NNLO Antenna Subtraction with One Hadronic Initial State

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HP2.3rd

The 3rd International Workshop on High Precision for Hard Processes at the LHC

Universität Zürich

Motivation:

- Tevatron and LHC: machines for QCD precision physics
  $\Rightarrow$ new discovery potential related to how good we understand what we already know
- For precise predictions we need a precise determination of
  - coupling constants
  - parton distributions
  - quark masses
  - ...
- Need higher order calculations: NLO, NNLO ...

Subtraction at NLO

- For an m-jet cross section, need to integrate numerically over phase space:
  - LO:

$$d\sigma_{\mathrm{LO}} = \int_{d\Phi_m} d\sigma_{\mathrm{tree}}$$

divergent numerical integral

  - NLO:

$$d\sigma_{\mathrm{NLO}} = \int_{d\Phi_{m+1}} d\sigma^{\mathrm{R}}_{\mathrm{NLO}} + \int_{d\Phi_m} d\sigma^{V}_{\mathrm{NLO}}$$

Problem: same divergent structure as virtual part but summation occur only after phase space integration

Subtraction at NLO

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$$d\sigma_{\mathrm{LO}} = \int_{d\Phi_m} d\sigma_{\mathrm{tree}}$$

  - NLO:

Local counter term integral

$$d\sigma_{\mathrm{NLO}} = \int_{d\Phi_{m+1}} \left(d\sigma^{\mathrm{R}}_{\mathrm{NLO}} - d\sigma^{\mathrm{S}}_{\mathrm{NLO}}\right) + \left[\int_{d\Phi_{m+1}} d\sigma^{\mathrm{S}}_{\mathrm{NLO}} + \int_{d\Phi_m} d\sigma^{V}_{\mathrm{NLO}}\right]$$

Solution: Introduce subtraction term which reproduces $\sigma^{R}_{\mathrm{NLO}}$ in all singular limits, and can be integrated analytically

[Z. Kunszt, D. Soper]

Subtraction at NLO

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Local counter term integral

$$d\sigma_{\mathrm{NLO}} = \int_{d\Phi_{m+1}} \left(d\sigma^{\mathrm{R}}_{\mathrm{NLO}} - d\sigma^{\mathrm{S}}_{\mathrm{NLO}}\right) + \left[\int_{d\Phi_{m+1}} d\sigma^{\mathrm{S}}_{\mathrm{NLO}} + \int_{d\Phi_m} d\sigma^{V}_{\mathrm{NLO}}\right]$$

Solution: Introduce subtraction term which reproduces $\sigma^{R}_{\mathrm{NLO}}$ in all singular limits, and can be integrated analytically

[Z. Kunszt, D. Soper]

- Different subtraction methods exists: dipole, FKS, antenna,...

[S. Catani, M. Seymour, S. Weinzierl, S. Frixione, Z. Kunszt, A. Signer, M. Grazzini, V. Del Duca, G. Somogy, Z. Trocsanyi, D. Kosower, J. Campbell, M. Cullen, N. Glover; A. Daleo, A. Gehrmann-De Ridder, T. Gehrmann, D. Maître]

NLO Antenna Subtraction

- How is $\mathrm{d}\sigma^{S}_{\mathrm{NLO}}$ constructed within the antenna frame work?

  It must satisfy:

  $$\mathrm{d}\sigma^{R}_{\mathrm{NLO}} \xrightarrow{\text{soft \& collinear limit}} \mathrm{d}\sigma^{S}_{\mathrm{NLO}}$$

  - Real correction $\mathrm{d}\sigma^{R}_{\mathrm{NLO}}$ given by

  $$\mathrm{d}\sigma^{R}_{\mathrm{NLO}} = \mathcal{N} \sum_{m+1} \mathrm{d}\Phi_{m+1} \frac{1}{S_{m+1}} \left|\mathcal{M}^{0}_{m+1}\right|^{2} J_{m}^{(m+1)}\left(k_1, \ldots, k_{m+1}\right)$$

  - Exploit factorization of phase space and matrix element in soft and coll. limit:

$$\mathrm{d}\Phi_{m+1}\left(\ldots, i, j, k, \ldots\right) \xrightarrow{j \text{ unresolved}} \mathrm{d}\Phi_{m}\left(\ldots, I, K, \ldots\right) \mathrm{d}\Phi_{X_{ijk}}\left(i, j, k, I, K\right)$$

$$\left|\mathcal{M}^{0}_{m+1}\left(\ldots, i, j, k, \ldots\right)\right|^{2} \xrightarrow{j \text{ unresolved}} \left|\mathcal{M}^{0}_{m}\left(\ldots, I, K, \ldots\right)\right|^{2} F\left(i, j, k\right) + \text{ regular terms}$$

$F\left(i, j, k\right)$: soft eikonal factor or collinear splitting function,

I, K: remapped on-shell momenta: $i + j + k = I + K$.

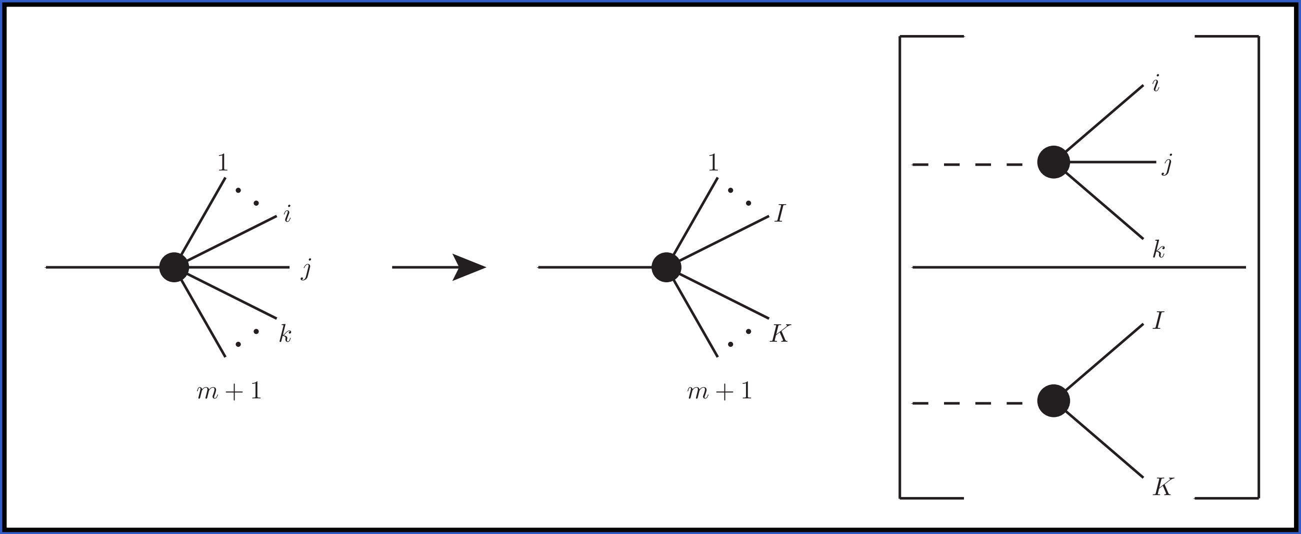
NLO Antenna Subtraction

- And thus $d\sigma^S_{\rm NLO}$ can be constructed as:

$$d\sigma^S_{\rm NLO} = \mathcal{N} \sum_{m+1} d\Phi_{m+1} \frac{1}{S_{m+1}} \sum_j X^0_{ijk} \, |\mathcal{M}_m|^2 J_m^{(m)} \, (k_1, \ldots, k_{m+1})$$

where $X_{ijk} \stackrel{j \text{ unresolved}}{\longrightarrow} F(i,j,k)$.

- Pictorially:



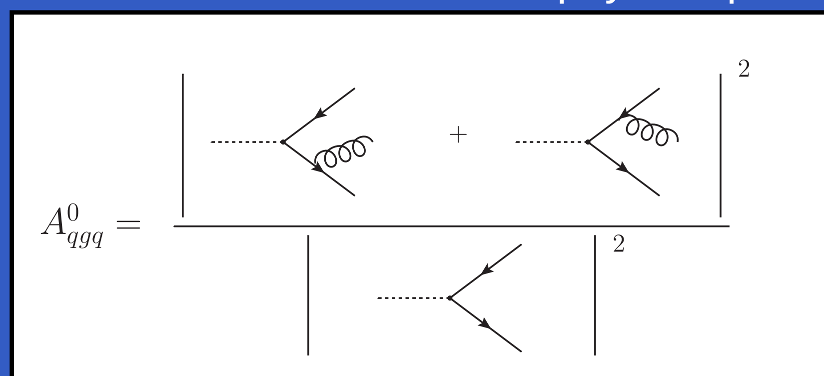
$$\sum_{m+1} d\Phi_{m+1} |\mathcal{M}_{m+1}|^2 J_m^{(m+1)} \longrightarrow \sum_{m+1} d\Phi_m |\mathcal{M}_m|^2 J_m^{(m)} \sum_j d\Phi_{X^0_{ijk}} X^0_{ijk}$$

NLO antenna subtraction

- NLO antenna function X^0_{ijk} contains all soft and collinear configuration of parton j emitted between two hard color-connected partons i and k

$$X^0_{ijk} = S_{ijk,IK} \frac{\left|M^0_{ijk}\right|^2}{\left|M^0_{IK}\right|^2} \qquad , \qquad \mathrm{d}\Phi_{X^0_{ijk}} = \frac{\mathrm{d}\Phi_3}{P_2}$$

- Antennae computed from matrix elements of physical processes

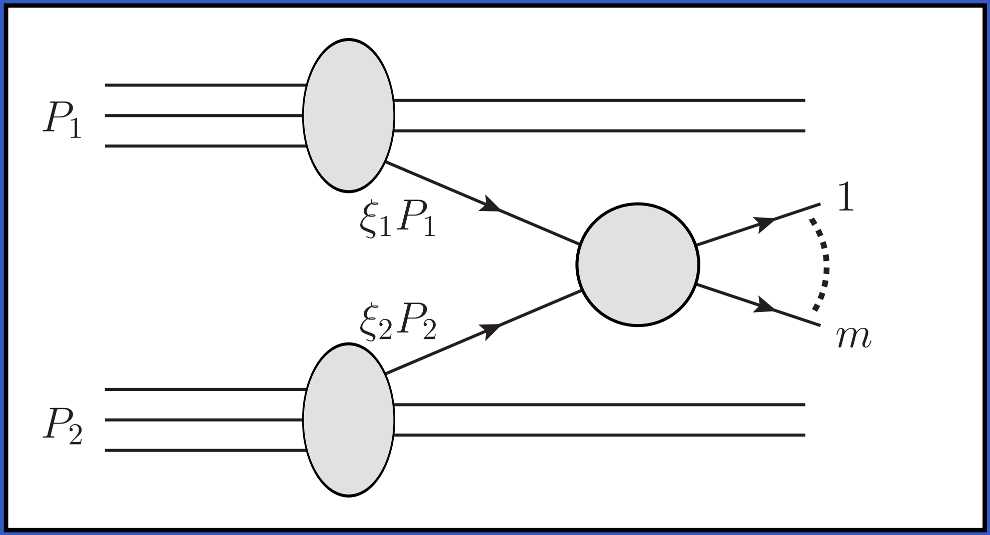


- Integrated subtraction term can be computed analytically

$$|M_m|^2 \, J_m^{(m)} \mathrm{d}\Phi_m \int \mathrm{d}\Phi_{X^0_{ijk}} X^0_{ijk} \;\propto\; |M_m|^2 \, J_m^{(m)} \mathrm{d}\Phi_m \int \mathrm{d}\Phi_3 \left|M^0_{ijk}\right|^2$$

Hadronic initial state

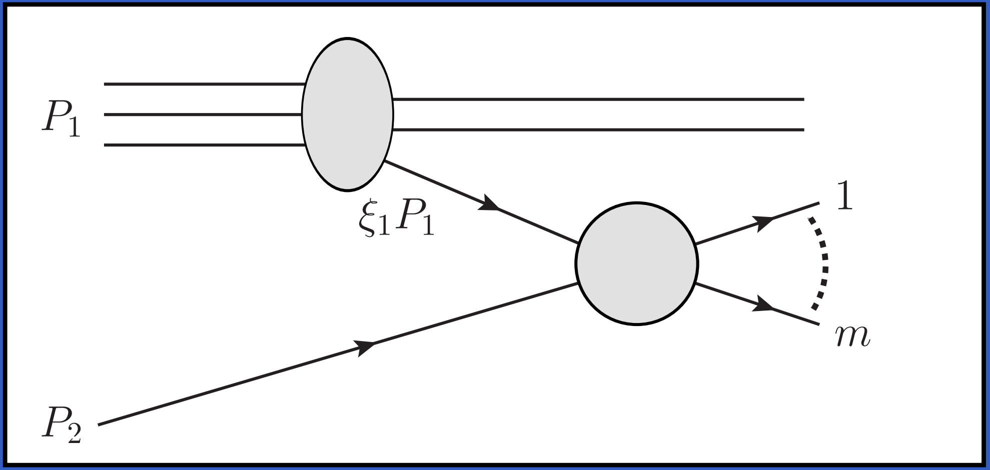
- Cross section for hadronic initial state: (pp,$p\bar{p}$)



$$\mathrm{d}\sigma = \sum_{h_1,h_2,a,b} \int_0^1 \frac{\mathrm{d}\xi_1}{\xi_1} \frac{\mathrm{d}\xi_1}{\xi_2} f_a^{h_1}\left(\xi_1, \mu_F^2\right) f_b^{h_2}\left(\xi_2, \mu_F^2\right) \mathrm{d}\hat{\sigma}_{ab}\left(\xi_1 P_1, \xi_2 P_2, \mu_F^2\right)$$

