Electroweak corrections in the determination of α_s

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Based on:

A.Denner, S.Dittmaier, T.Gehrmann, C.Kurz, Phys.Lett. B679 (2009) 219 [arXiv:0906.0372]

A.Denner, S.Dittmaier, T.Gehrmann, C.Kurz, Nucl.Phys. B836 (2010) 37 [arXiv:1003.0986]

S.Dittmaier, A.Huss, C.Speckner, JHEP 1211 (2012) 095 [arXiv:1210.0438]

S.Dittmaier, A.Huss, K.Rabbertz, to appear in the Les Houches Proceedings soon

Features of and issues in EW precision calculations

Relevance and size of EW corrections

generic size $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$ suggests NLO EW $\sim$ NNLO QCD

but systematic enhancements possible, e.g.

- by photon emission
  $\hookrightarrow$ kinematical effects, mass-singular log's $\propto \alpha \ln(m_\mu/Q)$ for bare muons, etc.
- at high energies
  $\hookrightarrow$ EW Sudakov log's $\propto (\alpha/s_W^2)\ln^2(M_W/Q)$ and subleading log's

EW corrections to PDFs at hadron colliders

induced by factorization of collinear initial-state singularities, new: photon PDF

Instability of W and Z bosons

- realistic observables have to be defined via decay products (leptons, γ's, jets)
- off-shell effects $\sim \mathcal{O}(\Gamma/M) \sim \mathcal{O}(\alpha)$ are part of the NLO EW corrections

Combining QCD and EW corrections in predictions

- how to merge results from different calculations
- reweighting procedures in MC's

Issue of this talk

- EW corrections to two process types important for α_s determination:
  - jet event-shape observables at e^+e^- colliders
  - jet production at hadron colliders
- review of the situation
  - EW corrections under control ?
  - future homework ?

Jet event-shape observables at e^+e^- colliders

Frequently used event-shape observables y

- Thrust: $T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$
- Normalized heavy jet mass: $\rho = \max\{M_1^2, M_2^2\}/s$

  ($M_i =$ inv. mass flowing into hemispheres H_i defined by plane perpendicular to thrust axis)
- Wide / total jet broadenings:

  $$B_\mathrm{W} = \max\{B_1, B_2\}, \quad B_\mathrm{T} = B_1 + B_2, \qquad B_i = \frac{\sum_{j\in H_i} |\vec{p}_j \times \vec{n}|}{2\sum_k |\vec{p}_k|}$$
- C parameter:

  $C = 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1), \quad \{\lambda_i\} =$ eigenvalues of $\Theta = \frac{1}{\sum_i |\vec{p}_i|} \sum_j \frac{\vec{p}_j \otimes \vec{p}_j}{|\vec{p}_j|}$
- Jet transition variable:

  $Y_3 =$ value of y_cut at which the event turns from 3-jet to 2-jet type

Note: 2-jet configuration appears at an endpoint of $\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}$ (e.g. at $T \to 1$)

$\hookrightarrow$ shapes of distributions sensitive to 3 and more jets, and thus to α_s

Theory prediction for jet event shapes ($e^+e^- \to n\,\text{jets},\ n\geq 3$)

$$\frac{1}{\sigma_{\text{had}}}\frac{d\sigma(y)}{dy} = \underbrace{\alpha_s\, C^{\text{QCD}}_{\text{LO}} + \alpha_s^2\, C^{\text{QCD}}_{\text{NLO}}} + \underbrace{\alpha_s^3\, C^{\text{QCD}}_{\text{NNLO}}}$$

R.K.Ellis, Ross, Terrano '81; Kunszt '81
Vermaseren, Gaemers, Oldham '81
Giele, Glover '92; Catani, Seymour '96

Gehrmann-DeRidder, Gehrmann,
Glover, Heinrich '07–'09; Weinzierl '08,'09

$+$ $\underbrace{\text{NLL resummation}}$ $+$ $\underbrace{\text{NLL/NNLO matching}}$ $(+$ $\underbrace{\text{NNLL resummation for } T}$ $)$

Catani, Turnock,
Webber, Trentadue '91,'93

Gehrmann, Luisoni,
Stenzel '08

Becher, Schwartz '08

$+$ $\underbrace{\text{non-perturbative hadronization effects}}$

Korchemsky, Sterman '95; Dokshitzer, Webber '95,'97
Dokshitzer, Lucenti, Marchesini, Salam '98

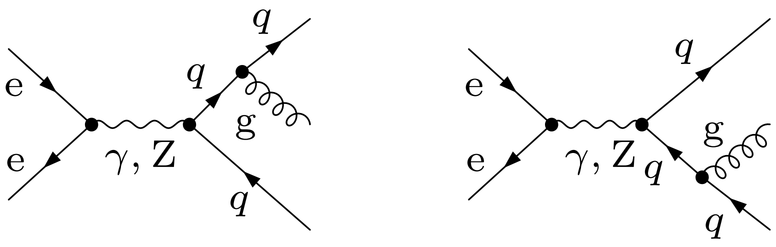
$$+ \underbrace{\alpha\, C^{\text{EW}}_{\text{LO}} + \alpha\alpha_s\, C^{\text{EW}}_{\text{NLO}} + \alpha^2\alpha_s\, C^{\text{ISR}}_{\text{LL}}}$$

Denner, S.D., Gehrmann, Kurz '09,'10

- Recent NNLO QCD results already included in α_s fit to event shapes
  Gehrmann, Luisoni, Stenzel '08; Dissertori et al. '08; Bethke et al. '08; Davison, Webber '08
- NLO EW corrections potentially of same size as NNLO QCD, since $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$

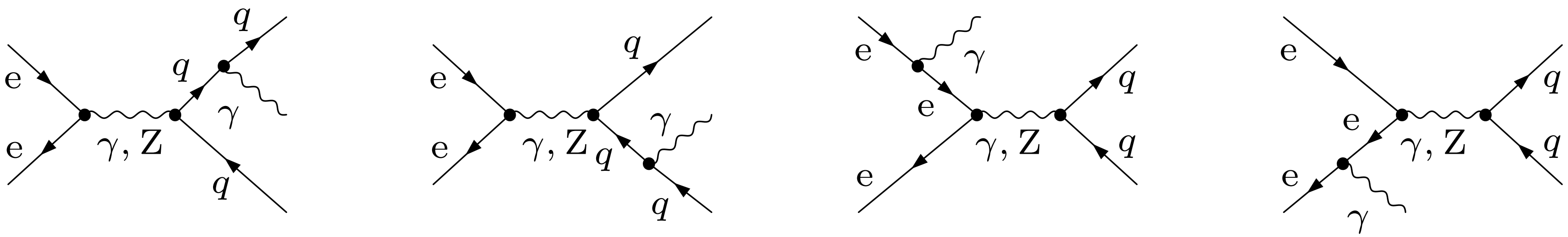
Calculation of NLO corrections

LO diagrams for $e^+e^- \to q\bar{q}g$: $\mathcal{O}(\alpha^2\alpha_s)$



$q = u, d, s, c, b$

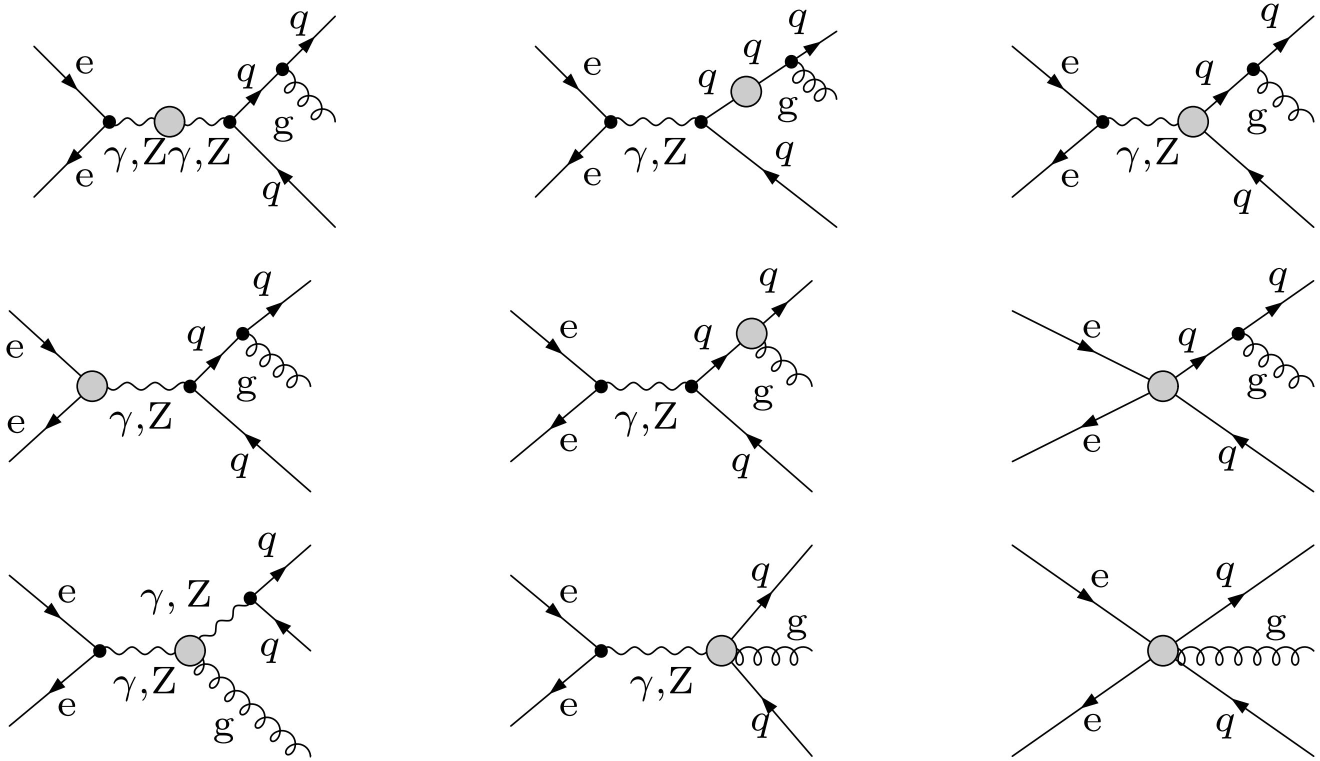
LO diagrams for $e^+e^- \to q\bar{q}\gamma$: $\mathcal{O}(\alpha^3)$



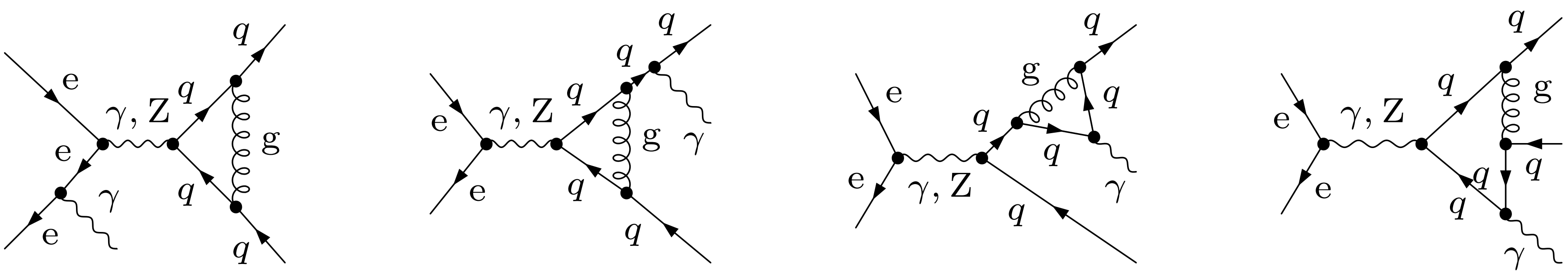
Comments:

- $q\bar{q}\gamma$ final states in LO deliver contributions if γ is merged with $q/\bar{q}$, i.e. near 2-jet configurations
- focus of our calculation: $\mathcal{O}(\alpha^3\alpha_s)$ = NLO EW correction to $q\bar{q}g$ production
  = NLO QCD correction to $q\bar{q}\gamma$ production

1PI loop insertions in EW one-loop corrections to $e^+e^- \to q\bar{q}g$ $\mathcal{O}(200)$ diagrams



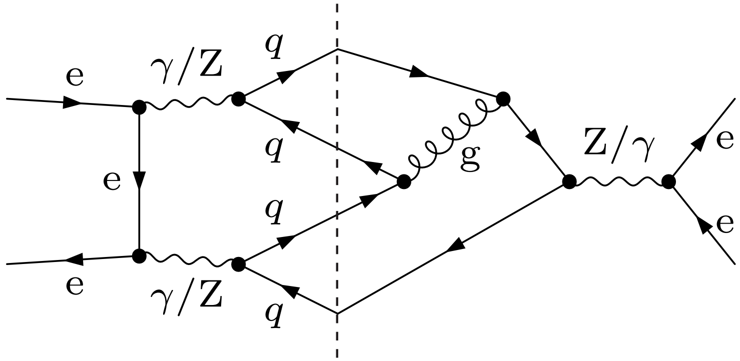
Sample QCD one-loop diagrams for $e^+e^- \to q\bar{q}\gamma$



Real emission corrections at $\mathcal{O}(\alpha^3\alpha_s)$ and beyond

- $e^+e^- \to q\bar{q}g\gamma$ = photon bremsstrahlung to $q\bar{q}g$ production
  = gluon bremsstrahlung to $q\bar{q}\gamma$ production

- QCD–EW interferences for $e^+e^- \to q\bar{q}q\bar{q}$



$\hookrightarrow$ non-singular contributions of $\mathcal{O}(\alpha^3\alpha_s)$ = same order as NLO EW

Interferences included in our calculation

$\hookrightarrow$ effect phenomenologically negligible ($< 0.1\%$)

- higher-order photonic ISR included via leading-log structure functions up to order LO $\times \mathcal{O}(\alpha^3)$

Definition of jet observables

Event selection: (closely following the procedure employed by ALEPH)

1. Discard particles too close to the beams, i.e. if $|\cos\theta_i| > \cos\theta_{\rm cut} = 0.965$.
2. Reject event if $M_{\rm visible} < 0.9 E_{\rm CM}$.
3. Boost to CM system of observed final-state particles.
4. Apply Durham jet algorithm with E recombination and $y_{\rm cut} = 0.002$ to $q, \bar{q}, {\rm g}, \gamma$
   $\hookrightarrow$ photons appear inside jets
5. Reject "photonic events" where photon energy fraction $z > z_{\rm cut} = 0.9$ in a jet.

