Next-to-leading order QCD calculation of jet production in pp collision

Asmita Mukherjee

IIT Bombay

International Workshop on Forward and Jet Physics at LHC
February 11-12,2019, Bose Institute, Kolkata

In collaboration with Tom Kaufmann and Werner Vogelsang, University of Tuebingen, Germany

Plan of Talk

- large p_T inclusive jet : calculation at NLO
- Analytic calculation at NLO : formalism
- Identified hadron in a jet
- Numerical results
- Conclusion

Single Inclusive Jets in Hadronic Collision

Large p_T inclusive jet in pp collision : cross section can be written in a factorized form

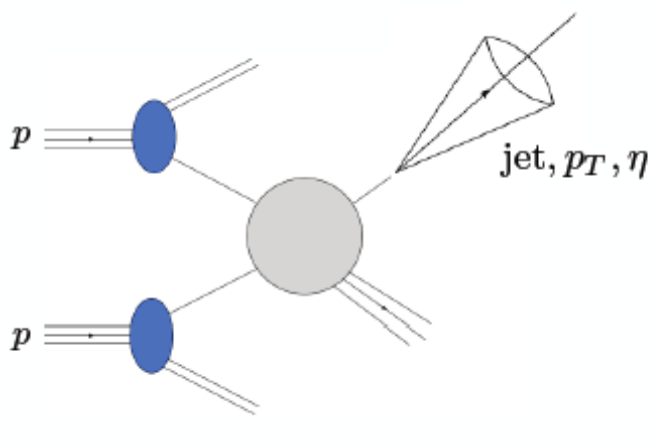


Figure by F. Ringer

Ellis, Kunszt, Soper (1990);

Aversa, Greco, Chiappetta, Guillet (1990)

Jaeger, Stratmann, Vogelsang (2004)

Log R resummation for semi-inclusive jets using SCET : Kang, Ringer, Vitev (2016)

Many more……..

Single inclusive large p_T jets in pp collision

Jets: Important tools at colliders for example RHIC and LHC

Single inclusive jet in polarized pp collision : probe for spin dependent parton distributions , in particular gluon distribution

No unique way to define a jet : depends on jet algorithm

Two main classes of jet algorithms (i) successive recombination , (ii) cone

Jet Algorithms

(i) Successive recombination algorithm (k_T, anti k_T, cambridge-aachen algorithms)

Ellis and Soper , PRD (1993); Catani *et al* , Nucl. Phys. B (1993); Dokshizer *et al*, JHEP (1997); Cacciari, Salam and Soyez, JHEP (2008)

(ii) Cone algorithm

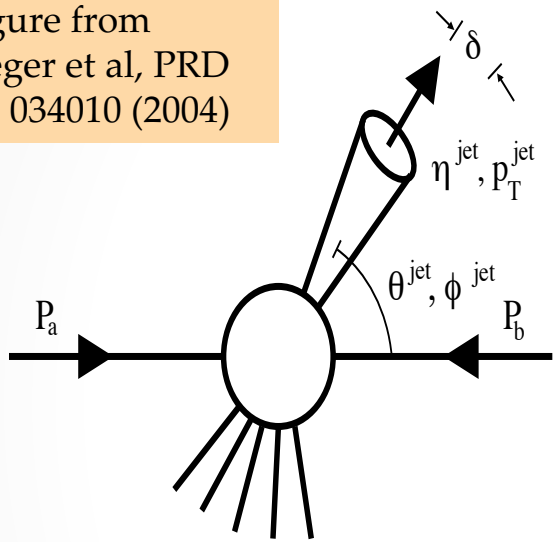
For a summary, see Blazey *et al* , "Proceedings of QCD and Weak Boson Physics " (2005)

Problem with cone algorithm : midpoint cone and iterative cone algorithms are IR unsafe, becomes an issue at NNLO

Solution : seedless IR safe cone ; IR safe

Cone Algorithm

Figure from Jaeger et al, PRD 70, 034010 (2004)



