QCD: Theoretical Developments

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Lepton Photon 2003

QCD

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- QCD today is becoming precision physics

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LEP precision physics:

Electroweak processes

Tevatron/LHC precision physics:

QCD processes

QCD

Precision physics with QCD

- precise determination of
  - strong coupling constant
  - quark masses
  - electroweak parameters
  - parton distributions
  - LHC luminosity (!)

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- precise determination of
  - strong coupling constant
  - quark masses
  - electroweak parameters
  - parton distributions
  - LHC luminosity (!)
- precise predictions for
  - new physics effects
  - and their backgrounds

Theoretical challenges in QCD

- QCD describes quarks and gluons; experiments observe hadrons
  - describe parton $\longrightarrow$ hadron transition (fragmentation)
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  - important higher order corrections

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  - frequent multiparticle final states
  - important higher order corrections
- observables involve different scales

$$m_Q, p_T, M_Z, m_T$$

$\longrightarrow$ large logarithms e.g. $\ln(p_T^2/M_Z^2)$

  - reorder (resum) perturbative series

Outline

- Heavy Quarks
- Jets and Multiparticle Production
- Photons
- Gauge and Higgs Bosons

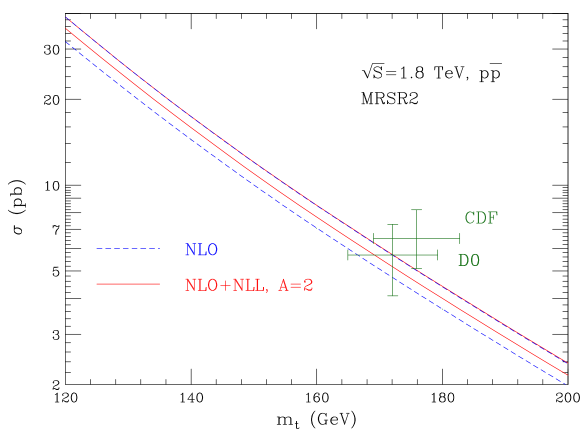
Heavy Quarks

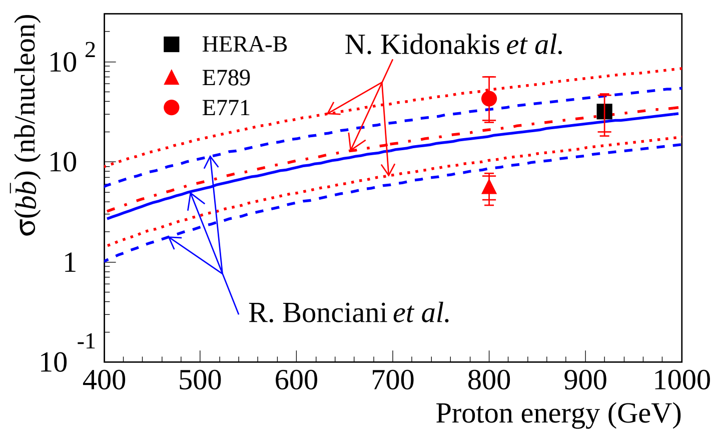
Heavy Quarks

Total cross sections

status: NLO + NLL soft gluon resummation

W. Beenakker et al., R. Bonciani, S. Catani, M. Mangano, P. Nason
N. Kidonakis, E. Laenen, S. Moch, R. Vogt





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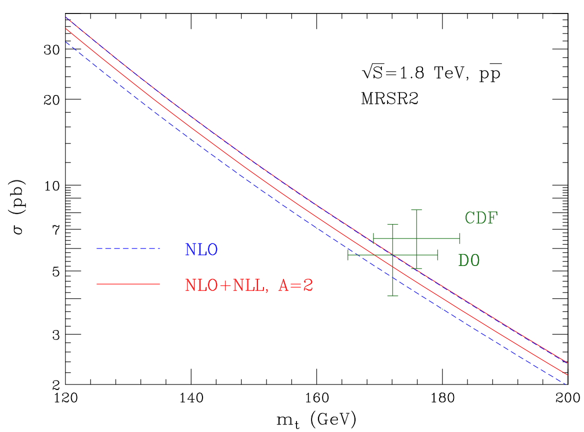

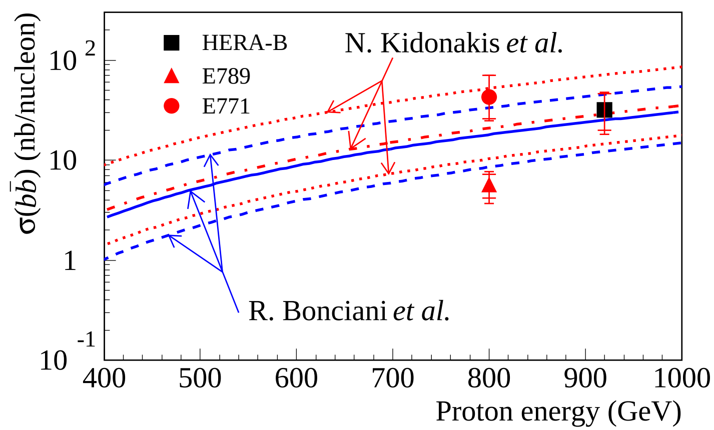

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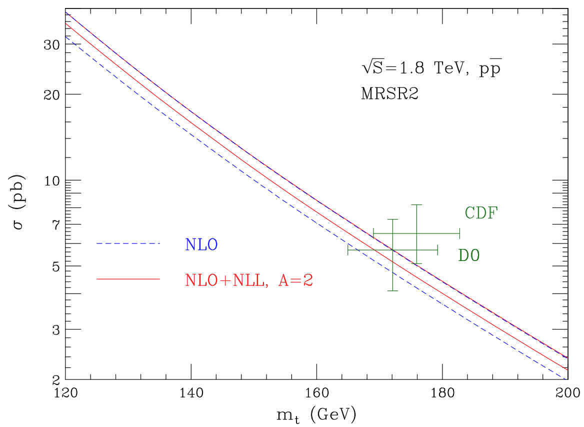

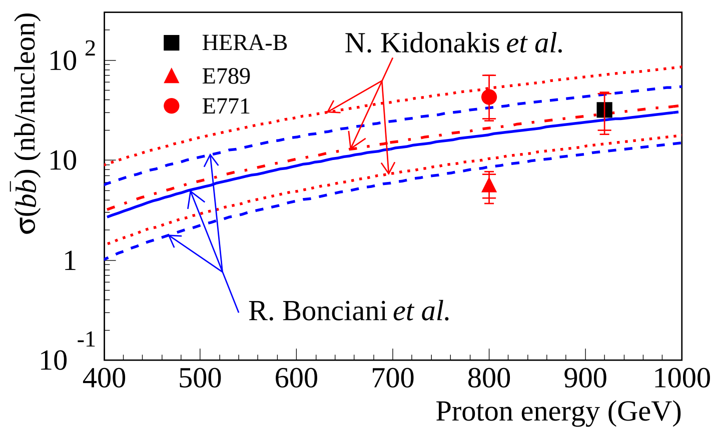

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- Soft gluon resummation enhances cross section and lowers theoretical uncertainty
- Theoretical uncertainty lower for $t\bar{t}$ than for $b\bar{b}$: $\alpha_s(m_b) \gg \alpha_s(m_t)$, $q\bar{q}$ dominance at Tevatron and gg dominance at HERA-B

