Photon splitting corrections to soft-photon resummation

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QCD@LHC
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Outline

Introduction

- QED corrections to leptonic final states are needed
- Either: QED parton shower in analogy to QCD
- Or: soft-photon resummation (YFS) Yennie, Frautschi, Suura '61
- Implemented in SHERPA with hard corrections up to NLO EW + NNLO QED Krauss, Schönherr '08
- Initial-state YFS also implemented in SHERPA Krauss, Price, Schönherr '22

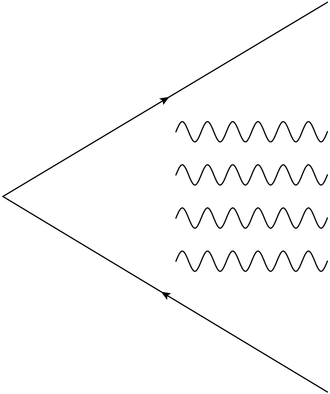
The YFS soft-photon resummation

$$\mathrm{d}\Gamma^{\mathrm{YFS}} = \mathrm{d}\Gamma_0\, e^{\alpha Y(\omega_{\mathrm{cut}})} \sum_{n_\gamma=0}^{\infty} \frac{1}{n_\gamma!} \left[\prod_{i=1}^{n_\gamma} \mathrm{d}\Phi_{k_i}\, \alpha\, \tilde{S}(k_i)\, \Theta(k_i^0 - \omega_{\mathrm{cut}})\, \mathcal{C} \right]$$

- $Y(\omega_{\mathrm{cut}})$ is the YFS form factor containing the real and virtual soft-photon divergences, $E_\gamma < \omega_{\mathrm{cut}}$
- $\tilde{S}$ is the eikonal (soft emission effects) for $E_\gamma > \omega_{\mathrm{cut}}$
- $\mathcal{C}$ corrects the eikonal to the full hard emission up to a given order (here NNLO)
- YFS contains no description of charged particle production, $\gamma \to \mathrm{f}\bar{\mathrm{f}}$ and the associated $\ln m_{\mathrm{f}}$

YFS and photon splittings

- All charged particles are massive within the YFS framework, which regulates collinear divergences
- Hence $\gamma \to \mathrm{f}\bar{\mathrm{f}}$ is IR finite but logarithmically enhanced for light flavours
- $\gamma \to e^+e^-$ will induce the largest corrections



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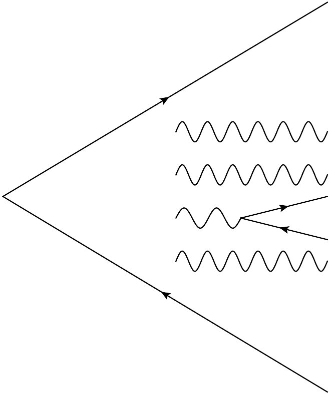


Photon splittings cont'd

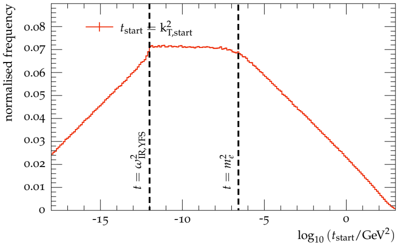
- We implemented a photon splitting algorithm which allows $\gamma \to \mathrm{f}\bar{\mathrm{f}}$ to occur, where $\mathrm{f} = e, \mu, \tau, \pi, K$
- The splittings into light charged hadrons (pions and kaons) use scalar QED (without a form factor as a first approximation)
- Note that we treat hadrons as the DoF instead of quarks since $E_\gamma \lesssim$ hadronisation scale

Photon splitting algorithm

- One-step dipole parton shower
- Input: primary charged particles and coherently emitted soft photons - works for any setup[1] given there is something to emit a photon and something to absorb recoil
- We reconstruct the scale t_{start} (GeV^2) from the input
- Evolution continues until the IR cutoff $t_0 = 4m_e^2$
- This algorithm applies a factor $\alpha_0 \log\left(t_{\text{start}}/4m_{\text{f}}^2\right)$ for each pair produced