Hadronic initial state

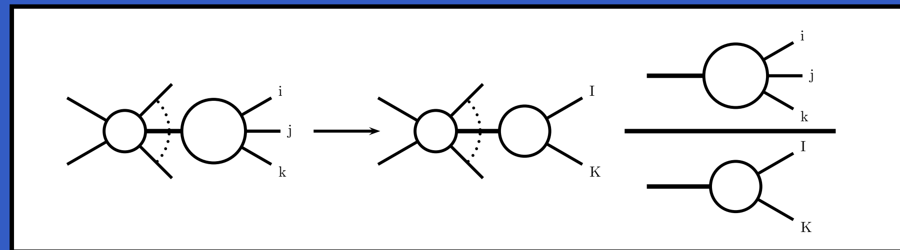
- Cross section for hadronic initial state: (ep)



$$\mathrm{d}\sigma = \sum_{h_1,a,b} \int_0^1 \frac{\mathrm{d}\xi_1}{\xi_1} \frac{\mathrm{d}\xi_1}{\xi_2} f_a^{h_1}\left(\xi_1, \mu_F^2\right) \delta\left(1-\xi_2\right) \mathrm{d}\hat{\sigma}_{ab}\left(\xi_1 P_1, \xi_2 P_2, \mu_F^2\right)$$

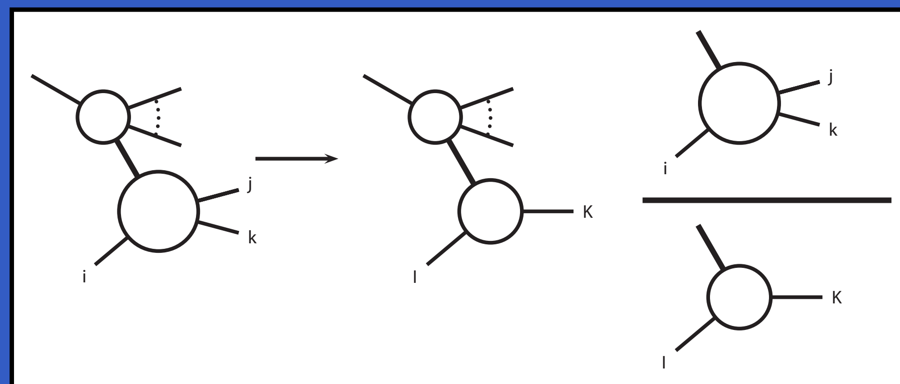
Hadronic initial state

- final-final:



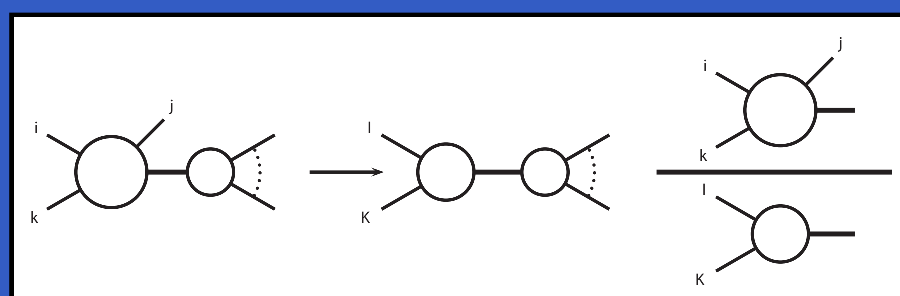
Applied to $e^+e^- \to$ 3 jets at NNLO [A. Gehrmann De-Ridder, T. Gehrmann, N. Glover, G. Heinrich; S. Weinzierl]

- initial-final:



Sufficient for DIS (2+1)-jet [A. Daleo, T. Gehrmann, D. Maître; A. Daleo, A. Gehrmann-De Ridder, T. Gehrmann, G. L]

- initial-initial:



Needed for vector boson plus jet production [A. Daleo, T. Gehrmann, D. Maître] [R. Boughezal, A. Gehrmann-De Ridder, M. Ritzmann]

m-jet cross section

n-parton contribution to the m-jet cross section ($p = \xi_1 P_1$, $r = \xi_2 P_2$):

$$\mathrm{d}\hat{\sigma}^{i}_{ab}(p,r) = \mathcal{N} \sum_{n} \mathrm{d}\Phi_n(k_1,\ldots,k_n;p,r) \frac{1}{S_n} |\mathcal{M}_n(k_1,\ldots,k_n;p,r)|^2 J_m^{(n)}(k_1,\ldots,k_n)$$

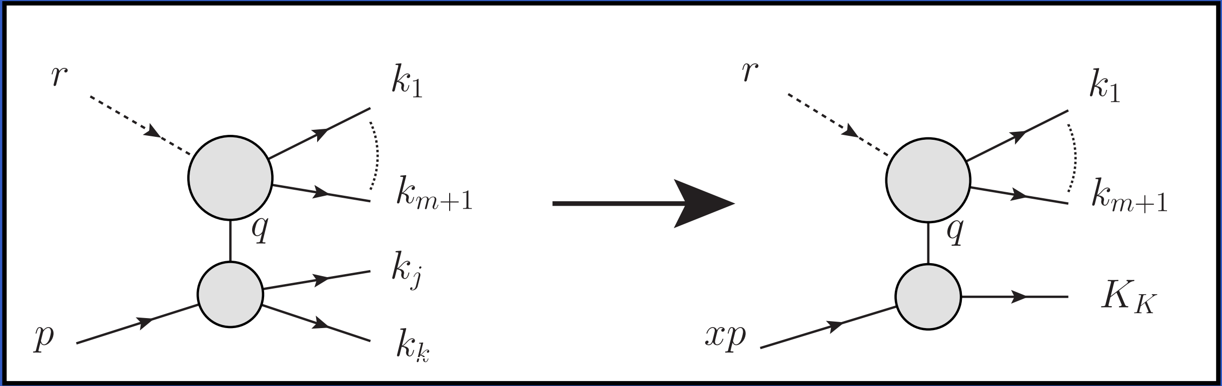
- LO: $n = m$
- NLO: $n = m+1$
- NNLO: $n = m+2$

