Precision calculations with SHERPA

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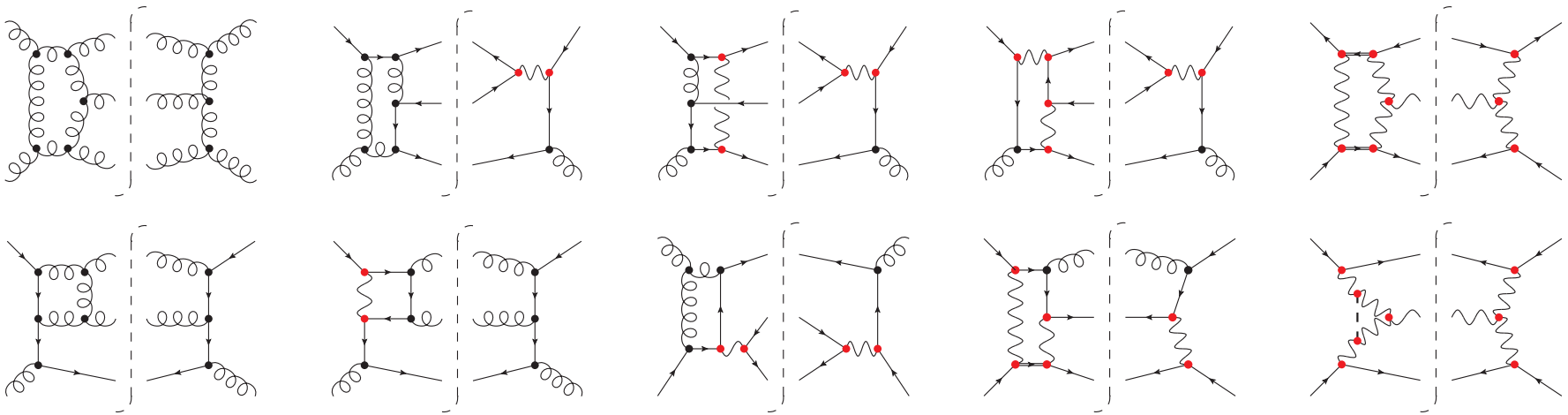
Higher order calculations

- NLO QCD
  (since SHERPA-1.2 Gleisberg, Krauss arXiv:0709.2881),
  matched to parton showers
  (since SHERPA-1.4 Höche, Krauss, MS, Siegert arXiv:1008.5399, 1111.1220),
  multijet merged
  (since SHERPA-2.0 Höche, Krauss, MS, Siegert arXiv:1207.5030)
- NNLO QCD
  (as plugin for sel. procs since SHERPA-2.1 Höche, Li, Prestel arXiv:1405.xxxx),
  matched to parton showers
  (as plugin for sel. procs since SHERPA-2.1 Höche, Li, Prestel arXiv:1405.xxxx),
- NLO EW and subleading orders
  (from Sherpa-3.0 MS arXiv:1712.07975)

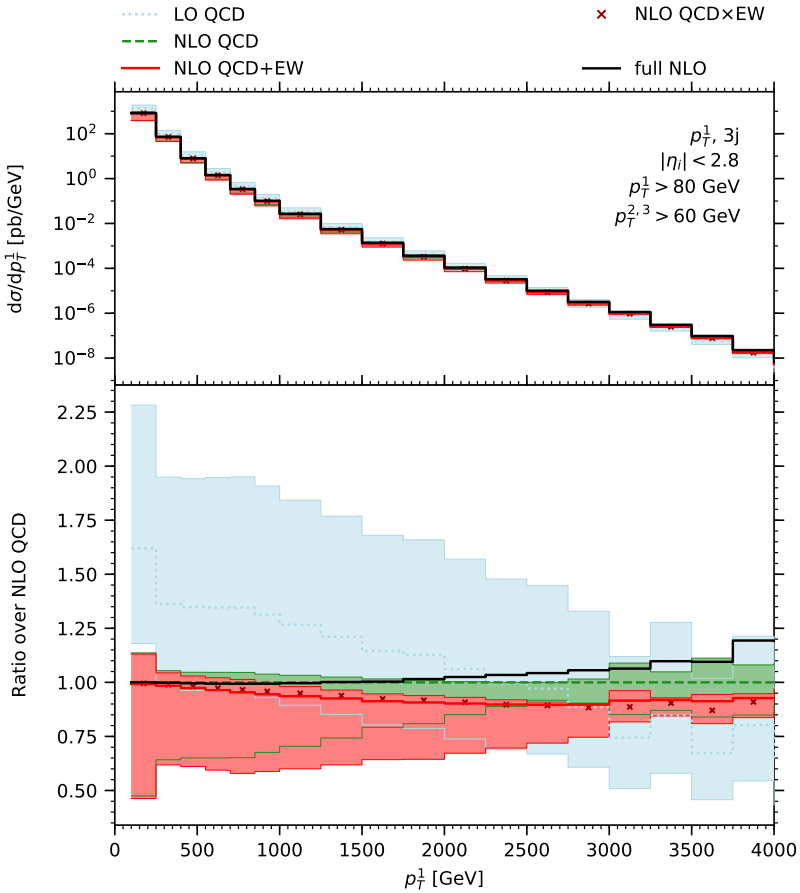
Three jet production at NLO

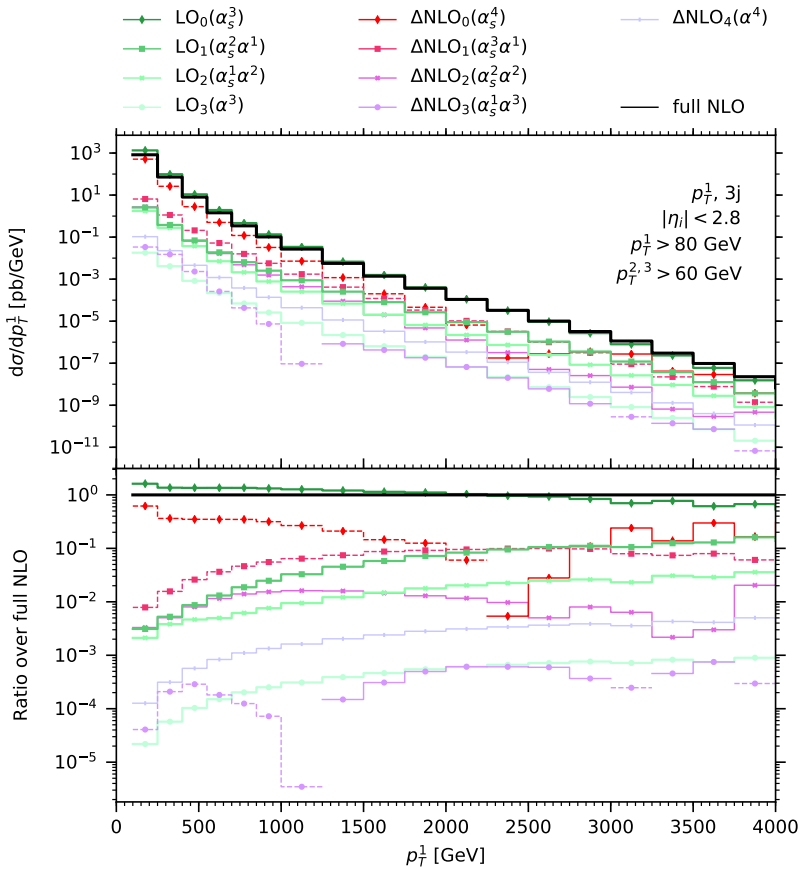


$\mathcal{O}(\alpha_s^4)$ $\mathcal{O}(\alpha_s^3\alpha)$ $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s\alpha^3)$ $\mathcal{O}(\alpha^4)$

- sensitive to the full SM spectrum, incl. top quark, Higgs boson, all lepton and neutrino flavours
- real emission corrections include: $\ell\nu qg$, $\ell\ell qg$, $\ell\ell\ell\ell$, $\ell\ell\ell\nu$ final states