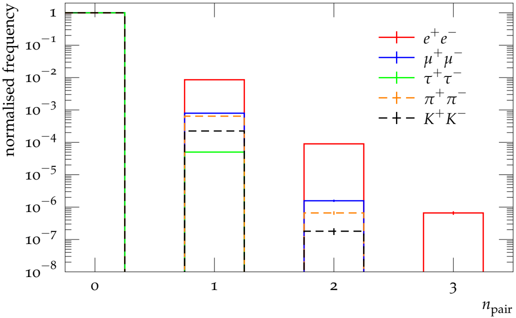
[1] Currently decays via Photons++, in future e^+e^- via YFS++

Scale choice



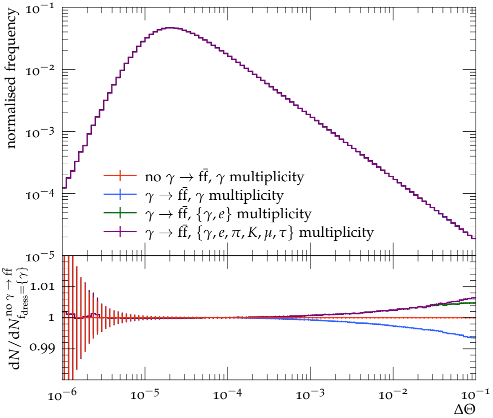
- What should we use as the ordering variable?
- $t = \mathrm{k}_\mathrm{T}^2$ for reconstructing starting scale ($\mathrm{f} \to \mathrm{f}\gamma$)
- $t = q^2$ for photon splittings ($\gamma \to \mathrm{f}\bar{\mathrm{f}}$)
- This is the most physical choice Brodsky, Lepage, Mackenzie '83

Secondary flavour distribution for $Z \to e^+e^-$



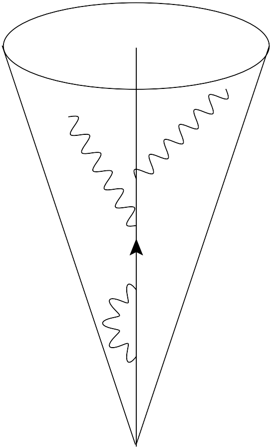
- Subsequent pair production decreases $\mathcal{P}(2) \sim \mathcal{P}(1)^2$
- Flavour suppression $\sim \log(m_{\mathrm{f}}^2)$

Angular structure of photon splitting corrections



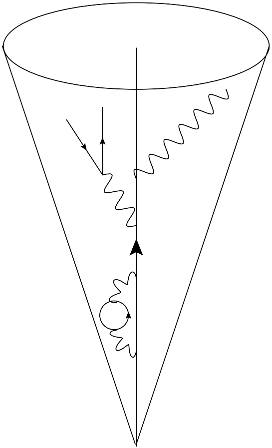
- On-shell $Z \to e^+e^-$
- For IR safety, $E_\gamma > 0.1\text{MeV}$
- Hard or wide-angle photons are more likely to split than soft or collinear ones
- At small $\Delta\Theta$, no difference in multiplicity
- At larger $\Delta\Theta$, we observe particles other than photons
- The majority of these are electrons

Rethinking object definitions



- For massless leptons, cone dressing with only photons is problematic
- Because we exclude real $\ell^+\ell^-$, there is nothing to cancel the virtual collinear singularity
- For massive leptons, there are contributions $\sim \log\left(m_\ell\right)$

Rethinking object definitions



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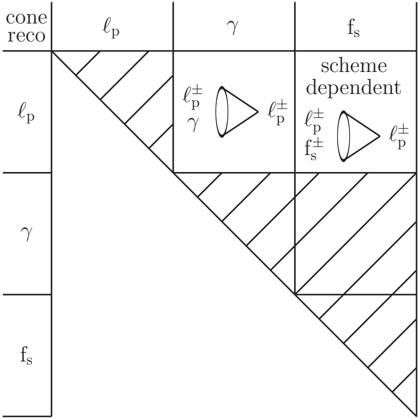
Flavour-aware lepton dressing



We consider the following schemes:

- $\mathrm{f}_{\text{dress}} = \{\gamma\}$
- $\mathrm{f}_{\text{dress}} = \{\gamma, e\}$
- $\mathrm{f}_{\text{dress}} = \{\gamma, e, \pi, K\}$
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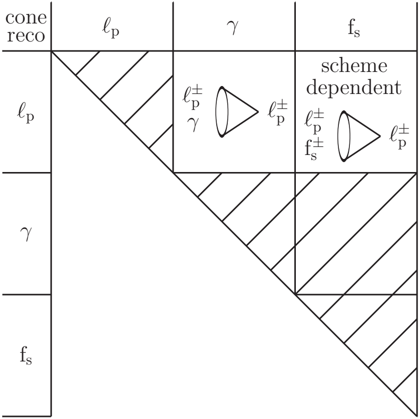
Flavour-aware lepton dressing



