Higher-order QCD and EW corrections to jet production

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HL/HE-LHC WG1 Meeting

CERN — March 2nd 2018

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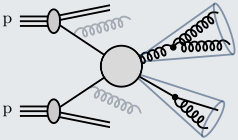
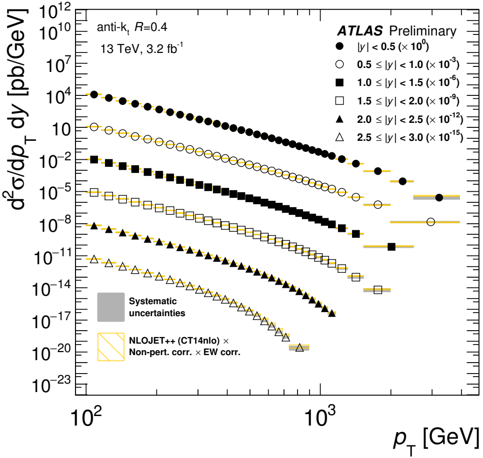
Jet Production at the LHC



$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{jet(s)} + X$

- jets produced in abundance
- precise measurements $(p_{\mathrm{T},j} \gtrsim 20 \text{ GeV})$
- wide kinematic range accessible

- test perturbative QCD
  ↪ study scale choices
- constrain PDFs
  ↪ sensitive to *gluon*
  ↪ probe wide x-range
- $\alpha_s(M_Z)$ and *running*
- search for BSM physics

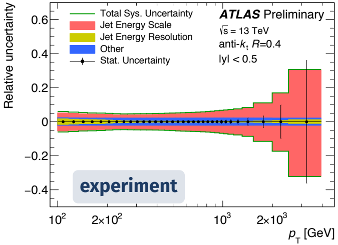


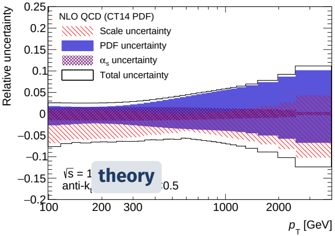
[ATLAS-CONF-2017-048]

Jet Production — Where do we stand?

(*very* incomplete list!)

- **NLO QCD** .... [Ellis, Kunszt, Soper '92] [Giele, Glover, Kosower '94] [Nagy '03]
- **NLO QCD** +PS (POWHEG) .... [Alioli, Hamilton, Nason, Oleari, Re '11]
- **NLO QCD** +Resummation .... [Dasgupta, Dreyer, Salam, Soyez '14] [Liu, Moch, Ringer '17]
- **NLO EW** .... [Dittmaier, AH, Speckner '12] [Campbell, Wackeroth, Zhou '16] [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro '17]
- **NNLO QCD** .... [Gehrmann-De Ridder, Gehrmann, Glover, Pires '13] [Currie, Gehrmann-De Ridder, Gehrmann, Glover, Pires, Wells '14] [Currie, Glover, Pires '16] [Currie, Gehrmann-De Ridder, Gehrmann, Glover, AH, Pires '17]



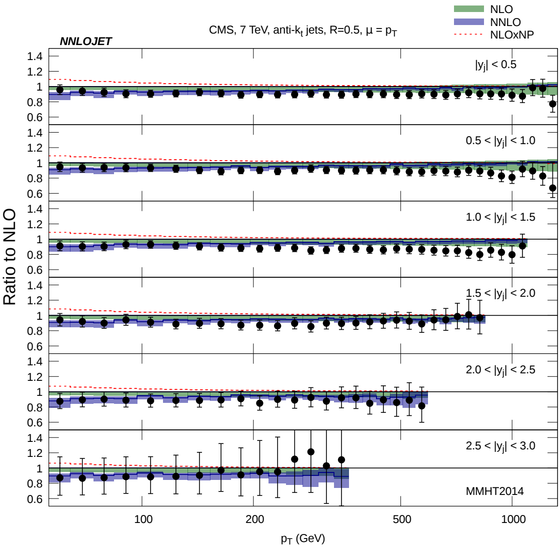


- up to $\sim 2\,\mathrm{TeV}$: sys. uncert. dominant
  ↪ jet energy scale ± 5–10%

