Identified Hadron or Photon in a jet

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Plan of Talk

- Motivation
- Hadrons in jets
- Analytic calculation at NLO ..formalism
- Photon fragmentation
- Numerical results
- Conclusion

Motivation

$pp \to jetX$

Large p_T jet : Cross section can be factorized into parton distribution and fragmentation functions and perturbative hard scattering part

Identified hadron in a jet : momentum correlation of hadron and jet : same-side observable

New probe of the fragmentation functions

e^+e^-

Procura and Waalewijn, PRD(2011), Jain, Procura, Waalewijn, JHEP (2011)

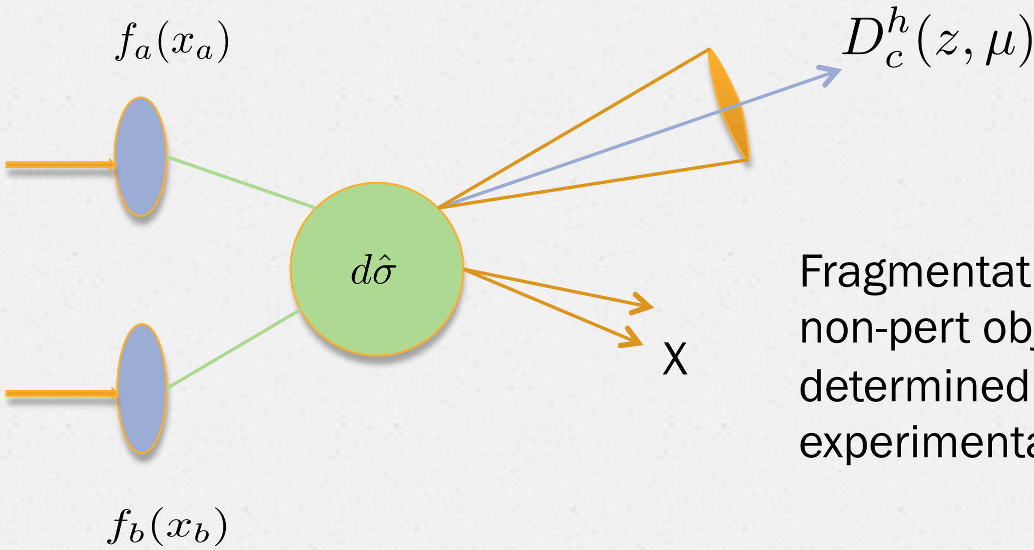
Studied in MC approach

F Arleo et al , J. High. En. Phys. 04 (2014) 147 Monte Carlo

Fragmentation function $D_c^h(z, \mu)$ is the probability that a parton c forms a hadron h

z : fraction of the parton's momentum transferred to the hadron

μ : momentum scale at which the fragmentation function is probed



Fragmentation function : non-pert object. To be determined from experimental data

Usually fragmentation functions are extracted from the measurements of $e^+e^- \to hX$

Gluon fragmentation : only at higher order in QCD

$pp \to hX$ Involves a convolution that forms an integration over z : information on D(z) smeared out

$pp \to jet\ hX$ Cross section differential in z_h : directly probes the fragmentation function at $z=z_h$

New information on fragmentation functions, particularly gluon frag. functions which are not well known

Identified hadrons : may provide new information on the structure of jets and hadronization

Photon Fragmentation :

- Photons produced in high energy scattering : sensitive probe of the medium produced in heavy ion collisions
- Plays an important role in searching for physics beyond standard model
- However there is a background from standard model sources

Two mechanisms for photon production in high energy collisions :

(1) Direct : photon produced in the hard process through pointlike QED coupling with a quark

(2) Fragmentation : a quark, antiquark or gluon coming from a QCD hard process fragments into a photon

Photon Fragmentation function

$D_c^\gamma(z,\mu)$ Non perturbative object; not well known. Presents large uncertainly in predictions of photon production cross sections. Minimized using isolation cuts.