Subtleties arising at NLO EW level:

- Step 3 minimizes boost effects from collinear ISR photons
  (otherwise two-jet configurations do not always appear at event-shape endpoints)

  But: at LEP two-jet events were shifted to endpoints "by hand"
  $\hookrightarrow$ renders confrontation between theory and LEP results difficult
- Step 5 is not collinear safe
  $\hookrightarrow$ perturbative result is plagued by quark-mass singularities $\propto \alpha \ln m_q$
  Solution: include photon fragmentation function with non-perturbative input

Photon–jet separation via photon fragmentation function $D_{q\to\gamma}$ Glover, Morgan '94

Why does a naive γ–jet separation by a jet algorithm not work ?

- collinear quarks and photons have to be recombined $\to$ $(q\gamma) =$ jet
  otherwise corrections $\propto \ln(m_q^2/Q^2)$ $\to$ perturbative "IR instability"
- quark and gluon jets cannot be distinguished event by event
  $\hookrightarrow$ common recombination required for quarks/gluons with photons

$\Rightarrow$ $\underbrace{(\mathrm{g_{hard}} + \gamma_{\mathrm{soft}})}_{\text{EW corr. to 3 jets}}$ and $\underbrace{(\mathrm{g_{soft}} + \gamma_{\mathrm{hard}})}_{\text{QCD corr. to 2 jets} + \gamma}$ both appear as 3 jets

Solution:

- exclude events with photon energy fraction $z_\gamma = \dfrac{E_\gamma}{E_{\mathrm{jet}} + E_\gamma} > z_0$
  for $(\mathrm{jet} + \gamma)$ quasiparticles
- subtract convolution of LO cross section with

$$D_{q\to\gamma}^{\overline{\mathrm{MS}}}(z_\gamma, \mu_{\mathrm{fact}})\Big|_{\mathrm{mass.reg.}} = P_{q\to\gamma}(z_\gamma)\left[\ln\frac{m_q^2}{\mu_{\mathrm{fact}}^2} + 2\ln z_\gamma + 1\right] \quad \leftarrow \text{cancels coll. singularities}$$

$$+ \; D_{q\to\gamma}^{\mathrm{ALEPH}}(z_\gamma, \mu_{\mathrm{fact}}) \quad \leftarrow$$ non-perturbative part fitted to ALEPH data on $\mathrm{e^+e^-} \to \mathrm{jet} + \gamma$

where $P_{q\to\gamma}(z_\gamma) = \frac{1+(1-z_\gamma)^2}{z_\gamma}$ = quark-to-photon splitting function

Numerical results

Total hadronic cross section

- largest EW corrections due to ISR

  (radiative return cut off by cut $M_{\mathrm{visible}} < 0.9\sqrt{s}$)

- ISR beyond one loop relevant (some $\%$) for $\sqrt{s} \sim M_{\mathrm{Z}}$

- weak corrs. of $\mathcal{O}(5\%)$, increasingly negative for large $\sqrt{s}$

- Note: σ_{had} calculated to same perturbative order as $\mathrm{d}\sigma/\mathrm{d}y$ to obtain a proper normalization

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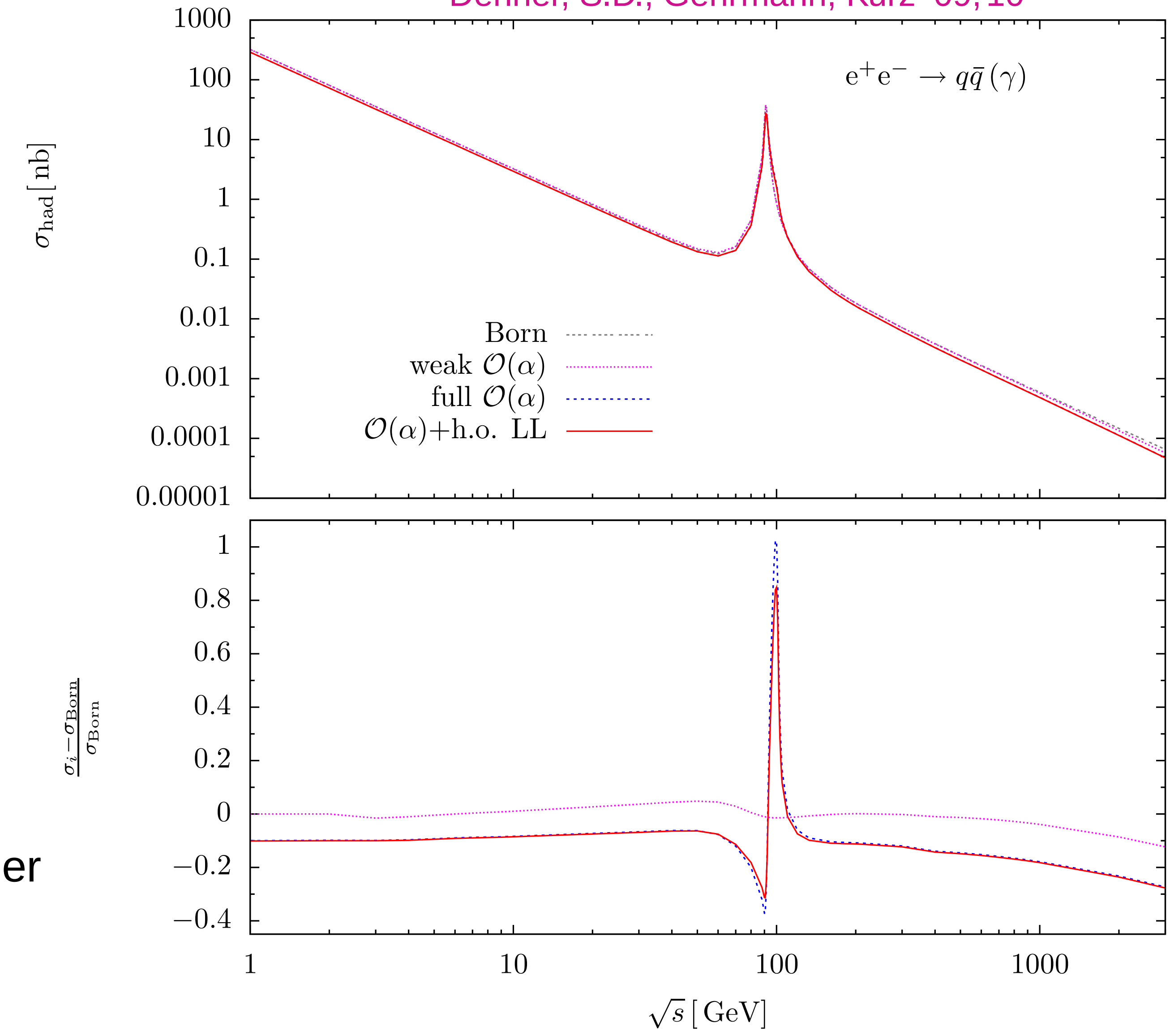

Thrust distribution — normalized to LO hadronic cross section σ_0

$\sqrt{s} = M_Z$

- large ISR effects as for $\sigma_{\rm had}$
- h.o. ISR $\sim$ some $\%$
- genuine weak effects of few $\%$, but flat
- $q\bar{q}\gamma$ final states visible for $T \to 1$

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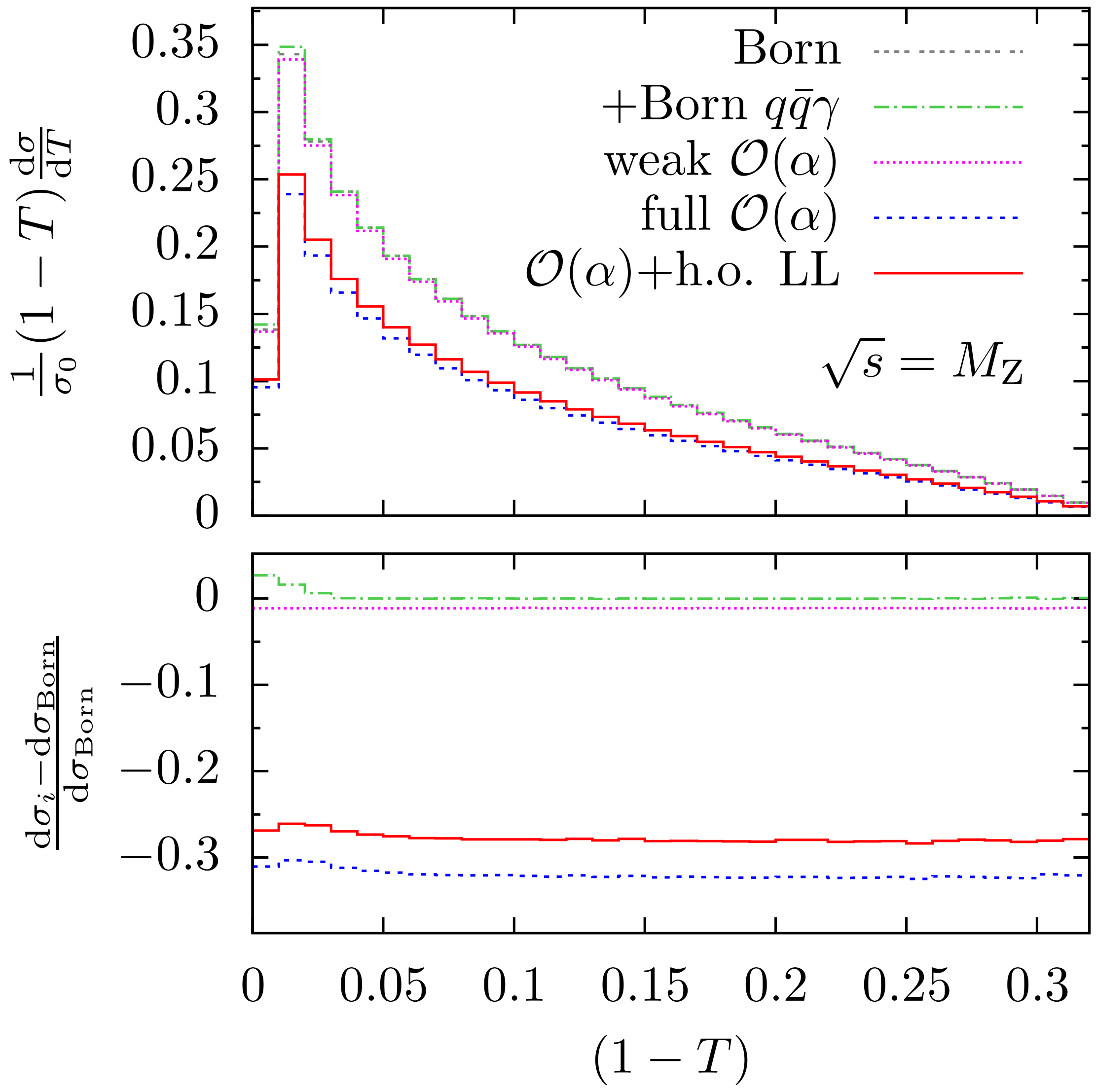

Thrust distribution — normalized to full hadronic cross section σ_{had}

$\sqrt{s} = M_Z$

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- large ISR effects in $\frac{d\sigma}{dT}$ cancel against σ_{had}

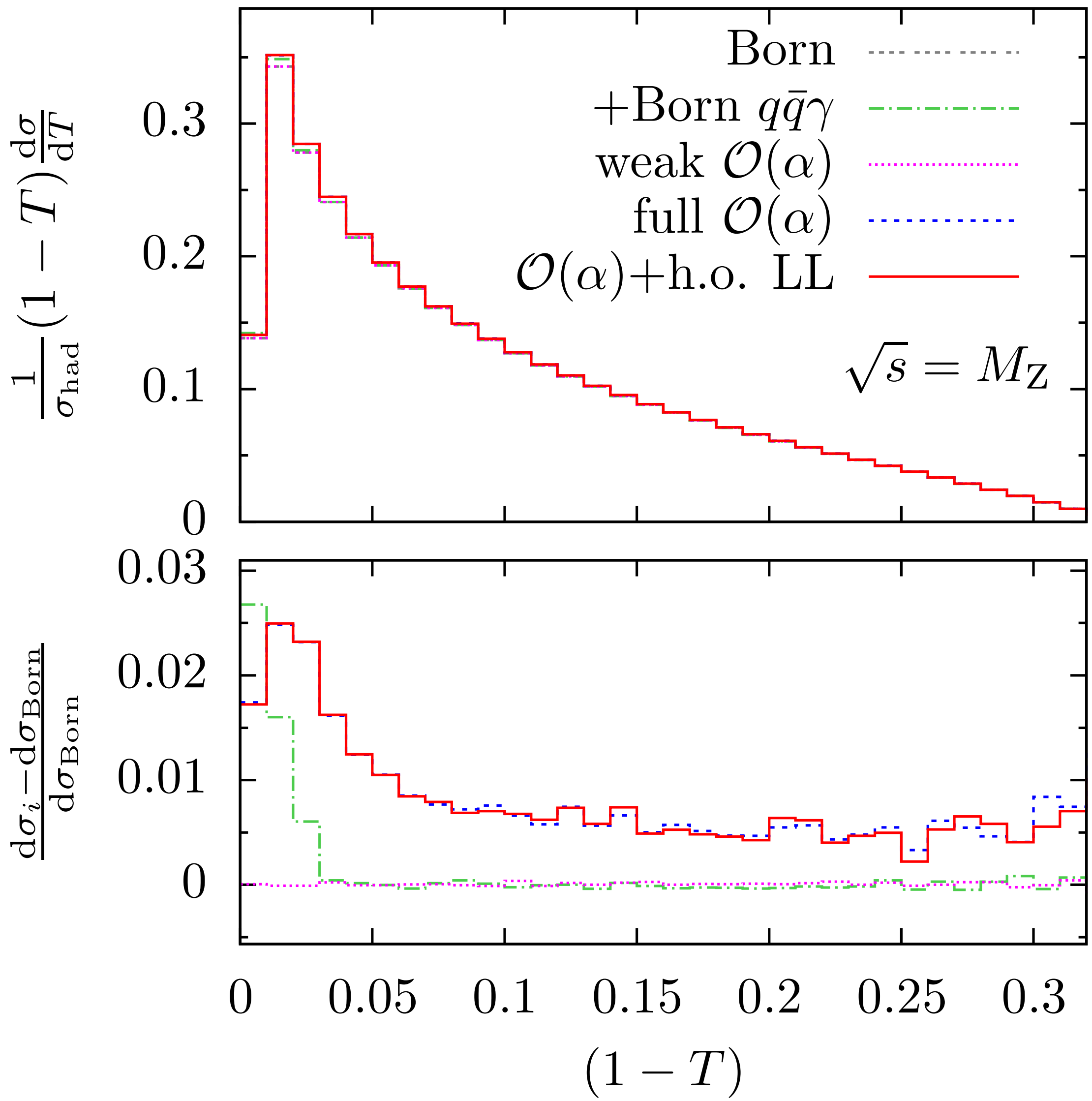
  $\hookrightarrow$ % effects

- h.o. ISR irrelevant

  (proper normalization important)

