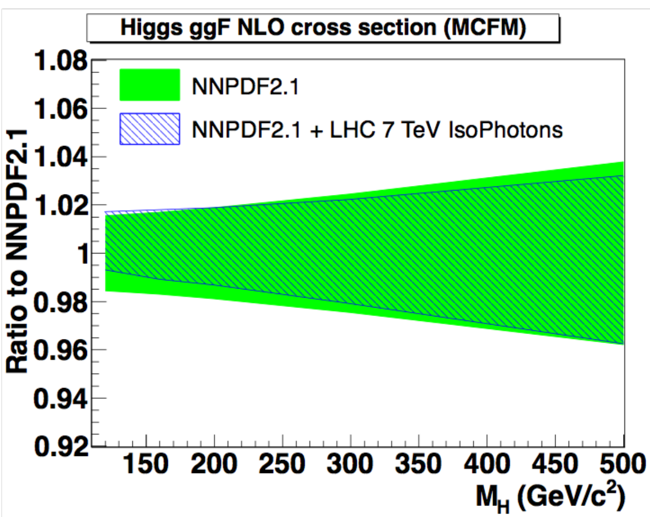
- Four phase space regions used: $n_{jets} \geq 1, 2, 3$, and $H_T > 300$ GeV.
- MADGRAPH+PYTHIA6 (LO+PS) and BALCKHAT (NLO) overestimates the data by a factor ~1.2, but with the same shape.
- These **results show that properties of the Z→νν process can be predicted by the measured γ + jets and the simulated ratio between Z → νν + jets and γ + jets.**

gluon PDFs with photons

Prompt photon production used in PDF fits (1)

Nuclear Physics B Volume 860, Issue 3, 21 July 2012, Pages 311-338

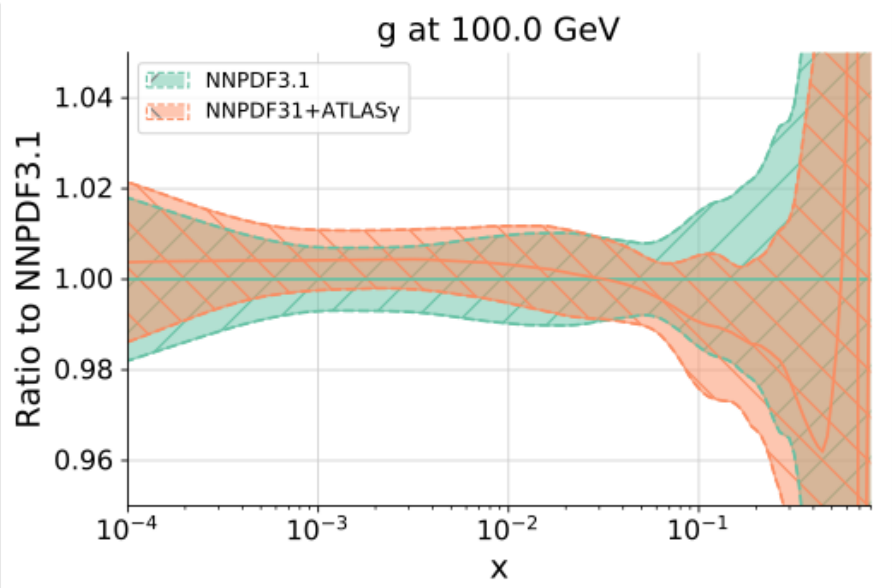


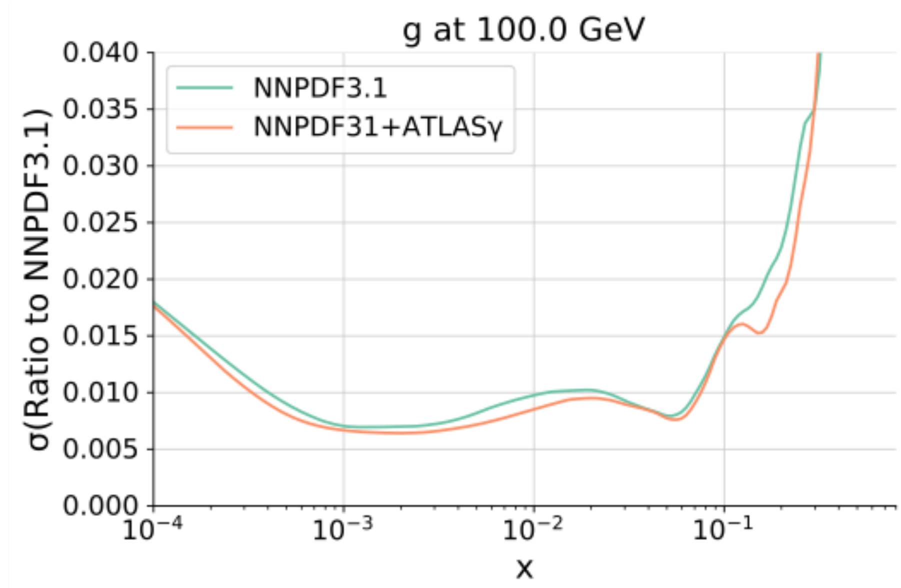


- Authors conclude *"….we have shown that* ***the available isolated-photon data provides constraints on the gluon PDFs and thus on many relevant LHC processes, most importantly Higgs production in gluon-gluon fusion.*** *Given that even more precise data as well as theoretical improvements will be available in the next future,* ***we see no objection why isolated-photon data should not become integral part of future global QCD analyses****.."*

Prompt photon production used in PDF fits (2)

Eur. Phys. J. C, 78 6 (2018) 470



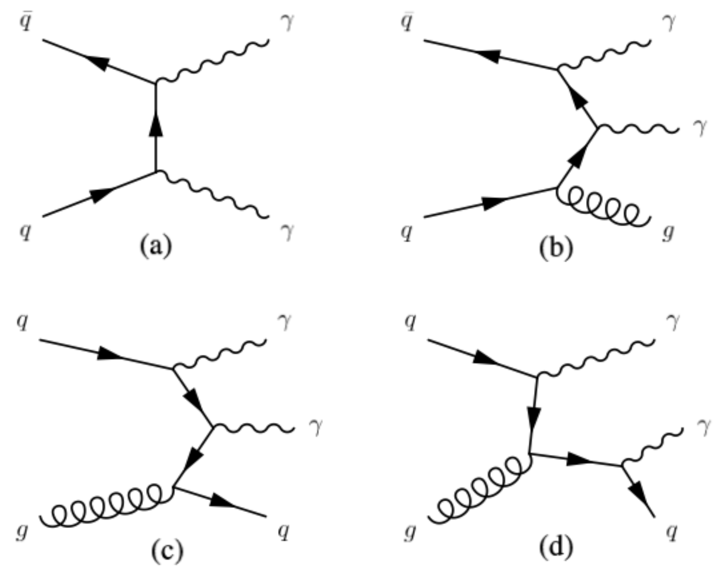


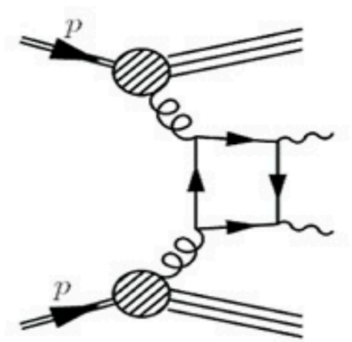
- Authors conclude *"….**that there is no reason, neither in principle nor in practice, for excluding collider direct photon data from a global PDF analysis.** Indeed, the most precise LHC measurements available agree well with state-of-the-art theoretical predictions, and the latter can be included in global PDF analyses using fast interpolation tables….. For these reasons, **collider direct photon production should be rightfully restored to its well-deserved position as a full member of the global PDF analysis toolbox**."*

Inclusive diphoton measurements

Diphoton non-resonant Production

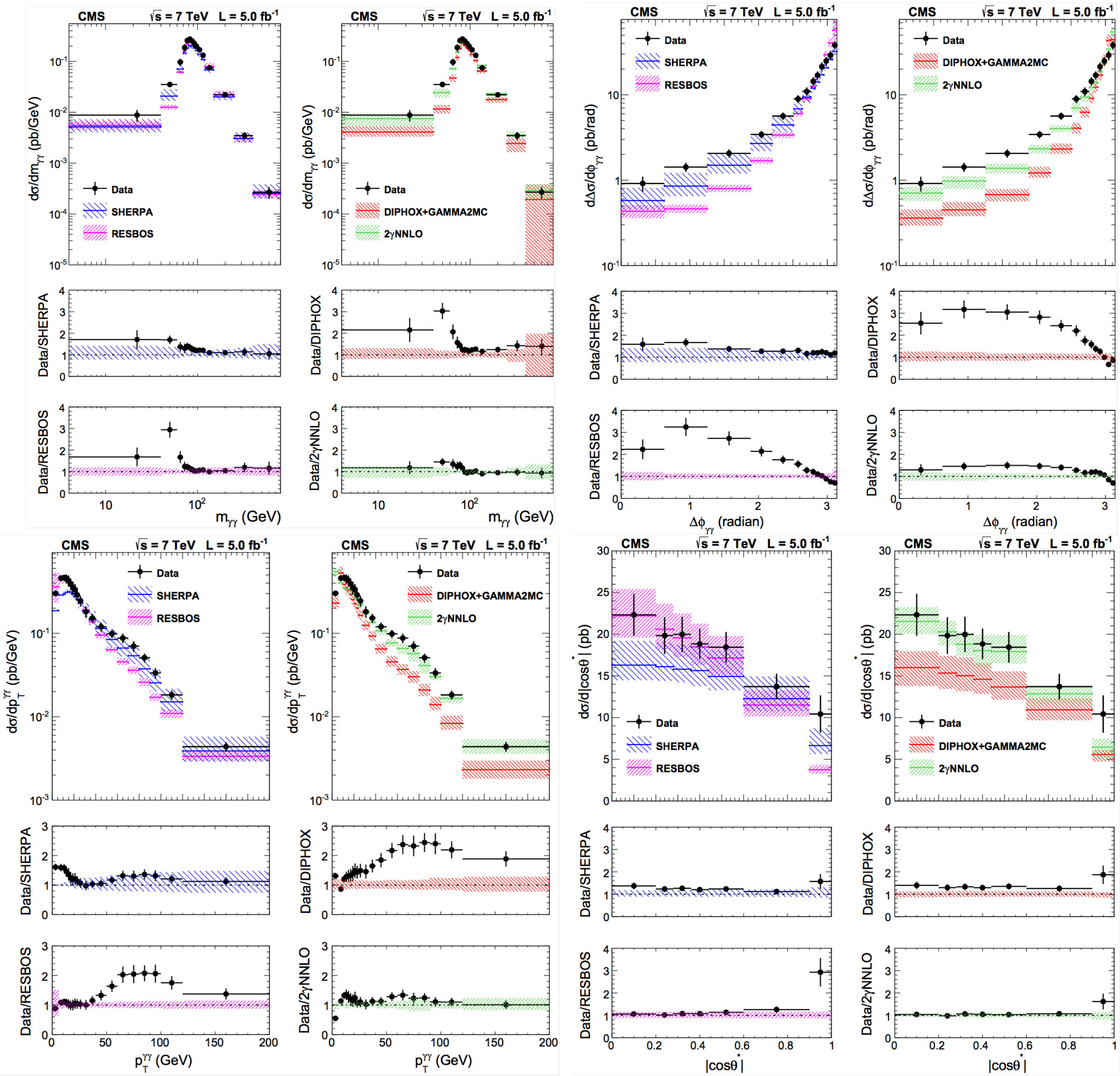
- Diphoton production important test of pQCD and non-perturbative QCD: **Rich phenomenology, making theoretical predictions challenging.**
- Experimental challenge: **distinguish it from non-prompt jet background.**
- **Irreducible background to Higgs diphoton decay channel**
- **Irreducible background to Non-resonant diphoton production from BSM physics.**





