Precision calculations for LHC (& ILC?): electroweak corrections and related issues

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Contents

1 Issues for the workshop:

- Comparison of precision calculations for single W and Z production at the LHC
  - ◇ electroweak corrections very important (M_{W}, Γ_{W}, high p_{T})
    EW and/or elmg. effects calculated by different groups:
    WGRAD (Baur/Wackeroth), Dittmaier/Krämer, HORACE (Montagna et al.),
    WINHAC (Jadach et al.), others?

    $\hookrightarrow$ tuned comparison desirable (inclusion of non-participants)
  - ◇ definition of common setup in progress (together with TEV4LHC people)
    (input parameters and schemes, PDFs, observables)
  - ◇ inclusion of EW effects beyond $\mathcal{O}(\alpha)$
  - ◇ combination of QCD $\oplus$ EW corrections
- EW corrections to hadronic processes
  - ◇ systematic enhancement in specific situations (kinematic effects, high scales)
  - ◇ Where are EW corrections relevant but still missing ?
  - ◇ relevance and correct use of new $\mathcal{O}(\alpha)$-corrected MRST2005QED PDFs
  - ◇ New results ? – E.g. weak $\mathcal{O}(\alpha)$ corrections to high-E_{T} jet production
    $\hookrightarrow$ presentation by S.Moretti

- Higgs cross sections at the LHC
  - ◇ New results ? – E.g. $\mathrm{pp} \to \mathrm{t\bar{t}A} + X$ in NLO QCD
    Dittmaier, Krämer, Spira '05
  - ◇ $\mathrm{b\bar{b}H}$ production: 4-flavour versus 5-flavour scheme
    What can and should be improved how ?
    Where is finite m_b relevant ? (b tagging or b-jet definition?)
  - ◇ What is not known with sufficient precision ?
    (missing EW and/or QCD corrections)
- Corrections to many-particle and background processes
  - ◇ Theoretical issue:
    What is feasible at present or in near future ?
    $\hookrightarrow$ presentation by G.Heinrich
  - ◇ Experimental issue:
    Which are the most important missing higher-order calculations (EW / QCD) ?
  - ◇ New results ? – E.g. progress on $\mathrm{pp} \to \mathrm{t\bar{t}} + \mathrm{jet} + X$ in NLO QCD
    $\hookrightarrow$ status report by P.Uwer
  - ◇ Should we perform technical comparisons or
    can be se up a common (challenging) project ?

- Precision calculations for the ILC

  Should we include this ?

  Enormous progress of last years, e.g.,

  - ◇ techniques for corrections to $2 \to 3$ processe at one loop established and results from different groups ($\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\mathrm{H}, \mathrm{t}\bar{\mathrm{t}}\mathrm{H}$, etc.)
  - ◇ first results for $2 \to 4$ processes at one loop
  - ◇ technical progress for $2 \to 2$ and $1 \to 3$ processes at two loops

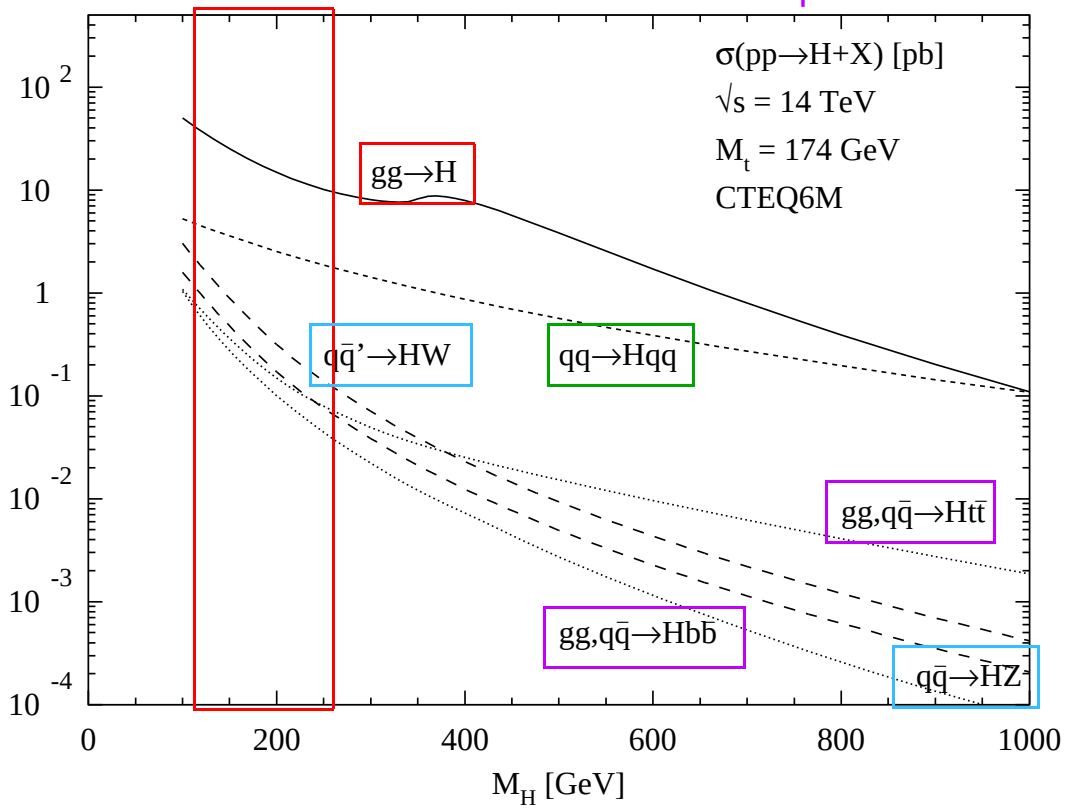
- More ?!

