Treatment of leptons in experiments

- **In ATLAS, it was in 2014 that it became clear that we needed to harmonise the treatment of leptons (at the generator level only!) as much as feasible. This was prompted mostly by complex exclusive measurements in the SM (V+jets) and top groups, where the run-1 analyses had encountered real issues with ambiguities and overlaps when dealing with final-state particles.**
- **At the same time, confusion at some level was created because some colleagues (experimentalists and theorists!) made loose statements of the type „ATLAS and CMS measure bare muons and dressed electrons"**
- **The outcome of these discussions was that we should publish always results with all three flavours of leptons, with a tendency to base the main plots on dressed leptons for exclusive measurements and Born leptons for inclusive precision DY measurements**
- **Today we see that we need to further discuss the precision DY case because we see now MC tools with state-of-the-art. QCD and QED/EW calculations implemented: with such tools, we have to treat the topic with even more care than done until now.**
- **Here I will give some examples of where we stand in ATLAS in this context**

Where are we with truth in DY MC?

- There was a lively discussion of Born versus dressed versus bare leptons, mostly because of some perhaps natural tendency to believe that one size fits all ☺

- I have recapped in the next few slides some of the main points related to these discussions
  - usually the most precise theoretical calculations in EW physics are not available in the „modern" MC generators.

    Today we know much more about precision DY measurements than we did in 2014:
    Z pT/phi* at 8 TeV, W/Z 2011 measurements, Ai measurements, W mass measurement, Z3D measurements, plus all the work ongoing on s2w 8 TeV measurements
    But our baseline MC remains Powheg+Pythia and it has a number of deficiencies. It is neither easy to remove these (see later slides) nor easy to move to another better event generator.

Where are we with truth in DY MC?

- Even though it was already rather obsolete in 2014 to look at lepton truth matching based on pre-data-taking releases and studies, I have yet to see appear an up-to-date table based on our current CP Z and W samples:

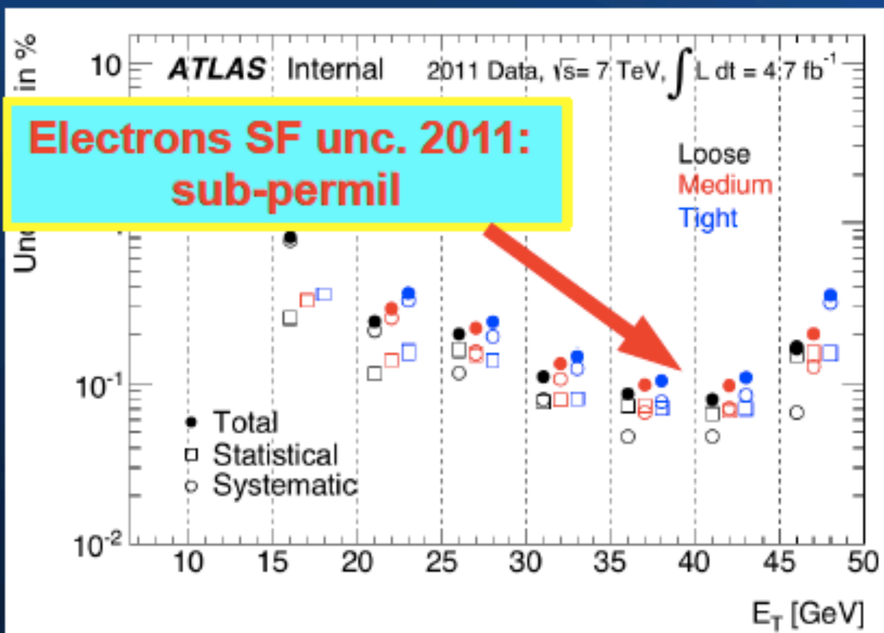
  a) this is important to eg establish that, unlike other CP groups, we do not need MC-dependent scale factors even when quoting uncertainties at the per mil level