NLO scale uncert. $\sim 10\,\%$
(limiting factor in α_s & PDF extraction)

- **NNLO needed!**

Inclusive Jet Production — CMS @ 7 TeV $(R = 0.5)$



NLO $(\rightsquigarrow 1)$

NNLO

NLO $\times$ **NP**

$\hookrightarrow$ high p_T:

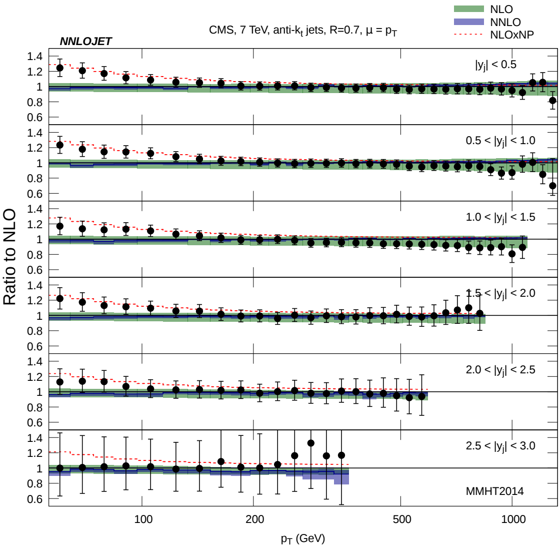
- small corrections: few %
- reduction of scale uncert.
- convergence of pert. series (central rapidity)

$\hookrightarrow$ low p_T:

- sizeable corrections: -10% (across rapidity bins)
- scale bands: NNLO $\simeq$ NLO (non-overlapping)
- NP effects relevant for $p_T \lesssim 100$ GeV
- NLO: asymmetric scale bands!

similar to ATLAS $(R = 0.4)$

Inclusive Jet Production — CMS @ 7 TeV $(R = 0.7)$



NLO $(\rightsquigarrow 1)$

NNLO

NLO $\times$ **NP**

larger cone size:

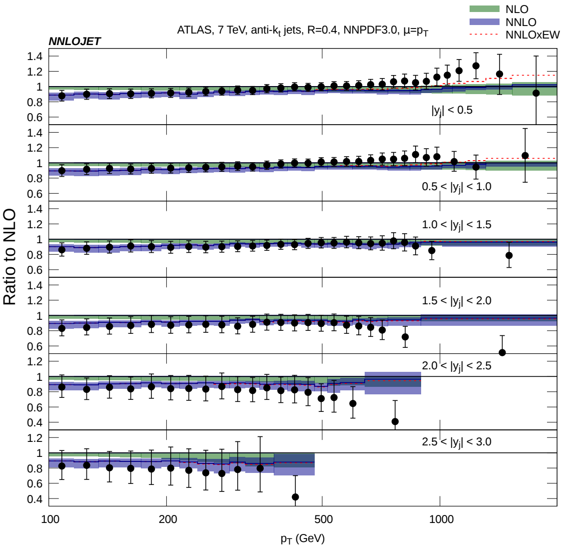
$\hookrightarrow$ stabilization of corrections:

- small NNLO corrections
- reduction of scale uncert.
- good pert. convergence
- across *all* p_{T}

$\hookrightarrow$ NP corrections:

- sizable at low-p_{T} $(R = 0.7)$

Inclusive Jet Production — ATLAS @ 7 TeV



NLO $(\rightsquigarrow 1)$

NNLO

$\hookrightarrow$ high p_T:

- small corrections: few %
- reduction of scale uncert.
- convergence of pert. series (central rapidity)

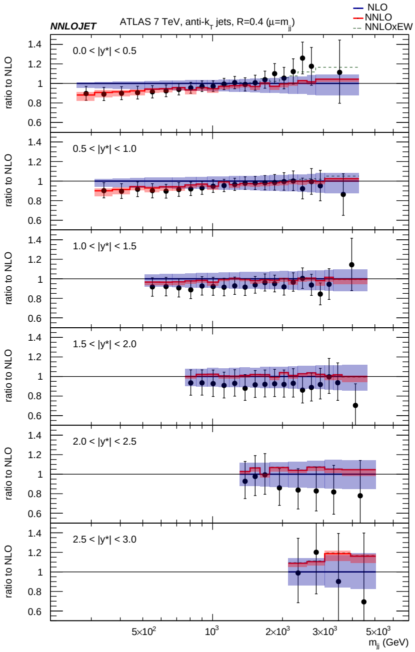
$\hookrightarrow$ low p_T:

- sizeable corrections: -10% (across rapidity bins)
- scale bands: NNLO $\gtrsim$ NLO (non-overlapping)
- NLO: asymmetric scale bands!

