QED corrections in Monte-Carlo event generators

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Process independent corrections

Will not discuss:

- process specific electroweak corrections
  - SANC — Andonov et.al Comput.Phys.Commun.174(2006)481-517
  - WINHAC/ZINHAC — Placzek, Jadach EPJC29(2003)325-339
  - HORACE — Carloni Calame et.al. Phys.Rev.D69(2004)037301

  ...

Will discuss:

- process independent/universal approximate corrections
- DGLAP – collinear photon resummation:
  - PHOTOS — Barberio, Wąs Comput.Phys.Commun.79(1994)291-308
  - PYTHIA8 — Sjöstrand, Mrenna, Skands Comput.Phys.Commun.178(2008)852-867
  - SHERPA — Höche, Schumann, Siegert Phys.Rev.D81(2010)034026
- YFS – soft photon resummation
  - HERWIG++ — Hamilton, Rchardson JHEP07(2006)010
  - SHERPA — MS, Krauss JHEP12(2008)018

QED corrections – DGLAP

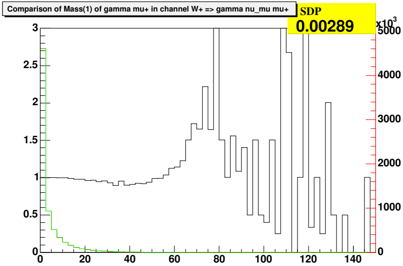
DGLAP

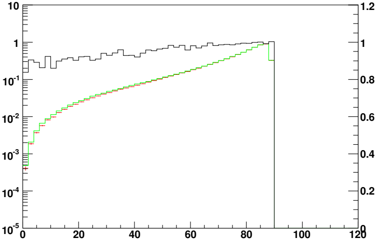
Gribov, Lipatov Sov.J.Nucl.Phys.15(1972)438-450, etc.

- resummation of collinear divergences
- strong ordering of emission scales
- soft-photon coherence not trivial
  achieved either through reweighting, inclusion of correct soft limit in splitting functions or ordering variable
- QED parton showers:
  PHOTOS (unordered); SHERPA/CSSHOWER++, PYTHIA8 ($p_\perp$-ordered)
  Seymour Z.Phys.C56(1992)161-170, etc.
  $\rightarrow$ importance of ordering variable in recovering DGLAP equations, see Skands, Weinzierl PRD79(2009)074021
- dedicated DY implementation in HORACE ($\mathcal{O}(\alpha_{\text{EW}})$ matched to QED-DGLAP)

PHOTOS

- implemented for particle decays $(1 \to n)$
- one-by-one photon emission with DGLAP-like splitting kernels
  $\to$ iterated for multiphoton em.
  $\to$ no ordering $\Rightarrow \frac{1}{n!}$ sym. factor
- ME corrections for $Z \to \ell\ell$, $W \to \ell\nu$
- YFS-like soft multiphoton correction
  $\to$ approximates multiphoton interferences





QED corrections – DGLAP

Ordered QED parton showers:

- strong ordering of emission scales
  → photons can be identified by their emission scales

  Seymour Z.Phys.C56(1992)161-170, etc.
- emissions off initial and final state charged particles
- interleaving with QCD evoultion crucial to obtain correct emission rates
- need probabilistic formulation
  → in QCD: large-N_C limit
  → in QED: neglect same-sign-charged dipoles
- real emission corrections possible through ME-reweighting
- QED-MEPS (CKKW merging) possible (but not practical)
  → matrix element corrections for multiple hard photon emissions

  Höche, Schumann, Siegert PRD81(2010)034026

QED corrections – YFS

YFS

Yennie, Frautschi, Suura Ann.Phys.13(1961)379-452

- resummation of soft-photon logarithms in massive Abelian theories
- construction through sum of dipole eikonals
- no ordering of emission, automatic soft-photon coherence
- universal collinear logarithms can be supplemented order-by-order, but not resummed
  → however, $\exp[-\alpha_{\text{QED}} L^2] \not\approx 1 - \alpha_{\text{QED}} L^2$ in extreme phase space regions
- process dependent fixed order corrections trivial
- used in universal implementation in HERWIG++ and SHERPA
  specific processes in e.g. WINHAC, ZINHAC
- heavily used in LEP-time high precission MCs
  YFSWW, YFSZZ, KORALW, KORALZ, KKMC, etc.

