Topics on NNLO calculations

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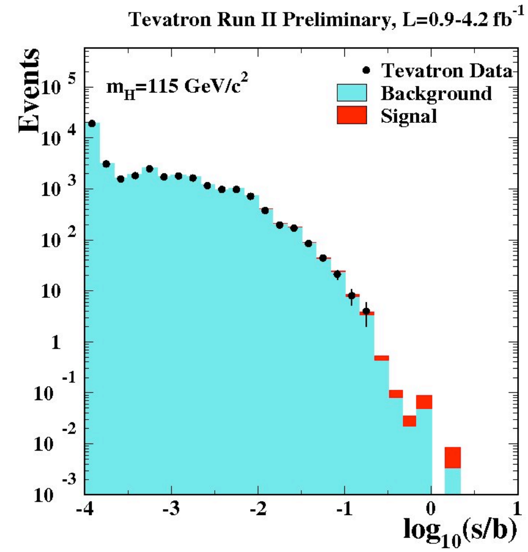
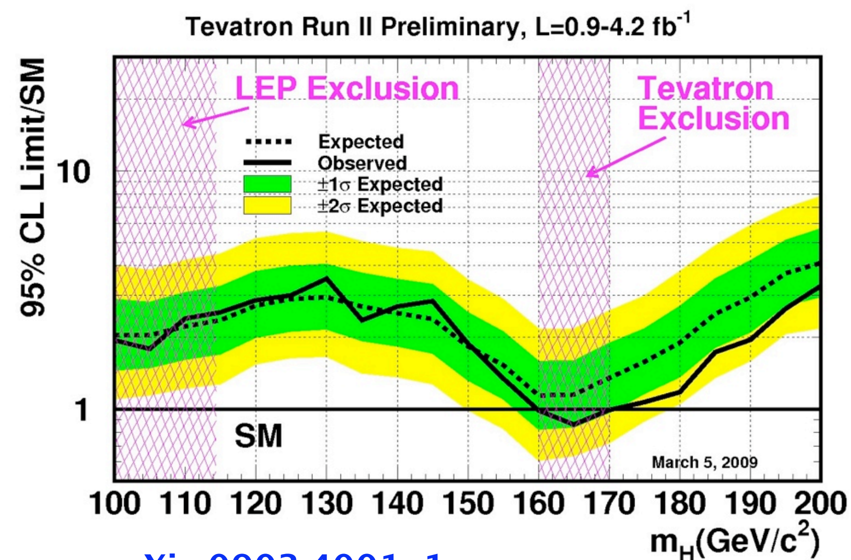
Tevatron is sensitive to a Higgs boson

- A complicated search for a very small number of signal events in a large background.

- Requires very precise knowledge of the Higgs total cross-section

- And every bit of information on kinematic differences for signal and background events





