Weak radiative corrections to dijet production at hadron colliders

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in collaboration with
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based on JHEP **1211** (2012) 095 [arXiv:1210.0438 [hep-ph]]

Motivation

Jet production at hadron colliders

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 in previously unexplored regions
- Search for physics beyond the SM (composite quarks, W', Z',...)
- Constrain PDFs (gluon distribution at high-x)

Hadron collider

- QCD effects dominant
- Electroweak effects suppressed by smaller coupling: $\alpha < \alpha_\mathrm{s}$
- Weak corrections: Sudakov logarithms (+ subleading logs)
  $\alpha_\mathrm{w} \ln^2\left(\frac{Q^2}{M_\mathrm{W}^2}\right)$, $\alpha_\mathrm{w} = \frac{\alpha}{\sin^2\theta_\mathrm{w}}$, 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

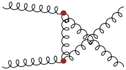
- Leading order $\mathcal{O}(\alpha_s^2)$ [Combridge, Kripfganz, Ranft '77]
- NLO QCD corrections $\mathcal{O}(\alpha_s^3)$
  [Ellis, Sexton '86], [Ellis, Kunszt, Soper '92], [Giele, Glover, Kosower '94]
- Currently substantial effort put into NNLO QCD $\mathcal{O}(\alpha_s^4)$
  [G. -D. Ridder, Gehrmann, Glover '05], [Gehrmann, Monni '06], [Daleo, Gehrmann, Maitre '07], [Luisoni, Daleo, G. -D. Ridder, Gehrmann '10], [G. -D. Ridder, Gehrmann, Glover, Pires '13]
- NLO Weak corrections $\mathcal{O}(\alpha_s^2\alpha)$:
  Single-jet inclusive [Moretti, Nolten, Ross '06]
  Dijet (preliminary results) [Scharf et al. '09]

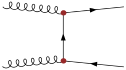
Contributing Subprocesses

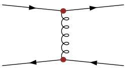
Process classes: Tree level

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

+ crossed processes

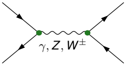






Squared Matrixelement

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



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]
  $$M_V^2 \rightarrow \mu_V^2 = M_V^2 - \mathrm{i} M_V \Gamma_V, \quad V = \mathrm{W}, \mathrm{Z}$$
  $$\cos^2\theta_{\mathrm{w}} \equiv c_{\mathrm{w}}^2 = \frac{\mu_{\mathrm{W}}^2}{\mu_{\mathrm{Z}}^2}, \quad \sin^2\theta_{\mathrm{w}} \equiv s_{\mathrm{w}}^2 = 1 - c_{\mathrm{w}}^2$$

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 (optionally mass regularization)

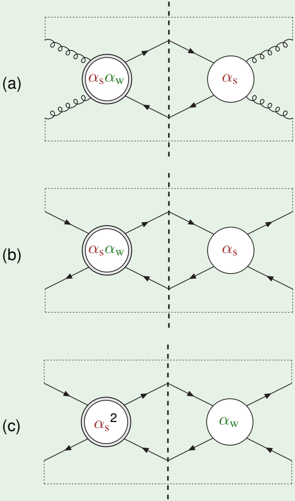
$g + g \to q + \bar{q}$ (a)

- 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)

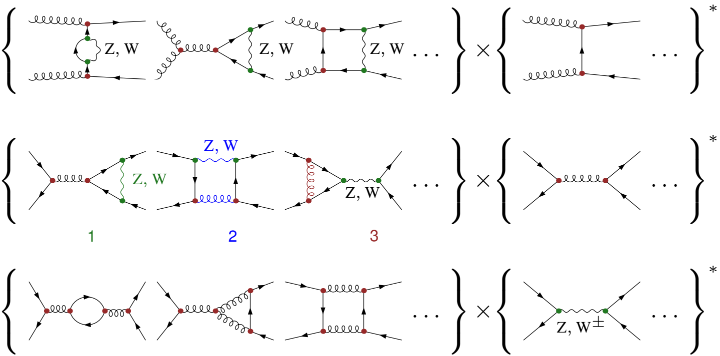
- LO amplitudes of $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_w)$
- Two types of interference terms contribute

Interference diagrams



Virtual Corrections

(a’) (b’) (c’)



Weak corrections (a’, b’1) (IR finite)

QCD corrections (c’, b’3)

“Mixed” (b’2)

} (IR divergent) ↔ Real corrections

Calculational setup

- Renormalization & Factorization scale: $\mu_R = \mu_F \equiv \mu = k_{T,1}$
- Basic cuts: $|y_{jet}| < 2.5, \quad k_{T,jet} > 25\,\mathrm{GeV}$, (jet: anti-$k_T$ with $R = 0.6$)