QED corrections – YFS

- coherent radiation off charged multipole
  all interferences due to emissions from different legs present
- unitary implementations for $1 \to n$
  finite virtual corrections affect relative rate of emission and no-emission

SHERPA:

matrix element	real $\mathcal{O}(\alpha_{\text{QED}})$	virtual $\mathcal{O}(\alpha_{\text{QED}})$
$V^0 \to F^+F^-$	✓	✓
$V^0 \to S^+S^-$	✓	✓
$S^0 \to F^+F^-$	✓	✓
$S^0 \to S^+S^-$	✓	✓
$W^\pm \to \ell^\pm\nu_\ell$	✓	✓
$\tau^\pm \to \ell^\pm\nu_\ell\nu_\tau$	✓	✗
$S^0 \to S^\mp\ell^\pm\nu_\ell$	✓	✓
$S^0 \to V^\mp\ell^\pm\nu_\ell$	✓	✗

- dedicated $\mathcal{O}(\alpha_{\text{QED}})$ corrections
  universal collinear emission corrections through CS dipoles (all)
- current limitation: $1 \to n$ processes
  $\to$ applied to hard process by means of narrow-width approximation to production of non-QCD final state
  $\to$ applied to all hadronic and τ decays

QED corrections – interplay with higher order QCD

QCD+QED DGLAP evolution

- must/can evolve simultaneously
  → compete for phase space
- may have different IR-cutoffs
- photon emissions off quarks drowned by gluon emissions
  → have little effect besides in dedicated searches

QCD DGLAP evolution & YFS exponentiation

- YFS does not evolve
  → "simultaneous" emission
- cannot be run interleaved with QCD DGLAP evolution

⇒ need to define mutualy distinct sets on QCD partons and non-QCD particles
→ sensible only if QCD evolution leaves non-QCD subset invariant

⇒ no QED rad. off quarks

- need some assumption about internal resonances (possibly multiple distinct non-QCD subsets)

⇒ same applies to PHOTOS + PS

Comparisons – DGLAP vs. YFS

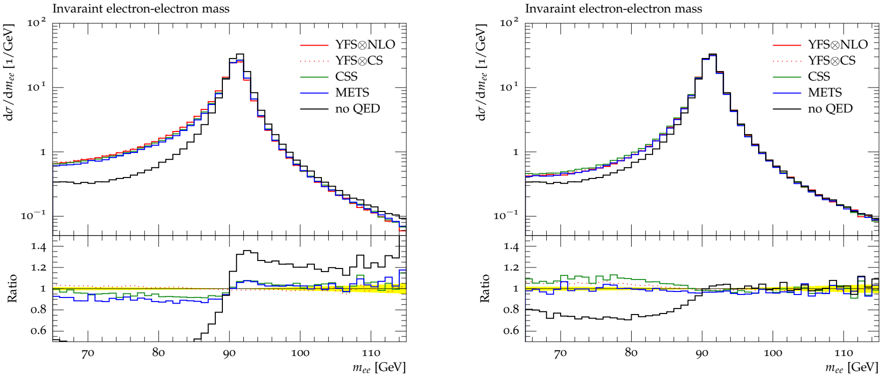
Definition of objects for pseudo-observables:

- bare electrons (electron object as is generated by MC)
  $\rightarrow$ due to soft-photon cut-off this includes some amount of soft/collinear photon radiation, not identical to electron of the QED Lagrangian
- dressed electrons (sum of 4-vectors of bare electron and photons within $\Delta R = 0.2$ around bare electron)
- identified photons (isolated by $\Delta R > 0.2$ from electron, $E_\gamma > 1$ GeV)

$\Rightarrow$ look at pseudo-observables characterising the radiation pattern

In the following:
left: pseudo-observables with bare electrons
right: pseudo-observables with dressed electrons
$\rightarrow$ closer to exp. observables

