Standard Model Theory

or

Theoretical uncertainties and their prospects for the HL-LHC

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IPPP, Durham University

ECFA High Luminosity LHC Experiments Workshop
Aix-les-Bains,
21 October 2014

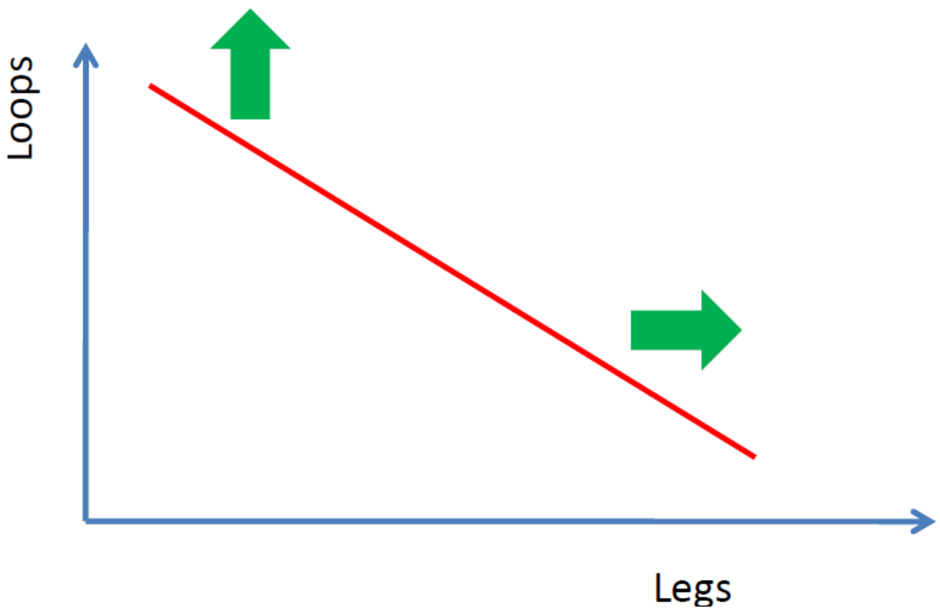
Theoretical Uncertainties

- Missing Higher Order corrections (MHO)
  - truncation of the perturbative series
  - often estimated by scale uncertainties - renormalisation/factorisation
  - ✓ systematically improvable by inclusion of higher orders
- Uncertainties in input parameters
  - parton distributions
  - masses, e.g., m_W, m_h, $[m_t]$
  - couplings, e.g., $\alpha_s(M_Z)$
  - ✓ systematically improvable by better description of benchmark processes
- Uncertainties in parton/hadron transition
  - fragmentation (parton shower)
  - ✓ systematically improvable by matching/merging with higher orders
  - hadronisation (model)
  - underlying event (tunes)

Goal: To fully exploit LHC, need to reduce theory uncertainties by a factor of two compared to where we are now in next decade

What is the hold up?

Rough idea of complexity of process $\sim$ #Loops + #Legs (+ #Scales)



- loop integrals are ultraviolet/infrared divergent
- complicated by extra mass/energy scales
- loop integrals often unknown
  - ✓ completely solved at NLO
- real (tree) contributions are infrared divergent
- isolating divergences complicated
  - ✓ completely solved at NLO
- currently far from automation
  - ✓ mostly solved at NLO

Current standard: NLO

1. Estimating uncertainties of MHO

✓ Consider a generic observable $\mathcal{O}$ (e.g. σ_H)

$$\mathcal{O}(Q) \quad \sim \quad \mathcal{O}_k(Q,\mu) + \Delta_k(Q,\mu)$$

where

$$\mathcal{O}_k(Q,\mu) \equiv \sum_{n=0}^{k} c_n(Q,\mu)\alpha_s(\mu)^n, \qquad \Delta_k(Q,\mu) \equiv \sum_{n=k+1}^{\cdots} c_n(Q,\mu)\alpha_s(\mu)^n$$

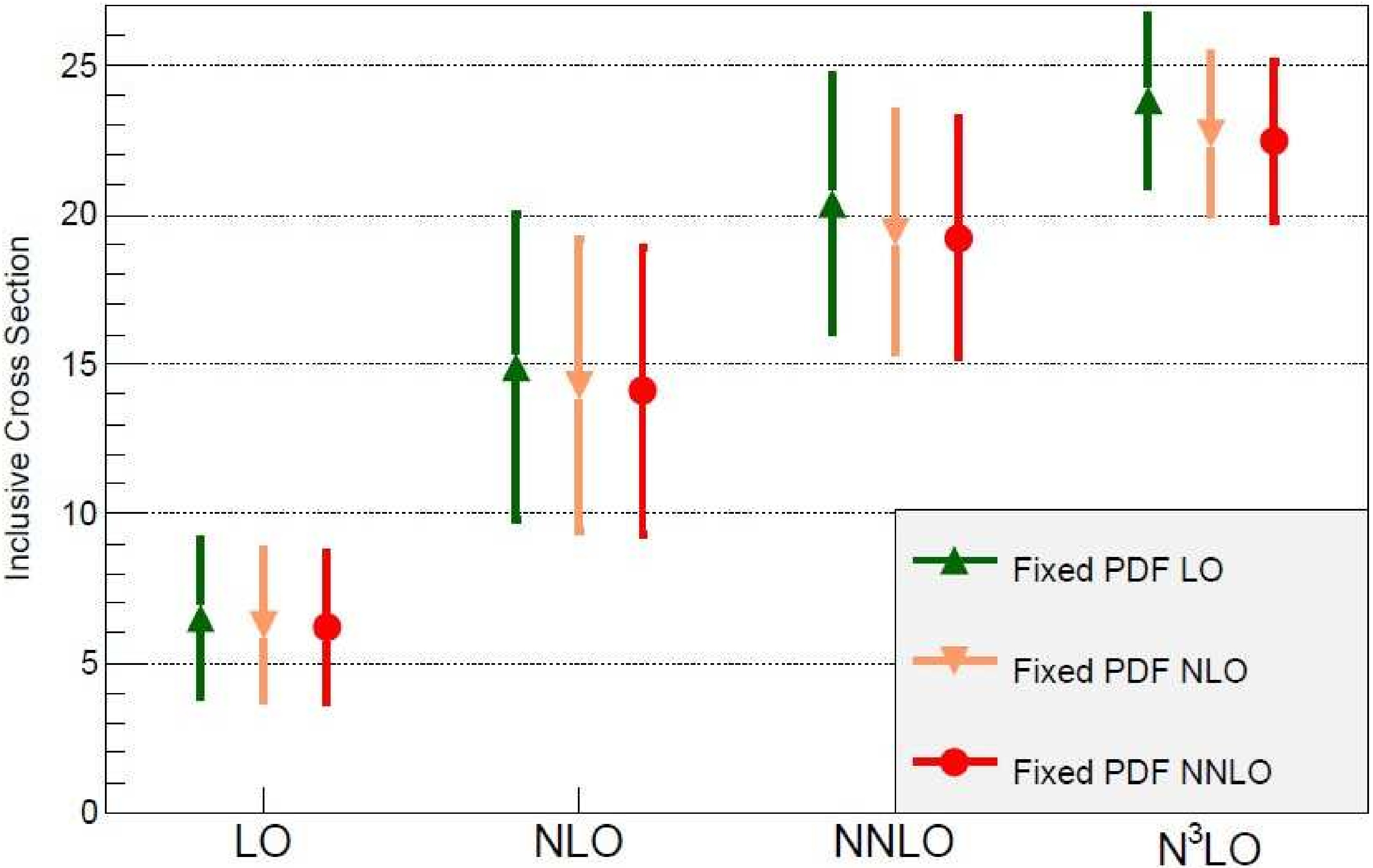
✓ Usual procedure is to use scale variations to estimate Δ_k,

$$\Delta_k(Q,\mu) \quad \sim \quad \max\left[\mathcal{O}_k\left(Q,\frac{\mu}{r}\right), \mathcal{O}_k(Q,r\mu)\right] \sim \alpha_s(\mu)^{k+1}$$

where μ is chosen to be a typical scale of the problem and typically $r = 2$.