Notation

LO: $\underbrace{\mathcal{O}(\alpha_s^2)}_{\sigma^0_{QCD}}$, $\boxed{\mathcal{O}(\alpha_s\alpha),\, \mathcal{O}(\alpha^2)} \rightsquigarrow \delta^{tree}_{EW}$

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

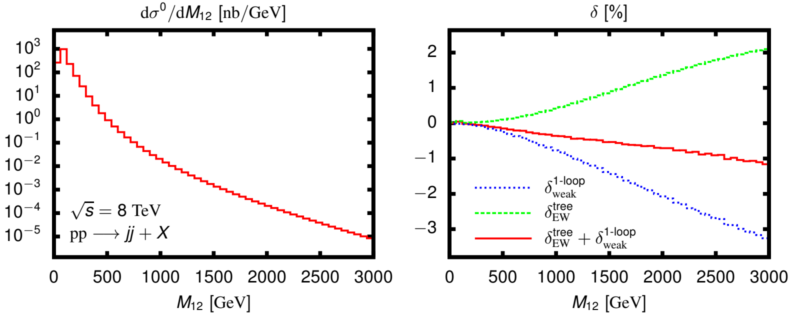
$$\sigma^0 = \sigma^0_{QCD} \times (1 + \delta^{tree}_{EW})$$

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

NLO: $\boxed{\mathcal{O}(\alpha_s^2\alpha_w)} \rightsquigarrow \delta^{1-loop}_{weak}$

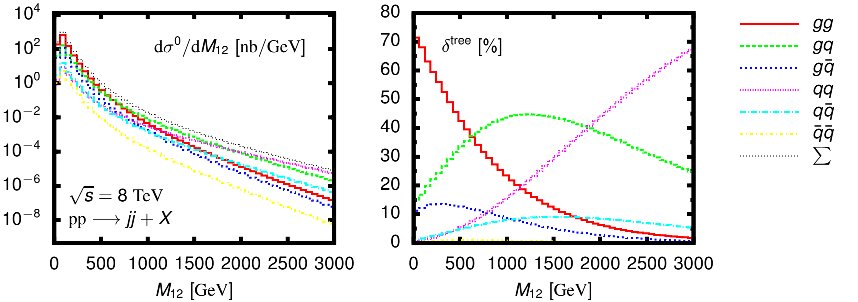
$$\sigma^{NLO} = \sigma^0 \times (1 + \delta^{1\text{-loop}}_{weak}) \simeq \sigma^0_{QCD} \times (1 + \delta^{tree}_{EW} + \delta^{1\text{-loop}}_{weak})$$

The dijet invariant mass M_{12} ($\sqrt{s} = 8$ TeV)



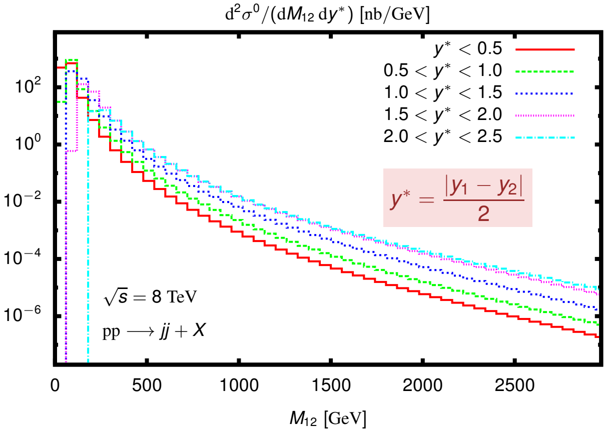
- Rapid decrease for higher M_{12} $\Rightarrow$ cross section & corrections dominated by the region with the lowest accepted M_{12} values
- Large cancellations between $\delta^{\text{1-loop}}_{\text{weak}}$ and $\delta^{\text{tree}}_{\text{EW}}$
- $\delta^{\text{1-loop}}_{\text{weak}}$ smaller than 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 ($\sqrt{s} = 8$ TeV)