Single inclusive jet production

$$pp \to jetX$$

Cone algorithm : all particles j that satisfy the following form a jet

$$R_{jJ}^2 = (\eta_j - \eta_J)^2 + (\phi_j - \phi_J)^2 \leq R^2$$

R : jet cone aperture

$$\delta = \frac{R}{cosh(\eta_J)} \qquad \eta = -log[tan(\theta/2)]$$

Jet 4-momentum forms the axis of the cone; usually defined as the sum of 4-momenta of the particles forming the jet

k_T Type Algorithm

For each pair of objects (initially particles) j,k; one defines a "distance"

$$d_{jk} \equiv \min(k_{T_j}^{2p}, k_{T_k}^{2p}) \frac{R_{jk}^2}{R^2},$$

Where p is a parameter that specifies the algorithm, k_{Tj} is the transverse momentum of particle j with respect to the beam direction, R is a parameter called the jet radius

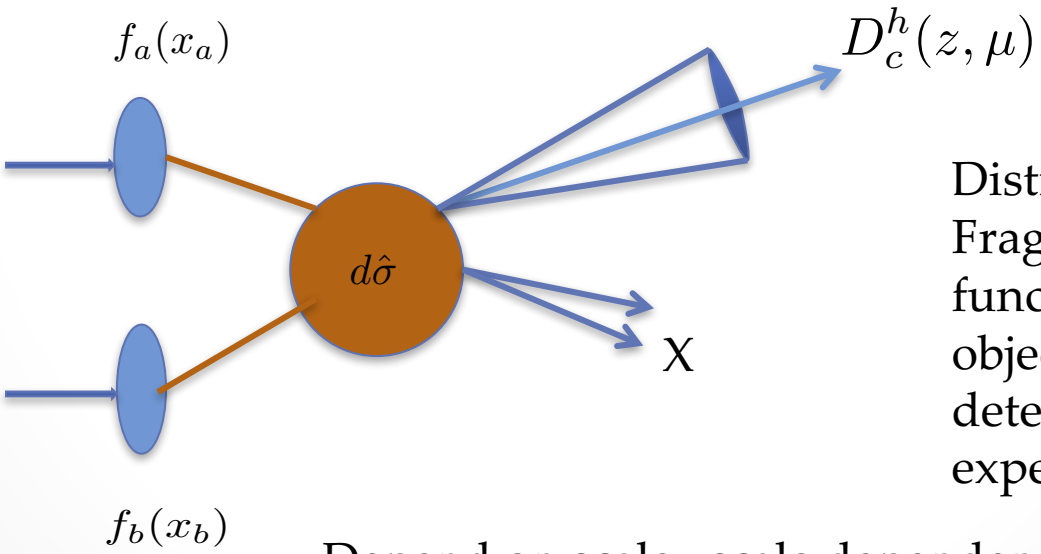
$$R_{jk}^2 = (\eta_j - \eta_k)^2 + (\phi_j - \phi_k)^2$$

Beam distance is defined as $d_{jB} = k_{Tj}^{2p}$

Algorithm identifies the smallest of d_{jk} and d_{jB} . If it is a beam distance the object is defined as a jet and is removed from the list of objects. If it is d_{jk}, the algorithm merges j and k together into a single one. Procedure repeated until no object is left.

High Energy pp Collision

Cross section for high p_T jet/hadron production can be factorized in terms of parton distribution and fragmentation functions and the hard scattering cross section



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

Depend on scale : scale dependence of cross section decreases when higher order corrections are included

Method to calculate single inclusive jet cross section in at NLO

$pp \to jetX$ Analytic approach

Aversa *et al*, Nucl. Phys. B (1989) ; 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

