NNLO QCD predictions for the LHC with antenna subtraction

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PARTICLEFACE WG1: Meeting
WorkStop/ThinkStart 3.0: paving the way to alternative NNLO strategies
Florence, November 4, 2019

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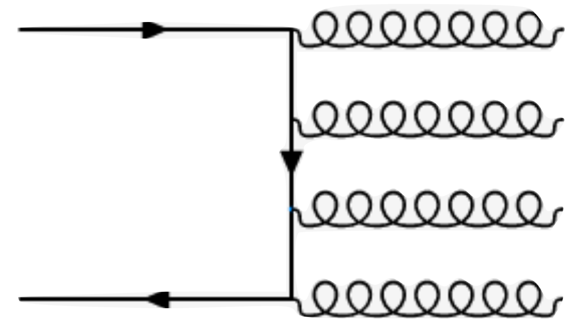
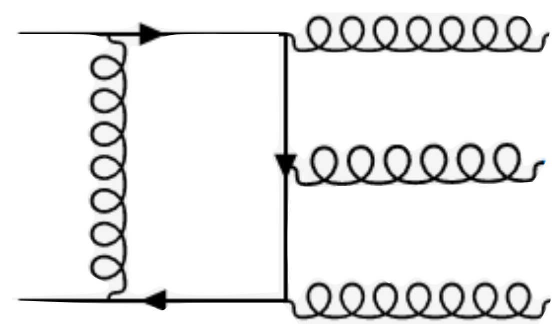
Anatomy of an NNLO calculation

$$d\hat{\sigma}_{NNLO} = \int_{d\Phi_4} d\hat{\sigma}^{RR}_{NNLO}$$



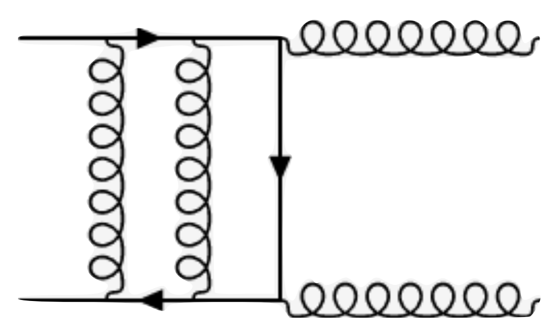
- double-unresolved
- single-unresolved

$$+ \int_{d\Phi_3} d\hat{\sigma}^{RV}_{NNLO}$$



- single-unresolved
- $1/\varepsilon^2$; $1/\varepsilon$

$$+ \int_{d\Phi_2} d\hat{\sigma}^{VV}_{NNLO}$$



- $1/\varepsilon^4$; $1/\varepsilon^3$; $1/\varepsilon^2$; $1/\varepsilon$;

Assume all matrix elements are available

- Tree level matrix elements (RR) 2→ n+2
- One-loop matrix elements (RV) 2→ n+1

} Form NLO correction to 2->n+1

- Two loop matrix elements (VV) 2→ n

Infrared singularities: real radiation

NLO

- single collinear: p_a // p_b
- single soft: $E_a \rightarrow 0$

NNLO

- Triple collinear: p_a // p_b // p_c
- Double single collinear: p_a // p_b ; p_c // p_d
- Soft/collinear: $E_a \rightarrow 0$, p_b // p_c
- Double soft: $E_a \rightarrow 0$, $E_b \rightarrow 0$
- One-loop virtual correction with NLO singularities

NNLO antenna subtraction

$$
\begin{aligned}
\mathrm{d}\hat{\sigma}_{NNLO} &= \int_{\mathrm{d}\Phi_4}\left(\mathrm{d}\hat{\sigma}^{RR}_{NNLO} - \mathrm{d}\hat{\sigma}^{S}_{NNLO}\right)\\
&+ \int_{\mathrm{d}\Phi_3}\left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{T}_{NNLO}\right)\\
&+ \int_{\mathrm{d}\Phi_2}\left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO} - \mathrm{d}\hat{\sigma}^{U}_{NNLO}\right)
\end{aligned}
$$

$\mathrm{d}\hat{\sigma}^{S}_{NNLO}$ $\mathrm{d}\hat{\sigma}^{T}_{NNLO}$

- mimic RR,RV in unresolved limits

$\mathrm{d}\hat{\sigma}^{T}_{NNLO}$ $\mathrm{d}\hat{\sigma}^{U}_{NNLO}$

- analytically cancel the poles in RV and VV matrix elements

- NNLO cross section with each line finite and integrable in d=4 dimensions

Implementation in parton-level event generator

- Generate particle momenta for (n), (n+1), (n+2)
- Reconstruct observable
- Weight with squared matrix elements
- Subtract/add real radiation singularities

Colour ordering

- QCD amplitudes in colour basis

All gluon

$$\mathcal{A}_n^{\text{tree}}(\{k_i, \lambda_i, a_i\}) = g^{n-2} \sum_{\sigma \in S_n/Z_n} \text{Tr}\left(T^{a_{\sigma(1)}} \cdots T^{a_{\sigma(n)}}\right) A_n^{\text{tree}}(\sigma(1^{\lambda_1}), \ldots, \sigma(n^{\lambda_n}))$$

Quark pair plus gluons

$$\mathcal{A}_n^{\text{tree}} = g^{n-2} \sum_{\sigma \in S_{n-2}} \left(T^{a_{\sigma(3)}} \cdots T^{a_{\sigma(n)}}\right)_{i_2}^{\bar{\jmath}_1} A_n^{\text{tree}}(1_{\bar{q}}^{\lambda_1}, 2_q^{\lambda_2}, \sigma(3^{\lambda_3}), \ldots, \sigma(n^{\lambda_n}))$$

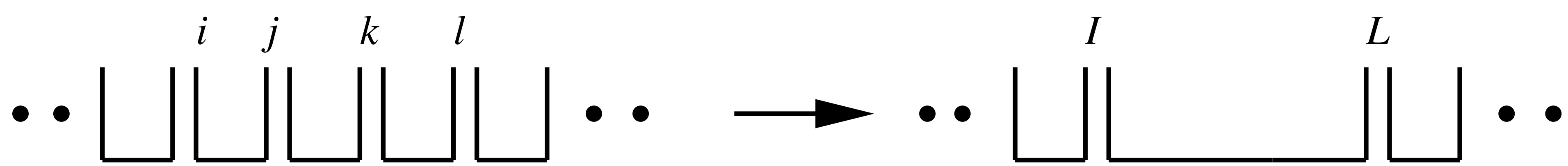
- Real radiation infrared singularities only between colour adjacent partons

- Well defined patterns from colour-connections

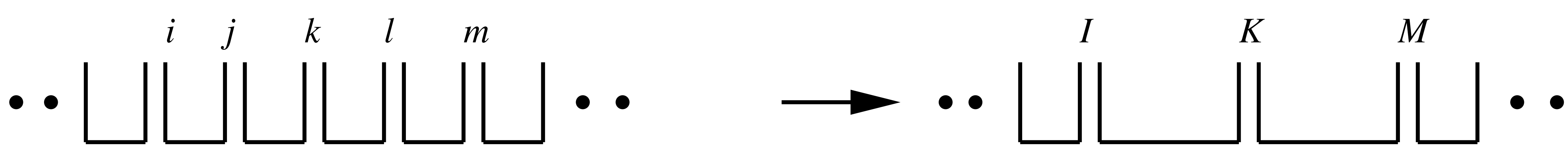
Antenna subtraction at NNLO (RR)

$$\mathrm{d}\sigma^{S}_{NNLO} = \mathrm{d}\sigma^{S,a}_{NNLO} + \mathrm{d}\sigma^{S,b}_{NNLO} + \mathrm{d}\sigma^{S,c}_{NNLO} + \mathrm{d}\sigma^{S,d}_{NNLO} + \mathrm{d}\sigma^{S,e}_{NNLO}$$

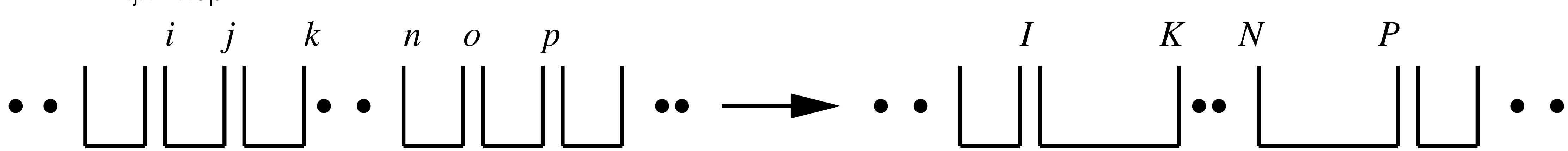
- (a) one unresolved parton → three parton antenna function X_{ijk}
- (b) two colour-connected unresolved partons → four parton antenna function X_{ijkl}



- (c) two almost colour connected unresolved partons → strongly ordered product of non-independent three parton antenna functions $X_{ijk}X_{Klm}$, $X_{klm}X_{ijK}$