We propose to extract it from the cross section of $pp \to jet\ \gamma X$

Direct information of z dependence

Dominant background from pion decay; need to be subtracted

Away side photon/hadron with jet : different kinematics

D. Florian, PRD 79, 114014 (2009)

Method to calculate cross section in pQCD at NLO

$$pp \to jetX$$

Jaeger, Stratmann, Vogelsang, PRD 70, 034010 (2004); AM, Vogelsang, PRD 86, 094009 (2012)

Narrow jet approximation (NJA) ; analytic method

Expand partonic cross section in jet parameter R

$ALogR + B + O(R^2)$ Keep only A and B

Advantage : collinear singularities cancel analytically; code faster

Cross section of $pp \to hX$ changed to the jet cross section at NLO

Start from single inclusive hadron production cross section at NLO

$$pp \to hX$$

h : hadron with large transverse momentum

Difference with jet cross section : phase space of all final state partons except the observed one are integrated : leads to final state collinear singularities that are absorbed in the parton to hadron fragmentation function

Jet cross section : defined within the jet algorithm. An observable.

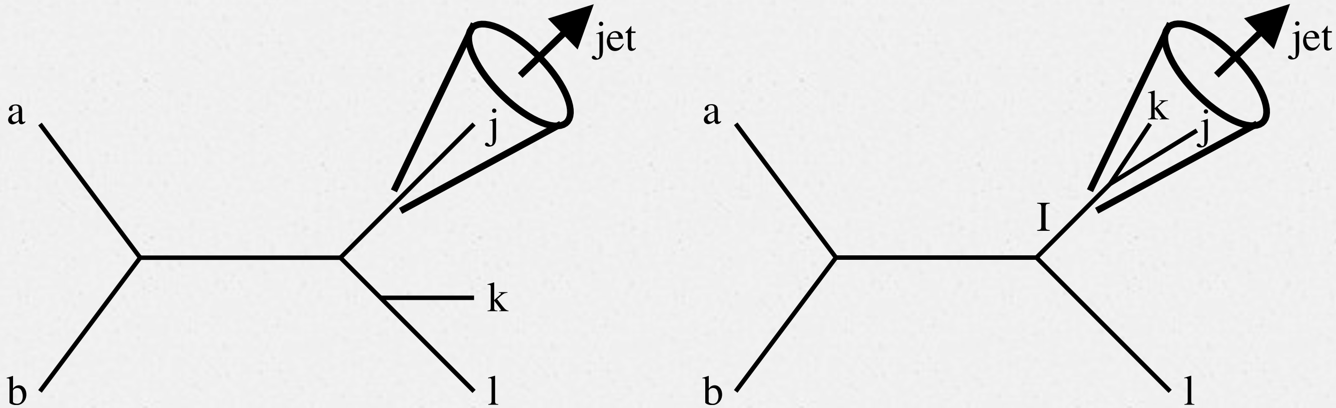
All final state singularities must cancel

$d\hat{\sigma}_{ab\to cX}$ ↘ Partonic cross section at NLO ↗ $pp \to hX$

Imagine a jet cone around the observed parton c

Single parton inclusive cross section : contains configurations when another parton d is there within this cone

For jets at NLO, both partons c and d that are in the cone and form the jet.



Jaeger, Stratmann, Vogelsang, PRD 70, 034010 (2004)

Calculation of Jet Cross Section at NLO

$$
\begin{aligned}
d\hat{\sigma}_{ab\to \mathrm{jet}X} = & [d\hat{\sigma}_c - d\hat{\sigma}_{c(d)} - d\hat{\sigma}_{c(e)}] \\
& + [d\hat{\sigma}_d - d\hat{\sigma}_{d(c)} - d\hat{\sigma}_{d(e)}] \\
& + [d\hat{\sigma}_e - d\hat{\sigma}_{e(c)} - d\hat{\sigma}_{e(d)}] \\
& + d\hat{\sigma}_{cd} + d\hat{\sigma}_{ce} + d\hat{\sigma}_{de}.
\end{aligned}
$$

a,b .....quark, antiquark or gluon : sum over all subprocesses

$d\hat{\sigma}_j$ Single parton inclusive cross section with virtual corrections

$d\hat{\sigma}_{j(k)}$ Parton observed but parton k also in the cone

$d\hat{\sigma}_{jk}$ Parton j and k inside the cone and form the jet

Dependence on Jet Algorithm

$d\hat{\sigma}_{jk}$ and $d\hat{\sigma}_{j(k)}$ Calculated analytically

Narrow jet approximation (NJA) :

