Calculation techniques for QCD final states at forward rapidity

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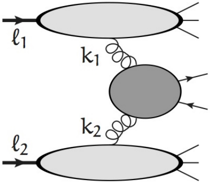
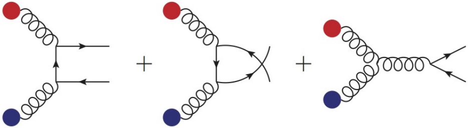
High-Energy-Factorisation

High-Energy-factorisation *(Catani,Ciafaloni,Hautmann, 1991 / Collins,Ellis, 1991)*





$$\sigma_{h_1,h_2 \to q\bar{q}} = \int d^2k_{1\perp}\, d^2k_{2\perp}\, dx_1\, dx_2\, \frac{dx_1}{x_1}\, \frac{dx_2}{x_2}\, f_g(x_1, k_{1\perp})\, f_g(x_2, k_{2\perp})\, \hat{\sigma}_{gg}\left(\frac{m^2}{x_1 x_2 s}, \frac{k_{1\perp}}{m}, \frac{k_{2\perp}}{m}\right)$$

where the f_g's are the gluon densities, obeying BFKL, BK, CCFM evolution equations.

Non negligible transverse momentum is associated to small x physics.

Momentum parameterization:

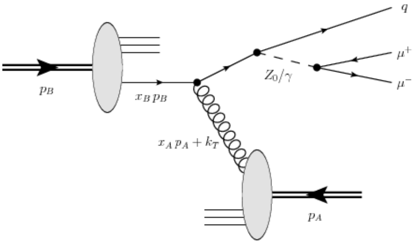
$$k_1^\mu = x_1\, l_1^\mu + k_{1\perp}^\mu \quad , \quad k_2^\mu = x_2\, l_2^\mu + k_{2\perp}^\mu$$

$$l_i^2 = 0, \quad l_i \cdot k_i = 0, \quad k_i^2 = -k_{i\perp}^2, \quad i = 1, 2$$

Hybrid High-Energy-Factorisation: forward final states

Hybrid HEF for forward jet production:
only one of the partons' momenta with non negligible transverse component

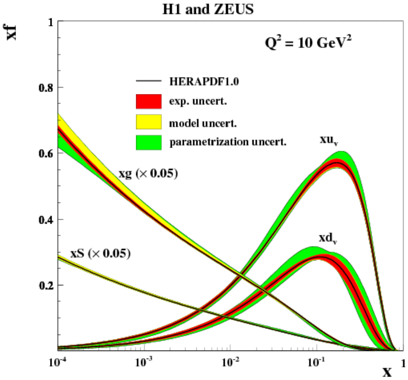
Deak, Hautmann, Jung, Kutak (2010, 2011)
van Hameren, Kotko, Kutak (2015)

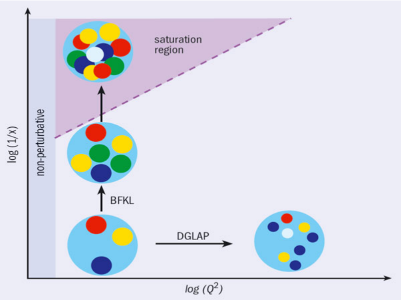


Applications:
- Production of forward dijets initiated with gluons : $gg^* \to gg$
- Production of forward dijets initiated with quarks : $q\bar{q}^* \to gg$
- Pilute-dense hadronic collisions in TMD factorization (Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren, 2015)

Small x-physics: GDF growth for small x

Growth of the gluon distribution function for small x
($\Rightarrow$ Mallot, Bradamante, Deshpande)
Non linear effects expected: see BK equation !





The hard-core of scattering: amplitudes !

WANTED:

Tree-level color-ordered partial amplitudes for (possibly) any number of legs
Kinematics and color are factorised like

$$\mathcal{M}_n = g^{n-2} \sum_{\sigma \in S_n/Z_n} \mathrm{Tr}(T_{\sigma(1)} \dots T_{\sigma(n)})\, \mathcal{A}(g_{\sigma(1)}, \dots, g_{\sigma(n)})$$

PROBLEM:

- Partonic processes must be described by gauge invariant amplitudes
- with ordinary Feynman rules gauge invariant scattering amplitudes only for all particles on-shell
- $\Rightarrow$ something else must be devised !