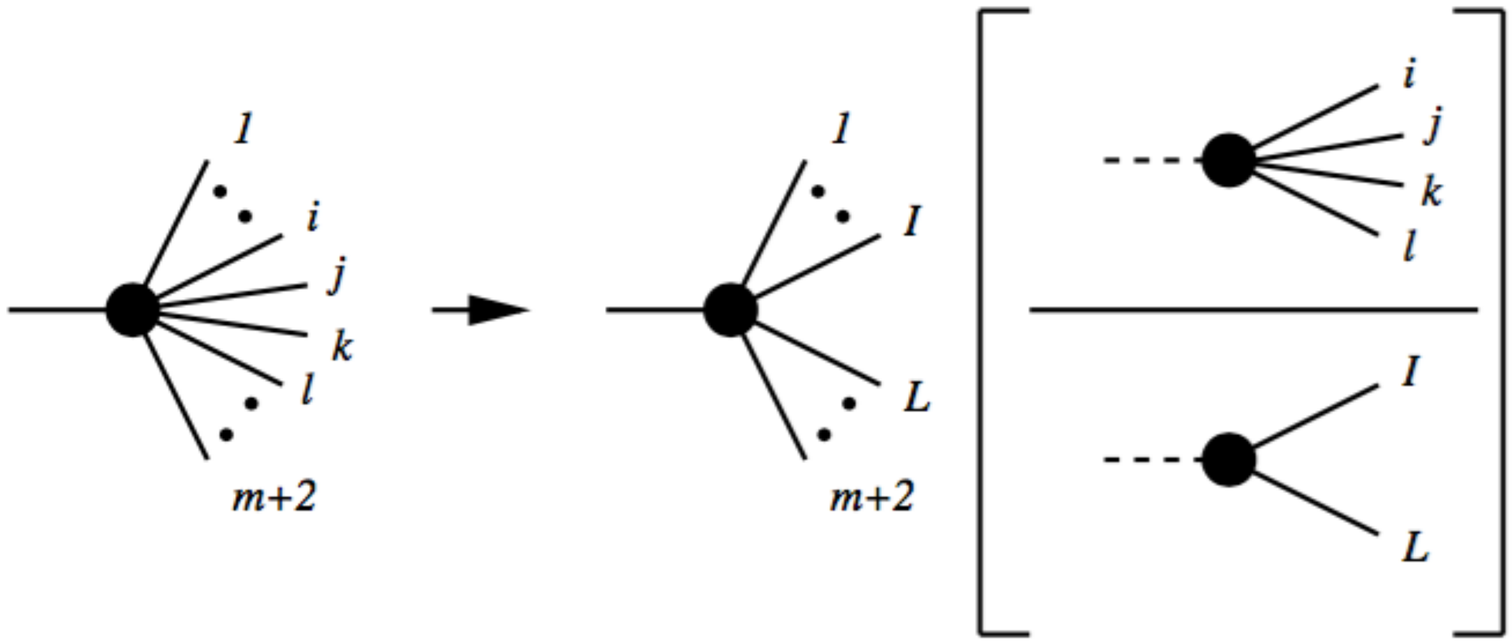


- (d) two colour unconnected unresolved partons → product of independent three parton antenna functions $X_{ijk}X_{nop}$



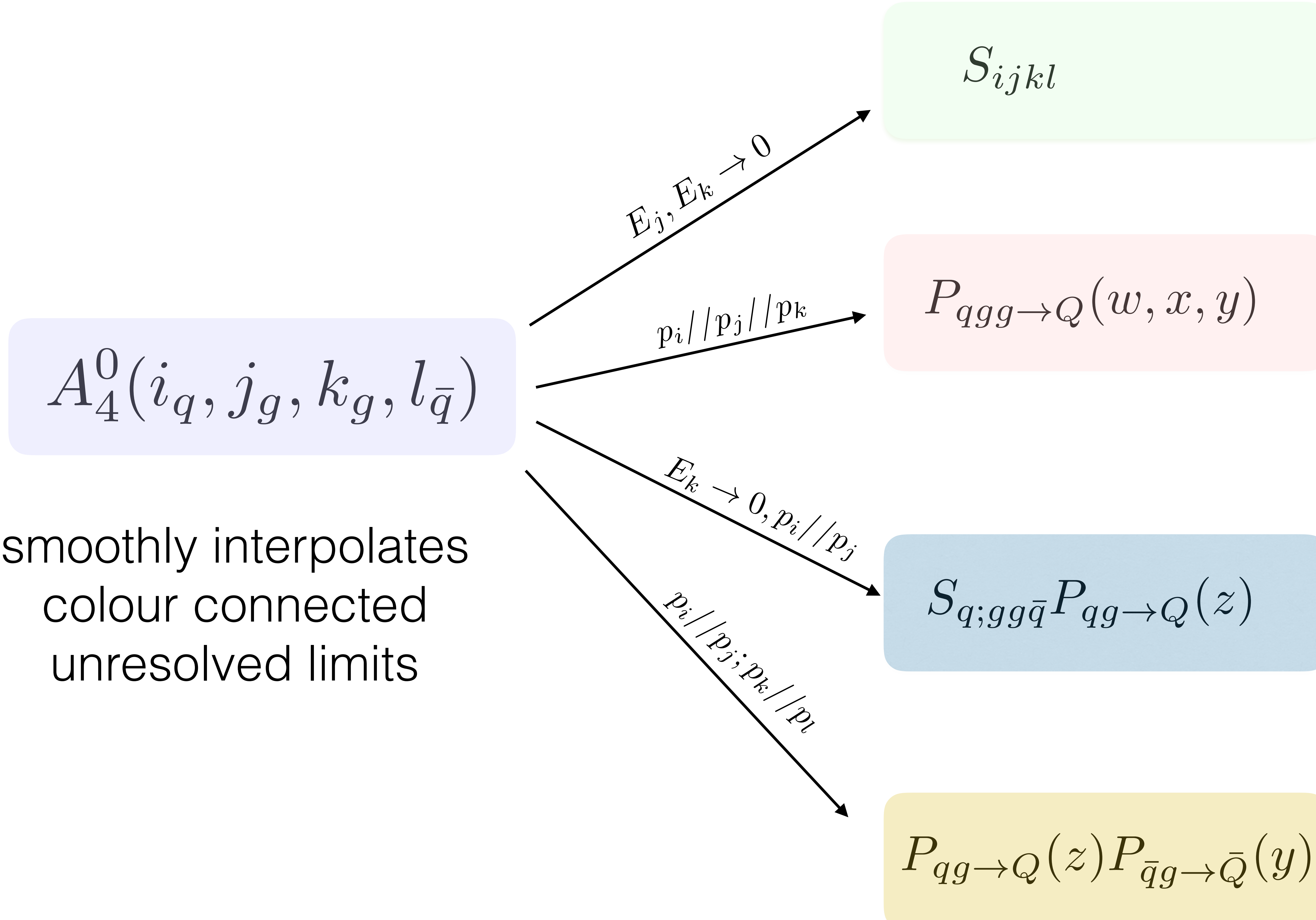
- (e) subtracts large angle soft radiation → soft factor S_{ajc}

Two colour connected partons



Four-parton antenna function

$$
\begin{aligned}
\mathrm{d}\sigma^{S,b}_{NNLO} &= \mathcal{N} \sum_{m+2} \mathrm{d}\Phi_{m+2}(p_1,\ldots,p_{m+2};q)\frac{1}{S_{m+2}} \\
&\times \left[\sum_{jk} \left(X^0_{ijkl} - X^0_{ijk}X^0_{IKl} - X^0_{jkl}X^0_{iJL} \right) \right. \\
&\times \left. |\mathcal{M}_m(p_1,\ldots,\tilde{p}_I,\tilde{p}_L,\ldots,p_{m+2})|^2 \, J^{(m)}_m(p_1,\ldots,\tilde{p}_I,\tilde{p}_L,\ldots,p_{m+2}) \right],
\end{aligned}
$$



smoothly interpolates
colour connected
unresolved limits

- Phase space mapping (i,j,k,l)→(I,L)

