High precision QCD at hadron colliders

New techniques and results for perturbative calculations

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Outline

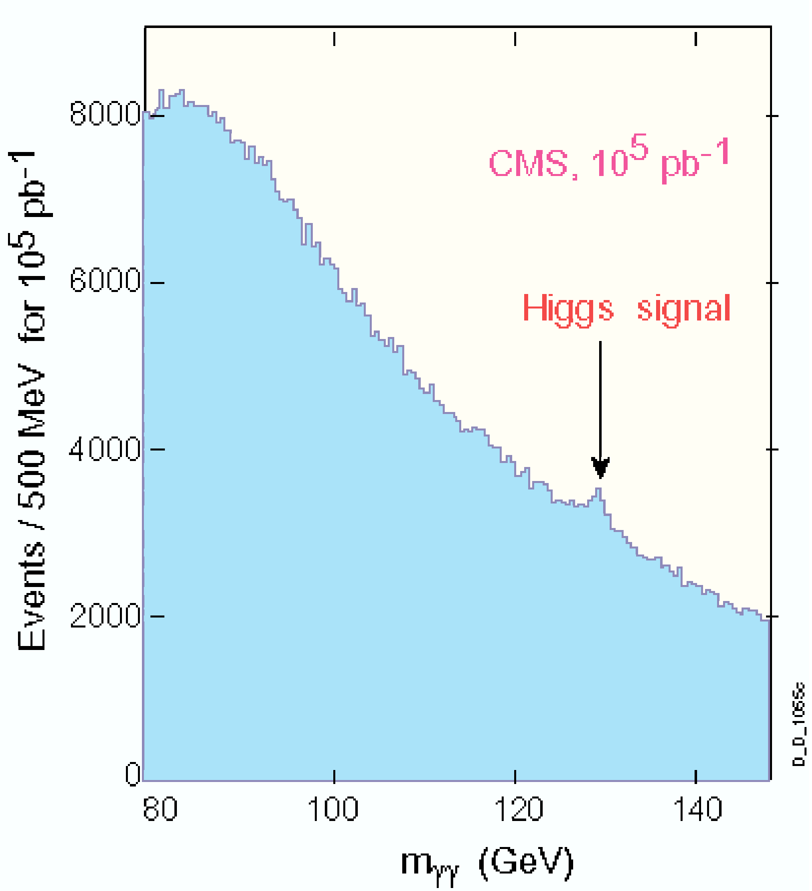
- Motivation and introduction
- Status of LO and NLO calculations
- Progress in NNLO calculations
  - Understanding infrared divergences at NNLO
    - "Semi-inclusive" observables and Drell-Yan rapidity distributions
    - An IR solution at NNLO and Higgs production at the LHC
- Conclusions and outlook

Experimental prospects

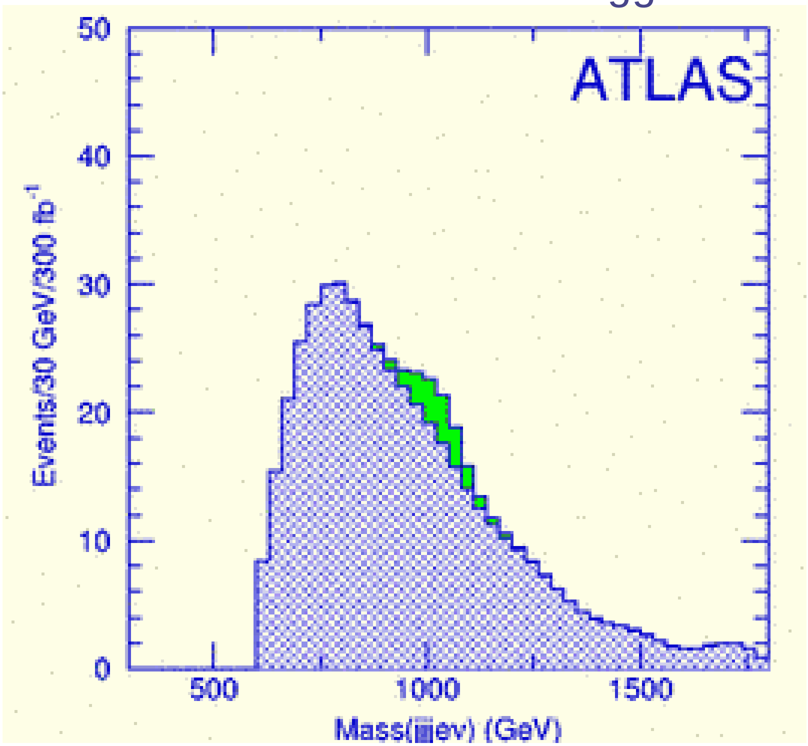
- Precision physics at colliders: past, present, future
  - At LEP, SLC
    - Precision EW data a primary constraint on new physics models
  - At the Tevatron
    - Expect $2 - 10\,\mathrm{fb}^{-1}$ by LHC turn-on
    - Reduction of Δm_t, ΔM_W by 50%
  - At the LHC
    - In 1 year at $10\,\mathrm{fb}^{-1}$: over 10^7 $W, Z, t\bar{t}$ events $\Rightarrow$ $\Delta\sigma_{stat} \ll 1\%$
    - Improved systematics (j, l energy scales, luminosity) from high statistics samples
  - LHC measurements are systematics limited