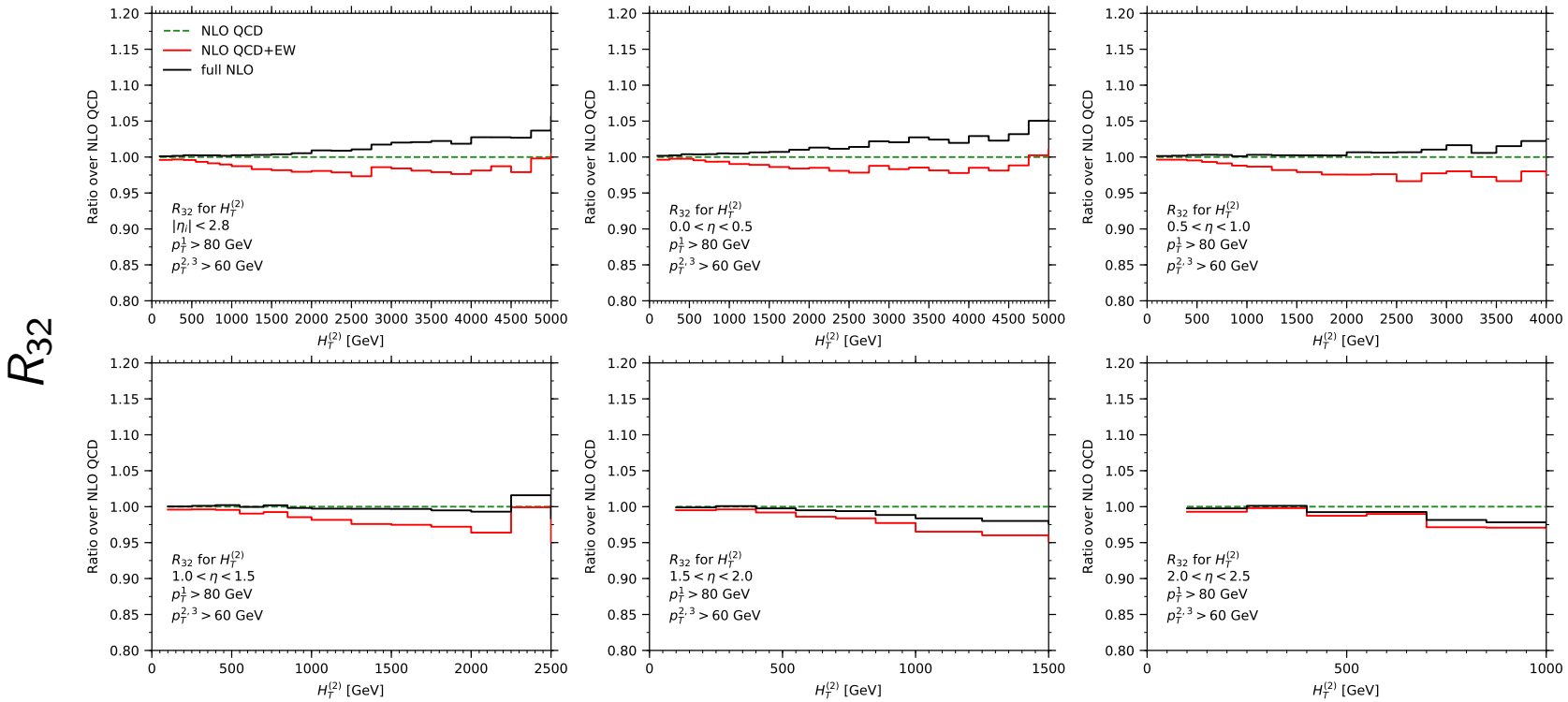
Leading jet transverse momenta in 3-jet production





- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.

R_{32} in different Δy-slices



- different net effects in different rapidity slices

Small transverse momentum and threshold resummation

→ work started with Ju Wan-Li

Idea:

- add observable specific analytic resummation
  → many effects already known, add a few interesting new ones
- focus on $\Delta\phi$ resummation in $\ell\ell$ and $\ell\nu$
  → provides another handle to transfer measured spectra from Z to W
  → related to q_{T} and ϕ^* resummation
- also applicable to other channels, e.g. $\Delta\phi(\ell\ell, \not{E}_{\mathrm{T}})$, $\Delta\phi(\ell\ell\ell, \not{E}_{\mathrm{T}})$
  → observable that is often used to apply a jet veto without the need to reconstruct jets

Resummed QED FSR

LHC experiments perform EW precision measurements (m_W, A_i, $\sin\theta^{\text{eff}}_{q,\ell}$, etc.) using Born lepton definitions.

Theory systematics on measured-lepton-to-Born-lepton correction are not routinely assessed.

Test with very simple setup, using bare and various dressed leptons as measured-lepton stand-in

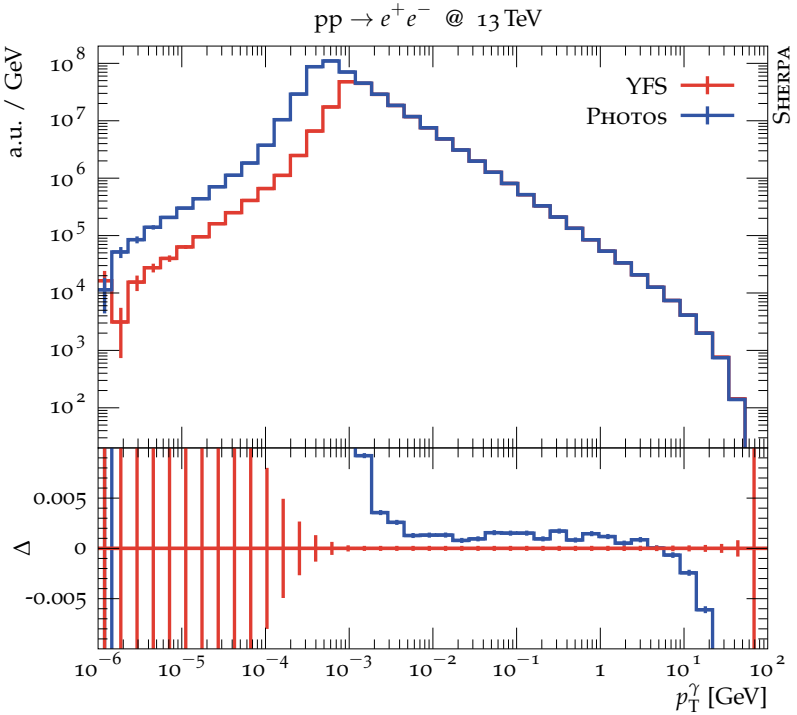
- $q\bar{q} \to \ell^+\ell^-$ LO+QED FSR, no QCD corrs to not blur QED effects (no parton shower, no non-perturbative effects, etc.)
- $|\eta(\ell)| < 2.4$, $p_{\text{T}}(\ell) > 7\,\text{GeV}$
- IR cutoffs
  YFS: 1 MeV in $\ell^+\ell^-$ rest frame after FSR
  PHOTOS: $10^{-6} \cdot m_{\ell\ell}$ in $\ell^+\ell^-$ rest frame before FSR

work in progress w/ Chris Gütschow

QED FSR in Drell-Yan – preliminary

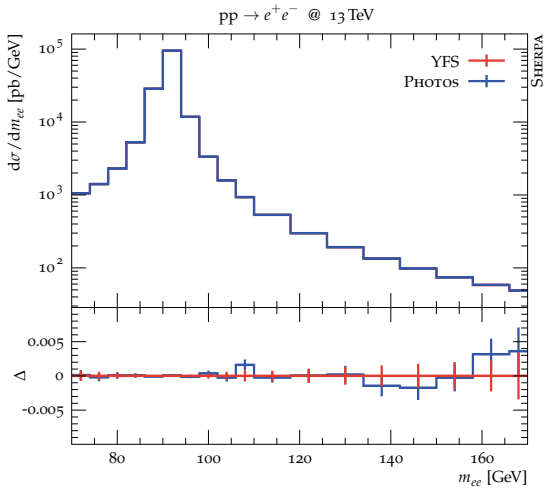
inclusive p_{T}^{γ} spectrum

- starts at $\mathcal{O}(\alpha)$
- difference in IR cutoff (in the range of MeV)
  $\rightarrow$ observables should be insensitive to even softer radiation at the investigated accuracy
- good agreement found, though YFS radiates slightly more throughout spectrum