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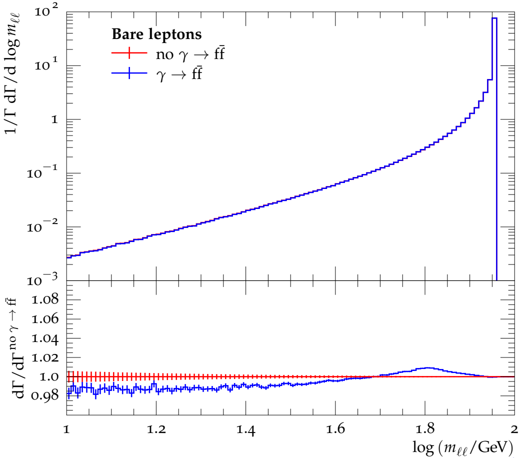
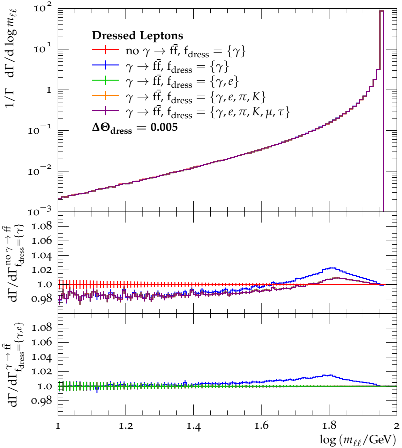
Dilepton invariant mass for on-shell $Z \to e^+e^-$



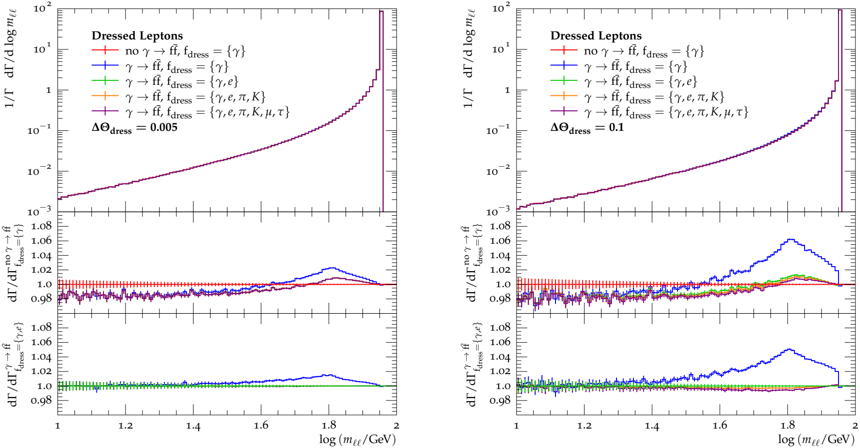
- Primary electrons identified using energy
- Small recoil effect on bare primary leptons visible below Z mass
- Reference is YFS (photon emission corrections only)

Dilepton invariant mass for on-shell $Z \to e^+e^-$

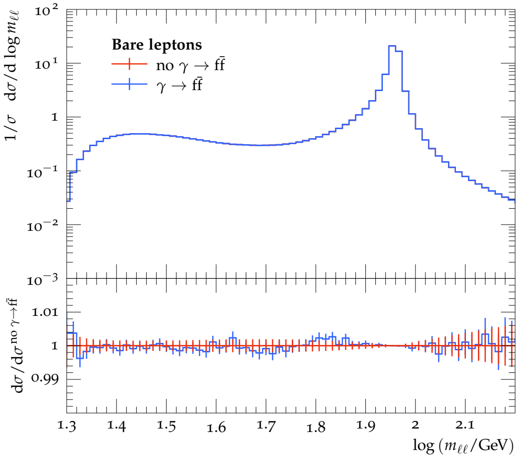


- Distance measure is $\Delta\Theta_{\text{dress}} = ((\Delta\theta)^2 + (\Delta\phi)^2)^{1/2}$
- Left: small dressing cone
- Upper ratio plot wrt. YFS (photon emission corrections only)
- Lower ratio plot wrt. YFS + photon splittings dressed with photons and electrons

