Maxime Gouzevitch

Photons production at the LHC including Higgs

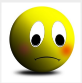
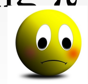
On behalf of CMS and ATLAS collaborations

DIS 2014 workshop

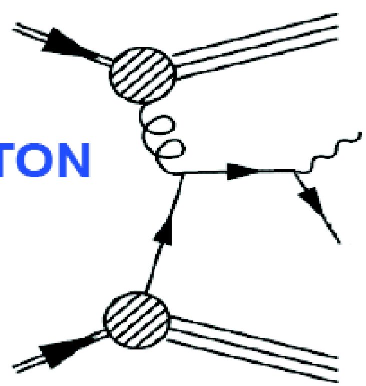
1) Photon physics in hadron colliders
2) Single photon production
3) Diphoton production
4) Higgs decay to two photons
5) Searches in multi Higgs production

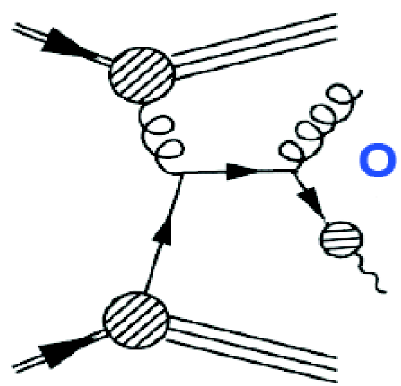
Photon physics in hadron colliders

1.1) Specificities of the photon program in hadron colliders

- Photons: witness of contribution of charged particles (quarks) to the QCD interactions.
- Appears at first glance to be very precise and appealing tools for QCD precise studies.
- In fact things are complicated since photons are massless:
  - Prompt photons: produced in large angle EM radiation by a quark. 
  - Fragmentation: HO effects - collinear singularities parametrized by fragmentation functions similar to proton PDF (from LEP). 
  - "Fakes": Jets hadronizing with leading π^0/ρ produces pairs of photons after EM decay with small opening angle.  
- Theory: pQCD photons are considered Prompt + Fragmentation
- Experimentally: "Fake" contribution have to be subtracted

COMPTON





ONE FRAG

1.2) Stairway to hell

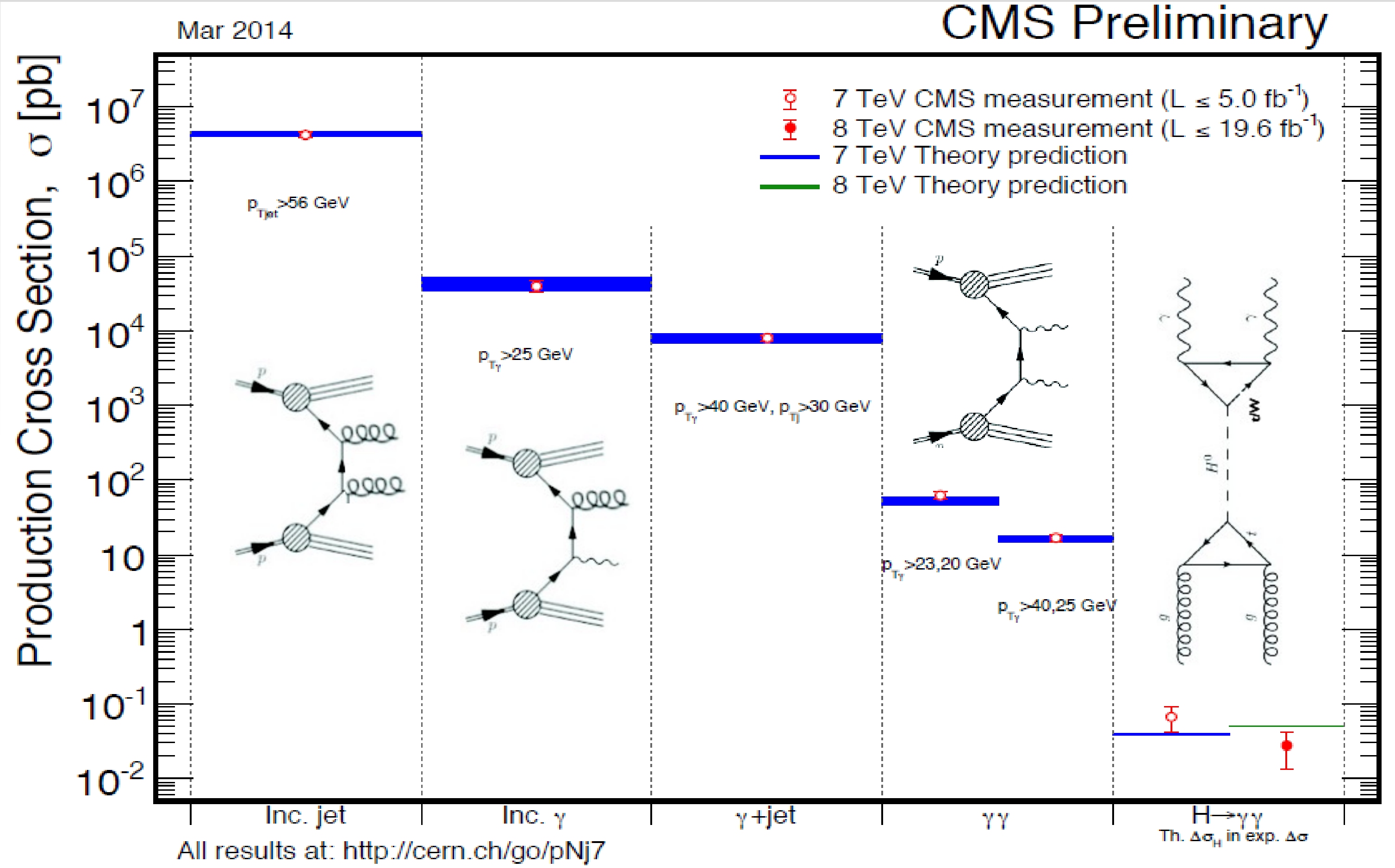
~100.000/sec

~1000/sec

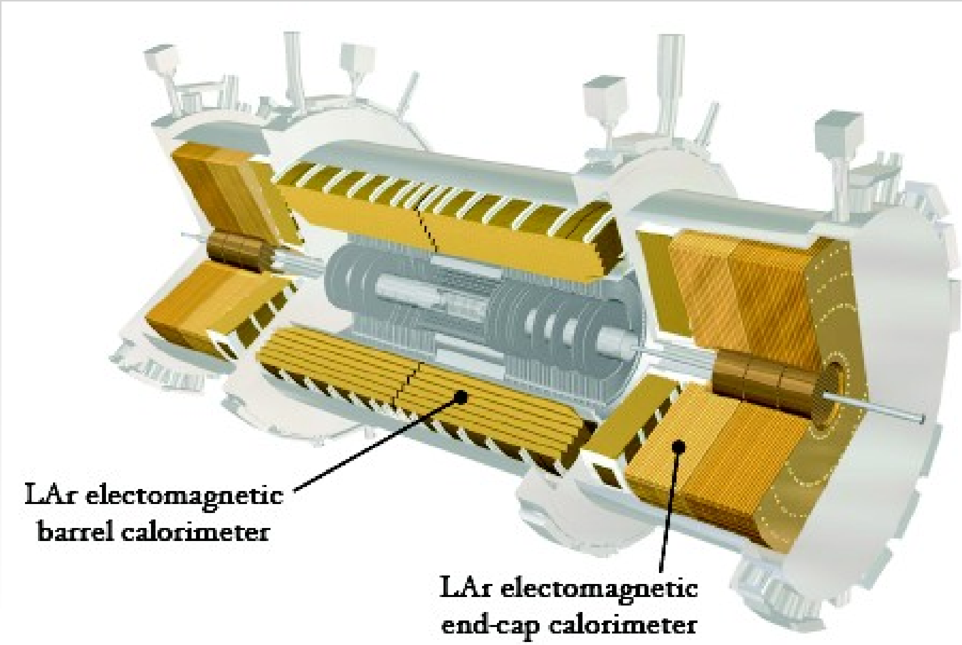
~100/sec

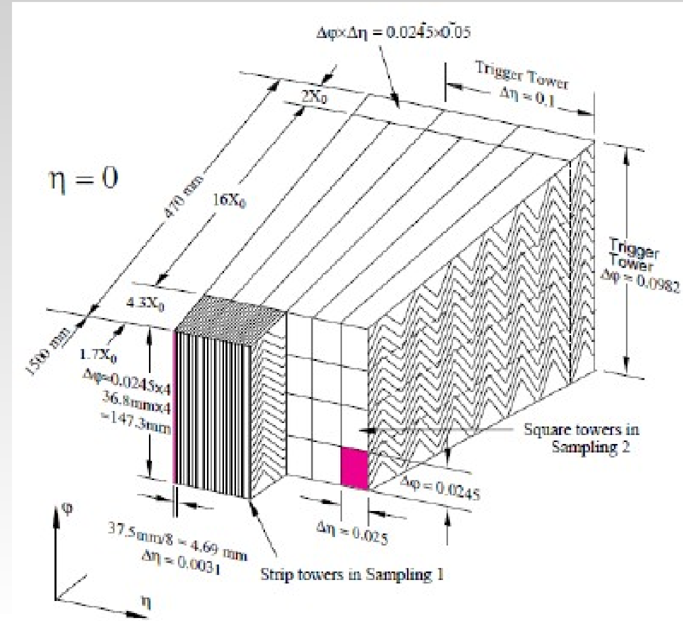
~1/sec

~1/hour

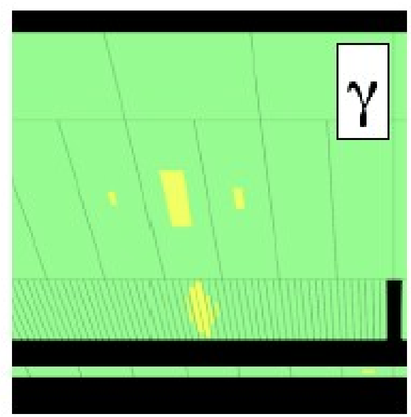


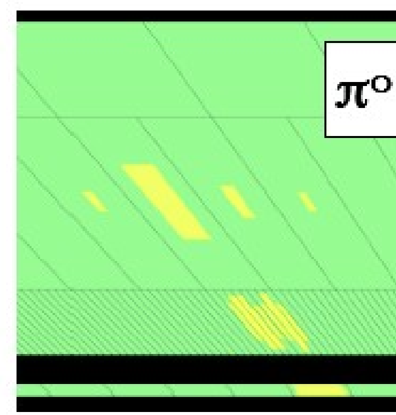
1.3) Photons setup in ATLAS





- Longitudinal segmentation:
  - PS: energy loss before ECAL
  - 1 layer: fine granularity << MR
    π^0/γ separation
  - 2 layer: coarser granularity ~ MR
    main energy deposit
  - 3 layer: high energy leakage
- Cluster made of combination of 3 layers.
  - Can be used for vertex pointing.

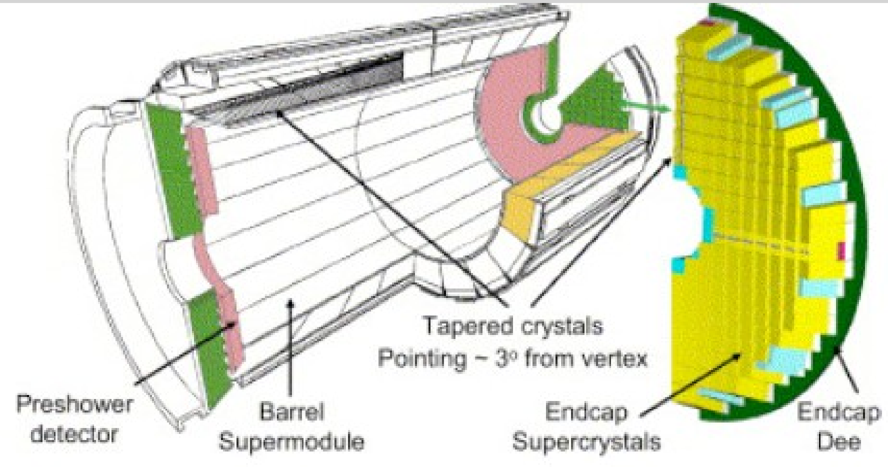


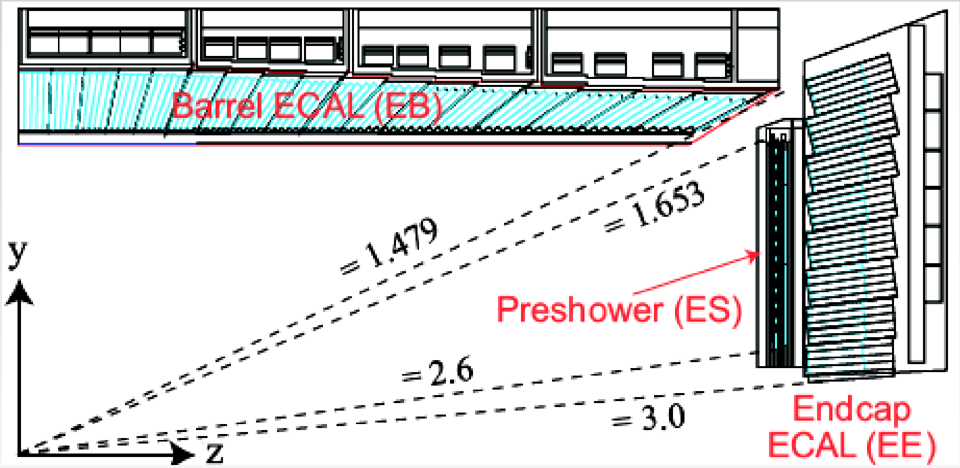


$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus c$$

a ~ 10-17%
c ~ 0.7%

1.4) Photons setup in CMS



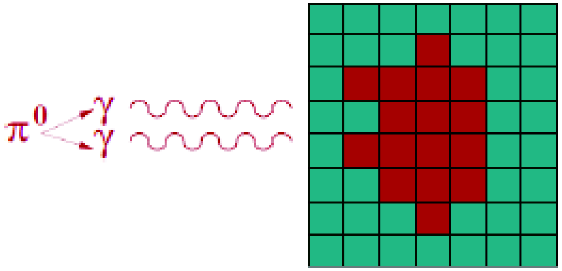


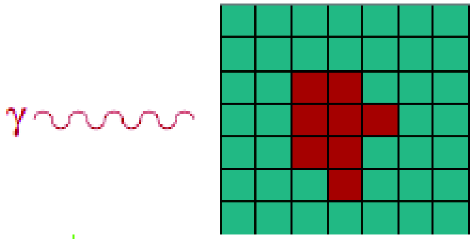
- No longitudinal segmentation:
  - Granularity ~ MR
- Pointing crystals
- Excellent energy resolution and linearity

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus \frac{b}{E(GeV)} \oplus c$$

a = 2.8%
b = 12%
c = 0.3%

- PS in Endcaps.
- Dense tracker in front of ECAL

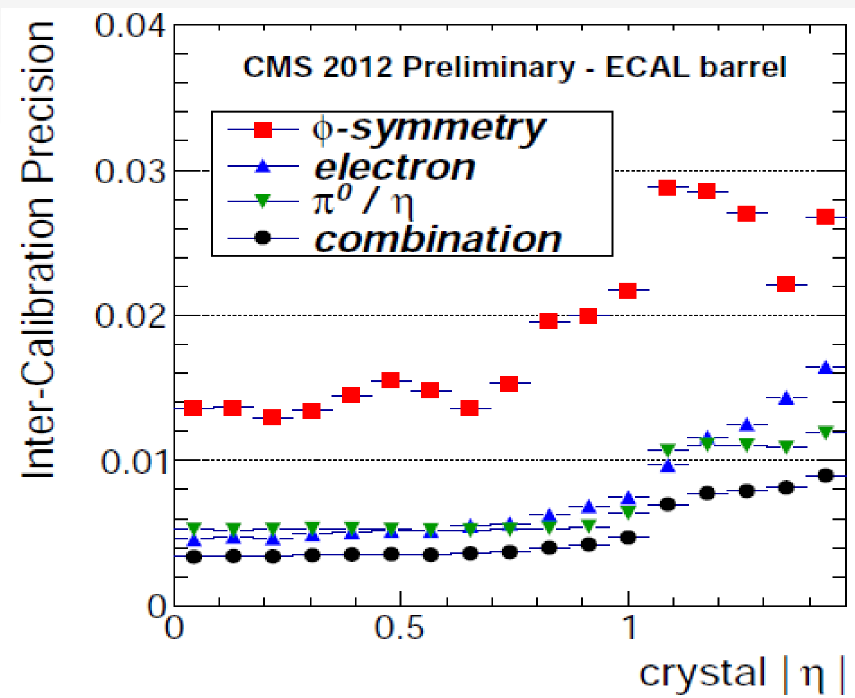


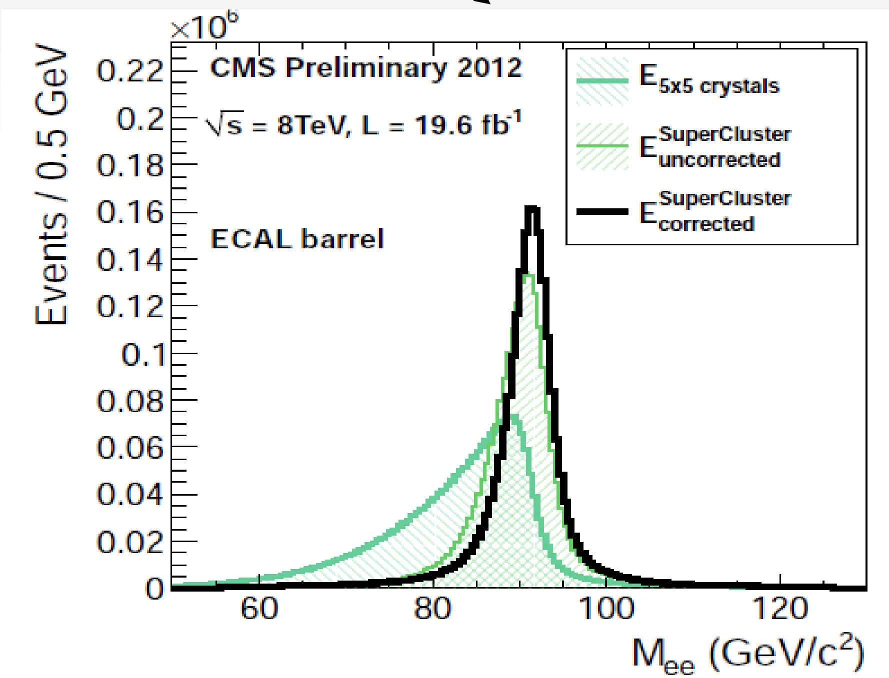


1.5) Photons calibration: example of CMS

CMS-DP-2013/007

Laser Manitoring → Crystal Intercalibration → Cluster Energy correction (MC): Regression → Absolute energy scale ($Z \to ee$)