- genuine weak effects below 0.1%

- $q\bar{q}\gamma$ final states $\sim \mathcal{O}(2\%)$ for $T \gtrsim 0.97$

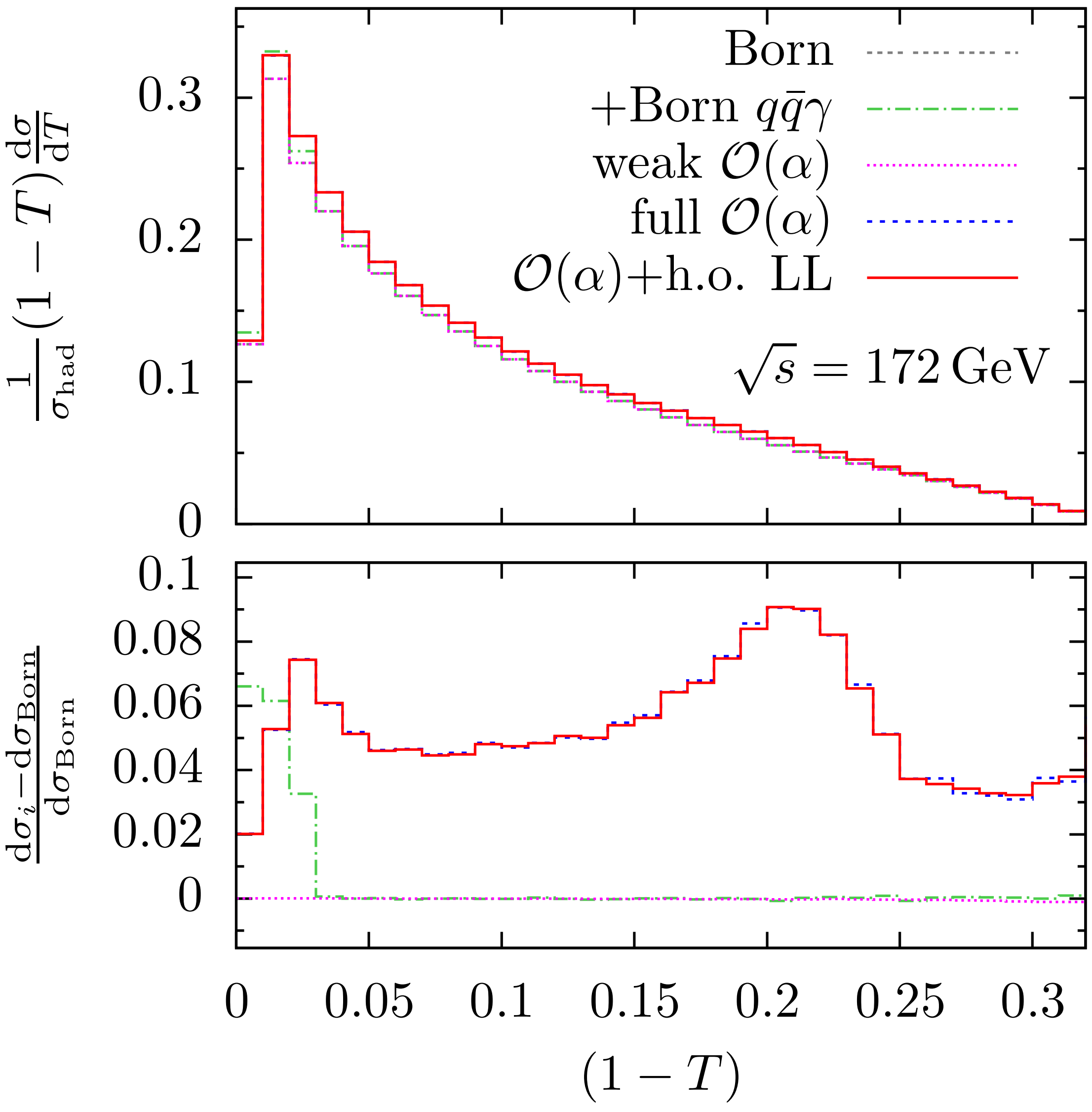


Normalized thrust distribution — increasing CM energy

$\sqrt{s} = 172\,\text{GeV}$

- ISR develops structures that depend on y_{cut} and on event selection
- h.o. ISR irrelevant
- genuine weak effects remain small (~ 1% at $\sqrt{s} = 500\,\text{GeV}$)
- $q\bar{q}\gamma$ final states ~ some % for $T \gtrsim 0.97$

Denner, S.D., Gehrmann, Kurz '09,'10

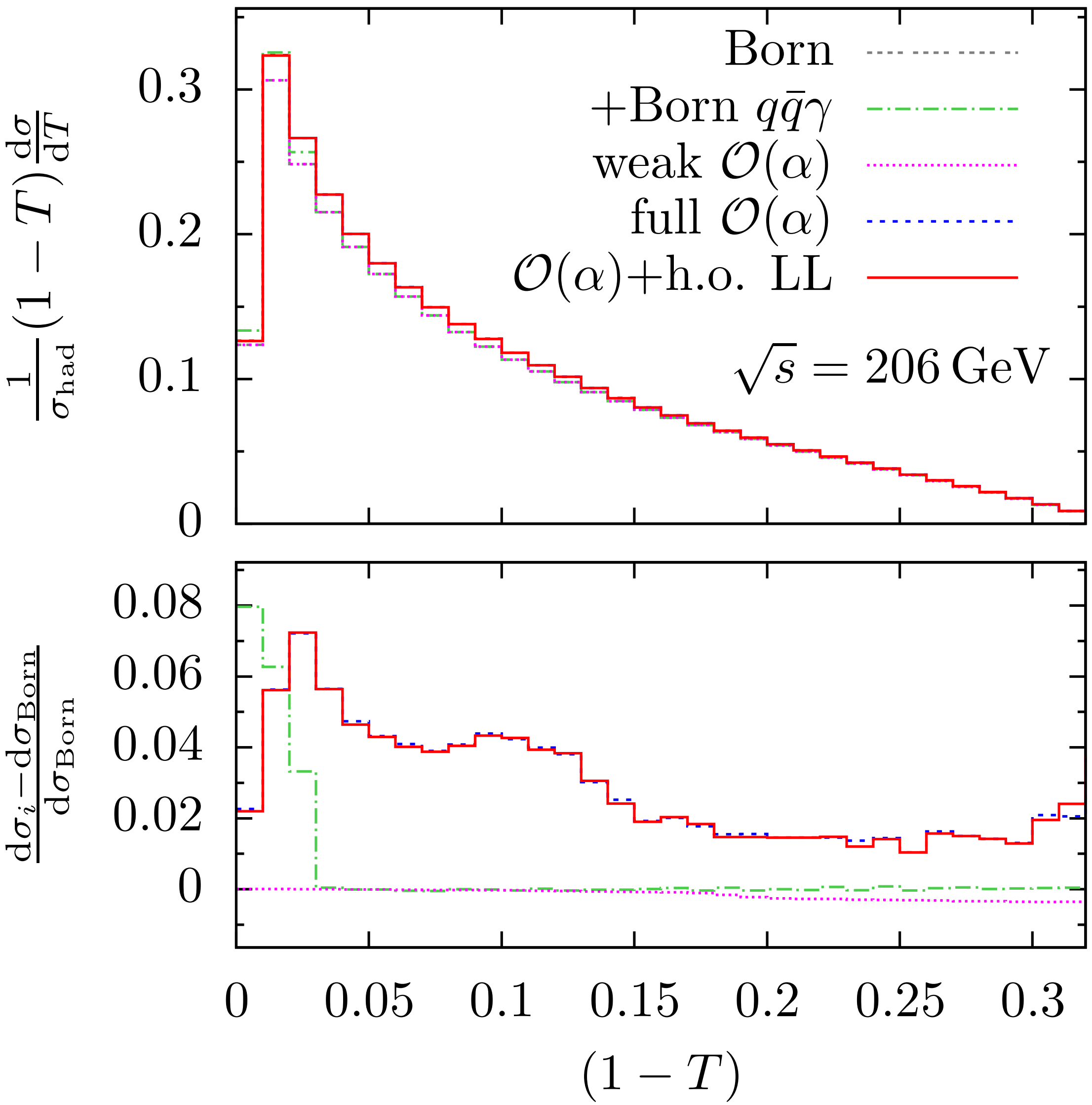


Normalized thrust distribution — increasing CM energy

$\sqrt{s} = 206\,\mathrm{GeV}$

Denner, S.D., Gehrmann, Kurz '09,'10

- ISR develops structures that depend on $y_{\rm cut}$ and on event selection
- h.o. ISR irrelevant
- genuine weak effects remain small ($\sim 1\%$ at $\sqrt{s} = 500\,\mathrm{GeV}$)
- $q\bar{q}\gamma$ final states $\sim$ some $\%$ for $T \gtrsim 0.97$



Normalized thrust distribution — increasing CM energy

$\sqrt{s} = 500\,\mathrm{GeV}$

- ISR develops structures that depend on y_{cut} and on event selection
- h.o. ISR irrelevant
- genuine weak effects remain small ($\sim 1\%$ at $\sqrt{s} = 500\,\mathrm{GeV}$)
- $q\bar{q}\gamma$ final states $\sim$ some $\%$ for $T \gtrsim 0.97$

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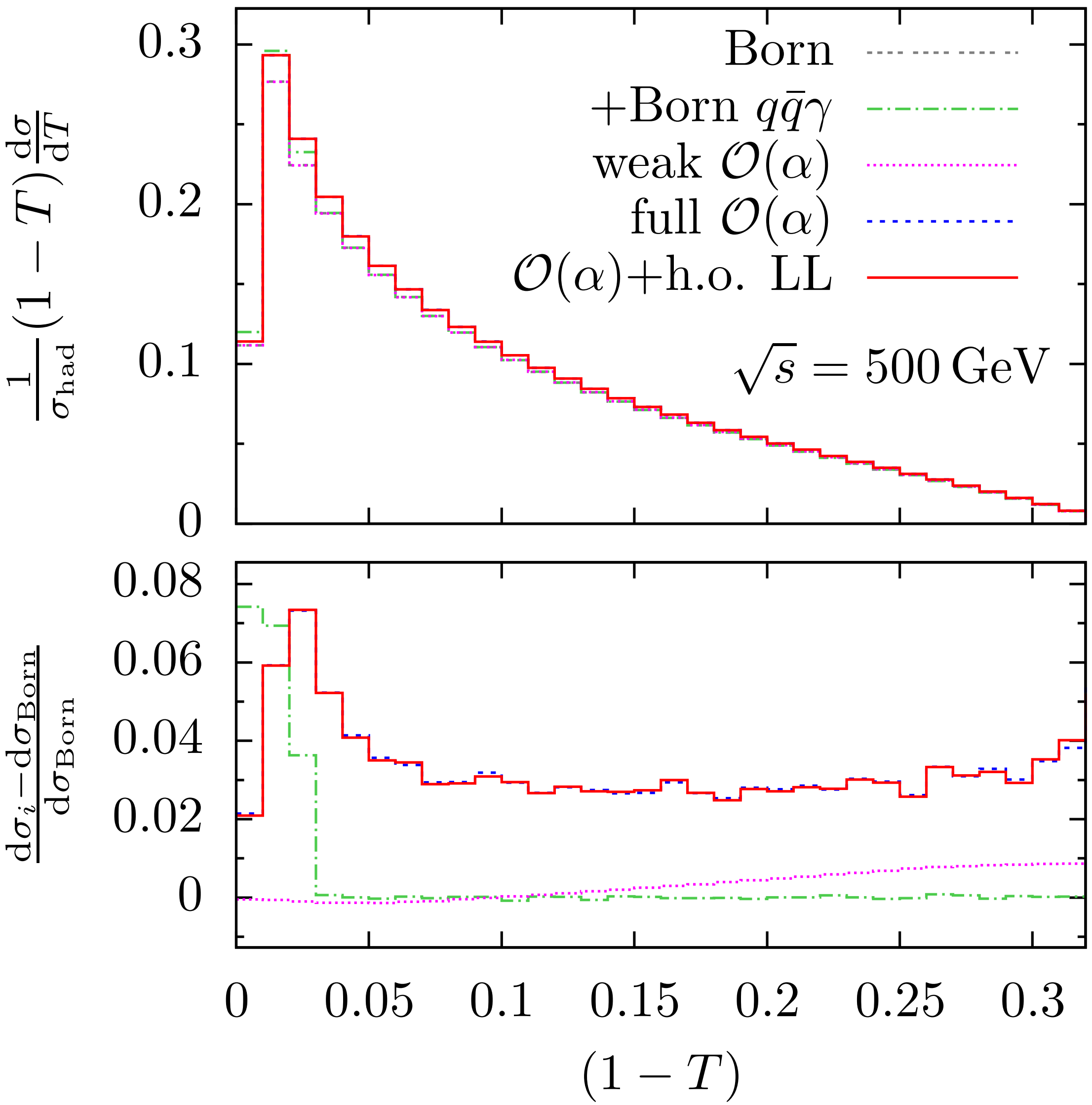
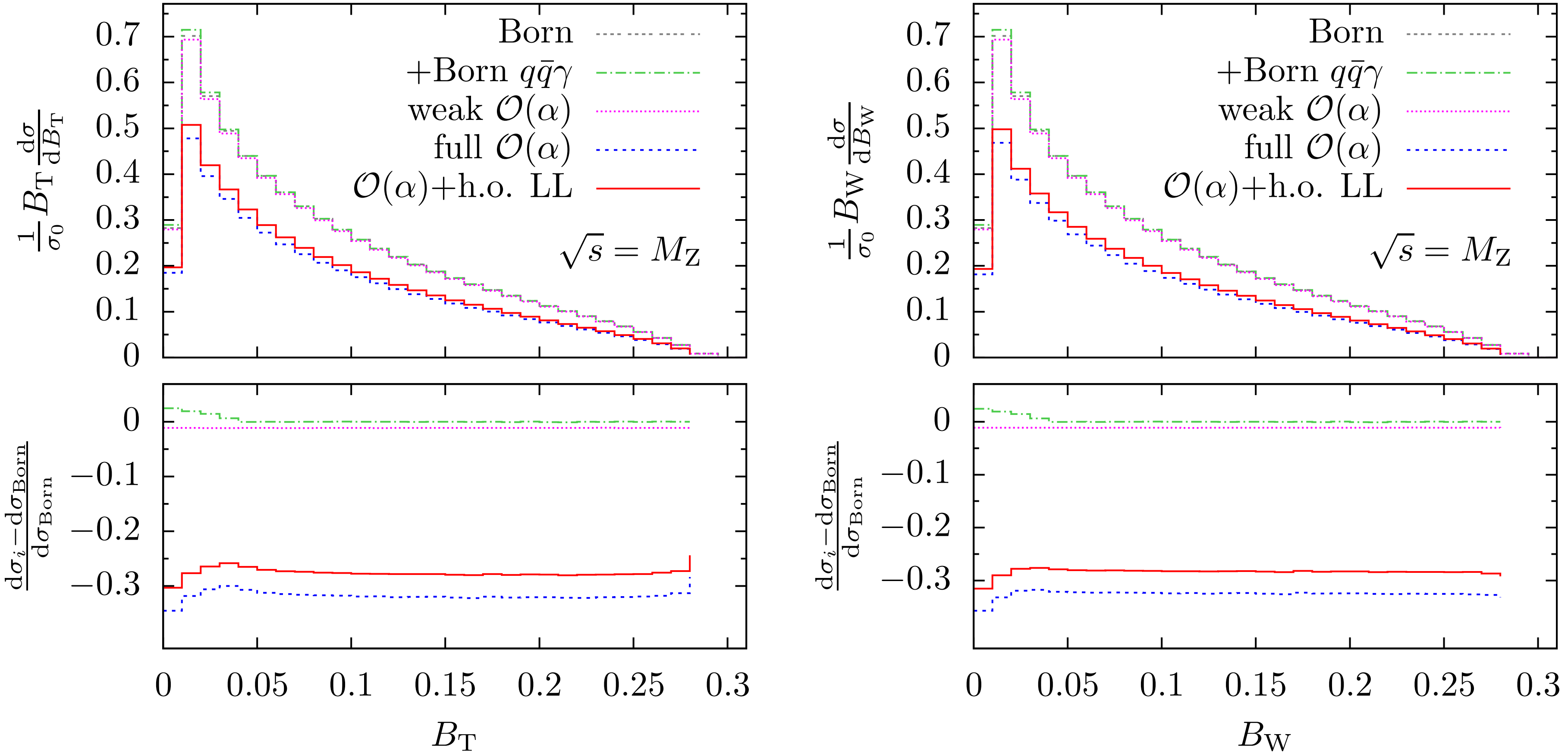


