NNLO corrections to jet production

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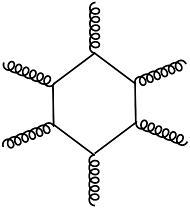
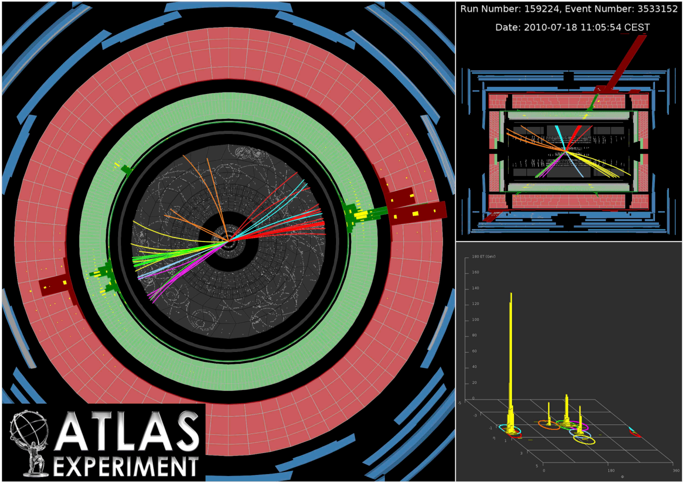


Jets in the real world

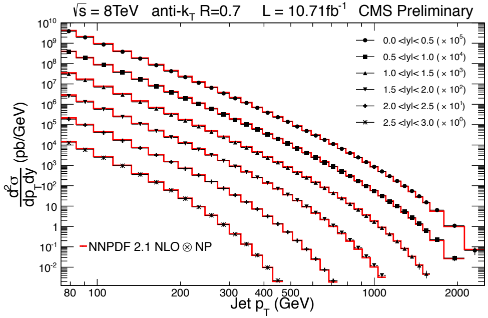


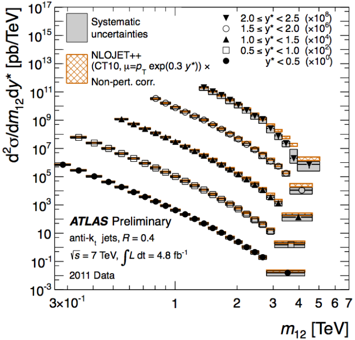
$m_{jj} \sim 2.55\text{TeV},\ p_{T_1} = 420\text{GeV},\ p_{T_2} = 320\text{GeV}$

Jets in the real world

Interested in cross sections in double differential form:

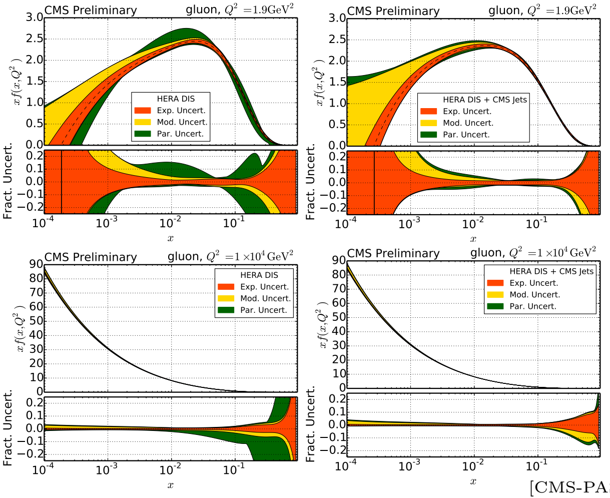
- single jet inclusive w.r.t p_T and $|y|$
- exclusive dijet w.r.t m_{jj} and y^*