$\Rightarrow$ expect percent level physics

The need for high precision



$T \to th$ in Little Higgs



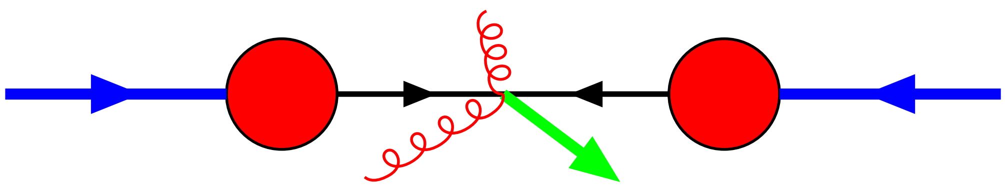
Hinchliffe

- Not all discovery channels produce dramatic signatures!
- Need control of distribution shapes, backgrounds, uncertainties, . . .
- Measurement of EW parameters, PDFs, luminosity, new physics parameters all require theory input

Precision QCD

- Everything at hadron colliders involves QCD!
- Factorization in hadronic collisions

$$N_{events} = L \int f_i(x_1, \mu^2)\, f_j(x_2, \mu^2)\, \sigma_{ij}(x_1, x_2, \mu^2)$$



  - luminosity measurement
  - parton distribution functions
  - scattering cross sections

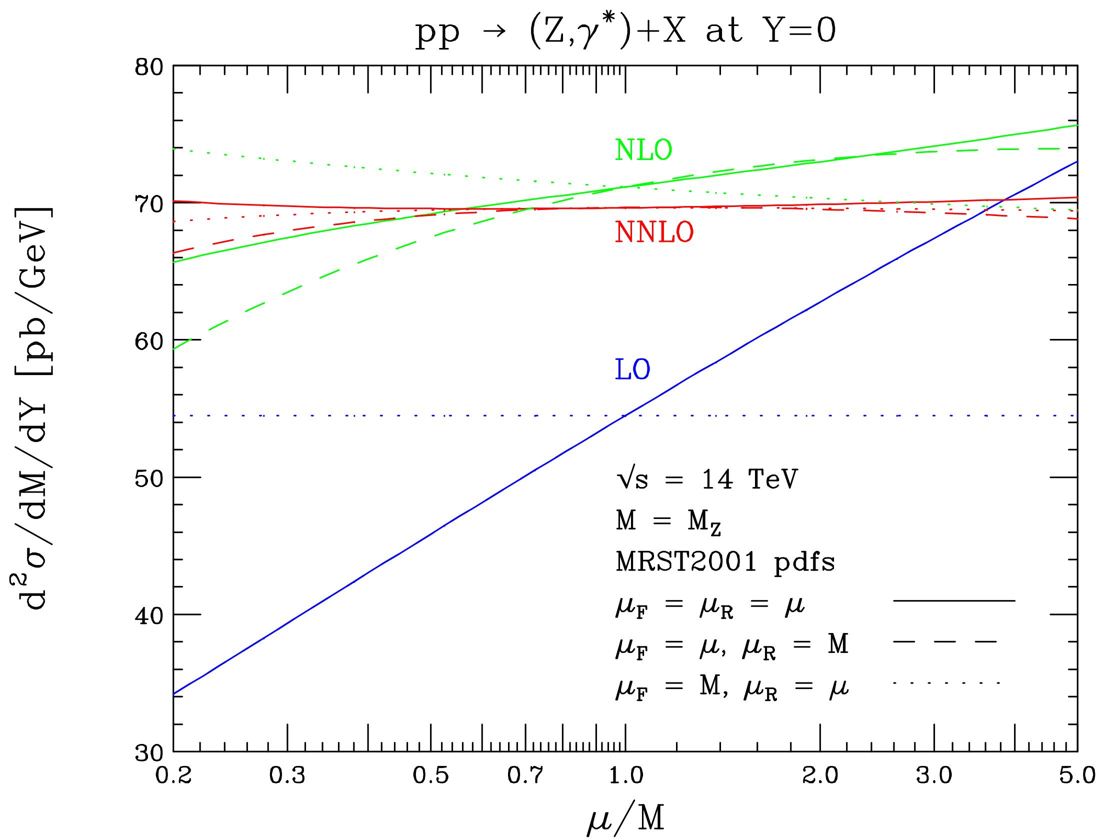
Cross sections in QCD

$$\sigma = \sigma_0 \left\{1 + \alpha_S \left(l + \sigma_1\right) + \alpha_S^2 \left(l^2 + l + \sigma_2\right) + \mathcal{O}(\alpha_S^3)\right\}$$

- Strong coupling constant not small
  - $\alpha_S(M_Z) \approx 0.12 \Rightarrow$ higher order corrections important
- Contains scales $l = \ln(\mu^2/Q^2)$
  - Get scales from UV and IR renormalization
  - Scales are arbitrary: $\frac{d\sigma}{d\mu} = 0$

  $\Rightarrow$ but truncation of expansion at $\mathcal{O}(\alpha_S^n)$ induces a scale dependence of $\mathcal{O}(\alpha_S^{n+1})$
  - Residual scale dependences provide estimate of neglected higher order effects
- Resummation needed in phase-space corners
- Matching with parton-showers (HERWIG, PYTHIA)