EW corrections - - - -
small – moderate @ high p_T & central rapidity

*no non-pert. corrections

Dijet Production — ATLAS @ 7 TeV ($R = 0.4$)



NLO ($\rightsquigarrow 1$)

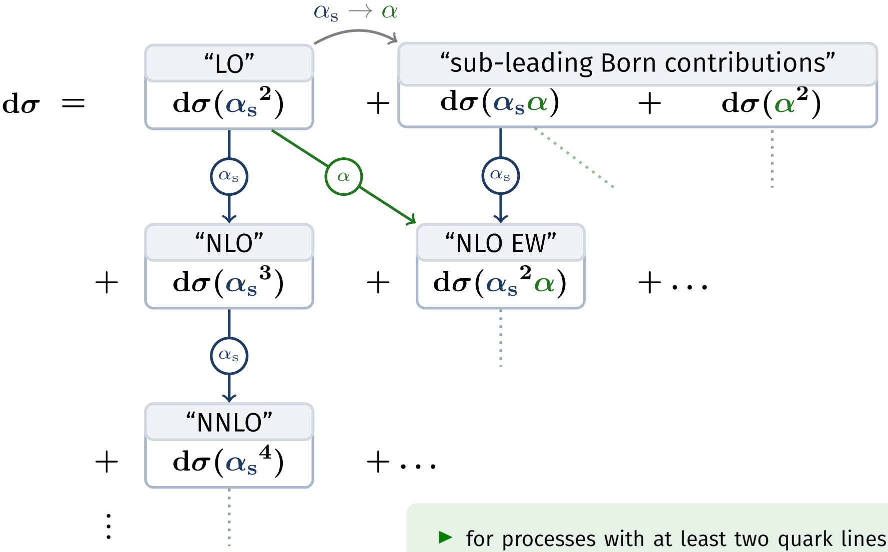
NNLO

- typically $\lesssim 10\%$
- relatively flat
- large reduction of scale uncert.

$\hookrightarrow$ low m_{jj} & low $|y^*|$:

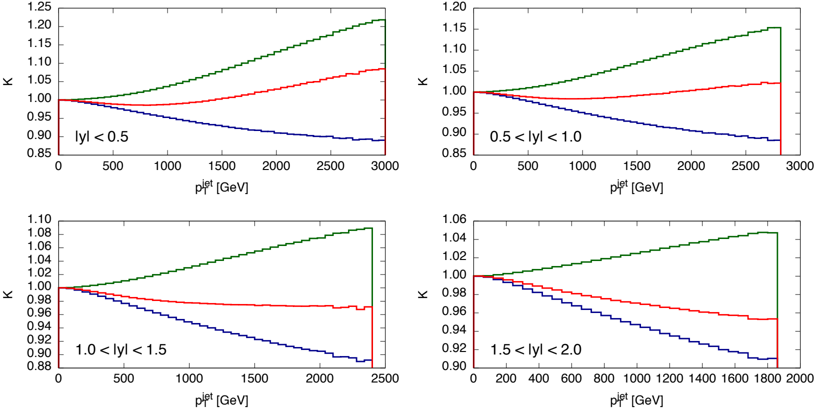
- shape distorted by NNLO
- scale bands: NNLO $\simeq$ NLO (NLO: asymmetric again)
- better data–theory agreement

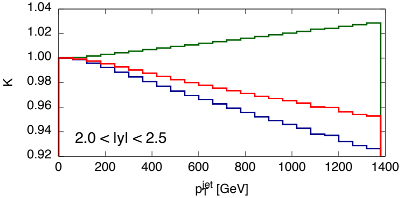
Perturbative power counting



- for processes with at least two quark lines
- no separation of QCD & EW corrections
- instead consider a fixed *perturbative order*