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

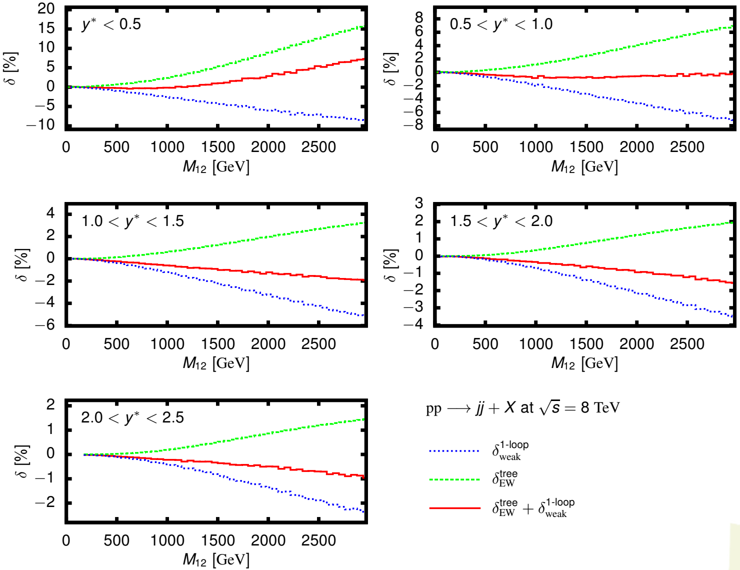
The dijet invariant mass M_{12} (y^* binning) ($\sqrt{s} = 8$ TeV)



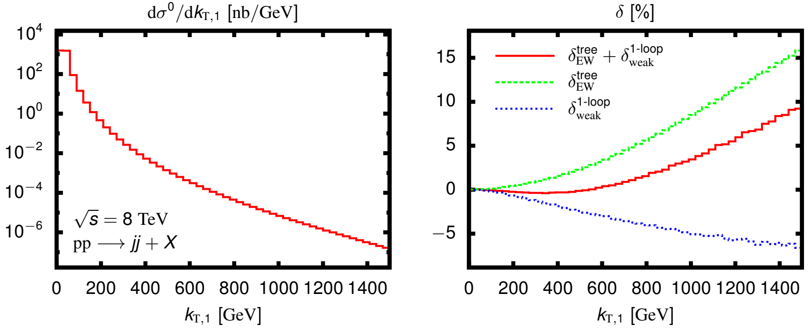
- $|\hat{y}_1| = |-\hat{y}_2| = y^*, \quad \hat{s} = M_{12}^2, \quad \hat{t} = -\frac{M_{12}^2}{1 + e^{\pm 2y^*}}, \quad \hat{u} = -\frac{M_{12}^2}{1 + e^{\mp 2y^*}}$

  ($2 \to 2$ kinematics)
- Small y^* (Sudakov regime) suppressed in the high M_{12} tail

The dijet invariant mass M_{12} (y^* binning) ($\sqrt{s} = 8$ TeV)

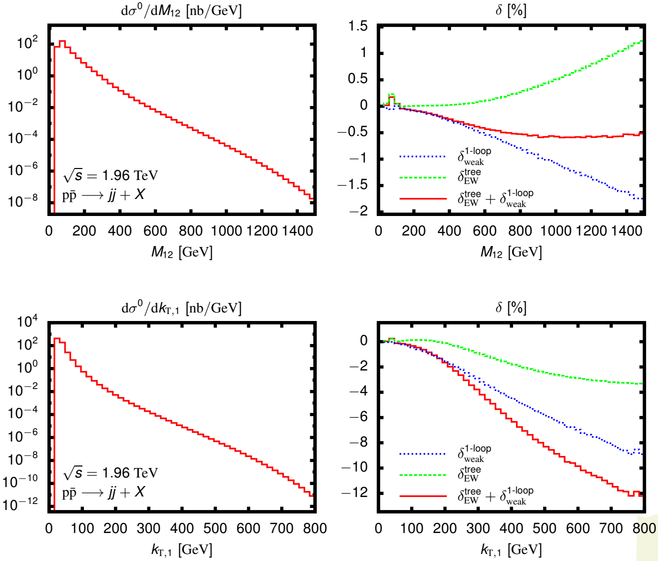


The leading jet $k_{\mathrm{T},1}$ ($\sqrt{s} = 8$ TeV)



- $k_{\mathrm{T},1} = \dfrac{M_{12}}{2\cosh(y^*)}$ (2 $\rightarrow$ 2 kinematics)
- For higher $k_{\mathrm{T},1}$, jets required to be produced more central.
- high $k_{\mathrm{T},1} \rightarrow$ Sudakov regime