2 Predictions for SM Higgs-boson production at the LHC

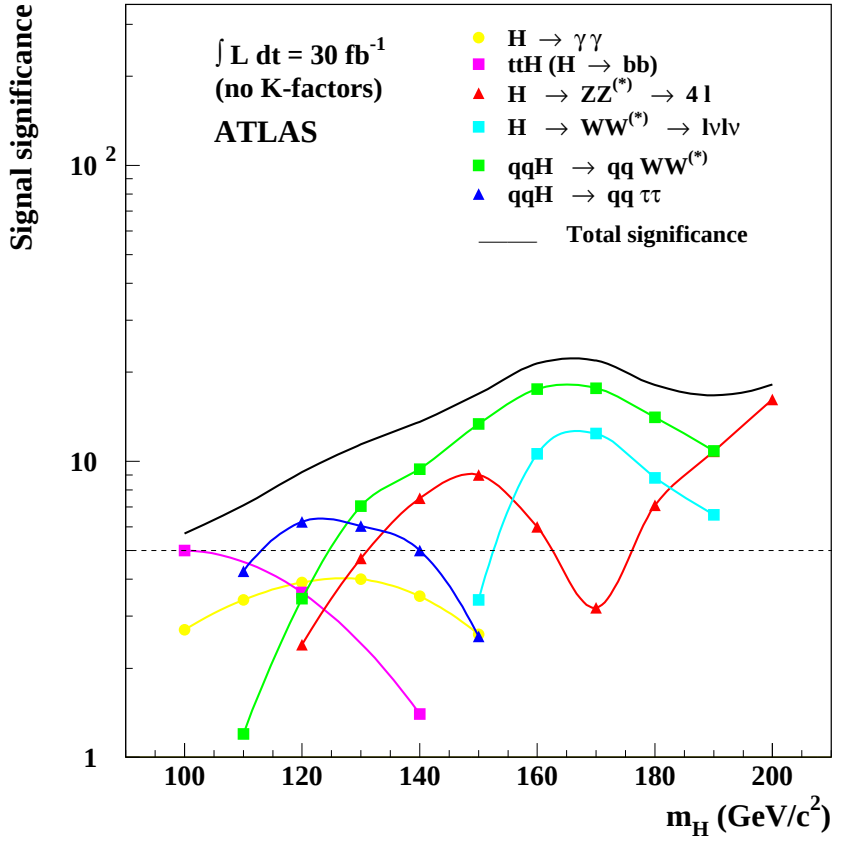
Overview of cross sections and significance of the Higgs signal at the LHC

