Production of Jets in Hadronic Collisions beyond NLO

Patriz Hinderer

Institute for Theoretical Physics
University of Tübingen

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TÜBINGEN

Outline

1. Single Inclusive Jet Production
2. Approximate NNLO Results de Florian, Hinderer, Mukherjee, Ringer, Vogelsang PRL '14
3. Toward NNLL-NNLO
4. Extension to A_{LL}
5. Conlusions

Single Inclusive Jet Production

$$H_1 + H_2 \to \mathrm{Jet}(p_T, \eta) + X$$

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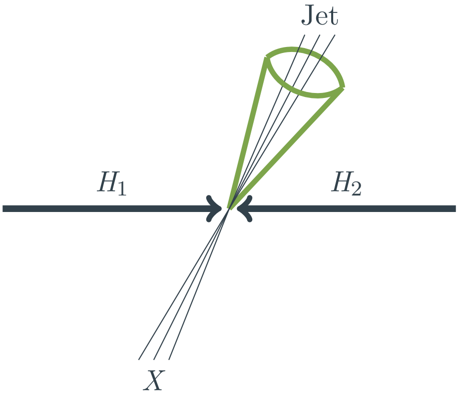
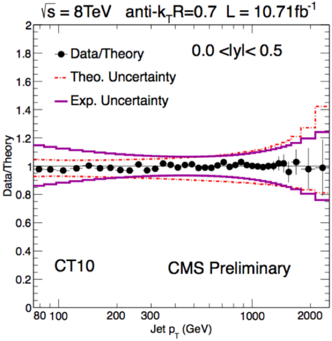
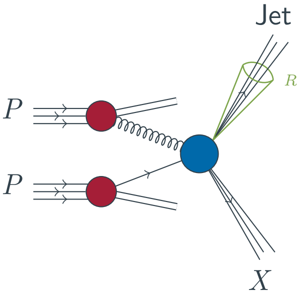


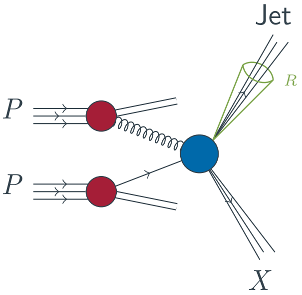
Single Inclusive Jet Production

- Large theoretical uncertainties especially at high p_T
- PDFs are constrained by collider jet data
- Determination of α_s



Single Inclusive Jet Production - Cross Section





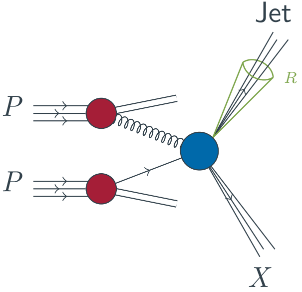
anti-k_T algorithm $\quad p = -1$

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

$$R_{jk}^2 = (\eta_j - \eta_k)^2 + (\Phi_j - \Phi_k)^2$$

(Cacciari, Salam, Soyez 2008)

Single Inclusive Jet Production - Cross Section



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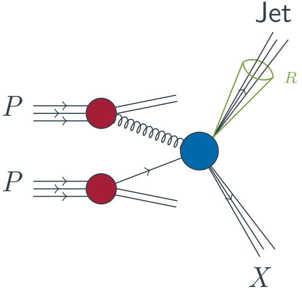
Single Inclusive Jet Production - Cross Section



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$$\frac{p_T^2 d^2\sigma}{dp_T^2 d\eta} = \sum_{ab} \int_0^{z_{\max}} dz \int_{v_{\min}}^{v_{\max}} dv \; x_a x_b \, f_a(x_a, \mu_F) f_b(x_b, \mu_F) \; \frac{d\hat{\sigma}_{ab}}{dv\, dz}(s, v, z, \mu_F, \mu_R; R)$$

$$z_{\max} = V(1-W), \quad v_{\min} = \frac{VW}{1-z}, \quad v_{\max} = 1 - \frac{V-z}{1-z},$$

$$V = 1 - \frac{p_T}{\sqrt{S}} e^{-\eta}, \quad VW = \frac{p_T}{\sqrt{S}} e^{-\eta}$$

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The Cross Section

$$\frac{p_T^2 d^2\sigma}{dp_T^2 d\eta} = \int_0^{z_{\max}} dz \int_{v_{\min}}^{v_{\max}} dv\; x_a x_b\; f_a(x_a, \mu_F) f_b(x_b, \mu_F)\; \frac{d\hat{\sigma}_{ab}}{dv\,dz}(s, v, z, \mu_F, \mu_R; R)$$