Putting jets to work - PDFs

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

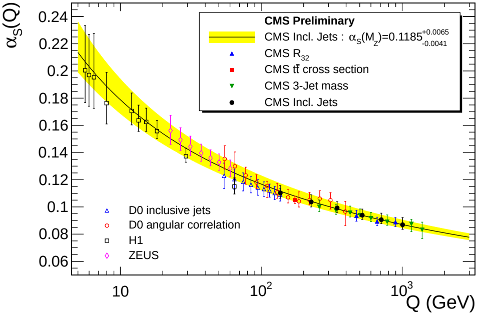


[CMS-PAS-SMP-12-028]

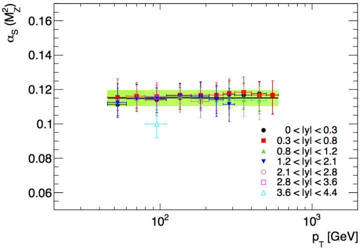
Putting jets to work - α_s

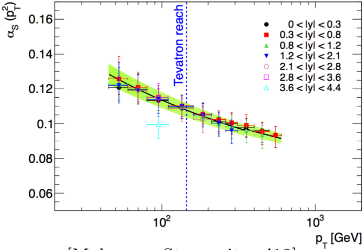
Can use single jet inclusive x-sec to fit:

- $\alpha_s(M_Z)$
- running coupling



[CMS-PAS-SMP-12-028]



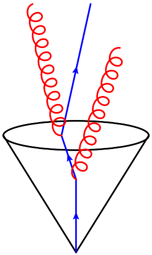


[Malaescu, Starovoitov '12]

Higher order corrections

Making the connection between real jets and theoretical jets:

- Large reduction in theoretical scale uncertainty
  - needed for a precise determination of α_s
- Improved perturbative convergence
- NNLO coefficient needed to fit NNLO PDFs
- Corrections change the normalization, but also the shape
- Jet algorithm much more realistic at NNLO
  - parton shower inside the jet using pQCD
  - additional jets from branching
- Initial-state radiation
  - more realistic final-state p_T, reduce the need for intrinsic p_T
- logarithmic corrections in pert. theory vs NP power corrections



We need NNLO pQCD corrections for a realistic simulation of the events

Recent developments

What have we been doing since Buenos Aires?

- colour explicit subtraction
  - see my radcor proceedings
- subtraction for sub-leading colour
- application to gluon scattering
  - full colour results for gluons-only
- leading colour $q\bar{q}$ channel
  - RR, RV and VV complete
- construction of `NNLOJET`

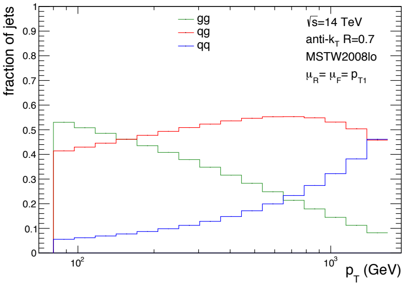
Gluon scattering

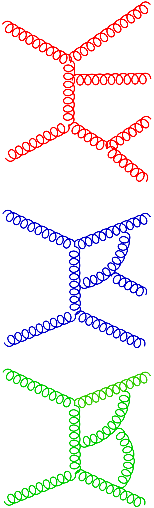
We consider the "gluons only" approximation:

- all external states are gluons, $N_F = 0$

leading colour:

- RR [Glover, Pires '10]
- RV [Gehrmann-De Ridder, Glover, Pires '11]
- VV [Gehrmann-De Ridder, Glover, Pires '12]





Gluon scattering - sub-leading colour

RR and RV matrix elements are colour incoherent interferences

$$
\begin{aligned}
|\boldsymbol{A}_6^0|^2 &= g^8 N^4 (N^2-1) \sum_{\sigma \in S_6/Z_6} \Big[A_6^0(\sigma) \\
&+ \frac{2}{N^2} \mathcal{A}_6^{0,\dagger}(\sigma) \Big(\mathcal{A}_6^0(\sigma') + \mathcal{A}_6^0(\sigma'') + \mathcal{A}_6^0(\sigma''') \Big) \Big]
\end{aligned}
$$

