QCD Anatomy of Photon Isolation

Samuel Favrod

In collaboration with
Thomas Becher and Xiaofeng Xu

University of Bern

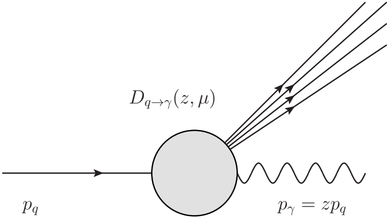
April 2022

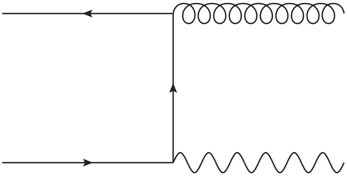
Outline

- Introduction and isolation cone
- Photon production factorization, fragmentation and resummation
- Results
- Conclusion

Intro: Source of photon in proton collision

- Emission from a parton
  - Perturbative emission
  - Non-perturbative fragmentation $D_{i \to \gamma}$





- Hadron decays, for example:

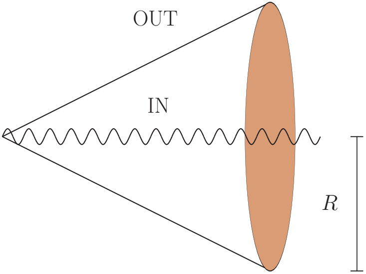
$$\pi^0 \to 2\gamma$$

- How do we separate photons from different origins?

Isolation cone

- Define a distance between parton i and photon γ:

$$r_i = \sqrt{(\eta_i - \eta_\gamma)^2 + (\phi_i - \phi_\gamma)^2}, \qquad \eta_i = \frac{1}{2}\log\left(\frac{|\vec{p}_i| + p_i^z}{|\vec{p}_i| - p_i^z}\right)$$



- For $r_i > R$ OUT: no restrictions
- For $r_i \leq R$ IN: restriction on E_{hadronic}
- Different types of energy restrictions: Fixed energy cone, Frixione cone

Isolation criteria

- Fixed energy cone ($E = E^T$ at hadron collider):

$$E_{\mathrm{had}} < E_{\mathrm{iso}} = \epsilon_\gamma E_\gamma + E_{\mathrm{threshold}} \qquad \text{for } r_i \leq R$$

  - Typically $E_{\mathrm{iso}} \ll E_\gamma$, $E_{\mathrm{threshold}}$ sometimes 0

- Smooth cone (Frixione, 9801442):

$$E_{\mathrm{had}}(r) < E_{\mathrm{iso}}(r) = \epsilon_\gamma E_\gamma \left(\frac{1 - \cos r}{1 - \cos R} \right)^n = E_\gamma \chi(\epsilon_\gamma, n, R; r) \quad \text{for } r \leq R$$

  - $\chi(r = R) = \epsilon_\gamma$ and $\chi(r = 0) = 0$

	Fixed Energy	Frixione
γ from hadronic decays suppressed	✓	✓
non-pertubative $D_{i\to\gamma}$ suppressed	✗	✓
NNLO computations done	✗	✓
Experimentally realisable	✓	✗

Factorization for γ isolation, wide cone

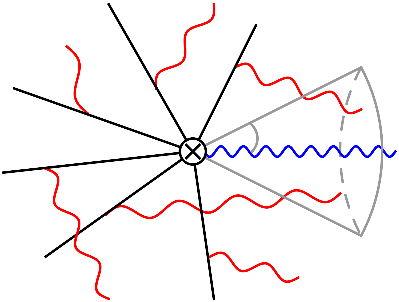
- e^+e^- or $pp \to \gamma + X$ with large cone, $\epsilon_\gamma E_\gamma = E_{\rm iso}$, $\epsilon_\gamma \ll 1$
- Factorization wide cone with $x_\gamma E_\gamma = \frac{Q}{2}$

$$\frac{d\sigma(\epsilon_\gamma, R)}{dx_\gamma} = \sum_{m=2}^{\infty} \langle \mathcal{H}_{\gamma+m}(\{\underline{n}\}, Q, R) \otimes \mathcal{S}_m(\{\underline{n}\}, Q\epsilon_\gamma, R)\rangle$$

  - Resummation of $\log \epsilon_\gamma$ in 1803.07045 ✓
  - Narrow cone, $\log R$ terms?