Is there a
general & efficient method
to compute such gauge-invariant amplitudes **analytically** ?

Formal interlude: Weyl spinors

In the high energy limit $\Rightarrow$ **massless particles** $\Rightarrow$ Weyl basis for spinors.

If $p^2 = 0$, it can be cast in the Pauli matrices language,

$$|p] = \begin{pmatrix} L(p) \\ \mathbf{0} \end{pmatrix} \qquad L(p) = \frac{1}{\sqrt{|p^0 + p^3|}} \begin{pmatrix} -p^1 + i\,p^2 \\ p^0 + p^3 \end{pmatrix}$$

$$|p\rangle = \begin{pmatrix} \mathbf{0} \\ R(p) \end{pmatrix} \qquad R(p) = \frac{\sqrt{|p^0 + p^3|}}{p^0 + p^3} \begin{pmatrix} p^0 + p^3 \\ p^1 + i\,p^2 \end{pmatrix}$$

and the charge-conjugated spinors

$$[p| = \left((\mathcal{E} L(p))^T \,, \mathbf{0} \right) \qquad \langle p| = \left(\mathbf{0}\ (\mathcal{E}^T R(p))^T \right) \qquad \text{where} \quad \mathcal{E} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

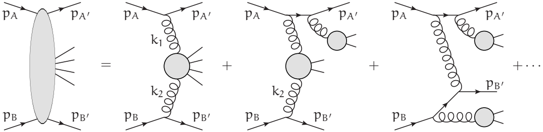
$$p \cong p^\mu\,\sigma_\mu = \begin{pmatrix} p^0 - p^3 & -p^1 + i\,p^2 \\ -p^1 - i\,p^2 & p^0 + p^3 \end{pmatrix} = |p]\langle p|$$

Prescription for off-shell gluons

ONE IDEA:

on-shell amplitudes are gauge invariant, so off-shell gauge-invariant amplitudes could be got by embedding them into on-shell processes...

...first result...: 1) For off-shell gluons: represent g^* as coming from a $\bar{q}qg$ vertex, with the quarks taken to be on-shell



- embed the scattering of the off-shell gluons in the scattering of two quark pairs carrying momenta $p_A^\mu = k_1^\mu$, $p_B^\mu = k_2^\mu$, $p_{A'}^\mu = 0$, $p_{B'}^\mu = 0$
- Assign the spinors $|p_1\rangle, |p_1]$ to the A-quark and the propagator $\frac{i\,\not{p}_1}{p_1 \cdot k}$ instead of $\frac{i\not{k}}{k^2}$ to the propagators of the A-quark carrying momentum k; the same goes for the B-quark line.
- multiply the amplitude by $g_s^{-1} x_1 \sqrt{-2\,k_{1\perp}^2} \times g_s^{-1} x_2 \sqrt{-2\,k_{2\perp}^2}$.
- ordinary Feynman rules must be used everywhere else and the procedure holds for any number of off-shell gluons.

K. Kutak, P. Kotko, A. van Hameren, JHEP 1301 (2013) 078

Prescription for off-shell gluons: derivation, 1

Auxiliary vectors (complex in general):
$$\begin{cases} p_3^\mu = \frac{1}{2}\langle p_2|\gamma^\mu|p_1] \\ p_4^\mu = \frac{1}{2}\langle p_1|\gamma^\mu|p_2] \\ p_1^2 = p_2^2 = p_3^2 = p_4^2 = 0 \\ p_{1,2}\cdot p_{3,4} = 0\,, \quad p_1\cdot p_2 = -p_3\cdot p_4 \end{cases}$$

Auxiliary momenta:
$$\begin{cases} p_A^\mu = (\Lambda + x_1)p_1^\mu - \frac{p_4\cdot k_{1\perp}}{p1\cdot p_2}p_3^\mu\,, \quad p_{A'}^\mu = \Lambda p_1^\mu + \frac{p_3\cdot k_{1\perp}}{p1\cdot p_2}p_4^\mu \\ p_B^\mu = (\Lambda + x_2)p_2^\mu - \frac{p_3\cdot k_{2\perp}}{p1\cdot p_2}p_4^\mu\,, \quad p_{B'}^\mu = \Lambda p_2^\mu + \frac{p_4\cdot k_{2\perp}}{p1\cdot p_2}p_3^\mu \end{cases}$$