Choice of μ and $r = 2$ is convention

Theoretical uncertainty on σ_H



Forte, Isgro, Vita

Warning: Scale variation may not give an accurate estimate of the uncertainty in the cross section!!

Going beyond scale uncertainties

- ✓ Series acceleration — David, Passarino

  sequence transformations gives estimates of some of the unknown terms in series

- ✓ Estimate coefficients using information on the singularity structure of the Mellin space cross section coming from all order resummation — Ball et al
  - large N (soft gluon, Sudakov)
  - small N (high energy, BFKL)

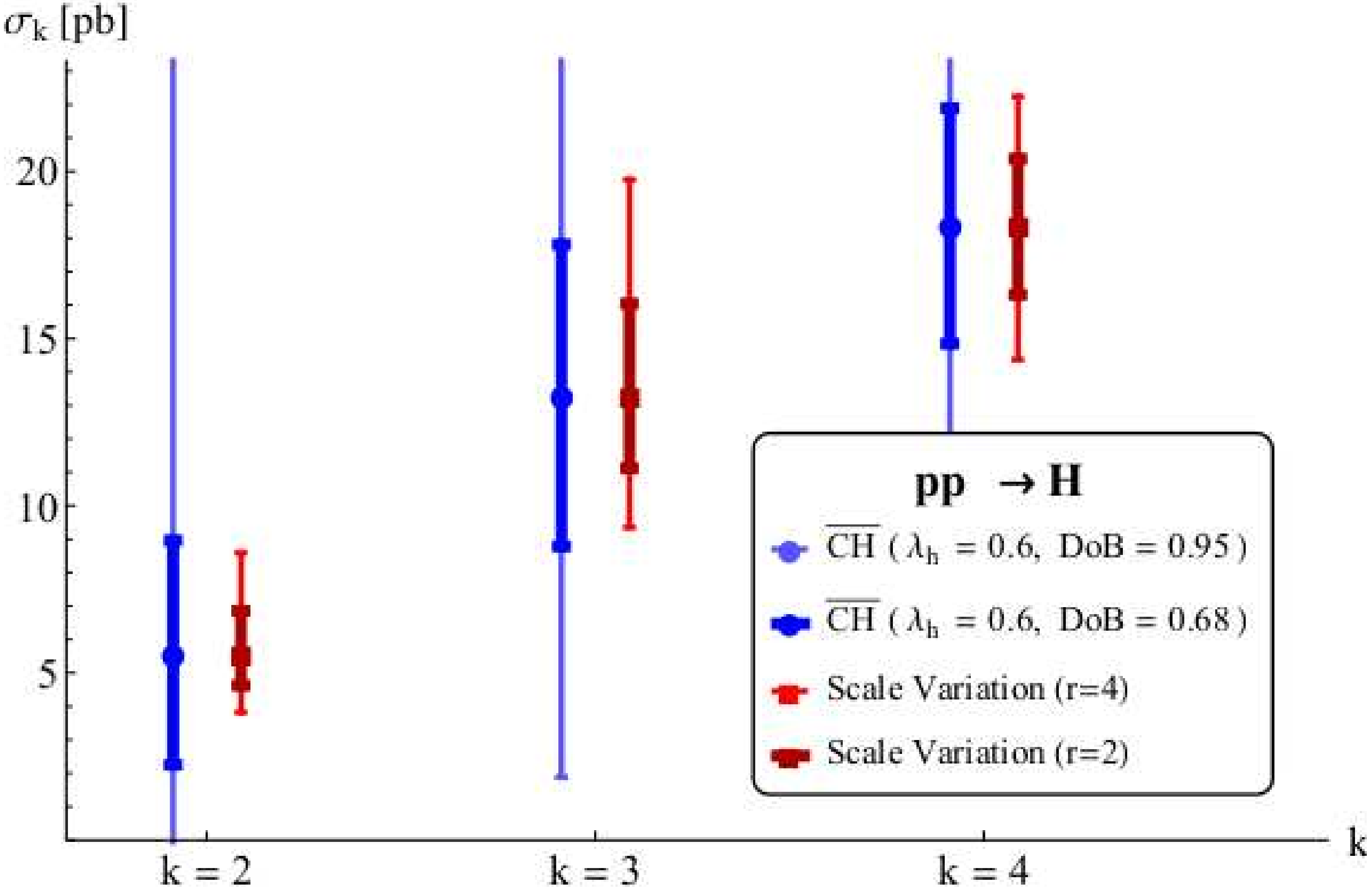
- ✓ Bayesian estimate of unknown coefficients — Cacciari, Houdeau

  make the assumption that all the coefficients c_n share a (process dependent) upper bound $\bar{c} > 0$ leading to density functions $f(c_n|\bar{c})$ and $f(\ln \bar{c})$
  recent refinement of method — Bagnaschi, Cacciari, Guffanti, Jenniches

- ✓ Accepting that scale variation does not give reliable error estimate, can predict the part of the N^{3}LO cross section coming from scale variations.

Pressure is building to better estimate MHO

Theoretical uncertainty on σ_H revisited



Bagnaschi, Cacciari, Guffanti, Jenniches

Errors in Modified CH approach larger but more realistic!!

2. Improved calculations wishlist

- ✓ From the 2013 Les Houches proceedings

  arXiv:1405.1067

- ✓ Counting of orders is done relative to LO QCD independent of absolute power of α_s in cross section
- ✓ $\alpha \sim \alpha_s^2$ so that NNLO QCD and NLO EW effects naively of same size
- ✓ List contains processes where improved precision motivated by experiment.
- ✓ Is ambitious, but doable over the remainder of LHC running

- LO $\equiv$ O(1)
- NLO QCD $\equiv$ O(α_s)
- NLO EW $\equiv$ O(α)
- NNLO QCD $\equiv$ O(α_s^2)
- NNLO QCD+EW $\equiv$ O($\alpha_s \alpha$)
- NNNLO QCD $\equiv$ O(α_s^3)

+ plus matching to parton shower for fully exclusive final states

- ✓ $d\sigma$ indicates fully differential cross section
- ✓ $d\sigma$ NNLO QCD+NLO EW indicates a single code including both NNLO QCD and NLO EW effects. Where possible full resonance production including interfererence and background to be taken into account.

Les Houches wishlist for Higgs

Process	State of the Art	Desired
H	$\mathrm{d}\sigma$ @ NNLO QCD (expansion in $1/m_t$) full m_t/m_b dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	$\mathrm{d}\sigma$ @ NNNLO QCD (infinite-m_t limit) full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects
$H+j$	$\mathrm{d}\sigma$ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	$\mathrm{d}\sigma$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
$H+2j$	σ_{tot}(VBF) @ NNLO(DIS) QCD $\mathrm{d}\sigma$(VBF) @ NLO EW $\mathrm{d}\sigma(gg)$ @ NLO QCD (infinite-m_t limit) and finite-quark-mass effects @ LO QCD	$\mathrm{d}\sigma$(VBF) @ NNLO QCD + NLO EW $\mathrm{d}\sigma(gg)$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
$H+V$	$\mathrm{d}\sigma$ @ NNLO QCD $\mathrm{d}\sigma$ @ NLO EW $\sigma_{\mathrm{tot}}(gg)$ @ NLO QCD (infinite-m_t limit)	with $H \to b\bar{b}$ @ same accuracy $\mathrm{d}\sigma(gg)$ @ NLO QCD with full m_t/m_b dependence
tH and $\bar{t}H$	$\mathrm{d}\sigma$(stable top) @ LO QCD	$\mathrm{d}\sigma$(top decays) @ NLO QCD and NLO EW
$t\bar{t}H$	$\mathrm{d}\sigma$(stable tops) @ NLO QCD	$\mathrm{d}\sigma$(top decays) @ NLO QCD and NLO EW
$gg \to HH$	$\mathrm{d}\sigma$ @ NLO QCD (leading m_t dependence) $\mathrm{d}\sigma$ @ NNLO QCD (infinite-m_t limit)	$\mathrm{d}\sigma$ @ NLO QCD with full m_t/m_b dependence

