Prospects for NNLO measurements using jets at the LHC

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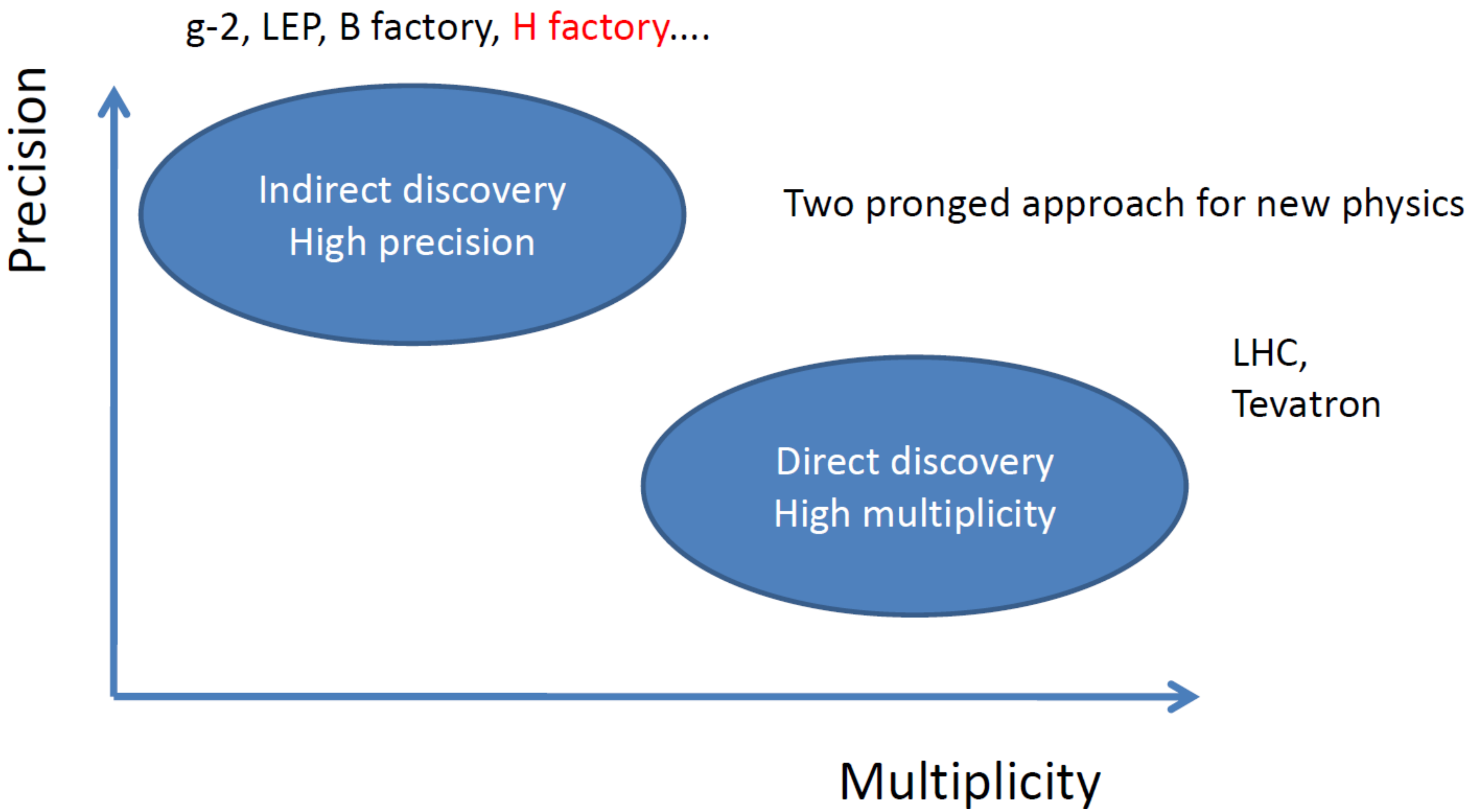
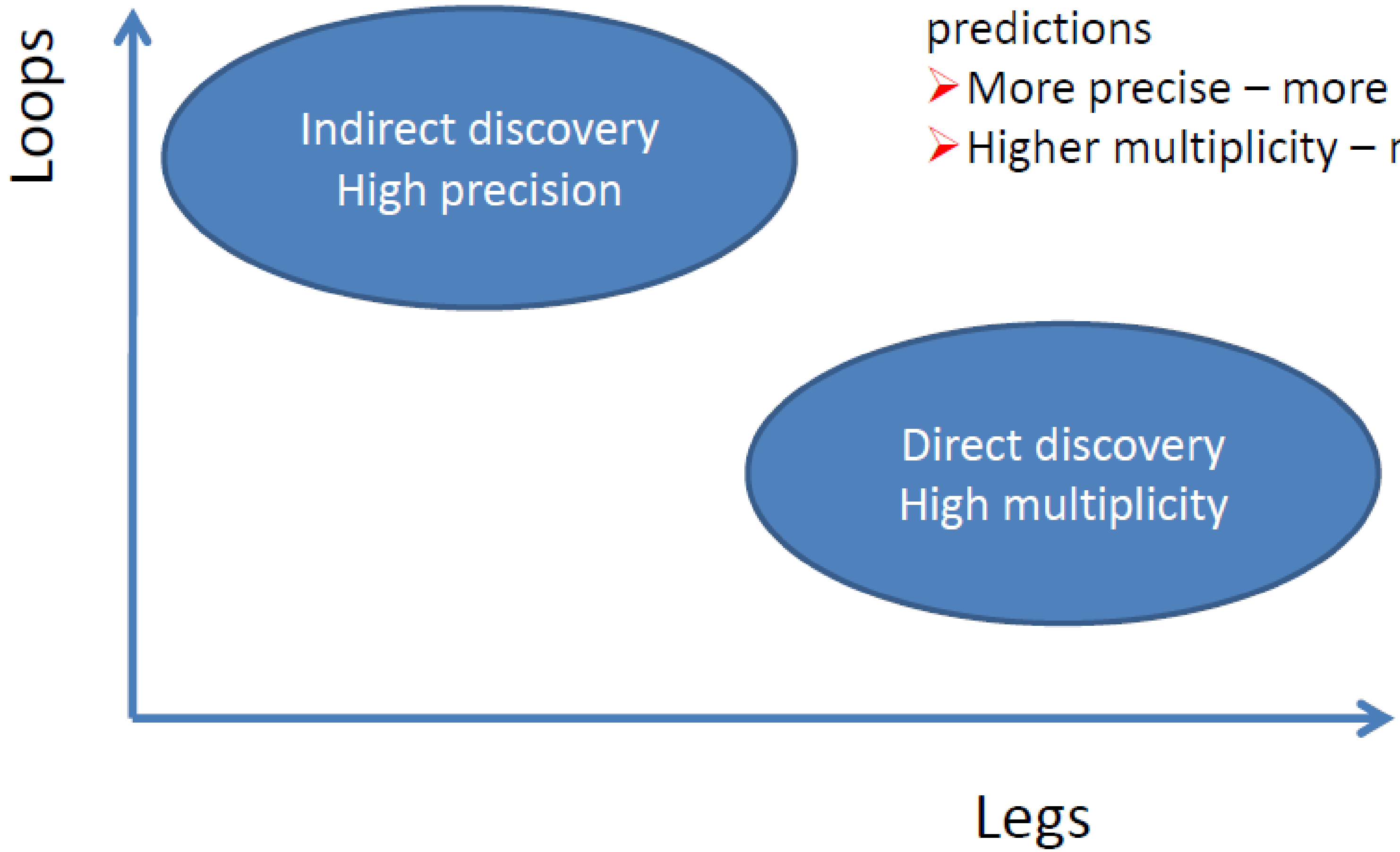
Contents

- Overview
- Status of fixed order parton-level predictions
- Motivation for NNLO corrections to LHC processes
- Applications to LHC processes
  - and what to measure to make the most of improved theoretical and experimental precision
- Outlook

The HEP Arena



The Task for Theoretical HEP



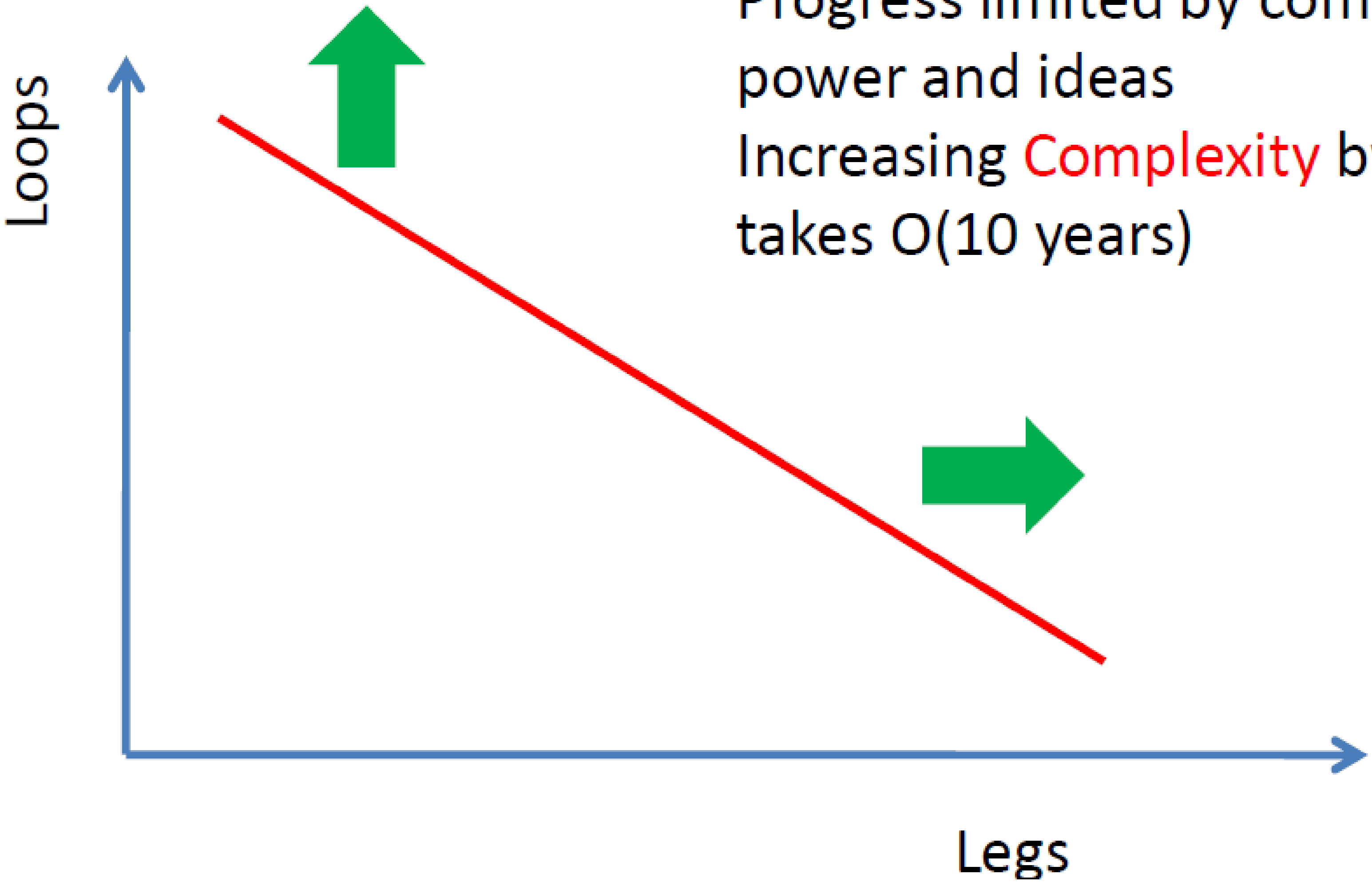
Perturbative field theory provides a systematic basis for making predictions

- More precise – more loops
- Higher multiplicity – more legs

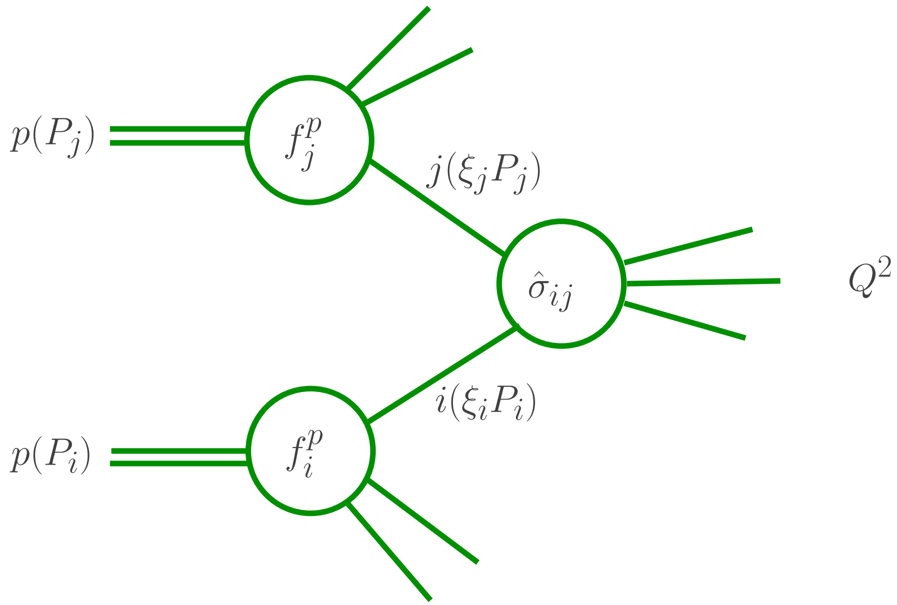
Complexity ∼ #legs + #loops

Progress limited by computing power and ideas

Increasing Complexity by 1 unit takes O(10 years)