Iso radius R	Total σ NLO
1.0	3765.1
0.4	4524.5
0.1	5431.1
No isolation	5217.9

Data from 0204023, $\log R$ resummed in 1306.6498 ✓

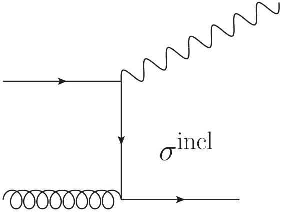


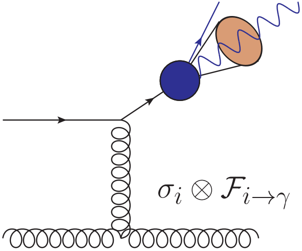
Narrow cone factorization

- For $R \ll 1$ then σ factorizes $z = \frac{E_\gamma}{E_{\text{emitting}}}$, E_{iso} is isolation energy

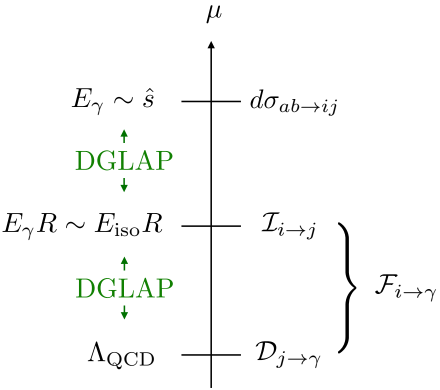
$$\frac{d\sigma(E_{\text{iso}}, R)}{dE_\gamma} = \frac{d\sigma^{\text{incl}}_{\gamma+X}}{dE_\gamma} + \sum_{i=q,\bar{q},g} \int dz \frac{d\sigma_{i+Y}}{dE_i} \mathcal{F}_{i\to\gamma}(z, E_\gamma, E_{\text{iso}}, R) + \mathcal{O}(R)$$

- σ^{incl} does not see the cone for $R \ll 1$ and σ_{iY} is $pp \to iY$ at LO
- $\mathcal{F}_{i\to\gamma}$ is the cone fragmentation function, what is it?





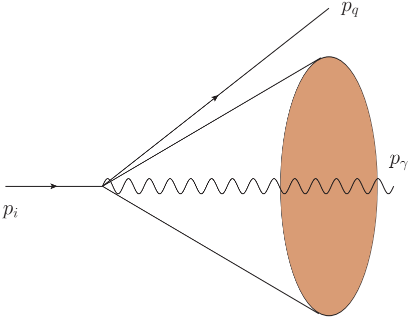
Narrow cone factorization, $E_{\text{iso}} \sim E_\gamma$

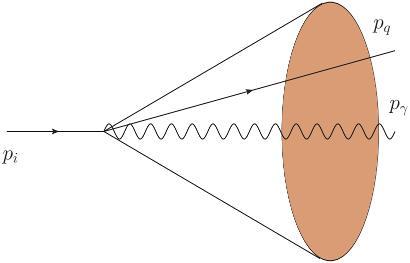


- Consider $R \ll 1$ and, $E_{\text{iso}} \sim E_\gamma$
- $\mathcal{F}^{\text{out}}$ is the same for Frixione and fixed energy cone
- $\mathcal{F}^{\text{out}}$ is independent of E_{iso}
- Frixione: $\mathcal{D}_{j\to\gamma}$ is suppressed
- Fixed energy cone and E_{iso} not small has non-perturbative part
- $\mathcal{F}$ depends on isolation parameters

$$\mathcal{F}^{\text{NLO}}_{q\to\gamma}(z, E_\gamma, E_{\text{iso}}, R, \mu) = \mathcal{F}^{\text{in}}_{q\to\gamma}(z, E_\gamma, E_{\text{iso}}, R, \mu) + \mathcal{F}^{\text{out}}_{q\to\gamma}(z, R\, E_\gamma, \mu)\,,$$