Jet broadenings — yet another example

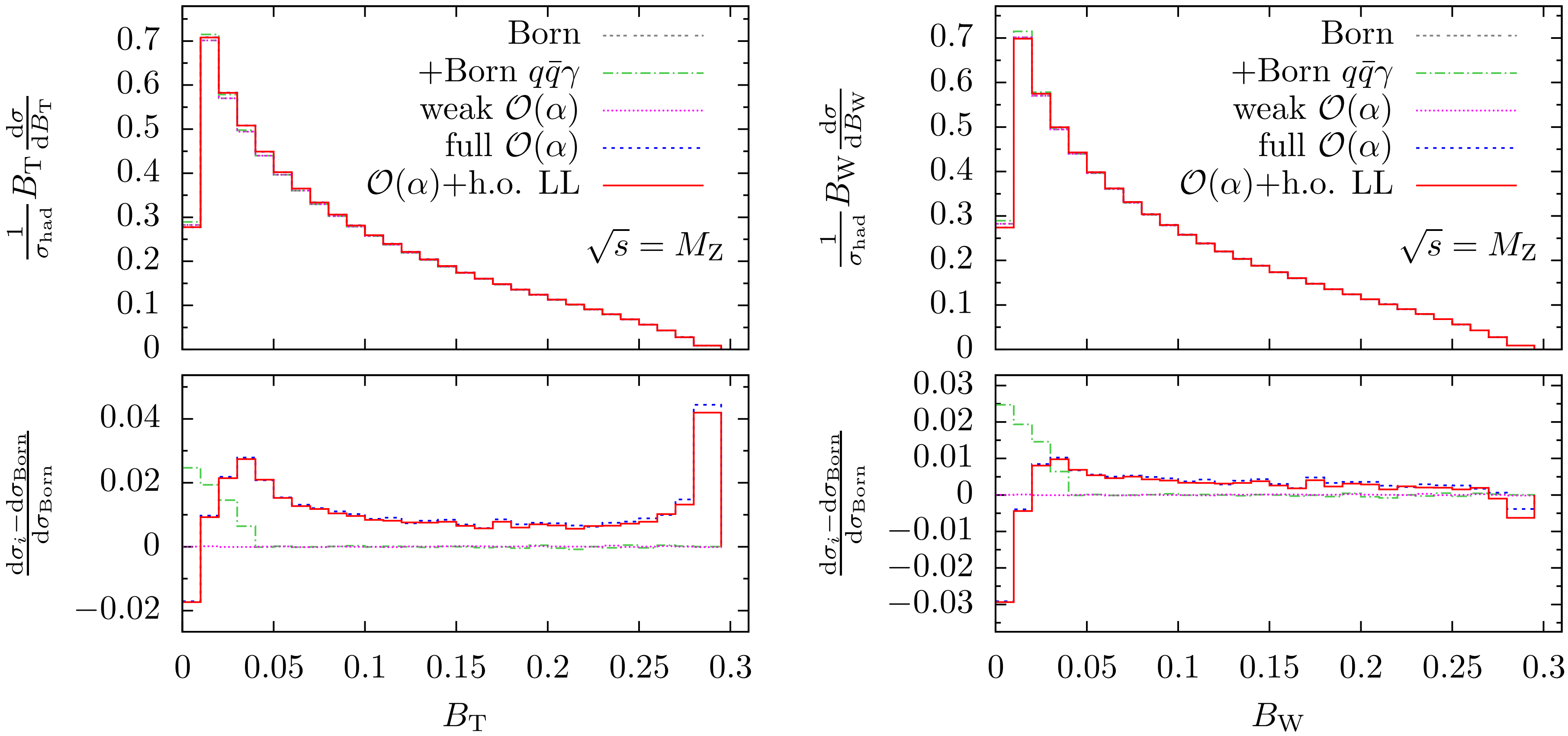
Denner, S.D., Gehrmann, Kurz '09,'10



Overall size, energy dependence, and qualitative features of EW effects similar for all event shapes.

Jet broadenings — yet another example

Denner, S.D., Gehrmann, Kurz ’09,’10



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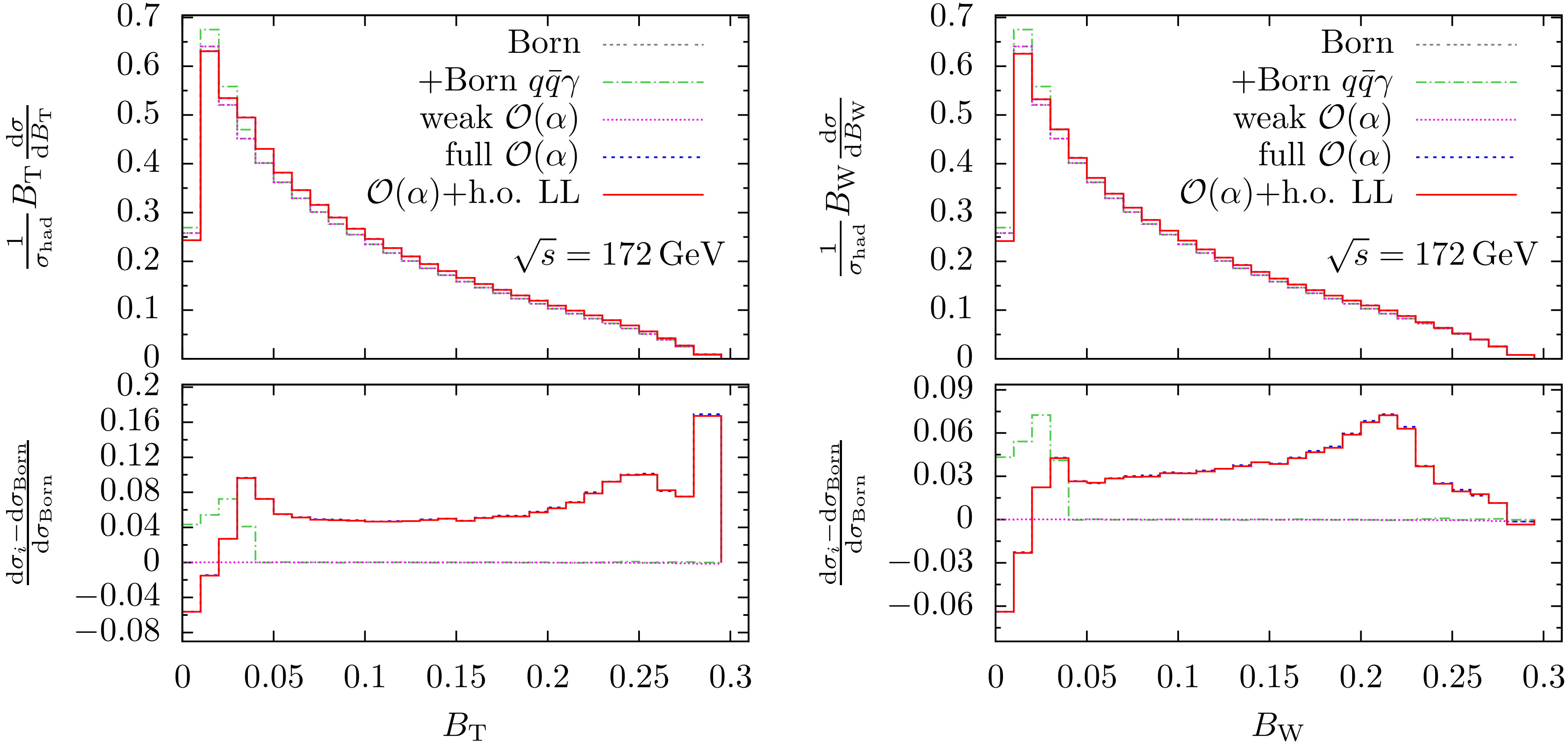

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Jet broadenings — yet another example

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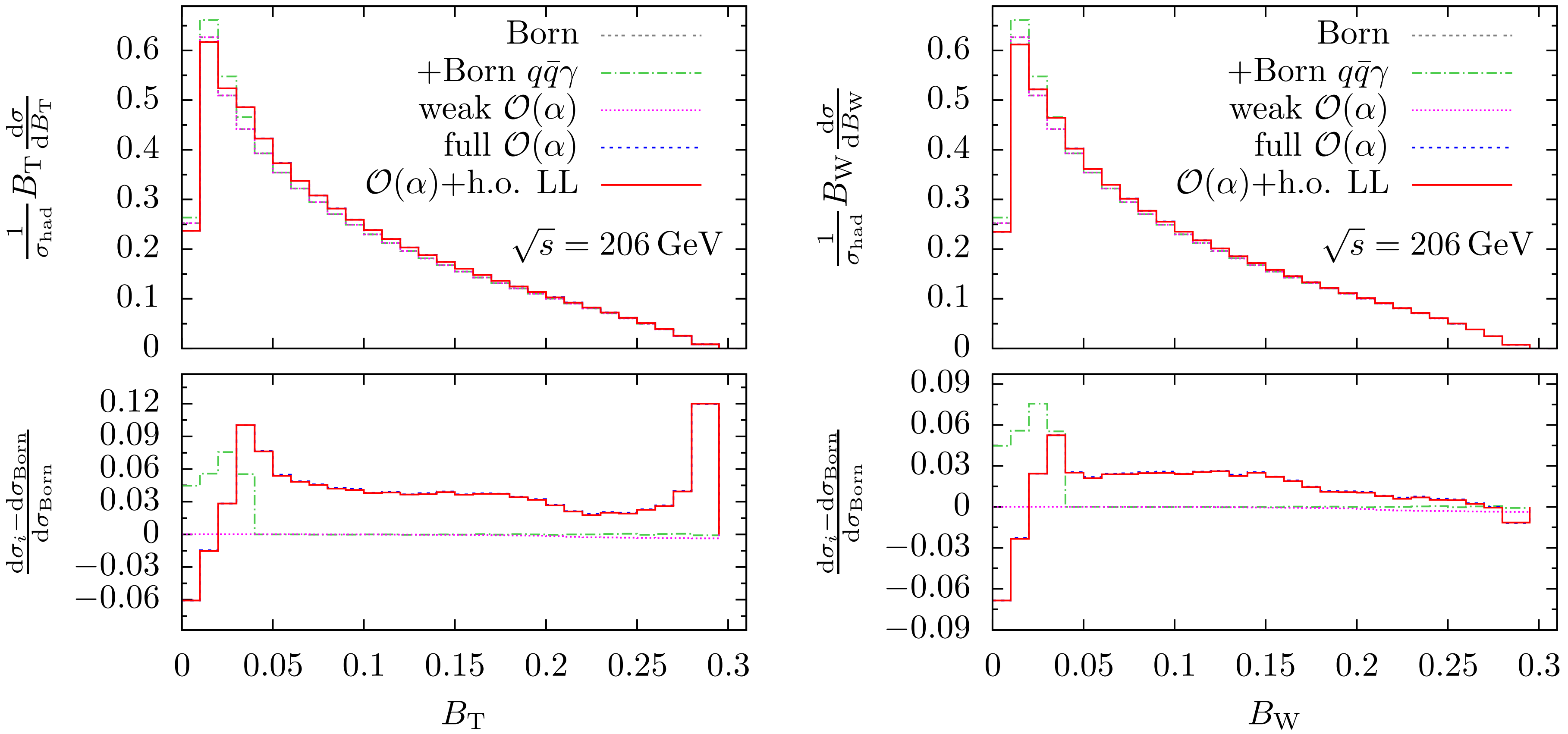