Theoretical Framework



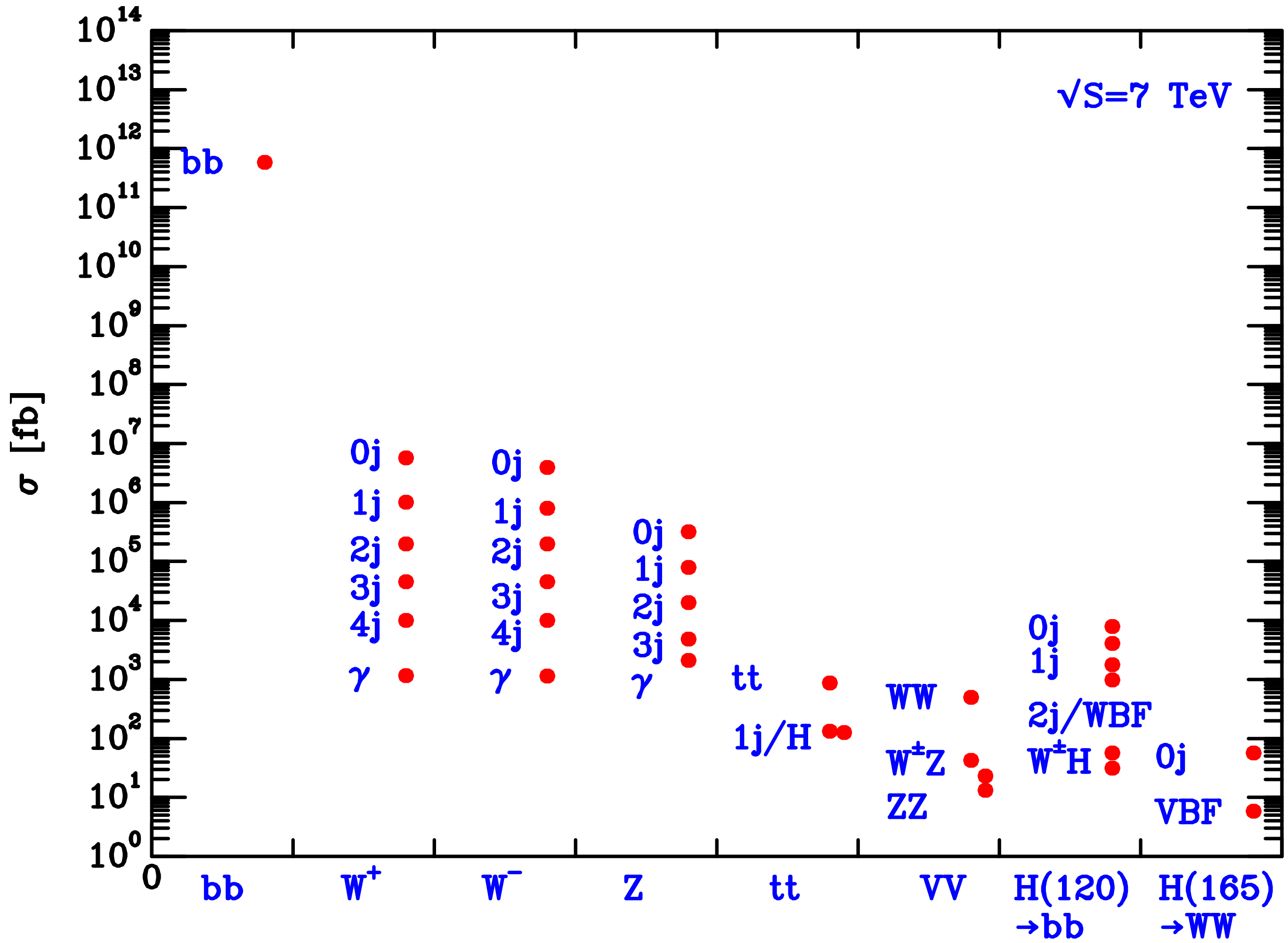
$$\sigma(Q^2) = \int \sum_{i,j} \left[d\hat{\sigma}_{ij}(\alpha_s(\mu_R), \mu_R^2/Q^2, \mu_F^2/Q^2) \otimes f_i^p(\mu_F) \otimes f_j^p(\mu_F) \right]$$

- ✓ 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
- ✓ jet algorithm + 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, ...

SM cross sections at the LHC Ellis (10)

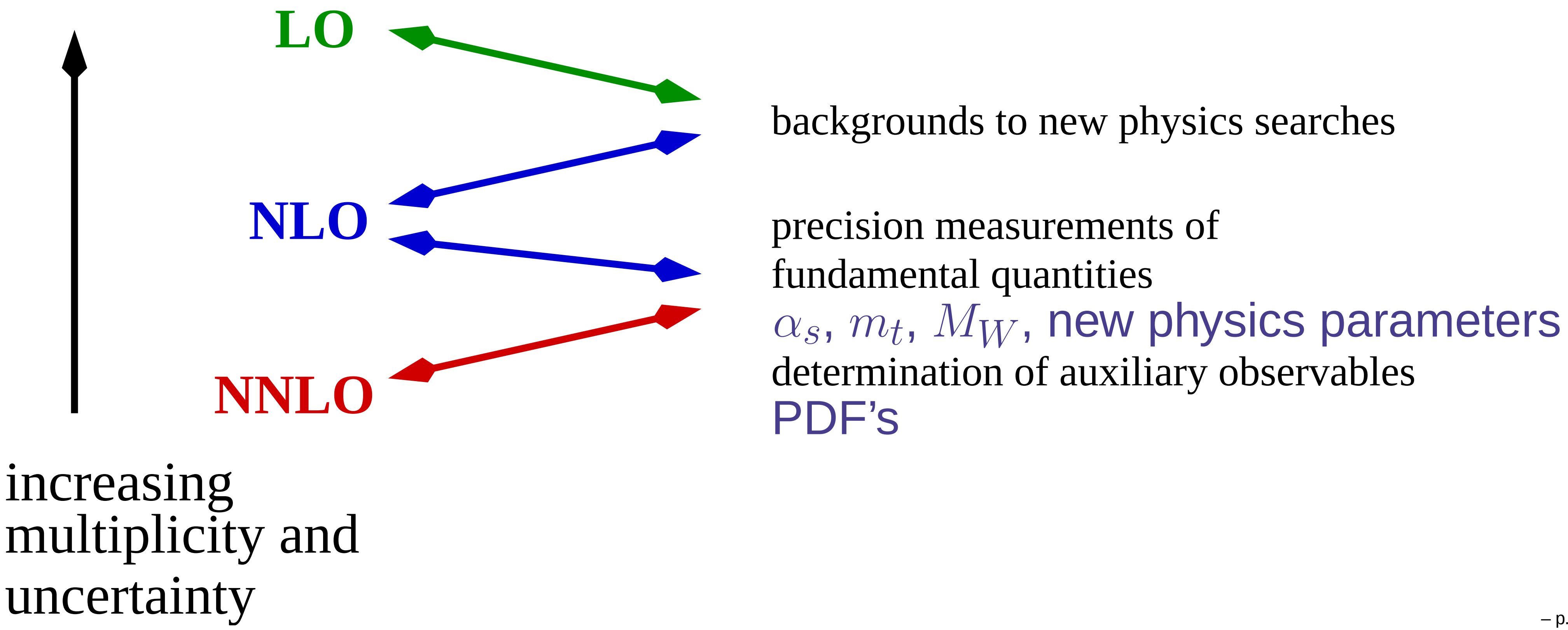


✓ Includes decay of W/Z to one species of charged lepton and semi-leptonic decay of top ($t \to b\ell\nu$) (where applicable) and jets, $E_T > 25$ GeV

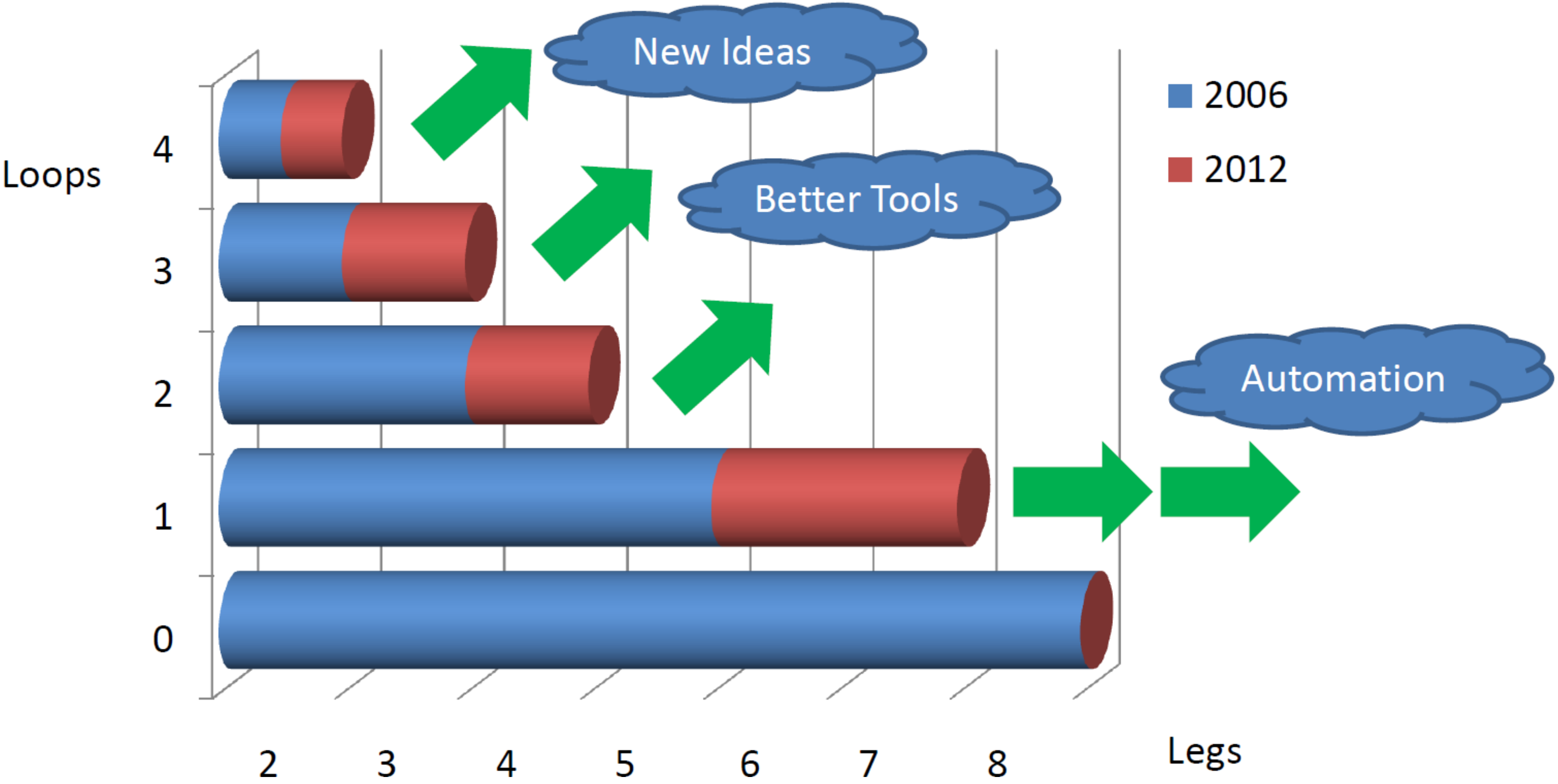
Matching onto Physics Goals

Twin Goals:

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



Progress over past few years

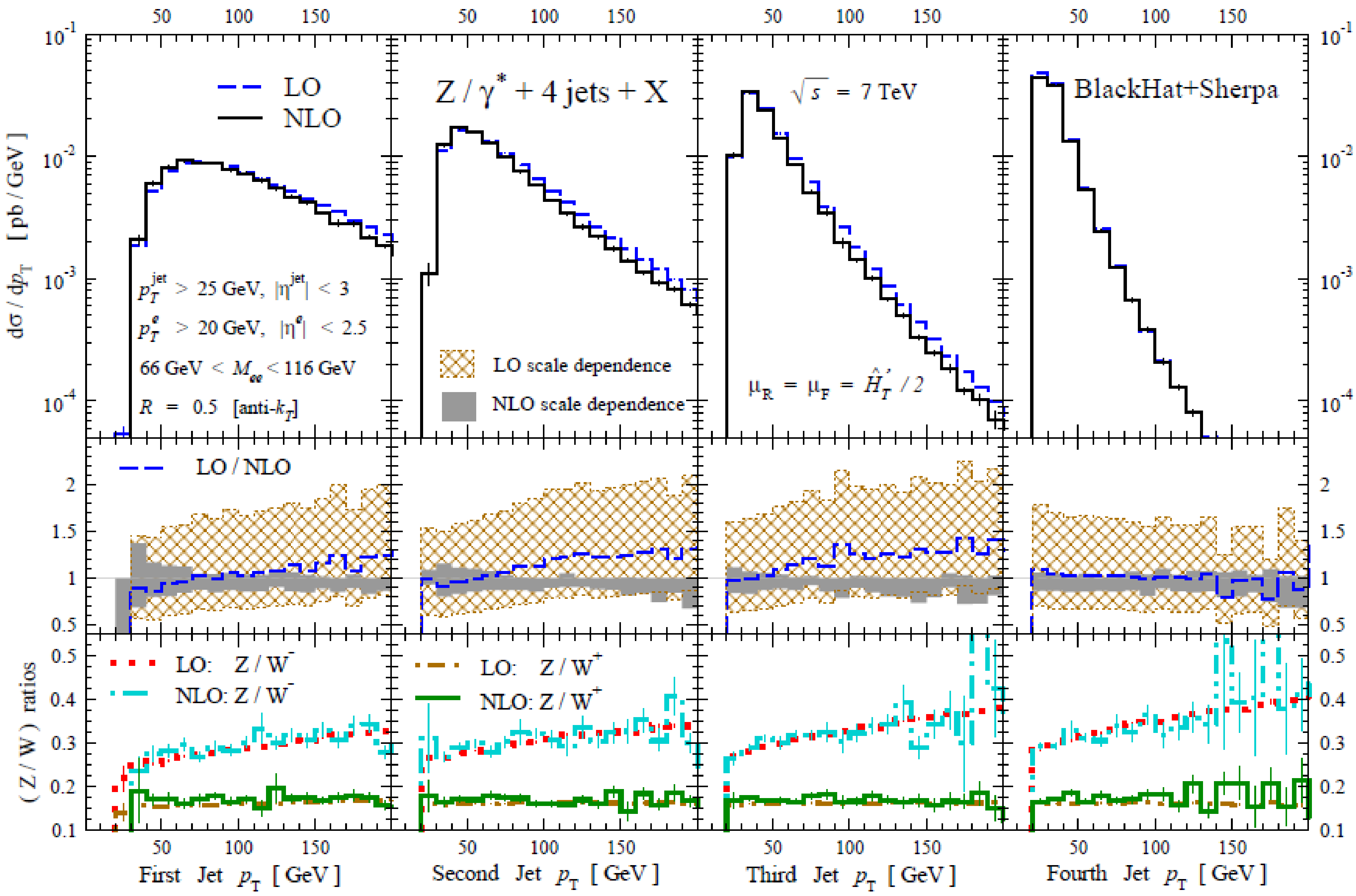


Limitations of Tree Level

Very large uncertainty for multiparticle final states

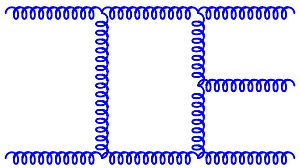
- ✘ Large renormalisation scale uncertainty, magnified by the large amount of radiation e.g. a $\pm 10\%$ uncertainty in α_s leads to a $\pm 30\%$ uncertainty for $W + 3$ jets
- ✘ Large factorisation scale uncertainty
  higher factorisation scales deplete partons at large x - may increase or decrease cross section
- ✘ Both of these effects change the shapes of distributions
- ✓ Partly stabilised by going to NLO
- ✓ New channels open up at higher orders qg + large gluon PDF
- ✓ Increased phase space allows more radiation
- ✓ Large π^2 coefficients in s-channel $\Rightarrow$ large NLO corrections 30% - 100%

NLO - the new standard

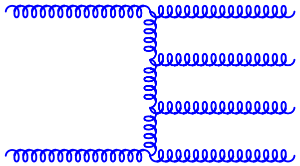


Anatomy of a NLO calculation

✓ one-loop $2 \to 3$ process
  - ✓ explicit infrared poles from loop integral
  - ✓ looks like 3 jets in final state



✓ tree-level $2 \to 4$ process
  - ✓ implicit poles from soft/collinear emission
  - ✓ looks like 3 or 4 jets in final state



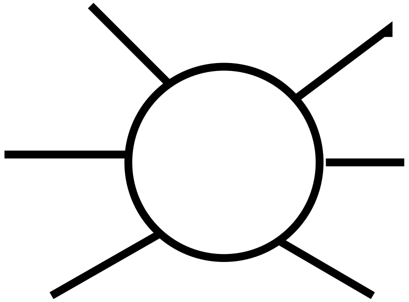
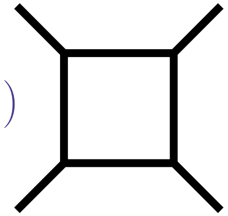
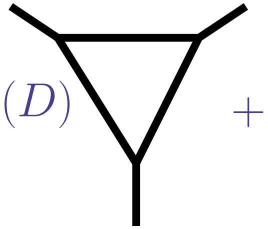
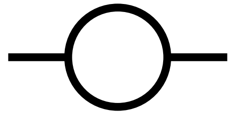
✓ plus method for combining the infrared divergent parts
  - dipole subtraction — Catani, Seymour; Dittmaier, Trocsanyi, Weinzierl, Phaf
  - residue subtraction — Frixione, Kunszt, Signer
  - antenna subtraction — Kosower; Campbell, Cullen, NG; Daleo, Gehrmann, Maitre

✓ automated subtraction tools Gleisberg, Krauss (SHERPA); Hasegawa, Moch, Uwer (AutoDipole); Frederix, Gehrmann, Greiner (MadDipole); Seymour, Tevlin (TeVJet), Czakon, Papadopoulos, Worek (Helac/Phegas) and Frederix, Frixione, Maltoni, Stelzer (MadFKS)

So far bottleneck has been one-loop matrix elements

The one-loop problem

Any (massless) one-loop integral can be written as


$= \sum_i d_i(D)$

$+ \sum_i c_i(D)$

$+ \sum_i b_i(D)$


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

- ✓ higher polygon contributions drop out
- ✓ scalar loop integrals are known analytically around $D = 4$ Ellis, Zanderighi (08)
- ✓ need to compute the D-dimensional coefficients $d(D)$ etc.

The 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.

Unitarity for one-loop diagrams

Several important breakthroughs

✓ Sewing trees together

Bern, Dixon, Dunbar, Kosower (94)

✓ Freezing loop momenta with quadruple cuts

Britto, Cachazo, Feng (04)

✓ OPP tensor reduction of integrand

Ossola, Pittau, Papadopoulos (06)

✓ D-dimensional unitarity

Giele, Kunzst, Melnikov (08)

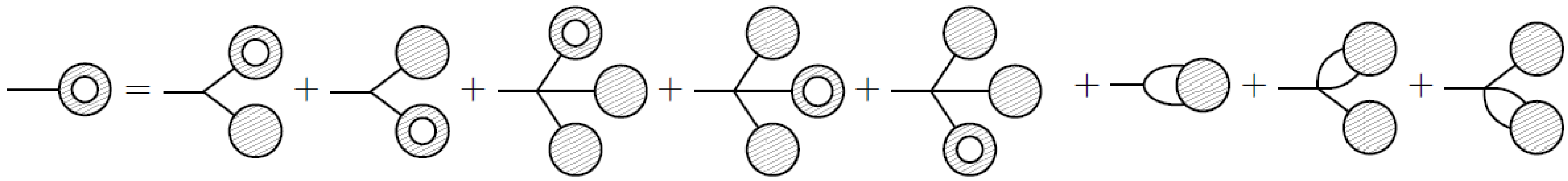
$\Longrightarrow$ automation

HELAC/CutTools, Rocket, BlackHat+SHERPA,
GoSam+SHERPA/MADGRAPH, NJet+SHERPA, MADLOOPS+MADGRAPH

Numerical recursion for one-loop diagrams

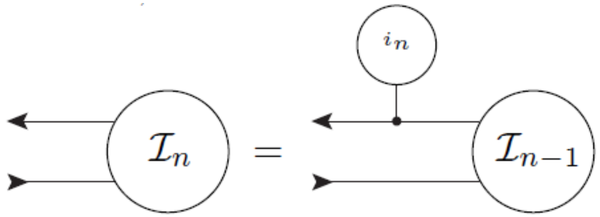
Breakthroughs on the “traditional" side

✓ One-loop Berends-Giele recursion — van Hameren (09)



✓ Recursive construction of tensor numerator — Cascioli, Maierhöfer, Pozzorini (11)

$\mathcal{N}_{\alpha}^{\beta}(\mathcal{I}_n; q) =$

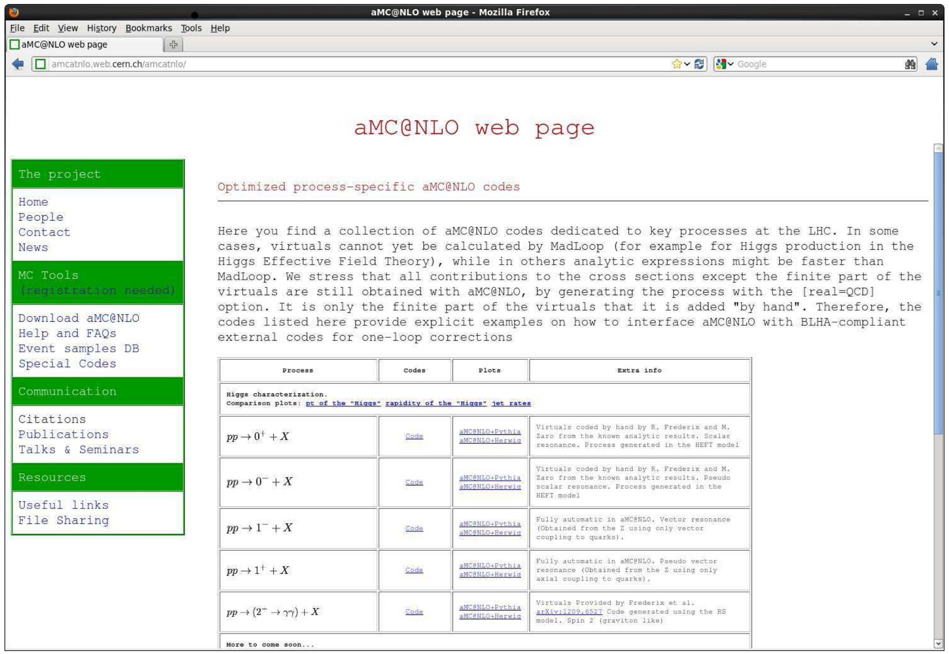


$\Longrightarrow$ automation

OpenLoops+SHERPA, RECOLA

NLO - the new standard

- ✓ A lot of progress, and the “best" solution is still to emerge. In the meantime, there are public codes with NLO capability that could only be dreamed of a few years ago.
- ✓ see http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=212260 for more details.



SHERPA

Process	BlackHat	GoSam	OpenLoops
jets	≤ 3	—	≤ 4
γ+jets	≤ 3	≤ 2	≤ 3
$\gamma\gamma$+jets	≤ 2	—	≤ 2
V+jets	≤ 4	≤ 3	≤ 3
$V + b\bar{b}$+jets	—	≤ 1	≤ 1
VV'+jets	≤ 2	≤ 2	≤ 2
$V\gamma$+jets	—	≤ 2	≤ 2
$W^{\pm}W^{\pm}qq$	—	0	0
$VV'V''$	—	—	≤ 1
$t\bar{t}$+jets	—	≤ 1	≤ 1
$t\bar{t} + V$+jets	—	—	≤ 1
$tb^{\dagger}$	—	—	≤ 1
$tj^{\dagger}$	—	—	≤ 1
$tW^{\dagger}$	—	—	≤ 1
h+jets	≤ 2	≤ 2	—
WBF: hqq'	—	—	≤ 1
VH	—	—	≤ 1
$t\bar{t}h$	—	—	0
$gg \to 4\ell$	—	0	0

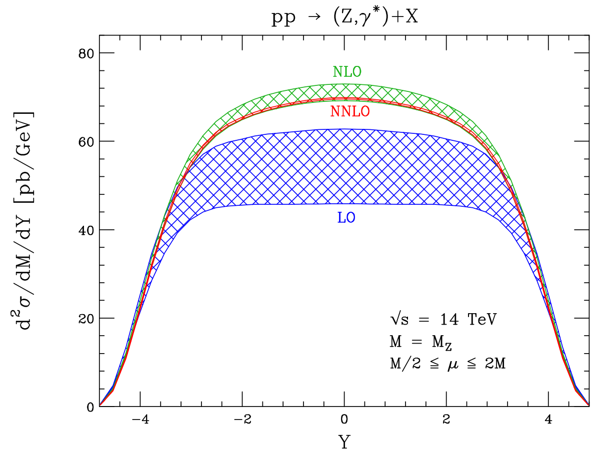
NNLO calculations for $2 \to 2$ processes

$$d\sigma = \sum_{i,j} \int \frac{d\xi_1}{\xi_1} \frac{d\xi_2}{\xi_2} f_i(\xi_1, \mu_F^2) f_j(\xi_2, \mu_F^2) d\hat{\sigma}_{ij}(\alpha_s(\mu_R), \mu_R, \mu_F)$$

$$d\hat{\sigma}_{ij} = d\hat{\sigma}_{ij}^{LO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right) d\hat{\sigma}_{ij}^{NLO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^2 d\hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3)$$

Processes of interest

- ✓ $pp \to 2$ jets
- ✓ $pp \to \gamma$+jets
- ✓ $pp \to \gamma\gamma$
- ✓ $pp \to V$+jet
- ✓ $pp \to t\bar{t}$
- ✓ $pp \to VV$
- ✓ $pp \to H$+jet
- ✓ $\ldots$

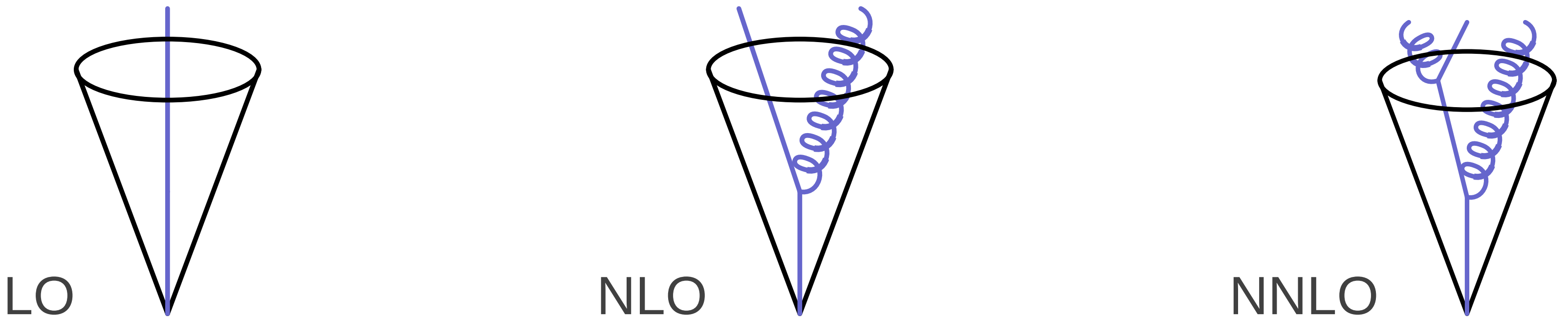


Massively reduced theoretical error

Anastasiou, Dixon, Melnikov, Petriello (04)

