Issues in matching theoretical predictions with data in photon measurements

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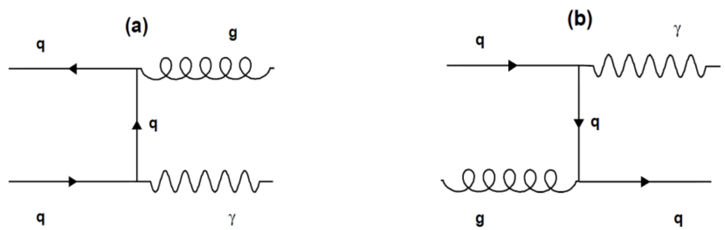
Prompt photon production:

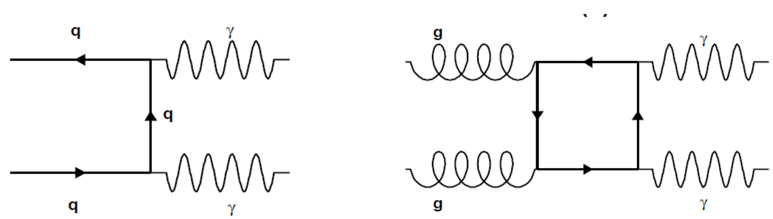
Look at events with one or two photons in the final state : mainly from purely QCD diagrams like the following

- Photon(+X) prompt photon production (LO), Direct process : true (almost) isolated photon!



sensitive to gluon density inside the colliding proton already at LO. Direct probe of the strong process: no complications due to jet related uncertainties

- Double prompt photon production

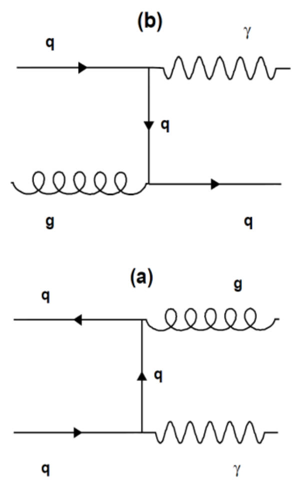


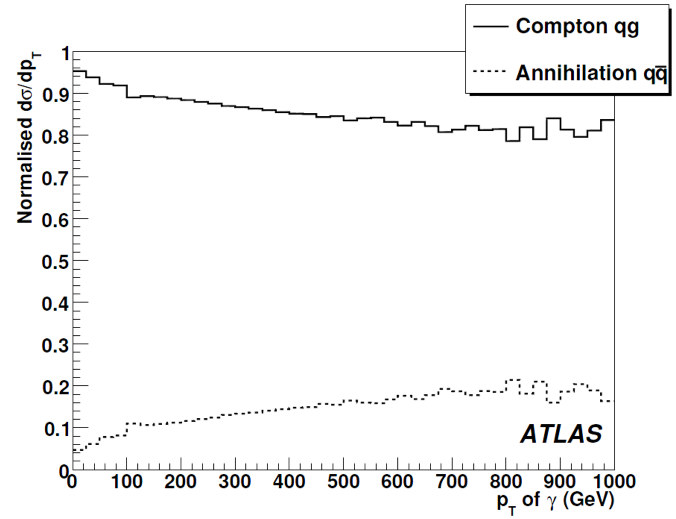
No need to mention that these are the main backgrounds to H gamma gamma

The ‘fragmentation’ issue :

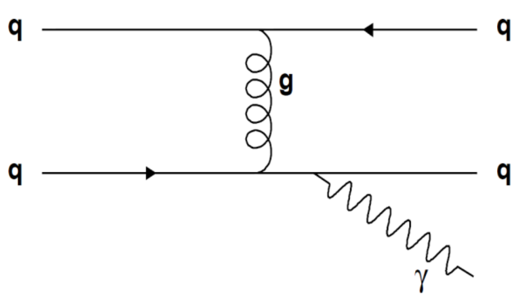
❑ Direct : at LO the contribution to direct prompt photon production is (relatively) easy. It is given by the processes in the plots : all these are order $O(\alpha\alpha_S)$.

❑ Fragmentation (a photon behaves like an anomalous hadron coming from the collinear fragmentation of a coloured high p_T parton)



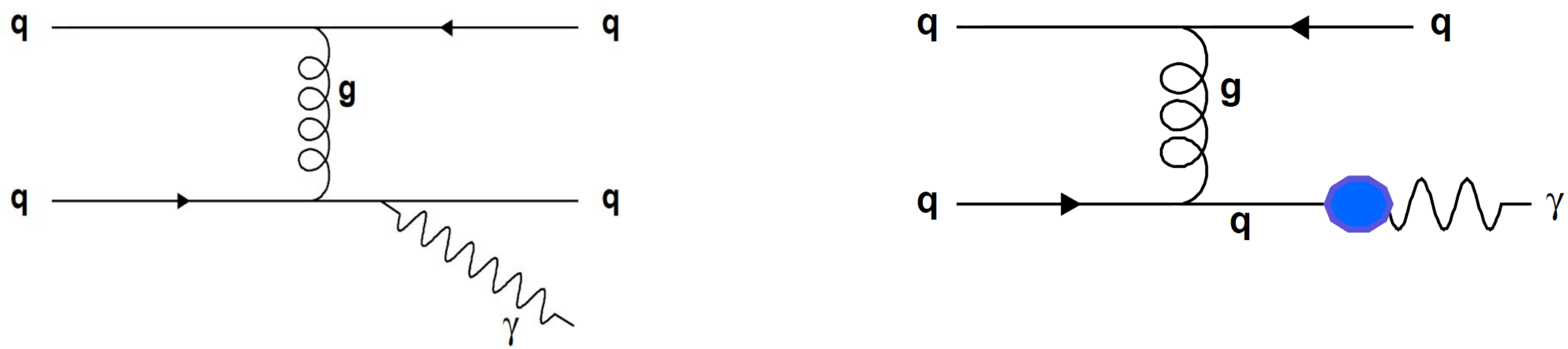


❑ Technically the fragmentation contribution emerges from the HO corrections to Born process: at NLO collinear singularities occur in the calculation of the contribution for example from the subprocess $qq \rightarrow qq\gamma$



These singularities are factorized and absorbed into q/g fragmentation functions into photons $D_{q\gamma}(M_F)$ and $D_{g\gamma}(M_F)$: these functions can’t be calculated and are determined experimentally (Aleph, hep-ex/9708020v1)

The 'fragmentation' within a full NLO calculation



$$d\sigma(AB \to \gamma X) = \sum_{a,b,c,d} \int dx_a \int dx_b F_{a/A}(x_a, M) F_{b/B}(x_b, M) \times \left[d\sigma^{dir} + d\sigma^{frag} \right]$$

$$d\sigma^{dir} = d\sigma^{ab\to cd}(x_a, x_b, \mu, M, M_F)$$

$$d\sigma^{frag} = \int \frac{dz}{z} D_{c/\gamma}(z, M_F) d\sigma^{ab\to cd}(x_a, x_b, \mu, M, M_F)$$

