Status Report of the Higgs & Standard Model Working Group

the SMH theory conveners

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Scott Willenbrock (Illinois Univ., Urbana)

- Substantial overlap with TeV4LHC, overlap with HERA-LHC
- Six working subgroups formed, some activity already started
- Question to be answered: how well do we know what we suppose to know well?

This is not a review of SM physics, but a summary of the activites which will likely take place during this workshop

Subgroups

- SM benchmarks for the LHC start (J. Huston)
- PDF uncertainties (J. Huston)
- Monte Carlos (S. Frixione, P. Richardson)
- Multi-parton and NNLO (V. del Duca), small-x (R. Ball)
- Precision Higgs cross sectiobs (S. Willenbrock)
- EW corrections for LHC and LC (S. Dittmaier)

SM benchmarks for the LHC start

A key point: standard candles must be fully understood by LHC experiments to believe any claim of new physics (unless spectacularly clear)

- $t\bar{t}$ production
- W and Z production (possibly with jets)
- Single-inclusive jet and dijet production
- Photon and di-photon production

Issues to be addressed here:

- Predicted cross sections, and their uncertainties
- Standard candles as luminometers

Some remarks:

- Must improve understanding of power-suppressed effects in jet production
- Single-inclusive photons still not well understood
- For which processes do we really need NNLO results?

$t\bar{t}$ production: theoretical ingredients

- Rates computed to NLO accuracy: Nason, Dawson, Ellis (1988); Beenakker, vNeerven, Meng, Schuler, Smith (1991)

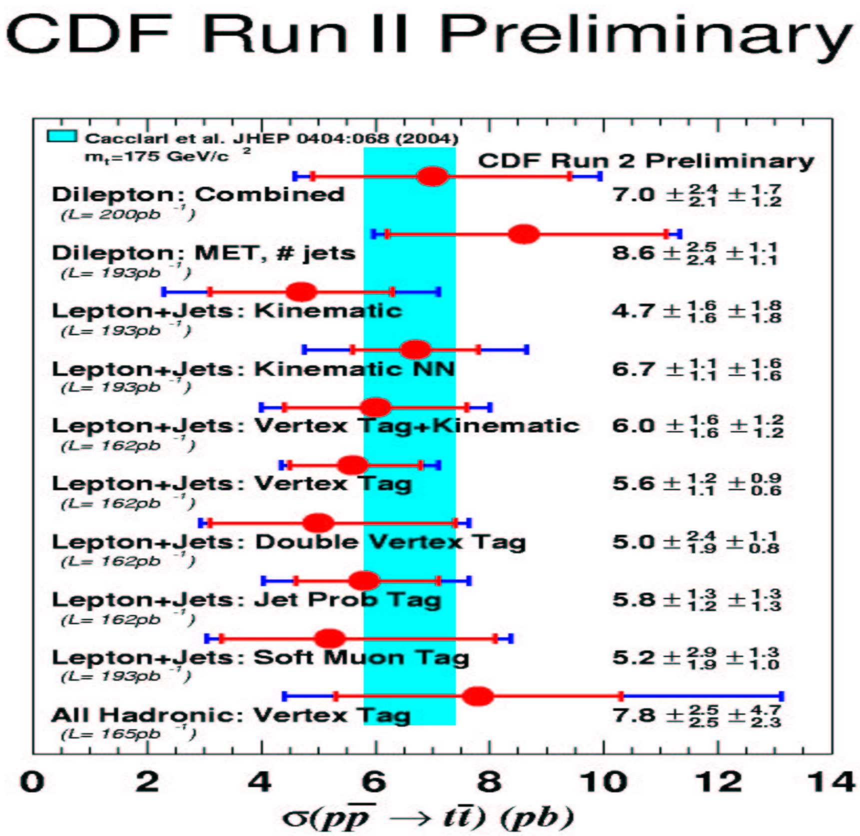
- Resummation of threshold logs available up to NLL: Sterman, Laenen, Contopanagos, Kidonakis, Oderda (1996–1998); Bonciani, Catani, Mangano, Nason (1997–1998). Rates don't change much, scale dependence reduced by a factor of two

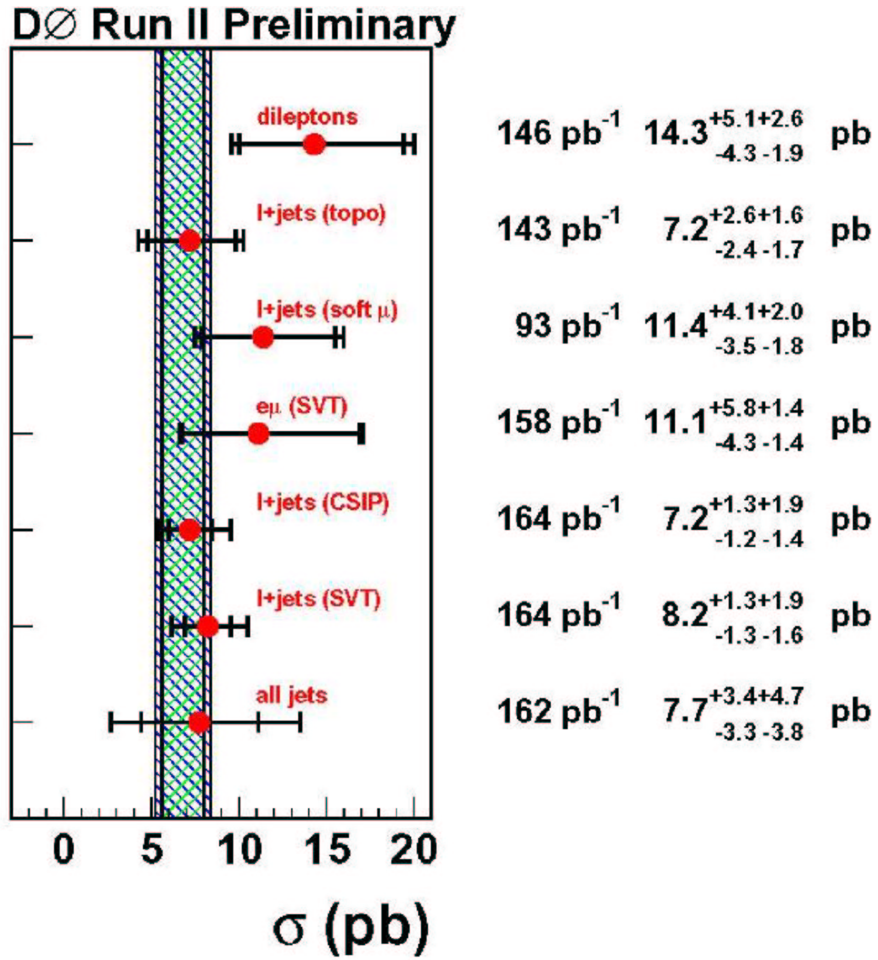
"NNLO/NNNLL" is a misleading notation

Technical note: the notation used by Kidonakis, Laenen, Moch & Vogt of N^{k}LL refers to logs after the expansion of the exponent. The so-called NNNLL-NNLO results (Kidonakis & Vogt) differ from the "standard" NLO+NLL computations by *some* higher-order terms; other terms of the same order are not included. In particular, no proper NNLO computation is available for heavy flavour production