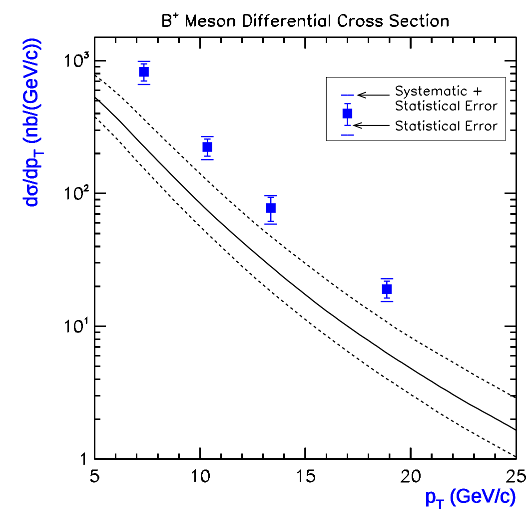
Heavy Hadron Production

Differential distributions

long-standing excess of b-quark transverse momentum

distributions in $p\bar{p}$, γp, $\gamma\gamma$

measured final state: B hadrons, e.g. CDF: $B^{\pm}$



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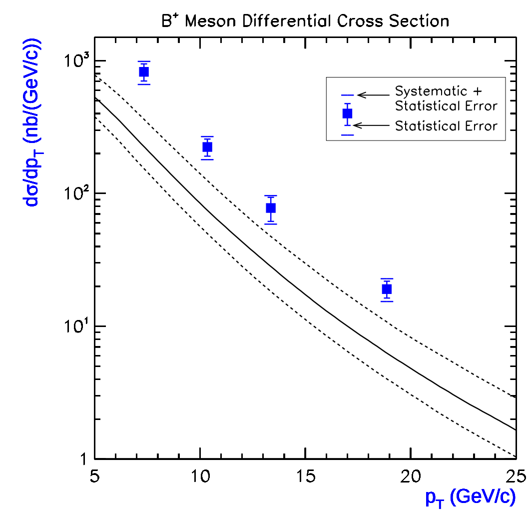


Theoretical prediction:

$$\frac{\mathrm{d}\sigma^{B^{\pm}}}{\mathrm{d}p_T} = f_{a/p} \otimes f_{b/\bar{p}} \otimes \frac{\mathrm{d}\sigma^{ab\to b\bar{b}}}{\mathrm{d}p_T} \otimes D_{b\to B^{\pm}}$$

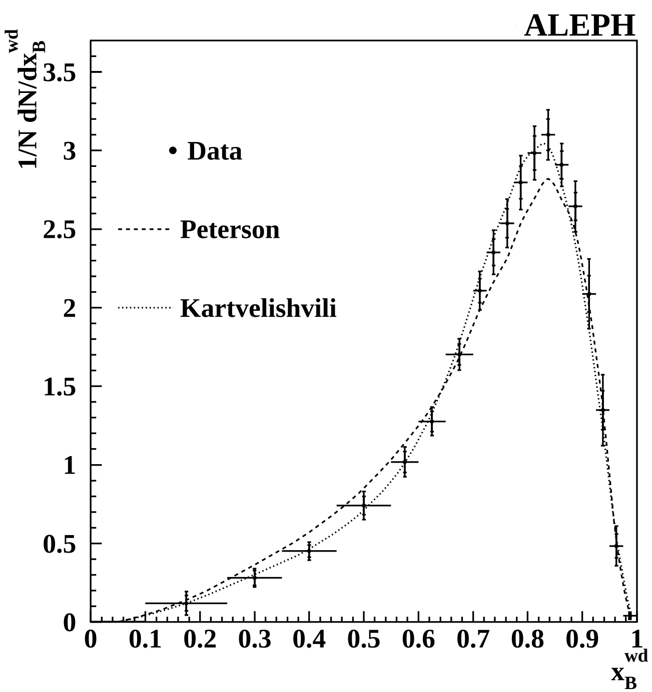
$f_{a/p}$: parton distribution function

$D_{b\to B^{\pm}}$: fragmentation function

Heavy Hadron Production

Fragmentation Functions

Extraction of $D_{b \to B^\pm}$ from LEP data on B meson spectra: many ambiguities



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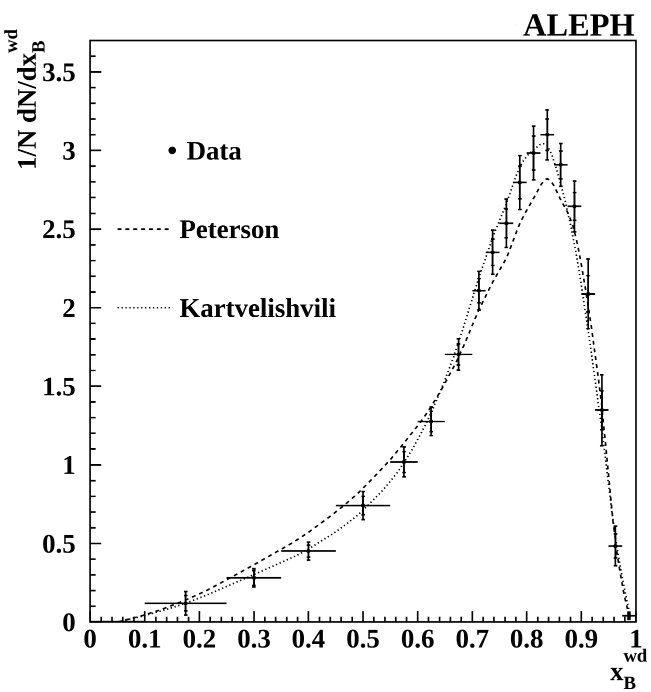

- order of perturbative calculation
- massless or massive hard matrix elements
- resummation of perturbative terms
- inclusion of power corrections $\mathcal{O}(\Lambda/m)$
  M. Cacciari, E. Gardi
- data corrected with parton showers ?
- parametric form of $D_{b \to B^\pm}$: e.g. Peterson:

$$D_{b \to B^\pm}(z, \mu_0) = N \frac{x(1-x)^2}{[(1-x)^2 + \epsilon x]^2}$$

fit ϵ, N

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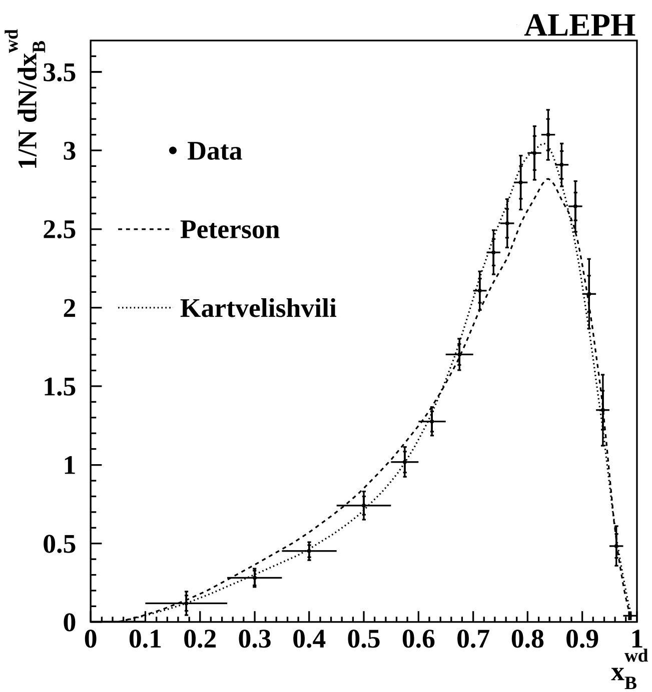