- F(x,M) are the parton distribution functions in the (anti) proton
- D(z,M_F) fragmentation function into a photon (z = $P_T(\gamma)/P_T(c)$)
- σ hard scattering cross section (short distance)
- μ,M,M_F renormalization/factorization (unphysical) scales

At NLO the definition of Direct vs Fragmentation becomes arbitrary (depends on the unphysical parameter M_F which discriminates between the 2 regimes), <u>only the sum is a consistent observable</u>

Signal definition : isolation

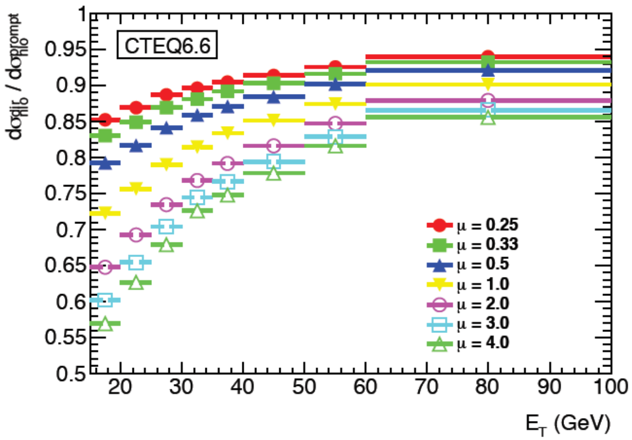
- "To be precise, the collider experiments at the Tevatron and at the forthcoming LHC do not perform inclusive photon measurements. The background of secondary photons coming from the decays of π^0,η, etc., overwhelms the signal by several orders of magnitude. To reject this background, the experimental selection of prompt photons requires isolation cuts" ("CROSS SECTION OF ISOLATED PROMPT PHOTONS IN HADRON–HADRON COLLISIONS" hep-ph-204023)
  - $E_T^{cone} < E_T^{iso}$ where E_T^{cone} is the sum of the energies in a cone R in the $\eta-\phi$ plane and E_T^{iso} can be $\varepsilon_h * E_T^{\gamma}$ or a fixed value E_T^{max}

- From the theoretical calculation point of view, isolation can be implemented without spoiling the properties of the calculation:
  - R has to be not too small (log R terms) : R > 0.3 should be adequate
  - E_T^{iso} allowed not too small : > 1 GeV should make calculations stable

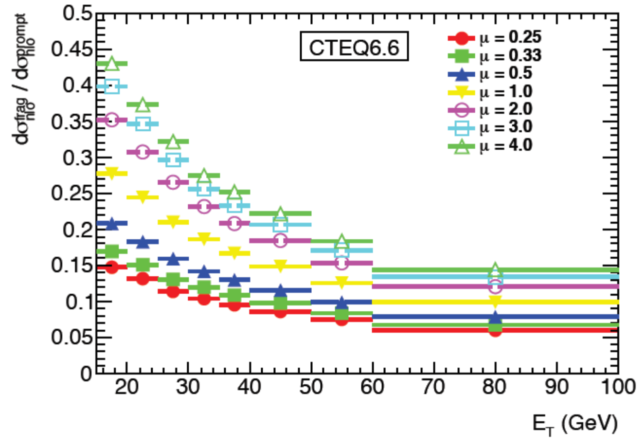
- Isolation also reduces the fragmentation contribution, although it does not kill it completely: a fraction survives with $z \geq (1+\varepsilon_h)^{-1}$. Since <z> ~ 0.6 or less at LHC then the fragmentation contribution is actually rather strongly suppressed
  - <u>The fragmentation contribution is part of the signal definition !</u>

The fragmentation component (from Jetphox)

Direct to prompt cross section ratio

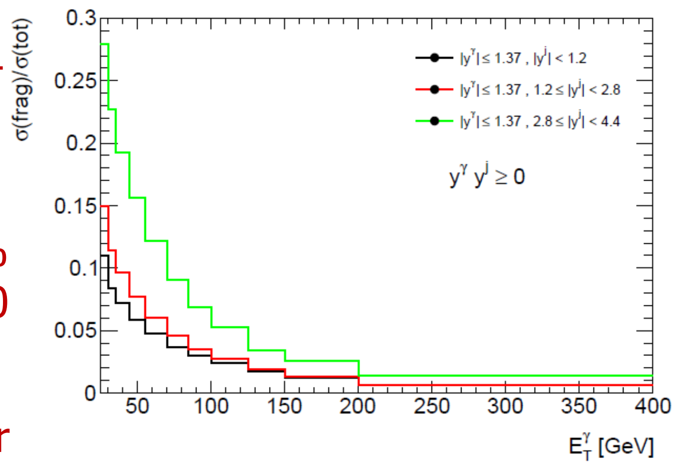


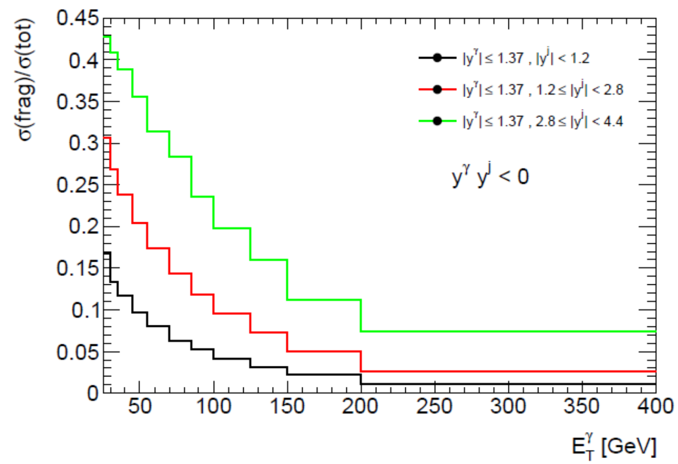
Fragmentation to prompt cross section ratio



- ❑ Fragmentation contribution for inclusive photon production (E_T^{iso} < 4 GeV in a 0.4 cone)
- ❑ Quite strong dependence on μ but still fragmentation is non negligible in the low E_T^{γ} (<50 GeV) region

- ❑Fragmentation contribution in photon+jet production (E_T^{iso} < 4 GeV in a 0.4 cone)
- ❑Only $\mu=E_T^{\gamma}$ is shown but fragmentation can be up to 40% for very forward jet low E_T^{γ} (<50 GeV) region
- ❑Good measurement to test our understanding of frag!