arXiv:0903.4001v1

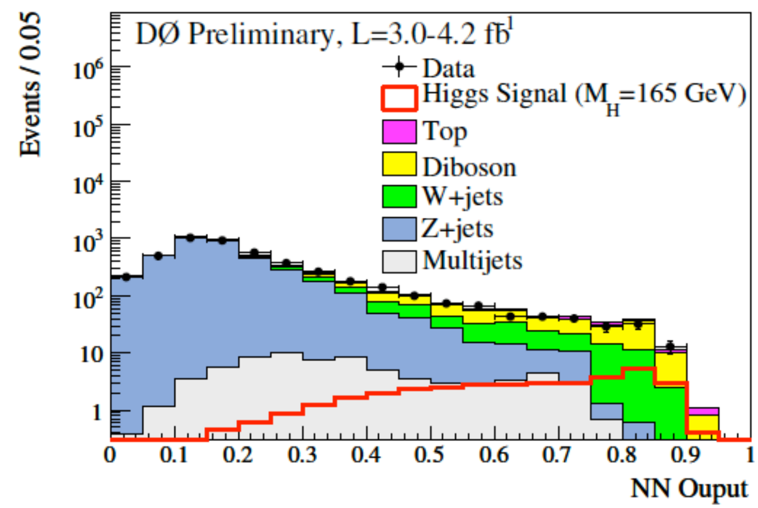
Role of NNLO computations

σ_{inc} [fb]	LO	NLO	NNLO	K^{NLO}	K^{NNLO}
$\mu = m_{\text{H}}/2$	1.998 ± 0.003	4.288 ± 0.004	5.252 ± 0.016	2.149 ± 0.008	2.629 ± 0.009
$\mu = m_{\text{H}}$	1.398 ± 0.001	3.366 ± 0.003	4.630 ± 0.010	2.412 ± 0.002	3.312 ± 0.008
$\mu = 2\,m_{\text{H}}$	1.004 ± 0.001	2.661 ± 0.002	4.012 ± 0.007	2.651 ± 0.008	3.996 ± 0.008

- Very large QCD corrections at NLO and NNLO. Tevatron is insensitive to a Higgs signal at NLO or LO.
- Very small theoretical uncertainty at NNLO (~ ±10% pdfs and ±11% scale variation)
- *CDF and D0 estimate the theoretical uncertainty on the NNLO cross-section to less than ±12%.*

Detailed kinematics description

	Final state	$e\mu$	ee	$\mu\mu$
Cut 0	Pre-selection	lepton ID, leptons with opposite charge and $p_T^{\mu} > 10$ GeV and $p_T^{e} > 15$ GeV invariant mass $M_{\ell\ell} > 15$ GeV $\mu\mu$: $n_{\rm jet} < 2$ for $p_T^{\rm jet} > 15$ GeV, $\Delta\mathcal{R}(\mu,{\rm jet}) > 0.1$ and $p_T^{\mu} > 15$ GeV for the leading μ		
Cut 1	Missing Transverse Energy $\not\!\!E_T$ (GeV)	> 20	> 20	
Cut 2	$\not\!\!E_T^{\rm Scaled}$	> 6	> 6	
Cut 3	M_T^{min} $(\ell, \not\!\!E_T)$ (GeV)	> 20	> 30	
Cut 4	$p_T^{\mu\mu}$ (GeV) for $n_{\rm jet} = 0$			> 20
	$\not\!\!E_T$ (GeV) for $n_{\rm jet} = 1$			> 20
Cut 5	$\Delta\phi(\ell, \ell)$	< 2.0	< 2.0	< 2.5



	ee pre-selection	ee final	$e\mu$ pre-selection	$e\mu$ final	$\mu\mu$ pre-selection	$\mu\mu$ final
$Z \to ee$	218695 ± 704	108 ± 14	280.6 ± 3.3	$0.0^{+0.1}_{-0.0}$	–	–
$Z \to \mu\mu$	–	–	274.6 ± 0.9	5.8 ± 0.1	235670 ± 158	3921 ± 22
$Z \to \tau\tau$	1135 ± 16	1.4 ± 0.5	3260 ± 3	7.3 ± 0.1	1735 ± 10	66 ± 2
$t\bar{t}$	131.4 ± 1.4	39.9 ± 0.8	272.0 ± 0.3	82.5 ± 0.2	19.93 ± 0.05	12.55 ± 0.04
W+jets	241 ± 5	98 ± 3	183 ± 4	78.6 ± 2.8	214 ± 7	134 ± 5
WW	172.2 ± 2.6	66.8 ± 1.6	421.2 ± 0.1	154.7 ± 0.1	159.0 ± 0.3	92.8 ± 0.3
WZ	112.5 ± 0.2	9.68 ± 0.05	20.5 ± 0.1	6.6 ± 0.1	47.3 ± 0.5	19.4 ± 0.3
ZZ	98.2 ± 0.2	7.68 ± 0.07	5.3 ± 0.1	0.60 ± 0.01	40.5 ± 0.2	15.1 ± 0.1
Multijet	1351 ± 55	$1.7^{+2.0}_{-1.7}$	279 ± 168	$1.1^{+9.6}_{-1.1}$	386 ± 20	64 ± 8
Signal ($M_H = 165$ GeV)	9.45 ± 0.01	6.13 ± 0.01	17.1 ± 0.01	12.2 ± 0.1	5.43 ± 0.01	4.85 ± 0.01
Total Background	221937 ± 707	332 ± 15	4995 ± 168	337 ± 10	238272 ± 159	4325 ± 24
Data	221530	336	4995	329	239923	4084