QED corrections – comparison – DY production



YFS⊗NLO YFS resummation with exact $\mathcal{O}(\alpha_{\text{QED}})$ correction

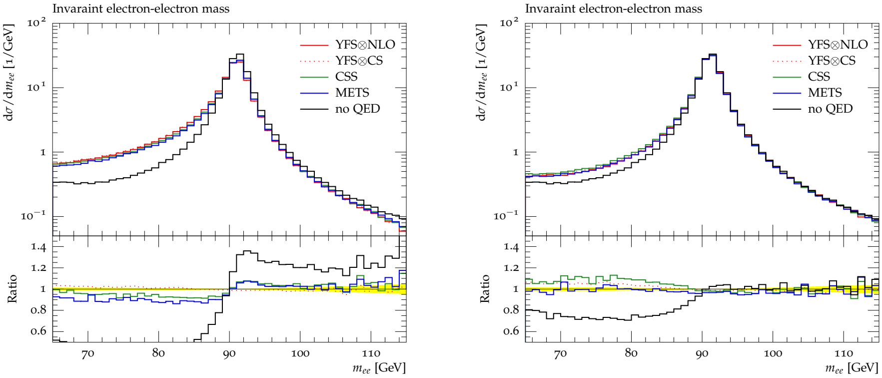
YFS⊗CS YFS resummation with approximate universal coll. approximation

CSS DGLAP resummation

METS DGLAP res. merged with ME with up to 2 photons ($Q_{\text{cut}} = 1$GeV)

no QED pure leading order $Z \to e^+e^-$

QED corrections – comparison – DY production

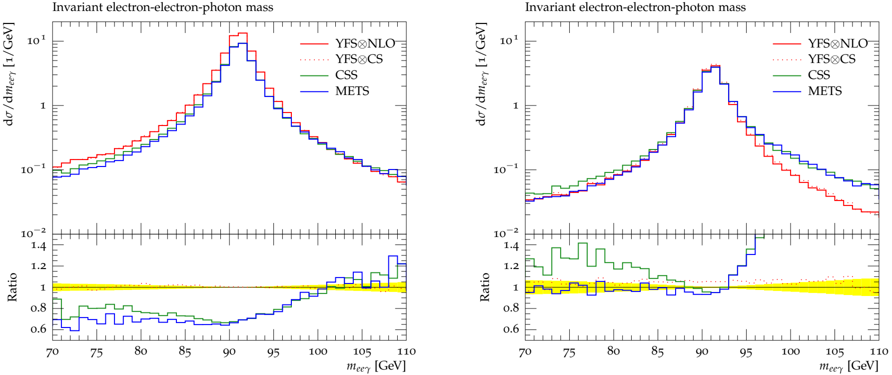


invariant dilepton mass

left: bare electrons, **right:** physical electrons (4-momentare of photons within $\Delta R = 0.2$ recombined bare electron)

bare quantities show rather large differences, but physical quantities show good agreement of all ME-corrected calculations

QED corrections – comparison – DY production

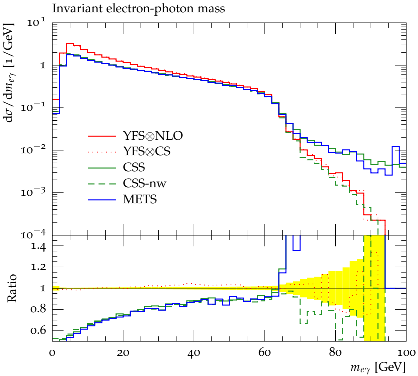


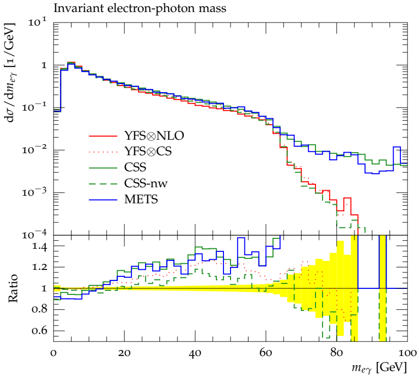
invariant e^+-e^--γ mass, isolated hard photons ($E_\gamma > 1$GeV, $\Delta R > 0.2$)

bare quantities show rather large differences, but physical quantities show good agreement of all ME-corrected calculations

difference at large $m_{ee\gamma}$ due to initial state radiation neglected in YFS approach

