Weak radiative corrections to dijet production at the LHC

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in collaboration with

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Workshop on electroweak corrections for LHC physics

Durham, September 25th, 2012

Outline

Motivation

Dijet production at the LHC

Unprecedented energy regime accessible:

Sensitive up to $M_{12} \approx 5\,\mathrm{TeV}$, $k_\mathrm{T} \approx 2\,\mathrm{TeV}$ (LHC @ $7\,\mathrm{TeV}$)

- Test of the Standard Model prediction
- Search for physics beyond the SM
  (composite quarks, heavy gauge bosons W', Z',...)

Hadron Collider

- QCD effects dominant
- Electroweak corrections suppressed by smaller coupling: $\alpha < \alpha_\mathrm{s}$
- Weak corrections: Sudakov logarithms (+ subleading logs)
  $\alpha_\mathrm{w} \ln^2\left(\frac{Q^2}{M_\mathrm{W}^2}\right)$, $\alpha_\mathrm{w} = \frac{\alpha}{\sin\theta_\mathrm{w}}$, Q^2: typical scale of hard scattering reaction
  (massless gauge bosons $\leftrightarrow$ IR singularities (cancel in phys. observables))
- Corrections sensitive to high scales should be investigated.

Motivation

Theoretical status

- Leading order $\mathcal{O}(\alpha_s^2)$ [Combridge, Kripfganz, Ranft '77]
- NLO QCD corrections $\mathcal{O}(\alpha_s^3)$
  [Ellis, Sexton '86], [Ellis, Kunszt, Soper '92], [Giele, Glover, Kosower '94]
- Currently substantial effort put into NNLO QCD $\mathcal{O}(\alpha_s^4)$
  [Gehrmann-De Ridder, Gehrmann, Glover '05], [Gehrmann, Monni '06], [Daleo, Gehrmann, Maitre '07], [Luisoni, Daleo, Gehrmann-De Ridder, Gehrmann '10]
- NLO Weak corrections $\mathcal{O}(\alpha_s^2\alpha)$:
  Single-jet inclusive [Moretti, Nolten, Ross '06]
  Dijet (preliminary results) [Scharf et al. '09]

Contributing Subprocesses

Process classes: Tree level

- $g + g \to g + g \quad [\mathcal{O}(\alpha_s)]$
- $g + g \to q + \bar{q} \quad [\mathcal{O}(\alpha_s)]$
- $q_1 + \bar{q}_2 \to q_3 + \bar{q}_4 \quad (V_{\mathrm{CKM}})_{ij} = \delta_{ij}, \quad (q = \mathrm{u, d, c, s, b})$
  - $u_i + \bar{d}_i \to u_i + \bar{d}_i \quad [\mathcal{O}(\alpha_s), \mathcal{O}(\alpha)]$
  - $u_i + \bar{d}_i \to u_j + \bar{d}_j$, different generation $(i \neq j) \quad [\mathcal{O}(\alpha)]$
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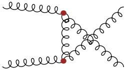
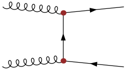
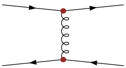
(+ crossed processes)

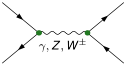
Squared Matrixelement

$|\mathcal{M}^{\mathrm{B}}|^2$: $\mathcal{O}(\alpha_s^2)$, $\mathcal{O}(\alpha_s \alpha)$, $\mathcal{O}(\alpha^2)$









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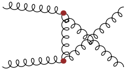

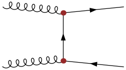

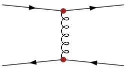

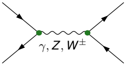

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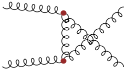

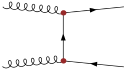

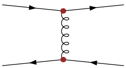

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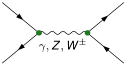


Calculational Setup

Next-to-Leading Order: $\mathcal{O}(\alpha_s^2\alpha)$

Each term can be uniquely assigned to contributions that includes *either* a photon *or* a weak gauge boson: $\sigma^{\mathrm{NLO}} = \sigma_\gamma^{\mathrm{NLO}} + \sigma_{\mathrm{weak}}^{\mathrm{NLO}}$