For any Λ:
$$\begin{cases} p_A^\mu - p_{A'}^\mu = x_1\,p_1^\mu + k_{1\perp}^\mu \\ p_B^\mu - p_{B'}^\mu = x_2\,p_2^\mu + k_{2\perp}^\mu \\ p_A^2 = p_{A'}^2 = p_B^2 = p_{B'}^2 = 0 \end{cases}$$

Prescription for off-shell gluons: derivation, 2

Momentum flowing through a propagator of an auxiliary quark line:

$$k^\mu = (\Lambda + x_k) p_1^\mu + y_k\, p_2^\mu + k_\perp$$

Final step: remove complex components taking the $\Lambda \to \infty$ limit.

$$\frac{\not{k}}{k^2} = \frac{(\Lambda + x_k)\not{p}_1 + y_k\, \not{p}_2 + \not{k}}{2(\Lambda + x_k) y_k\, p_1 \cdot p_2 + k_\perp^2} \xrightarrow{\Lambda \to \infty} \frac{\not{p}_1}{2\, y_k\, p_1 \cdot p_2} = \frac{\not{p}_1}{2 p_1 \cdot k}$$

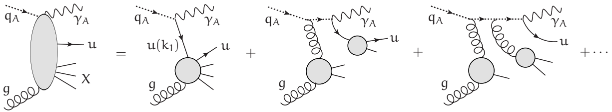
...and the factor $x_1 \sqrt{-k_\perp^2/2}$ is to match the collinear limit.

In agreement with other approaches (e.g. Lipatov's effective action)

Prescription for off-shell quarks

... and second result:

2) for off-shell quarks: represent q^* as coming from a $\gamma\bar{q}q$ vertex, with a 0 momentum and $\bar{q}$ on shell (and vice-versa)



- embed the scattering of the quark with whatever set of particles in the scattering of an auxiliary quark-photon pair, q_A and γ_A carrying momenta $p^\mu_{q_A} = k^\mu_1$, $p^\mu_{\gamma_A} = 0$
- Let q_A-propagators of momentum k be $\frac{i\not{p}_1}{p_1 \cdot k}$ and assign the spinors $|p_1\rangle, |p_1]$ to the A-quark.
- Assign the polarization vectors $\epsilon^\mu_+ = \frac{\langle q|\gamma^\mu|p_1]}{\sqrt{2}\langle p_1 q\rangle}$, $\epsilon^\mu_- = \frac{\langle p_1|\gamma^\mu|q]}{\sqrt{2}[p_1 q]}$ to the auxiliary photon, with q a light-like auxiliary momentum.
- Multiply the amplitude by $x_1\sqrt{-k^2_{1\perp}/2}$ and use ordinary Feynman rules everywhere else.

K. Kutak, T. Salwa, A. van Hameren, Phys.Lett. B727 (2013) 226-233

Reminds us of BCFW...

The analytical results derived with the mentioned trick are strikingly similar to the ones obtained in the on-shell case via, for example, the BCFW recursion relation (which does not require auxiliary particles).

Computing scattering amplitudes in Yang-Mills theories via ordinary Feynman diagrams: soon overwhelming !

Number of Feynman diagrams at tree level on-shell:

# of gluons	4	5	6	7	8	9	10
# of diagrams	4	25	220	2485	34300	559405	10525900

And there are even more with the proposed method for amplitudes with off-shell particles due to the gauge-restoring terms.