Diphoton Production at 8 TeV : CMS

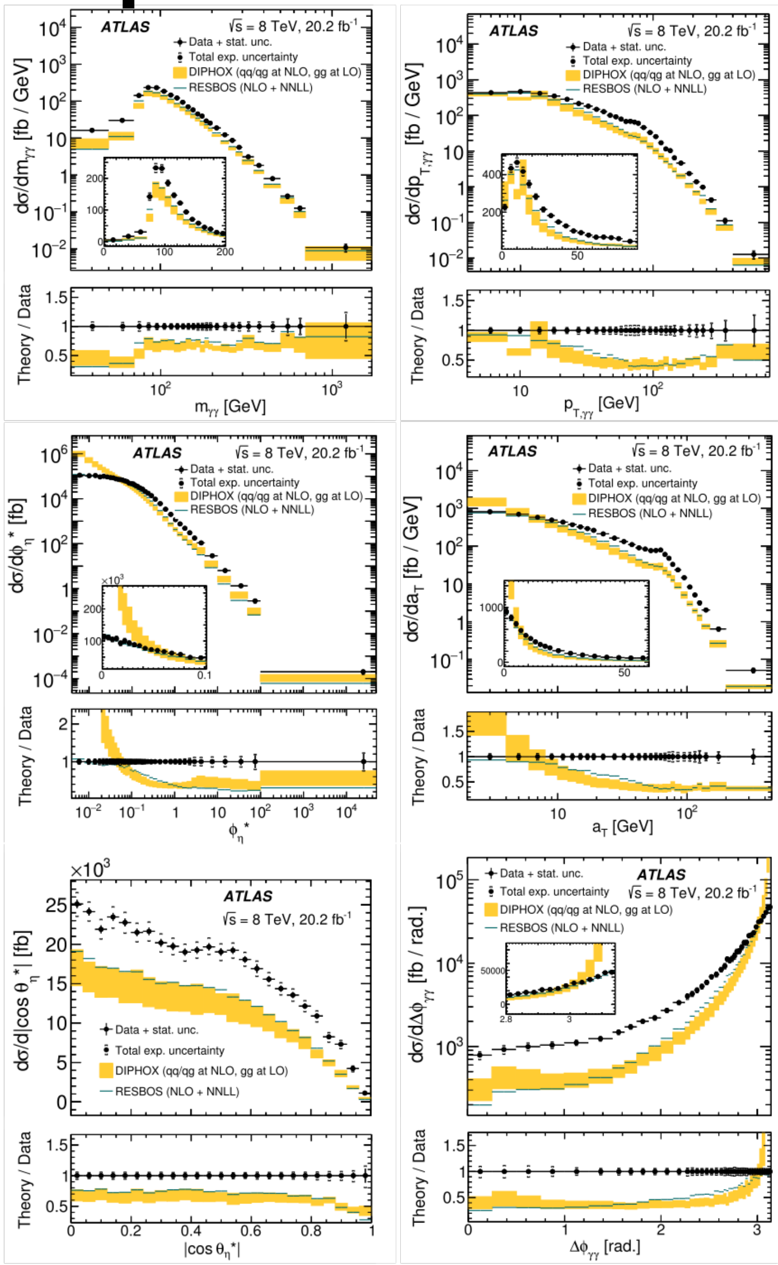
Eur. Phys. J. C (2014) 74:3129

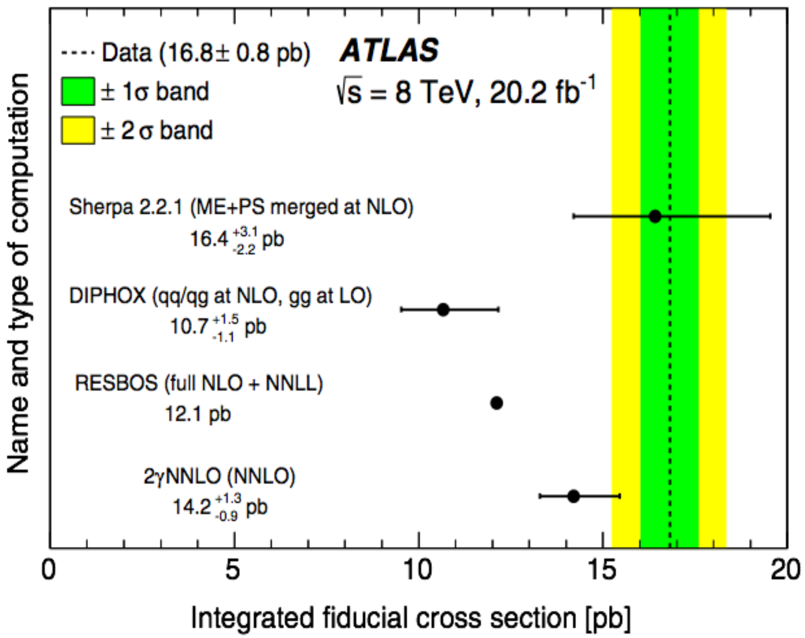


- The **2γNNLO and SHERPA predictions show an improved agreement** in shape with the data for the kinematic distributions **with respect to the DIPHOX + GAMMA2MC and RESBOS** predictions, **especially in the low $m_{\gamma\gamma}$, low $\Delta\varphi_{\gamma\gamma}$ regions, which are the most sensitive to higher-order corrections.**

Diphoton Production at 8 TeV : ATLAS

PHYSICAL REVIEW D 95, 112005 (2017)

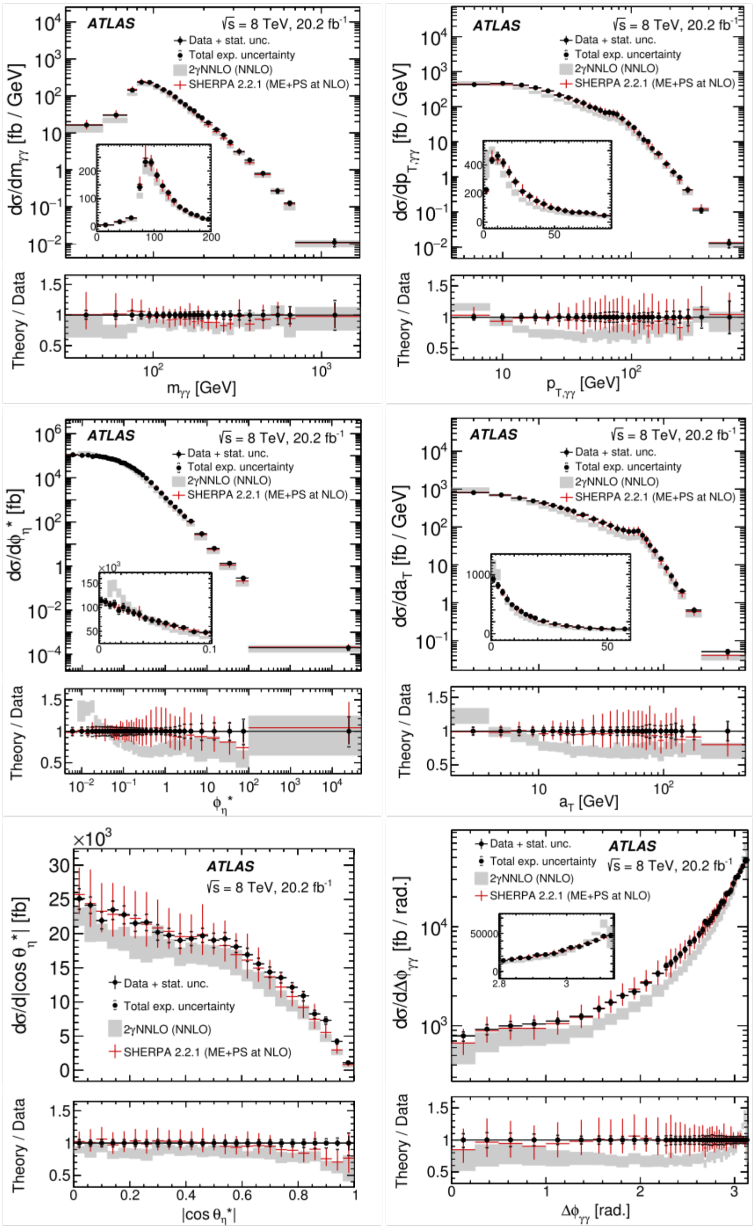




- The predictions of DIPHOX and RESBOS show significant deviations from the data for all variables under consideration.

Diphoton Production at 8 TeV : ATLAS

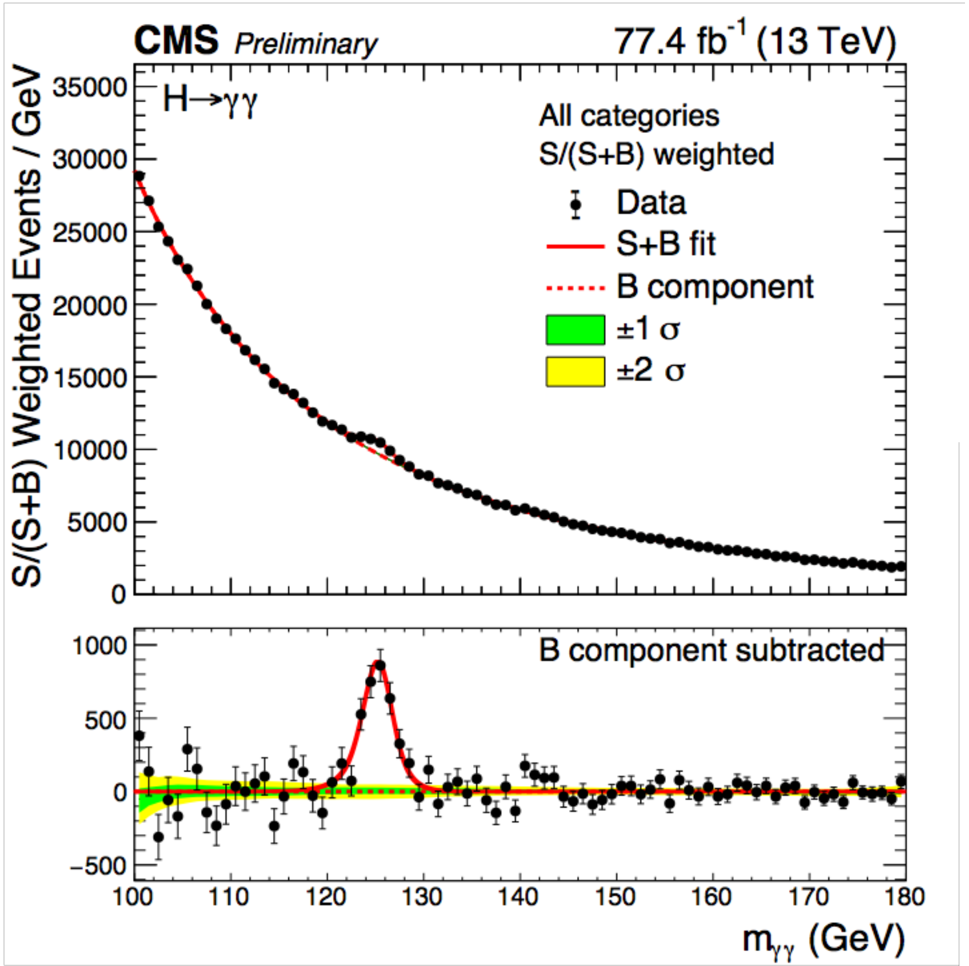
PHYSICAL REVIEW D 95, 112005 (2017)