Dilepton invariant mass for on-shell $Z \to e^+e^-$

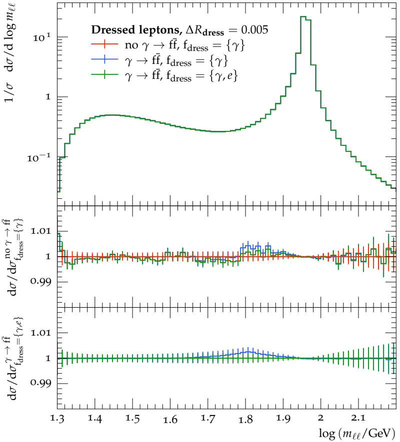


Dilepton invariant mass for $pp \to e^+e^-$ (preliminary)



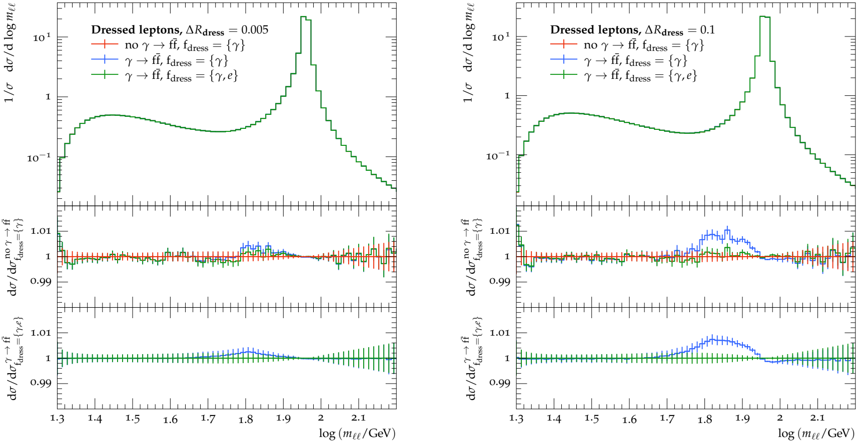
- Reference is YFS (photon emission corrections only)
- No significant correction without improved statistics

Dilepton invariant mass for $pp \to e^+e^-$ (preliminary)



- Distance measure is $\Delta R_{\text{dress}} = ((\Delta\eta)^2 + (\Delta\phi)^2)^{1/2}$
- Left: small dressing cone
- Correction from $\gamma \to f\bar{f}$ now statistically significant due to recombination of momenta
- Upper ratio plot wrt. YFS
- Lower ratio plot wrt. YFS + photon splittings dressed with photons and electrons

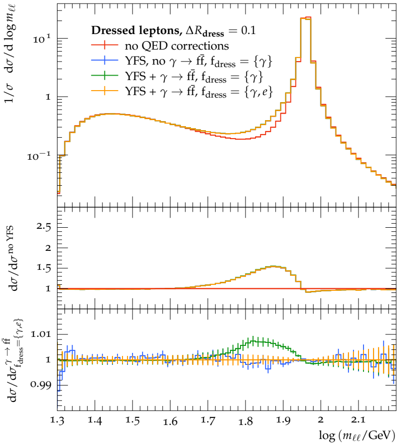
Dilepton invariant mass for $pp \to e^+e^-$ (preliminary)



Conclusions

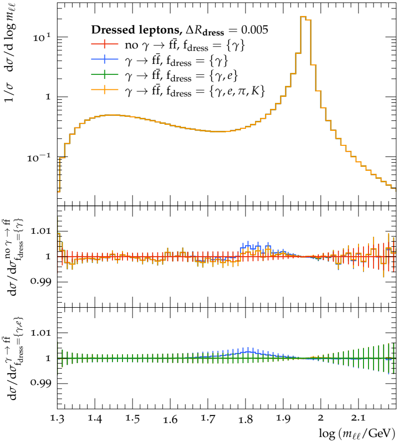
- We introduced an automated method for including photon splitting corrections to the YFS implementation in SHERPA
- $\gamma \to f\bar{f}$ introduces corrections at the per mille level for bare leptons and at the percent level for photon-dressed leptons
- By introducing novel flavour-aware dressing strategies, we limit these corrections and reduce dependence on the cone size
- Both the photon splitting method and the dressing strategies are general and applicable to a wide range of setups
- Included in 3.0beta release - see Eno's talk