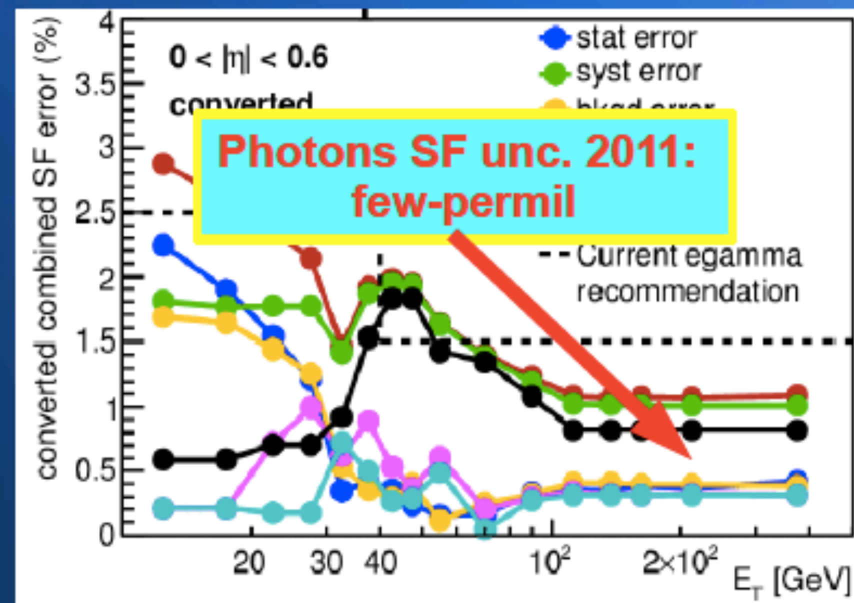
  b) it is also important to close the loop once again with the energy scale and resolution uncertainties on the leptons since it has been claimed (reasonably but not to my taste demonstrated in an ironclad way) that residual FSR mismodelling effects are perhaps accounted for in our calibration and scale factor recipes.

  c) when the FSR modelling issues (experimental and theoretical) have been considered explicitly in the past, the uncertainties quoted have probably been conservative at the time, but they were at the level of 0.3%, i.e. potentially dominant over others! See more in later slide.

Where are we with truth in DY MC?

- Quoted systematics may be small now!
  - and with them our tolerance for different physics modeling





Where are we with truth in DY MC?

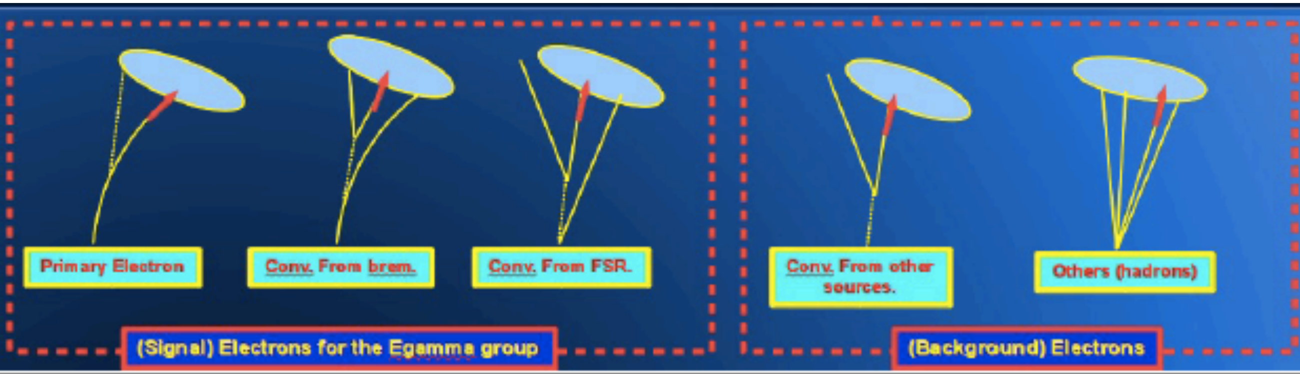
Rel 15

Electron origin (%) E_T = 35-40 GeV Probe for $Z\rightarrow ee$	$Z\rightarrow ee$ Tight tag All ee	$Z\rightarrow ee$ Tight tag e^+e^-	$W\rightarrow e\nu$ Correct e charge	$W\rightarrow e\nu$ Any e charge	$Z\rightarrow ee$ Tight tag Medium probe
Primary electron	94.6 ± 0.04	96.9 ± 0.03	96.7 ± 0.02	94.0 ± 0.03	99.2 ± 0.01
Conversion from primary electron	4.1 ± 0.02	2.3 ± 0.02	2.5 ± 0.01	4.4 ± 0.01	0.7 ± 0.01
Conversion from FSR photon	0.5 ± 0.02	0.3 ± 0.02	0.3 ± 0.01	0.5 ± 0.01	<< 0.1
Total of above	99.2 ± 0.02	99.5 ± 0.02	99.5 ± 0.01	98.9 ± 0.01	99.9 ± 0.01
Conversion from other sources	0.1 ± 0.02	0.1 ± 0.02	0.1 ± 0.01	0.2 ± 0.01	<< 0.1
Undefined (mostly hadrons)	0.7 ± 0.02	0.4 ± 0.02	0.4 ± 0.01	0.9 ± 0.01	0.1 ± 0.01

Signal Electrons

9

Where are we with truth in DY MC?