Works when R is not too large; roughly 0.2 < R <0.7

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

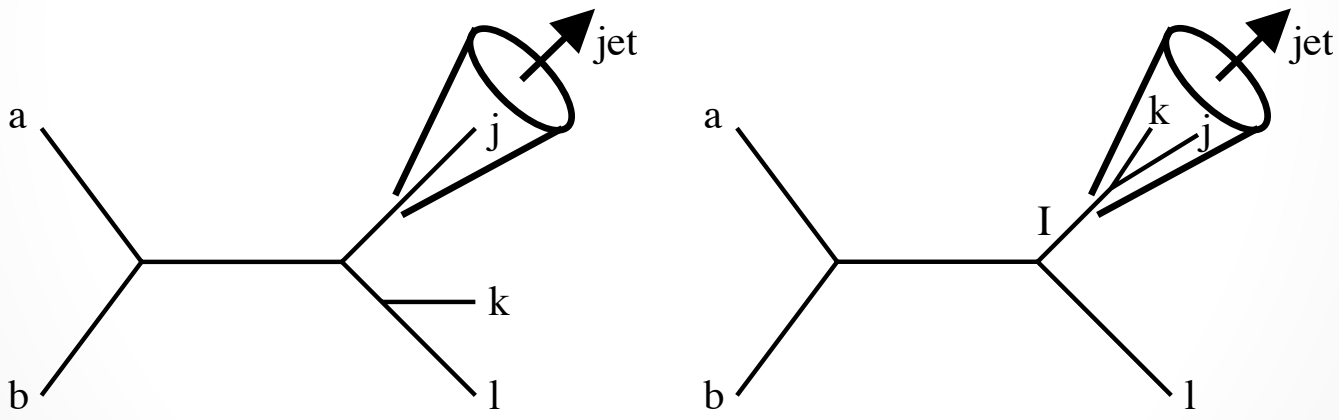
$d\hat{\sigma}_{ab\to cX}$ $\qquad$ $pp \to hX$

↘ Partonic cross section at NLO ↗

Imagine a jet cone around the observed parton j

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

For jets at NLO, both partons j and k 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 j 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

Single parton inclusive cross section contains collinear singularities that are subtracted in the $\overline{MS}$ scheme

$d\hat{\sigma}_{j(k)} + d\hat{\sigma}_{k(j)} - d\hat{\sigma}_{jk}$ Also contains collinear singularities, must match those in $\frac{d\hat{\sigma}_j + d\hat{\sigma}_k}{2}$

Similar subtraction needs to be done so that cross section is finite

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

AM and Vogelsang, PRD 86, 094009 (2012)

Technique remains the same both for polarized and unpolarized cross sections

Single inclusive jet production cross section

$$\frac{d\sigma^{H_1 H_2 \to \mathrm{jet} X}}{dp_T^{\mathrm{jet}} d\eta^{\mathrm{jet}}} = \frac{2p_T^{\mathrm{jet}}}{S} \sum_{abc} \int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a^{H_1}(x_a, \mu_F) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b^{H_2}(x_b, \mu_F) \times$$
$$\int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(\hat{s}, \hat{p}_T, \hat{\eta}, \mu_F, \mu'_F, \mu_R)}{v dv dw} \mathcal{J}_c\left(z_c, \frac{\mathcal{R}\, p_T^{\mathrm{jet}}}{\mu'_F}, \mu_R\right) ,$$

$\mathcal{J}_{q/g}$ Jet function, calculated perturbatively

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

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

Scale dependence

μ_R : Renormalization scale , μ_F : Initial state factorization scale, μ_F' final state factorization scale

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

μ_F' dependence gets canceled in the cross section

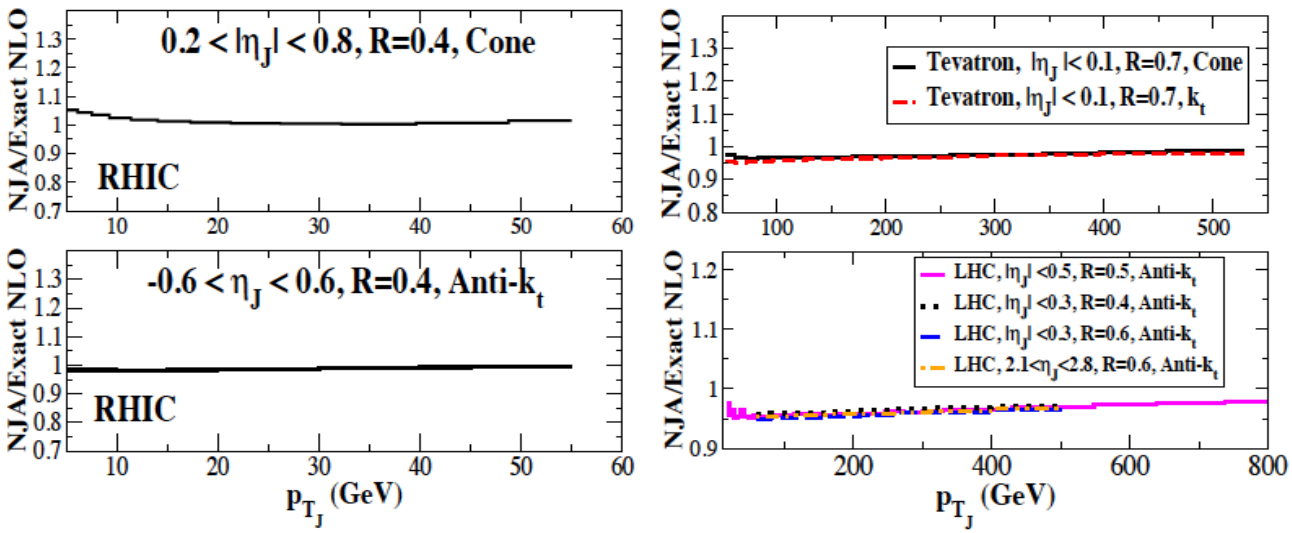
z_c : fraction of parton momentum forming the jet

