LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Photons and Jets

SM@LHC 2022

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11/04/2022

Outline

Introduction

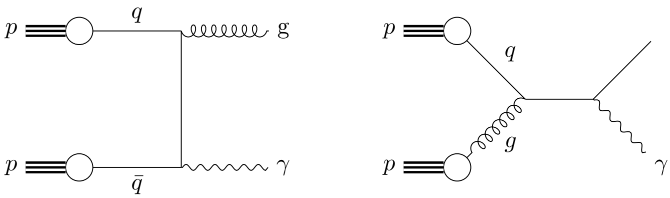
- photon production at hadron colliders
- photon isolation: basics
- photon isolation: cone based isolations

Phenomenology

- comparison of isolation prescriptions at NNLO
- impact of photon fragmentation
- observable to access the fragmentation: z_{rec}

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])



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Experimental status

- exp. uncertainties on σ_{tot} and distributions pushed down to $\mathcal{O}$(few %)

CMS	[1505.06520]	$\gamma + j$	8TeV	
	[1807.00782]	$\gamma + X/j$	13TeV	
	[1907.08155]	$\gamma + j$	8TeV	triple differential
ATLAS	[1605.03495]	$\gamma + X$	8TeV	
	[1801.00112]	$\gamma + j$	13TeV	
	[1901.10075]	$\gamma + X$	$R^{\gamma}_{13/8}$	
	[1908.02746]	$\gamma + X$	13TeV	
	[1912.09866]	$\gamma + 2j$	13TeV	

Photon production at hadron colliders

- probe of the hard QCD dynamics
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Theoretical status

- NLO QCD theory uncertainty $> \mathcal{O}(10\%)$
  $\rightarrow$ need higher order QCD corrections

MCFM	[1703.10109]	NNLO QCD, smooth cone isolation
NNLOJET	[1904.01044]	NNLO QCD, hybrid isolation
	[22xx.xxxxx]	NNLO QCD+NLO EW, hybrid isolation
	[2201.06982,22xx.xxxxx]	NNLO QCD, fixed cone isolation

Photon isolation - I

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

primary photons

photons created in the hard scattering

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

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

secondary photons

- photons emitted after the actual scattering, e.g. during the hadronization process ($\pi \to \gamma\gamma, \ldots$)
- not a contribution associated with the underlying hard process under consideration $\to$ huge background

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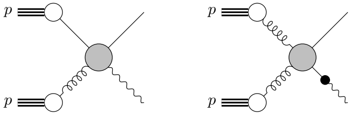

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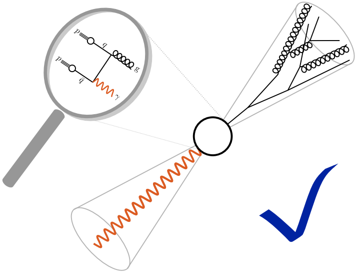

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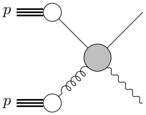

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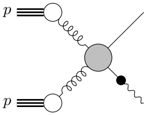
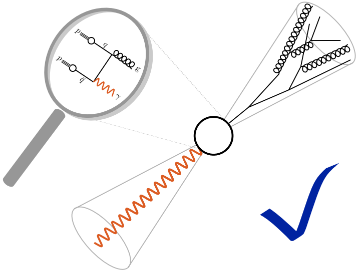


(fragmentation)



residual $q\gamma$-collinear singularities:
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$$D_{a\to\gamma} \sim \mathcal{O}(\alpha)$$

Photon isolation - I

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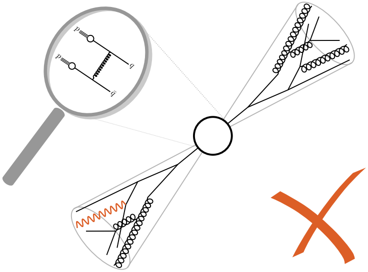

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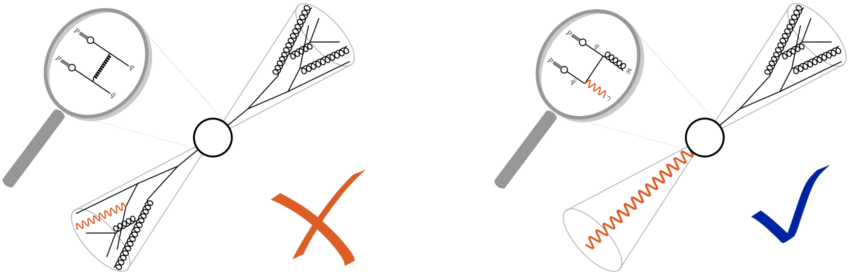
Photon isolation - II

