Weak corrections to hadronic observables

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Corrections to hadronic observables: QCD vs EW

- Large scale dependence of higher order corrections often dominates theoretical uncertainties !
- QCD corrections typically largest:

$$\alpha_S \approx \; 10\; \alpha_{EW} \qquad (\alpha_{EW} = \alpha_{EM}/\sin^2\theta_W).$$

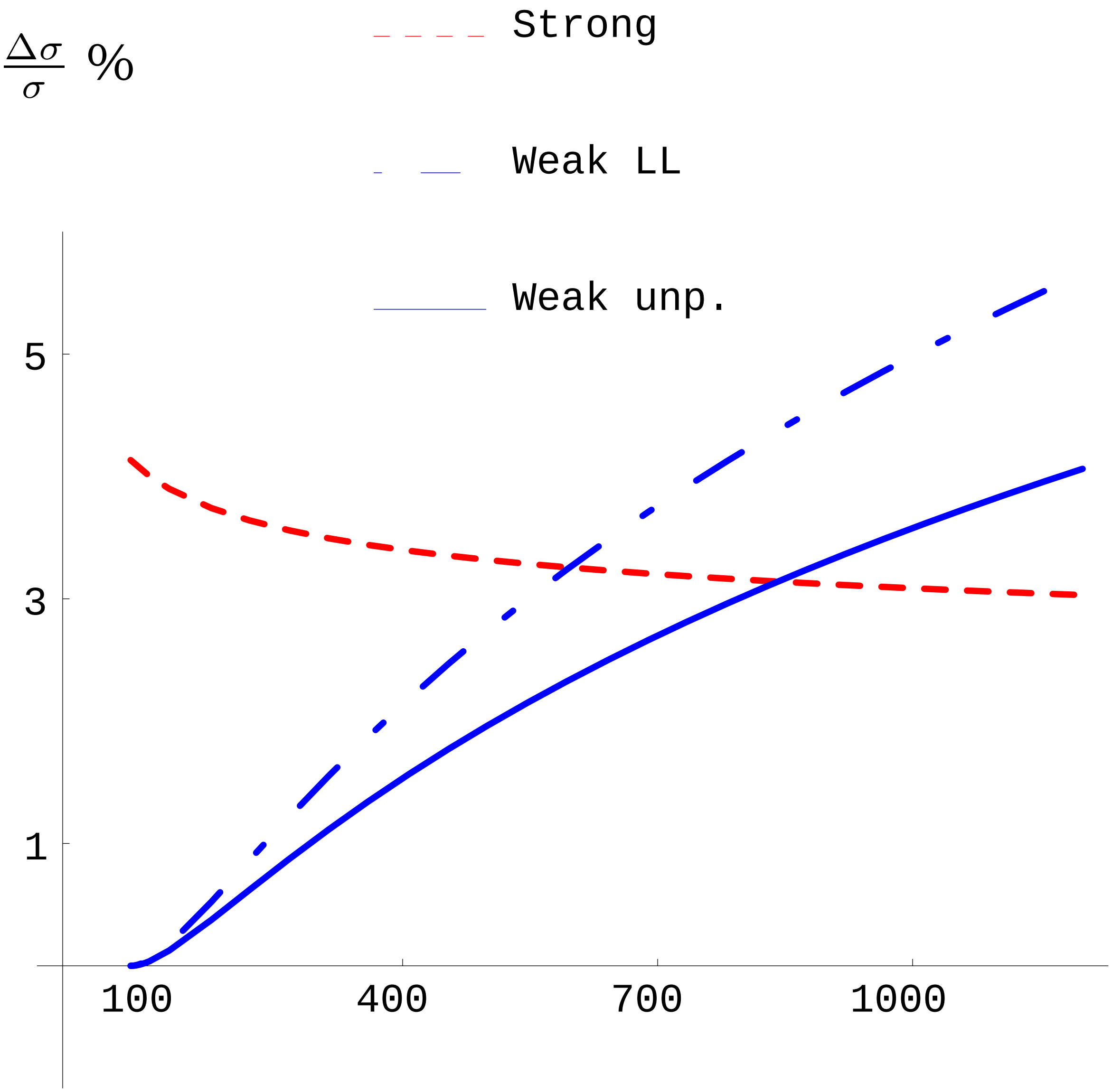
BUT ....

- There are large log around in EW case: at $\sqrt{s} = \; 1\,\mathrm{TeV}$

$$\frac{\alpha}{4\pi s_{\mathrm{w}}^2}\log^2\frac{s}{M_{\mathrm{W}}^2} = 6.6\%, \qquad \frac{\alpha}{4\pi s_{\mathrm{w}}^2}\log\frac{s}{M_{\mathrm{W}}^2} = 1.3\%.$$

- NNLO QCD corrections will soon be available: recall $\alpha_S^2 \approx \alpha_{EW}$!

- CONSIDER LEPTONIC COLLISIONS: AT HIGH ENERGIES, $\sqrt{s} \gg M_W$ (ILC, 0.5 TO 3 TEV), EW INTERACTIONS BECOME STRONG:



TOTAL (INCLUSIVE) HADRONIC CROSS SECTION

ENERGY (GEV)

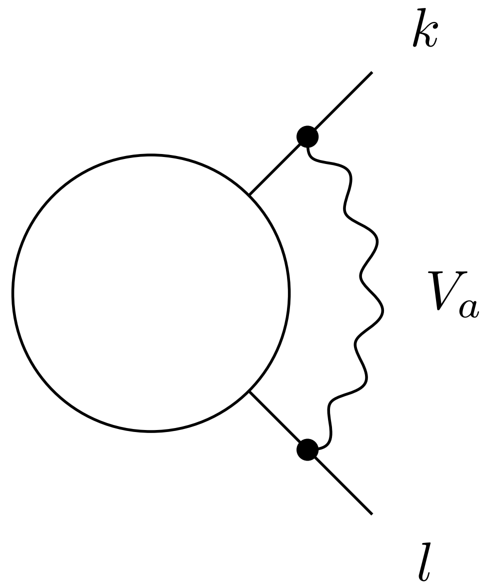
Sudakov logs^2 in a nutshell

- Correspond to soft and collinear singularities in theories with massless bosons, where they are canceled by real radiation.
- Regulated by boson mass in EW case: they are finite !

  Physical dependence on IR cut-off M_W remains

- In Feynman gauge they are associated with virtual graphs where soft-collinear bosons are exchanged between external legs. (In axial gauge they are associated with self energy graphs on external legs.)
- DL are universal: only depend on external particles !