R not too large (jet cone radius); can be as large as 0.7

$d\hat{\sigma}_{jk}$ Introduces dependence on algorithm

AM and Vogelsang, PRD 86, 094009 (2012)

All collinear singularities cancel and the final result is finite

$$\frac{d\sigma^{H_1 H_2 \to \text{jet} X}}{dp_T^{\text{jet}} d\eta^{\text{jet}}} = \frac{2p_T^{\text{jet}}}{S} \sum_{abc} \int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a^{H_1}(x_a, \mu_F) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b^{H_2}(x_b, \mu_F) \times$$

$$\int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(\hat{s}, \hat{p}_T, \hat{\eta}, \mu_F, \mu_F', \mu_R)}{v dv dw} \mathcal{J}_c\left(z_c, \frac{\mathcal{R}\, p_T^{\text{jet}}}{\mu_F'}, \mu_R\right) ,$$

Single Inclusive Jet Cross Section

$\mathcal{J}_{q/g}$ are the jet functions, calculated perturbatively

$$\hat{p}_T = p_T^{\rm jet}/z_c \qquad v \equiv 1 - \frac{\hat{p}_T {\rm e}^{-\hat{\eta}}}{\sqrt{\hat{s}}}\,, \qquad w \equiv \frac{\hat{p}_T^2}{\hat{s} v(1-v)}\,.$$

Cross section has a factorized structure in the final state

In the hard scattering, a parton c "fragments" into the observed jet via the jet function ,

z_c Fraction of the parton's momentum carried by the jet

Factorized structure for jet+hadron has been obtained in SCET

e^+e^-

Procura and Waalewijn, PRD(2011), Jain, Procura, Waalewijn, JHEP (2011)

Hadron Produced Inside Jets

$$pp \to jet\ hX$$

Cross section specified by $p_T^{jet}, \eta^{jet}, z_h = \frac{p_T}{p_T^{jet}}$

z_h: fraction of jet transverse momentum carried by hadron

Factorized form of the cross section at NLO :

$$\frac{d\sigma^{H_1 H_2 \to (jet\, h) X}}{dp_T^{jet} d\eta^{jet} dz_h} = \frac{2p_T^{jet}}{S} \sum_{a,b,c} \int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a^{H_1}(x_a, \mu_F) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b^{H_2}(x_b, \mu_F) \times$$
$$\int_{z_h}^1 \frac{dz_p}{z_p} \frac{d\hat{\sigma}_{ab}^{(\mathrm{jet,c})}(\hat{s}, p_T^{jet}, \hat{\eta}, \mu_F, \mu_F', \mu_R, \mathcal{R}, z_p)}{v dv dw dz_p} D_c^h\left(\frac{z_h}{z_p}, \mu_F'\right),$$

$d\hat{\sigma}^{jet\ c}$ Partonic cross section for producing a final state jet (subject to a jet algorithm), inside of which the parton c fragments to a hadron

