QCD
at
hadron colliders

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Queen Mary 3 November 2005

QCD

- an unbroken Yang-Mills gauge field theory featuring asymptotic freedom and confinement
- in non-perturbative regime (low Q^2) many approaches: lattice, Regge theory, χ PT, large N_c, HQET
- in perturbative regime (high Q^2) QCD is a precision toolkit for exploring Higgs & BSM physics
- LEP was an electroweak machine
- Tevatron & LHC are QCD machines

Precision QCD

Precise determination of

- strong coupling constant α_s
- parton distributions
- electroweak parameters
- LHC parton luminosity

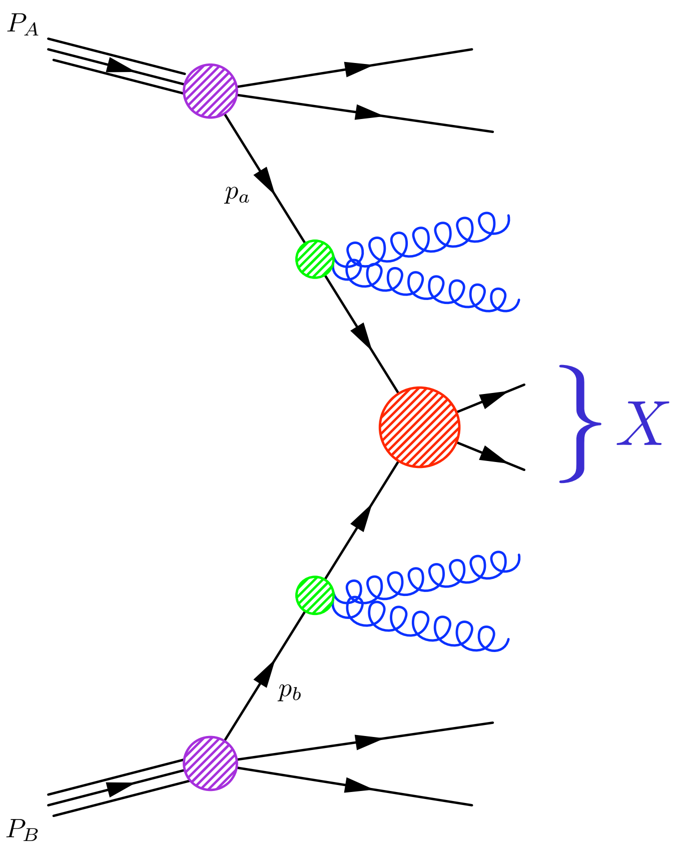
Precise prediction for

- Higgs production
- new physics processes
- their backgrounds

Strong interactions at high Q^2

- Parton model
- Perturbative QCD
  - factorisation
  - universality of IR behaviour
  - cancellation of IR singularities
  - IR safe observables: inclusive rates
    - jets
    - event shapes

Factorisation



is the separation between
the short- and the long-range interactions

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{a/A}(x_1, \mu_F^2)\, f_{b/B}(x_2, \mu_F^2)$$
$$\times\ \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

$$X = W, Z, H, Q\bar{Q}, \text{high-}E_T\text{jets}, ...$$

$\hat{\sigma}$ is known as a fixed-order expansion in α_S

$$\hat{\sigma} = C\alpha_S^n(1 + c_1\alpha_S + c_2\alpha_S^2 + \ldots)$$

$c_1 =$ NLO $\qquad c_2 =$ NNLO

or as an all-order resummation

$$\hat{\sigma} = C\alpha_S^n[1 + (c_{11}L + c_{10})\alpha_S + (c_{22}L^2 + c_{21}L + c_{20})\alpha_S^2 + \ldots]$$

where $L = \ln(M/q_T), \ln(1-x), \ln(1/x), \ln(1-T), \ldots$

$c_{11}, c_{22} =$ LL $\qquad c_{10}, c_{21} =$ NLL $\qquad c_{20} =$ NNLL

Factorisation-breaking contributions

- underlying event (see Rick Field's studies at CDF)
- power corrections
  - MC's and theory modelling of power corrections laid out and tested at LEP where they provide an accurate determination of α_S models still need be tested in hadron collisions (see e.g. Tevatron studies at different $\sqrt{s}$) ⇨
- diffractive events ⇨

Is double-parton scattering breaking factorisation ?

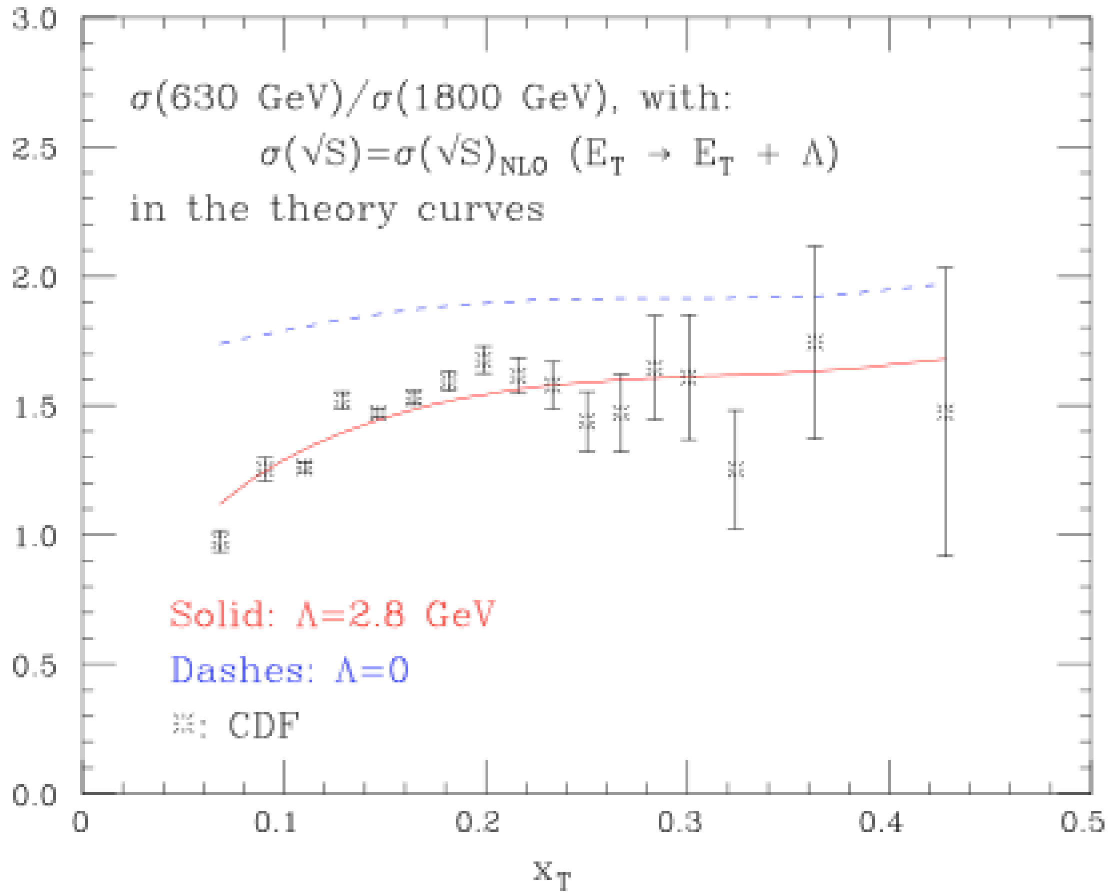
- observed by Tevatron CDF in the inclusive sample

  $p\bar{p} \to \gamma + 3 \text{ jets}$

  potentially important at LHC $\sigma_D \propto \sigma_S^2$

Power corrections at Tevatron

Ratio of inclusive jet cross sections at 630 and 1800 GeV



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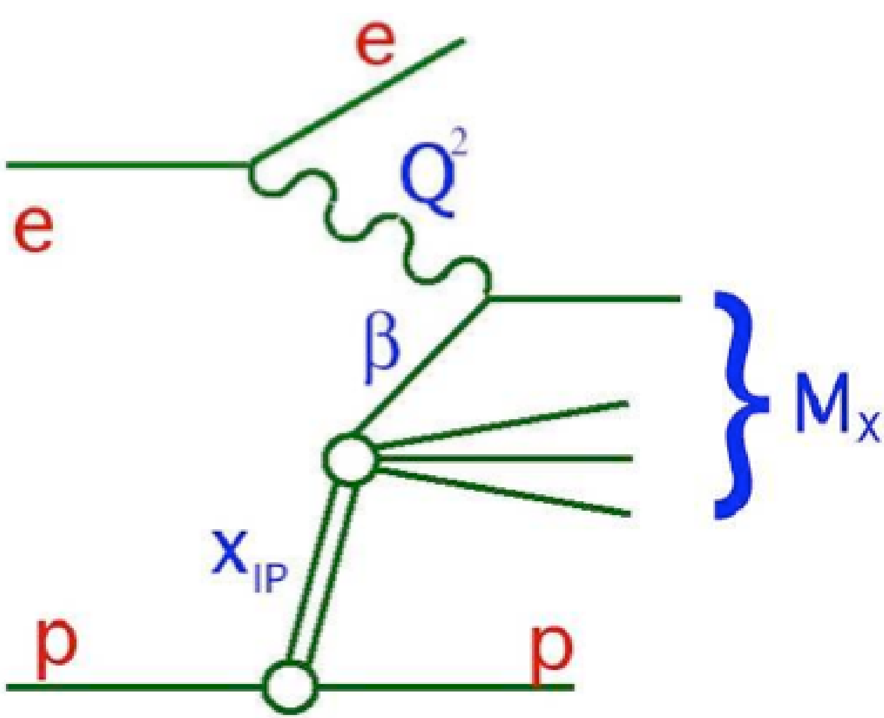
KITP collider conf 2004

Bjorken-scaling variable

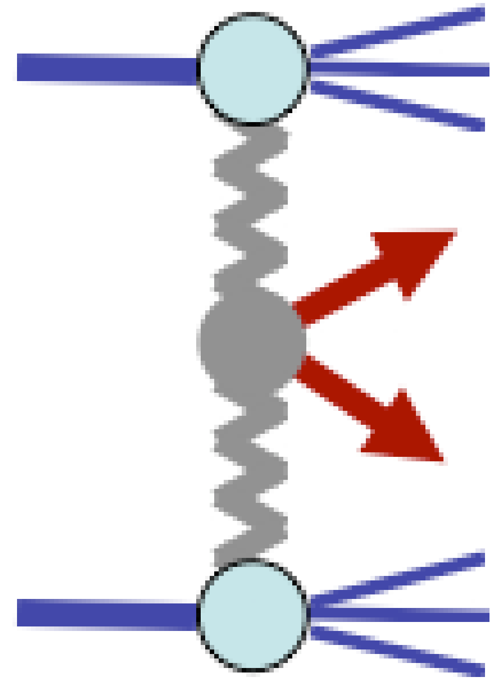
$$x_T = \frac{2E_T}{\sqrt{s}}$$

- In the ratio the dependence on the pdf's cancels
- dashes: theory prediction with no power corrections
- solid: best fit to data with free power-correction parameter Λ in the theory

Factorisation in diffraction ??