Perturbative expansion of the hard part:

$$s\frac{d\hat{\sigma}_{ab}}{dv\,dz} = \left(\frac{\alpha_s}{\pi}\right)^2 \left\{\omega_{ab}^{(0)} + \left(\frac{\alpha_s}{\pi}\right)\omega_{ab}^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \omega_{ab}^{(2)} + \mathcal{O}\left(\alpha_s^3\right)\right\}$$

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Analytical Results at NLO

Full analytical results at NLO in "Narrow Jet Approximation"

Jäger, Stratmann, Vogelsang 2004
Mukherjee, Vogelsang 2013
Kaufmann, Mukherjee, Vogelsang 2015

- $\omega_{ab}^{(1)} \sim A + B\log(R) + \mathcal{O}(R^2)$
- different algorithms
  - anti - k_T algorithm
  - cone algorithm
  - maximized jet function
- accuracy better than 2-3 % for $R \leq 0.7$

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The Partonic Cross Section

Perturbative expansion of the hard part:

$$\frac{s d\hat{\sigma}_{ab}}{dv\ dz} = \left(\frac{\alpha_s}{\pi}\right)^2 \left\{ \omega_{ab}^{(0)} + \left(\frac{\alpha_s}{\pi}\right) \omega_{ab}^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \omega_{ab}^{(2)} + \mathcal{O}\left(\alpha_s^3\right) \right\}$$

The Partonic Cross Section

Perturbative expansion of the hard part:

$$\frac{s d\hat{\sigma}_{ab}}{dv\ dz} = \left(\frac{\alpha_s}{\pi}\right)^2 \left\{\omega_{ab}^{(0)} + \left(\frac{\alpha_s}{\pi}\right)\omega_{ab}^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \omega_{ab}^{(2)} + \mathcal{O}\left(\alpha_s^3\right)\right\}$$

- threshold logarithms $\alpha_s^k \omega_{ab}^{(k)} \sim \alpha_s^k \left(\frac{\log(z)^m}{z}\right)_+$, with $0 \leq m \leq 2k-1$
- threshold logarithms dominate at partonic threshold: $z = \frac{s_4}{s} \rightarrow 0$

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Threshold resummation determines all order structure of logarithms

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Mellin Transformation

mellin transformation

$$\tilde{\omega}_{ab}(v, N) = \int_0^1 dz\,(1-z)^{N-1}\, s\frac{d\sigma^2}{dv\,dz}$$

threshold logarithms

$$\left(\frac{\ln^{2k-1}(z)}{z}\right)_+ \to \ln^{2k} N + \ldots.$$

threshold limit

$$N \to \infty$$

Accuracy of Resummation

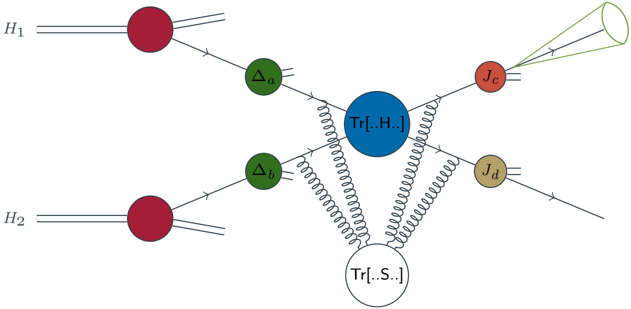
Fixed Order →

Resummation ↓

LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	$\cdots$	...	...	...	
$\mathrm{N^kLO}$	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...

↓ LL ↓ NLL ↓ NNLL

Resummed Cross Section



$$\Omega^{\rm res}_{ab}(v,N) = \sum_{cd} \Delta_a(N_a)\,\Delta_b(N_b)\,J_c^{(\rm Jet)}(N)\,J_d^{(\rm recoil)}(N)\,\Delta^{\rm int}_{ab\to cd}(N,v)\,\Delta_c^{(\rm ng)}(N)$$

