NNLO dijets at the LHC

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CUNY, New York

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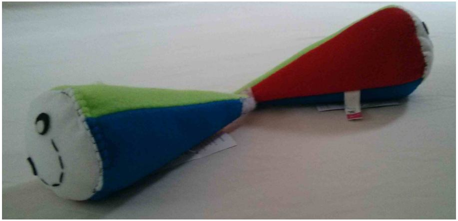
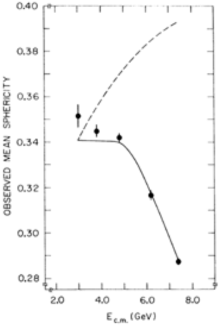
Based upon work with A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, J. Pires, S. Wells

Jets in the Wild

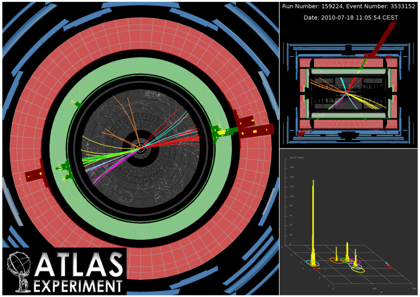


Jets in the Detector

Jets are the only available high energy experimental QCD object



[Phys. Rev. Lett. 35: 1609 (1975)]



$m_{jj} \sim 2.55\text{TeV},\ p_{t_1} = 420\text{GeV},\ p_{t_2} = 320\text{GeV}$

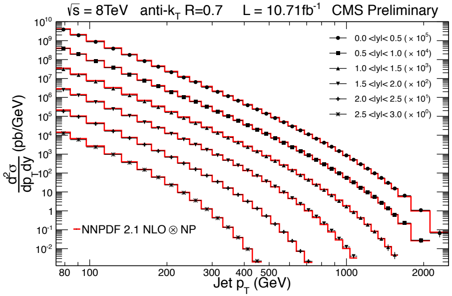
Jet Cross Sections

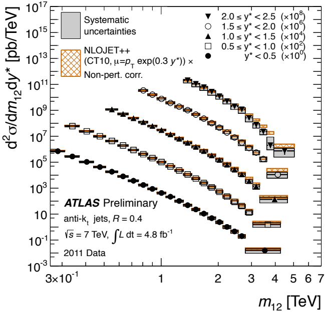
Many process of interest at LHC involve at least one jet in the final state:

$$pp \to jj(j),\ H + j(j),\ V + j(j),\ t\bar{t}(j),\ \gamma + j$$

Cross sections accurately measured and presented in differential form, e.g.

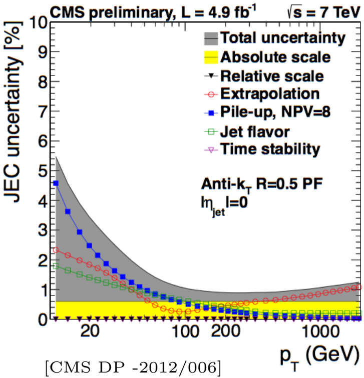
- single jet inclusive in p_T and $|y|$
- exclusive dijet in m_{jj} and y^*



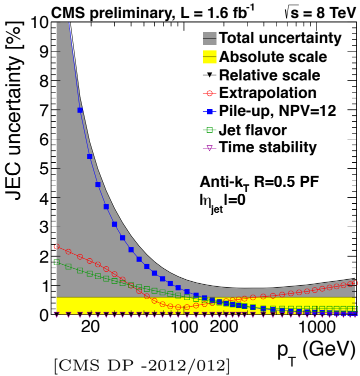


Experimental Uncertainties

- JES uncertainty ~1% for $p_T > 150$ GeV central jets
- translates to $< 10\%$ uncertainty on single jet incl. cross section
- onus on theory community to better this



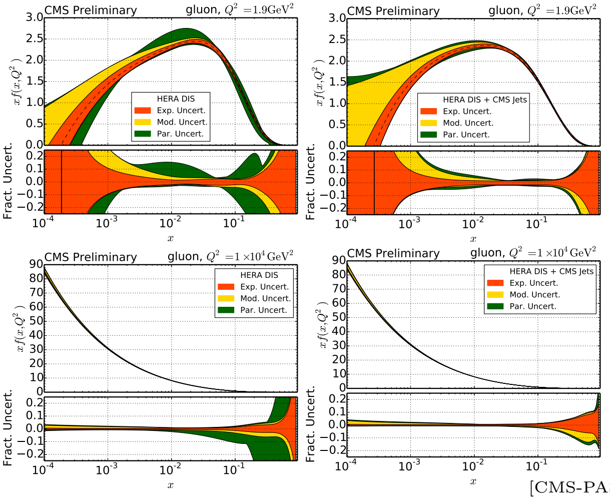
[CMS DP -2012/006]