Top production

Run I results are in good agreement with QCD predictions

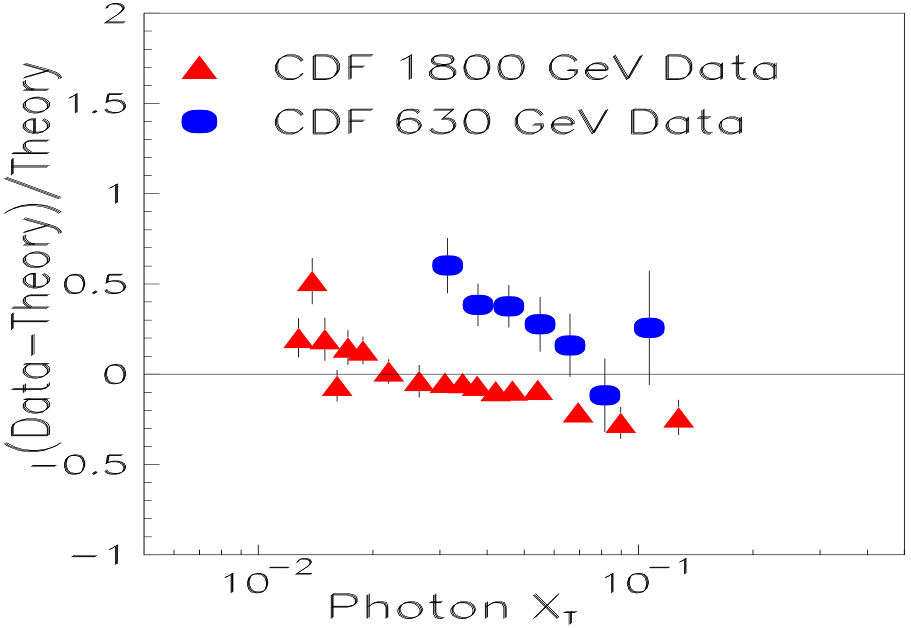


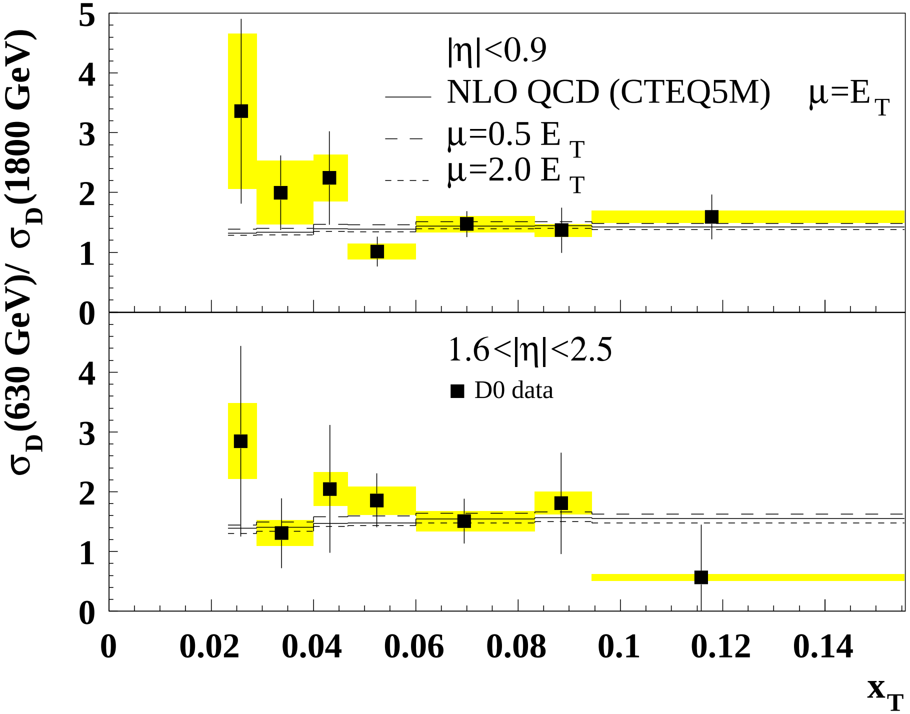


Data: winter conferences 2005; Theory: NLO+NLL

♦ No major theory progress expected before 2007

Photon production





$\sqrt{S} = 1.8$ TeV and $\sqrt{S} = 0.63$ TeV CDF data cannot be simultaneously described by pQCD. The situation is better for D0

- Mismatch between theoretical and experimental isolation criteria?
- The narrow cones used by experiments are unlikely to be sensible perturbatively
- Impact of underlying event on isolation?

Experiments shouldn't rely on theory here (precision not an issue!)

W and Z production

Theoretical predictions under fairly good control

- Fully-differential NNLO results
- NLO results matched with parton showers
- q_T, joint resummations
- $W + n$ jets observables sensibly predicted by Monte Carlos
- EW corrections available (more later)

Best candidates as luminometers? We do need precision here, if we have to improve mass measurements of LEP and Tevatron

PDF uncertainties

Pre-LHC results from Tevatron and HERA are essential. Recent progress

- Three-loop AP kernels computed exactly (Moch, Vermaseren, Vogt)
- PDF uncertainties are routinely used

Issues to be addressed here:

- How will HERA II and Tevatron Run II improve the current situation?
- Will we be able to get a consistent NNLO picture by the start of LHC?
- Do we need it?
- Are EW corrections relevant? If so, for which processes? (estimate $\Delta\mathrm{PDF} \sim 0.3\%(1\%)$ for $x < 0.1(0.4)$)

Systematic comparisons between CTEQ and MRST will be made during the workshop (other sets with errors?)

Monte Carlos

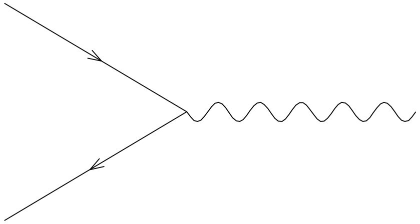
Substantial progress in the past few years. Many-jet, large-K-factor events can be now treated in a fairly solid manner

At the workshop:

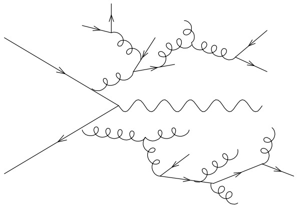
- Comparisons of NLO and MC predictions for "precision" observables
- Selected topics for MC@NLO (tutorial)
- Many-jet observables with CKKW-like approaches
- Underlying event (extrapolation to LHC energies?)
- How to exploit the flexibility of C++ codes?