$$\sum_{k=1}^{n} \sum_{l<k} \sum_{V_a=\mathrm{A,Z,W}^{\pm}}$$

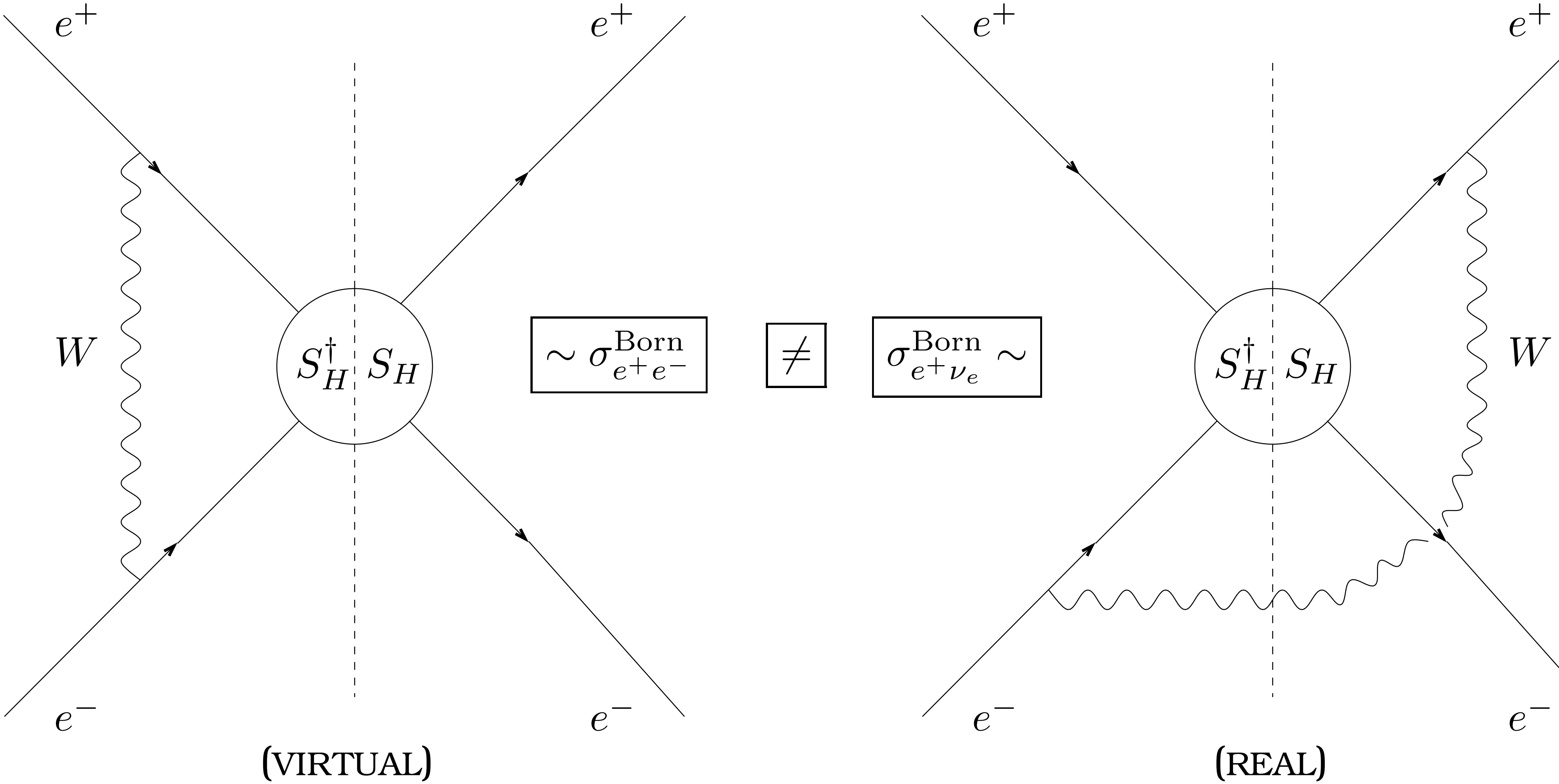


$$= \sum_{k=1}^{n} \sum_{l<k} \sum_{V_a=\mathrm{A,Z,W}^{\pm}} \alpha/4\pi \log^2(r_{kl}/M^2) T_{kl}$$

$$\log^2 \frac{r_{kl}}{M^2} = \log^2 \frac{s}{M^2} + 2 \log \frac{s}{M^2} \log \frac{r_{kl}}{s} + \log^2 \frac{r_{kl}}{s} \qquad r_{kl} = (p_k \pm p_l)^2$$

- Numerically at TeV energies there are large cancellations between Double Log (DL) and Single Log (SL) contributions.
- DL (and SL) do not cancel in inclusive measurements (aka violation of Bloch-Nordsieck theorem in non-abelian theories).

- Colourless hadrons force summation/averaging over initial colour states: cancellation is recovered in QCD.
- EW case: analogous would be flavour/isospin summation/averaging, impossible experimentally.
- SL are not universal !
- Non-log (finite) terms are process dependent.



- EXAMPLE: e^+e^- WOULD CANCEL AGAINST $e^+\nu_e$

- Consider exclusive final states, Z/W radiation easily resolved experimentally:

Real & virtual logs are finite, <u>need not</u> be summed.

- Hence additional DL and SL in case of Z exchange.

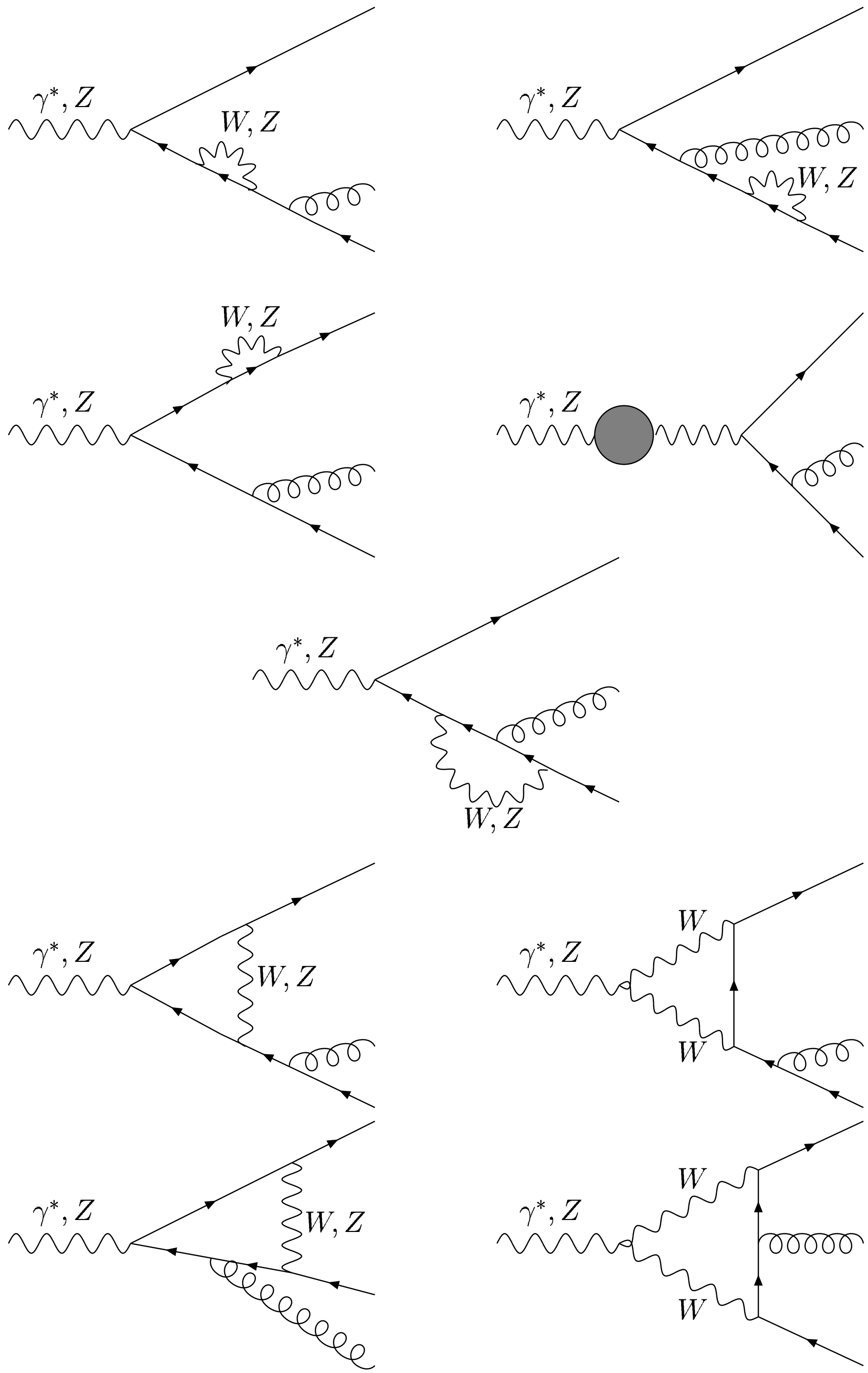
- Compute only virtual contributions: negative effects dominate inclusively.

- Non-trivial helicity structure: introduce parity-violating asymmetries (background to New Physics).

- Leading ($\sim \alpha_{\rm W}^n \log^{2n}(s/M_W^2)$), sub-leading ($\sim \alpha_{\rm W}^n \log^{2n-1}(s/M_W^2)$) and sub-sub-leading ($\sim \alpha_{\rm W}^n \log^{2n-2}(s/M_W^2)$) logs can be resummed (inclusive final states).

- Consider fixed order (including finite terms).

- Can separate Weak from QED corrections in some processes.