Kidonakis, Oderda, Sterman 1998

$$\Delta^{\rm int}_{ab\to cd}(N,v) = \mathrm{Tr}(..S..H)$$

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Resummed Cross Section

$$\Omega_{ab}^{\mathrm{res}}(v, N) = \sum_{cd} \Delta_a(N_a)\, \Delta_b(N_b)\, J_c^{(\mathrm{Jet})}(N)\, J_d^{(\mathrm{recoil})}(N)\, \Delta_{ab\to cd}^{\mathrm{int}}(N, v) \Delta_c^{(\mathrm{ng})}(N)$$

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Resumed Cross Section

$$\Omega_{ab}^{\mathrm{res}}(v,N)=\sum_{cd}\boxed{\Delta_a(N_a)\,\Delta_b(N_b)}\,J_c^{(\mathrm{Jet})}(N)\,J_d^{(\mathrm{recoil})}(N)\,\Delta_{ab\to cd}^{\mathrm{int}}(N,v)\Delta_c^{(\mathrm{ng})}(N)$$

- initial state, soft-collinear gluon emission:

$$\Delta_i(N_i)=R_i\left(\alpha_s\left(\mu_r\right)\right)\,\exp\left\{\int_0^1 dz\,\frac{z^{N_i-1}-1}{1-z}\left[\int_{\mu_F^2}^{(1-z)^2 s}\frac{d\mu^2}{\mu^2}A_i\left(\alpha_s\left(\mu\right)\right)+D_i\left(\alpha_s((1-z)s)\right)\right]\right\}$$

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Resummed Cross Section

$$\Omega^{\mathrm{res}}_{ab}(v,N) = \sum_{cd} \Delta_a(N_a)\,\Delta_b(N_b)\,J_c^{(\mathrm{Jet})}(N)\,\boxed{J_d^{(\mathrm{recoil})}(N)}\,\Delta^{\mathrm{int}}_{ab\to cd}(N,v)\Delta_c^{(\mathrm{ng})}(N)$$

- initial state, soft-collinear gluon emission:

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- unobserved final state, soft-collinear gluon emission:

$$J_i^{(\mathrm{recoil})} = R_i^J\left(\alpha_s\left(\mu_r\right)\right)\exp\left\{\int_0^1 dz\,\frac{z^{N-1}-1}{1-z}\left[\int_{(1-z)^2 s}^{(1-z)s}\frac{d\mu^2}{\mu^2}A_i\left(\alpha_s\left(\mu\right)\right)+\frac{1}{2}B_i\left(\alpha_s((1-z)s)\right)\right]\right\}$$

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Resumed Cross Section

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- non global contribution $\Delta_c^{(NG)}$

  3rd tower effect starting at NNLO, arising from boundary of the jet

Dasgupta, Salam 2001; Banfi, Dasgupta 2004

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Resummed Cross Section

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- trace part

$$\Delta_{ab\to cd}^{\mathrm{int}}(N,v) = \mathrm{Tr}\left\{H(\alpha_s(\mu_r^2)\mathcal{S}^\dagger S(\alpha_s(S/\bar{N}))\mathcal{S}\right\}$$

matrices in space of color exchange operators (2-,3-,8-dimensional)

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Resumed Cross Section

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Resumed Cross Section

$$\Delta^{\text{int}}_{ab\to cd}(N,v) = \mathrm{Tr}\left\{H(\alpha_s(\mu_r^2)\mathcal{S}^{\dagger}\boxed{S(\alpha_s(S/\bar{N}))}\mathcal{S}\right\}$$

- soft matrix
  - soft, large angle gluon emission

  $$S = S^{(0)} + \frac{\alpha_s}{\pi}S^{(1)}$$

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Resummed Cross Section

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$$\mathcal{S} = \mathcal{P}\exp\left[\frac{1}{2}\int_s^{s/\bar{N}^2} \frac{d\mu^2}{\mu^2}\Gamma_S^{(f)}(\alpha_s(\mu^2))\right]$$

$$(\Gamma_S^{(f)})_{KL} = (\Gamma_{S'}^{(f)})_{KL} + \delta_{KL}\frac{\alpha_s}{\pi}\sum_{i=a,b,c,d} C_{f_i}\frac{1}{2}\left[-\ln(2\nu_i) + 1 - i\pi\right]$$

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- hard scattering matrix
  - contains far off shell part

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$$\left(\frac{\alpha_s}{\pi}\right)^k \frac{\sum_i A_i^{(1)}}{(k-1)!}\mathrm{Tr}\underbrace{\left\{H^{(1)}S^{(0)} + H^{(0)}S^{(1)}\right\}}_{\text{matching to NLO}\rightarrow\text{NLL accuracy}} \ln^{2k-2}\bar{N}$$