$$p_I = xp_i + r_1 p_j + r_2 p_k + z p_l$$

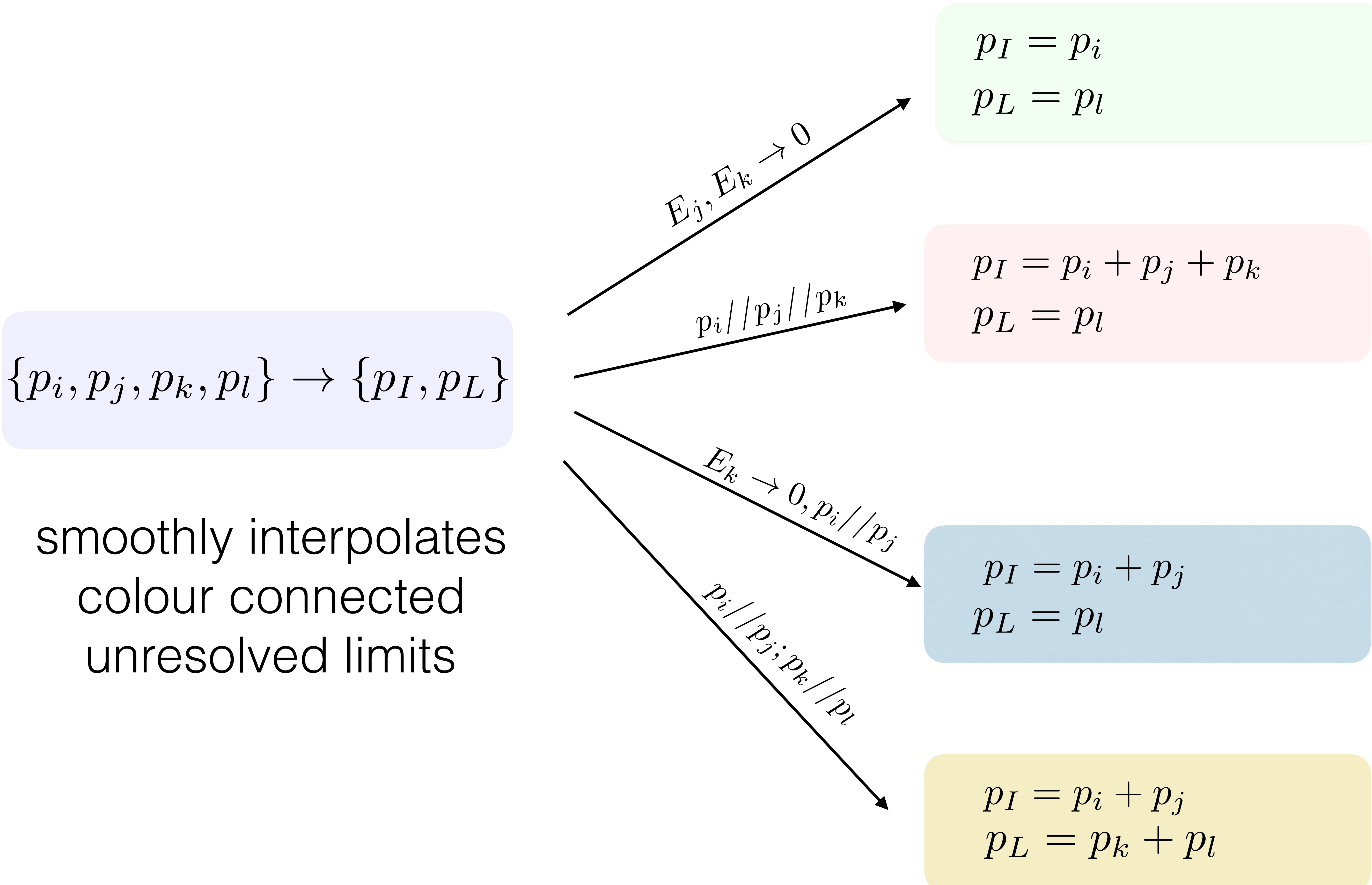
$$p_L = (1-x)p_i + (1-r_1)p_j + (1-r_2)p_k + (1-z)p_l$$

$$\begin{aligned}
x =& \frac{1}{2(s_{12}+s_{13}+s_{14})}\Big[(1+\rho)\, s_{1234} \\
&-r_1\,(s_{23}+2\,s_{24}) - r_2\,(s_{23}+2\,s_{34}) \\
&+(r_1-r_2)\frac{s_{12}s_{34}-s_{13}s_{24}}{s_{14}}\Big] \\
z =& \frac{1}{2(s_{14}+s_{24}+s_{34})}\Big[(1-\rho)\, s_{1234} \\
&-r_1\,(s_{23}+2\,s_{12}) - r_2\,(s_{23}+2\,s_{13}) \\
&-(r_1-r_2)\frac{s_{12}s_{34}-s_{13}s_{24}}{s_{14}}\Big] \\
\rho =& \Big[1+\frac{(r_1-r_2)^2}{s_{14}^2\, s_{1234}^2}\,\lambda(s_{12}\,s_{34}, s_{14}\,s_{23}, s_{13}\,s_{24}) \\
&+\frac{1}{s_{14}\,s_{1234}}\Big\{2\,(r_1\,(1-r_2)+r_2(1-r_1))(s_{12}s_{34}+s_{13}s_{24}-s_{23}s_{14}) \\
&\qquad +4\,r_1\,(1-r_1)\,s_{12}s_{24}+4\,r_2\,(1-r_2)\,s_{13}s_{34}\Big\}\Big]^{\frac{1}{2}},
\end{aligned}$$

$$r_1 = \frac{s_{23}+s_{24}}{s_{12}+s_{23}+s_{24}}$$

$$r_2 = \frac{s_{34}}{s_{13}+s_{23}+s_{34}}$$

$$\mathrm{d}\Phi_{m+2}(p_1,\ldots,p_{m+2}) = \mathrm{d}\Phi_m(p_1,\ldots,p_I,p_L,\ldots,p_{m+2})\cdot \mathrm{d}\Phi_{X_{ijkl}}(p_i,p_j,p_k,p_l;p_I,p_L)$$



smoothly interpolates colour connected unresolved limits

Antenna functions and types

- all antennae can be derived from physical matrix elements in QCD
- colour ordered pair of hard partons (radiators) with radiation in between
  - hard quark-antiquark pair
  - hard quark-gluon pair
  - hard gluon-gluon pair
- three parton antennae → one unresolved parton
- four-parton antennae → two unresolved partons
- can be at tree level or one loop
- can be massless or massive
- all have three antenna types
  - final-final antenna
  - initial-final antenna
  - initial-initial antenna

$$\boxed{X_3^0(i,j,k)}$$

$$\boxed{X_4^0(i,j,k,l)}$$

$$\boxed{X_3^1(i,j,k)}$$

Angular averaging

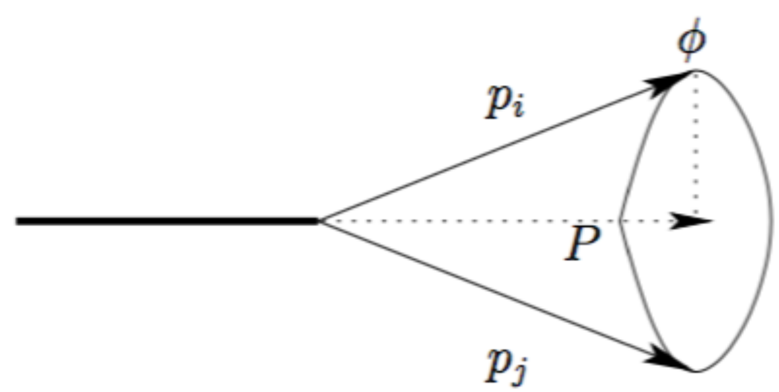
- Antenna functions are scalar objects → do not subtract angular correlations in gluon splitting

- Angular correlations vanish after integration over the azimuthal angle

$$\frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\phi\,(p_l\cdot k_\perp) = 0\,, \qquad \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\phi\,(p_l\cdot k_\perp)^2 = -k_\perp^2\,\frac{p\cdot p_l\, n\cdot p_l}{p\cdot n}$$

$$\Theta_{F_3^0}(i,j,z,k_\perp) \sim A\cos(2\phi+\alpha)$$

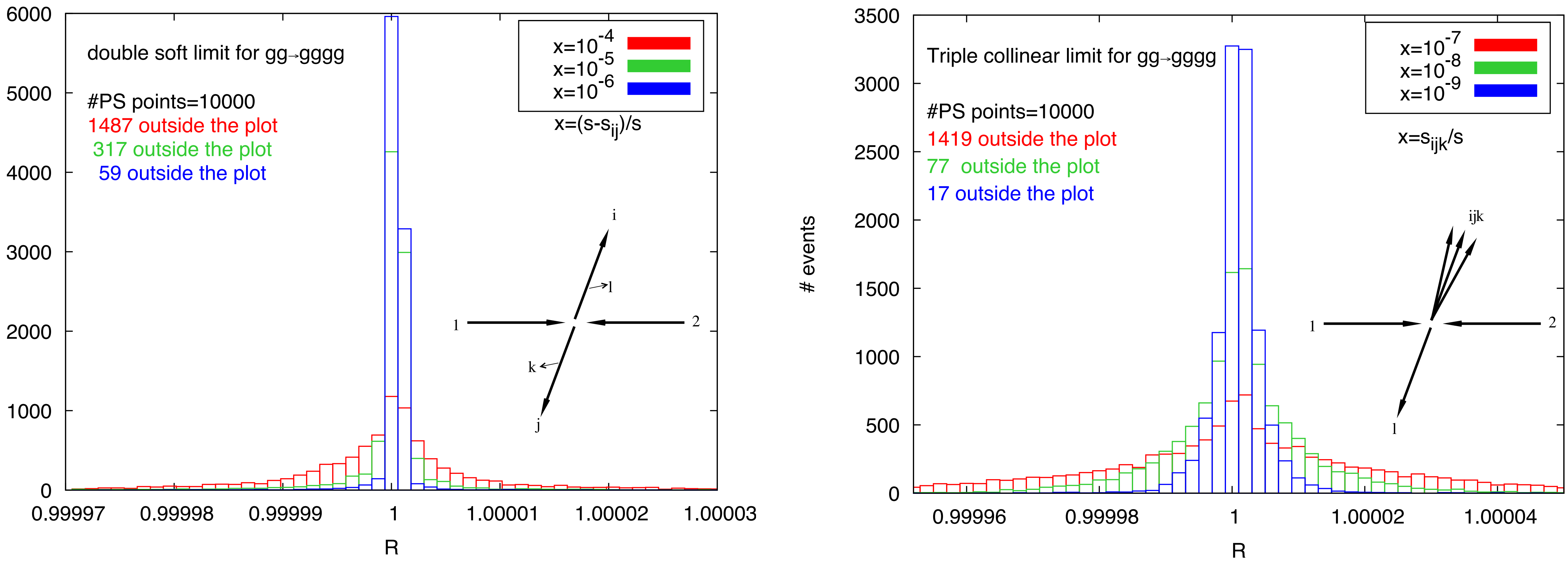
- Make fully local subtraction by combining phase space points related to each other by a 90 degree rotation of the system of unresolved partons



$$p_i^\mu = zp^\mu + k_\perp^\mu - \frac{k_\perp^2}{z}\frac{n^\mu}{2p\cdot n}\,, \qquad p_j^\mu = (1-z)p^\mu - k_\perp^\mu - \frac{k_\perp^2}{1-z}\frac{n^\mu}{2p\cdot n}\,,$$

$$\text{with } 2p_i\cdot p_j = -\frac{k_\perp^2}{z(1-z)}\,, \qquad p^2 = n^2 = k_\perp.p = k_\perp.n = 0$$