Rel 15

Efficiency (%) E_T = 35-40 GeV Probe for Z→ee	Z→ee Tight tag All ee	Z→ee Tight tag e^+e^-	W→eν Correct e charge	W→eν Any e charge
Primary electron	95.1 ± 0.06	95.1 ± 0.06	95.4 ± 0.03	95.4 ± 0.03
Conversion from primary electron	55.6 ± 0.6	55.1 ± 0.9	55.6 ± 0.5	56.3 ± 0.4
Conversion from FSR photon	39.6 ± 1.6	36.6 ± 2.12	40.6 ± 1.4	42.4 ± 1.1
Average of above	93.2 ± 0.07	94.0 ± 0.06	93.8 ± 0.04	92.4 ± 0.04
Conversion from other sources	4.0 ± 1.4	5.1 ± 2.3	4.0 ± 1.0	3.4 ± 0.7
Undefined (mostly hadrons)	1.8 ± 0.4	1.7 ± 0.7	3.7 ± 0.4	2.2 ± 0.2

Signal Electrons

10

Born versus dressed (round 3)

- **Coming back to FSR uncertainties:**

The QED FSR model used (usually Photos for precision measurements) has its own uncertainties but it also impacts the detector-level corrections and appropriate systematics need to be quoted here.
Only estimates ever done as far as I know for ATLAS were for initial W/Z paper and for first Z phi* paper at 7 TeV and later on for 8 TeV phi* paper.

Very conservatively, an uncertainty of 0.3% was assigned (dressed or Born is irrelevant here) for the possible impact of detector mismodelling on FSR in the initial W/Z paper (and was reduced to negligibly small in W/Z 2011 paper, I am almost sure there was in the end no effort available to quantify this properly)

In 7 TeV Z phi* paper, the theoretical uncertainty was conservatively evaluated to be 0.3% based on comparisons of Photos versus Sherpa with the help of Zbyszek Was (thesis of Oanh).

Born versus dressed (round 3)

Systematic uncertainties: QED FSR (1/2)

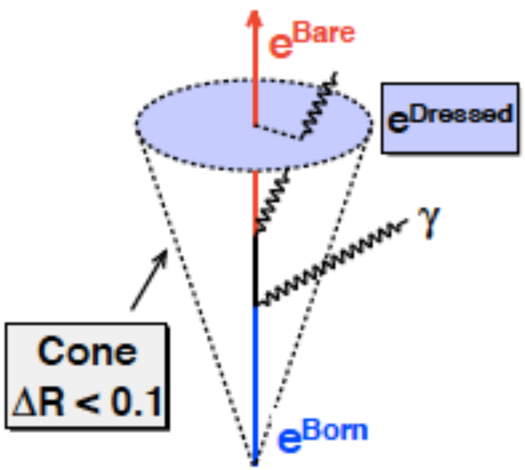
- $Z \to ee$ POWHEG+PYTHIA6 (reference signal MC sample) uses PHOTOS to simulated QED FSR
(PHOTOS is a process-independent module for adding multi-photon emission)

- $Z \to ee$ SHERPA uses YFS formalism to simulated QED FSR
(YFS-resummation of soft logarithms for QED radiation)

$\to$ Compare $Z \to ee$ POWHEG+PYTHIA6 with $Z \to ee$ SHERPA

- To extract pure QED FSR effect:

$$\mathrm{QED_{Bare}} = \frac{\left(\left(\frac{1}{\sigma}\right)_{fid} \left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta\,i}}\right)_{fid} \right)_{\mathrm{Bare}}}{\left(\left(\frac{1}{\sigma}\right)_{fid} \left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta\,i}}\right)_{fid} \right)_{\mathrm{Born}}}$$