Issues in matching theory with data

- The main point when comparing data to theory is that there's no (yet) a NLO full event generator. The available NLO/NNLO calculations are parton level so they don't include hadronization effects, UE, pileup etc
  - From the photon side this affect the isolation cut choice due to UE/pileup effect
  - From the jet side (in a photon+jet measurement) this affect the hadronization (in jetphox we only have parton jets)

- Fragmentation contribution makes theorists somehow uncomfortable :
  - it can't be computed analytically (it enters through fragmentation functions)
  - Would it be useful to completely kill the fragmentation contribution through a proper isolation definition ? (Frixione isolation)

- Even if we compare the measurements with NLO/NNLO calculations, from the experimental point of view we need a model in full event generators to estimate efficiencies, unfolding factors etc

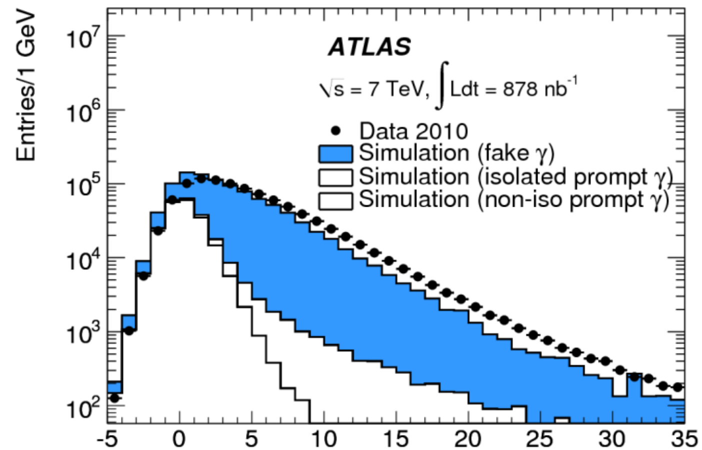
Isolation requirements

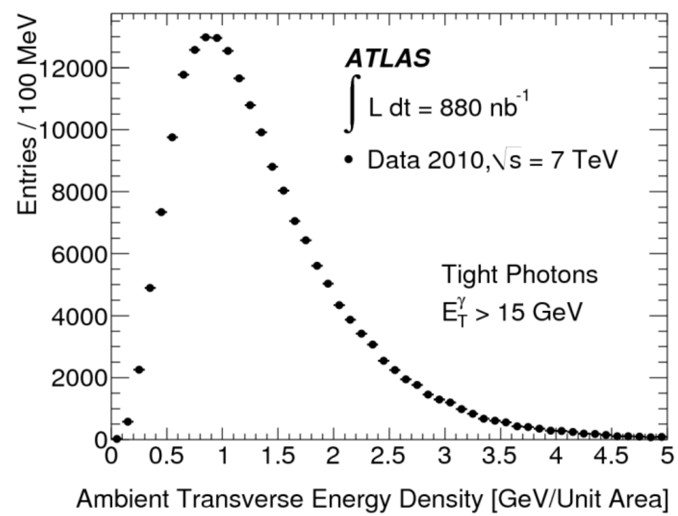
- Maintain a high efficiency for retaining real photons while removing most of the backgrounds coming from jet fragmentation
  - want to require the isolation energy in a cone surrounding the photon be as small as possible while retaining a high (80-90%) efficiency for retaining real photons
- Be relatively independent of the instantaneous luminosity
  - Need a dynamic definition of isolation, taking into account the instantaneous luminosity for that particular event : energy to be subtracted from the isolation cone is determined by looking at either the number of reconstructed vertices for the event, or looking at the p_T density for soft jet production
- Be relatively independent of the photon energy
  - Isolation energy has to increase for high p_T photons since there is a leakage outside of the cluster. This allows additional energy to be anywhere inside the isolation cone, while the *extra* photon energy will be close to the original cluster: frixione isolation naturally implements this
- Match to perturbative predictions
  - Cone isolation is perfectly fine but the parameters have to be choosen carefully in order to preserve consistency with the theory: cone size not too small and energy in the cone not too small (few %?)

Towards a consistent experimental photon isolation definition

Try to make the isolation variable as close as possible to the theoretical one:

- ❑ Calorimeter isolation
  - ❑ Sum of energies in cells in cone R<0.4 in η-φ around the photon, removing the 5x7 cells core
- ❑ Corrections for residual leakage of photon energy outside the cluster into the isolation cone, using single photon MC samples
- ❑ Corrections for underlying event : avoid model dependent UE correction
  - ❑ Using ambient energy density estimated with low-p_T jets, (M. Cacciari, G. P. Salam, S. Sapeta, "On the characterisation of the underlying event", JHEP 04 (2010) 65)
  - ❑ In 2010 data (<NPV>~2) average correction ~540 MeV + ~170 MeV (per vertex). MC : PYTHIA 440 MeV, HERWIG 550 MeV
- ❑ Is this correction 'allowed' ? We modifying data : is this rigorous ?





Parton-particle-experimental isolation

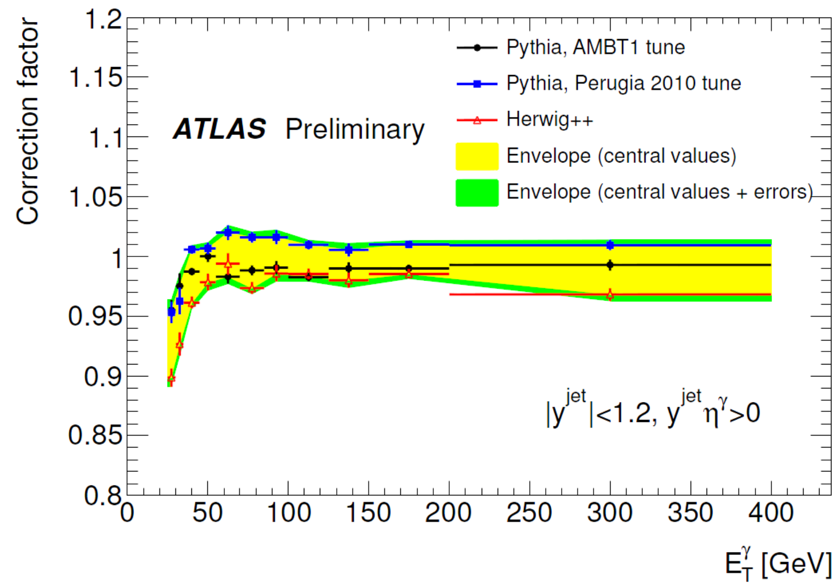
- Even if we correct isolation energy by UE/Pileup the correction might not be perfect and we also have to take into account residual UE/hadronization effects

- in the first papers we used a cone of 0.4 and applied a cut of 3 GeV at the experimental level and 4 GeV at the jetphox level.
  - This correspondence was obtained running on pythia samples and computing the truth isolation at the parton level, particle level and reco level. The parton level cut was choosen in such a way to have the same efficiency of a 3 GeV cut at the reco level.
  - It was shown that parton level isolation is close to particel level isolation.
  - This parton level cut is ~ 4GeV and it was used for JETPHOX.
  - Despite the procedure is not very orthodox the possible variations are well covered by the systematic uncertainties (we vary the cut on Jetphox by ± 1 GeV.)

- Can we simply apply the same cut on data (to corrected isolation) and jetphox and correct jetphox prediction for this? The correction for jetphox extracted running pythia (or any other full event generator) standard and pythia with no UE/HAD.
  - Need to remove parton shower also ? In this way we loose part of the signal !
  - Can we agree on a prescription to threat this ?