Antenna subtraction at work



Double unresolved emission

- Generate phase space trajectories that approach singular region of the phase space
- Infrared behaviour of subtraction term mimics the behaviour of the matrix element

$$R = \frac{d\sigma^{R}_{NNLO}}{d\sigma^{S}_{NNLO}} \xrightarrow{l_g, k_g \to 0} 1$$

Double virtual antenna contribution

	a	b	b,c	d	e
$\mathrm{d}\hat{\sigma}^{S}_{NNLO}$	$X_3^0\lvert\mathcal{M}^0_{m+3}\rvert^2$	$X_4^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	$X_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	$X_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	$\mathcal{S}X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$
$\int_1 \mathrm{d}\hat{\sigma}^{S,1}_{NNLO}$	$\mathcal{X}_3^0\lvert\mathcal{M}^0_{m+3}\rvert^2$	–	$\mathcal{X}_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	–	$\mathcal{S}X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$
$\int_2 \mathrm{d}\hat{\sigma}^{S,2}_{NNLO}$	–	$\mathcal{X}_4^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	–	$\mathcal{X}_3^0\mathcal{X}_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	–

- Integrated double unresolved emission of RR process ∝ tree level double soft function
- Integrated iterated NLO emissions of RR process

- Integrated single unresolved emission from RV process ∝ tree level single soft function
- Integrated single unresolved emission of RV process ∝ one loop single soft function

	$\mathrm{d}\hat{\sigma}^{T}_{NNLO}$		
Final State Particles	a	a	(b,c)
$m+1$	$X_3^1\lvert\mathcal{M}^0_{m+2}\rvert^2$	$X_3^0\lvert\mathcal{M}^1_{m+2}\rvert^2$	$\mathcal{X}_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$
m	$\mathcal{X}_3^1\lvert\mathcal{M}^0_{m+2}\rvert^2$	$\mathcal{X}_3^0\lvert\mathcal{M}^1_{m+2}\rvert^2$	$\mathcal{X}_3^0\mathcal{X}_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$

Double virtual antenna contribution

	a	b	b,c	d	e
$\mathrm{d}\hat{\sigma}^{S}_{NNLO}$	$X_3^0\lvert\mathcal{M}^0_{m+3}\rvert^2$	$X_4^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	$X_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	$X_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	$\mathcal{S}X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$
$\int_1 \mathrm{d}\hat{\sigma}^{S,1}_{NNLO}$	$\mathcal{X}_3^0\lvert\mathcal{M}^0_{m+3}\rvert^2$	–	$\mathcal{X}_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	–	$\mathcal{S}X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$
$\int_2 \mathrm{d}\hat{\sigma}^{S,2}_{NNLO}$	–	$\mathcal{X}_4^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	–	$\mathcal{X}_3^0\mathcal{X}_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$	–

$$\mathcal{P}oles(\mathrm{d}\hat{\sigma}^{U,a}_{NNLO}) \quad \sim \quad \mathbf{J^1}(\epsilon,\hat{1}_g,\hat{2}_g,i_g,j_g)\Big(A_4^1(\hat{\bar{1}}_g,\hat{\bar{2}}_g,i_g,j_g)-\frac{b_0}{\epsilon}A_4^0(\hat{\bar{1}}_g,\hat{\bar{2}}_g,i_g,j_g)\Big)$$

$$\mathcal{P}oles(\mathrm{d}\hat{\sigma}^{U,b}_{NNLO}) \quad \sim \quad \mathbf{J^1}(\epsilon,\hat{1}_g,\hat{2}_g,i_g,j_g)\otimes\mathbf{J^1}(\epsilon,\hat{1}_g,\hat{2}_g,i_g,j_g)A_4^0(\hat{\bar{1}}_g,\hat{\bar{2}}_g,i_g,j_g)$$

$$\mathcal{P}oles(\mathrm{d}\hat{\sigma}^{U,c}_{NNLO}) \quad \sim \quad \mathbf{J^2}(\epsilon,\hat{1}_g,\hat{2}_g,i_g,j_g)\,A_4^0(\hat{\bar{1}}_g,\hat{\bar{2}}_g,i_g,j_g)$$

	$\mathrm{d}\hat{\sigma}^{T}_{NNLO}$		
Final State Particles	a	a	(b,c)
$m+1$	$X_3^1\lvert\mathcal{M}^0_{m+2}\rvert^2$	$X_3^0\lvert\mathcal{M}^1_{m+2}\rvert^2$	$\mathcal{X}_3^0X_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$
m	$\mathcal{X}_3^1\lvert\mathcal{M}^0_{m+2}\rvert^2$	$\mathcal{X}_3^0\lvert\mathcal{M}^1_{m+2}\rvert^2$	$\mathcal{X}_3^0\mathcal{X}_3^0\lvert\mathcal{M}^0_{m+2}\rvert^2$

- integrated operators $\mathbf{J}_2^{(2,1)}$ in analytic one-to-one correspondence with $(\mathbf{I}_1)^2$ operator of Catani