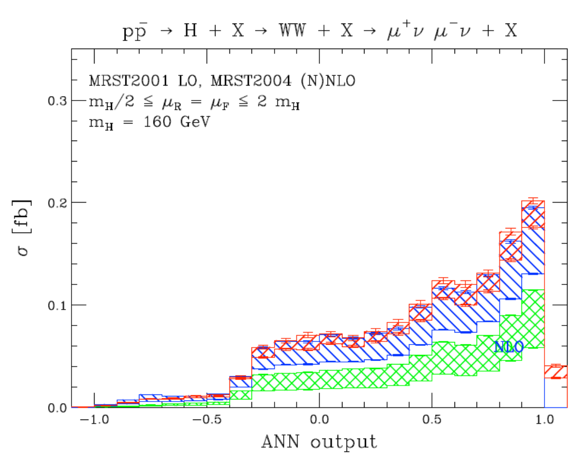
NN Analysis Variables	
p_T of leading lepton	$p_T(\ell_1)$
p_T of trailing lepton	$p_T(\ell_2)$
Minimum of both lepton qualities	$\min(q_{\ell 1}, q_{\ell 2})$
Vector sum of the transverse momenta of the leptons:	$p_T(\ell_1) + p_T(\ell_2)$
Scalar sum of the transverse momenta of the jets:	$H_T = \sum_i \lvert p_T({\rm jet}_i)\rvert$
Invariant mass of both leptons	$M_{\rm inv}(\ell_1, \ell_2)$
Minimal transverse mass of one lepton and $\not\!\!E_T$	M_T^{min}
Missing transverse energy	$\not\!\!E_T$
Scalar transverse energy	$E_T^{\rm scalar}$
Azimuthal angle between selected leptons	$\Delta\phi(\ell_1, \ell_2)$
Solid angle between selected leptons ($e\mu$ only)	$\Delta\Theta(\ell_1, \ell_2)$
ΔR between selected leptons ($e\mu$ only)	$\Delta R(\ell_1, \ell_2)$
Azimuthal angle between leading lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_1)$
Azimuthal angle between trailing lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_2)$

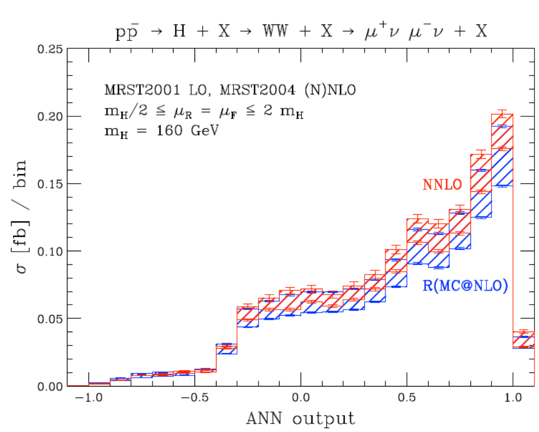
TABLE III: Input variables for the NN.