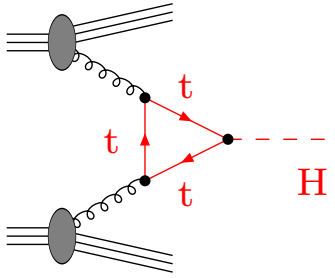
favoured

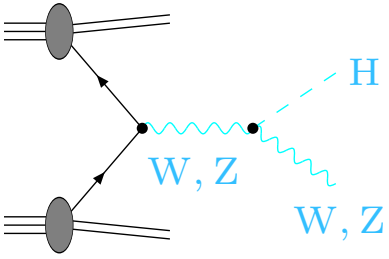
Spira et al. '05

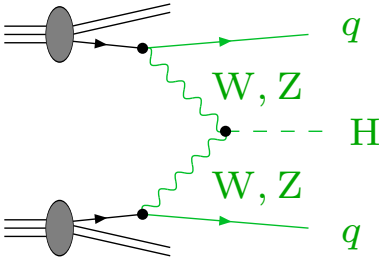


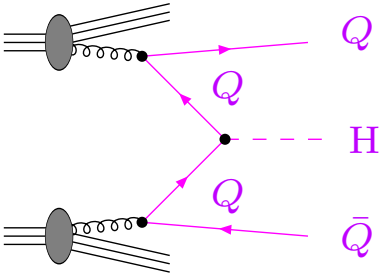
ATLAS '03



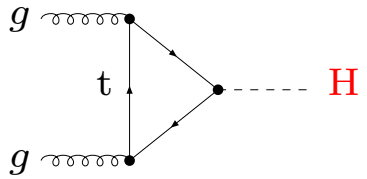








Higgs production via gluon fusion



- complete NLO QCD correction known

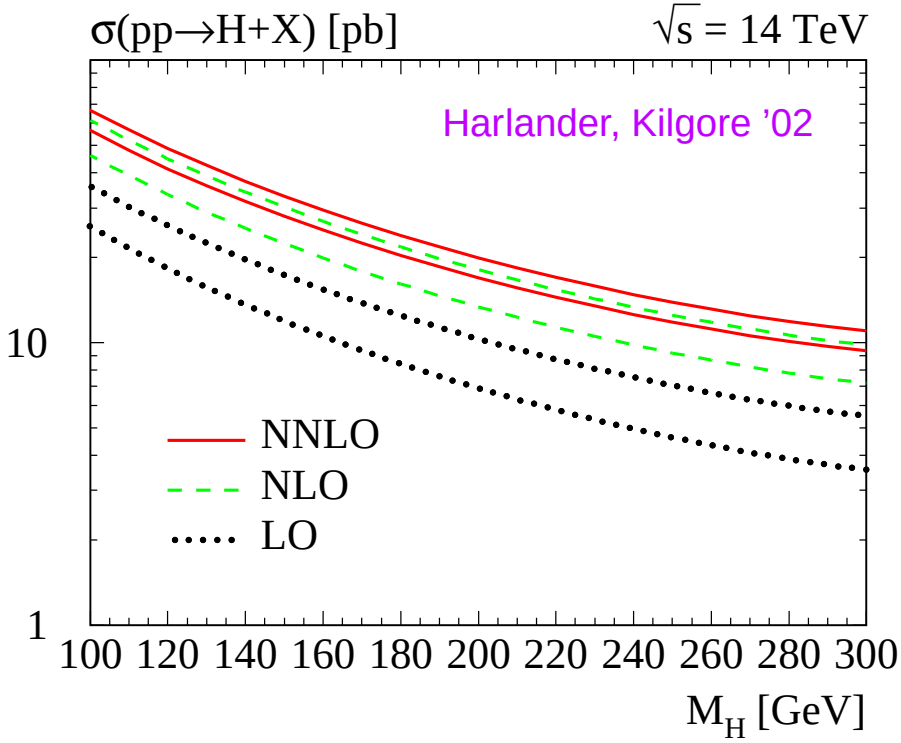
  Graudenz, Spira, Zerwas '93
  Spira, Djouadi, Graudenz, Zerwas '95

- NNLO QCD correction known
  in limit $m_{\rm t} \to \infty$

  Harlander, Kilgore '02
  Anastasiou, Melnikov '02
  Ravindran, Smith, van Neerven '03

$$K = \frac{\sigma_{\rm NNLO}}{\sigma_{\rm LO}} \sim 2.0$$

$\hookrightarrow$ scale uncertainty reduced to $\sim 10\%$



- improvements by soft-gluon resummations

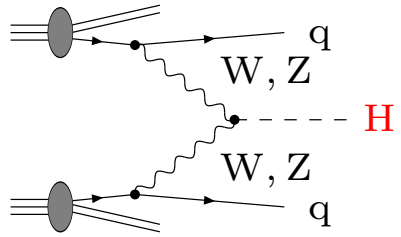
  Krämer, Laenen, Spira '96; Balazs, Yuan '00
  Catani, de Florian, Grazzini, Nason '03

- electroweak $\mathcal{O}(\alpha)$ correction completed recently

  Aglietti, Bonciani, Degrassi, Vicini '04
  Degrassi, Maltoni '05

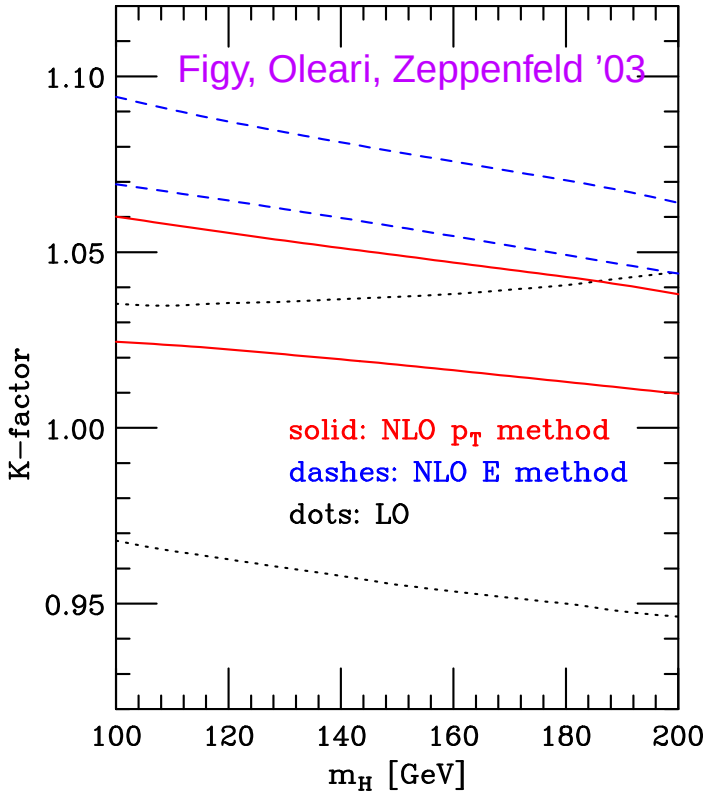
$\hookrightarrow$ corrections $\sim$ 5–8% for $115\,\text{GeV} \lesssim M_{\rm H} \lesssim 2M_{\rm W}$

Higgs production via vector-boson fusion



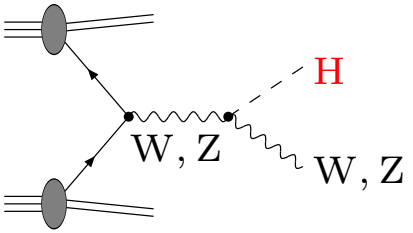
- NLO QCD corrections known
  - ◇ for total cross section
    Han, Valencia, Willenbrock '92
    ↪ small corrections
    (suppressed colour exchange between the two quark lines)
  - ◇ for differential cross sections
    Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04
    ↪ larger corrections and distortion of distributions

- electroweak corrections not yet known
  ↪ expected to be of the order of QCD scale uncertainty or larger