γ*, Z
W, Z
γ*, Z
W, Z
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W, Z
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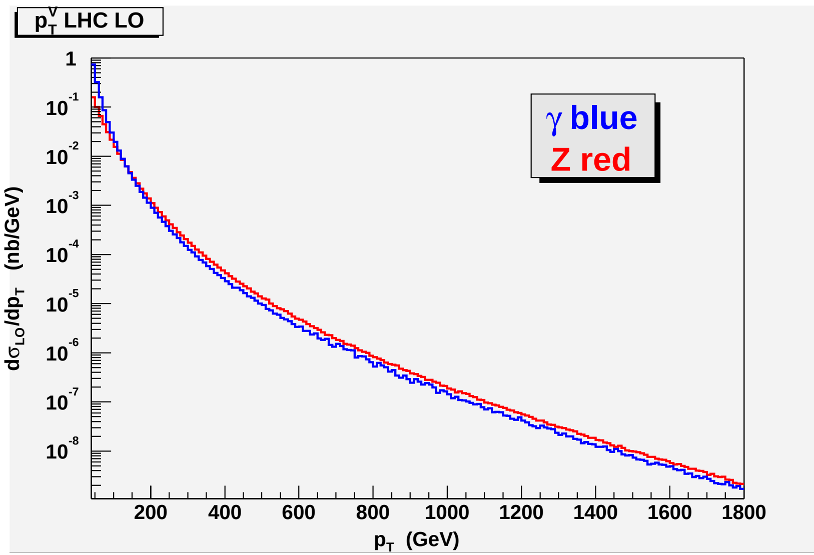
W, Z
γ*, Z
W, Z
γ*, Z
W
W
γ*, Z
W, Z
γ*, Z
W
W

$p\bar{p}, pp \longrightarrow Z(\gamma) + j$ [Phys.Lett. B593:143,2004]

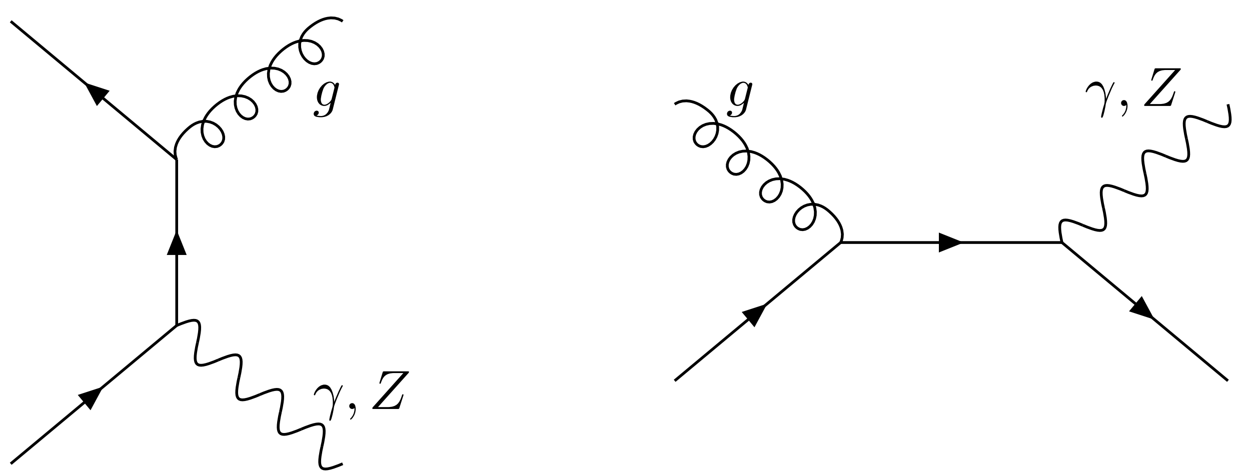
- Large cross section process: at LHC in LO $\sigma_{\gamma+j}(p_T > 40\,\mathrm{GeV}) \approx 1.4 \times 10^7\ fb$, $\sigma_{Z+j}(p_T > 40\,\mathrm{GeV}) \approx 4.9 \times 10^6\ fb$



- Contribute to Drell-Yan cross section: Z easily separated using $Z \rightarrow l^+l^-,\ l = e, \mu$.
- Gives access to q and especially g PDFs.
- Useful for absolute jet energy calibration.
- Possible LHC luminometer: will affect all LHC cross sections.

- $m_b = 0$, $m_t = 175\,\mathrm{GeV}$
- $M_Z = 91.19\,\mathrm{GeV}$, $M_W = 80.35\,\mathrm{GeV}$
- $\sin^2\theta_W = 1 - M_W^2/M_Z^2$
- $\mu = M_Z$, $\alpha^{-1} = 128.07$
- PDFs: MRSTLO20001

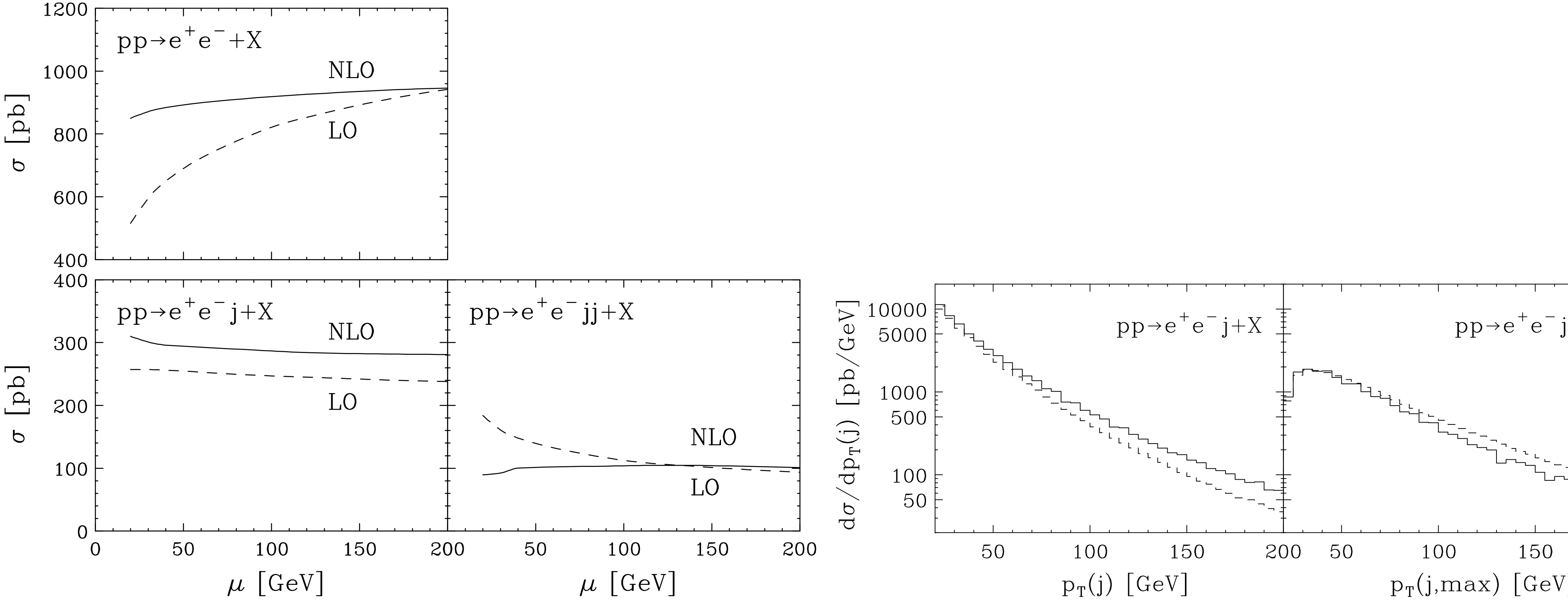
Tree Level



+ CROSSED

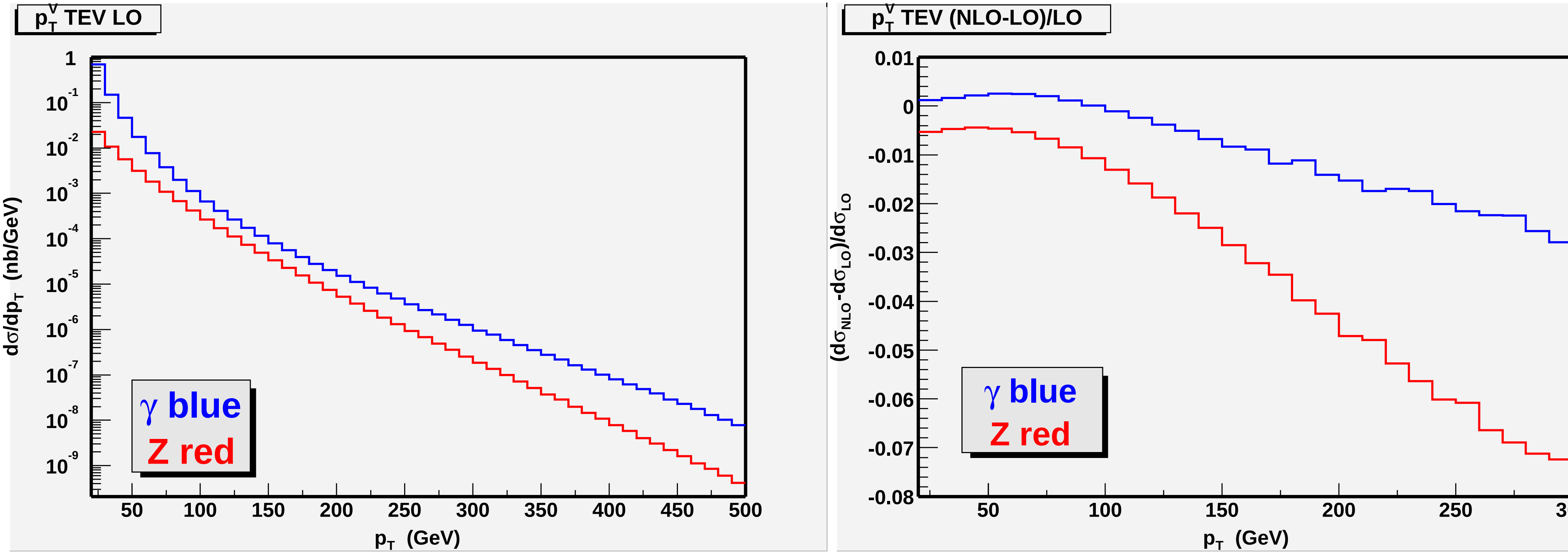
LHC: $pp \to \gamma^*, Z^* + j$: QCD CORRECTIONS

- CAMPBELL, ELLIS AND RAINWATER, PHYS.REV. D68:094021,2003.
- ARNOLD, ELLIS AND RENO PRD40:912,1989; ARNOLD AND RENO NPB319:37,1989.
- GIELE, GLOVER AND KOSOWER NPB403:633,1993.