[CMS DP -2012/012]

Constraining PDFs

Single jet inclusive x-sec, constrain PDFs, in particular the gluon at large x

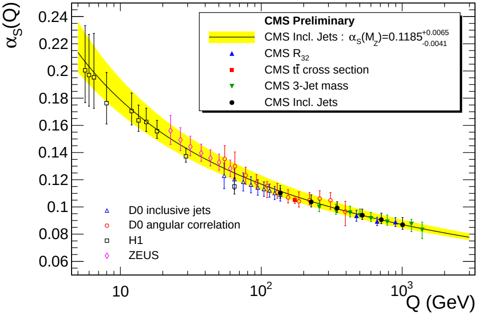


[CMS-PAS-SMP-12-028]

Measuring α_s

Can use single jet inclusive x-sec to fit:

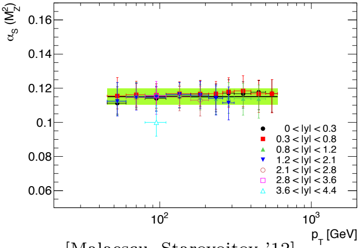
- $\alpha_s(M_Z)$
- running coupling



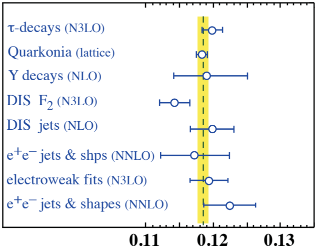
[CMS-PAS-SMP-12-028]

$$\alpha_s(M_Z) = 0.1184 \pm 0.007$$

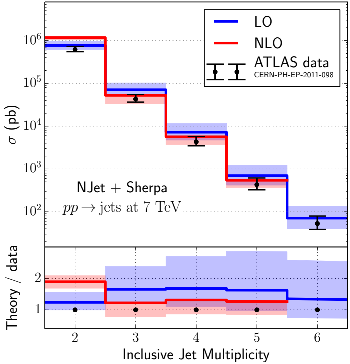
No hadronic jet data in world average, yet



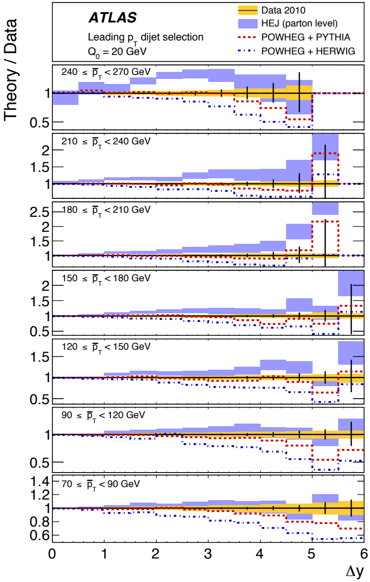
[Malaescu, Starovoitov '12]



- Separated jets, BFKL vs DGLAP
- dijet cross section
  - NLO fixed order too high
  - sensitive to higher order effects

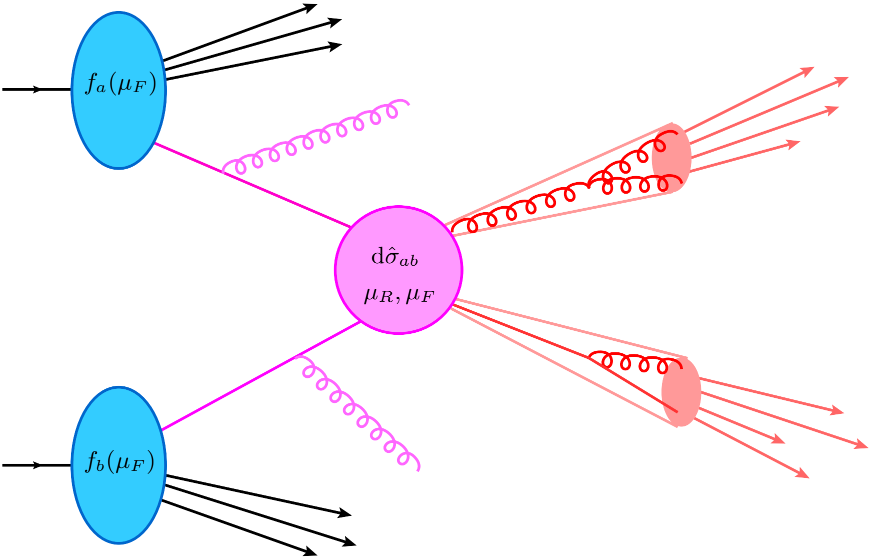


[Badger, Biedermann, Uwer, Yundin, '13]