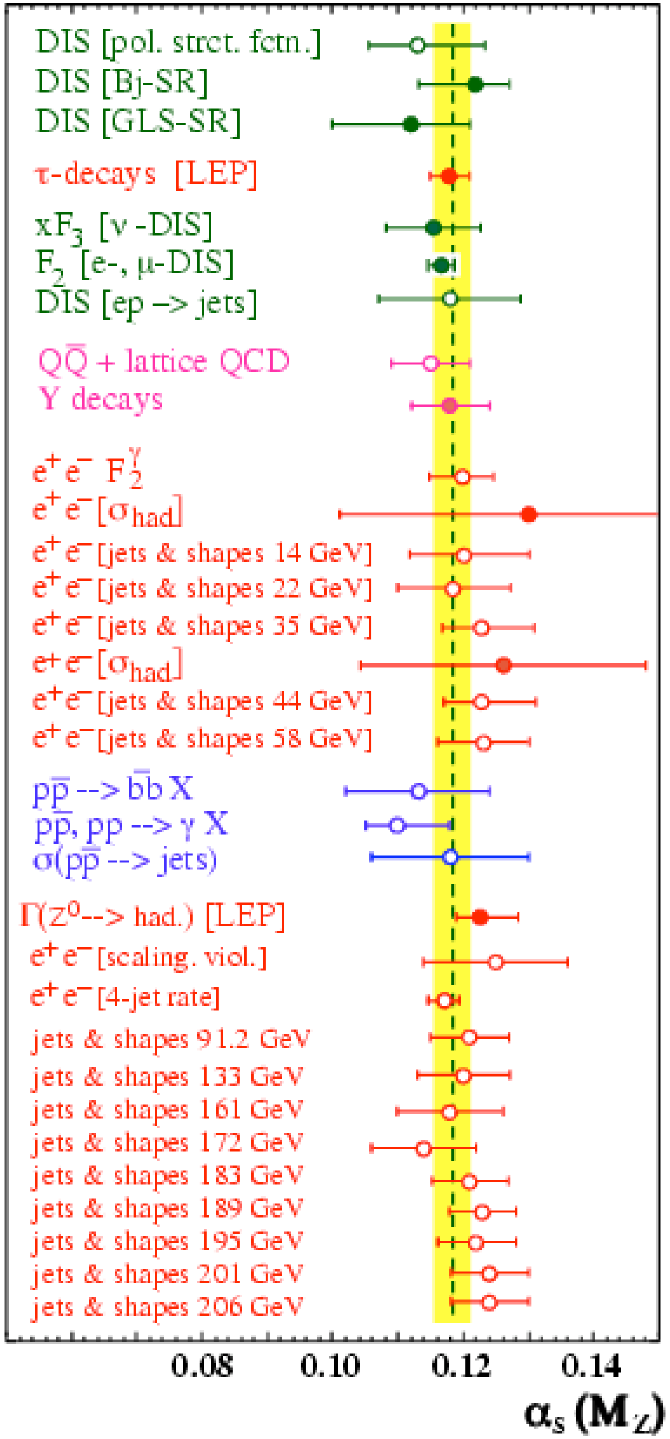


diffraction in DIS



double pomeron exchange in $p\bar{p}$

- no proof of factorisation in diffractive events
- data do not support it



filled symbols are NNLO results

Summary of $\alpha_S(M_Z)$

S. Bethke hep-ex/0407021

world average of $\alpha_S(M_Z)$
using $\overline{\mathrm{MS}}$ and NNLO results only

$$\alpha_S(M_Z) = 0.1182 \pm 0.0027$$

(cf. 2002 $\alpha_S(M_Z) = 0.1183 \pm 0.0027$
outcome almost identical
because new entries wrt 2002
- LEP jet shape observables and
4-jet rate, and HERA jet rates
and shape variables - are NLO)

3 complementary approaches to $\hat{\sigma}$

	matrix-elem MC's	fixed-order x-sect	shower MC's
final-state description	hard-parton jets. Describes geometry, correlations, ...	limited access to final-state structure	full information available at the hadron level
higher-order effects: loop corrections	hard to implement: must introduce negative probabilities	straightforward to implement (when available)	included as vertex corrections (Sudakov FF's)
higher-order effects: hard emissions	included, up to high orders (multijets)	straightforward to implement (when available)	approximate, incomplete phase space at large angles
resummation of large logs	?	feasible (when available)	unitarity implementation (i.e. correct shapes but not total rates)

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Matrix-element MonteCarlo generators

- multi-parton generation: processes with many jets (or W/Z/H bosons)
  - ALPGEN M.L.Mangano M. Moretti F. Piccinini R. Pittau A. Polosa 2002
  - MADGRAPH/MADEVENT W.F. Long F. Maltoni T. Stelzer 1994/2003
  - COMPHEP A. Pukhov et al. 1999
  - GRACE/GR@PPA T. Ishikawa et al. K. Sato et al. 1992/2001
  - HELAC C. Papadopoulos et al. 2000
- processes with 6 final-state fermions
  - PHASE E. Accomando A. Ballestrero E. Maina 2004
- merged with parton showers
  - all of the above, merged with HERWIG or PYTHIA
  - SHERPA F. Krauss et al. 2003

Shower MonteCarlo generators

- HERWIG B. Webber et al. 1992

  being re-written as a C++ code (HERWIG++)

- PYTHIA T. Sjostrand 1994

and more

- CKKW S. Catani F. Krauss R. Kuhn B. Webber 2001

  a procedure to interface parton subprocesses with
  a different number of final states to parton showers

- MC@NLO S. Frixione B. Webber 2002

  a procedure to interface NLO computations to shower MC's

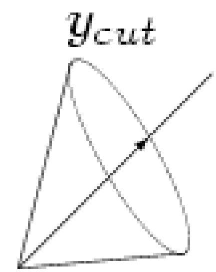
NLO features

- Jet structure: final-state collinear radiation
- PDF evolution: initial-state collinear radiation
- Opening of new channels
- Reduced sensitivity to fictitious input scales: μ_R, μ_F
  - predictive normalisation of observables
    - first step toward precision measurements
    - accurate estimate of signal and background for Higgs and new physics
- Matching with parton-shower MC's: MC@NLO

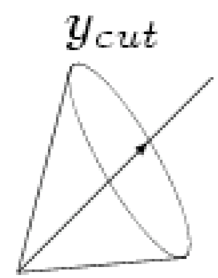
Jet structure

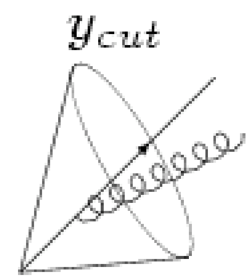
the jet non-trivial structure shows up first at NLO

leading order

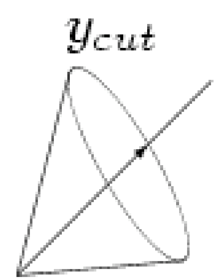


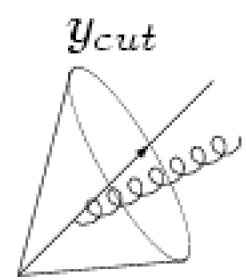
NLO

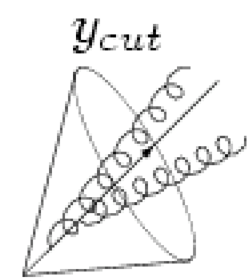




NNLO







Desired NLO cross sections

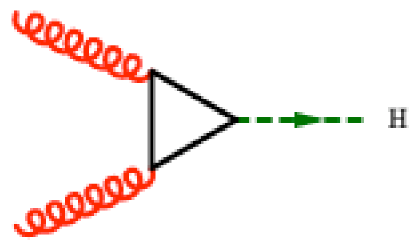
Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

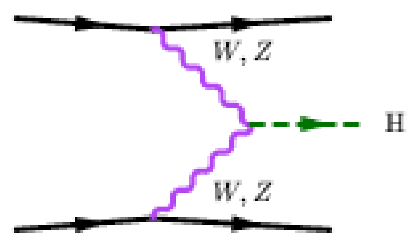
Higgs Production Modes at LHC

In proton collisions at 14 TeV, and for $M_H > 100$ GeV the Higgs is produced mostly via

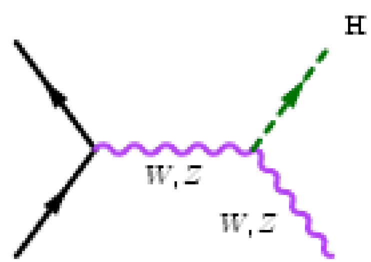
- gluon fusion $gg \to H$
  - largest rate for all M_H
  - proportional to the top Yukawa coupling y_t



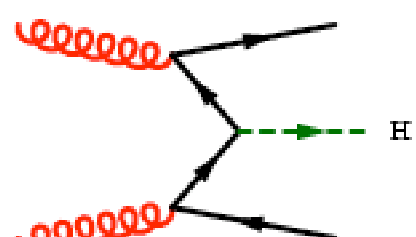
- weak-boson fusion (WBF) $qq \to qqH$
  - second largest rate (mostly $u\,d$ initial state)
  - proportional to the WWH coupling



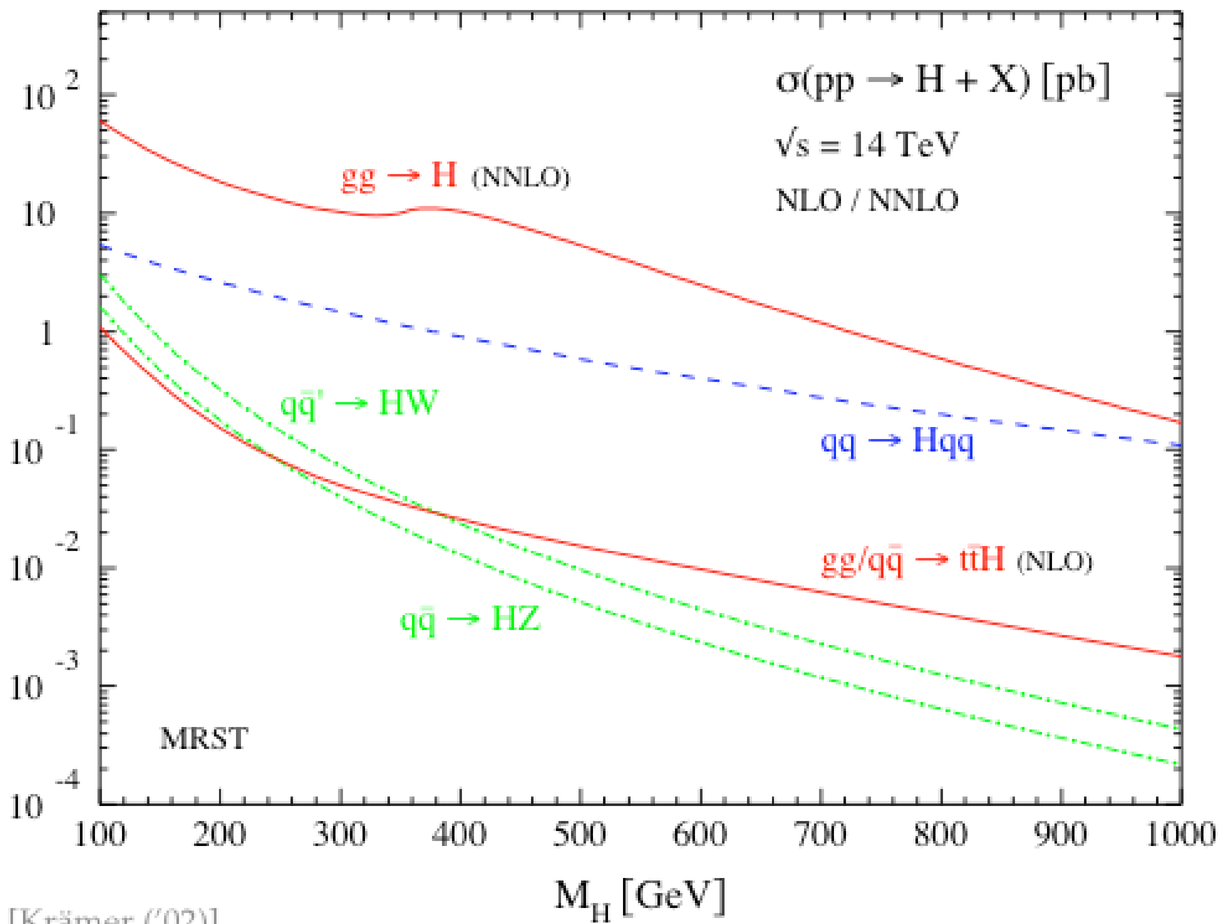
- Higgs-strahlung $q\bar{q} \to W(Z)H$
  - third largest rate
  - same coupling as in WBF



- $t\bar{t}(b\bar{b})H$ associated production
  - same initial state as in gluon fusion, but higher x range
  - proportional to the heavy-quark Yukawa coupling y_Q