Physics processes with standard MC's

1) Compute the LO cross section in perturbation theory



2) Let the shower emit as many gluons and quarks as possible



Advantages

- The analytical computations are trivial
- Very flexible
- Resum (at least) leading logarithmic contributions

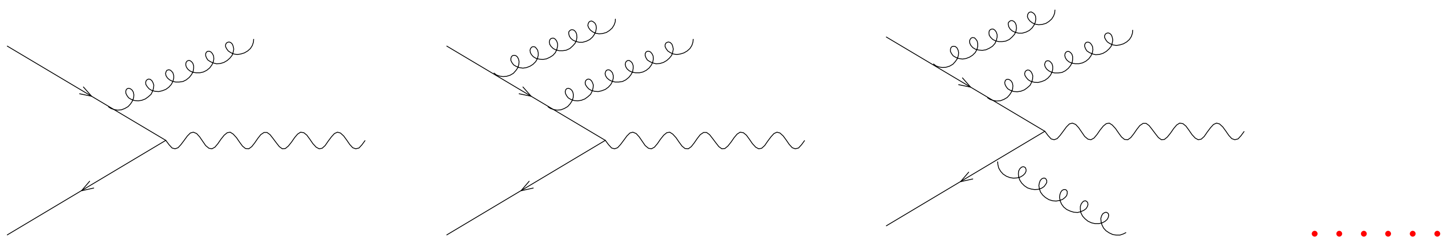
Drawbacks

- The high-p_T and multijet configurations are not properly described
- The total rate is computed to LO accuracy

These problems stem from the fact that the MC's perform the showers assuming that all emissions are collinear

Matrix Element Corrections

Just compute (exactly) more real emission diagrams before starting the shower



Problems

- Double counting (the shower can generate the same diagrams)
- The diagrams are divergent

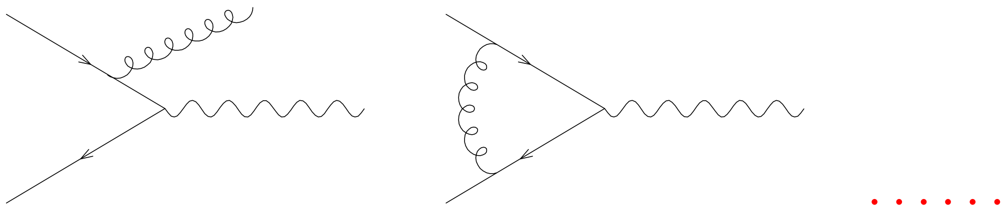
Solution (CKKW – see also MLM, Lönnblad)

Cut the divergences off by means of an arbitrary parameter δ_{sep}
$\Longrightarrow$ physical observables will depend on the unphysical δ_{sep} cutoff

This entails a modification of the matrix elements *and* of the shower (through a veto) in such a way as to reduce as much as possible the δ_{sep} dependence on physical observables

Adding virtual corrections: NLOwPS

Compute all NLO diagrams before starting the shower



Problems

- Double counting (the shower can generate the same diagrams)
- The diagrams are divergent

Solution (MC@NLO – see also Kurihara et al*; Dobbs; Soper, Krämer, Mrenna, Nagy)*

Remove the divergences locally by adding and subtracting the MC result that one would get after the first emission (yes, this is sufficient!)

Virtual diagrams cancel the divergences of the real diagrams, and therefore it is not necessary to introduce δ_{sep}; as a by-product, total rates are computed to NLO accuracy. No parameter tuning is involved in the procedure (there are no arbitrary parameters)

C++ Monte Carlos

The final goal of writing codes in C++ is that of permitting the user to generate the hard process with A, the shower with B, and the hadronization with C

Apart from the fact that C++ codes for hadron collisions are well beyond schedule, it's not clear that the goal above will be achieved

On May 17^{th} we shall have a discussion on a few key points:

- Can we agree on a minimal set of modules (say, shower, hard event, UE, hadronization, ...) with well-documented interfaces that the non-expert can understand?
- Definition of a few stardard classes that all MC authors should use

Another Les Houches Accord?

Multi-parton and NNLO

Progress is being made on understanding the general structure of IR singularities at the NNLO, but it's very unlikely that this will have any impact on physics results included in the workshop proceedings

What we should discuss here:

- Will twistors help us computing cross sections more efficiently (also beyond LO)?
- Progress in NLO computations (numerics)
- Which strong cases can be made for NNLO results?

Although by now standard, we shouldn't neglect the importance of selected NLO results for LHC physics. Typically, these are background processes (such as $t\bar{t}b\bar{b}$) for which sidebands methods can't be used

NNLO, gg-initiated processes may also be added to NLO results. Theoretically unpleasant, but probably OK if done carefully (typical example: WW production)

Small x

When the available c.m. energy is much larger than the typical invariant mass produced in the hard reaction, large logarithms may spoil the "convergence" of the series, and must be resummed

The Bjorken x's relevant to the process also enter a region where AP kernels computed at fixed order are not reliable any longer, since $\alpha_S \log 1/x \sim 1$

Substantial progress has been made in the understanding of higher-order corrections (Altarelli, Ball, Forte; Ciafaloni, Colferai, Salam), and consistent resummed result can now be achieved

What we should discuss here:

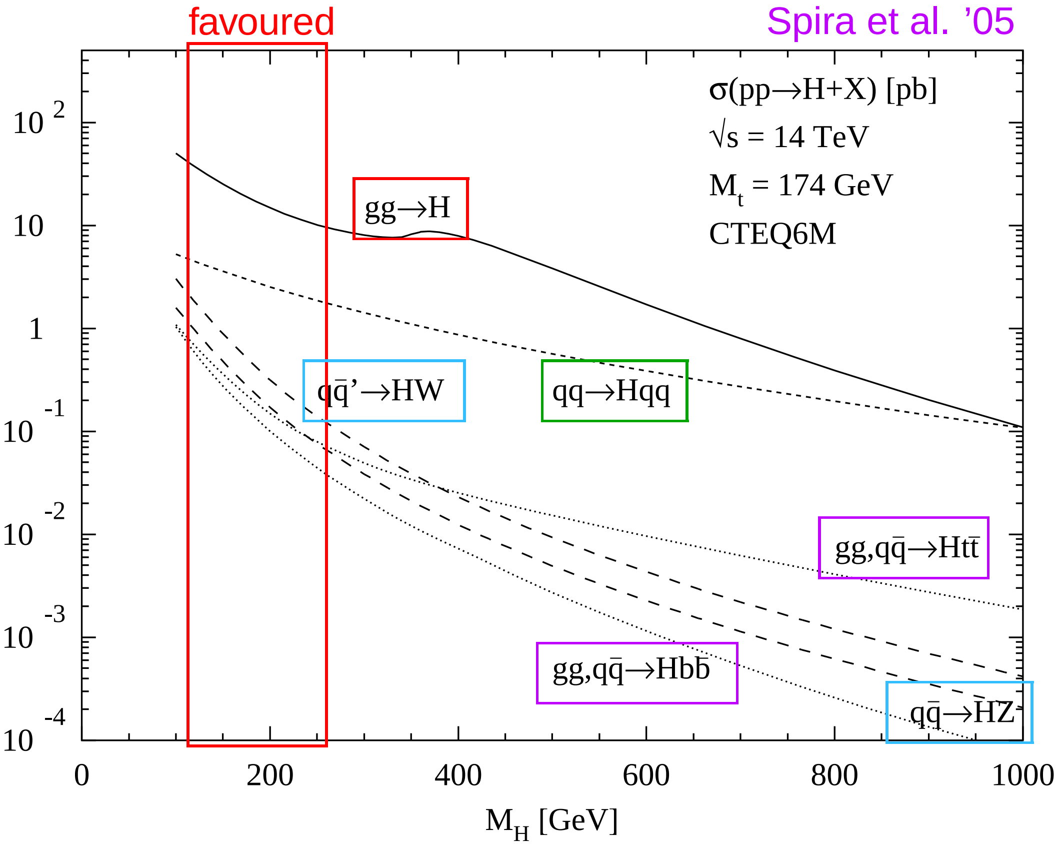
- Status of phenomenological predictions, and tools to produce them
- Possible impact of small x on benchmark LHC cross-sections
- Strategies to study small-x physics at the LHC

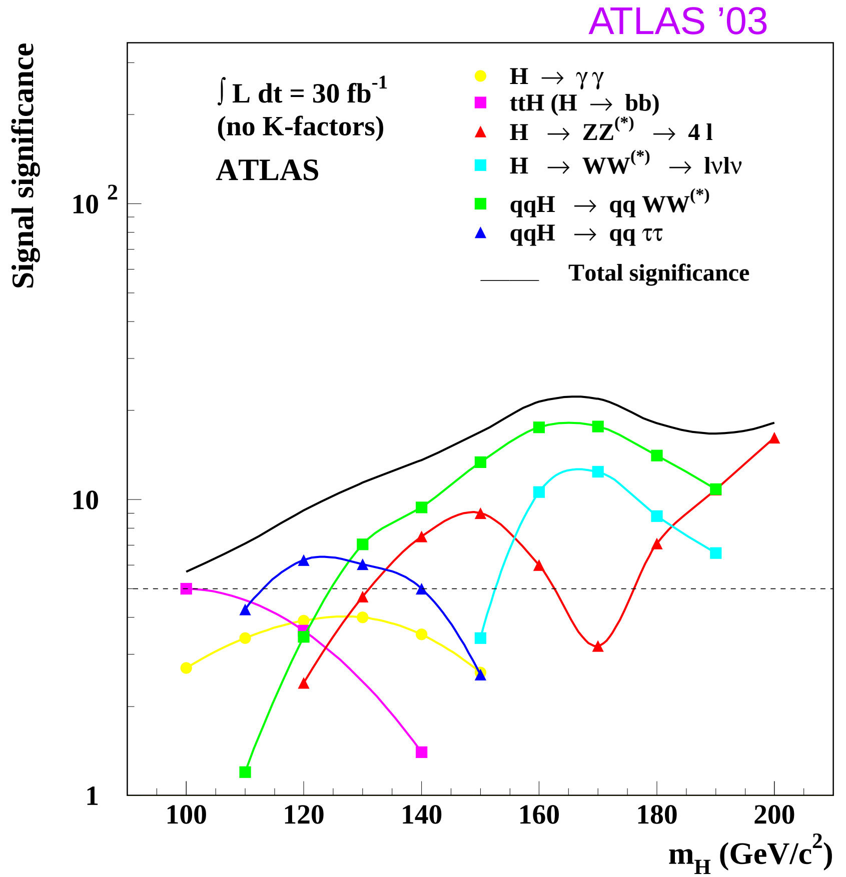
SM Higgs

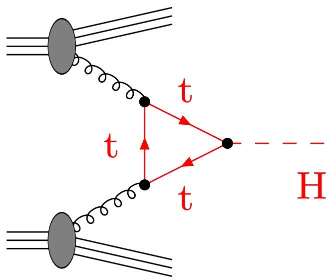
- That of SM Higgs is possibly the most difficult of the discoveries at the LHC
- Huge backgrounds have to be efficiently subtracted, and this implies the necessity of accurate predictions for all of the processes involved in the discovery
- Many results are available for the signal

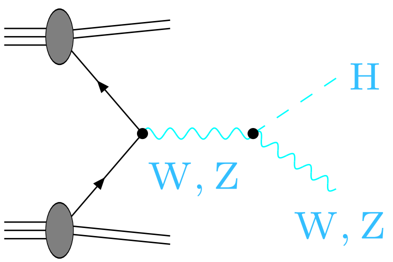
Predictions for SM Higgs-boson production at the LHC

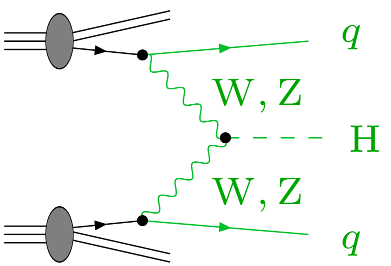
Overview of cross sections and significance of the Higgs signal at the LHC

