CIEMAT – Madrid April 2014

Standard Model at LHC

Electroweak corrections

for the high energy LHC run

Markus Schulze

CERN

General properties of electroweak corrections

Electroweak corrections at high energies

- Estimate for the size of electroweak corrections:

$$\mathcal{O}(\alpha) \;\sim\; \mathcal{O}(\alpha_s^2) \;\approx\; \text{a few percent}$$

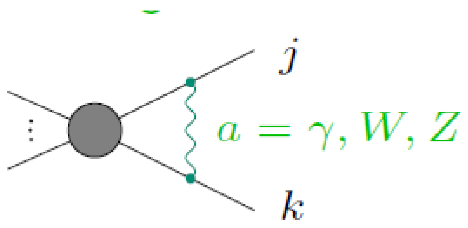
Hence, expect NLO EW $\sim$ NNLO QCD

- This naïve estimate is generally correct for observables that are dominated by threshold production.

- Significantly larger corrections can arise in tails of kinematic distributions at high energies $\sim \log^2(\hat{s}/M_Z^2)$

Electroweak corrections at high energies

- Origin of logarithmically enhanced corrections



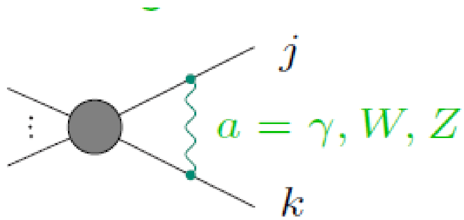
$\sim \log^2(s_{jk}/M_a^2)$ + sub-leading logs

- Typical size for $\sqrt{\hat{s}} = 1\,\mathrm{TeV}$

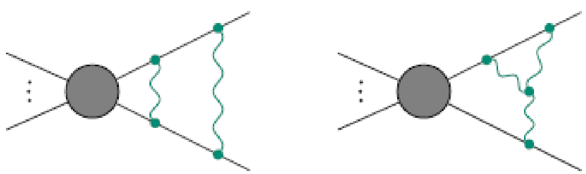
$$\delta\sigma_{\mathrm{LL}}^{\mathrm{1loop}} = -\frac{\alpha}{\pi s_w^2}\log^2(\hat{s}/M_W^2) \approx -26\% \qquad \delta\sigma_{\mathrm{NLL}}^{\mathrm{1loop}} = +\frac{3\alpha}{\pi s_w^2}\log(\hat{s}/M_W^2) \approx 16\%$$

Electroweak corrections at high energies

- Origin of logarithmically enhanced corrections



$$\sim \log^2(s_{jk}/M_a^2) \qquad + \text{sub-leading logs}$$



$$\sim \log^4(s_{jk}/M_a^2) \qquad + \text{sub-leading logs}$$

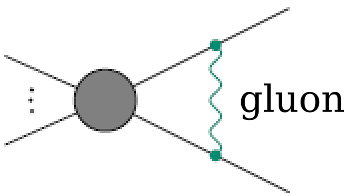
- Typical size for $\sqrt{\hat{s}} = 1\,\mathrm{TeV}$

$$\delta\sigma_{\mathrm{LL}}^{\mathrm{1loop}} = -\frac{\alpha}{\pi s_w^2}\log^2(\hat{s}/M_W^2) \approx -26\% \qquad \delta\sigma_{\mathrm{NLL}}^{\mathrm{1loop}} = +\frac{3\alpha}{\pi s_w^2}\log(\hat{s}/M_W^2) \approx 16\%$$

$$\delta\sigma_{\mathrm{LL}}^{\mathrm{2loop}} = +\frac{\alpha^2}{\pi^2 s_w^4}\log^4(\hat{s}/M_W^2) \approx +7\% \qquad \delta\sigma_{\mathrm{NLL}}^{\mathrm{2loop}} = -\frac{3\alpha^2}{\pi^2 s_w^4}\log^3(\hat{s}/M_W^2) \approx -4\%$$

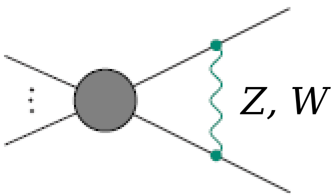
Electroweak corrections at high energies

- Analogy and differences to QCD corrections



soft-collinear exchange

$\sim 1/\varepsilon^2$ or $\log^2(\hat{s}/\lambda_g^2)$



quasi soft-collinear exchange

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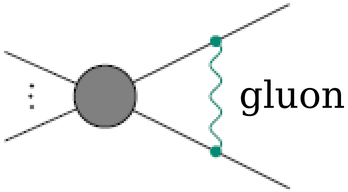
Electroweak corrections at high energies

- Analogy and differences to QCD corrections



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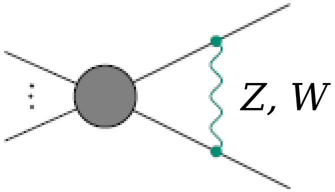

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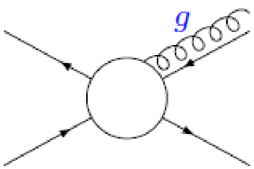


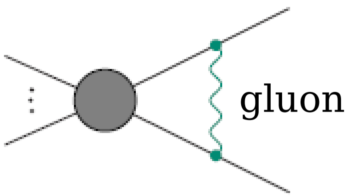
soft-collinear emission

$\sim -1/\varepsilon^2$ or -$\log^2(\hat{s}/\lambda_g^2)$

→ Unphysical singularities cancel

Electroweak corrections at high energies

- Analogy and differences to QCD corrections



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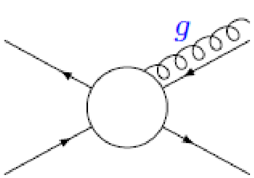

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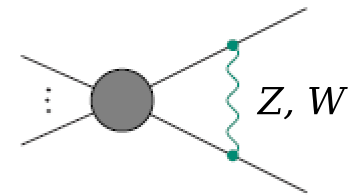
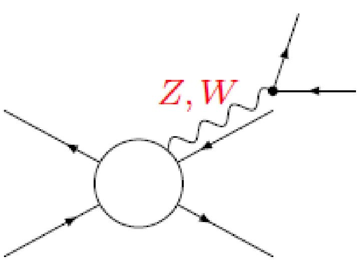


quasi soft-collinear exchange

$$\sim \log^2(\hat{s}/M_V^2)$$



$$\sim -\log^2(\hat{s}/M_V^2)$$

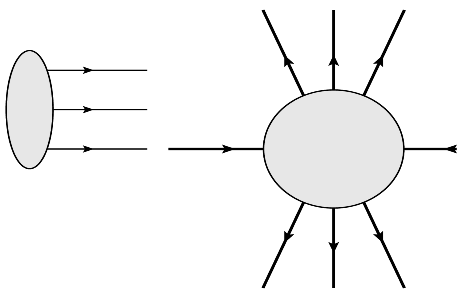
→ Logarithms do not cancel

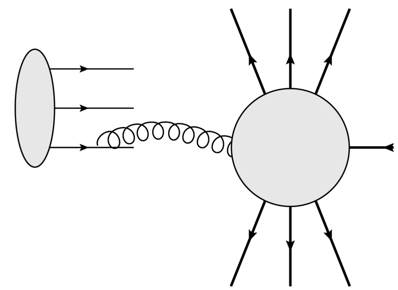
- real emission leads to observable effects
- no complete summation of SU(2) charges