More on non perturbative corrections : the photon + jet case

- Jetphox (v. 1.3) can generate four momenta of the photon and 1 or 2 partons in the final state
- Run jet finding algorithm (antikt 0.4) through fast jet to create parton-jets
- But in real life we have particle jets and also a contribution coming from underlying event.
  - Hadronization spread energy outside the cone
  - UE increase the jet energy

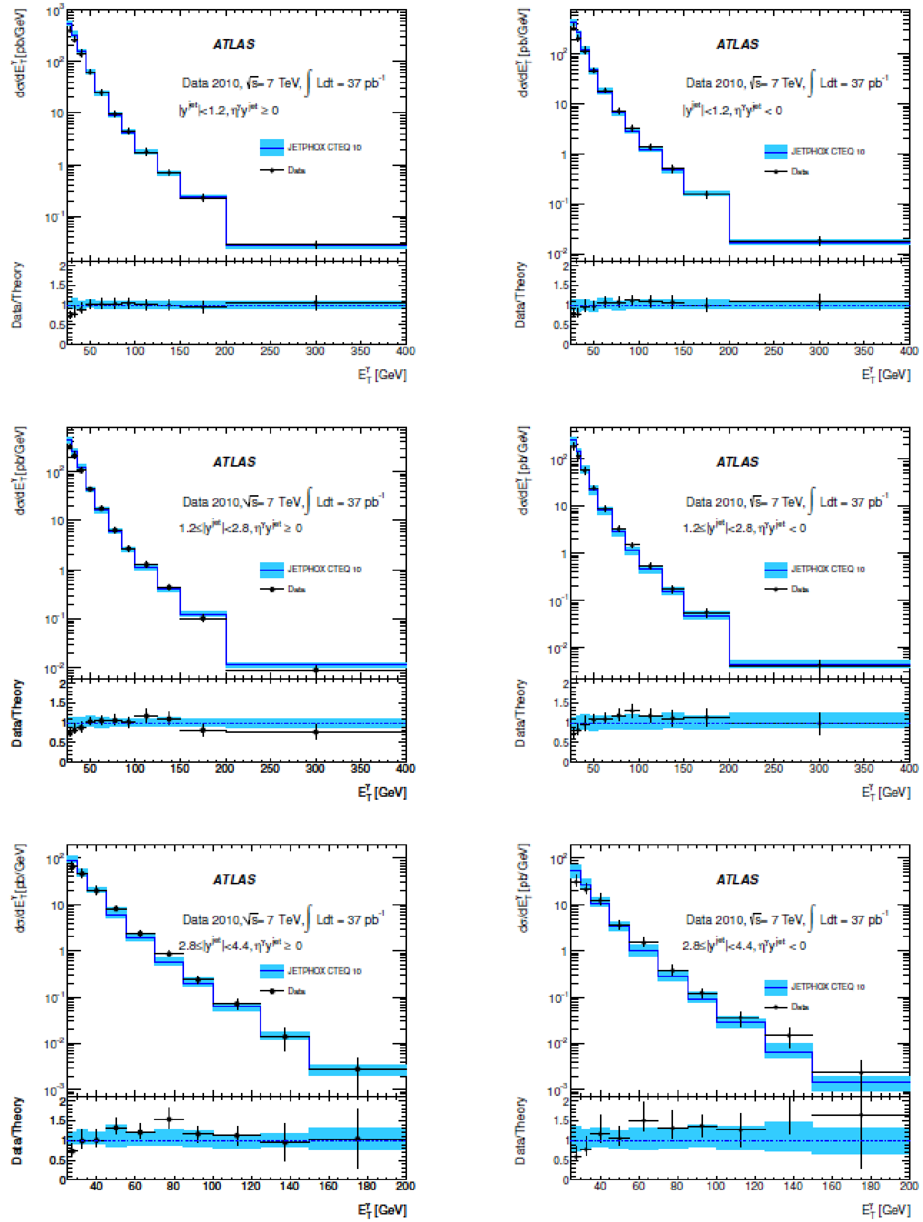


- Correction for jetphox computed running Pythia (2 different tunes) and Herwig++ in nominal conditions and switching off hadronization and UE
  - Not dramatic, but can be up to 10% at low E_T^{γ}
  - Correction is less than 1 : hadronization is more important than UE contribution

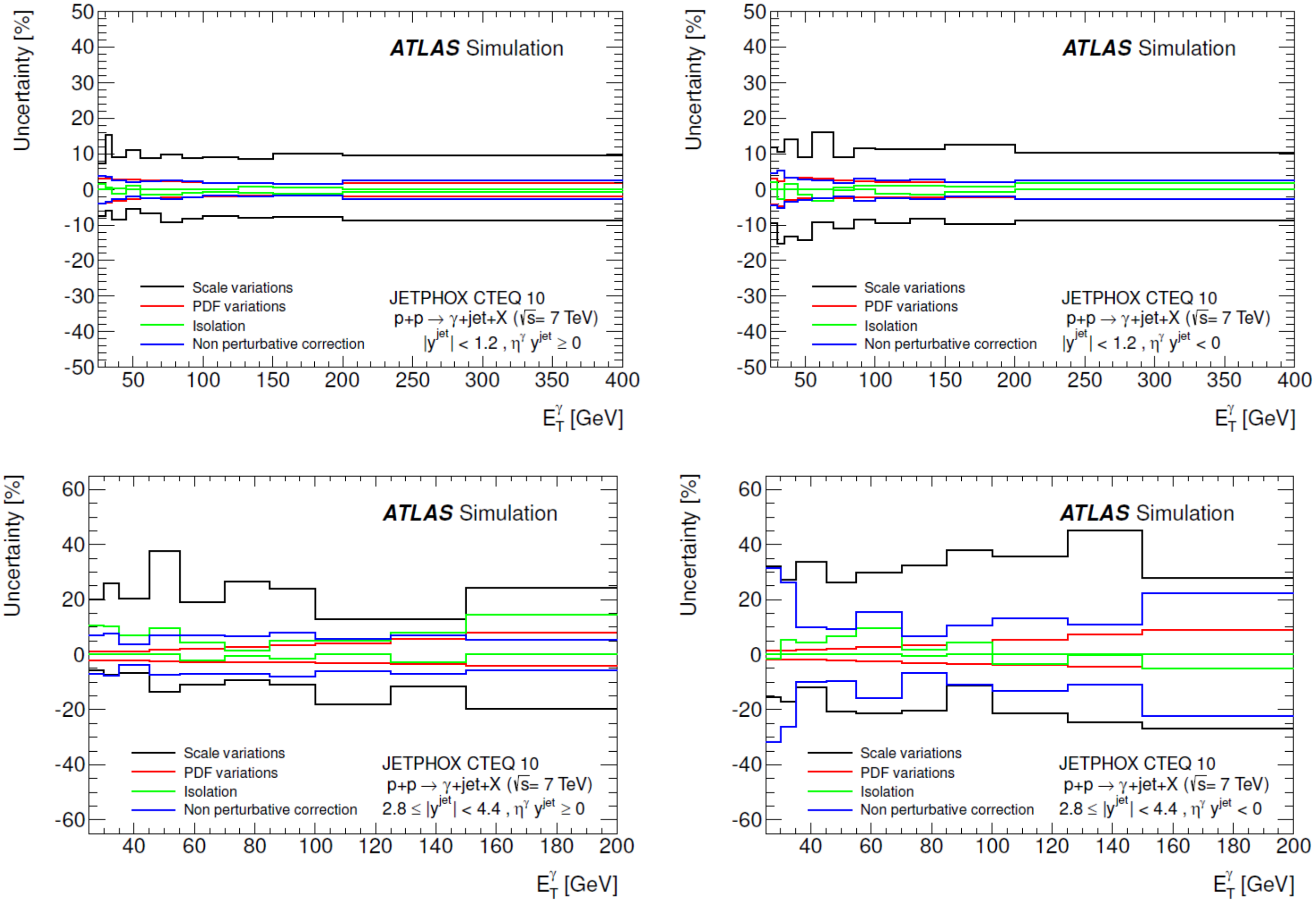
- Central value and uncertainty from the envelope of the values obtained with the 3 generations : is this prescription accettable ?