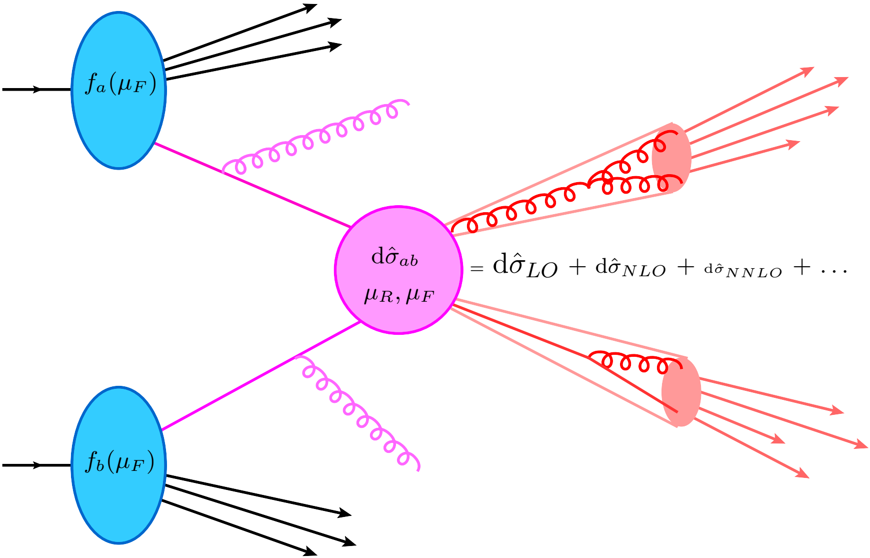


[ATLAS, '11]

