# QED corrections in SHERPA

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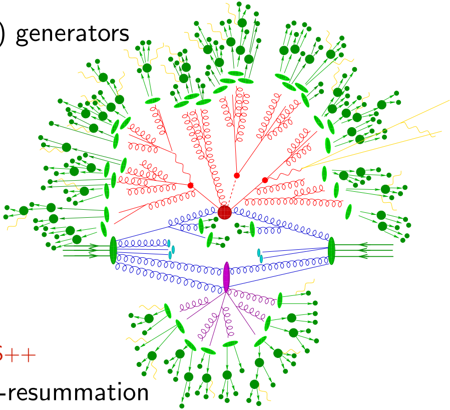
JHEP02(2009)007

# The SHERPA event generator framework



- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044
  COMIX JHEP12(2008)039
- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381
- A hadron and $\tau$ decay package HADRONS++
- A higher order QED generator using YFS-resummation
  PHOTONS++ JHEP12(2008)018

**Sherpa's traditional strength is the perturbative part of the event**
MEPS (CKKW), MC@NLO, MENLOPS, MEPS@NLO

→ QCD-NLO calculations through automated CS-subtraction EPJC53(2008)501

# Recent progress

## MC@NLO

Höche, Krauss, MS, Siegert arXiv:1111.1220

Höche, MS arXiv:1208.2815

- full assessment of perturbative and non-perturbative uncertainties
  → renormalisation and factorisation scales $\mu_R$, $\mu_F$
  → resummation scale $\mu_Q$
  → MPI modelling, hadronisation modelling

## MEPS@NLO – extension of CKKW to NLO

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

- consistent combination of multiple NLO+PS matched (MC@NLO) samples of successive jet multiplicities
- individual jet-multiplicities are described at NLO accuracy while logarithmic accuracy wrt. inclusive sample is preserved

⇒ will be published in next major release

# 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
- real emission corrections possible through ME-reweighting
- QED parton showers:
  PHOTOS ($E$-ordered); SHERPA/CSSHOWER++, PYTHIA8 ($p_\perp$-ordered)
  $\rightarrow$ importance of ordering variable in recovering DGLAP equations, see
  Skands, Weinzierl PRD79(2009)074021
- dedicated DY implementation in HORACE ($\mathcal{O}(\alpha_{\mathsf{EW}})$ matched to QED-DGLAP)

# QED corrections – DGLAP in SHERPA

CSSHOWER++

Schumann, Krauss JHEP03(2008)038
Höche, Schumann, Siegert PRD81(2010)034026

- dipole shower using Catani-Seymour dipoles
- ordered in relative transverse momentum $\mathbf{k}_\perp$
- IS and FS evolution
- need probabilistic formulation
  $\rightarrow$ in QCD: large-$N_C$ limit
  $\rightarrow$ in QED: neglect same-sign-charged dipoles
- infrared cut-off in $\mathbf{k}_\perp$
  at the moment identical to QCD infrared cut-off
- QED-MEPS (CKKW merging) possible
- usable only for corrections to hard interaction (default: off)

# 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
  $\rightarrow$ 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 in SHERPA

## SHERPA/PHOTONS++

MS, Krauss JHEP12(2008)018

- coherent radiation off charged multipole
  all interferences due to emissions from different legs present
- unitary implementation
  → event norm unchanged
  finite virtual corrections affect relative rate of emission and no-emission
- IR-regularisation through energy cut-off in multipole rest frame

| 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
  → applied to hard process by means of narrow-width approximation to production of non-QCD final state
  → applied to all hadronic and $\tau$ decays