inclusive p_{T}^{γ} spectrum

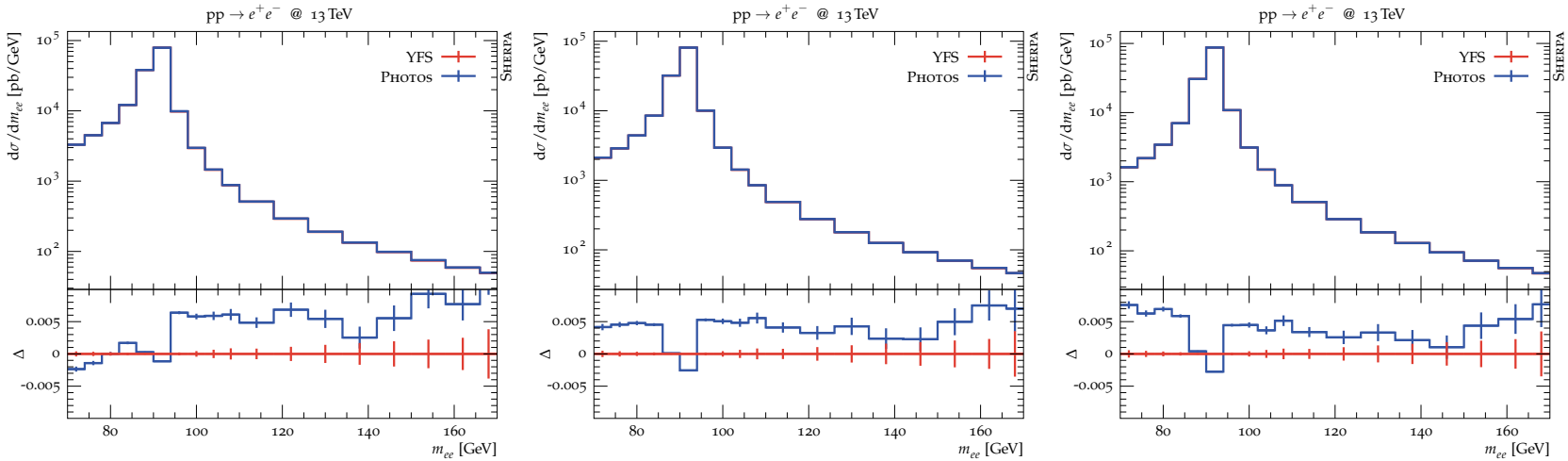
QED FSR in Drell-Yan – preliminary



Born leptons
(from event record)

- lepton-definition dependent level of agreement on the 0.5% level
  → slightly different radiation patterns
- except on-peak YFS predicts consistently lower cross sections,
  in-line with findings in incl. photon spectrum

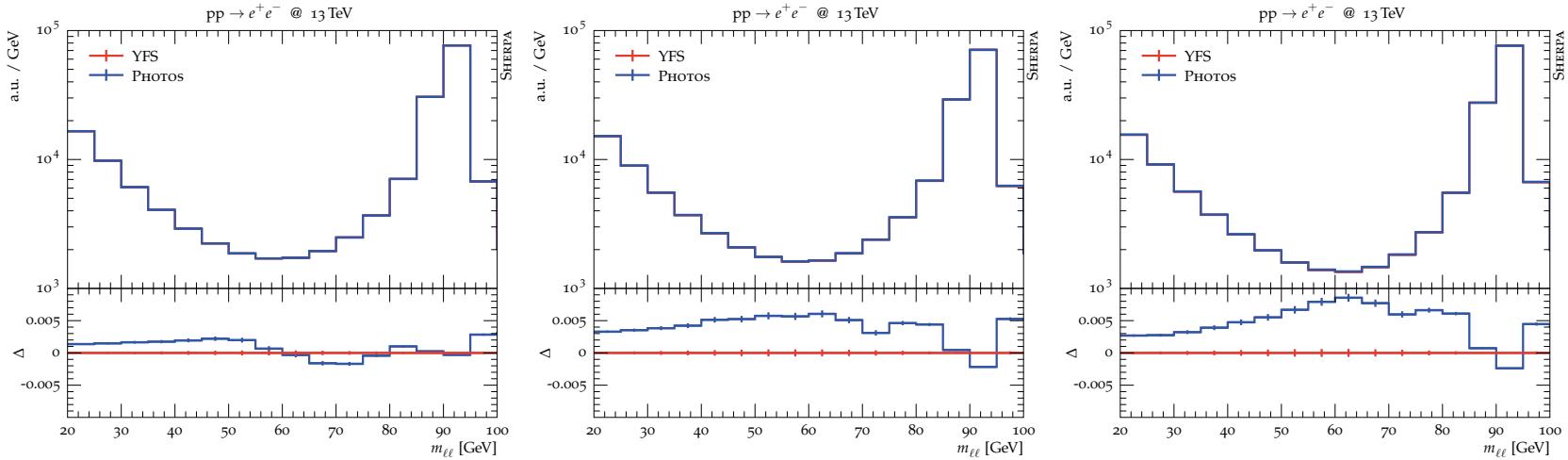
QED FSR in Drell-Yan – preliminary



bare leptons | dressed leptons $\Delta R = 0.005$ | dressed leptons $\Delta R = 0.1$

- lepton-definition dependent level of agreement on the 0.5% level
  $\rightarrow$ slightly different radiation patterns
- except on-peak YFS predicts consistently lower cross sections,
  in-line with findings in incl. photon spectrum

QED FSR in Drell-Yan – preliminary

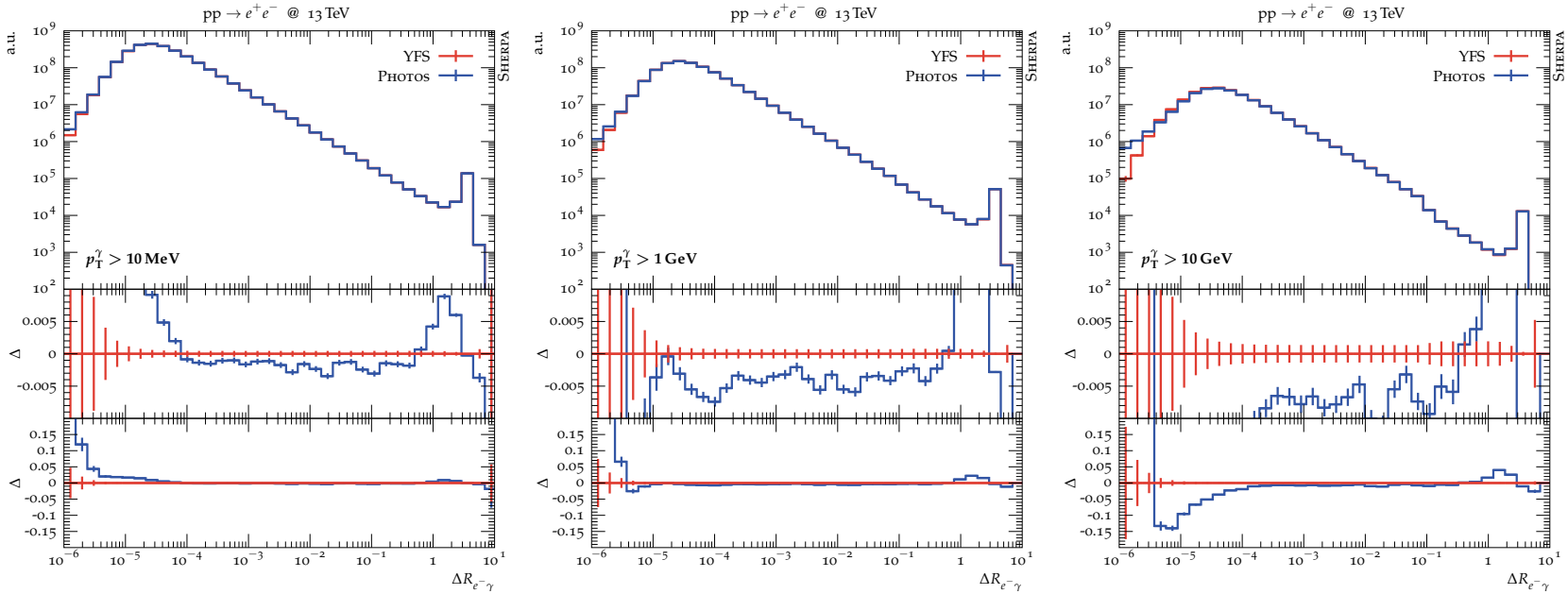


bare leptons | dressed leptons $\Delta R = 0.005$ | dressed leptons $\Delta R = 0.1$

- lepton-definition dependent level of agreement below the 1% level
  $\rightarrow$ slightly different radiation patterns
- except on-peak YFS predicts consistently lower cross sections,
  in-line with findings in incl. photon spectrum

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, e^-)$



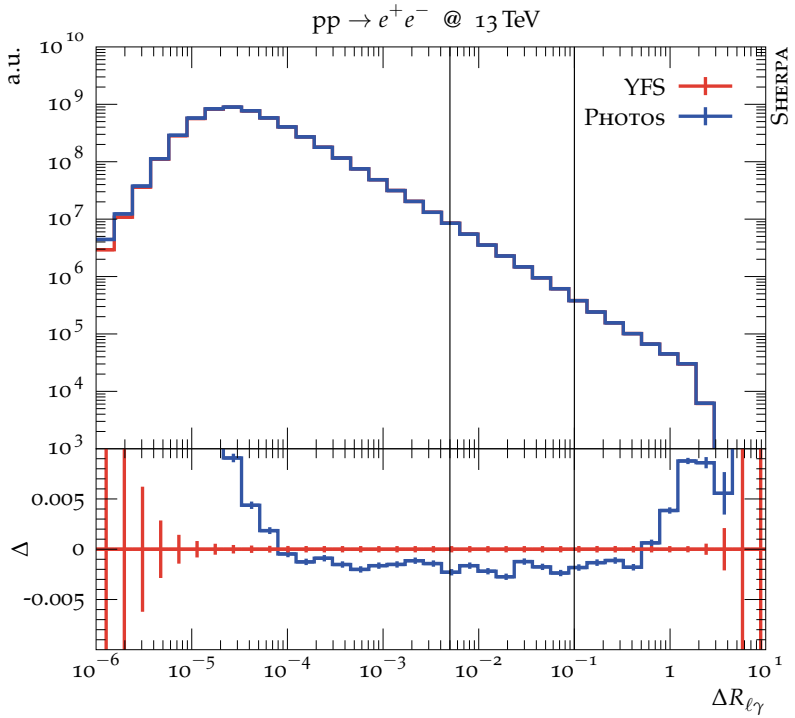
$p_T^\gamma > 10\,\text{MeV}$ $p_T^\gamma > 1\,\text{GeV}$ $p_T^\gamma > 10\,\text{GeV}$