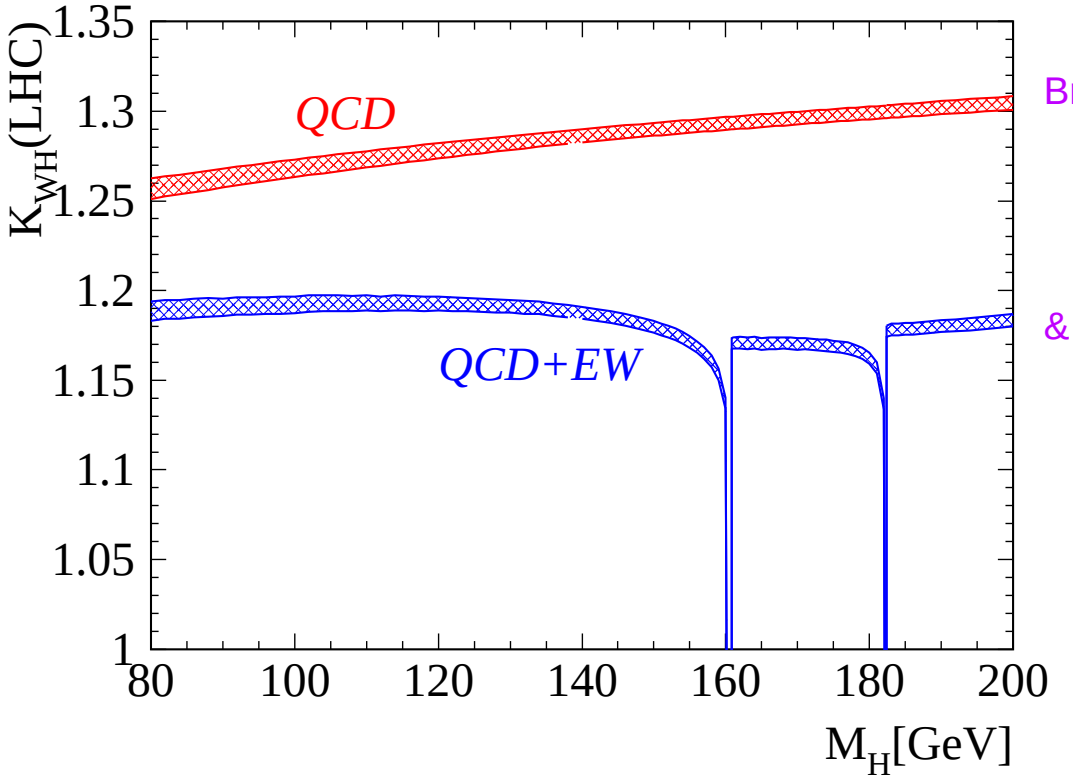
band widths:
$Q_i/2 < \mu_{\rm ren}=\mu_{\rm fact} < 2Q_i$

“Higgs-strahlung”:



- NLO and NNLO QCD corrections
  similar to Drell–Yan process $q\bar{q} \to \mathrm{Z} \to \mu^+\mu^-$
- electroweak corrections relevant & known

NNLO QCD and electroweak corrections to $\mathrm{pp} \to \mathrm{WH} + X$ at the LHC



Brein, Djouadi, Harlander ’03

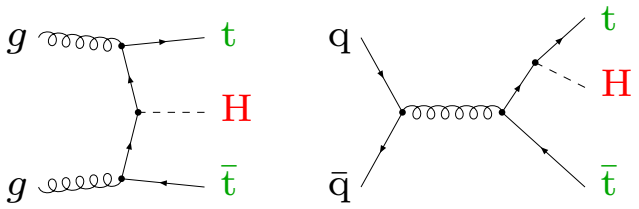
& Ciccolini, Dittmaier, Krämer ’03

band widths:

$\frac{1}{3} M_{\mathrm{WH}} < \mu_{\mathrm{ren/fact}} < 3 M_{\mathrm{WH}}$

size of the corrections: $\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha) \sim 5\text{–}10\%$

Higgs production with $t\bar{t}$ pairs



- NLO QCD corrections known
  - ◇ for total cross section

    Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01
    Dawson, Orr, Reina, Wackeroth '02

  - ◇ for differential cross sections

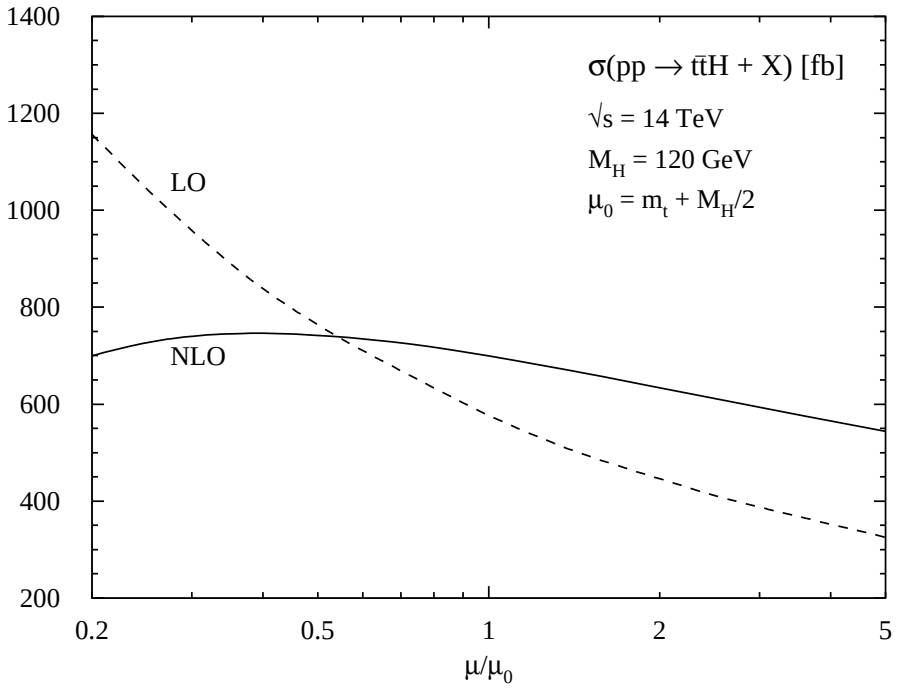
    Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '02