$p_T(l) > 15\,\text{GeV},\ |\eta_l| < 2.4,\ p_T(j) > 20\,\text{GeV},\ |\eta_j| < 4.5,\ \Delta R_{lj} > 0.4,\ \Delta R_{ll} > 0.2$

$\sqrt{s} = 2\,\mathrm{TeV}$: $p\bar{p} \to \gamma, Z + j,\ p_{Tj}$

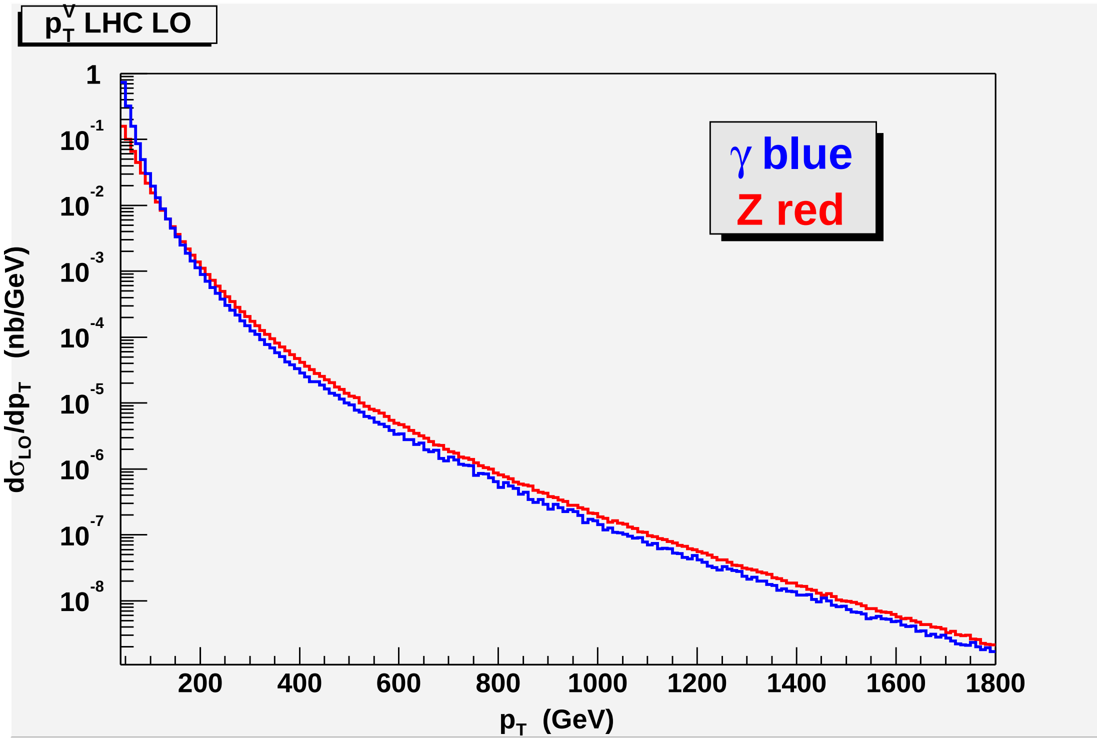


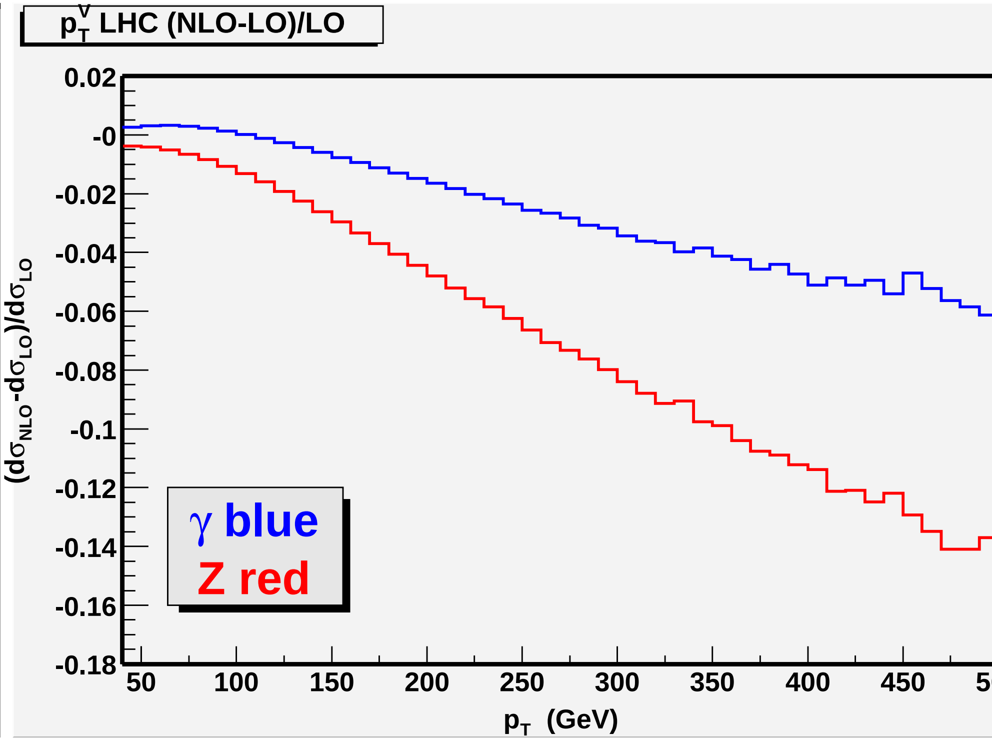
$p_T > 20\,\mathrm{GeV},\ |\eta_j| < 3$

$L = 2 - 20 fb^{-1}$, $BR(Z \to e, \mu) \approx 6.5\%$ IN A WINDOW OF 10 GeV AT $p_T = 100\,\mathrm{GeV}$ WE EXPECT ABOUT 500-5000±22-71 $Z + j$ EVENTS

$\delta\sigma/\sigma \approx -1.2\%$ CORRESPONDS TO 6-60 EVENTS

LHC $\sqrt{s} = 14\,\mathrm{TeV}$: $pp \to \gamma, Z + j,\ p_{Tj}$





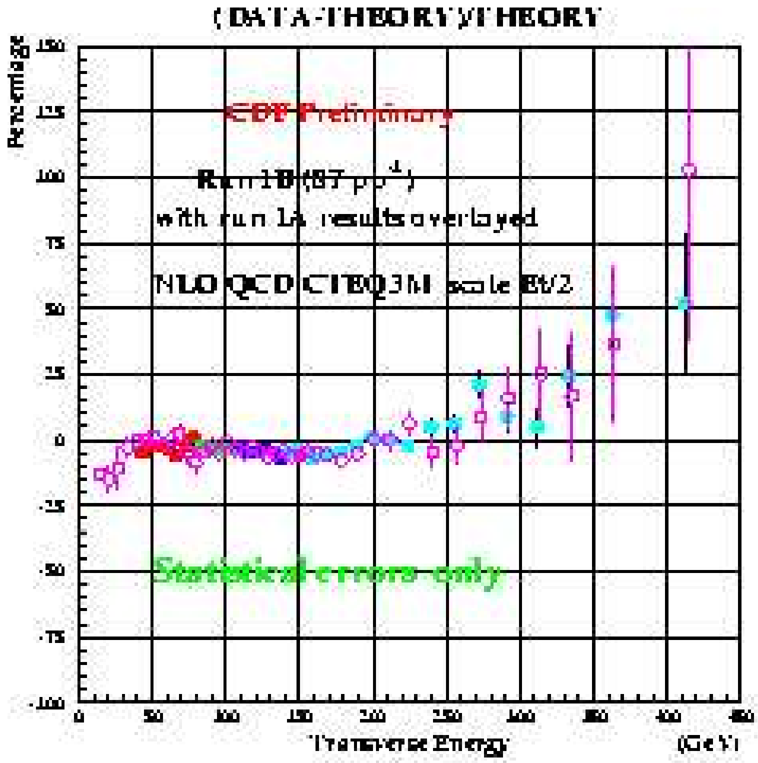
$p_T > 40\,\mathrm{GeV},\ |\eta_j| < 4.5$