- $\sigma_\gamma^{\mathrm{NLO}}$ gauge-invariant subset $(SU(3)_{\mathrm{C}} \times U(1)_{\mathrm{QED}})$
- $\Rightarrow \sigma_{\mathrm{weak}}^{\mathrm{NLO}} = \sigma^{\mathrm{NLO}} - \sigma_\gamma^{\mathrm{NLO}}$ gauge-invariant! $\rightarrow \mathcal{O}(\alpha_s^2\alpha_{\mathrm{w}})$ (in this work)

- G_μ scheme:

$$\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_{\mathrm{W}}^2 \left(1 - \frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2}\right)$$

- Complex-mass scheme:

[Denner, Dittmaier, Roth, Wackeroth '99], [Denner, Dittmaier, Roth, Wieders '05]

$$M_V^2 \rightarrow \mu_V^2 = M_V^2 - \mathrm{i} M_V \Gamma_V, \quad V = \mathrm{W}, \mathrm{Z}$$

$$\cos^2\theta_{\mathrm{w}} \equiv c_{\mathrm{w}}^2 = \frac{\mu_{\mathrm{W}}^2}{\mu_{\mathrm{Z}}^2}, \quad \sin^2\theta_{\mathrm{w}} \equiv s_{\mathrm{w}}^2 = 1 - c_{\mathrm{w}}^2$$

Calculational Setup

Two independent calculations (in mutual agreement)

1st calculation [AH]

- All tree contributions by hand Weyl–van-der-Waerden spinor formalism
- Virtual corrections: FEYNARTS 3.6 [Hahn '01] FORMCALC 6.2 [Hahn, Perez-Victoria '99]
- Loop integrals: LOOPTOOLS 2.4 (modified) [Hahn, Perez-Victoria '99] or COLLIER [Denner, Dittmaier]
- Integration VEGAS [Lepage '78]

2nd calculation

[S. Dittmaier, C. Speckner]

- Born, Virtual corrections: FEYNARTS 1.0 [Kublbeck, Bohm, Denner '90] in-house MATHEMATICA routines
- Real corrections, dipoles: O'MEGA [Moretti, Ohl, Reuter '01]
- Loop integrals: COLLIER [Denner, Dittmaier]
- Integration VAMP [Ohl '99]
- IR regulator: DimReg or mass

Virtual Corrections

Virtual corrections

- UV divergences regularized dimensionally ($D = 4 - 2\epsilon$)
- Renormalization scheme: On-shell, $\overline{\text{MS}}$ for α_s
- IR divergences in DimReg (2nd calculation: optionally mass regularization)

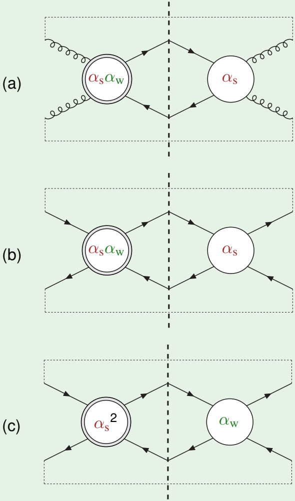
$g + g \to q + \bar{q}$ (a)

- purely weak corrections to the LO $\mathcal{O}(\alpha_s^2)$ cross section.

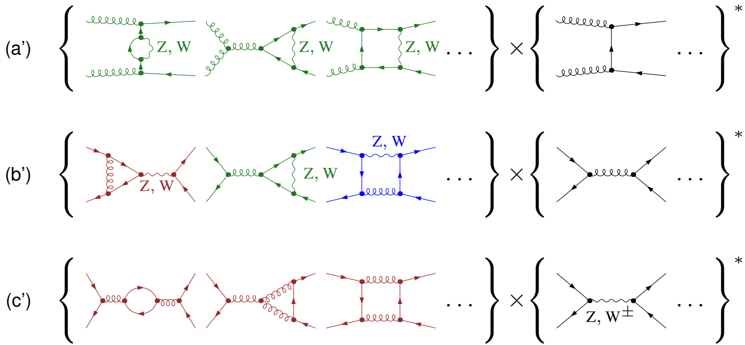
$q_1 + \bar{q}_2 \to q_3 + \bar{q}_4$ (b,c)

