QCD at the LHC

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Physics at the Terascale

Helmholtz-Alliance workshop

DESY Hamburg

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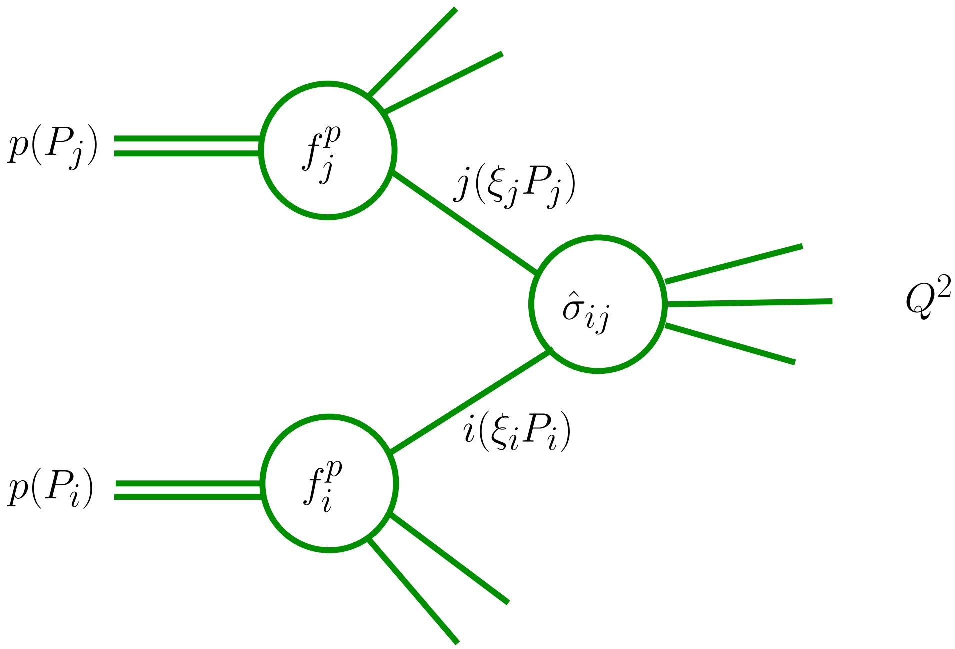
Present Status of QCD

- ✓ Thanks to LEP, HERA and the TEVATRON
  QCD now firmly established theory of strong interactions
- ✓ We have gained a lot of confidence in comparing theoretical predictions with experimental data
- ✓ No major areas of discrepancies
- ✓ Now prepared to enter a new era of precision physics for QCD

Theoretical Framework - Leading Twist



$$\sigma(Q^2) = \int \sum_{i,j} \left[d\hat{\sigma}_{ij}(\alpha_s(\mu_R), \mu_R^2/Q^2, \mu_F^2/Q^2) \otimes f_i^p(\mu_F) \otimes f_j^p(\mu_F) \right]$$

- ✓ partonic cross sections $d\hat{\sigma}_{ij}$
- ✓ running coupling $\alpha_s(\mu_R)$
- ✓ parton distributions $f_i(x, \mu_F)$
- ✓ renormalization/factorization scale μ_R, μ_F
- ✓ + parton shower + hadronisation model + underlying event + ...

The challenge

- ✓ Everything at the LHC (signals, backgrounds, luminosity measurement) involves QCD
- ✓ Strong coupling is not small: $\alpha_s(M_Z) \sim 0.12$ and running is important
  - ⇒ events have high multiplicity of hard partons
  - ⇒ each hard parton fragments into a cluster of collimated particles jet
  - ⇒ higher order perturbative corrections can be large
  - ⇒ theoretical uncertainties can be large
- ✓ Processes can involve multiple energy scales: e.g. p_T^W and M_W
  - ⇒ may need resummation of large logarithms
- ✓ Parton/hadron transition introduces further issues, but for suitable (infrared safe) observables these effects can be minimised
  - ⇒ importance of infrared safe jet definition
  - ⇒ accurate modelling of underlying event, hadronisation, ...

What is covered in this talk

Will focus on status of fixed order parton-level predictions

- ✓ Systematic to higher order/higher multiplicity in perturbation theory
- ✓ Appropriate for hard well separated final states
- ✓ Lead to a systematic reduction in renormalisation/factorisation scale uncertainties
- ✓ Many recent theoretical developments and new calculations/numerical programmes available

caveat Parton-level, relies on matching to experimental observables
e.g. merging with parton showers, etc

CKKW, MLM, MCNLO, POWHEG

✗ No time for many important topics;

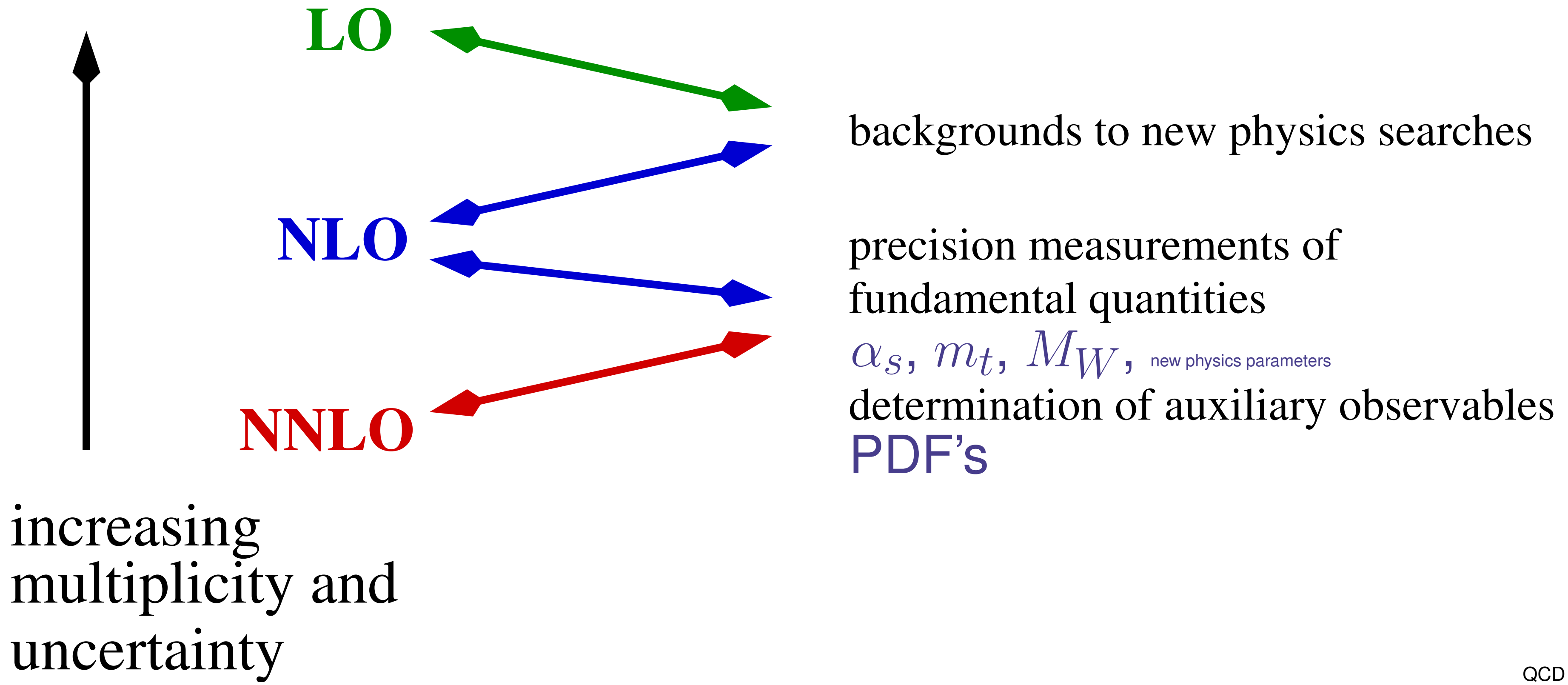
- ✗ parton distributions
- ✗ soft gluon resummation
- ✗ small x issues
- ✗ central exclusive diffractive production
- ✗ studies of jet definitions; fast k_T algorithm, infrared safe cone algorithms,...

