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Photon production at NNLO with realistic photon isolation (based on 2205.01516)

LHC EW WG General Meeting

Marius Höfer (LMU Munich)

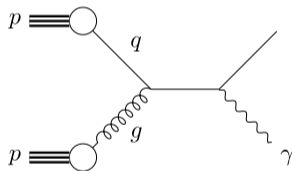
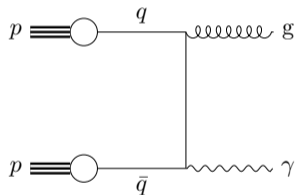
m.hoefer@physik.uni-muenchen.de

with X. Chen, T. Gehrmann, E.W.N. Glover, A. Huss, R. Schürmann

15/11/2022

Photon production at hadron colliders

- probe of the hard QCD dynamics
- direct sensitivity to the gluon distribution in the proton
- background estimates in new physics (NP) searches (see e.g. [[1705.04664](#)])



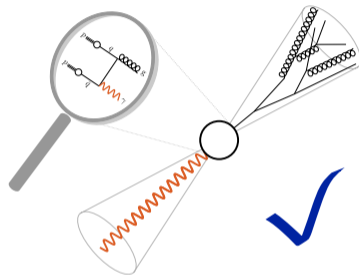
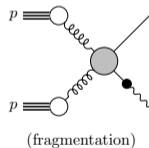
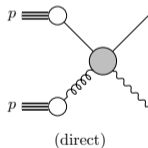
Photon isolation - I

For any collider process with final state (FS) photons:

primary photons

photons created in the hard scattering

$$d\hat{\sigma}^{\gamma+X} = \underbrace{d\hat{\sigma}^{\gamma+X}}_{\text{direct}} + \underbrace{\sum_a d\hat{\sigma}^{a+X}}_{\text{fragmentation}} \otimes D_{a \rightarrow \gamma}$$



scattering,
ess

the
sideration

residual $q\gamma$ -collinear singularities:
absorbed into fragmentation function

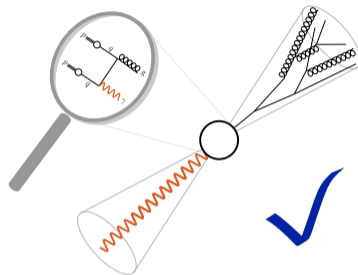
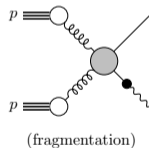
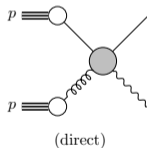
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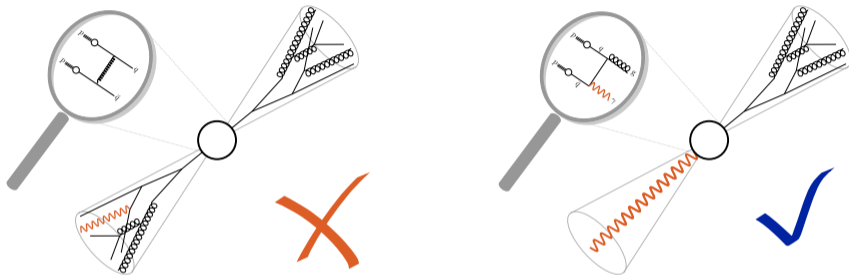
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residual $q\gamma$ -collinear singularities:
absorbed into fragmentation function

$$D_{a \rightarrow \gamma} \sim \mathcal{O}(\alpha)$$

Photon isolation - II

Idea: look for photons isolated from hadronic radiation



Photon Isolation

⇒ Most of the (transverse) energy in the vicinity of the candidate isolated photon must be carried by the photon itself.

Here: cone based isolations

Fixed/Hard cone isolation

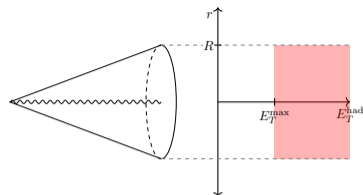
Idea/Concept

- define cone around photon with fixed $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- integrate all hadronic E_T within the cone
- set upper limit: $E_T^{\text{had}} \leq E_T^{\text{max}}(p_T^\gamma) = \varepsilon p_T^\gamma + E_T^{\text{thres}}$

technical complications

[Les Houches 2009, 2011, 2015 ...]