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Jet broadenings — yet another example

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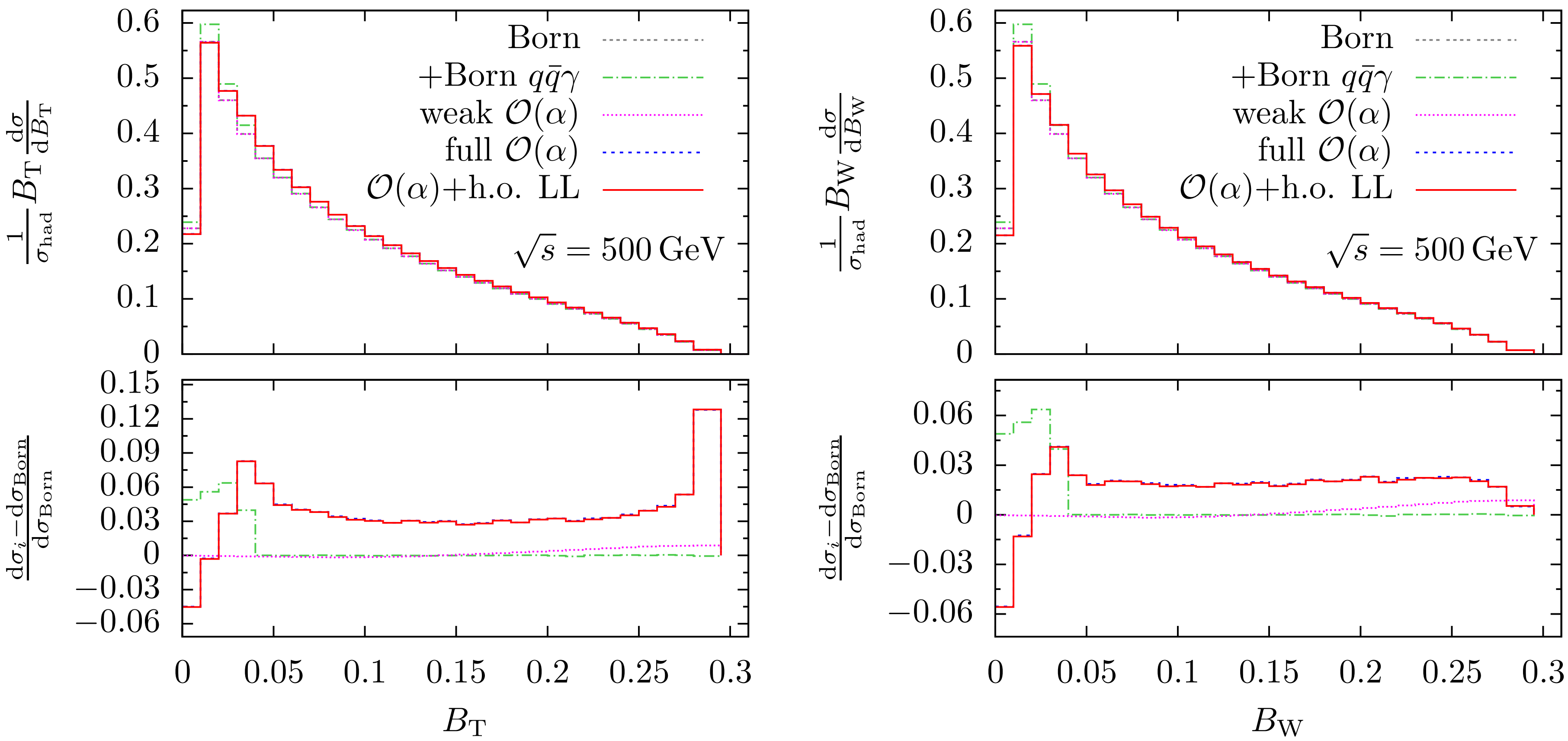


Overall size, energy dependence, and qualitative features of EW effects similar for all event shapes.

Jet production at hadron colliders

NLO EW corrections to jet and heavy-quark production

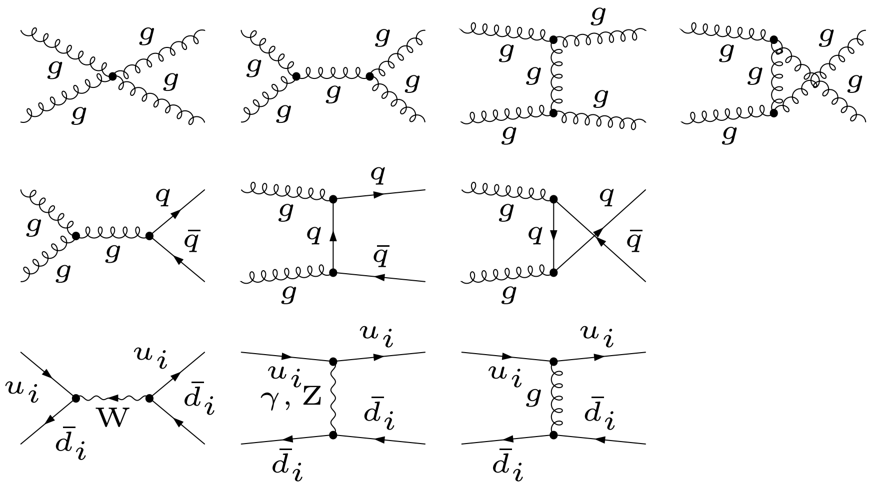
- $\mathrm{pp} \to 2\,\mathrm{jets}$
  - ◇ purely weak NLO corrections known — Moretti, Nolten, Ross '05,'06 (disagree with others); Scharf (prelim.) '09; S.D., Huss, Speckner '12
  - ◇ photonic NLO corrections unknown (but expected to be $\lesssim 1\%$)
  - ◇ no EW corrections available for $\mathrm{pp} \to \geq 3\,\mathrm{jets}$

- $\mathrm{pp} \to \mathrm{t\bar{t}}$
  - ◇ SM correction — Beenakker et al. '94; Moretti, Nolten, Ross '06; Kühn, Scharf, Uwer '06,'13; Bernreuther, Fücker, Si '08; Hollik, Kollar '08
  - ◇ THDM and MSSM — Hollik, Mösle, Wackeroth '97
  - ◇ no EW corrections with top-quark decays yet

- $\mathrm{pp} \to \mathrm{b\bar{b}}$ — Maina, Moretti, Nolten, Ross '03; Kühn, Scharf, Uwer '09

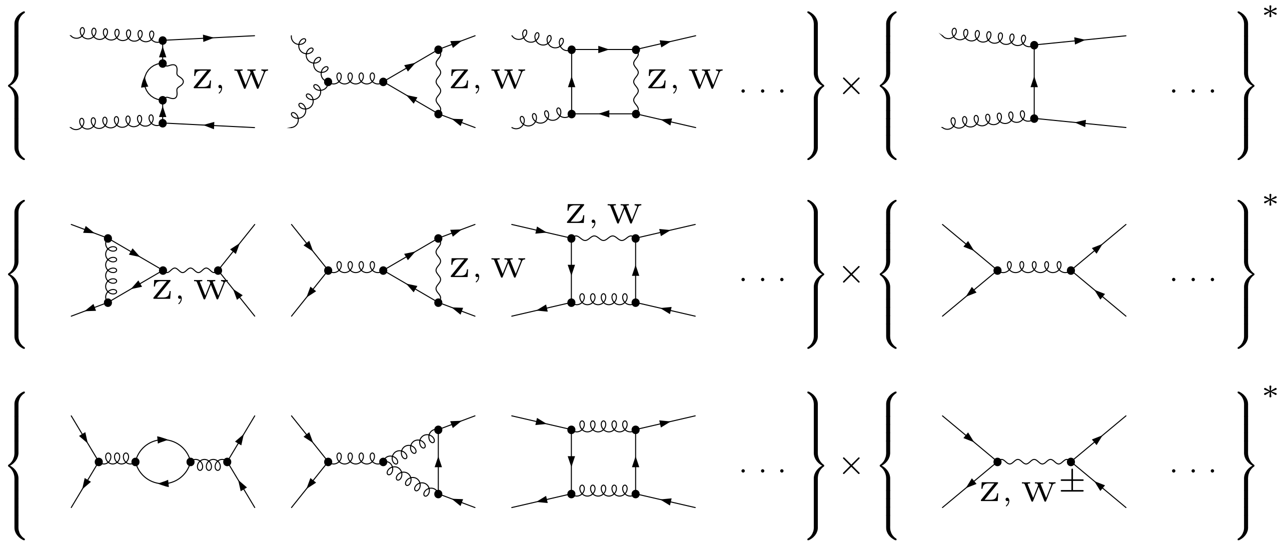
EW corrections to dijet production – typical contributions

Tree contributions: $\mathcal{O}(\alpha_s^2)$, $\mathcal{O}(\alpha_s\alpha)$, $\mathcal{O}(\alpha^2)$



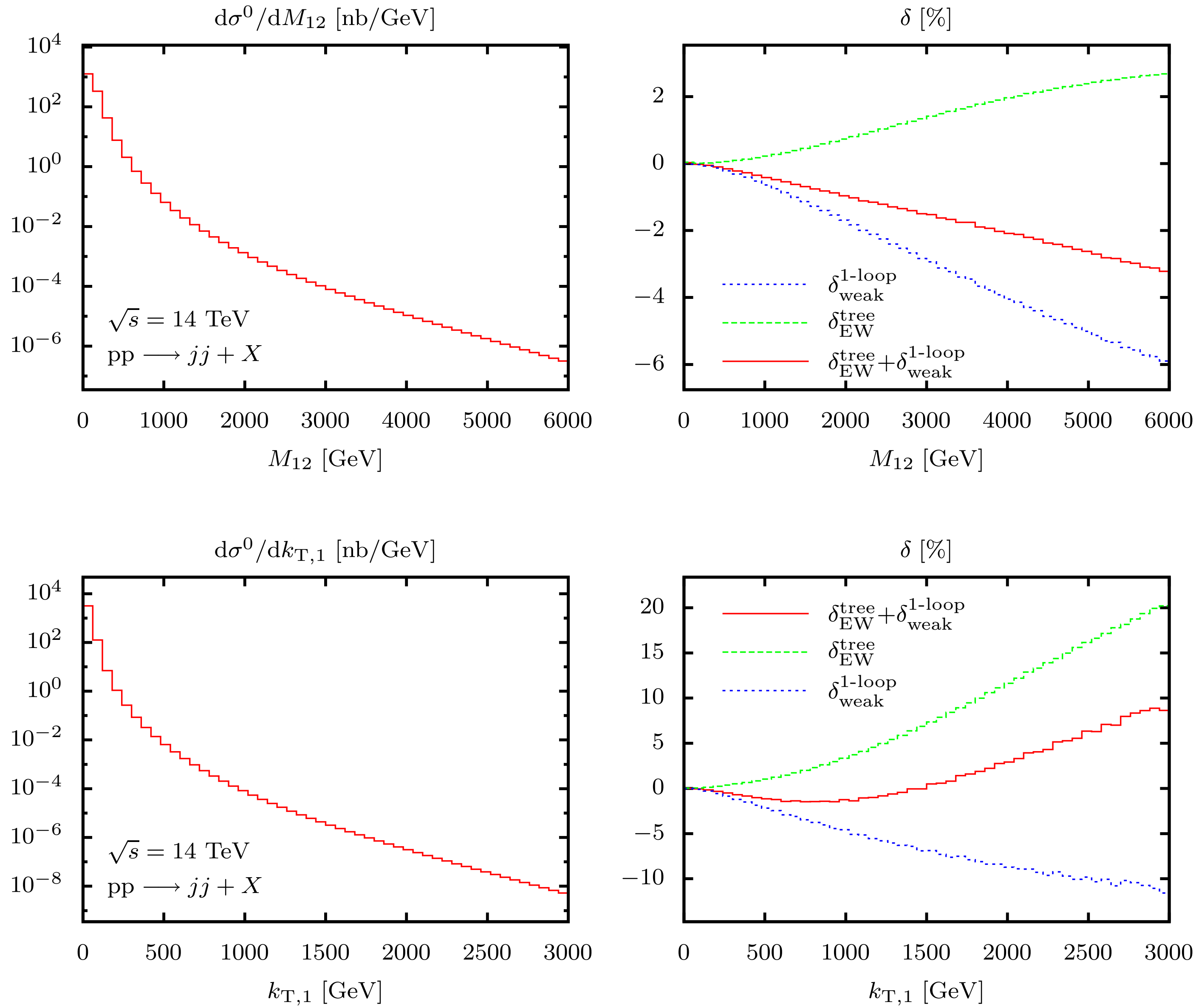
Loop contributions: $\mathcal{O}(\alpha_s^2\alpha)$

Note: involves 3-jet final states as well !