Salam et al

Matching onto Physics Goals

Twin Goals:

1. Identification and study of New Physics
2. Precision measurements (e.g. α_s, PDF's) leading to improved theoretical predictions



State of the Art - at a glance

Relative Order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		NNLO	NLO	LO		
α_s^4				NLO	LO	
α_s^5					NLO	LO

LO Well under control, even for multiparticle final states

NLO Well understood for $2 \to 1$ and $2 \to 2$

NLO Many new $2 \to 3$ calculations, new developments

NLO Still waiting for first $2 \to 4$ LHC cros section

NNLO Recent breakthroughs for inclusive and exclusive $2 \to 1$

NNLO Recent landmark calculation of NNLO splitting functions

Moch, Vermaseren, Vogt

NNLO Still waiting for $2 \to 2$

Leading order

Many available programs for automatic evaluation of LO cross sections

✓ Feynman diagrams: matrix elements automatically generated up to $2 \to 6$
MADGRAPH, COMPHEP, GRACE, ...

✓ Off-shell recursion relations:

Berends, Giele; Caravaglios, Moretti

matrix elements automatically generated up to $2 \to 8$ or more
HELAC, AMEGIC++, ALPHA, ...

✓ (Twistor inspired) On-shell recursion relations:

Cachazo, Svrcek, Witten; Britto, Cachazo, Feng, Witten

AMEGIC++; Dinsdale, Ternick, Weinzierl

✓ plus automatic integration over phase space
HELAC/PHEGAS, MADGRAPH/MADEVENT, SHERPA/AMEGIC++, ALPHA/ALPGEN, ...

✓ very good for estimating importance of various processes in different models - properly populate phase space with multiple hard objects

✓ able to interface with parton showers CKKW in SHERPA, MLM in ALPGEN, ...

Comparison of algorithms

- ✓ On-shell recursion relations (CSW, BCF) yield compact analytic results
- ✓ Numerical implementations show that Berends-Giele (BG) is faster

Final state	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
2g	0.24	0.28	0.28	0.33	0.31	0.26
3g	0.45	0.48	0.42	0.51	0.57	0.55
4g	1.20	1.04	0.84	1.32	1.63	1.75
5g	3.78	2.69	2.59	7.26	5.95	5.96
6g	14.20	7.19	11.90	59.10	27.80	30.60
7g	58.50	23.70	73.60	646	146	195
8g	276	82.10	597	8690	919	1890
9g	1450	270	5900	127000	6310	29700
10g	7960	864	64000		48900	

Duhr, Hoche, Maltoni

- ✓ Remains to be seen whether hybrid can be even faster

Example at LO

Multi-jet production at the LHC using HELAC/PHEGAS

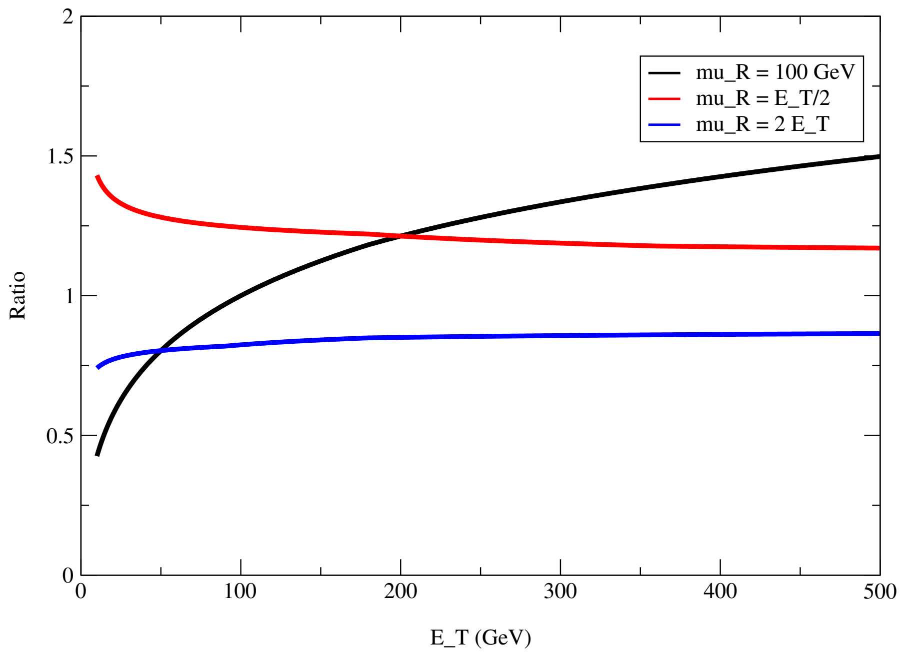
Draggiotis, Kleiss, Papadopoloulos

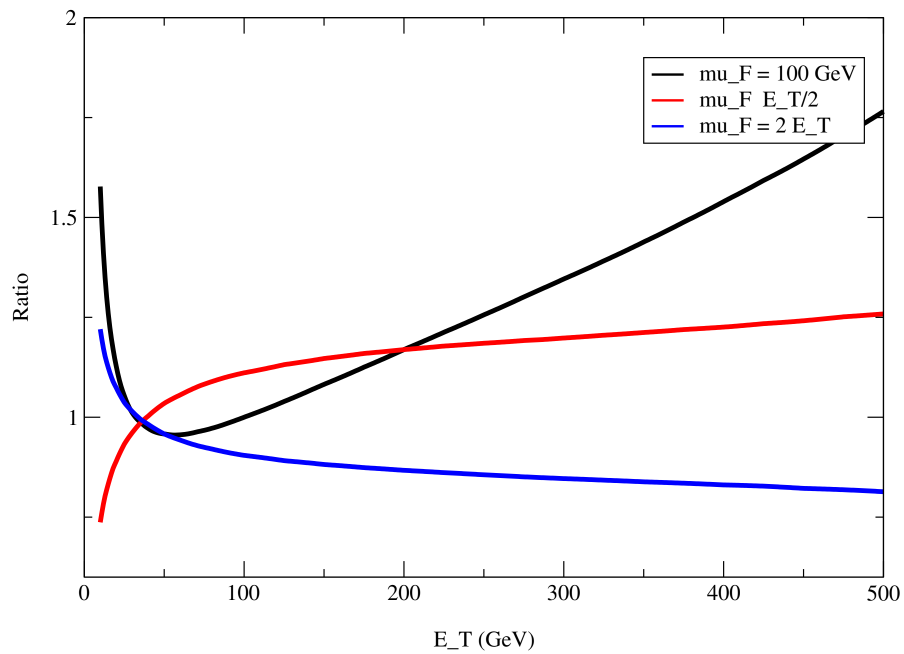
# of jets	2	3	4	5	6	7	8
# of dist.processes	10	14	28	36	64	78	130
total # of processes	126	206	621	861	1862	2326	4342
$\sigma(nb)$	-	91.41	6.54	0.458	0.030	0.0022	0.00021
% Gluonic	-	45.7	39.2	35.7	35.1	33.8	26.6

- ✓ For each final state, there are many distinct contributing processes e.g. $gg \to gg$, $gg \to q\bar{q}$, $q\bar{q} \to gg$, $qg \to qg$, $q\bar{q} \to Q\bar{Q}$, $qQ \to qQ$ etc
- ✓ Assigning different quark flavours gives even more
- ✓ Bookkeeping, phase space generation and evaluation done automatically
- ✓ ALPGEN also very fast for multiparticle SM processes
- ✓ MADGRAPH slower, but adapted for other models, effective H, MSSM, 2HDM, ...