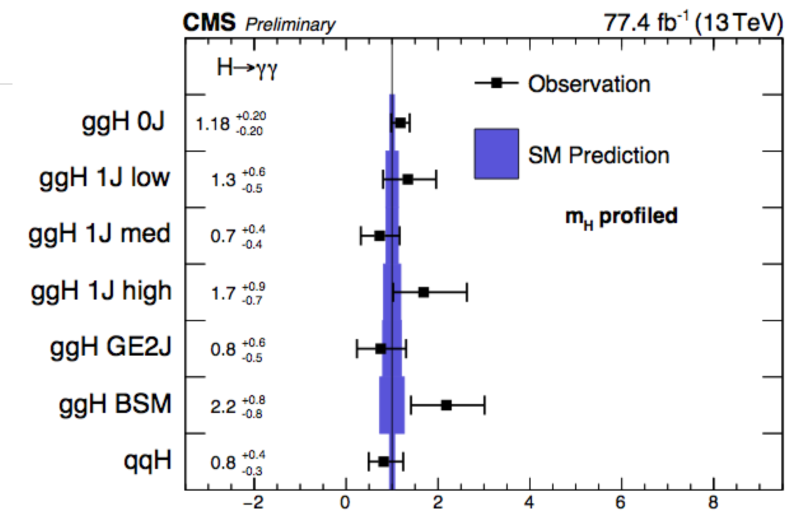


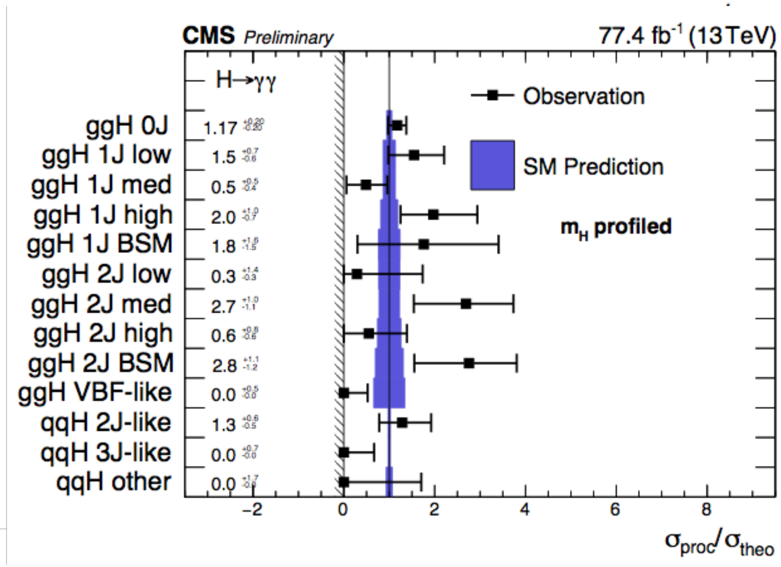
- The predictions of **a parton-level calculation of varying jet multiplicity up to NLO matched to a parton-shower algorithm in SHERPA 2.2.1 provide an improved description of the data.**