$$
\begin{aligned}
\mathrm{d}\sigma_{VV} &= 2\boldsymbol{I}^{(1)}(\epsilon,\hat{1}_g,\hat{2}_g,i_g,j_g)\, A_4^1(\hat{1}_g,\hat{2}_g,i_g,j_g) \\
&- 2\boldsymbol{I}^{(1)}(\epsilon,\hat{1}_g,\hat{2}_g,i_g,j_g)^2\, A_4^0(\hat{1}_g,\hat{2}_g,i_g,j_g) \\
&+ \boldsymbol{I}^{(2)}(\epsilon,\hat{1}_g,\hat{2}_g,i_g,j_g)) \\
&+ \mathrm{Finite}(A_2^2(\hat{1}_g,\hat{2}_g,i_g,j_g))
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{d}\sigma_{U} &= \mathbf{J}_4^1(1_g,2_g,i_g,j_g)A_4^1(1_g,2_g,i_g,j_g) \\
&+ \frac{1}{2}\mathbf{J}_4^1(1_g,2_g,i_g,j_g)\otimes\mathbf{J}_4^1(1_g,2_g,i_g,j_g)A_4^0(1_g,2_g,i_g,j_g) \\
&+ \mathbf{J}_4^2(1_g,2_g,i_g,j_g)A_4^0(1_g,2_g,i_g,j_g)
\end{aligned}
$$

```
[Joaos-MacBook-Pro:jet pires$ form autoA4g2XU.frm
FORM 4.1 (Oct 25 2013) 64-bits                    Run: Sun Apr  9 17:19:06 2017
    #-

   poles = 0;

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$$
\boxed{\mathcal{P}oles\left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO}-\mathrm{d}\hat{\sigma}^{U}_{NNLO}\right)=0}
$$

Subtraction at Subleading Colour

- gluons only double-real colour summed cross section

$$d\hat{\sigma}^{RR}_{NNLO} = \left(\frac{\alpha_s}{2\pi}\right)^2 N^4(N^2-1)\, d\Phi_4(p_3,\ldots,p_6;p_1;p_2)\, J_2^{(4)}(p_3,\ldots,p_6)\,\frac{1}{4!}$$
$$\sum_{\sigma\in S_6/Z_6}\left[|A_6^{(0)}(\sigma)|^2 + \frac{2}{N^2}A_6^0(\sigma)\Big(A_6^{\dagger 0}(\sigma\cdot\rho_1)+A_6^{\dagger 0}(\sigma\cdot\rho_2)+A_6^{\dagger 0}(\sigma\cdot\rho_3)\Big)\right]$$

- double-real sub-leading contribution written as three interferences summed over permutations. For σ=(1,2,3,4,5,6)

$(\sigma.\rho_1)=(1,3,5,2,6,4)$ $(\sigma.\rho_2)=(1,3,6,4,2,5)$ $(\sigma.\rho_3)=(1,4,2,6,3,5)$

- $(\sigma.\rho_{1,2,3})$ are the only three independent orderings that exist for six gluon scattering which have no common two or three particle poles in common with σ

⇒ no single, double or triple collinear singularities at subleading colour ✔

- subtract divergences associated with single soft and double soft gluons

Subtraction at Subleading Colour