Limitations of LO

Very large uncertainty for multiparticle final states





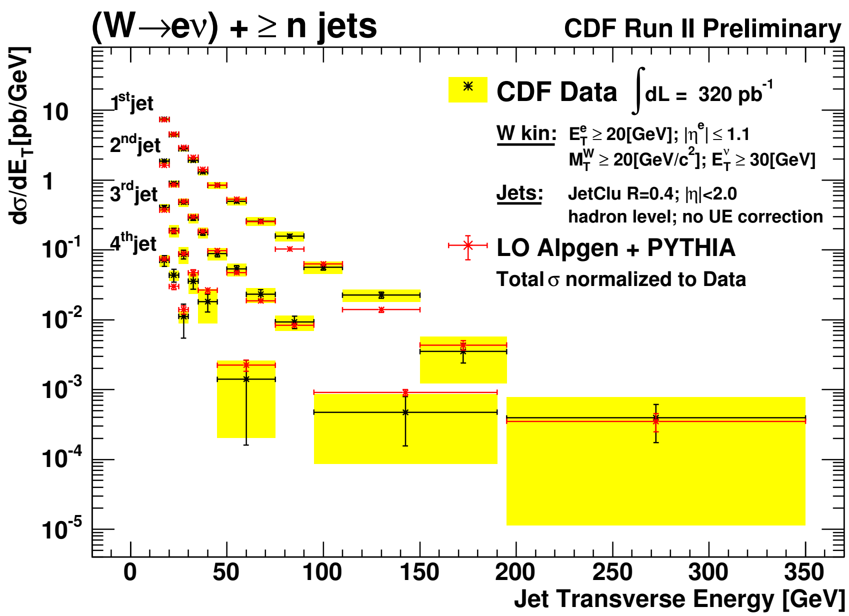
scale uncertainty on α_s^2 parton luminosity uncertainty

✓ New channels open up at higher orders qg + large gluon PDF

✓ Increased phase space

✓ Large π^2 coefficients in s-channel $\Rightarrow$ large NLO corrections 30% - 100%

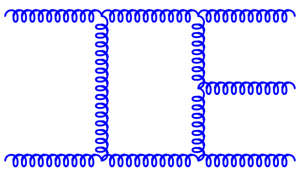
W + Jets at CDF Run II with 320 pb^{-1}



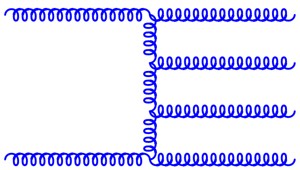
cross sections for the leading jet in $W+\ \geq\ 1$ jet events, second jet in $W+\geq 2$ jets events, etc

- ✓ ALPGEN+PYTHIA merged LO+PS prediction normalised to the inclusive cross section for each jet multiplicity
- ✓ Excellent qualitative agreement

Anatomy of a NLO calculation



- ✓ one-loop $2 \to 3$ process
  looks like 3 jets in final state



- ✓ tree-level $2 \to 4$ process
  looks like 3 or 4 jets in final state
- ✓ plus method for combining the infrared divergent parts - dipole subtraction

Catani, Seymour; Dittmaier, Trocsanyi, Weinzierl, Phaf

- ✓ automated dipole subtraction

Gleisberg, Krauss; Weinzierl

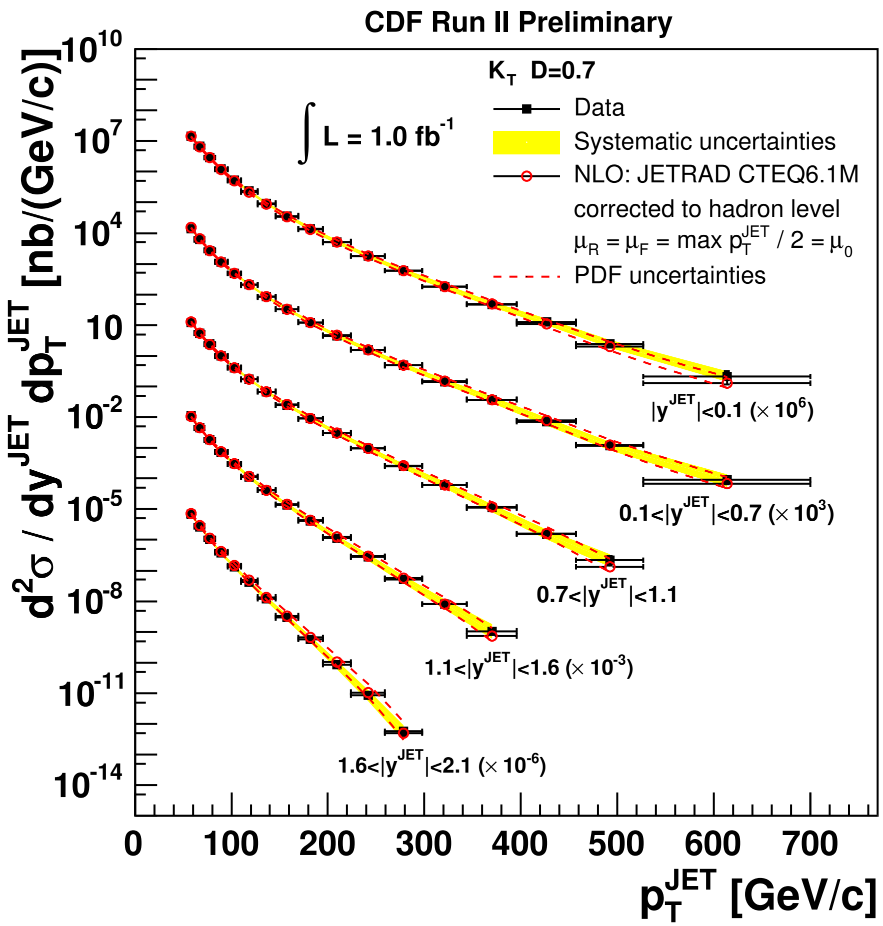
Bottleneck: one-loop matrix elements

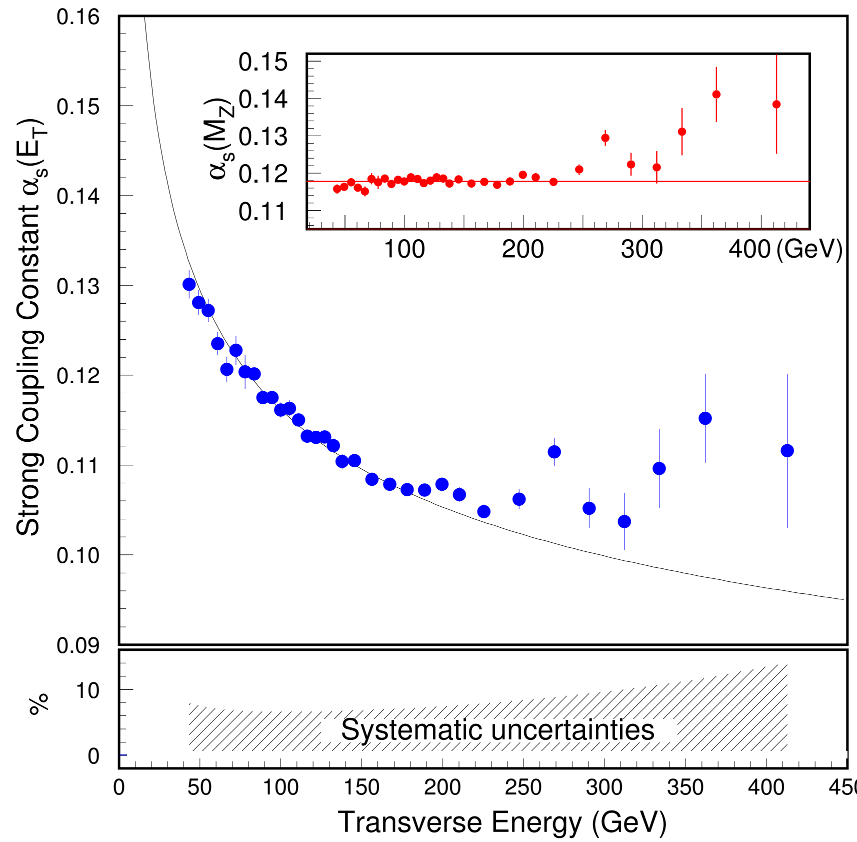
Availability of NLO calculations

- ✓ $2 \to 2$ processes
  - ✓ parton level integrators available for all $2 \to 2$ Standard Model and MSSM processes for some time
  - ✓ extensively used at LEP, TEVATRON and HERA
    EVENT, JETRAD, MCFM, DISENT, DIPHOX, HQQB, NLOJET++, VBFNLO etc
  - ✓ can be matched with parton shower MC@NLO, POWHEG – Frixione, Webber; Nason, Oleari, Ridolfi; Krämer, Soper
- ✓ $2 \to 3$ processes
  - ✓ many $2 \to 3$ processes now available at NLO
    e.g. backgrounds $pp \to 3$ jets, $V + 2$ jets, $\gamma\gamma$ + jet, $V + b\bar{b}$, VV + jet, $t\bar{t}$+ jet
    as well as signals $pp \to t\bar{t}H$, $b\bar{b}H$, $H + 2$ jets, HHH, $t\bar{t}$+jet

  http://www.cedar.ac.uk/hepcode
- ✗ no $2 \to 4$ LHC cross sections known (yet)