Resonant Diphoton Production : CMS

CMS PAS HIG-18-029



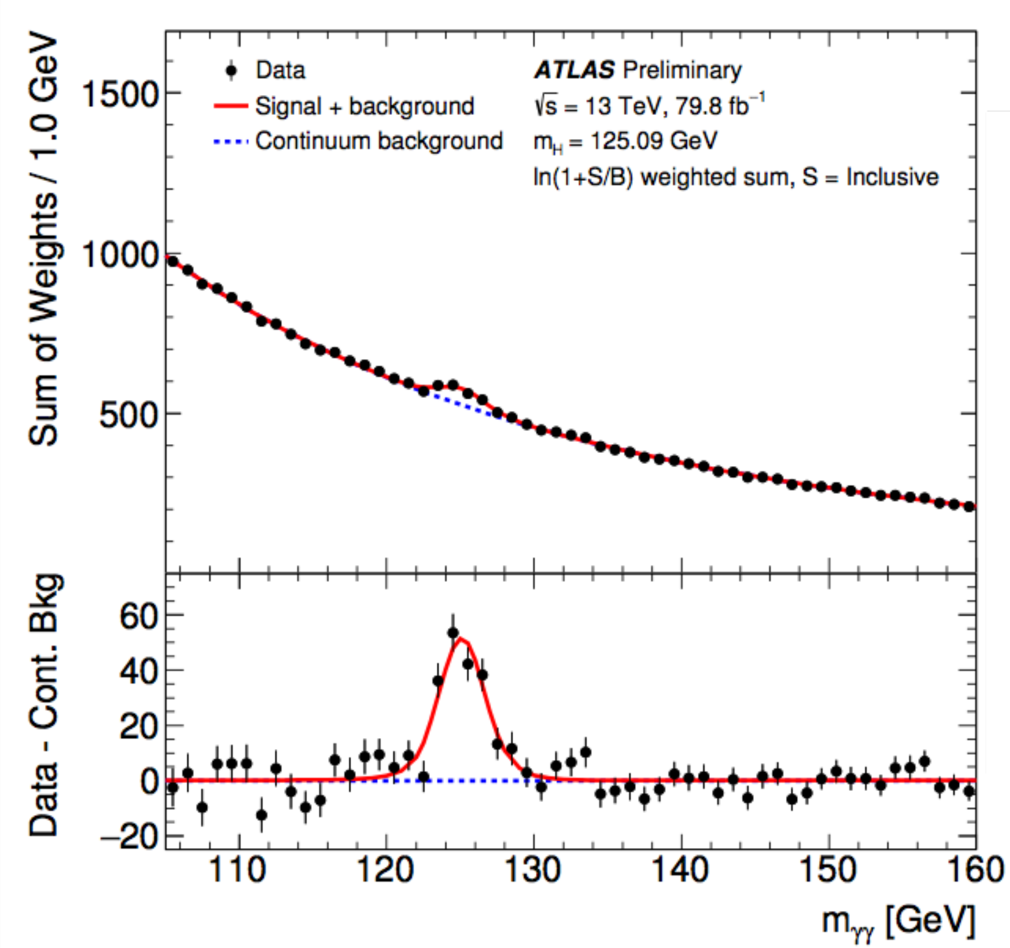


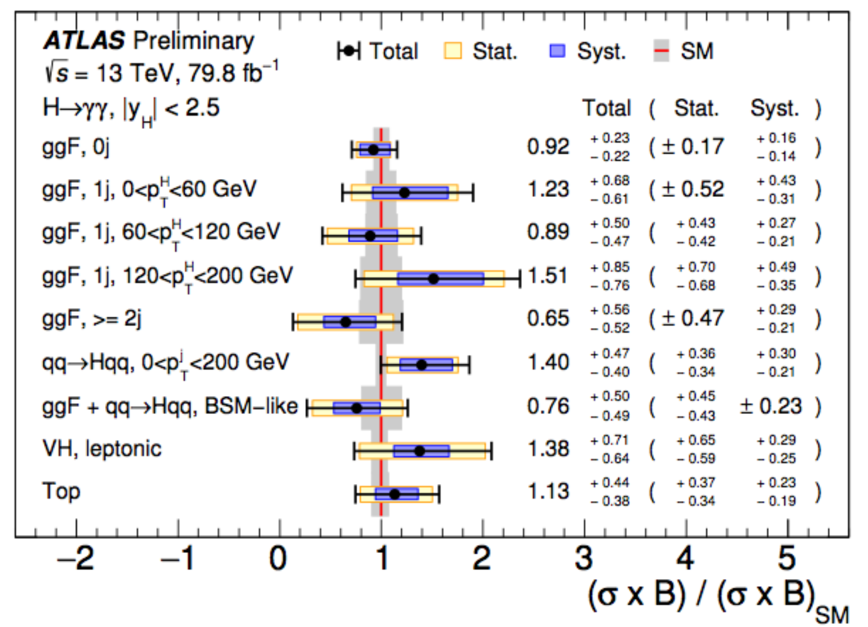


- **Photon “SM” measurement yielding major discoveries**

Resonant Diphoton Production : ATLAS

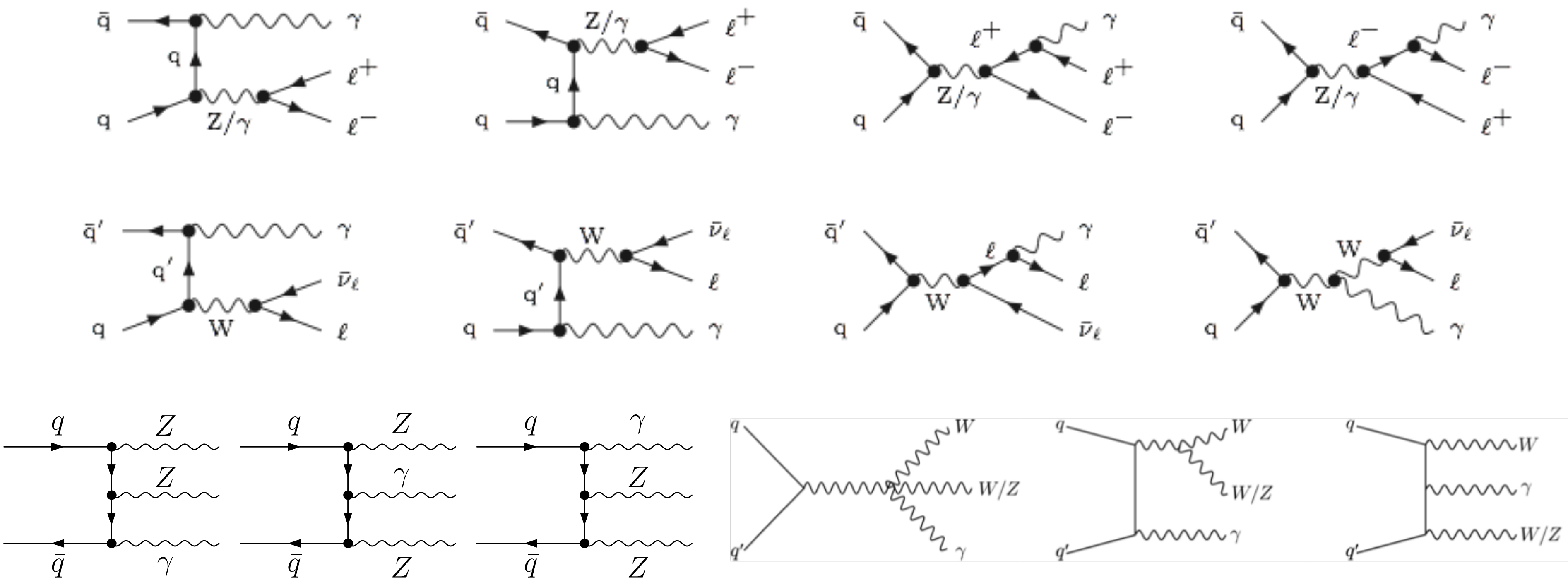
ATLAS-CONF-2018-028





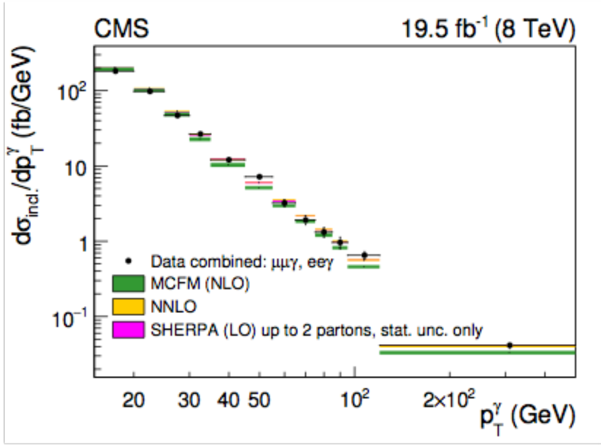
- **Photon “SM” measurement yielding major discoveries**

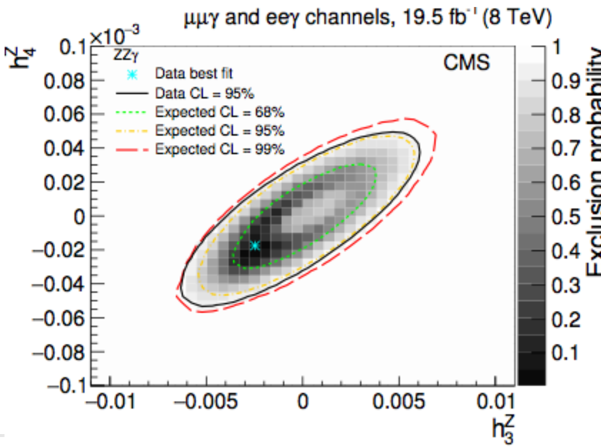
Diboson Production: Vγ , VVγ, Vγγ

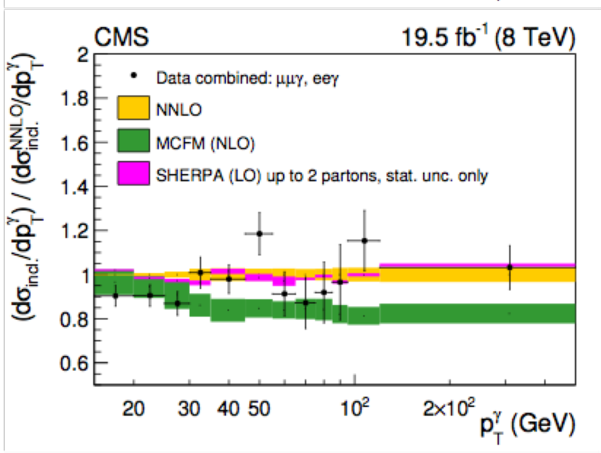


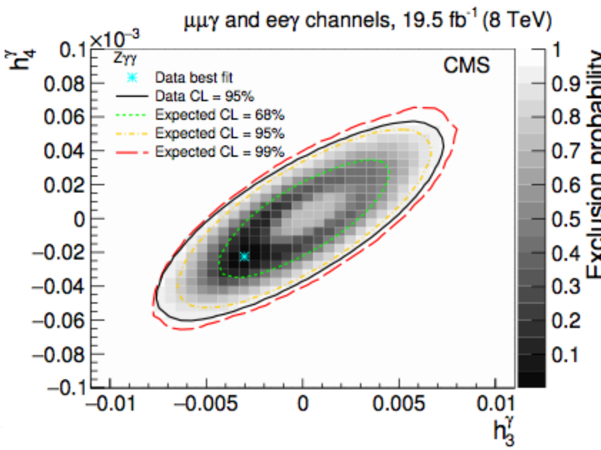
- **Test the electroweak sector** of the SM with high accuracy.
- **Probe the $SU(2)_L \times U(1)_Y$ gauge symmetry** that determines the **structure and self-couplings of the vector bosons**
- Search for **signs of new physics through anomalous triple and quartic gauge-boson coupling** (aTGC and aQGC)
- **Tune MCs** for main backgrounds in SM and BSM analyses.

Zγ @ 8 TeV : CMS







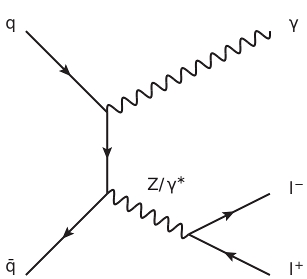


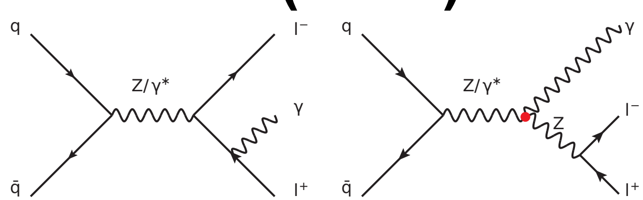
- At high pTs measurement well described **by the NNLO calculation and by the SHERPA prediction including up to two additional partons at matrix element level**,

- A clear excess is observed with respect to the MCFM (NLO) calculation. **This emphasizes the importance of NNLO QCD corrections for this measurement.**

- **Place limits on NP (aTGC)**

JHEP04 (2015) 164

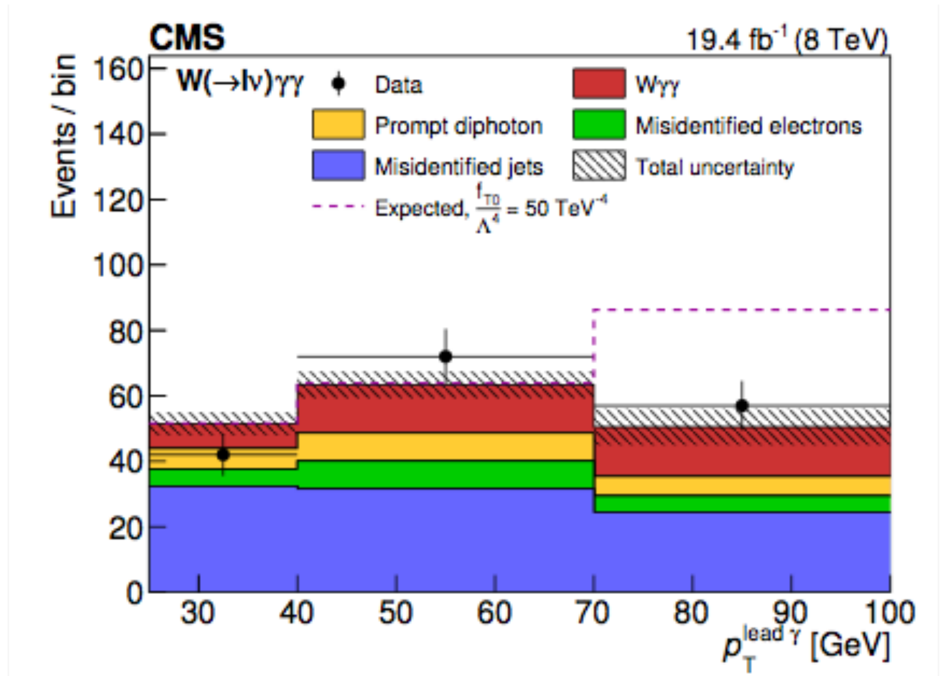




Wγγ - Zγγ @ 8 TeV : CMS

JHEP10(2017)072

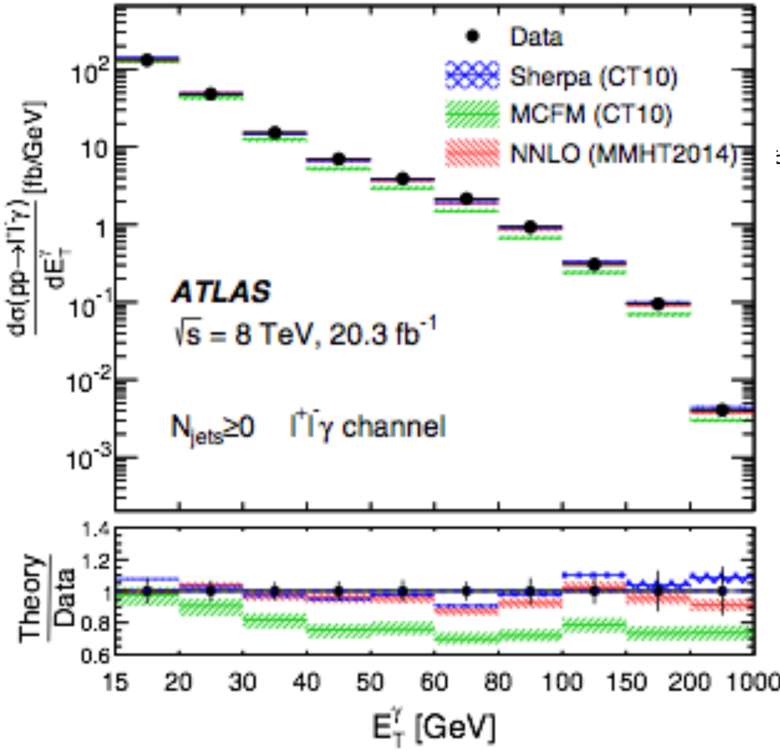
Channel	Measured fiducial cross section
$W\gamma\gamma \to e^{\pm}\nu\gamma\gamma$	$4.2 \pm 2.0\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$W\gamma\gamma \to \mu^{\pm}\nu\gamma\gamma$	$6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})$ fb
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	$4.9 \pm 1.4\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$Z\gamma\gamma \to e^{+}e^{-}\gamma\gamma$	$12.5 \pm 2.1\,(\text{stat}) \pm 2.1\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \mu^{+}\mu^{-}\gamma\gamma$	$12.8 \pm 1.8\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	$12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
Channel	**Prediction**
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	4.8 ± 0.5 fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	13.0 ± 1.5 fb