Motivation for NNLO computations

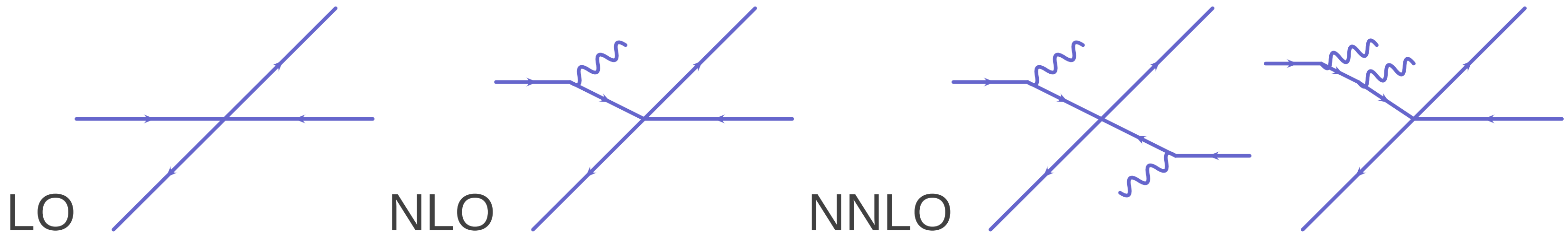
- ✓ Reduced renormalisation scale dependence
- ✓ Event has more partons in the final state so perturbation theory can start to reconstruct the shower
  $\Rightarrow$ better matching of jet algorithm between theory and experiment



- ✓ Reduced power correction as higher perturbative powers of $1/\ln(Q/\Lambda)$ mimic genuine power corrections like $1/Q$

Motivation for NNLO computations

✓ Better description of transverse momentum of final state due to double radiation off initial state



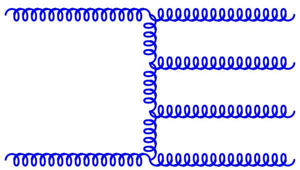
- ✓ At LO, final state has no transverse momentum
- ✓ Single hard radiation gives final state transverse momentum, even if no additional jet
- ✓ Double radiation on one side, or single radiation of each incoming particle gives more complicated transverse momentum to final state

✓ NNLO provides the first serious estimate of the error

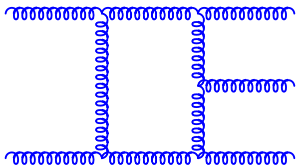
✓✓✓ and most importantly, the volume and quality of the LHC data!!

Anatomy of a NNLO calculation e.g. $pp \to 2j$

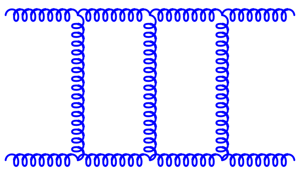
- ✓ double real radiation matrix elements $\mathrm{d}\hat{\sigma}^{RR}_{NNLO}$
  - ✓ implicit poles from double unresolved emission



- ✓ single radiation one-loop matrix elements $\mathrm{d}\hat{\sigma}^{RV}_{NNLO}$
  - ✓ explicit infrared poles from loop integral
  - ✓ implicit poles from soft/collinear emission



- ✓ two-loop matrix elements $\mathrm{d}\hat{\sigma}^{VV}_{NNLO}$
  - ✓ explicit infrared poles from loop integral
  - ✓ including square of one-loop amplitude



$$\mathrm{d}\hat{\sigma}_{NNLO} \sim \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\hat{\sigma}^{RR}_{NNLO} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\hat{\sigma}^{RV}_{NNLO} + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\hat{\sigma}^{VV}_{NNLO}$$

- ✓ Antenna method to extract implicit poles developed for $e^+e^- \to 3$ jets

NNLO - double virtual

- ✓ small number of two loop matrix elements known
  - ✓ $2 \to 1$: $q\bar{q} \to V$, $gg \to H$, ($q\bar{q} \to VH$)
  - ✓ $2 \to 2$: massless parton scattering, e.g. $gg \to gg$, $q\bar{q} \to gg$, etc
  - ✓ $2 \to 2$: processes with one offshell leg, e.g. $q\bar{q} \to V$+jet, $gg \to H$+jet
  - ✓ $2 \to 2$: $q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}$ known numerically Bärnreuther, Czakon, Mitov
  - ✓ $2 \to 2$: $q\bar{q} \to VV$, $gg \to VV$ in progress
- ?? Automation
- ✘ Basis set of integrals not known!
  - ✓ search for basis set and generalisations of new methods from one-loop

    Gluza, Kajda, Kosower (10); Mastrolia, Ossola (11); Kosower, Larsen (11); Badger, Frellesvig, Zhang (12); Larsen; Caron-Huet (12), Larsen (12); Zhang (12); Mastrolia, Mirabella, Ossola, Peraro (12); Kleiss, Malamos, Papadopoulos, Verheyn (12); Johansson, Kosower, Larsen (12); Feng, Huang (12)

IR subtraction at NNLO

✓ The aim is to recast the NNLO cross section in the form

$$\begin{aligned} d\hat{\sigma}_{NNLO} &= \int_{d\Phi_{m+2}} \left[d\hat{\sigma}^{RR}_{NNLO} - d\hat{\sigma}^{S}_{NNLO} \right] \\ &+ \int_{d\Phi_{m+1}} \left[d\hat{\sigma}^{RV}_{NNLO} - d\hat{\sigma}^{T}_{NNLO} \right] \\ &+ \int_{d\Phi_{m}} \left[d\hat{\sigma}^{VV}_{NNLO} - d\hat{\sigma}^{U}_{NNLO} \right] \end{aligned}$$

where the terms in each of the square brackets is finite, well behaved in the infrared singular regions and can be evaluated numerically.

NNLO - double real

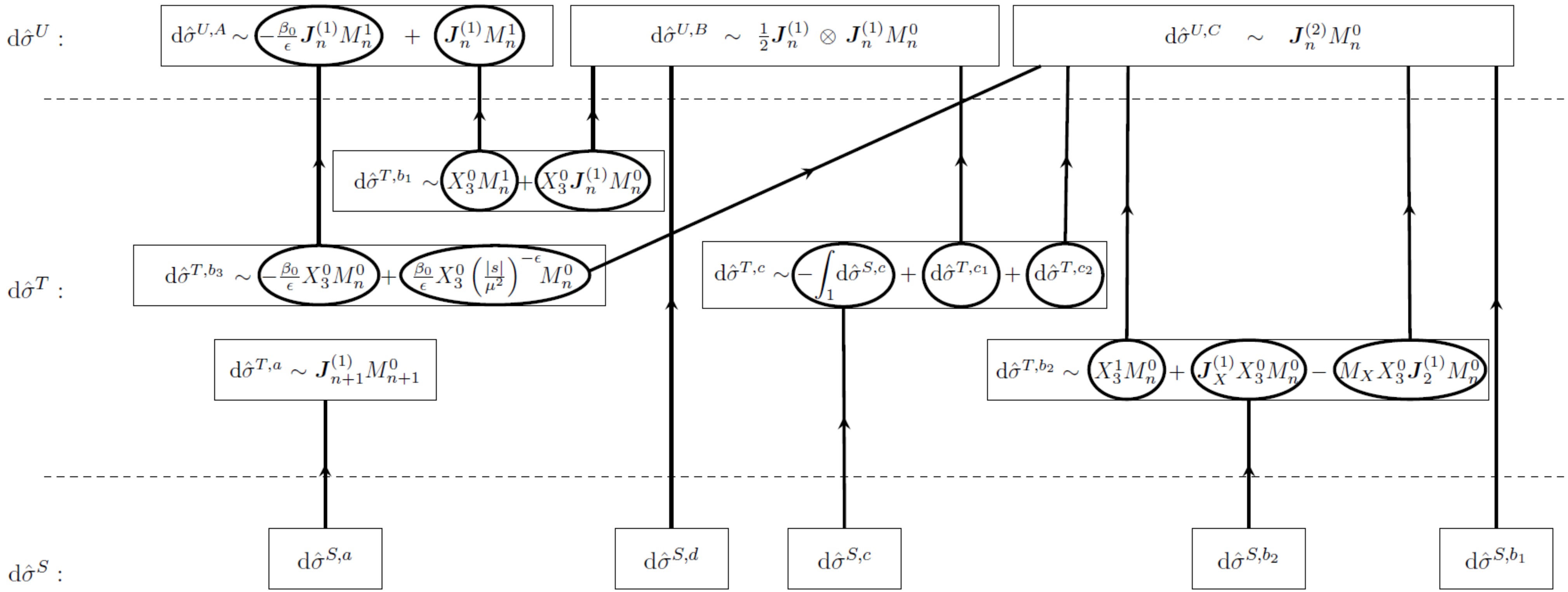
- ✓ IR subtraction schemes
  - ✓ sector decomposition Heinrich; Anastasiou, Melnokov, Petriello; Binoth, Heinrich
    - – $pp \to H$, $pp \to V$

      Anastasiou, Melnikov, Petriello; Melnikov, Petriello; Anastastiou, Dissertori, Stockli; Anastasiou, Herzog, Lazopoulos
  - ✓ q_T subtraction Catani, Grazzini
    - – $pp \to H$, $pp \to V$, $pp \to VH$, $pp \to \gamma\gamma$

      Grazzini; Catani, Cieri, Ferrera, de Florian, Grazzini; Catani, Ferrera, Grazzini; Fererra, Grazzini, Tramontano; Catani, Cieri, de Florian, Ferrera, Grazzini
  - ✓ STRIPPER - sector improved residue subtraction Czakon
    - – $pp \to t\bar{t}$ Czakon; Czakon, Mitov
  - ✓ Antenna subtraction Gehrmann, Gehrmann-De Ridder, NG
    - – $e^+e^- \to 3$ jet Gehrmann, Gehrmann-De Ridder, NG, Heinrich; Weinzierl
    - – $pp \to 2$ jet

      Pires, NG; Gehrmann-De Ridder, Pires, NG; Gehrmann, Gehrmann-De Ridder, Pires, NG

IR subtraction at NNLO



- ✓ X_4^0 and X_3^1 antenna - and their integrals $\mathcal{X}_4^0$ and $\mathcal{X}_3^1$
- ✓ Much more complicated cancellations between the double-real, real-virtual and double virtual contributions - but now well understood

Currie, Wells, NG

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

Method thoroughly tried and tested for partons only in the final state

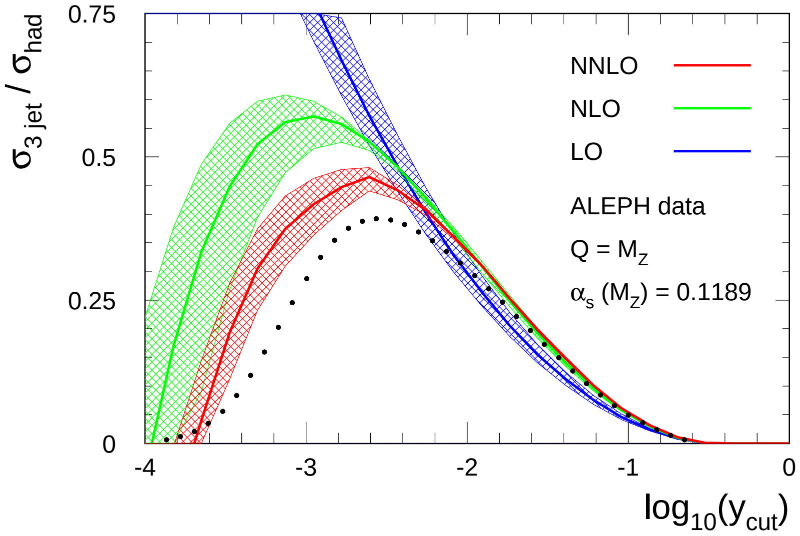
Gehrmann-De Ridder, Gehrmann, Heinrich, NG (07)

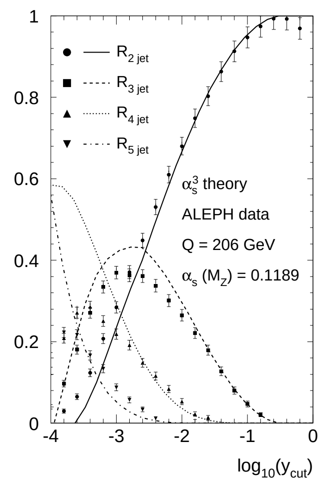
- ✓ NNLO corrections to jet rate small
  - ✓ stable perturbative prediction
  - ✓ resummation not needed
  - ✓ theory error below 2%
  - ✓ small hadronisation corrections
- ✓ α_s extraction from jet rates

Dissertori, Gehrmann-De Ridder, Gehrmann, Heinrich, Stenzel, NG (09)