Resummed Cross Section

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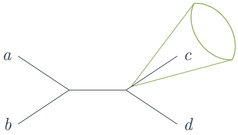
Jet Mass at Threshold

LO:



$\Rightarrow$ jet massless

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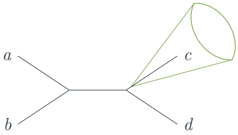

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- Scheme 1: keep jet massless at threshold

$$\exp\left[\frac{\alpha_s}{\pi}\ln^2\bar{N}\left(C_a + C_b - \frac{1}{2}C_c - \frac{1}{2}C_d\right)\right]$$

Kidonakis, Owens 2000
Moch, Kumar 2013

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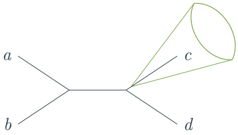

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no dependence on R

Kidonakis, Owens 2000
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Threshold NLO Results

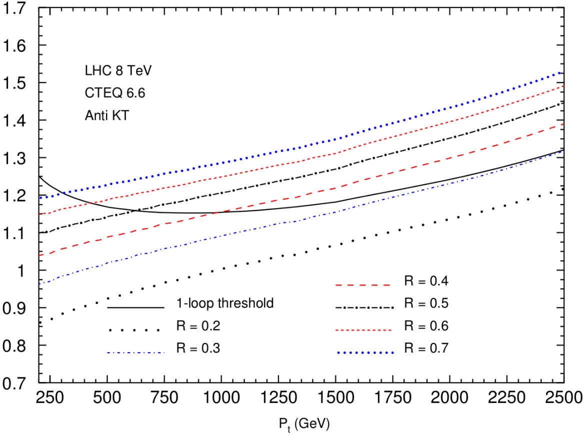

Figure : Moch/Kumar 13'

Jet Mass at Threshold

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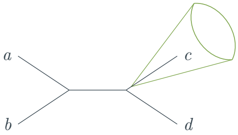

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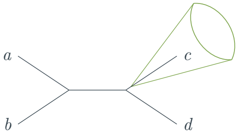

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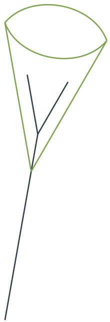
no dependence on R

Kidonakis, Owens 2000
Moch, Kumar 2013

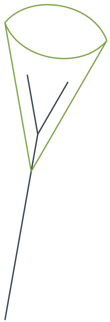
- Scheme 2: jet allowed to be massive at threshold

$$\exp\left[\frac{\alpha_s}{\pi}\ln^2\bar{N}\left(C_a + C_b - \frac{1}{2}C_d\right) + \frac{\alpha_s}{\pi}\boxed{C_c\ln(R)\ln(\bar{N})}\right]$$

Jet Mass At Threshold



Jet Mass At Threshold

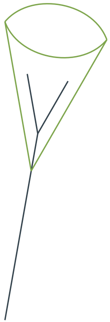


Jet massless at threshold:

- Two partons in the jet, restrictions:
  - one must be arbitrarily soft or
  - they are exactly collinear

$\rightarrow$ no R-dependence in $J_c^{(\mathrm{Jet})}$

Jet Mass At Threshold



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Jet massive at threshold:

- more possible final states

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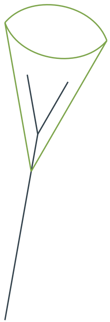
Jet Mass At Threshold



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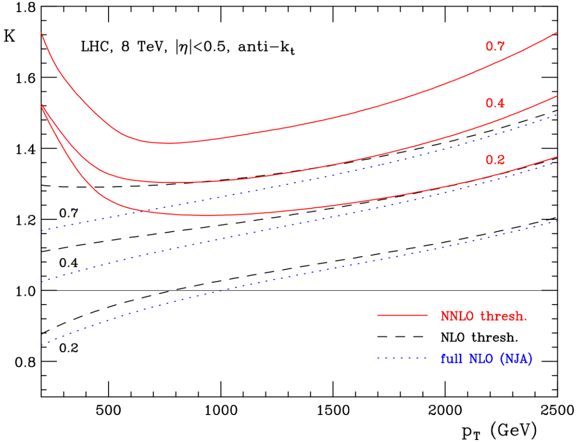
$$J_c^{(\mathrm{Jet})}(\bar{N}, R) = \exp\left\{ \int_s^{s/\bar{N}^2} \frac{dq^2}{q^2} \alpha_s(q^2) \left[-\frac{C_c}{2\pi} \log\left(\frac{p_T^2 R^2}{s} \right) \right] \right\}$$