- agreement from coll. peak ($\frac{4m_e}{m_Z}$) to wide angle better than 1%
- disagreement on ultracollinear dependent on p_T^γ
- normal dressing cone $\Delta R_{\text{dress}} = 0.1$ (narrow $\Delta R_{\text{dress}} = 0.005$)

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- inclusive selection
- dead-cone (mass-suppression of ultra-collinear radiation) equally well described
- bulk of radiation well within dressing cones of 0.1 and 0.005

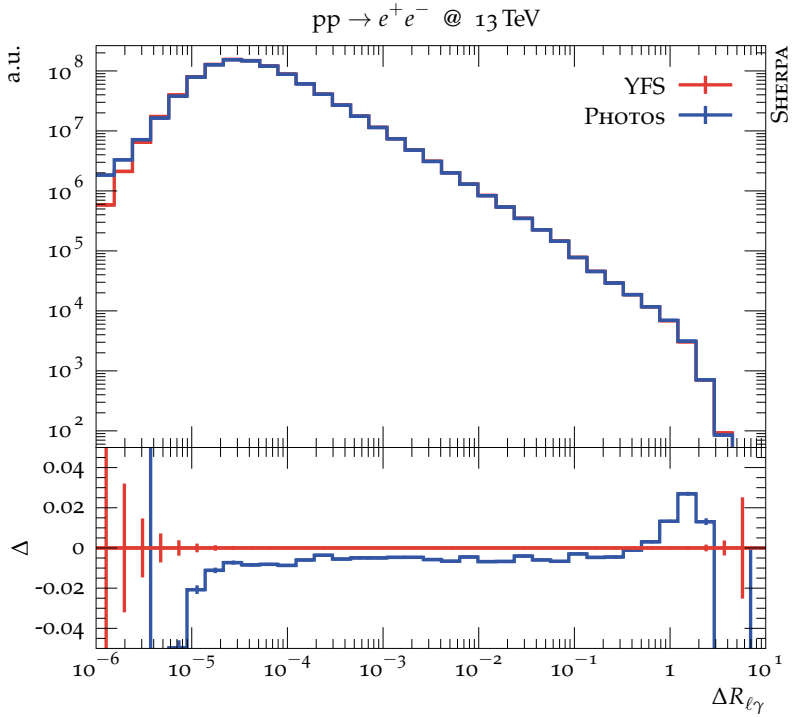


incl. lepton selection

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

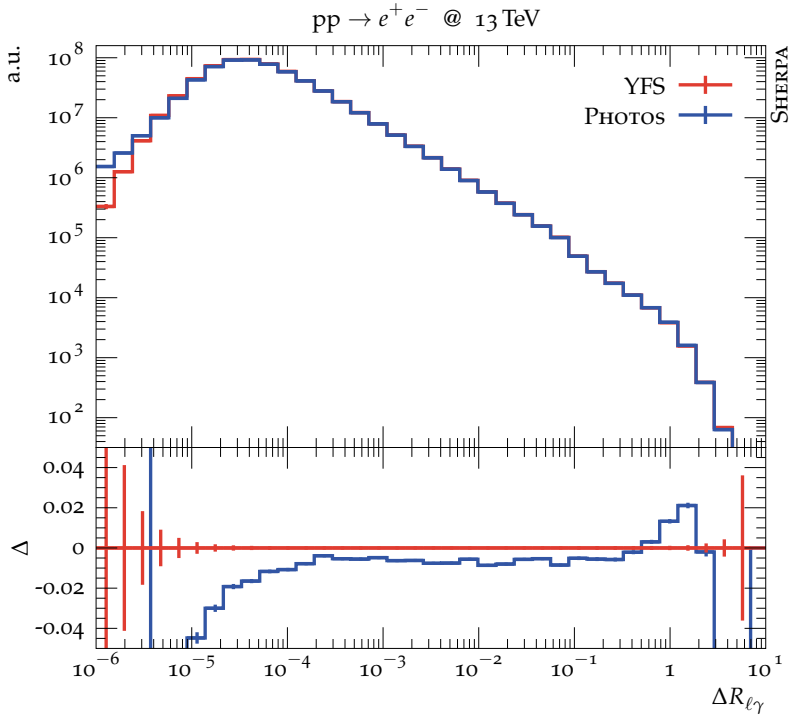


$$p_{\mathrm{T}}^{\gamma} > 1.1 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

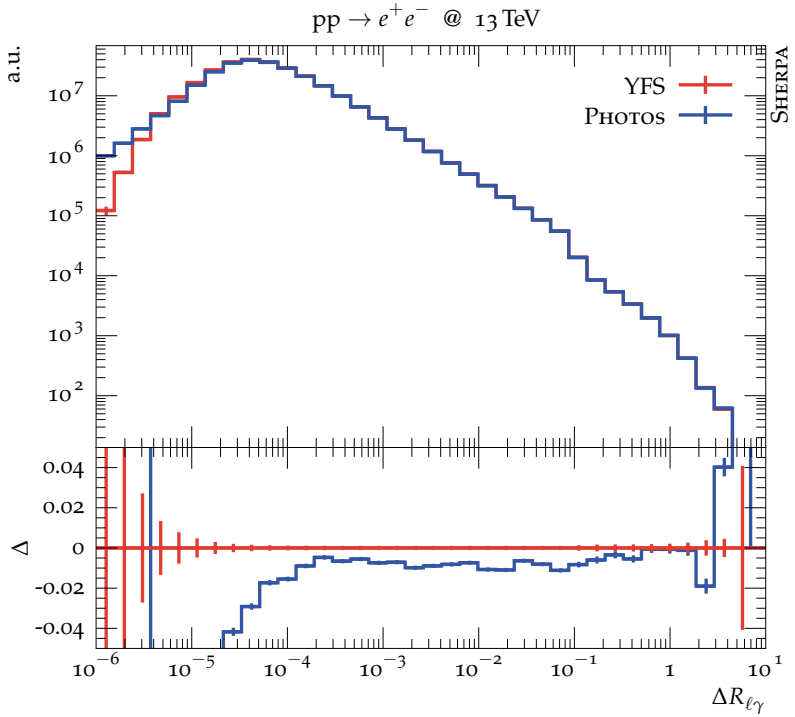


$$p_{\mathrm{T}}^{\gamma} > 1.2 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

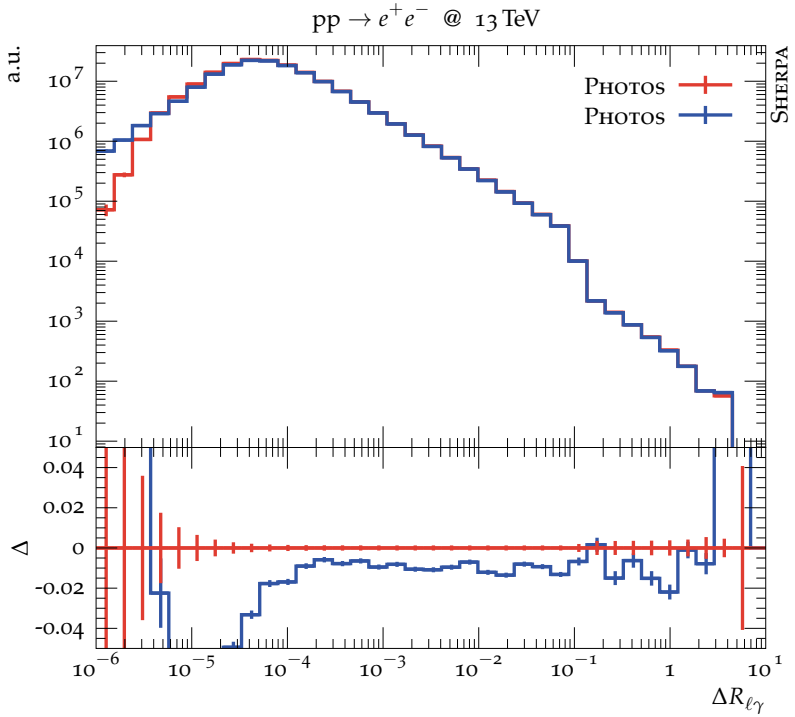


$$p_{\mathrm{T}}^{\gamma} > 1.5 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