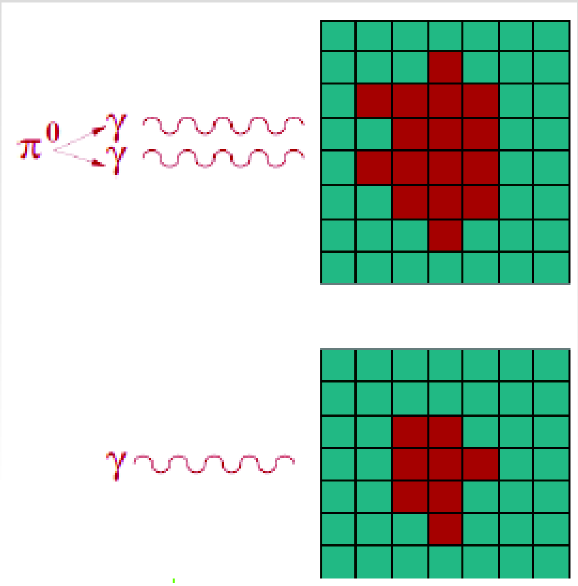


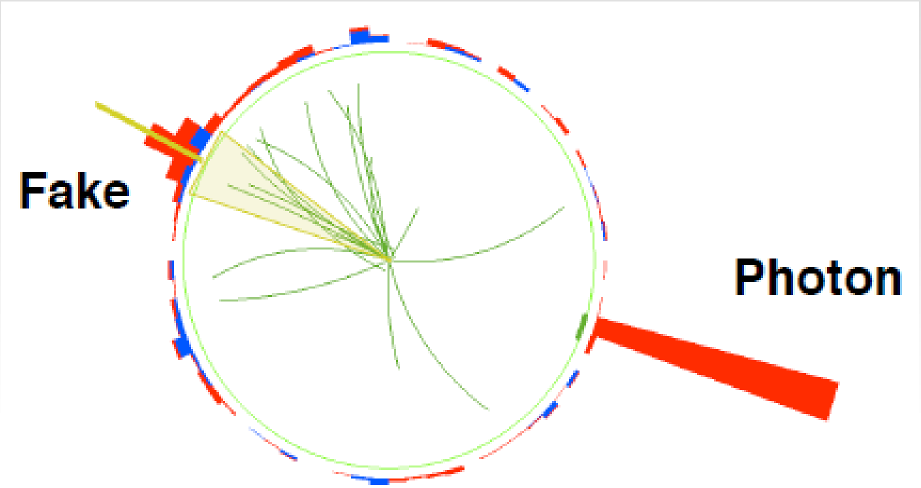


1.6) Photons signal extraction in a nut-shell

Shower shape

Isolation

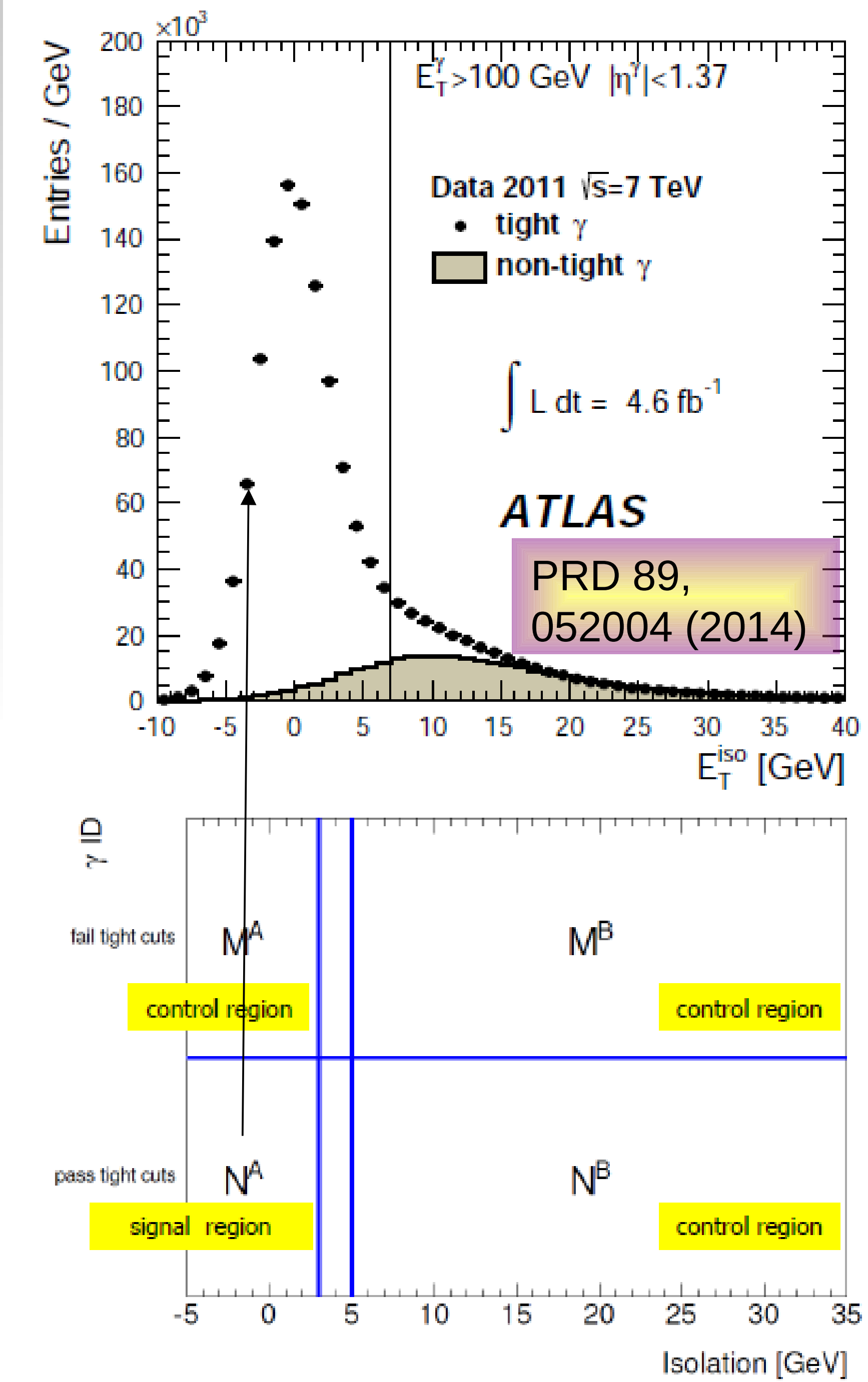




- To separate prompt/frag photon from "fake" photon we can play with 2 almost independent variables:
  - Shower shape: *peaky* for prompt and *double humpy* for fake.
  - Isolation: *low activity* around prompt and *dense activity* around fake
- CMS/ATLAS uses similar ABCD method for template building and prompt/frag signal extraction.

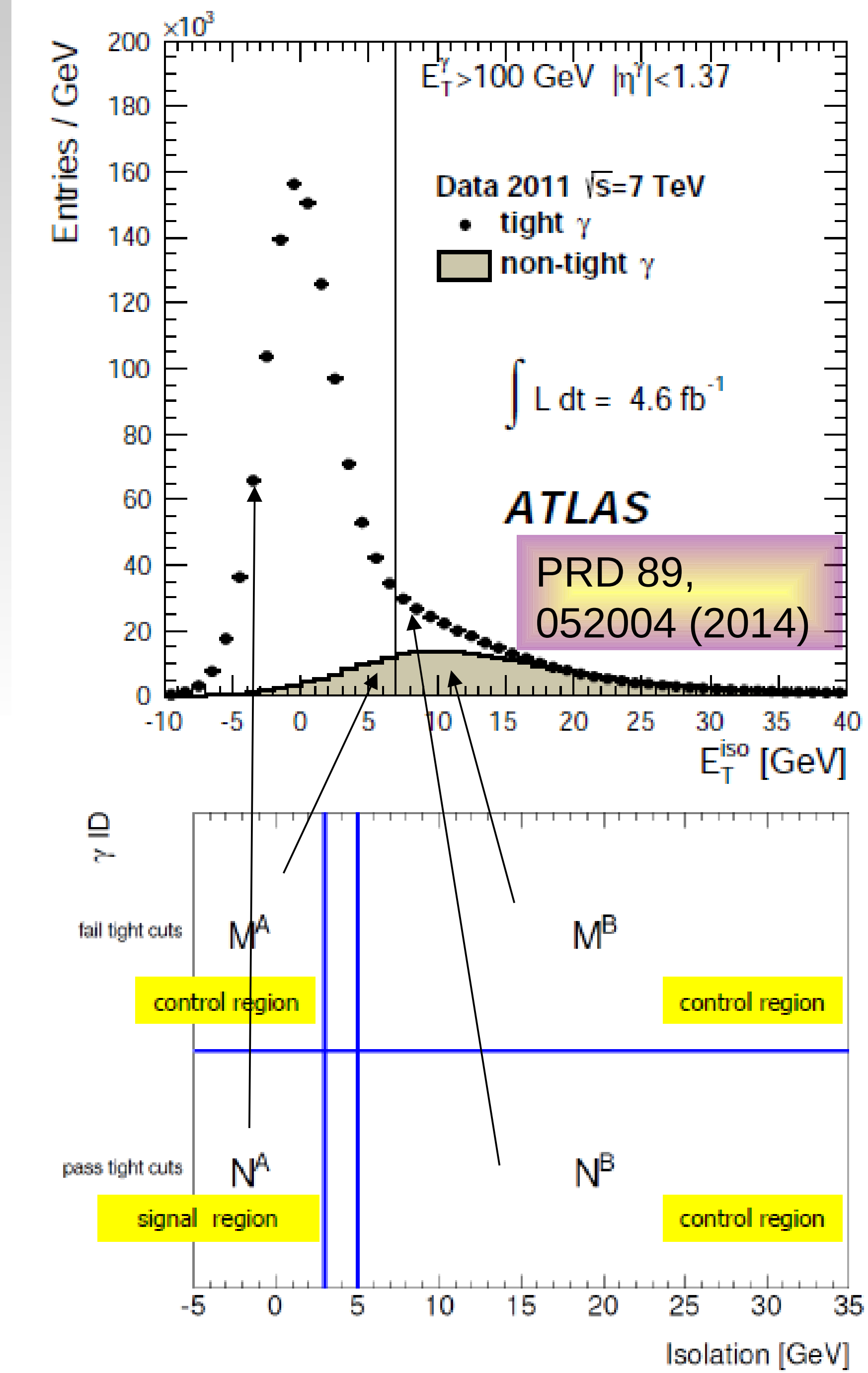
1.7) Photons signal extraction in a nut-shell

- A: signal region



1.7) Photons signal extraction in a nut-shell

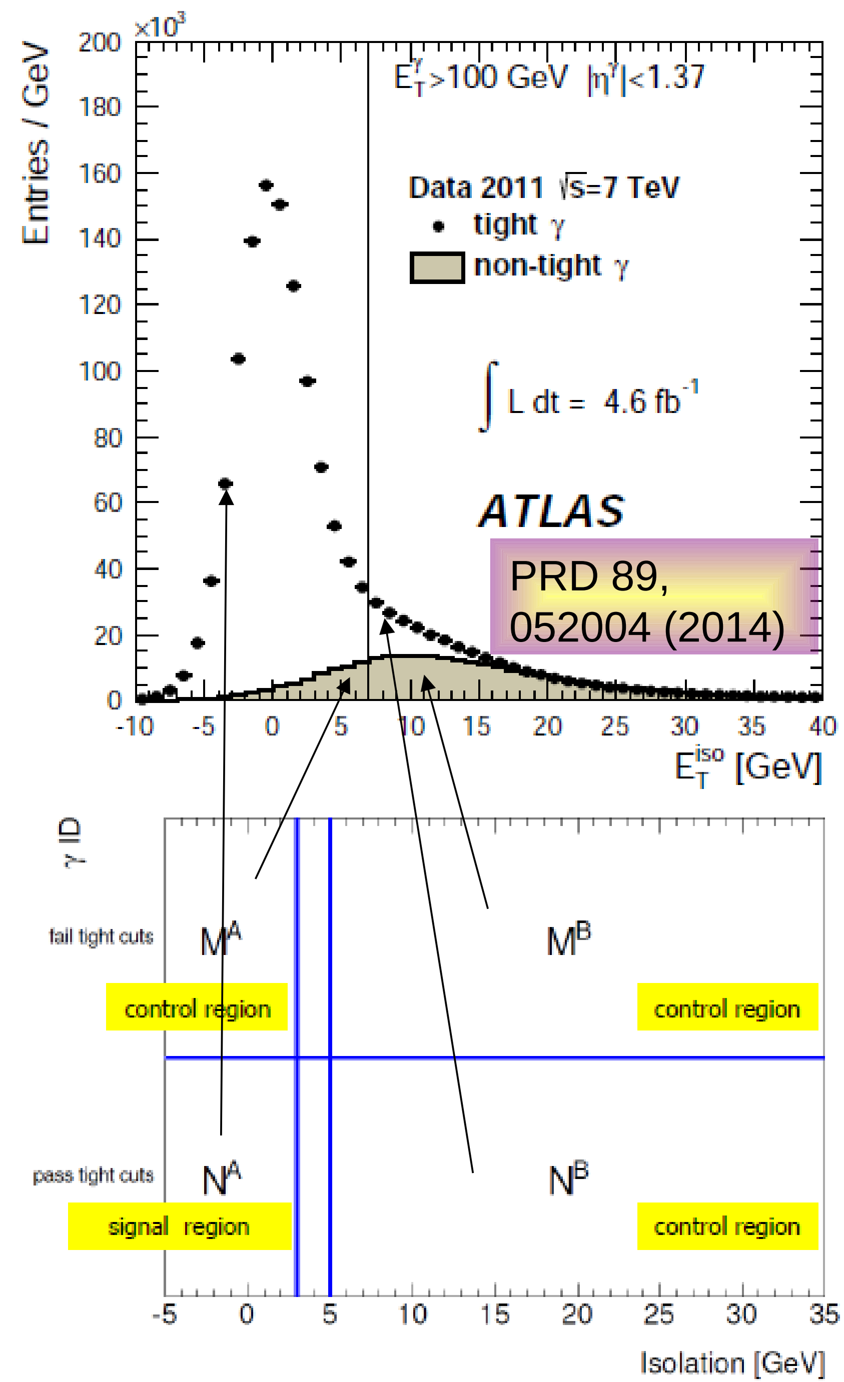
- A: signal region
- B,C,D: background regions

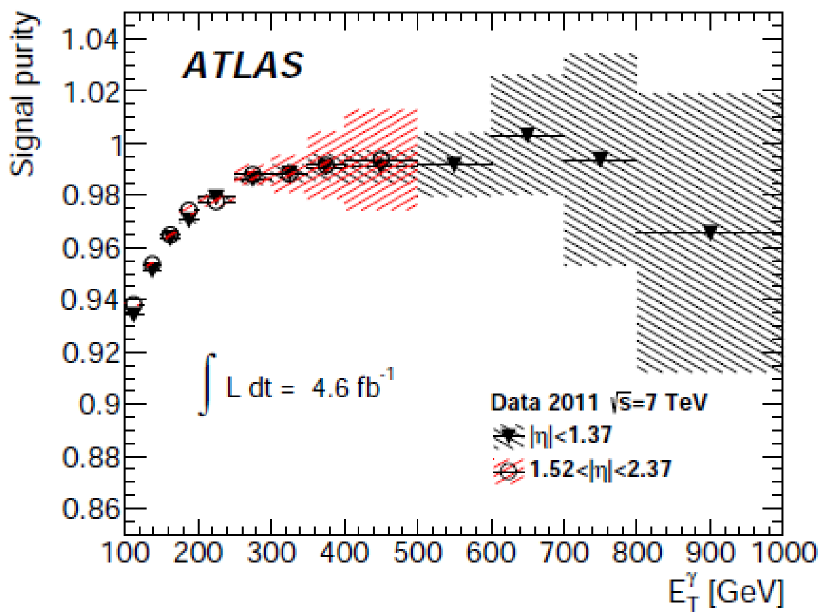


1.7) Photons signal extraction in a nut-shell

- A: signal region
- B,C,D: background regions
- Assumptions:
  - Signal negligible in B,C,D.
  - Isolation, cluster shape uncorrelated.