Electroweak corrections at high energies

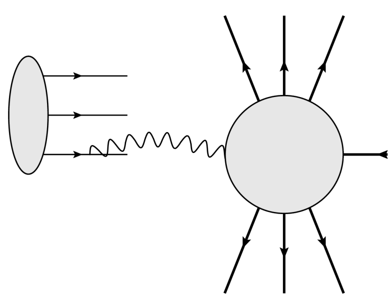
- Parton distribution functions

pure QCD: proton = gluons+quarks





+ el.weak: proton = gluons+quarks**+photons**



γ-initial states enter at $O(\alpha)$

expect enhancements in fwd-direction

Modern pdf sets include photons:

[MSTW08, NNPDF2.3]

LHC Phenomenology

Electroweak corrections at high energies

- EW corrections known for most important $2 \rightarrow 2$ processes at the LHC

  Drell-Yan like production: $pp \rightarrow Z,W$

  Vector bosons at large p_T: $pp \rightarrow V + \text{jet}$

  Di-boson production: $pp \rightarrow VV$

  Fermion pairs: $pp \rightarrow jj$, $pp \rightarrow t\text{-}tb$, $pp \rightarrow b\text{-}bbar$

Electroweak corrections at high energies

- EW corrections known for most important $2 \rightarrow 2$ processes at the LHC

Drell-Yan like production: $pp \rightarrow Z,W$

Dittmaier, Krämer; Zykunov;
Baur, Wackeroth; Arbuzov;
Carloni Calame; Dittmaier,Huber;
Baur, Keller, Sakumoto; Baur, Wackeroth;
Brein, Hollik, Schappacher; Zykunov;
Arbuzov; Carloni, Calame; Dittmaier, Huber;

Vector bosons at large p_T: $pp \rightarrow V$ + jet

Kühn, Kulesza, Pozzorini, M.S.; Hollik, Kasprzik, Kniehl;
Denner, Dittmaier, Kasprzik, Mück;
Maina, Moretti, Ross;
Denner, Dittmaier, Kasprzik, Mück;
Z+jj: Denner, Hofer, Scharf, Uccirati

Di-boson production: $pp \rightarrow VV$

Accomando, Denner, Pozzorini, Meier, Kaiser
Bierweiler, Kasprzik, Kühn;

Fermion pairs: $pp \rightarrow jj$, $pp \rightarrow t\text{-}tb$, $pp \rightarrow b\text{-}bbar$

Moretti, Nolten, Ross; Dittmaier, Huss, Speckner;
Beenakker; Moretti, Nolten, Ross; Kühn, Scharf, Uwer;
Bernreuther, Fücker, Si; Hollik, Kollar;
Maina, Moretti, Nolten, Ross;

Electroweak corrections at high energies

- EW corrections known for most important 2 → 2 processes at the LHC

Higgs production: *pp* → *H, VBF, H+V*

Higgs decay: *H* → *f-fbar, VV, gg*

Automation: RECOLA
(in progress) GoSam

Electroweak corrections at high energies

- EW corrections known for most important 2 → 2 processes at the LHC

Higgs production: *pp → H, VBF, H+V*

LHC Higgs XS WG
Aglietti, Bonciani, Degrassi, Vicini; Degrassi, Maltoni;
Actis, Passarino, Sturm, Uccirati;
Ciccolini, Denner,Dittmaier; Figy, Palmer, Weiglein;
Ciccolini, Dittmaier, Krämer; Denner, Dittmaier, Kallweit, Mück;
mixed QCD+el.weak: Anastasiou, Boughezal, Petriello

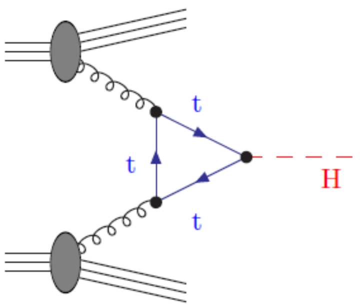
Higgs decay: *H → f-fbar, VV, gg*

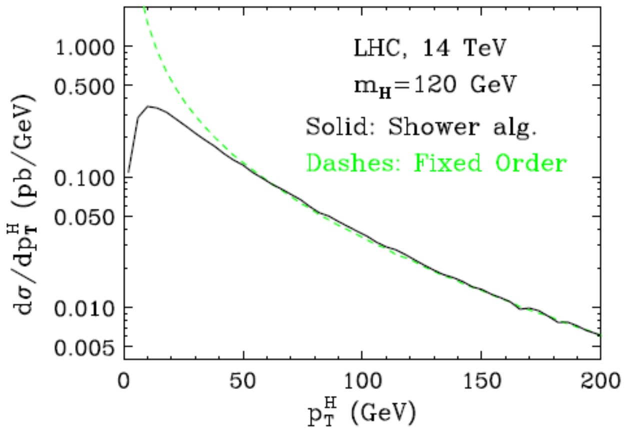
Bardin, Vilenskii, Khristova; Dabelstein, Hollik; Kniehl, Actis;
Passarino, Sturm, Uccirati;
Actis, Passarino, Sturm, Uccirati;
Fleischer, Jegerlehner; Kniehl; Bardin, Vilenskii, Khristova;
Bredenstein, Denner, Dittmaier, Weber;

Automation: RECOLA — Actis, Denner, Hofer, Scharf, Uccirati
(in progress) GoSam — Cullen, van Deurzen, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, Ossola, Peraro,Reichel, Schlenk, von Soden-Fraunhofen, Tramontano