From LO to NNLO



- Precision predictions at NNLO
- Also miss qualitative effects at lower orders
  - Few initial channels open; sensitivity to pdfs underestimated
  - Few jets in final state
  - Jets modeled by too few partons
  - Incorrect kinematics, e.g., no p_T

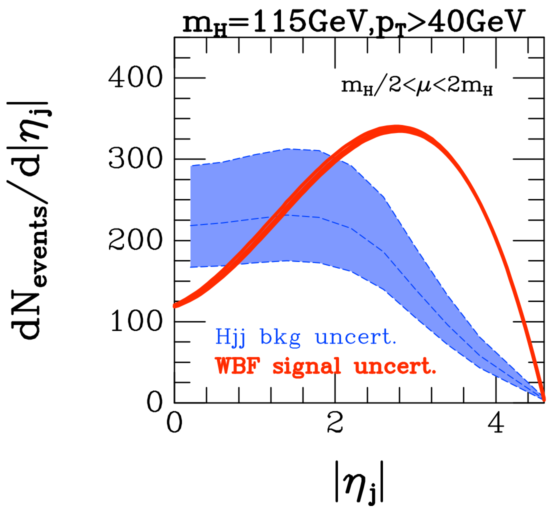
Anastasiou, Dixon, Melnikov, FP

Progress at LO

- Efficient algorithms for multi-parton amplitudes known
  - Use spinor helicity, color-ordering for amplitudes
  - Need efficient phase-space generation; 20 variables describe final-state
  - Automation achieved: ALPHGEN, COMPHEP, GRACE, HELAC, MAGRAPH, VECBOS (Mangano et.al.; Boos et.al.; Minami-Tateya coll.; Papadopoulos et.al.; Steltzer et.al.; Giele et.al.)
  - Programs available for:
    - $W/Z/\gamma + N\,\mathrm{jets}, N \leq 6$
    - $W/Z/\gamma + Q\bar{Q} + N\,\mathrm{jets}, N \leq 4$
    - $Q\bar{Q} + N\,\mathrm{jets}, N \leq 4$
    - $Q_1\bar{Q}_1Q_2\bar{Q}_2 + N\,\mathrm{jets}, N \leq 2$
    - $Q\bar{Q}H + N\,\mathrm{jets}, N \leq 3$
    - $nW + mZ + kH + N\,\mathrm{jets}, n + m + k + N \leq 8, N \leq 2$
    - $N\,\mathrm{jets}, N \leq 8$

Progress at NLO

- Many Higgs signal processes recently computed to NLO
  - $pp \to t\bar{t}H, b\bar{b}H$: Beenaker et.al.; Dawson et.al.
  - $pp \to jjH$ (WBF): Figy et.al; Berger, Campbell
- Matching to experimental Monte Carlos known: MC@NLO (Frixione, Webber)
- Programs available for $2 \to 2$ and some $2 \to 3$ processes: DIPHOX, HQQB, JETRAD, MCFM, NLOJET++ (Aurenche et.al.; Dawson et.al.; Giele et.al.; Campbell, Ellis; Nagy)
  - Missing many needed background processes:
  - No automation for $2 \to 3, 4$ virtual corrections (Giele et.al.; Nagy, Soper; Binoth et.al.)
  - Want flexible approach for LHC analyses
    - Many scales
    - Enormous expressions
    - Numerical instabilities
  - Much work needed before LHC!



Berger, Campbell

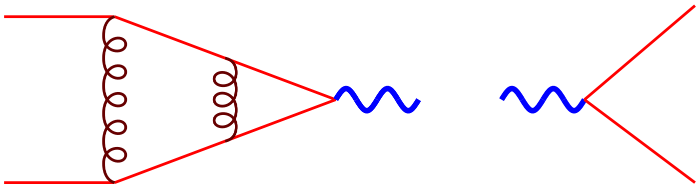
The NNLO revolution

- Tremendous progress recently in NNLO computations
  - New computational techniques developed
  - Many new phenomenological results
- Is NNLO necessary?
  - Reduced scale dependence
  - More partons $\Rightarrow$ more realistic
  - Several concrete physical applications that require NNLO:
    - Higgs production at hadron colliders
    - Drell-Yan (luminosity monitor, PDF measurements)
    - Jet production at hadron colliders (PDFs, α_S extraction)
    - Jet production at e^+e^- colliders

$$\alpha_S(M_Z) = 0.1202 \pm 0.0003(\mathrm{stat}) \pm 0.0009(\mathrm{sys}) \pm 0.0009(\mathrm{had}) \pm 0.0047(\mathrm{th})$$

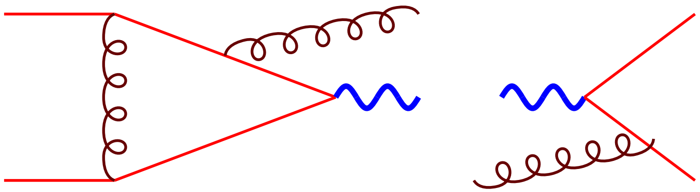
Anatomy of a NNLO calculation

- Virtual-Virtual



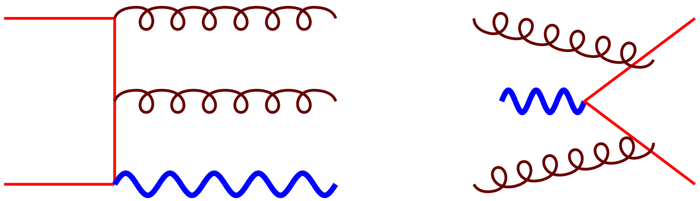
+ 100 terms

- Real-Virtual



+ 300 terms

- Real-Real



+ 500 terms

$\Rightarrow$ Need clever algorithms to handle!