# QED corrections – YFS in SHERPA

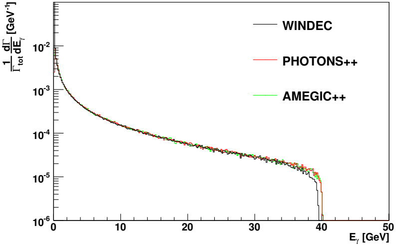
Validation: radiative decay rates

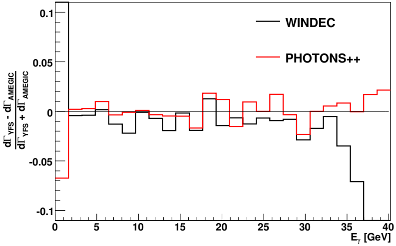
| | $\frac{\Gamma(\mu \to e\,\nu_e\,\nu_\mu\,\gamma)}{\Gamma(\mu \to e\,\nu_e\,\nu_\mu, incl.)}$ | $\frac{\Gamma(\tau \to e\,\nu_e\,\nu_\tau\,\gamma)}{\Gamma(\tau \to e\,\nu_e\,\nu_\tau, incl.)}$ | $\frac{\Gamma(\tau \to \mu\,\nu_\mu\,\nu_\tau\,\gamma)}{\Gamma(\tau \to \mu\,\nu_\mu\,\nu_\tau, incl.)}$ |
|---|---|---|---|
| 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 $\mu$ and $\tau$ 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 spectrum vs WINDEC vs. AMEGIC++ in $W \to \ell\nu$



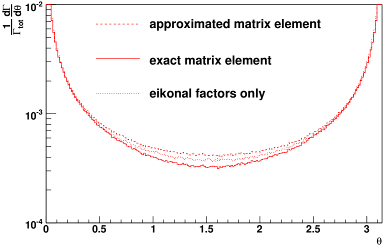



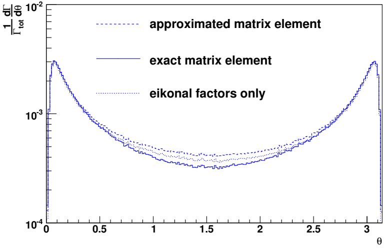

PHOTONS++ – YFS resummation and $\mathcal{O}(\alpha_{\text{QED}})$ correction
WINDEC – $W$-decay routine of WINHAC
YFS resummation and $\mathcal{O}(\alpha_{\text{QED}})$ correction
AMEGIC++ – fixed order $W \to e\nu_e\gamma$
no virtual correction $\to$ rescaled

deviation at large $E_\gamma$ due to diff. phase space mapping and $m_\nu \neq 0$ in WINHAC
deviation at small $E_\gamma$ due to different functional form of IR-cutoff

# 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)

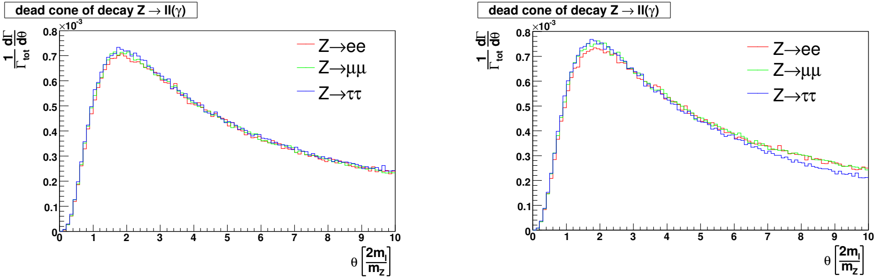
**solid** exact $\mathcal{O}(\alpha_{\text{QED}})$ correction