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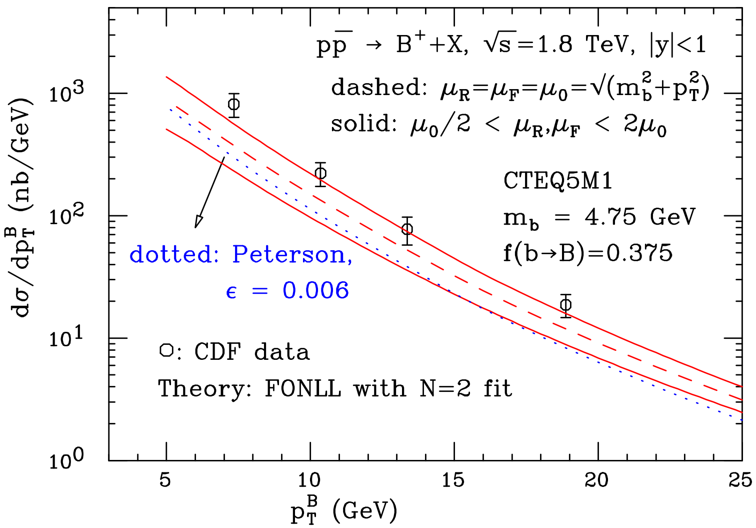
Prediction for $p\bar{p}$ must use same assumptions as made in the extraction from e^+e^-

Heavy Hadron Production

Resummation of $\ln(m_b^2/p_T^2)$ and $\ln(m_b^2/s)$

M. Cacciari, P. Nason



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- done in moment space to expose information content relevant to $p\bar{p}$
- use of the resummed (FONLL) scheme enhances transverse momentum spectrum

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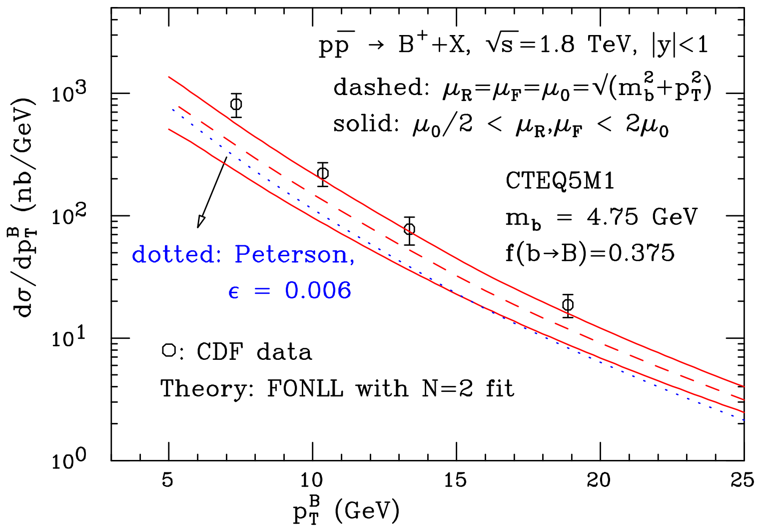
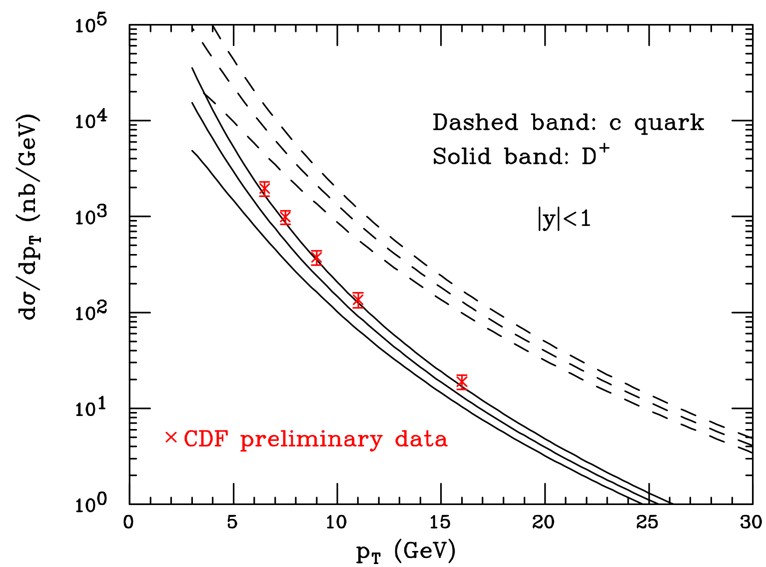


recently extended to D hadrons:
considerable improvement between data and theory



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- higher precision measurements (Tevatron-Run II, LHC) will require NNLO corrections

Jets and Multiparticle Production

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QCD jet final states very frequent at colliders

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- sensitive probe of standard model parameters
  - measure α_s from $e^+e^- \to 3j$, $ep \to (2+1)j$, $pp \to j + X,\ 2j + X$
  - measure M_W, M_Z from $pp \to V + X,\ V + j + X$

$\longrightarrow$ want QCD prediction as precise as possible

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$\longrightarrow$ want QCD prediction as precise as possible

- multijet final states frequent: $pp \to nj \sim \alpha_s^n$
  - important background for searches

$\longrightarrow$ want robust QCD prediction as guidance

$\longrightarrow$ also might want QCD to predict the full hadronic final state

Jets and Multiparticle Production

State-of-the-art: leading order

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State-of-the-art: leading order

- several efficient codes available for multiparton matrix element generation (from helicity amplitudes or fully numerically): $2 \to 8$ and beyond feasible on current computers
  - VECBOS W. Giele
  - COMPHEP E. Boos et al.
  - MADGRAPH T. Stelzer et al.
  - GRACE Minami–Tateya Group
  - HELAC C. Papadopoulos et al.
  - ALPHGEN M. Mangano et al.
  - AMEGIC++ F. Krauss et al.
- combined with automatic integration over multiparticle phase space
  - RAMBO R. Kleiss et al.
  - PHEGAS C. Papadopoulos
  - MADEVENT T. Stelzer et al.

Jets and Multiparticle Production

State-of-the-art: leading order

- generic procedure to interface partonic final state with parton shower:
  modified matrix element plus vetoed parton shower
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Leading order QCD is good tool to estimate relative magnitudes of processes and to design searches. Once precision is required (e.g. to identify a discovery with a particular model), it is not sufficient.