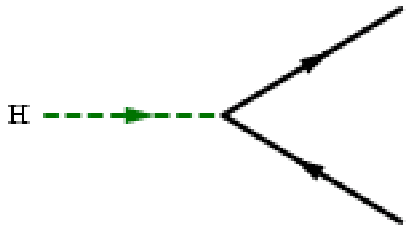
Higgs Production at LHC



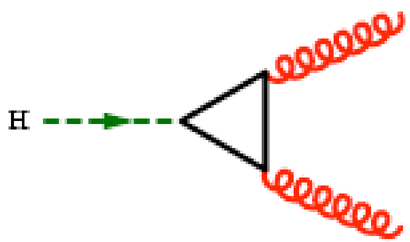
[Krämer ('02)]

- in the intermediate Higgs mass range $M_H \sim 100 - 200 \text{ GeV}$
  - gluon fusion cross section is $\sim 20 - 60 \text{ pb}$
  - WBF cross section is $\sim 3 - 5 \text{ pb}$
  - $WH, ZH, t\bar{t}H$ yield cross sections of $\sim 0.2 - 3 \text{ pb}$

Higgs Decay Modes at LHC

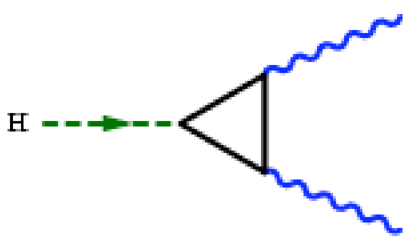


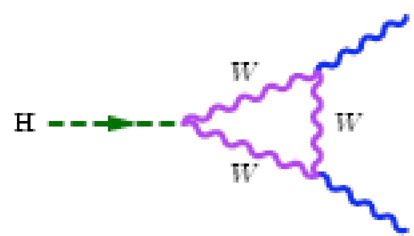
proportional to the Yukawa coupling squared, and thus to m_f^2



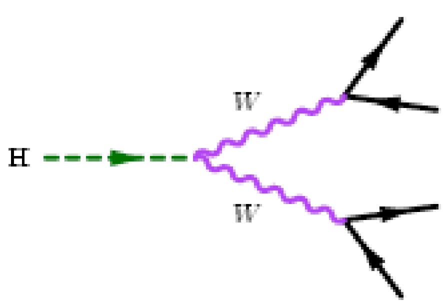
proportional to m_f^4/m_H^4

but dominated by top quark Yukawa coupling





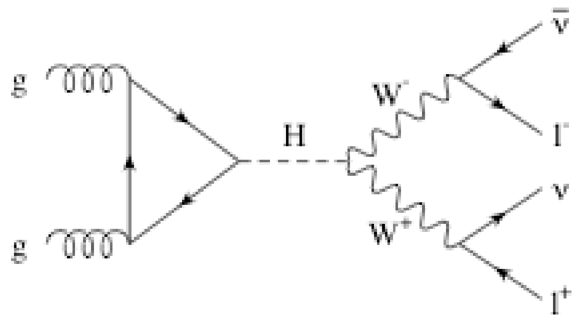
dominated by EW coupling



proportional to α_W

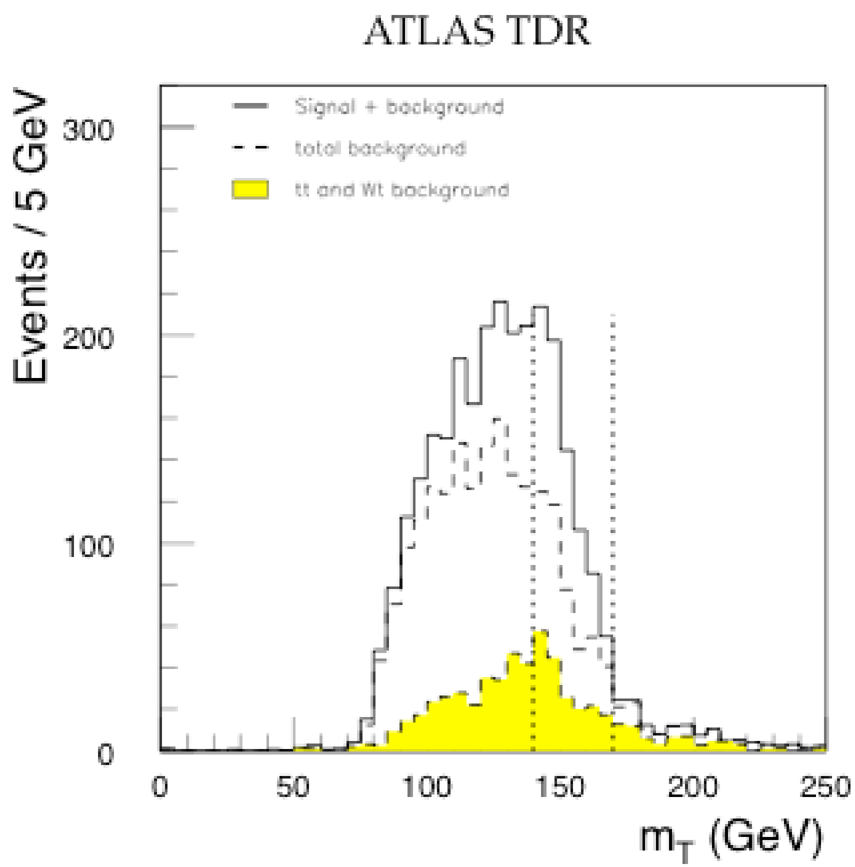
Decay width into W^*W^* plays a significant role

INCLUSIVE SEARCHES: $H \to WW \to l^+\nu l^-\bar{\nu}$



- Exploit l^+l^- angular correlations

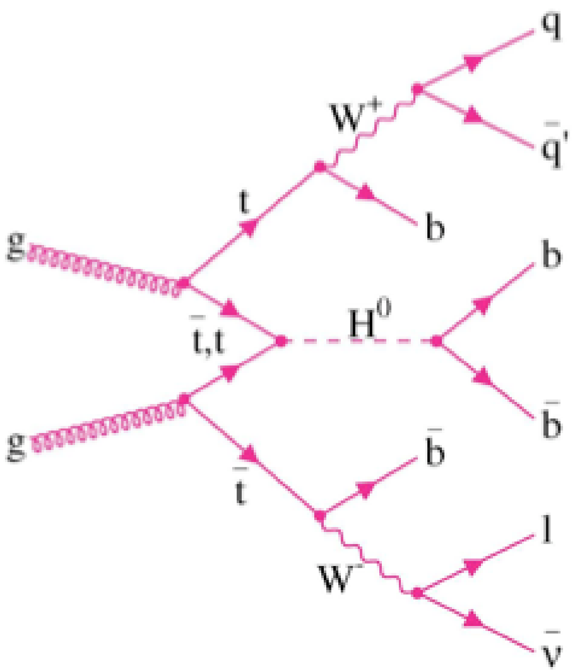
- Signal and background have similar shapes: must know background normalisation well

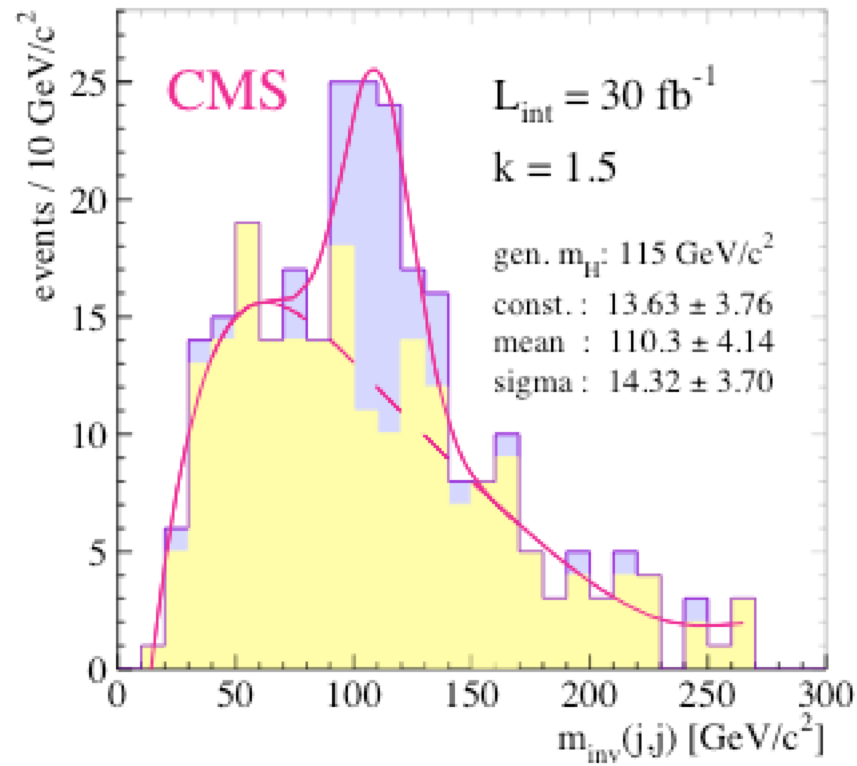


$m_H = 170$ GeV

integrated luminosity: $20\ \text{fb}^{-1}$

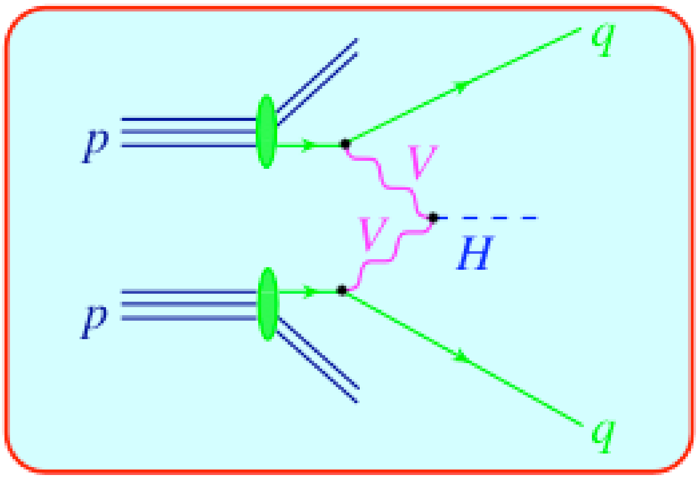
ASSOCIATED PRODUCTION: $Ht\bar{t} \to t\bar{t}b\bar{b}$

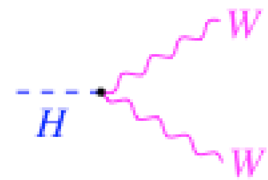




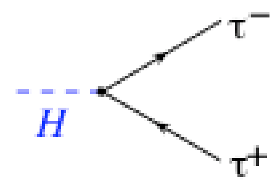
- Search channel for $m_H = 120 - 130\ \mathrm{GeV}$
- Measure $h_t^2\ \mathrm{BR}(H \to b\bar{b})$ with $h_t = Ht\bar{t}$ Yukawa coupling
- must know background normalisation well