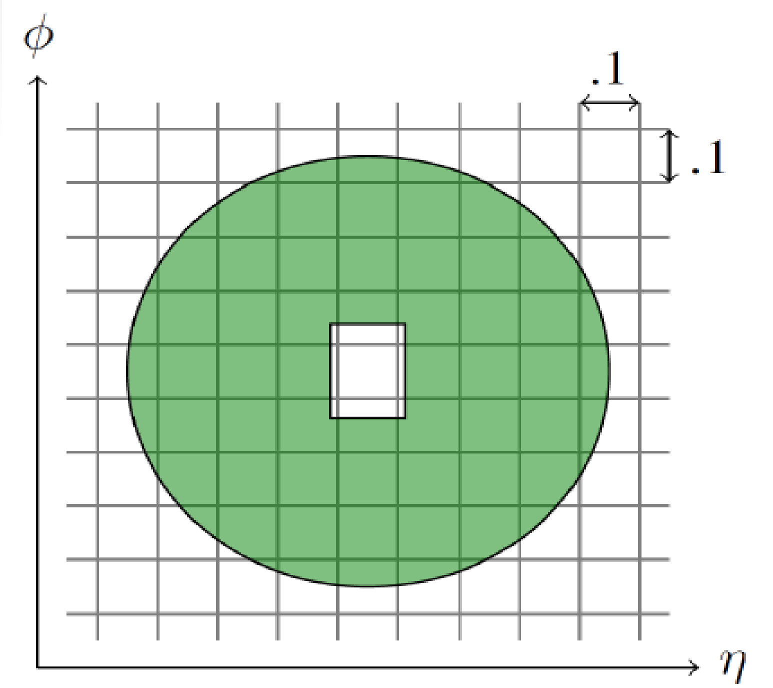
$$N^A_{sig} = N^A - N^B \frac{M^A}{M^B}$$



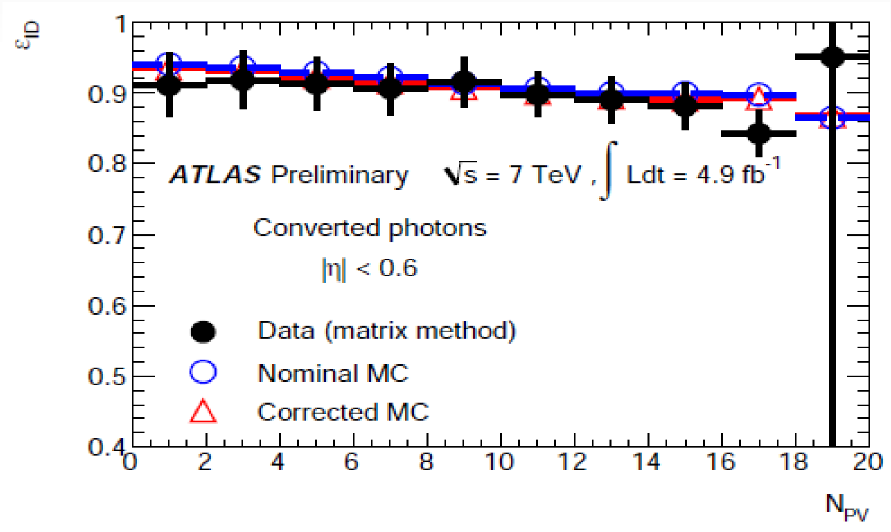


1.8) Isolation and pile-up: example of ATLAS

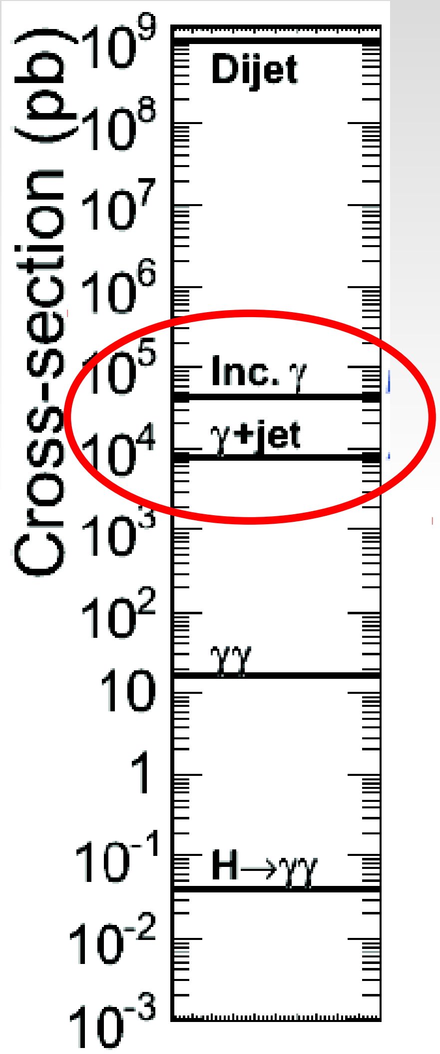
- The isolation is computed within $\Delta R < 0.4$ using ECAL/HCAL cells.
- An annulus of 5 x 7 second layers ECAL is removed.
- Average E_T dependent leakage from photon to iso cone removed based on MC.
- Isolation cone corrected for PU using the jet area substraction technique.

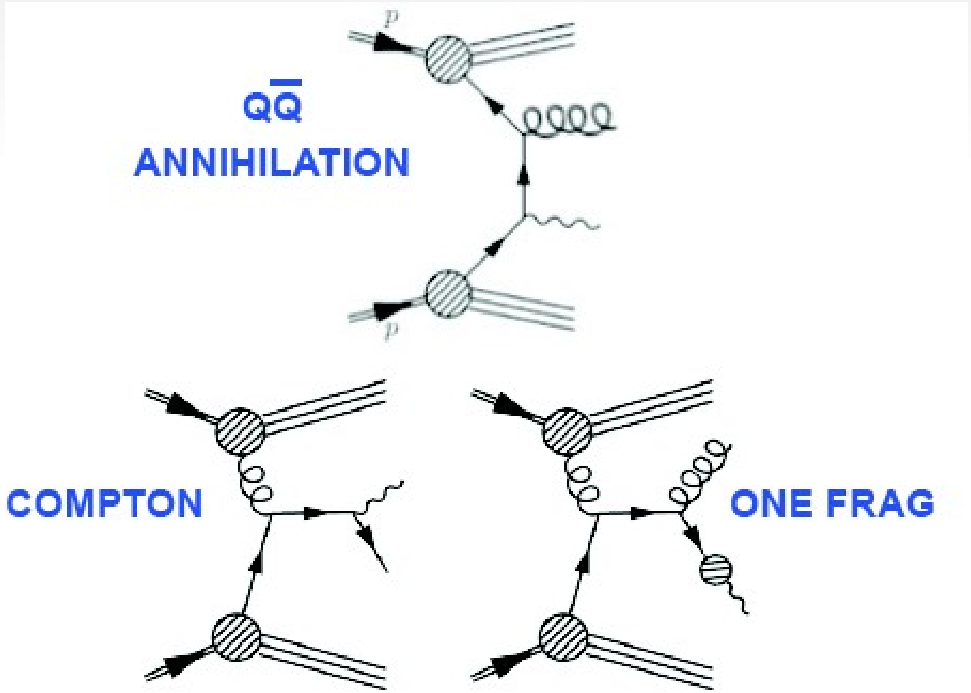


ATLAS-CONF-2012-123



Single photon production

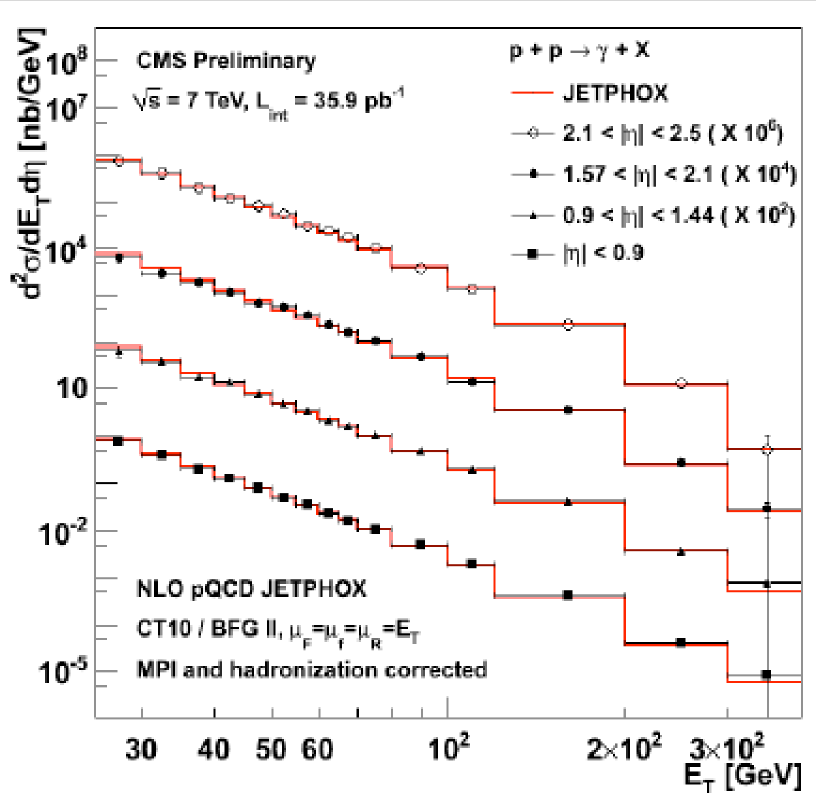


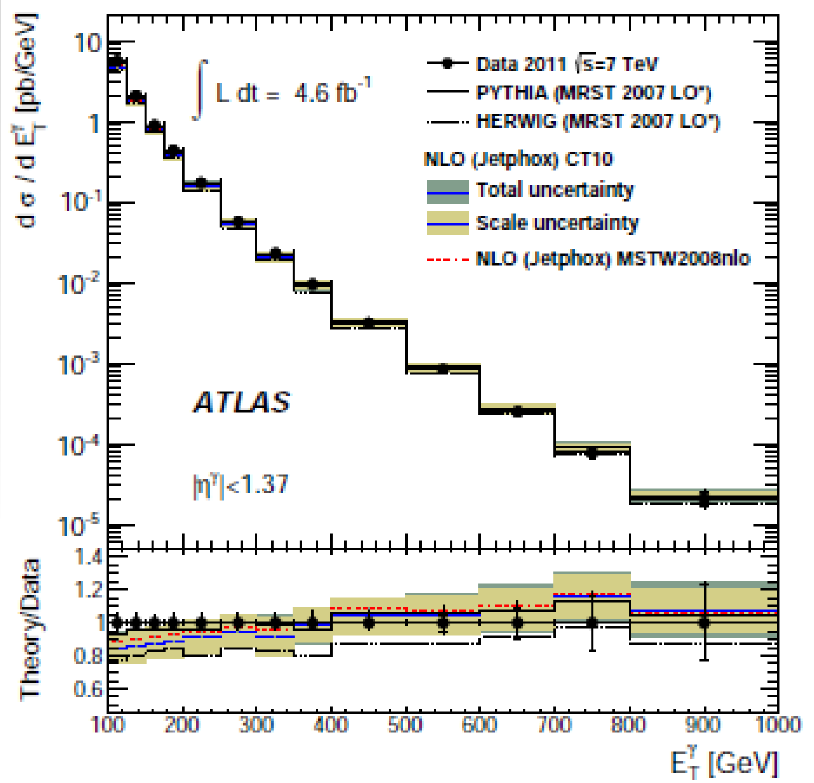


2.1) Single jet production

PRD 84, 052011 (2011)

PRD 89, 052004 (2014)





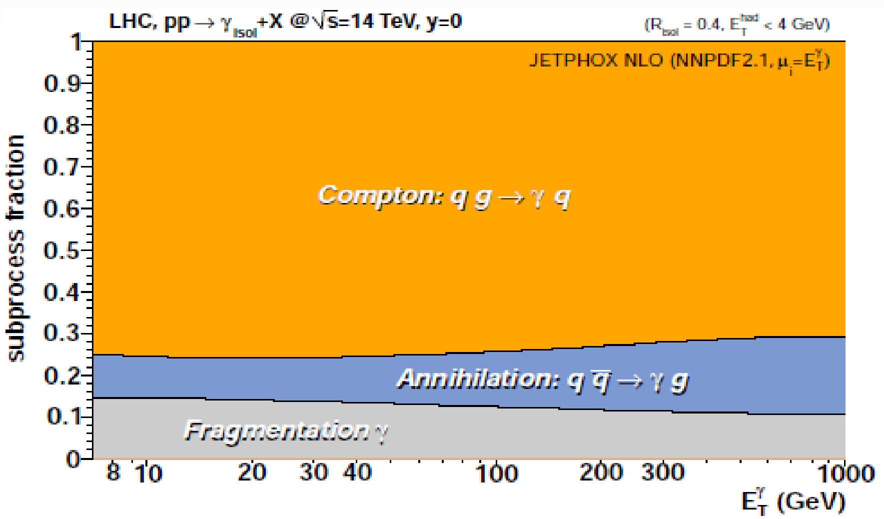
- Single photon production well described by the NLO and even LO+PS.
- Scale uncertainties (ren., fact., frag.) are 10-15%. Not so small for an EM probe.
- PDF and α_s uncertainties from 5 to 15% depending on the region.
- *PS*: see also PRL.106:082001,2011

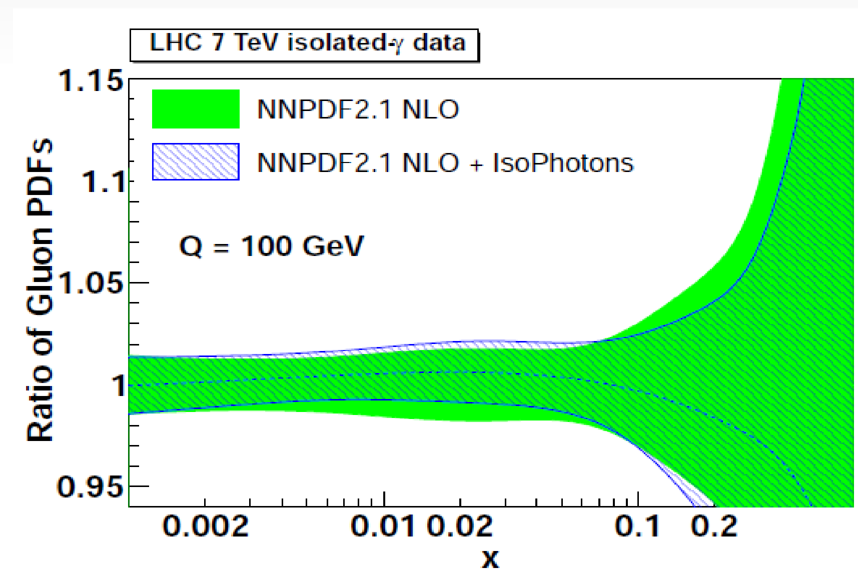
2.2) Sensitivity to PDFs

arXiv:1202.1762 (D'Enterria, Rojo)

- LHC photons helps to constrains gluon PDF at high Q^2 and intermediate x.
- Larger statistics than single Z production.
- Need NNLO predictions to go further since the scale uncertainties are still important and to be used in NNLO PDFs which becomes a standard now.