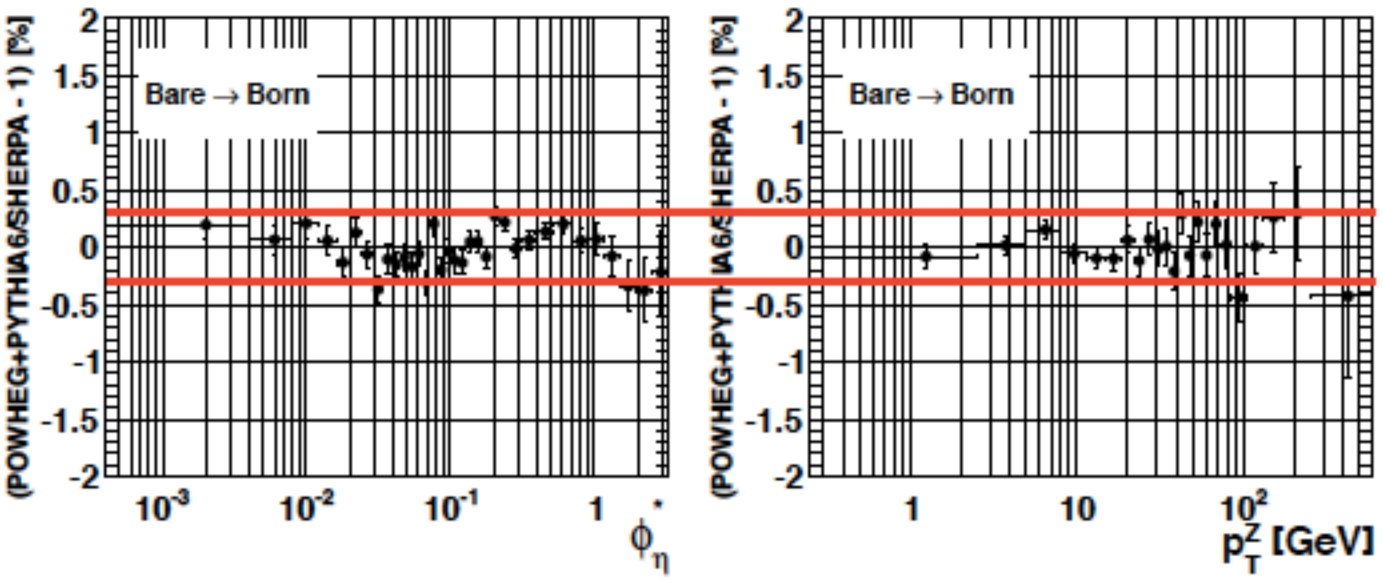


Born versus dressed (round 3)

Systematic uncertainties: QED FSR (2/2)

- To extract systematic uncertainty:

$(\text{QED}_{\text{Bare}})_{\text{POWHEG+PYTHIA6}} \big/ (\text{QED}_{\text{Bare}})_{\text{SHERPA}} - 1$



→ Uncertainty of 0.3% for ϕ^*_η (p_T^Z) distributions at the "Born", "Dressed" and "Bare" levels.

(This conclusion was discussed with the authors of PHOTOS.)

Born versus dressed (round 3)

- **Coming back to FSR uncertainties:**

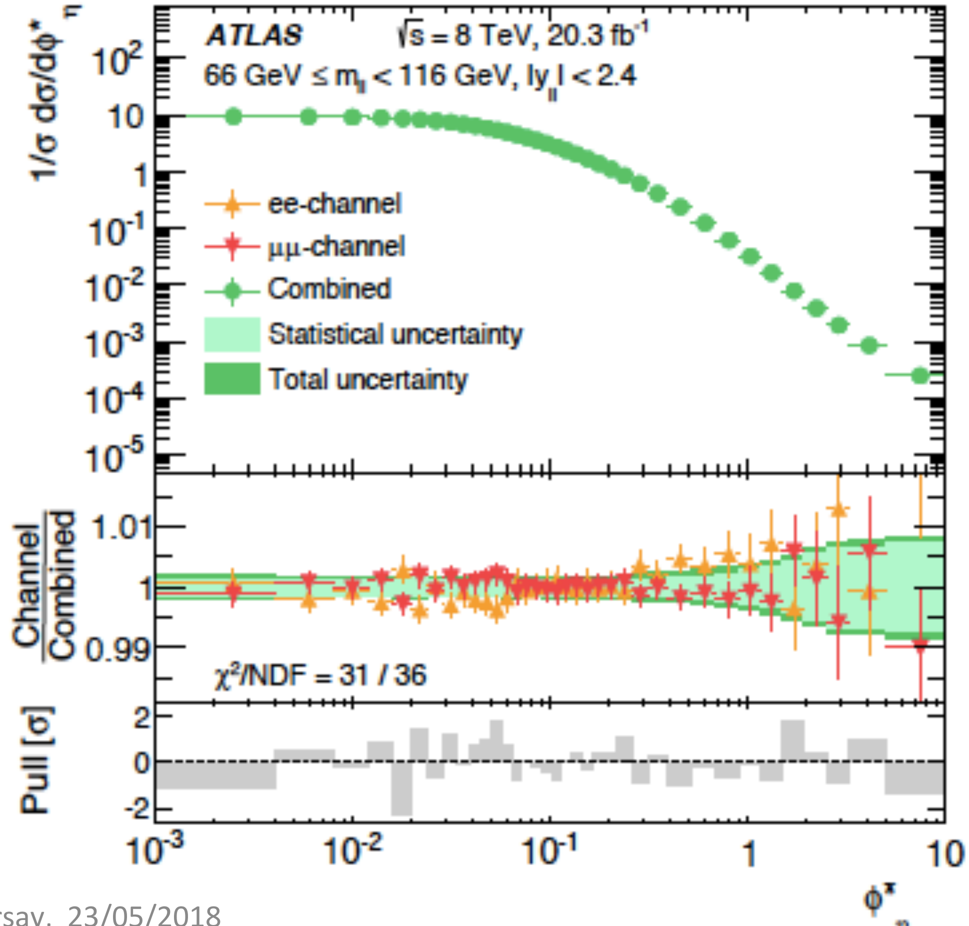
  In the 8 TeV paper, the modelling uncertainties dues to FSR were also looked at between Photos and Sherpa and found to be a dominant source