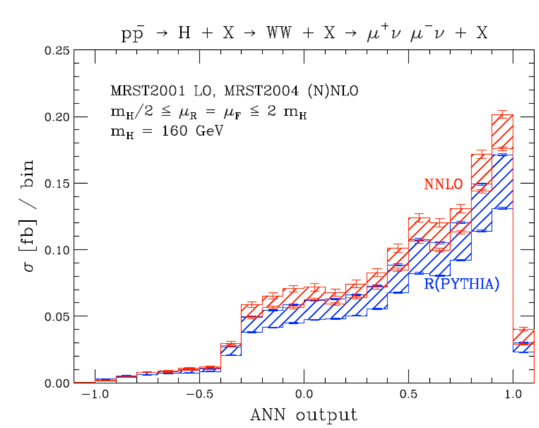
Kinematics through NNLO

σ_{acc} [fb]	LO	NLO	NNLO	K^{NLO}	K^{NNLO}
$\mu = m_H/2$	0.750 ± 0.001	1.410 ± 0.003	1.459 ± 0.003	1.880 ± 0.005	1.915 ± 0.025
$\mu = m_H$	0.525 ± 0.001	1.129 ± 0.003	1.383 ± 0.004	2.150 ± 0.007	2.594 ± 0.052
$\mu = 2\,m_H$	0.379 ± 0.001	0.903 ± 0.002	1.242 ± 0.001	2.383 ± 0.008	3.261 ± 0.048

Higher order effects vary with selection cuts







CA, Dissertori, Grazzini, Stoeckli, Webber

Kinematics at the LHC

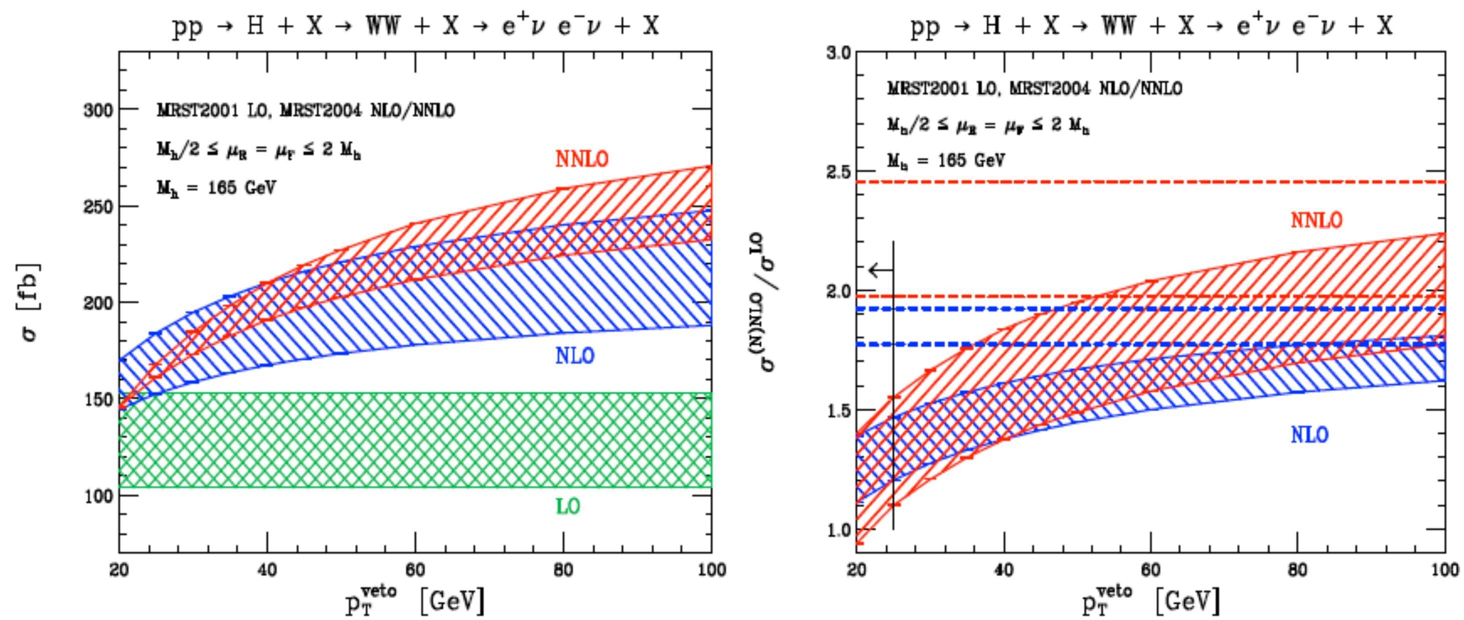


Figure 1: On the left plot, the cross-section to produce a Higgs boson vetoing events with jets in the central region $|\eta| < 2.5$ and $p_T^{\rm jet} > p_T^{\rm veto}$ (no other cut is applied). On the right plot, the K-factor as a function of $p_T^{\rm veto}$. The dashed horizontal lines correspond to the NLO and NNLO K-factors for the inclusive cross-section. The vertical solid line denotes the value of $p_T^{\rm veto}$ in the *signal cuts* of Section 3.