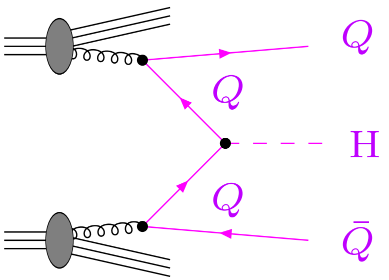




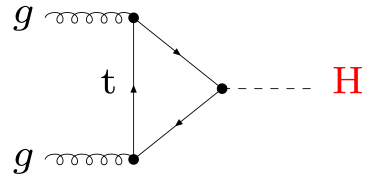






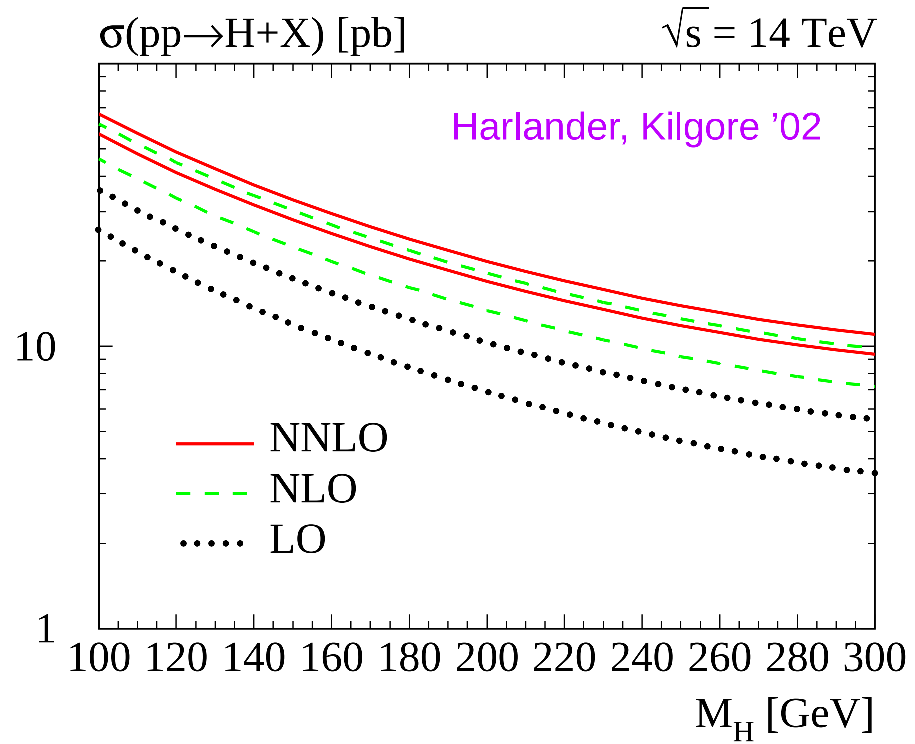


Higgs production via gluon fusion



- complete NLO QCD correction known

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



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

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

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

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

- improvements by soft-gluon resummations

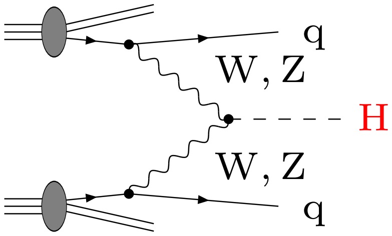
  Krämer, Laenen, Spira '96; Balazs, Yuan '00
  Catani, de Florian, Grazzini, Nason '03

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

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

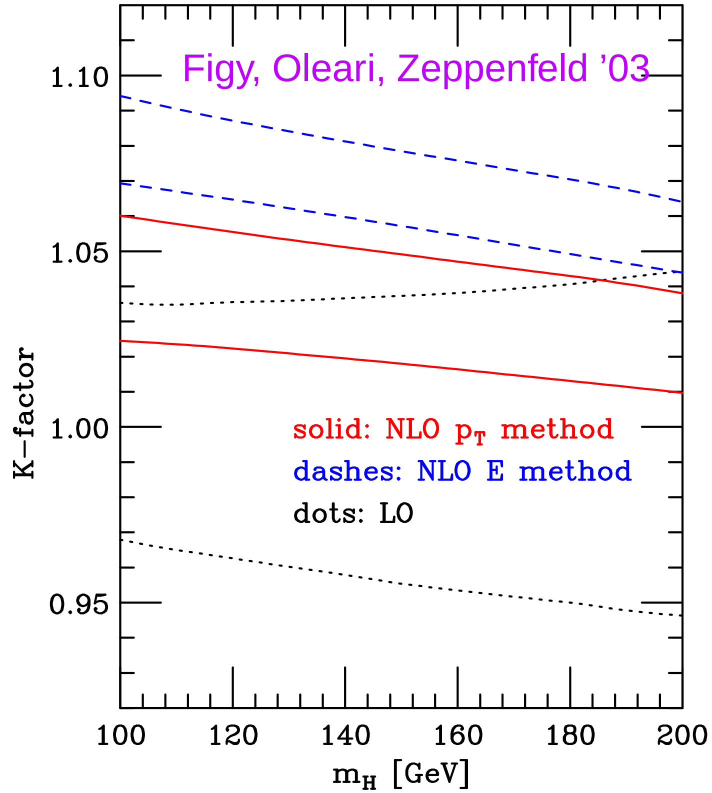
$\hookrightarrow$ corrections $\sim$ $5{-}8\%$ for $115\,\mathrm{GeV} \lesssim M_{\mathrm{H}} \lesssim 2M_{\mathrm{W}}$

Higgs production via vector-boson fusion



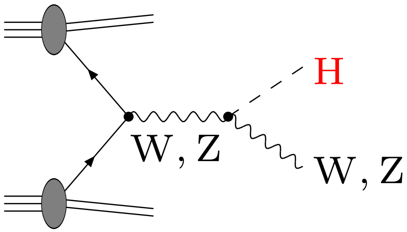
- NLO QCD corrections known
  - ◇ for total cross section
    Han, Valencia, Willenbrock '92
    ↪ small corrections
    (suppressed colour exchange between the two quark lines)
  - ◇ for differential cross sections
    Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04
    ↪ larger corrections and
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

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



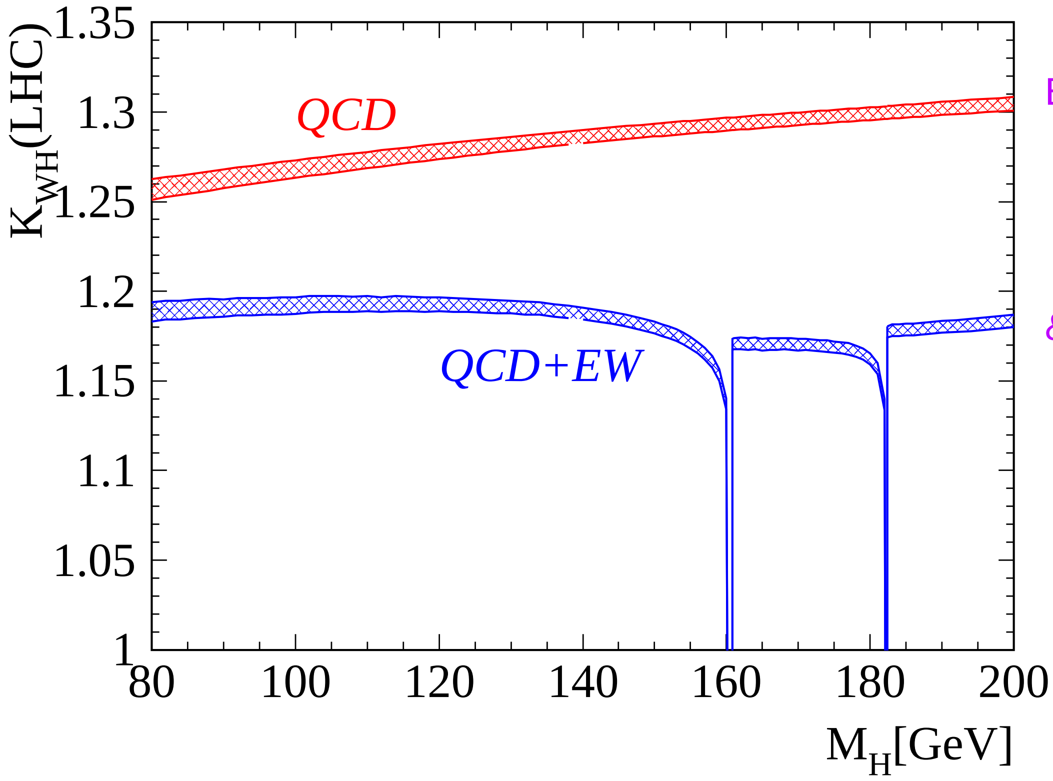
band widths:
$Q_i/2 < \mu_{\rm ren}=\mu_{\rm fact} < 2Q_i$