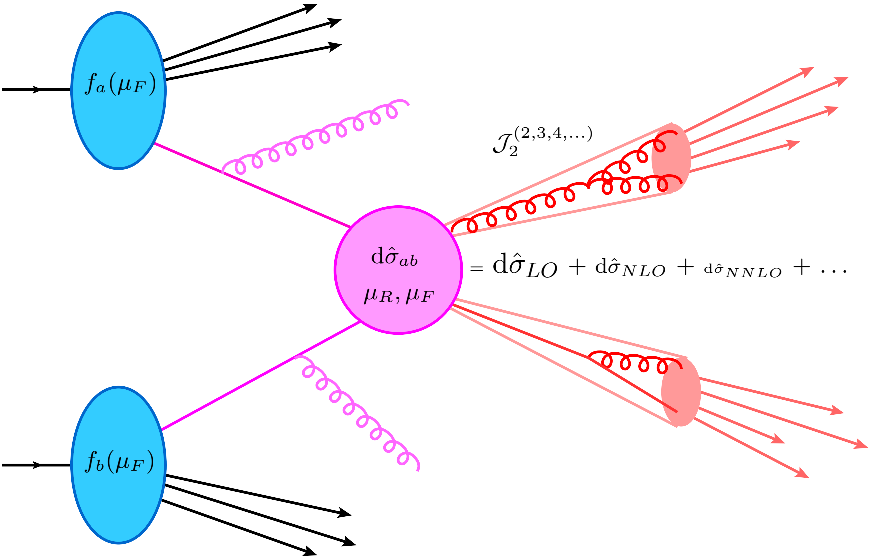
Theoretical improvements



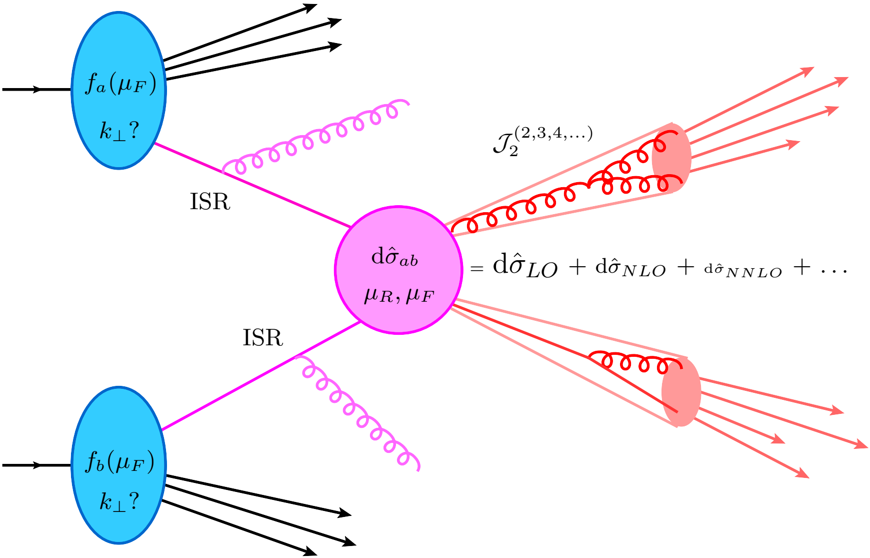
Theoretical improvements



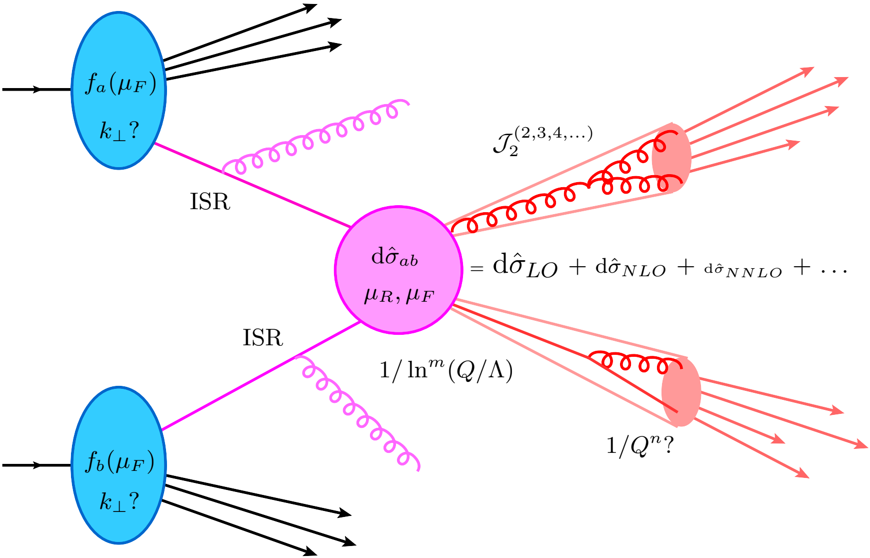
Theoretical improvements



Theoretical improvements



Theoretical improvements



The NNLO Marketplace

In recent years many new tools developed for NNLO

- all have advantages and disadvantages

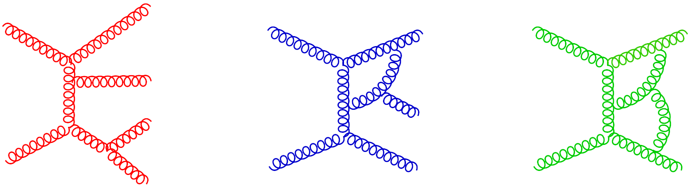
	analytic	FS colour	IS colour	local
antenna subtraction	✓	✓	✓	✗
`STRIPPER`	✗	✓	✓	✓
q_T subtraction	✓	✗	✓	✓
reverse unitarity	✓	✗	✓	-
Trócsányi et al	✗	✓	✗	✓

Antenna subtraction is the only method for computing cross sections with:

- hadronic initial-states
- jets in the final-state (especially more than one jet)
- analytic pole cancellation

Subtraction at NNLO

$$
\begin{aligned}
\mathrm{d}\hat{\sigma}_{ab,NNLO} &= \int_{\Phi_{m+2}} \mathrm{d}\hat{\sigma}^{RR}_{ab,NNLO} \\
&+ \int_{\Phi_{m+1}} \left[\mathrm{d}\hat{\sigma}^{RV}_{ab,NNLO} + \mathrm{d}\hat{\sigma}^{MF,1}_{ab,NNLO}\right] \\
&+ \int_{\Phi_{m}} \left[\mathrm{d}\hat{\sigma}^{VV}_{ab,NNLO} + \mathrm{d}\hat{\sigma}^{MF,2}_{ab,NNLO}\right]
\end{aligned}
$$