Inclusive Jet Production using the Kt Algorithm





Single jet inclusive differential cross section in different rapidity slices

✓ Described by NLO QCD

✓ Excellent quantitative agreement $\Longrightarrow$ Run I α_s measurement

LHC priority wish list, Les Houches 2005

process	background	status
$pp \to VV + 1$ jet	WBF $H \to VV$	$W^+W^- + 1$ jet, (07)
$pp \to t\bar{t} + b\bar{b}$	$t\bar{t}H$	
$pp \to t\bar{t} + 2$ jets	$t\bar{t}H$	$t\bar{t} + 1$ jet, (07)
$pp \to VV + b\bar{b}$	WBF $H \to VV$, $t\bar{t}H$, new physics	
$pp \to VV + 2$ jets	WBF $H \to VV$	
$pp \to V + 3$ jets	new physics	
$pp \to VVV$	SUSY trilepton	ZZZ, (07)

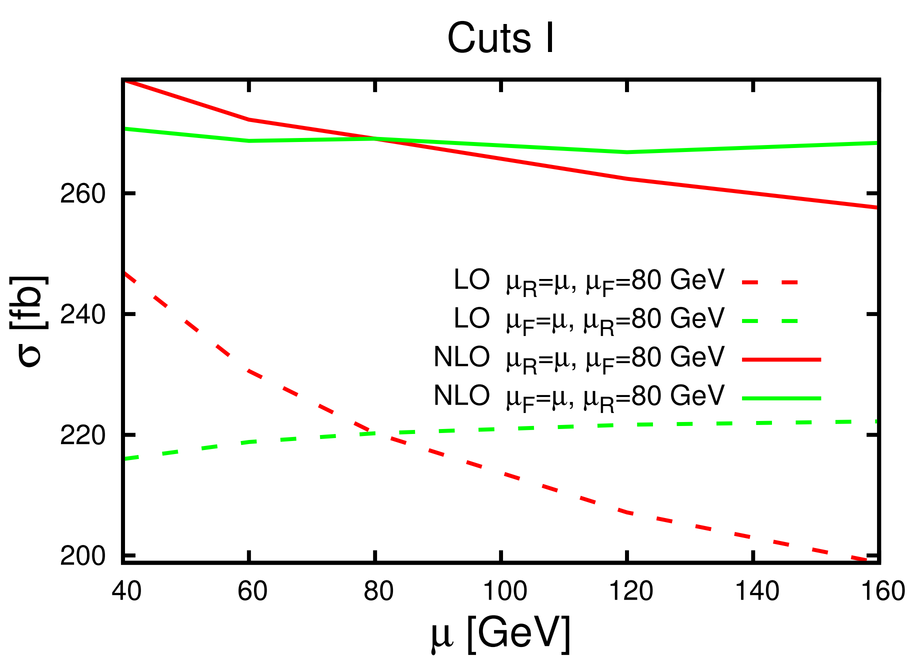
- ✓ A lot of progress in past 18 months - plus
- ✓ $pp \to H + 2$ jets via gluon fusion — Campbell, Ellis, Zanderighi, hep-ph/0608194
- ✓ $pp \to VV + 2$ jets via WBF — Bozzi, Jäger, Oleari, Zeppenfeld, hep-ph/0701105
- ✓ $pp \to H + 2$ jets via WBF, electroweak and QCD corrections — Ciccolini, Denner, Dittmaier, arXiv/0710.4749
- ✓ $pp \to H + 3$ jets via WBF, — Figy, Hankele, Zeppenfeld, arXiv/0710.5621
- ✓ ....

Vector boson pair plus jet

QCD corrections to $pp \to W^+W^-j + X$ recently completed

Dittmaier, Kallweit, Uwer, arXiv/0710.1577; Campbell, Ellis, Zanderighi, arXiv/0710.1832

✓ Background to Higgs in both WBF, GF channels - $H \to W^+W^-$ with one jet missed, or Higgs recoiling against jet



✓ For inclusive cuts, NLO increases cross section by about 25%

✓ Factorisation scale uncertainty small, renormalisation scale uncertainty reduced by $\sim$ 50%

✓ Shapes of NLO inclusive distributions very similar to LO

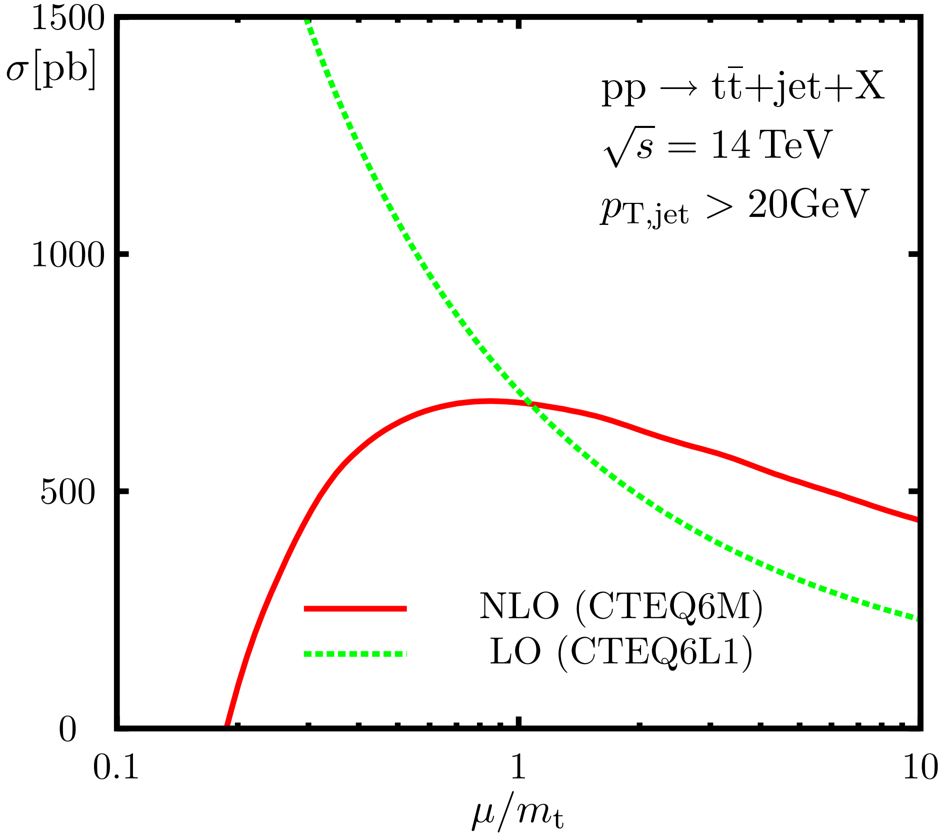
✓ For WBF cuts, with one or both jets forward, WWj is one of dominant backgrounds
NLO increased by $\sim$ 70% cf LO

Top pair plus jet

QCD corrections to $pp \to t\bar{t}j + X$

Dittmaier, Uwer, Weinzierl hep-ph/0703120

- ✓ Background to Higgs in WBF, $t\bar{t}H$ channels
- ✓ measurement of t properties