$L = 30 fb^{-1}$, $BR(Z \to e, \mu,) \approx 6.5\%$ IN A WINDOW OF 40 GeV AT $p_T = 450\,\mathrm{GeV}$ WE EXPECT ABOUT 2000±45 $Z + j$ EVENTS

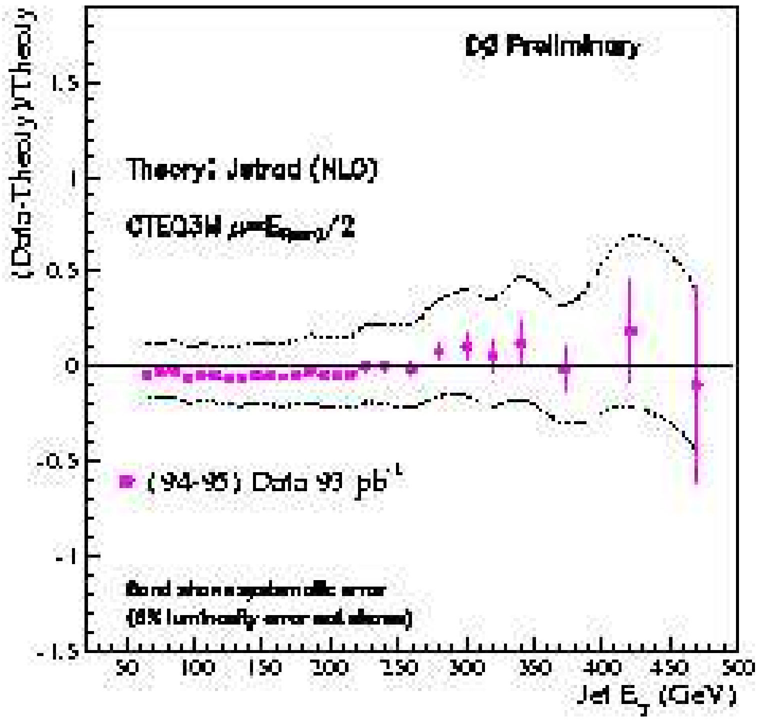
$\delta\sigma/\sigma \approx -12\%$ CORRESPONDS TO 240 EVENTS

(Di-)Jet hadro-production

- CDF High E_T excess !

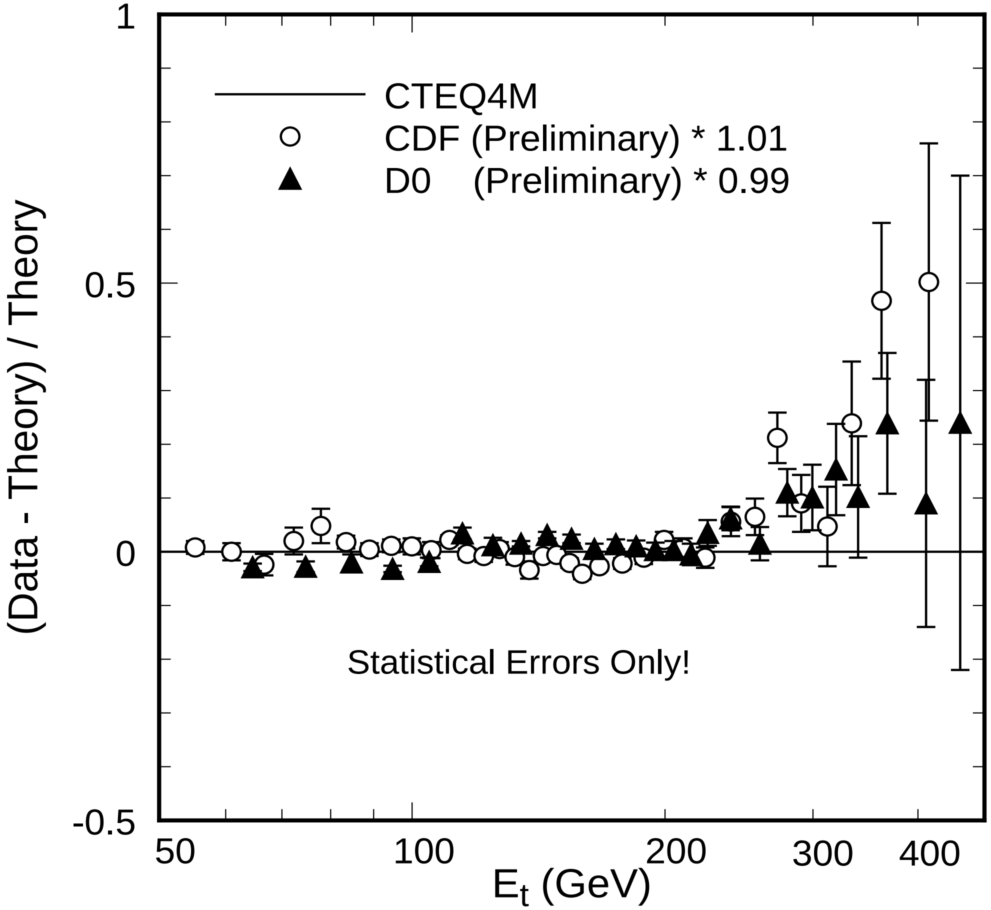


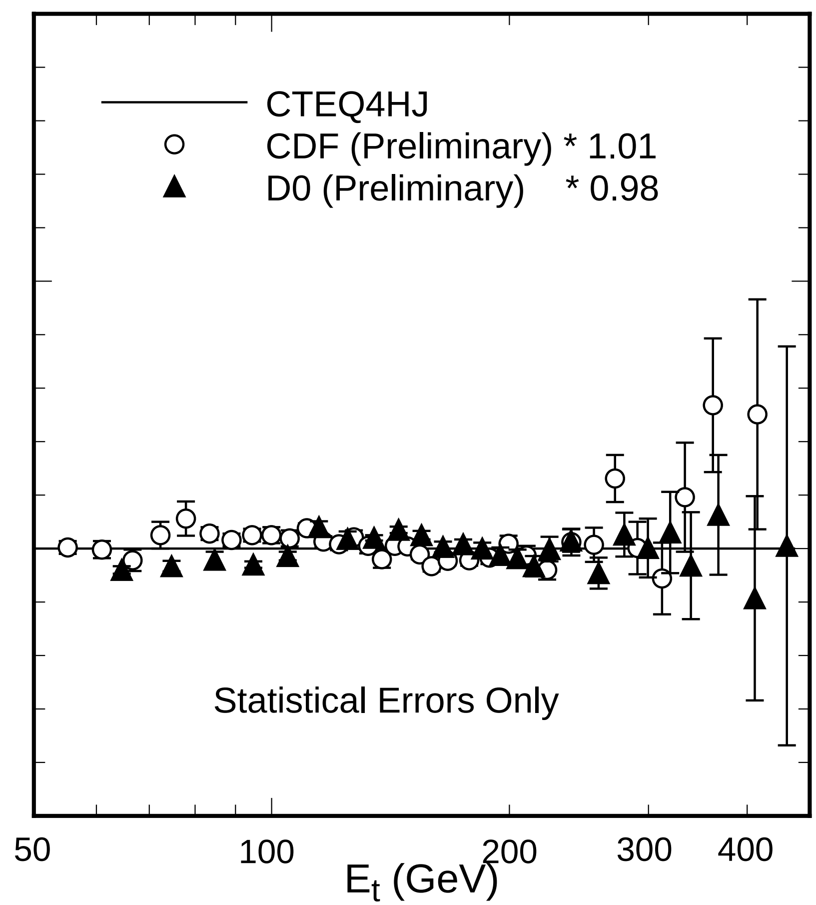
(c) CDF data vs. theory



(d) D∅ data vs. theory

- Can be cured by reshaping gluon at medium x:





- Or can it not ?