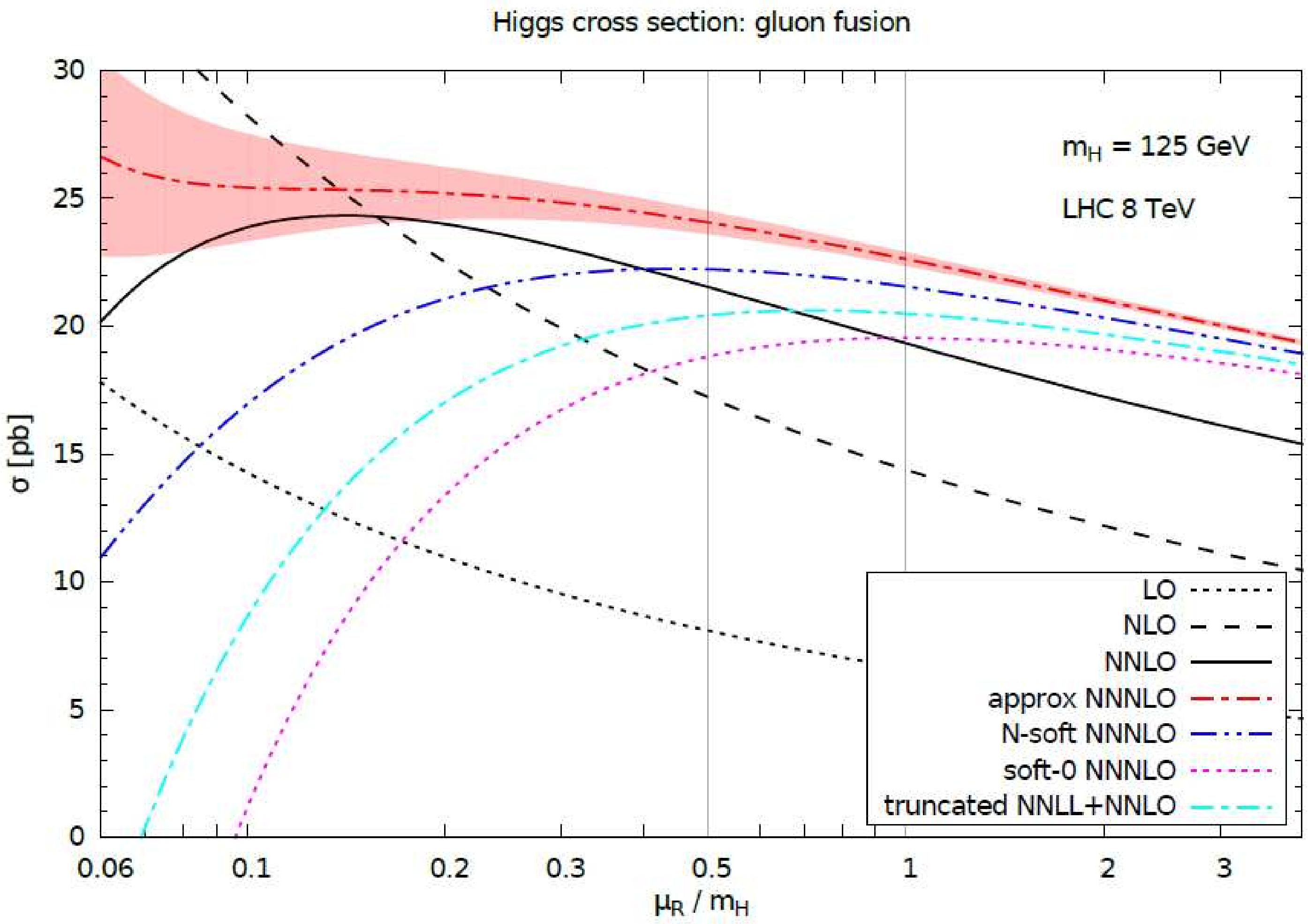
First assault on Higgs production at N3LO $m_t \to \infty$

- ✓ Currently, σ_H via gluon fusion known to NNLO QCD in infinite top mass limit, with finite quark mass effects at NLO QCD and NLO EW. Theoretical uncertainties $\mathcal{O}(15\%)$ with HO and PDF+α_s uncertainties roughly equal.
- ✓ Aim to reduce the theoretical error for the inclusive Higgs cross section via gluon fusion to $\mathcal{O}(5\%)$ by computing NNNLO QCD effects.
- ✓ Ingredients: Three-loop H+0 parton, Two-loop H+1 parton, One-loop H+2 parton, Tree-level H+3 parton - all known as matrix elements for $m_t \to \infty$
  - key part is to extract the infrared singularities so the parts can be combined
- ✓ Threshold corrections: Major new result

  Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger

- ✓ Opens up the possibility of full N3LO corrections in future.

Higgs cross section at approximate N3LO



Bonvini, Ball, Forte, Marzani and Ridolfi

pp $\rightarrow$ H + jet production at NNLO $m_t \rightarrow \infty$

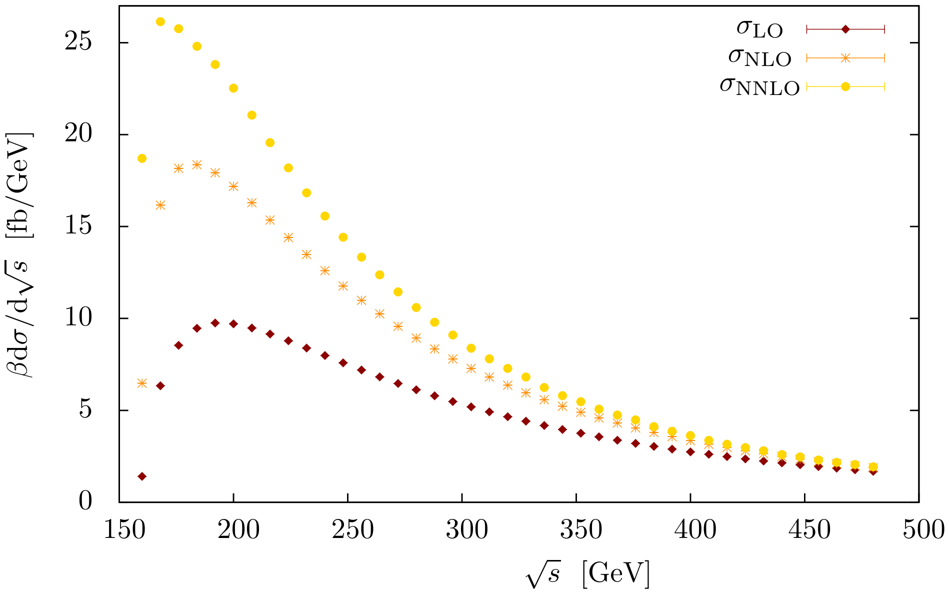
- ✓ Key goal: Establish properties of the Higgs boson!
- ✓ experimental event selection according to number of jets
  - ✓ different backgrounds for different jet multiplicities
  - ✓ H+0 jet known at NNLO

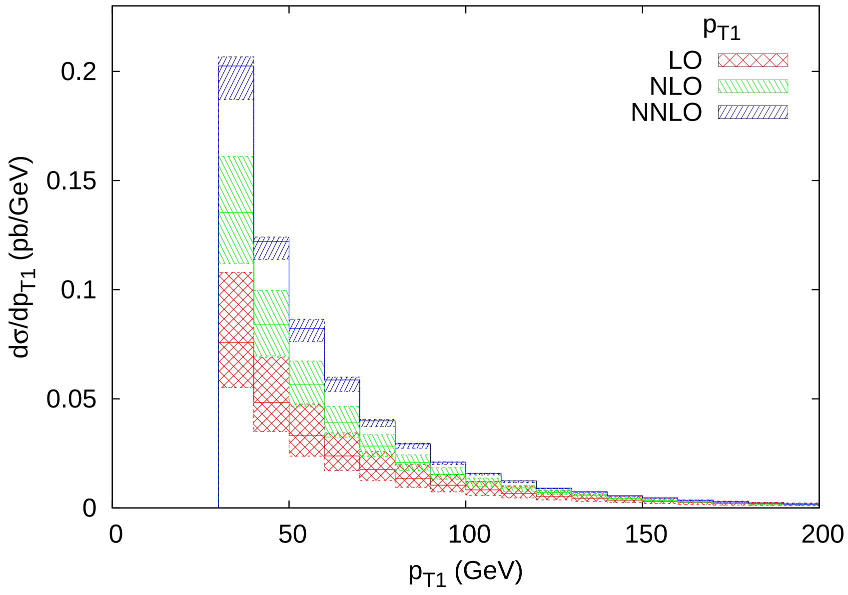
    Anastasiou, Melnikov, Petriello; Catani, Grazzini
  - ✓ H+n jets (n=1,2,3) known at NLO
  - ✓ H+0 jet and H+1 jet samples of similar size
- ✓ NNLO H+1 jet crucial, particularly for WW channel
  - ✓ gluons-only total cross section