de Florian, Vogelsang 2013

Approximate NNLO Results



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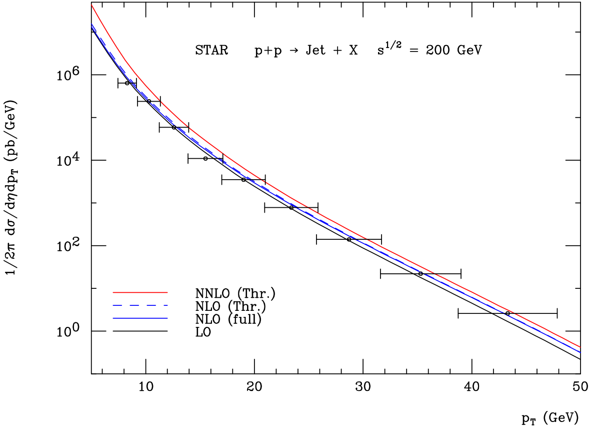


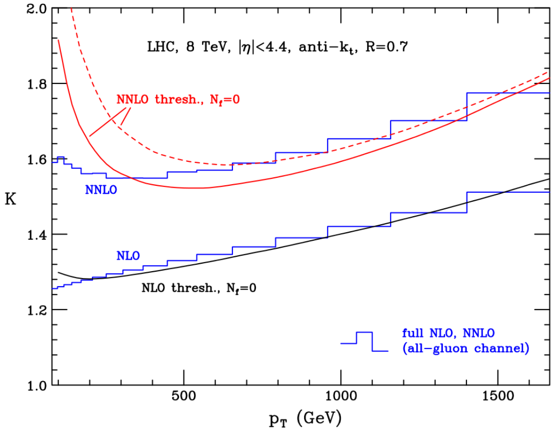
K-factors in the gluon only channel

$$v = \frac{u}{t+u}$$

$$v' = \frac{t+s}{s}$$

scale choice

$$p_{T,1} \neq p_T$$



Currie, Gehrmann-De-Ritter,Glover, Pires 2013

Towards NNLL accuracy

Fixed Order

Resummation

LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	$\cdots$	...	...	...	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...

LL NLL NNLL

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Towards NNLL accuracy

- resummed exponents $\Delta(N_a),\ J_C^{\mathrm{jet}}(N,R),\ J_d^{\mathrm{recoil}}(N)$
- Gamma Matrix $\Gamma^{(2)}$ Aybat, Dixon, Sterman 2006
- Matrices $H^{(1)},\ S^{(1)}$ needed for 4th tower

$$H = H^{(0)} + \frac{\alpha_s}{\pi}\boxed{H^{(1)}}$$

Hinderer, Ringer, Sterman, Vogelsang 2014

Kelley, Schwartz 2010

$$S = S^{(0)} + \frac{\alpha_s}{\pi}\boxed{S^{(1)}}$$

- for Di-Hadron Production

Hinderer, Ringer, Sterman, Vogelsang 2014

- for Single Inclusive Hadron and Jets

Hinderer, Ringer, Sterman, Vogelsang (work in progress)

Upcoming Work

Approximate NNLO results for A_{LL}

- measured at STAR

$$\Omega_{ab}^{\mathrm{res}}\,(v, N) = \sum_{cd}\, \Delta_a(N_a)\, \Delta_b(N_b)\; J_c^{(\mathrm{Jet})}(N)\; J_d^{(\mathrm{recoil})}(N)\; \mathrm{Tr}(..S..H)\, \Delta_c^{(\mathrm{ng})}(N)$$

Soft gluon emission is spin independent

- $\Delta_i(N_i),\; J_c^{\mathrm{Jet}}(N),\; J_d^{\mathrm{recoil}},\; \Delta^{\mathrm{NG}}(N),\; S$ remain unchanged
  see eg. de Florian, Vogelsang, Wagner 2008
- $H_{UU} \neq H_{LL}$, they are related to hard radiation

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Conclusions

- Single inclusive jet production
- Full result is available up to NLO (NJA)
- NLL-NNLO
- Observed jet should be massive at threshold
- Extension to NNLL-NNLO is crucial
- A_{LL}

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