Hadron Produced Inside Jets

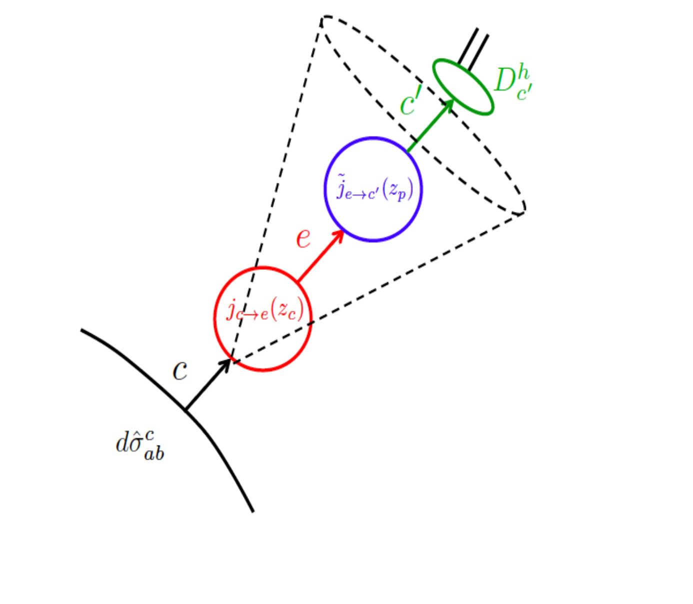
$$p_T^c = z_p p_T^{jet}$$

At LO, only one parton forms the jet, and this also fragments into the observed hadron

NLO : consider the same combination as for the single inclusive jet production but do not sum over over the parton c : because we need different fragmentation functions

Double poles cancel, single pole are factorized in the fragmentation functions for parton c

Hadrons inside Jets



In NJA, production of a jet with an observed hadron factorizes into a production cross section of parton c, a jet function

$j_{c\to e}$ that describes formation of a “jet”

consisting of parton e that has taken a fraction z_c of the momentum of c

$\tilde{j}_{e\to c'}$ partonic fragmentation of parton e to parton c’

C’ then fragments into a hadron

Identified Hadron Inside Jet at NLO

$$\frac{d\sigma^{H_1 H_2 \to (jet\, h) X}}{dp_T^{jet} d\eta^{jet} dz_h} = \frac{2p_T^{jet}}{S} \sum_{a,b,c} \int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a^{H_1}(x_a, \mu_F) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b^{H_2}(x_b, \mu_F) \times$$

$$\int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(\hat{s}, \hat{p}_T, \hat{\eta}, \mu_F, \mu_F', \mu_R)}{v dv dw} \sum_e j_{c\to e}\left(z_c, \frac{\mathcal{R}\, p_T^{\rm jet}}{\mu_F'}, \mu_R\right) \times$$

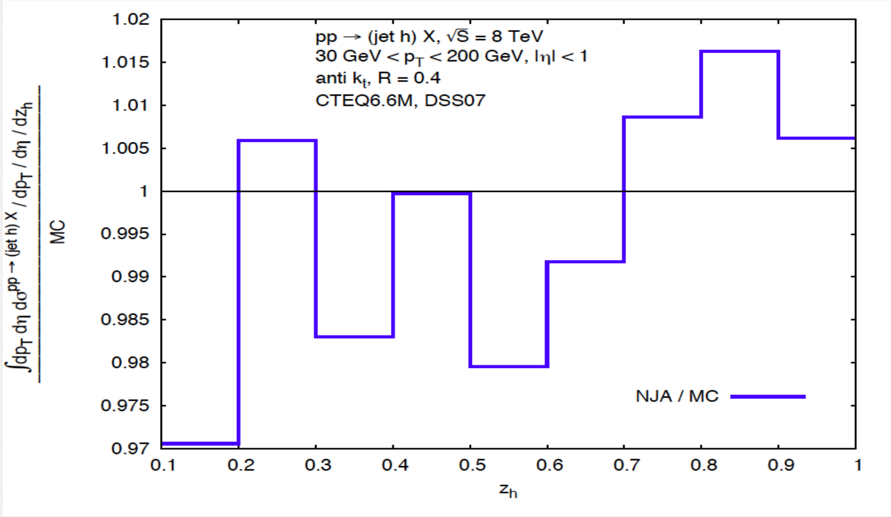
$$\sum_{c'} \int_{z_h}^1 \frac{dz_p}{z_p} \tilde{j}_{e\to c'}\left(z_p, \frac{\mathcal{R}\, p_T^{\rm jet}}{\mu_F''}, \mu_R\right) D_{c'}^h\left(\frac{z_h}{z_p}, \mu_F''\right).$$

Jet Functions : calculated analytically

SCET result agrees with us

Kang, Ringer and Vitev, JHEP 1610, 125 (2016)