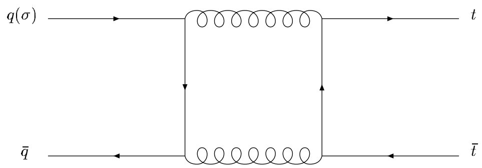
- There are 14 subprocesses to be corrected:

```
if(iproc.eq. 0)write(*,*)'g g -> g g'
if(iproc.eq. 1)write(*,*)'g g -> q q-bar'
if(iproc.eq. 2)write(*,*)'q q-bar -> g g'
if(iproc.eq. 3)write(*,*)'q(-bar) g -> q(-bar) g'
if(iproc.eq. 4)write(*,*)'q q -> q q'
if(iproc.eq. 5)write(*,*)'q-bar q-bar -> q-bar q-bar'
if(iproc.eq. 6)write(*,*)'q Q -> q Q (same gen)'
if(iproc.eq. 7)write(*,*)'q-bar Q-bar -> q-bar Q-bar (same gen)'
if(iproc.eq. 8)write(*,*)'q Q -> q Q (diff gen)'
if(iproc.eq. 9)write(*,*)'q-bar Q-bar -> q-bar Q-bar (diff gen)'
if(iproc.eq.10)write(*,*)'q q-bar + q-bar q -> q q-bar + q-bar q'
if(iproc.eq.11)write(*,*)'q q-bar -> Q Q-bar (same gen)'
if(iproc.eq.12)write(*,*)'q q-bar -> Q Q-bar (diff gen)'
if(iproc.eq.13)write(*,*)'q Q-bar -> q Q-bar (same gen)'
if(iproc.eq.14)write(*,*)'q Q-bar -> q Q-bar (diff gen)'
```

- 4-quark processes (soft and collinear) divergent: use Catani-Seymour subtraction method.

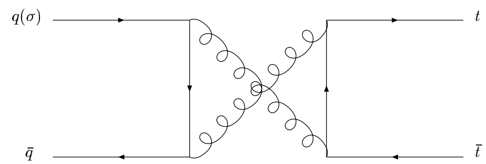
$q\bar{q} \to Q\bar{Q}$ (DIFF GEN)

ff_qq_GGbox



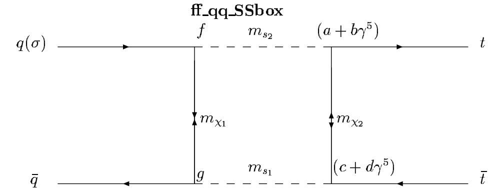
Colour factor and QCD couplings set to one.
Infrared divergences removed in $\bar{DR}$ scheme.
(crossed box considered sepatately)

ff_qq_GGXbox



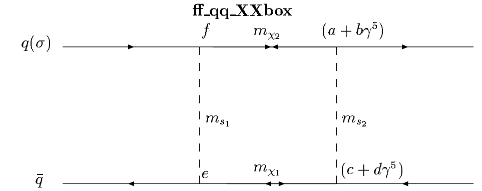
Colour factor and QCD couplings set to one.
Infrared divergences removed in $\bar{DR}$ scheme.

ff_qq_SSbox



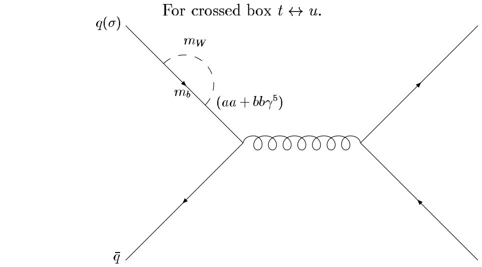
For crossed box $t \leftrightarrow u$.

ff_qq_XXbox



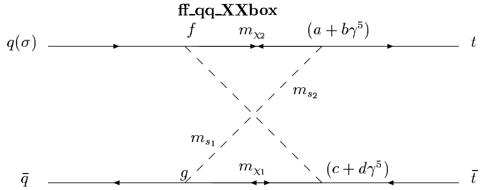
For crossed box $t \leftrightarrow u$.

ff_qq_sigextSq



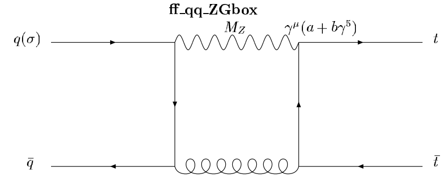
QCD couplings set to 1.
Combinatorial factor of one half for each incoming quark (or antiquark)

ff_qq_XXbox



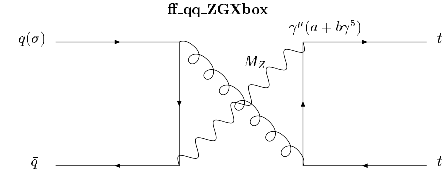
For crossed box $t \leftrightarrow u$.

ff_qq_ZGbox



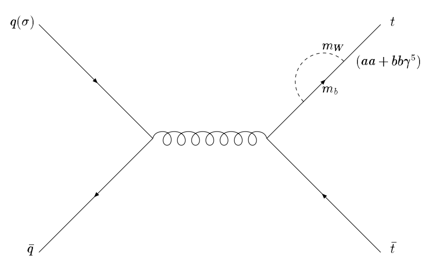
Colour factor and QCD couplings set to one.
coupling of Z to incoming quark set to one (this depends on the helicity, σ of the incoming quark and is a multiplicative factor).
Infrared divergences removed in $\bar{DR}$ scheme.
Combinatorial factor of 2 required.

ff_qq_ZGXbox



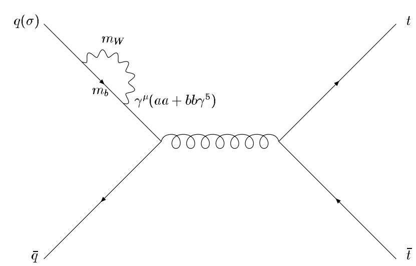
Colour factor and QCD couplings set to one.
coupling of Z to incoming quark set to one (this depends on the helicity, σ of the incoming quark and is a multiplicative factor).
Infrared divergences removed in $\bar{DR}$ scheme.
Combinatorial factor of 2 required.

ff_qq_sigextSt



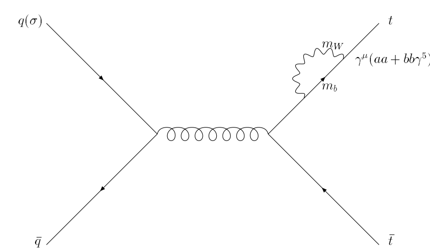
QCD couplings set to 1.
Combinatorial factor of one half for each outgoing $t-$ (or $\bar{t}-$) quark

ff_qq_sigextWq



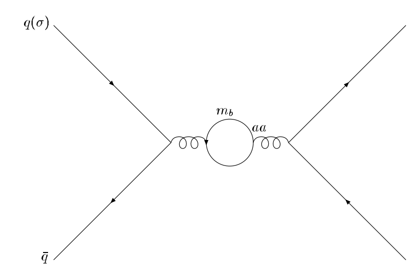
QCD couplings set to 1.
Combinatorial factor of one half for each incoming quark (or antiquark)

ff_qq_sigextWt



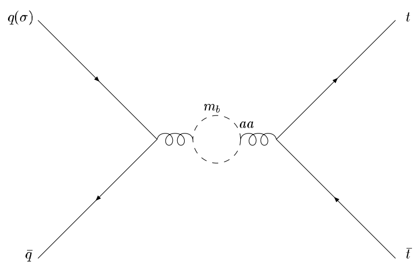
QCD couplings set to 1.
Combinatorial factor of one half for each outgoing $t-$ (or $\bar{t}-$) quark

ff_qq_sigintfg



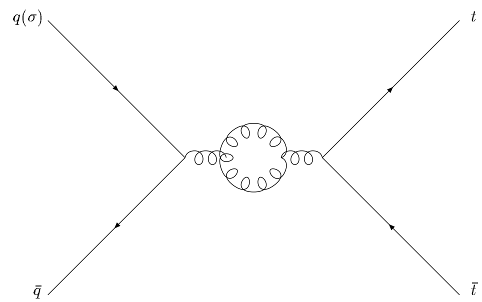
QCD couplings set to 1.
aa is the colour factor for the fermion loop.
m_b is the mass of the internal fermion
For a loop of Majorana particles a combinatorial factor of $\frac{1}{2}$ is required.