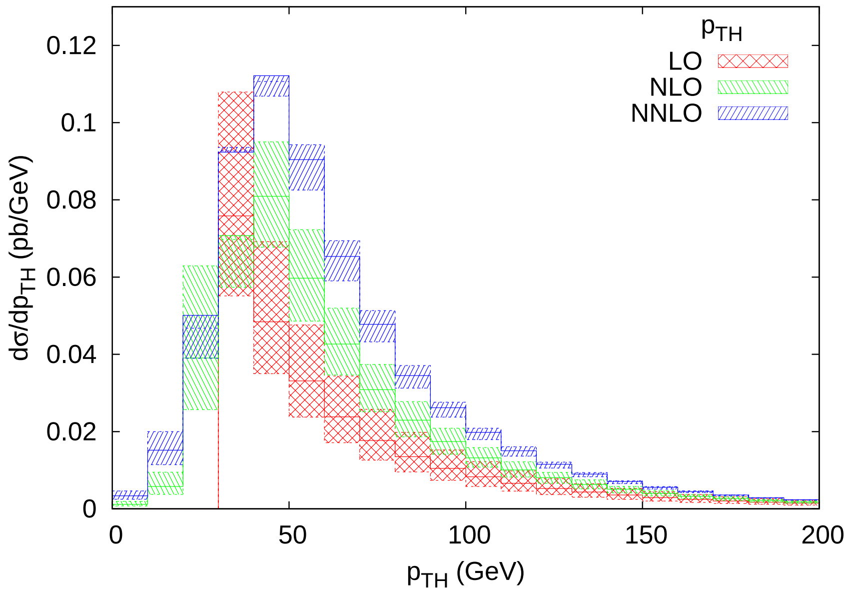
    Boughezal, Caola, Melnikon, Petriello, Schulze
  - ✓ gluons-only differential cross sections

    Chen, Gehrmann, NG, Jacquier
  - ✓ gg-channel dominant - at NLO gg(70%), qg (30%)
  - ⚠ other channels in progress

pp $\rightarrow$ H + jet at NNLO $m_t \rightarrow \infty$





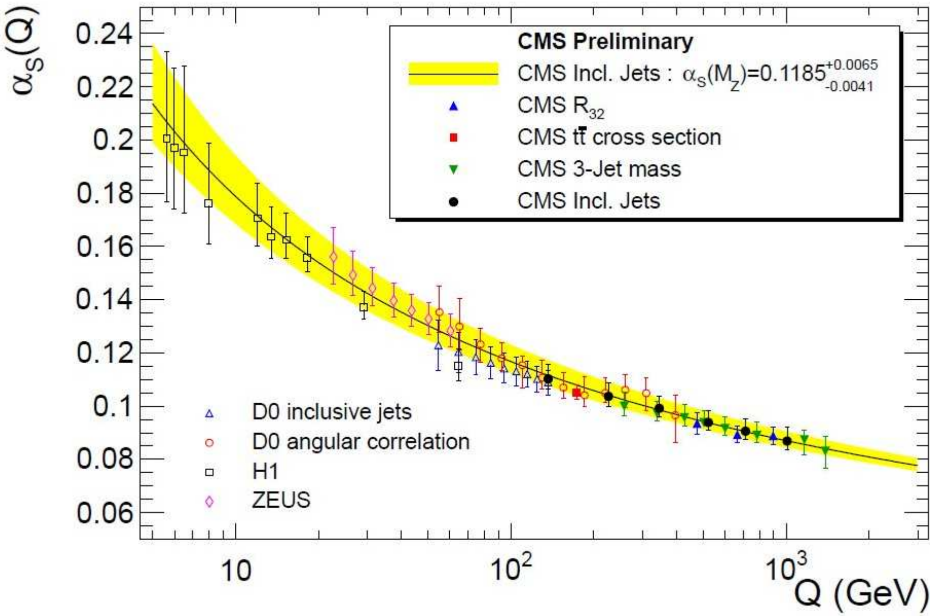


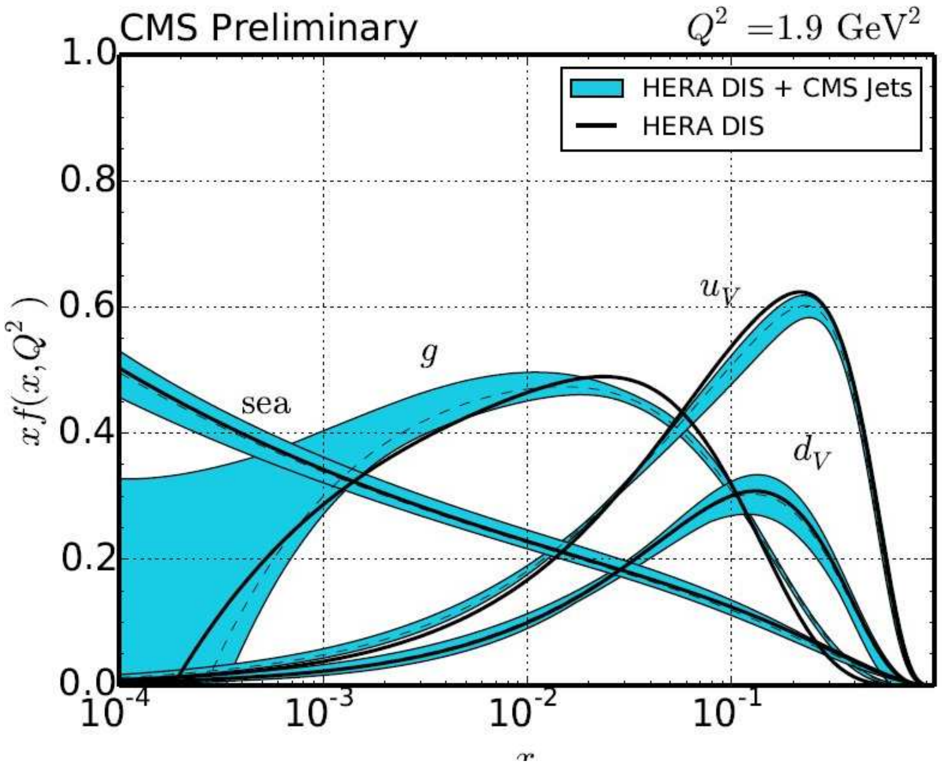
- ✓ large effects near partonic threshold
- ✓ large K-factor

$$\sigma_{NLO}/\sigma_{LO} \sim 1.6$$
$$\sigma_{NNLO}/\sigma_{NLO} \sim 1.3$$

- ✓ significantly reduced scale dependence $\mathcal{O}(4\%)$

3. Improved precision for input parameters





✓ More precise measurements of strong coupling

✓ Improved parton distributions

Les Houches wishlist for Top/Jet processes

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\rm tot}$(stable tops) @ NNLO QCD $\mathrm{d}\sigma$(top decays) @ NLO QCD $\mathrm{d}\sigma$(stable tops) @ NLO EW	$\mathrm{d}\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$\mathrm{d}\sigma$(NWA top decays) @ NLO QCD	$\mathrm{d}\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$\mathrm{d}\sigma$(stable tops) @ NLO QCD	$\mathrm{d}\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$\mathrm{d}\sigma$(NWA top decays) @ NLO QCD	$\mathrm{d}\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$\mathrm{d}\sigma$ @ NNLO QCD (g only) $\mathrm{d}\sigma$ @ NLO EW (weak)	$\mathrm{d}\sigma$ @ NNLO QCD + NLO EW
$3j$	$\mathrm{d}\sigma$ @ NLO QCD	$\mathrm{d}\sigma$ @ NNLO QCD + NLO EW
$\gamma + j$	$\mathrm{d}\sigma$ @ NLO QCD $\mathrm{d}\sigma$ @ NLO EW	$\mathrm{d}\sigma$ @ NNLO QCD + NLO EW