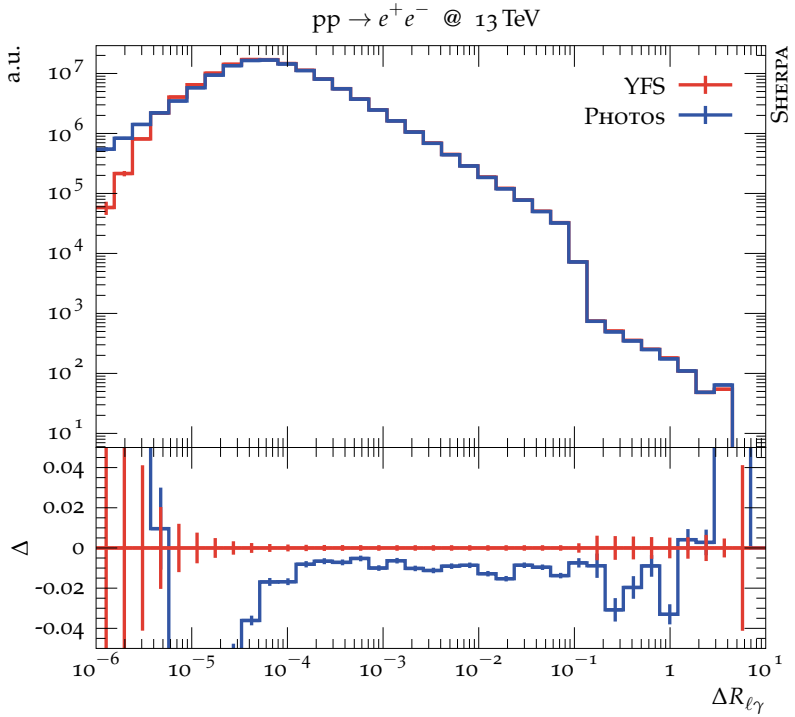


$$p_{\mathrm{T}}^{\gamma} > 1.8 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

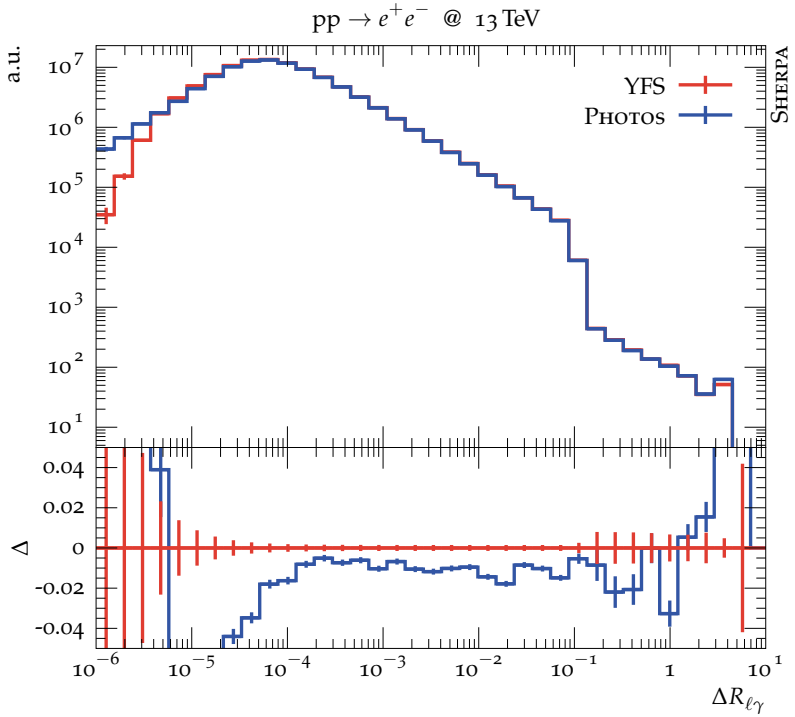


$$p_{\mathrm{T}}^{\gamma} > 2.0 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

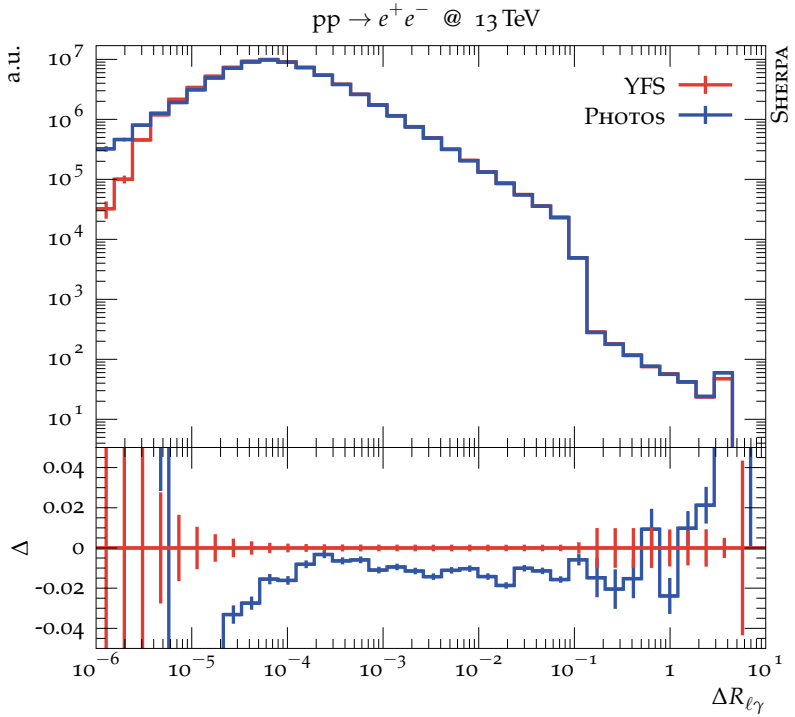


$$p_{\mathrm{T}}^{\gamma} > 2.2 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

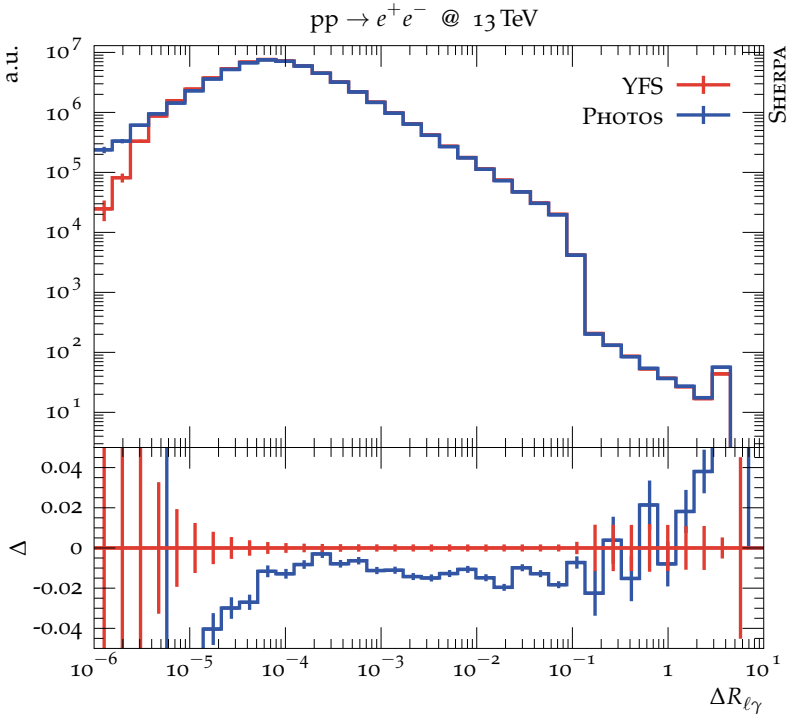


$$p_{\mathrm{T}}^{\gamma} > 2.5 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