Photon+jet cross section

- ❑ Theoretical predictions obtained with JETPHOX 1.3 using CTEQ10
  - ❑ isolation cut at 4 GeV in a R=0.4 cone
- ❑ Cross section corrected for non pert. effects :
  - ❑ ~0.9 at low E_T^γ rapidly reaching 1.
- ❑ Systematic uncertainties :
  - ❑ varying scales incoherently from $E_T^\gamma/2$ to $2E_T^\gamma$, 10% up to 40% (jet very forward)
  - ❑ varying PDF eigenvalues within 68% confidence level intervals (5% to 10% maximum)
  - ❑ parton isolation cut varied from 3 to 5 GeV (2% to 10% with a very forward jet)
  - ❑ uncertainty on non perturbative correction (3% up to 20%) using pythia/herwig and different pythia tunes.
- ❑ Also used MSTW2008 and NNPDF2.1 always within the total uncertainty



Photon+jet cross section : theoretical systematic uncertainty



What we learned playing with jetphox :

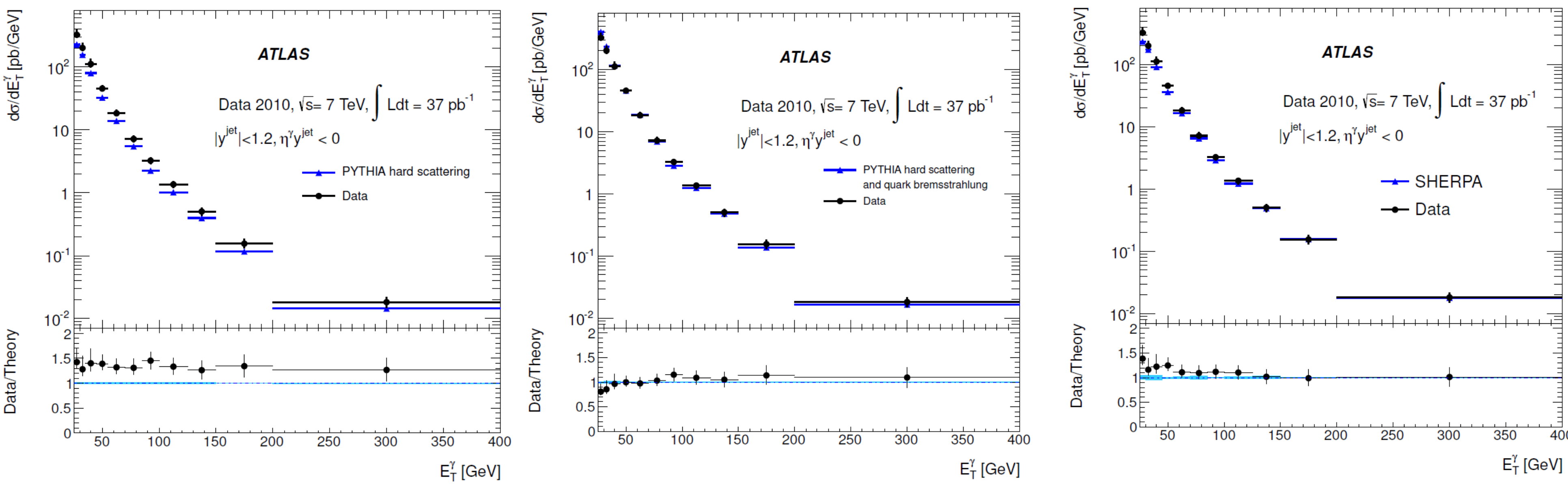
- ❑ (un-coherent) scales variation ($E_T^{\gamma}/2$ to $2E_T^{\gamma}$) always dominant
- ❑ coherent variation of the scales underestimate the true theoretical systematic ?
- ❑ Small impact of PDF and isolation cut variation
- ❑ Non perturbative corrections becomes important at high jet rapidity

❑ In general : is the theoretical systematic uncertainty estimated in this way a good estimator ? In other words : in the low E_T^{γ} discrepancy observed by ATLAS and CDF significant ?

Photon+jet cross section

The main full event generators used in ATLAS has been stressed comparing the predictions in the different configurations against data :

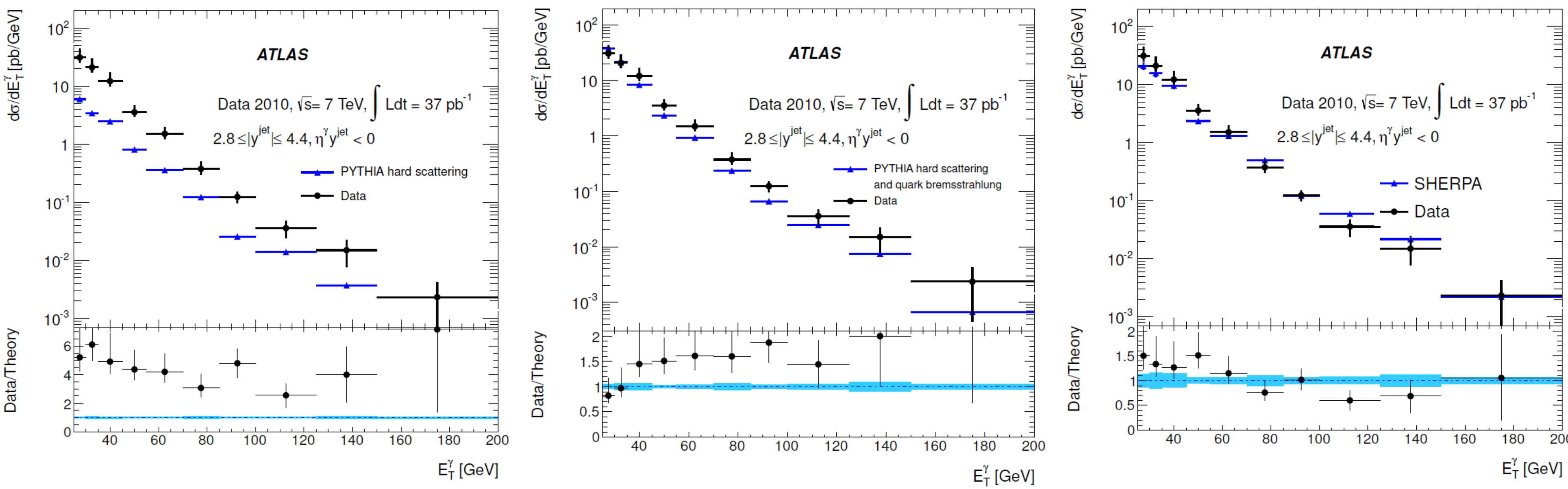
- ❑ pure hard scattering photons (qg->qgamma + qqbar->ggamma) in PYTHIA 6
- ❑ hard scattering + brem photons (from quark radiation in QCD 2->2) in PYTHIA 6
- ❑ Sherpa