The systematic uncertainty due to the choice of signal MC generator used to correct the data is evaluated as follows. For ϕ^*_η an uncertainty envelope is chosen that encompasses the difference in the bin-by-bin correction factors obtained using any individual signal MC sample compared to the central values. (As described in Section 3.5, the central values are obtained from an average over all available signal MC samples.) For $p_{\mathrm{T}}^{\ell\ell}$ the uncertainty is quoted as the difference in the results obtained when unfolding the data with SHERPA, as compared to POWHEG+PYTHIA, which is used for the central values. This source results in a significant contribution to the systematic uncertainty in both ϕ^*_η and $p_{\mathrm{T}}^{\ell\ell}$ for the $m_{\ell\ell}$ region around the Z-boson mass peak. The systematic uncertainty on the Born-level measurements below the Z-boson mass peak receives a significant contribution due to the differences in FSR modelling between PHOTOS and SHERPA.

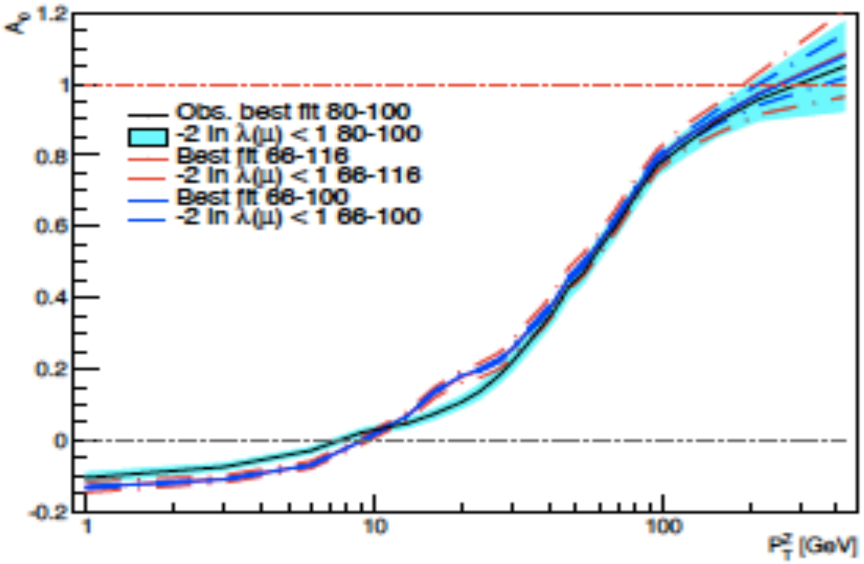
Born versus dressed (round 3)

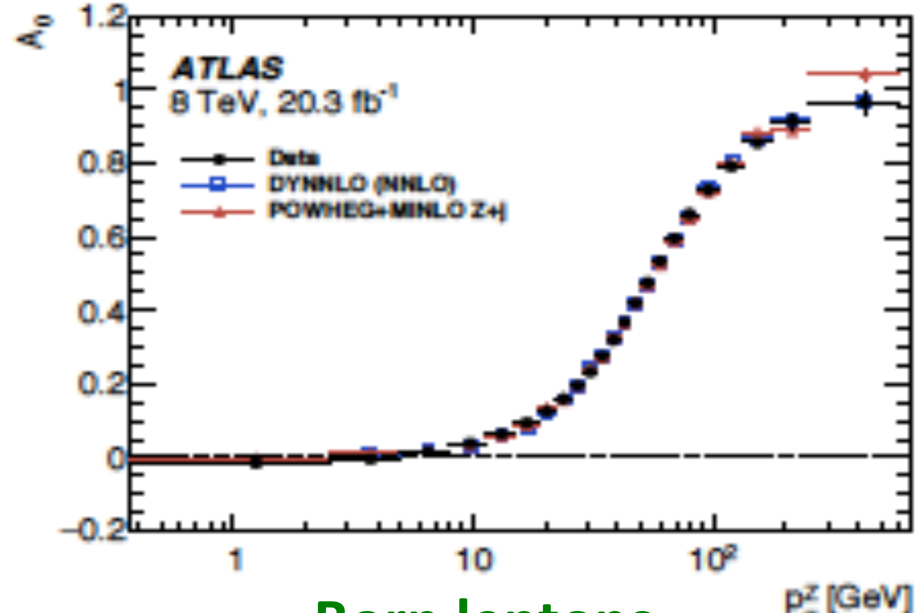
- **Coming back to FSR uncertainties:**

  In the 8 TeV paper, the modelling uncertainties dues to FSR were also looked at between Photos and Sherpa and found to be a dominant source