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

**dotted** soft eikonals only

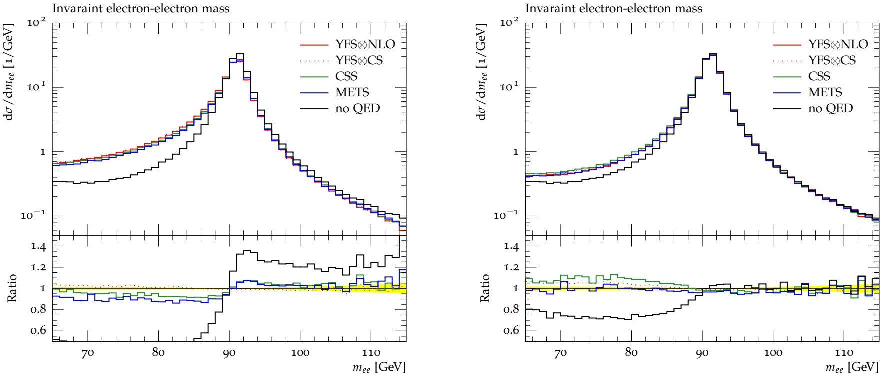
# QED corrections – YFS in SHERPA

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




angle between charged lepton and photon in units of $m_\ell/m_Z$
left: soft eikonals only, right: exact $\mathcal{O}(\alpha_{\text{QED}})$ ME

# QED corrections – comparison – DY production




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

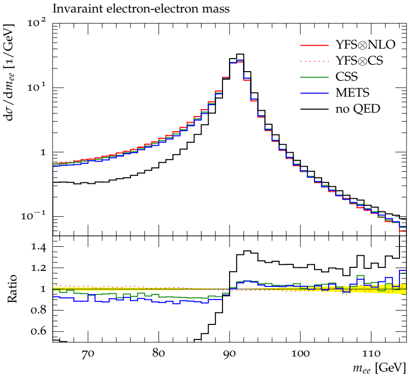
**YFS⊗CS** YFS resummation with approximate universal coll. approximation

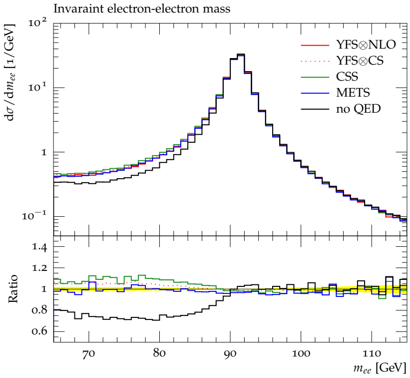
**CSS** DGLAP resummation

**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

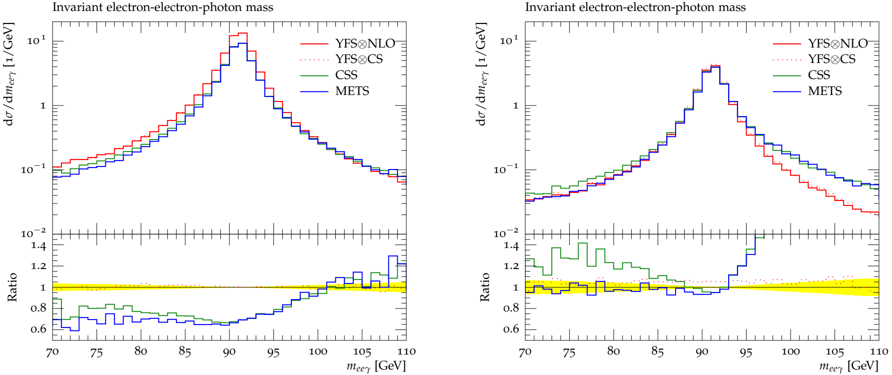



invariant dilepton mass
**left:** bare electrons, **right:** physical electrons (4-momentare of photons within $\Delta R = 0.2$ recombined bare electron)