One can go directly from single inclusive hadron production cross section to jet cross section by replacing the fragmentation function by a jet function

Jet function depends on jet algorithm

NJA vs exact NLO

NJA vs. exact NLO



Upper left: Ratio of single-inclusive jet cross sections at RHIC for the cone algorithm, as computed within the NJA and with *fastNLO*. Lower left: Same for the jet cross sections for the k_t-type algorithms. Here, the exact NLO calculation was performed with the *FastJet* code. Right: Similar comparisons for Tevatron (upper, $\sqrt{S} = 1960$ GeV) and LHC (lower, $\sqrt{S} = 7$ TeV) energies. The exact NLO results for Tevatron and for LHC with $R = 0.5$ were obtained from *fastNLO*, the others from *FastJet*

AM and Vogelsang, PRD (2012)

Identified hadron inside a jet

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

New probe of the fragmentation functions as a function of z

Hadrons in a jet observables were studied in e^+e^- collision

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

For pp scattering, these have been studied in MC approach

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

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

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

Hadron Produced Inside Jets

$pp \to jet\ hX$

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

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

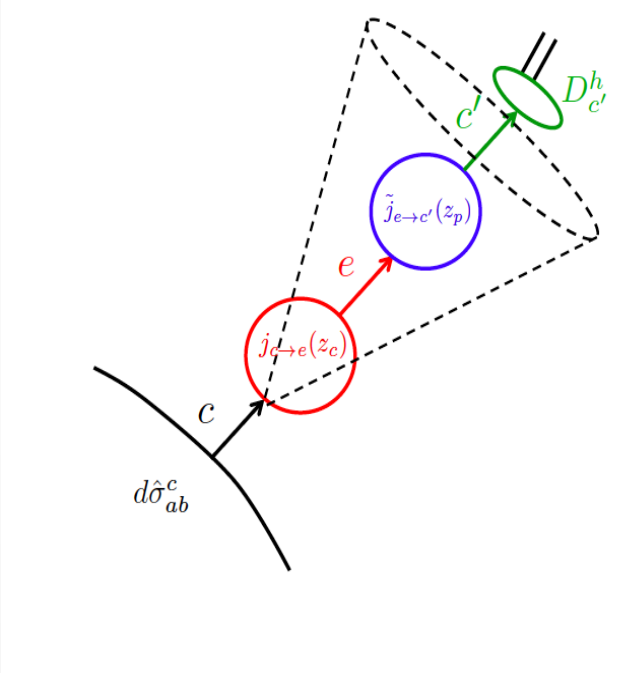
NLO : consider the same combination as for the single inclusive jet production but do not sum over over the parton c : because we need different fragmentation functions

$$d\hat{\sigma}_{j(k)} + d\hat{\sigma}_{k(j)} - d\hat{\sigma}_{jk}$$

No sum over parton j (c)

Double poles cancel, single poles 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 $\hat{p}_T = p_T^{jet}/z_c$

Calculation based on soft collinear effective theory (SCET)

Chien, Kang, Ringer,Vitev, Xing; JHEP 1605, 125 (2016)