σ', σ'', σ''' have no common neighbours with σ, e.g.,

$$
\sigma' = (\sigma(1), \sigma(4), \sigma(2), \sigma(6), \sigma(3), \sigma(5))
$$

$$
|\boldsymbol{A}_5^1|^2 = g^8 N^4 (N^2-1) \sum_{\rho \in S_5/Z_5} \Big[A_5^1(\rho) + \frac{12}{N^2} 2\mathrm{Re}\Big(\mathcal{A}_5^{0,\dagger}(\rho) \mathcal{A}_{5,1}^1(\rho') \Big) \Big]
$$

- No collinear divergences
- only single and double soft singularities

Single soft limits of incoherent interferences

$$\mathcal{A}_6^{0,\dagger}(\cdots,a,i,b,\cdots)\mathcal{A}_6^0(\cdots,c,i,d,\cdots)\xrightarrow{i\to 0}$$
$$\frac{1}{2}\Big[S_{aid}+S_{bic}-S_{aic}-S_{bid}\Big]\mathcal{A}_5^{0,\dagger}(\cdots,a,b,\cdots)\mathcal{A}_5^0(\cdots,c,d,\cdots)$$

Promote each eikonal factor to an antenna,

$$+\frac{1}{2}X_3^0(a,i,d)\;\mathcal{A}_5^{0,\dagger}(\cdots,A,b,\cdots)\mathcal{A}_5^0(\cdots,c,D,\cdots)$$
$$+\frac{1}{2}X_3^0(b,i,c)\;\mathcal{A}_5^{0,\dagger}(\cdots,a,B,\cdots)\mathcal{A}_5^0(\cdots,C,d,\cdots)$$
$$-\frac{1}{2}X_3^0(a,i,c)\;\mathcal{A}_5^{0,\dagger}(\cdots,A,b,\cdots)\mathcal{A}_5^0(\cdots,C,d,\cdots)$$
$$-\frac{1}{2}X_3^0(b,i,d)\;\mathcal{A}_5^{0,\dagger}(\cdots,a,B,\cdots)\mathcal{A}_5^0(\cdots,c,D,\cdots)$$

- antennae contain collinear divergences
- cancel in the combination leaving only soft singularities

Double soft limits of incoherent interferences

Two types of soft singularity:

- colour connected $\sim S_{aijb}$ ... absent! $\Rightarrow$ no X_4^0 needed
- iterated single soft $\sim S_{aib} S_{cjd}$

$$\mathcal{SLC}\left(|\boldsymbol{A}_6^0|^2\right) \xrightarrow{5,6\to 0} g^8 N^4 (N^2-1)$$

$$\frac{1}{4}\Big[\Big(S_{153}+S_{254}-S_{154}-S_{254}\Big)\Big(S_{163}+S_{264}-S_{162}-S_{364}\Big)A_4^0(\hat{1},\hat{2},3,4)$$

$$+\Big(S_{153}+S_{254}-S_{154}-S_{254}\Big)\Big(S_{162}+S_{364}-S_{164}-S_{263}\Big)A_4^0(\hat{1},\hat{2},4,3)$$

$$+\Big(S_{152}+S_{354}-S_{154}-S_{253}\Big)\Big(S_{162}+S_{364}-S_{163}-S_{264}\Big)A_4^0(\hat{1},3,\hat{2},4)\Big]$$

- promote to X_3^0 antennae with appropriate PS mapping
- collinear divergences cancel leaving only soft singularities

Single soft limits of incoherent one-loop interferences

$$(1\text{--loop}) \quad \longrightarrow \quad (\text{tree} \times \text{loop}) + (\text{loop} \times \text{tree})$$

For SLC 5-gluon scattering, 1-loop soft gluon current absent!