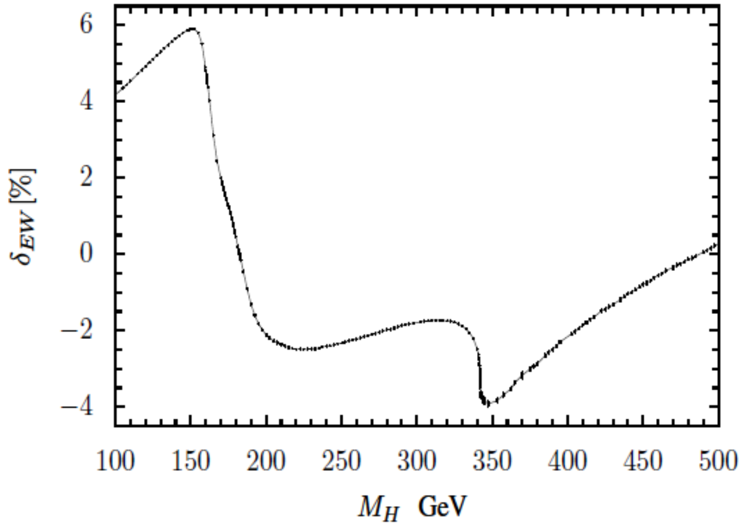
Electroweak corrections at high energies

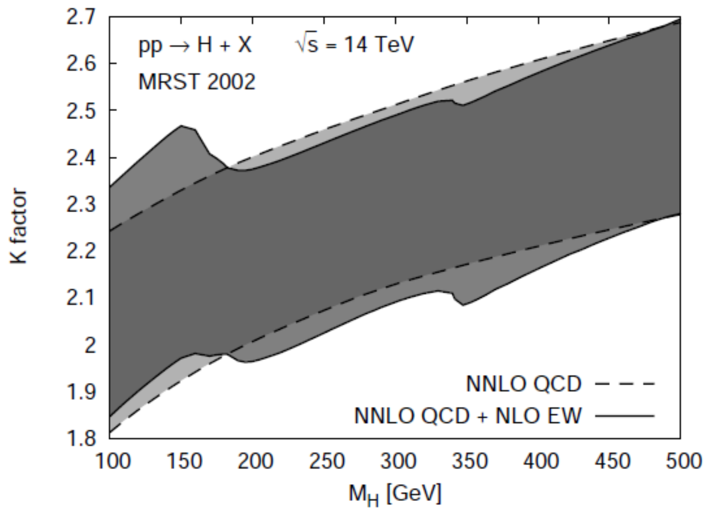
- Example 1: **Higgs production in gluon fusion at the LHC**





[Actis, Passarino, Sturm, Uccirati]





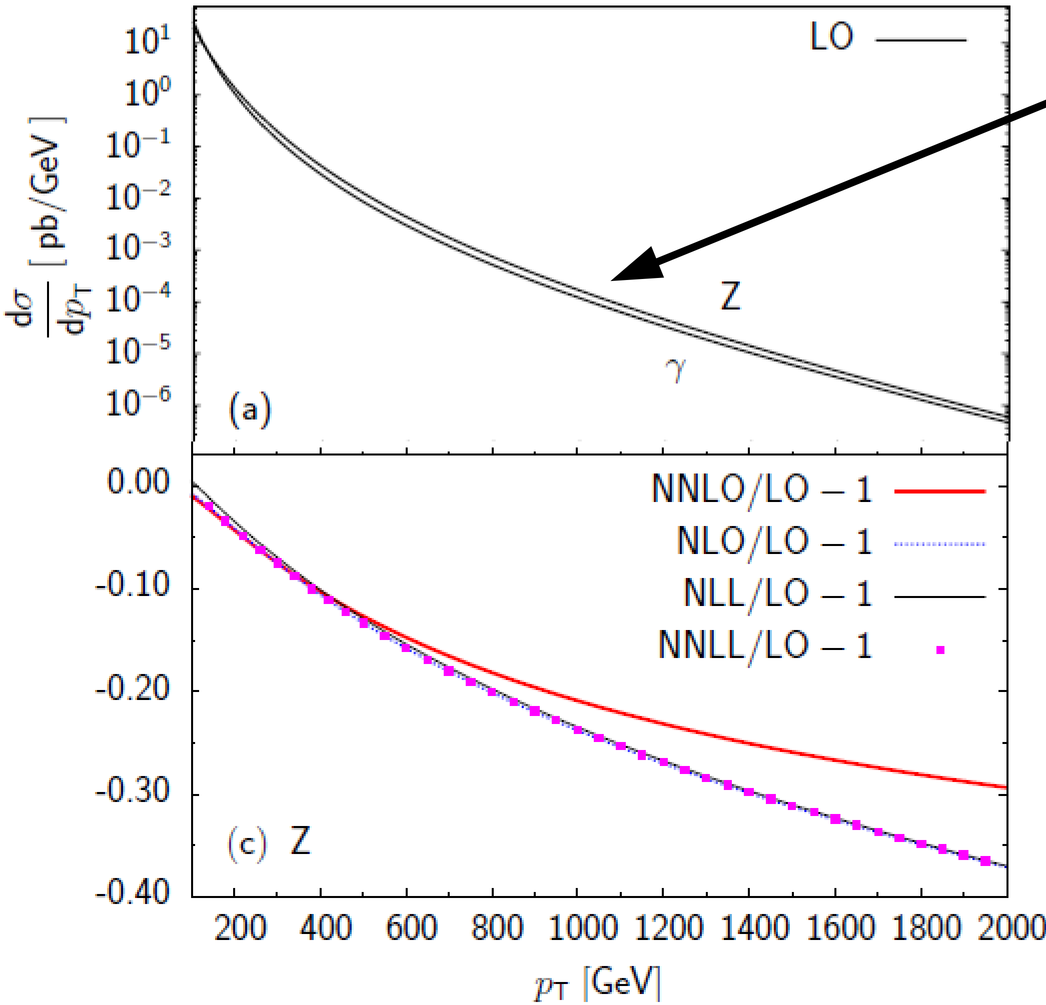
Mixed QCD el.weak corrections: +5% for M_H=125 GeV

[Anastasiou, Boughezal, Petriello]

Electroweak corrections at high energies

- Example 2: ***pp → Z/W/γ + jet***

[Kühn,Kulesza,Pozzorini,M.S.]