- Subtraction term for initial-final singularity:

$$\mathrm{d}\hat{\sigma}^{S(if)} = \mathcal{N} \sum_{m+1} \mathrm{d}\Phi_{m+1}(k_1,\ldots,k_{m+1};p,r) \frac{1}{S_{m+1}} \times \sum_{j} X^0_{i,jk} |\mathcal{M}_m(k_1,\ldots,k_{m+1};xp,r)|^2 J_m^{(m)}(k_1,\ldots,k_{m+1})$$

I-F NLO phase space factorization

- Kinematics is now: $q + p \to k_j + k_k \quad \Rightarrow \quad q + xp \to K_K$



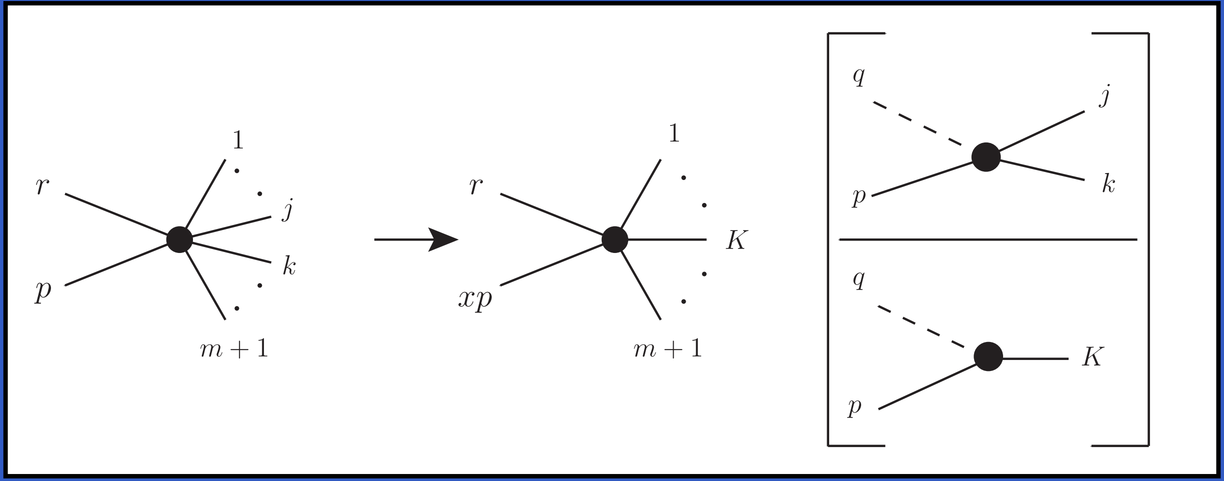
- Limits:
  - $xp \to p$ $\quad K_K \to k_k$ $\quad$ when j soft
  - $xp \to p$ $\quad K_K \to k_j + k_k$ $\quad$ when $j \,||\, k$
  - $xp \to p - k_j$ $\quad K_K \to k_k$ $\quad$ when $j \,||\, i$

- Phase space factorization for $m+1$ particles:

$$\mathrm{d}\Phi_{m+1}(k_1, \ldots, k_{m+1}; p, r) = \mathrm{d}\Phi_m(k_1, \ldots, K_K, \ldots, k_{m+1}; xp, r) \times \frac{Q^2}{2\pi} \mathrm{d}\Phi_2(k_j, k_k; p, q) \frac{\mathrm{d}x}{x}$$

I-F NLO matrix element factorization

- Obtain antennae functions by crossing final-final NLO antennae



$$\sum_{m+1} d\Phi_{m+1} |M_{m+1}|^2 J_m^{(m+1)} \longrightarrow \sum_{m+1} d\Phi_m |M_m|^2 J_m^{(m)} \sum_j \frac{Q^2}{2\pi} d\Phi_2 \frac{dx}{x} X^0_{i,jk}$$

- Again integrated subtraction term can be computed analytically:

$$\mathcal{X}^0_{i,jk}(x) = \frac{1}{C(\epsilon)} \int d\Phi_2 \frac{Q^2}{2\pi} X^0_{i,jk} \quad , \quad C(\epsilon) = (4\pi)^\epsilon \frac{e^{-\epsilon\gamma_E}}{8\pi^2}$$

[A. Daleo, T. Gehrmann, D. Maître]

NLO integrated subtraction term

- Integrated subtraction term has to be convoluted with PDFs
- Make change of variable and obtain

$$\mathrm{d}\sigma^{S(if)}(p,r) = \sum_{m+1}\sum_{j}\frac{S_m}{S_{m+1}}\int\frac{\mathrm{d}\xi_1}{\xi_1}\int\frac{\mathrm{d}\xi_2}{\xi_2}\int_{\xi_1}^{1}\frac{\mathrm{d}x}{x}f_a^{h_1}\left(\frac{\xi_1}{x}\right)f_b^{h_2}(\xi_2)$$
$$\times\, C(\epsilon)\,\mathcal{X}^0_{i,jk}(x)\,\mathrm{d}\hat{\sigma}^B(\xi_1 P_1,\xi_2 P_2)$$

- Mass factorization can be carried out
- Phase space integration in $\mathrm{d}\hat{\sigma}^B$ and convolutions can be done numerically

Subtraction at NNLO

- Structure of NNLO m-jet cross section

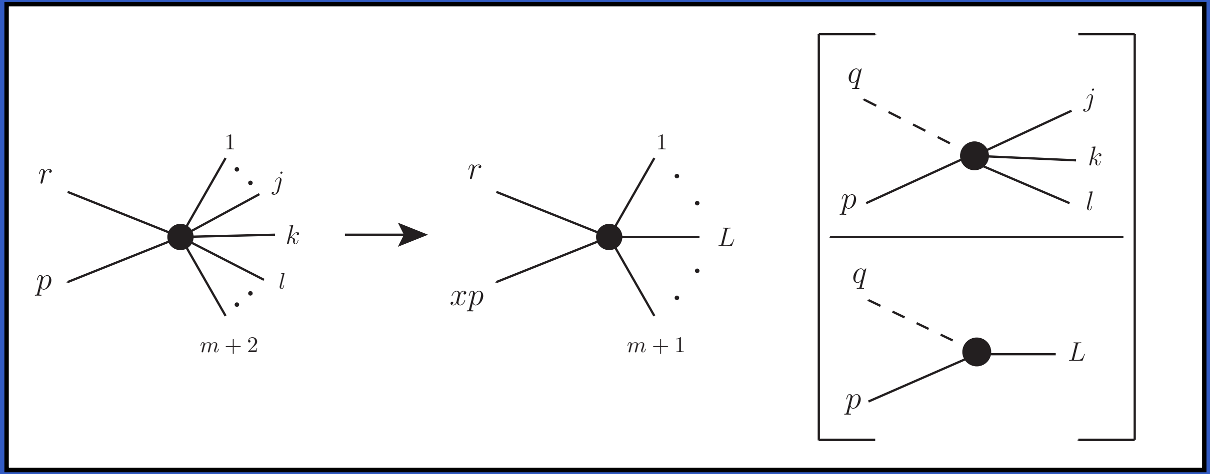
$$\mathrm{d}\sigma_{\mathrm{NNLO}} = \int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NNLO}}\right) + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NNLO}}$$
$$+ \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{\mathrm{V},1}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{\mathrm{VS},1}_{\mathrm{NNLO}}\right) + \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{\mathrm{VS},1}_{\mathrm{NNLO}} + \mathrm{d}\sigma^{\mathrm{MF},1}_{\mathrm{NNLO}}\right)$$
$$+ \int_{\mathrm{d}\Phi_{m}} \left(\mathrm{d}\sigma^{\mathrm{V},2}_{\mathrm{NNLO}} + \mathrm{d}\sigma^{\mathrm{MF},2}_{\mathrm{NNLO}}\right).$$