Subtraction at NNLO

$$
\begin{aligned}
d\hat{\sigma}_{ab,NNLO} &= \int_{\Phi_{m+2}} \left[d\hat{\sigma}^{RR}_{ab,NNLO} - d\hat{\sigma}^{S}_{ab,NNLO} \right] \\
&+ \int_{\Phi_{m+1}} \left[d\hat{\sigma}^{RV}_{ab,NNLO} - d\hat{\sigma}^{T}_{ab,NNLO} \right] \\
&+ \int_{\Phi_{m}} \left[d\hat{\sigma}^{VV}_{ab,NNLO} - d\hat{\sigma}^{U}_{ab,NNLO} \right]
\end{aligned}
$$

$$
\begin{aligned}
d\hat{\sigma}^{T}_{ab,NNLO} &= -\int_1 d\hat{\sigma}^{S}_{ab,NNLO} + d\hat{\sigma}^{V,S}_{ab,NNLO} - d\hat{\sigma}^{MF,1}_{ab,NNLO} \\
d\hat{\sigma}^{U}_{ab,NNLO} &= -\int_2 d\hat{\sigma}^{S}_{ab,NNLO} - \int_1 d\hat{\sigma}^{V,S}_{ab,NNLO} - d\hat{\sigma}^{MF,2}_{ab,NNLO}
\end{aligned}
$$

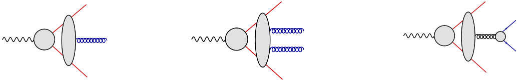
What is an antenna?

Constructed from physical matrix elements

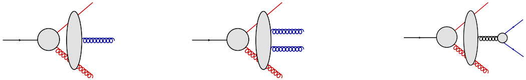
$$X_3^0(i,j,k) \sim \frac{|\mathcal{M}_3^0(i,j,k)|^2}{|\mathcal{M}_2^0(I,K)|^2}, \qquad X_4^0(i,j,k,l) \sim \frac{|\mathcal{M}_4^0(i,j,k,l)|^2}{|\mathcal{M}_2^0(I,L)|^2}$$

Three main types:

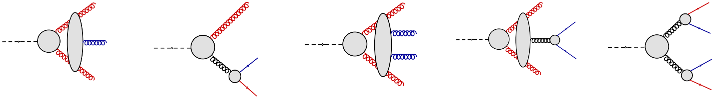
- Quark-antiquark. Derived from the process $\gamma^* \to q\bar{q} + \cdots$



- Quark-gluon. Derived from the process $\tilde{\chi}^0 \to \tilde{g}g + \cdots$

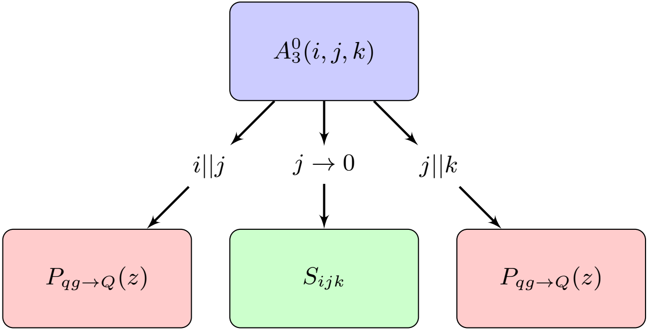


- Gluon-gluon. Derived from the process $H \to gg + \cdots$



How are they useful?

- smoothly interpolates many unresolved limits



- analytically integrable. . . and integrated

Antenna Subtraction Toolbox

Many tools needed for implementation:

- final-final phase space mappings [Kosower '03]
- FF X_3^0, X_4^0, X_3^1 antennae [Gehrmann-De Ridder, Gehrmann, Glover, '04, '05]
- integrated FF antennae [Gehrmann-De Ridder, Gehrmann, Glover, '05]

$\Rightarrow$ $e^+e^- \to$ 3 jets at NNLO [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich, '07, Weinzierl '08]

Since then, extended for hadronic initial-states:

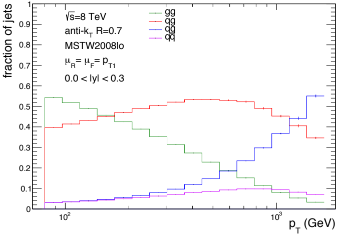
- initial-final + initial-initial mappings [Daleo, Gehrmann, Maître, '07]
- integrated IF X_3^1, X_4^0 [Daleo, Gehrmann-De Ridder, Gehrmann, Luisoni, '10]
- integrated II X_4^0 [Boughezal, Gehrmann-De Ridder, Ritzmann, '11. Gehrmann, Ritzmann '12]
- integrated II X_3^1 [Gehrmann, Monni, '11]

All tools exist for hadron-hadron scattering

[Glover, Pires, '10. Gehrmann De-Ridder, Glover, Pires, '12. Gehrmann De-Ridder, Gehrmann, Glover, Pires ,'13. JC, Glover, Wells, '13. JC, Gehrmann De-Ridder, Glover, Pires, '14.]