- LO amplitudes of $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_w)$
- Two types of interference terms contribute

Interference diagrams



Virtual Corrections

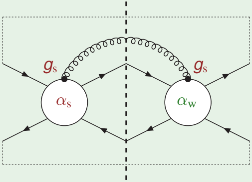


Weak corrections (IR finite)

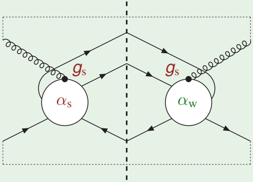
QCD corrections
Mixed
} (IR divergent) ↔ Real corrections

Real Corrections

Real corrections



$q_1 + \bar{q}_2 \rightarrow q_3 + \bar{q}_4 + g$

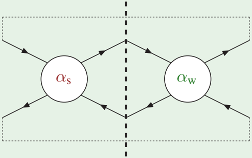


$g + q_1 \rightarrow q_2 + q_3 + \bar{q}_4$

Subtraction Method [Catani, Seymour ’97]

$$\hat{\sigma}^{\mathrm{NLO}} = \int_3 \mathrm{d}\sigma^{\mathrm{R}} + \int_2 \mathrm{d}\sigma^{\mathrm{V}} + \int_2 \mathrm{d}\sigma^{\mathrm{C}} = \int_3 \left[\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{A}}\right] + \int_2 \left[\mathrm{d}\sigma^{\mathrm{V}} + \mathrm{d}\sigma^{\mathrm{C}} + \int_1 \mathrm{d}\sigma^{\mathrm{A}}\right]$$

$$\mathrm{d}\sigma^{\mathrm{A}} = \sum_{\text{dipoles}} \Bigg($$



$$\otimes \underbrace{\mathrm{d}V_{\text{dipole}}}_{\mathcal{O}(\alpha_s)} \Bigg)$$

Calculational setup

- Renormalization & Factorization scale: $\mu_R = \mu_F \equiv \mu = k_{T,1}$
- Basic cuts: $|y_{jet}| < 2.5, \quad k_{T,jet} > 25\,\text{GeV}$
- Bottoms $\approx 3\%$

Notation

Leading-order cross sections:

- σ^0: Full LO cross section through $\mathcal{O}(\alpha_s^2,\, \alpha_s\alpha,\, \alpha^2)$
- σ^0_{QCD}: LO QCD cross section through $\mathcal{O}(\alpha_s^2)$

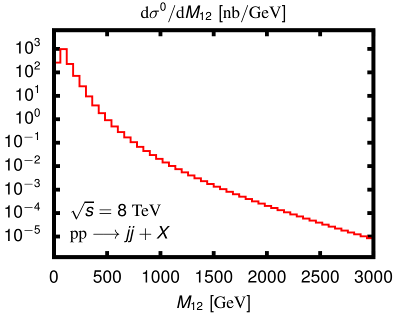
$$\sigma^0 = \sigma^0_{QCD} \times (1 + \delta^{tree}_{EW})$$

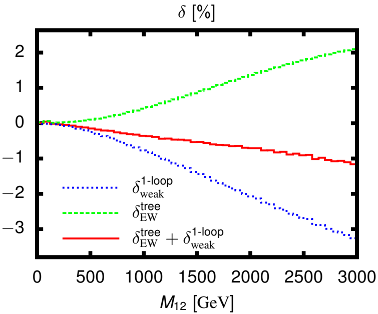
(Remaining $\mathcal{O}(\alpha_s\alpha,\, \alpha^2)$ contribution as a correction)

Next-to-leading order cross section:

$$\sigma^{NLO} = \sigma^0 \times (1 + \delta^{1\text{-loop}}_{weak}) \simeq \sigma^0_{QCD} \times (1 + \delta^{tree}_{EW} + \delta^{1\text{-loop}}_{weak})$$