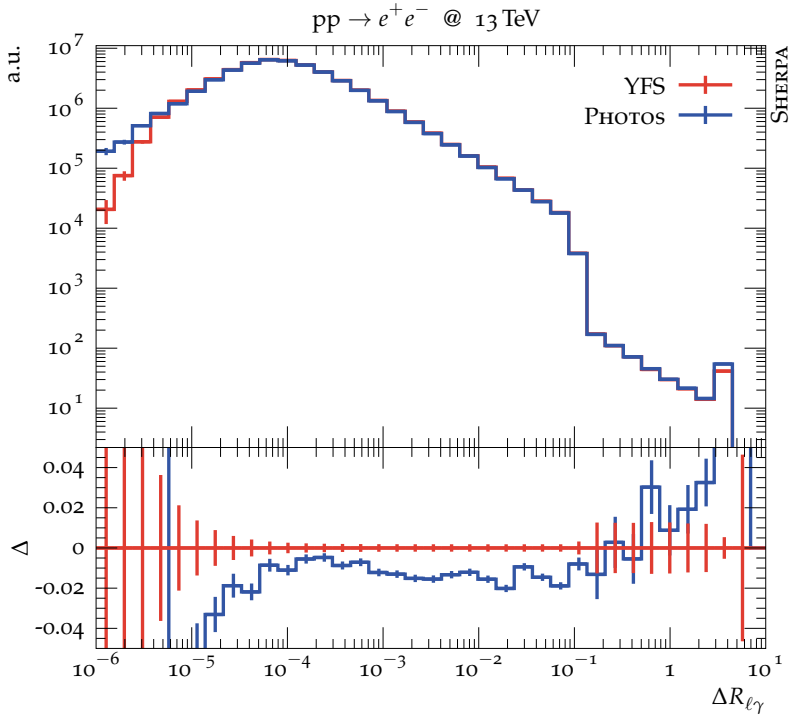


$$p_{\mathrm{T}}^{\gamma} > 2.8 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

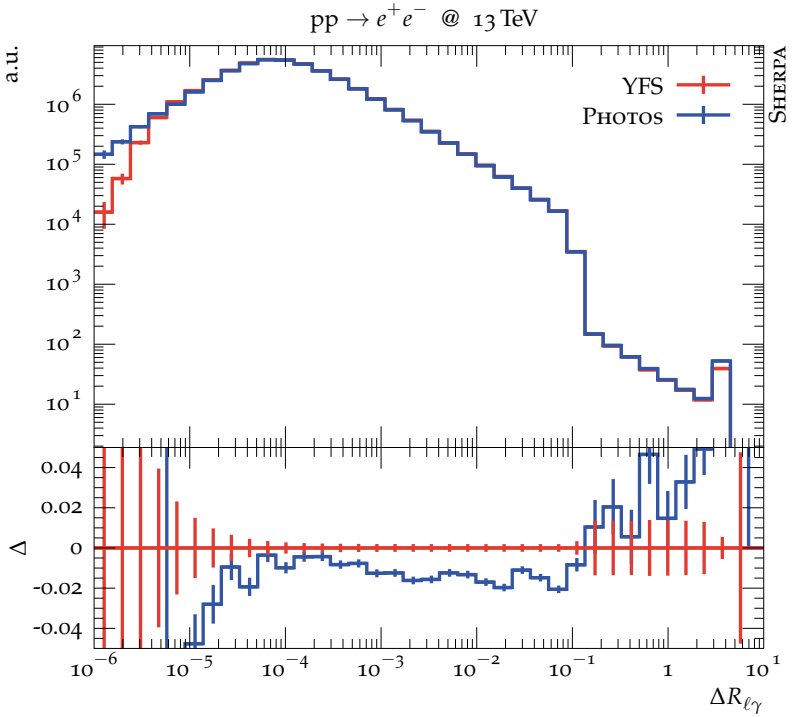


$$p_{\mathrm{T}}^{\gamma} > 3.0 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

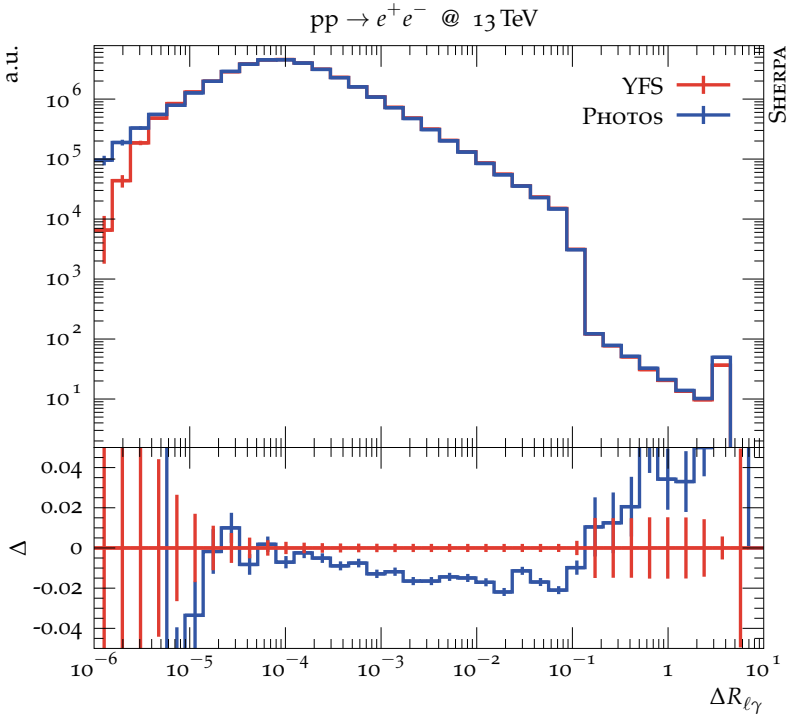


$$p_{\mathrm{T}}^{\gamma} > 3.2 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with photons harder than the lepton
- some difference in ultra-collinear behaviour

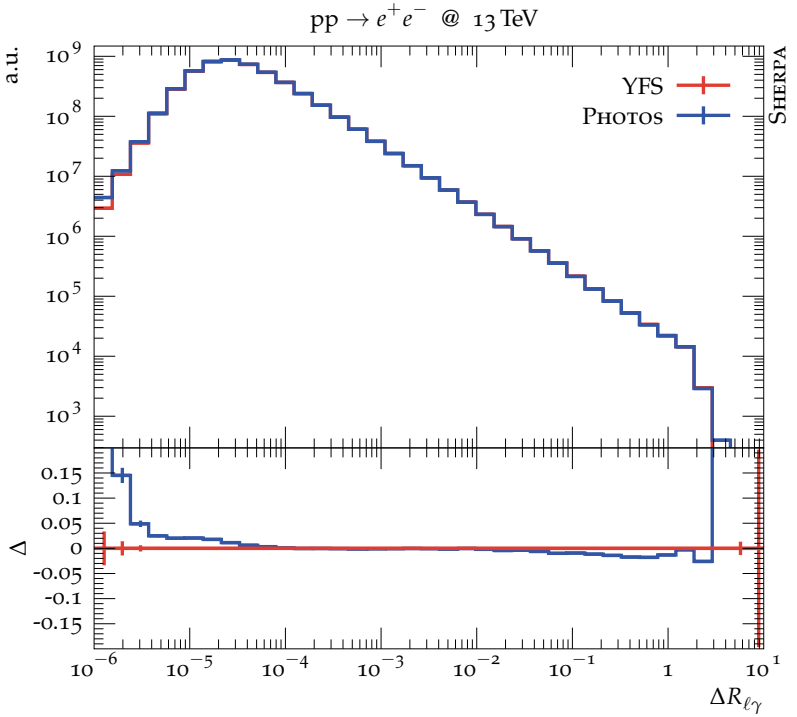


$$p_{\mathrm{T}}^{\gamma} > 3.5 \cdot p_{\mathrm{T}}^{\text{bare } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with significant radiative energy loss
- again largest difference in ultra-collinear region
- relevance for theory dependence of correction to Born leptons