μ_F'' : factorization scale in the fragmentation function

A Few Jet Functions

$$j_{q\to q}(z,\lambda,\mu_R) \equiv \delta(1-z) - \frac{\alpha_s(\mu_R)}{2\pi}\left[2C_F(1+z^2)\left(\frac{\log(1-z)}{1-z}\right)_+ + P_{qq}(z)\log\left(\lambda^2\right)\delta(1-z)I_q^{\rm algo} + C_F(1-z)\right]$$

$$j_{q\to g}(z,\lambda,\mu_R) \equiv -\frac{\alpha_s(\mu_R)}{2\pi}\left[P_{gq}(z)\log\left(\lambda^2(1-z)^2\right) + C_F z\right] ,$$

$$\lambda = \mathcal{R}\, p_T^{\rm jet}/\mu_F' \qquad \kappa = \mathcal{R}\, p_T^{\rm jet}/\mu_F'' \qquad p_T^c = z_p p_T^{jet}$$

$$\tilde{j}_{q\to q}(z_p,\kappa,\mu_R) \equiv \delta(1-z_p) + \frac{\alpha_s(\mu_R)}{2\pi}\left[2C_F(1+z_p^2)\left(\frac{\log(1-z_p)}{1-z_p}\right)_+ + P_{qq}(z_p)\log\left(\kappa^2\right) + C_F(1-z_p) + \mathcal{I}_{qq}^{\rm algo}(z_p) + \delta(1-z_p)I_q^{\rm algo}\right]$$

$$\tilde{j}_{q\to g}(z_p,\kappa,\mu_R) \equiv \frac{\alpha_s(\mu_R)}{2\pi}\left[P_{gq}(z_p)\log\left(\kappa^2(1-z_p)^2\right) + C_F z_p + \mathcal{I}_{gq}^{\rm algo}(z_p)\right] ,$$

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

Jet+hadron Production

If we drop the terms with sum over the parton c′, and perform a sum over the parton e, we would get the single inclusive jet cross section

Terms with sum over c′ thus describes the production of an identified hadron in the jet

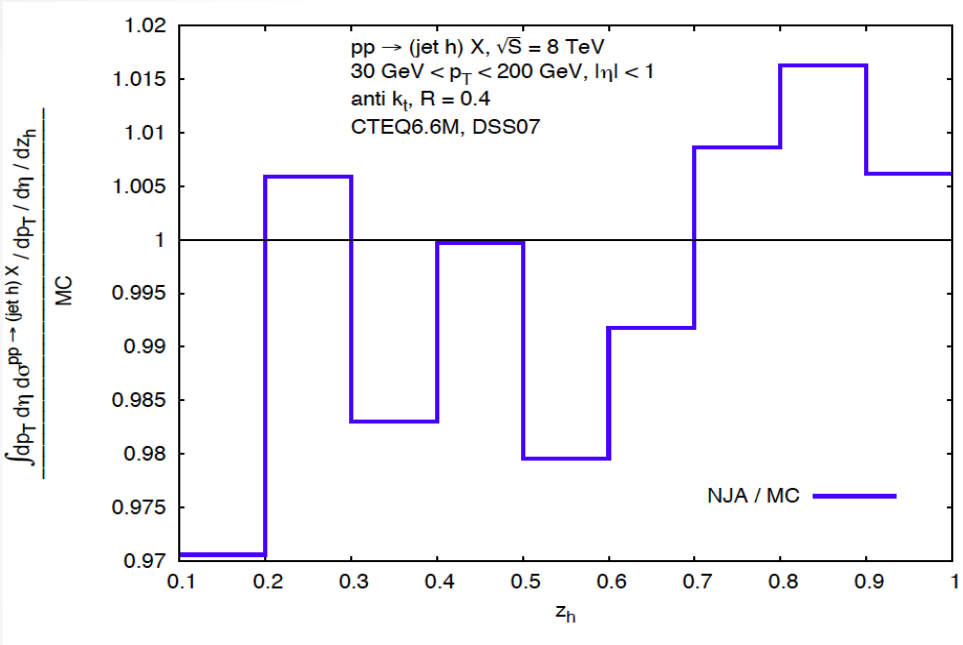
The two jet functions may be combined to give

$$\mathcal{K}_{c\to c'}(z, z_p; \lambda, \kappa, \mu_R) = \sum_e j_{c\to e}(z, \lambda, \mu_R)\, \tilde{j}_{e\to c'}(z_p, \kappa, \mu_R) \ ,$$