Jets and Multiparticle Production

State-of-the-art: next-to-leading order (NLO)

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- nature of calculations: parton level Monte Carlo integrator

Jets and Multiparticle Production

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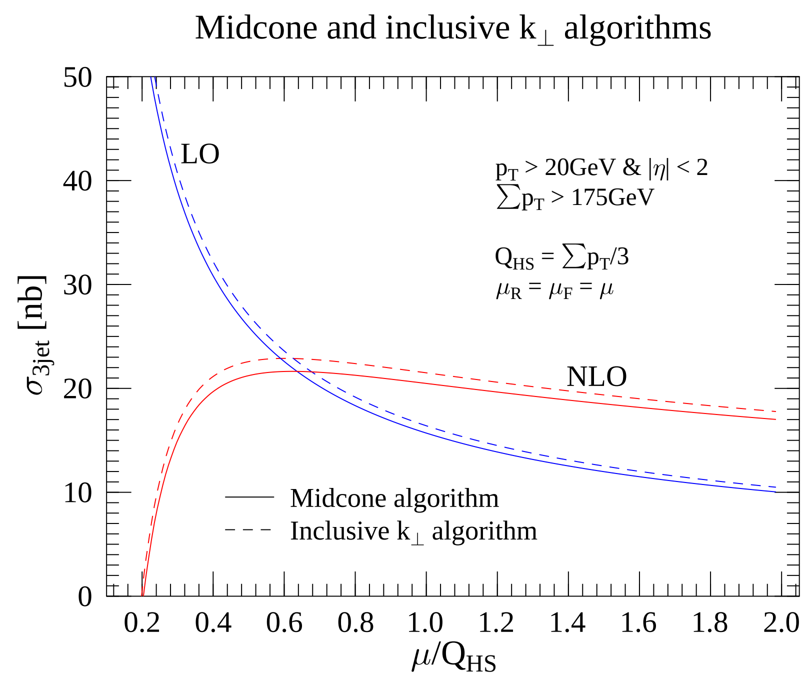
recent results

- $pp \to V + 2j$
  J.M. Campbell, R.K. Ellis
- $ep \to (3+1)j$
  Z. Nagy, Z. Trocsanyi
- $pp \to 3j$
  Z. Nagy
- $pp \to t\bar{t}H$
  W. Beenakker, S. Dittmaier, M. Krämer, B. Plumper, M. Spira, P. Zerwas
  S. Dawson, L. Orr, L. Reina, D. Wackeroth
- $pp \to H + 2j$
  C. Oleari, D. Zeppenfeld



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  - virtual one-loop matrix element n partons
  - real matrix element $n+1$ partons
  - procedure to extract infrared singularities from both and to combine them
- last two points solved for arbitrary n some time ago
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- no generic procedure for automatic computation of one-loop integrals
- but many ideas (CERN workshop MC for LHC)
  - analytic reduction of hexagon integrals T. Binoth, J.P. Guillet, G. Heinrich
  - subtraction formalism for virtual corrections Z. Nagy, D. Soper
  - numerical evaluation of hexagon amplitudes
    T. Binoth, N. Kauer

Interfacing NLO calculations with parton showers

MC@NLO approach

S. Frixione, B. Webber

- introduces modified NLO subtraction method
- modified real and virtual contributions become initial conditions for parton shower

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- avoids double counting
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- hard radiation from NLO matrix element
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- NLO result explicitly recovered from expansion
- so far applied to VV, $b\bar{b}$, $t\bar{t}$
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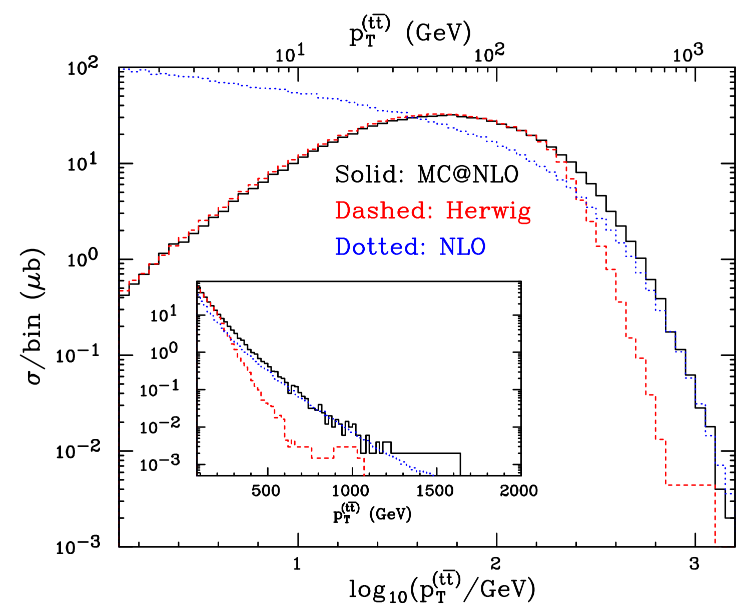
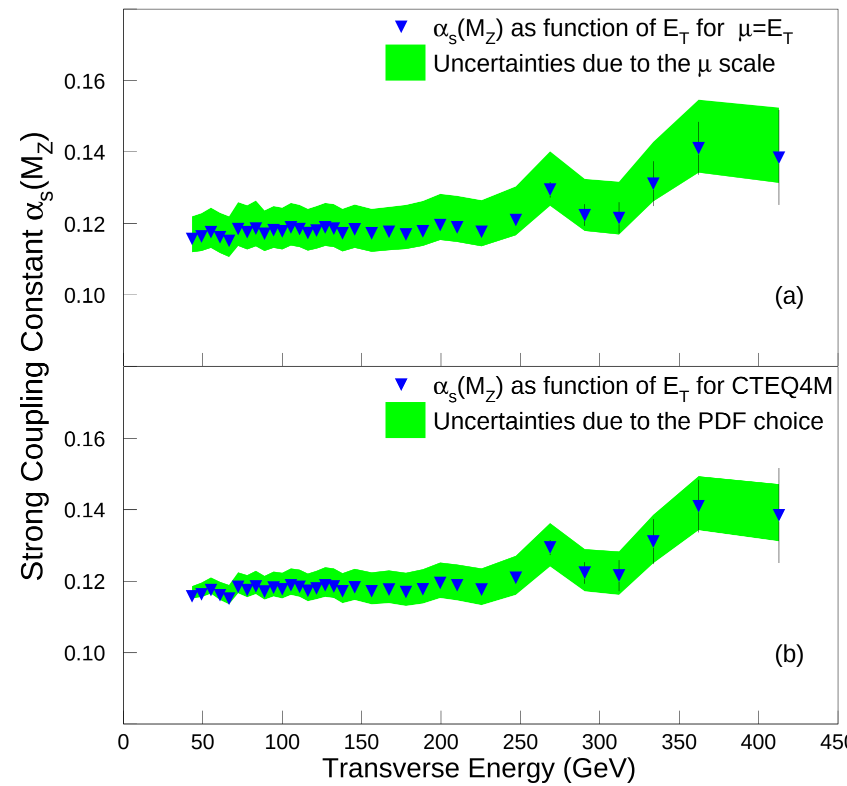


NLO jet physics precise enough ?