$$p_{\mathrm{T}}^{\text{bare } \ell} < 1.00 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
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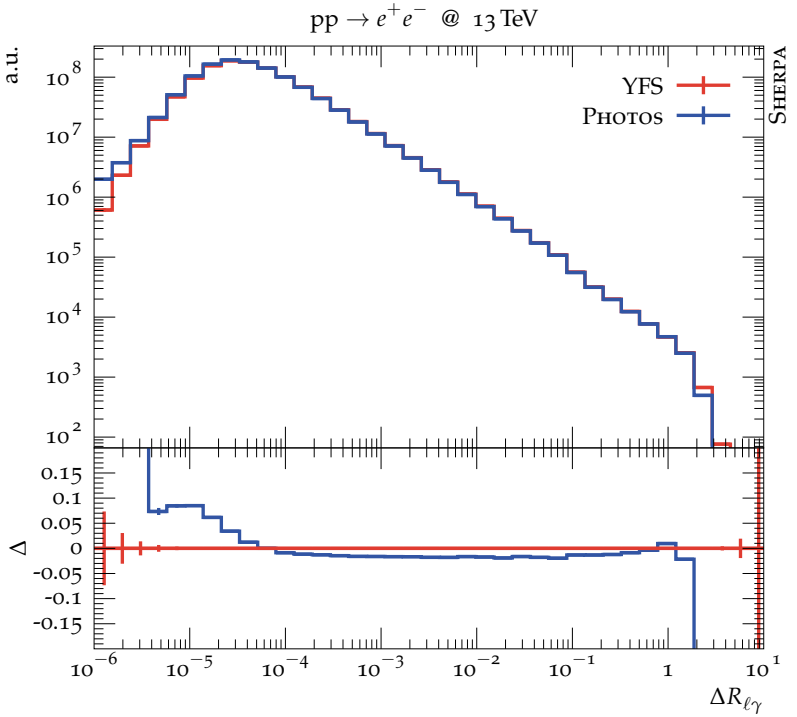
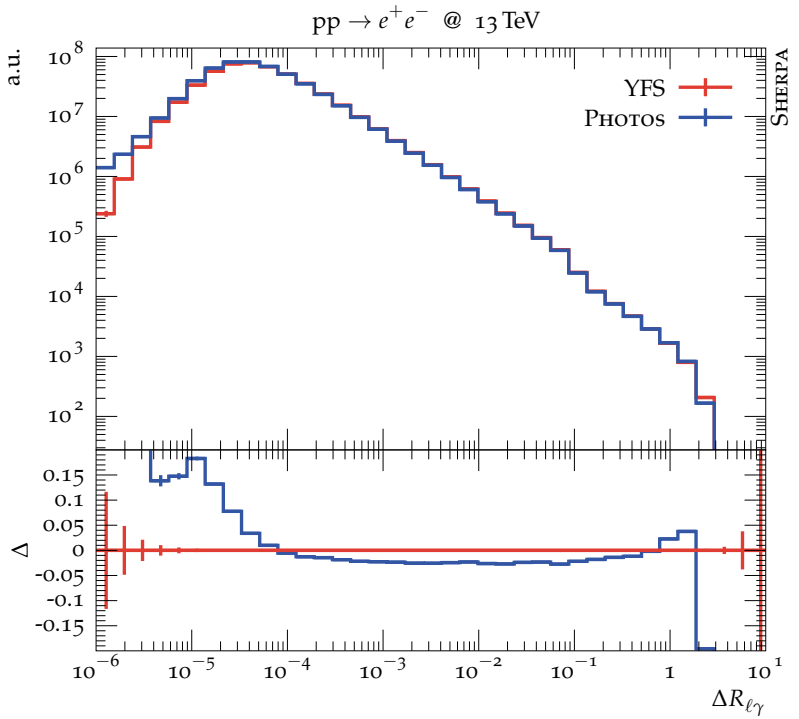


$$p_{\mathrm{T}}^{\text{bare } \ell} < 0.90 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with significant radiative energy loss
- again largest difference in ultra-collinear region
- relevance for theory dependence of correction to Born leptons

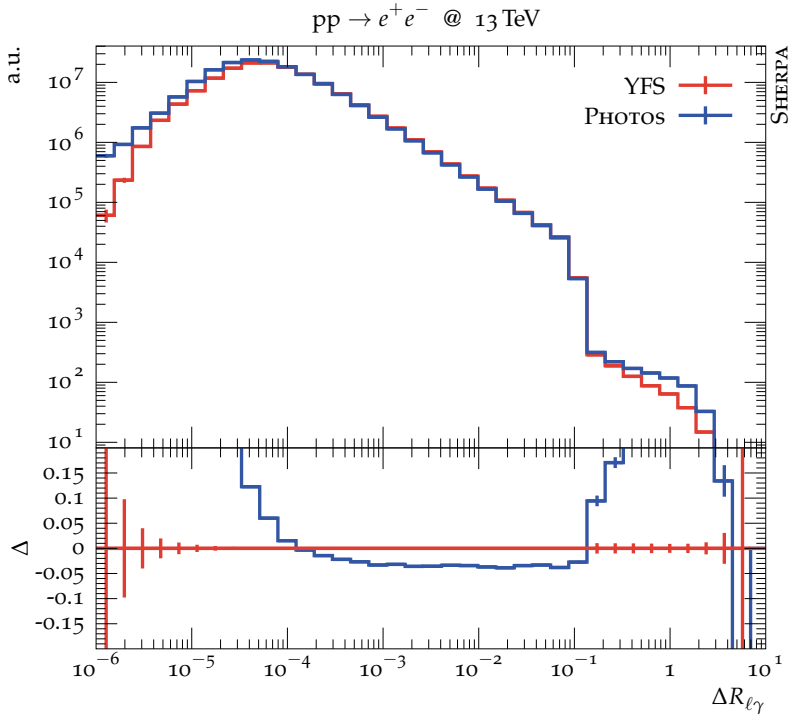


$$p_{\mathrm{T}}^{\text{bare } \ell} < 0.75 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with significant radiative energy loss
- again largest difference in ultra-collinear region
- relevance for theory dependence of correction to Born leptons

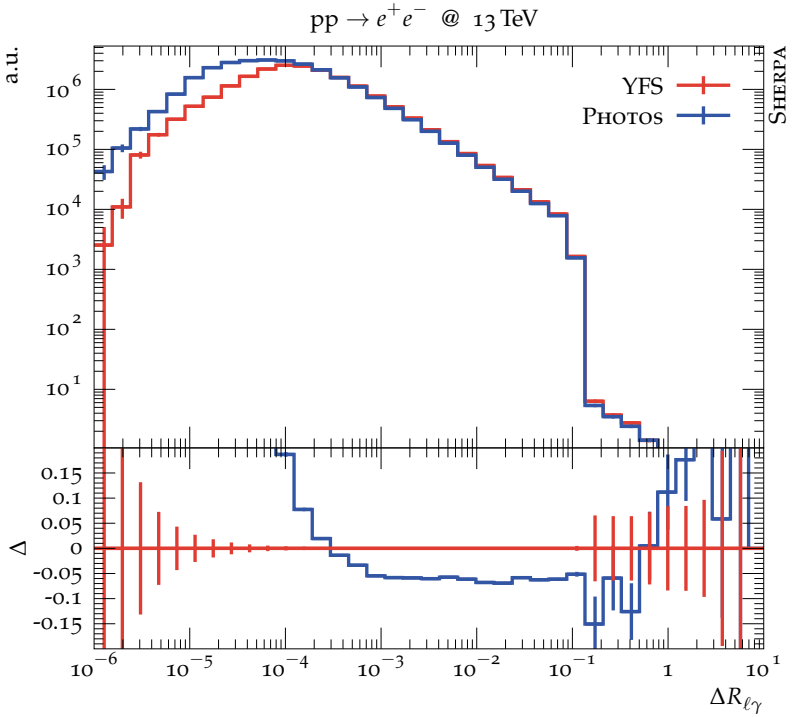


$$p_{\mathrm{T}}^{\text{bare } \ell} < 0.50 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with significant radiative energy loss
- again largest difference in ultra-collinear region
- relevance for theory dependence of correction to Born leptons

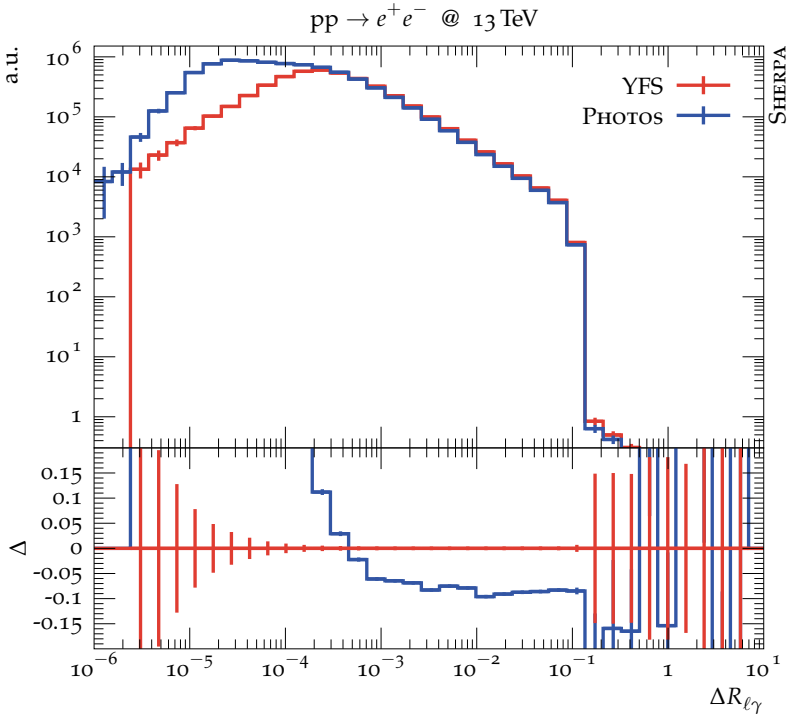


$$p_{\mathrm{T}}^{\text{bare } \ell} < 0.20 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events with significant radiative energy loss
- again largest difference in ultra-collinear region
- relevance for theory dependence of correction to Born leptons