- *PS:* see also Nucl. Phys, B 875 (2013) 483-535

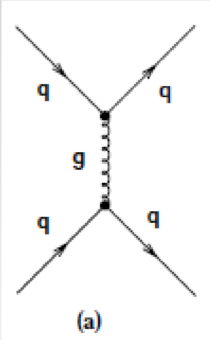


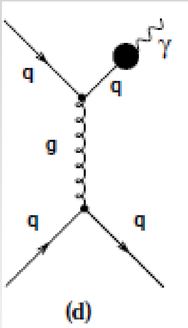


2.3) Tensor structure of γ+jet (1)

Nucl. Phys, B 875 (2013) 483-535

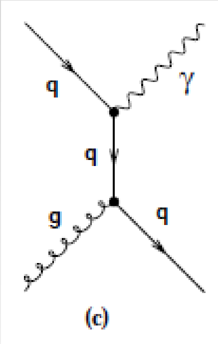
- t-channel γ+jet production diverges toward cos θ* = 0





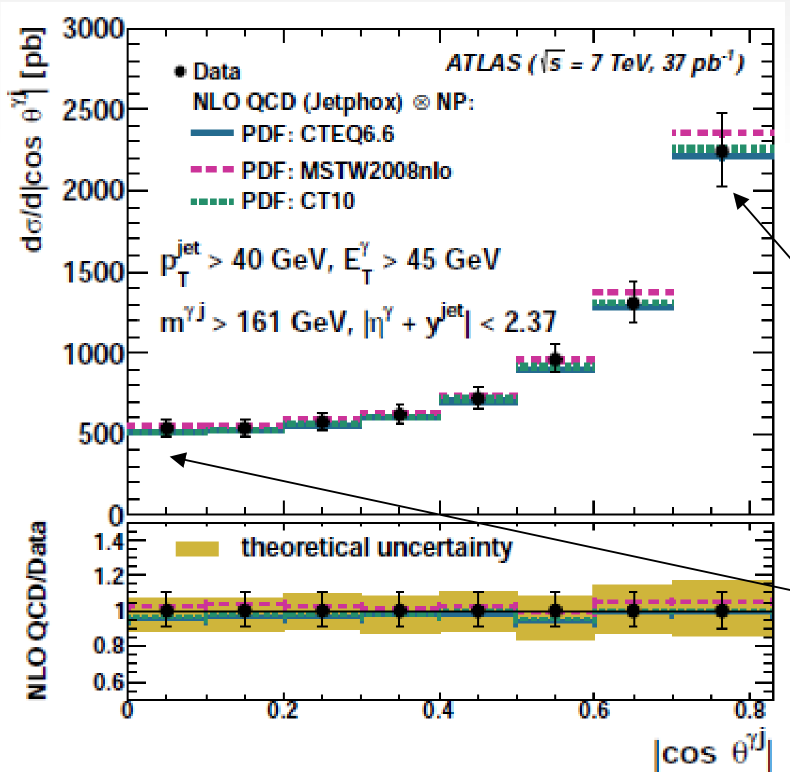
Fragmentation
&&
dijet

$(1-|\cos\theta^*|)^{-2}$



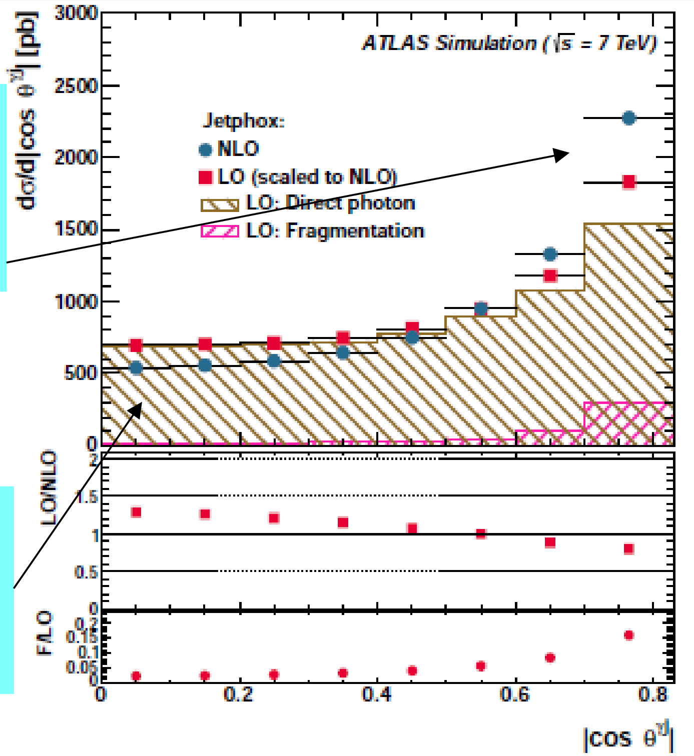
Prompt

$(1-|\cos\theta^*|)^{-1}$



T-channel and fragmentation enriched

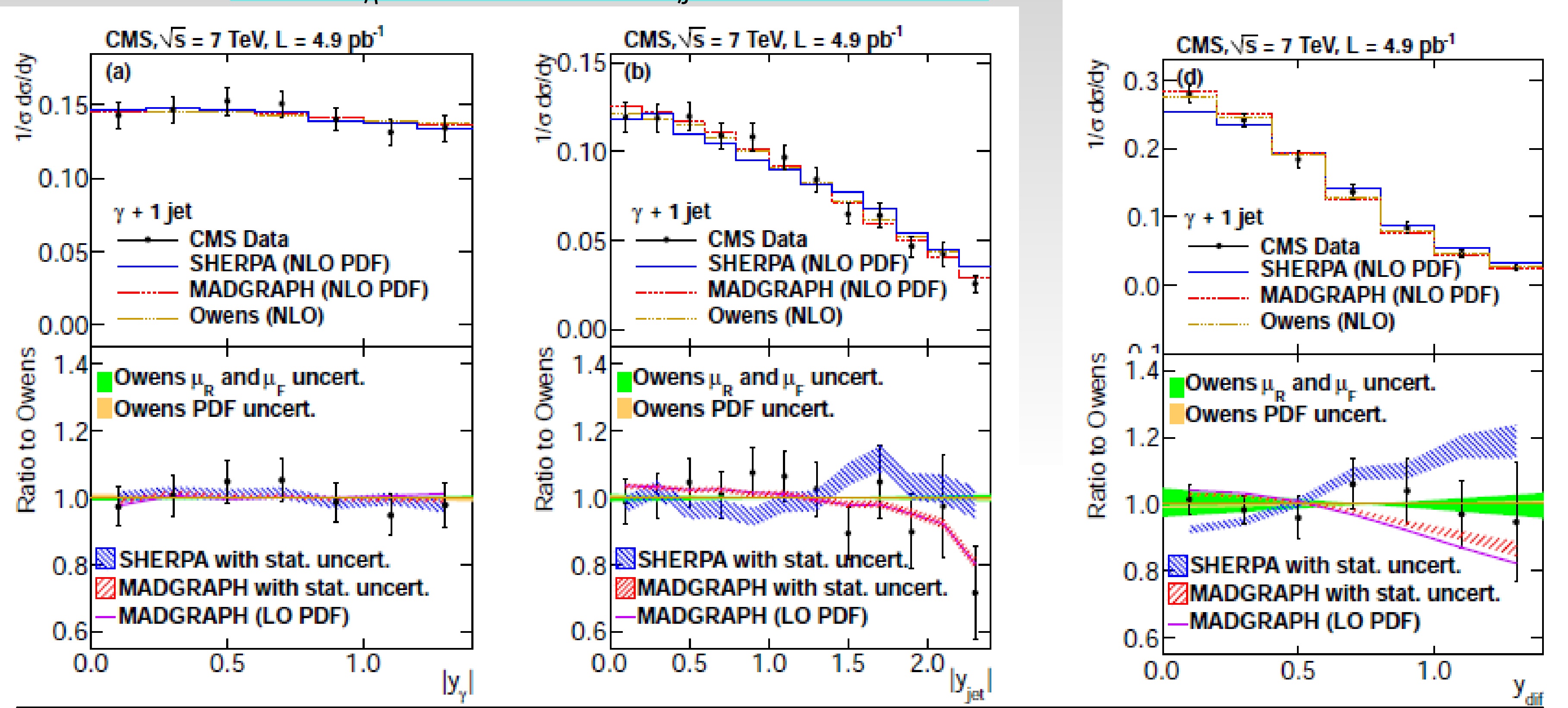
S-channel and prompt enriched



2.3) Tensor structure of γ+jet (2)

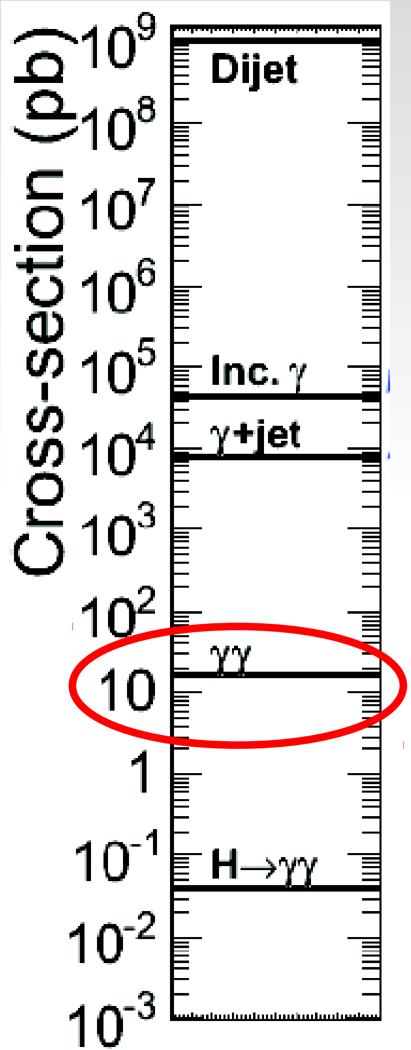
PRD 88, 112009 (2013)

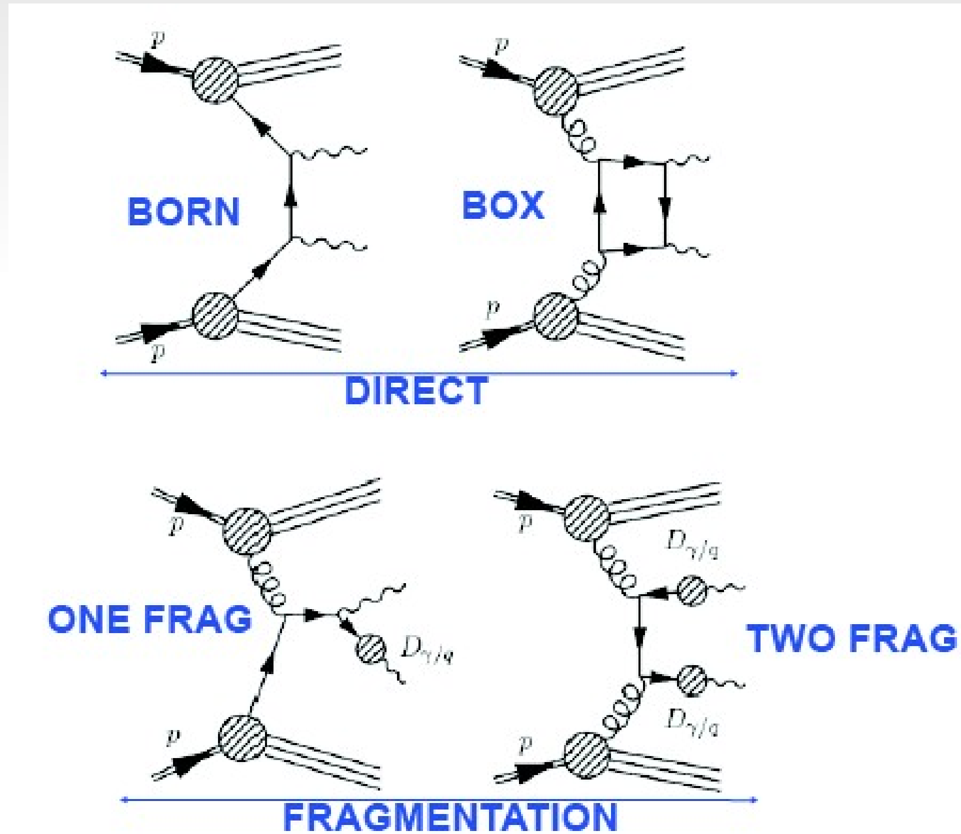
$p_{T,\gamma} > 40$ GeV $p_{T,j} > 30$ GeV



- For SUSY searches: γ+jets ME+PS multileg MCs can be used to estimate Z→νν+jets.
- Y is described better than ΔY (related to cos θ*) especially for Sherpa.
- What seems to matter here is the ME – PS matching scheme:
  - MADGRAPH: MLM scheme – rejection of similar topologies.
  - SHERPA: CKKW scheme – weights based on shower topology.
- PS: see also arXiv:1311.6141

Diphoton production



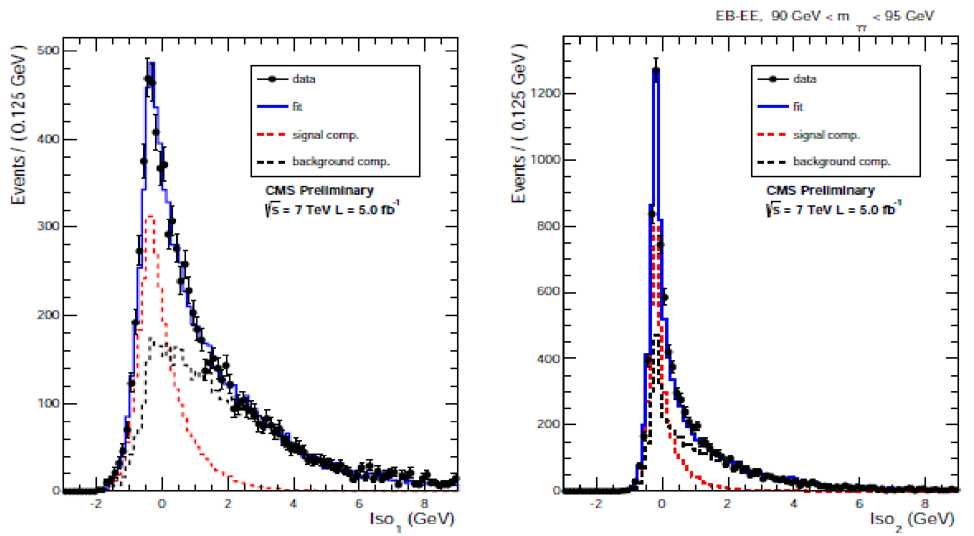


3.1) Diphoton challenge

CMS-PAS-SMP-13-001

$p_{T,\gamma 1} > 40$ GeV $p_{T,\gamma 2} > 25$ GeV

- γγ analysis more challenging than γ : more fake contribution.
- Correlation exist between isolation of the two photons. Typically multi-dimensionnal analysis: ABCD*ABCD.

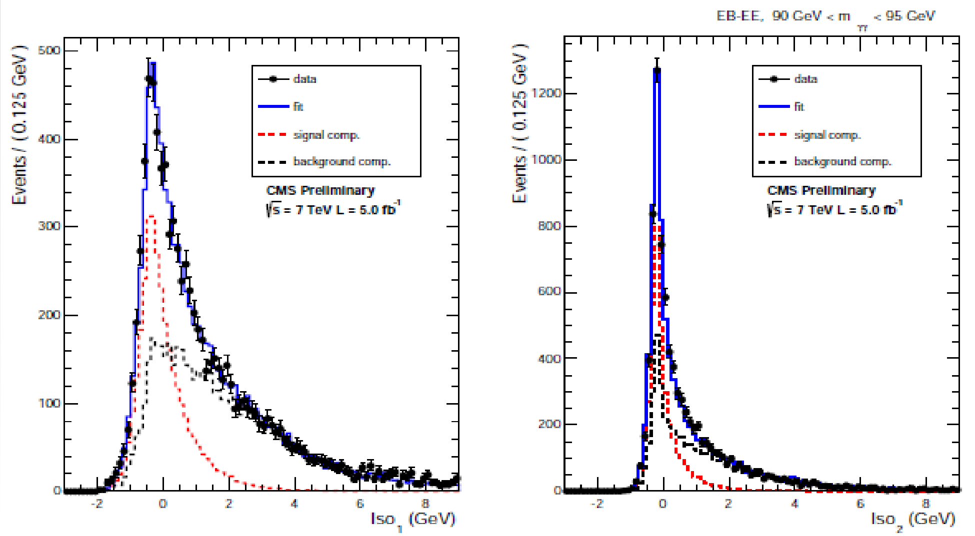


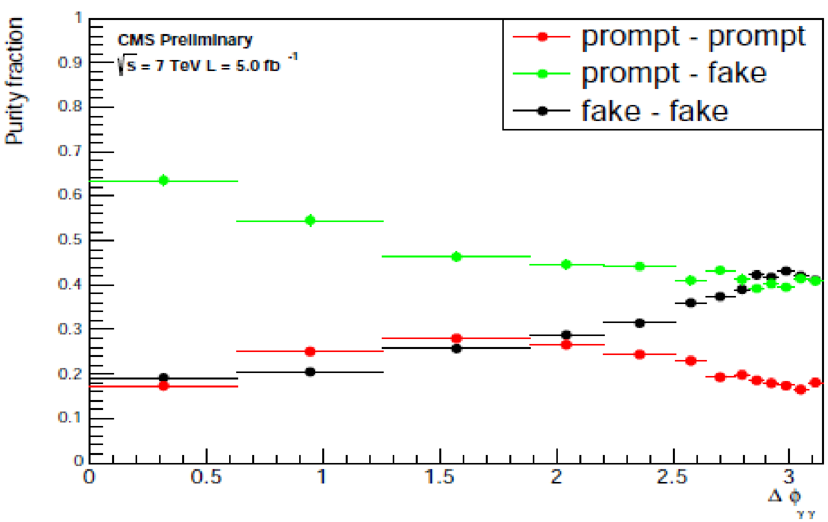
3.1) Diphoton challenge

CMS-PAS-SMP-13-001

$p_{T,\gamma 1} > 40$ GeV $p_{T,\gamma 2} > 25$ GeV

- γγ analysis more challenging than γ : more fake contribution.
- Correlation exist between isolation of the two photons. Typically multi-dimensionnal analysis: ABCD*ABCD.
- Templates: trade purity vs efficiency.
- The dominant systematic is related to template building.



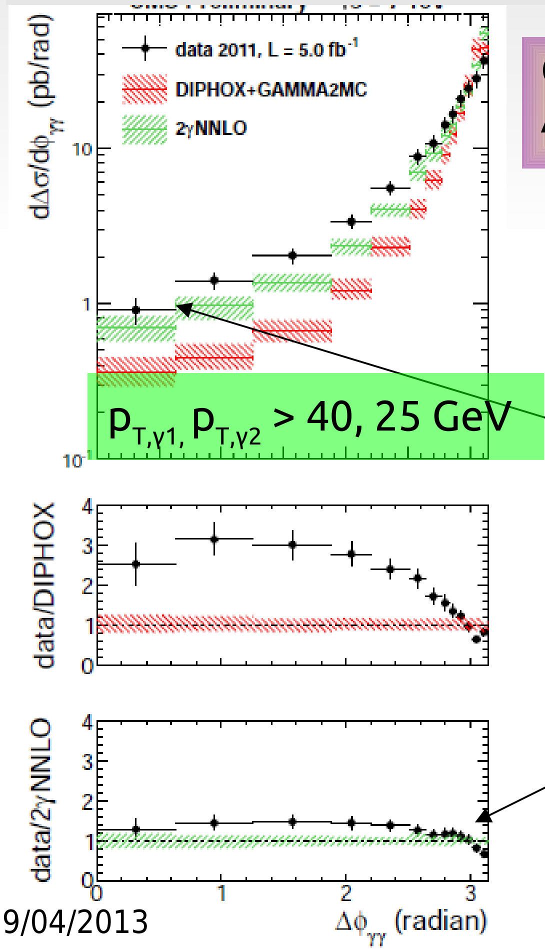


Prompt template shape EB	3%
Prompt template shape EE	5%
Fakes template shape EB	5%
Fakes template shape EE	10%
Effect of fragmentation component	1.5%
Template stat. fluctuation	3%
Selection efficiency	2-4%
Integrated luminosity	2.2%

~ 10% uncertainty in total.