Measurement of strong coupling constant α_s from single jet inclusive cross section

CDF collaboration



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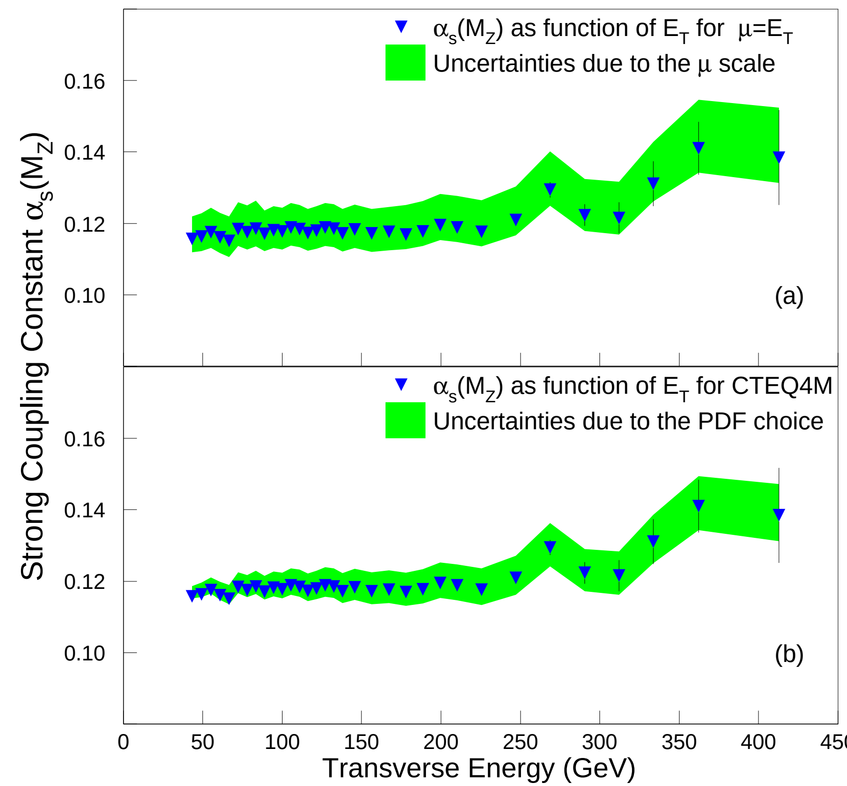

$$\alpha_s(M_Z) \;=\; 0.1178 \pm 0.0001(\text{stat})^{+0.0081}_{-0.0095}(\text{sys})$$
$$^{+0.0071}_{-0.0047}(\text{scale}) \pm 0.0059(\text{pdf})$$

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Does NLO do a better job in describing e^+e^- or ep jet physics ?

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- 3-jet type observables at LEP (preliminary)

$$\begin{aligned}\alpha_s(M_Z) &= 0.1202 \pm 0.0003(\text{stat}) \pm 0.0009(\text{sys}) \\ &\pm 0.0009(\text{had}) \pm 0.0047(\text{scale})\end{aligned}$$

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- (2+1) jet observables in DIS at HERA

$$\alpha_s^{\text{ZEUS}}(M_Z) = 0.1190 \pm 0.0017(\text{stat})^{+0.0049}_{-0.0023}(\text{sys}) \pm 0.0026(\text{th})$$

$$\alpha_s^{\text{H1}}(M_Z) = 0.1186 \pm 0.0030(\text{exp})^{+0.0039}_{-0.0045}(\text{scale}) \pm 0.0023(\text{pdf})$$

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NLO scale uncertainty dominates the error on α_s from jets at colliders

NLO jet physics precise enough ?

More reasons to go beyond NLO

- better matching of parton level jet algorithm with experimental hadron level jet algorithm

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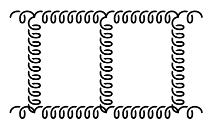
- modified power corrections as higher perturbative powers $1/\ln(Q^2/\Lambda^2)$ can mimic genuine power corrections Q/Λ
- allow full NNLO global fits to parton distributions $\longrightarrow$ lower error on benchmark processes at LHC and Tevatron

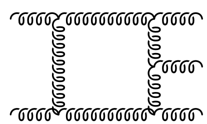
Towards NNLO jet physics

Ingredients to NNLO n-jet calculations:

- Two-loop matrix elements

  $|\mathcal{M}|^2_{\text{2-loop},n \text{ partons}}$ 

- One-loop matrix elements

  $|\mathcal{M}|^2_{\text{1-loop},n+1 \text{ partons}}$ 

- One-loop one-particle subtraction terms

  $\int |\mathcal{M}^{R,1}|^2_{\text{1-loop},n+1 \text{ partons}} \, d\Phi_1$

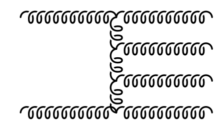
  D. Kosower, P. Uwer

  S. Catani, M. Grazzini

  Z. Bern et al.

  S. Weinzierl

- Tree level matrix elements

  $|\mathcal{M}|^2_{\text{tree},n+2 \text{ partons}}$ 

- Tree-level one-particle subtraction terms

  $\int |\mathcal{M}^{R,1}|^2_{\text{tree},n+2 \text{ partons}} \mathrm{d}\Phi_1$

  W. Giele, N. Glover

  S. Catani, M. Seymour

- Tree-level two-particle subtraction terms

  $\int |\mathcal{M}^{R,2}|^2_{\text{tree},n+2 \text{ partons}} \mathrm{d}\Phi_2$

  remain to be calculated

Towards NNLO jet physics

Virtual two-loop corrections to jet observables have seen enormous progress in the past years

Technical breakthroughs:

- algorithms to reduce the ~ 10000's of integrals to a few $(10-30)$ master integrals
  - Integration-by-parts (IBP)
    K. Chetyrkin, F. Tkachov
  - Lorentz Invariance (LI)
    E. Remiddi, TG
  - and their implementation in computer algebra
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    S. Laporta
- new methods to compute master integrals
  - Mellin-Barnes Transformation V. Smirnov, O. Veretin; B. Tausk
  - Differential Equations E. Remiddi, TG
  - Sector Decomposition (numerically) T. Binoth, G. Heinrich
  - Nested Sums S. Moch, P. Uwer, S. Weinzierl

Towards NNLO jet physics

Virtual two-loop matrix elements have recently been computed for:

- Bhabha-Scattering: $e^+e^- \to e^+e^-$
  Z. Bern, L. Dixon, A. Ghinculov
- Hadron-Hadron 2-Jet production: $qq' \to qq'$, $q\bar{q} \to q\bar{q}$, $q\bar{q} \to gg$, $gg \to gg$
  C. Anastasiou, N. Glover, C. Oleari, M. Yeomans-Tejeda
  Z. Bern, A. De Freitas, L. Dixon [SUSY-YM]
- Photon pair production at LHC: $gg \to \gamma\gamma$, $q\bar{q} \to \gamma\gamma$
  Z. Bern, A. De Freitas, L. Dixon
  C. Anastasiou, N. Glover, M. Yeomans-Tejeda
- Three-jet production: $e^+e^- \to \gamma^* \to q\bar{q}g$
  L. Garland, N. Glover, A.Koukoutsakis, E. Remiddi, TG
  S. Moch, P. Uwer, S. Weinzierl
- DIS (2+1) jet production: $\gamma^* g \to q\bar{q}$, Hadronic (V+1) jet production: $qg \to Vq$
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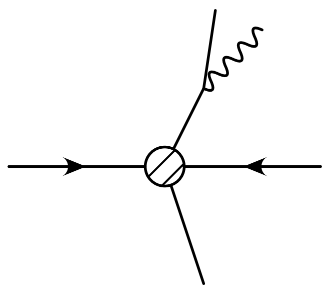
Ongoing:

- Matrix elements with internal masses: $\gamma^* \to Q\bar{Q}$
  R. Bonciani, P. Mastrolia, E. Remiddi; U. Aglietti, R. Bonciani

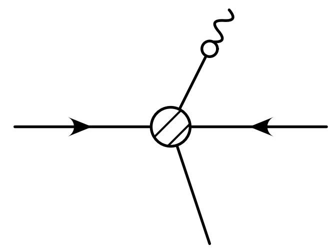
Photons

Photons

Two production processes for photons



direct



fragmentation

Photons

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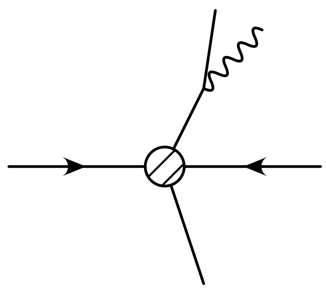

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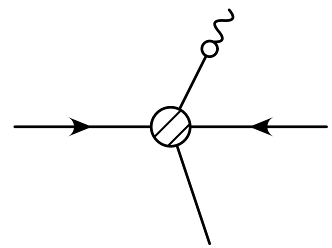

fragmentation

Photons never fully isolated from hadrons

- isolation cone: $E^{\rm had} < E^{\rm isol}$ for $R < R^{\rm isol}$
- cluster photon into jet: $E^{\gamma} > z_{\rm cut} E^{\rm jet}$ N. Glover, A. Morgan

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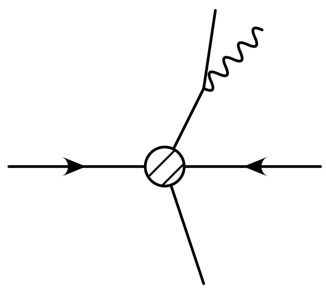

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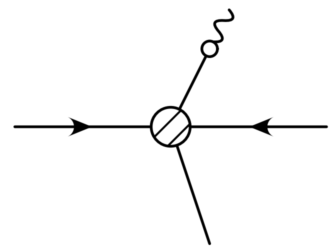

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- cluster photon into jet: $E^{\gamma} > z_{\text{cut}} E^{\text{jet}}$ N. Glover, A. Morgan

Both isolation criteria

- are infrared safe
- induce contribution from non-perturbative quark-to-photon fragmentation function

Cone-based isolation fails for small cones:

S. Catani, M. Fontannaz, J.P. Guillet, E. Pilon

$$\sigma^{\text{isol}} > \sigma^{\text{incl}} \quad \text{for } R \le 0.1 \quad (\alpha_s \ln R^{-2} \sim 1)$$

Photon Pairs

$pp \to \gamma\gamma X$: background to Higgs search in $H \to \gamma\gamma$ decay mode

- Subprocesses: $q\bar{q} : \mathcal{O}(\alpha_s^0), \quad qg : \mathcal{O}(\alpha_s^1), \quad gg : \mathcal{O}(\alpha_s^2)$
  comparable magnitude due to large gluon luminosity

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  DIPHOX: T. Binoth, J.P. Guillet, E. Pilon, M. Werlen

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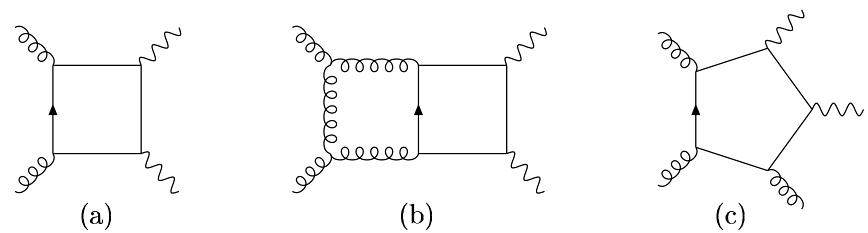

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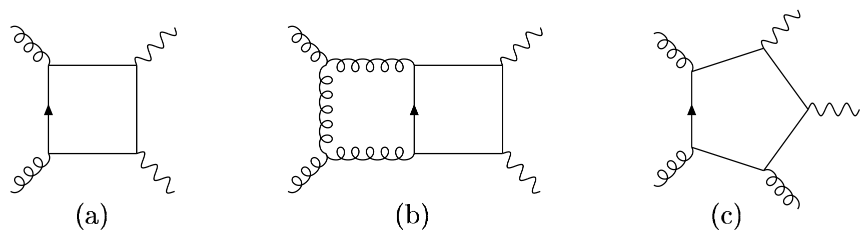
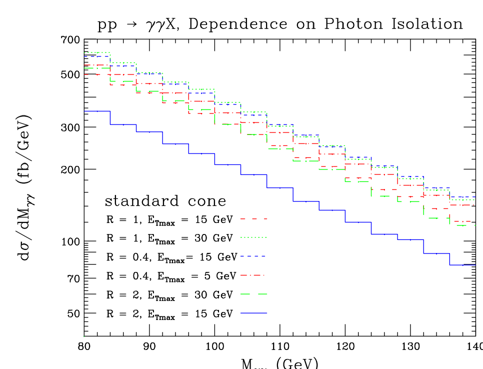


- cross section depends on photon isolation



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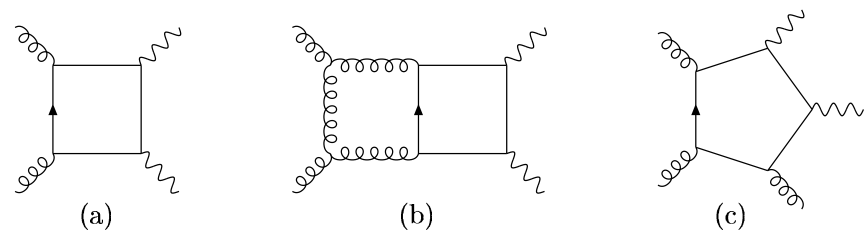
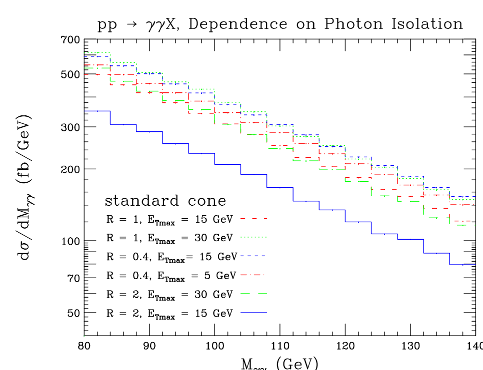