ff_qq_sigintSg



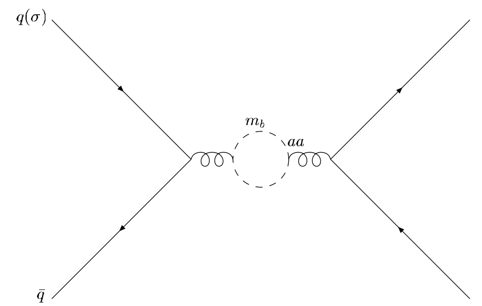
QCD couplings set to 1.
Scalar coupling to gluon set to aa (usually this is the QCD coupling).
m_b is the mass of the scalar

ff_qq_sigintgg



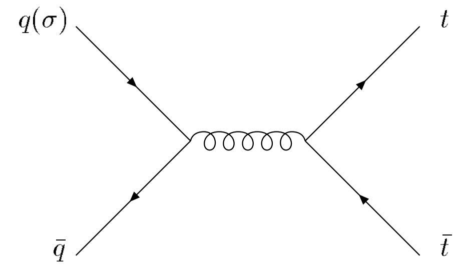
QCD couplings set to 1.
aa is the colour factor for the gluon loop (=CA).

ff_qq_sigintSg



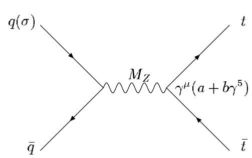
QCD couplings set to 1.
aa is the colour factor for the scalar loop.
m_b is the mass of the scalar .

ff_qq_tree



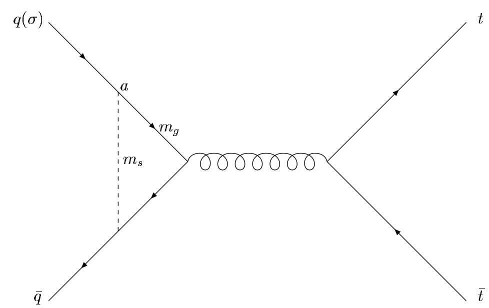
All couplings and colour factors set to 1

ff_qq_treeZ



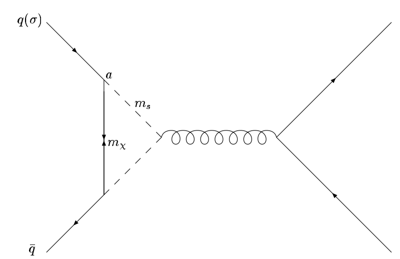
Colour factors set to 1
Coupling of Z to incoming quarks set to 1 (this depends on the incoming quark helicity, σ and is a multiplicative constant.

ff_qq_vertSq



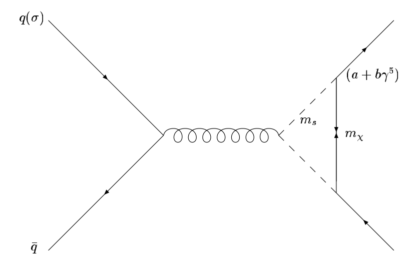
Colour factor and QCD couplings set to one.
Internal fermion is gluino.
Left-right squark mixing neglected.

ff_qq_vertSSq



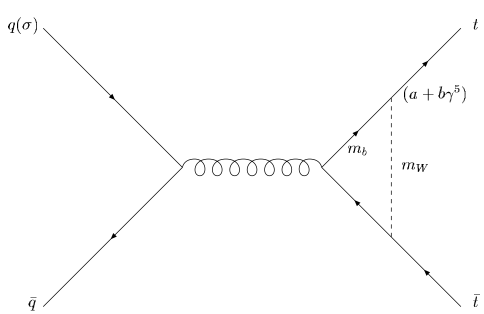
QCD couplings set to one.
Coupling a, depends on helicity,σ.
If χ is a Majorana fermion the arrow may be reversed leading to an overall sign and possible reversal of the sign of m_χ.

ff_qq_vertSSt



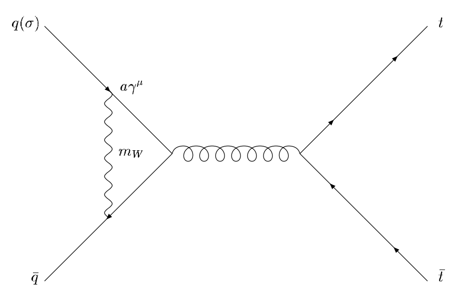
QCD couplings set to one.
If χ is a Majorana fermion the arrow may be reversed leading to an overall sign and possible reversal of the sign of m_χ.

ff_qq_vertSt



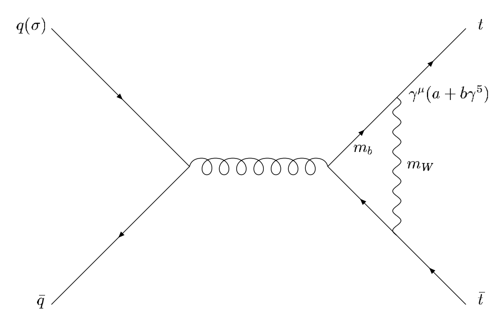
Colour factor and QCD couplings set to one.

ff_qq_vertWq



Colour factor and QCD couplings set to one.
Internal incoming quark assumed massless.
Coupling constant a depends on incoming quark helicity, σ

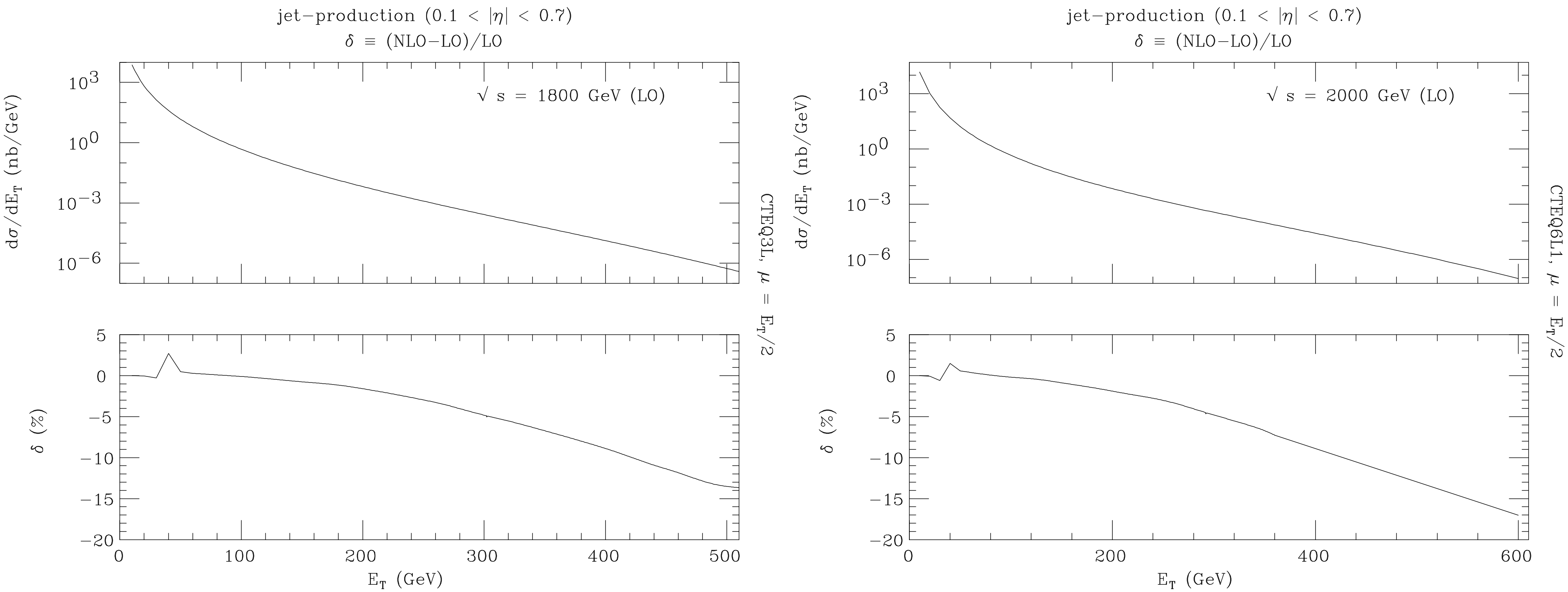
ff_qq_vertWt



Colour factor and QCD couplings set to one.