Inclusive jet production





$K_{\mathrm{EW}}^{\mathrm{tree}}$

$K_{\mathrm{weak}}^{1-\mathrm{loop}}$

} large cancellations

$K \equiv K_{\mathrm{EW}}^{\mathrm{tree}} \cdot K_{\mathrm{weak}}^{1-\mathrm{loop}}$

$+10\%$ $(|y| < 0.5)$

-5% $(2.0 < |y| < 2.5)$

Summary & Outlook

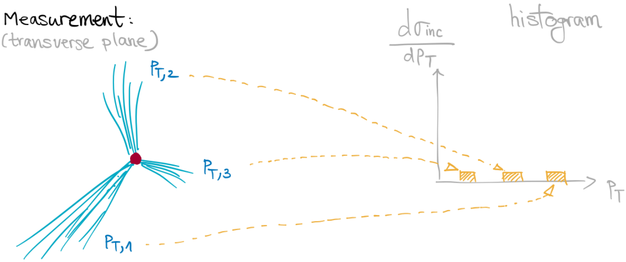
NNLO QCD & NLO EW corrections for jet production

- inclusive-jet production:
  - ↪ intermediate – high p_{T}: good perturbative convergence (NLO → NNLO)
  - ↪ low p_{T}: larger scale uncertainties & scale ambiguities ($p_{\mathrm{T},1}$ vs. p_{T})
- dijet production:
  - ↪ inclusion of NNLO largely removes scale ambiguities (even for $\langle p_{\mathrm{T}} \rangle$)
  - ↪ improvement in comparison to data
- EW corrections:
  - ↪ accidental cancellations between "sub-leading Born" and "Sudakov logs"
  - ⇒ small – moderate @ high-p_{T}, -m_{jj} and central rapidities

Thank you

Backup Slides

Inclusive Jet Production



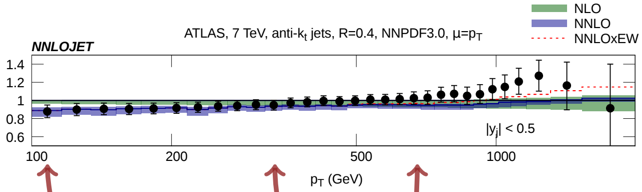
$\left\{ \begin{array}{c} n \text{ reconstructed jets} \\ \text{in the event} \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} n \text{ binnings to} \\ \text{the histogram} \end{array} \right\} \Rightarrow \sum_{\text{bins}} \frac{d\sigma_{\text{inc}}}{dp_T} \neq \sigma_{\text{tot}}$

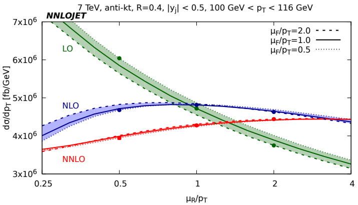
scale choices ⇝ **binning of *individual jets* vs. *events***

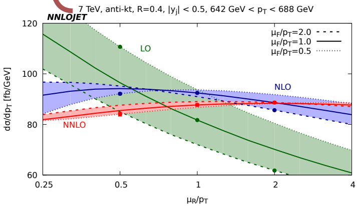
- "global" scales (event): $p_{T,\max}$, $\langle p_T \rangle, \ldots$
- "local" scales (jet): $p_T, \ldots$

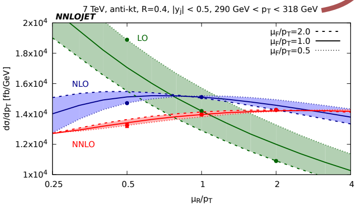
Inclusive Jet Production — Scale Variation

$|y_j| < 0.5$









NLO: turn-over @ $\mu_\mathrm{R}/p_\mathrm{T} \sim 0.5\text{–}1$

↪ asymmetric bands

↪ pert. uncert. underestimated?!