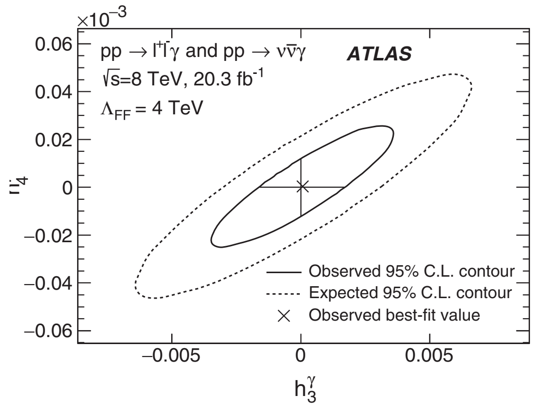


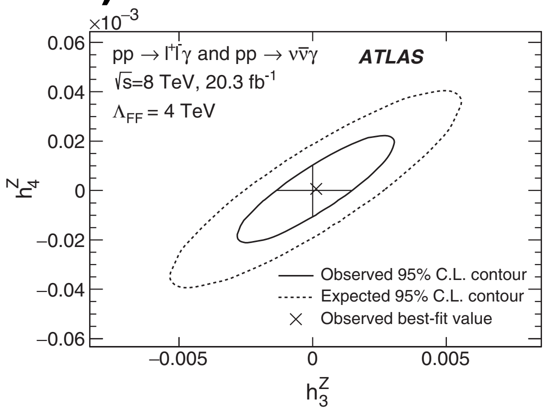
- **NLO calculations and observations agree.**
- **Stringent limits on NP (aQGC)**

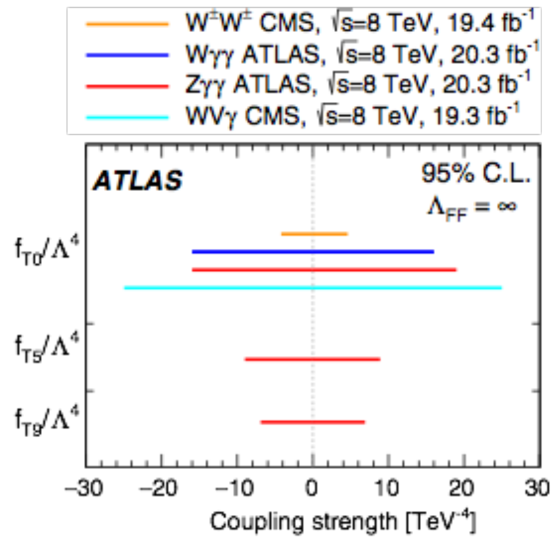
Zγ, Zγγ @8 TeV : ATLAS

PHYSICAL REVIEW D 93, 112002 (2016)





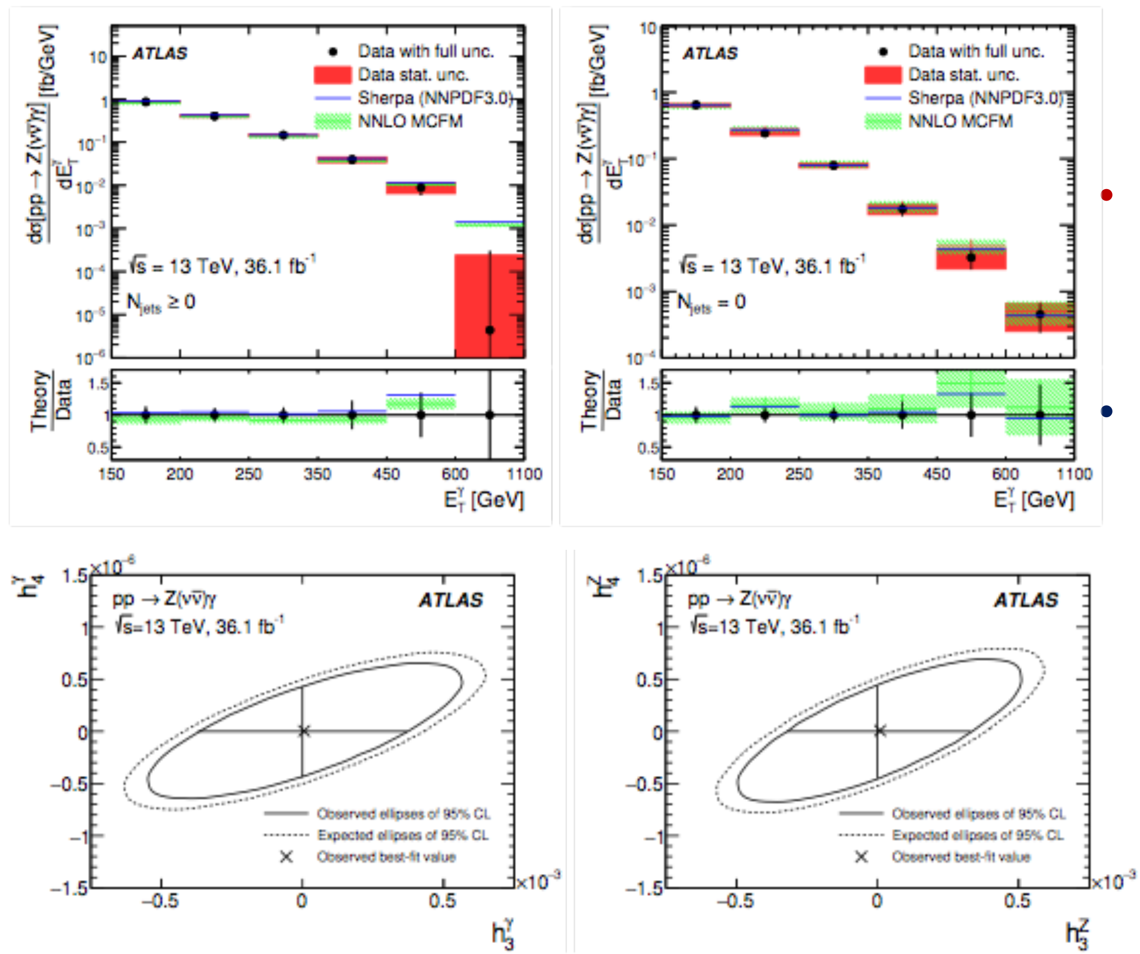




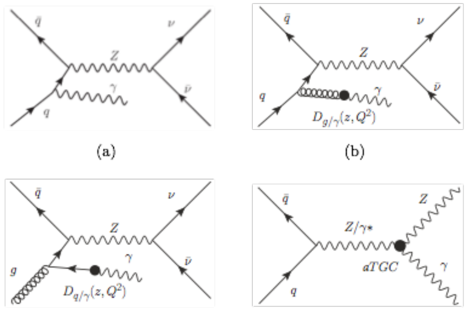
- Very **consistent** results with the ones obtained **with CMS, both in terms of the SM measurements**, and in **terms of searches for NP**

Z(νν)γ @13 TeV : ATLAS

JHEP12 (2018) 010



- **Z(νν)γ process is less contaminated with hadrons** by a large multijet background.
- A higher branching ratio of **Z→νν yields higher sensitivity to bosonic couplings.**
- This channel is **sensitive to anomalous neutrino dipole moments,** although a higher integrated luminosity would be required to improve over previous LEP results.

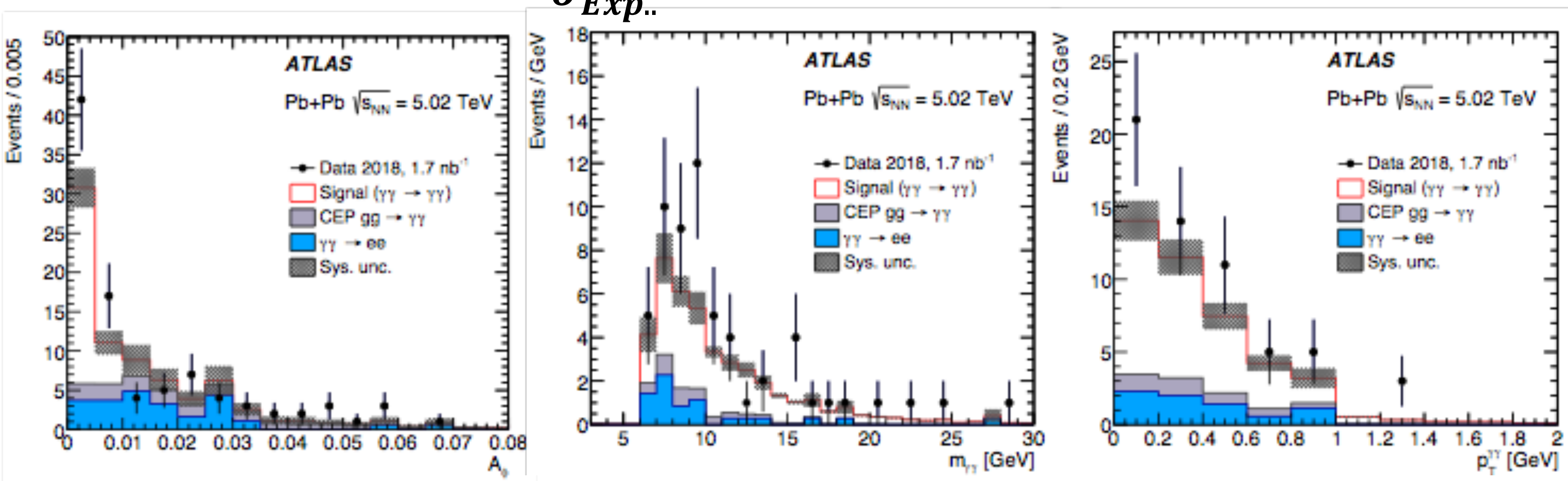


Results in agreement with the leptonic channels

Light by Light Scattering : ATLAS

arXiv:1904.03536v1

$$\frac{\sigma_{obs.}}{\sigma_{Exp..}} = 1.53 \pm 0.33$$



- Exclusive light-by-light scattering occurs at impact parameters larger than about twice the radius of the ions. **The strong interaction becomes less significant and the electromagnetic (EM) interaction becomes more important in these ultraperipheral collision (UPC) events.**

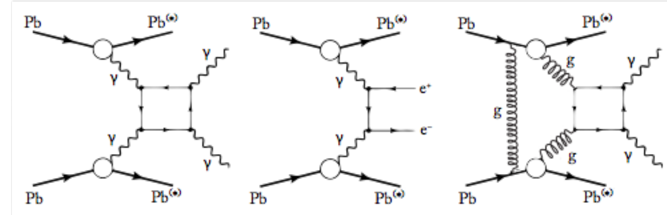
- **Light-by-light scattering**, γγ → γγ proceeds via virtual box diagrams involving electrically charged fermions (leptons and quarks) or W bosons, **at order α^4_{EM}**

- In various BSM models extra contributions are possible, making the measurement of **γγ → γγ scattering sensitive to new physics**