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

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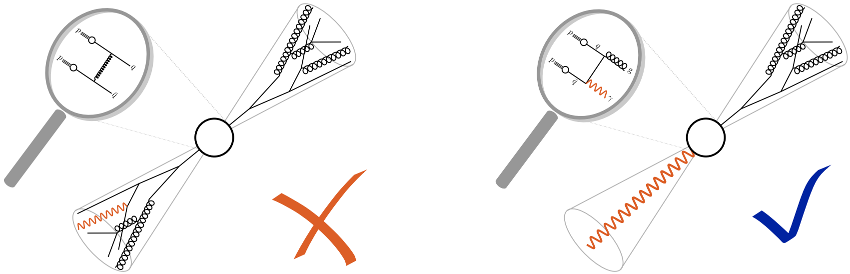

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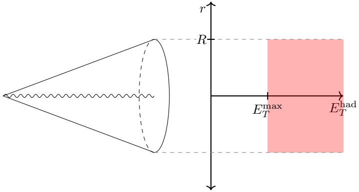
Fixed/Hard cone isolation



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: $E_T^{\text{had}} \leq E_T^{\max}(p_T^\gamma) = \varepsilon p_T^\gamma + E_T^{\text{thres}}$

Standard procedure used in all modern collider experiments

technical complications

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

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

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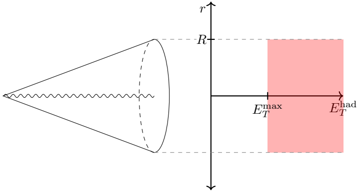

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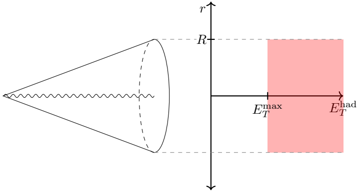

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Idealised cone isolation

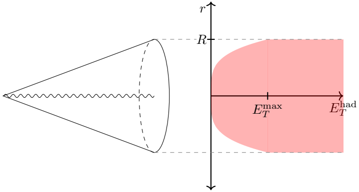
Idea/Concept

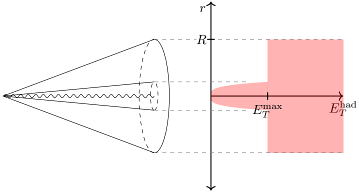
[S.Frixione,hep-ph/9801442] [F.Siegert,1611.07226; X.Chen et al.,1904.01044]

- make isolation condition r-dependent:

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

- $\chi(r) \underset{r\to 0}{\longrightarrow} 0$ (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 ($\mathcal{O}$(few %)) between isolation prescriptions in experiment and theory

Common procedure for theory calculations

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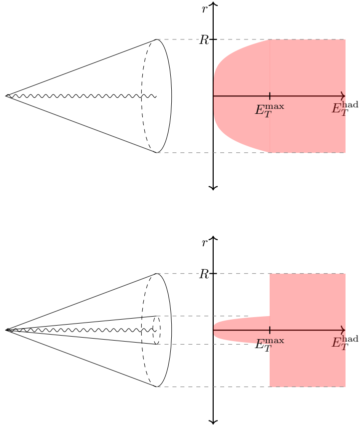

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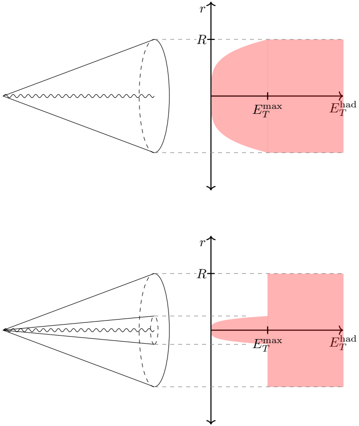

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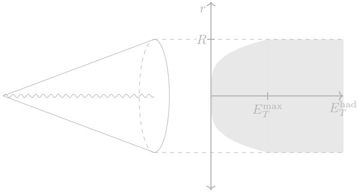
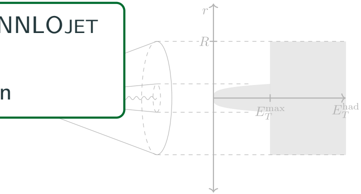


Implementation of fragmentation contribution in NNLOJET

$\Rightarrow$

NNLO QCD with realistic photon isolation



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Common procedure for theory calculations