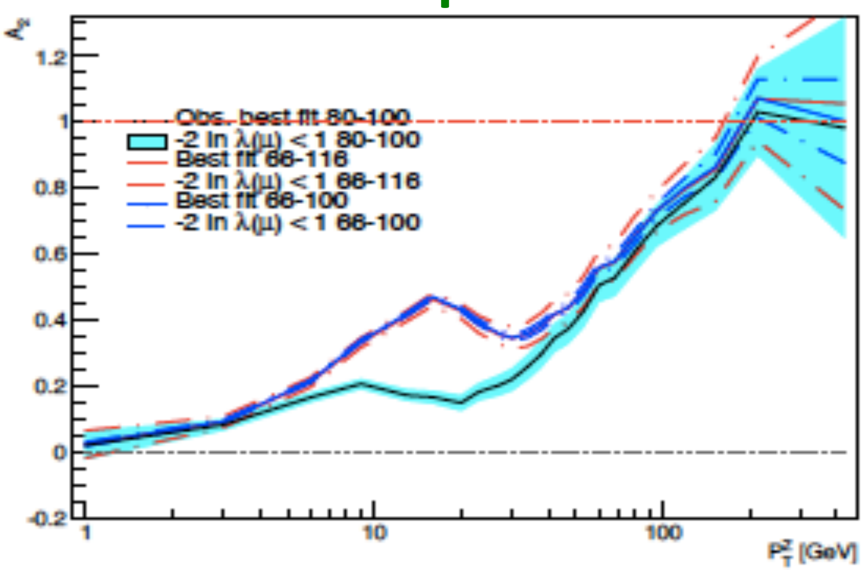
Born versus dressed (round 3)

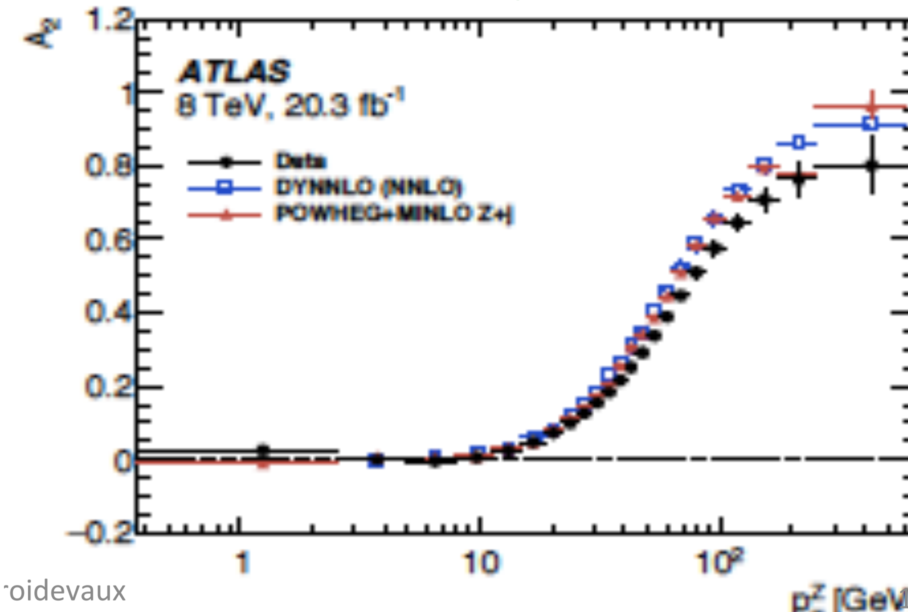




Bare leptons

Born leptons





Bare/Dressed/Born leptons

- **Bare:**
  MC generators give „bare leptons" as final-state objects, independently of the level of the calculations. QED radiation (wide-angle part) means that electrons and muons cannot be combined. They correspond to precisely defined off-shell kinematics at a given order, meaning one has a clear picture of what are the virtual/real corrections and their precision.
- **Dressed (all γ with $\Delta R < 0.1$ added to lepton):**
  This concept is ill-defined (compared to the other two) in the language of Feynman diagrams used in calculations to provide e.g. Z lineshape. Some assumptions have to be made on the kinematics of the dressed object (off-shell, on-shell) with consequences also on its direction. The definition will be sensitive to the („unphysical") threshold which does exist in the calculation on the photon radiation. Will any distribution produced in this way be an infrared-safe observable (what about soft and wide-angle photons)? What about the normalisation of such a distribution?
- **Born:**
  Brings the kinematics of the event observables back to the „lowest-order Feynman diagramme" relevant to the process under consideration. Allows to absorb higher-order corrections into the normalisation through „effective couplings".
  Requires however some care when being defined e.g. for $W\gamma/Z\gamma$ final states etc.