“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



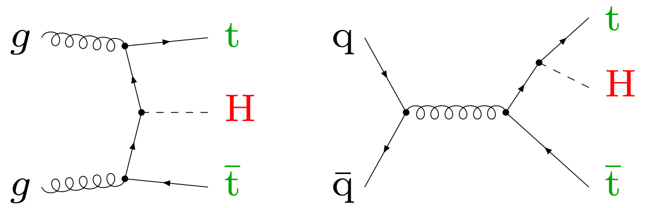
Brein, Djouadi, Harlander ’03

& Ciccolini, Dittmaier, Krämer ’03

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

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

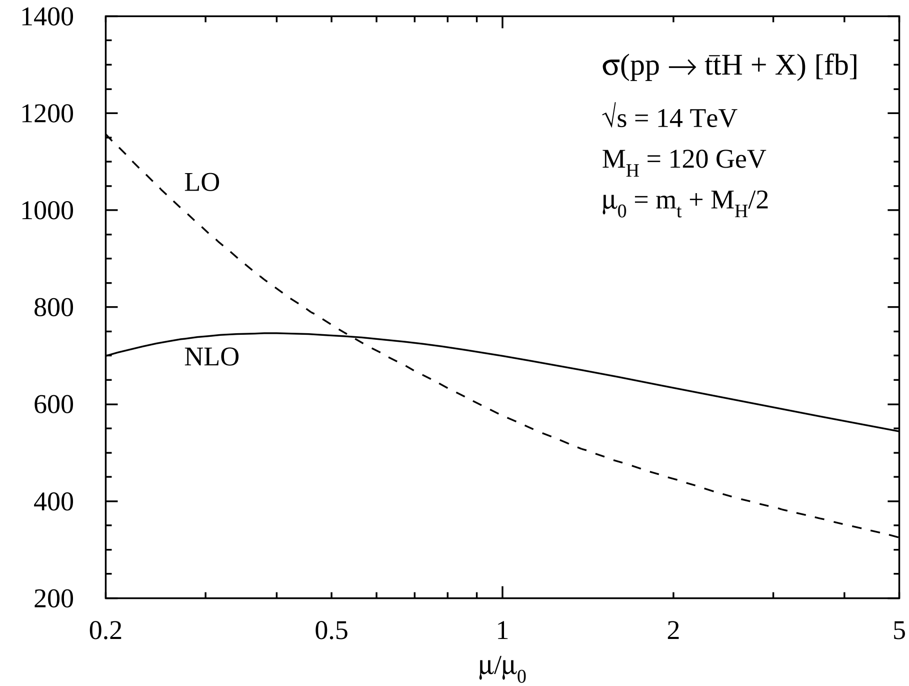
    Beenakker, Dittmaier, Krämer,
    Plümper, Spira, Zerwas '02

  $\hookrightarrow$ K-factor rescaling insufficient

  Remaining scale uncertainty

  $\sim\ 20\%$

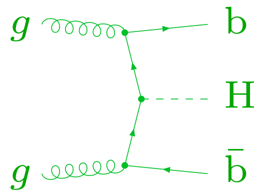
Beenakker et al. '01



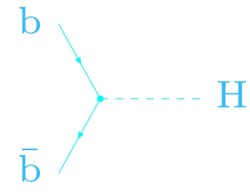
- electroweak correction not known

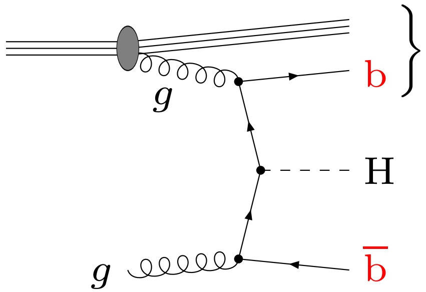
  (but seem to be less important than for W fusion)

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



versus





small b transversal momenta lead to potentially large corrections

$\propto \ \alpha_s \ln(m_b/\mu_{fact})$

resummation of higher orders necessary !

Two complementary approaches:

- Four-flavour scheme:

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

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

  (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 $p_{T,b} > \text{several GeV}$

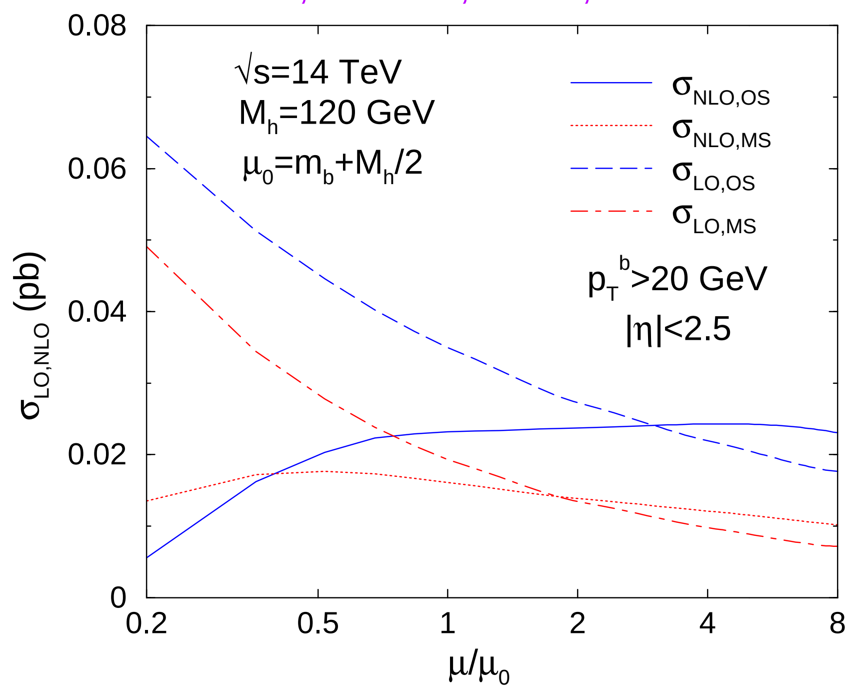
  $\hookrightarrow$ perturbative approach ok !