QED corrections – comparison – DY production



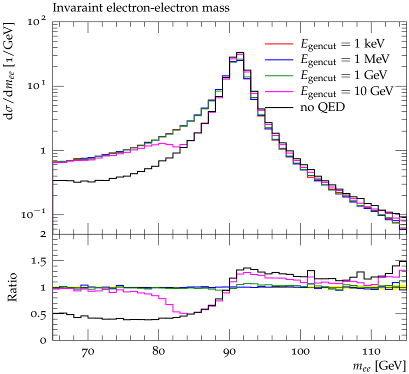


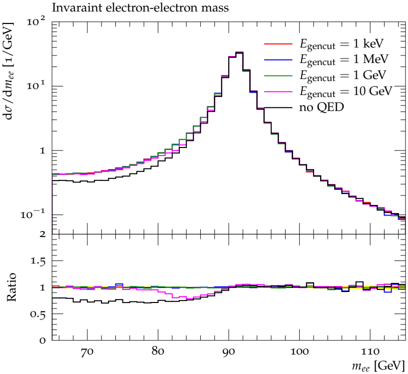
invariant mass of hardest photon and closest $e^{\pm}$, isolated hard photons ($E_\gamma > 1$GeV, $\Delta R > 0.2$)

CSS-nw neglects ISR, same large $m_{e\gamma}$ as YFS
in bare spectrum missing collinear resummation of YFS visible
$\rightarrow$ could be remedied by inclusion of higher order coll. approximation

QED corrections – comparison – DY production

Cut-off dependence in SHERPA/PHOTONS++ (YFS):

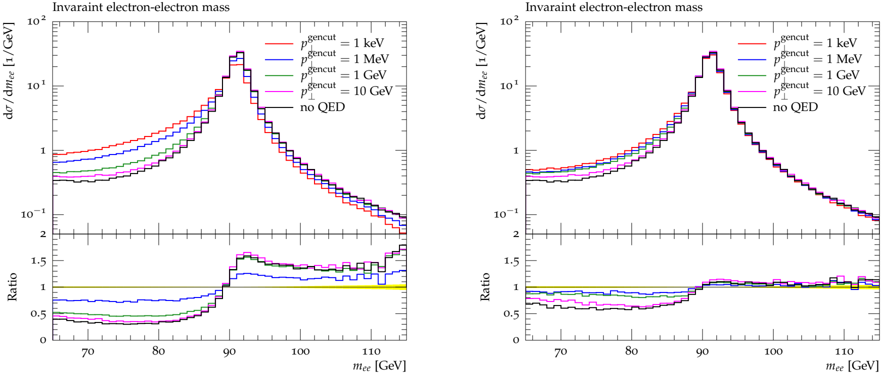




cut-off as minimum photon energy in multipole rest frame
bare quantities stable for $E_{\text{gencut}} < 1\text{GeV}$

QED corrections – comparison – DY production

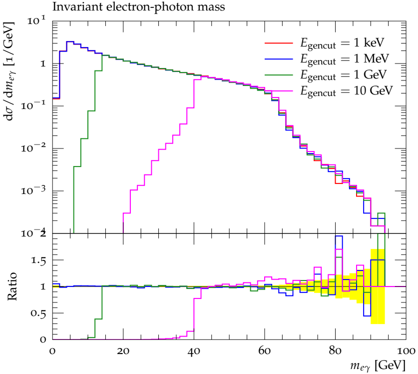
Cut-off dependence in SHERPA/CSSHOWER++ (DGLAP):