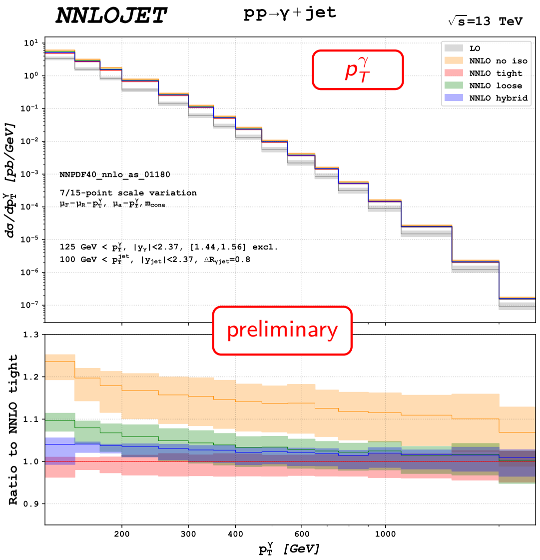
Loose vs. tight vs. no vs. hybrid isolation

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

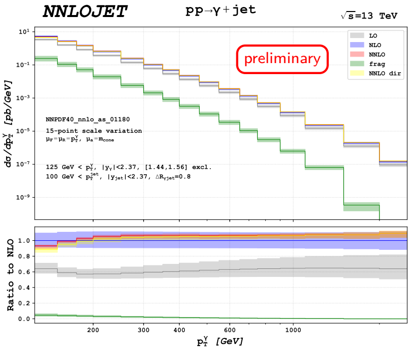
Isolations ($R = 0.4$)

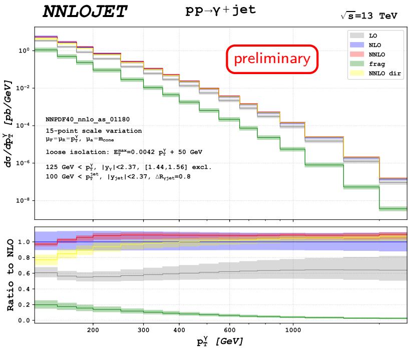
- tight isolation: $E_T^{\max} \approx 10$ GeV
- hybrid isolation: $E_T^{\max} \approx 10$ GeV ($R_{\text{inner}} = 0.1$)
- loose isolation: $E_T^{\max} \approx 50$ GeV



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

Loose isolation: $E_T^{\max} = 0.0042 p_T^\gamma + 50$ GeV

Accessing $D_{a\to\gamma}$ through $z_{\rm rec}$

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

direct @ lowest order

fragmentation @ lowest order

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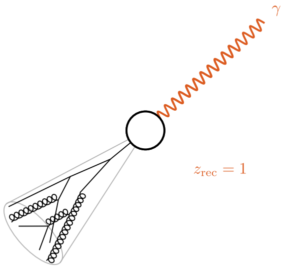
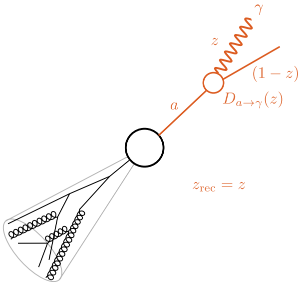


fragmentation @ lowest order



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

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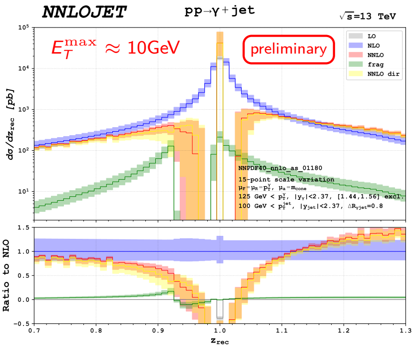

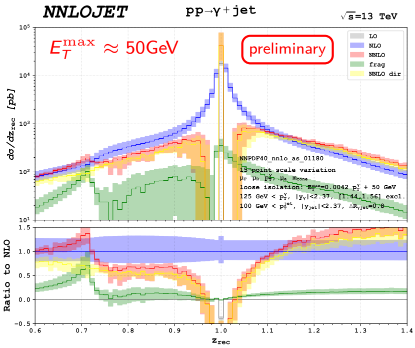

- $z_{\mathrm{rec}} \to 1$ sensitive to soft emissions $\Rightarrow$ requires resummation of large logarithms

Conclusions

- precision phenomenology at the percent level **demands** overcoming mismatch between theory and experiment in isolation prescriptions
- consistent treatment of direct and fragmentation contribution at NNLO QCD is now a possibility!