- $\mathrm{d}\sigma^{S}_{\mathrm{NNLO}}$: real radiation subtraction term for $d\sigma^{R}_{\mathrm{NNLO}}$,
- $\mathrm{d}\sigma^{VS,1}_{\mathrm{NNLO}}$: one loop real subtraction term for $d\sigma^{V,1}_{NNLO}$,
- $\mathrm{d}\sigma^{V,2}_{\mathrm{NNLO}}$: two loop virtual corrections,
- $\mathrm{d}\sigma^{MF,i}_{\mathrm{NNLO}}$: mass factorization counter terms (i=1,2).

Each column is numerically finite and free of IR ϵ-poles

I-F NNLO: double real radiation

- Obtain antennae functions by crossing final-final NNLO antennae



- Phase space factorization similar to NLO, with one particle more

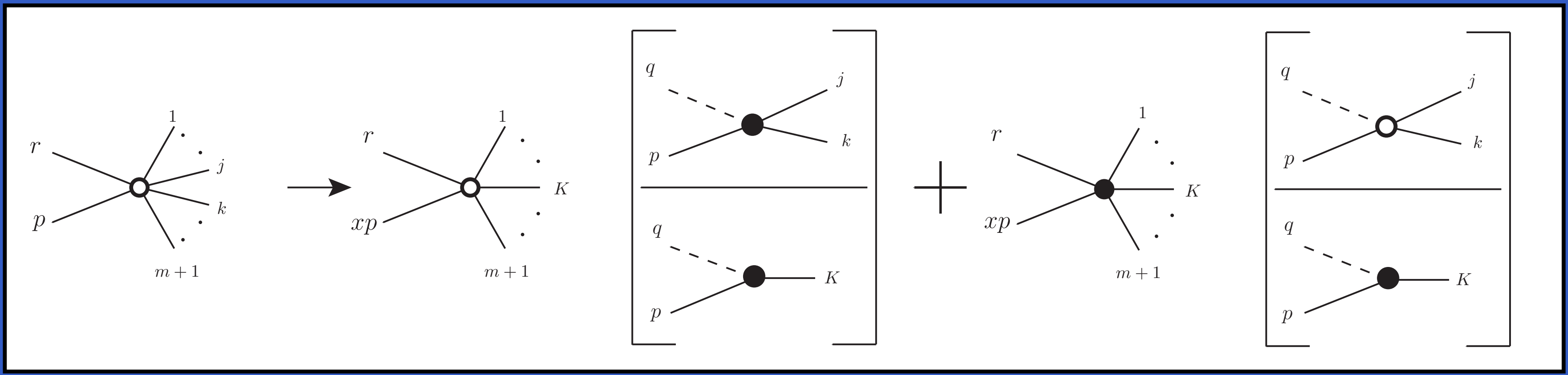
$$d\Phi_{m+2}(k_1, \ldots, k_j, k_k, k_l, \ldots, k_{m+2}; p, r) =$$

$$d\Phi_m(k_1, \ldots, K_L, \ldots, k_{m+2}; xp, r) \frac{Q^2}{2\pi} d\Phi_{X_{i,jkl}}(k_j, k_k, k_l, p, q) \frac{dx}{x}$$

- Again integrated subtraction term can be computed analytically

- 2 $\rightarrow$ 3 particle phase space

I-F NNLO: one-loop real radiation



- Single unresolved limit of 1-loop amplitude:

$$Loop_{m+1} \stackrel{j\ \text{unresolved}}{\longrightarrow} Split_{tree} \times Loop_{m} + Split_{loop} \times Tree_{m}$$

[Z. Bern, L.D. Dixon, D. Dunbar, D. Kosower; S. Catani, M. Grazzini; D. Kosower, P. Uwer]
[Z. Bern, V. Del Duca, W.B. Kilgore, C.R. Schmidt]
[Z. Bern, L.D. Dixon, D. Kosower; S. Badger, E.W.N. Glover]

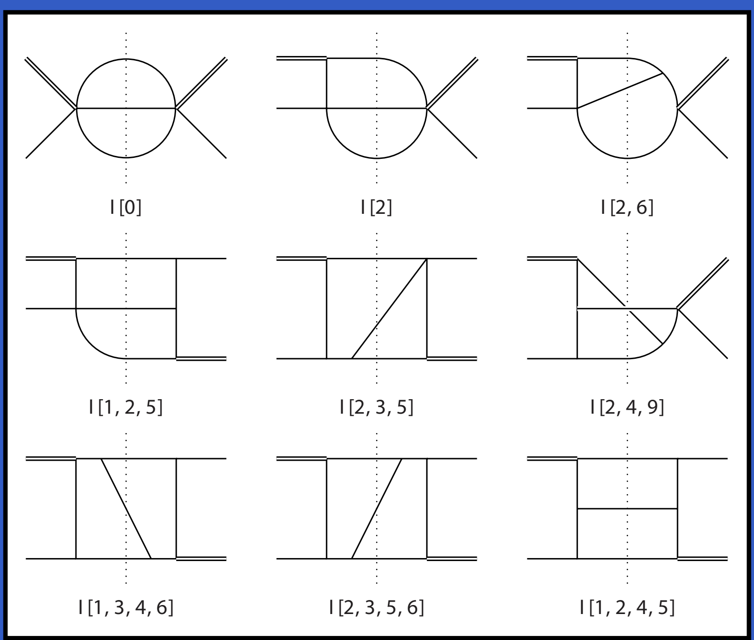
- Thus: $$X^1_{i,jk} = S_{i,jk;I,K} \frac{\left|\mathcal{M}^1_{i,jk}\right|^2}{\left|\mathcal{M}^0_{I,K}\right|^2} - X^0_{i,jk} \frac{\left|\mathcal{M}^1_{I,K}\right|^2}{\left|\mathcal{M}^0_{I,K}\right|^2}$$