3.2) Sensitivity to the missing orders in QCD

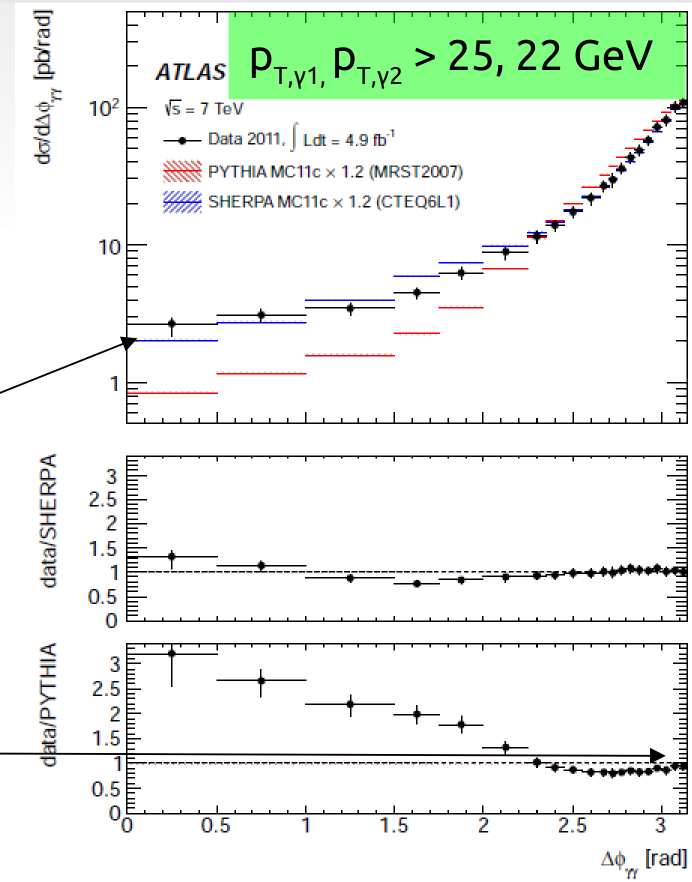
Generator	ME/PS	Resum.	Born	1-frag	2-frag	Box
2γNNLO	ME	-	NNLO	-	-	LO
DIPHOX + GAMMA2MC	ME ME	- -	NLO -	NLO -	NLO -	(LO) NLO
SHERPA	ME+PS	LL	LO + up to 3 jets			LO
PYTHIA	ME+PS	LL	LO	LO	LO	LO



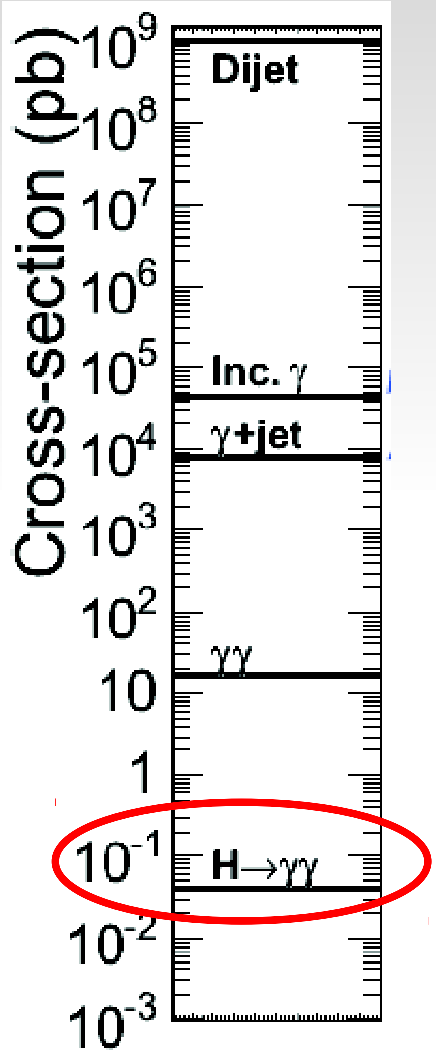
CMS-PAS-SMP-13-001
ATLAS: JHEP01 (2013) 086

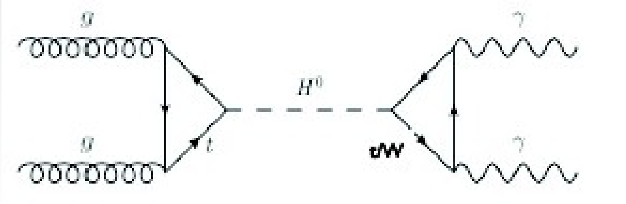
Region where NNLO needed

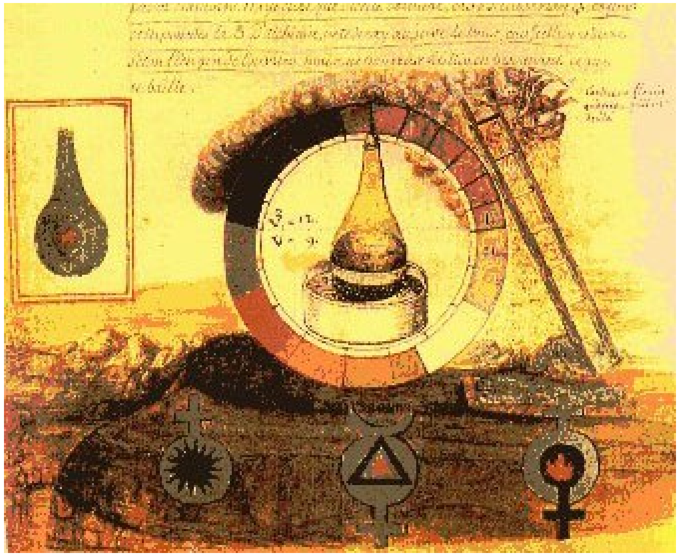
Region where resummation needed



Higgs decay to two photons

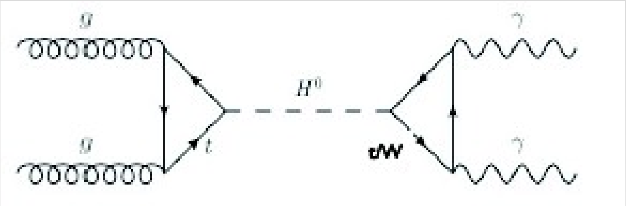






4.0) Trivia about SM Higgs

- Main production mechanism: ggH

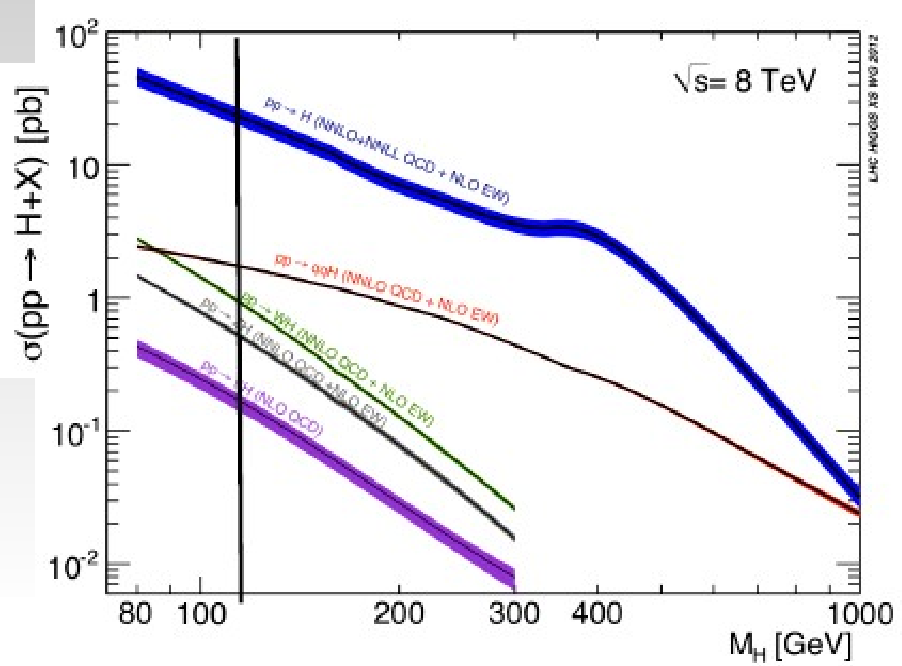


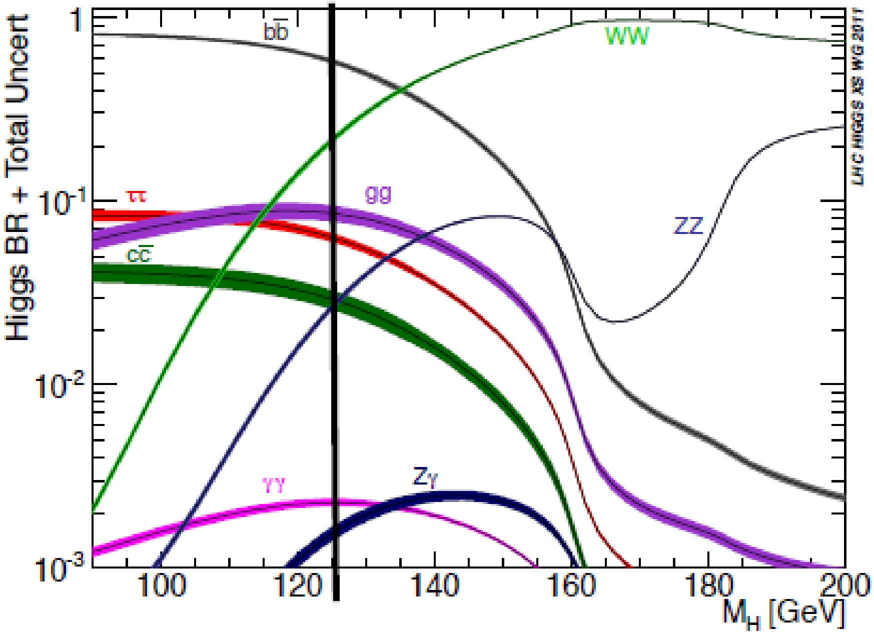
- Properties of ggH:

rather central, no extra jets at LO.

- Number of H produced at the LHC:

  2 exp. * 25 fb^{-1} * 20 pb = 1M H



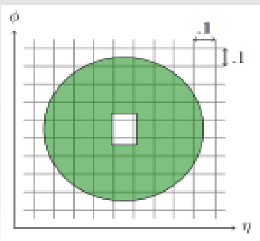


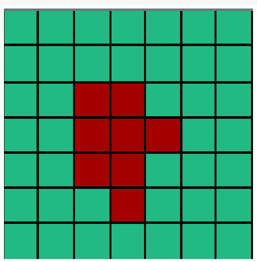
- BF: H→gg only 0.23% -
  - ggH: 1150/experiment
  - VBF: ~ 120/experiment
  - VH: ~ 100/experiment

4.0) H→ γγ search in a nut-shell

Phys. Lett. B 726 (2013), pp. 88-119
CMS-PAS-HIG-13-001
ATLAS-CONF-2013-072
CMS-PAS-HIG-13-016

1) SELECT
2 calibrated
photons



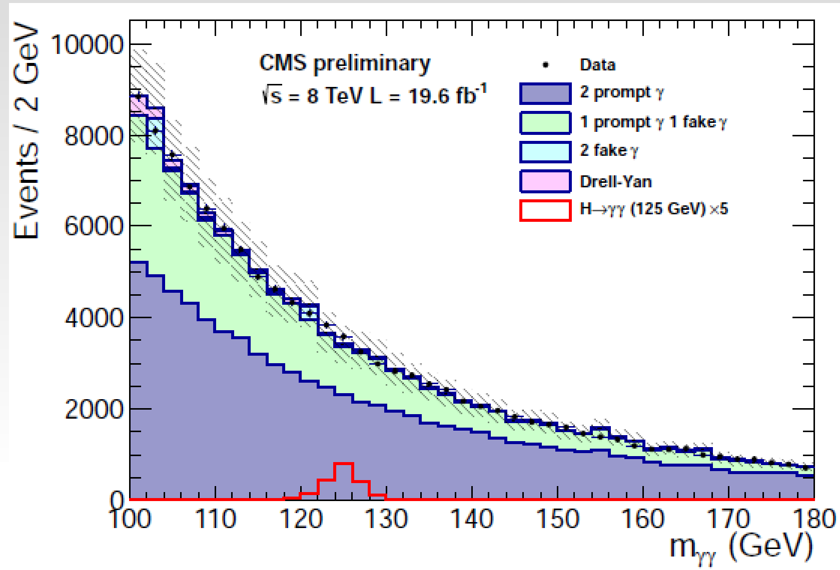


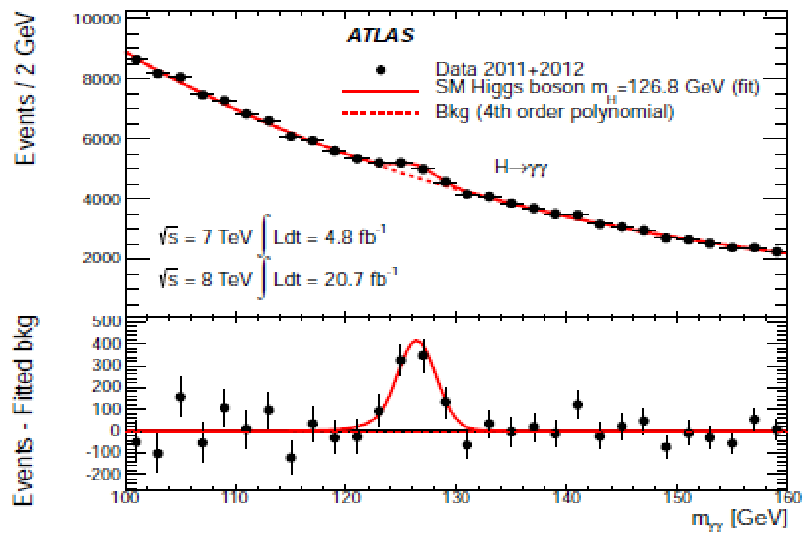
2) Classify the signal into categories in S/B

3) Build signal model in $M_{\gamma\gamma}$: bump

4) Build background model in Mγγ: smoothly falling

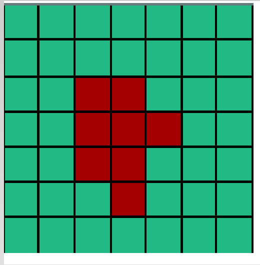
5) Perform a smoothness test: search for a bump over a smooth background

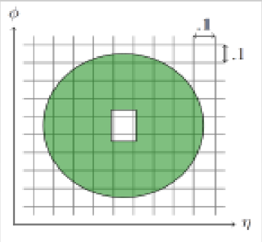




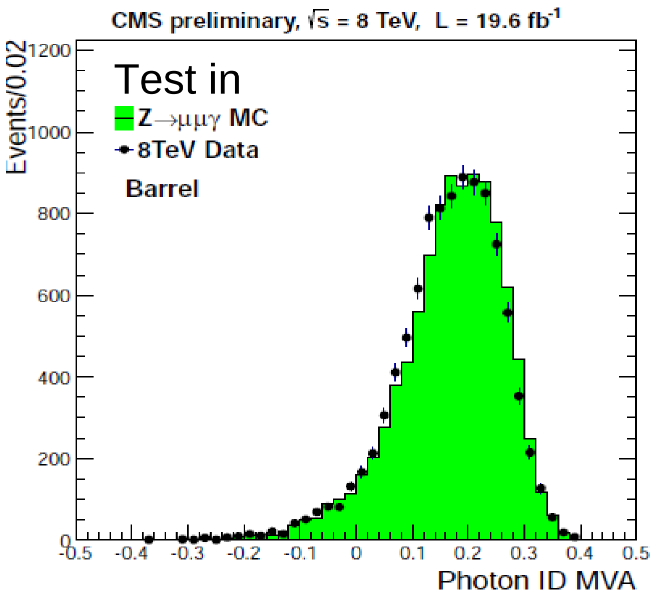
4.1) Select 2 calibrated photons

- Apply a tight quality selection in shape/isolation to enrich the sample in prompt/frag photons.