Numerical results

Weak corrections to dijet production – differential cross sections



S.D., Huss, Speckner '12

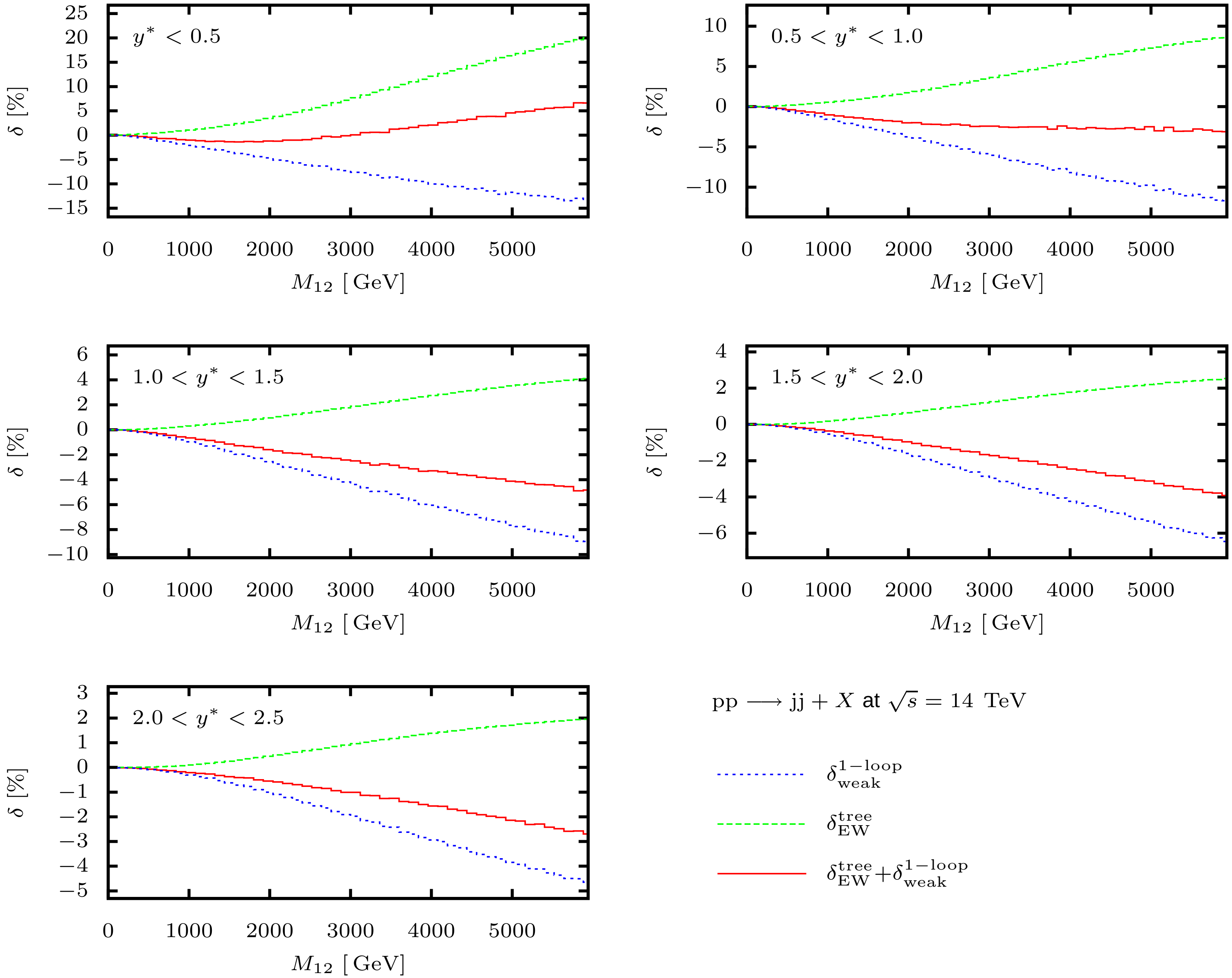
Weak corrections

- small for integrated XS
- growing in distributions for larger scales

Cancellations between tree and loop corrections (cut-sensitive!)

Weak corrections to dijet production – double-differential cross sections

S.D., Huss, Speckner ’12



Sudakov-like regime

(M_{12} large, y^* smallp)

$\hookrightarrow$ larger corrections

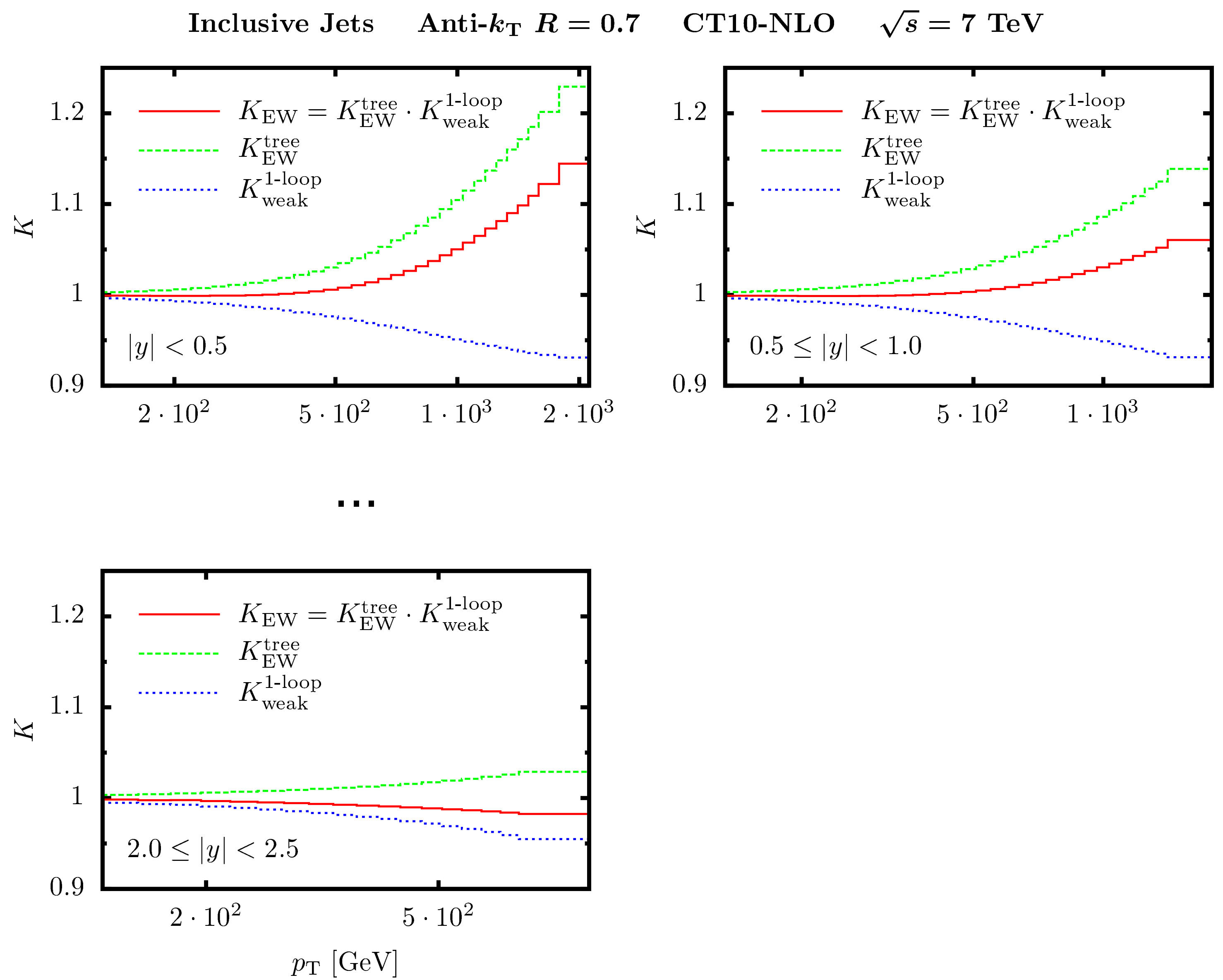
Regge-like regime

(M_{12}, $|y^*|$ large)

Inclusive jet production @ LHC7 – CMS data and EW corrections

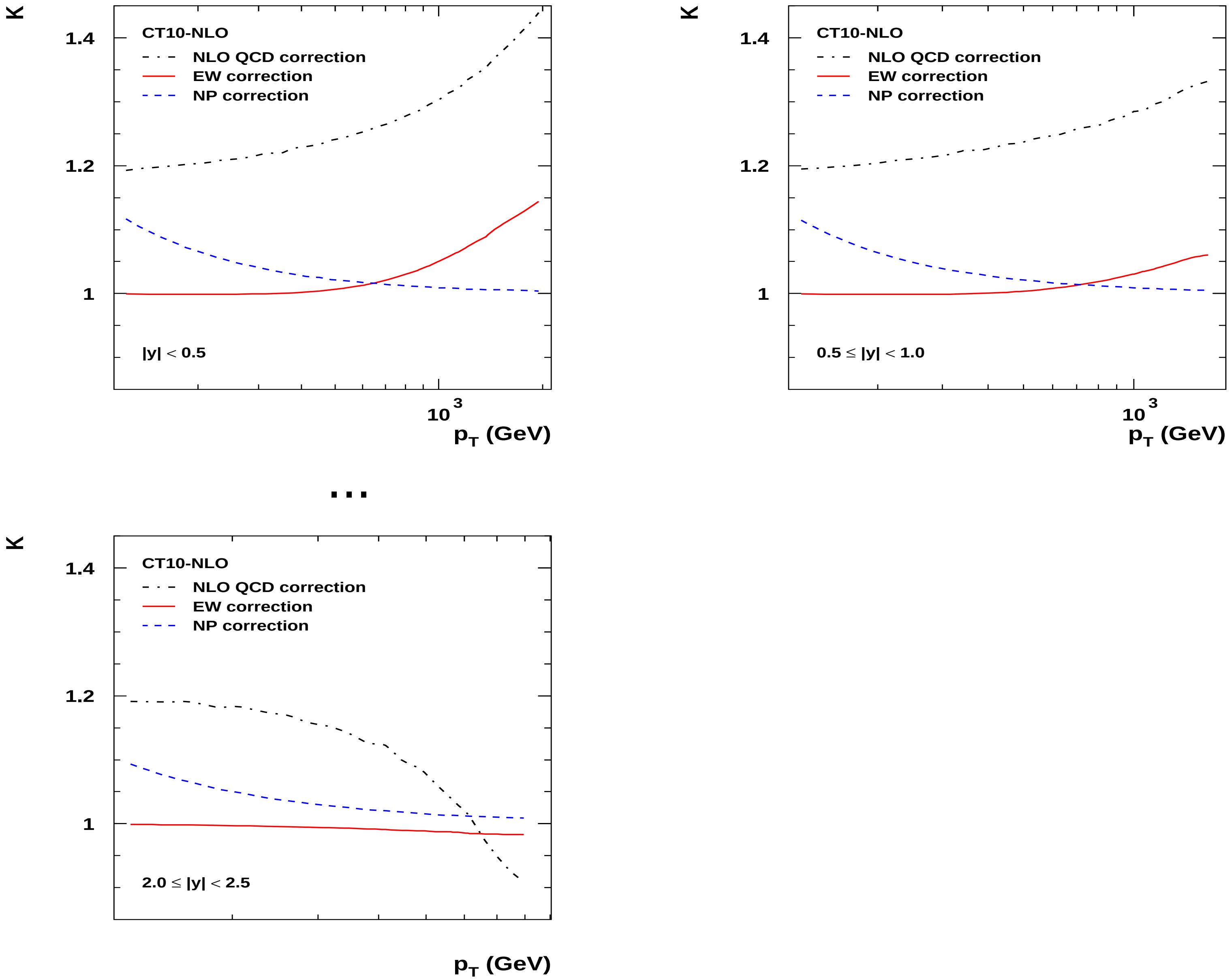
Weak corrections

S.D., Huss, Rabbertz ’14



Inclusive jet production @ LHC7 – CMS data and EW corrections

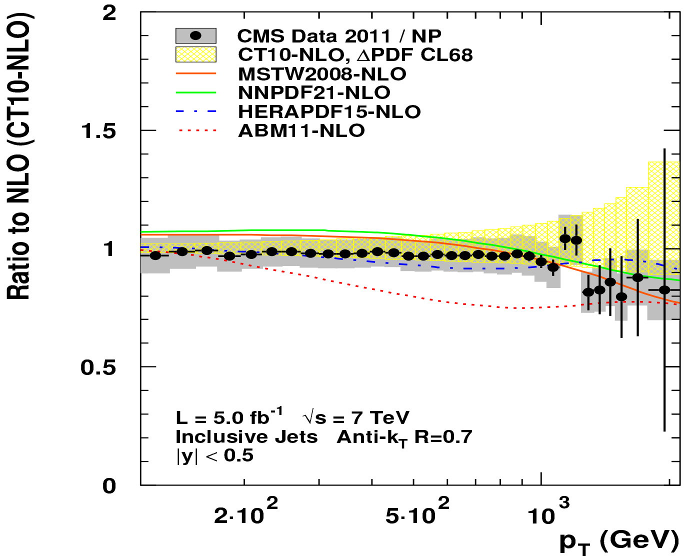
NLO weak, NLO QCD, and non-perturbative corrections   S.D., Huss, Rabbertz ’14