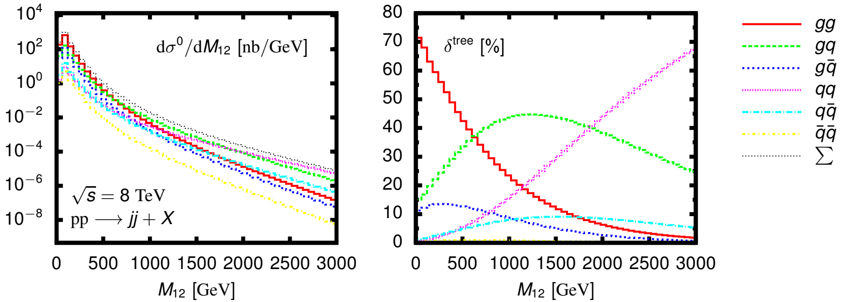
The dijet invariant mass M_{12}





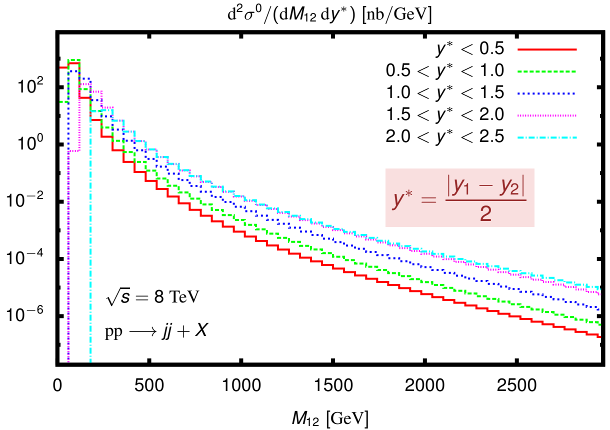
- Rapid decrease for higher M_{12} $\Rightarrow$ cross section & corrections dominated by the region with the lowest accepted M_{12} values
- Large cancellations between $\delta^{\text{1-loop}}_{\text{weak}}$ and $\delta^{\text{tree}}_{\text{EW}}$
- $\delta^{\text{1-loop}}_{\text{weak}}$ smaller than expected for typical Sudakov corrections
  - Sudakov regime: All scales $\hat{s}, |\hat{t}|, |\hat{u}| \gg M_W^2$
  - Here: Regge (forward) regime: $\hat{s}$ large, $|\hat{t}|$ remains small

The dijet invariant mass M_{12}: LO channels



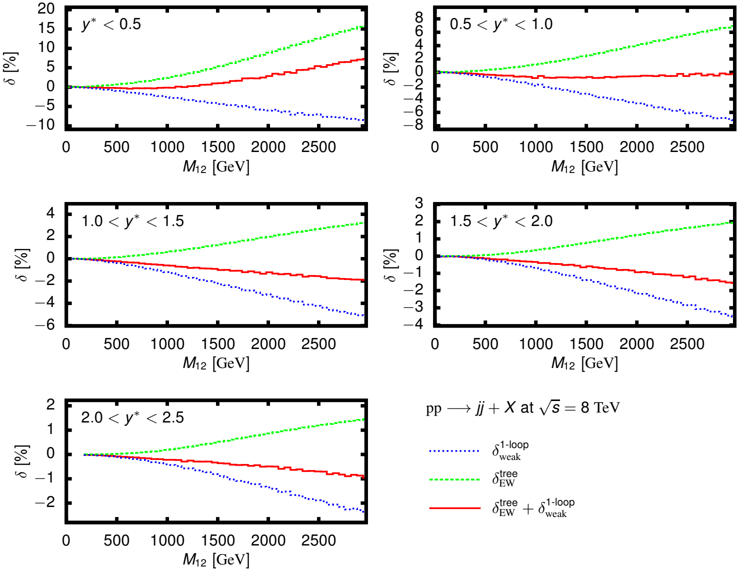
- Low M_{12}: gg, gq channels dominant $\quad \delta_{EW}^{tree} \equiv 0$
- High M_{12}: qq channel dominant $\quad \delta_{EW}^{tree} \neq 0$