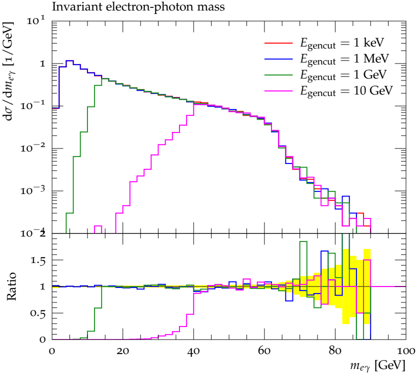


cut-off as minimum relative transverse momentum
physical quantities still show some dependence on $p_\perp^{\text{gencut}}$

QED corrections – comparison – DY production

Cut-off dependence in SHERPA/PHOTONS++ (YFS):

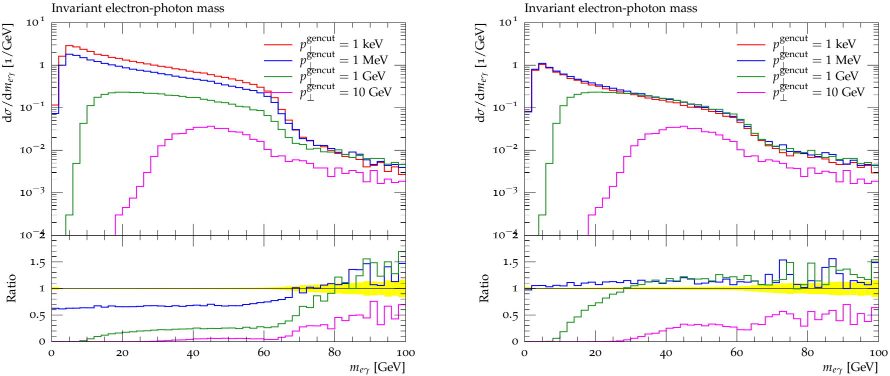




cut-off as minimum photon energy in multipole rest frame

QED corrections – comparison – DY production

Cut-off dependence in SHERPA/CSSHOWER++ (DGLAP):

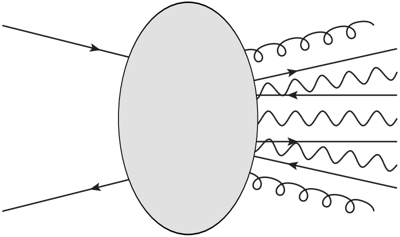


cut-off as minimum relative transverse momentum

QED corrections – effects of resonance assumptions

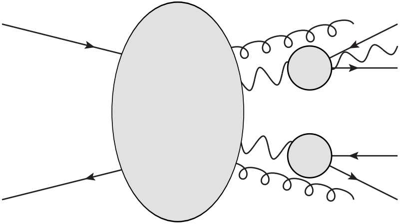
implementation depending on whether resonant decays specified or not, e.g.

$pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$+jets



- photons may recoil against full non-QCD system

$pp \to Z[\to \ell^+\ell^-]Z[\to \nu_\ell\bar{\nu}_\ell]$+jets



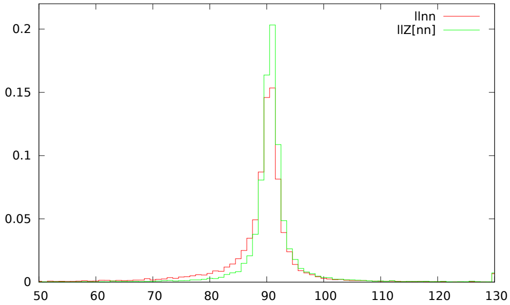
- photons may recoil only within their specified decay subsystem

$\Rightarrow$ different phase space volume for hard wide-angle emissions

$\Rightarrow$ soft and collinear limits the same, differences beyond formal accuracy, must be fixed by exact higher order corrections

QED corrections – effects of resonance assumptions

$m_{\nu\nu}$ in $pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$+jets vs. $pp \to Z[\to \ell^+\ell^-]Z[\to \nu_\ell\bar{\nu}_\ell]$+jets



The question is: How much energy is QED-bremsstrahlung allowed to remove from the system? So much that the $Z[\to \nu_\mu\bar{\nu}_\mu]$ is forced off-shell? Beyond formal accuracy, needs to be answered by exact matrix-element corrections.