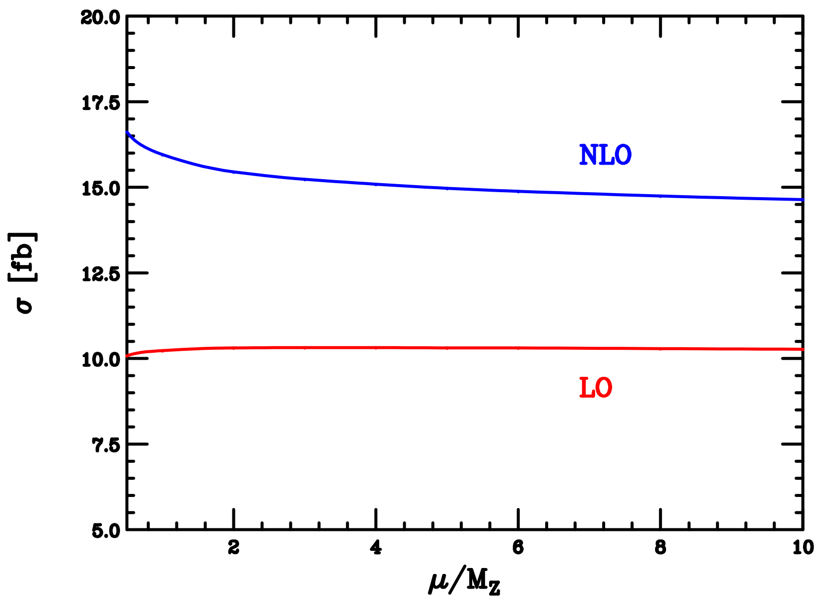
- ✓ Residual scale dependence reduced
- ✓ NLO corrections essentially eliminate forward-backward charge asymmetry at Tevatron

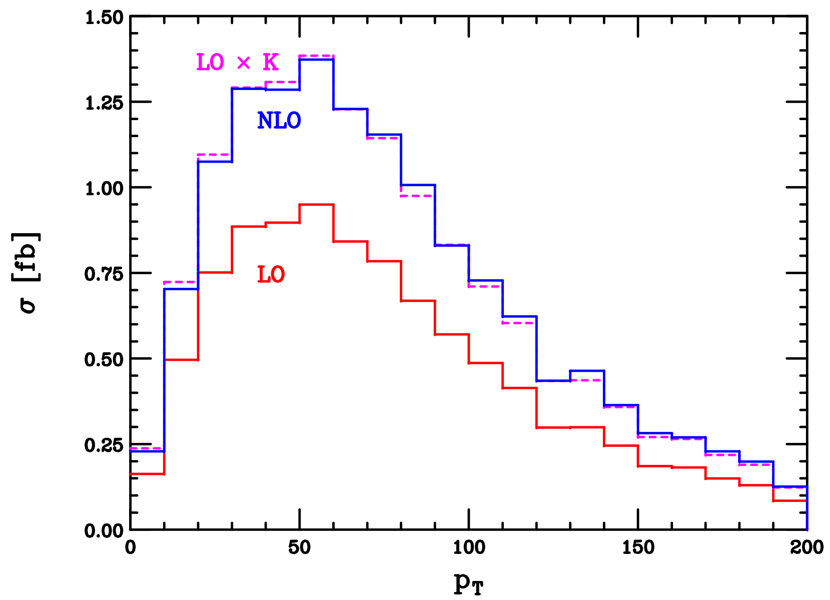
Triple Vector Boson Production

QCD corrections to $pp \to ZZZ + X$

Lazopoulos, Melnikov, Petriello, hep-ph/0703273

✓ Background to various SUSY tri-lepton signatures, gauge boson coupling measurments,





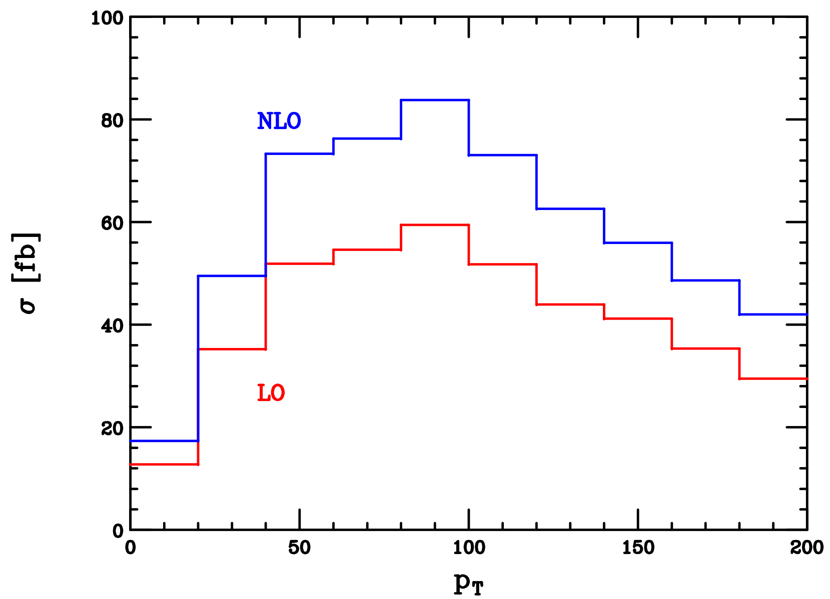
✓ Large, 50% corrections not seen by LO scale variation!
15% shift from pdfs, 35% shift from π^2 terms

Top pair plus Z Production

QCD corrections to $gg \to t\bar{t}Z + X$

Lazopoulos, Melnikov, Petriello, arXiv/0709.4044

- ✓ Background to various SUSY tri-lepton signatures, gauge boson coupling measurments,
- ✓ Fully numerical calculation - using sector decomposition and contour deformation
- ✓ First step towards $pp \to t\bar{t}Z$
- ✓ For reasonable choices of μ, corrections as large as 75%



The one-loop problem

Any one-loop integral can be written as

$$\mathcal{M} = \sum a(D)\mathrm{boxes} + \sum b(D)\mathrm{triangles} + \sum c(D)\mathrm{bubbles} + \sum d(D)\mathrm{tadpoles}$$

- ✓ most of the scalar loop integrals boxes etc are known analytically
- ✓ only problem is to compute the D-dimensional coefficients $a(D)$ etc.

Sometimes its better to compute

$$\mathcal{M} = \sum a(4)\mathrm{boxes} + \sum b(4)\mathrm{triangles} + \sum c(4)\mathrm{bubbles} + \sum d(4)\mathrm{tadpoles} + \mathrm{R}$$

where the cofffícients are now 4-dimensional and R is a rational (non-logarithmic) term

The only problem is complexity - the number of terms generated is too large to deal with, even with computer algebra systems, and there can be very large cancellations.

The one-loop problem - continued

Lots of ideas and strategies

- ✓ Improved tensor reduction: Denner, Dittmaier; Binoth, Guillet, Heinrich, Pilon, Schubert, . . .
- ✓ Numerical evaluation of recursion relations Giele, Ellis, Zanderighi
- ✓ 4-d Unitarity and cut constructibility Bern, Dixon, Dunbar, Kosower; Britto, Cachazo, Feng; . . .
- ✓ D-dimensional unitarity Anastasiou, Britto, Cachazo, Feng, Kunszt, Mastrolia
- ✓ Numerical loop integration: accuracy only has to match real emission contribution Nagy, Soper, hep-ph/0610028
  Sector decomposition plus contour deformation automated by Anastasiou, Beerli, Daleo, hep-ph/0703282
- ✓ Reduction of the integrand
  Ossola, Papadopoulos, Pittau, hep-ph/0609007; Ellis, Giele, Kunszt, arXiv/0708.2398
- ✓ . . . . . .