Weak Boson Fusion: $qq \to qqH$

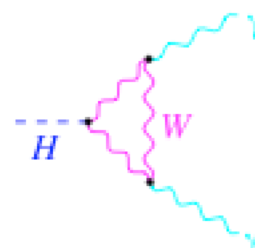




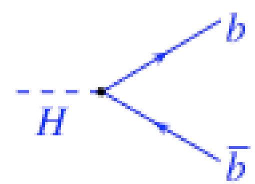
$m_H > 120$ GeV



$m_H < 140$ GeV



$m_H < 150$ GeV

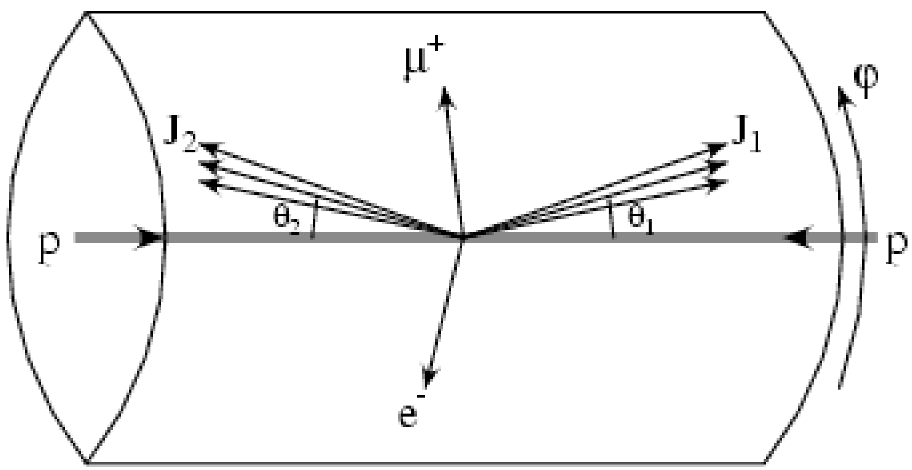


$m_H < 140$ GeV

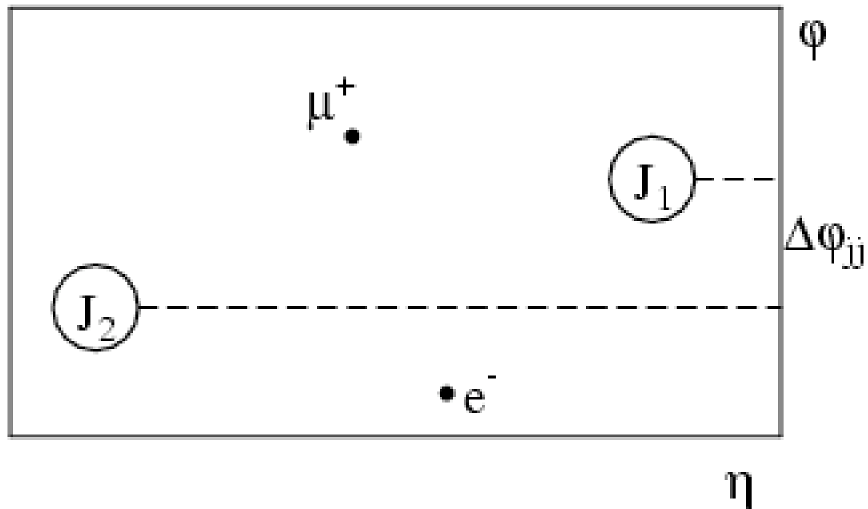
- WBF can be measured with good statistical accuracy: $\sigma \times \mathrm{BR} \approx \mathcal{O}(10\%)$

Weak Boson Fusion

A WBF event



Lego plot

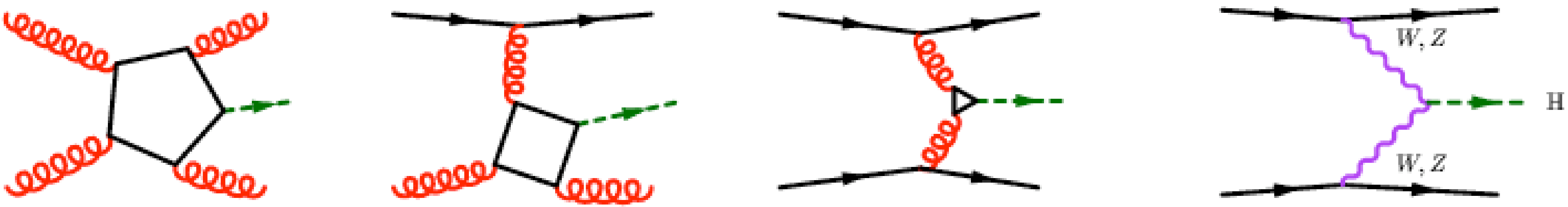


$$\eta = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta}$$

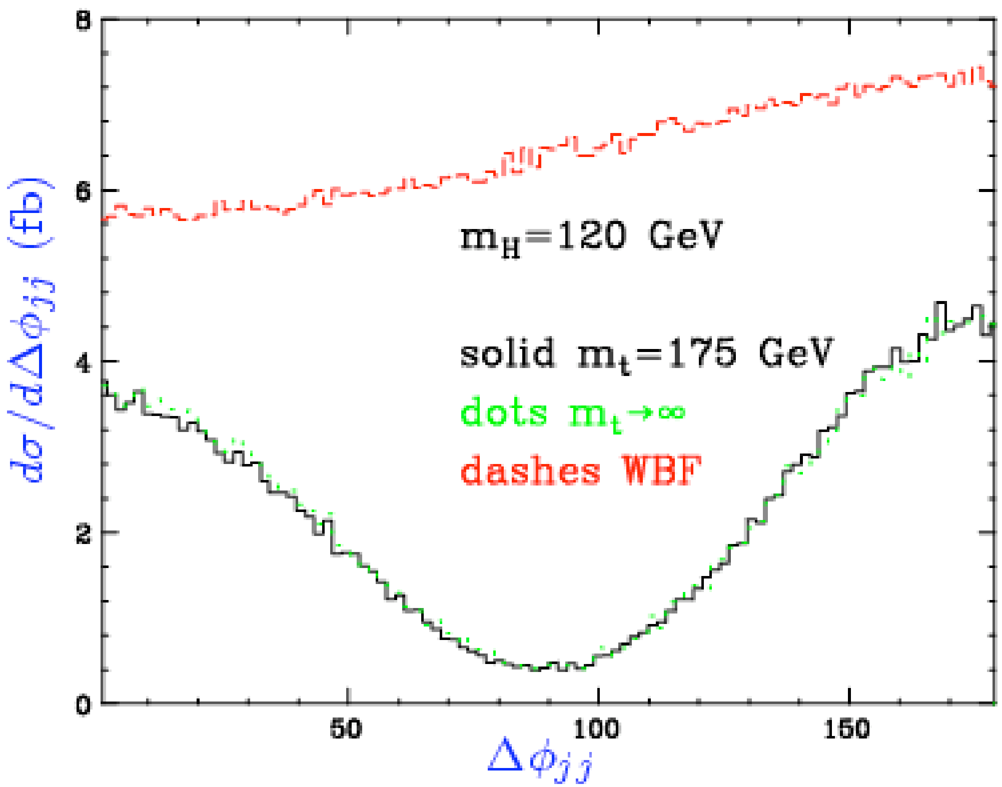
- WBF features
  - energetic jets in the forward and backward directions
  - Higgs decay products between the tagging jets
  - sparse gluon radiation in the central-rapidity region, due to colourless W/Z exchange
  - NLO corrections increase the WBF production rate by about $10\,\%$, and thus are small and under control

Campbell, Ellis; Figy, Oleari, Zeppenfeld 2003

Higgs + 2 jets



azimuthal angle distribution



WBF cuts

$$\left\{ \begin{array}{l} p_{j\perp} > 20 \text{ GeV} \\ |\eta_j| < 5 \\ R_{jj} > 0.6 \end{array} \right. + \left\{ \begin{array}{l} \eta_{j_1} \cdot \eta_{j_2} < 0 \\ |\eta_{j_1} - \eta_{j_2}| > 4.2 \\ m_{jj} > 600 \text{ GeV} \end{array} \right.$$

Kilgore Oleari Schmidt Zeppenfeld VDD 2001

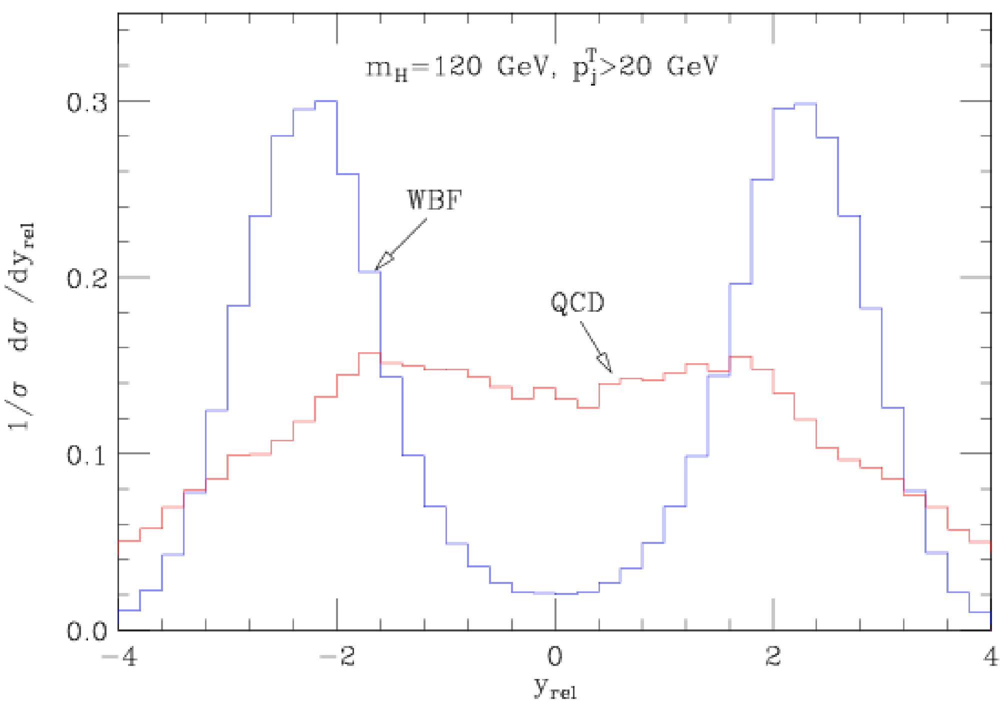
- the azimuthal angle distribution discriminates between gluon fusion and WBF

THE CENTRAL JET VETO

- In WBF no colour is exchanged in the t channel
- The central-jet veto is based on the different radiation pattern expected for WBF versus its major backgrounds, i.e. $t\bar{t}$ production and WW + 2 jet production

Barger, Phillips & Zeppenfeld hep-ph/9412276

- The central-jet veto can also be used to distinguish between Higgs production via gluon fusion and via WBF



Frizzo, Maltoni, VDD hep-ph/0404013

Distribution in rapidity of the third jet wrt to the rapidity average of the tagging jets

NLO history of final-state distributions

- $e^+e^- \to 3$ jets K. Ellis, D. Ross, A. Terrano 1981
  $e^+e^- \to 4$ jets Z. Bern et al., N. Glover et al., Z. Nagy Z. Trocsanyi 1996-97
- $pp \to 1, 2$ jets K. Ellis J. Sexton 1986, W. Giele N. Glover D. Kosower 1993
  $pp \to 3$ jets Z. Bern et al., Z. Kunszt et al. 1993-1995, Z. Nagy 2001
- $pp \to \gamma\gamma$ B. Bailey et al 1992, T. Binoth et al 1999
  $pp \to \gamma\gamma + 1$ jet Z. Bern et al. 1994, V. Del Duca et al. 2003
- $pp \to V + 1$ jet W. Giele N. Glover & D. Kosower1993
  $pp \to V + 2$ jet Bern et al., Glover et al. 1996-97, K. Ellis & Campbell 2003
- $pp \to V b\bar{b}$ K. Ellis & J. Campbell 2003
- $pp \to VV$ Ohnemus & Owens, Baur et al.1991-96, Dixon et al. 2000
- $pp \to Q\bar{Q}$ Dawson K. Ellis Nason 1989, Mangano Nason Ridolfi 1992
  $pp \to Q\bar{Q} + 1$ jet A. Brandenburg et al. 2005-6 ?
- $pp \to H + 1$ jet C. Schmidt 1997, D. De Florian M. Grazzini Z. Kunszt 1999
- $pp \to H + 2$ jets (WBF) Campbell, K. Ellis; Figy, Oleari, Zeppenfeld 2003
- $pp \to HQ\bar{Q}$ W. Beenakker et al. ; S. Dawson et al. 2001
- $e^+e^- \to 4$ fermions Denner Dittmaier Roth Wieders 2005