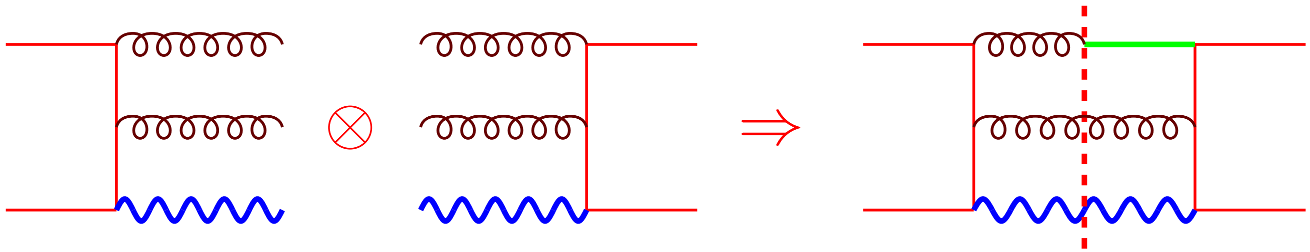
Calculations at NNLO

- Loop integrals satisfy recurrence relations arising from Poincare invariance
  - Reduce to a small set of master integrals: efficient, automated algorithms available
  - Calculate the master integrals; known for many $2 \to 2$ processes
- Real radiation is currently the sticking point
  - Until recently, only fully inclusive results known for Drell-Yan, Higgs
  - $\Rightarrow$ can't include experimental cuts, jet algorithms
- Tree graphs, so what's the problem?
  - Understanding IR singular structure when partons become unresolved
  - Recurrence relations, other algorithms, don't seem applicable, especially when phase-space constraints included
  - No apparent way of automating real radiation calculation
  - Problems with extracting IR singular structure before numerical integration

Methods for real radiation

- Semi-inclusive observables
  (Anastasiou, Dixon, Melnikov, FP)
  - Basic idea: use optical theorem to adapt multi-loop techniques to phase-space integrals

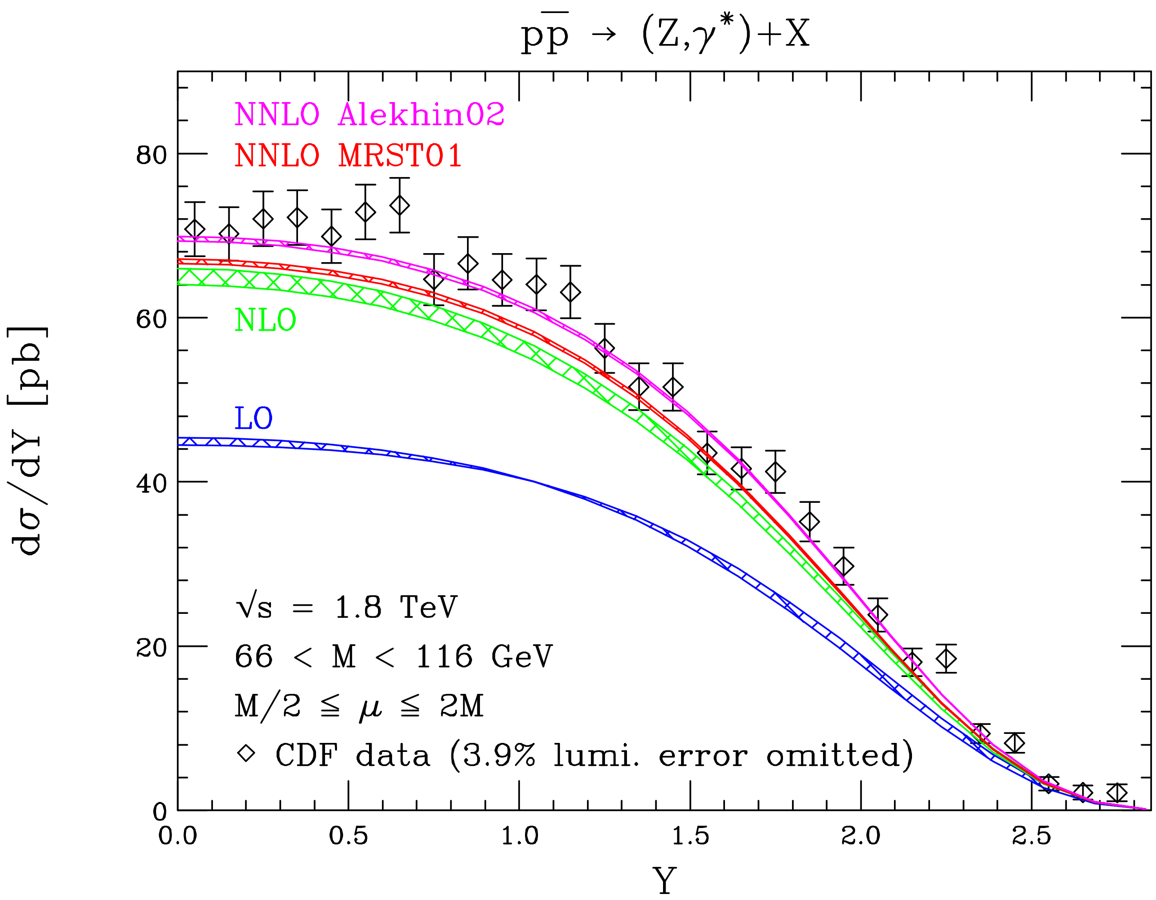
  $\Rightarrow$ Introduce a fictitious particle, whose mass-shell constraint $\Leftrightarrow$ phase-space constraint