CA, Dissertori, Stoeckli

Higgs production at NNLO

- Indispensable for setting exclusion limits at Tevatron (and at the LHC)
- Indispensable for testing the Higgs theory amid the discovery of a Higgs boson.
- This is the simplest new physics we are searching for: *NNLO will be very important for any simple, statistically clear, new physics search and new couplings measurements.*

When is NNLO necessary?

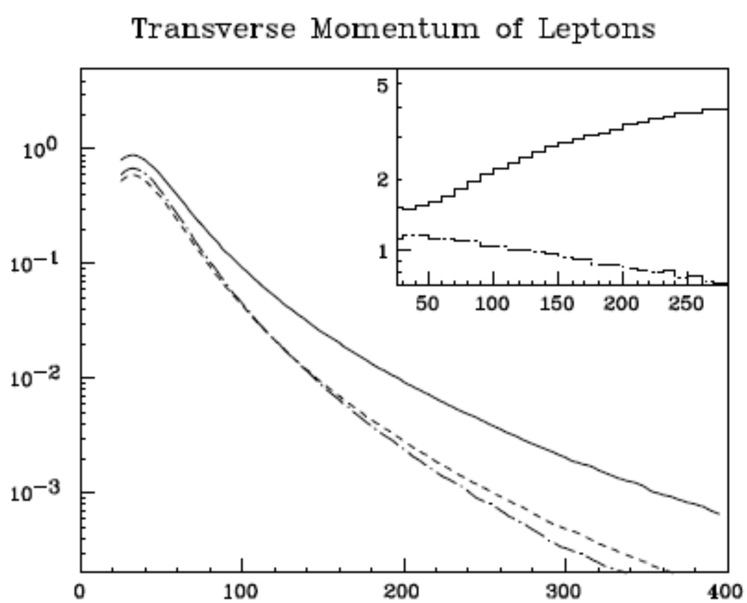
- In the Standard Model, I believe that NNLO is important for every known (2 to 1) and (2 to 2) LHC process.
- *This includes, W, Z, Higgs, WW, ZZ, ZW, (W,Z)+1-jet, Higgs+1-jet, single top, 1-jet inclusive.*
- If W+3-jets or W+4-jets is an important measurable background, then NNLO effects in W+1 or 2 jets must also be measurable.
- Theory cross-section errors are an error guess.
  I guess, such an error guess must be combined linearly with experimental uncertainties (not in quadrature!)

no small NLO K-factors @ LHC

$$pp \to t\bar{t} \quad \frac{\text{NLO}}{\text{LO}}(@Tevatron) = 1.24 \quad \frac{\text{NLO}}{\text{LO}}(@LHC) = 1.48$$

$$\frac{\Delta\sigma_{1-jet}(p_t > 30GeV)}{\sigma_{NLO}} \sim 60\%$$

(from a review by Campbell, Huston, Stirling)



	ZZ		W^+W^-		W^-Z		W^+Z	
	LO	NLO	LO	NLO	LO	NLO	LO	NLO
σ^{tot}(MRST)	11.4	15.2	77.9	115	11.0	19.0	17.6	30.1
σ^{tot}(CTEQ)	11.8	15.8	81.3	120	11.4	19.6	18.6	31.9
σ^{cut}(MRST)	3.95	5.31	24.6	40.4	3.41	6.44	5.08	9.38
σ^{cut}(CTEQ)	4.09	5.51	25.6	42.0	3.59	6.72	5.32	9.83

(Dixon, Kunszt, Signer)