Results for the Tevatron



Summary and Outlook

Weak radiative corrections

- Negligible in the total cross section (below per-cent level)
- Can reach $\sim 10\%$ in the high-energy tail of distributions (Sudakov logarithms)
- Deifnition of observables
  - **M_{12} based:** Regge (forward) regime (large $\hat{s}$ but small angles: $|\hat{t}|$ remains small)
    $\hookrightarrow$ smaller corrections
  - **k_T based:** Sudakov regime (all scales simultaneously large: $\hat{s}$, $|\hat{t}|$, $|\hat{u}| \gg M_W^2$)
    $\hookrightarrow$ larger corrections
- δ_{EW}^{tree} of the same generic size as $\delta_{weak}^{1\text{-loop}}$
  - positive at the LHC $\rightarrow$ large cancellations
  - negative at the Tevatron

Outlook

- Not included: QED contributions
- Real radiation of weak gauge bosons (highly dependent on the experimental setup)

Backup Slides

Calculational Setup

Two independent calculations (in mutual agreement)

1st calculation [AH]

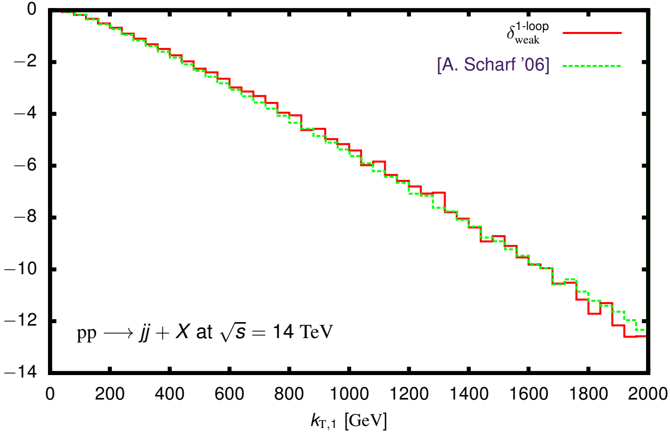
- All tree contributions by hand
  Weyl–van-der-Waerden spinor formalism
- Virtual corrections:
  FeynArts 3.6 [Hahn '01]
  FormCalc 6.2 [Hahn, Perez-Victoria '99]
- Loop integrals:
  LoopTools 2.4 (modified)
  [Hahn, Perez-Victoria '99]
  or Collier [Denner, Dittmaier]
- Integration Vegas [Lepage '78]

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

Comparison to other work



Calculation at NLO

Hard scattering cross section to NLO accuracy:

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

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

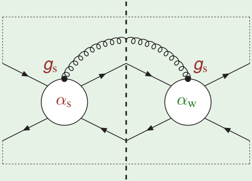
$\hat{\sigma}^{\mathrm{NLO}}_{ab}(p_a, p_b, \mu_{\mathrm{F}}^2) \to \sigma^{\mathrm{NLO}}_{ab}(p_a, p_b) + \sigma^{\mathrm{C}}_{ab}(p_a, p_b, \mu_{\mathrm{F}}^2)$ (separately IR divergent; σ^{C}_{ab}: collinear subtraction term)

$\sigma^{\mathrm{NLO}}_{ab}(p_a, p_b) \to \sigma^{\mathrm{R}}_{ab}(p_a, p_b) + \sigma^{\mathrm{V}}_{ab}(p_a, p_b)$ (real, virtual)

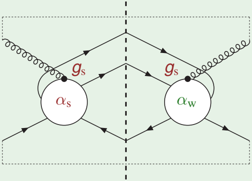
All singularities regularized *dimensionally* in $D = 4 - 2\epsilon$ dimensions

- UV ($\frac{1}{\epsilon}$): cancellations within 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 between σ^{V}, σ^{R}, σ^{C} (different phase space)
  Dipole-Subtraction Method [Catani Seymour '97]

Real corrections



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

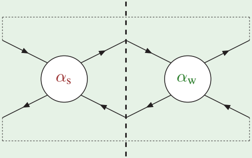


$g + q_1 \to q_2 + q_3 + \bar{q}_4$

Subtraction Method [Catani, Seymour '97]

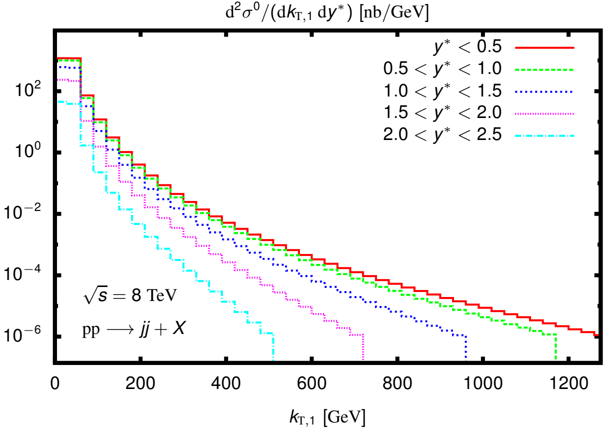
$$\hat{\sigma}^{\mathrm{NLO}} = \int_3 \mathrm{d}\sigma^{\mathrm{R}} + \int_2 \mathrm{d}\sigma^{\mathrm{V}} + \int_2 \mathrm{d}\sigma^{\mathrm{C}} = \int_3 \left[\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{A}}\right] + \int_2 \left[\mathrm{d}\sigma^{\mathrm{V}} + \mathrm{d}\sigma^{\mathrm{C}}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