NNLO: monotonic behaviour

↪ symmetric bands

solid: analytic RGE, *points:* NNLOJET

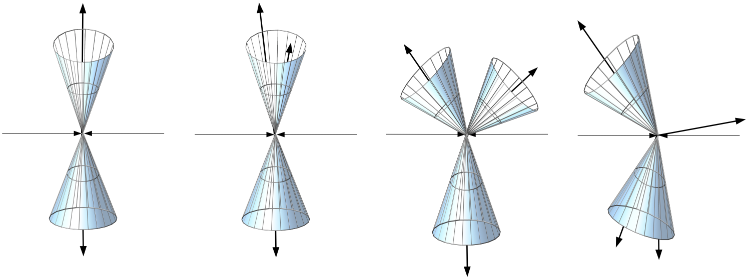
Inclusive Jet Production — Scale Choices

Two common scale choices

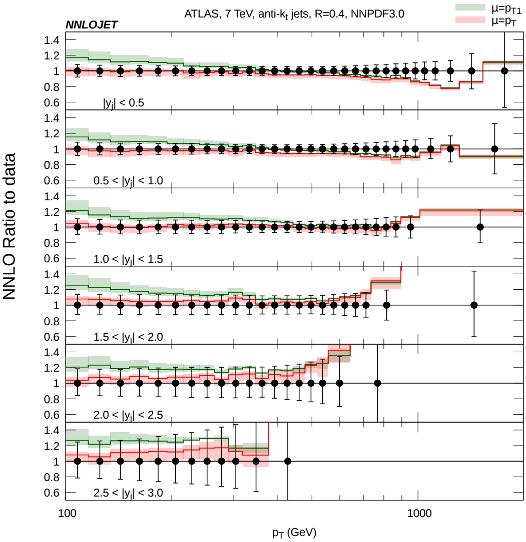
$p_{\mathrm{T,max}}$ the *leading-jet* transverse momentum

p_{T} transverse momentum of the *individual jets*

- identical at LO ($2 \to 2$ kinematics)
- high-p_{T} jets are mostly back-to-back: $\Rightarrow\ p_{\mathrm{T,max}} \sim p_{\mathrm{T}}$
- differences:
  $\hookrightarrow$ ≥ 3 jets in the event
  $\hookrightarrow$ jets outside of fiducial cuts
- sensitive to the cone size R



Inclusive Jet Production — $p_{\mathrm{T,max}}$ vs. p_{T}



Inclusive Jets @ NNLO

$\mu_0 = p_{\mathrm{T,max}}$

$\mu_0 = p_{\mathrm{T}}$

high p_{T}: both scales coincide

(as expected)

low p_{T}: significant differences 15–20%

$\hookrightarrow$ $p_{\mathrm{T,max}}$ away from data

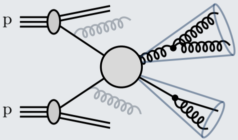
$\hookrightarrow$ p_{T} in line with data

(non-overlapping bands)

large effects from scale ambiguity!

$\Rightarrow$ requires more studies!

Dijet Production



$\mathrm{p} + \mathrm{p} \;\to\; 2\ \text{jets} + X$ (# jets $\geq$ 2)

j_1: leading jet
j_2: sub-leading jet
$\rightsquigarrow$ dijet system

- $m_{jj} = (p_{j_1} + p_{j_2})^2$
- $y^* = \dfrac{1}{2}\,(y_{j_1} - y_{j_2})$

$m_{jj} = 2\,p_{\mathrm{T}} \cosh y^*$ (back-to-back)

$\hookrightarrow$ scattering angle in part. system $\leftrightarrow$ x smeared out

- sensitivity to x:

$$\bar{y} = \frac{1}{2}\,(y_{j_1} + y_{j_2})$$ longitudinal boost

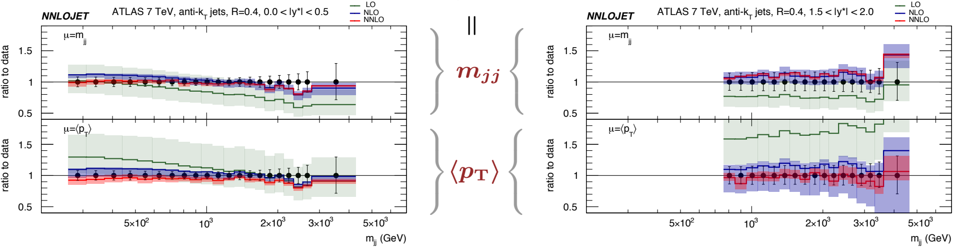
$$y_{\max} = \max\,(y_{j_1},\, y_{j_2})$$ scattering angle in lab