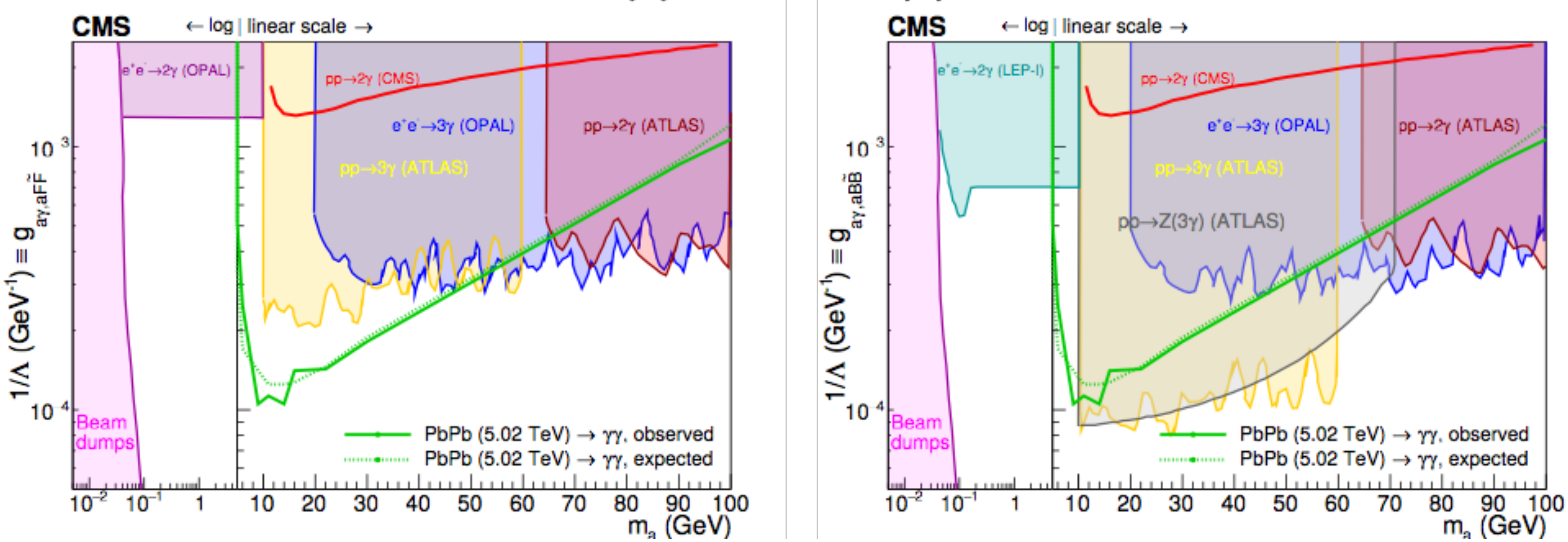
Light by Light Scattering : CMS

$$\sigma_{\rm fid}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46\,(\rm stat) \pm 28\,(\rm syst) \pm 4\,(\rm theo)\ nb,$$

$$\sigma_{\rm fid}(\gamma\gamma \to \gamma\gamma) = 138 \pm 14\,\rm nb.$$ **Theoretical**



$$\gamma\gamma \to a \to \gamma\gamma.$$



CMS-FSQ-16-012, CERN-EP-2018-271

- In various BSM models extra contributions are possible, making the measurement of **γγ → γγ scattering sensitive to new physics.**

- **CMS sets best limits on the production of a pseudoscalar-axion like particle.**

Photons and the Future : HL-LHC, HE-LHC

P. Giacommeli, P. Janot, A. Blondel & others

The Future Circular Colliders
CDR and cost review to appear Q4 2018 for ESU

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- *Ultimate goal:* ~16 T magnets
  100 TeV pp-collider (FCC-hh)

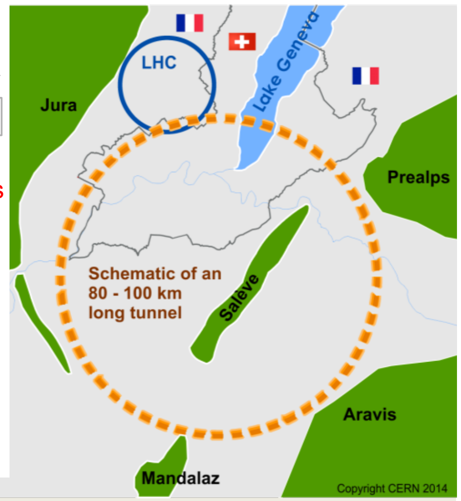
→ defining infrastructure requirements

Two possible first steps:

- e^+e^- collider (*FCC-ee*)
  High Lumi, E_{CM} =90-400 GeV
- *HE-LHC* 16T ⇒ 27 TeV
  in LEP/LHC tunnel

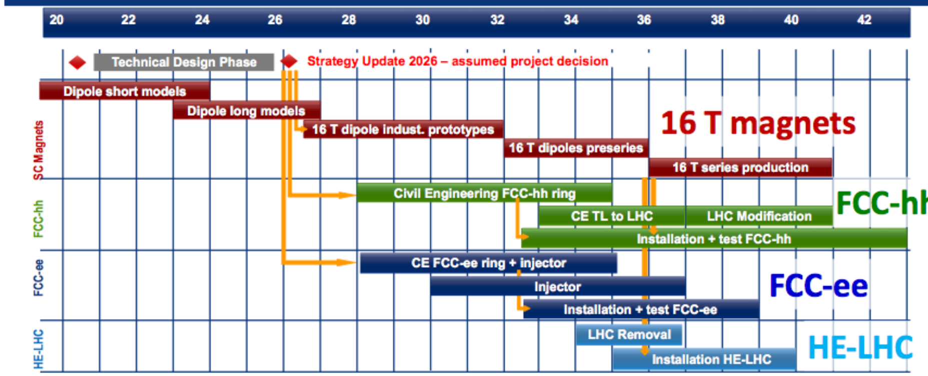
Possible addition:

- *p-e* (*FCC-he*) option



From European Strategy in 2013: "ambitious post-LHC accelerator project"
Study kicked-off in Geneva in Feb 2014

Technical Schedule for each of the 3 options



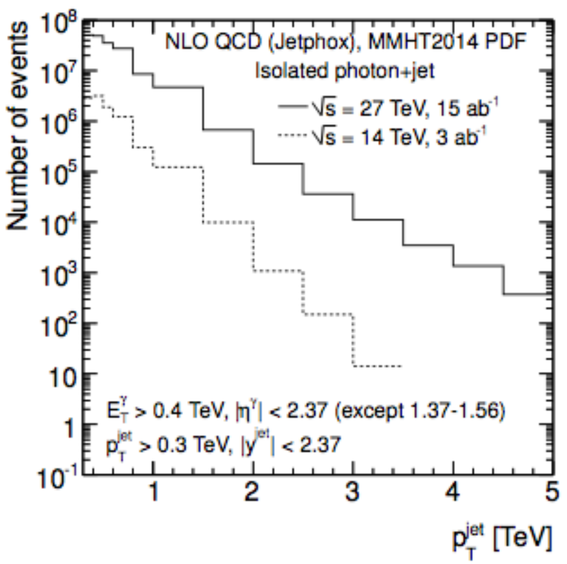
schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates
- FCC-ee: 2039
- FCC-hh: 2043
- HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)

- The high luminosity LHC is an approved upgrade of the LHC accelerator complex and the experiments.
- The HE-LHC is an option under discussion, going up to energies of 27 TeV at centre of mass.
- **There are many options for the future, including linear colliders, muon colliders …**