A method to efficiently compute helicity amplitudes: **BCFW recursion relation**

Britto, Cachazo, Feng, Nucl.Phys. B715 (2005) 499-522

BCFW recursion relation

Two very simple ideas for tree level amplitudes:

1. Cauchy's residue theorem: if the amplitude is formally treated as a function of a complex variable z and if it is rational and vanishes for $z \to \infty$, then the integral extended to an infinite contour enclosing all poles vanishes

$$\lim_{z\to\infty} \mathcal{A}(z) = 0 \Rightarrow \frac{1}{2\pi i} \oint dz \, \frac{\mathcal{A}(z)}{z} = 0$$

   implying that the value at $z = 0$ (physical amplitude) can be determined as a sum of the residues at the poles:

$$\mathcal{A}(0) = -\sum_i \frac{\lim_{z\to z_i}[(z - z_i)\, \mathcal{A}(z)]}{z_i}$$

   where z_i is the location of the i-th pole
2. Unitarity: Poles in Yang-Mills tree level amplitudes can only be due to gluon propagators dividing the n-point amplitude into two on-shell sub-amplitudes with $k+1$ and $n-k+1$ gluons $\Rightarrow$ it is all about finding the proper way to "complexify" an amplitude.

To properly "complexify" $\mathcal{A}$: for helicities $(h_1, h_n) = (-,+)$ (no loss of generality...)

$$\begin{array}{ccl} |1] & \rightarrow & |\hat{1}] \equiv |1] - z\,|n] \Rightarrow p_1 \rightarrow \hat{p}_1 = |1]\langle 1| - z|1]\langle n| \\ |n\rangle & \rightarrow & |\hat{n}\rangle \equiv |n\rangle + z|1\rangle \Rightarrow p_n \rightarrow \hat{p}_n = |n]\langle n| + z|1]\langle n| \end{array}$$

With such a choice

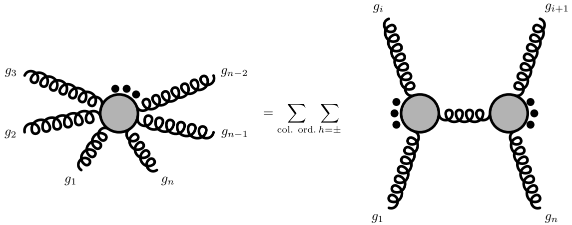
- On-shellness, gauge invariance and momentum conservation preserved throughout.
- then, in order to have $\lim_{z\rightarrow\infty} \mathcal{A}(z) = 0$, either shift $(+,+)$ or $(-,-)$, relying on *Cachazo,Svrcek and Witten JHEP 0409 (2004) 006*
- or shift always $(-,+)$ and skip twistor-inspired proofs right away, *Britto, Cachazo, Feng, Witten, Phys.Rev.Lett. 94 (2005) 181602*.

The result is an amazingly simple recursive relation:

any tree-level color-ordered amplitude is the sum of residues of the poles it develops when it is made dependent on a complex variable as above.
Such residues are simply products of color-ordered lower-point amplitudes evaluated at the pole times an intermediate propagator.
Shifted particles are always on opposite sides of the propagator.

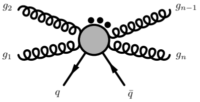
$$\mathcal{A}(g_1,\ldots,g_n) = \sum_{i=2}^{n-2} \sum_{h=+,-} \mathcal{A}(g_1,\ldots,g_i,\hat{P}^h)\,\frac{1}{(p_1+\cdots+p_i)^2}\,\mathcal{A}(-\hat{P}^{-h},g_{i+1},\ldots,g_n)$$

$z_i = \dfrac{(p_1+\cdots+p_i)^2}{[1|p_1+\cdots+p_i|n\rangle}$ location of the pole corresponding for the "i-th" partition



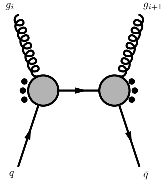
The inclusion of fermions and MHV amplitudes

The BCFW recursion was promptly extended to Yang-Mills theories with fermions:
M. Luo, C. Wen, JHEP 0503 (2005) 004

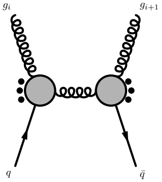


$\sim$

$\sum_{\text{col. ord.}} \sum_{h=\pm}$



$+$



A couple of MHV amplitudes:

$$\mathcal{A}(g_1^+, g_2^+, \ldots, g_i^-, \ldots, g_j^-, \ldots, g_n^+) = \frac{\langle ij\rangle^4}{\langle 12\rangle\langle 23\rangle \ldots \langle n-1\, n\rangle\langle n1\rangle}$$

$$\mathcal{A}(q^-, g_1^-, g_2^+, \ldots, g_n^+, \bar{q}^+) = \frac{\langle q1\rangle^3\langle \bar{q}1\rangle}{\langle \bar{q}q\rangle\langle q1\rangle\langle 12\rangle \ldots \langle n\bar{q}\rangle}$$

