Photon production @ the LHC with realistic photon isolation

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Zurich PhD Seminar, 08.09.2020

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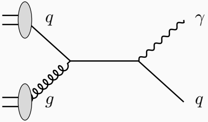
Outline

- photon isolation
- antenna subtraction (AS) and identified photons
- preliminary NLO results

Photon Production @ the LHC

γ (+jet) important observable:

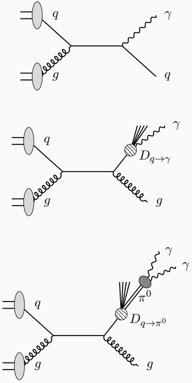
1. testing ground for precise QCD predictions
   $\rightarrow$ precise data from experiment available
   [ATLAS, 2018], [CMS, 2018]
2. high sensitivity on gluon PDF
   $\rightarrow$ Compton scattering @ LO
3. important background for new physics searches
   $\rightarrow$ dark matter, mono-jet signature



Photons @ the LHC

three different kinds of photons in hadronic collisions

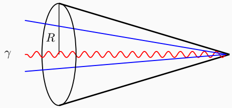
- direct photons: point-like coupling of quarks and photons
- partons fragmenting into photons
  $\rightarrow$ fragmentation functions (FF) $D_{k\rightarrow\gamma}(z)$
- hadronic decays ($\pi^0 \rightarrow \gamma\gamma$)



separate direct photons $\rightarrow$ impose photon isolation

Photon isolation

Fixed Cone Isolation

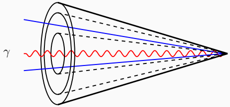


$R^2 = \Delta\eta^2 + \Delta\phi^2$

$$E_T^{\rm had} < E_T^{\rm max}(E_T^\gamma)$$

- used in experimental analysis
- $q \parallel \gamma$ singularity
- σ contains fragmentation contribution

Dynamical Cone Isolation [S. Frixione, 1998]



arbitrary cones with $r_d < R$

$$E_T^{\rm had}(r_d) < \epsilon\, E_T^\gamma \left(\frac{1-\cos r_d}{1-\cos R}\right)^n$$

- idealised photon isolation
- no $q \parallel \gamma$ singularity
- σ has no fragmentation contribution

combining both procedures $\rightarrow$ *Hybrid Isolation*

Theory predictions

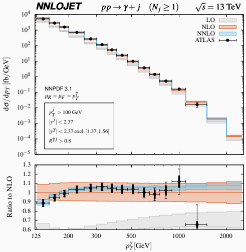
cross section for $\gamma + X$ production:

$$\mathrm{d}\hat{\sigma}^{\gamma+X} = \mathrm{d}\hat{\sigma}^{\gamma+X}_{direct} + \underbrace{\left(\sum_k \mathrm{d}\hat{\sigma}^{k+X} \otimes D_{k\to\gamma}\right)}_{\text{only with fixed cone isolation}}$$

NNLO QCD with idealised photon isolation
[J.M. Campbell et al., 2017] , [X. Chen et al., 2019]

NLO QCD with *fixed cone isolation*
[P. Aurenche et al., 1993] , [S. Catani et al., 2002]

Goal of my work:
NNLO QCD with *fixed cone isolation*



QCD beyond LO

general cross section ($2 \to n$) as a perturbative expansion in α_s:

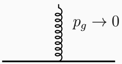
$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_s\,\mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_s^2\,\mathrm{d}\sigma_{\mathrm{NNLO}} + \mathcal{O}(\alpha_s^3)$$

$\underline{\mathrm{d}\sigma_{\mathrm{NLO}}:}$ consists of two contributions

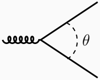
$$\mathrm{d}\sigma_{\mathrm{NLO}} = \int \mathrm{d}\Phi_n\,\mathrm{d}\sigma^V + \int \mathrm{d}\Phi_{n+1}\,\mathrm{d}\sigma^R$$

$\mathrm{d}\sigma^V$: virtual corrections (loop diagrams) with explicit poles in ϵ (dimensional regularisation $d = 4 - 2\epsilon$)
$\mathrm{d}\sigma^R$: real corrections (one additional parton) implicit singular