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



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

The leading jet $k_{T,1}$ (y^* binning) ($\sqrt{s} = 8$ TeV)



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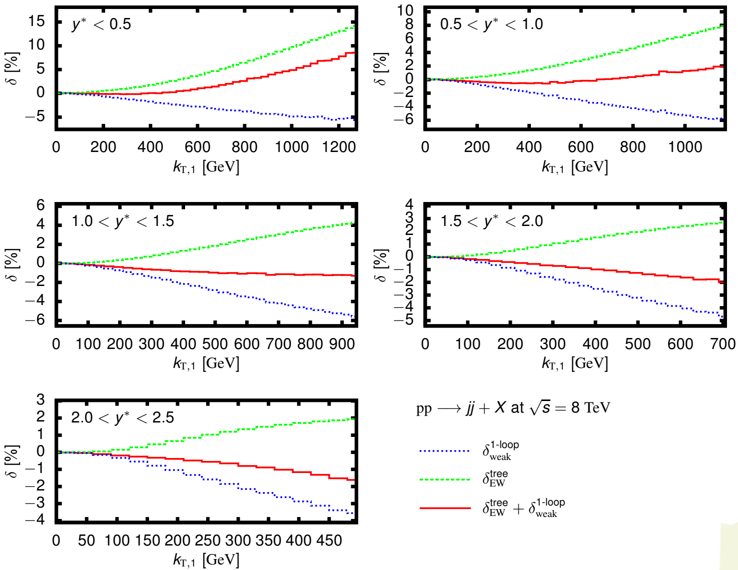
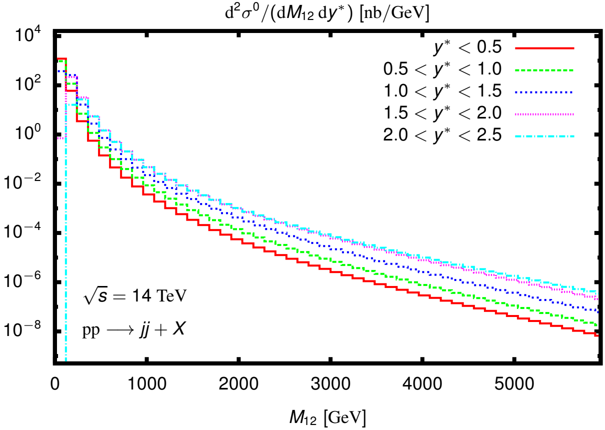


The dijet invariant mass M_{12} (y^* binning) ($\sqrt{s} = 14$ TeV)



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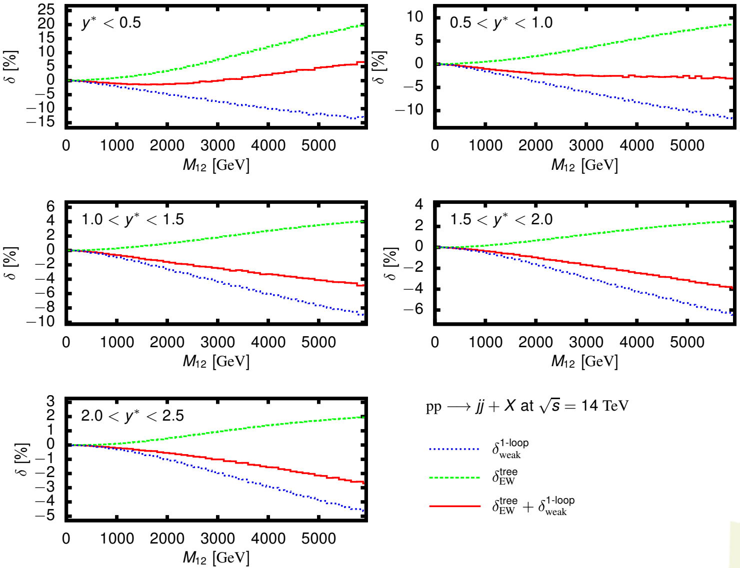

The leading jet $k_{T,1}$ ($\sqrt{s} = 14$ TeV)