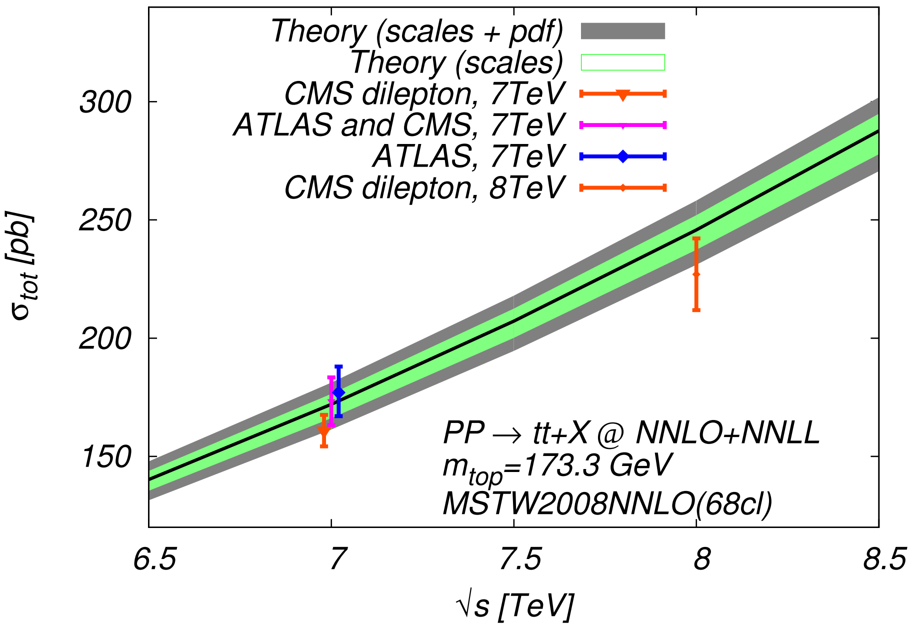
pp $\rightarrow t\bar{t}$ at NNLO

- ✓ Top production important as possible venue for new physics and for determination of gluon PDF ar large x
- ✓ Experimental uncertainties $\mathcal{O}(5\%)$
- ✓ NNLO total cross section known

Czakon, Fielder, Mitov

⚠ distributions in progress

- ✓ NNLO theory uncertainty $\mathcal{O}(4\%)$



Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	+0.259(3.7%) −0.374(5.3%)	+0.169(2.4%) −0.121(1.7%)
LHC 7 TeV	167.0	+6.7(4.0%) −10.7(6.4%)	+4.6(2.8%) −4.7(2.8%)
LHC 8 TeV	239.1	+9.2(3.9%) −14.8(6.2%)	+6.1(2.5%) −6.2(2.6%)
LHC 14 TeV	933.0	+31.8(3.4%) −51.0(5.5%)	+16.1(1.7%) −17.6(1.9%)

NNLO

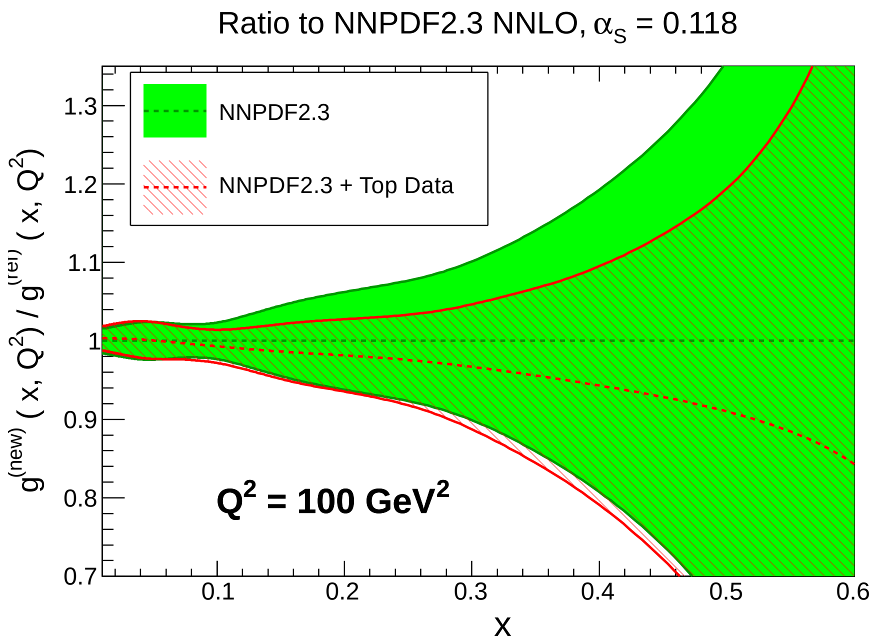
Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

NNLO+NNLL

Impact on gluon distribution

- ✓ Top production at the LHC dominated by qg and gg channels
- ✓ Total cross section sensitive to gluon PDF
- ✓ Impacts the NNLO global parton distribution fit

Czakon, Mangano, Mitov, Rojo



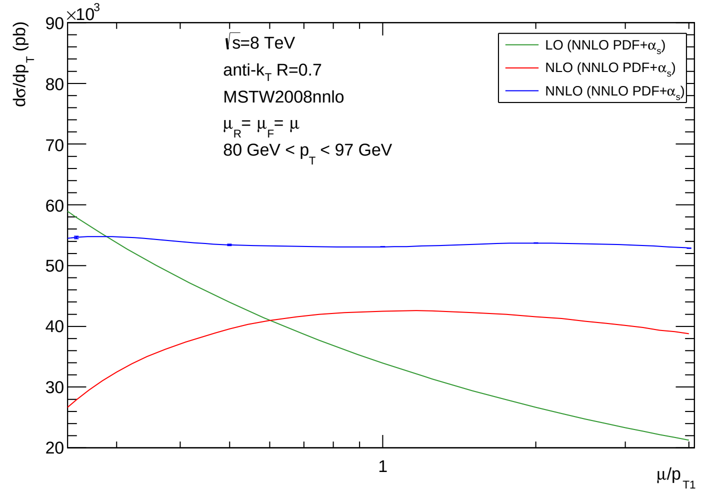
- ✓ leads to reduced gluon uncertainty at large x

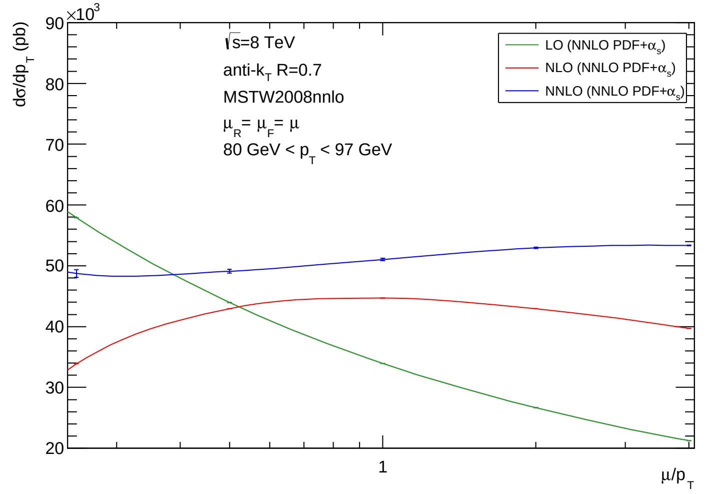
pp $\to$ 2 jets at NNLO

- ✓ One of key processes for perturbative QCD
- ✓ Current experimental precision $\mathcal{O}$(5-10%) for jets from 200 GeV/c-1 TeV/c
  - Need NNLO QCD and NLO EW
- ✘ Only process currently included in global PDF fits that is not known at NNLO
  - ✓ gg channel