- soft gluon:
  $|M_{n+1}|^2 \to S_{\mathrm{eik.}}|M_n|^2$



- collinear partons:
  $|M_{n+1}|^2 \to \frac{1}{s_{ab}} P_{ab\to c}|M_n|^2$



QCD beyond LO

general cross section ($2 \to n$) as a perturbative expansion in α_s:

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_s\,\mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_s^2\,\mathrm{d}\sigma_{\mathrm{NNLO}} + \mathcal{O}(\alpha_s^3)$$

$\underline{\mathrm{d}\sigma_{\mathrm{NNLO}}}$: consists of three contributions

$$\mathrm{d}\sigma_{\mathrm{NNLO}} = \int \mathrm{d}\Phi_n\,\mathrm{d}\sigma^{VV} + \int \mathrm{d}\Phi_{n+1}\,\mathrm{d}\sigma^{RV} + \int \mathrm{d}\Phi_{n+2}\,\mathrm{d}\sigma^{RR}$$

$\mathrm{d}\sigma^{VV}$: double-virtual corrections with explicit poles in ϵ
$\mathrm{d}\sigma^{RV}$: real-virtual correction with explicit poles in ϵ and implicit singular
$\mathrm{d}\sigma^{RR}$: double-real corrections implicit singular

- sector decomposition [T. Binoth und G. Heinrich, 2000] , [C. Anastasiou et al., 2004]
- sector-improved residue subtraction [M. Czakon, 2010], [R. Boughezal et al., 2012]
- q_T-subtraction [S. Catani und M. Grazzini, 2007]
- N-jetiness subtraction [R. Boughezal et al., 2015] , [J. Gaunt et al., 2015]
- **antenna subtraction (AS)**
  [A. Gehrmann-De Ridder et al., 2005], [A. Daleo et al., 2007], [J. Currie et al., 2013]

Subtraction

idea: construct subtraction terms, which

- ...have the same IR behaviour as $\mathrm{d}\sigma^{R/RV/RR}$
- ...can be analytically integrated over the singular phase space

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \underbrace{\int \mathrm{d}\Phi_{n+1}\left(\mathrm{d}\sigma^{R} - \mathrm{d}\sigma^{S}\right)}_{\text{numerical integrable}} + \underbrace{\int \mathrm{d}\Phi_{n}\left(\mathrm{d}\sigma^{V} - \mathrm{d}\sigma^{T}\right)}_{\epsilon\text{−poles cancel, numerical integrable}}$$

$\mathrm{d}\sigma^{T} = -\int \mathrm{d}\Phi_A\,\mathrm{d}\sigma^{S}$

@ NNLO three terms for $\mathrm{d}\sigma^{VV}$, $\mathrm{d}\sigma^{RV}$ and $\mathrm{d}\sigma^{RR}$

using antenna subtraction:

@ NLO $\mathrm{d}\sigma^{S} = \sum X_3^0 \times |M_n|^2$

@ NNLO $\mathrm{d}\sigma^{S} = \sum X_3^0 \times X_3^0 \times |M_n|^2 + \sum X_4^0 \times |M_n|^2$

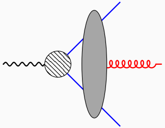
→ **antenna functions (AF)** $X^0_{3/4}$

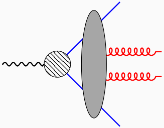
Antenna functions

constructed from physical matrix elements:

for example $\gamma \to qg(g)\bar{q}$: *hard radiators*, *unresolved partons*

$$A_3^0(i,j,k) = \mathcal{S}\frac{|M_3^0(i,j,k)|^2}{|M_2^0(I,K)|^2} \quad , \quad A_4^0(i,j,k,l) = \mathcal{S}\frac{|M_4^0(i,j,k,l)|^2}{|M_2^0(I,L)|^2}$$





used for subtraction of:

$g \parallel q$: $A_3^0 \to \frac{1}{s_{qg}} P_{qg\to Q}$

$p_g \to 0$: $A_3^0 \to S_{\text{eik.}}$

used for subtraction of:

$g' \parallel g \parallel q$

$p_g \to 0$ and $g' \parallel q$

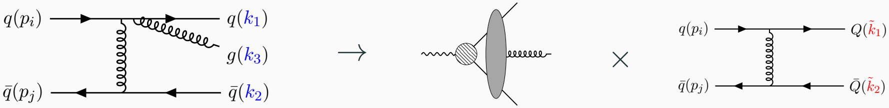
$p_g \to 0$ and $p_{g'} \to 0$

$d\sigma^S = A_3^0\,|M_n|^2$ mimics behaviour of $|M_{n+1}|^2$ in the IR limit

(e.g. $|M_{n+1}|^2 \to S_{\text{eik.}}|M_n|^2$ for $p_g \to 0$)

Antenna subtraction

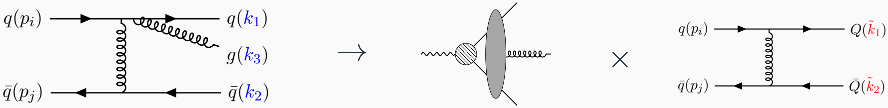
subtraction term for QCD singularities



$$\mathrm{d}\sigma^S \propto A_3^0(q(k_1), g(k_3), \bar{q}(k_2))\,|M_2^0(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2)\,\mathrm{d}\Phi_3(k_1, k_2, k_3; p_i, p_j)$$

Antenna subtraction

subtraction term for QCD singularities



$$d\sigma^S \propto A_3^0(q(k_1), g(k_3), \bar{q}(k_2))\,|M_2^0(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2)\, d\Phi_3(k_1, k_2, k_3; p_i, p_j)$$

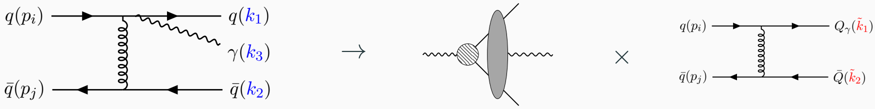
only the antenna function depends on the original momenta $\{k_1, k_2, k_3\}$
reduced matrix element and jet function only depend on mapped momenta
$\rightarrow$ phase space can be factorized

$$d\sigma^T \propto \underbrace{\left(\int d\Phi_A\, A_3^0(q(k_1), g(k_3), \bar{q}(k_2))\right)}_{\mathcal{A}_3^0} |M_2^0(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2)\, d\Phi_2$$

explicit ϵ-poles in $\mathcal{A}_{3/4}^0$

Antenna subtraction for photon production

subtraction term for photonic singularities



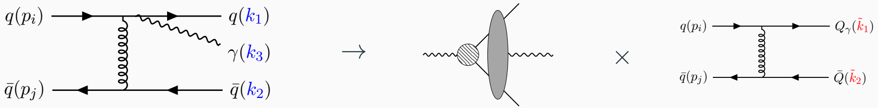
$$\mathrm{d}\sigma_\gamma^S \propto A_3^0(q(k_1), \gamma(k_3), \bar{q}(k_2))\, |M_2^0(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2; z)\, \mathrm{d}\Phi_3$$

jet function needs information about the momentum fraction z of the photon within the quark-photon cluster Q_γ

$$z = \frac{s_{23}}{s_{23} + s_{12}} \xrightarrow{\gamma \| q} \frac{E_\gamma}{E_\gamma + E_q}$$

Antenna subtraction for photon production

subtraction term for photonic singularities



$$\mathrm{d}\sigma^S_\gamma \propto A^0_3(q(k_1), \gamma(k_3), \bar{q}(k_2))\, |M^0_2(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2; z)\, \mathrm{d}\Phi_3$$

photon isolation is part of the jet function

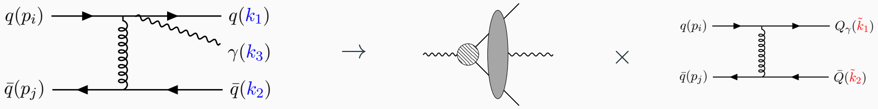
reconstruction of the photon momentum necessary for the algorithm:

$$\tilde{k}_1 \rightarrow \{\underbrace{z\,\tilde{k}_1}_{k_\gamma}, \underbrace{(1-z)\,\tilde{k}_1}_{k_q}\}$$