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

  corrections $\propto \ \alpha_s \ln(m_b/\mu_{fact})$ with $\mu_{fact} \sim M_H/4$

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

Dawson, Jackson, Reina, Wackeroth '03



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

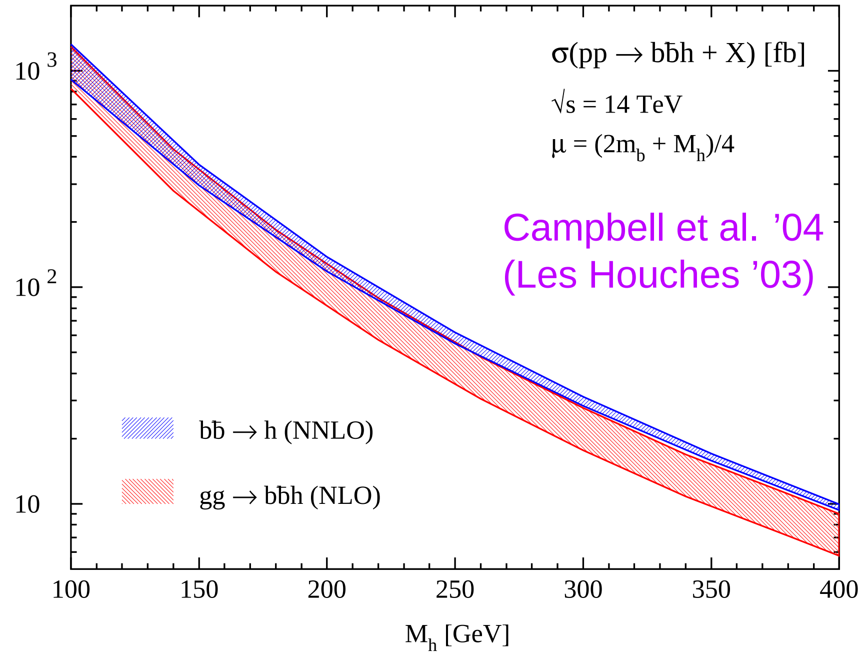
  $\hookrightarrow$ introduction of a b-quark distribution $\mathrm{b}(x, \mu_{\mathrm{fact}})$ with DGLAP evolution and implicit resummation of $[\alpha_{\mathrm{s}} \ln(m_{\mathrm{b}}/\mu_{\mathrm{fact}})]^n$ terms

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

  - ◇ $\mathrm{b}\bar{\mathrm{b}} \to \mathrm{H}$: 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

  $K = \frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}} \sim 1.9$ $\to$ 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

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. $\mathrm{WW} \to \mathrm{H}$, 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

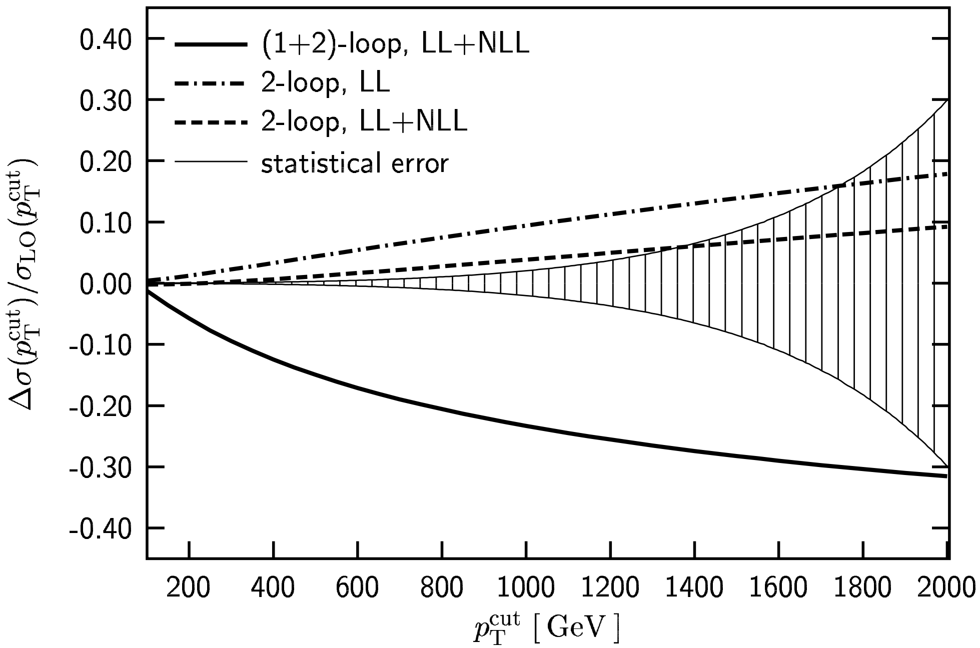
EW corrections to gauge-boson + jet production

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

    Maina, Moretti, Ross '04

    $\delta_{\mathrm{weak}} \sim -(5{-}15)\%$ 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

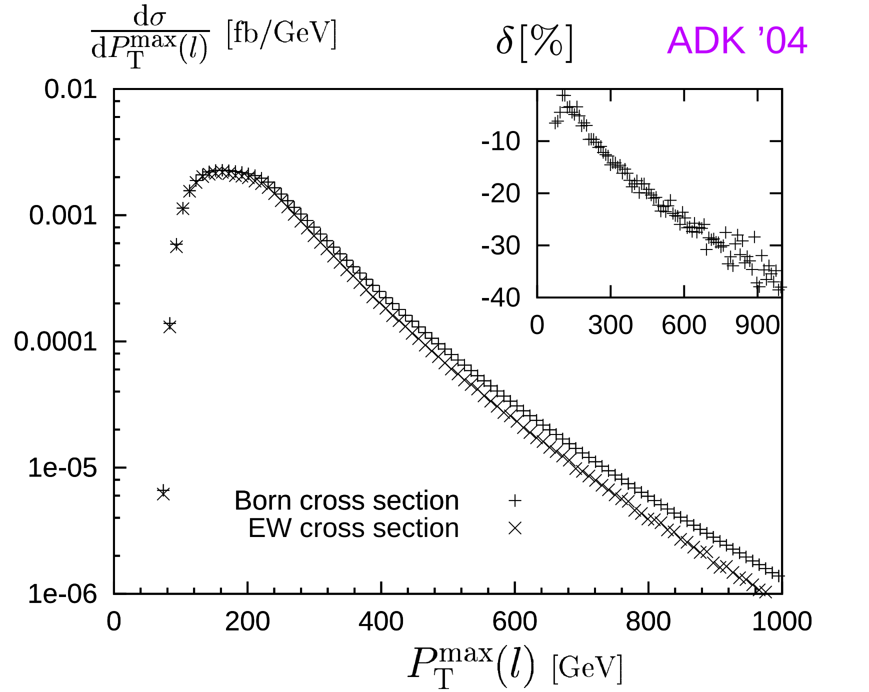
  $\hookrightarrow\ \delta \sim -20\%$ for $M_{\gamma\mathrm{Z}} \lesssim 2\,\mathrm{TeV}$