Conclusions

- very good description of higher order QED effects not only necessary for precission physics, but to estimate acceptances, isolations, etc.
- DGLAP best describes hard collinear radiation
  usually gets recombined with charged particle to physical objects
  hard wide-angle photon emission through fixed-order correction (MEPS)
  $\rightarrow$ natively incorporates initial state radiation
- YFS best describes comparably soft wide-angle radiation
  ends up as separate noise depleting energy from its production process
  hard wide-angle photon emission through fixed-order correction
  $\rightarrow$ currently limited to $1 \rightarrow n$ type (sub)processes
  $\Rightarrow$ good enough for all observables considered so far
- good agreement for physical quantities after (at least) real emission corrections
- good description of rather inclusive quantities needs well understood wide-angle soft emissions

Thank you for your attention!

QED corrections – YFS in SHERPA

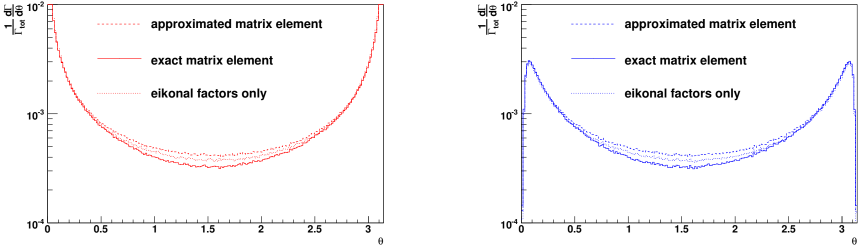
Validation: radiative decay rates

	$\frac{\Gamma(\mu \to e\,\nu_e\,\nu_\mu\,\gamma)}{\Gamma(\mu \to e\,\nu_e\,\nu_\mu, incl.)}$	$\frac{\Gamma(\tau \to e\,\nu_e\,\nu_\tau\,\gamma)}{\Gamma(\tau \to e\,\nu_e\,\nu_\tau, incl.)}$	$\frac{\Gamma(\tau \to \mu\,\nu_\mu\,\nu_\tau\,\gamma)}{\Gamma(\tau \to \mu\,\nu_\mu\,\nu_\tau, incl.)}$
PDG	0.014(4)	0.09(1)	0.021(3)
SHERPA	0.0147(1)	0.0999(3)	0.0233(2)

branching ratios of the radiative leptonic μ and τ decay mode ($E_\gamma > 10$MeV) in relation to their inclusive leptonic mode calculated by SHERPA/PHOTONS++ and the PDG world average

QED corrections – YFS in SHERPA

Validation: photon emission interferences in $Z \to \ell\ell$



angle of individual photons in dipole rest frame after radiation
$Z \to e^+e^-$ (left), $Z \to \tau^+\tau^-$ (right)

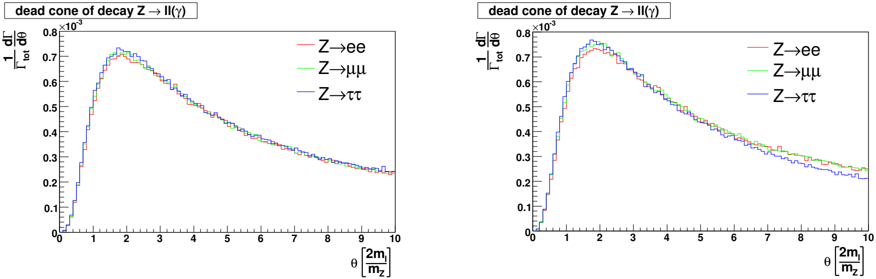
solid exact $\mathcal{O}(\alpha_{\text{QED}})$ correction

dashed universal $\mathcal{O}(\alpha_{\text{QED}})$ collinear approximation

dotted soft eikonals only

QED corrections – YFS in SHERPA

Validation: dead cone of charged massive particle in $Z \to \ell\ell$



angle between charged lepton and photon in units of m_ℓ/m_Z

left: soft eikonals only, right: exact $\mathcal{O}(\alpha_{\text{QED}})$ ME