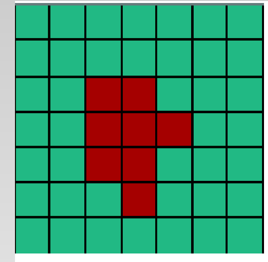


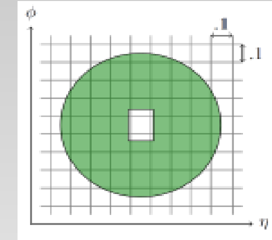
Cut based or MVA



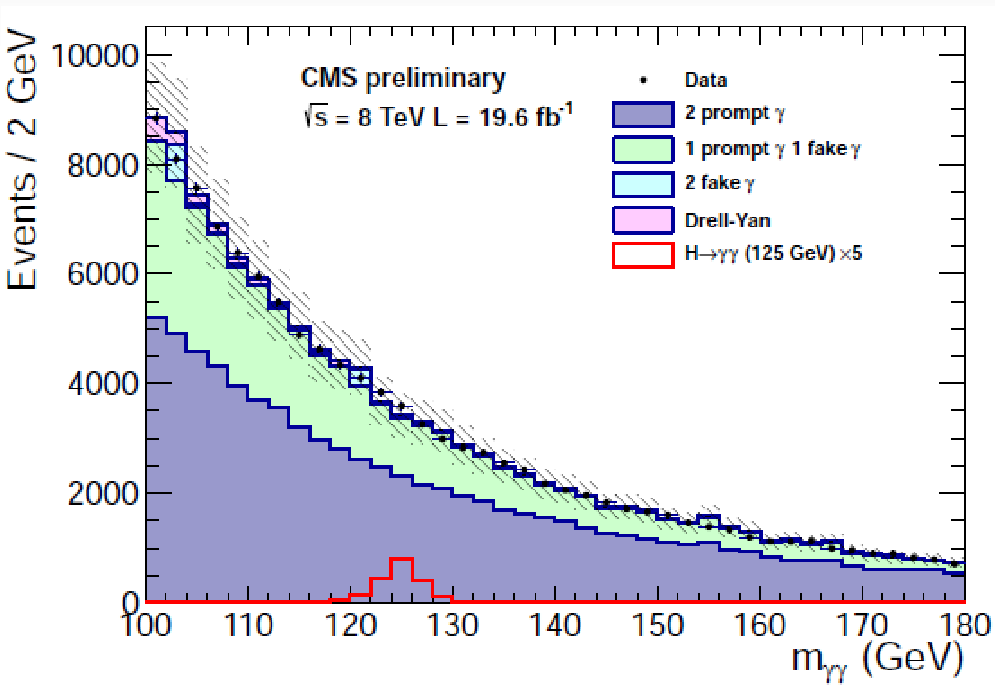
4.1) Select and calibrate 2 photons

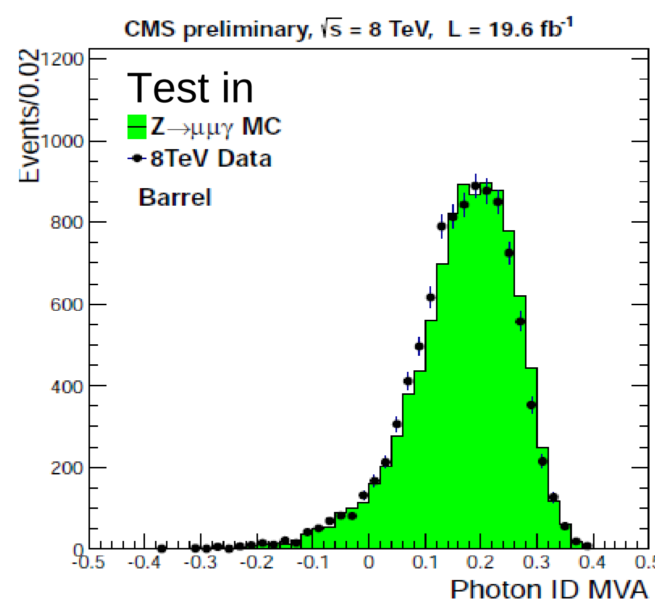
- Apply a tight quality selection in shape/isolation to enrich the sample in prompt/frag photons.
- Different from SM measurements. Why?
  - Background is smooth in M for prompt/frag/fake.
  - Signal: prompt only.
- Typically sliding cut applied to keep the spectrum smoothly falling: $p_{T\gamma 1}, p_{T\gamma 2} > M_{\gamma\gamma}/3, M_{\gamma\gamma}/4$





Cut based or MVA

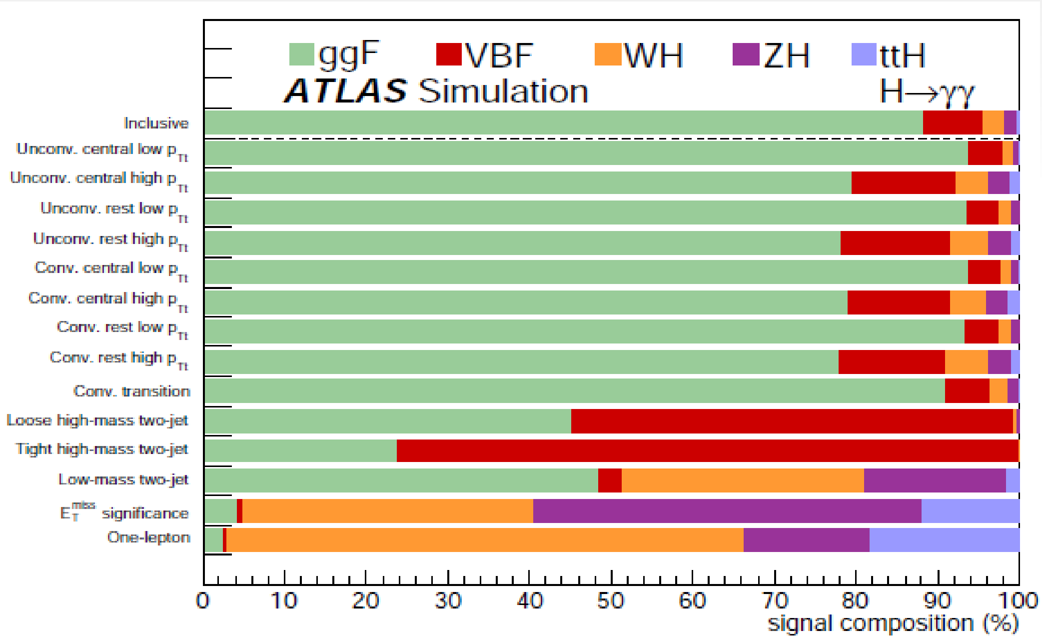




4.2) Classify the signal into categories

- Diphotons properties: (un)converted; ENDCAP/BARREL; Higgs boost;
- Production channel and signature properties: VBF, VH, ttH

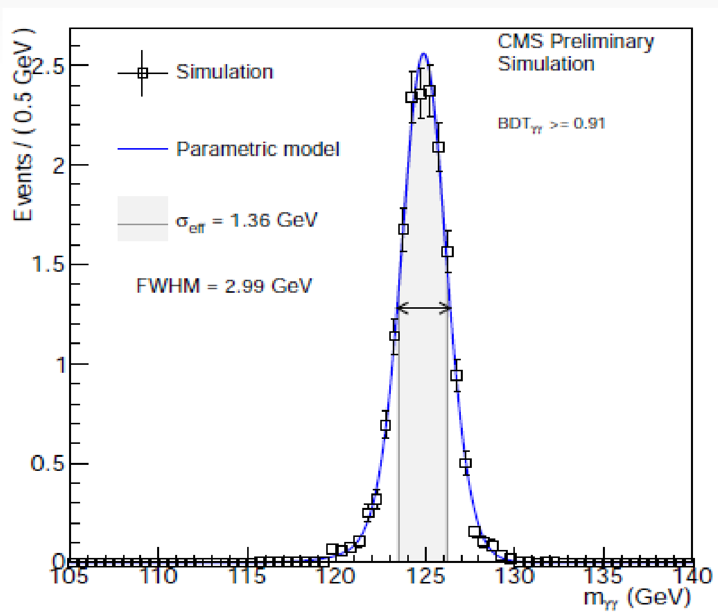
- Categories defined using cuts or Boosted Decision Trees.



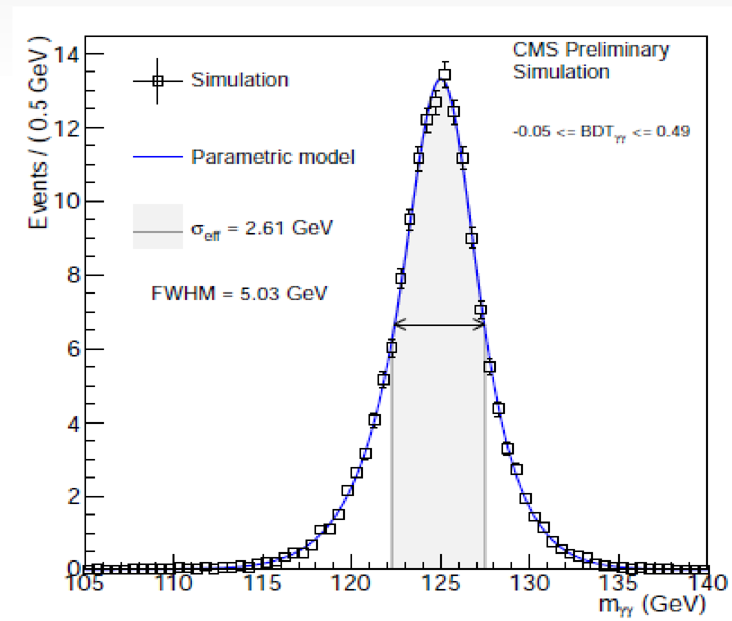
- Highest significance category: Tight VBF – S/B ~ 0.5.
- Total number of expected Higgs events
  - ~350 in ATLAS
  - ~470 in CMS

4.3) Build signal model in $M_{\gamma\gamma}$

- Higgs boson: narrow resonance.
- Signal model in $M_{\gamma\gamma}$: Gaussian and/or CB with $\sigma_M/M \sim 1\%$
- Depend on:
  - Photons properties: (un)converted; ENDCAP/BARREL
  - Angular resolution: at LO primary vertex without tracks! Need to find PV within few cm for a good resolution.



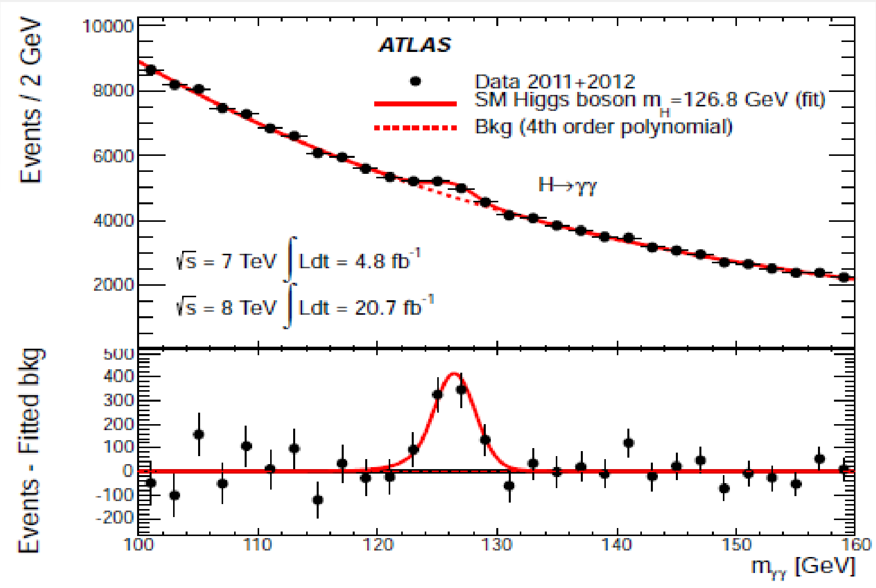
Best category: typically central unconverted

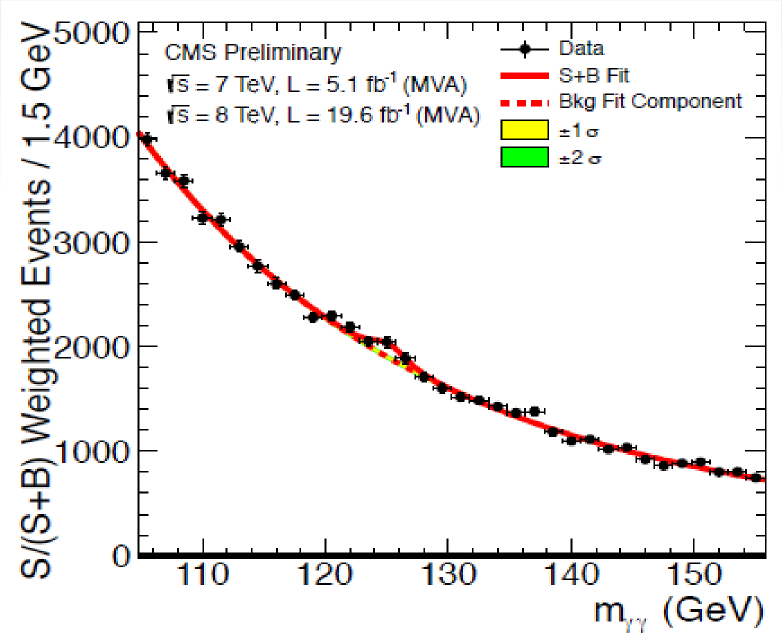


Worse category: typically forward converted

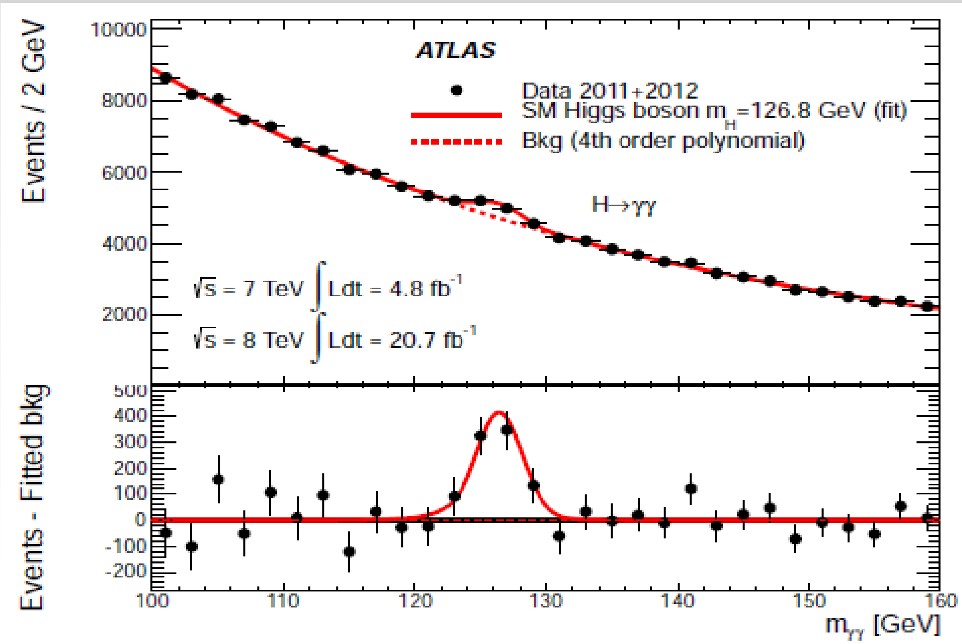
4.4) Build background model in $M_{\gamma\gamma}$

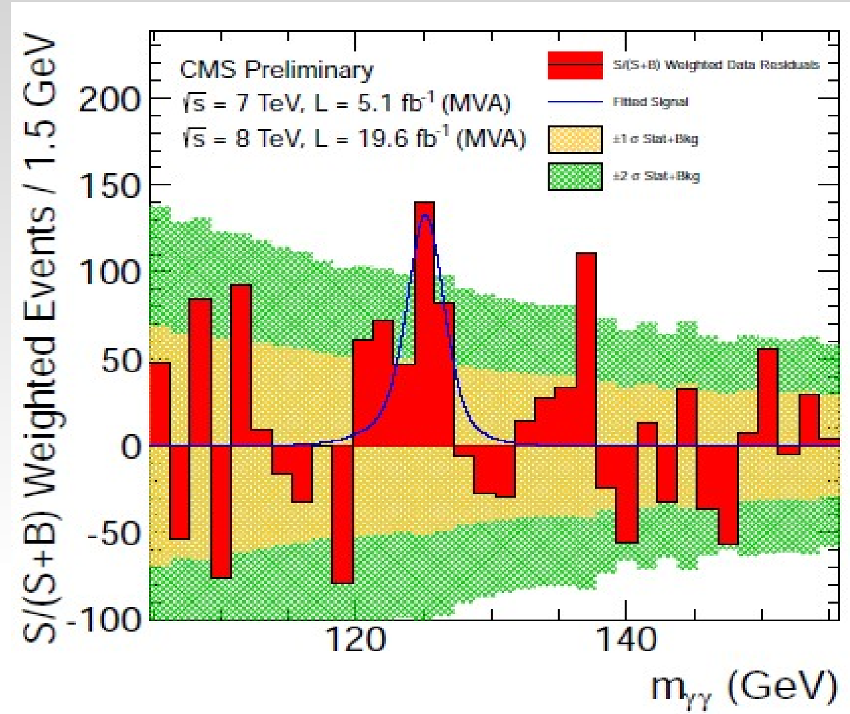
- Background model: steeply falling smooth spectrum.
- In each category a model with minimal number of parameters is chosen.
- Bias studies used to assess the background model systematic.