Numerical Result



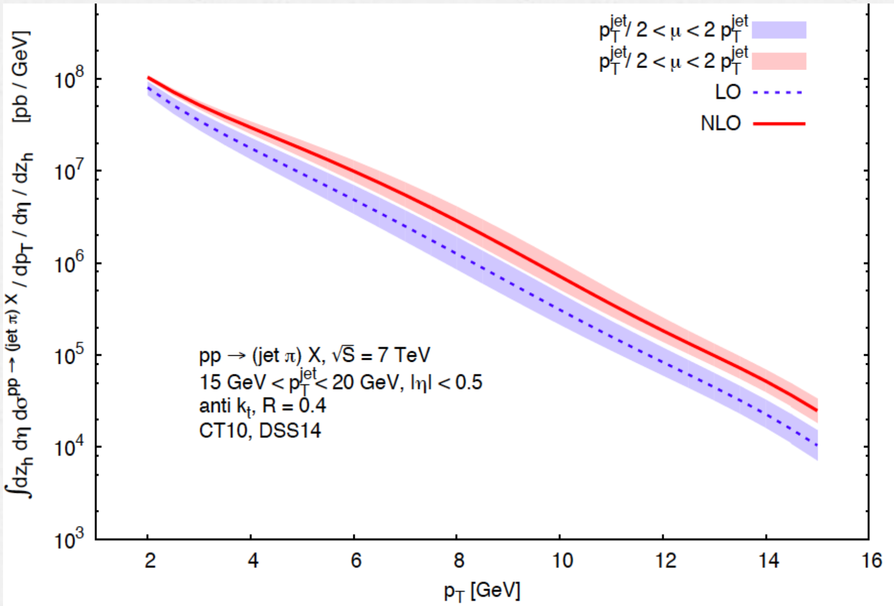
Our results(NJA) compared with MC (F. Arleo et al, JHEP 04 (2014), 147)

LHC, CM energy 8 TeV, anti-kt, R=0.4

Kaufmann, AM, Vogelsang, PRD 92, 054015 (2015)