  - ✓ fit at $y_{cut} = 0.02$
  - ✓ consistent results at other y_{cut}

$\alpha_s(M_Z) = 0.1175 \pm 0.0020(exp) \pm 0.0015(th)$





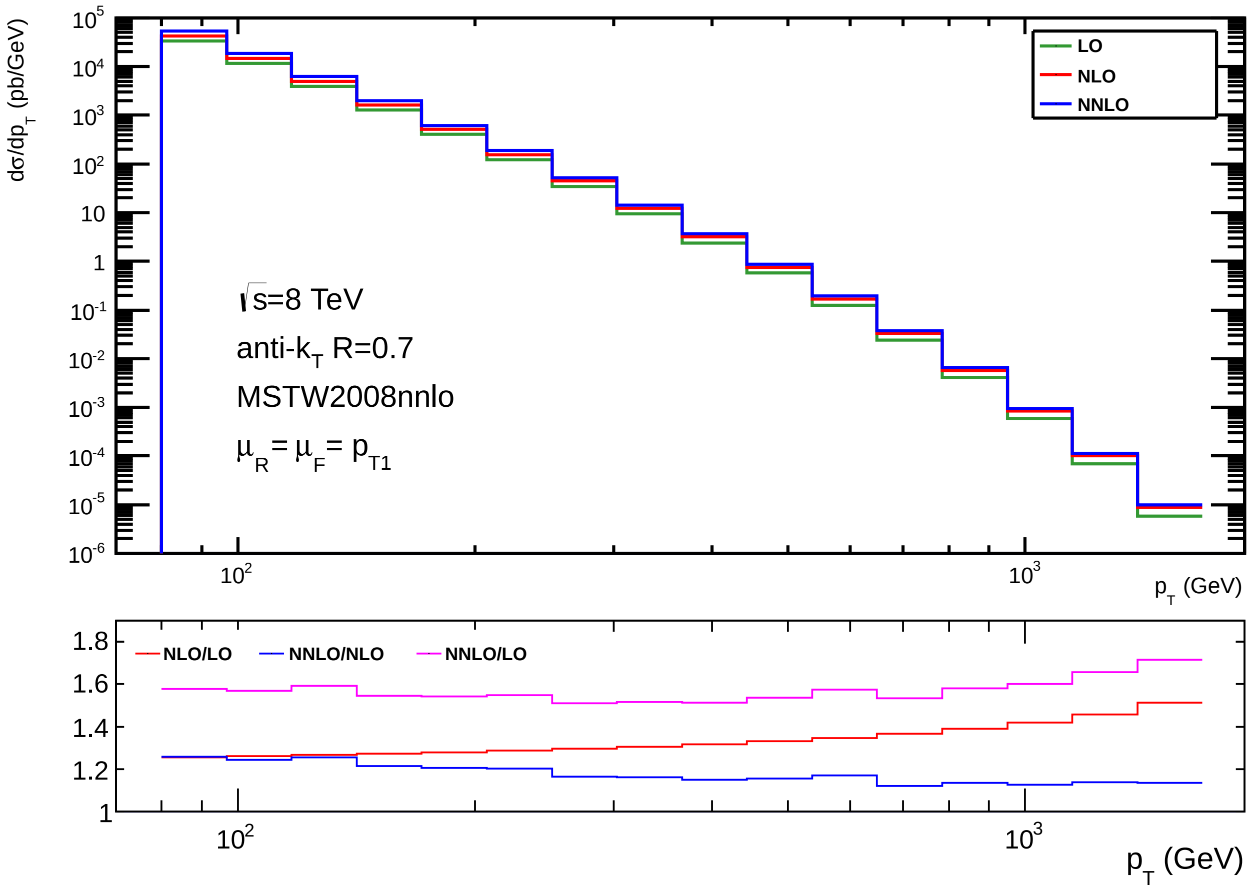
Preliminary results for gluons only dijets at NNLO

Gehrmann-De Ridder, Gehrmann, Pires, NG, in preparation

- ✓ pp collisions at $\sqrt{s} = 8$ TeV
- ✓ jets identified with anti-k_T algorithm with $R = 0.7$
- ✓ jets accepted with rapidities up to 4.4
- ✓ leading jet with transverse momentum $p_T > 80$ GeV
- ✓ additional jets with transverse momentum $p_T > 60$ GeV
- ✓ MSTW2008nnlo PDF set
- ✓ factorisation and renormalisation scales set equal to (multiple) of leading jet transverse momentum $\mu_R = \mu_F = \mu = p_{T1}$
- ✓ only gluonic matrix elements included
- !! NLO and LO curves also gluons only, and using same α_s and PDF set

NNLO QCD corrections to inclusive jet p_T distribution (gluons only)

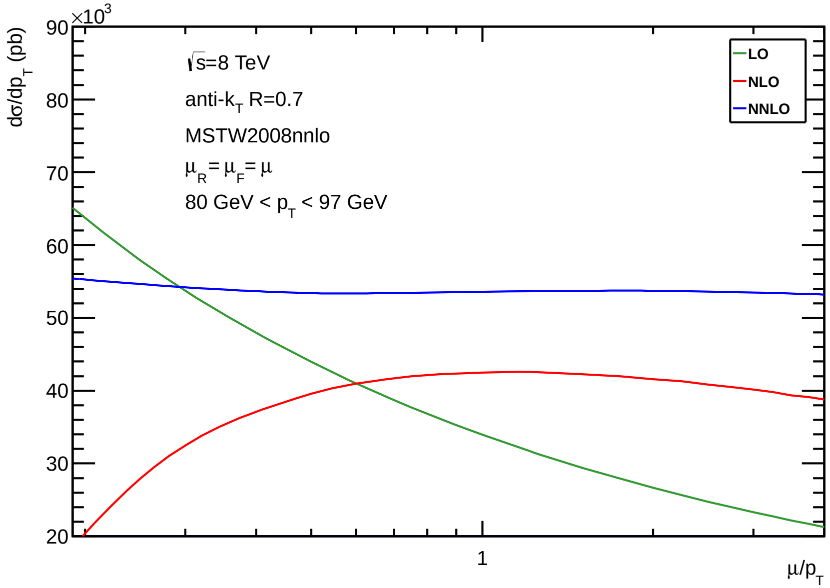
Gehrmann-De Ridder, Gehrmann, Pires, NG, in preparation



✓ $|y| < 4.4$: NNLO corrections 25-15% wrt NLO

NNLO QCD corrections to inclusive jet p_T distribution (gluons only)

Gehrmann-De Ridder, Gehrmann, Pires, NG, in preparation

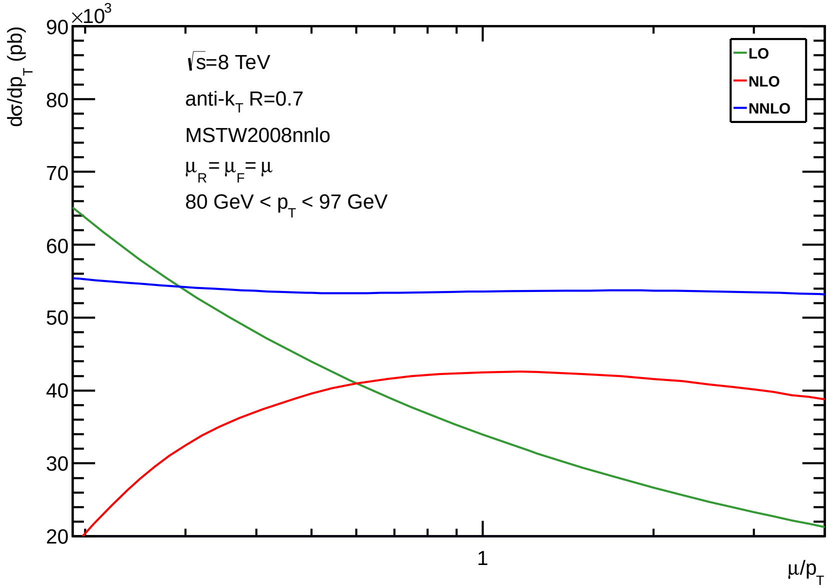


$|y| < 4.4$, 80 GeV $< p_T <$ 97 GeV

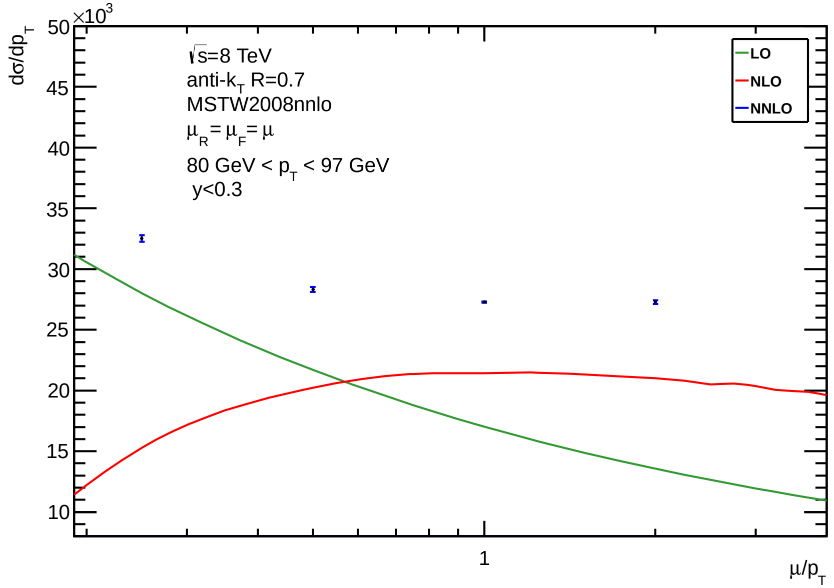
✓ Scale variation much reduced for $0.5 < \mu/p_T < 2$.

NNLO QCD corrections to inclusive jet p_T distribution (gluons only)

Gehrmann-De Ridder, Gehrmann, Pires, NG, in preparation



$|y| < 4.4$, 80 GeV $< p_T <$ 97 GeV

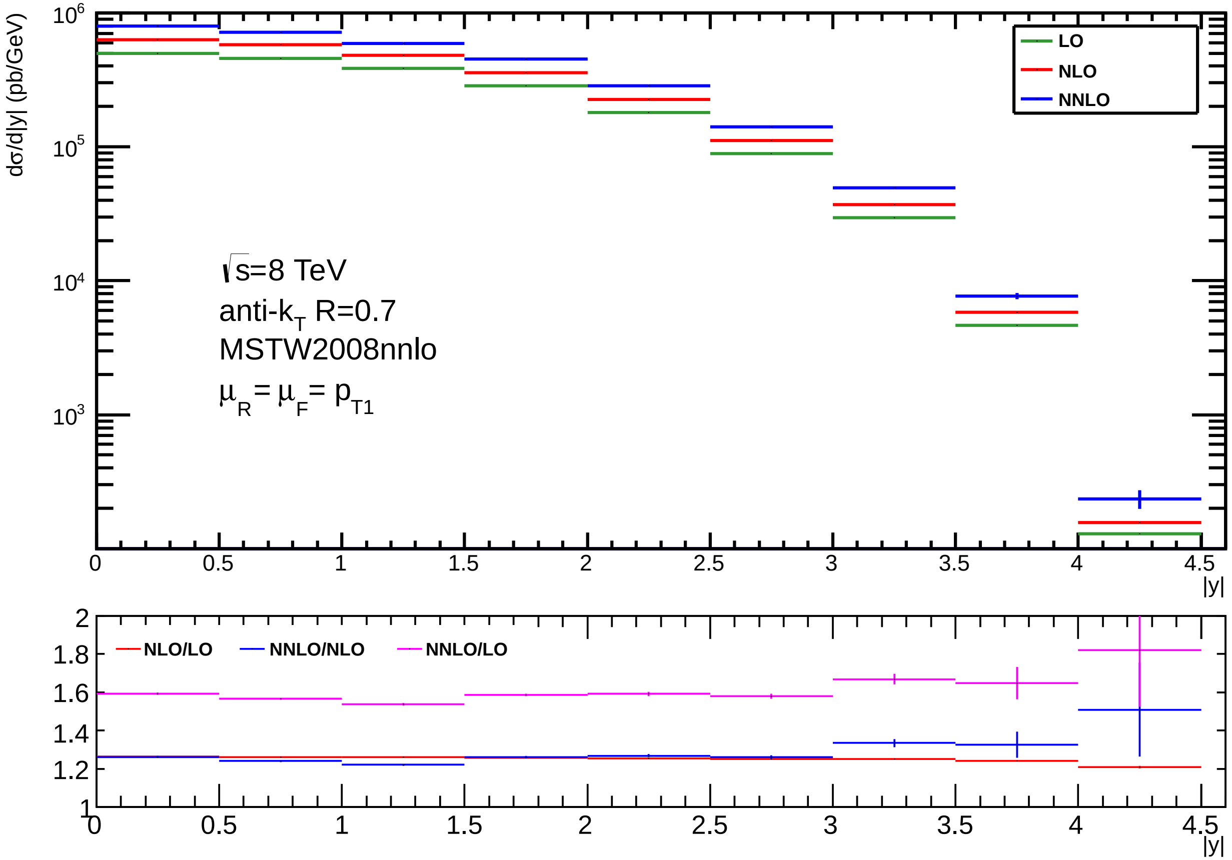


$|y| < 0.3$, 80 GeV $< p_T <$ 97 GeV

- ✓ Scale variation much reduced for $0.5 < \mu/p_T < 2$.
- ✓ . . . but depends on rapidity slice

NNLO QCD corrections to inclusive jet y distribution (gluons only)