- direct component ✓, fragmentation component ✓
- fragmentation functions $D_{a \rightarrow \gamma}$ [M.Gluck et al. 1995; L.Bourhis et al., hep-ph/9704447] are complicated to include into theory calculations
- $E_T^{\text{max}} \rightarrow 0$: no frag. contribution but not infrared (IR) safe

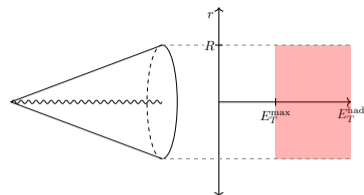


Standard procedure
used in all modern
collider experiments

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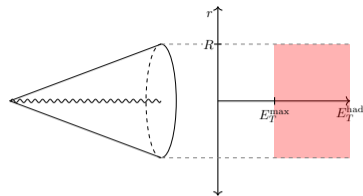
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Idealised cone isolation

Idea/Concept

[S.Frixione,hep-ph/9801442] [F.Siegert,1611.07226; X.Chen et al.,1904.01044]

- make isolation condition r -dependent:

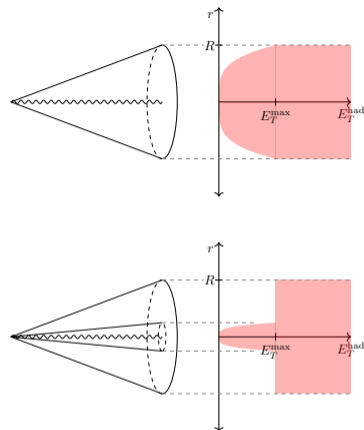
$$E_T^{\text{had}}(r) \leq E_T^{\text{max}}(p_T^\gamma) \chi(r) \quad \forall r \leq R$$

- $\chi(r) \xrightarrow[r \rightarrow 0]{} 0$ (smoothly): direct comp. ✓, frag. comp. ✗
- IR safe

technical complications

[Les Houches 2013, 2015, 2019; S.Catani et al.,1802.02095; X.Chen et al.,1904.01044]

- problem: smooth profile cannot be implemented in experiment
- fix isolation parameters to mimic experimental isolation
- systematic discrepancy ($\mathcal{O}(\text{few } \%)$) between isolation prescriptions in experiment and theory



Common procedure
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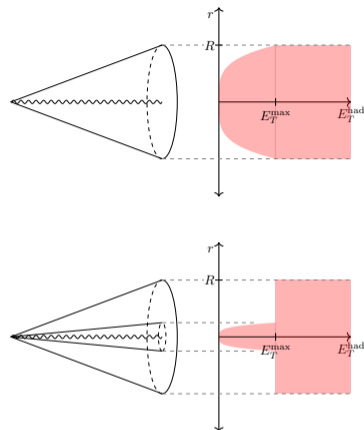
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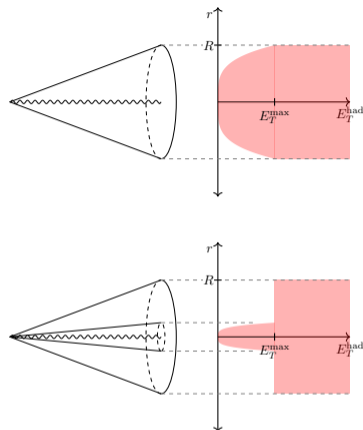
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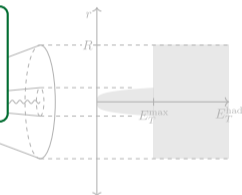
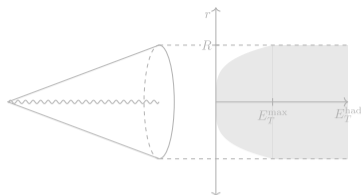
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Implementation of fragmentation contribution in NNLOJET