- in the single soft limit the interferences factorize in the following way

$$
\begin{aligned}
\mathcal{M}^{0,\dagger}_{n+1}(\cdots,a,i,b,\cdots)\mathcal{M}^{0}_{n+1}(\cdots,c,i,d,\cdots) &\xrightarrow{i\to 0} \\
& J_\mu(p_a,p_i,p_b)\epsilon^\mu(p_j)J_\nu(p_c,p_i,p_d)\epsilon^\nu(p_i)\mathcal{M}^{0,\dagger}_{n}(\cdots,a,b,\cdots)\mathcal{M}^{0}_{n}(\cdots,c,d,\cdots) \\
= & \frac{1}{2}(S_{aid}+S_{bic}-S_{aic}-S_{bid})\mathcal{M}^{0,\dagger}_{n}(\cdots,a,b,\cdots)\mathcal{M}^{0}_{n}(\cdots,c,d,\cdots)
\end{aligned}
$$

where $S_{ajc}=2s_{ac}/s_{aj}/s_{jc}$ is the squared eikonal factor

- eikonal factor with uniquely identified radiators and unresolved momenta is mapped to a three parton antenna function

- single unresolved subtraction term constructed from a product of differences of tree-level three parton antenna function and reduced colour ordered interferences

Subtraction at Subleading Colour

- in the double soft limit the interferences factorize in the following way

$$\mathcal{M}^{0,\dagger}_{n+1}(\cdots,a,i,j,b,\cdots)\mathcal{M}^{0}_{n+1}(\cdots,c,i,d,\cdots,e,j,f,\cdots) \xrightarrow{i,j\to 0}$$
$$J_{\mu 1\mu 2}(p_a,p_i,p_j,p_b)\epsilon^{\mu 1}(p_i)\epsilon^{\mu 2}(p_j)J_{\nu 1}(p_c,p_i,p_d)J_{\nu 2}(p_e,p_j,p_f)\epsilon^{\nu 1}(p_i)\epsilon^{\nu 2}(p_j)$$
$$\times\mathcal{M}^{0,\dagger}_{n}(\cdots,a,b,\cdots)\mathcal{M}^{0}_{n}(\cdots,c,d,\cdots,e,f,\cdots)$$

- when summing the subleading colour contribution explicitly over all colour permutations the tree level double soft current drops out from the limit

- the double soft limit at subleading colour can be written completely in terms of contractions of tree-level single soft currents

$$\begin{aligned}
\mathbf{A}^0_6(p)|_{slc} \overset{5,6\to 0}{\propto} \quad & (S_{153}+S_{254}-S_{154}-S_{254})\,(S_{163}+S_{264}-S_{162}-S_{364})\,|A^0_4(1,2,3,4)|^2 \\
+ \quad & (S_{153}+S_{254}-S_{154}-S_{254})\,(S_{162}+S_{364}-S_{164}-S_{263})\,|A^0_4(1,2,4,3)|^2 \\
+ \quad & (S_{152}+S_{354}-S_{154}-S_{253})\,(S_{162}+S_{364}-S_{163}-S_{264})\,|A^0_4(1,3,2,4)|^2