$pp \to \gamma + X$ and fragmentation $\mathcal{F}$ for Frixione isolation





$$P_{q\to\gamma}(z) = P(z) = \frac{z^2 - 2z + 2}{z} \qquad p_\gamma^T = z p_i^T$$

$$\mathcal{F}^{\mathrm{out}}_{q\to\gamma}(\epsilon_\gamma, n, R, z) = \frac{\alpha e_q^2}{2\pi}\left[P(z)\left(\frac{1}{\epsilon} - \ln\left(\frac{R^2 Q^2}{\mu^2} z^2 (1-z)^2\right)\right) - z\right]$$

$$\mathcal{F}^{\mathrm{in}}_{q\to\gamma}(\epsilon_\gamma, n, R, z) = \frac{\alpha e_q^2}{2\pi}\theta\left(z - \frac{1}{1+\epsilon_\gamma}\right)\frac{P(z)}{n}\ln\left(\frac{1-z}{z\epsilon_\gamma}\right)$$

$pp \to \gamma + X$ and fragmentation $\mathcal{F}$ for fixed energy cone

- Same outside cone fragmentation

$$\mathcal{F}^{\text{out}}_{q\to\gamma}(\epsilon_\gamma, R, z) = \frac{\alpha e_q^2}{2\pi}\left[P(z)\left(\frac{1}{\epsilon} - \ln\left(\frac{R^2 Q^2}{\mu^2} z^2 (1-z)^2\right)\right) - z\right]$$

- Inside at NLO

$$\mathcal{F}^{\text{in}}_{i\to\gamma}(z, R, E_\gamma,\ E_{\text{iso}}, \mu) = \left[\mathcal{D}_{i\to\gamma}(E_\gamma, z, \mu) + \mathcal{I}^{\text{in}}_{i\to\gamma}(z, R, E_\gamma, \mu)\right] \theta\left(z - \frac{1}{1+\epsilon_\gamma}\right)$$

- Perturbative part

$$\mathcal{I}^{\text{in}}_{q\to\gamma}(\epsilon_\gamma, n, R, z) = -\mathcal{F}^{\text{out}}_{q\to\gamma}(\epsilon_\gamma, R, z)$$

$pp \to \gamma + X$ and fragmentation $\mathcal{F}$

- Our fragmentation prediction vs MG5_aMCNLO NLO: predictions should be in agreement for small R
- Compute $\Delta\sigma$:

$$\Delta\sigma\left(\epsilon_\gamma, n, R; \epsilon_\gamma^{ref}, n^{ref}, R^{ref}\right) = \sigma\left(\epsilon_\gamma, n, R\right) - \sigma(\epsilon_\gamma^{ref}, n^{ref}, R^{ref})$$

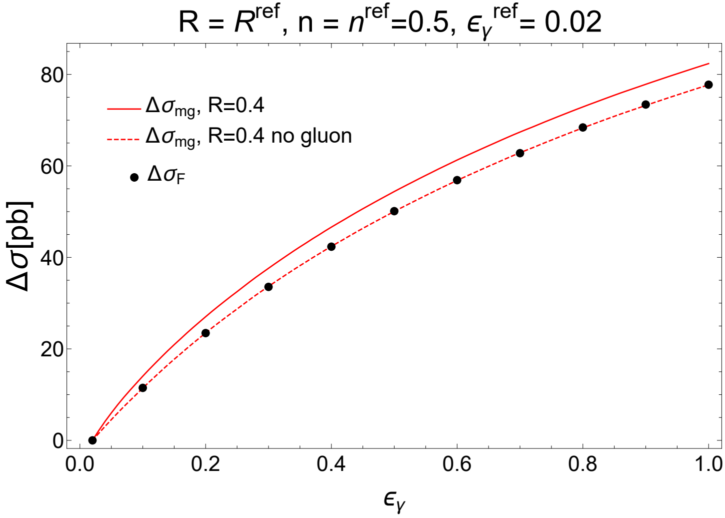
- Compute $\Delta\sigma$ using $\mathcal{F}_{i\to\gamma}$:

$$\sum_{i=q,\bar{q}} \int_0^1 \mathrm{d}z \frac{\mathrm{d}\sigma_{iY}}{\mathrm{d}z} \left[\mathcal{F}_{i\to\gamma}\left(z, R, \epsilon_\gamma, n\right) - \mathcal{F}_{i\to\gamma}\left(z, R^{ref}, \epsilon_\gamma^{ref}, n^{ref}\right)\right]$$