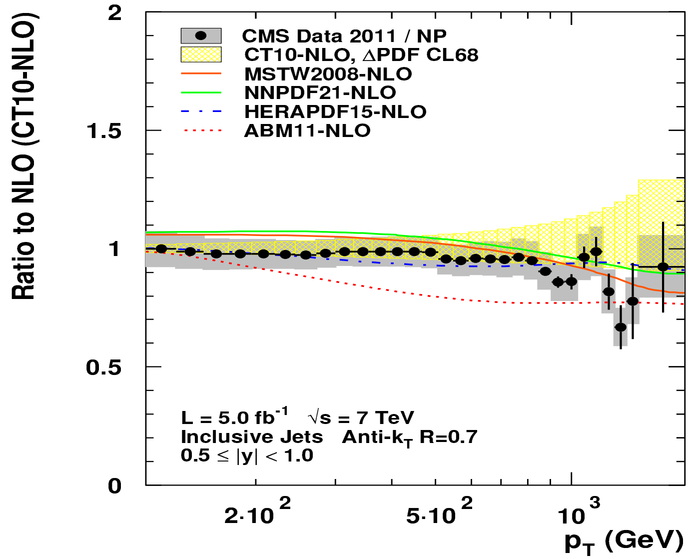


Inclusive jet production @ LHC7 – CMS data and EW corrections

Data w/o EW corrections

S.D., Huss, Rabbertz ’14





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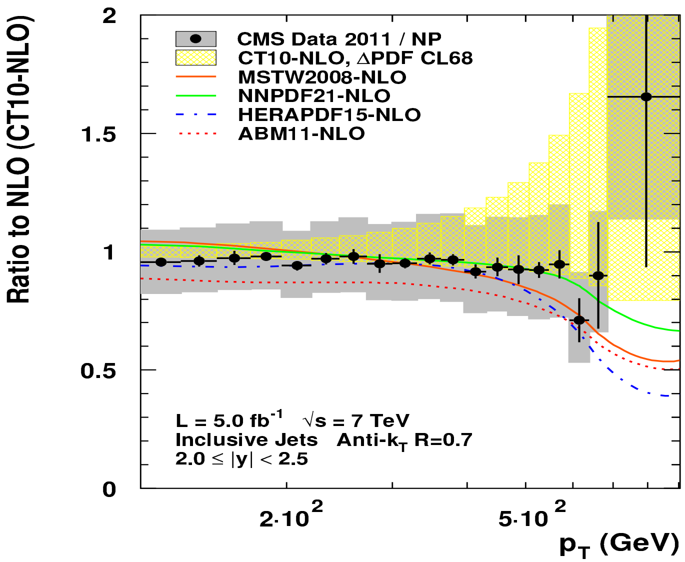
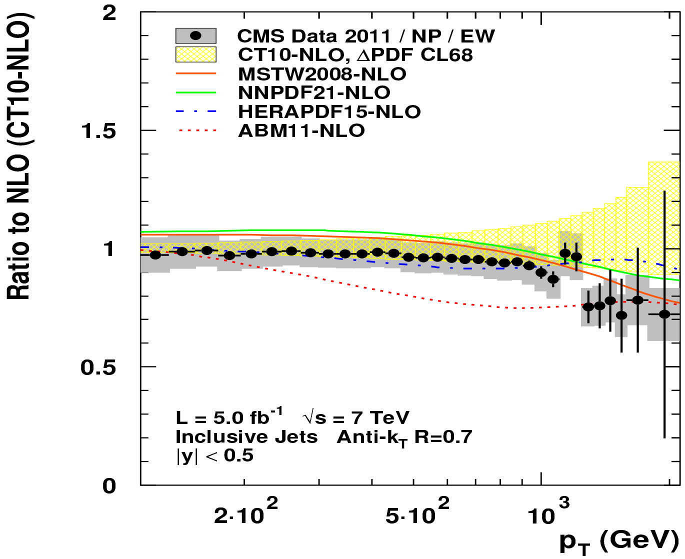
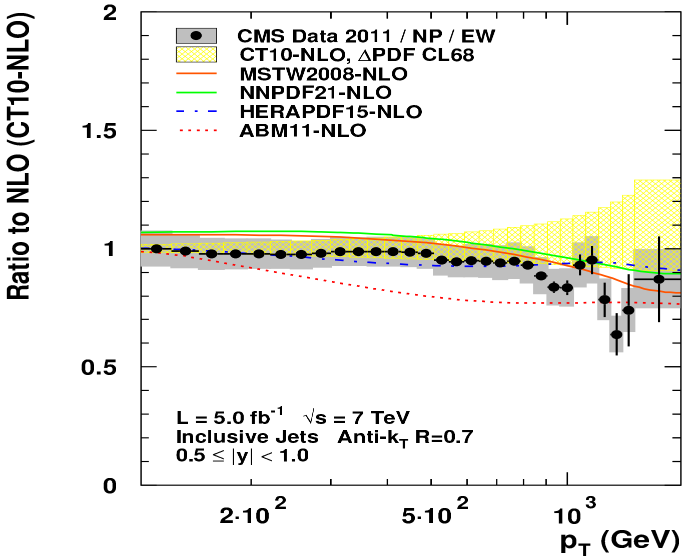


Inclusive jet production @ LHC7 – CMS data and EW corrections

Data w/ EW corrections

S.D., Huss, Rabbertz '14





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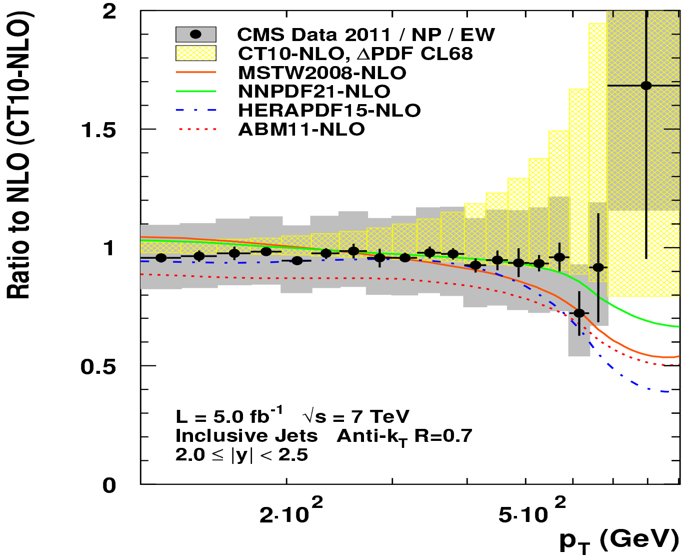


EW effects hardly visible @ $7\,\mathrm{TeV}$,

but certainly relevant @ $13{-}14\,\mathrm{TeV}$ with higher luminosity

Conclusions

EW corrections to hadronic event shapes at e^+e^- colliders

- largest EW corrections due to ISR,
  but reduction to $\%$ effects by normalization to σ_{had}
- genuine weak effects negligible for LEP energies, at $\%$ level for $500\,\mathrm{GeV}$ ILC
- $q\bar{q}\gamma$ final states separated from 3-jet events via photon fragmentation function
  $\hookrightarrow$ $\%$ effects near 2-jet endpoints of event shapes

$\Rightarrow$ NLO EW corrections completely known and sufficient
(minor relevance for JADE/LEP, but relevant at ILC)

EW corrections to jet production at hadron colliders

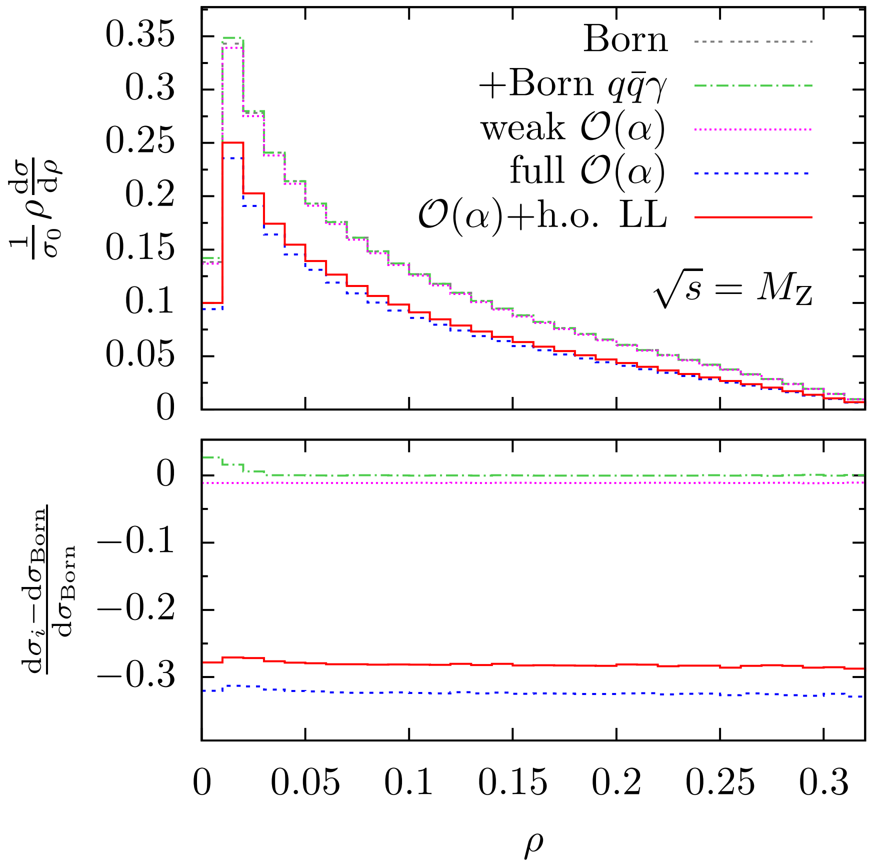
- weak corrections to dijet and inclusive-jet production $\sim 5{-}10\%$ in TeV range
  (significant cancellations between EW tree and loop contributions)
- yet unknown:
  - photonic corrections ($\lesssim 1\%$ expected)
  - EW corrections to (3-jet)/(2-jet) cross-section ratio
    $\hookrightarrow$ significant cancellations expected (but certainly less dramatic than in e^+e^-)

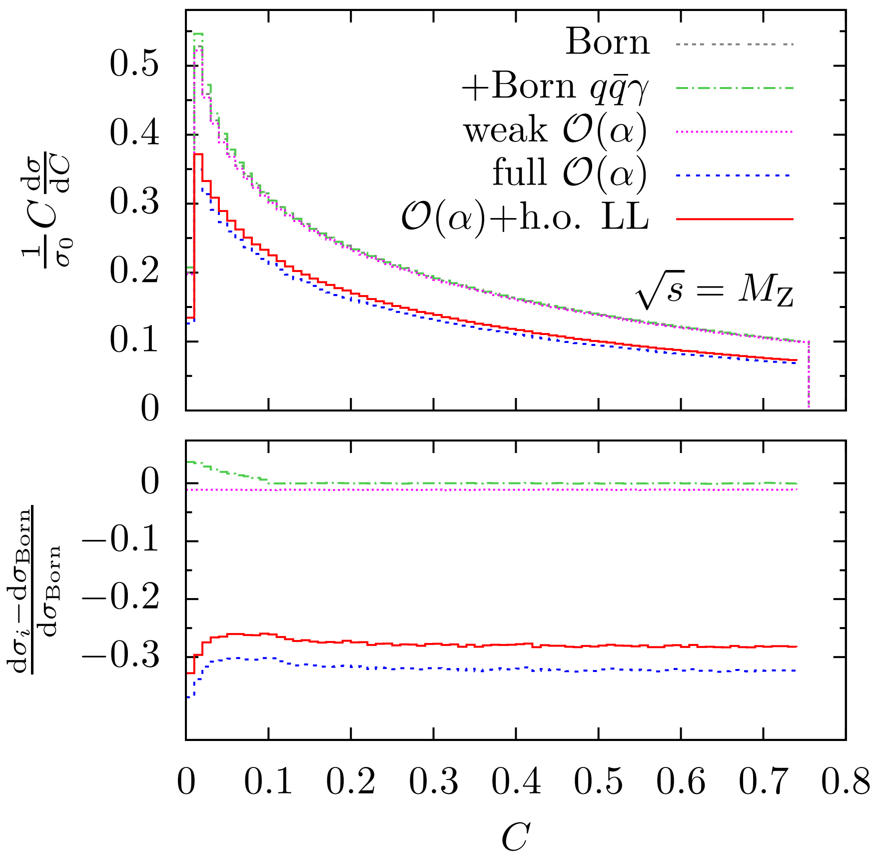
$\Rightarrow$ Further work required !

Backup slides

Heavy jet mass and C parameter

Denner, S.D., Gehrmann, Kurz '09,'10





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Heavy jet mass and C parameter

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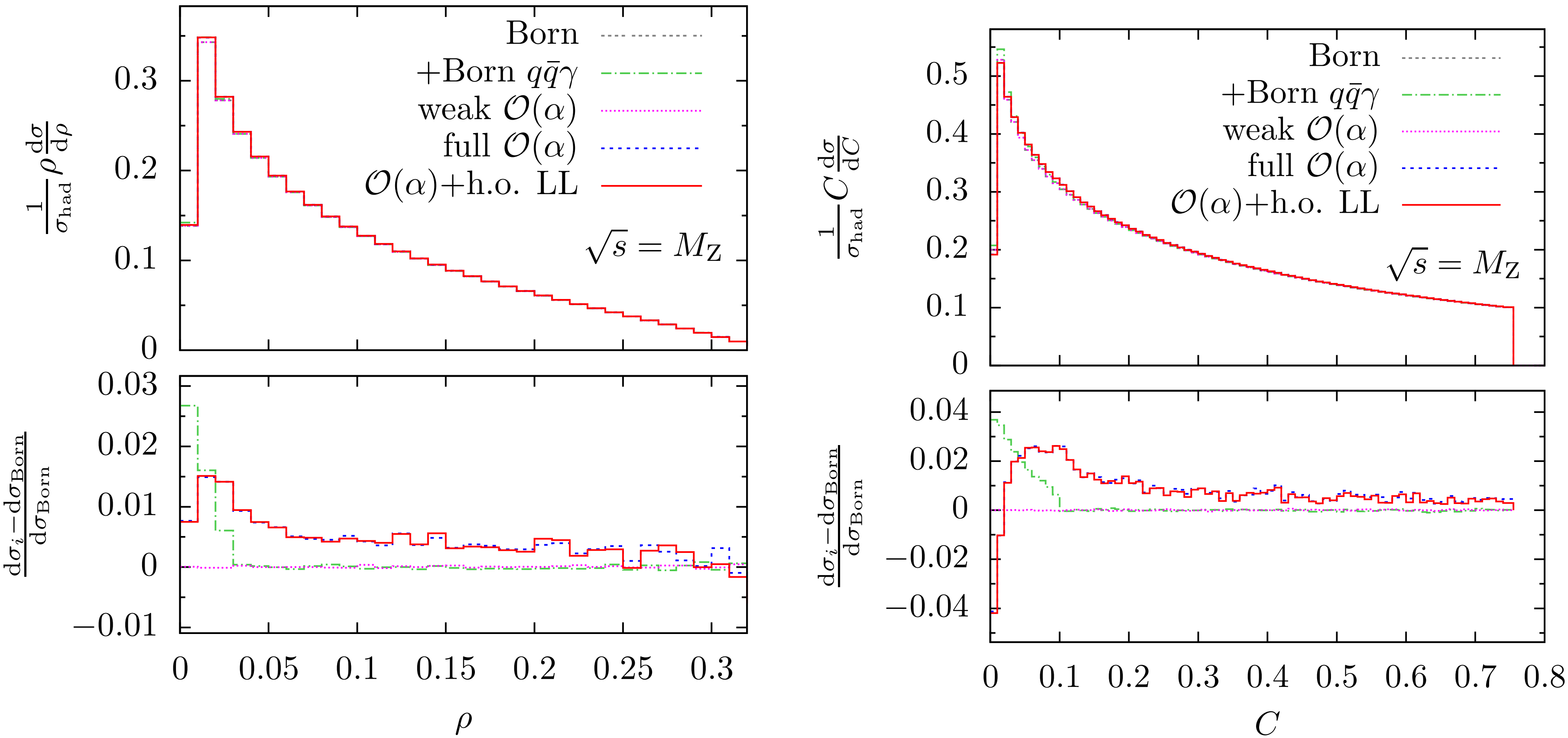