    $\hookrightarrow$ K-factor rescaling insufficient

  Remaining scale uncertainty

  $\sim$ 20%

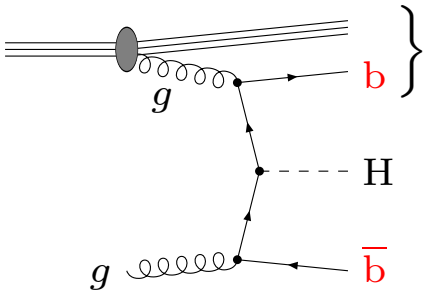
Beenakker et al. '01



- electroweak correction not known

  (but seem to be less important than for W fusion)

Higgs production with $\mathrm{b\bar{b}}$ pairs



small b transversal momenta lead to potentially large corrections

$\propto \alpha_\mathrm{s} \ln(m_\mathrm{b}/\mu_\mathrm{fact})$

resummation of higher orders necessary !

Two complementary approaches:

- Four-flavour scheme:

  splitting $g \to \mathrm{b\bar{b}}$ appears outside proton

  $\hookrightarrow$ (N)LO calculation as for $\mathrm{t\bar{t}H}$

  (apart from running b-mass in Yukawa coupling)

  - ◇ 2 tagged b's — Dittmaier, Krämer, Spira '03; Dawson, Jackson, Reina, Wackeroth '03

    no large log's if $p_{\mathrm{T,b}} > \text{several GeV}$

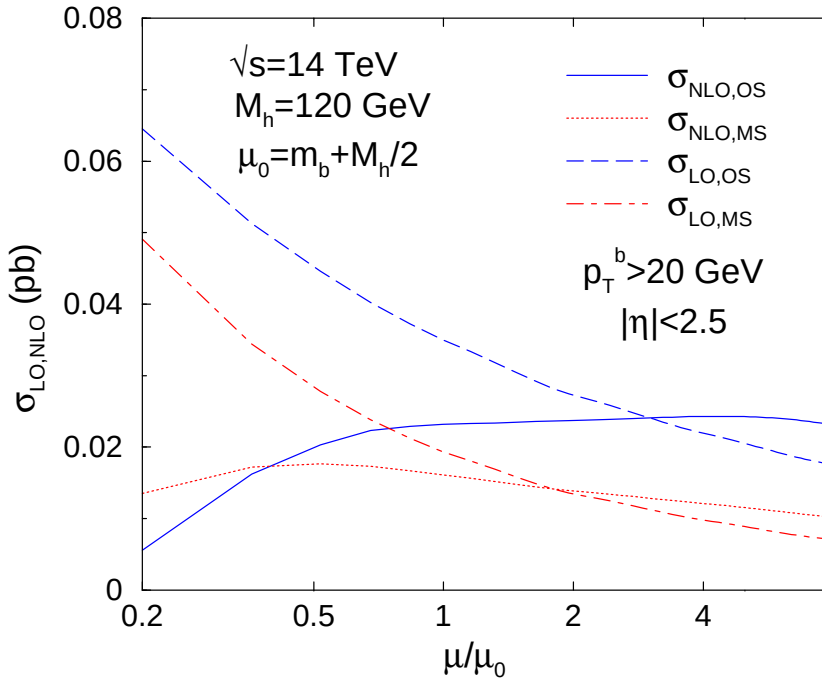
    $\hookrightarrow$ perturbative approach ok !

  - ◇ inclusive b's — Dittmaier, Krämer, Spira '03

    corrections $\propto \alpha_\mathrm{s} \ln(m_\mathrm{b}/\mu_\mathrm{fact})$ with $\mu_\mathrm{fact} \sim M_\mathrm{H}/4$

    $\hookrightarrow$ resummations needed (but not included yet)

Dawson, Jackson, Reina, Wackeroth '0



- Five-flavour scheme: splitting $g \to \mathrm{b\bar{b}}$ as part of the proton system

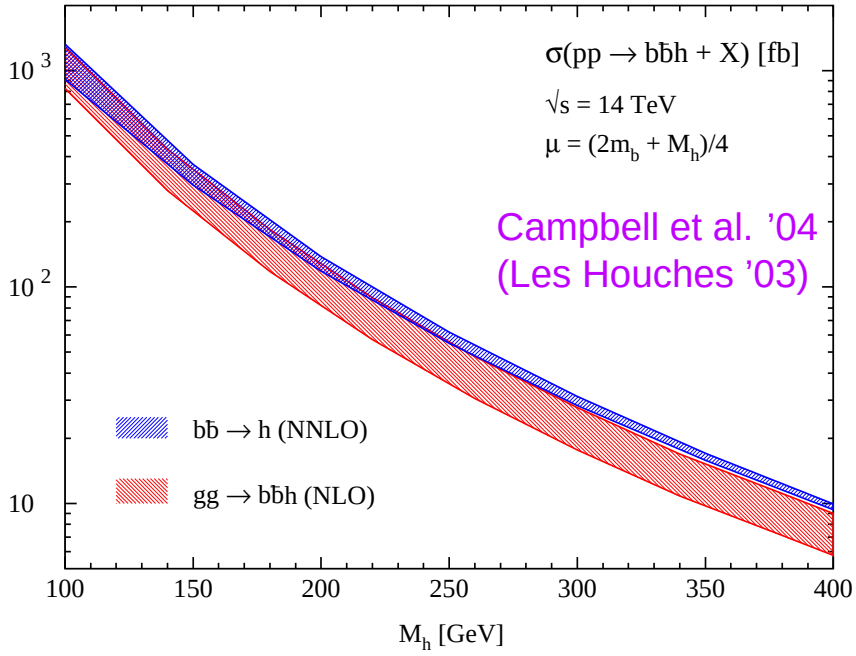
  $\hookrightarrow$ introduction of a b-quark distribution $\mathrm{b}(x, \mu_{\mathrm{fact}})$ with DGLAP evolution and implicit resummation of $[\alpha_{\mathrm{s}} \ln(m_{\mathrm{b}}/\mu_{\mathrm{fact}})]^n$ terms