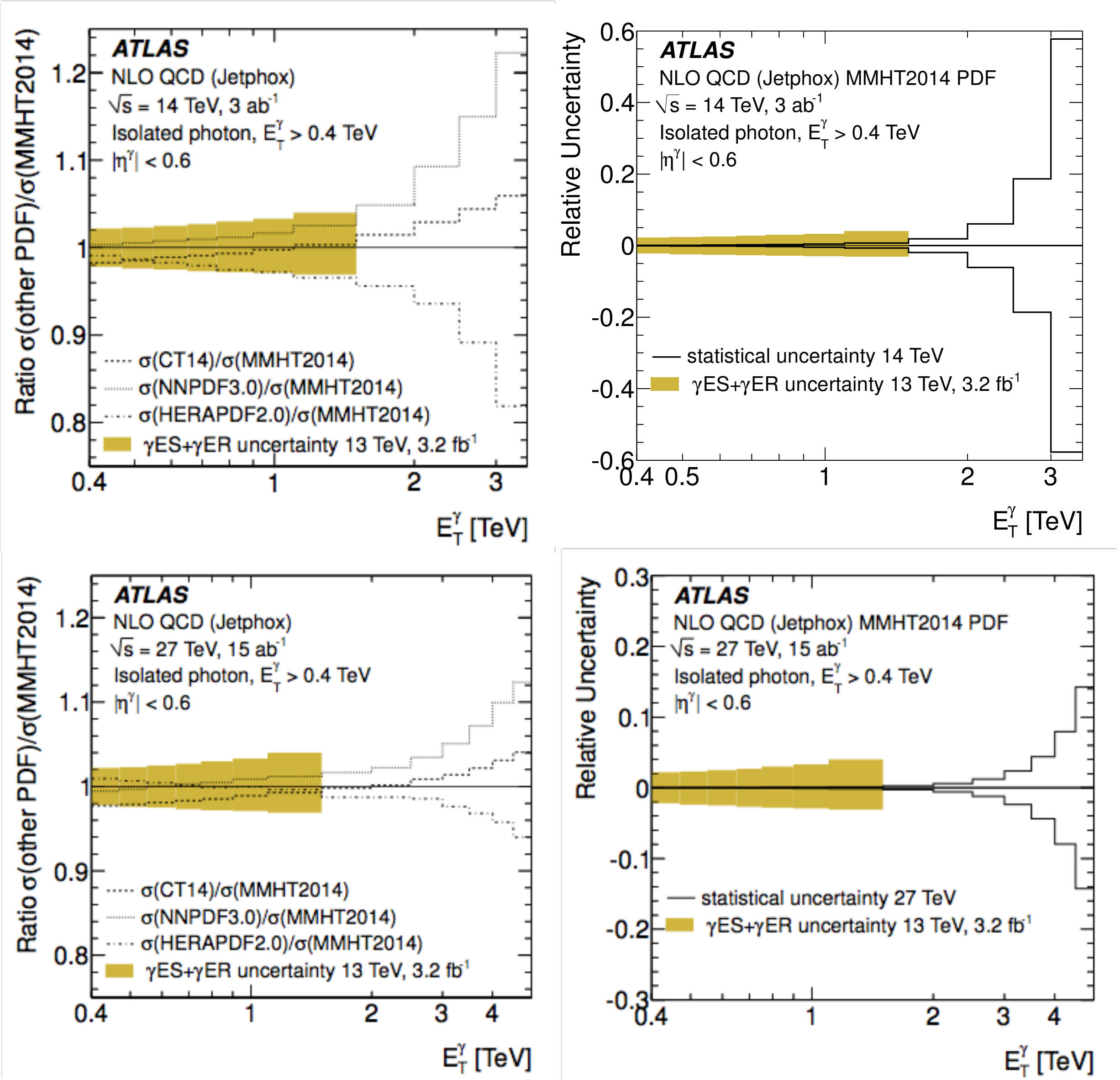
Photons and the Future : HL-LHC, HE-LHC

ATL-PHYS-PUB-2018-051

- **Significantly increase statistics and probe much higher energies!**

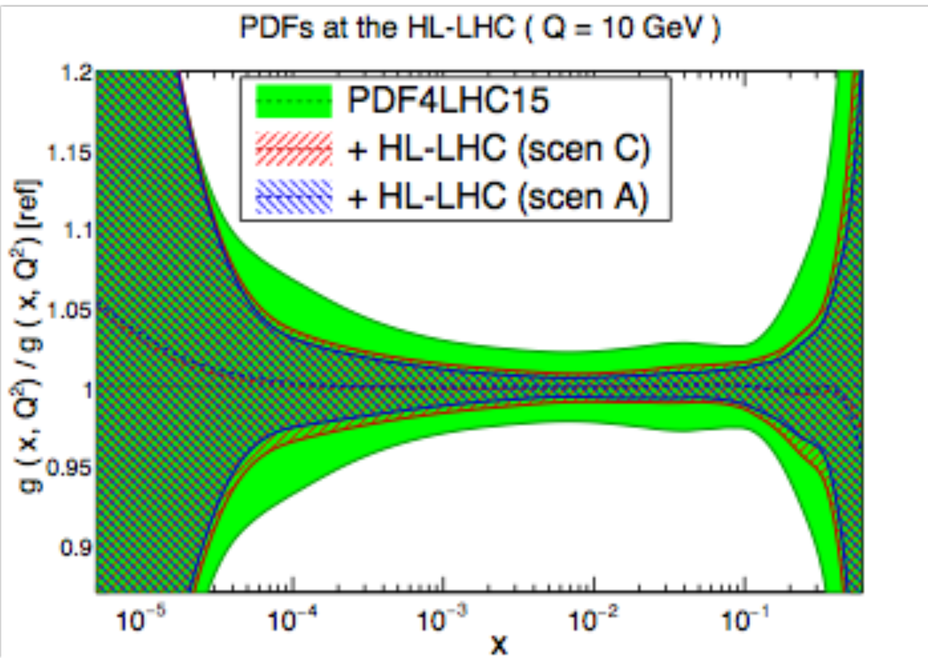


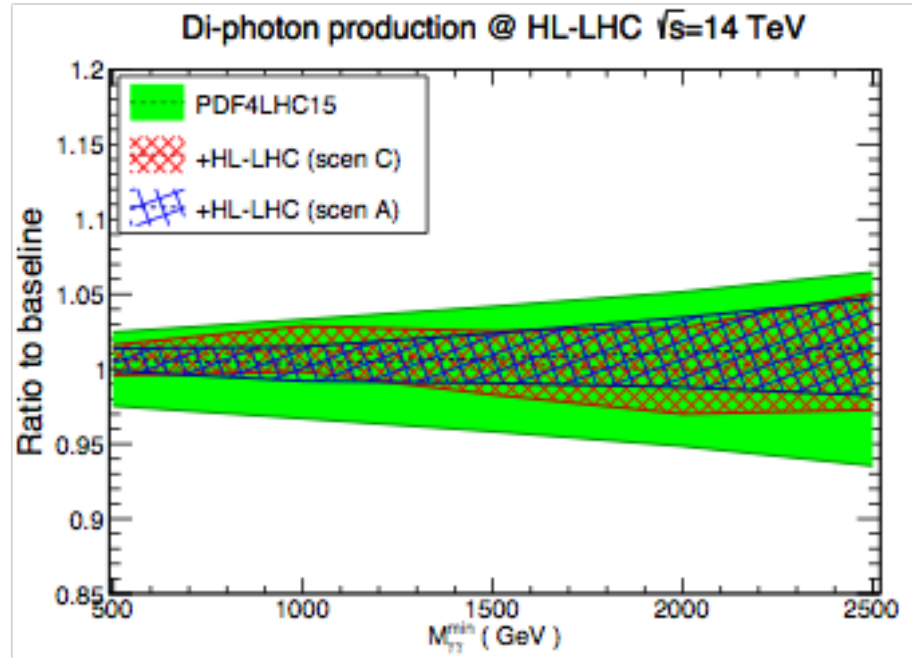
arXiv:1902.04070v2



Photons and the Future : HL-LHC, HE-LHC

arXiv:1902.04070v2





- Inclusive photon and photon+jet measurements **aid in decreasing gluon PDF uncertainties.**

- Diphoton production at higher energies **significantly benefits from reduced PDF uncertainties**

Summary - Conclusions

- Photons **are excellent probes of the EW and QCD sector of the SM.**

- Photon measurements **reduce main theoretical uncertainties for precision SM measurements and BSM searches.**

- Photon measurements **yielded a monumental discovery at the LHC, that of the Higgs Boson**

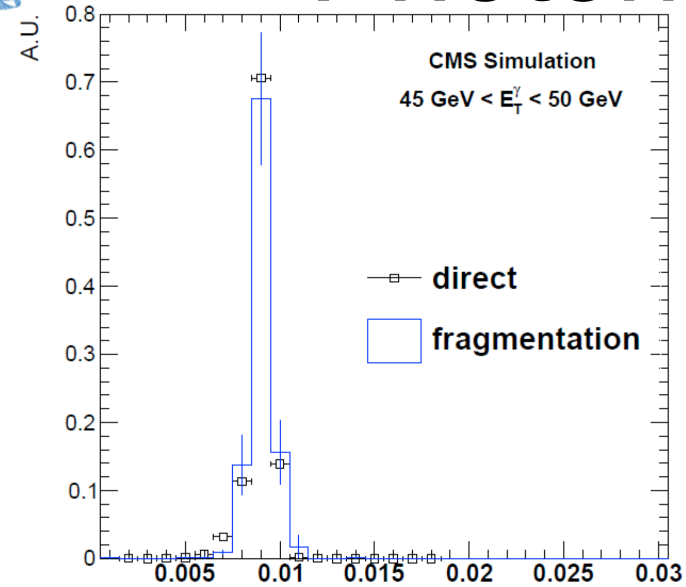
- Photon measurements **are also clean probes of BSM physics.**

Phos = Φως in Greek means "light" and "bright"

and the Photon Physics near and longer term future is Bright!

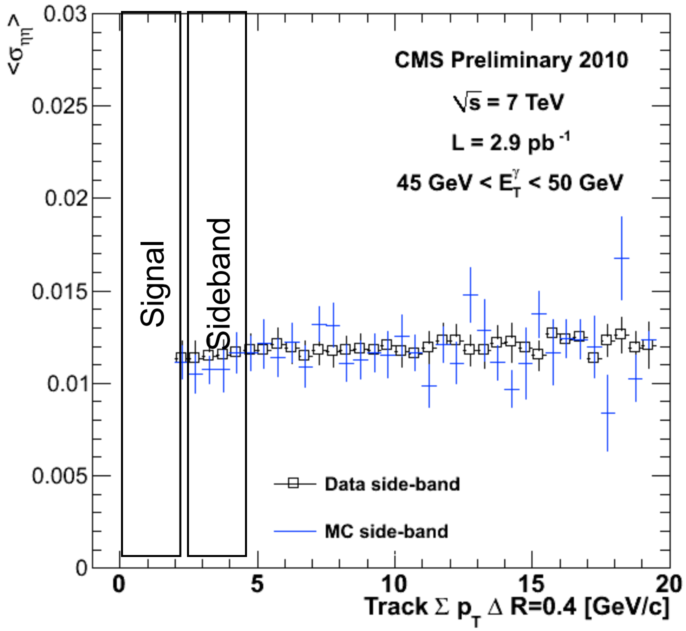
BACKUP

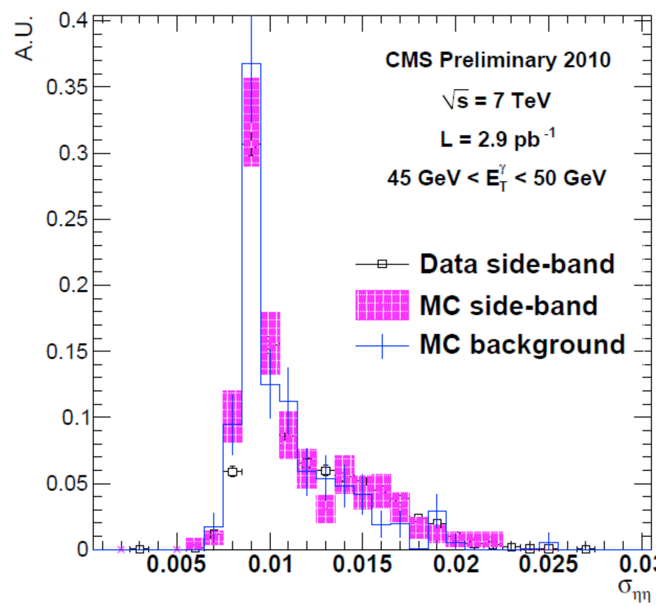
Photon Shower Shape



Signal shape : Pythia MC

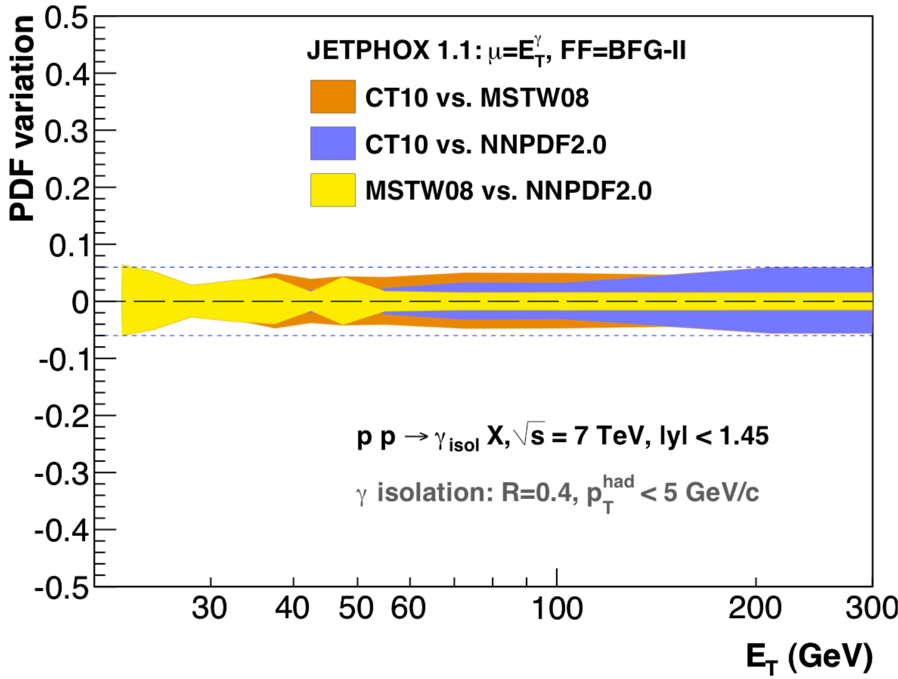
Background Shape: Track Isolation Sideband