- no X_3^1 needed
- same as tree-level factorization
- 1-loop reduced incoherent interferences

$$\begin{aligned}
+ \quad & X_3^0(a,i,c)\, \mathcal{A}_4^{0,\dagger}(\cdots, A, b, \cdots)\mathcal{A}_{4,1}^1(\cdots, C, d, \cdots) \\
+ \quad & X_3^0(b,i,d)\, \mathcal{A}_4^{0,\dagger}(\cdots, a, B, \cdots)\mathcal{A}_{4,1}^1(\cdots, c, D, \cdots) \\
- \quad & X_3^0(a,i,d)\, \mathcal{A}_4^{0,\dagger}(\cdots, A, b, \cdots)\mathcal{A}_{4,1}^1(\cdots, c, D, \cdots) \\
- \quad & X_3^0(b,i,c)\, \mathcal{A}_4^{0,\dagger}(\cdots, a, B, \cdots)\mathcal{A}_{4,1}^1(\cdots, C, d, \cdots)
\end{aligned}$$

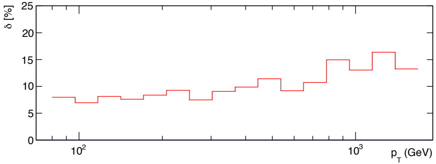
Sub-leading colour gluon scattering - summary

- no collinear divergences
- no X_4^0 or X_3^1 antennae needed
- but more complicated factorization pattern

"The Lord giveth and the Lord taketh away"

All challenges met:

- all divergences subtracted ✓
- poles cancelled analytically ✓
- stable numerical integration ✓
- overall positive $\sim 2\%$ correction

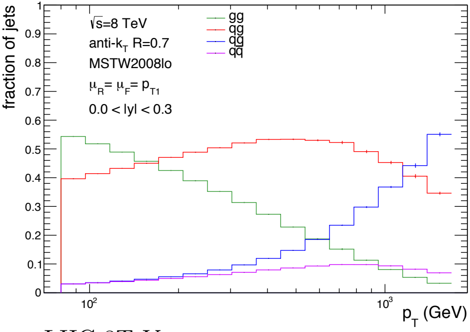


[Currie, Gehrmann-De Ridder, Glover, Pires '13]

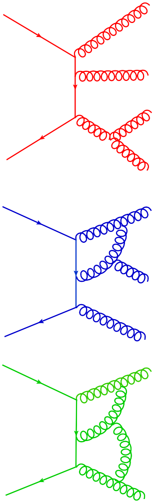
$q\bar{q}$ scattering into gluon jets

One of many channels that need to be added:

- complicated 4-gluon RR final state
- leading colour subtraction terms [Currie, Glover, Wells '13]



LHC 8TeV



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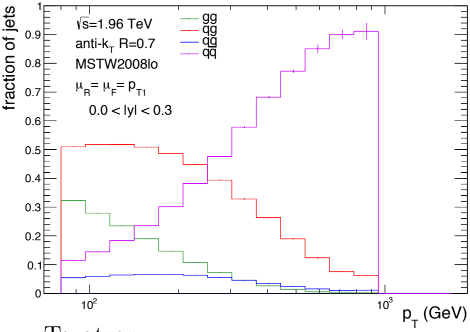
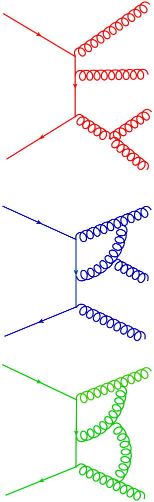