NNLO collider processes

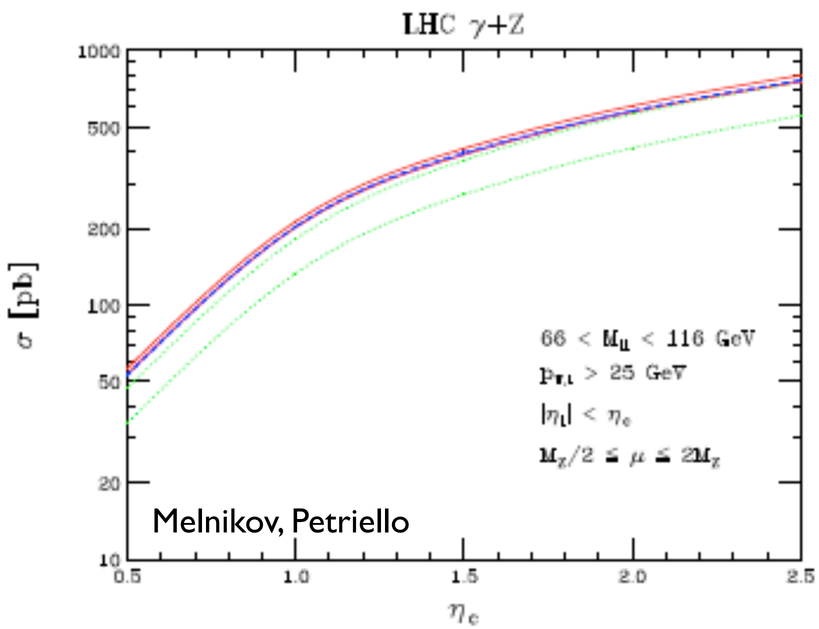
- Drell-Yan production:
  - inclusive cross-section (Hamberg, van Neerven, Matsuura (1991); Harlander, Kilgore (2002))
  - Rapidity distribution (CA, Dixon, Melnikov,Petriello (2003))
  - Fully differential (Melnikov, Petriello (2006); Catani,Cieri,Ferrera,de Florian, Grazzini (2009))

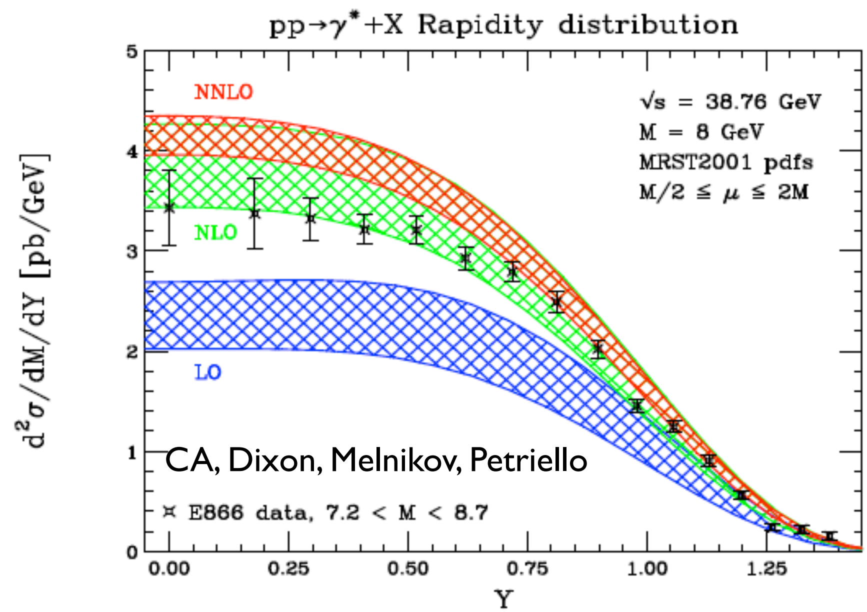
- Higgs production:
  - inclusive cross-section (Harlander, Kilgore (2002); CA, Melnikov (2002); Ravindran,Smith,Neerven (2003))
  - fully differential cross-section (CA, Melnikov, Petriello(2004); Catani, Grazzini (2007))

NNLO collider processes (2)

- electron-positron to 3 jets:
  - Gehrmann, Gehrmann-de Ridder, Glover, Heinrich (2007)
  - Weinzierl (2008)