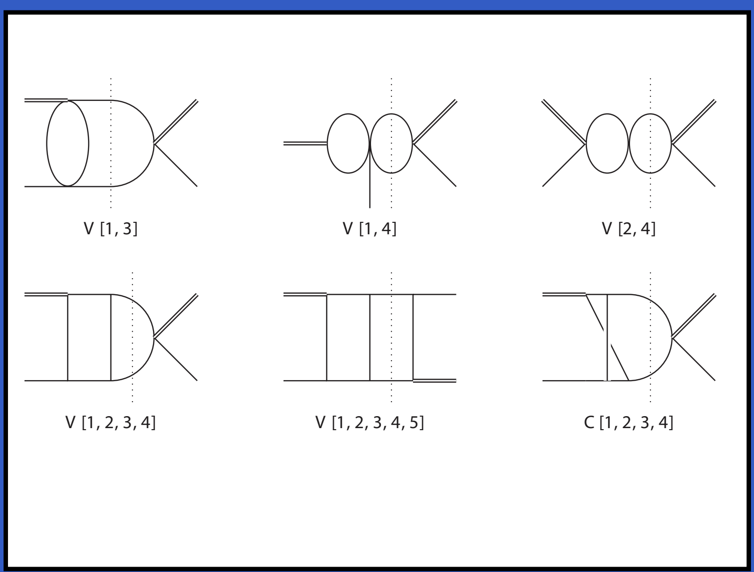
Initial-final antenna functions

Quark initiated	tree level	one loop
quark-quark		
$q \to gq$	$A^0_{q,gq}$	$A^1_{q,gq}$, $\tilde{A}^1_{q,gq}$, $\hat{A}^1_{q,gq}$
$q \to ggq$	$A^0_{q,ggq}$,$\tilde{A}^0_{q,ggq}$	
$q \to q'\bar{q}'q$	$B^0_{q,q'\bar{q}'q}$	
$q' \to q\bar{q}q'$	$B^0_{q',q\bar{q}q'}$	
$q \to q\bar{q}q$	$C^0_{q,q\bar{q}q}$, $C^0_{\bar{q},\bar{q}q\bar{q}}$, $C^0_{\bar{q},q\bar{q}\bar{q}}$	
quark-gluon		
$q \to gg$	$D^0_{q,gg}$	$D^1_{q,gg}$, $\hat{D}^1_{q,gg}$
$q \to ggg$	$D^0_{q,ggg}$	
$q \to q'\bar{q}'$	$E^0_{q,q'\bar{q}'}$	$E^1_{q,q'\bar{q}'}$, $\tilde{E}^1_{q,q'\bar{q}'}$, $\hat{E}^1_{q,q'\bar{q}'}$
$q \to q'\bar{q}'g$	$E^0_{q,q'\bar{q}'g}$, $\tilde{E}^0_{q,q'\bar{q}'g}$	
$q' \to q'q$	$E^0_{q',q'q}$	$E^1_{q',q'q}$, $\tilde{E}^1_{q',q'q}$, $\hat{E}^1_{q',q'q}$
$q' \to q'qg$	$E^0_{q',q'qg}$, $\tilde{E}^0_{q',q'qg}$	
gluon-gluon		
$q \to qg$	$G^0_{q,qg}$	$G^1_{q,qg}$, $\tilde{G}^1_{q,qg}$, $\hat{G}^1_{q,qg}$
$q \to qgg$	$G^0_{q,qgg}$, $\tilde{G}^0_{q,qgg}$	
$q \to qq'\bar{q}'$	$H^0_{q,qq'\bar{q}'}$	

Integrated antenna computation

- Reduce phase space integrals to master integrals
- Integration over inclusive 2- or 3-particle phase space using differential equations in q^2 and $x = -\frac{q^2}{2\,p \cdot q}$
- Boundary condition from explicit computation at $x = 1$
- 9 real and 6 virtual masters:





Computation of master integrals

- Masters computed using differential equations
- Example: ($d = 4 - 2\epsilon$)

$$\begin{cases} x\frac{\partial I[2]}{\partial x} = & -\frac{d-4}{2} I[2] + \frac{3d-8}{2}\left(1+\frac{1}{x-1}\right)\frac{I[0]}{Q^2} \\ Q^2\frac{\partial I[2]}{\partial Q^2} = & (d-4)\, I[2] \qquad \Rightarrow I[2] \propto \left(Q^2\right)^{-2\epsilon} \end{cases}$$

  - boundary condition from explicit computation at $x = 1$
  - putting all together:

$$I[2] = \frac{2^{-7+4\epsilon}}{\pi^{3-2\epsilon}}\frac{\Gamma(1-\epsilon)^3}{\Gamma(3-3\epsilon)\,\Gamma(2-2\epsilon)}\frac{3\epsilon-2}{1-2\epsilon}(1-x)^{1-2\epsilon}x^{\epsilon}(Q^2)^{-2\epsilon}\,{}_2F_1(1-2\epsilon,1-\epsilon,2-2\epsilon,1-x)$$

- For simple masters exact result in $\epsilon \rightarrow$ expanded with HypExp

  [T. Huber, D. Maître]
- For the others expansion up to needed power of ϵ

Check with DIS structure functions

- Completed full set of integrated $2 \to 3$ tree-level and $2 \to 2$ one-loop antennae
- Cross check with NNLO DIS structure functions
  - DIS cross section for photon exchange

$$\frac{d^2\sigma}{dx\,dy} = \frac{2\pi\alpha^2}{Q^4} s \left[\left(1 + (1-y)^2\right) F_2(x,Q^2) - y^2 F_L(x,Q^2) \right]$$

  - Checks $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ type antenna functions
  - At NLO (before mass factorization)

[E. Zijlstra, W. van Nerveen; S. Moch, J. Vermaseren, A. Vogt]

$$\begin{aligned} \frac{1}{C_f}\left(F_{2,q}^{(1)} - \frac{d-1}{d-2}F_{L,q}^{(1)}\right) &= 4\mathcal{A}_{q,gq}^0 + 8\delta\left(1-z\right)F_q^{(1)} \\ \frac{1}{d-2}\left(F_{2,g}^{(1)} - \frac{d-1}{d-2}F_{L,g}^{(1)}\right) &= -4\mathcal{A}_{g,q\bar{q}}^0 \end{aligned}$$

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[E. Zijlstra, W. van Nerveen; S. Moch, J. Vermaseren, A. Vogt]

$$\frac{1}{C_f}\left(F_{2,q}^{(1)} - \frac{d-1}{d-2} F_{L,q}^{(1)}\right) = \ldots (1-z)\, F_q^{(1)}$$

$$\frac{1}{d-2}\left(F_{2,g}^{(1)} - \frac{d-1}{d-2} F_{L,g}^{(1)}\right) = -4\mathcal{A}_{g,q\bar{q}}^{0}$$

Full agreement!