SCET calculation agrees with our result

Chien, Kang, Ringer, Vitev, Xing; JHEP 1605, 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

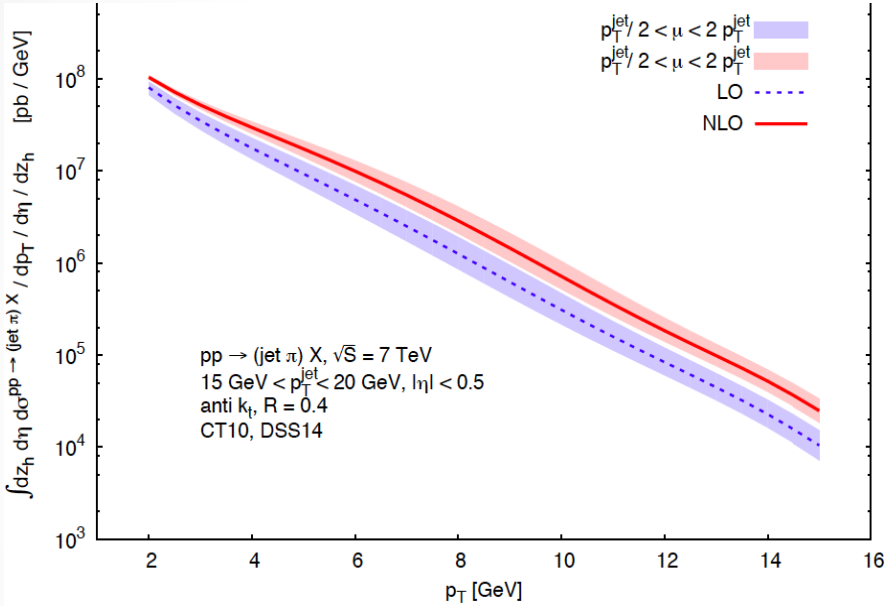
All scales equal to p_T

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

Agreement very good, deviation within 3 %

Definition of z_h differ by terms $O(R^2)$, in the limit z_h close to 1, two definitions are equivalent. Agreement is also better

Numerical Results (ALICE)



Fragmentation into charged pions

LO and NLO results for ALICE kinematics

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

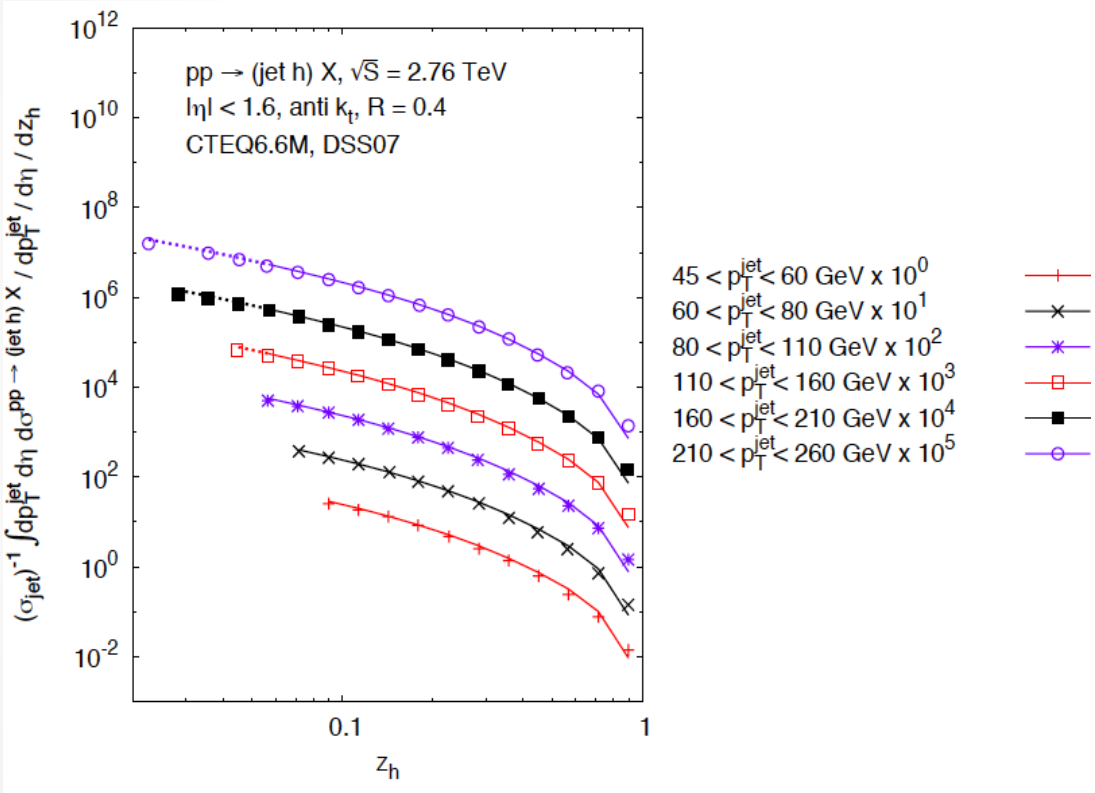
Factorization and renormalization scales are set equal, bands show scale dependence