Testing ground: Six-photon amplitude hep-ph/0610028, hep-ph/0703311 hep-ph/0704.1271

One-loop six gluon amplitude

✓ Analytic computation
Bedford, Berger, Bern, Bidder, Bjerrum-Bohr, Brandhuber, Britto, Buchbinder, Cachazo, Dixon, Dunbar, Feng, Forde, Kosower, Mastrolia, Perkins, Spence, Travaglini, Xiao, Yang, Zhu

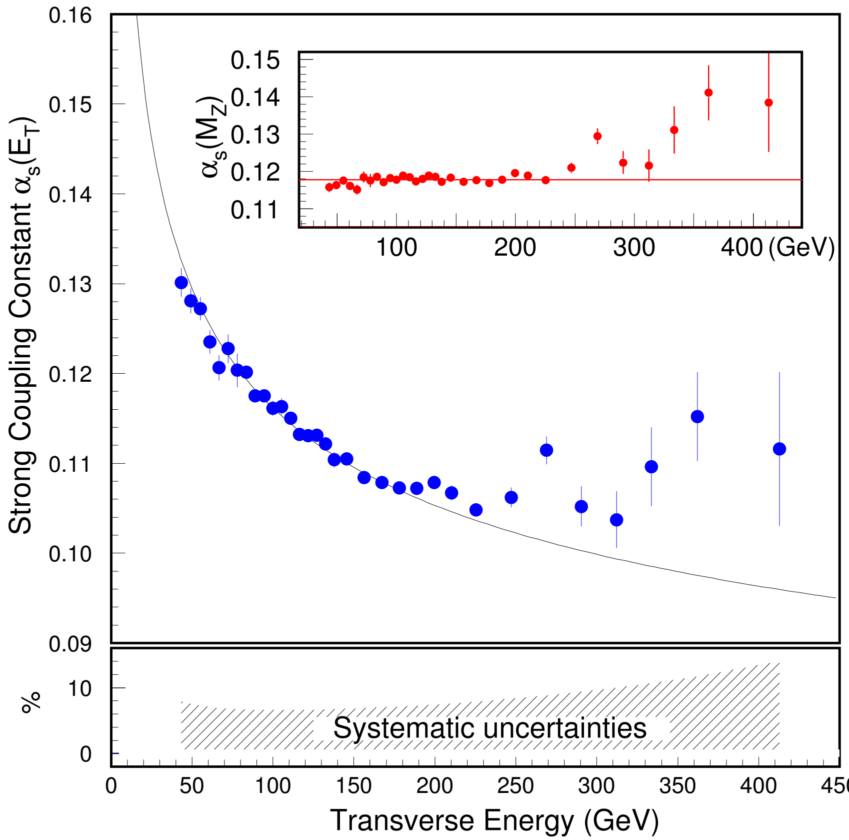
Amplitude	$\mathcal{N}=4$	$\mathcal{N}=1$	$\mathcal{N}=0$ (cut)	$\mathcal{N}=0$ (rat)
$--++++$	BDDK (94)	BDDK (94)	BDDK (94)	BDK (94)
$-+-+++$	BDDK (94)	BDDK (94)	BBST (04)	BBDFK (06), XYZ (06)
$-++-++$	BDDK (94)	BDDK (94)	BBST (04)	BBDFK (06), XYZ (06)
$---+++$	BDDK (94)	BDDK (94)	BBDI (05), BFM (06)	BBDFK (06), XYZ (06)
$--+-++$	BDDK (94)	BBDP (05), BBCF (05)	BFM (06)	XYZ (06)
$-+-+-+$	BDDK (94)	BBDP (05), BBCF (05)	BFM (06)	XYZ (06)

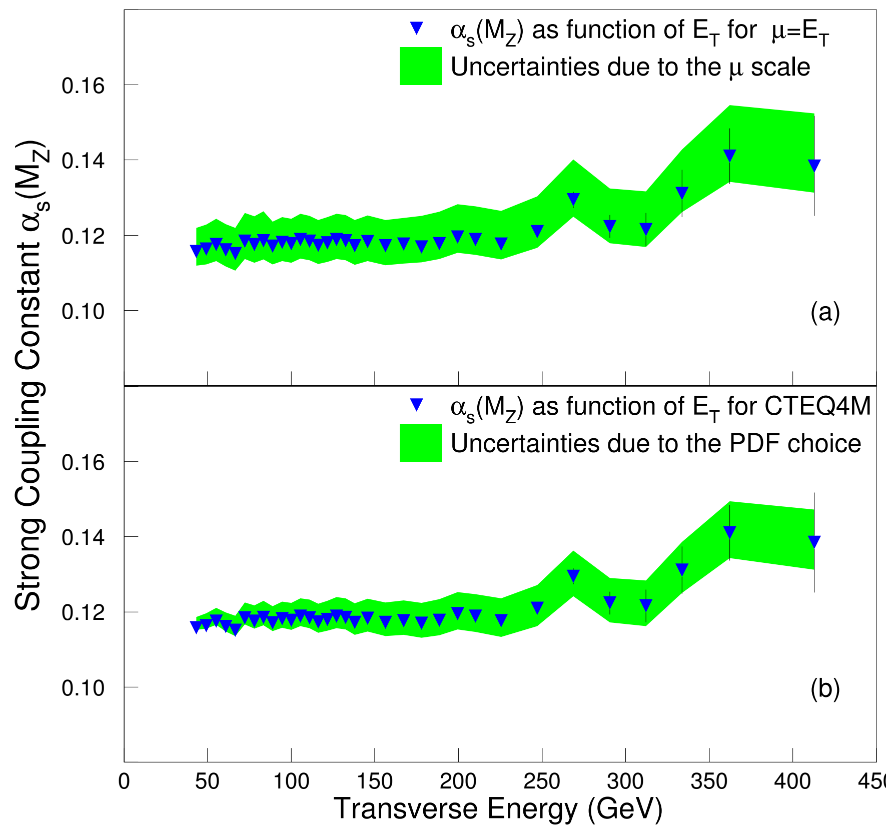
✓ Numerical evaluation via recursion Ellis, Giele, Zanderighi (06)

✓ Numerical evaluation based on unitarity Ellis, Giele, Kunszt (07)

Why go beyond NLO?

In many cases, the uncertainty from the pdf's and from the choice of renormalisation scale still give NLO uncertainties that are as big or bigger than the experimental errors.





$$\alpha_s(M_Z) = 0.1178 \; {}^{+6\%}_{-4\%}(scale) \; {}^{+5\%}_{-5\%}(pdf)$$

Why go beyond NLO? - continued

When is NNLO needed?

- ✓ When corrections are large - e.g. H production
- ✓ For benchmark measurements where experimental errors are small

What is known so far?

- ✓ Inclusive cross sections for W, Z and H production

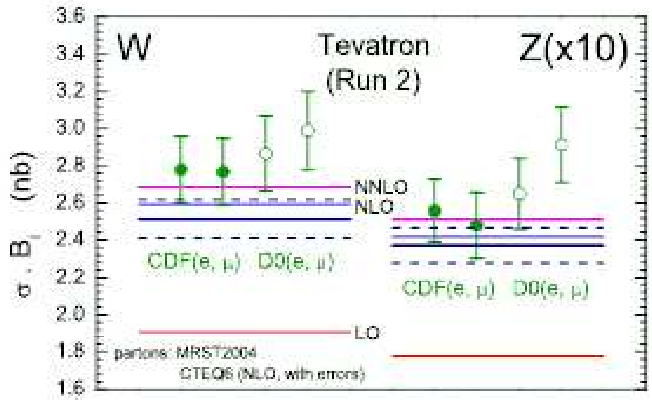
  van Neerven, Harlander, Kilgore, Anastasiou, Melnikov, Ravindram, Smith

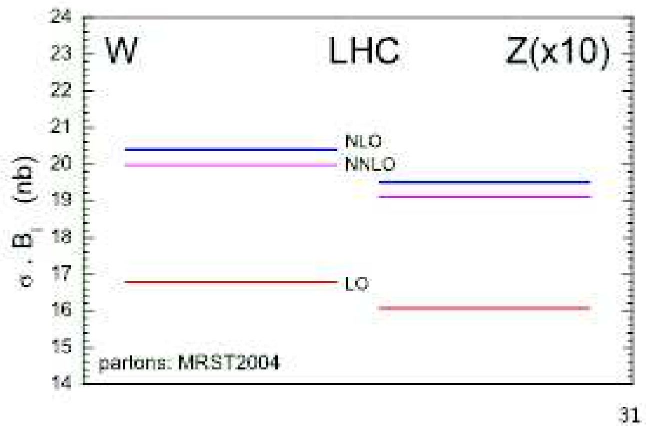
- ✓ Semi-inclusive $2 \to 1$ distributions - W, Z and H rapidity distributions