\Rightarrow

NNLO QCD with realistic photon isolation



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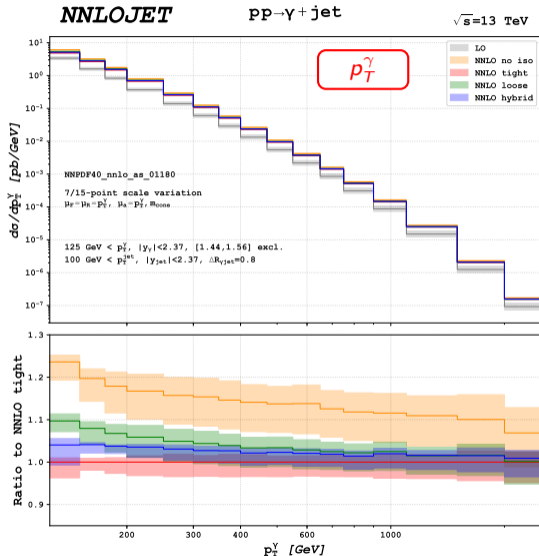
Loose vs. tight vs. no vs. hybrid isolation

photon transverse momentum

- highest isolation sensitivity in low p_T^γ region
- in high p_T^γ regime: photon well separated from additional hadronic energy
- moderate impact of photon isolation on **prompt** photon production

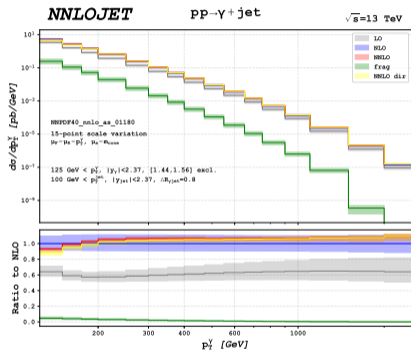
Isolations ($R = 0.4$)

- tight isolation:** $E_T^{\max} \approx 10$ GeV
- hybrid isolation:** $E_T^{\max} \approx 10$ GeV ($R_{\text{inner}} = 0.1$)
- loose isolation:** $E_T^{\max} \approx 50$ GeV

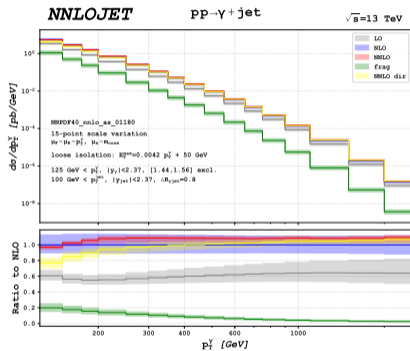


Size/impact of fragmentation contribution

direct vs. fragmentation contribution: increase sensitivity to fragmentation using looser criterion



Tight isolation: $E_T^{\max} = 0.0042 p_T^\gamma + 10$ GeV

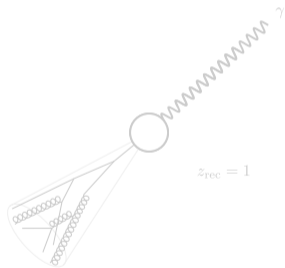


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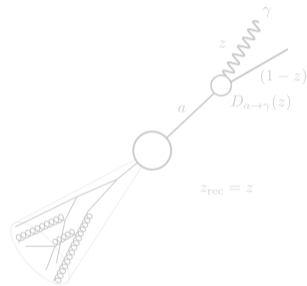
Accessing $D_{a \rightarrow \gamma}$ through z_{rec}

- $z_{\text{rec}} = p_T^\gamma / p_T^{\text{jet}}$: imbalance of the transverse momenta of the photon and the leading jet
- At LO: one-to-one correspondence to the momentum fraction in $D_{a \rightarrow \gamma}(z)$