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

# QED corrections – comparison – DY production

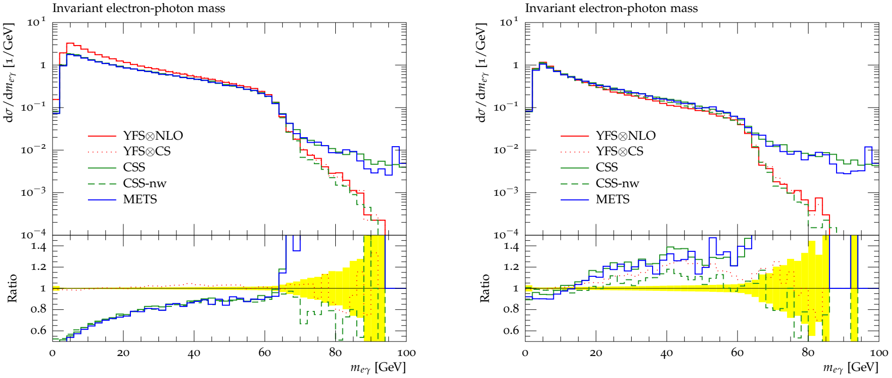



invariant $e^+$-$e^-$-$\gamma$ mass, isolated hard photons ($E_\gamma > 1$GeV, $\Delta R > 0.2$)

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

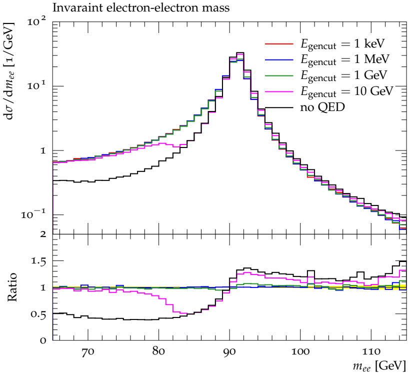


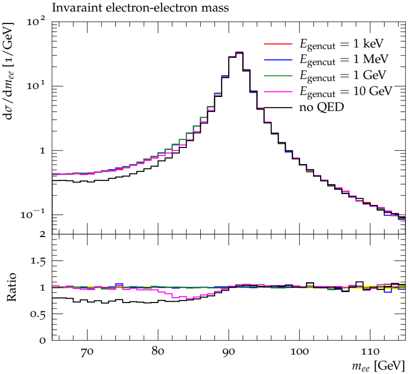

invariant mass of hardest photon and closest $e^{\pm}$, isolated hard photons ($E_\gamma > 1$GeV, $\Delta R > 0.2$)

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):

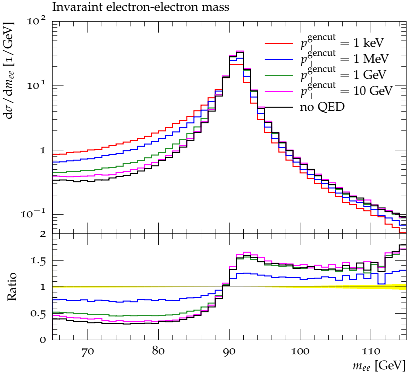


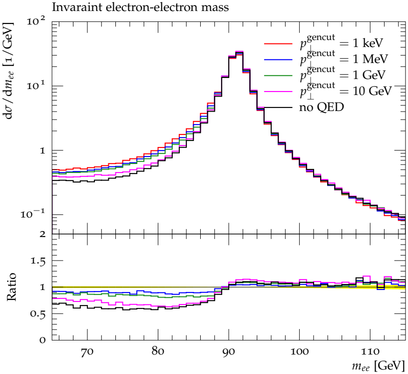




cut-off as minimum photon energy in multipole rest frame
bare quantities stable for $E_{gencut} < 1\text{GeV}$

# QED corrections – comparison – DY production

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

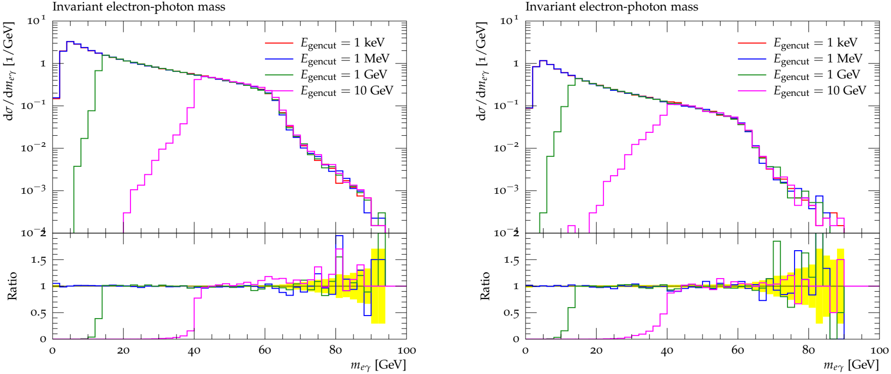



cut-off as minimum relative transverse momentum
physical quantities still show some dependence on $p_\perp^{\text{gencut}}$