Currie, Gehrmann-De Ridder, Gehrmann, Pires, NG

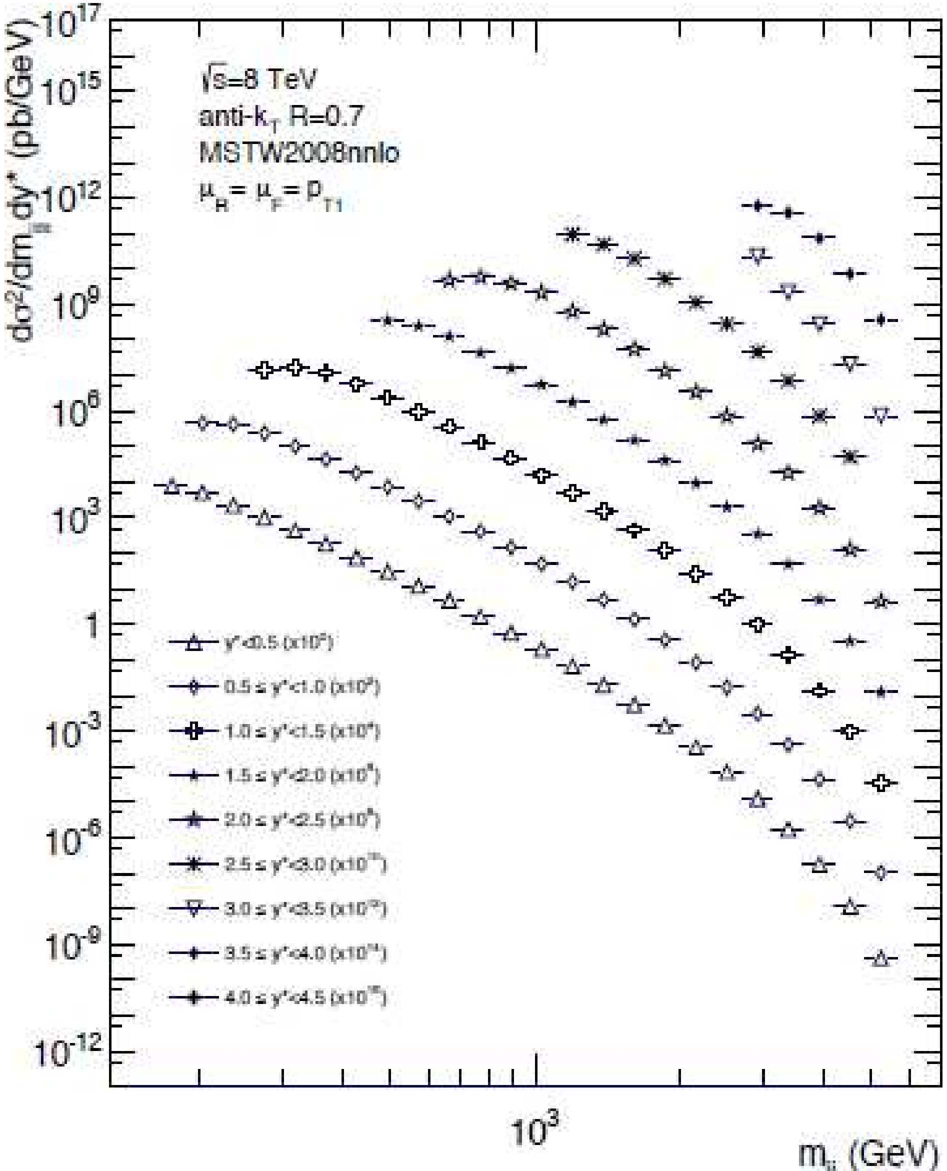
- ✓ Scale variation much reduced for $0.5 < \mu/p_T < 2$.
- ✓ Size of corrections, and uncertainty, still depends on scale choice p_{T1} v p_T.