NNLO calculations under way

- $pp \to jj$ [JC, Gehrmann De-Ridder, Gehrmann, Glover, Pires, Wells]
  - $gg \to jj$ leading colour ✓
  - $gg \to jj$ sub-leading colour ✓
  - $q\bar{q} \to jj$ leading colour ✓
  - $qg \to jj$ leading colour nearly there!
  - $gg \to jj$ leading N_F in preparation



LHC 8TeV

- $ep \to (2+1)j$ [JC, Gehrmann, Niehues]

- $pp \to H + j$ [Chen, Gehrmann, Glover, Jaquier]

- $pp \to V + j$ [JC, Gehrmann De-Ridder, Gehrmann, Glover, Morgan, Piebinga]

NNLO calculations under way

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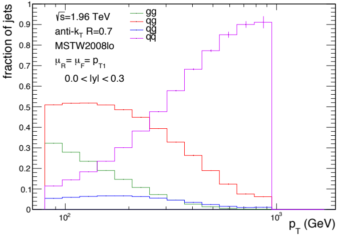


Tevatron

- $ep \to (2+1)j$ [JC, Gehrmann, Niehues]

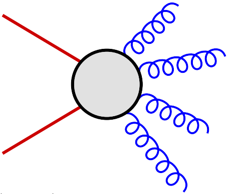
- $pp \to H + j$ [Chen, Gehrmann, Glover, Jaquier]

- $pp \to V + j$ [JC, Gehrmann De-Ridder, Gehrmann, Glover, Morgan, Piebinga]

Example, $q\bar{q} \to gggg$

Need to perform subtraction for

$$|M_6^0|^2 \sim \sum_{P(i,j,k,l)} M_6^0(1_q, i, j, k, l, 2_{\bar{q}})$$

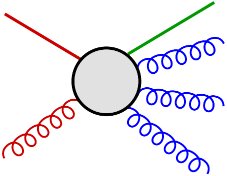


Double unresolved limits subtracted using,

$$\begin{aligned} d\hat{\sigma}^b_{NNLO} \sim \sum \quad & + \quad D_4^0(1,i,j,k)\; M_4^0(\bar{1},(\widetilde{ijk}),l,2) \\ & + \quad F_4^0(i,j,k,l)\; M_4^0(1,(\widetilde{ijk}),(\widetilde{jkl}),2) \\ & + \quad D_4^0(2,l,k,j)\; M_4^0(1,i,(\widetilde{jkl}),\bar{2}) \\ & - \quad \tilde{A}_4^0(1,i,k,2)\; M_4^0(\bar{1},\tilde{j},\tilde{l},\bar{2}) \end{aligned}$$

- full subtraction term successfully removes all single and double unresolved divergence

Quark-gluon channel: identity changing collinear limits



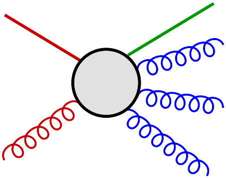
Need to perform subtraction for

$$|M_6^0|^2 \sim \sum_{P(2,i,j,k)} M_6^0(1_q, 2_g, i, j, k, Q)$$

Matrix element can collapse onto different initial states

- quark-gluon, e.g., $2|i|j$, $i|j|k$, $Q|i|j$ etc
- quark-antiquark e.g., $2|i|Q$ etc
- gluon-gluon e.g. $1|i|Q$ etc

Quark-gluon channel: identity changing collinear limits



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- quark-antiquark e.g., $2|i|Q$ etc
- gluon-gluon e.g. $1|i|Q$ etc

But subtraction term must make a choice

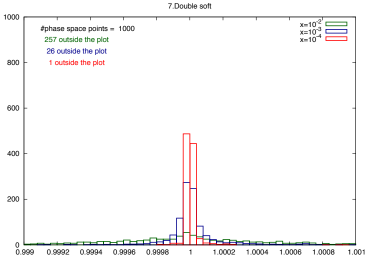
$$D_4^0(Q, i, j, 2)\ M_4^0(1, k, \bar{2}, (\widetilde{ijQ}))$$