Tevatron



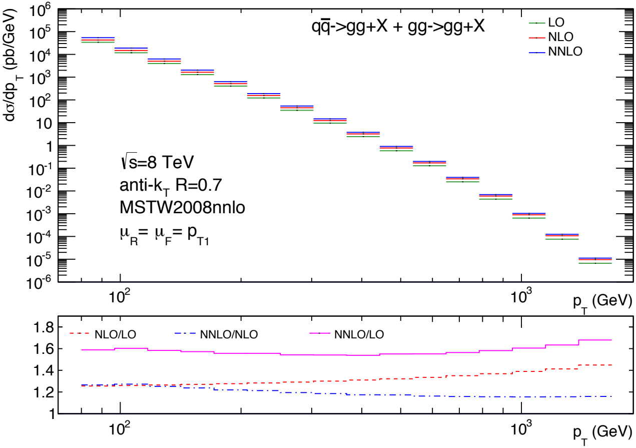
Preliminary results

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

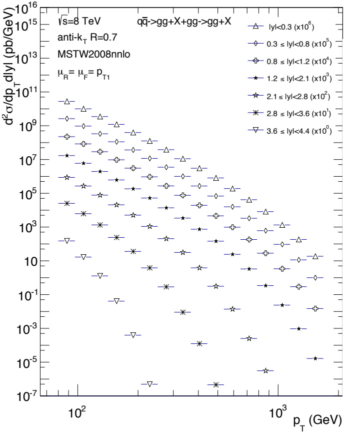
We show here preliminary results for full colour "gluons only" scattering and leading colour $q\bar{q}$ scattering combined

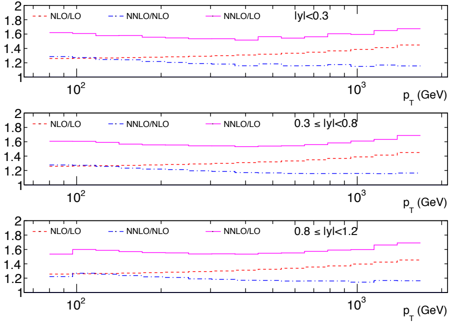
Inclusive jet p_T distribution



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

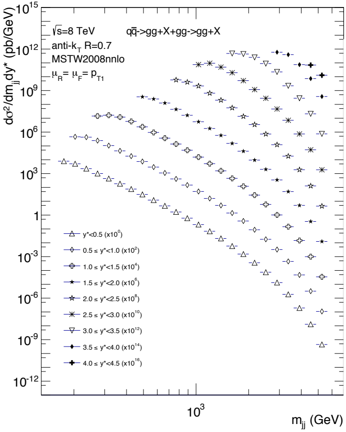
Double differential inclusive jet p_T distribution

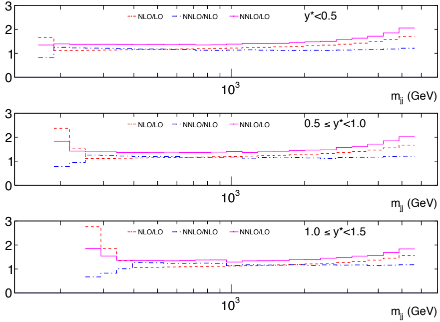




- NNLO correction between $\sim 15\%$ and 26% w.r.t NLO
- similar effects in other rapidity slices

Double differential exclusive dijet distribution

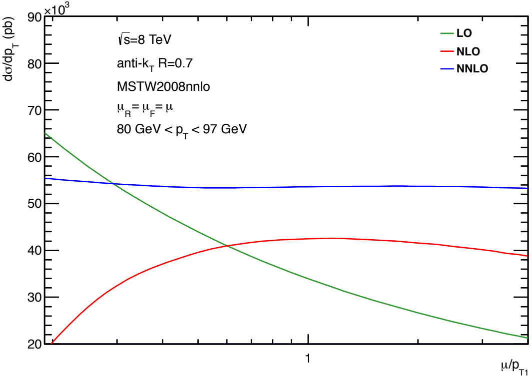




- NNLO correction $\sim 20\%$ w.r.t NLO
- similar effects in other y^* slices

Inclusive jet p_T scale dependence

Full colour gluons only contribution



Very slightly more variation than for leading colour

- SLC enters for the first time at NNLO

Summary

Much progress in 2013:

- first results for NNLO dijets
- numerical results for full colour gg and LC $q\bar{q} \to$ gluon jets
- antenna method extended to deal with sub-leading colour
- construction of `NNLOJET` well under way

Priorities for the future:

- quark-gluon channel - anticipate a significant effect
- N_F contributions at leading colour
- quark-quark channel - high p_T
- sub-leading colour, where necessary

Watch this space...