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Heavy jet mass and C parameter

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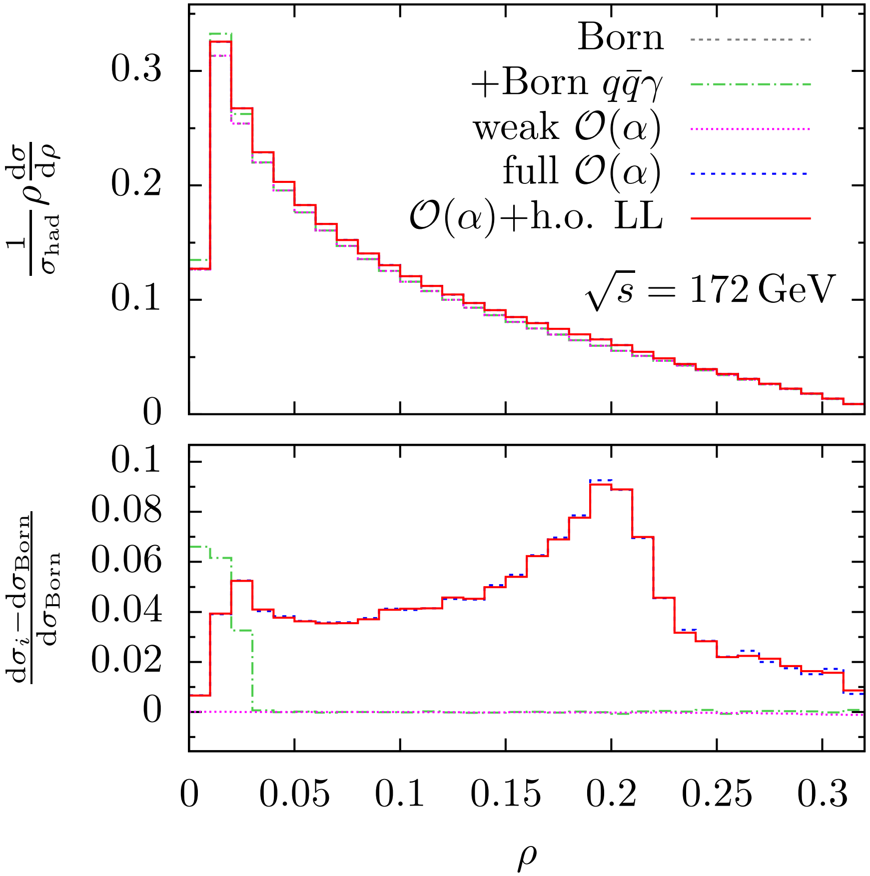

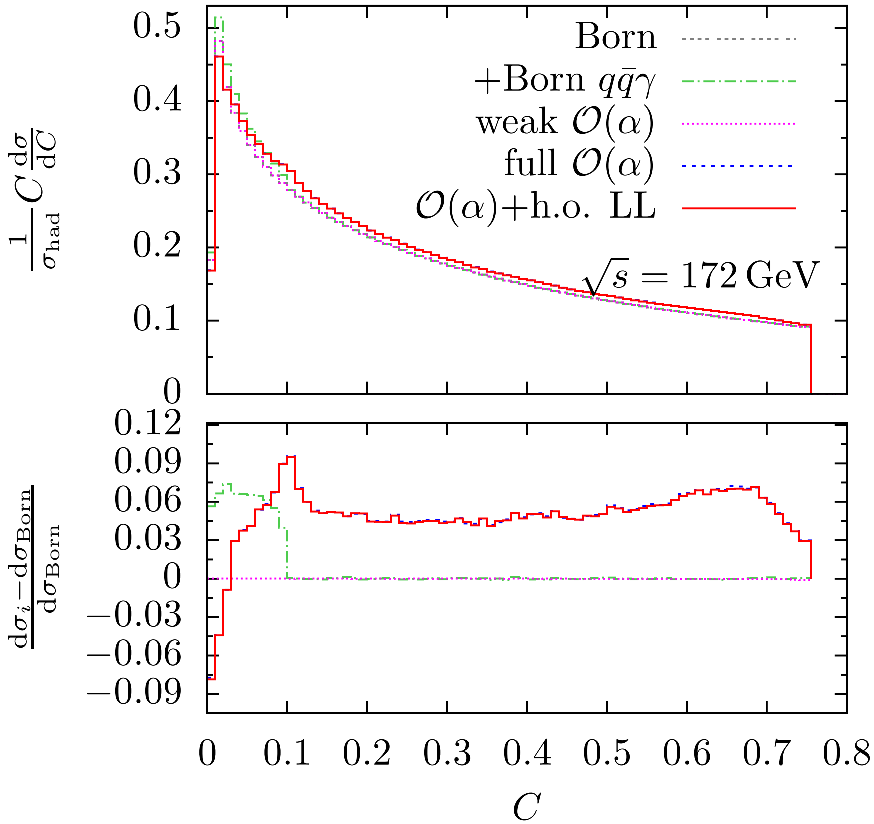

Overall size, energy dependence, and qualitative features of EW effects similar for all event shapes.

Heavy jet mass and C parameter

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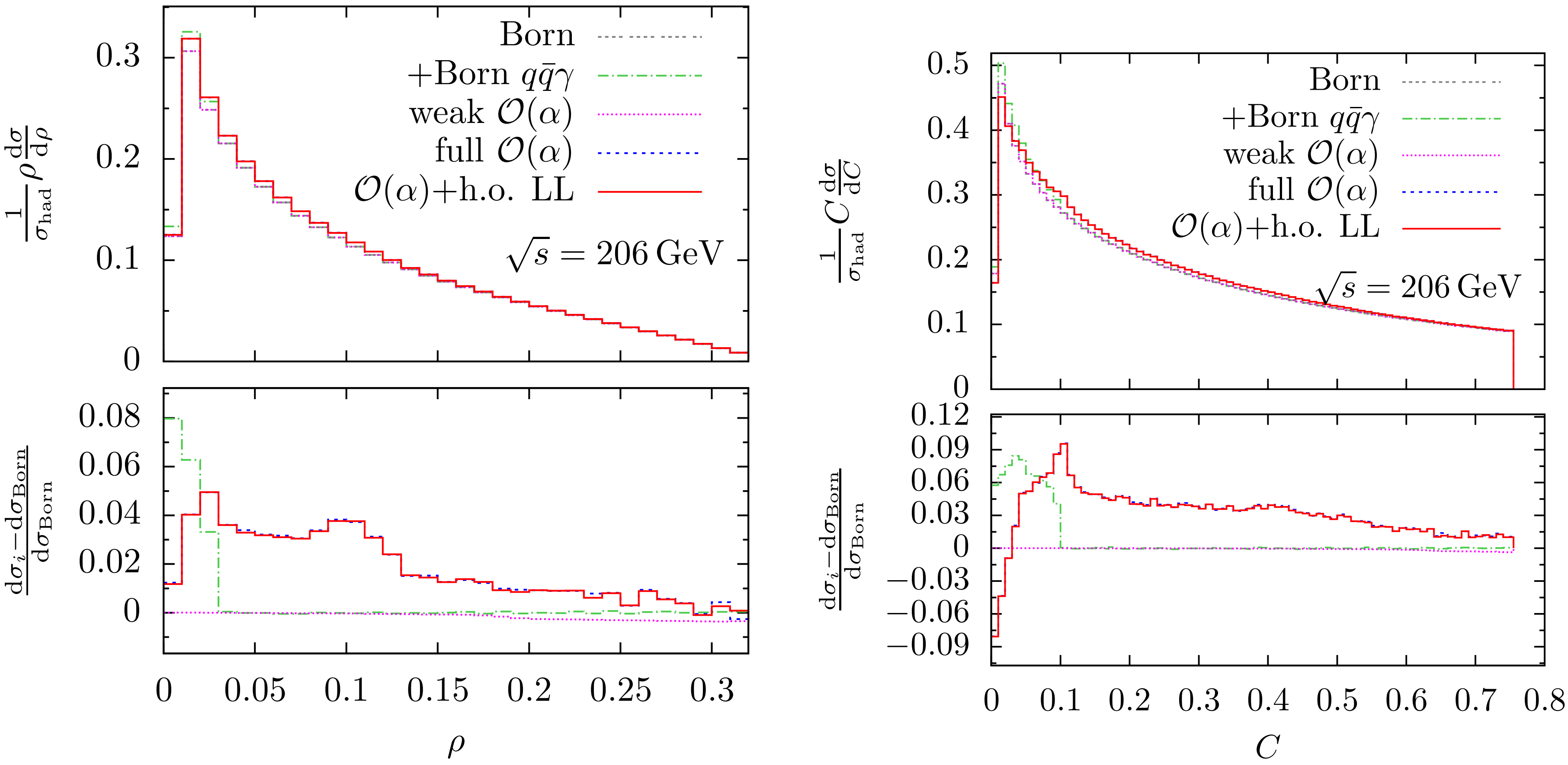

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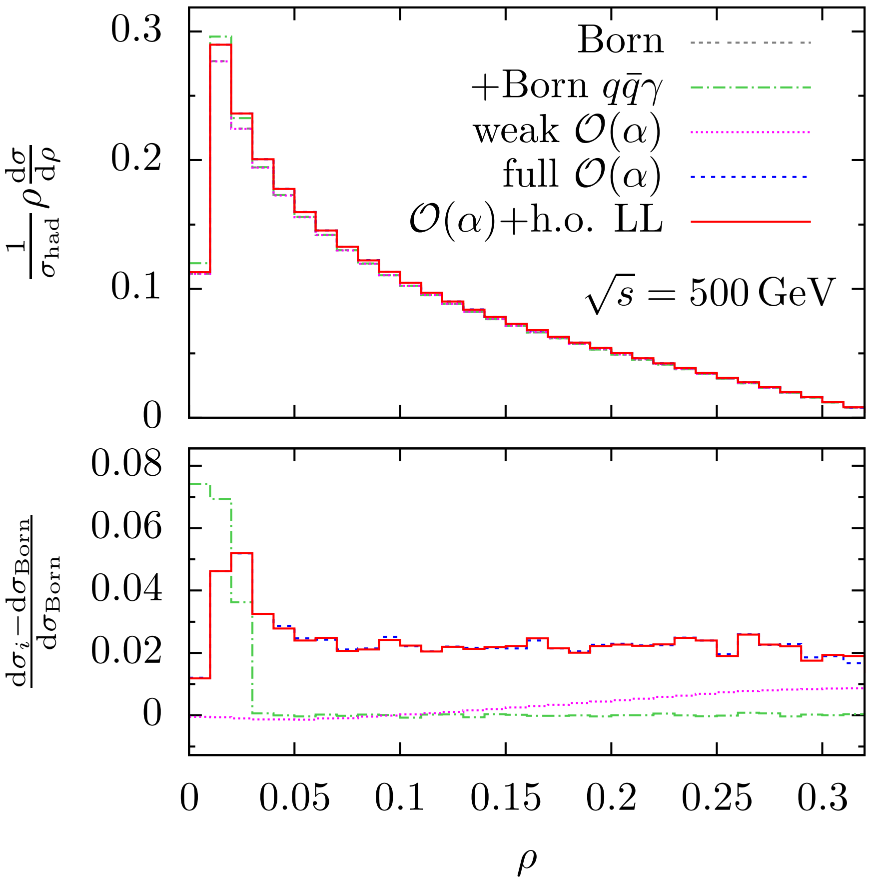

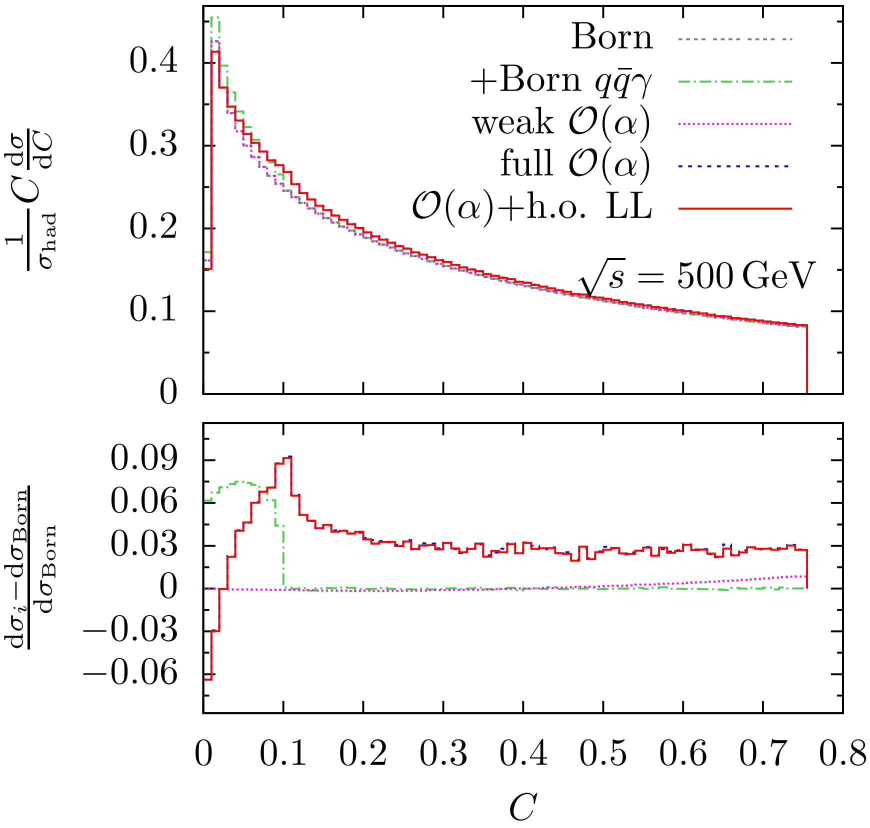

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