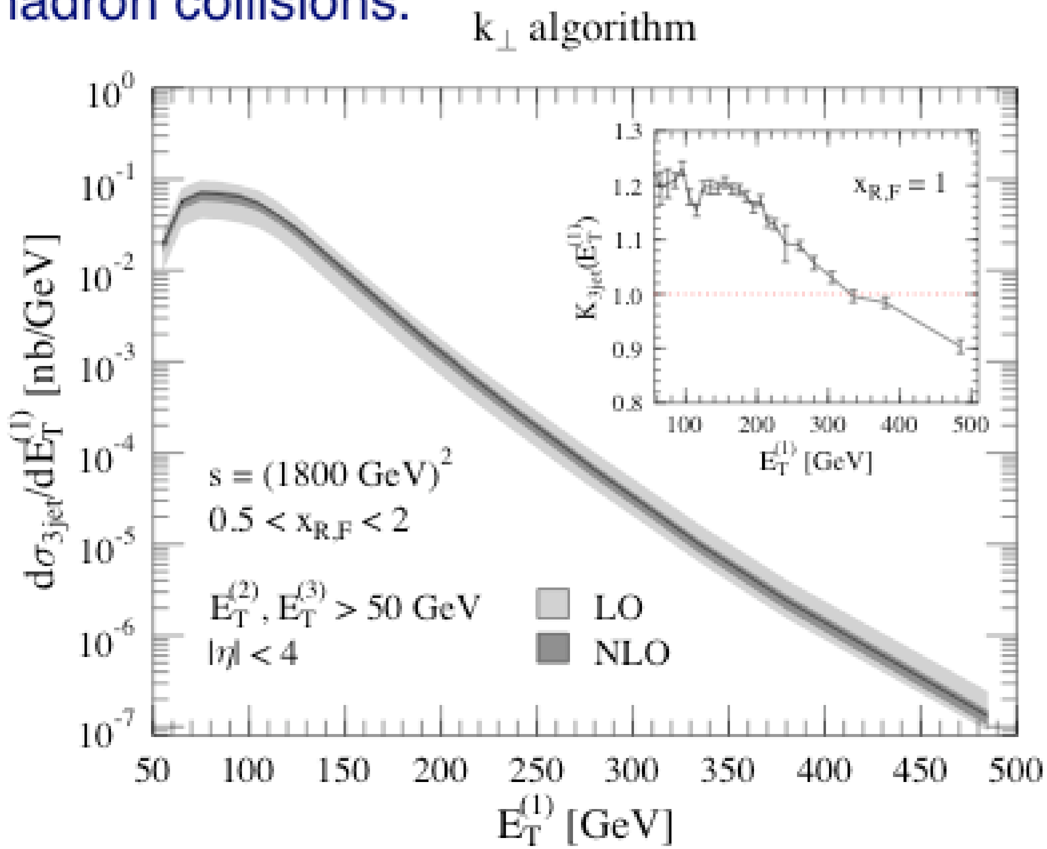
NLOJET++

Author(s): Z. Nagy
http://www.ippp.dur.ac.uk/~nagyz/nlo++.html
Multi-purpose C++ library for calculating jet cross-sections in e^+e^- annihilation, DIS and hadron-hadron collisions.

$e^+e^- \longrightarrow \ \leq 4$ jets

$ep \longrightarrow (\leq 3+1)$ jets

$p\bar{p} \longrightarrow \ \leq 3$ jets



hep-ph/0110315

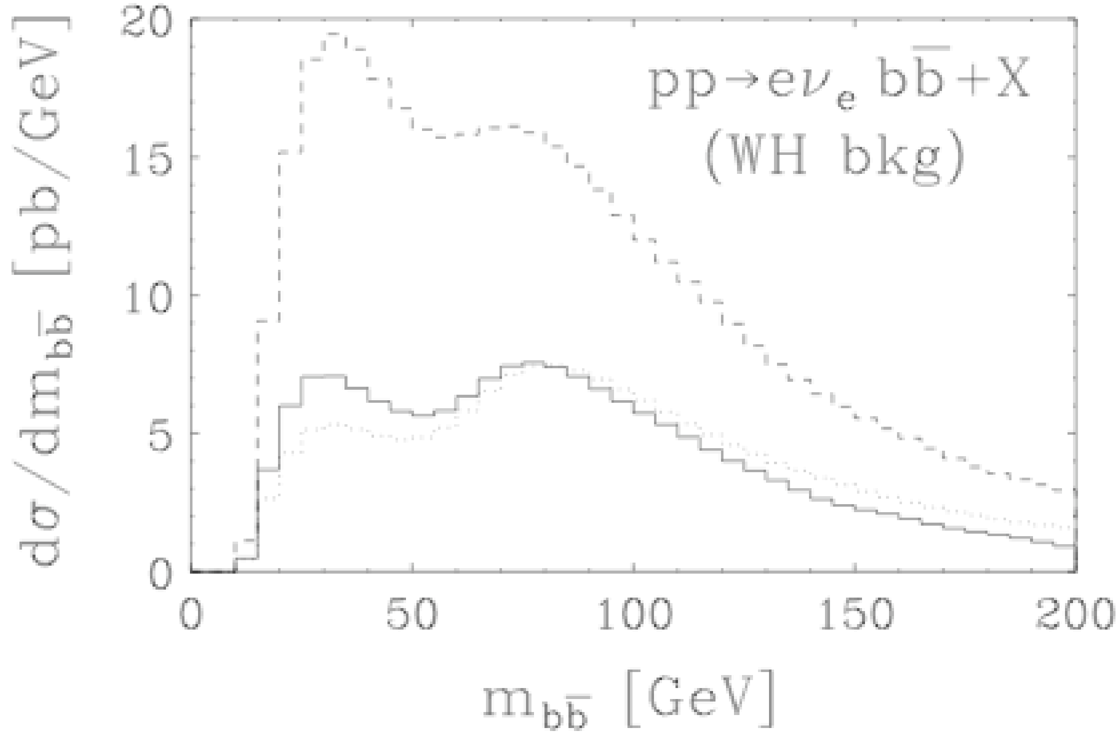
MCFM

Author(s): JC, R. K. Ellis
http://mcfm.fnal.gov
Fortran package for calculating a number of processes involving vector bosons, Higgs, jets and heavy quarks at hadron colliders.

$p\bar{p} \longrightarrow V+ \leq 2$ jets

$p\bar{p} \longrightarrow V + b\bar{b}$

with $V = W, Z$.

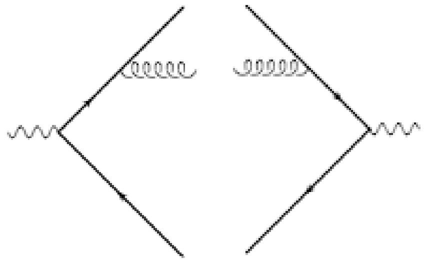


hep-ph/0308195

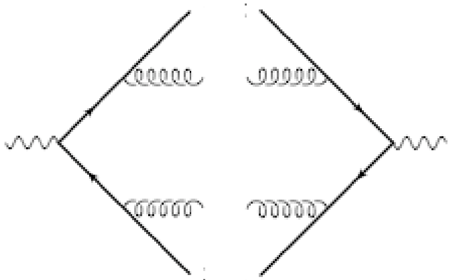
NLO assembly kit

$e^+e^- \to 3$ jets

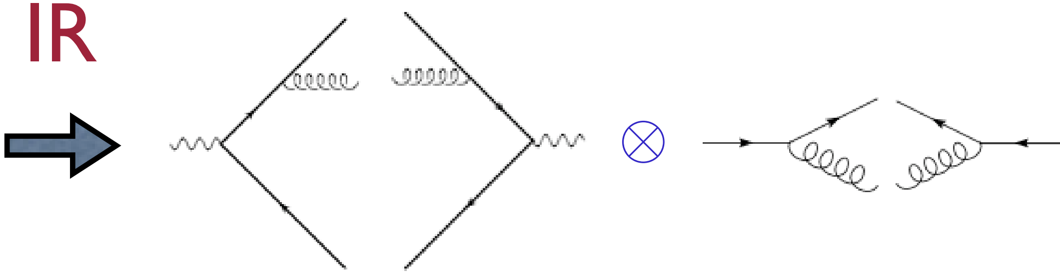
leading order $|\mathcal{M}_n^{tree}|^2$



NLO real



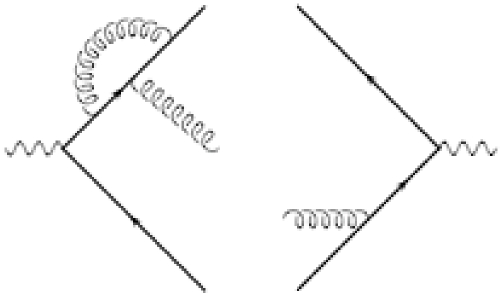
IR



$$|\mathcal{M}_{n+1}^{\rm tree}|^2 \quad \to \quad |\mathcal{M}_n^{\rm tree}|^2 \quad \times \quad \int dPS|P_{\rm split}|^2$$

$$= \quad -\left(\frac{A}{\epsilon^2}+\frac{B}{\epsilon}\right)$$

NLO virtual



$d = 4 - 2\epsilon$

$$\int d^dl \; 2(\mathcal{M}_n^{loop})^*\mathcal{M}_n^{tree} \quad = \quad \left(\frac{A}{\epsilon^2}+\frac{B}{\epsilon}\right)|\mathcal{M}_n^{tree}|^2 + fin.$$

NLO production rates

Process-independent procedure devised in the 90's

- slicing — Giele Glover & Kosower
- subtraction — Frixione Kunszt & Signer; Nagy & Trocsanyi
  - dipole — Catani & Seymour
  - antenna — Kosower; Campbell Cullen & Glover

$$\sigma = \sigma^{\rm LO} + \sigma^{\rm NLO} = \int_m d\sigma_m^B \; J_m + \sigma^{\rm NLO}$$

$$\sigma^{\rm NLO} = \int_{m+1} d\sigma_{m+1}^{\rm R} J_{m+1} + \int_m d\sigma_m^{\rm V} J_m$$

the 2 terms on the rhs are divergent in d=4

use universal IR structure to subtract divergences

$$\sigma^{\rm NLO} = \int_{m+1} \left[d\sigma_{m+1}^{\rm R} J_{m+1} - d\sigma_{m+1}^{\rm R,A} J_m \right] + \int_m \left[d\sigma_m^{\rm V} + \int_1 d\sigma_{m+1}^{\rm R,A} \right] J_m$$

the 2 terms on the rhs are finite in d=4

Observable (jet) functions

J_m vanishes when one parton becomes soft or collinear to another one

$$J_m(p_1, ..., p_m) \to 0\,, \quad \text{if} \quad p_i \cdot p_j \to 0$$

$\Rightarrow$ $d\sigma_m^{\mathrm{B}}$ is integrable over 1-parton IR phase space

J_{m+1} vanishes when two partons become simultaneously soft and/or collinear

$$J_{m+1}(p_1, ..., p_{m+1}) \to 0\,, \quad \text{if} \quad p_i \cdot p_j \text{ and } p_k \cdot p_l \to 0 \quad (i \neq k)$$