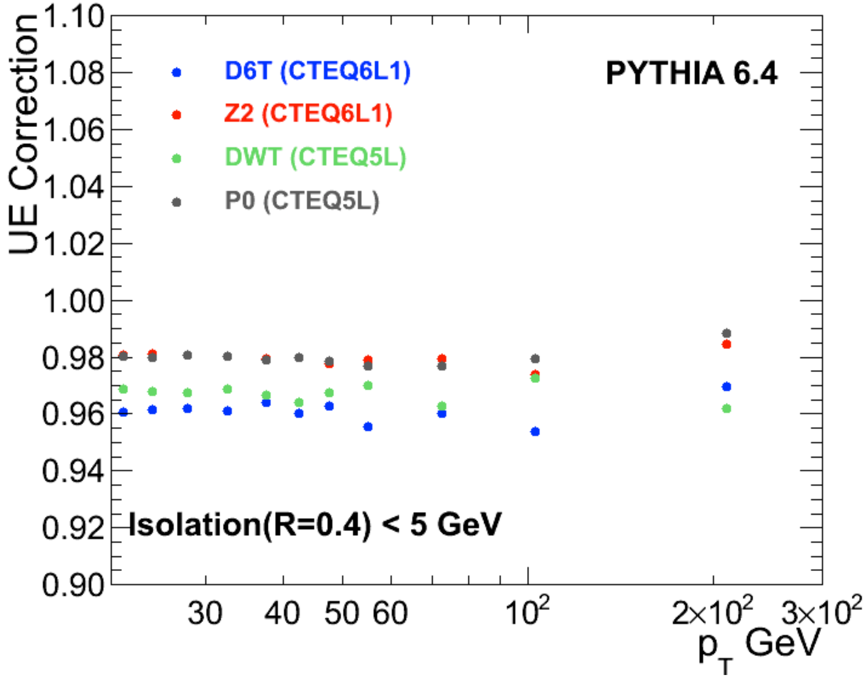
JetPhox Predictions

- NLO pQCD
  - JETPHOX1.1,CT10 PDFs, BFG II FF
  - Renormalization, fragmentation, and factorization scales set to ET
  - Require "isolated" definition: ΣET<5 GeV within R<0.4
- Scale uncertainty
  - 30 to 11% with ET, change all scales to ET/2 and 2ET
- PDF uncertainty
  - 6% over full ET range
- Envelope of CT10, MSTW08 and NNPDF2.0 (PDF4LHC recommendation)
- CTEQ6M instead of CT10: 3%
- BFG I instead of BFG II: <1%



Non Perturbative Corrections

- Non-perturbative effects increase energy in isolation cone
- Correction is obtained by comparing the efficiency of isolation cut of 5GeV in a cone of radius 0.4 with and without:
  - Multi-parton interaction
  - Hadronization
- Final correction is the mean of the four different tunes considered
  - D6T
  - Z2
  - DWT
  - P0
- ~3% overall correction applied to the NLO calculation

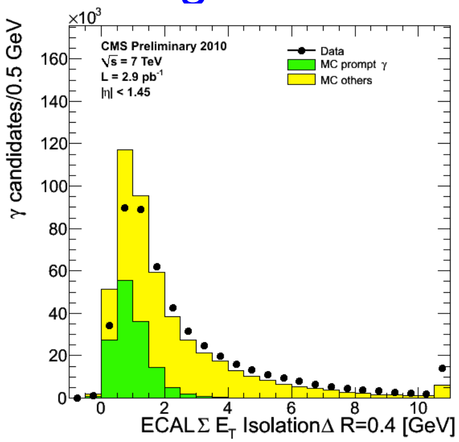


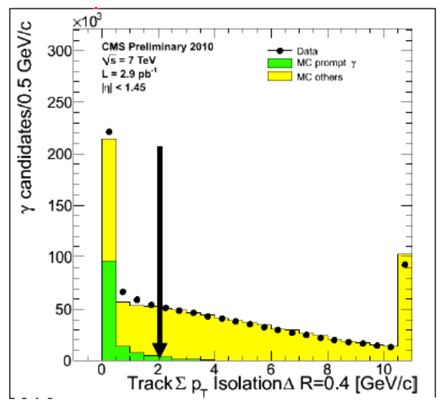
Photon Reconstruction

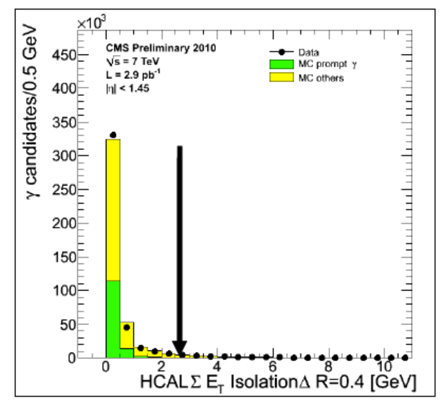
Photons are key objects for both calibration and major discoveries.

(H->γγ and BMS searches)

- Photons are isolated energy deposits in the ECAL, with no charged track pointing to them, and with a shape compatible with a photon electromagnetic Shower.





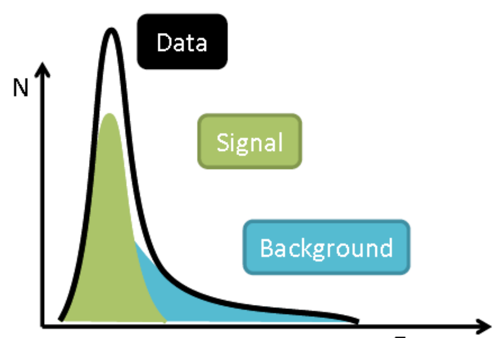


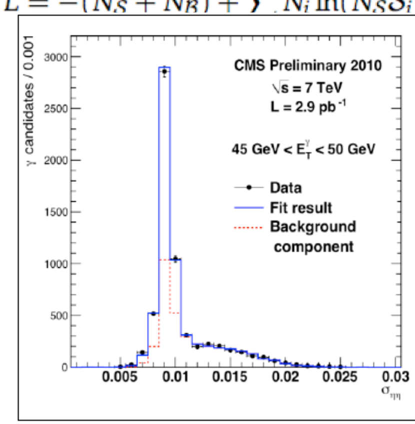
$$\mathcal{L} = -\ln L = -(N_S + N_B) + \sum^{n} N_i \ln(N_S \mathcal{S}_i + N_B \mathcal{B}_i)$$

Shower shape definition

$$\sigma_{i\eta i\eta}^{2} = \frac{\sum (\eta_i - \bar{\eta})^2 w_i}{w_i}, \quad \bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}$$

$$w_i = \max(0, 4.7 + \log(E_i / E_{5X5}))$$





Photon reconstruction & identification

ATLAS efficiency

E_T [GeV]	unconverted γ: $\varepsilon_{ID} \pm (\sum_i(\frac{1}{(\delta x_i)^2}))^{-\frac{1}{2}}$	unconverted γ: $\varepsilon_{ID}{}^{MC} \pm$ stat	unconverted γ: $\varepsilon_{ID}{}^{corrected\,MC} \pm$ stat	converted γ: $\varepsilon_{ID} \pm (\sum_i(\frac{1}{(\delta x_i)^2}))^{-\frac{1}{2}}$	converted γ: $\varepsilon_{ID}{}^{MC} \pm$ stat	converted γ: $\varepsilon_{ID}{}^{corrected\,MC} \pm$ stat
$0 \le \lvert\eta\rvert < 0.6$						
20–25	0.597 ± 0.021	0.621 ± 0.001	0.613 ± 0.001	0.648 ± 0.024	0.667 ± 0.002	0.679 ± 0.002
25–30	0.689 ± 0.025	0.697 ± 0.002	0.686 ± 0.002	0.733 ± 0.035	0.761 ± 0.003	0.759 ± 0.003
30–35	0.769 ± 0.024	0.756 ± 0.002	0.746 ± 0.002	0.777 ± 0.033	0.821 ± 0.004	0.818 ± 0.004
35–40	0.792 ± 0.023	0.793 ± 0.003	0.784 ± 0.003	0.820 ± 0.025	0.851 ± 0.005	0.849 ± 0.005
40–45	0.816 ± 0.026	0.822 ± 0.004	0.806 ± 0.004	0.893 ± 0.049	0.886 ± 0.006	0.882 ± 0.006
45–50	0.847 ± 0.022	0.846 ± 0.001	0.835 ± 0.001	0.911 ± 0.036	0.899 ± 0.002	0.896 ± 0.002
50–60	0.874 ± 0.018	0.864 ± 0.001	0.856 ± 0.001	0.930 ± 0.029	0.923 ± 0.002	0.919 ± 0.002
60–80	0.902 ± 0.013	0.889 ± 0.001	0.883 ± 0.001	0.956 ± 0.027	0.939 ± 0.002	0.936 ± 0.002
80–100	0.918 ± 0.008	0.908 ± 0.001	0.905 ± 0.001	0.962 ± 0.030	0.956 ± 0.001	0.955 ± 0.001
100–125	0.926 ± 0.005	0.914 ± 0.001	0.912 ± 0.001	0.969 ± 0.023	0.962 ± 0.001	0.961 ± 0.001
125–150	0.934 ± 0.006	0.918 ± 0.001	0.917 ± 0.002	0.977 ± 0.023	0.969 ± 0.001	0.968 ± 0.002
150–175	0.930 ± 0.008	0.920 ± 0.001	0.918 ± 0.001	0.985 ± 0.017	0.971 ± 0.001	0.970 ± 0.001
175–250	0.933 ± 0.008	0.918 ± 0.001	0.917 ± 0.001	0.987 ± 0.016	0.971 ± 0.001	0.971 ± 0.001

ECAL Barrel ($\lvert\eta\rvert < 1.4442$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	84.18 ± 0.20%	86.73 ± 1.69%	1.032 ± 0.003
35 - 45	87.27 ± 0.19%	89.28 ± 1.27%	1.025 ± 0.004
45 - inf	88.50 ± 0.23%	89.04 ± 1.83%	1.005 ± 0.005
TOT	86.30 ± 0.12%	88.41 ± 0.89%	1.012 ± 0.002

ECAL Barrel ($\lvert\eta\rvert < 1.4442$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	69.38 ± 0.18%	69.58 ± 2.80%	1.060 ± 0.004
35 - 45	72.78 ± 0.18%	71.94 ± 2.09%	1.047 ± 0.007
45 - inf	74.93 ± 0.22%	72.48 ± 2.92%	0.995 ± 0.008
TOT	71.90 ± 0.11%	71.31 ± 1.47%	1.028 ± 0.003

ECAL Endcap ($1.566 < \lvert\eta\rvert < 2.5$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	87.40 ± 0.25%	92.24 ± 2.70%	1.035 ± 0.003
35 - 45	91.33 ± 0.22%	91.43 ± 2.43%	1.008 ± 0.005
45 - inf	92.55 ± 0.26%	91.06 ± 3.23%	1.013 ± 0.005
TOT	90.05 ± 0.14%	91.59 ± 1.60%	1.009 ± 0.002

ECAL Endcap ($1.566 < \lvert\eta\rvert < 2.5$)

ET	MC	DATA	MC Ratio γ/e
20 - 35	71.30 ± 0.28%	71.07 ± 3.94%	1.074 ± 0.006
35 - 45	77.63 ± 0.24%	75.19 ± 3.34%	1.028 ± 0.008
45 - inf	80.87 ± 0.31%	73.48 ± 4.98%	1.006 ± 0.009
TOT	75.85 ± 0.15%	73.31 ± 2.31%	1.019 ± 0.004

CMS Purity