Check with ϕ-DIS structure functions

- Structure functions for a scalar particle coupling only to gluons
- Permits to check integrated $\mathcal{F}$, $\mathcal{G}$ and $\mathcal{H}$-type antenna functions
  - DIS cross section for scalar exchange has only one structure function: $T_{\phi,i}$, for $i = q, g$
  - Some example

$$
\begin{aligned}
T^{(1)}_{\phi,g} &= 2N\,\mathcal{F}^{0}_{g,gg} + 2n_f \mathcal{G}_{g,q\bar{q}} + 4\,\delta\,(1-z)\,F^{(1)}_{g} \\
\frac{1}{C_f\,(1-\epsilon)}\,T^{(1)}_{\phi,q} &= -4N\,\mathcal{G}^{0}_{q,qg} \\
T^{(2)}_{\phi,g}\Big|_{N^2} &= \mathcal{F}^{0}_{g,ggg} + 4\mathcal{F}^{1}_{g,gg} + \delta\,(1-z)\left(8F^{(2)}_{g} + 4F^{(1)}_{g}\right)
\end{aligned}
$$

[S. Moch, G.Soar, J. Vermaseren, A. Vogt]

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  - Some example

$$T^{(1)}_{\phi,g} = 2N\,\mathcal{F}^{0}_{g,gg} + \ldots {}_{,q\bar{q}} + 4\,\delta\,(1-z)\,F^{(1)}_{g}$$

$$\frac{1}{C_f\,(1-\epsilon)}\,T^{(1)}_{\phi,q} = -4N\,\ldots$$

$$\left.T^{(2)}_{\phi,g}\right|_{N^2} = \ldots {}_{gg} + 4\mathcal{F}^{1}_{g,gg} + \delta\,(1-z)\left(8F^{(2)}_{g} + 4F^{(1)}_{g}\right)$$

Full agreement!

[S. Moch, G.Soar, J. Vermaseren, A. Vogt]

Conclusions

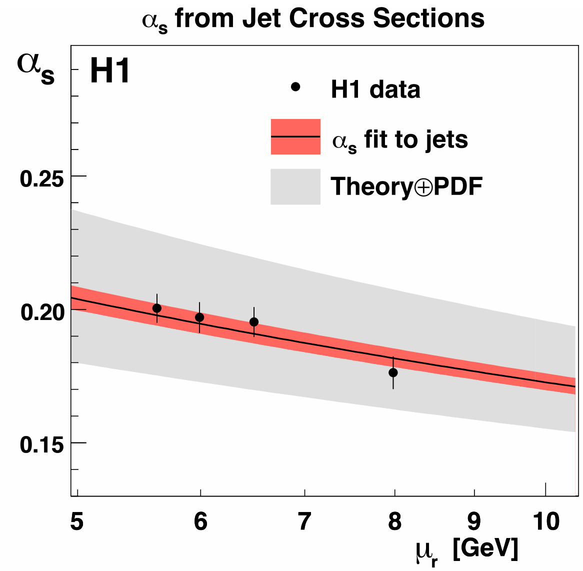
- Antenna subtraction scheme
  - subtraction method based on collecting all IR and collinear radiation between two pair of color connected hard partons
  - final-final case applied successfully at NNLO for $e^+e^- \to$ 3-jet
  - all ingredient for initial-final subtraction now available
  - cross check of initial-final antennae with DIS structure functions is completed
- Potential applications:
  - NNLO DIS (2+1)-jet production
  - contribution to hadron-collider jet production

Outlook:

DIS (2+1)-jet production @ NNLO

- Needed for several reasons:

Determination of α_S



- Simultaneous fit to all 62 measurements of inclusive, 2- and 3-jet cross sections
- result dominated by theoretical uncertainty, missing higher orders

NNLO calculations needed

Roman Kogler, MPI Munich, DIS 2010

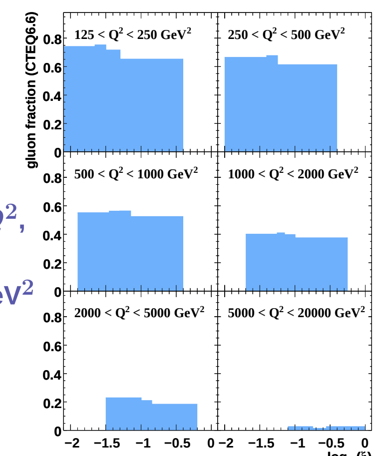
Gluon pdfs

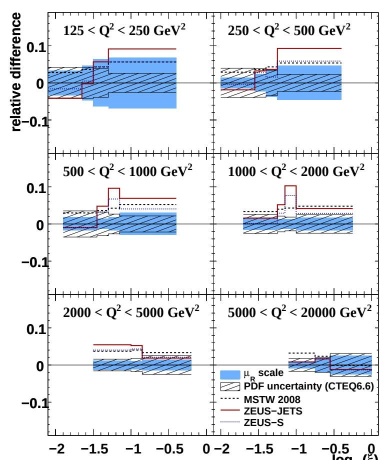
DIS 2010, Florence, Italy — Jet cross sections in NC DIS at HERA — 6

Dijet cross sections: constraints on pPDFs

- Gluon fraction and theoretical uncertainties in the phase-space region of the measurements:

Predicted Gluon fraction:
75% at low Q^2, $> 60\%$ at $Q^2 \sim 500$ GeV^2





Theoretical uncertainties

→ PDF uncertainty large in regions of phase space where the gluon fraction is still sizeable
→ high precision dijet data have the potential to constrain further the proton PDFs when included in the global fits

ZEUS Collab, ZEUS-pub-10-005

April 19-23, 2010 — C Glasman (Universidad Autónoma de Madrid)

Outlook:

DIS (2+1)-jet production @ NNLO

- All ingredients present
  - real matrix elements,
    [K. Hagiwara, D. Zeppenfeld, F. A. Berends, W. Giele, H. Kuijf, N. K. Falck, D. Graudenz, G. Kramer]
  - mixed real-virtual matrix elements,
    [Z. Bern, L. J. Dixon, D. A. Kosower, S. Weinzierl, E. W. N. Glover, D. J. Miller, J. M.Campbell]
  - two loop matrix elements,
    [L. W. Garland, T. Gehrmann, E. W. N. Glover, A. Koukoutsakis, E. Remiddi]
  - subtraction terms.
    [A. Daleo, A. Gehrmann De-Ridder, T. Gehrmann, D. Maître, G. L.]
- Next steps:
  - implementation of a parton level Monte Carlo event generator.