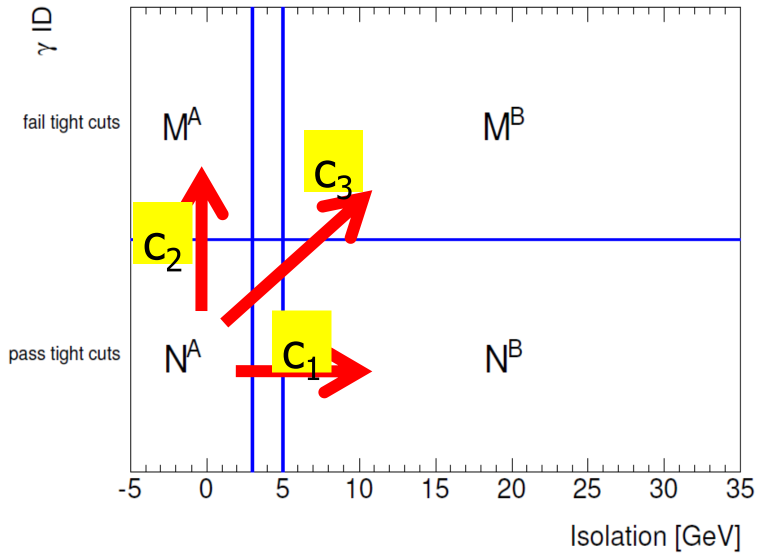
- ❑ Pure hard scattering sample is clearly missing the fragmentation component (central jet, opposite-side configuration)
- ❑ Good agreement with PYTHIA6 hard+brem photons and SHERPA

Photon+jet cross section

- ❑ The trend in the previous slide is even more visible when looking at the very forward jet, opposite side configuration where the fragmentation contribution is larger
  - ❑ pure hard scattering photons sample in PYTHIA 6 is unreliable
  - ❑ hard scattering + brem photons in PYTHIA 6 is not working properly in this 'extreme' configuration (although slightly better than in the previous case)
  - ❑ Sherpa is performing nicely over all configurations

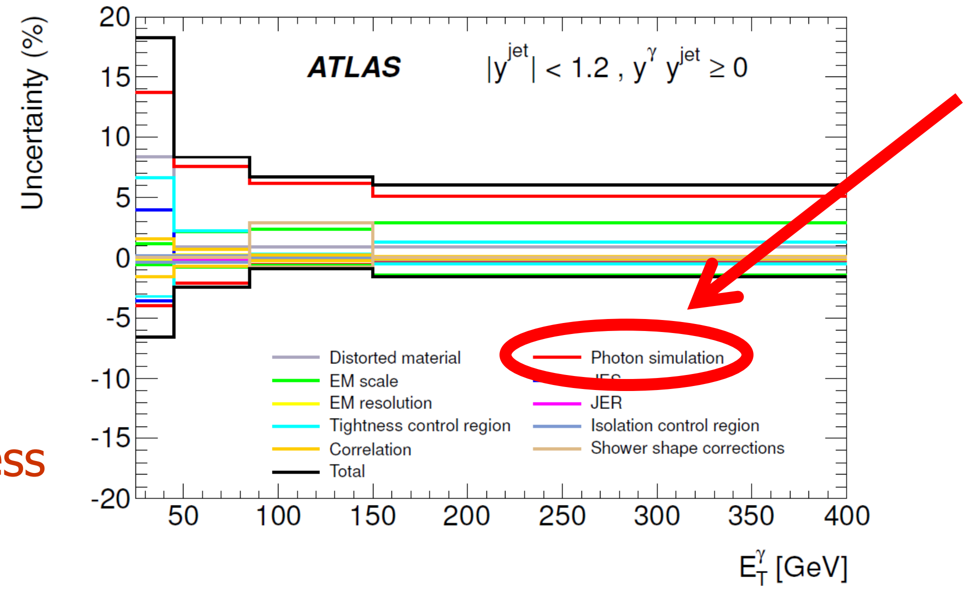


Why we need a model of the fragmentation contribution ?



- ❑ Background contamination in the signal region from an ABCD method. Mostly data-drive but need to consider the signal leakage in control regions -> MC !
- ❑ Using PYTHIA and HERWIG : estimate coefficients using purely hard scattering photons and purely brem photons in both generators
- ❑ Uncertainty from the maximum spread

- ❑ In some cases this becomes the dominant source of systematic uncertainty.
- ❑ How reliable are the descriptions of fragmentation contribution through parton showers in pythia/herwig ?
- ❑ Can we reduce this sytematic trying to be less conservative ?



More sophisticated isolation ?

In the spirit of the cone approach, an alternative definition of the isolated photon has been proposed [27]. After drawing a cone of half-angle R_0 around the photon axis, all the cones of half-angle $R \leq R_0$ are considered; their definition is identical to the one given in eq. (2), with R_0 replaced by R. Denoting by $E_{T,had}(R)$ the total amount of hadronic transverse energy found in each of these cones, the photon is isolated if the following inequality is satisfied:

$$E_{T,had}(R) \leq \epsilon_\gamma p_{T\gamma} \mathcal{Y}(R), \tag{4}$$

for *all* $R \leq R_0$. A sensible choice for the function $\mathcal{Y}$ is the following

$$\mathcal{Y}(R) = \left(\frac{1 - \cos R}{1 - \cos R_0} \right)^n, \qquad n = 1. \tag{5}$$

It has been proved in ref. [27] that such a choice allows the definition of an isolated-photon-plus-jet cross section, which is infrared-safe to all orders in QCD perturbation theory and still does not receive any contribution from the fragmentation mechanism. In this case, therefore,

- This isolation criterium works in theory but not exactly from the experimental point of view: the photon has a finite size in our calo and we can't go arbitrarily close