  Two expansion parameters in pert. series: α_{s} and $l = 1/\ln(m_{\mathrm{b}}/\mu_{\mathrm{fact}})$

  - $\mathrm{b\bar{b}} \to \mathrm{H}$: NNLO Harlander, Kilgore '03
  - $g\mathrm{b} \to \mathrm{bH}$: NLO Campbell, Ellis, Maltoni, Willenbrock '03

Total cross section (no b's tagged):

- bands for (N)NLO predictions overlap
  $\hookrightarrow$ consistency of approaches
- 4FS: more appropriate for m_{b}-sensitive observables
- 5FS: more appropriate for m_{b}-insensitive observables



band with: $\mu/2 < \mu_{\mathrm{ren}} = \mu_{\mathrm{fact}} < 2\mu$

Further interesting processes for SM Higgs production

- $pp \to \mathrm{HH} + X$: NLO QCD correction in limit $m_\mathrm{t} \to \infty$

  Dawson, Dittmaier, Spira '98

  $$K = \frac{\sigma_\mathrm{NLO}}{\sigma_\mathrm{LO}} \sim 1.9 \quad \to \text{ scale uncertainty reduced to } \sim 20\%$$

- $pp \to \mathrm{H} + \mathrm{jets}$: NLO QCD correction in limit $m_\mathrm{t} \to \infty$

  de Florian, Grazzini, Kunszt '99
  Ravindran, Smith, van Neerven '02
  Glosser, Schmidt '02

  $$K = \frac{\sigma_\mathrm{NLO}}{\sigma_\mathrm{LO}} \sim 1.4\text{–}1.7$$

  improvements by soft-gluon resummation

  Kauffman '91;
  Bozzi, Catani, de Florian, Grazzini '03

- $gg \to \mathrm{H} + 2\mathrm{jets}$: LO QCD

  Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '01

- $gg \to \mathrm{H} + 3\mathrm{jets}$: LO QCD in limit $m_\mathrm{t} \to \infty$

  Del Duca, Frizzo, Maltoni '04

3 Electroweak corrections and PDFs

Analogy to QCD-improved parton model:

Collinear splittings $q \to q\gamma$, $\gamma \to q\bar{q}$ lead to quark mass singularities

$\hookrightarrow$ absorb $\alpha \ln m_q$ singularities via factorization into redefined PDFs

Previous approach: no $\mathcal{O}(\alpha)$-corrected PDFs available

$\hookrightarrow$ factorization of collinear singularities in $\mathcal{O}(\alpha)$ in $\overline{\rm MS}$ scheme
but: neglect $\mathcal{O}(\alpha)$ effects in PDFs

Estimate of neglected $\mathcal{O}(\alpha)$ effects in PDFs: Spiesberger '95, '99; Roth, Weinzierl '04

$$\Delta(\mathrm{PDF}) \lesssim 0.3\%\ (1\%) \quad \text{for} \quad x < 0.1\ (0.4), \quad \mu_{\rm fact} \sim M_{\rm W}$$

New situation: MRST2004QED set of $\mathcal{O}(\alpha)$-corrected PDFs Martin, Roberts, Stirling, Thorne '0

$\hookrightarrow$ new PDFs should be used if EW $\mathcal{O}(\alpha)$ corrections are included

- use appropriate factorization scheme for $\mathcal{O}(\alpha)$ corrections
- additional real corrections from photons in initial state
- find processes to measure $\mathcal{O}(\alpha)$ induced photon distribution

MRST2004QED: start PDF from model assumption,
but agreement with $\sigma_{\rm ep\to e\gamma+X}$ at HERA

4 Electroweak corrections to processes at Tevatron and the LHC

General considerations about EW corrections at hadron colliders:

- generic size: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$, i.e. NNLO QCD $\sim$ NLO EW
- however: systematic enhancement of EW effects due to
  - ◇ logarithms $\alpha \ln^n(M_W/Q)$, $n = 2, 1$ (Sudakov and subleading) at high scales Q
    $\hookrightarrow$ important for new-physics searches
  - ◇ kinematic effects from photon radiation off leptons (e.g. Drell–Yan)
    $\hookrightarrow$ important for reconstruction of W's, Z's, etc.
- particular relevance if QCD corrections are suppressed
  (in specific cross sections, e.g. $WW \to H$, or in cross-section ratios)

EW corrections to gauge-boson production

- $\mathrm{pp}(\to \mathrm{W}) \to l\bar{\nu}_l + X$
  - $\mathcal{O}(\alpha)$ correction in pole approximation (PA) Baur, Keller, Wackeroth '98; Dittmaier, Krämer '02
  - complete $\mathcal{O}(\alpha)$ correction Dittmaier, Krämer '02; Baur, Wackeroth '04