~ 1000 Z+jet events/year with p_T>1 TeV

Electroweak corrections at high energies

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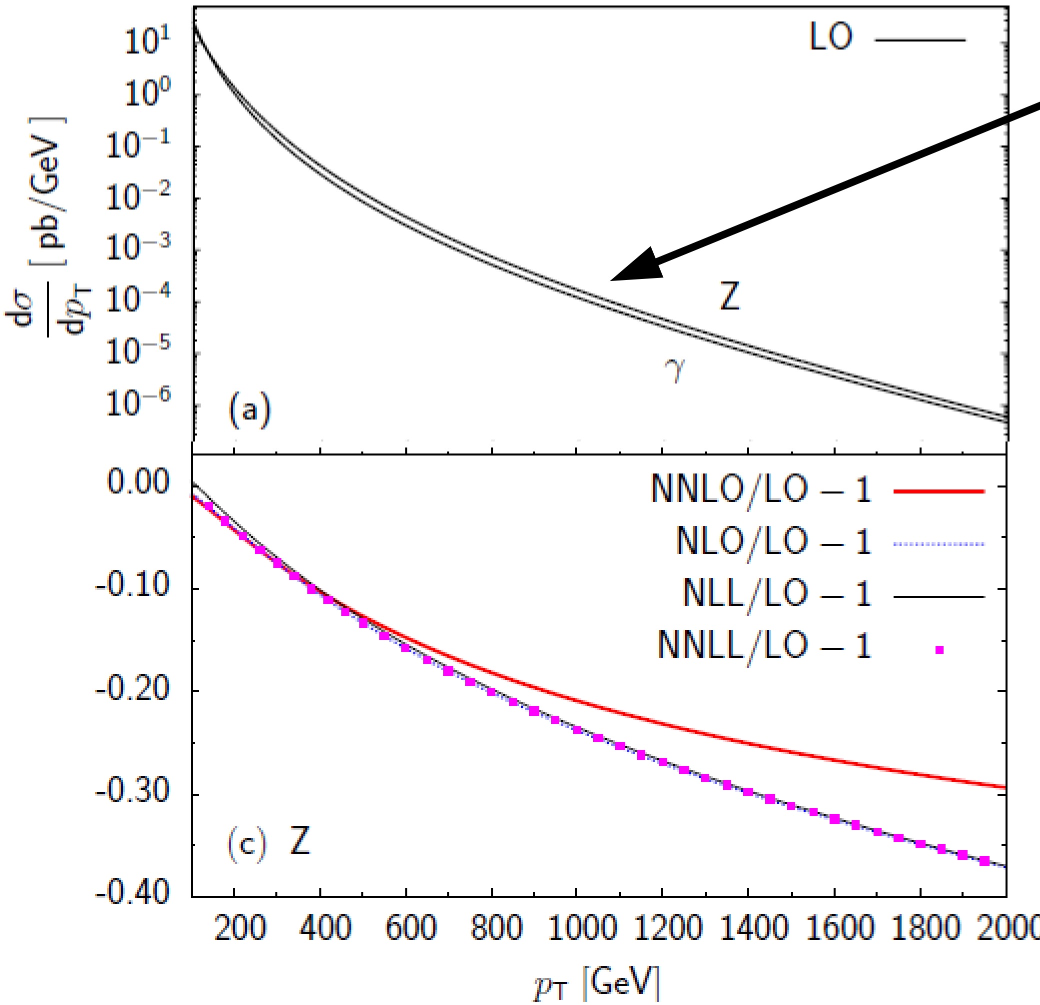
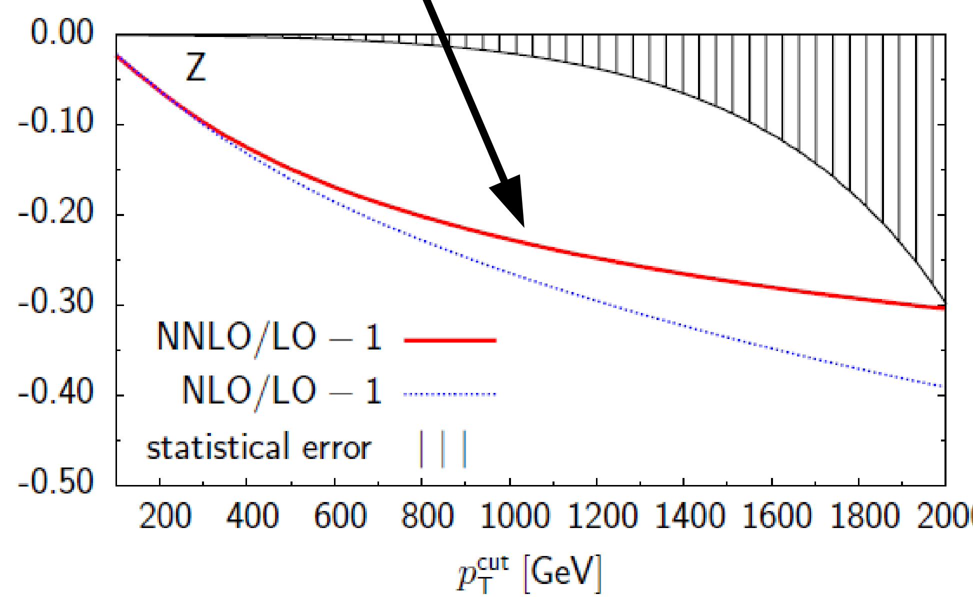