- Compute $\Delta\sigma$ using only MG5_aMCNLO
- Do it for both Frixione and fixed energy for different parameters
- Compare $\Delta\sigma$ fixed order MG5_aMCNLO and $\Delta\sigma$ from $\mathcal{F}_{i\to\gamma}$

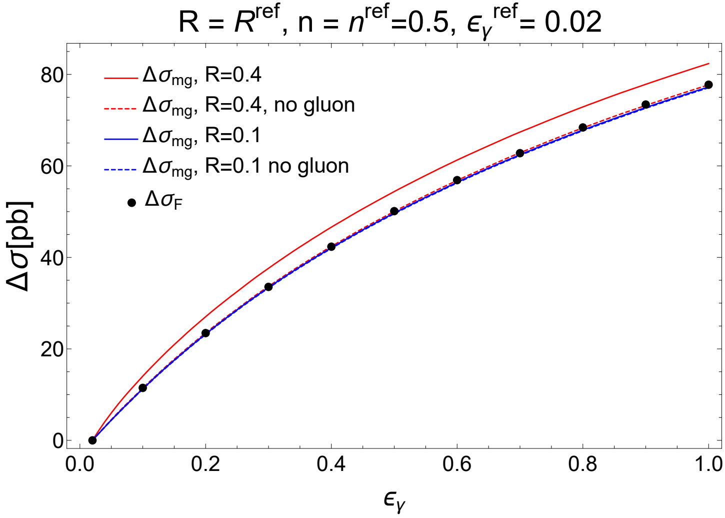
Results: Frixione cone ϵ_γ dependence

$$\mathcal{F}^{\text{in}}_{i\to\gamma}(\epsilon_\gamma, n, R, z) \sim \frac{P(z)}{n} \ln\left(\frac{1-z}{z\epsilon_\gamma}\right)$$

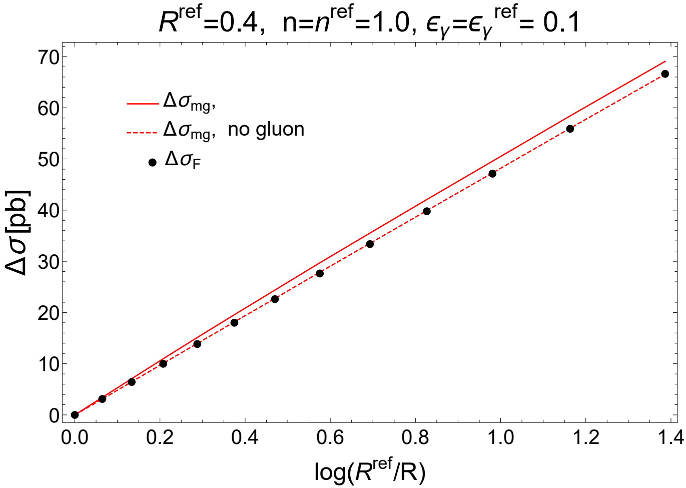


Results: Frixione cone ϵ_γ dependence

$$\mathcal{F}^{\text{in}}_{i\to\gamma}\left(\epsilon_\gamma, n, R, z\right) \sim \frac{P(z)}{n}\ln\left(\frac{1-z}{z\epsilon_\gamma}\right)$$