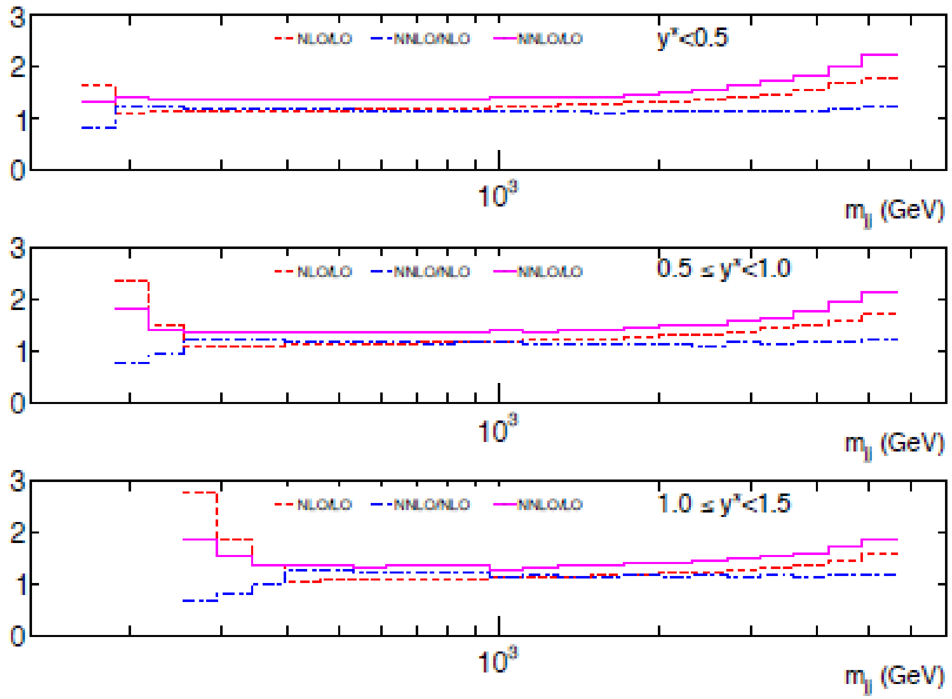




Di-jet mass distribution (gluons only) at NNLO

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



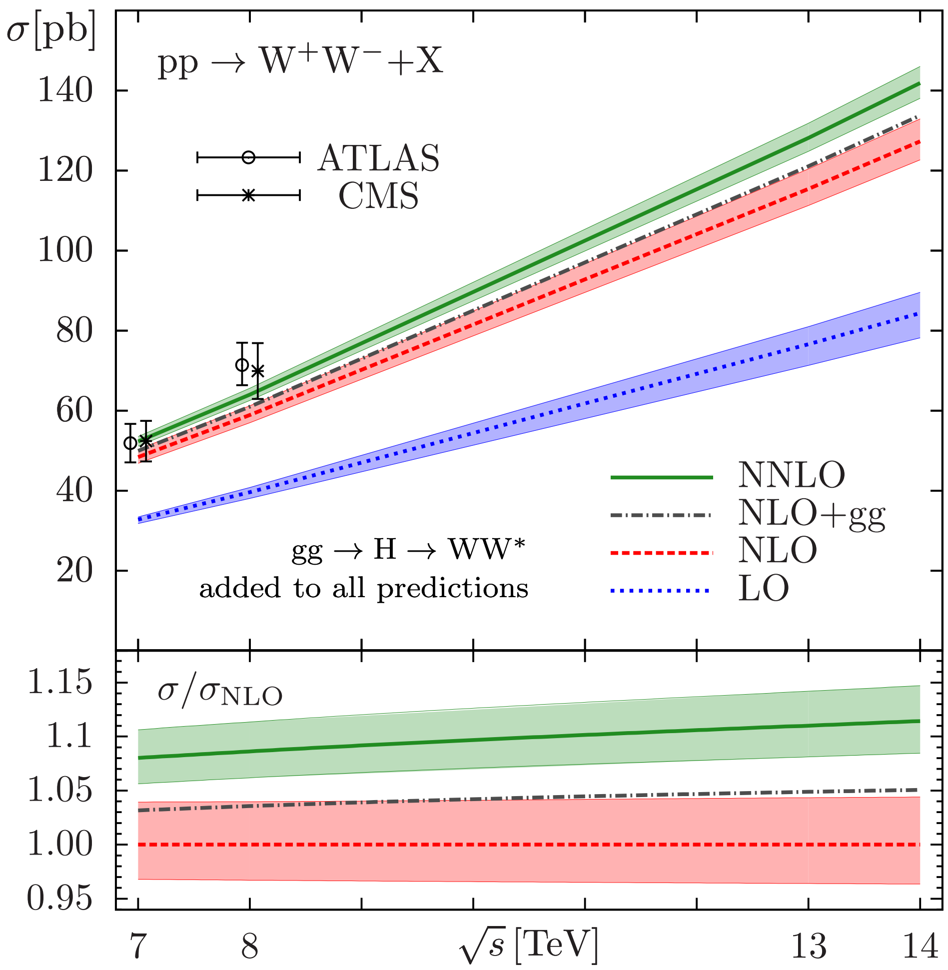


- ✓ NNLO corrections ∼25% wrt NLO
- ✓ similar behavior for different rapidity slices

Les Houches wishlist for W/Z processes

Process	State of the Art	Desired
V	$\mathrm{d}\sigma$(lept. V decay) @ NNLO QCD $\mathrm{d}\sigma$(lept. V decay) @ NLO EW	$\mathrm{d}\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS
$V + j(j)$	$\mathrm{d}\sigma$(lept. V decay) @ NLO QCD $\mathrm{d}\sigma$(lept. V decay) @ NLO EW	$\mathrm{d}\sigma$(lept. V decay) @ NNLO QCD + NLO EW
VV'	$\mathrm{d}\sigma$(V decays) @ NLO QCD $\mathrm{d}\sigma$(on-shell V decays) @ NLO EW	$\mathrm{d}\sigma$(decaying off-shell V) @ NNLO QCD + NLO EW
$gg \to VV$	$\mathrm{d}\sigma$(V decays) @ LO QCD	$\mathrm{d}\sigma$(V decays) @ NLO QCD
$V\gamma$	$\mathrm{d}\sigma$(V decay) @ NLO QCD $\mathrm{d}\sigma$(PA, V decay) @ NLO EW	$\mathrm{d}\sigma$(V decay) @ NNLO QCD + NLO EW
$Vb\bar{b}$	$\mathrm{d}\sigma$(lept. V decay) @ NLO QCD massive b	$\mathrm{d}\sigma$(lept. V decay) @ NNLO QCD + NLO EW, massless b
$VV'\gamma$	$\mathrm{d}\sigma$(V decays) @ NLO QCD	$\mathrm{d}\sigma$(V decays) @ NLO QCD + NLO EW
$VV'V''$	$\mathrm{d}\sigma$(V decays) @ NLO QCD	$\mathrm{d}\sigma$(V decays) @ NLO QCD + NLO EW
$VV' + j$	$\mathrm{d}\sigma$(V decays) @ NLO QCD	$\mathrm{d}\sigma$(V decays) @ NLO QCD + NLO EW
$VV' + jj$	$\mathrm{d}\sigma$(V decays) @ NLO QCD	$\mathrm{d}\sigma$(V decays) @ NLO QCD + NLO EW
$\gamma\gamma$	$\mathrm{d}\sigma$ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

pp $\to W^+W^-$ at NNLO



Gehrmann et al

- ✓ Provides a handle on the determination of triple gauge couplings, and possible new physics
- ✓ Severe contamination of the W^+W cross section due to top-quark resonances

$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$

- ✓ The NNLO QCD corrections increase the NLO result by an amount varying from 9% to 12% as $\sqrt{s}$ goes from 7 to 14 TeV.
- ✓ Scale uncertainties at the $\pm 3\%$ level.

4. Improved precision for event simulation

Fixed order calculations

- ✓ Expansion in powers of the coupling constant
- ✓ Correctly describes hard radiation pattern
- ✓ Final states are described by single hard particles
- ✓ NLO: up to two particles in a jet, NNLO: up to three..
- ✓ Soft radiation poorly described

Parton shower

- ✓ Exponentiates multiple soft radiation (leading logarithms)
- ✓ Describes multi-particle dynamics and jet substructure
- ✓ Allows generation of full events (interface to hadronization)
- ✓ Basis of multi-purpose generators (SHERPA, HERWIG, PYTHIA)
- ✓ Fails to account for hard emissions

Ideally: combine virtues of both approaches

Matrix Element improved Parton Shower

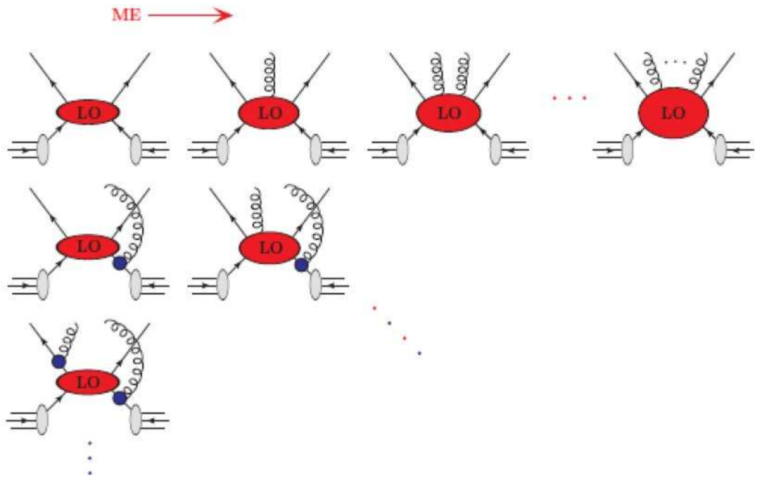
matrix elements and parton showers are approximations in different regions of phase space