direct @ lowest order



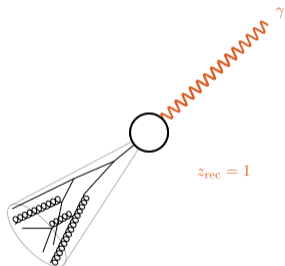
fragmentation @ lowest order



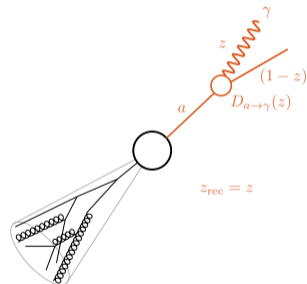
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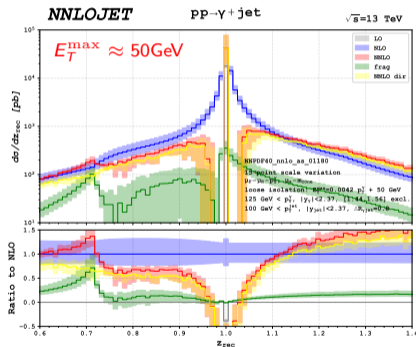
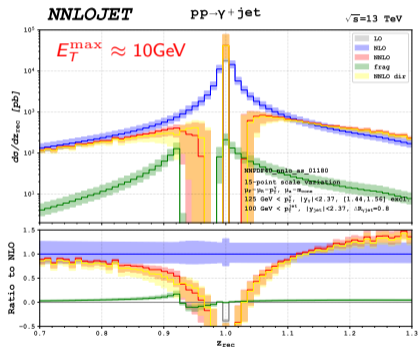


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- $z_{\text{rec}} \rightarrow 1$ sensitive to soft emissions \Rightarrow requires resummation of large logarithms

Backup slides

Contributions to the Cross Section

- $d\hat{\sigma}_i$ cross section for production of identified particle/parton i

$$d\hat{\sigma}_i = d\hat{\sigma}_i^{\text{LO}} + \frac{\alpha_s}{2\pi} d\hat{\sigma}_i^{\text{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 d\hat{\sigma}_i^{\text{NNLO}} + \mathcal{O}(\alpha_s^3)$$

- composition of the photon production cross section:

$$d\hat{\sigma}^{\gamma+X,\text{LO}} = d\hat{\sigma}_\gamma^{\text{LO}}$$

$$d\hat{\sigma}^{\gamma+X,\text{NLO}} = d\hat{\sigma}_\gamma^{\text{NLO}} + d\hat{\sigma}_g^{\text{LO}} \otimes D_{g \rightarrow \gamma} + \sum_q d\hat{\sigma}_q^{\text{LO}} \otimes D_{q \rightarrow \gamma} - \sum_q d\hat{\sigma}_q^{\text{LO}} \otimes \mathbf{F}_{q \rightarrow \gamma}^{(0)}$$

$$d\hat{\sigma}^{\gamma+X,\text{NNLO}} = d\hat{\sigma}_\gamma^{\text{NNLO}} + d\hat{\sigma}_g^{\text{NLO}} \otimes D_{g \rightarrow \gamma} + \sum_q d\hat{\sigma}_q^{\text{NLO}} \otimes D_{q \rightarrow \gamma} - \sum_q d\hat{\sigma}_q^{\text{NLO}} \otimes \mathbf{F}_{q \rightarrow \gamma}^{(0)} \\ - d\hat{\sigma}_g^{\text{LO}} \otimes \frac{\alpha_s}{2\pi} \mathbf{F}_{g \rightarrow \gamma}^{(1)} - \sum_q d\hat{\sigma}_q^{\text{LO}} \otimes \frac{\alpha_s}{2\pi} \mathbf{F}_{q \rightarrow \gamma}^{(1)}$$

$\mathbf{F}_{a \rightarrow \gamma}$: combination of mass factorization terms and fragmentation functions

Loose vs. tight vs. no vs. hybrid isolation

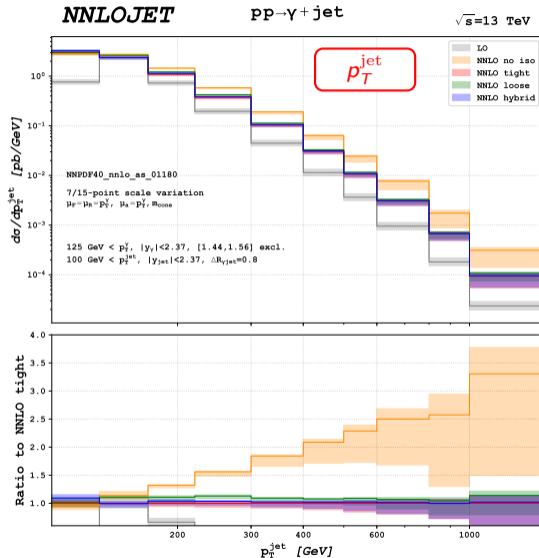
leading jet transverse momentum

in high p_T^{jet} regime:

- dominated by dijet events (effectively NLO)
- w/o isolation: main contribution from fragmentation with small momentum transfer

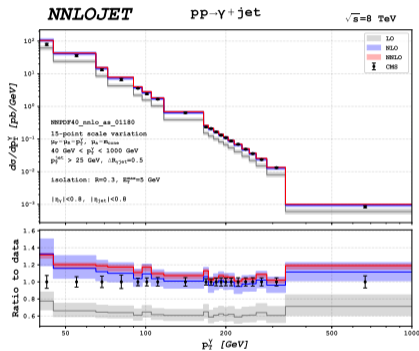
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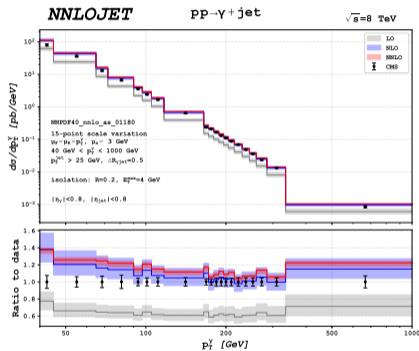


CMS triple differential measurement

Comparison between CMS data [1907.08155] and NNLO predictions with realistic isolation



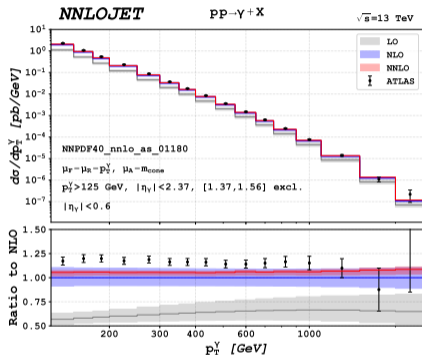
$$R = 0.3, E_T^{\max} = 5 \text{ GeV}$$



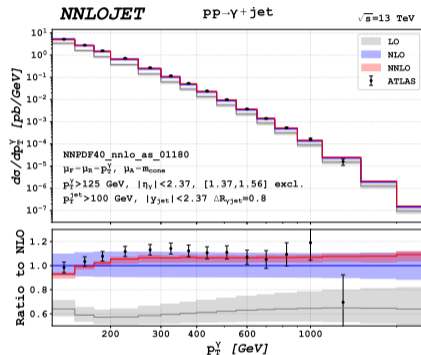
$$R = 0.2, E_T^{\max} = 4 \text{ GeV}$$

ATLAS inclusive photon and photon + jet at 13TeV

Comparison between ATLAS data [1908.02746, 1801.00112] and NNLO predictions with realistic isolation



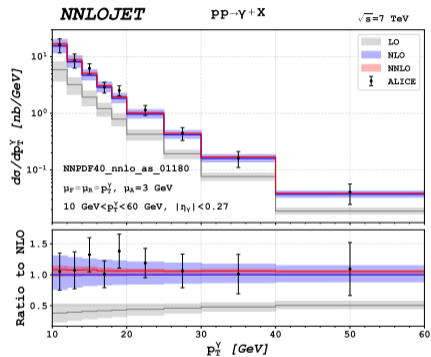
$$R = 0.4, E_T^{\max} = 0.0042 p_T^\gamma + 4.8 \text{ GeV}$$



$$R = 0.4, E_T^{\max} = 0.0042 p_T^\gamma + 10 \text{ GeV}$$

ALICE inclusive photon at 7TeV

Comparison between ALICE data [1906.01371] and NNLO predictions with realistic isolation



$$R = 0.4, E_T^{\text{max}} = 2\text{GeV}$$