\end{aligned}$$

- subleading colour subtraction reuses the same building blocks/antennae as at leading colour

Pros and cons

Antenna subtraction

- local method with phase space averaging → good control on the numerical accuracy of the final result, RR, RV, VV separately finite
- analytic IR pole cancellation at NNLO → good control on the correctness of the pole cancellation
- double precision
- universal method works for general jet multiplicity → no additional building blocks needed
- subtraction terms for a fixed colour structure reusable
- involves many mappings/subtraction terms as expected for a local method → needs caching system to store mappings

NNLOJET

NNLO fully differential parton-level generator*

- Based on antenna subtraction for the analytic cancellation of IR singularities at NNLO

Infrastructure

- Process management
- Phase space, histogram routines
- Validation and testing
- Applgrid and FastNLO interface in progress

Processes implemented at NNLO

- Z+(0,1) jet, W+(0,1) jet
- H+(0,1) jet
- DIS-2jet
- VBF H+2jet
- Inclusive jet production

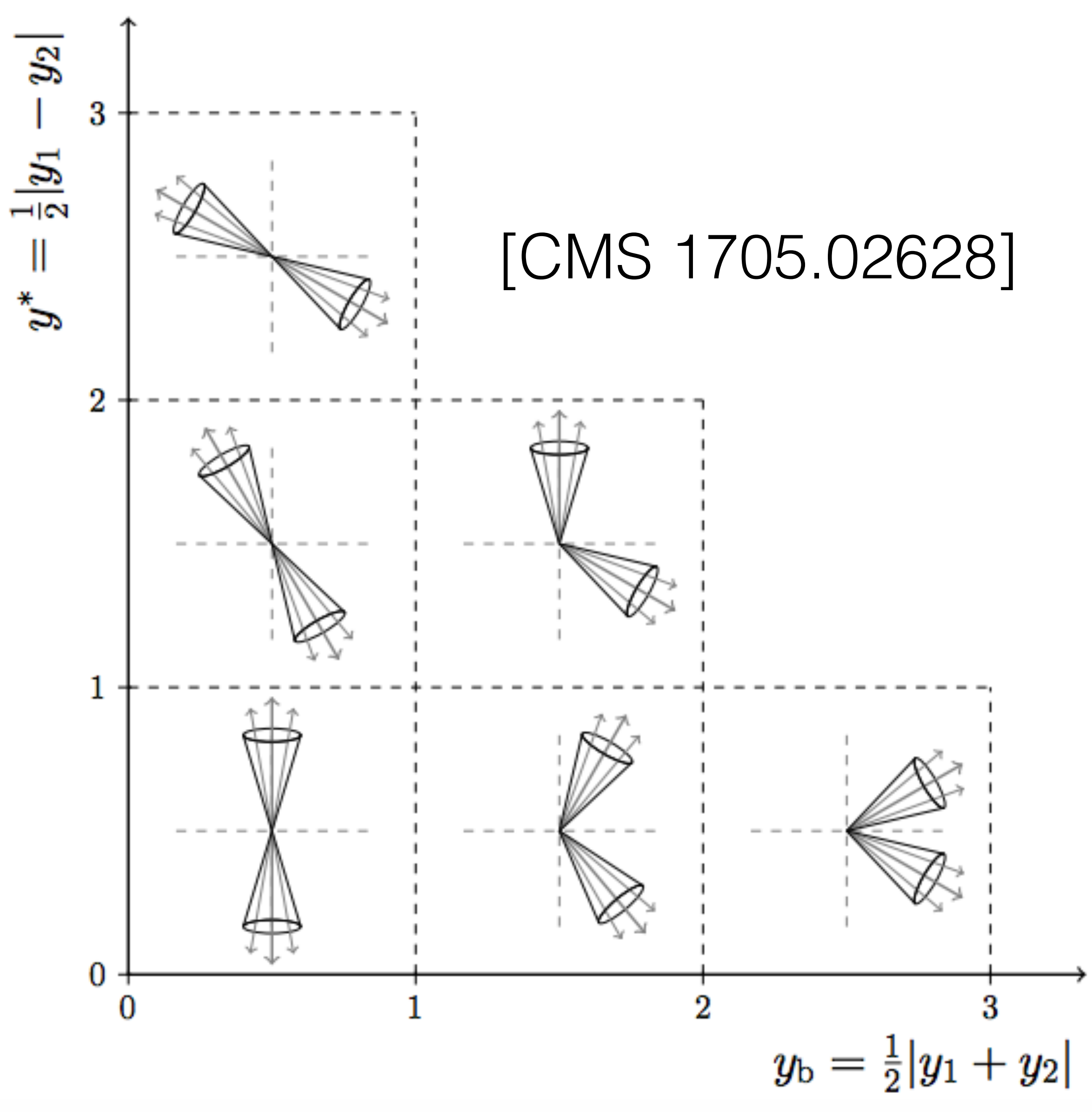
- In use by the experimental collaborations ATLAS and CMS
- New processes can be added using input from the experimental community as guidance

X.Chen,J.Cruz-Martinez, J.Currie, R.Gauld, T.Gehrmann, A.Gehrmann-De Ridder,E.W.N.Glover, M.Höfer, A.Huss, T.Morgan, I.Majer, J.Niehues, D.Walker, JP* *[arXiv: 1801.06415]*** *and references therein*

Dijet triple differential measurement - CMS

- Obtain the maximal sensitivity from the dijet cross section to the parton densities from multi-differential distributions

- Explore the shape of the dijet cross section in triple differential form to constrain PDFs at small to moderate x-values: interplay between the parton luminosities and the scattering matrix elements



[CMS 1705.02628]

- 2 jet observables built from the two-leading jets in the event, with the caveat that the assignment of the hardest jet in the event is not infra-red safe