4.5) Signal extraction: smoothness test in $M_{\gamma\gamma}$





ATLAS cut based classification (except for VBF):

$$\sigma/\sigma_{SM} = 1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst})$$

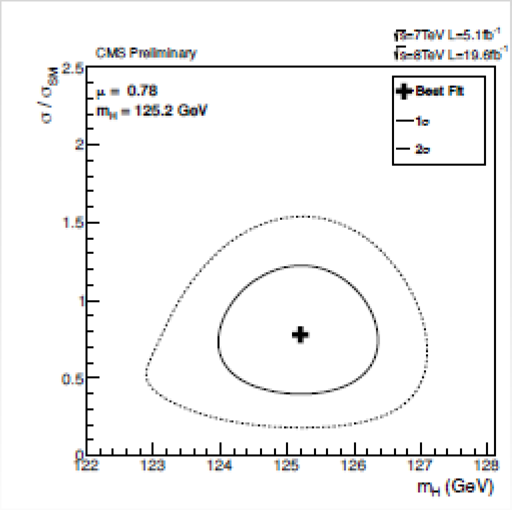
CMS BDT based classification:

$$\sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$$

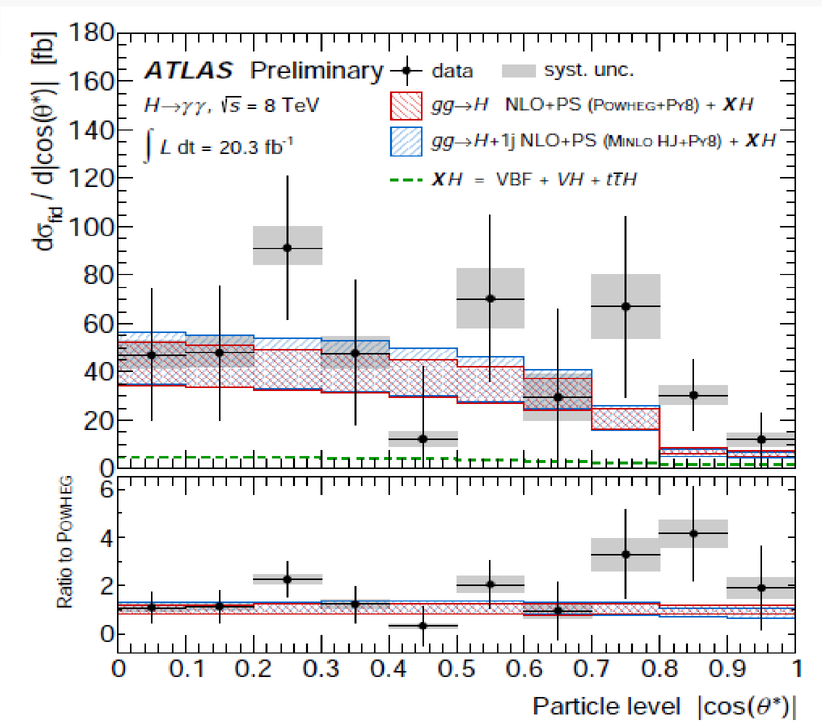
4.6) Higgs properties in γγ

- The topic would be presented in dedicated talks. Here meals from γγ Top Chief.

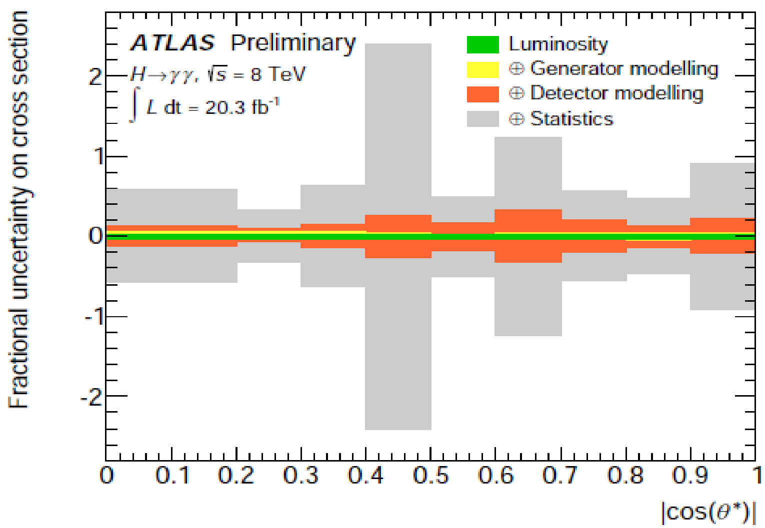
1) Higgs Mass
CMS: 125.4 ± 0.5 (stat) ± 0.6 (sys)
ATLAS: 126.8 ± 0.2 (stat) ± 0.7 (sys)



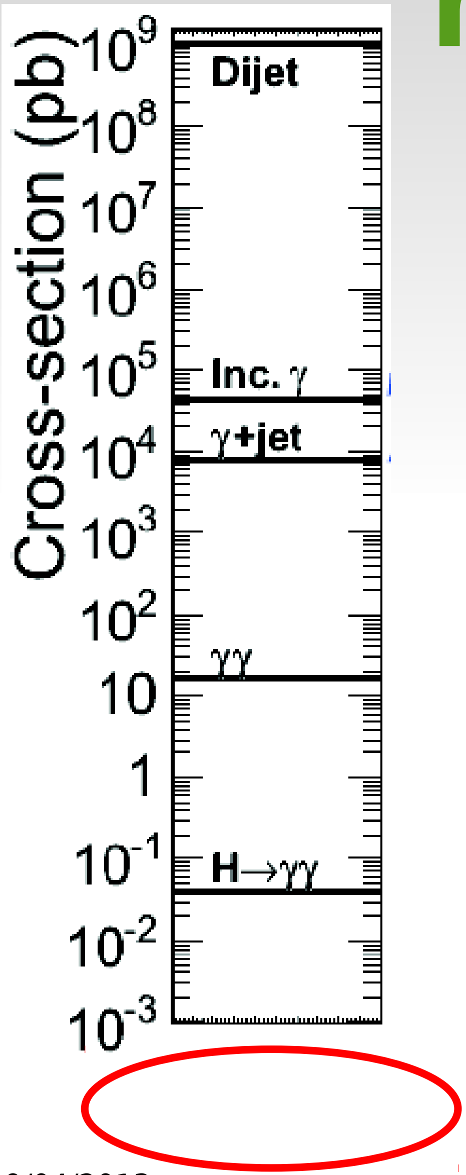
2) Higgs spectrum

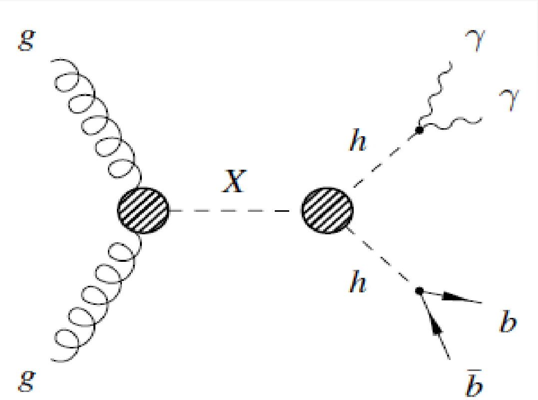


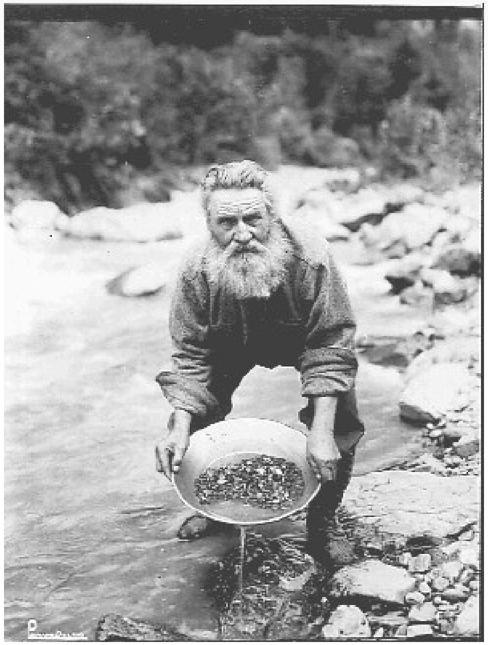
(c) |cos θ*|



Searches in multi-Higgs final states

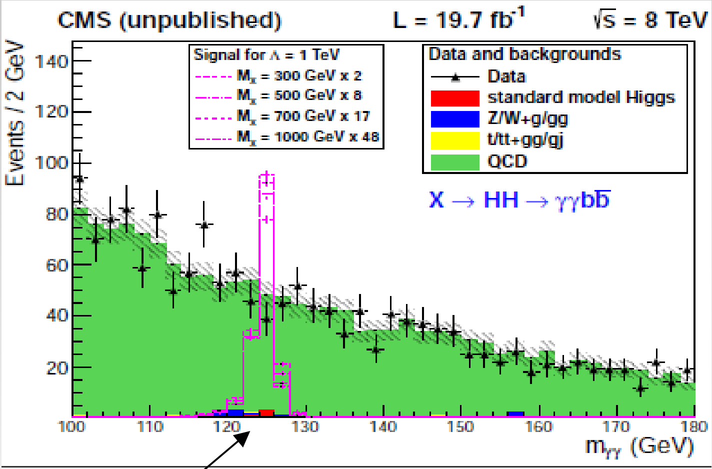


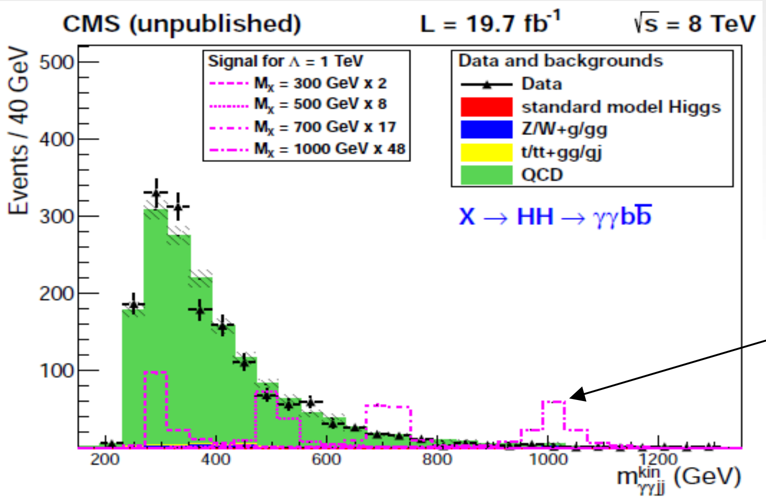


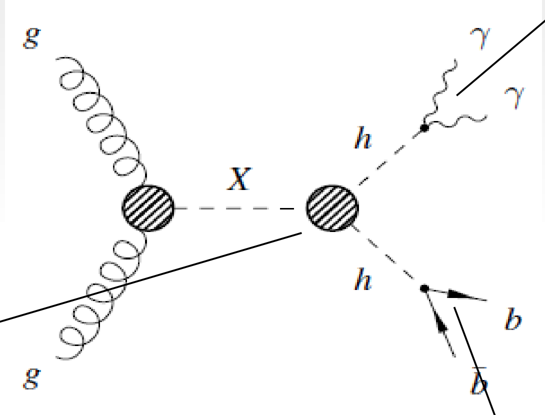


4.6) New physics with Higgs bosons: X→HH

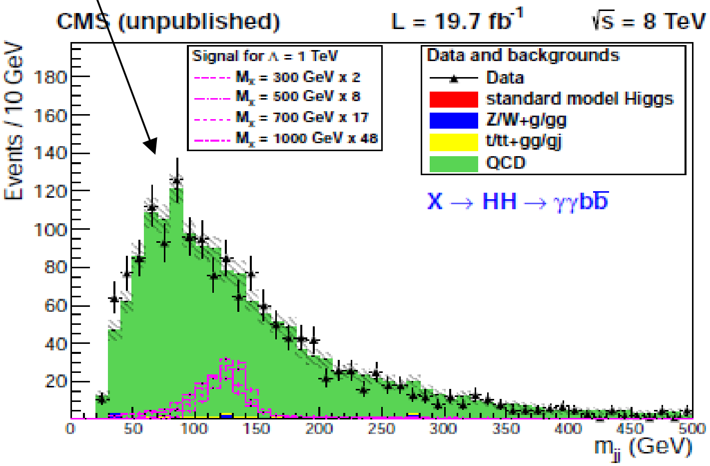
- Look for resonant double Higgs production in fully reconstructible γ final state (0.26%).
- First insight in this final state interesting for SM HH production (too small at 8 TeV: 10 fb)







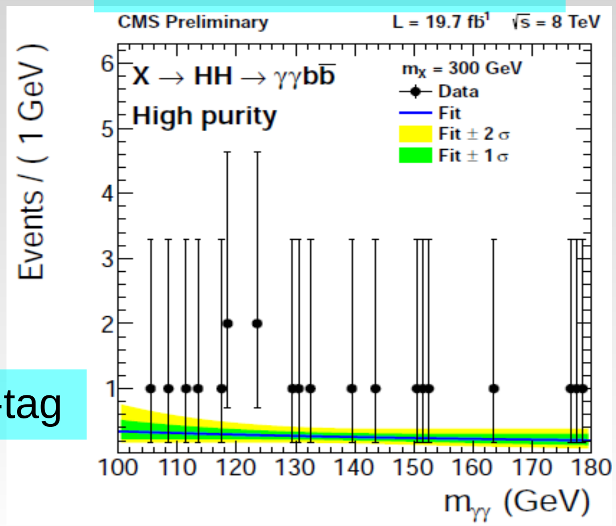
CMS-PAS-HIG-13-032



Main backgrounds:
- Non-resonant QCD = γγbb (>80%) + γjbb+jjbb (<20%). γγbb simulated with SHERPA
- Resonant: SM H production – less than 1 event in final selection. SM HH 0.2 events expected.

4.6) New physics with Higgs bosons: X→HH

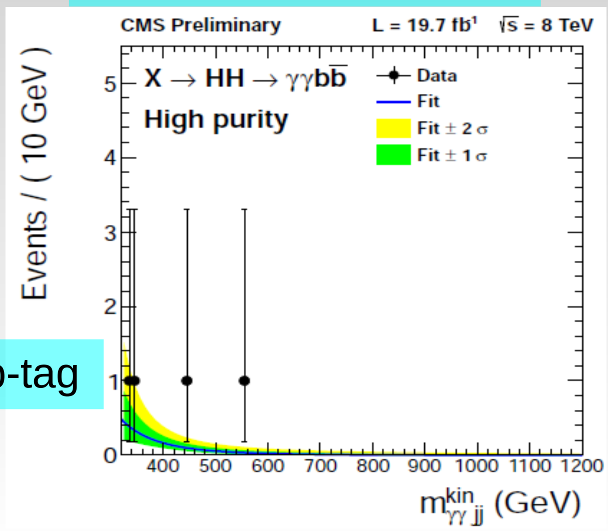
Cut in Mbb and Mγγbb



2 b-tag

+ 1 b-tag low purity

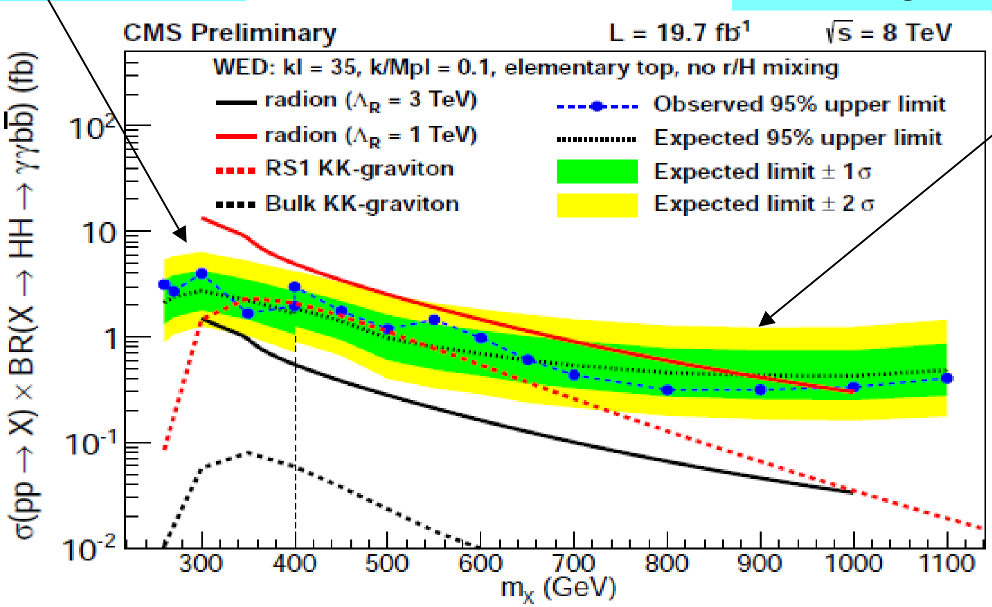
Cut in Mbb and Mγγ



2 b-tag

+ 1 b-tag low purity

Observation compatible with SM production. No anomalious resonant production observed.



See T. Du Pree talk

SUMMARY

1) LHC has explored the photons production physics starting from single photon and up to Higgs/multi-Higgs production.

2) QCD photons production are measured with 7 TeV while 8 TeV is expected to come (stay tuned …).

3) QCD production is rather well described by NNLO or SHERPA (multi-leg LO + PS).