  Anastasiou, Dixon, Melnikov, Petriello

- ✓ Fully differential $pp \to H, W, Z + X$ — Anastasiou, Melnikov, Petriello
- ✓ DGLAP splitting kernels — Moch, Vermaseren, Vogt
- ✓ NNLO parton distributions — Martin, Stirling, Thorne, Watt

Drell Yan production





Most accurate prediction yet

✓ NNLO splitting functions

✓ NNLO PDF fits

✓ NNLO Drell-Yan cross section

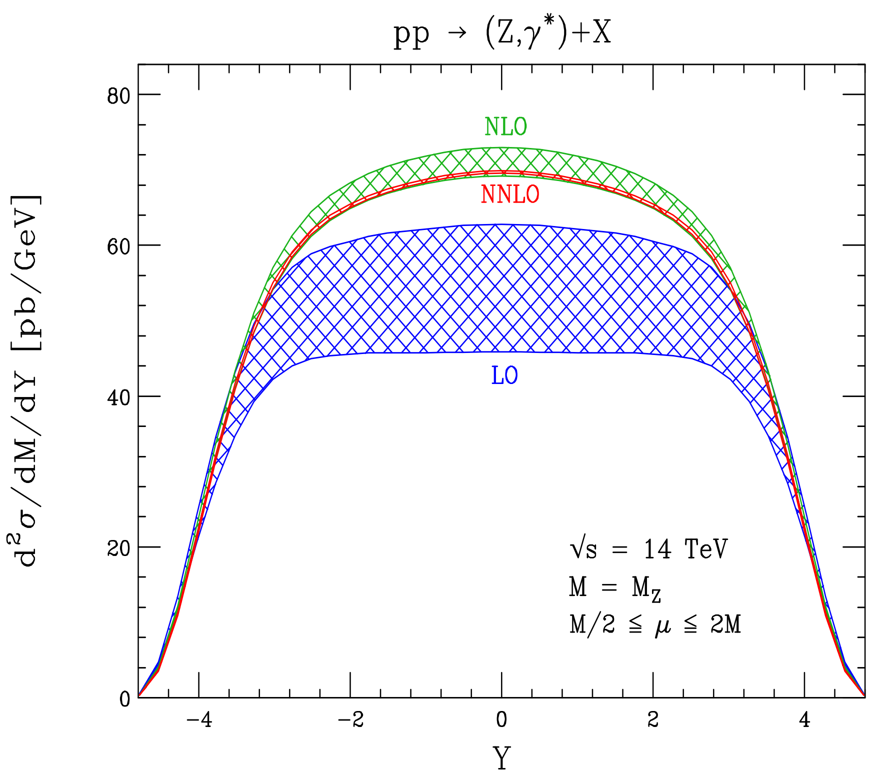
$\Longrightarrow$ High precision

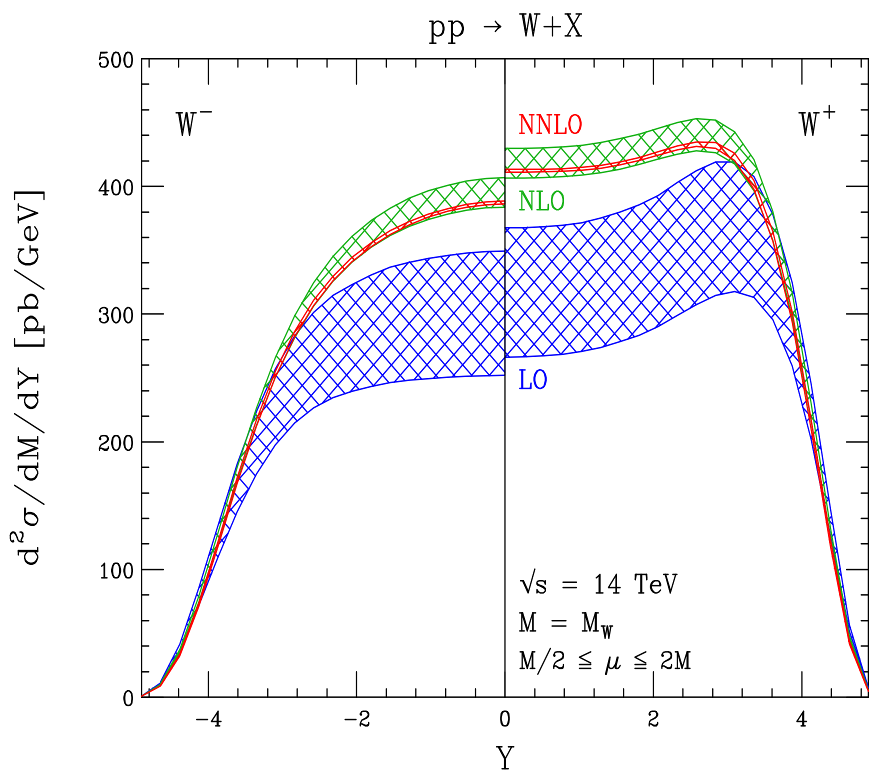
Total error of $4\% - -5.5\%$

Martin et al

Aim to able to use as Standard Candle for luminosity measurements.