Pros and cons of dressed vs Born

- It is a misconception to argue about bare muons being closer to what we measure or about dressed electrons being closer to what we measure. But there is some truth in these statements. The question is what does it mean?
- Starting with electrons (muons are on next slide): what the above means is that the dressed electrons are the closest one can get to minimising coupling between detector effects and the FSR modelling itself.
  This coupling is usually ignored (even by SM W/Z!) and matters only at the few permil accuracy level
- Advantages of dressed electrons: they can be corrected for improved wide-angle FSR calculations and they can be used for assignment of final-state photons to the electron itself or a nearby jet.
- Disadvantages of dressed electrons: they rely on a somewhat arbitrary cone definition and they are particles with a mass different from the electron mass. Another important disadvantage is that they cannot be combined in an exact way with muons. ATLAS has reached long ago a level of precision (both statistical and systematics) such that we can really quantitatively test the theory even at NNLO QCD and the lepton combination is a major asset in this.

Back-up slides

Higher-order QED/EW:

an interesting example of seeing a loop when it becomes real

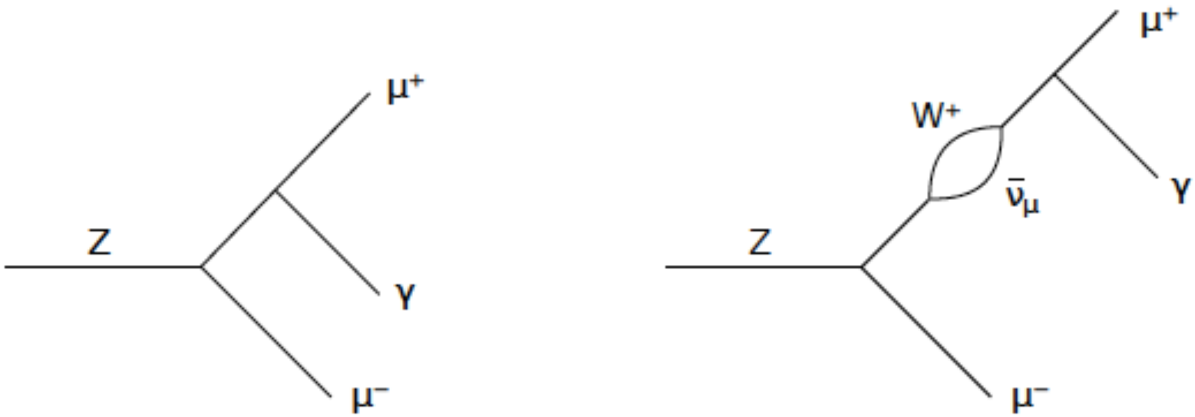


Figure 2: Main part of process $Z \to 2l\gamma$ is FSR (left), and weak vacuum polarization (right, in the form of $W - \nu$ loop) gives an additional contribution to the process.

Higher-order QED/EW:

an interesting example of seeing a loop when it becomes real

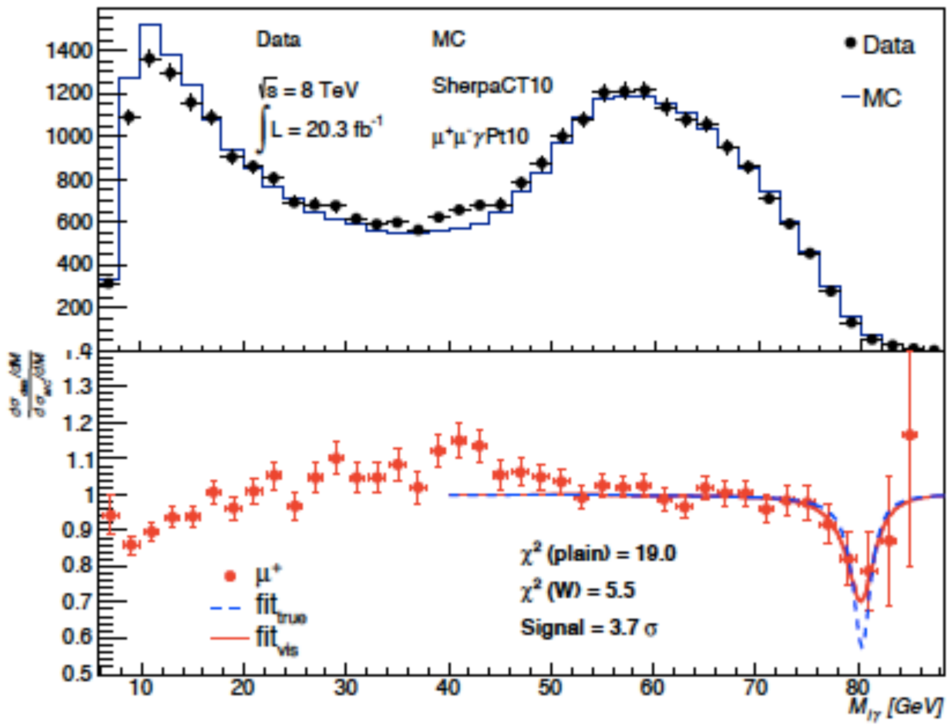


Figure 1: Destribution of an invariant mass of $\mu^+\gamma$ for $Z \to \mu^+\mu^-\gamma$ and ratio of data to MC.

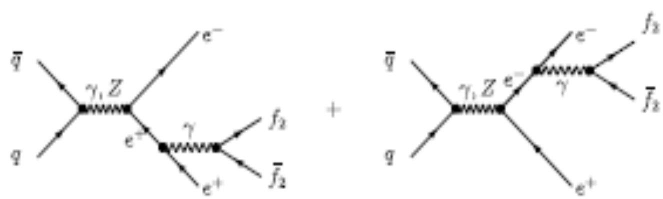
QED corrections and ϕ^* observable:

at high enough level of precision, using dressed or Born leptons cannot be argued to automatically be the best or even an adequate solution

- **Pair creation:**
  syst. error below 0.1-0.2%

Eur. Phys. J. C (2013) 73:2625
DOI 10.1140/epjc/s10052-013-2625-1

- **Initial-final state interference:**
  below 0.1% for events after parton shower



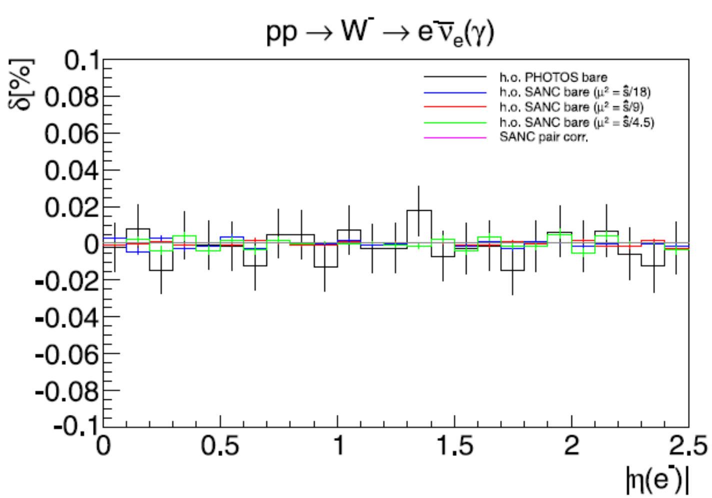


Fig. 19 Higher order photonic and pair corrections (δ in %) for basic distributions from PYTHIA+PHOTOS and SANC in $W^- \to e^- \bar{\nu}$ decay

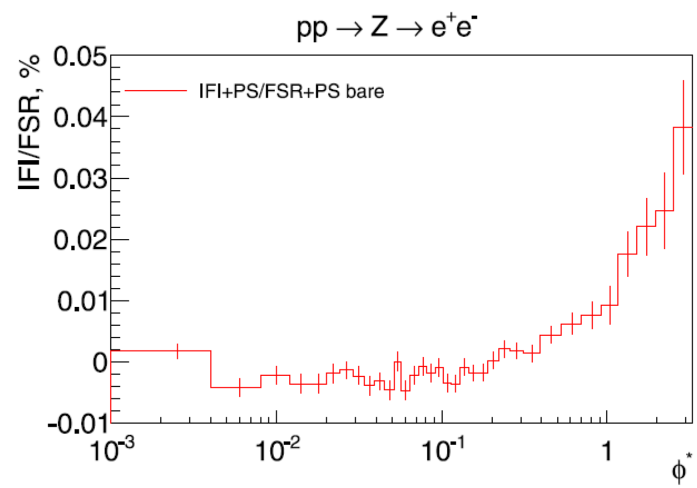


Fig. 21 IFI/FSR ratio in Z decay for ϕ^* distribution combined with parton showers