∼ 1000 Z+jet events/year with p_T>1 TeV

at p_T=1 TeV:
1-loop: -26 %
2-loop: +4 %
stat.: 2 %



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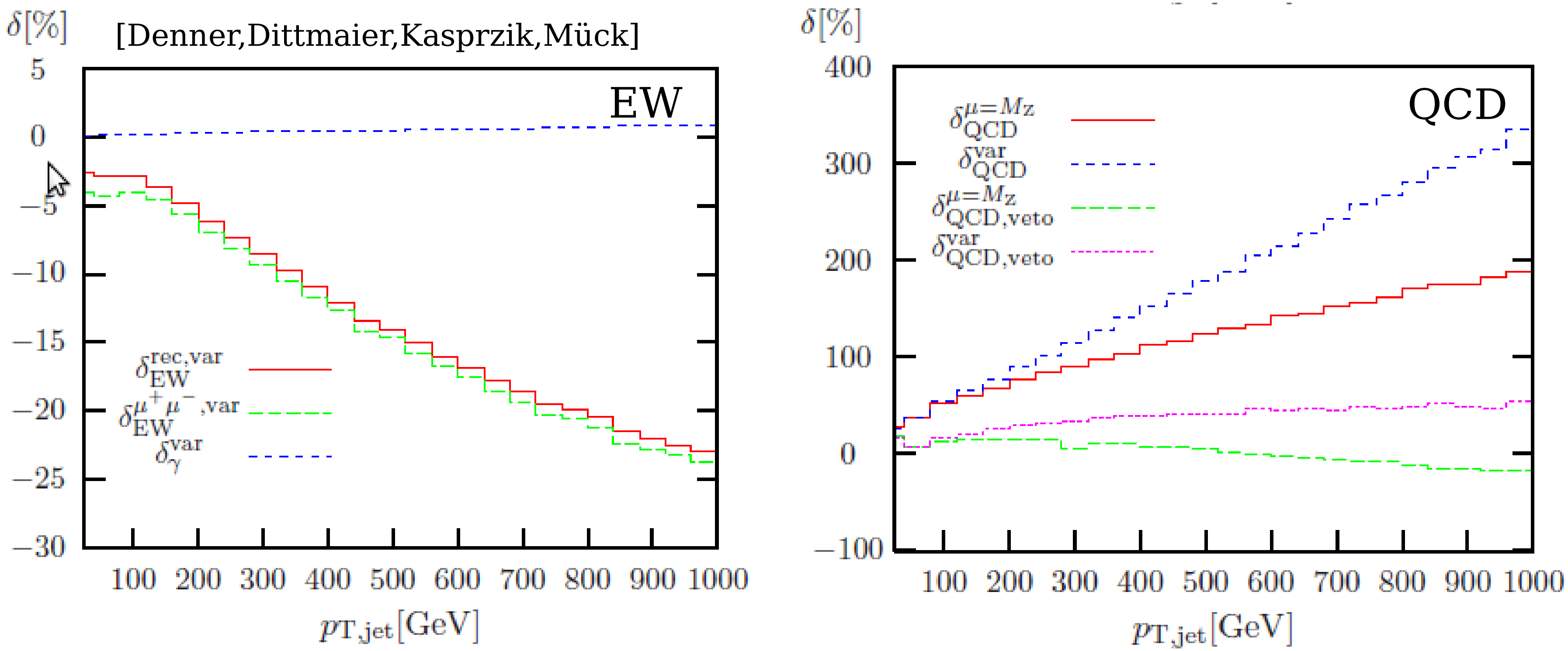

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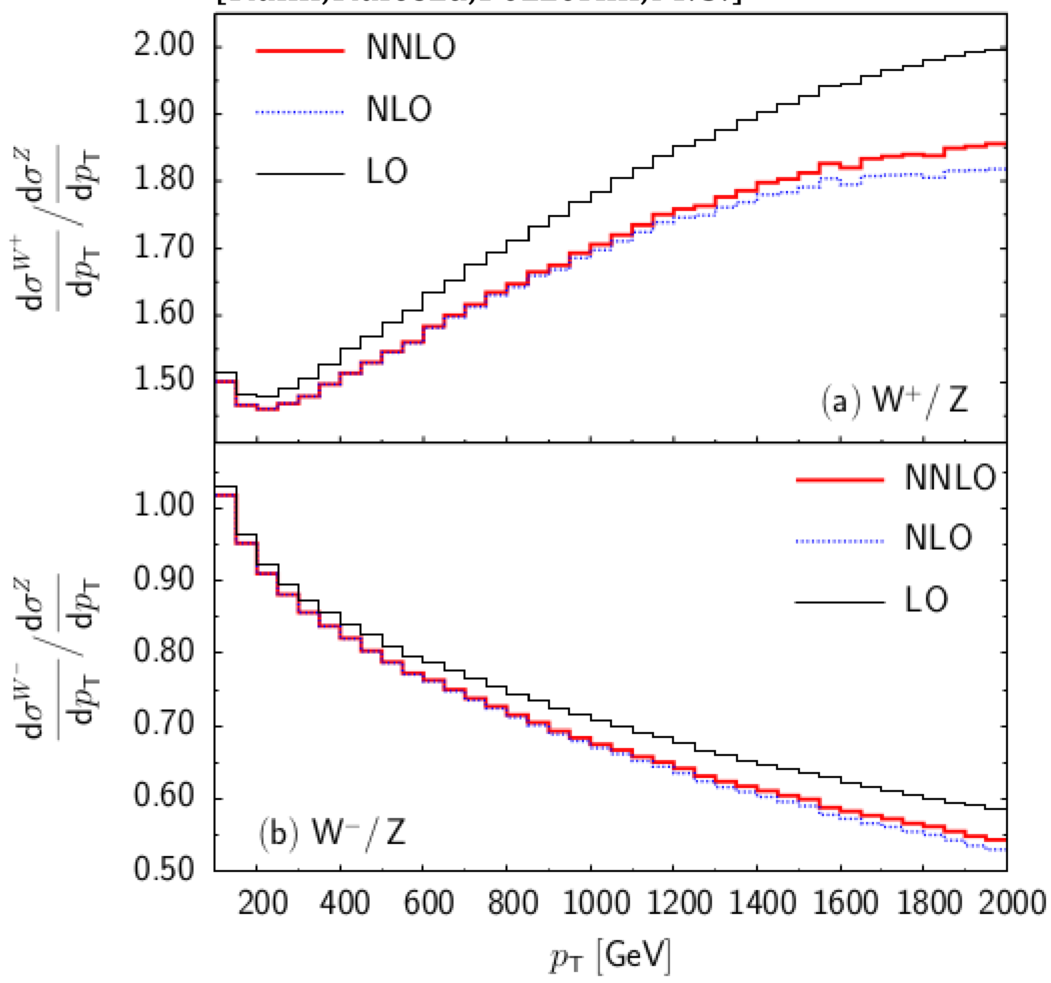


Cross section ratios:

- many uncertainties cancel (α_s, pdfs, luminosity,...)