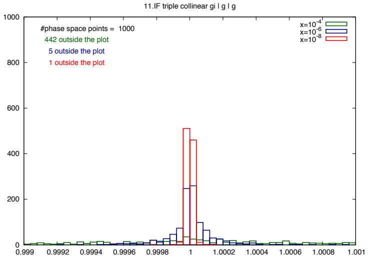
or

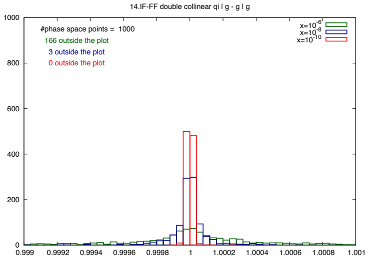
$$D_4^0(Q, i, j, 2)\ M_4^0(1, k, (\widetilde{ijQ}), \bar{2})$$

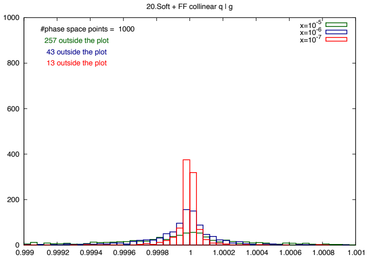
- many spurious divergences

Double real quark-gluon channel tests

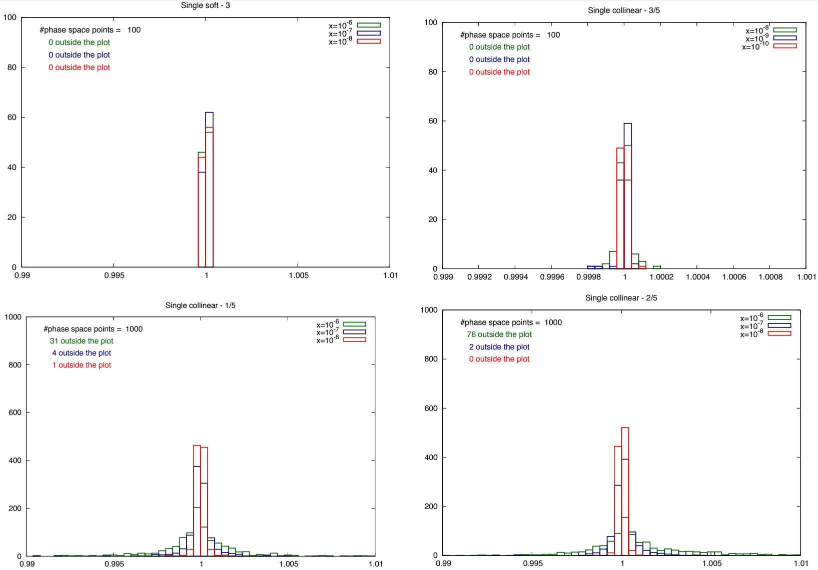








Real-virtual quark-gluon channel tests



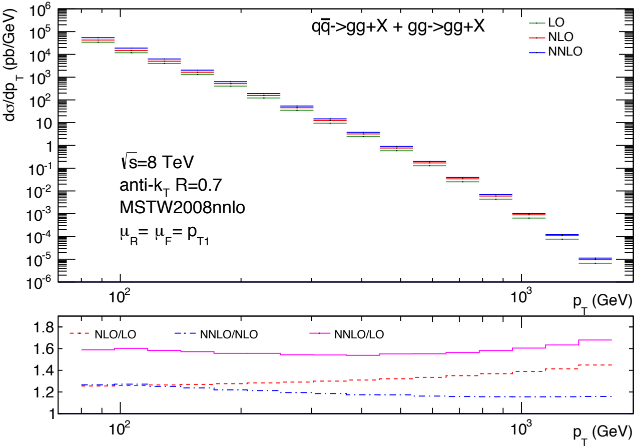
Preliminary dijet results

Preliminary results for full-colour "gluons only" scattering and leading colour $q\bar{q}$ scattering combined

Numerical setup and cuts:

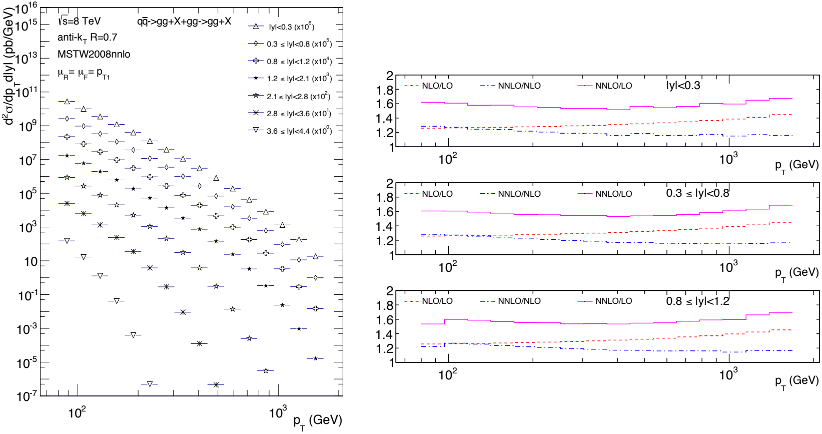
- leading jet transverse momentum $p_{T_1} > 80$ GeV
- all other jets with at least $p_T > 60$ GeV
- jets with rapidities $|y| < 4.4$ considered
- anti-k_T jet algorithm with $R = 0.7$
- all scales taken to be common dynamical scale $\mu = p_{T_1}$
- MSTW2008NNLO PDF set