Agreement very good, deviation within 3 %

Numerical Results



LO and NLO results for ALICE kinematics

$$pp \to jet\ \pi X$$

Factorization and renormalization scales are set equal

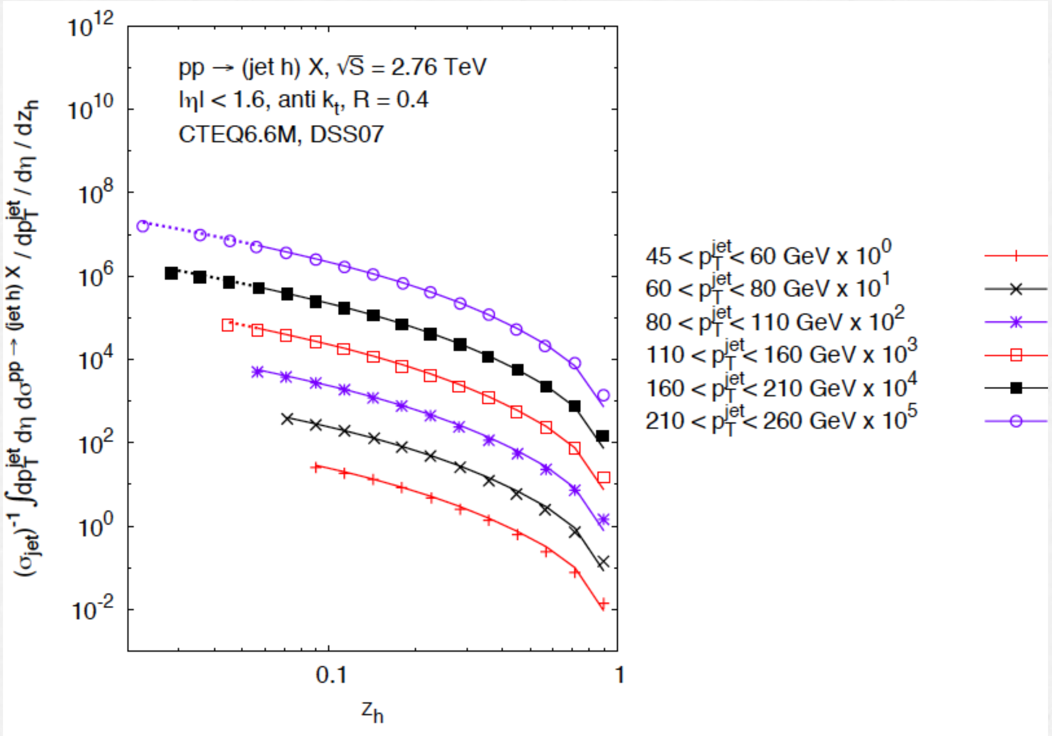
Fragmentation into charged pions

Anti-kt, R=0.4

CT10 pdf (Lai et al, PRD 82, 074024 (2010)) , Frag fn DSS14 (De Florian et al , PRD 91 (2015) 014035)

Kaufmann, AM, Vogelsang, PRD 92, 054015 (2015)

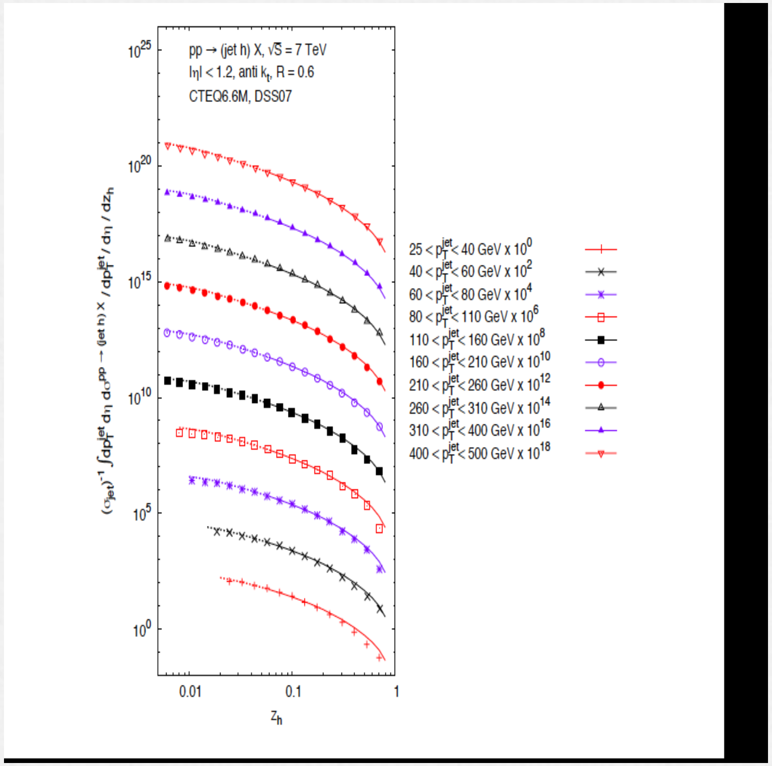
Numerical Results



Kaufmann, AM, Vogelsang, PRD 92, 054015 (2015)

Results compared with data from ATLAS (charged hadron)

Numerical Results



ATLAS charged hadron 2011, EPJC

Kaufmann, AM, Vogelsang, PRD 92, 054015 (2015)

Jet+Photon

Photon fragmentation functions : not well known

LEP experiment : results on photon frag. fn have large uncertainty

Fragmentation of photon contributes about 10-30 % to the cross section for $pp \to \gamma X$ (fixed target)

Estimated to be 10 % at colliders : one imposes isolation cuts

Size of the fragmentation function presents uncertainty in predictions in photon production cross section

Jet+Photon

"same side" photon-jet observables : identify photon as fully reconstructed jet

$$z_\gamma = \frac{p_T}{p_T^{jet}}$$

p_T : transverse momentum of the photon

Background from $\pi^0 \to \gamma\gamma$ decay

This is different from "away-side" photon+jet in

Belghobsi et al PRD 79, 114024 (2009)