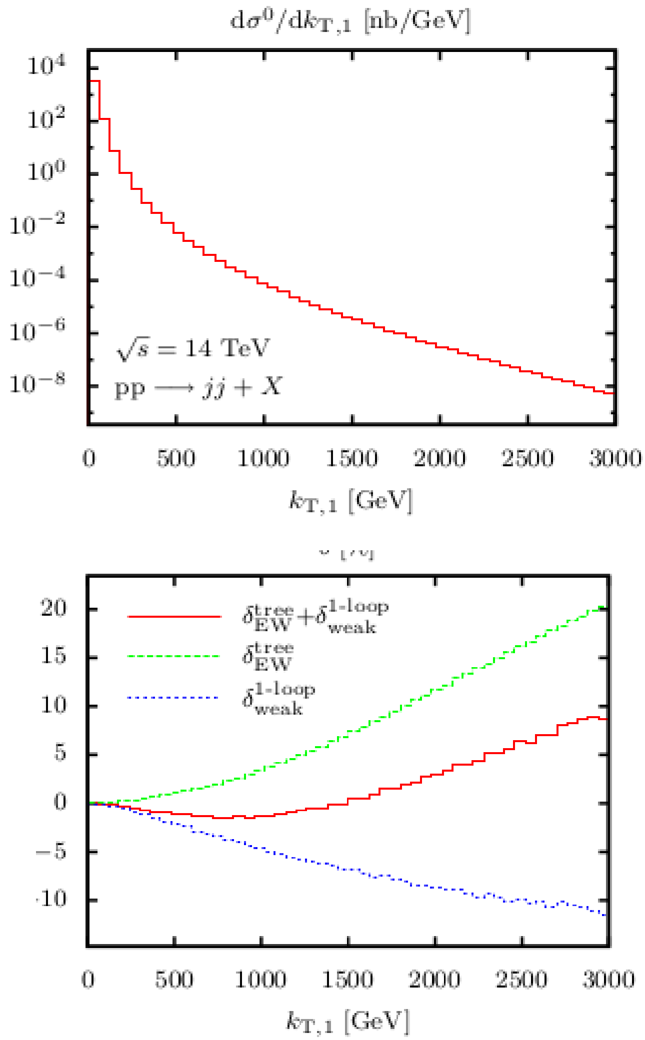
- stable wrt. QCD corrections

- EW corrections: ~ 10%

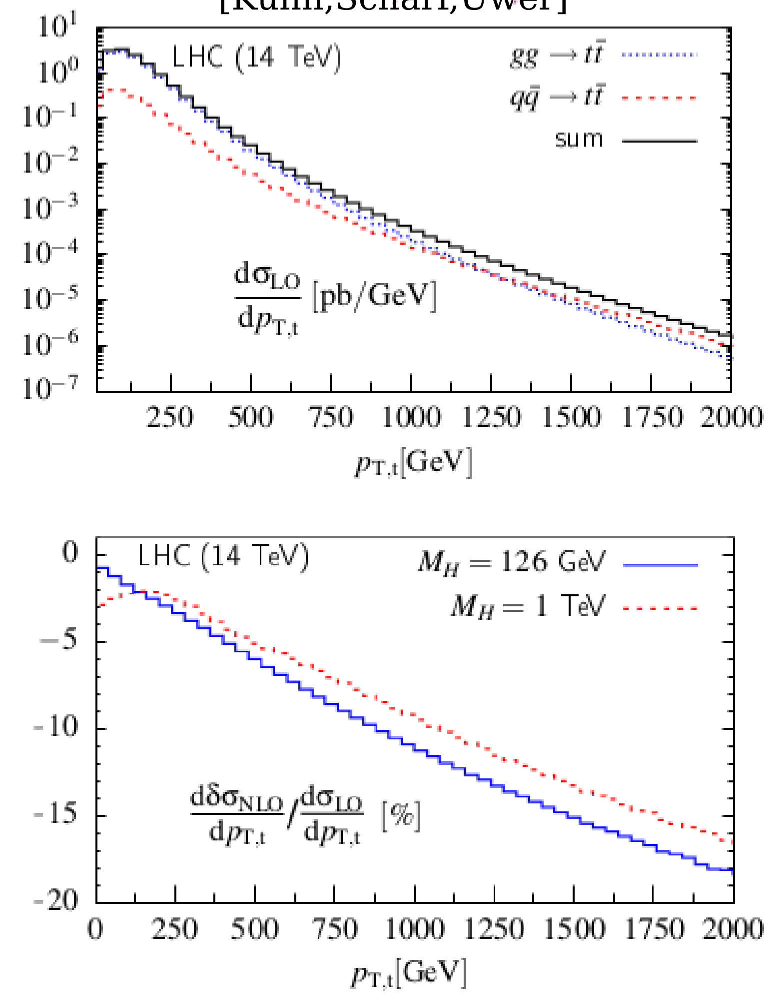
Electroweak corrections at high energies

- Example 3: ***pp → jj* and *pp → ttbar***

[Dittmaier,Huss,Speckner]



[Kühn,Scharf,Uwer]



Electroweak corrections at high energies

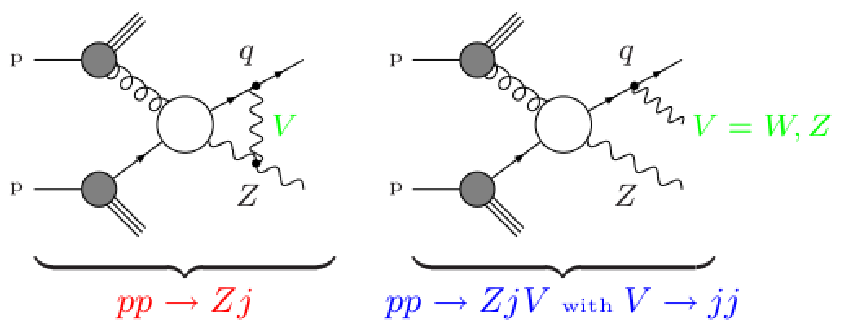
- **Real emission of Z and W bosons**

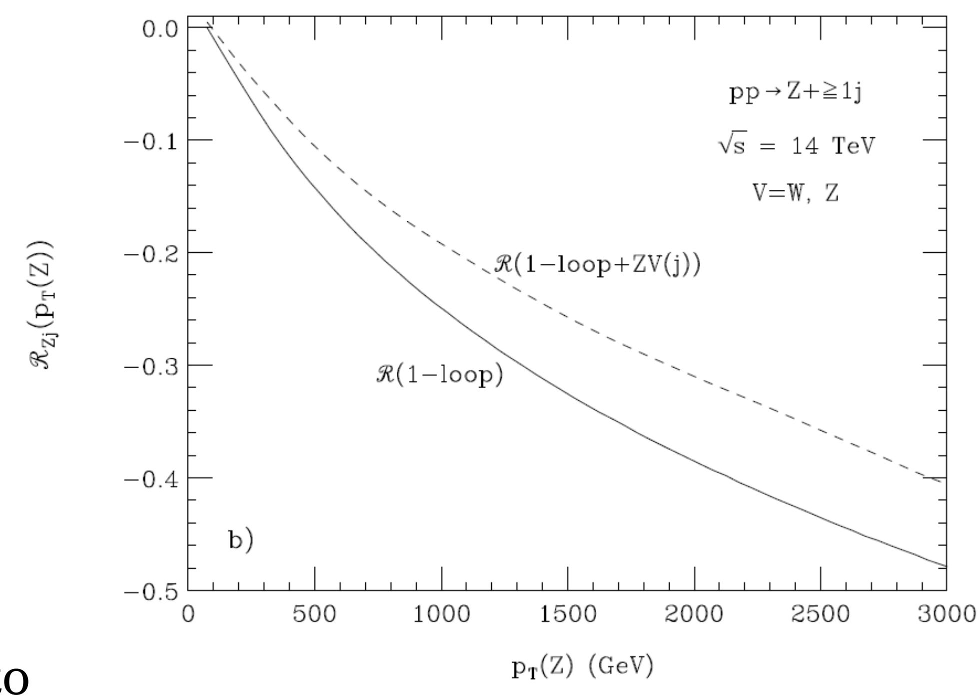
Model study: [Bell,Kühn,Rittinger]