- cross section depends on photon isolation
- sensitive on photon fragmentation function $D_{q\to\gamma}$ at large momentum transfer
  (only experimental constraint: LEP)



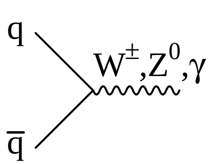
Gauge and Higgs Boson Production

Gauge and Higgs Boson Production

Inclusive Production: NNLO corrections

Drell–Yan process

$q\bar{q} \rightarrow W^{\pm}, Z^0, \gamma^*$

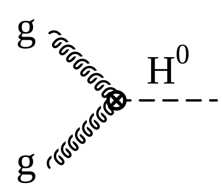


T. Matsuura, R. Hamberg, W. van Neerven

R. Harlander, W. Kilgore

Higgs production

$gg \rightarrow H^0$



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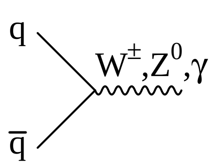

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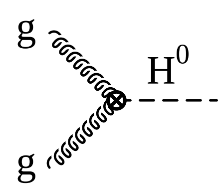

R. Harlander, W. Kilgore
C. Anastasiou, K. Melnikov
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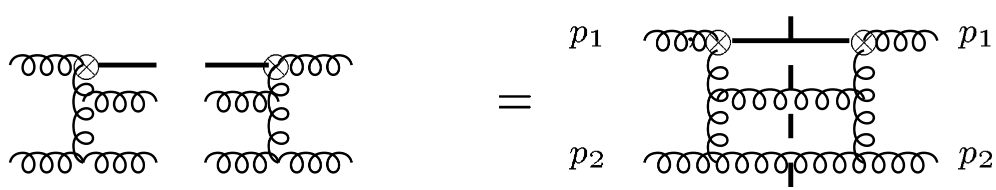
New calculational techniques:

- expansion around the soft limit
  R. Harlander, W. Kilgore
- extension of multi-loop techniques (IBP and LI, differential equations) to phase space integrals



C. Anastasiou, K. Melnikov

Inclusive Higgs Boson Production

Recent NNLO results

- Standard model Higgs from gluon fusion
  $gg \to H + X$
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  C. Anastasiou, K. Melnikov
- including NNLL soft gluon resummation
  S. Catani, D. de Florian, M. Grazzini, P. Nason
- Pseudoscalar Higgs from gluon fusion
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- Higgs from bottom quark fusion $b\bar{b} \to H + X$
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  supports b-density approach
- Higgs-Strahlung
  $q\bar{q} \to W^{\pm}H + X$, $q\bar{q} \to Z^{0}H + X$
  O. Brein, A. Djouadi, R. Harlander

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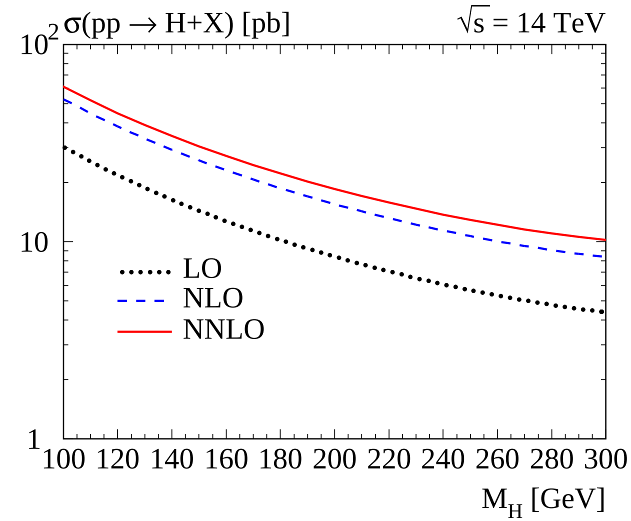
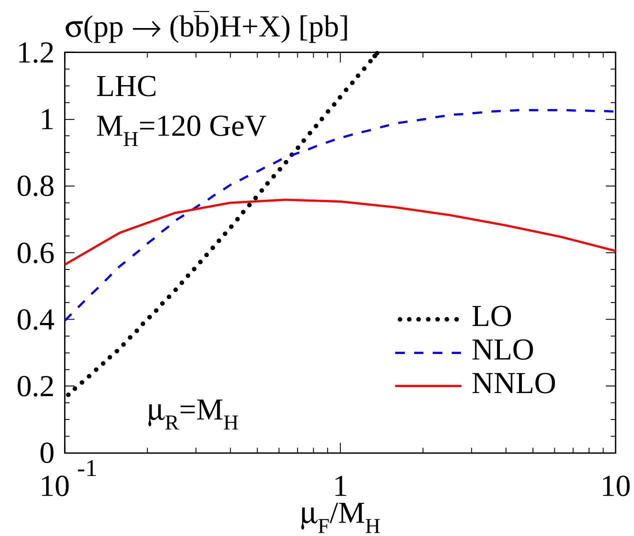
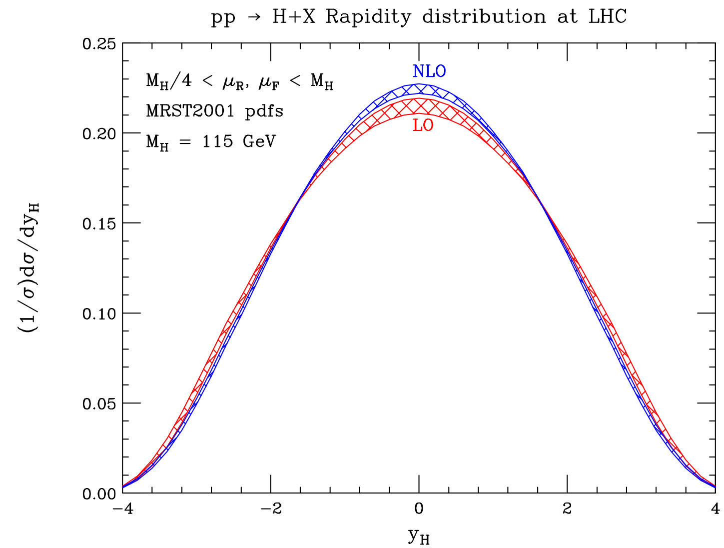




Higgs Boson Spectra

Rapidity distribution

- experiments cover only limited range in rapidity
- recently computed to NLO $\mathcal{O}(\alpha_s)$
  C. Anastasiou, L. Dixon, K. Melnikov