R and V are integrable over 2-parton IR phase space

observables are IR safe

$$J_{n+1}(p_1, .., p_j = \lambda q, .., p_{n+1}) \to J_n(p_1, ..., p_{n+1}) \quad \text{if} \quad \lambda \to 0$$
$$J_{n+1}(p_1, .., p_i, .., p_j, .., p_{n+1}) \to J_n(p_1, .., p, .., p_{n+1}) \quad \text{if} \quad p_i \to zp\,,\ p_j \to (1-z)p$$

for all $n \geq m$

NLO complications

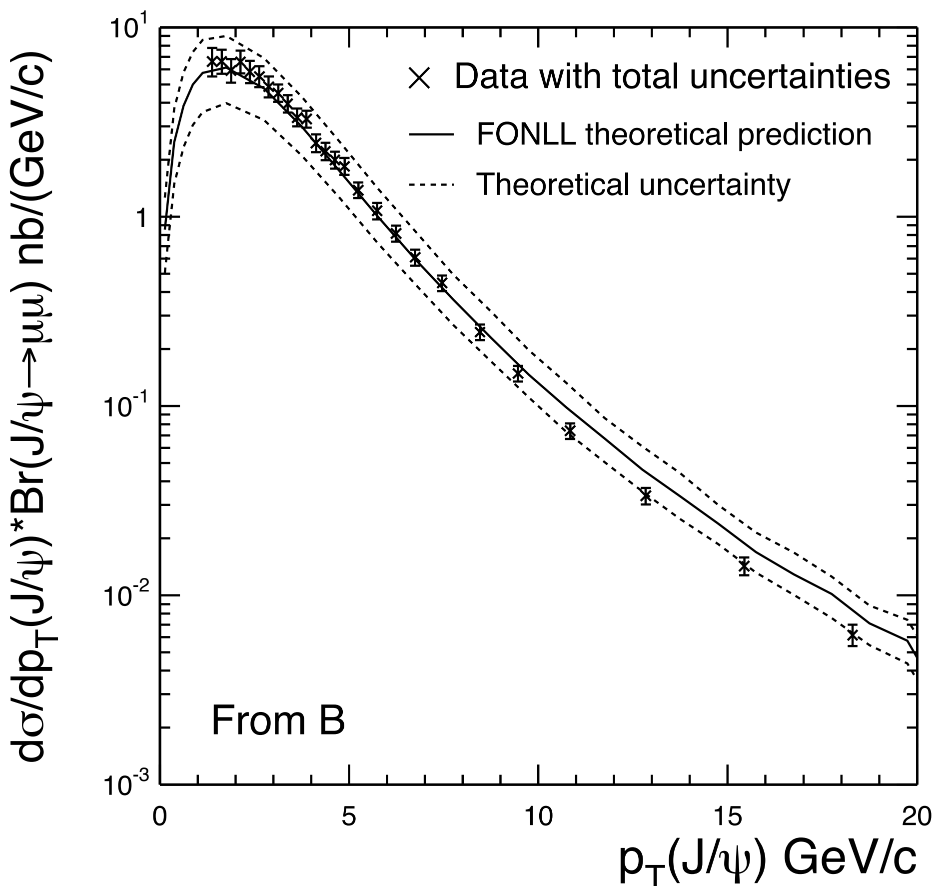
- loop integrals are involved and process-dependent
- more particles $\Rightarrow$ many scales $\Rightarrow$ lenghty analytic expressions
  - even though it is known how to compute loop integrals with $2 \to n$ particles no one-loop amplitudes with $n > 4$ have been computed (either analytically or numerically)
- no fully numeric methods yet for hadron collisions
  - counterterms are subtracted analytically

Is NLO enough to describe data ?

b cross section in $p\bar{p}$ collisions at 1.96 TeV

$d\sigma(p\bar{p} \to H_b X, H_b \to J/\psi\ X)/dp_T(J/\psi)$

CDF hep-ex/0412071



total x-sect is

$19.4 \pm 0.3(stat)^{+2.1}_{-1.9}(syst)$ nb

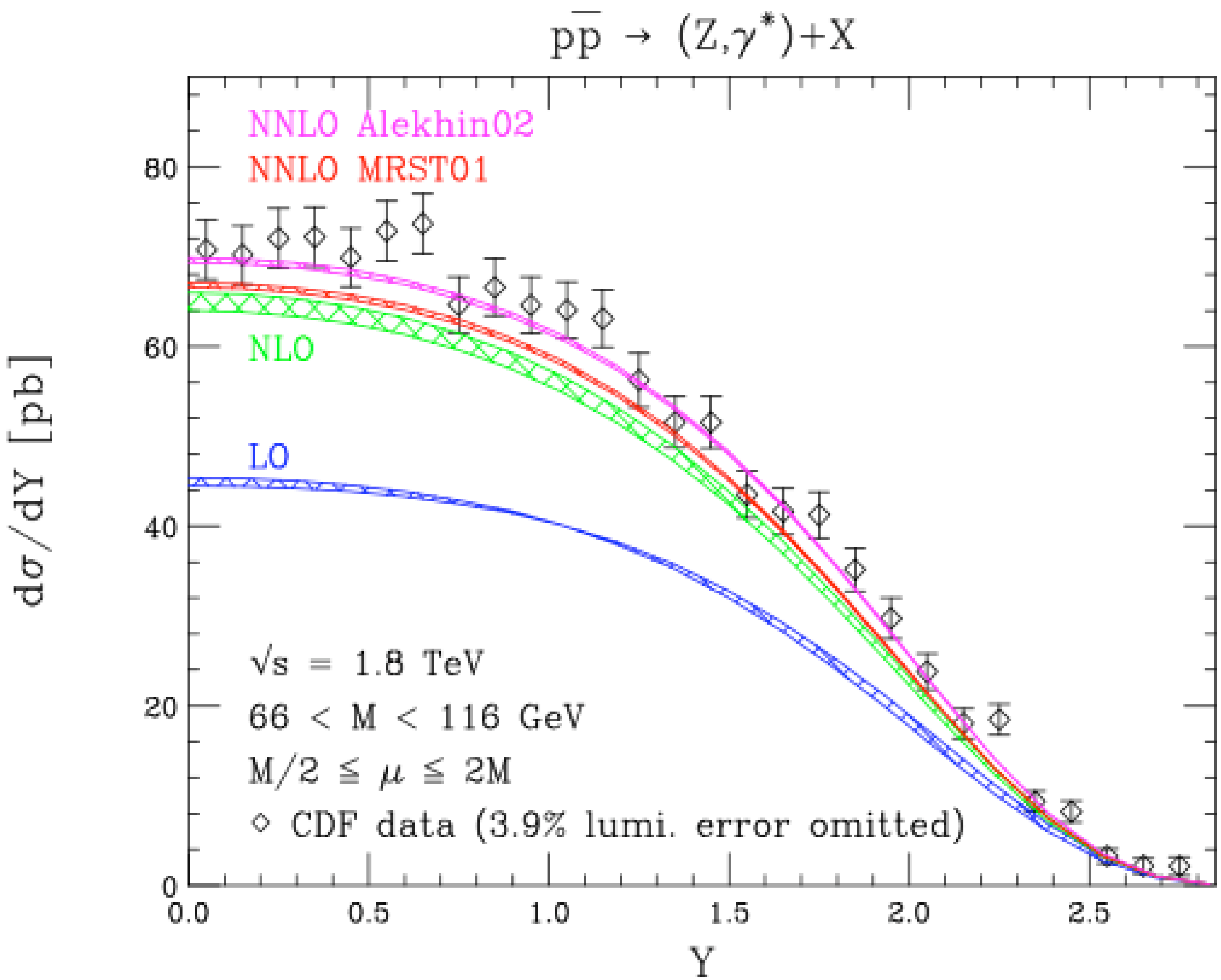
FONLL = NLO + NLL

Cacciari, Frixione, Mangano, Nason, Ridolfi 2003

good agreement with data (with use of updated FF's by Cacciari & Nason)

Is NLO enough to describe data ?

di-lepton rapidity distribution for (Z, γ^*) production vs. Tevatron Run I data



LO and NLO curves are for the MRST PDF set

no spin correlations

C. Anastasiou L. Dixon K. Melnikov F. Petriello 2003

Is NLO enough to describe data ?

Drell-Yan W cross section at LHC with leptonic decay of the W

Cuts A $\longrightarrow |\eta^{(e)}| < 2.5,\ p_T^{(e)} > 20$ GeV, $p_T^{(\nu)} > 20$ GeV

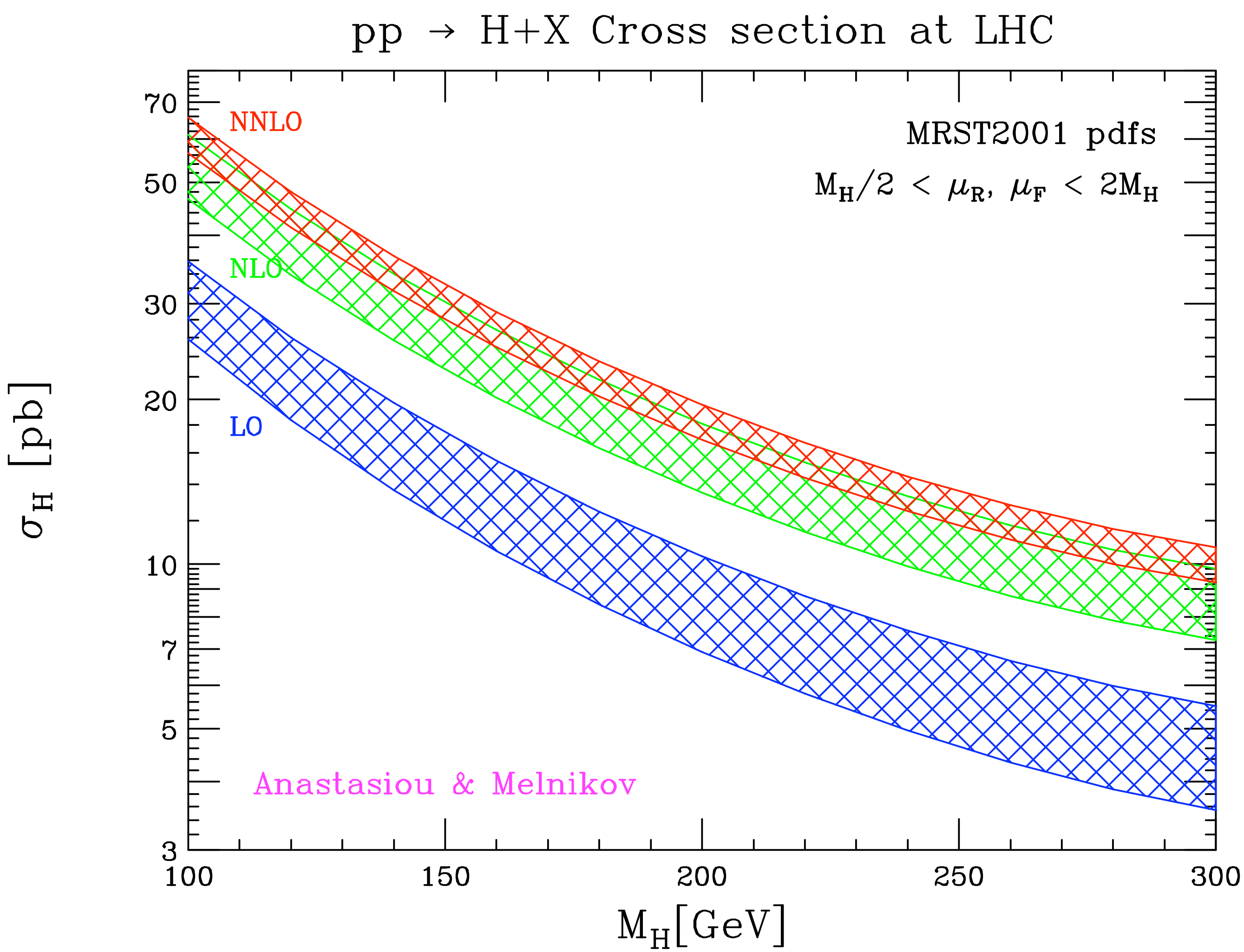
Cuts B $\longrightarrow |\eta^{(e)}| < 2.5,\ p_T^{(e)} > 40$ GeV, $p_T^{(\nu)} > 20$ GeV

	LO		LO+HW	NLO		MC@NLO
Cuts A	0.5249	$\xrightarrow{-7.7\%}$	0.4843	0.4771	$\xrightarrow{+1.5\%}$	0.4845
	$\downarrow 5.4\%$			$\downarrow 7.0\%$		$\downarrow 6.3\%$
Cuts A, no spin	0.5535			0.5104		0.5151
Cuts B	0.0585	$\xrightarrow{+208\%}$	0.1218	0.1292	$\xrightarrow{+2.9\%}$	0.1329
	$\downarrow 29\%$			$\downarrow 16\%$		$\downarrow 18\%$
Cuts B, no spin	0.0752			0.1504		0.1570

- $|\mathrm{MC@NLO} - \mathrm{NLO}| = \mathcal{O}(2\%)$ S. Frixione M.L. Mangano 2004
- NNLO useless without spin correlations
- Precisely evaluated Drell-Yan W, Z cross sections could be used as ``standard candles'' to measure the parton luminosity at LHC

Is NLO enough to describe data ?