Earlier studied in e^+e^- and ep processes

Gluon-to-photon fragmentation function in these processes can be probed indirectly by evolution or higher order correction

Jet+Photon

Similar factorized formula in terms of the jet functions

But intermediate partons can now be photon

Photon fragmentation function has both direct and fragmentation part :

$$\mathcal{D}_{c'}^{\gamma}(z,\mu) \equiv \delta(1-z)\delta_{c'\gamma} + D_{c'}^{\gamma}(z,\mu)\left(1-\delta_{c'\gamma}\right),$$

Direct Fragmentation

Partonic cross sections are calculated in perturbative order

$$d\hat{\sigma}_{ab}^{\gamma} = \alpha\alpha_s\left[d\hat{\sigma}_{ab}^{\gamma,(0)} + \frac{\alpha_s}{\pi}d\hat{\sigma}_{ab}^{\gamma,(1)} + \mathcal{O}(\alpha_s^2)\right]$$

$$d\hat{\sigma}_{ab}^{c} = \alpha_s^2\left[d\hat{\sigma}_{ab}^{c,(0)} + \frac{\alpha_s}{\pi}d\hat{\sigma}_{ab}^{c,(1)} + \mathcal{O}(\alpha_s^2)\right].$$

Jet+Photon

μ_R : Renormalization scale , μ_F : Initial state factorization scale, μ_F' and μ_F'' are final state factorization scales

μ_F' : present in single inclusive partonic cross section $d\hat{\sigma}^c_{ab}$

One can write schematically

$$\sum_{c,d,c'} d\hat{\sigma}^c_{ab} \otimes j_{c\to d} \otimes \tilde{j}_{d\to c'} \otimes \mathcal{D}^{\gamma}_{c'} \, .$$

c, d, c' are partons, but can also represent a photon

Jet+Photon

Jet functions where both c and c' are not photon contribute only to the fragmentation

At LO these jet functions are delta functions

At NLO there is a direct part of the contribution : when c = γ or c' = γ. Photon fragmentation function is then a delta function

Various possibilities at O(α) :

$$\sum_d \underbrace{d\hat{\sigma}^{\gamma}_{ab}}_{\mathcal{O}(\alpha\alpha_s)} \otimes j_{\gamma\to d} \otimes \tilde{j}_{d\to\gamma} \otimes \underbrace{\mathcal{D}^{\gamma}_{\gamma}}_{\mathcal{O}(1)}$$

Case (i) c=c' = γ

d=γ otherwise higher order

$$j_{\gamma\to\gamma} = \delta(1-z_c), \;\; \tilde{j}_{\gamma\to\gamma} = \delta(1-z_p)$$

Comes with $\delta(1-z_\gamma)$

Direct part of full NLO photon production cross section

Kaufmann, AM, Vogelsang, PRD93, 114021 (2016)

Jet+Photon

Case (ii) and (iii) : c=q and c'= γ

$$\sum_d \underbrace{d\hat{\sigma}^q_{ab}}_{\mathcal{O}(\alpha_s^2)} \otimes j_{q\to d} \otimes \tilde{j}_{d\to\gamma} \otimes \underbrace{\mathcal{D}^\gamma_\gamma}_{\mathcal{O}(1)} \; .$$

c= q, c'=γ

$$\tilde{j}_{\gamma\to\gamma} = \delta(1 - z_p)$$

Contribution comes with $\delta(1 - z_\gamma)$

c=q, c'=γ, d=q

$$j_{q\to q} = \delta(1 - z_c)$$

Only direct part of the cross section contributing at $z_\gamma < 1$

NLO contribution

Jet+Photon

c= g, c'=γ

Gluon from hard process converted to observed photon

$\dot{j}_{g\to q}\,\tilde{\dot{j}}_{q\to\gamma}$

Total contribution including the hard part here is higher order in α_s

Collect all contributions as given above : Jet function in $\overline{MS}$ scheme shows log divergence as $z \to 1$