Gauge boson production at the LHC





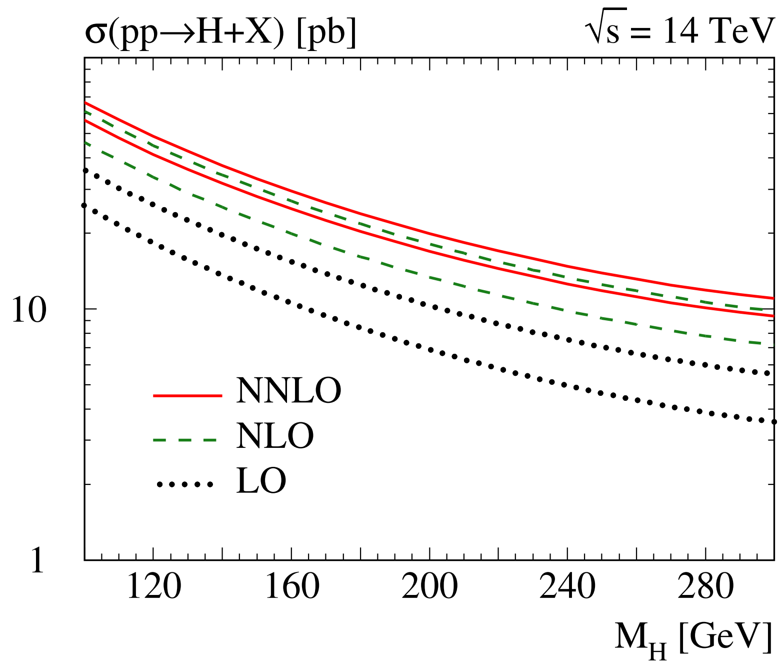
Gold-plated process

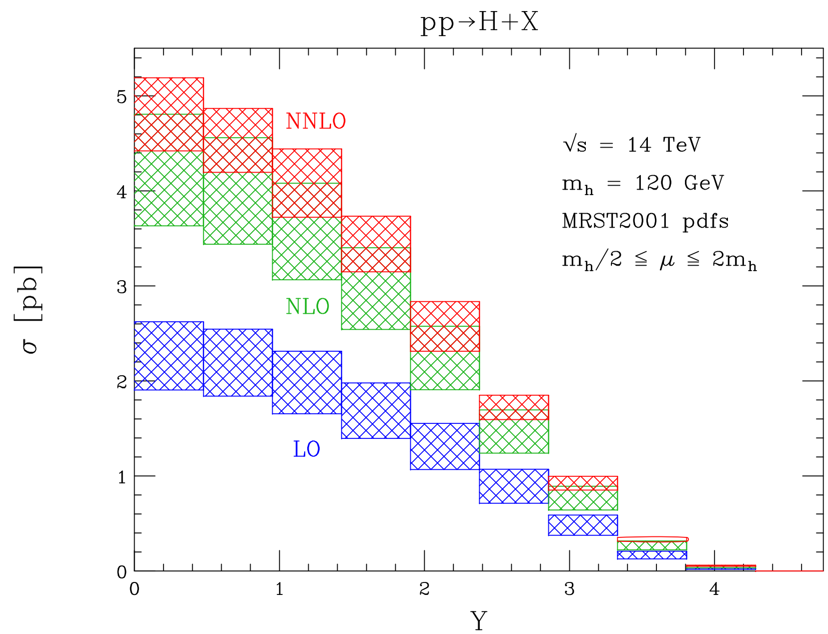
Anastasiou, Dixon, Melnikov, Petriello

At LHC NNLO perturbative accuracy better than 1%

⇒ use to determine parton-parton luminosities at the LHC

Higgs boson production at the LHC





Total cross section

Harlander, Kilgore; Anastasiou, Melnikov, Petriello; . . .

Fully differential

Anastasiou, Melnikov, Petriello

NNLO needed for reliable predictions

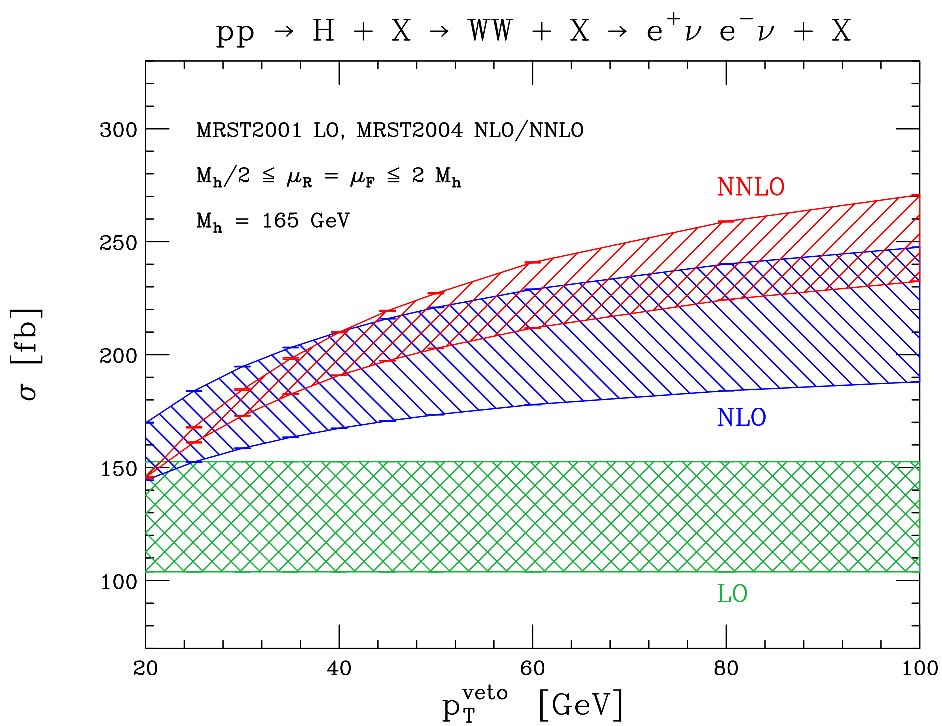
Higgs boson production at the LHC

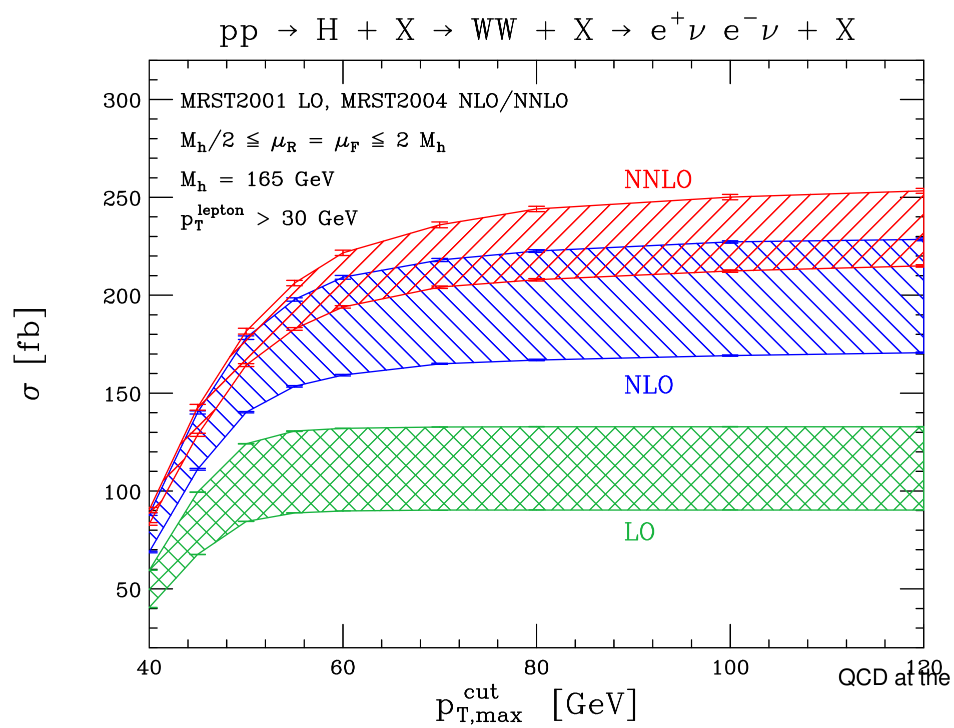
- ✓ First study of fully inclusive $pp \to H \to WW \to \ell\nu\ell\nu$ with $m_H \sim 165$ GeV

  Anastasiou, Dissertori, Stöckli, arXiv/0707.2373

- ✓ Apply experimental cuts to reduce backgrounds from $t\bar{t}$, non-resonant W^+W^- production
- ✓ Cuts affect LO/NLO/NNLO cross sections differently

$\Longrightarrow$ shouldn't use inclusive K-factor





Other NNLO calculations on horizon

- ✓ $pp \to jet$ +X
  - ✓ needed to constraint PDF's and fix strong coupling
  - ✓ matrix elements known for some time

    Anastasiou et al, Bern et al

  - ✓ antenna subtraction terms worked out

    Daleo, Gehrmann, Maitre

- ✓ $pp \to t\bar{t}$
  - ✓ necessary for precise m_t determination
  - ✓ matrix elements recently worked out

    Czakon, Mitov, Moch, arxiv/0707.4139

- ✓ $pp \to VV$
  - ✓ signal: to study the gauge structure of the Standard Model
  - ✓ background: for Higgs boson production and decay in the intermediate mass range
  - ✓ large NLO corrections

    Chachamis, Czakon, Eiras

Summary

QCD A lot still to do, but progress being made towards main targets

LO largely solved (plus BSM models)

✓ high multiplicity merged with parton shower, ALPGEN, SHERPA, ...

✗ large theoretical uncertainty

NLO QCD corrections generally large 30% – 100% - much larger than scale variation suggests

✓ Cuts tend to spoil use of inclusive K-factor

✓ Serious effort on Les Houches NLO wish list, several new NLO calculations this year, WWj, $t\bar{t}j$, ZZZ, $t\bar{t}Z$

✗ ✓ $2 \longrightarrow 4$ barrier yet to be breached for LHC, but several new techniques available

NNLO Inclusive and exclusive results for H, W, Z production

✓ DGLAP splitting kernels $\Longrightarrow$ NNLO PDF fits

✗ ✓ $2 \longrightarrow 2$ calculations coming onto horizon

✓ Crucial role of Loops and Legs workshops in stimulating community