  - Loop integral methods now permit analytic calculations
- Fully differential observables
  (Anastasiou, Melnikov, FP)
  - $\mathrm{d}\Phi_n$ structure permits an automated structure of IR divergences
  - Derive cross-section as series in $1/\epsilon$; cancel poles numerically
  - No need for analytic integrations, automatically finds singular regions

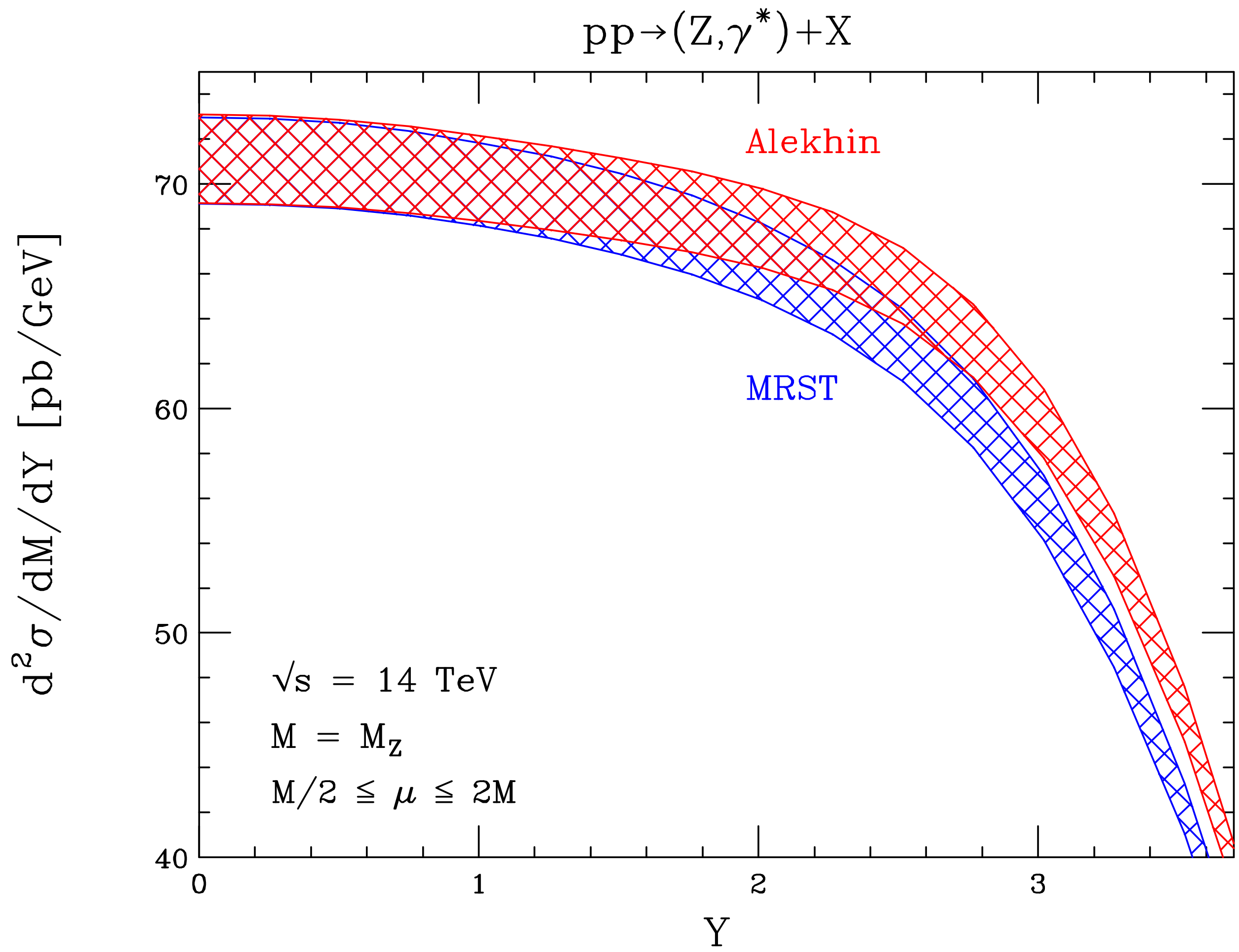
Drell-Yan rapidity distributions

- Used for pdf extraction, luminosity monitor



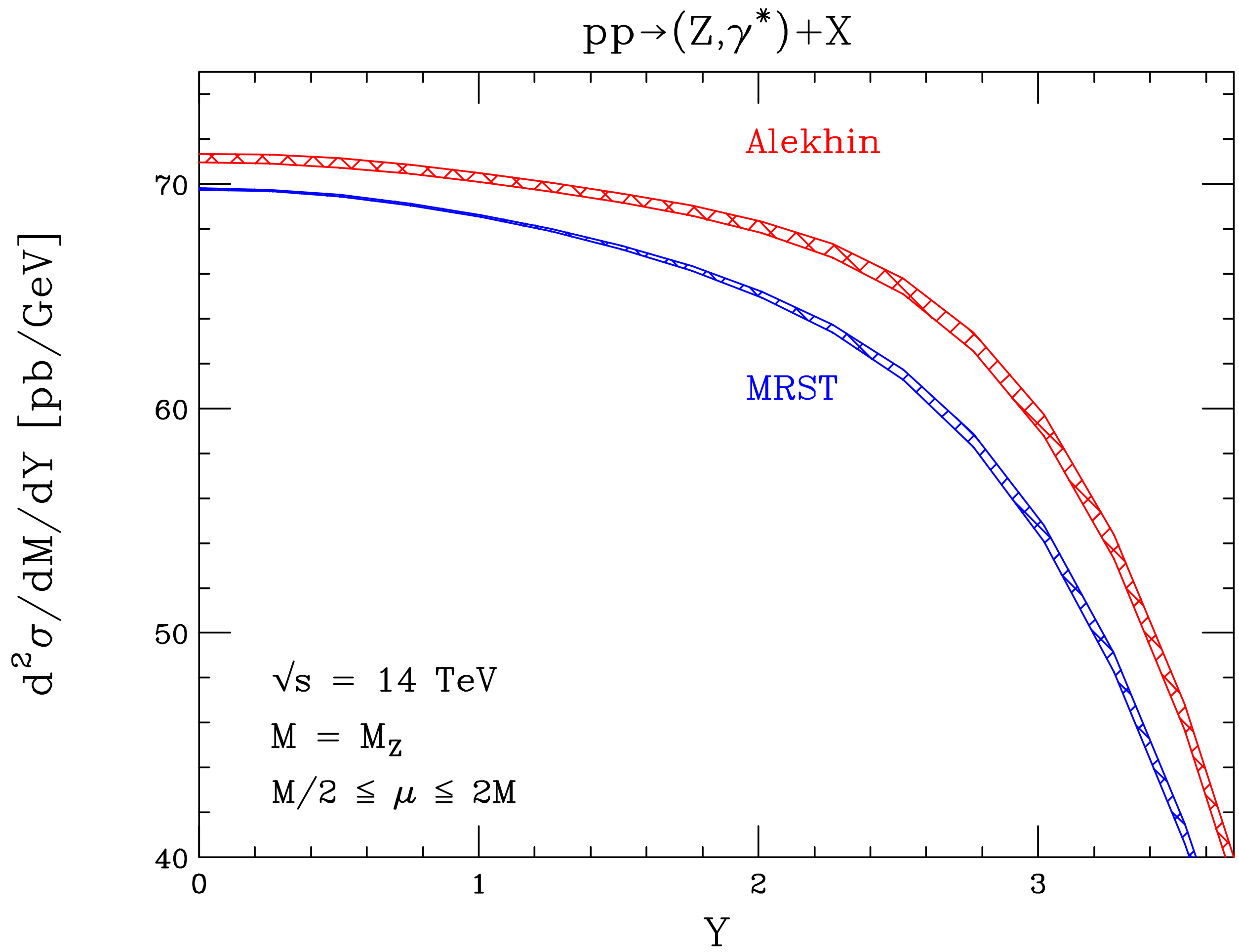
- NNLO corrections increase NLO result by 3-5%
- Scale variations 3-6% at NLO, $< 1\%$ at NNLO
- Drell-Yan now a high precision probe of QCD