scale choices

m_{jj}, $\langle p_{\mathrm{T}} \rangle = \frac{1}{2}(p_{\mathrm{T},1} + p_{\mathrm{T},2})$, $p_{\mathrm{T},1}$, $p_{\mathrm{T},1}\, \mathrm{e}^{-0.3 y^*}$, $m_{jj}/2$, ...

Dijet Production — m_{jj} vs. $\langle p_T \rangle$

$\mathbf{0.0 < |y^*| < 0.5}$ $\qquad\qquad$ $\boldsymbol{\mu_0}$ $\qquad\qquad$ $\mathbf{1.5 < |y^*| < 2.0}$



LO $\qquad$ NLO $\qquad$ NNLO

small $|y^*|$:

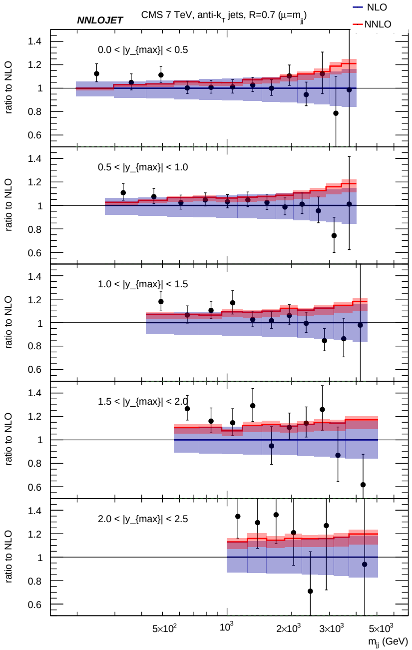
- both scales give reasonable predictions:
  - $\hookrightarrow$ overlapping bands, perturbateive convergence, …

large $|y^*|$:

- m_{jj}: similarly good to small $|y^*|$
- $\langle p_T \rangle$: large NLO corrections with huge scale uncertainties
  - $\hookrightarrow$ for $|y^*| > 2.0$ even *negative* cross sections @ NLO!
  - $\hookrightarrow$ inclusion of NNLO resolves these issues

$\rightsquigarrow$ choose $\mu_0 = m_{jj}$ $\quad$ (based on pert. convergence and residual scale uncertainties)

Dijet Production — CMS @ 7 TeV



NLO ($\rightsquigarrow 1$)

NNLO

- large reduction of scale uncert.
- overlapping bands

↪ low $|y_{\mathrm{max}}|$:

- shape distorted by NNLO
- small @ low-m_{jj}
- $+20\%$ @ high-m_{jj}

↪ high $|y_{\mathrm{max}}|$:

- relatively flat: 10–20%

↪ NP corrections $\sim$ 5–10% @ low-m_{jj}

scales in dijet production
better behaved

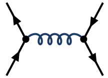
Perturbative power counting: In a “QCD world” ...

$$d\sigma = \underbrace{d\sigma(\alpha_s{}^2)}_{\text{“LO”}} + \underbrace{d\sigma(\alpha_s{}^3)}_{\text{“NLO”}} + \underbrace{d\sigma(\alpha_s{}^4)}_{\text{“NNLO”}} + \ldots$$

“LO” $d\sigma(\alpha_s{}^2)$ → α_s → “NLO” $d\sigma(\alpha_s{}^3)$ → α_s → “NNLO” $d\sigma(\alpha_s{}^4)$ ⋮

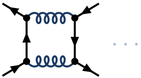
Example: $u\bar{u} \to d\bar{d}$

tree



$\mathcal{O}(\alpha_s)$

1-loop



$\mathcal{O}(\alpha_s{}^2)$

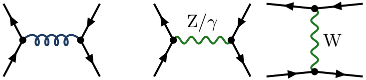
⋮

Perturbative power counting: … with EWK interactions

$$d\sigma = d\sigma(\alpha_s^2)$$
$$+ \; d\sigma(\alpha_s^3)$$
$$+ \; d\sigma(\alpha_s^4)$$
$$\vdots$$