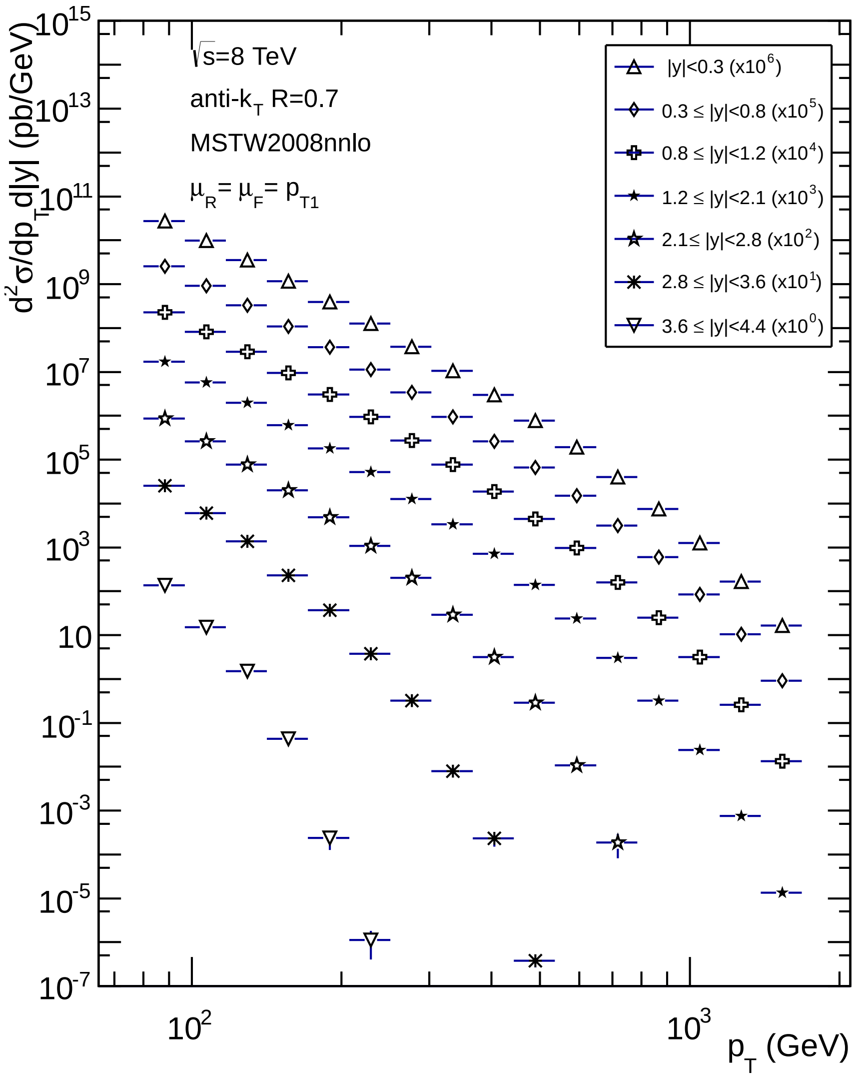
Gehrmann-De Ridder, Gehrmann, Pires, NG, in preparation

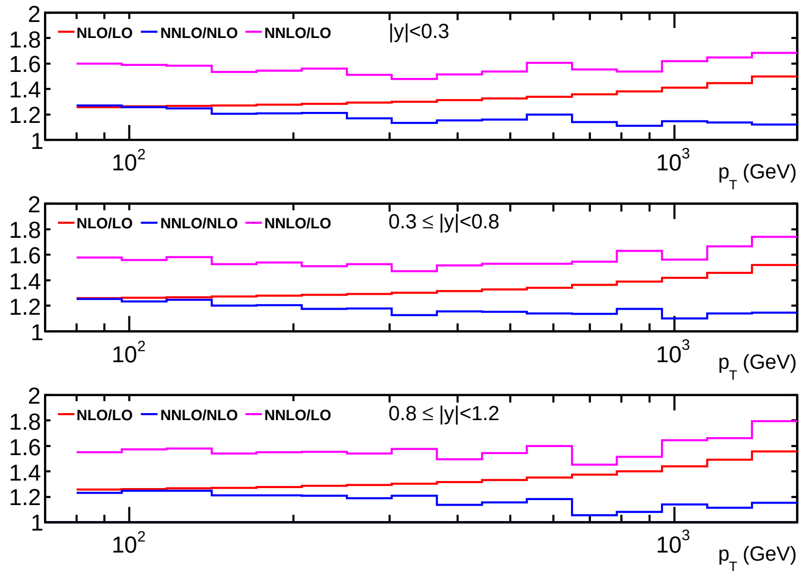


✓ NNLO corrections ∼25% wrt NLO

Double differential inclusive jet p_T distribution (gluons only)

De Ridder, Gehrmann, Pires, NG, in preparation

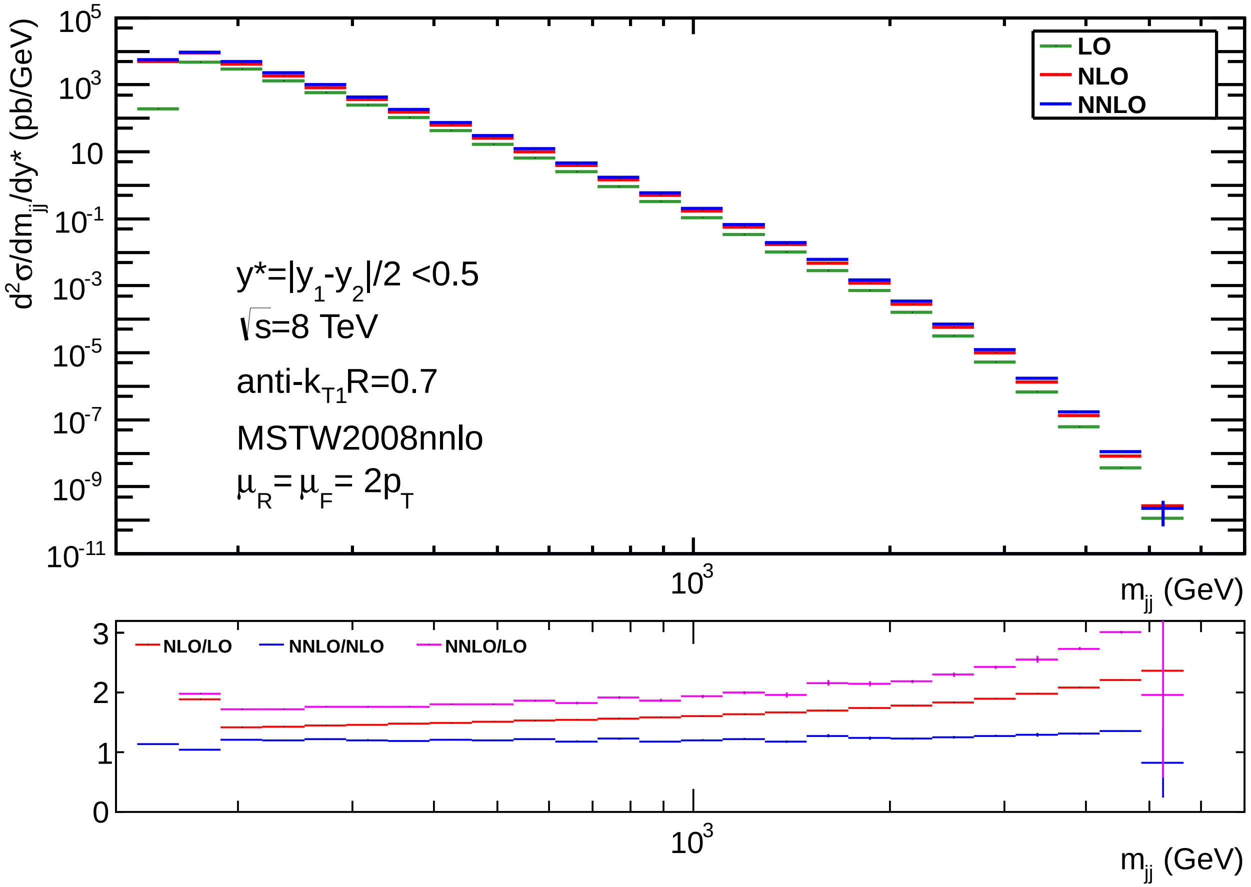




- ✓ NNLO corrections ∼25% wrt NLO
- ✓ similar behavior for different repidity slices

NNLO QCD corrections to di-jet mass distribution (gluons only)

Gehrmann-De Ridder, Gehrmann, Pires, NG, in preparation



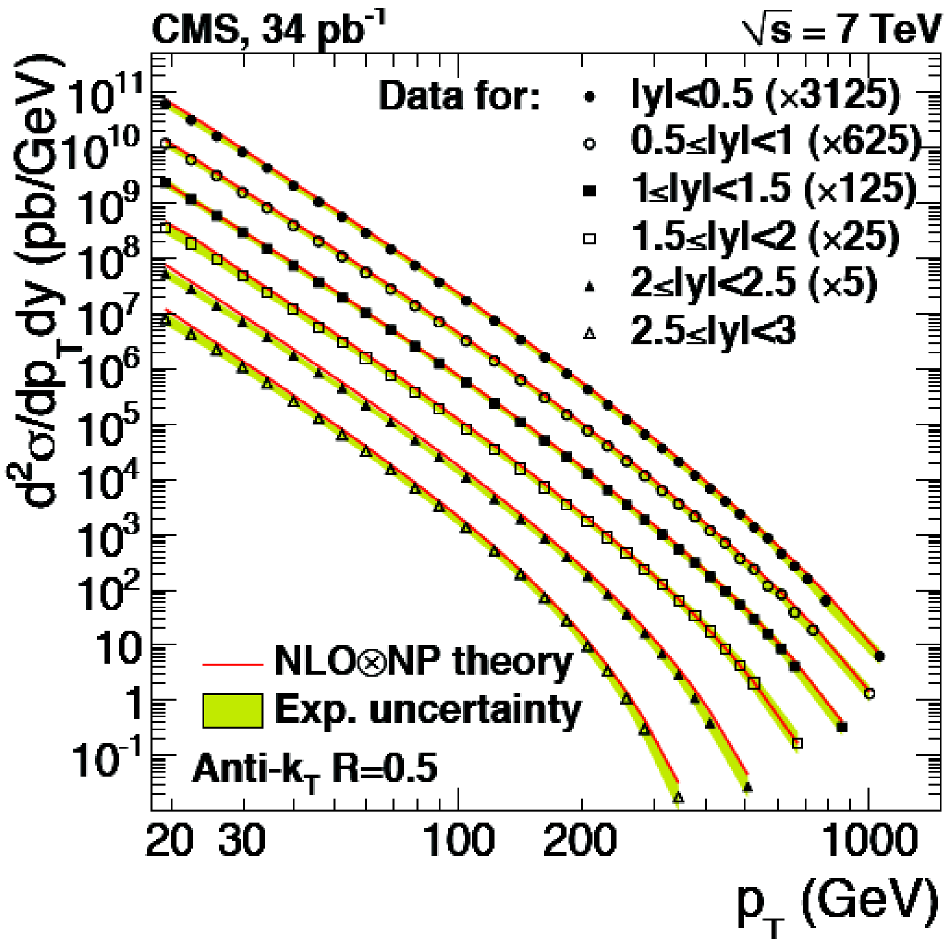
✓ NNLO corrections ∼25% wrt NLO

Applications to LHC processes

- ✓ All relevant matrix elements for $pp \to 2$ jet, $pp \to V+1$ jet and $pp \to H+1$ jet processes available for some time
- ✓ Can expect to have parton-level NNLO predictions for $pp \to 2$ jet, $pp \to V+1$ jet and $pp \to H+1$ jet in next couple of years
- ✓ Hope for significant reduction in theory (renormalisation scale/factorisation scale) dependence
- ✓ LHC already has increased dynamic range for jet studies - rapidity, transverse energy.
- ✓ Combined with excellent experimental jet energy scale uncertainty, there is the opportunity for improved measurements of
  - ✓ Parton distributions
  - ✓ Strong coupling
  - ✓ Internal structure of the jet
  - ✓ Rapidity gaps between the jets

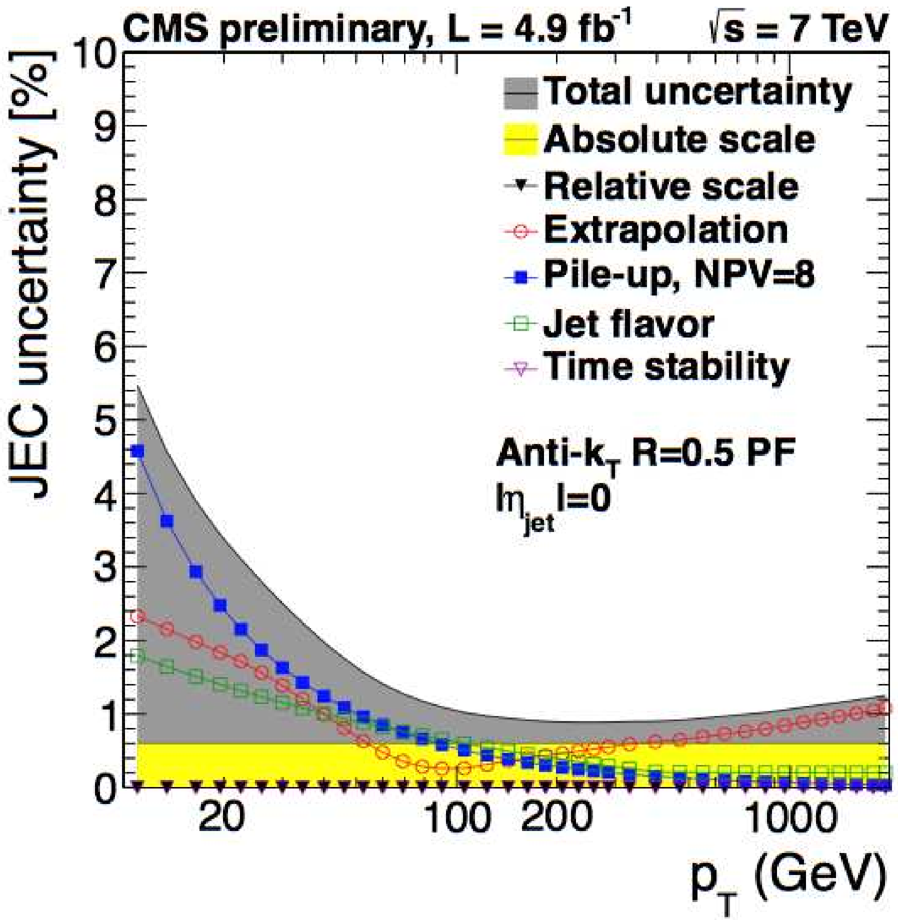
Traditional Jet Observables

- ✓ e.g. Double-differential inclusive jet cross section vs jet p_T and y
- ✓ using anti-k_T Particle Flow jets with $R = 0.5$
- ✓ p_T range up to 1.1 TeV (2011 data up to 2 TeV)
- ✘ NP correction (estimated by Pythia6 and Herwig++)
- ✓ Overall, data and theoretical predictions are compatible
- ✓ Data are described well by pQCD @ NLO in the TeV scale
- ? But can we actually measure something of significance?