Di-bosons: [Bierweiler,Kasprzik,Kühn]

Compreh. MC study: [Baur], [Vryonidou,Stirling]

[Baur]: ***pp* → *Z*+jet**





- Numerical size of cancellation depends strongly on cuts
- Can be reduced by additional jet veto

Electroweak corrections at high energies

- **Real emission of *Z* and *W* bosons**

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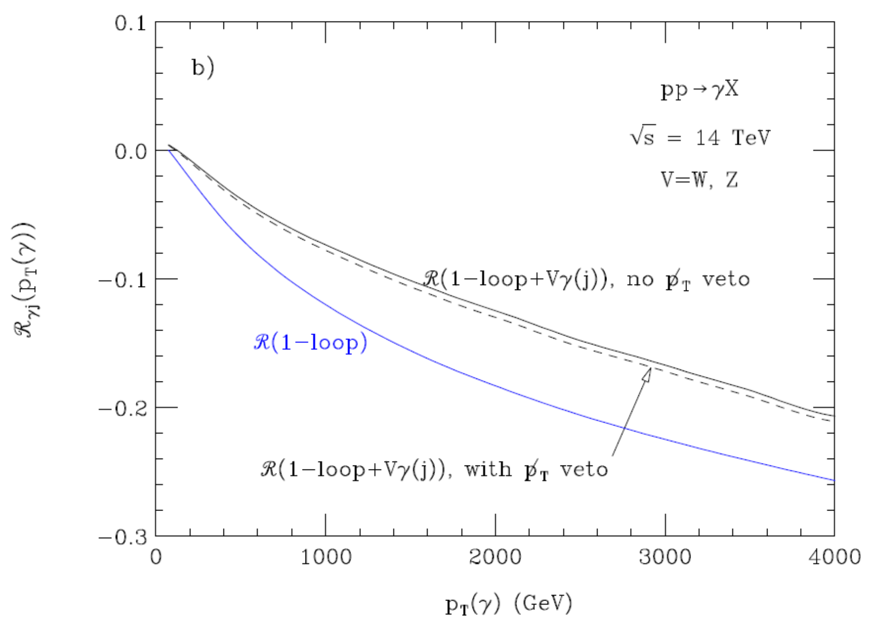
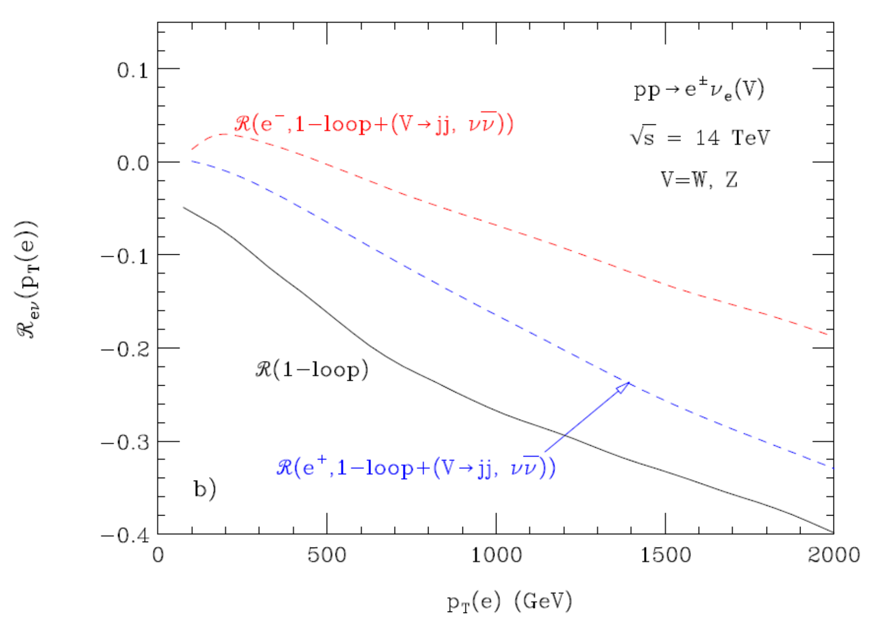
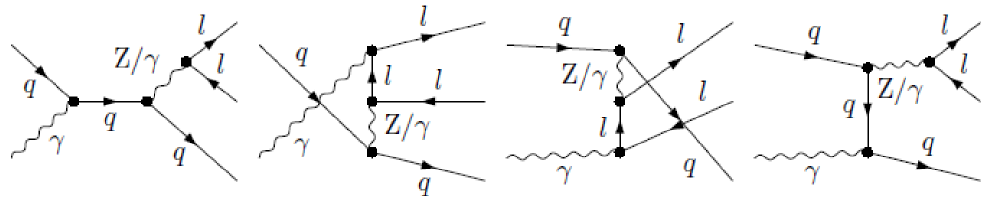