Inclusive jet p_T distribution



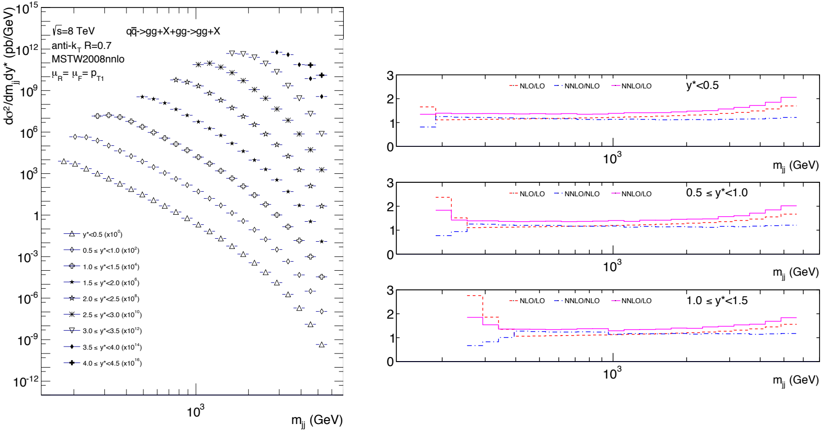
- NNLO correction between $\sim 15\%$ and 26% w.r.t NLO
- K-factor at high p_T brought under control

Double differential inclusive jet p_T distribution



- NNLO correction between ∼ 15% and 26% w.r.t NLO
- similar effects in other rapidity slices

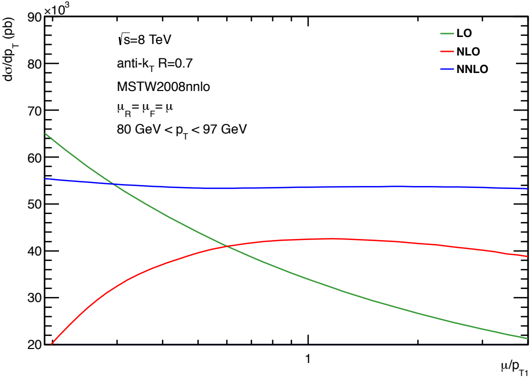
Double differential exclusive dijet distribution



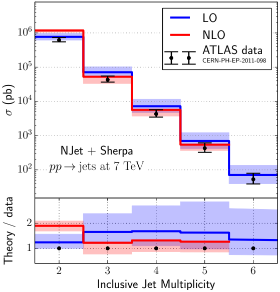
- NNLO correction $\sim 20\%$ w.r.t NLO
- similar effects in other y^* slices

Inclusive jet p_T scale dependence

Full colour gluons only contribution



Looking to the future

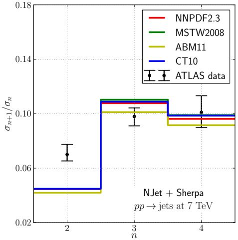


Gluons-only dijet cross section:

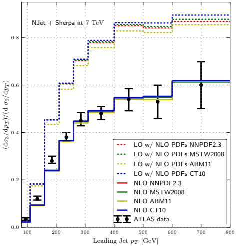
- LO: 4.82470×10^5 pb
- NLO: 8.52570×10^5 pb
- NNLO: 7.63620×10^5 pb

Gluons-only NNLO 3/2-jet?

- achievable in near future
- α_s determination



[Badger, Biedermann, Uwer, Yundin, '13]



Summary

Antenna subtraction a powerful and versatile method for NNLO:

- allows hadronic initial states
- can cope with several final-state jets
- analytic pole cancellation

Dijet observables have a lot to give:

- plentiful data
- much exciting phenomenology to do
- expect quark-gluon channel and phenomonological dijet results soon

Thank you for your attention!