The dijet invariant mass M_{12} (y^* binning)

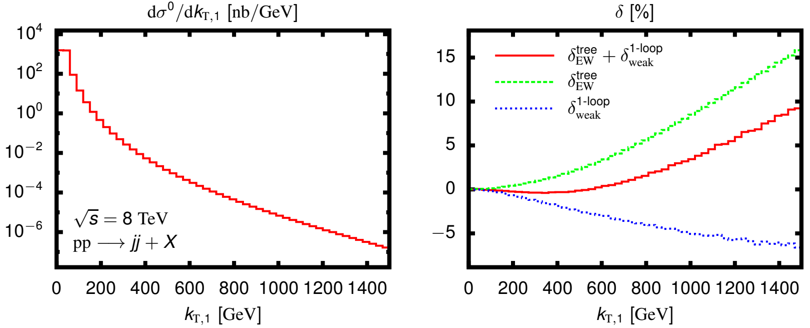


- $|\hat{y}_1| = |-\hat{y}_2| = y^*, \quad \hat{s} = M_{12}^2, \quad \hat{t} = -\frac{M_{12}^2}{1 + e^{\pm 2y^*}}, \quad \hat{u} = -\frac{M_{12}^2}{1 + e^{\mp 2y^*}}$
  ($2 \to 2$ kinematics)
- Small y^* (Sudakov regime) suppressed in the high M_{12} tail

The dijet invariant mass M_{12} (y^* binning)

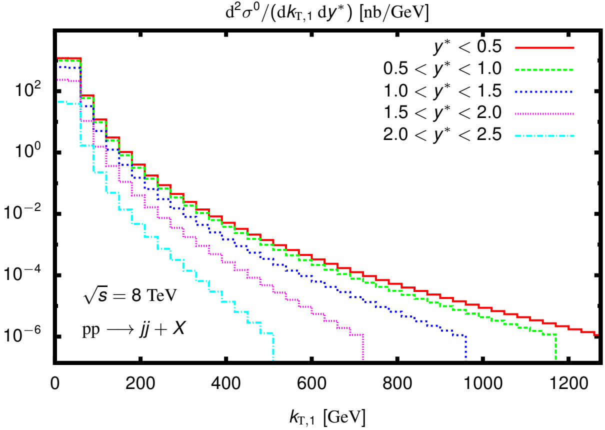


The leading jet $k_{T,1}$



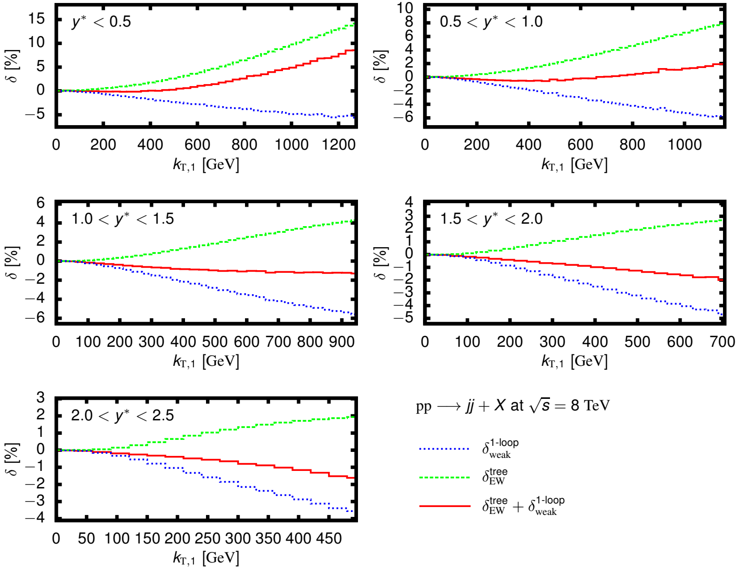
- $k_{T,1} = \dfrac{M_{12}}{2\cosh(y^*)}$ (2 → 2 kinematics)
- high $k_{T,1} \rightarrow$ Sudakov regime