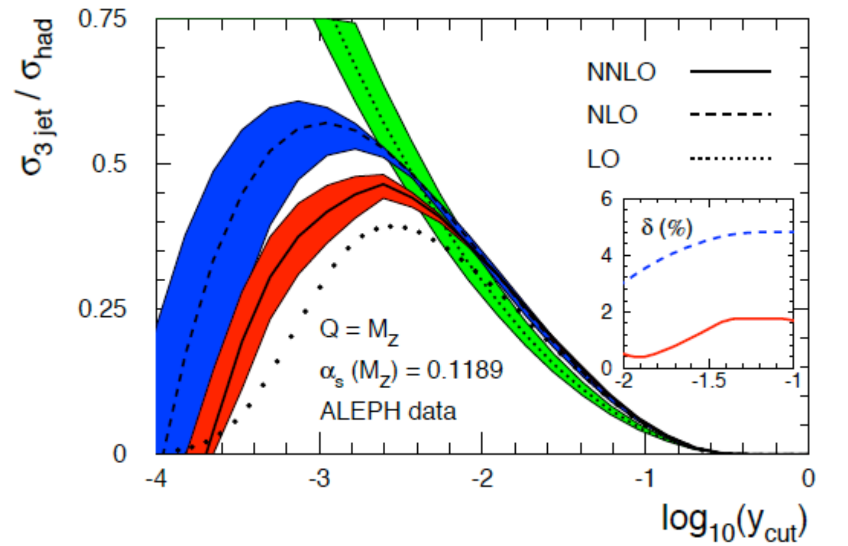
Drell-Yan at NNLO



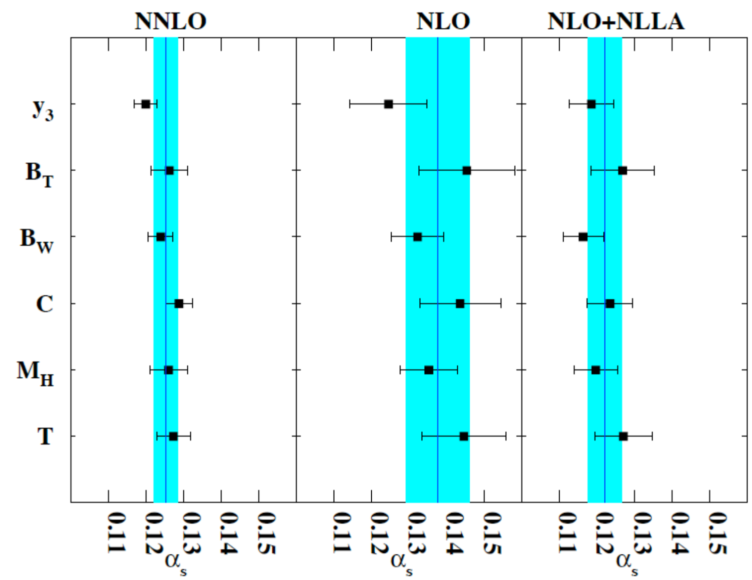


pdf extraction, luminosity monitor,
W-mass measurement,
Weinberg angle measurement,
sanity check at the LHC!

LEP three-jet production at NNLO



A. Gehrmann-De Ridder[a], T. Gehrmann[b], E.W.N. Glover[c], G. Heinrich[c]



G. Dissertori A. Gehrmann–De Ridder T. Gehrmann
E.W.N. Glover G. Heinrich H. Stenzel

Amazingly precise data,
Beautiful synthesis of diverse QCD effects
Precise determination of the strong coupling!

This is a school... no more reviewing!

- Active field of research... many opinions... and very difficult technical problems...
- Methods work for everything I described... but it is not yet clear to anyone how to do "2 to 2" NNLO calculations
- I will focus on methods that I have personal working experience.

Recipe for an NNLO computation

- Decide it is worth the effort! (or be out of your mind..)
- Compute 2-loop amplitudes
- Figure out a method to extract infrared divergences from phase-space integrals over phase-space.