Backup Slides

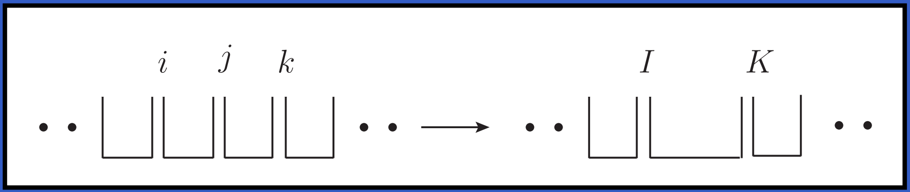
NNLO double real subtraction

- $d\sigma^S_{\rm NNLO}$: double real subtraction $\rightarrow$ different configurations

$d\sigma^S_{\rm NNLO}$ →
- (a) one unresolved parton
- (b) two color-connected unresolved partons
- (c) two almost color-connected unresolved partons
- (d) two color-unconnected unresolved partons

[A. Gehrmann De-Ridder, T. Gehrmann, N. Glover]

(a): one unresolved parton:



- one unresolved parton but the experimental observable selects only m jets,
- three parton antenna function $X^0_{i,jk}$ can be used (like at NLO)

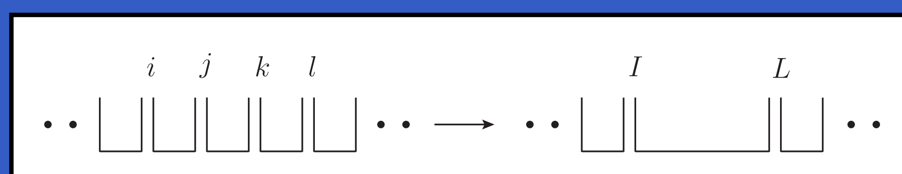
NNLO double real subtraction

- $d\sigma^{S}_{\rm NNLO}$: double real subtraction $\rightarrow$ different configurations

$d\sigma^{S}_{\rm NNLO}$ →
- (a) one unresolved parton
- (b) two color-connected unresolved partons
- (c) two almost color-connected unresolved partons
- (d) two color-unconnected unresolved partons

[A. Gehrmann De-Ridder, T. Gehrmann, N. Glover]

(b): two color-connected unresolved partons:



- four parton antenna function $X^0_{i,jkl}$
- complete set of four parton antennae for i-f configuration is now available

NNLO double real subtraction

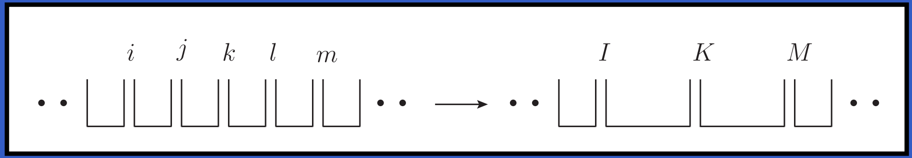
- $d\sigma^{S}_{\mathrm{NNLO}}$: double real subtraction $\rightarrow$ different configurations

$d\sigma^{S}_{\mathrm{NNLO}}$ →

- (a) one unresolved parton
- (b) two color-connected unresolved partons
- (c) two almost color-connected unresolved partons
- (d) two color-unconnected unresolved partons

[A. Gehrmann De-Ridder, T. Gehrmann, N. Glover]

(c): two almost color-connected unresolved partons:



- share a common radiator
- accounted for by products of two tree-level three-parton antennae functions
- distinguish cases where common radiator is in the initial or final configuration

NNLO double real subtraction

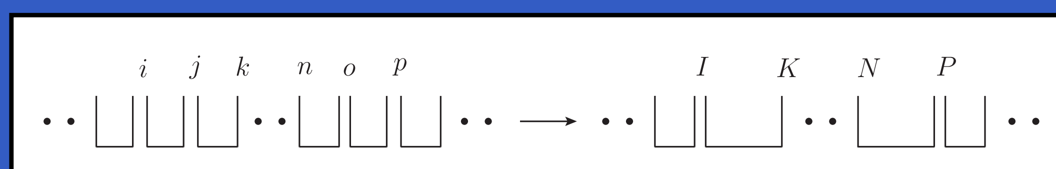
- $d\sigma^S_{\mathrm{NNLO}}$: double real subtraction → different configurations

$d\sigma^S_{\mathrm{NNLO}}$ →

- (a) one unresolved parton
- (b) two color-connected unresolved partons
- (c) two almost color-connected unresolved partons
- (d) two color-unconnected unresolved partons

[A. Gehrmann De-Ridder, T. Gehrmann, N. Glover]

(d): two color-unconnected unresolved partons:



- two well separated partons in the colour chain
- product of independent three-parton antenna functions

NNLO Antenna subtraction

- $d\sigma_{\text{NNLO}}^{VS,1}$: one loop real subtraction $\rightarrow$ several requirements

$d\sigma_{\text{NNLO}}^{VS,1}$ →
- (a) remove explicit IR poles from loop
- (b) subtract single unresolved limits
- (c) remove oversubtracted terms

(a): remove poles from loop integral:

[A. Gehrmann De-Ridder, T. Gehrmann, N. Glover]

- virtual correction has IR poles which have to be removed by means of the real counterpart
- subtraction term contains integrated antenna $\mathcal{X}_{i,jk}^{0}$

NNLO Antenna subtraction

- $d\sigma^{VS,1}_{\text{NNLO}}$: one loop real subtraction $\rightarrow$ several requirements

$d\sigma^{VS,1}_{\text{NNLO}}$

(a) remove explicit IR poles from loop

(b) subtract single unresolved limits

(c) remove oversubtracted terms

[A. Gehrmann De-Ridder, T. Gehrmann, N. Glover]

(b): subtraction of single unresolved limits:

- subtraction of singular configurations originating when the real radiation correction to the one loop amplitude becomes soft or collinear.
- subtraction term is a combination of three-parton tree-level $X^0_{i,jk}$ and three parton one-loop $X^1_{i,jk}$ antenna functions.

NNLO Antenna subtraction

- $d\sigma^{VS,1}_{\mathrm{NNLO}}$: one loop real subtraction $\rightarrow$ several requirements

$d\sigma^{VS,1}_{\mathrm{NNLO}}$

(a) remove explicit IR poles from loop

(b) subtract single unresolved limits

(c) remove oversubtracted terms

(c): remove oversubtracted terms:

[A. Gehrmann De-Ridder, T. Gehrmann, N. Glover]

- remove terms which are common to both previous contributions and are oversubtracted
- subtraction term contains initial-final and final-final antenna