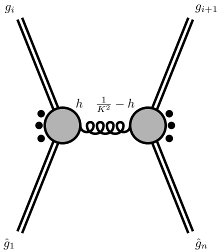
It is natural to ask whether something like a BCFW recursion relation exists with off-shell particles. For off shell, gluons, the answer was first found in *A. van Hameren, JHEP 1407 (2014) 138*

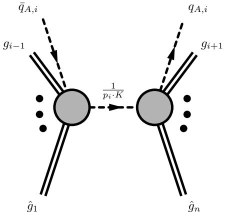
$$\mathcal{A}(0) = \sum_{s=g,f} \left(\sum_{p} \sum_{h=+,-} \mathrm{A}^{s}_{p,h} + \sum_{i} \mathrm{B}^{s}_{i} + \mathrm{C}^{s} + \mathrm{D}^{s} \right) ,$$

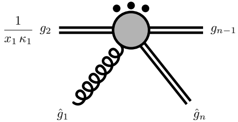
- $\mathrm{A}^{g/f}_{p,h}$ are due to the poles which appear in the original BCFW recursion for on-shell amplitudes. The pole appears because one of the intermediate virtual gluon, whose shifted momentum squared $K^2(z)$ goes on-shell.
- $\mathrm{B}^{g/f}_{i}$ are due to the poles appearing in the propagator of auxiliary eikonal quarks. This means $p_i \cdot \hat{K}(z) = 0$ for $z = -\frac{2\, p_i \cdot K}{2\, p_i \cdot e}$. $\hat{K}$ is the momentum flowing through the eikonal propagator.
- $\mathrm{C}^{g/f}$ and $\mathrm{D}^{g/f}$ show up us the first/last shifted particle is off-shell and their external propagator develops a pole.
  The external propagator for off-shell particles is necessary to ensure

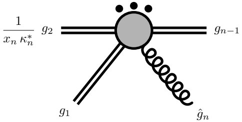
$$\lim_{z \to \infty} \mathcal{A}(z) = 0$$

Classification of poles in the gluon case

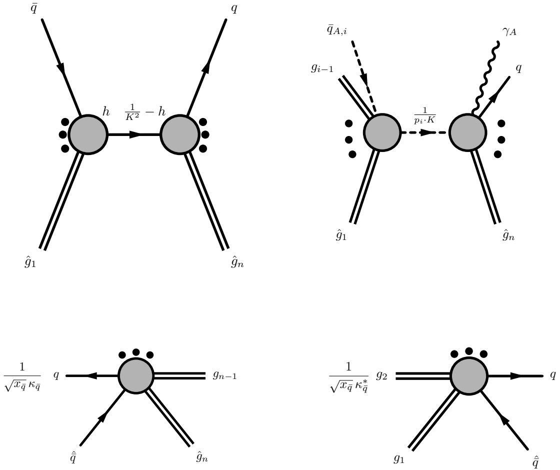








Classification of poles in the fermion case



Some simple amplitudes

Transverse momentum parameterization:

$$\begin{cases} k^{\mu}_{T\,i} = -\frac{\kappa_i}{2}\,\frac{\langle p_i|\gamma^\mu|q]}{[p_i q]} - \frac{\kappa_i^*}{2}\,\frac{\langle q|\gamma^\mu|p_i]}{\langle q p_i\rangle} \\ \kappa_i \equiv \frac{\langle q|\not{k}_i|p_i]}{\langle q p_i\rangle} \qquad \kappa_i^* \equiv \frac{\langle p_i|\not{k}_i|q]}{[p_i q]} \\ q^2 = 0 \qquad \text{auxiliary momentum} \end{cases}$$

Subleading contribution: this is zero in the on-shell case !