4) The legacy papers about Higgs production in 2 photons about to be published, all data explored. This channel has proved to be a golden one:

- Discovery channel
- Fully reconstructible final state
- Good statistics for kinematic studies

BACKUP

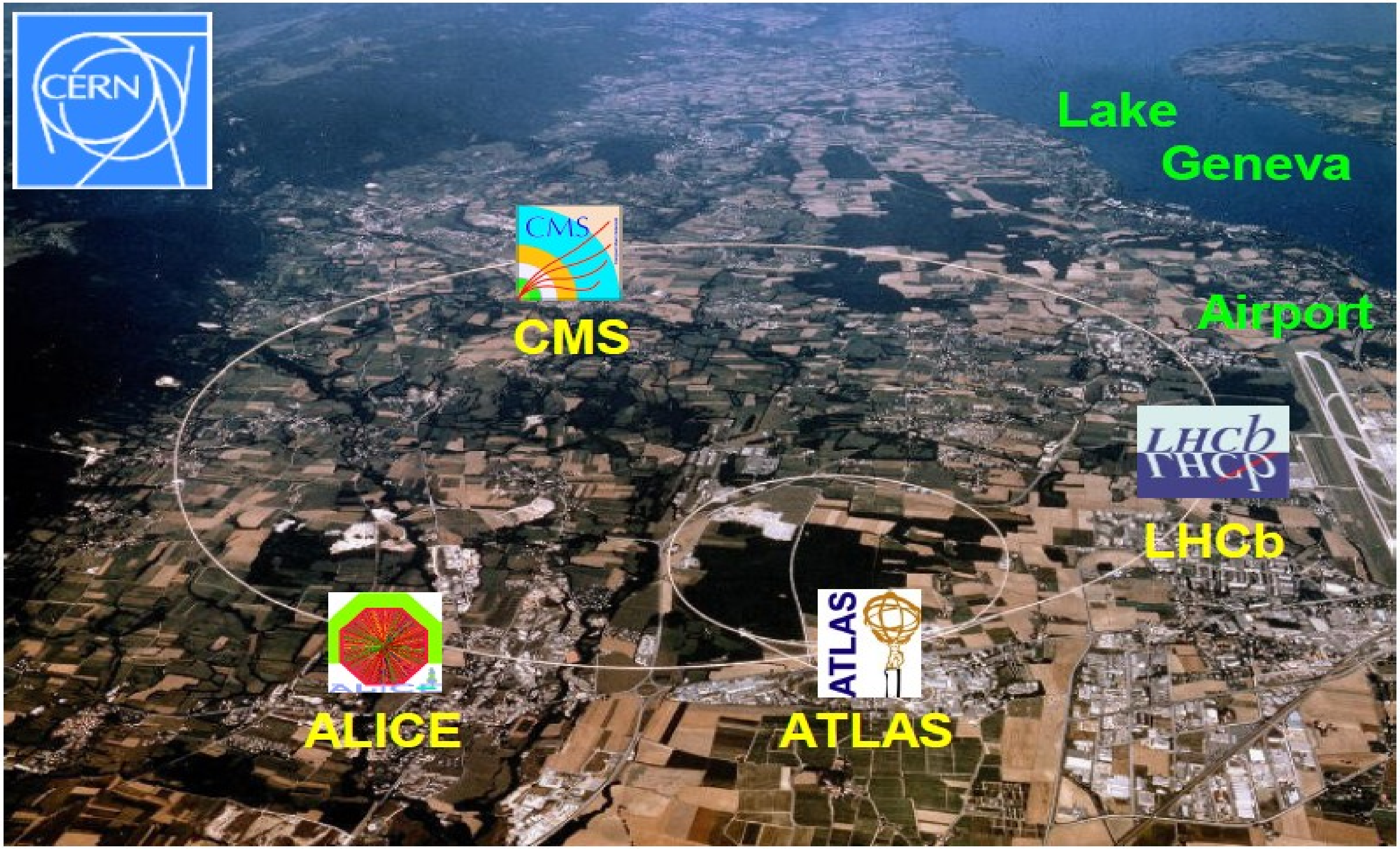
0) To put you in the mood

LHC: 2009 – present

Collisions of p-p, Pb-Pb, and p-Pb

E_{cms} = 0.9, 2.36, 2.76, 7, 8 TeV

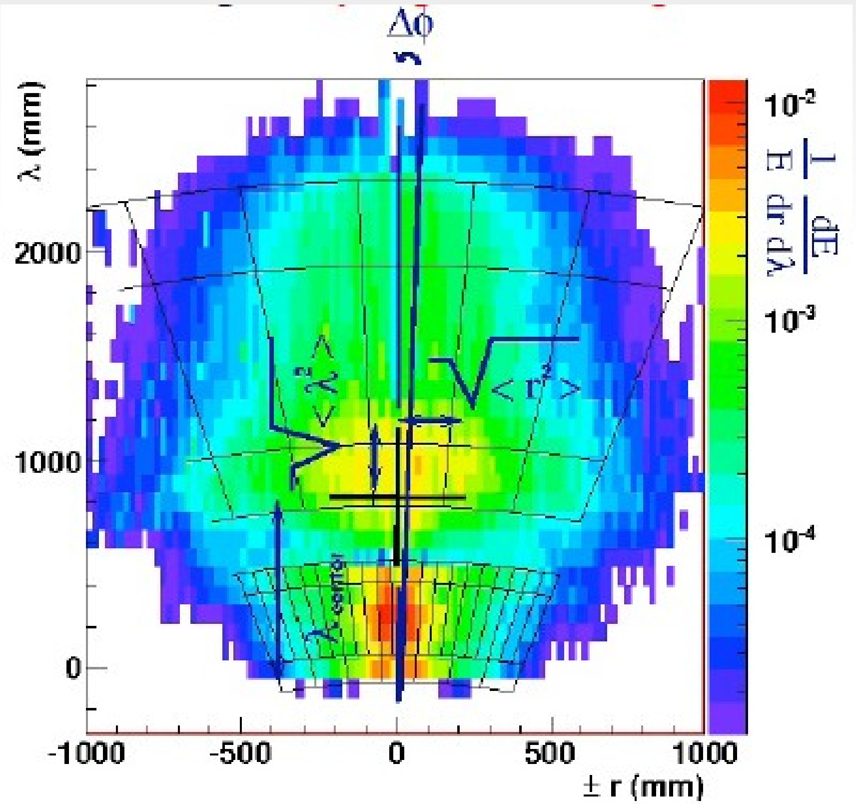
Peak inst. Luminosity: ~ 8 x 10^{33} $cm^{-2}s^{-1}$



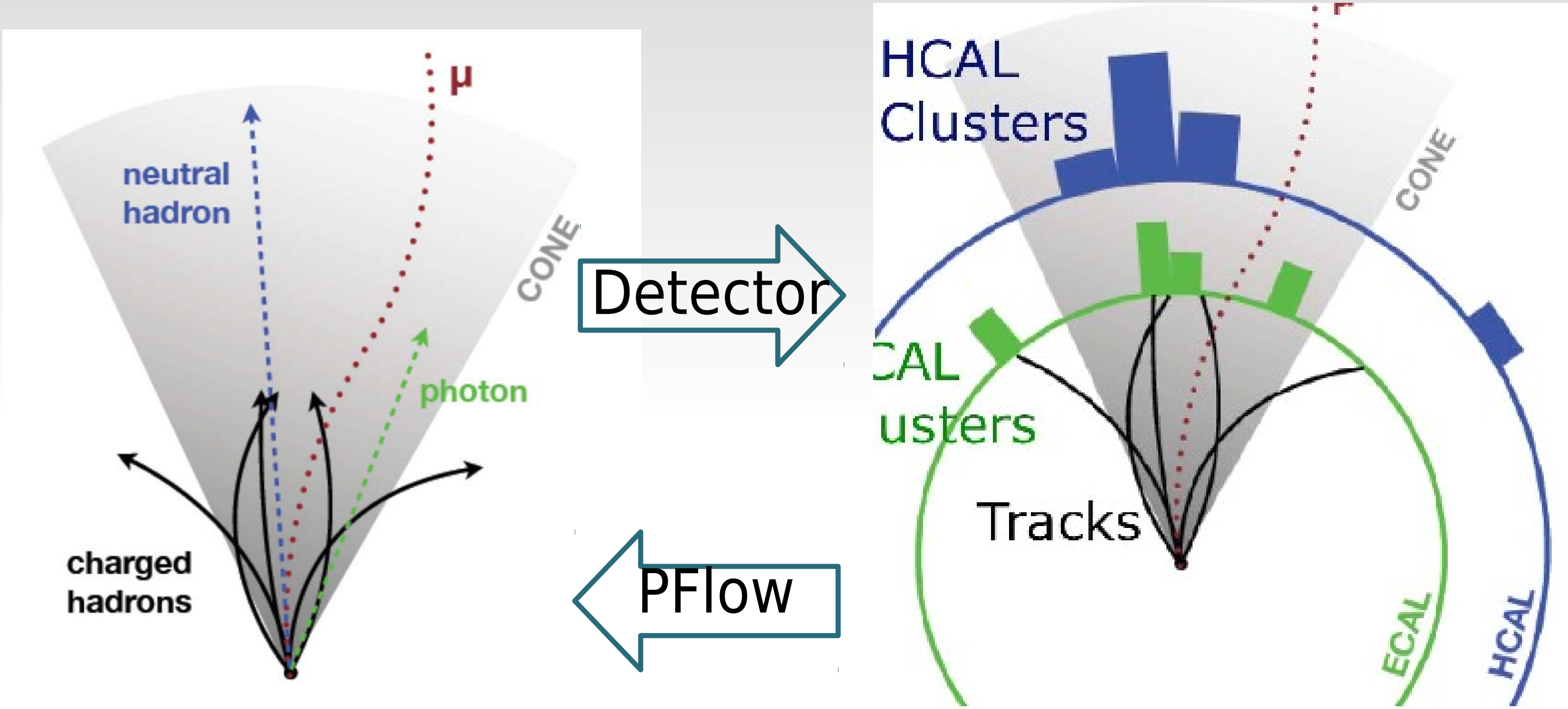
Calo jets in ATLAS

- Calo jets: calibrated topo clusters (heritage of non compensating LAr calorimeters H1/CDF).
- Track jets: tracks coming from the primary vertex.

- Find seed cells above noise threshold.
- Proceed with a 3D clustering around it.
- Consider topo-clusters calibration by reweighting the different layers to bring the response to the EM scale.
- 4-momentum build under assumptions:
  - Massless particles
  - Coming from primary vertex



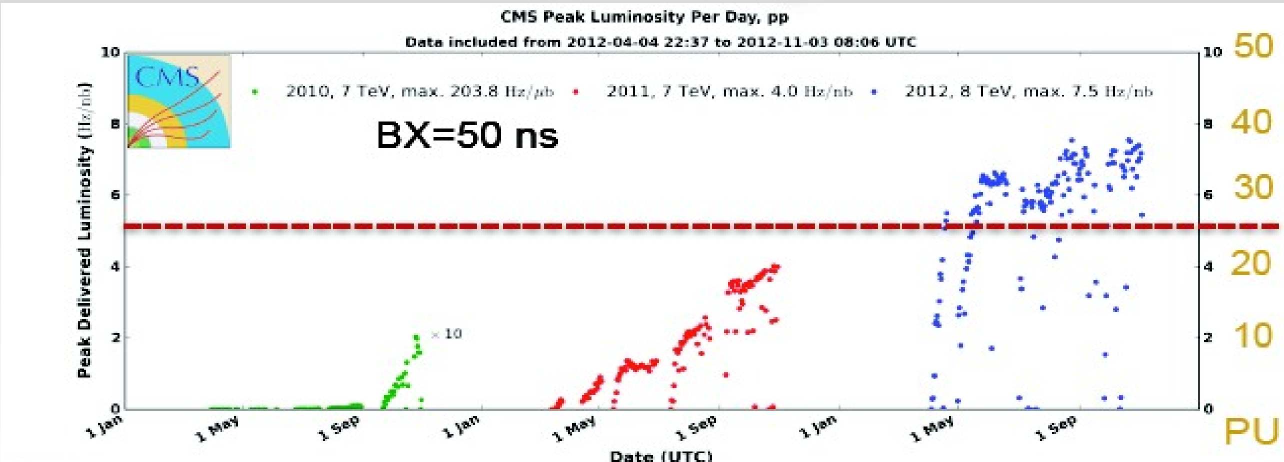
Particle Flow at CMS



Particles

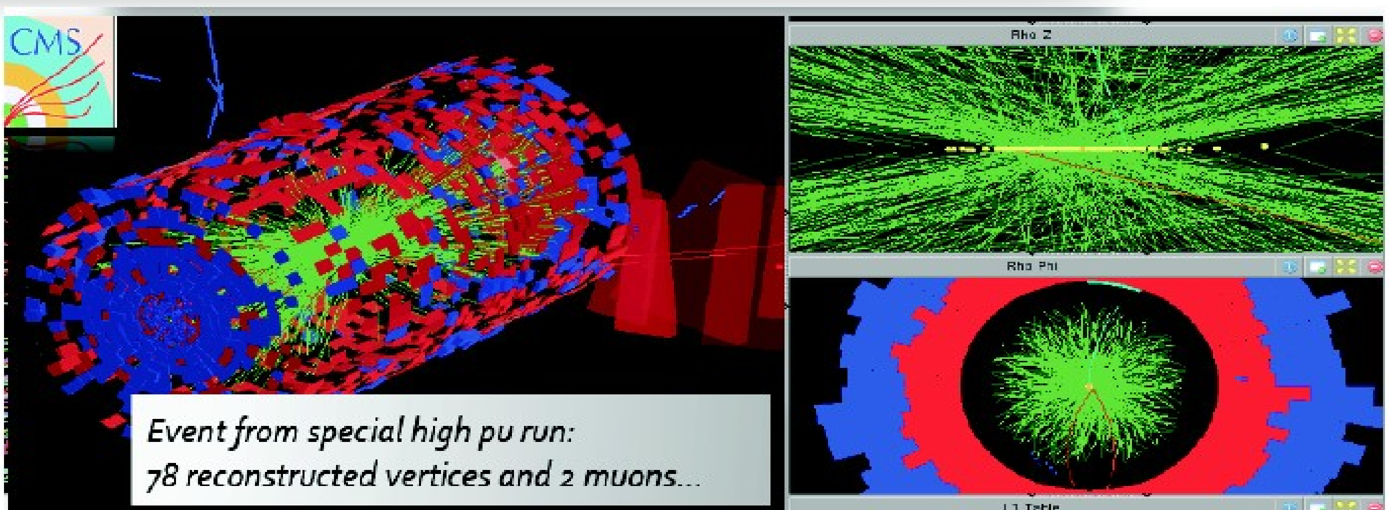
Clusters and tracks

PU

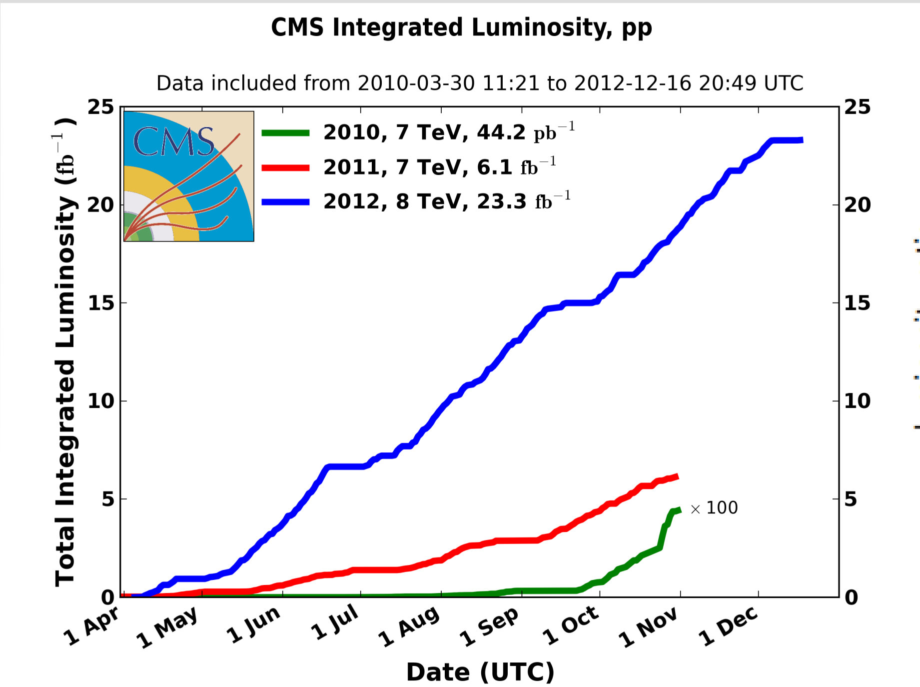


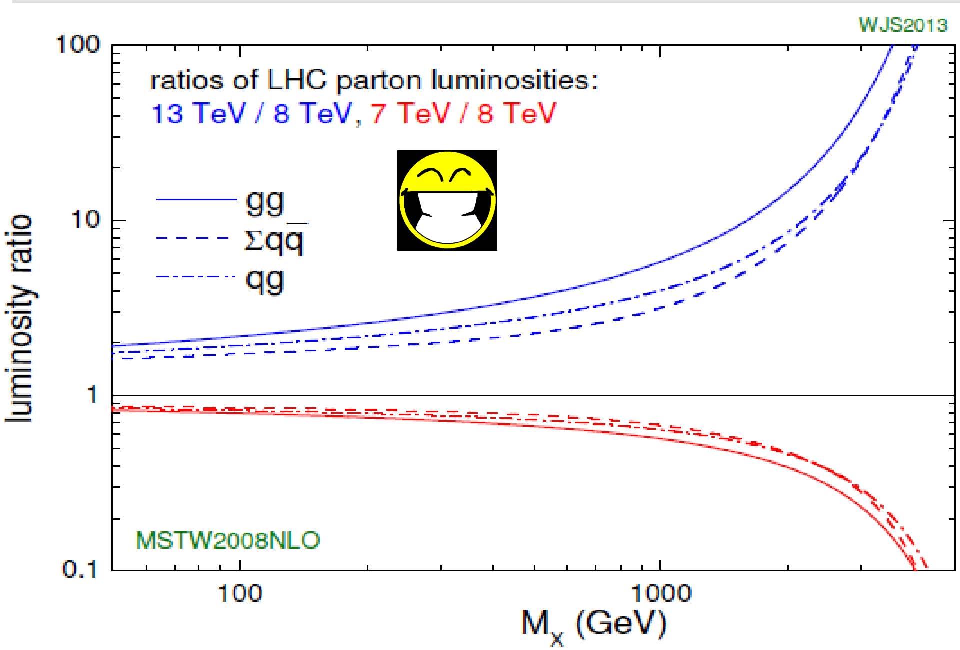
Peak: 37 pileup events

Design value
25 pileup events
($L=10^{34}$, BX=25 ns)



Luminosity





- Produced Higgs bosons: 25 fb-1 * 2 experiments * 20 000 fb ~ 1 million!
- LHC project costed : 5 billion dollars