The leading jet $k_{\mathrm{T},1}$ (y^* binning)

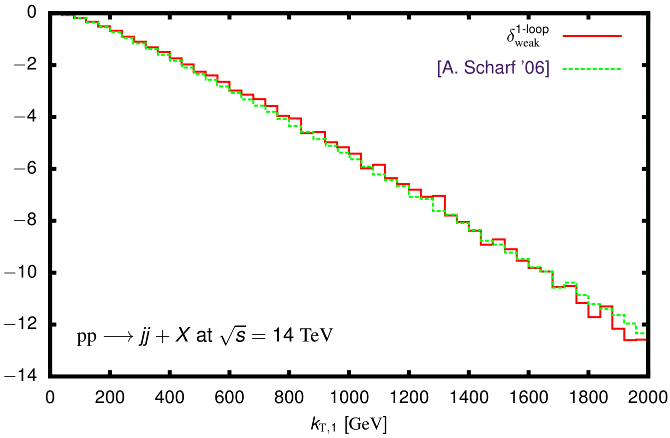


- For higher $k_{\mathrm{T},1}$, jets required to be produced more central.

The leading jet $k_{T,1}$ (y^* binning)



Comparison to other work



Summary and Outlook

Weak corrections

- Negligible in the total cross section (below per-cent level)
- Differential distributions strongly affected (Sudakov logarithms)
- Can reach $\sim 10\%$ (At TeV scales)
- Definition of the observable
  - M_{12} based: Regge regime $\rightarrow$ smaller corrections
  - k_{T} based: Sudakov regime $\rightarrow$ larger corrections
- Large cancellations between $\delta_{\mathrm{EW}}^{\text{tree}}$ and $\delta_{\mathrm{weak}}^{\text{1-loop}}$
  - Inclusion of only $\delta_{\mathrm{EW}}^{\text{tree}}$ strongly discouraged
  - cut dependence $\rightarrow$ full calculation needed

Outlook

- Not (yet?) included: photonic contributions (no recent photon PDFs)
- Real radiation of weak gauge bosons (highly dependent on the experimental setup)

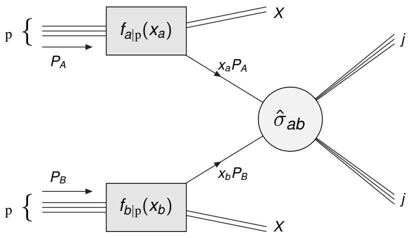
Backup Slides

Dijet Production at the LHC

Hadronic cross section: $\mathrm{pp} \longrightarrow jj + X$

$$\sigma_{AB}(P_A, P_B) = \sum_{a,b} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a|A}(x_a, \mu_\mathrm{F}^2) \; f_{b|B}(x_b, \mu_\mathrm{F}^2) \; \hat{\sigma}_{ab}(p_a, p_b, \mu_\mathrm{F}^2)$$

- $f_{a|A}(x_a, \mu_\mathrm{F}^2)$: Parton distribution function (PDF) $(p_a = x_a P_A, \; p_b = x_b P_B)$
- $\hat{\sigma}_{ab}(p_a, p_b, \mu_\mathrm{F}^2)$: Partonic hard scattering cross section (IR finite!)



- External particles:
  $a, b, j = g, q, \bar{q}$
  $q = \mathrm{u, d, c, s, b} \quad (q \neq \mathrm{t})$
- PDF set: CTEQ6L1
- Jet algorithm:
  anti-k_T $(\Delta R = 0.6)$

Calculation at NLO

Hard scattering cross section to NLO accuracy:

$$\hat{\sigma}_{ab}(p_a, p_b, \mu_F^2) = \hat{\sigma}_{ab}^{\mathrm{LO}}(p_a, p_b) + \hat{\sigma}_{ab}^{\mathrm{NLO}}(p_a, p_b, \mu_F^2)$$ IR finite

$\hat{\sigma}_{ab}^{\mathrm{LO}}(p_a, p_b) \rightarrow \sigma_{ab}^{\mathrm{B}}(p_a, p_b)$