Outlook

- Is there a way to constrain $D_{a\to\gamma}$ from LHC data?
  $\Rightarrow$ $z_{\rm rec}$: a possible observable
- fragmentation contribution can be enhanced by **looser** isolation and **smaller cones** (to be studied)
  $\Rightarrow$ what is feasible experimentally?

Conclusions

- precision phenomenology at the percent level **demands** overcoming mismatch between theory and experiment in isolation prescriptions
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Thank you!

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Backup slides

Contributions to the Cross Section

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

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

- composition of the photon production cross section:

$$\begin{aligned}
\mathrm{d}\hat{\sigma}^{\gamma+X,\mathrm{LO}} &= \mathrm{d}\hat{\sigma}_\gamma^{\mathrm{LO}} \\
\mathrm{d}\hat{\sigma}^{\gamma+X,\mathrm{NLO}} &= \mathrm{d}\hat{\sigma}_\gamma^{\mathrm{NLO}} + \mathrm{d}\hat{\sigma}_g^{\mathrm{LO}} \otimes D_{g\to\gamma} + \sum_q \mathrm{d}\hat{\sigma}_q^{\mathrm{LO}} \otimes D_{q\to\gamma} - \sum_q \mathrm{d}\hat{\sigma}_q^{\mathrm{LO}} \otimes \mathbf{F}_{q\to\gamma}^{(0)} \\
\mathrm{d}\hat{\sigma}^{\gamma+X,\mathrm{NNLO}} &= \mathrm{d}\hat{\sigma}_\gamma^{\mathrm{NNLO}} + \mathrm{d}\hat{\sigma}_g^{\mathrm{NLO}} \otimes D_{g\to\gamma} + \sum_q \mathrm{d}\hat{\sigma}_q^{\mathrm{NLO}} \otimes D_{q\to\gamma} - \sum_q \mathrm{d}\hat{\sigma}_q^{\mathrm{NLO}} \otimes \mathbf{F}_{q\to\gamma}^{(0)} \\
&\quad - \mathrm{d}\hat{\sigma}_g^{\mathrm{LO}} \otimes \frac{\alpha_s}{2\pi}\mathbf{F}_{g\to\gamma}^{(1)} - \sum_q \mathrm{d}\hat{\sigma}_q^{\mathrm{LO}} \otimes \frac{\alpha_s}{2\pi}\mathbf{F}_{q\to\gamma}^{(1)}
\end{aligned}$$

$\mathbf{F}_{a\to\gamma}$: 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

Isolations ($R = 0.4$)

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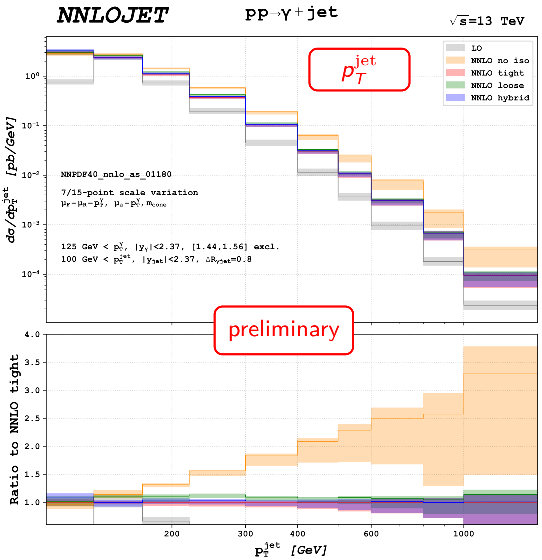
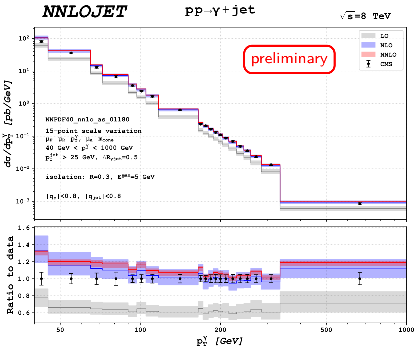
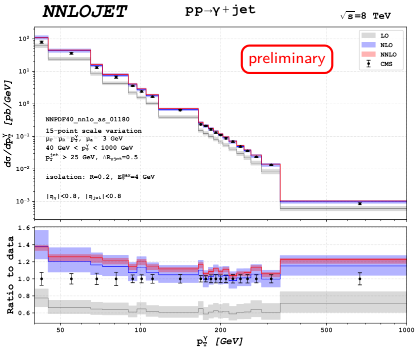


CMS triple differential measurement

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



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



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