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

  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

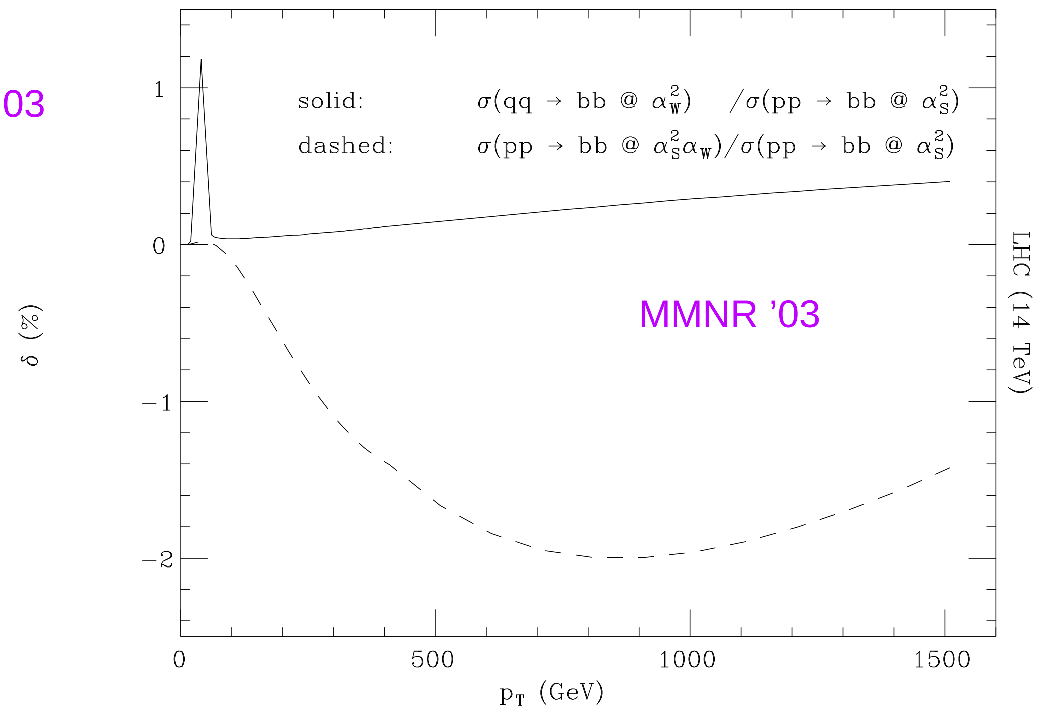
- $\mathrm{pp} \to \mathrm{t\bar{t}} + X$
  - ◇ weak $\mathcal{O}(\alpha)$ correction to σ_{tot} Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth '94

    $\delta_{\mathrm{weak}} \sim$ 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

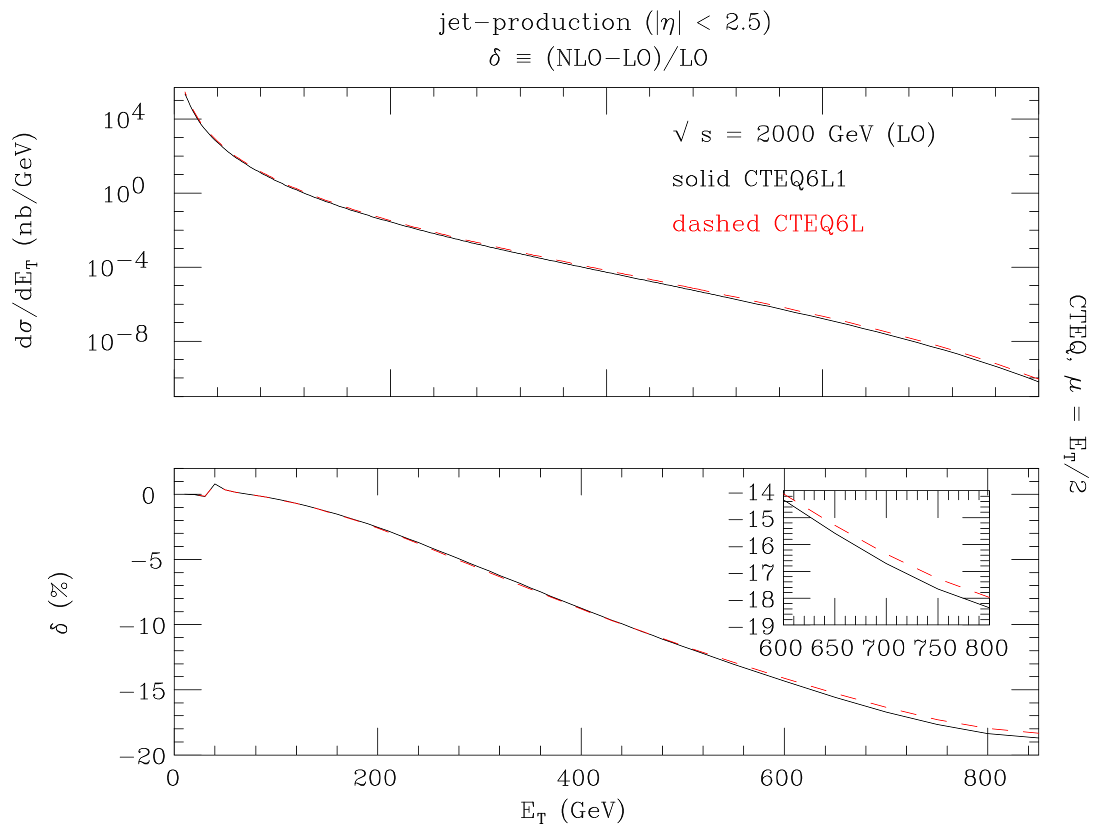


EW corrections to jet production

- high-E_T jets at Tevatron

  Moretti, Nolten, Ross ’05

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



Conclusions

My personal list of realistic (theoretical) goals for the workshop:

- Assess as accurately as possible the uncertainties affecting standard candles. Give a compact set of results, and indicate the theoretical approximations involved
- Come up with a list of badly needed NLO results, and start computing them, possibly with numerical techniques
- Understand where EW corrections are most relevant, and combine them with QCD corrections if possible
- Various improvements in Monte Carlos
- Find processes/observables suitable for small-x studies