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 (ATLAS)



Results compared with data from ATLAS (charged hadron in leading jet)

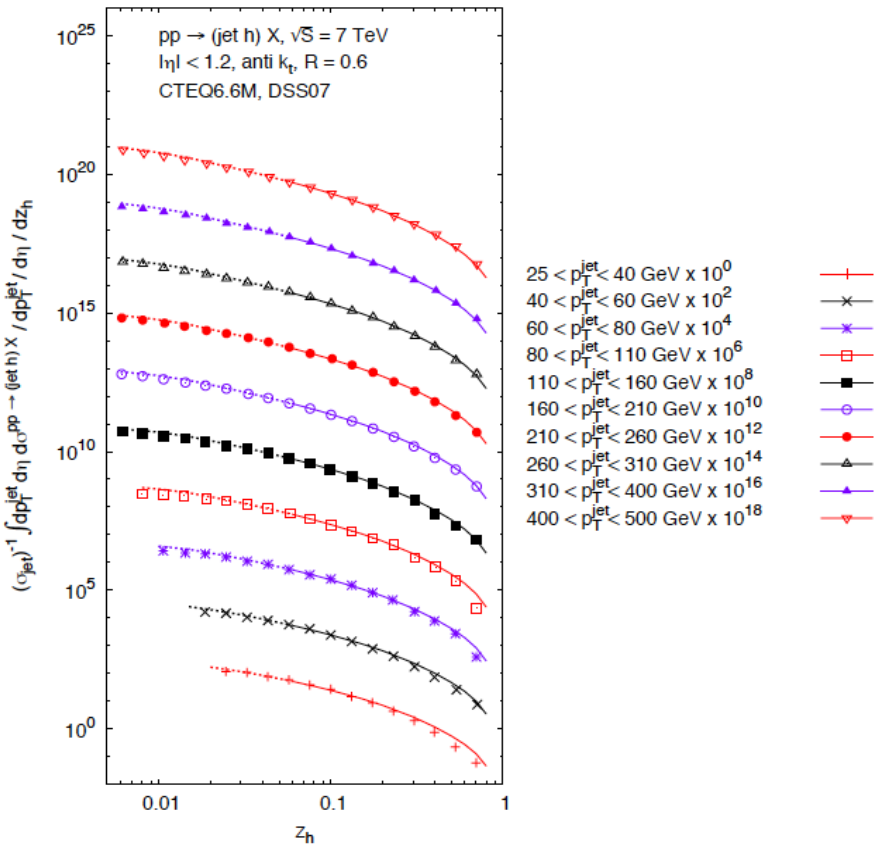
Cross section normalized to total jet rate

Directly maps out fragmentation functions

Overall good agreement, even down to low z_h

Kaufmann, AM, Vogelsang, PRD 92 (2015) 054015
ATLAS-CONF-2015-022, ATLAS-COM-CONF-2015-027
(Preliminary)

Numerical Results (ATLAS)