# QED corrections – comparison – DY production

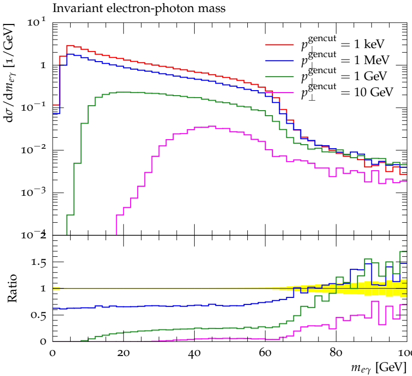
## Cut-off dependence in SHERPA/PHOTONS++ (YFS):

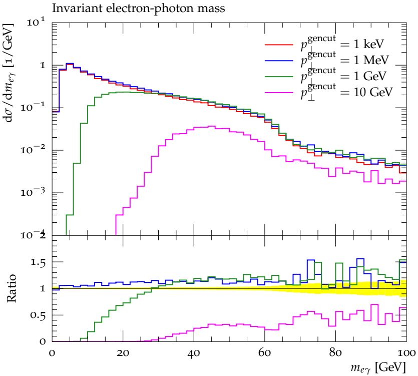



cut-off as minimum photon energy in multipole rest frame

# QED corrections – comparison – DY production

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




cut-off as minimum relative transverse momentum

# QED corrections – interplay with higher order QCD

## QCD+QED DGLAP evolution

- must/can evolve simultaneously
  → fight 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 know of any evolution
  → emissions happen "simultaneously"
- cannot be run "simultaneously"
  ⇒ must be run on predefined mutually distict subsets of an event

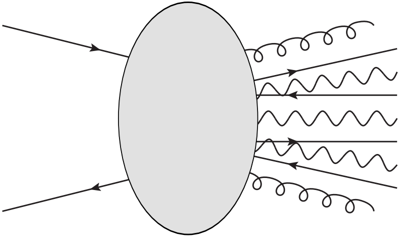
**SHERPA:** QCD DGLAP on all QCD partons, YFS on all non-QCD partons

(taking explicit resonances into account, possibly multiple distict non-QCD subsets)

# QED corrections – be aware of what you ask for

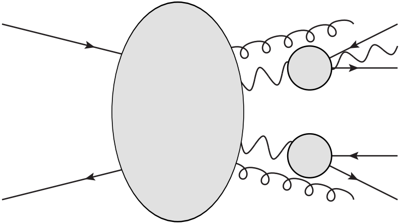
implementation depending on whether resonant decays specified or not, e.g.

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



- photons may recoil against full non-QCD system

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



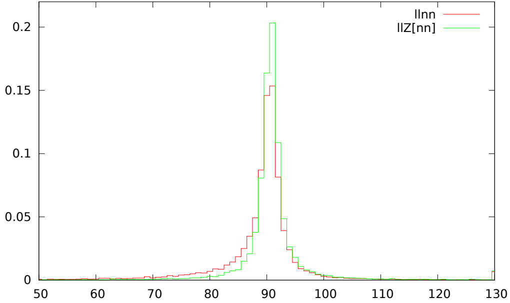
- photons may recoil only within their specified decay subsystem

$\Rightarrow$ 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 – be aware of what you ask for

$m_{\nu\nu}$ 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 necessary for precission physics
- 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
  $\rightarrow$ default in SHERPA both for hard non-QCD production and hadron decays
  $\rightarrow$ 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