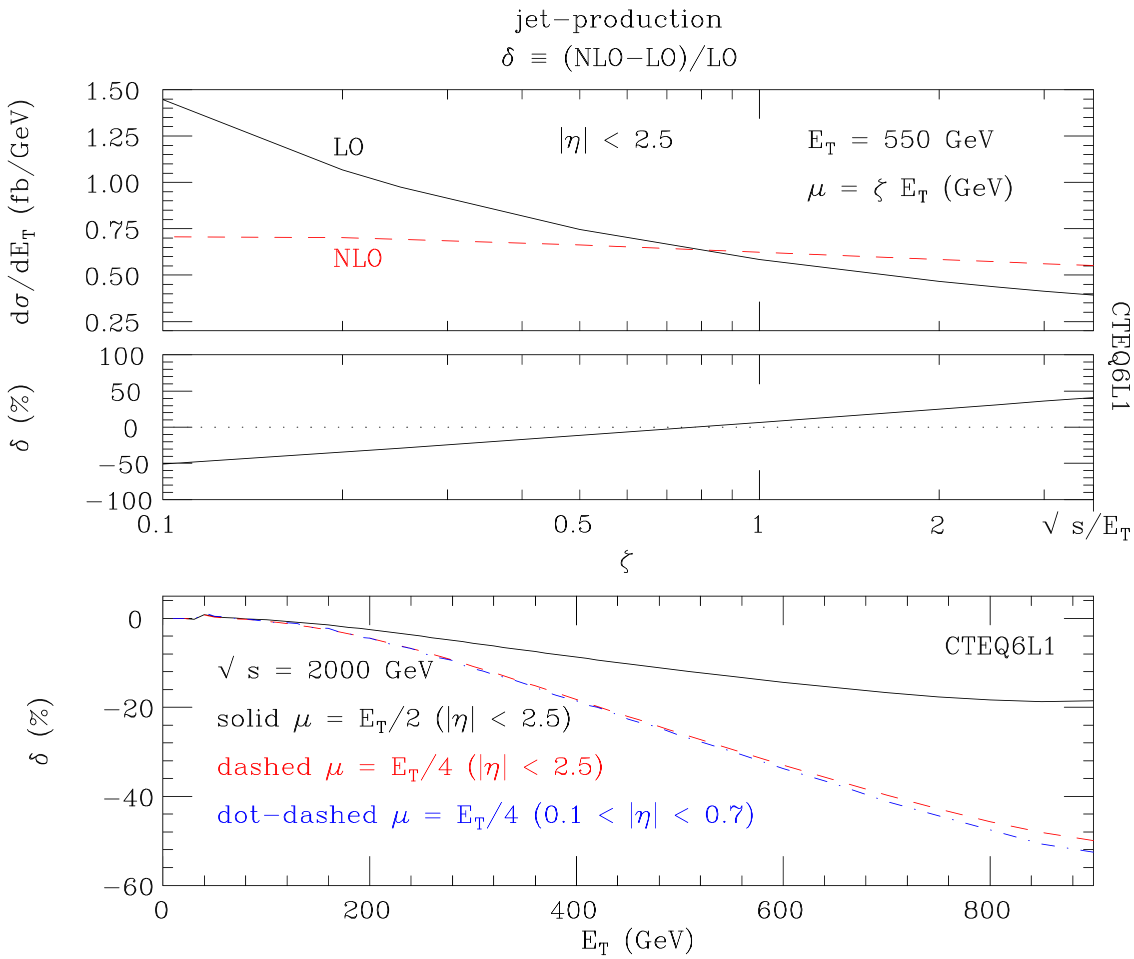
+ BREMSSTRAHLUNG !

TEVATRON: $p\bar{p} \to jj \quad \sqrt{s} = 2\,\mathrm{TeV}$



(THE CUT $0.1 < |\eta| < 0.7$ HAS BEEN ENFORCED, ALONGSIDE THE STANDARD JET CONE REQUIREMENT $\Delta R > 0.7$.)

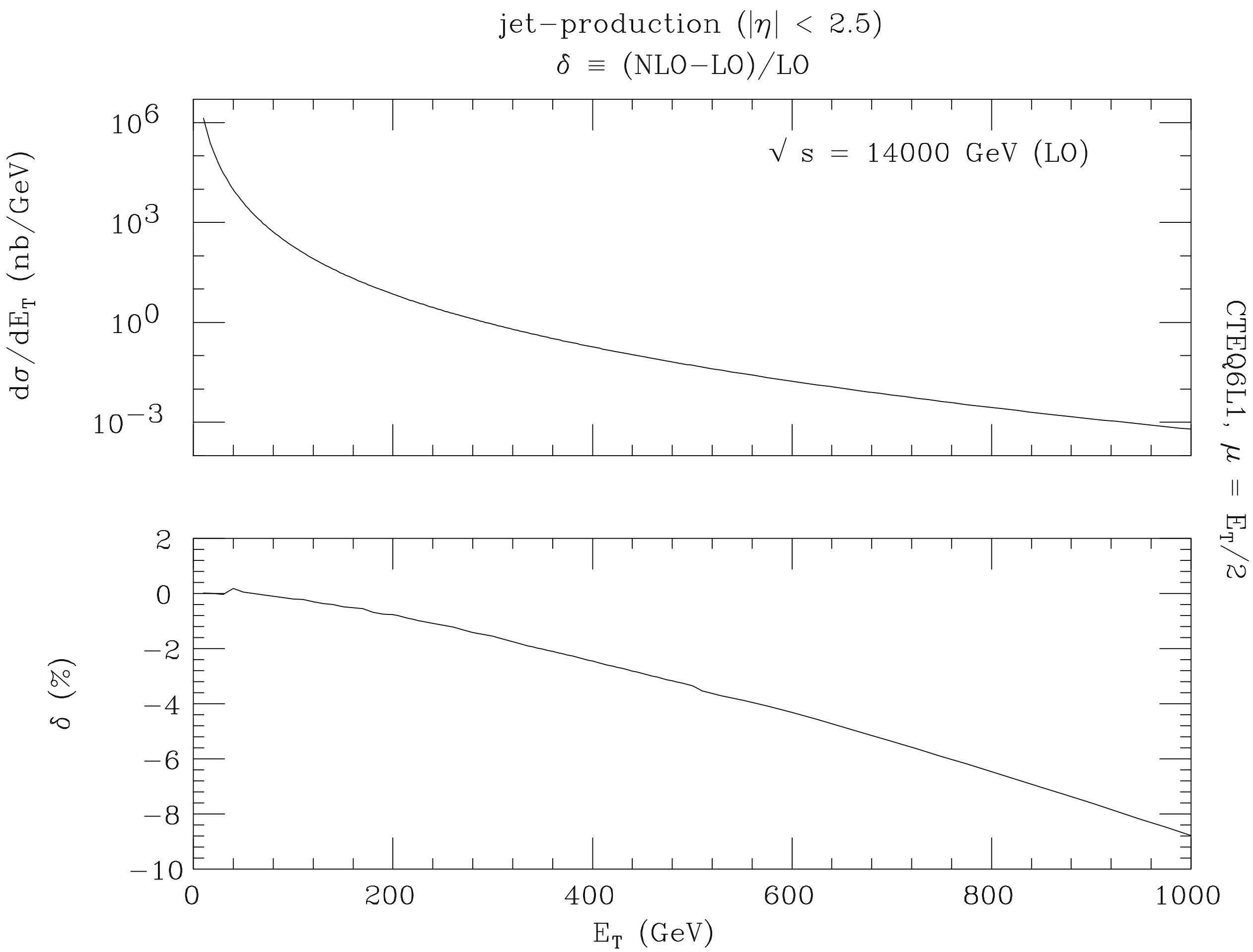
• FACTORISATION/RENORMALISATION SCALE DEPENDENCE



(THE CUT $|\eta| < 2.5$ HAS BEEN ENFORCED, ALONGSIDE THE STANDARD JET CONE REQUIREMENT $\Delta R > 0.7$.)

• CAN BE FIT BY ($\alpha_{\rm W} \equiv \alpha/\sin\theta_{\rm W}$) $\delta \;\approx\; -c\,\frac{C_F\alpha_{\rm W}}{\pi}\log^2(E_T^2/M_W^2)$, WITH $c \approx 2/3(4/3)$ FOR $\mu = E_T/2(E_T/4)$.

LHC: $pp \to jj \quad \sqrt{s} = 14\,\mathrm{TeV}$



(The cut $|\eta| < 2.5$ has been enforced, alongside the standard jet cone requirement $\Delta R > 0.7$.)

Conclusions

Weak corrections are available for:

- $pp, p\overline{p} \to j + Z, \gamma$.
- $pp, p\overline{p} \to b\bar{b}$ and jj.

In progress for:

- $pp, p\overline{p} \to t\bar{t}$ (with top-polarisation retained).

Next steps:

- $2 \to 2$ W processes (require QED contribution).
- $2 \to 3$ (off-shell gauge bosons and non-factorisable corr.s):
  require filly massive 5-point functions (pentagons)

They are relevant for:

- High energy and high p_T processes.
- Asymmetry-like observables.

Outstanding issues:

- Need to clarify treatment of W, Z real radiation: exp. input (will study this with Joey) !
- Need to be combined with QCD corrections.
- In general, EW tools needed: implement results in exclusive Monte Carlo (MC) event generation, easier: no double counting for W, Z radiation with parton shower, problem solved for QED radiation (abelian QCD).
- Define EW PDFs and (more importantly) PS ?