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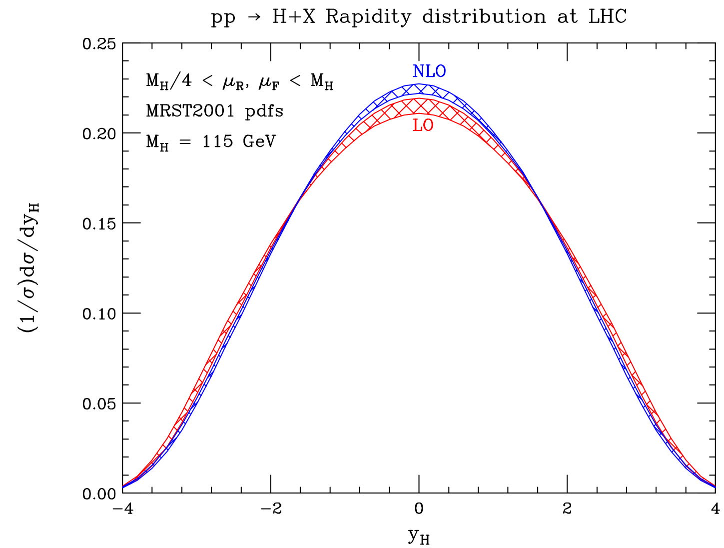
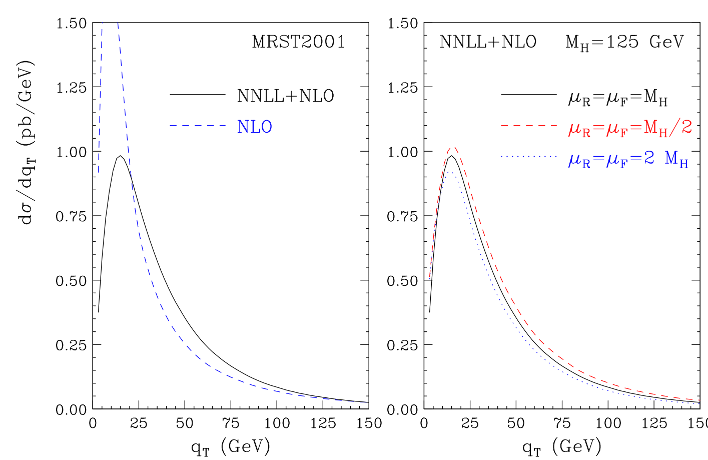


Transverse momentum distribution

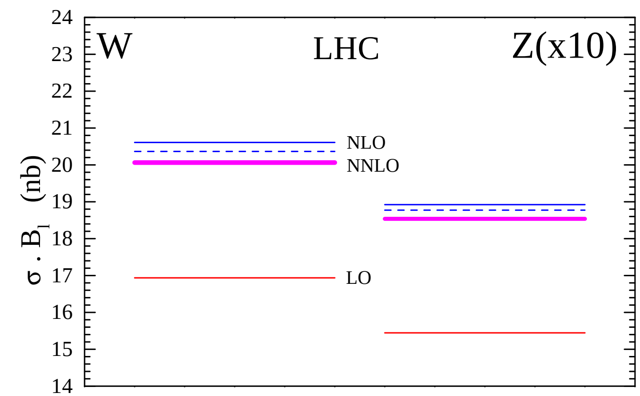
- fixed order NLO $\mathcal{O}(\alpha_s^2)$ reliable only for $q_T \geq M_H$
  D. de Florian, M. Grazzini, Z. Kunszt
  V. Ravindran, J. Smith, W. van Neerven
- small $q_T \ll M_H$ require soft gluon resummation (NNLL) of $\ln(q_T/M_H)$
  G. Bozzi, S. Catani, D. de Florian, M. Grazzini



Vector Boson Production

Inclusive cross section

- can be measured precisely
- are theoretically well understood
  - NNLO corrections known
  - relevant partons well constrained
- benchmark reaction for LHC
  (luminosity monitor)



A. Martin, J. Stirling, R. Roberts, R. Thorne

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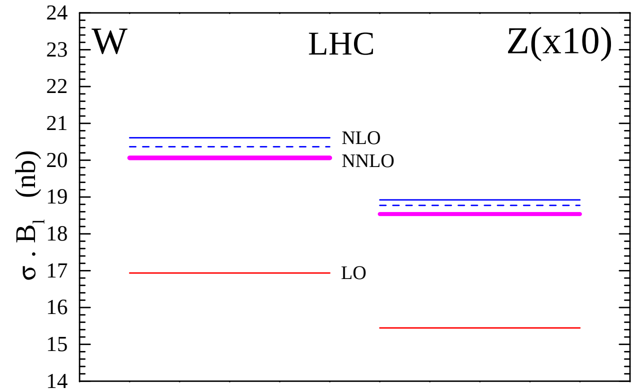
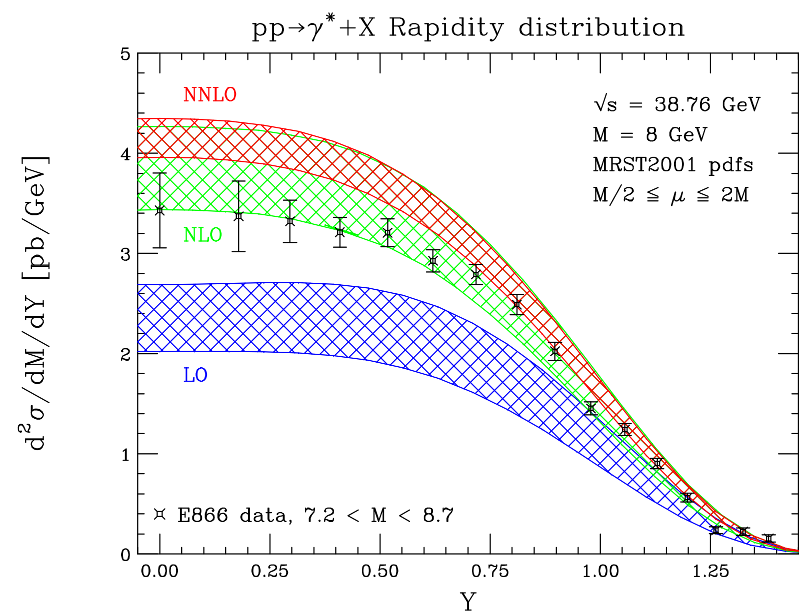


A. Martin, J. Stirling, R. Roberts, R. Thorne

Rapidity distribution

- probes antiquark distribution
- recently computed to NNLO
  (further extension of multi-loop tools)
  C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello



Parton Distributions at NNLO

Parton distributions from global fit (⟶ R. Thorne)

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Parton distributions from global fit ($\longrightarrow$ R. Thorne)

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  - deep inelastic scattering: neutral and charged current
  - Drell-Yan process
  - jet production
  - (direct photon production)
- need splitting kernels (Altarelli-Parisi splitting functions) to NNLO
  - technique: evaluate $\gamma^* q \to \gamma^* q$ and $\phi g \to \phi g$ at three loops (in moment space)
  - some fixed moments known
    S. Larin, P. Nogueira, T. van Ritbergen, J. Vermaseren; A. Retey
  - allow approximate reconstruction
    W. van Neerven, A. Vogt
  - non-singlet n_f piece known
    S. Moch, J. Vermaseren, A. Vogt
  - remaining pieces under way

Summary and Conclusions

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- QCD is ubiquitous at high energy colliders

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- QCD is becoming precision physics
  - LO is an estimate to design search strategies
    - many generic tools available
    - interface to parton shower and hadronization
  - NLO important to refine searches and to identify signals
    - current frontier $2 \to 3$; $2 \to 4$ requires new tools
    - interface to parton showers
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- resummation often important
- many predictions require input from LEP data (e.g. fragmentation functions)