Merging

Several fixed order calculations of increasing multiplicity supplemented by PS

CKKW: Catani, Krauss, Kuhn, Webber

MLM: Mangano

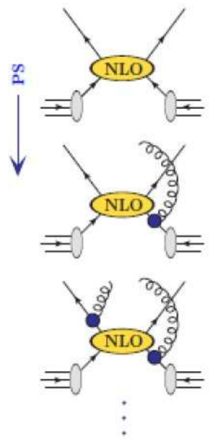


Matching

One fixed order calculation supplemented by PS

MC@NLO: Frixione, Webber,

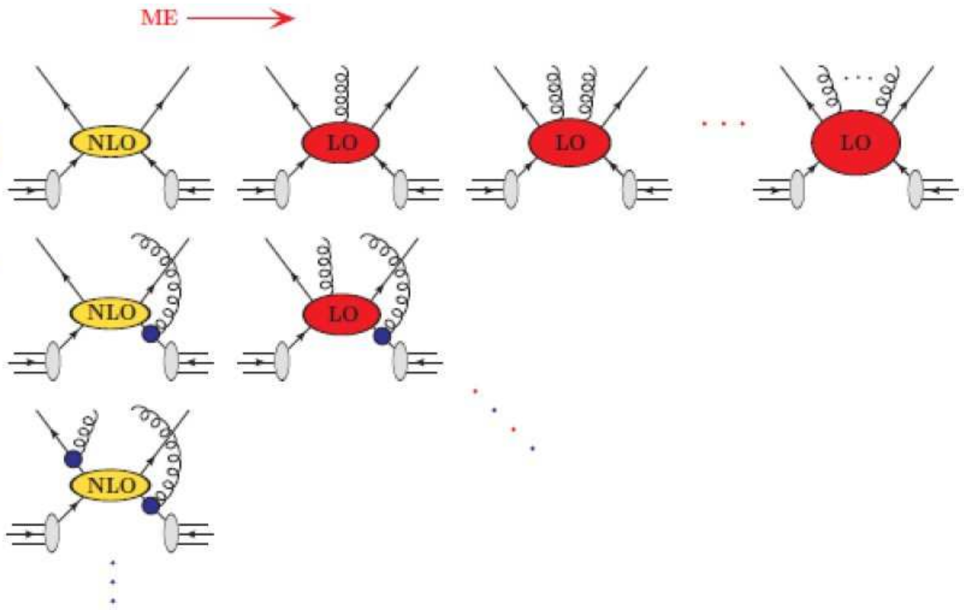
POWHEG: Nason, Oleari



Now benefitting from automation of NLO

aMC@NLO: Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli

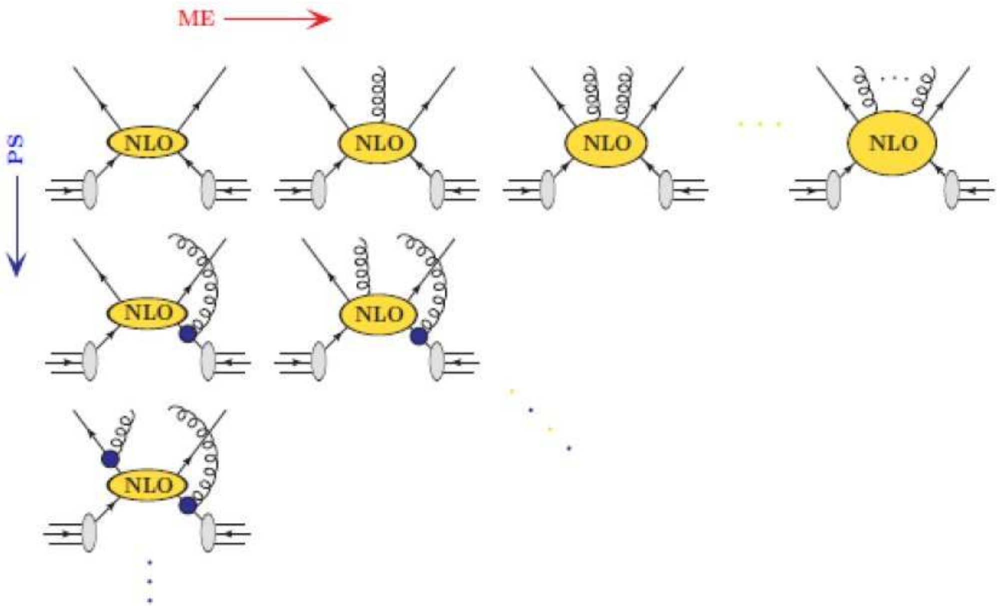
Matrix Element improved Parton Shower



MENLOPS

Supplements core NLOPS with higher multiplicity LOPS

Hamilton, Nason; Hoeche, Krauss, Schonherr, Siegert; Lonnblad, Prestel



MEPS@NLO

Combines multiple NLOPS

Lavesson, Lonnblad; Hoeche, Krauss, Schonherr, Siegert; Frederix, Frixione

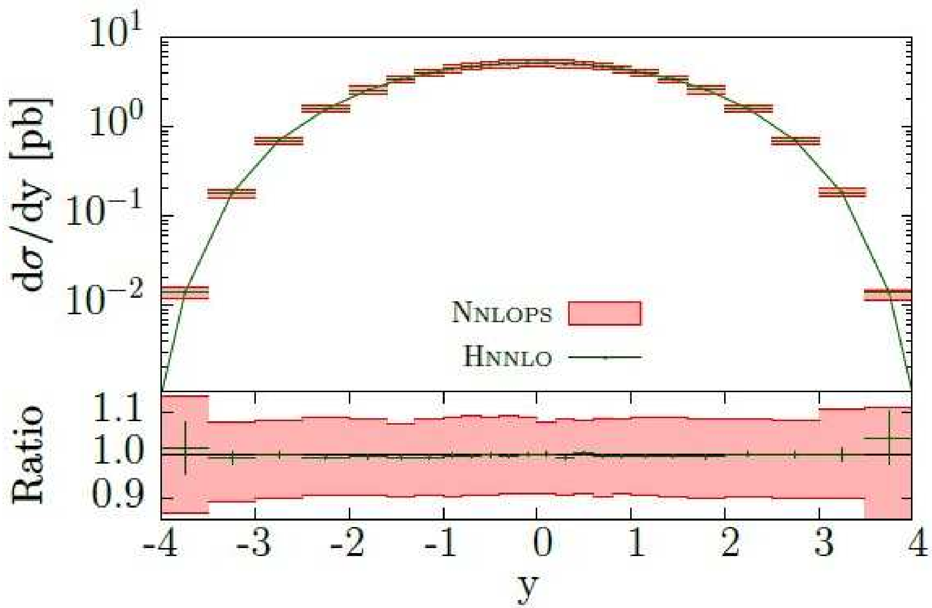
Reaching NNLOPS accuracy

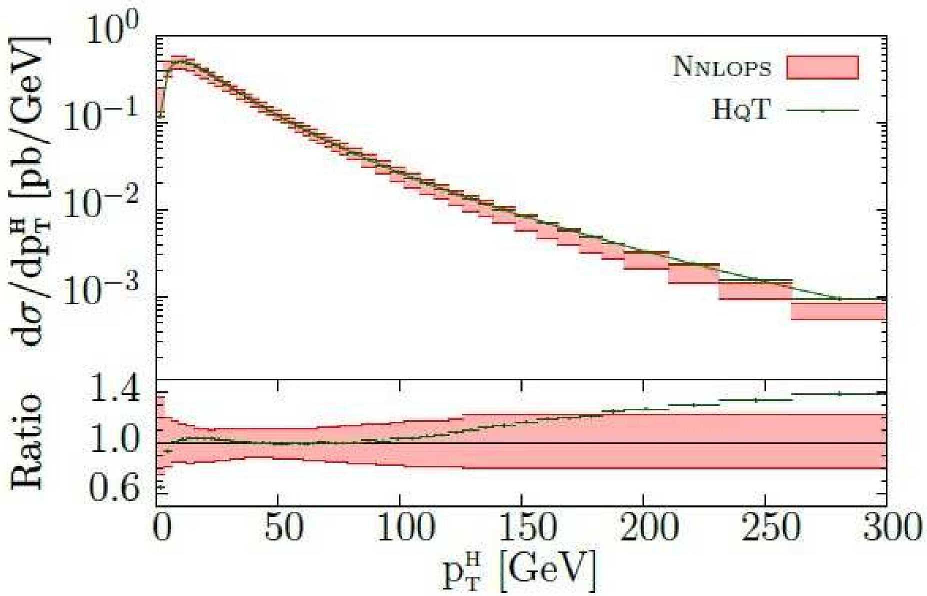
MINLO

Multiscale improved NLO CKKW scale for Born pieces
Sudakov form factors for Born functions in POWHEG

Hamilton, Nason, Zanderighi

Exciting idea! starting from HJ@NLO+PS generate H rapidity distribution at NNLO





Hamilton, Nason, Oleari, Re, Zanderighi

Summary: Where are we now?

- ✓ Witnessed a revolution that has established NLO as the new standard
  - previously impossible calculations now achieved
  - very high level of automation for numerical code
  - standardisation of interfaces - linkage of one-loop and real radiation providers
  - take up by experimental community
- ✓ Substantial progress in NNLO in past couple of years
  - several different approaches for isolating IR singularities
  - several new calculations available
  - codes typically require significant CPU resource

Summary: Where are we going?

- ✓ NNLO automation?
  - as we gain analytical and numerical experience with NNLO calculations, can we benefit from (some of) the developments at NLO, and the improved understanding of amplitudes
  - automation of two-loop contributions?
  - automation of infrared subtraction terms?
  - standardisation of interfaces - linkage to one-loop and real radiation providers?
  - interface with experimental community

Next few years:

- ✓ Les Houches wishlist to focus theory attention
- ✓ New high precision calculations that will appear such as, e.g. N3LO σ_H, could reduce Missing Higher Order uncertainty by a factor of two
- ✓ NNLO will emerge as standard for benchmark processes such as dijet production leading to improved pdfs etc. could reduce theory uncertainty due to inputs by a factor of two