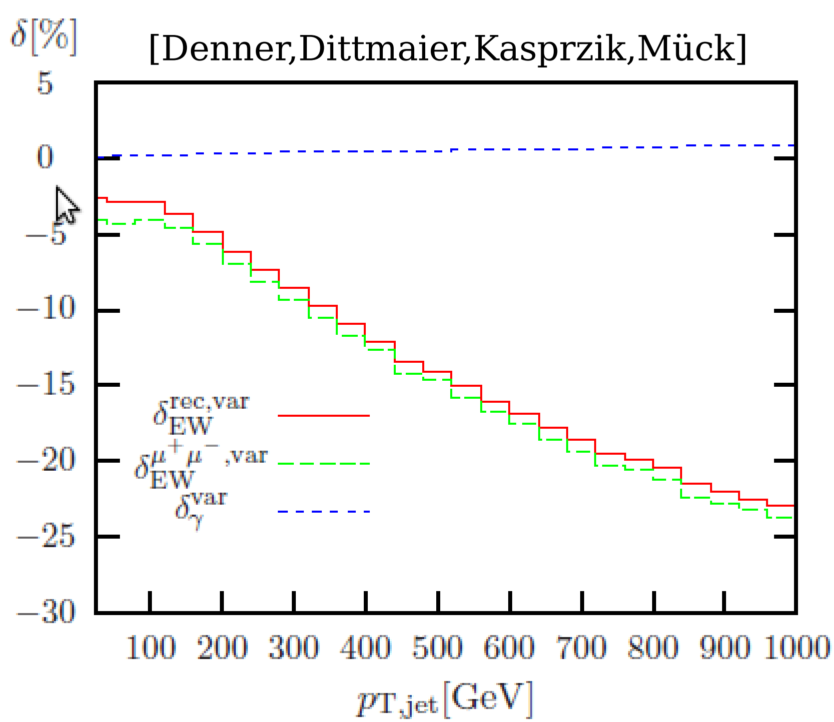


Electroweak corrections at high energies

- **Photonic initial states**

***pp* → *Z*+jet:**





$\mathrm{pp} \to l^+l^-\ \mathrm{jet} + X$ at $\sqrt{s} = 14\,\mathrm{TeV}$

$M_{ll}/\,\mathrm{GeV}$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	$2000-\infty$
$\sigma_0^{\mu=M_Z}/\,\mathrm{fb}$	123491(7)	7696.9(8)	628.47(6)	49.380(6)	5.1124(6)	0.27096(3)
$\sigma_0^{\mathrm{var}}/\,\mathrm{fb}$	122024(7)	7558.2(8)	602.45(5)	45.750(5)	4.5919(6)	0.23433(3)
$\sigma_0^{\mathrm{var},M_{ll}}/\,\mathrm{fb}$	121888(7)	7419.8(8)	539.74(5)	34.102(4)	2.7958(4)	0.10831(1)
$\delta_{\mathrm{EW}}^{\mu^+\mu^-,\mathrm{var}}/\%$	-4.2	$-9.3(1)$	-5.7	-9.5	$-15.1(1)$	$-23.8(1)$
$\delta_{\mathrm{EW}}^{\mathrm{rec,var}}/\%$	-2.8	-5.2	-3.0	-5.8	$-10.3(1)$	$-17.1(1)$
$\delta_{\mathrm{QCD}}^{\mu=M_Z}/\%$	35.8(1)	28.9(1)	12.0(1)	$-11.3(1)$	$-34.4(1)$	$-62.7(1)$
$\delta_{\mathrm{QCD}}^{\mathrm{var}}/\%$	35.9(1)	29.7(1)	14.7(1)	$-5.7(1)$	$-25.8(1)$	$-50.8(1)$
$\delta_{\mathrm{QCD}}^{\mathrm{var},M_{ll}}/\%$	36.1(1)	30.8(1)	24.7(1)	23.6(1)	25.9(3)	31.4(3)
$\delta_{\mathrm{QCD,veto}}^{\mu=M_Z}/\%$	13.1(1)	6.8(1)	$-9.5(1)$	$-32.9(1)$	$-56.3(1)$	$-85.3(1)$
$\delta_{\mathrm{QCD,veto}}^{\mathrm{var}}/\%$	14.1(1)	8.7(1)	$-5.4(1)$	$-25.4(1)$	$-46.0(1)$	$-71.3(1)$
$\delta_{\mathrm{QCD,veto}}^{\mathrm{var},M_{ll}}/\%$	14.3(1)	10.7(2)	7.4(1)	8.0(1)	10.9(3)	16.7(3)
$\delta_{\gamma}^{\mathrm{var}}/\%$	0.1	0.9	2.7	2.9	2.6	2.3
$\sigma_{\mathrm{full,veto}}^{\mu^+\mu^-,\mathrm{var}}/\,\mathrm{fb}$	134266(49)	7580(9)	551.9(4)	31.10(5)	1.906(4)	0.0167(3)

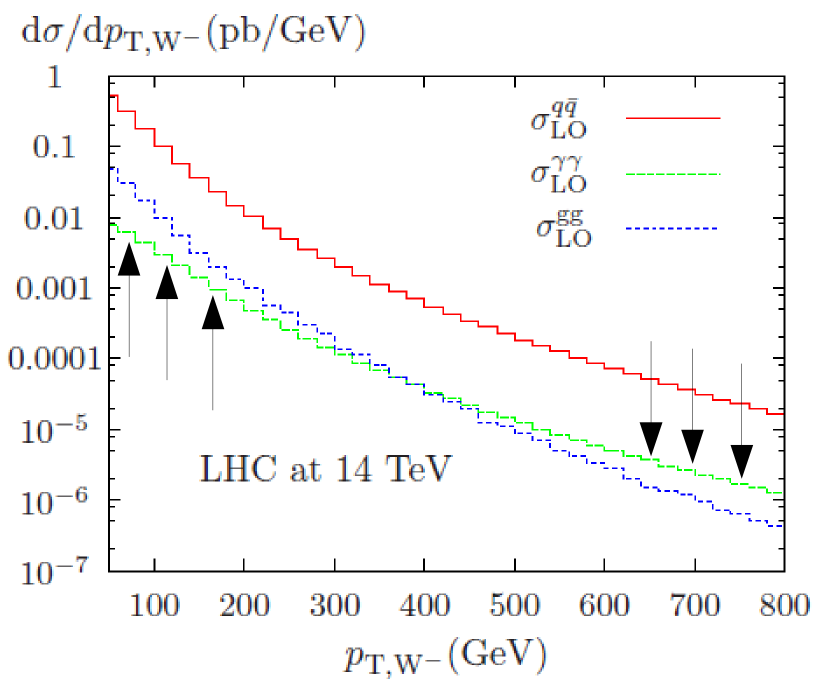
Electroweak corrections at high energies

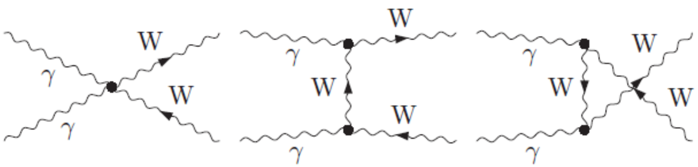
- **Photonic initial states**

***pp* → ttbar** [Hollik, Kollar]

Process	σ_{tot} without cuts [pb]	
	Born	correction
$u\bar{u}$	34.25	-1.41
$d\bar{d}$	21.61	-0.228
$s\bar{s}$	4.682	-0.0410
$c\bar{c}$	2.075	-0.0762
gg	407.8	2.08
$g\gamma$		4.45
pp	470.4	4.78

***pp* → WW** [Bierweiler,Kasprzik,Kühn]





SUMMARY

- Electroweak corrections are known for the most important $2 \to 2$ processes at the LHC
- Electroweak *Sudakov* corrections typically grow with energy and can reach tens of percent at energies of $\sim$ 1 TeV
- Effects of real *W,Z* bremsstrahlung lead to mild partial cancellations, very dependent on the acceptance cuts
- Photon pdfs play a role at the level of a few percent, more important at high energies

The high energy and large luminosity of the upcoming LHC run promises large event samples at transverse momenta in the TeV region. This is where EW effects are most dominant and need to be accounted for.