Total cross section for inclusive Higgs production at LHC



contour bands are

lower

$\mu_R = 2M_H \quad \mu_F = M_H/2$

upper

$\mu_R = M_H/2 \quad \mu_F = 2M_H$

scale uncertainty is about 10%

NNLO prediction stabilises the perturbative series

NNLO corrections may be relevant if

- the main source of uncertainty in extracting info from data is due to NLO theory: α_S measurements
- NLO corrections are large: Higgs production from gluon fusion in hadron collisions
- NLO uncertainty bands are too large to test theory vs. data: b production in hadron collisions
- NLO is effectively leading order: energy distributions in jet cones

in short, NNLO is relevant where NLO fails to do its job

NNLO state of the art

- Drell-Yan W, Z production
  - total cross section — Hamberg, van Neerven, Matsuura 1990; Harlander, Kilgore 2002
  - rapidity distribution — Anastasiou Dixon Melnikov Petriello 2003
- Higgs production
  - total cross section — Harlander, Kilgore; Anastasiou, Melnikov 2002; Ravindran, Smith, van Neerven 2003
  - fully differential cross section — Anastasiou, Melnikov, Petriello 2004
- $e^+e^- \to 3$ jets
  - the $1/N_c^2$ term — the Gehrmanns, Glover 2004-5

NNLO cross sections

- ## Analytic integration

Hamberg, van Neerven, Matsuura 1990
Anastasiou Dixon Melnikov Petriello 2003

⇑ first method

⇒ flexible enough to include a limited class of acceptance cuts by modelling cuts as ``propagators''

- ## Sector decomposition

Denner Roth 1996; Binoth Heinrich 2000
Anastasiou, Melnikov, Petriello 2004

⇑ flexible enough to include any acceptance cuts

⇑ cancellation of divergences is performed numerically

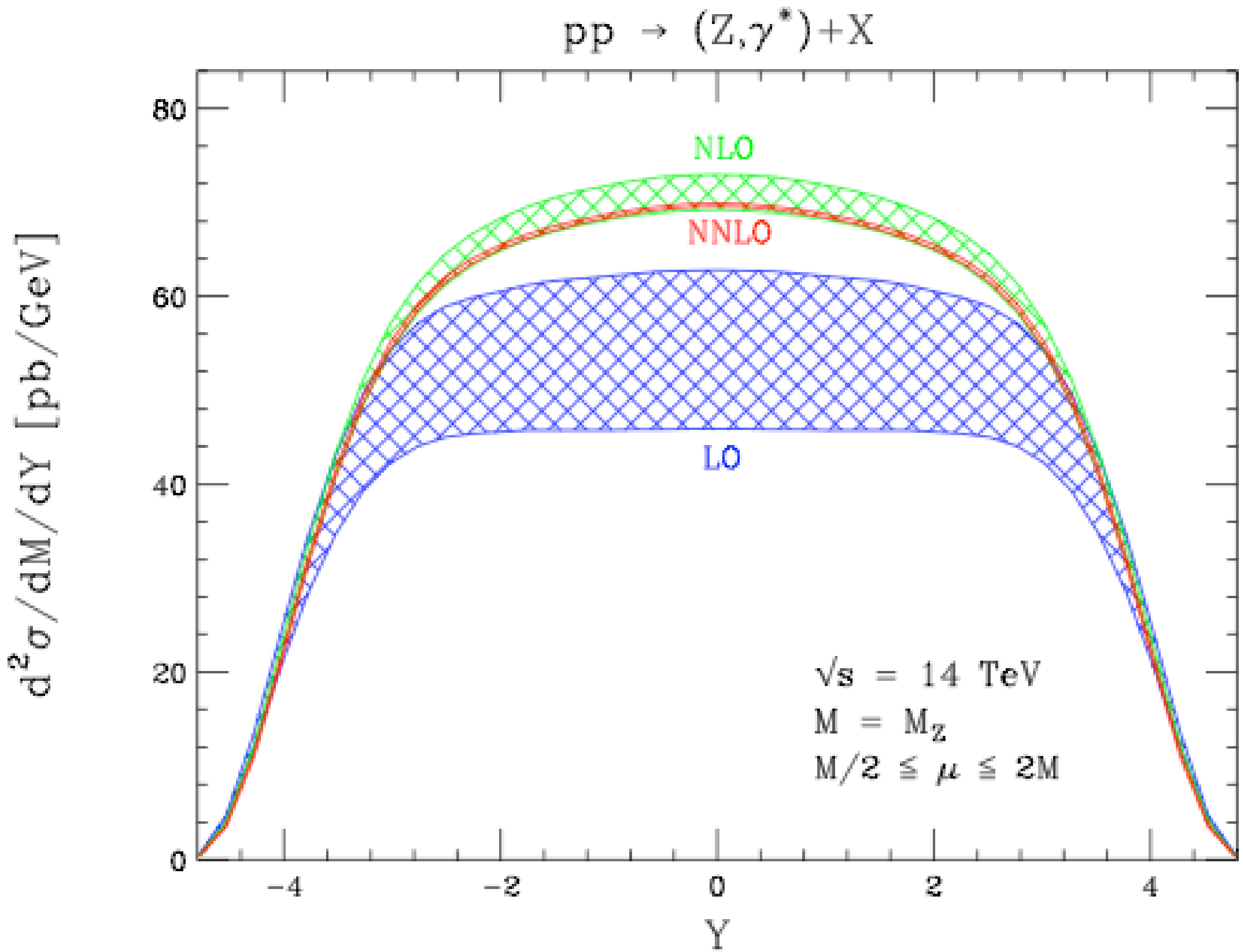
⇒ can it handle many final-state partons ?

- ## Subtraction

⇑ process independent

⇒ cancellation of divergences is semi-analytic
can it be fully automatised ?

Drell-Yan Z production at LHC

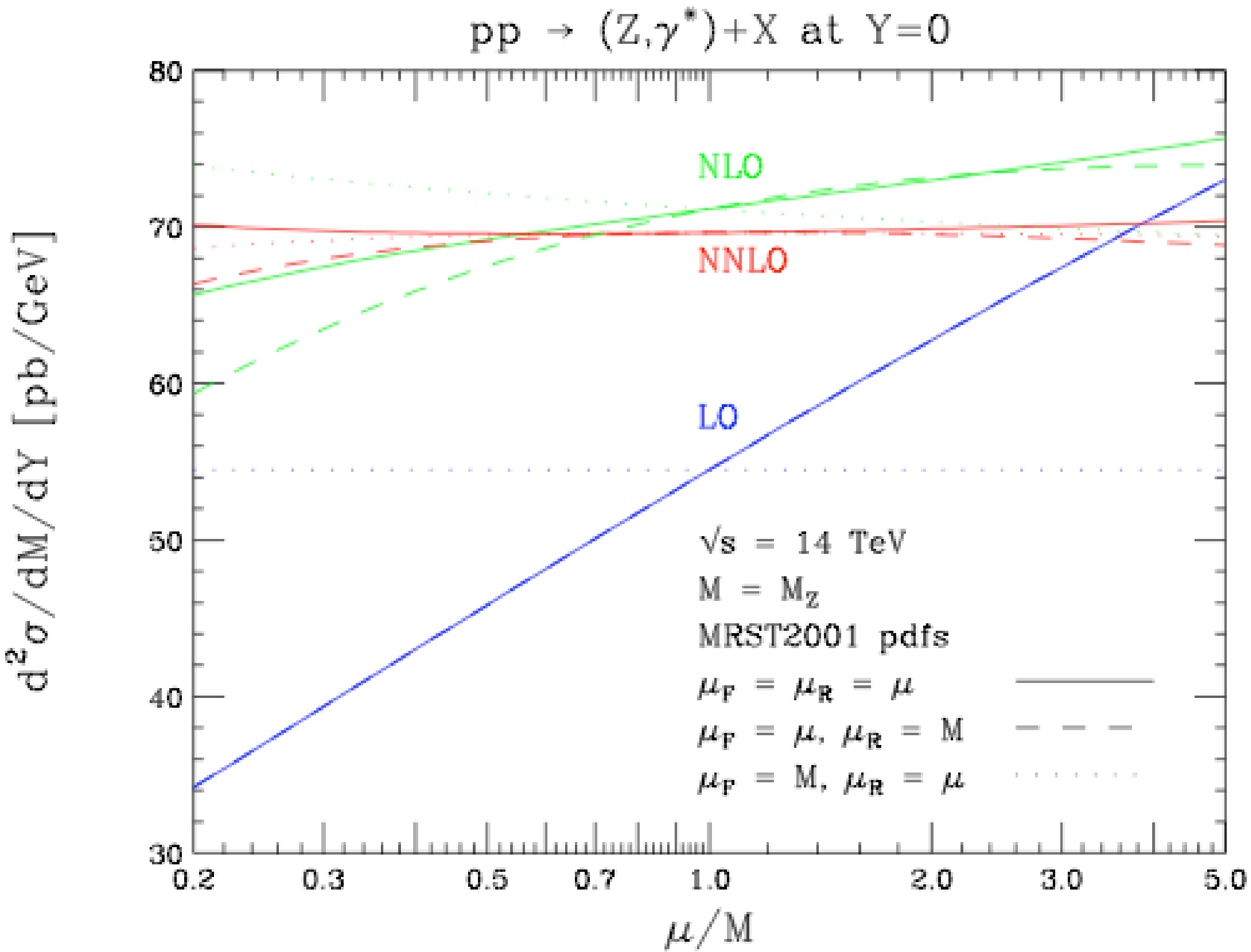


Rapidity distribution for an on-shell Z boson

- $30\%(15\%)$ NLO increase wrt to LO at central Y's (at large Y's) NNLO decreases NLO by $1-2\%$
- scale variation: $\approx 30\%$ at LO; $\approx 6\%$ at NLO; less than 1% at NNLO