$\hat{\sigma}_{ab}^{\mathrm{NLO}}(p_a, p_b, \mu_F^2) \rightarrow \sigma_{ab}^{\mathrm{NLO}}(p_a, p_b) + \sigma_{ab}^{\mathrm{C}}(p_a, p_b, \mu_F^2)$ — separately IR divergent; σ_{ab}^{C}: collinear subtraction term

$\sigma_{ab}^{\mathrm{NLO}}(p_a, p_b) \rightarrow \sigma_{ab}^{\mathrm{R}}(p_a, p_b) + \sigma_{ab}^{\mathrm{V}}(p_a, p_b)$ — real, virtual

All singularities regularized *dimensionally* in $D = 4 - 2\epsilon$ dimensions

- UV ($\frac{1}{\epsilon}$): cancellations <u>within</u> σ^{V} (between *loops* and the *counterterms*)
  finite after *renormalization* (on-shell, $\overline{\mathrm{MS}}$ for α_s)
- IR ($\frac{1}{\epsilon}$ soft, collinear, $\frac{1}{\epsilon^2}$ overlapping): cancellation <u>between</u> $\sigma^{\mathrm{V}}, \sigma^{\mathrm{R}}, \sigma^{\mathrm{C}}$ (<u>different</u> phase space)
  Dipole-Subtraction Method [Catani Seymour '97]

Real Corrections

- $q_1 + \bar{q}_2 \to q_3 + \bar{q}_4 + g$
- $g + q_1 \to q_2 + q_3 + \bar{q}_4$

Subtraction Method [Catani, Seymour '97]

$$\begin{aligned}
\hat{\sigma}^{\mathrm{NLO}} &= \int_{m+1} \mathrm{d}\sigma^{\mathrm{R}} + \int_{\mathrm{m}} \mathrm{d}\sigma^{\mathrm{V}} + \int_{\mathrm{m}} \mathrm{d}\sigma^{\mathrm{C}} \\
&= \int_{m+1} \left(\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{A}}\right) + \int_{m} \left(\mathrm{d}\sigma^{\mathrm{V}} + \mathrm{d}\sigma^{\mathrm{C}} + \int_{1} \mathrm{d}\sigma^{\mathrm{A}}\right) \\
&= \int_{m+1} \left(\mathrm{d}\sigma^{\mathrm{R}} - \sum \mathrm{d}\sigma^{\mathrm{B}} \otimes \mathbf{V}_{\mathrm{dip}}\right) \quad \text{Dipole Subtraction term} \\
&\quad + \int_{m} \left(\mathrm{d}\sigma^{\mathrm{V}} + \mathrm{d}\sigma^{\mathrm{B}} \otimes \mathbf{I}(\epsilon)\right) \quad \text{contains all } \epsilon\text{-poles} \\
&\quad + \int_0^1 \mathrm{d}x \int_{\mathrm{m}} \mathrm{d}\sigma^{\mathrm{B}} \otimes \left(\mathbf{K}(x) + \mathbf{P}(x, \mu_{\mathrm{F}}^2)\right) \quad \text{IR finite: } \mathbf{P}\text{: Splitting functions, } \mathbf{K}\text{: fac. scheme}
\end{aligned}$$

Operators $\mathbf{V}_{\mathrm{dip}}$, $\mathbf{I}$, $\mathbf{K}$, and $\mathbf{P}$ of $\mathcal{O}(\alpha_{\mathrm{s}})$

$\Rightarrow$ Only interference terms $\mathcal{O}(\alpha_{\mathrm{s}}\alpha)$ in $d\sigma^{\mathrm{B}}$!