Use DISγ scheme

$$\tilde{j}^{\mathrm{DIS}_\gamma}_{q\to\gamma}(z,\lambda) \equiv \tilde{j}^{\overline{\mathrm{MS}}}_{q\to\gamma}(z,\lambda) - \frac{\alpha}{2\pi}e_q^2\left[P_{\gamma q}(z)\log\left(z^2(1-z)\right) - 2\frac{1-z}{z}\right]$$
$$= \frac{\alpha}{2\pi}e_q^2\,P_{\gamma q}(z)\left[\log\left(\lambda^2(1-z)\right)+1\right].$$

Gluck, Reya, Vogt, PRD 48, 116 (1993); PRD 51, 1427 (1995)

Remaining log removed by scale choice $(\mu''_F)^2 \propto (1-z_\gamma)$

Jet+Photon

$\pi^0 \rightarrow \gamma\gamma$ Pion decay background need to be estimated

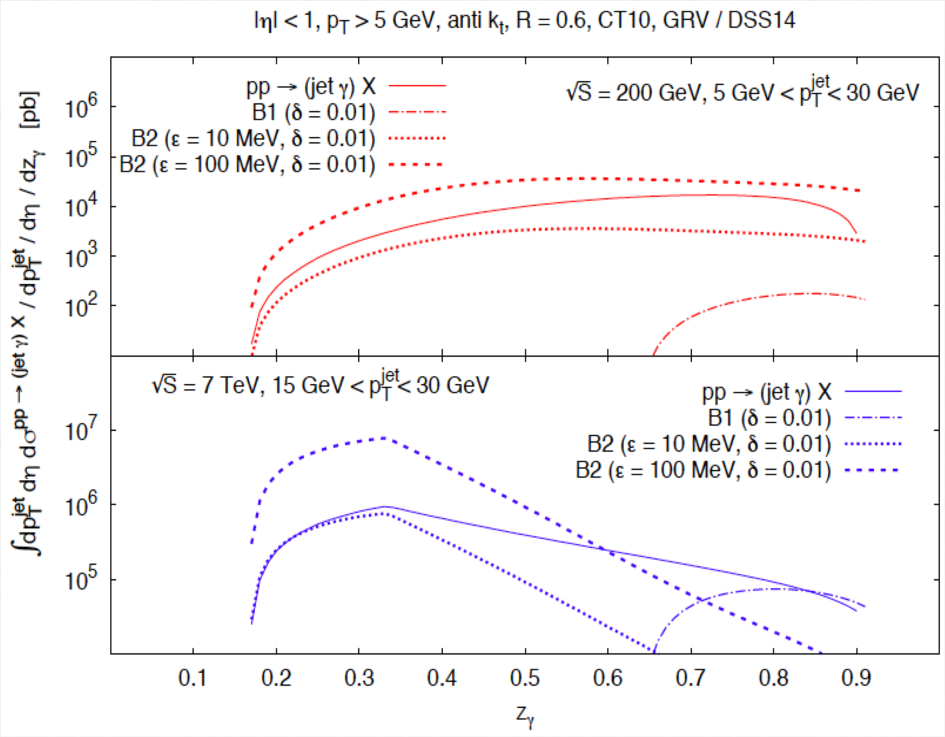
B1 : Two decay photons almost collinear (high transverse momentum) ; are not resolved as two photons

B2 : one of the photons relatively soft, only the other high energy photon is detected and mistaken as a single prompt photon (low transverse momentum)

Estimated both the backgrounds

Kaufmann, AM, Vogelsang, PRD93, 114021 (2016)

Numerical Results



Upper : RHIC
Lower : LHC

Detector resolution : for azimuth and rapidity 0.01

ε : threshold energy for the photon detection

Kaufmann, AM, Vogelsang, PRD93, 114021 (2016)

Conclusion

NLO calculation of Identified hadrons inside a jet : hadron fragmentation function as a function of z

Analytic approach in NJA : good agreement with full MC, results confirmed in SCET

Photon Fragmentation function in photon +Jet : large background from pion decay

Resummation contributions, Higher order dependence on R …