C. Anastasiou L. Dixon K. Melnikov F. Petriello 2003

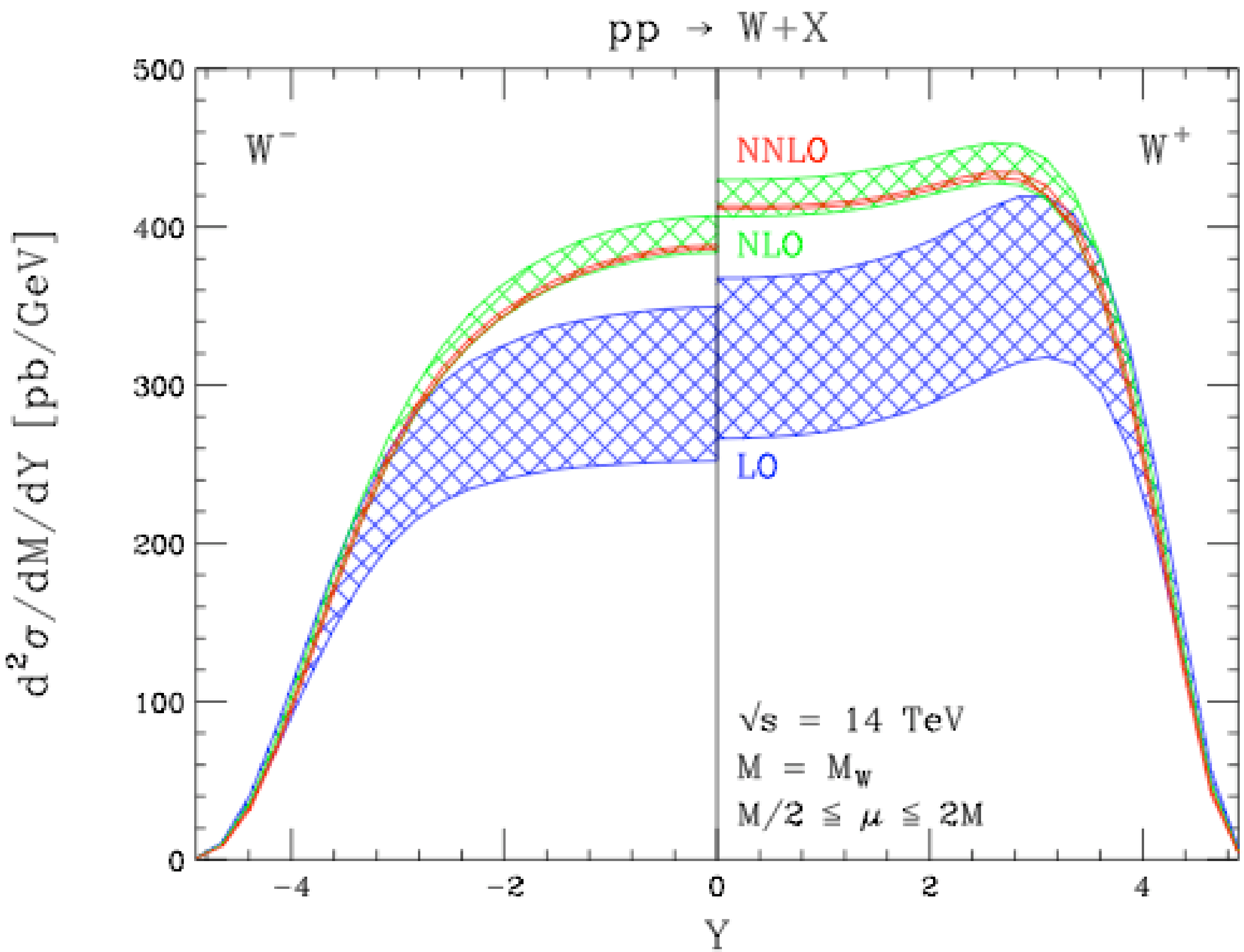
Scale variations in Drell-Yan Z production



- solid: vary μ_R and μ_F together
- dashed: vary μ_F only
- dotted: vary μ_R only

C. Anastasiou L. Dixon K. Melnikov F. Petriello 2003

Drell-Yan W production at LHC



Rapidity distribution for an on-shell W^- boson (left) W^+ boson (right)

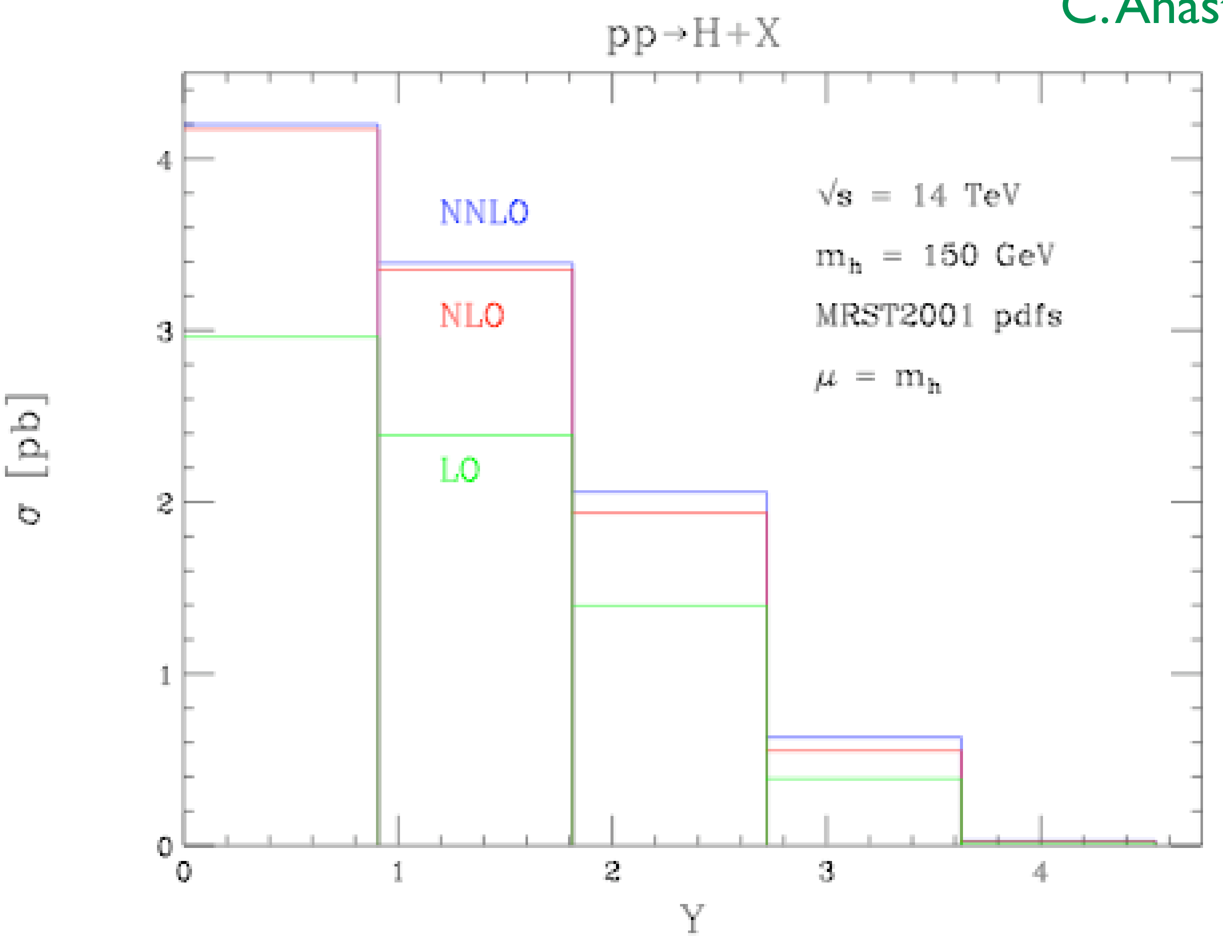
- distributions are symmetric in Y
- NNLO scale variations are $1\%(3\%)$ at central (large) Y

C. Anastasiou L. Dixon K. Melnikov F. Petriello 2003

Higgs production at LHC

a fully differential cross section:
bin-integrated rapidity distribution, with a jet veto

C. Anastasiou K. Melnikov F. Petriello 2004



jet veto: require

$$R = 0.4$$

$$|\mathbf{p}_T^j| < p_T^{veto} = 40 \text{ GeV}$$

for 2 partons

$$R_{12}^2 = (\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2$$

if $R_{12} > R$

$$|\mathbf{p}_T^1|, |\mathbf{p}_T^2| < p_T^{veto}$$

if $R_{12} < R$

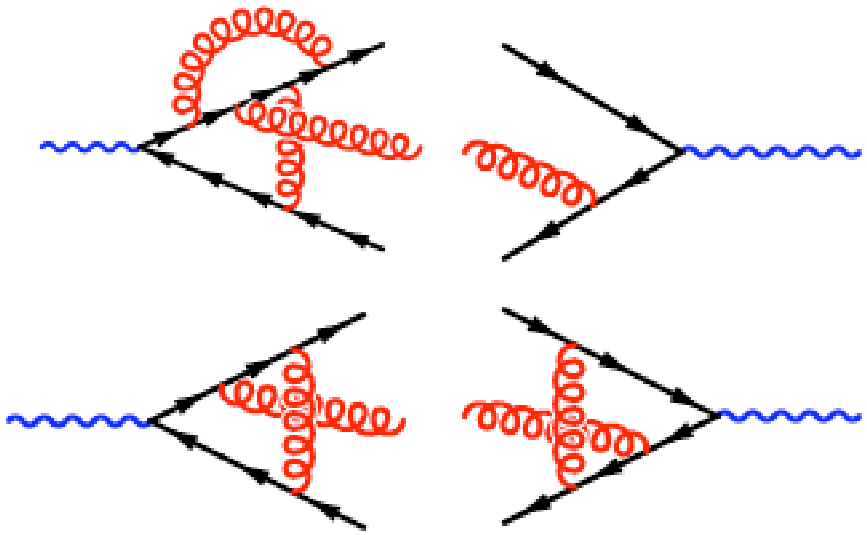
$$|\mathbf{p}_T^1 + \mathbf{p}_T^2| < p_T^{veto}$$

- $M_H = 150$ GeV (jet veto relevant in the $H \to W^+W^-$ decay channel)
- K factor is much smaller for the vetoed x-sect than for the inclusive one: average $|\mathbf{p}_T^j|$ increases from NLO to NNLO: less x-sect passes the veto

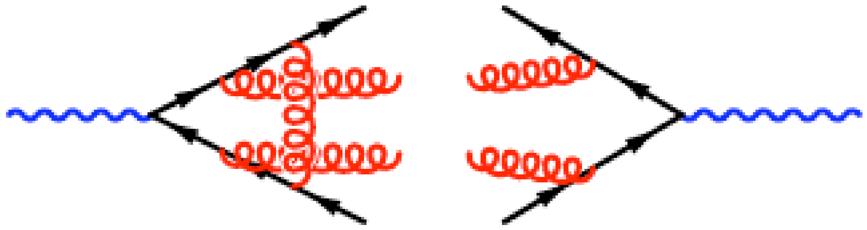
NNLO assembly kit

$e^+e^- \to 3$ jets

double virtual



real-virtual



double real

Two-loop matrix elements

- two-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. Tejeda-Yeomans 2000-01

  Z. Bern A. De Freitas L. Dixon 2002

- photon-pair production $q\bar{q} \to \gamma\gamma, \; gg \to \gamma\gamma$

  C. Anastasiou N. Glover M. Tejeda-Yeomans 2002
  Z. Bern A. De Freitas L. Dixon 2002

- $e^+e^- \to 3$ jets $\quad \gamma^* \to q\bar{q}g$

  L. Garland T. Gehrmann N. Glover A. Koukoutsakis E. Remiddi 2002

- $V + 1$ jet production $q\bar{q} \to Vg$

  T. Gehrmann E. Remiddi 2002

- Drell-Yan V production $q\bar{q} \to V$

  R. Hamberg W. van Neerven T. Matsuura 1991

- Higgs production $gg \to H$ (in the $m_t \to \infty$ limit)

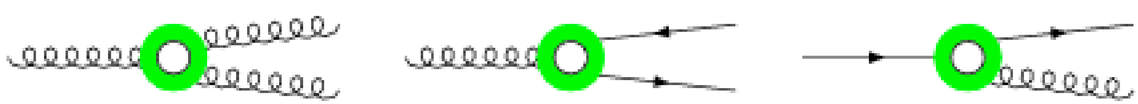
  R. Harlander W. Kilgore; C. Anastasiou K. Melnikov 2002

NNLO cross sections

- universal IR structure ⟹ process-independent procedure
- universal collinear and soft currents
  - 3-parton tree splitting functions

J. Campbell N. Glover 1997; S. Catani M. Grazzini 1998; A. Frizzo F. Maltoni VDD 1999; D. Kosower 2002

  - 2-parton one-loop splitting functions



Z. Bern L. Dixon D. Dunbar D. Kosower 1994;
Z. Bern W. Kilgore C. Schmidt VDD 1998-99;
D. Kosower P. Uwer 1999; D. Kosower 2003

- universal subtraction counterterms
  - several ideas and works in progress

D. Kosower; S. Weinzierl; the Gehrmanns & G. Heinrich 2003
S. Frixione M. Grazzini 2004; G. Somogyi Z. Trocsanyi VDD 2005

  - but completely figured out only for $e^+e^- \to 3$ jets

the Gehrmanns & N. Glover 2005

Conclusions

- QCD is an extensively developed and tested gauge theory
- a lot of progress in the last 4-5 years in
  - MonteCarlo generators
  - NLO cross sections with one more jet
  - NNLO computations
- better and better approximations of signal and background for Higgs and New Physics