Measuring fundamental quantities with Jets

- ✓ Impressive control over experimental uncertainties
- ✓ With 2011 data CMS Jet Energy Scale Uncertainty below 1% for $p_T = 150 - 600$ GeV in barrel at $|y| < 1.3$.
- ⇒ Experimental uncertainties in Single Jet Inclusive distribution at the 5-10% level
- ⇒ Need for pQCD predictions at NNLO accuracy



Measuring the PDF's with Jets

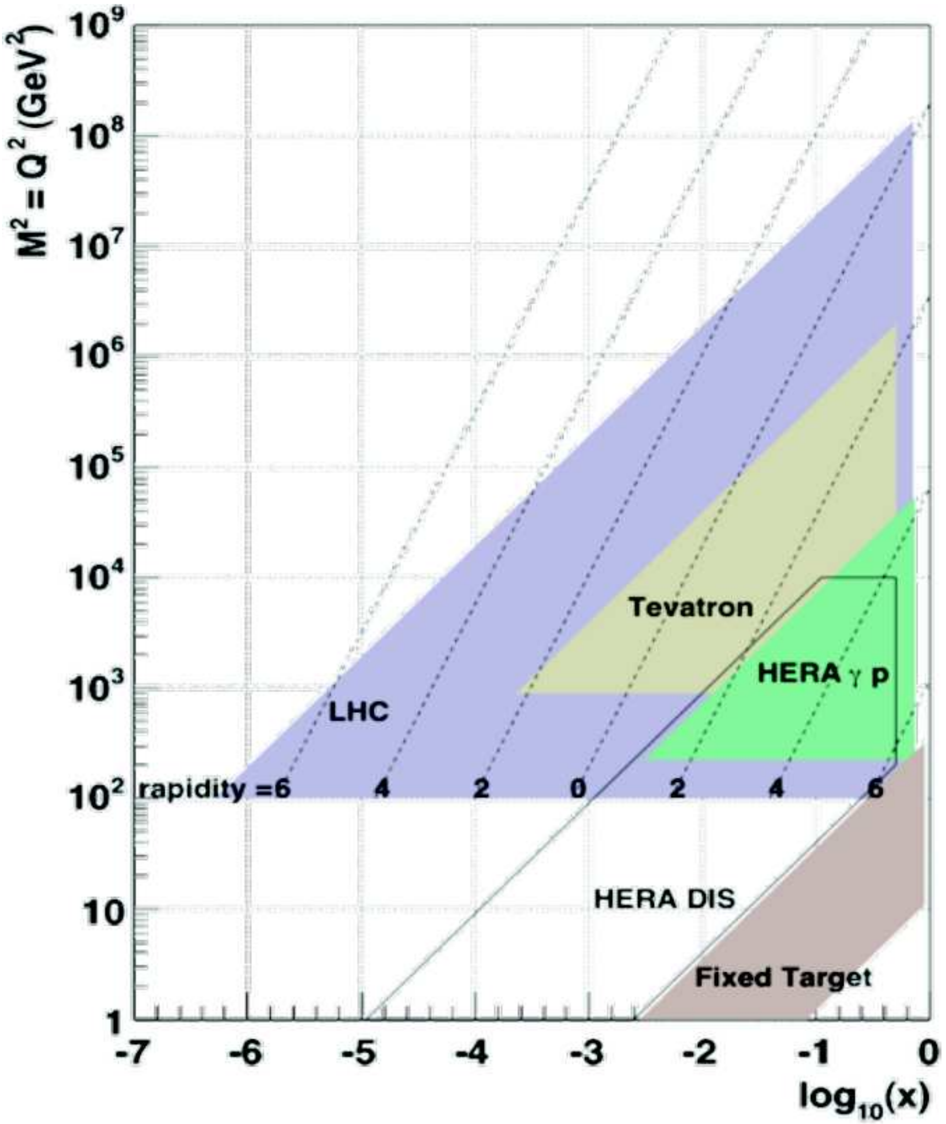
✓ LHC range covers bigger range of Q^2 and x than previous experiments

✓ LHC detectors significantly better than earlier detectors

? Is it possible to measure PDF's to NNLO precision using only high energy data?

? Can enough measurements be made to constrain all the PDF's?

⇒ Need to systematically organise and study full data set!



Maximising the impact of NNLO calculations

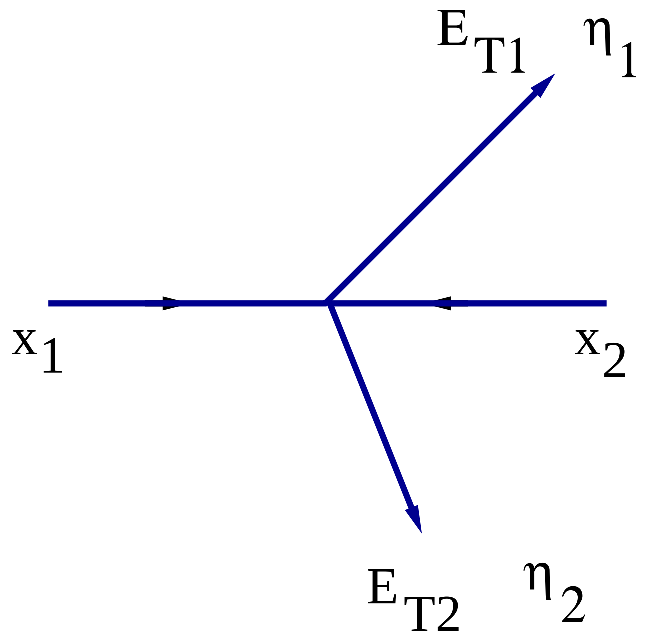
Triple differential form for a $2 \to 2$ cross section

$$\frac{d^3\sigma}{dE_T d\eta_1 d\eta_2} = \frac{1}{8\pi} \sum_{ij} x_1 f_i(x_1, \mu_F)\; x_2 f_j(x_2, \mu_F)\; \frac{\alpha_s^2(\mu_R)}{E_T^3} \frac{|\mathcal{M}_{ij}(\eta^*)|^2}{\cosh^4 \eta^*}$$

✓ Direct link between observables E_T, η_1, η_2 and momentum fractions/parton luminosities

$$x_1 = \frac{E_T}{\sqrt{s}} \left(\exp(\eta_1) + \exp(\eta_2)\right),$$

$$x_2 = \frac{E_T}{\sqrt{s}} \left(\exp(-\eta_1) + \exp(-\eta_2)\right)$$

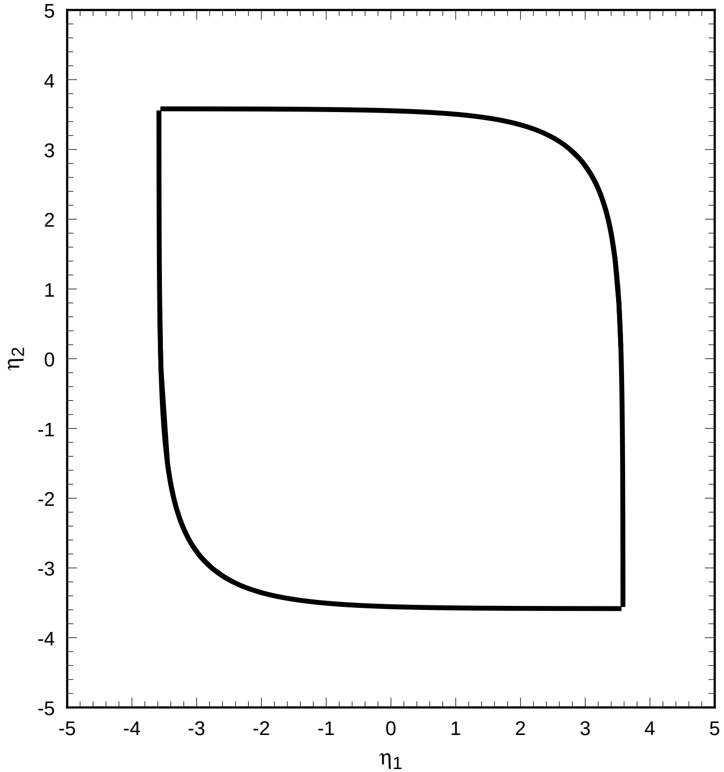


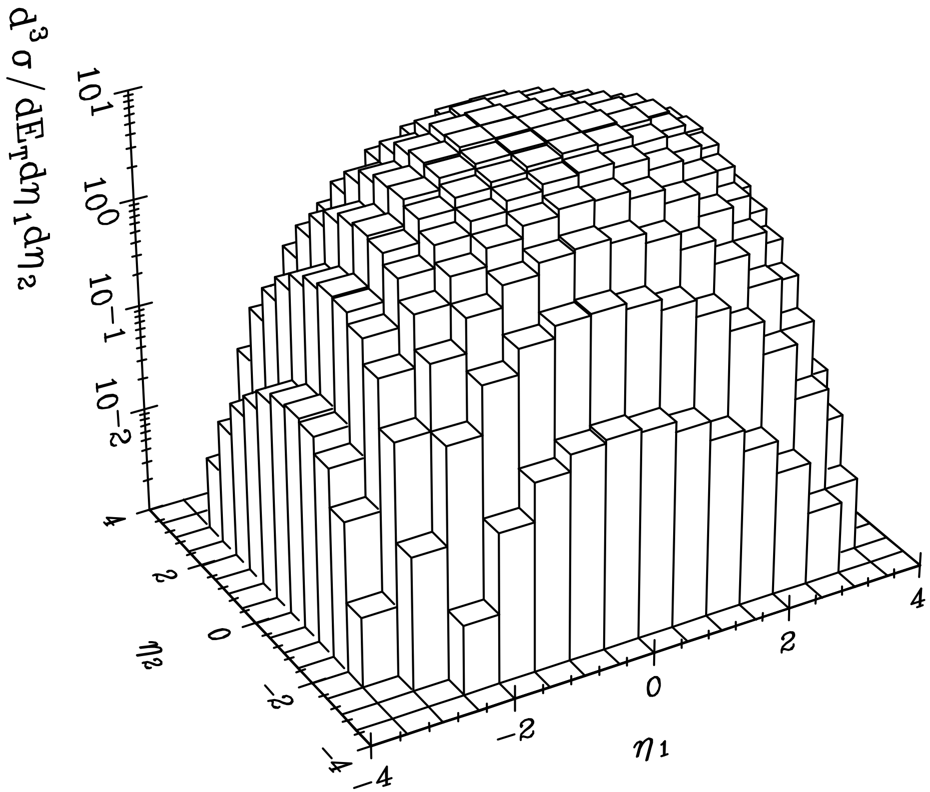
✓ and matrix elements that only depend on

$$\eta^* = \frac{1}{2}\left(\eta_1 - \eta_2\right)$$

Triple differential distribution

✓ Range of x_1 and x_2 fixed allowed LO phase space for jets
$E_T \sim 200$ GeV at $\sqrt{s} = 7$ TeV





✓ Shape of distribution can be understood by looking at parton luminosities and matrix elements (in for example the single effective subprocess approximation)

Giele, NG, Kosower, hep-ph/9412338

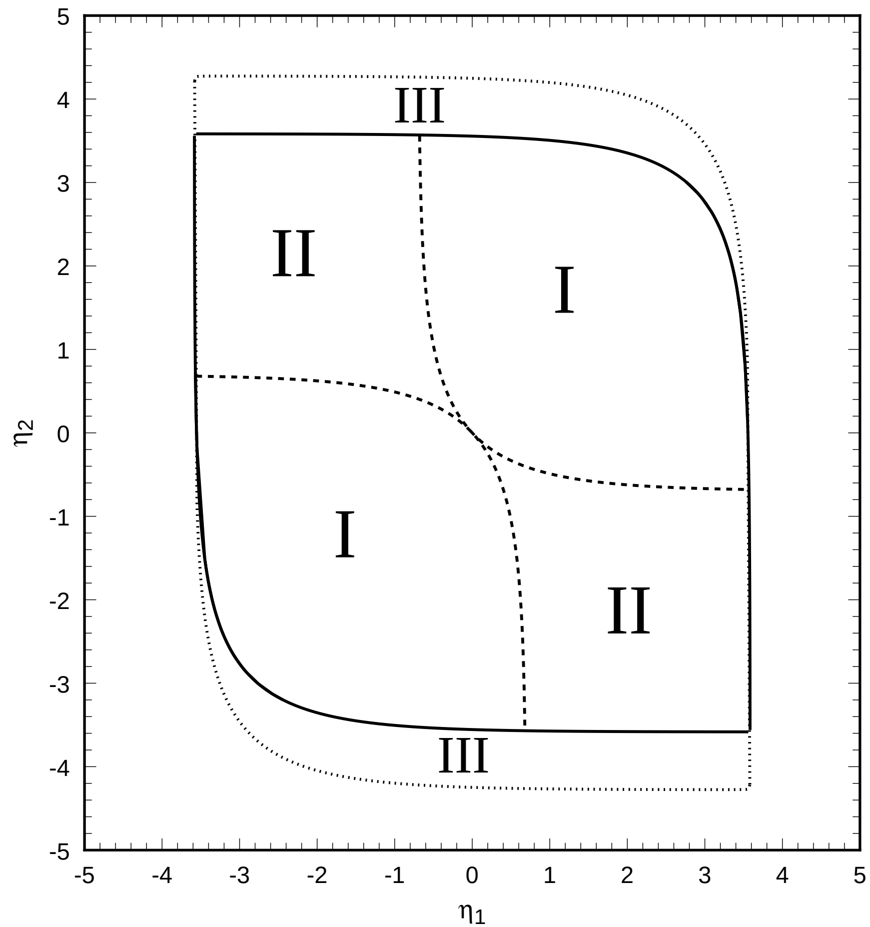
Phase space considerations

✓ Phase space boundary fixed when one or more parton fractions $\to 1$.