$\rightarrow$ complete phase space factorization (as in the QCD case) not possible

Antenna subtraction for photon production

subtraction term for photonic singularities



$$\mathrm{d}\sigma_\gamma^S \propto A_3^0(q(k_1), \gamma(k_3), \bar{q}(k_2))\, |M_2^0(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2; z)\, \mathrm{d}\Phi_3$$

integration over antenna phase space must remain differential in z

$$\mathrm{d}\sigma_\gamma^T = -\int_0^1 \mathrm{d}z \underbrace{\left(\int \frac{\mathrm{d}\Phi_A}{\mathrm{d}z} A^0_{q\gamma\bar{q}}\right)}_{\mathbf{A^0_{q\gamma\bar{q}}}(z)} |M_2^0(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2; z)\, \mathrm{d}\Phi_2$$

z-integration performed numerically with fragmentation contribution

ϵ-poles in $\mathbf{A^0_{q\gamma\bar{q}}}(z)$ cancel with mass factorization terms of the FF

NLO results

- implemented subtraction terms and fragmentation contribution in the NNLOJET Monte Carlo event generator
- compare to JetPhox $\mathrm{d}\hat{\sigma}^{\gamma+\mathrm{jet}}$-calculation @ NLO including fragmentation contribution
- fragmentation contribution fully coincides
- 1% agreement on the NLO direct coefficient

$$\mathrm{d}\sigma^{\gamma+\mathrm{jet}} = \underbrace{\mathrm{d}\sigma^{\gamma+\mathrm{jet}}_{\mathrm{LO,dir}}}_{\checkmark} + \alpha_s \underbrace{\mathrm{d}\sigma^{\gamma+\mathrm{jet}}_{\mathrm{NLO,dir}}}_{(\checkmark)} + \underbrace{\sum_k \mathrm{d}\sigma^{k+X}_{\mathrm{LO}} \otimes D_{k\to\gamma}}_{\checkmark}$$

$$\mathrm{d}\sigma^{\gamma+\mathrm{jet,NJ}}_{\mathrm{NLO,dir}} = (9.26 \pm 0.01) \times 10^4\ \mathrm{fb}$$

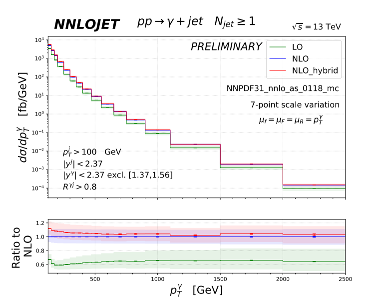
$$\mathrm{d}\sigma^{\gamma+\mathrm{jet,JP}}_{\mathrm{NLO,dir}} = (9.16 \pm 0.07) \times 10^4\ \mathrm{fb}$$

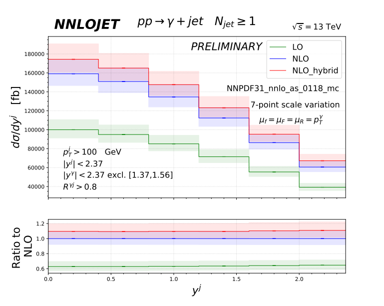
NLO results

hybrid isolation vs. fixed cone isolation:

set-up: ATLAS 13 TeV photon + jet study [ATLAS, 2018]

fragmentation function: BFG2 set [L. Bourhis et al.,1998]





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

hybrid isolation:

dynamical cone $(R_d = 0.1$, $\epsilon = 0.1$, $n = 2) +$ fixed cone [X. Chen et al., 2019]

NNLO?