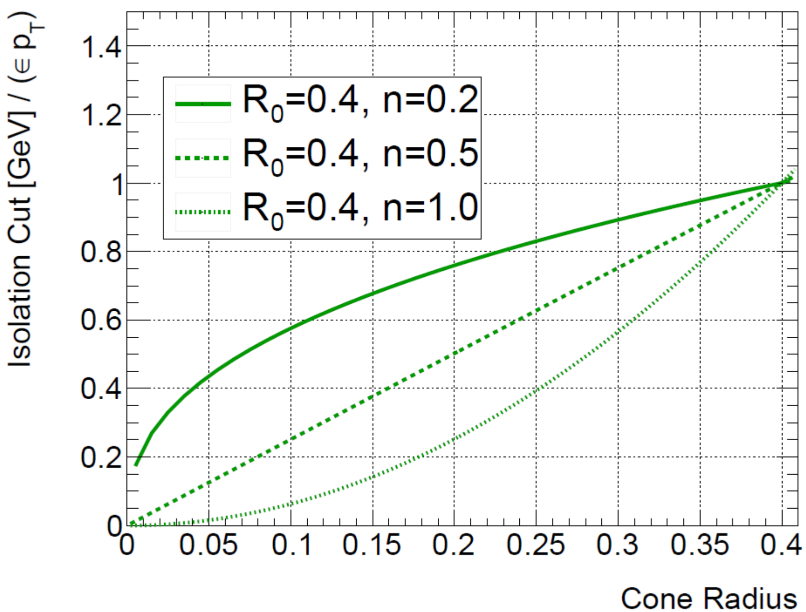
- In some configurations of n (small) and ε_γ the performance in terms of signal efficiency – background rejection is accettable

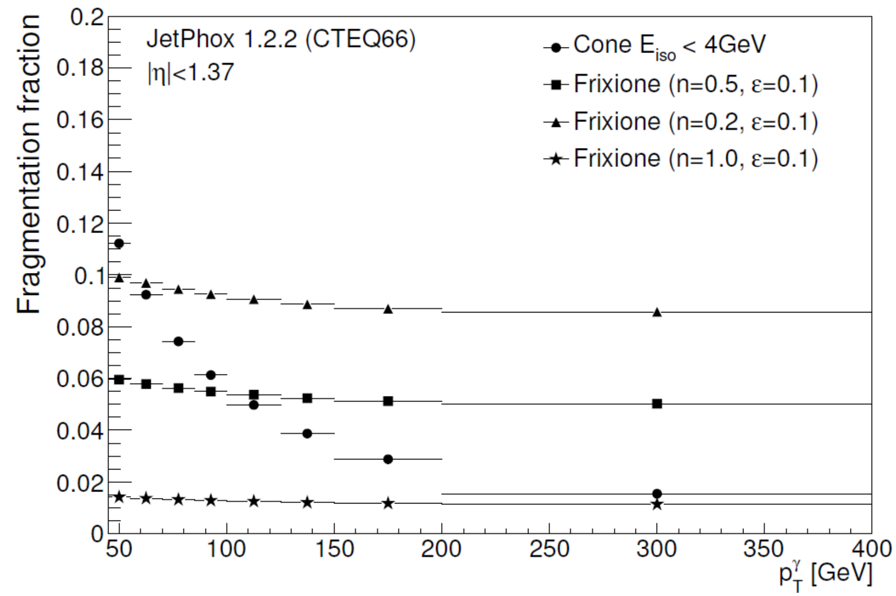
More on isolation : Frixione prescription

❑ A proposal by S. Frixione in 1998 (hep-ph/9809397) to get rid completely of the fragmentation contribution: considering all possible R from R_0 to 0

$$E_T^{isolation}(R) < (\epsilon_s \cdot E_T^{\gamma}) \cdot \left(\frac{1-\cos(R)}{1-\cos(R_0)}\right)^n$$

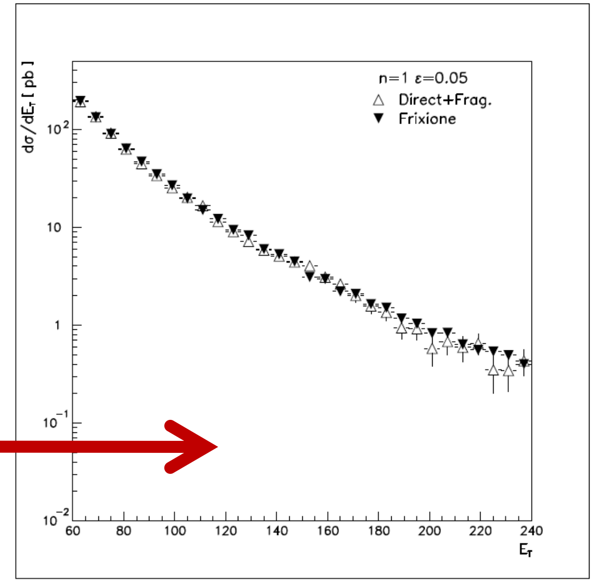
❑ Modified to allow a minimum central cone (the size of the photon) and the fact that the nested cones are discrete