Backup: Dilepton invariant mass for $pp \to e^+e^-$



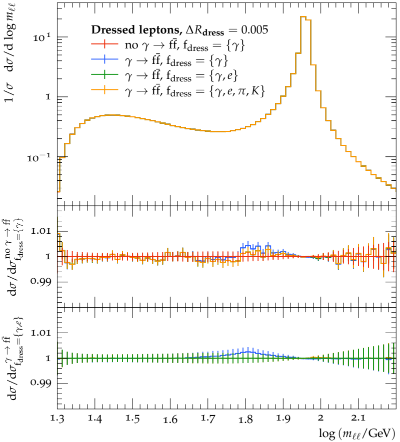
- QED corrections are $\sim 50\%$
- Photon splittings give a 1% correction to photon-dressed leptons
- This correction disappears when electrons are included in the dressing

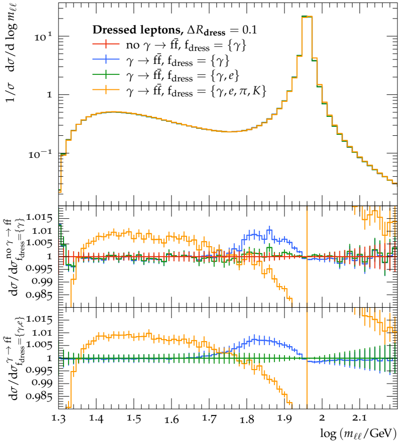
Dilepton invariant mass for $pp \to e^+e^-$ (preliminary)



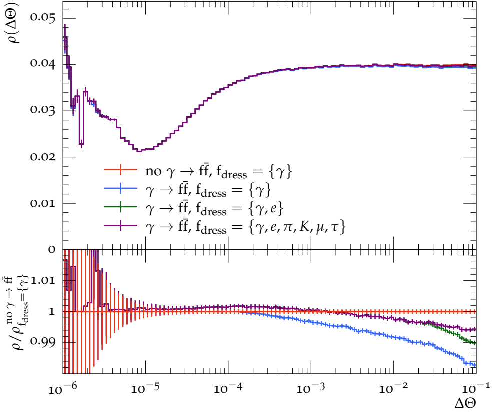
- Include light charged hadrons in dressing
- Does this work in a hadron collider environment?
- Left: small dressing cone - no further benefit
- Right: larger dressing cone - detrimental

Dilepton invariant mass for $pp \to e^+e^-$ (preliminary)





Backup: Energy density of a dressed lepton



- Distance measure is $\Delta\Theta_{\text{dress}} = ((\Delta\theta)^2 + (\Delta\phi)^2)^{1/2} = 0.1$
- Photon splittings cause loss in energy of dressed lepton
- Including electrons in dressing recoups most of lost energy

Splitting functions

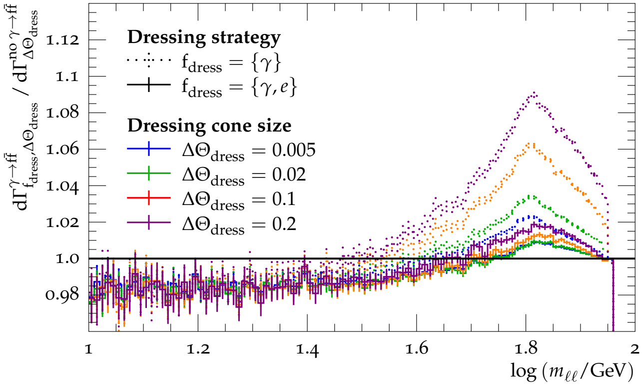
$$S_{s_{\widetilde{ij}}(\tilde{k})\to s_i\gamma_j(k)} = -\,Q^2_{\widetilde{ij}\tilde{k}}\,\alpha(0)\left[\frac{2}{1-z+zy}-\frac{\tilde{v}_{\widetilde{ij},\tilde{k}}}{v_{ij,k}}\left(2+\frac{m_i^2}{p_ip_j}\right)\right]$$

$$S_{f_{\widetilde{ij}}(\tilde{k})\to f_i\gamma_j(k)} = -\,Q^2_{\widetilde{ij}\tilde{k}}\,\alpha(0)\left[\frac{2}{1-z+zy}-\frac{\tilde{v}_{\widetilde{ij},\tilde{k}}}{v_{ij,k}}\left(1+z+\frac{m_i^2}{p_ip_j}\right)\right]$$

$$S_{\gamma_{\widetilde{ij}}(\tilde{k})\to s_i\bar{s}_j(k)} = S_{\gamma_{\widetilde{ij}}(\tilde{k})\to f_i\bar{f}_j(k)} = -\,Q^2_{\widetilde{ij}\tilde{k}}\,\alpha(0)\left[1-2z(1-z)-z_+z_-\right]$$