    $\mathrm{pp} \to \nu_\mu \mu^+ (+\gamma)$ at $\sqrt{s} = 14\,\mathrm{TeV}$ DK '02

$p_{\mathrm{T},l}/\mathrm{GeV}$	25–∞	50–∞	100–∞	200–∞	500–∞	1000–∞
$\delta_{\mu^+\nu_\mu}/\%$	$-2.9(1)$	$-4.9(1)$	$-8.5(1)$	$-13.1(1)$	$-23.4(1)$	$-34.5(1)$
$\delta_{\mu^+\nu_\mu,\mathrm{PA}}/\%$	$-2.8(1)$	$-3.5(1)$	$-4.0(1)$	$-4.4(1)$	$-6.2(1)$	$-8.5(1)$

  - multi-photon radiation via leading logs
    Baur, Stelzer '99; Carloni Calame, Montagna, Nicrosini, Treccani '03; Placzek, Jadach '04

- $\mathrm{pp}(\to \mathrm{Z}) \to l^+l^- + X$
  - photonic $\mathcal{O}(\alpha)$ correction Baur, Keller, Sakumoto '97
  - weak $\mathcal{O}(\alpha)$ correction Baur, Wackeroth '99; Brein, Hollik, Schappacher '99
  - multi-photon radiation via leading logs
    Baur, Stelzer '99; Carloni Calame, Montagna, Nicrosini, Treccani '05

EW corrections to gauge-boson + jet production

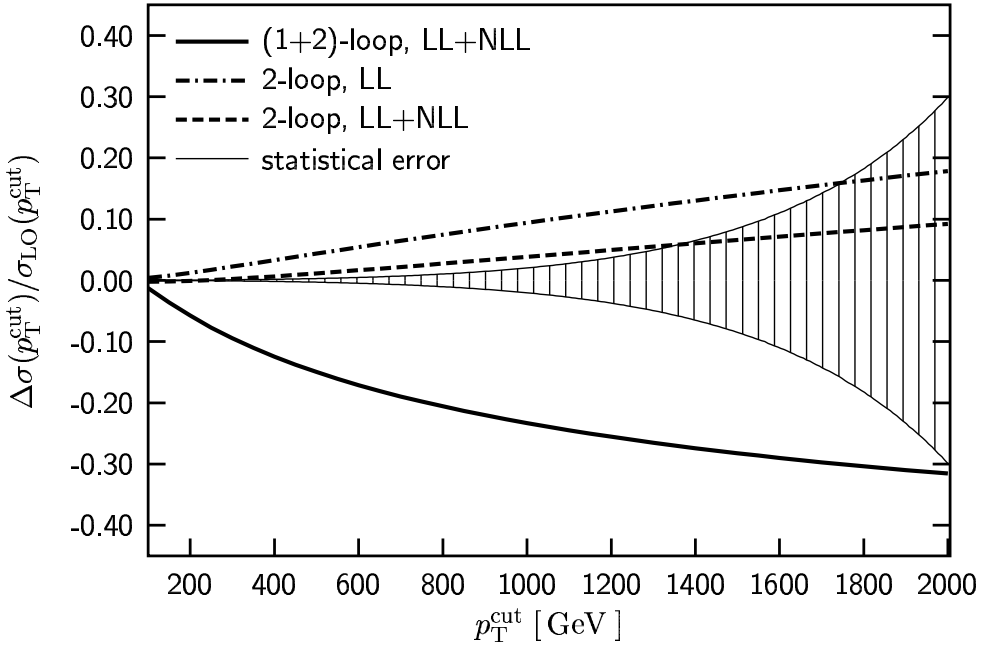
- $\mathrm{pp} \to \mathrm{V} + \mathrm{jet} + X \quad (\mathrm{V} = \gamma, \mathrm{Z})$
  - ◇ weak $\mathcal{O}(\alpha)$ correction

    Maina, Moretti, Ross '04

    $\delta_{\mathrm{weak}} \sim -(5\text{–}15)\%$ for $p_{\mathrm{T}} \lesssim 500\,\mathrm{GeV}$

  - ◇ (1+2)-loop high-energy logarithmic corrections (LL+NLL) for $\mathrm{V} = \mathrm{Z}$

    Kühn, Kulesza, Pozzorini, Schulze '04



$\sqrt{s} = 14\,\mathrm{TeV}$

- $\mathrm{pp} \to \mathrm{W} + \mathrm{jet} + X$

  no results on EW corrections yet

EW corrections to gauge-boson pair production

- $\mathrm{pp}(\to \mathrm{W}\gamma) \to l\bar{\nu}\gamma + X$ Accomando, Denner, Pozzorini '01

  $\mathcal{O}(\alpha)$ correction in high-energy and pole approximations

  $\hookrightarrow\ \delta\ \sim\ -5\%\,(-24\%)$ for $p_{\mathrm{T},\gamma} \gtrsim 350\,\mathrm{GeV}\,(700\,\mathrm{GeV})$