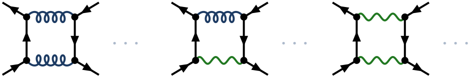
Example: $u\bar{u} \to d\bar{d}$

tree



$\mathcal{O}(\alpha_s)$ $\quad$ $\mathcal{O}(\alpha)$

1-loop

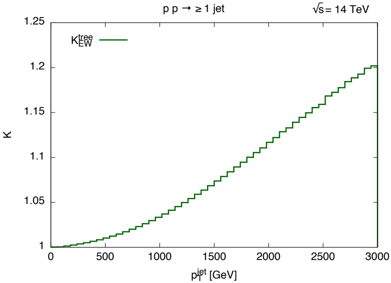


$\mathcal{O}(\alpha_s^2)$ $\quad$ $\mathcal{O}(\alpha_s\alpha)$ $\quad$ $\mathcal{O}(\alpha^2)$

$\vdots$

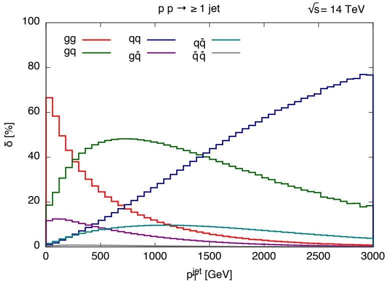
Sub-leading Born contributions

$$K_{\mathrm{EW}}^{\mathrm{tree}} \equiv \frac{\mathrm{d}\sigma(\alpha_s{}^2 + \alpha_s\alpha + \alpha^2)}{\mathrm{d}\sigma(\alpha_s{}^2)} \equiv \frac{\mathrm{d}\sigma^0}{\mathrm{d}\sigma^0_{\mathrm{QCD}}}$$



Inclusive jet production

- total cross section $\lesssim 0.1\%$
- large impact on high-p_T tail
  $\hookrightarrow \sim 20\%$ for $p_T = 3$ TeV



- partonic channels
  - gg
  - gq
  - $g\bar{q}$
  - $q\bar{q}$ $\begin{cases} q\bar{q} \to gg \\ q_1\bar{q}_2 \to q_3\bar{q}_4 \end{cases}$
  - $\bar{q}\bar{q}$
  - qq

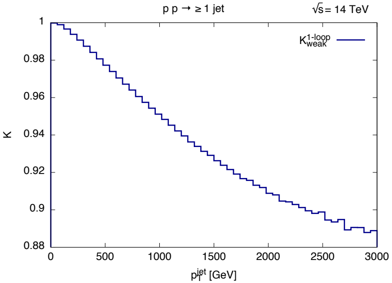
  (gg, gq, $g\bar{q}$, $q\bar{q} \to gg$): $K_{\mathrm{EW}}^{\mathrm{tree}} \equiv 0$

  ($q_1\bar{q}_2 \to q_3\bar{q}_4$, $\bar{q}\bar{q}$, qq): $K_{\mathrm{EW}}^{\mathrm{tree}} \neq 0$

- α_s running $(\mu_R = p_{T,1})$

NLO EW corrections

$$K_{\rm weak}^{1-\rm loop} \equiv \frac{d\sigma^0 + d\sigma({\alpha_s}^2\alpha)}{d\sigma^0}$$



Inclusive jet production

- negligible total cross section
- large impact on high-$p_{\rm T}$ tail
  $\hookrightarrow \sim -11\%$ for $p_{\rm T} = 3$ TeV

logarithmic enhancement $\longleftrightarrow$ "Sudakov regime": All sclaes $\hat{s}, |\hat{t}|, |\hat{u}| \gg M_{\rm W}^2$

Dijet invariant mass

high-m_{jj} tail:

- $\hat{s} \gg M_{\rm W}^2$
- dominated by forward regime $|\hat{t}|$ small

Inclusive-jet $p_{\rm T}$

high-$p_{\rm T}$ tail:

- $\hat{s} \gg M_{\rm W}^2$
- also $|\hat{t}|, |\hat{u}| \gg M_{\rm W}^2$

Dijet production