Weak NLO: General Setup

Next-to-Leading Order: $\mathcal{O}(\alpha_s^2\alpha)$

- Only purely weak corrections (gauge invariant subset)
- Photonic contributions neglected (do not involve Sudakov logarithms)
- Real radiation of weak gauge bosons not considered

All singularities regularized *dimensionally* in $D = 4 - 2\epsilon$ dimensions

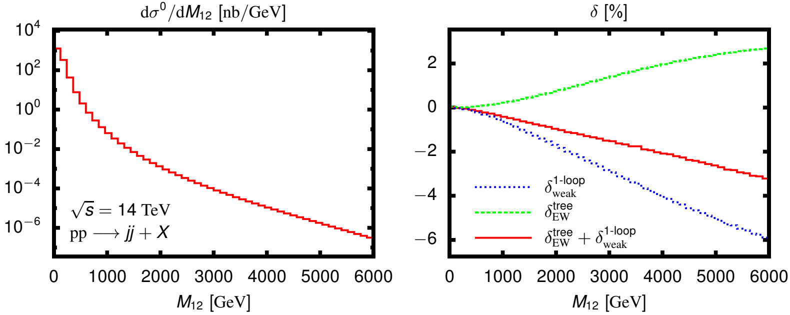
- UV ($\frac{1}{\epsilon}$): cancellation within σ^{V} (between *loops* and the *counter terms*)

  finite after *renormalization* (on-shell, $\overline{\mathrm{MS}}$ for α_s)

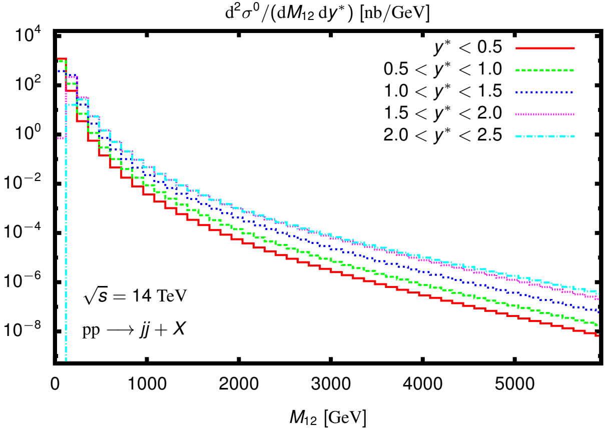
- IR ($\frac{1}{\epsilon}$soft, collinear, $\frac{1}{\epsilon^2}$overlapping): cancellation between σ^{V},σ^{R}, σ^{C} (different phase space)

  Dipole-Subtraction Method [Catani Seymour '97]

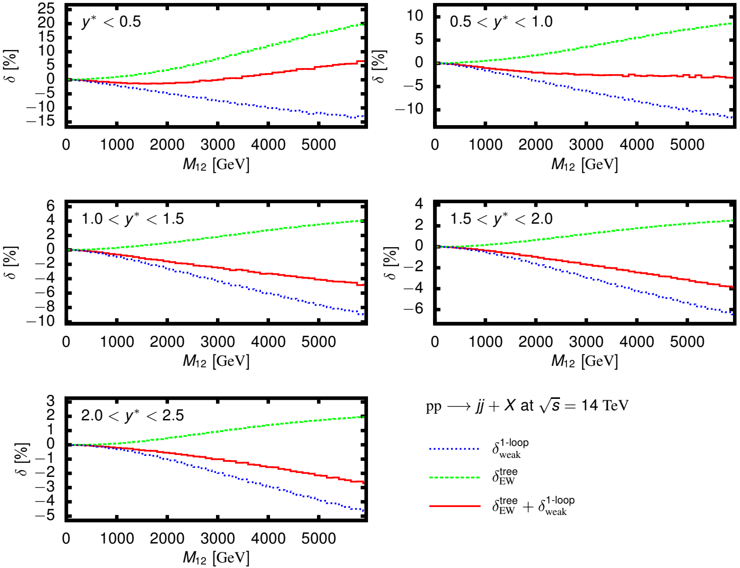
The dijet invariant mass M_{12} ($\sqrt{s} = 14$ TeV)



The dijet invariant mass M_{12} (y^* binning) ($\sqrt{s} = 14$ TeV)



The dijet invariant mass M_{12} (y^* binning) ($\sqrt{s} = 14$ TeV)



The leading jet $k_{T,1}$ ($\sqrt{s} = 14$ TeV)