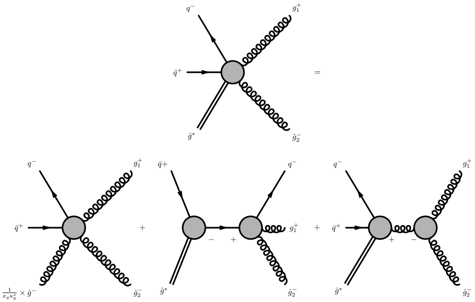
$$\mathcal{A}(g_1^+, g_2^+, \ldots, g_{n-1}^+, \bar{q}, q, g_n^+) = \frac{\langle \bar{q} q\rangle^3}{\langle 12\rangle\langle 23\rangle \ldots \langle \bar{q} q\rangle\langle q n\rangle\langle n1\rangle}$$

Structure of MHV amplitudes

$$\mathcal{A}(g_1^+, g_2^+, \ldots, g_{n-1}^+, \bar{q}^*, q^+, g_n^-) = \frac{1}{\kappa_{\bar{q}}^*}\,\frac{\langle \bar{q} n\rangle^3\langle q n\rangle}{\langle 12\rangle\langle 23\rangle \ldots \langle \bar{q} q\rangle\langle q n\rangle\langle n1\rangle}$$

$$\mathcal{A}(g^*, \bar{q}^+, q^-, g_1^+, g_2^+, \ldots, g_n^+) = \frac{1}{\kappa_g^*}\,\frac{\langle g q\rangle^3\langle g \bar{q}\rangle}{\langle g \bar{q}\rangle\langle \bar{q} q\rangle \ldots \langle n-1|n\rangle\langle n g\rangle}$$

But not everything is so smooth...



$$
\begin{aligned}
\mathcal{A}(g^*,\bar{q}^+,q^-,g_1^+,g_2^-) \quad &= \quad \frac{1}{\kappa_g^*}\frac{[\bar{q}1]^3\langle 2g\rangle^4}{[\bar{q}q]\langle g|\not{p}_2+\not{k}_g|1]\langle 2|\not{k}_g\;(\not{k}_g+\not{p}_2)\,|g]\langle 2|\not{k}_g|\bar{q}]} \\
&+\frac{1}{\kappa_g}\frac{1}{(k_g+p_{\bar{q}})^2}\frac{[g\bar{q}]^2\langle 2q\rangle^3\langle 2|\not{k}_g+\not{p}_{\bar{q}}|g]}{\langle 1q\rangle\langle 12\rangle\left\{(k_g+p_{\bar{q}})^2[\bar{q}g]\langle 2q\rangle-\langle 2|\not{k}_g+\not{p}_{\bar{q}}|g]\langle q|\not{k}_g|\bar{q}]\right\}} \\
&+\frac{\langle gq\rangle^3[g1]^4}{\langle\bar{q}q\rangle[12][g2]\langle q|\not{p}_1+\not{p}_2|g]\langle g|\not{p}_1+\not{p}_2|g]\langle g|\not{k}_g+\not{p}_2|1]}
\end{aligned}
$$

General outline of the results

- It is necessary to understand which shifts are legitimate in the off-shell case, i.e. for which choices $\lim_{z\to\infty} \mathcal{A}(z) = 0$. Full classification of the possible shifts.
- All 4-point amplitudes are always MHV, just as in the on-shell case.
- First calculation of 5-point amplitudes in the literature
- Some amplitudes absent in the on-shell case do not vanish here
- **Cross-checked (numerically) !** Tests were performed cross checked with a program implementing **Berends-Giele** recursion relation, *A. van Hameren, M. Bury, arXiv:1503.08612*

Thorough technical discussion is found in

A. van Hameren, M.S. JHEP 1507 (2015) 010 .

Conclusions and perspectives

- High-energy factorisation requires gauge invariant scattering amplitudes with off-shell partons.
- BCFW construction was extended to Yang Mills with fermions with off-shell particles. This implies identifying a new set of poles in the auxiliary complex variable. To obtain the scattering amplitudes with more off-shel partons...just some more work of the same kind.
- we are working on automation...
- Next natural step in phenomenology: applications of these results to multi-jet production in HEF factorisation. 4 jets production in k_T-factorisation is first.
- Want to go for loops: next standard for on-shell QCD will be NNLO. For loops there is no direct analogous of BCFW. In that case it would be useful to extend Berends-Giele to NNLO starting from *van Hameren, JHEP 0907 (2009) 088*

The end

THANK YOU FOR YOUR ATTENTION