- Follow the setup of the 8 TeV CMS measurement that overcomes the problem

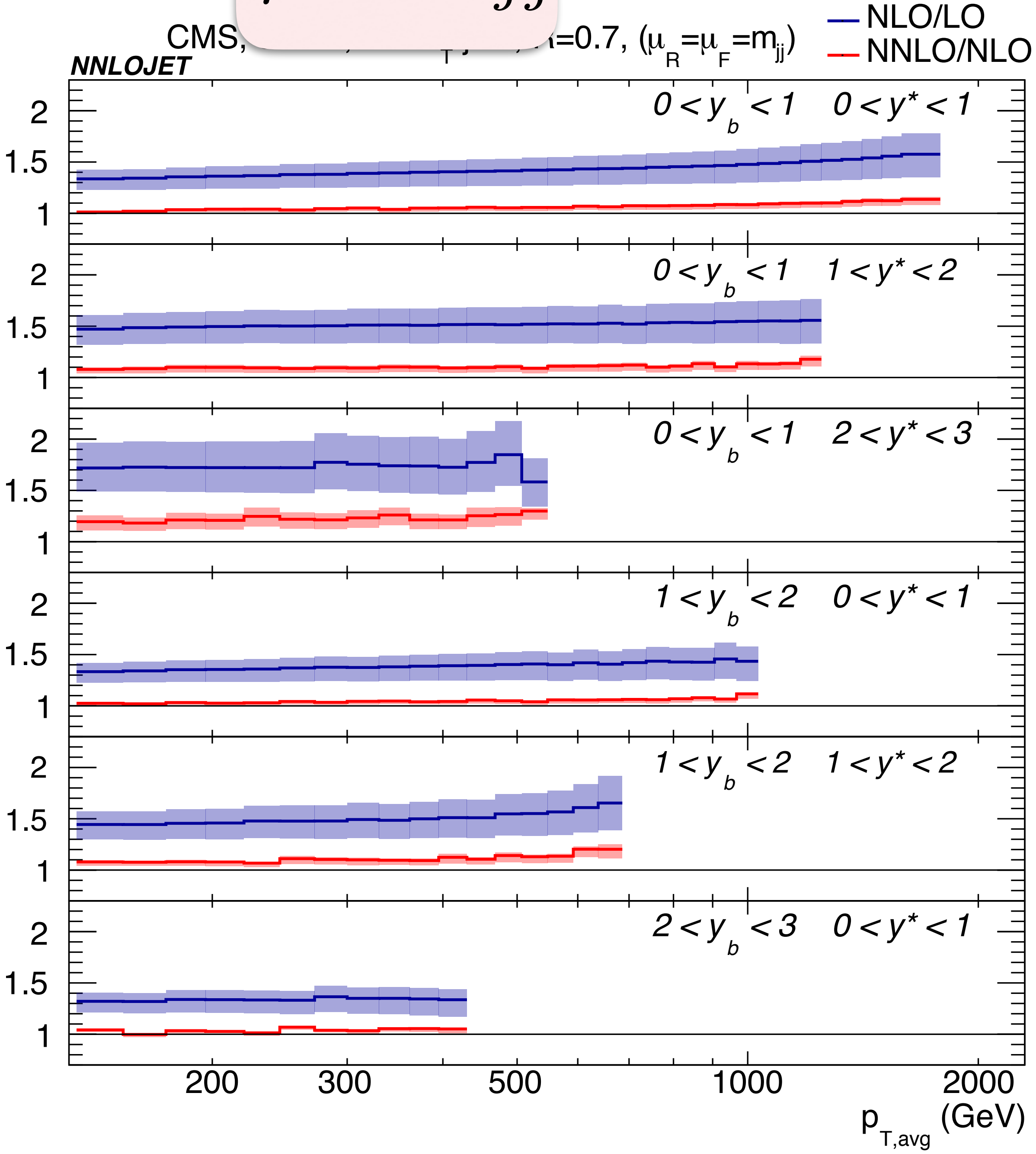
$$p_{T,\mathrm{avg}} = (p_{T,1} + p_{T,2})/2$$

$$y^* = |y_1 - y_2|/2$$

$$y_b = |y_1 + y_2|/2$$

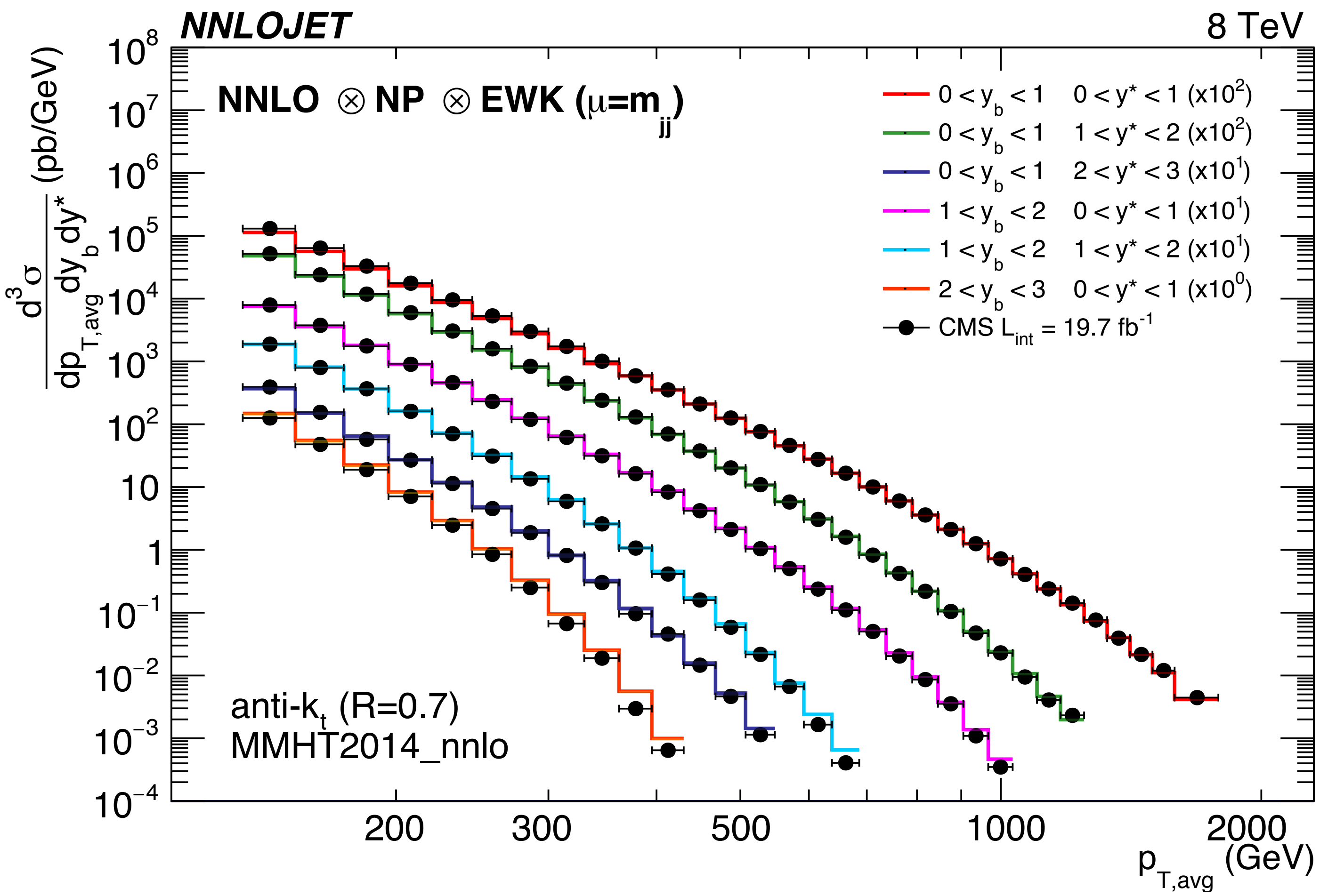
CMS $\sqrt{s}$=8 TeV anti-k_T R=0.7

$\mu = m_{jj}$



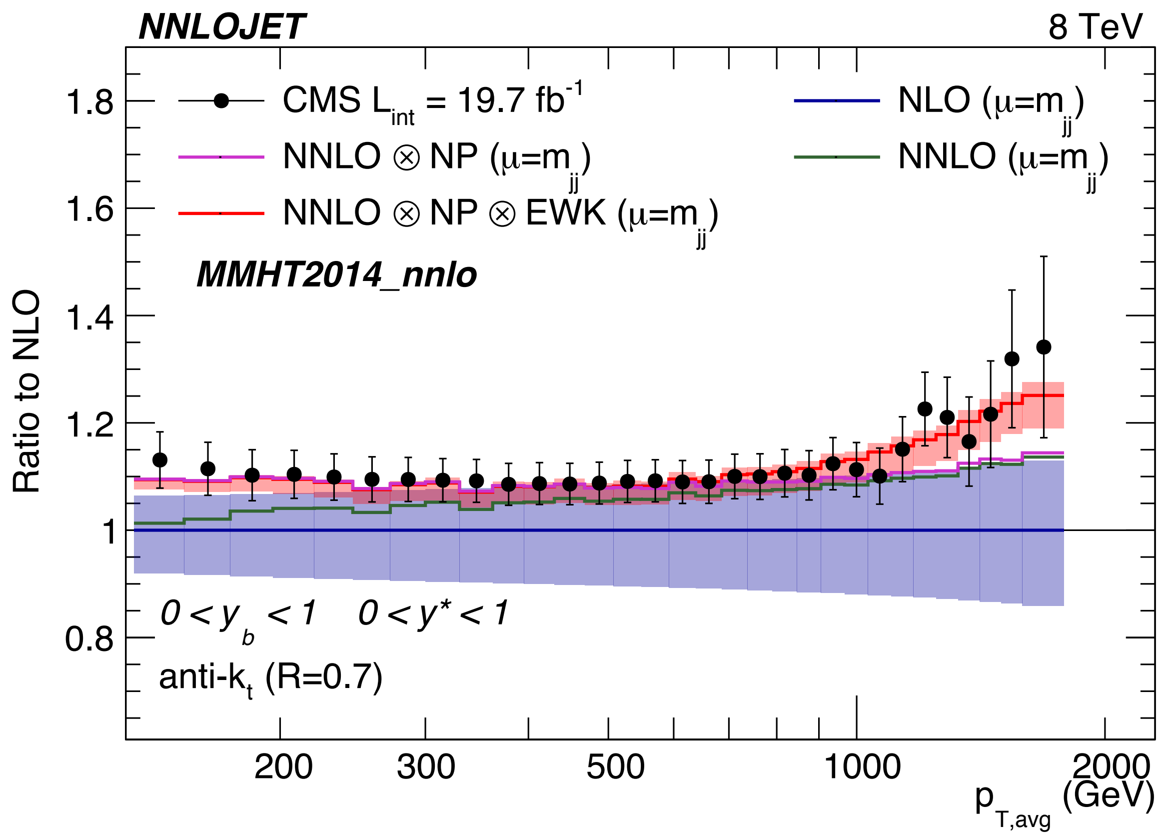
Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP

[arXiv: 1905.09047] Phys. Rev. Lett. 123, 102001 (2019)



- size of the corrections varies significantly as a function of $p_{T,avg}$ and the applied cuts on y^* and y_b
- NNLO correction changes both the shape and normalisation of the NLO result
- QCD scale choice $\mu_R = \mu_F = m_{jj}$

CMS $\sqrt{s}$=8 TeV $0 < y_b < 1$



MMHT2014_nnlo

- **NNLO** correction changes both the shape and normalisation of the **NLO** result

→ good agreement with NNLO⊗NP⊗EWK for the central y_b slice

Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP
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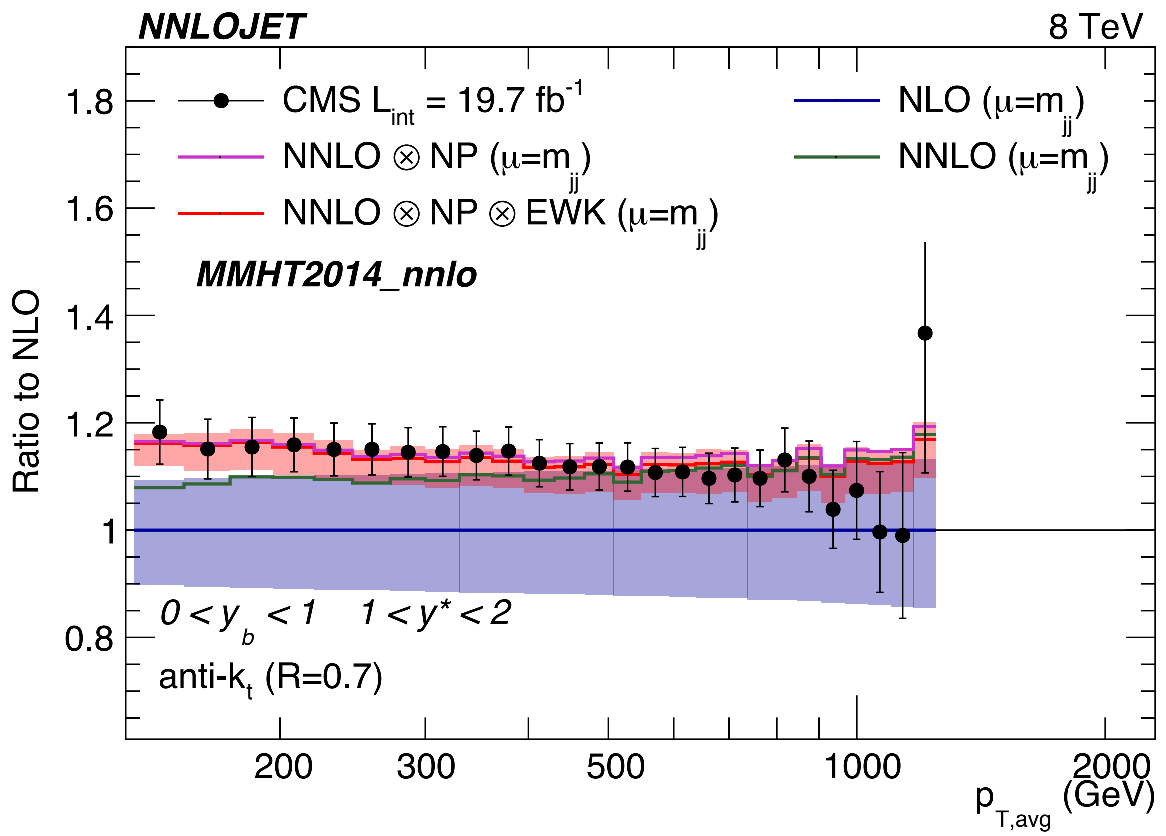
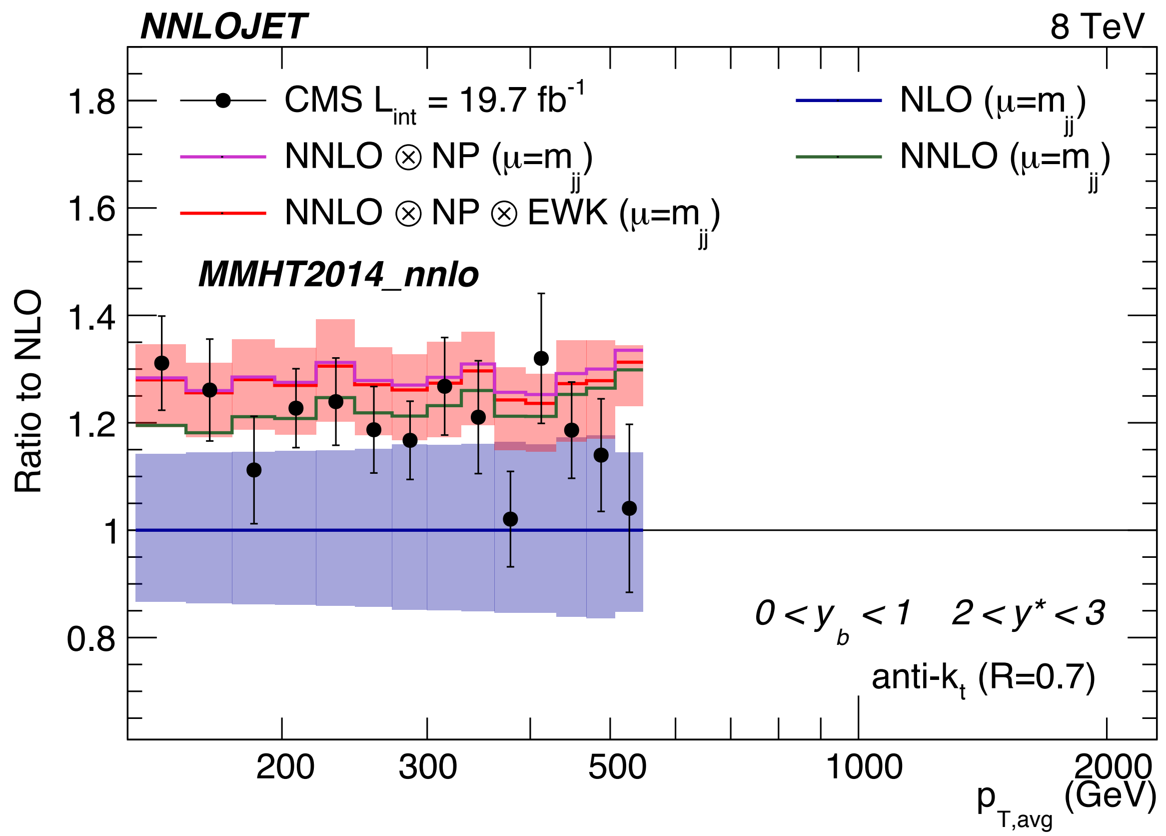
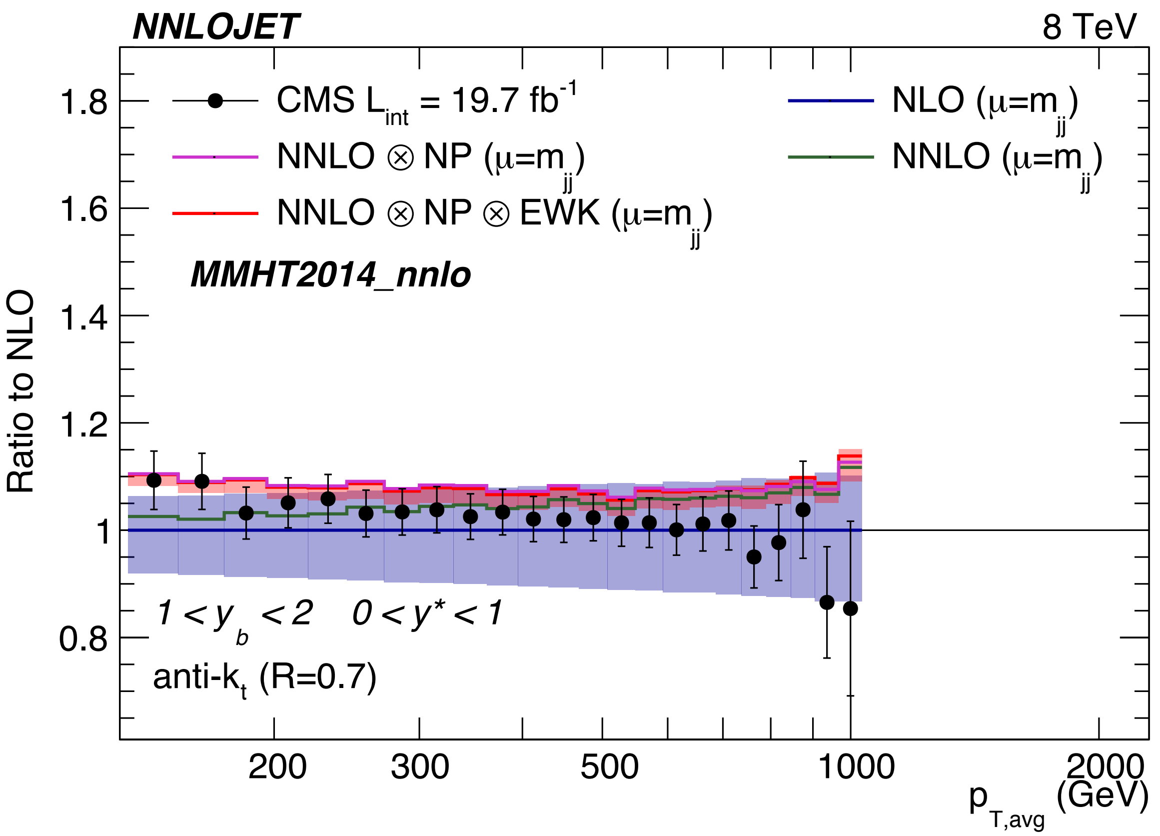


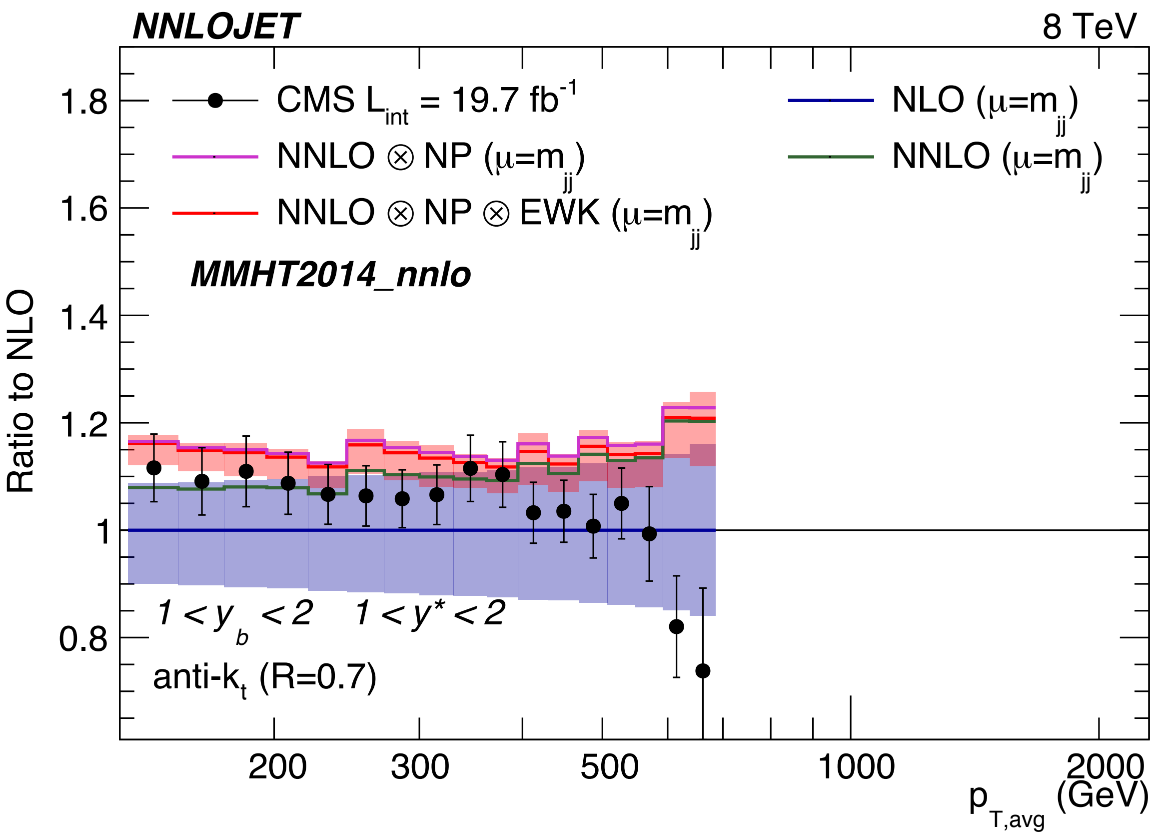


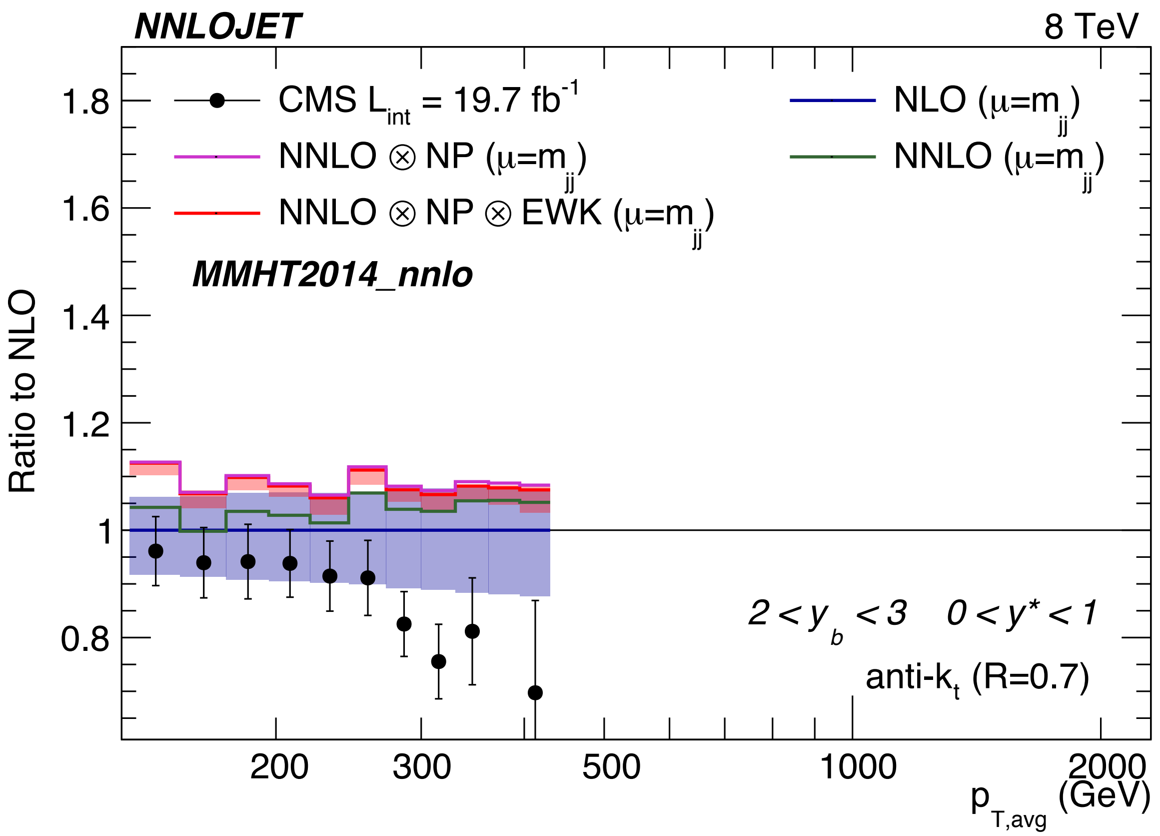
CMS $\sqrt{s}$=8 TeV $y_b > 1$



MMHT2014_nnlo

- y_b variation probes the scattering of a high-x parton off a low-x parton; → large PDF uncertainty
- data sits below the central value of the MMHT2014 **NNLO** central value
- PDF effect since matrix element contribution invariant under y_b variation





Conclusions

Substancial progress in NNLO calculations in past couple of years

- several different approaches for isolating IR singularities
- several new calculations available

<u>Antenna subtraction</u>

- local IR phase space subtraction scheme with analytic pole cancellation
- RR, RV, VV contributions separately finite and integrable in d=4
- formalism developed for color charged final/initial states
- formalism implemented in a fully flexible parton level generator
- new processes can be added using the existing common syntax structures