- $\mathrm{pp} \to \mathrm{Z}\gamma + X$ Hollik, Meier '04

  complete $\mathcal{O}(\alpha)$ correction for on-shell Z bosons

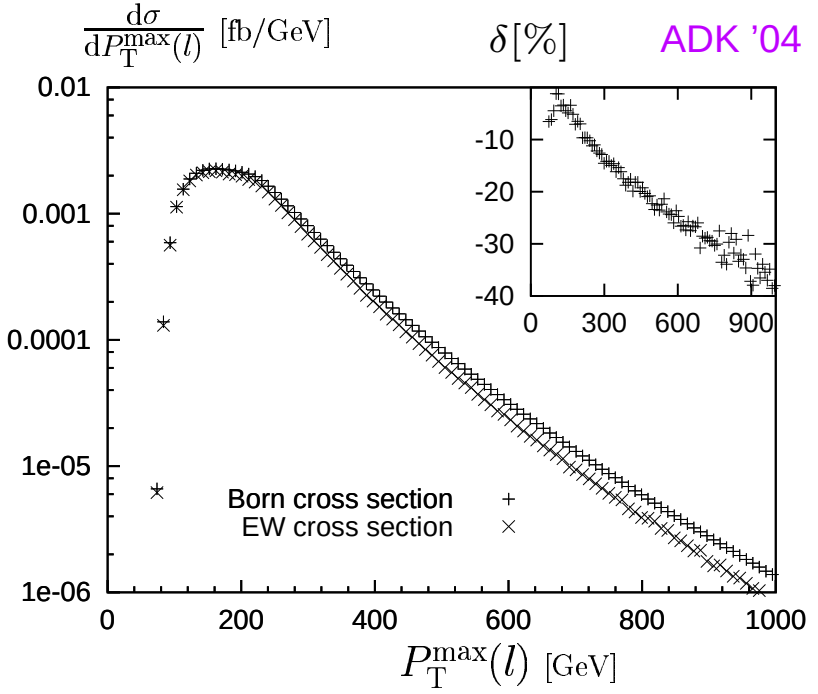
  $\hookrightarrow\ \delta\ \sim\ -20\%$ for $M_{\gamma\mathrm{Z}} \lesssim 2\,\mathrm{TeV}$

- $\mathrm{pp}(\to \mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}) \to 4\,\mathrm{leptons} + X$

  Accomando, Denner, Pozzorini '01
  Accomando, Denner, Kaiser '04

  $\mathcal{O}(\alpha)$ correction in high-energy and pole approximations

$\mathrm{pp} \to \mathrm{WZ} \to \mathrm{e}\nu_\mathrm{e}\mu^+\mu^-$ at $\sqrt{s} = 14\,\mathrm{TeV}$



EW corrections to heavy-quark production

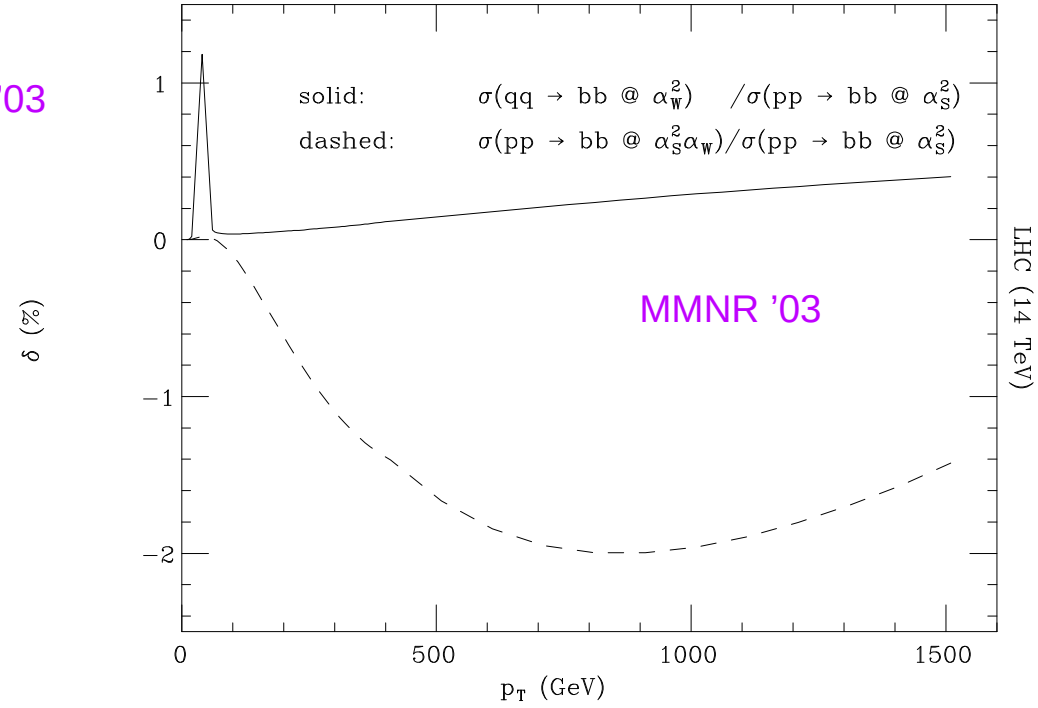
- $\mathrm{pp} \to \mathrm{t\bar{t}} + X$
  - ◇ weak $\mathcal{O}(\alpha)$ correction to σ_{tot} Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth '94

    $\delta_{\mathrm{weak}} \sim$ a few %
  - ◇ weak $\mathcal{O}(\alpha)$ correction to σ_{tot} in THDM and MSSM Hollik, Mösle, Wackeroth '97

    $\delta_{\mathrm{weak}} \lesssim 10\%$

- $\mathrm{pp} \to \mathrm{b\bar{b}} + X$ Maina, Moretti, Nolten, Ross '03

  weak $\mathcal{O}(\alpha)$ correction



EW corrections to jet production

- high-E_{T} jets at Tevatron

  Moretti, Nolten, Ross '05

  weak $\mathcal{O}(\alpha)$ correction