PDF comparisons



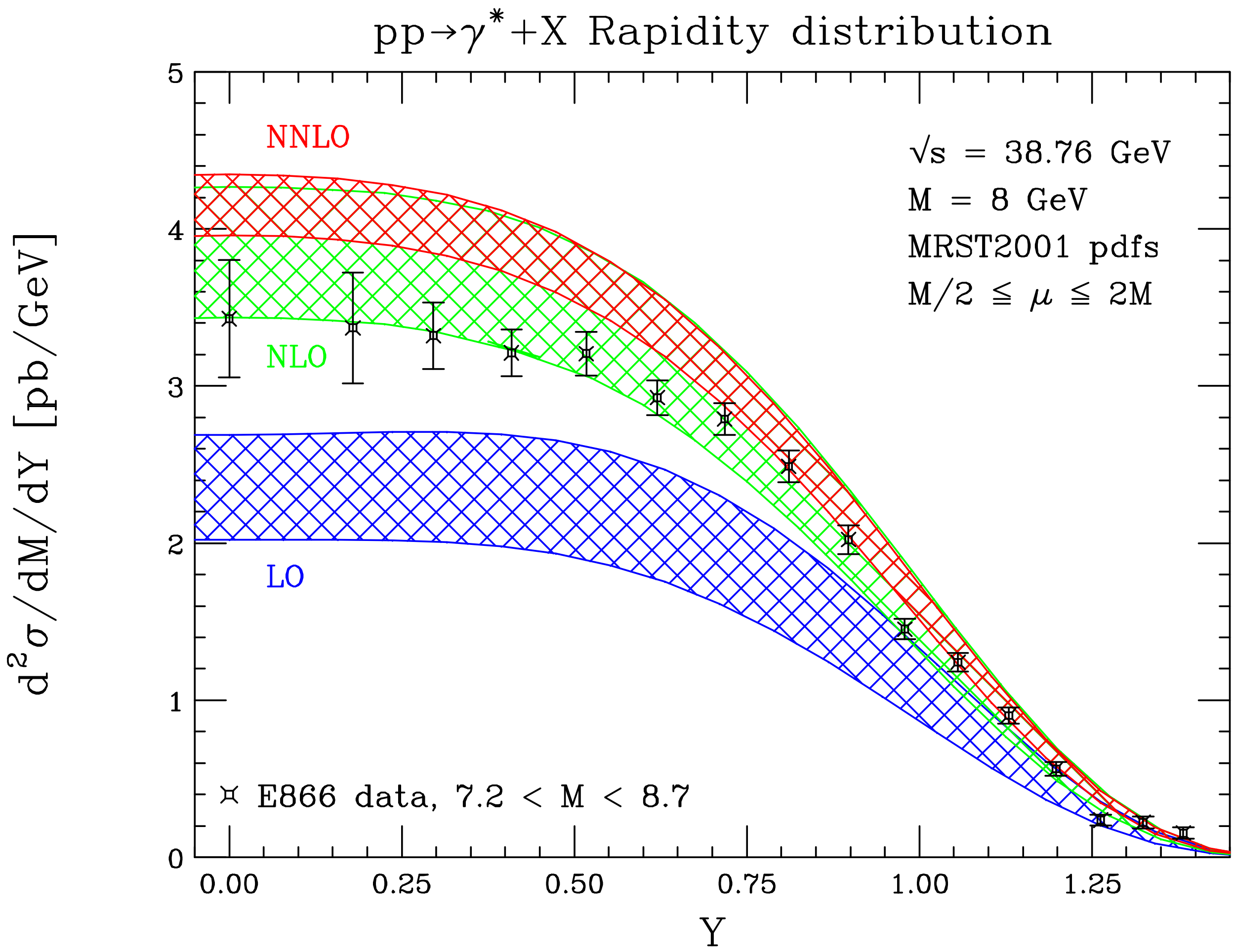
- Alekhin parameterization fits only to DIS data; MRST fits to DIS, DY, jets
- Scale variations render undistinguishable at NLO

PDF comparisons



- Alekhin parameterization fits only to DIS data; MRST fits to DIS, DY, jets
- Scale variations render undistinguishable at NLO
- Resolved at NNLO

Fixed target DY (E866)

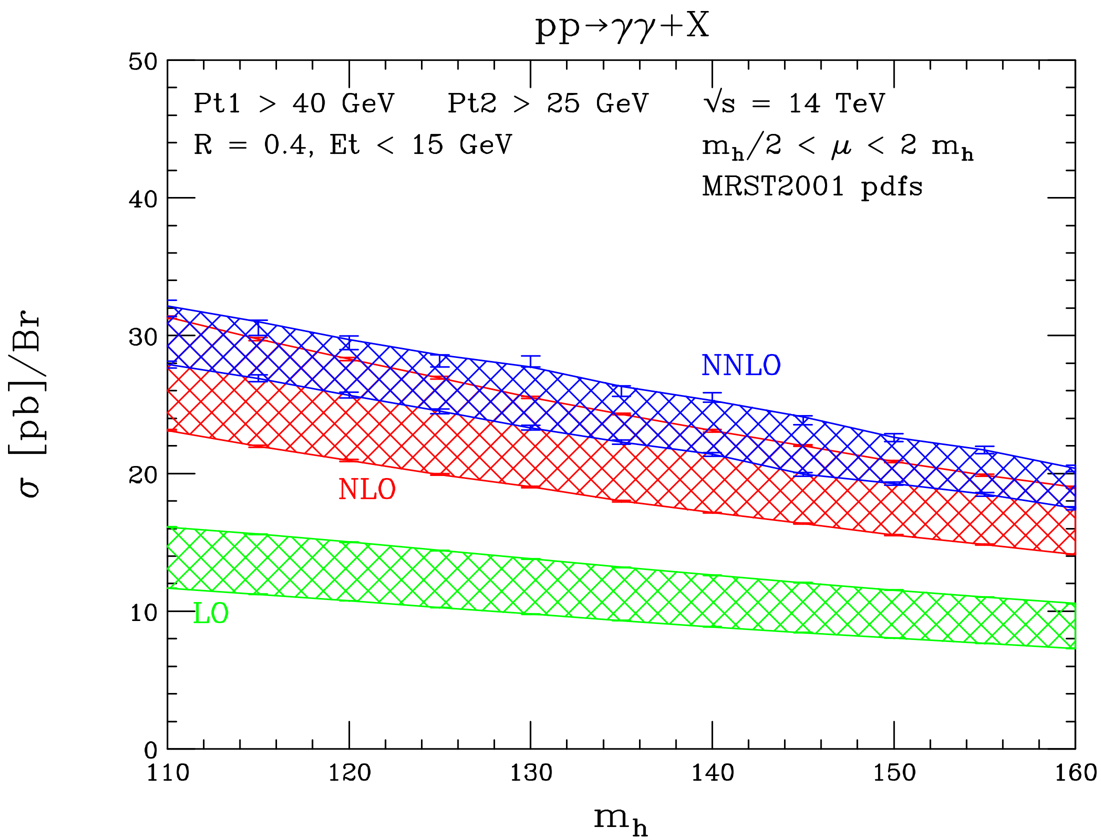


- Strong constraint on $\bar{q}$ and $x \to 1$ q_{val} distribution functions
- Reduced μ dependence at NNLO reveals discrepancy with data