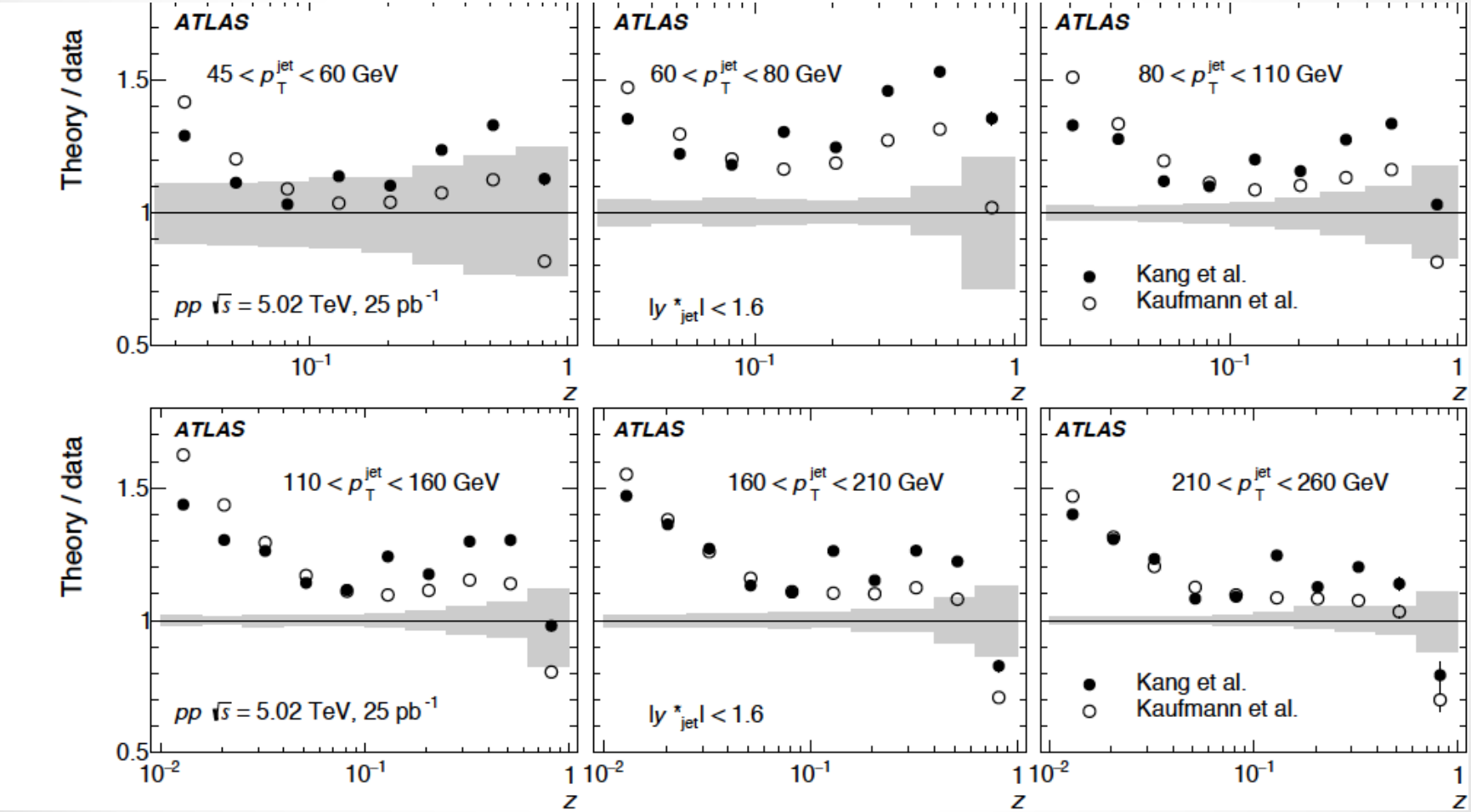
ATLAS charged hadron in leading jet data

EPJC 71, 1795 (2011)

DSS07 fragmentation function for the charged hadrons : extrapolated

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

ATLAS results



ATLAS Collaboration, e-Print: arXiv:1706.02859 [hep-ex]

Conclusion

Analytic calculation of high p_T jet production cross section in pp collision : narrow jet approximation works for RHIC and LHC energies

NLO calculation of identified hadrons/photons inside a jet : 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 …