Many challenges @ NNLO:

- compatible z definitions within the different subtraction terms ✓
  $\rightarrow$ consistent treatment on RR, RV and VV level
- embedding the mass factorization terms of the FF into the subtraction framework ✓
- integration of the X_4^0 and X_3^1 photonic antenna functions ✓
  $\rightarrow$ complicated phase space integrals
- construction and testing of subtraction terms ×

Conclusion

state of the art predictions for $\mathrm{d}\sigma^{\gamma+X}$:

good agreement with data
However, idealised photon isolation $\rightarrow$ systematic uncertainty

predictions with realistic photon isolation for $\mathrm{d}\sigma^{\gamma+X}$:

contain fragmentation contribution

for $\gamma+$ jet production : NLO results (preliminary) undershoot NLO results with hybrid isolation

NNLO: work in progress

modification in antenna subtraction:

- final-state photon must be identified
  (in contrast to massless partons!)
- reconstruction of photon momentum
- integration of photonic antenna functions

Backup

Integration photonischer AF @ NLO

$$\mathrm{d}\sigma_\gamma^T = -\int_0^1 \mathrm{d}z \underbrace{\left(\int \frac{\mathrm{d}\Phi_A}{\mathrm{d}z} A^0_{q\gamma\bar{q}}\right)}_{\mathbf{A^0_{q\gamma\bar{q}}}(z)} |M_2^0(\tilde{k}_1, \tilde{k}_2; p_i, p_j)|^2 J(\tilde{k}_1, \tilde{k}_2; z)\,\mathrm{d}\Phi_2$$

$\mathbf{A^0_{q\gamma\bar{q}}}(z)$: integrierte photonische AF

z-Integration numerisch zusammen mit Fragmentationsbeitrag

Beispiel: Integration von final-final $A_3^0(q(k_1), \gamma(k_3), \bar{q}(k_2))$, $\mathrm{d}\Phi_A \propto \mathrm{d}\Phi_{1\to 3}$

$$\begin{aligned}\mathbf{A}^0_{q\gamma\bar{q}}(z) &= \frac{e^{\gamma_E \epsilon} s^{-1+2\epsilon}(1-z)^{-\epsilon} z^{-\epsilon}}{2\Gamma(1-\epsilon)} \int_0^s \mathrm{d}s_{13}(s-s_{13})^{-2\epsilon} s_{13}^{-\epsilon} A_3^0(s_{13}, z) \\ &= s^{-\epsilon}\Bigg(-\frac{1}{2\epsilon} P_{q\gamma}(z) + P_{q\gamma}(z)(\log(z) + \log(1-z)) \\ &\qquad - \frac{3 - 4z + z^2}{4z} + \mathcal{O}(\epsilon)\Bigg)\end{aligned}$$

mit $z = \frac{s_{23}}{s_{23}+s_{12}}$ und $P_{q\gamma}(z) = \frac{1+(1-z)^2}{z}$

ϵ-Pol wird von Massenfaktorisierung der FF aufgehoben

Integration of photonic X_3^1 antenna functions

antenna phase space for initial-final X_3^1:

$$\mathrm{d}\Phi_A \propto \mathrm{d}\Phi(q(Q^2) + p \to k_1 + \gamma(k_2))$$

no actual integration has to be performed

$$\begin{aligned}\mathbf{X}_3^1(x, z) &= \frac{1}{C(\epsilon)} \int \frac{\mathrm{d}\Phi_2}{\mathrm{d}z} \frac{Q^2}{2\pi} X_3^1 \\ &= \frac{Q^2}{2} \frac{e^{\gamma_E \epsilon}}{\Gamma(1-\epsilon)} \left(Q^2\right)^{-\epsilon} \mathcal{J}^{\gamma}(x, z)\, X_3^1\end{aligned}$$

however, X_3^1 has to be cast into a form suitable for an expansion in distributions in $1 - x$ and z

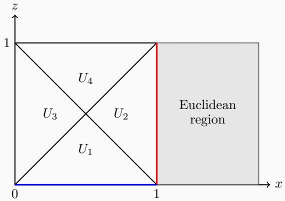
Integration of photonic X_3^1 antenna functions

X_3^1 can be expressed in terms of Box and Bubble MIs

$$X_3^1(x,z) = \sum_{i=1}^{3} f_i(x,z)\,\mathrm{Box}_i(x,z) + \sum_{k=1}^{4} g_k(x,z)\,\mathrm{Bub}_k(x,z) + h(x,z)$$

$$\mathrm{Box}_i(x,z) \propto \sum_{j=1}^{3} (r_{i,j}(x,z))^{-\epsilon}\,{}_2F_1(-\epsilon,-\epsilon;1-\epsilon;a_{i,j}(x,z))$$