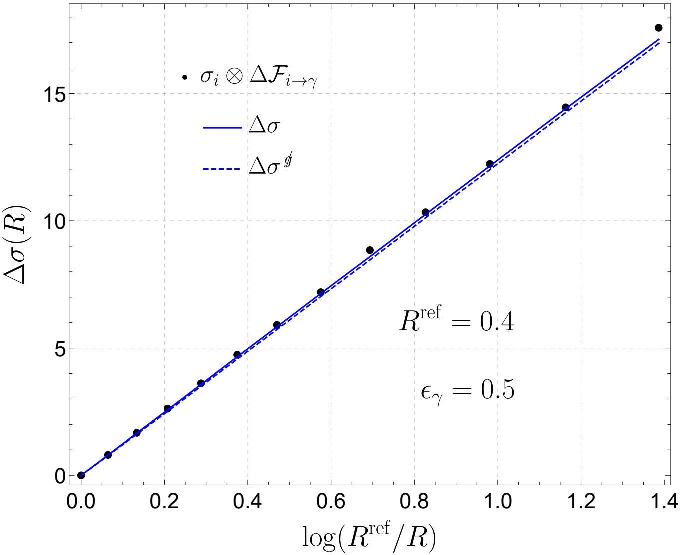


Results: Frixione cone R dependence



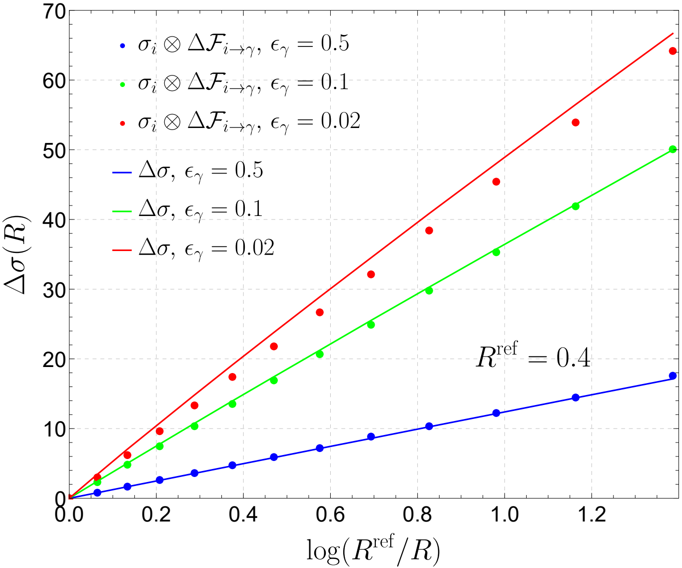
- Our calculation for $\mathcal{F}$ allows us to understand the dependence of $\Delta\sigma$ on its parameters, similar results for n dependence
- Good agreement even for $R = 0.4$

Results: fixed energy cone R dependence



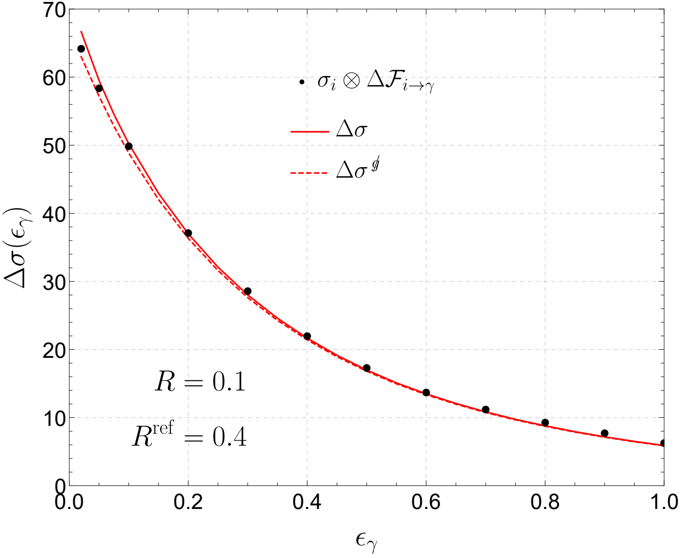
- Unlike Frixione, slope depends on ϵ_γ, note that $\epsilon_\gamma = \epsilon_\gamma^{\text{ref}}$

Results: fixed energy cone R dependence



- Unlike Frixione, slope depends on ϵ_γ, note that $\epsilon_\gamma = \epsilon_\gamma^{\mathrm{ref}}$

Results: fixed energy cone ϵ_γ dependence



- $\epsilon_\gamma = \epsilon_\gamma^{\text{ref}}$, to avoid $D_{i\to\gamma}$

Resummation of $\log R$

- Need to resum $\log R$ in $\mathcal{F}$
- Non-homogeneous DGLAP:

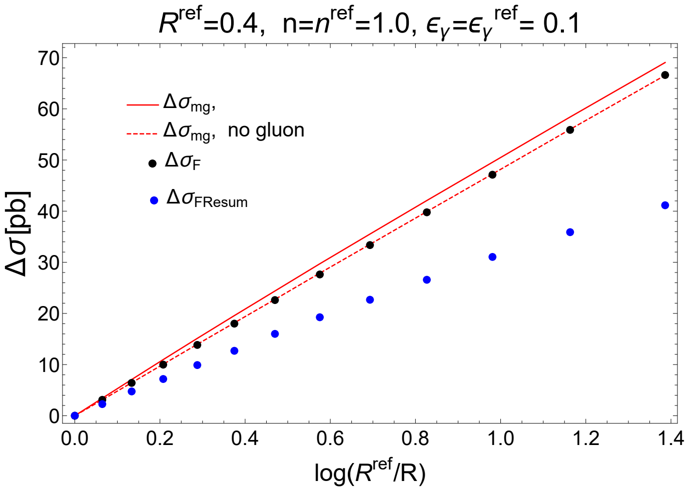
$$\frac{d}{d\ln\mu}\mathcal{F}_{i\to\gamma}(z, E_j, E_t, \mu) = \mathcal{P}_{i\to\gamma}(z) + \sum_{j=q,\bar{q},g} \mathcal{P}_{i\to j} \otimes \mathcal{F}_{j\to\gamma}$$

- Need non-homogeneous up to $\mathcal{O}(\alpha\alpha_s)$ (from 1512.00612) e.g.

$$P_{g\to\gamma} = \frac{\alpha}{2\pi}\frac{\alpha_s}{2\pi}\frac{T_F \sum_{q=1}^{n_f} e_q^2}{2}\left(\frac{20z^2}{3} + 8z + \frac{4}{3z} - 2(z+1)\log^2(z) - (10z+6)\log(z) - 16\right)$$

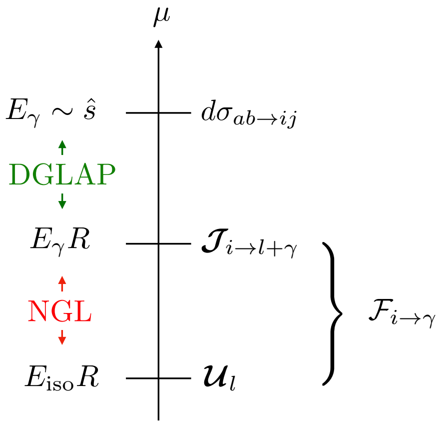
- Solve it using Mellin transform or in z space directly
  - Both agree
  - Mellin is here more efficient

Resummation of log R: preliminary results



Resummation of $\log \epsilon_\gamma$, $R \ll 1$ and $\epsilon_\gamma = E_{\rm iso}/E_\gamma \ll 1$

$$\mathcal{F}_{i\to\gamma}(z, R\,E_\gamma, R\,E_{\rm iso}, \mu) = \sum_{l=1}^{\infty} \langle \mathcal{J}_{i\to\gamma+l}(\{\underline{n}\}, R\,E_\gamma, z, \mu) \otimes \mathcal{U}_l\,(\{\underline{n}\},\ R\,E_{\rm iso}, \mu)\rangle$$



- Small isolation energy $E_{\rm iso}$, at LO $\mathcal{U}_l = 1$:
- $E_{\rm iso} \ll E_\gamma$ non-perturbative suppressed
- Use code NGL_resum, performs a parton shower to resum the log
- Cone is narrow $\to$ boost the system: cone is half hemisphere.

Summary

- Factorization theorem for narrow isolation cone: for both large and small E_{iso}
- We compute the cone fragmentation function $\mathcal{F}$ at LO
- Test our predictions versus MG5_aMCNLO $\rightarrow$ small power corrections, also for $R = 0.4$
- Better understanding of the dependence of the cross section on its parameters
- We performed resummations of large logarithms of small radius R
- Next step: numerics of $\log \epsilon_\gamma$ resummation using parton shower code NGL_resum: see `https://pypi.org/project/ngl-resum/` 2006.00014

Thank you for your attention!