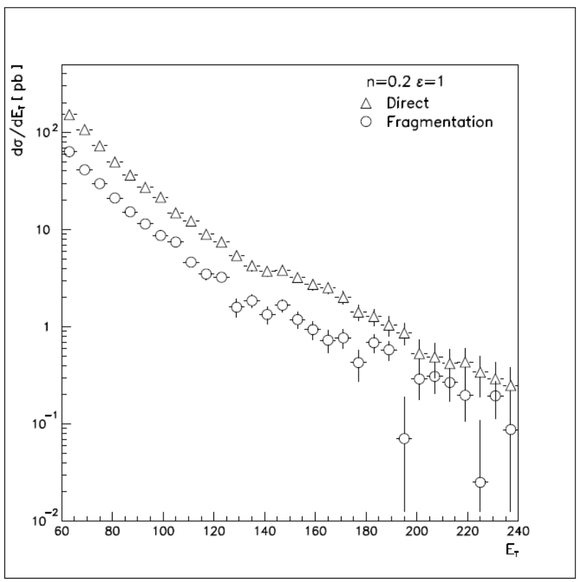


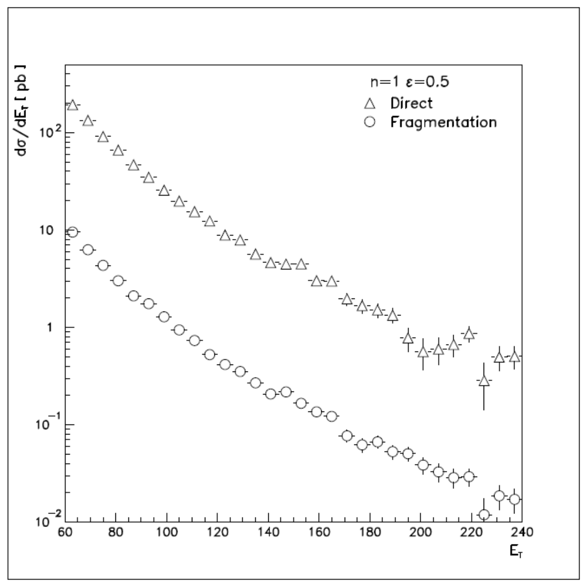


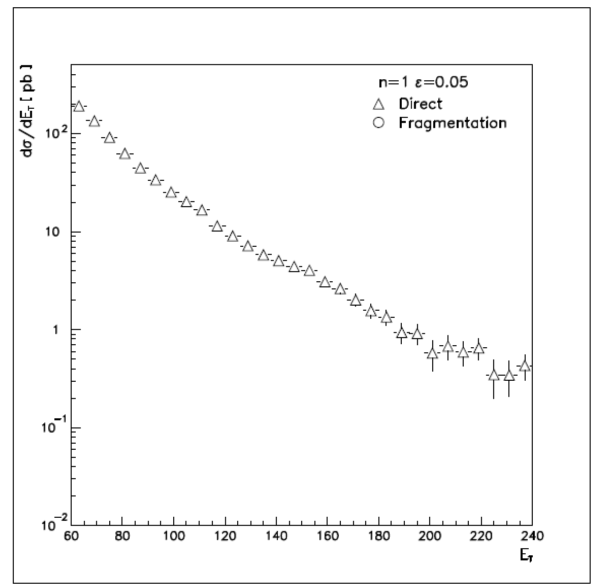
A bit more about isolation

- Frixione prescription actually kill the fragmentation contribution (especially large n and small ε)
- Frixione prescription only driven by theoretical reasons:
  - From the experimental point of view we can only define a finite set of discrete nested cones
  - Photon has a non-zero size: minimum cone ~0.1
  - Does it still preserve the good theoretical behaviour ?
- The 'experimental' version of the Frixione isolation still works





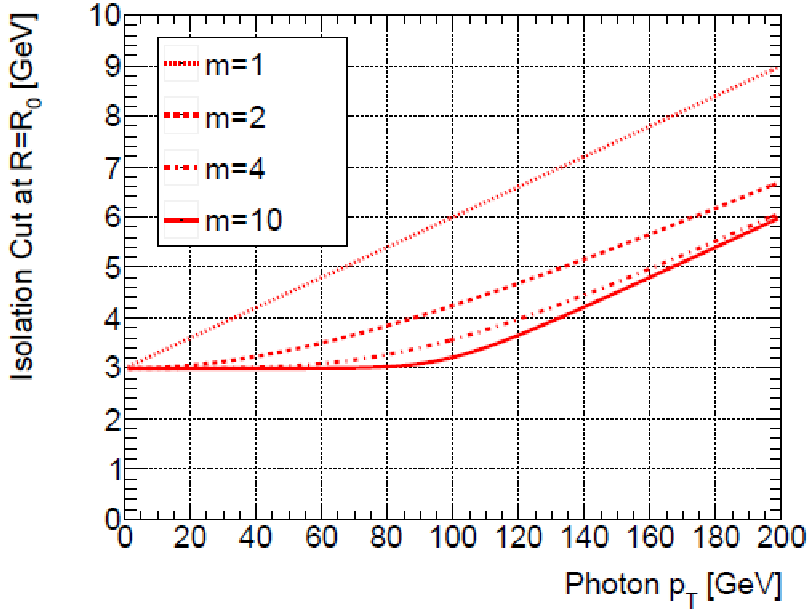


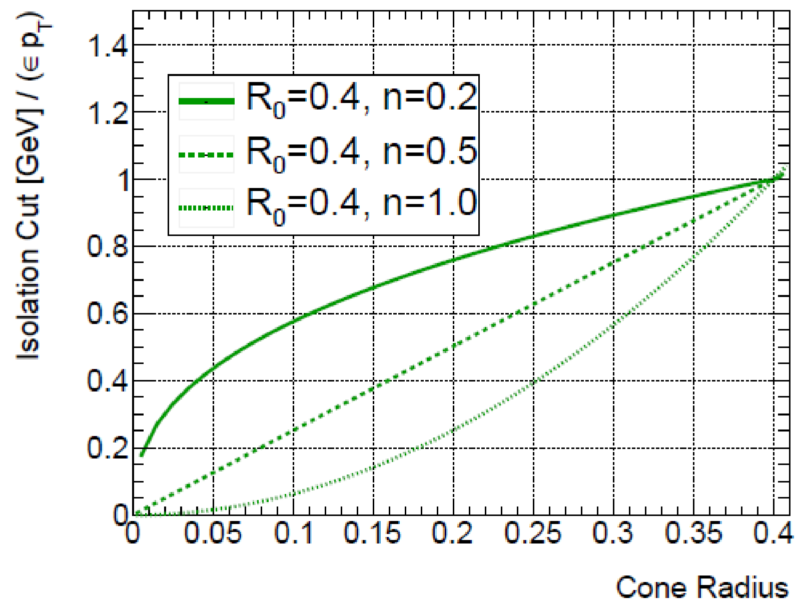


More on isolation : generalized Frixione isolation prescription (E. Pilon)

- In the original Frixione prescription for a given R the amount of energy allowed in the cone goes to 0 when E_t^γ goes to 0, not suitable for experiments

$$E_T^{\text{isolation}}(R) < \left(\left(E_T^{R_0}\right)^m + \left(\epsilon_s \cdot E_T^\gamma\right)^m \right)^{1/m} \cdot \left(\frac{1-\cos(R)}{1-\cos(R_0)} \right)^n$$





- This formulation should satisfy everyone : plateau at low pt and allow more energy in the isolation cone at high pt

Conclusion : points for the discussion

The proper matching between theoretical predictions and data is not a trivial task:

- From the experimental point of view : is the attempt to clean the measured isolation for non perturbative effects acceptable/reasonable/recommended ? Is UE subtraction using energy density ok ? Anything else ?
- How to properly relate the parton level cut to the experimental one ?
- How to properly compute non-perturbative corrections (especially for jets) ?
- Or in any case are we always swamped by the scale uncertainty ?
- Model of photon fragmentation in full event generators is mandatory :
    - Can we use radiation photons in Pythia/Herwig/other ?
- Is there any gain to move to a more sophisticated isolation criterium (i.e. getting rid completely of fragmentation contribution) ? Non negligible amount of work for experiments to re-asses the analysis and systematic!

Issues in photon cross sections measurements : isolation

- Isolation is a key quantity in photon analysis : it's not only an additional selection cut, it has to do with physics.
  - Reject the background and reduces the impact of the fragmentation contribution
  - Theorists tend to prefer a loose cut in large cones to avoid instabilities to large
  - Experimentalist tend to prefer exactly the opposite

- Facts on isolation :
  - photon has an intrinsic size : can be raftly ~0.05
  - some % of the photon energy might leak into the isolation cone
  - underlying event does contribute some energy inside the cone : in situ subtraction with (eg) energy density technique (ATLAS)
  - detector effects (noise) can contribute some energy inside the cone

- A large number of flavors are used in different experiments:
  - Calorimeter isolation, track based isolation with different tunings of the parameters (size of the core to be removed, cut on tracks pt etc…)
  - The cut is also applied in different ways : fixed or pt dependent cut.
  - A fixed cut might become too tight at high p_T.
  - A linear p_T dependent cut might become too tight at low p_T (where some instrumental effects might provide some extra energy)