$\Rightarrow$ Tune $\bar{q}$ pdfs

Fully differential Higgs signal at NNLO

- Study full decay chain $pp \to H + X \to \gamma\gamma + X$ at NNLO

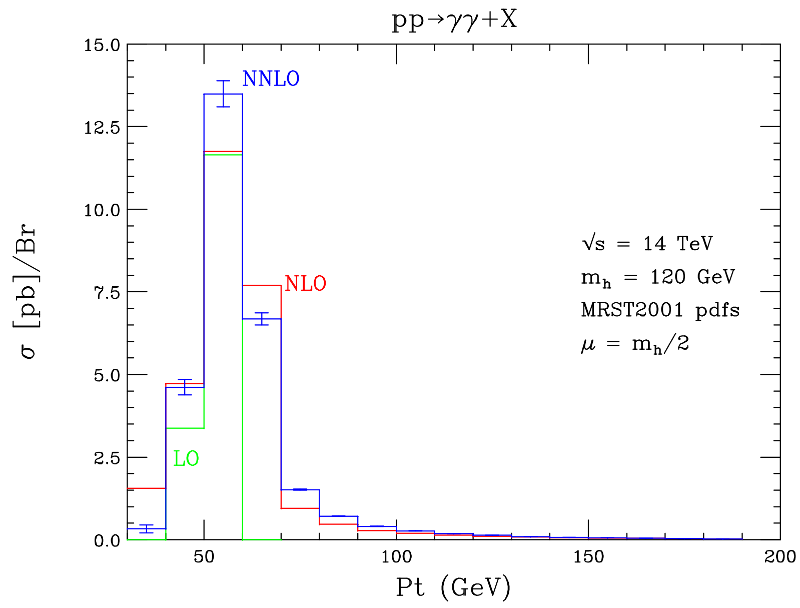


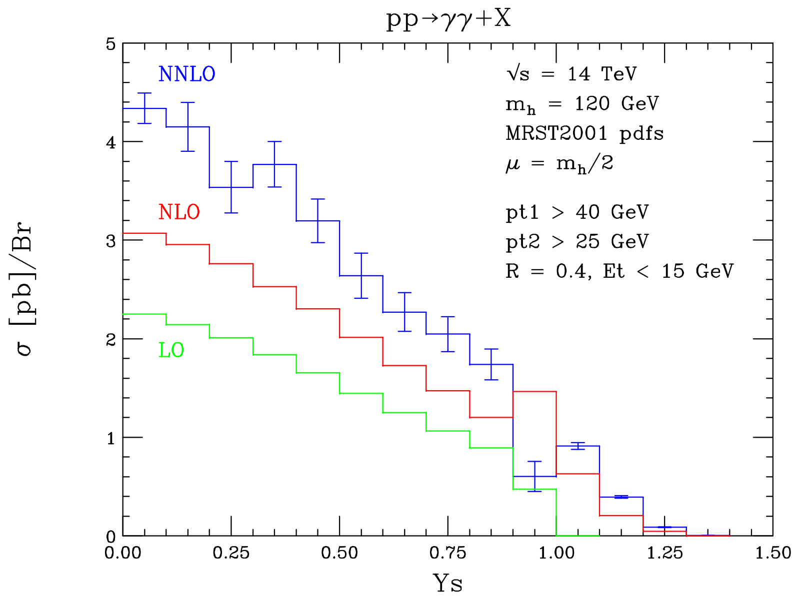
- $\sigma_{\mathrm{cut}}/\sigma_{\mathrm{inc}} \approx 0.55 - 0.70$
- $K_{\mathrm{cut}}/K_{\mathrm{inc}} \approx 1.02 - 1.08$
- Can study $H \to WW, ZZ, \ldots$
- Can simulate Higgs signal at NNLO with all experimental cuts

- All ATLAS experimental cuts included
  - $p_\perp^{\gamma,1} > 40$ GeV, $p_\perp^{\gamma,1} > 25$ GeV; $|\eta^\gamma| < 2.5$
  - Isolation cut: $E_\perp < 15$ GeV within cone of $R = 0.4$

Di-photon distributions

- Photonic η and p_T distributions can be used to discriminate between signal and background





- $p_t = (p_\perp^{\gamma,1} + p_\perp^{\gamma,2})/2$; $Y_s = |\eta^{\gamma,1} - \eta^{\gamma,2}|/2$
- p_t background distribution has no peak at $m_h/2$
- Y_s background distribution is flat (Bern, Dixon, Schmidt)
- Shapes are stable under perturbative corrections

Lessons

- We know how to handle IR singular structure at $\mathrm{N^nLO}$
- It's possible to perform NNLO calculations with all experimental cuts included
- Many applications now possible
  - Fully differential Drell-Yan
  - Jet production at hadron colliders
  - Radiative W decays
  - Top decays
  - $b \to c$, $b \to u$ transitions

Conclusions

- Exciting prospects for precision physics at future colliders
- Need theoretical work to fully utilize results
- Much more to do before LHC start
- Expect continued progress on several fronts
  - Quantification and reduction of pdf errors
  - Practical implementations of algorithms for NLO calculations
  - More completely differential NNLO calculations for high-value observables ($W, Z, H, \ldots$)
- Lots of room for new ideas!