Box-integrals real-valued and well-defined in Euclidean region
→ analytic continuation needed



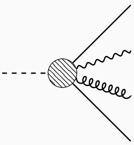
branch cuts ($a_{i,j}(x,z) = 1\,,\ \pm\infty$) within the physical region
→ distinguish different regions in x-z-plane

required antenna functions integrated

Definition of z @ NNLO

@ NNLO: γ and one additional parton are unresolved

How to define z in this case?



$$z_4 = \frac{s_{23}}{s_{23} + s_{12} + s_{24}}$$

Is this a reasonable definition of the momentum fraction of the photon?

triple collinear: $\gamma \parallel q \parallel g$ ✓

soft collinear: $\gamma \parallel q, p_g \to 0$ ✓

double collinear: $\gamma \parallel q$ and $g \parallel \bar{q}$ ✓

single collinear: $\gamma \parallel q$ ×

$\to$ no simple definition of z_4 working in all limits

$\to$ non trivial interplay between the different subtraction terms

(especially at the real-virtual level)

Integration of photonic X_4^0 antenna functions

necessary photonic X_4^0 antenna functions:

- $\tilde{A}^0_{q,\gamma g\bar{q}}$ subtracts $q \parallel g \parallel \gamma$ limit
- $\tilde{E}^0_{q,q'\bar{q}'\gamma}$ subtracts $q' \parallel \gamma \parallel \bar{q}'$ limit

initial-final antenna PS: $\mathrm{d}\Phi_A \propto \mathrm{d}\Phi_3(q(Q^2) + p \to k_1 + k_2 + \gamma(k_3))$

additional δ-function in the PS integrals to fix z

$$\mathbf{X}_4^0(x, z) \propto \int \mathrm{d}^d k_1 \, \mathrm{d}^d k_2 \, \delta(k_1^2) \, \delta(k_2^2) \, \delta((p + q - k_1 - k_2)^2) \times \delta\left(z - \frac{s_{p3}}{s_{p1} + s_{p2} + s_{p3}}\right) X_4^0$$

in the IF configuration additional dependence on the initial-state momentum fraction x

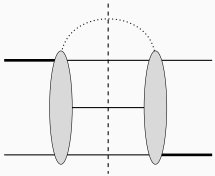
Integration of photonic X_4^0 antenna functions

strategy:

unitarity $\rightarrow$ replace all δ-functions by propagators

$$2\pi i\delta(k_1^2) = \frac{1}{k_1^2 + i\epsilon} - \frac{1}{k_1^2 - i\epsilon}$$

phase space integral $=$
cut through loop integral



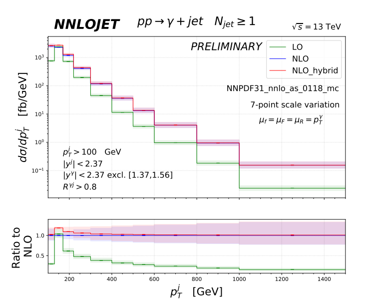
- reduction of integrals using IBP-relations to 9 master integrals (MI)
- MI are calculated by solving the differential equations in x and z
- fix integration constants by integrating over z and comparing to the inclusive result

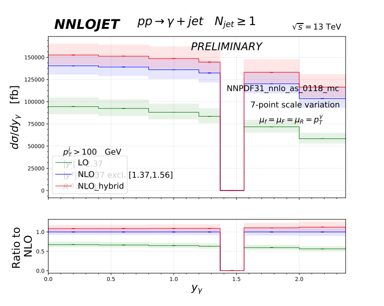
NLO results

hybrid isolation vs. fixed cone isolation:

set-up: ATLAS 13 TeV photon + jet study [ATLAS, 2018]

fragmentation function: BFG2 set [L. Bourhis et al.,1998]





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

hybrid isolation:

dynamical cone ($R_d = 0.1$, $\epsilon = 0.1$, $n = 2$) + fixed cone [X. Chen et al., 2019]