Catani et al. '02, Dittmaier et al. '08, Schumann, Krauss '08

Backup: Dressing cone size dependence

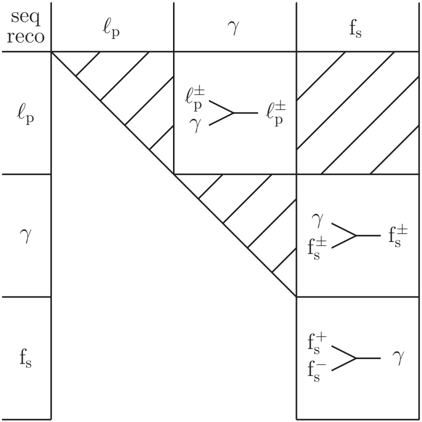


Backup: Leptonic W decay

- The W is charged and the neutrino is not, so instead of an FF dipole we have an FI dipole $W - \ell$
- Large W mass suppresses photon emissions, so neglect it as an emitter
- Modify kinematic variables and splitting functions – we keep the W eikonal term

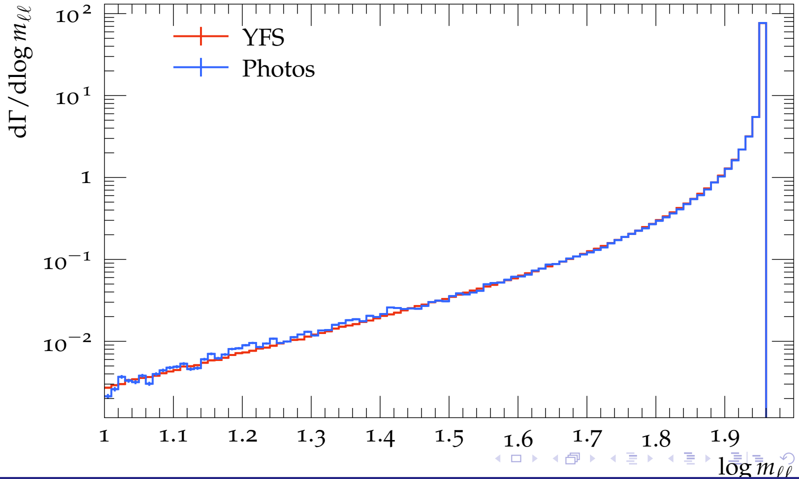
Basso et al. '16

Backup: Sequential recombination dressing



- Similarities with QCD jets & ability to distinguish flavour
- Flavour-$k_\perp$ algorithm?
- Future work only - this would not be backwards-compatible

Backup: Comparison with Photos



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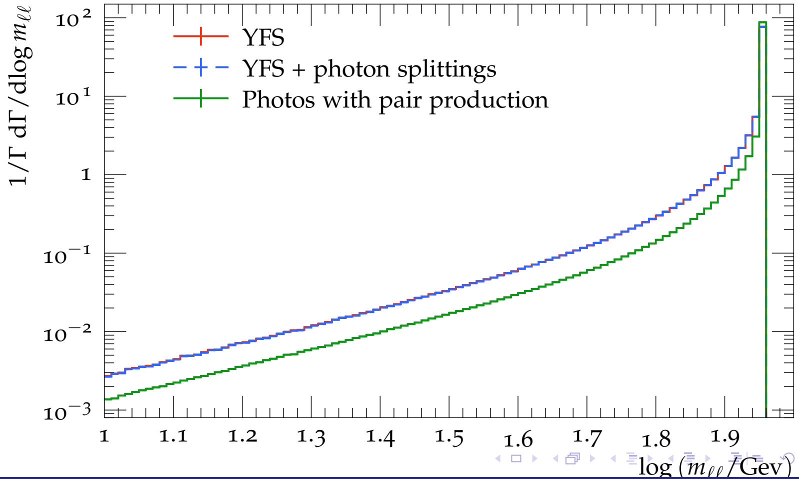

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