I $\eta_1 > 0$ and $\eta_2 > 0$ OR $\eta_1 < 0$ and $\eta_2 < 0$
$\Rightarrow$ one x_1 or x_2 is less than x_T
- small x

II $\eta_1 > 0$ and $\eta_2 < 0$ OR $\eta_1 < 0$ and $\eta_2 > 0$
$\Rightarrow$ both x_1 and x_2 are bigger than x_T
- large x

III growth of phase space at NLO (if $E_{T1} > E_{T2}$)



$$\left[x_T^2 < x_1 x_2 < 1 \qquad \text{and} \qquad x_T = 2E_T/\sqrt{s} \right]$$

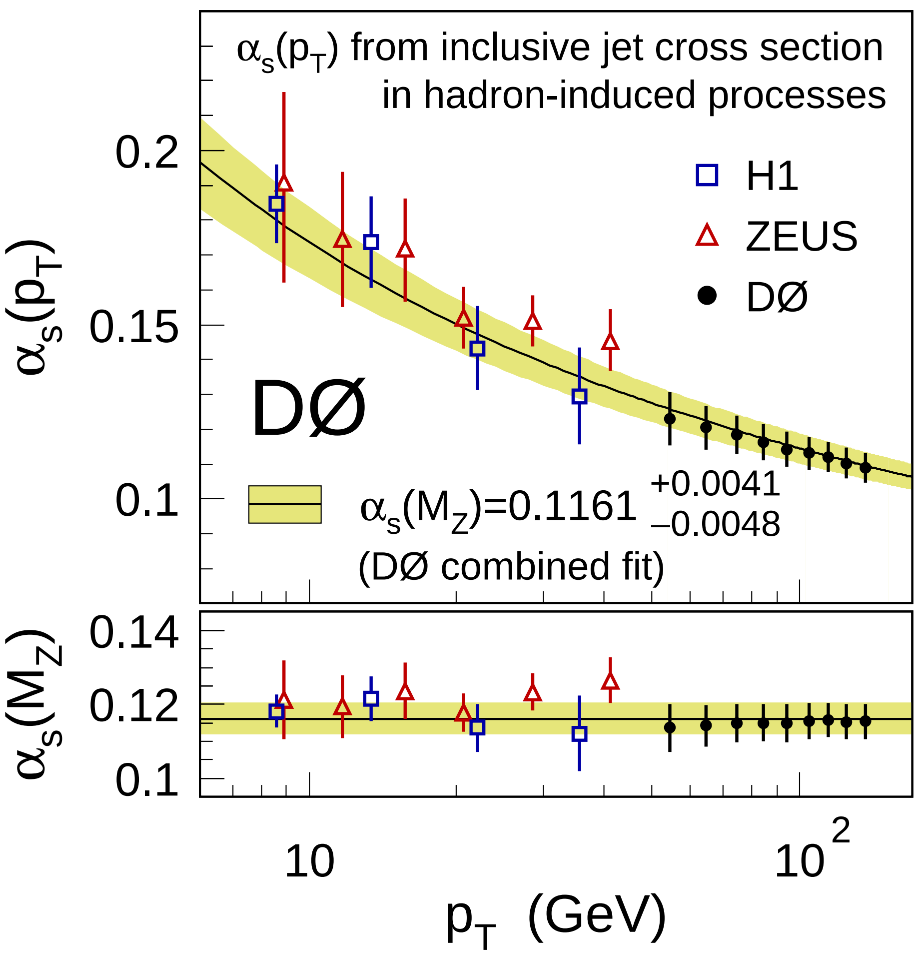
Measuring PDF's at the LHC?

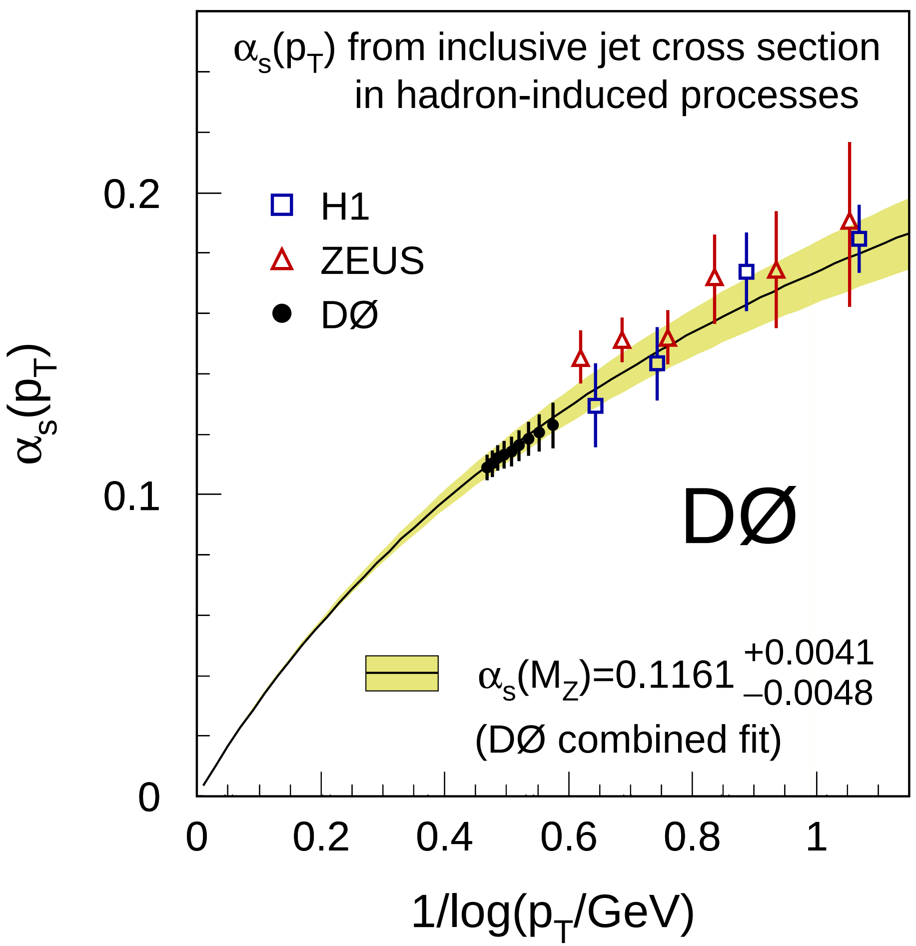
Should be goal of LHC to be as self sufficient as possible!
Study triple differential distribution for as many $2 \to 2$ processes as possible!

- ✓ Medium and large x gluon and quarks
  - ✓ $pp \to$ di-jets — dominated by gg scattering
  - ✓ $pp \to \gamma$ + jet — dominated by qg scattering
  - ✓ $pp \to \gamma\gamma$ — dominated by $q\bar{q}$ scattering
- ✓ Light flavours and flavour separation at medium and small x
  - ✓ Low mass Drell-Yan
  - ✓ W lepton asymmetry
  - ✓ $pp \to Z$+jet
- ✓ Strangeness and heavy flavours
  - ✓ $pp \to W^{\pm} + c$ — probes $s,\ \bar{s}$ distributions
  - ✓ $pp \to Z + c$ — probes c distribution
  - ✓ $pp \to Z + b$ — probes b distribution

Measurements of strong coupling

We can extract α_s using input PDF's (with varying α_s) fixed by DIS, etc e.g.





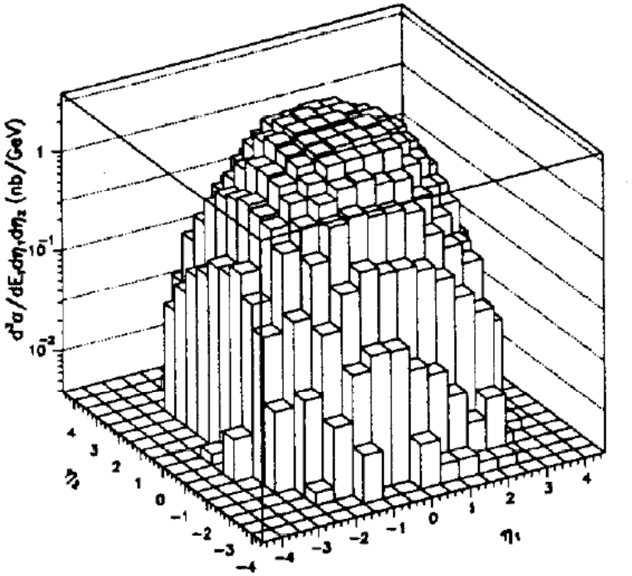
D0, arXiv:0911.2710

Measurements of strong coupling

- ✓ With incredible jet energy resolution, the LHC can do better!!
- ✓ by simultaneously fitting the parton density functions and strong coupling
- ✓ If the systematic errors can be understood, the way to do this is via the triple differential cross section

Giele, NG, Yu, hep-ph/9506442

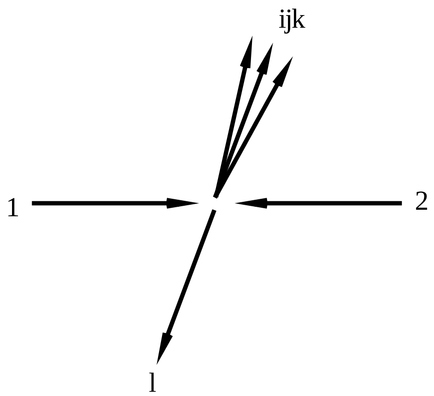
- ✓ and add NNLO $W^{\pm}$+jet, Z+jet, γ+jet calculations (with flavour tagging) as they become available

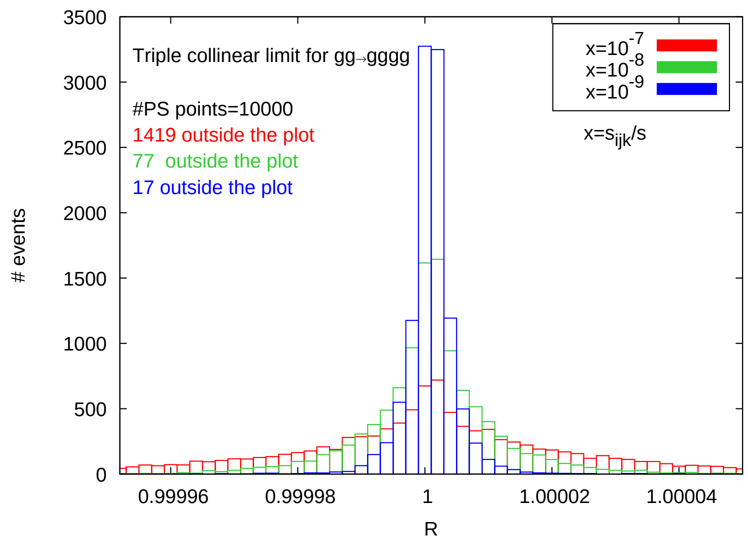


D0 preliminary, 1994

NNLO applications to LHC processes - status

- ✓ All relevant matrix elements for $pp \to 2$ jet, $pp \to V+1$ jet and $pp \to H$+jet processes available for some time
- ✓ Aim to push “leading colour gluons-only" $pp \to 2$ jets all the way to the end to demonstrate proof of concept
- ✓ Double unresolved subtraction terms for leading colour six-gluon process tested





(a) Example configuration of a triple collinear event with $s_{ijk} \to 0$.
(b) Distribution of $\mathrm{d}\hat{\sigma}^{RR}_{NNLO}/\mathrm{d}\hat{\sigma}^{S}_{NNLO}$ for 10000 triple collinear phase space points.

Pires, NG, (10)

NNLO applications to LHC processes - status

- ✓ Real Virtual subtraction terms for one-loop five-gluon process complete, explict poles cancel and subtraction term cancels unresolved singularities Gehrmann-De Ridder, Pires, NG (11)
- ✓ Explicit poles in ϵ in double virtual subtraction term $\mathrm{d}\hat{\sigma}^{U}_{NNLO}$ cancel against double virtual contribution $\mathrm{d}\hat{\sigma}^{VV}_{NNLO}$ Gehrmann, Gehrmann-De Ridder, Pires, NG (12)
- ✓ Now have “leading colour gluons-only" $pp \to 2$ jet parton level monte carlo - proof of concept for antenna subtraction method in hadron colliders
- ⚠ In parallel, coding of sub-leading colour contributions, quark processes, $pp \to H + 1$ jet and $pp \to V + 1$ jet underway
- ⚠ Looking to produce results in format that can be used for pdf fits (Ntuples, Applgrid, fastNLO, ...)

Outlook

- ✘ New Physics does not seem to be hiding in plain sight
- ✓ Demands better SM calculations to dig out complex signatures
- ✓ Incredible conceptual breakthroughs has produced a number of automated NLO solutions for multiparticle processes
- ✓ plus merging with parton showers, etc

CKKW, MLM, MCNLO, POWHEG, MENLOPS

- ✓ NLO QCD predictions establish a new standard of theoretical prediction for the LHC
- ✓ NNLO predictions are the new frontier, and results for $2 \to 2$ processes are in sight

- ✓ Challenge is to make precision measurements of α_s, PDF's, . . .
- ✓ . . . and increase sensitivity to more subtle signs of New Physics