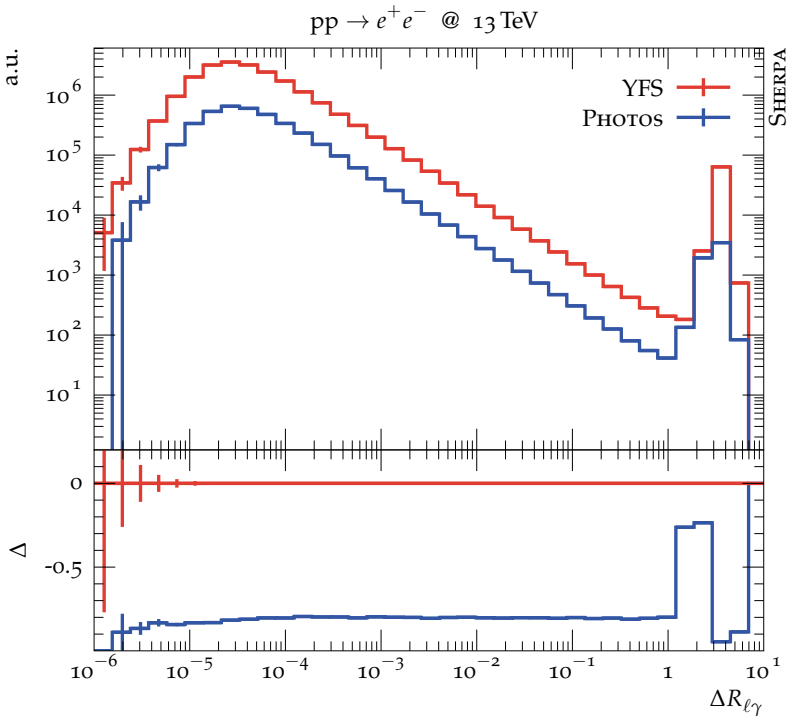


$$p_{\mathrm{T}}^{\text{bare } \ell} < 0.10 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events where bare lepton picked up energy from elsewhere
- very rare events, but large difference
- relevance for theory dependence of correction to Born leptons



$$p_{\mathrm{T}}^{\text{bare } \ell} > 1.00 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV}$, $p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
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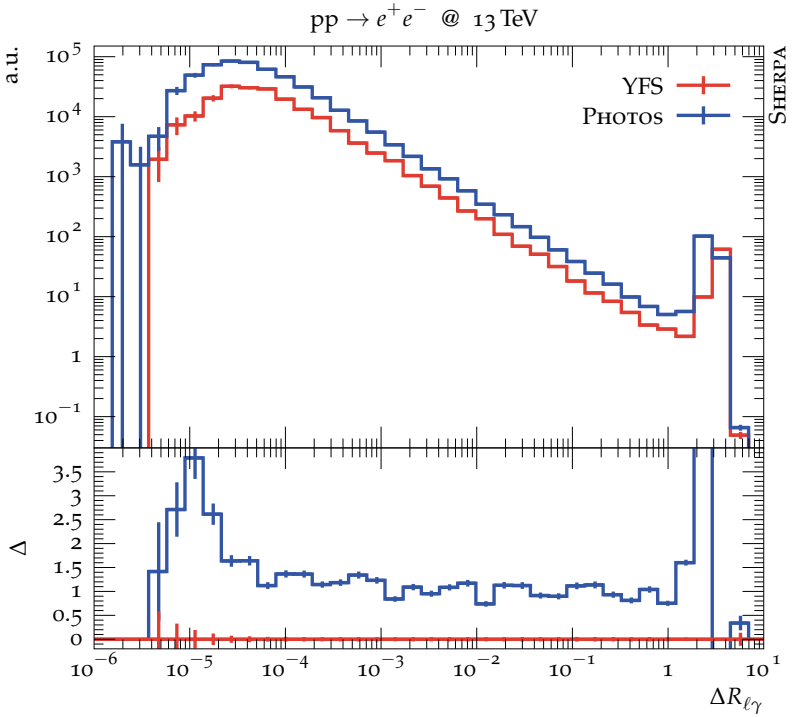

$$p_{\mathrm{T}}^{\text{bare } \ell} > 1.10 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events where bare lepton picked up energy from elsewhere
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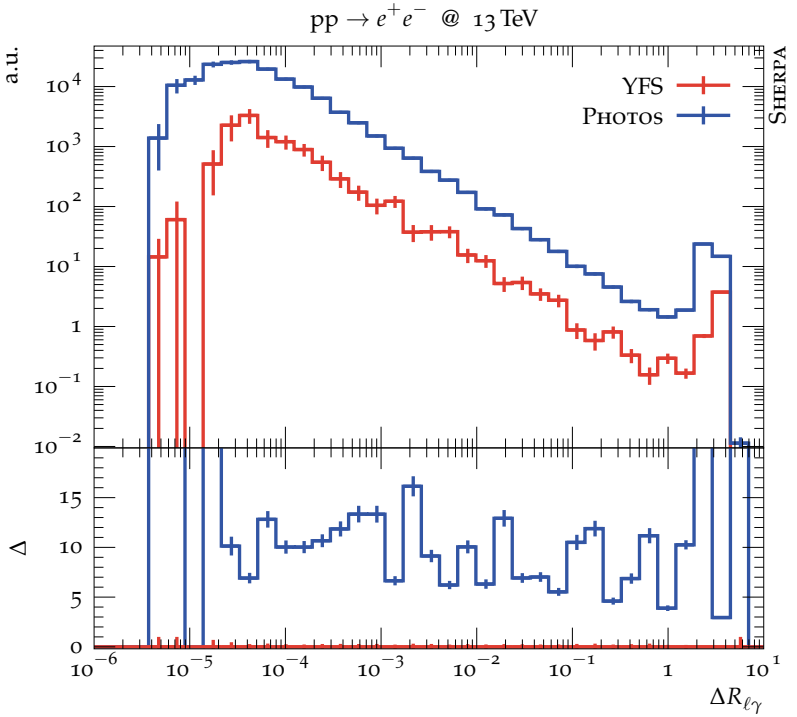
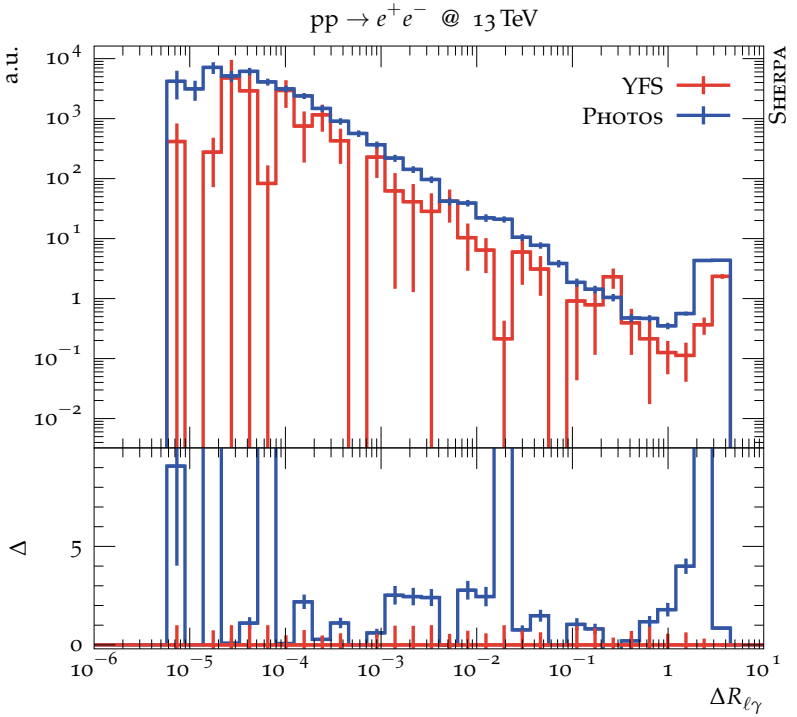


$$p_{\mathrm{T}}^{\text{bare } \ell} > 1.25 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

QED FSR in Drell-Yan – preliminary

Investigate photon radiation pattern – $\Delta R(\gamma, \text{closest bare } \ell)$

- $p_{\mathrm{T}}^{\text{bare } \ell} > 7\,\text{GeV},\ p_{\mathrm{T}}^{\gamma} > 10\,\text{MeV}$
- events where bare lepton picked up energy from elsewhere
- very rare events, but large difference
- relevance for theory dependence of correction to Born leptons



$$p_{\mathrm{T}}^{\text{bare } \ell} > 1.50 \cdot p_{\mathrm{T}}^{\text{Born } \ell}$$

Conclusions

- many developments, more to come

Thank you!

Backup