Developments in perturbative QCD for hadron collider phenomenology

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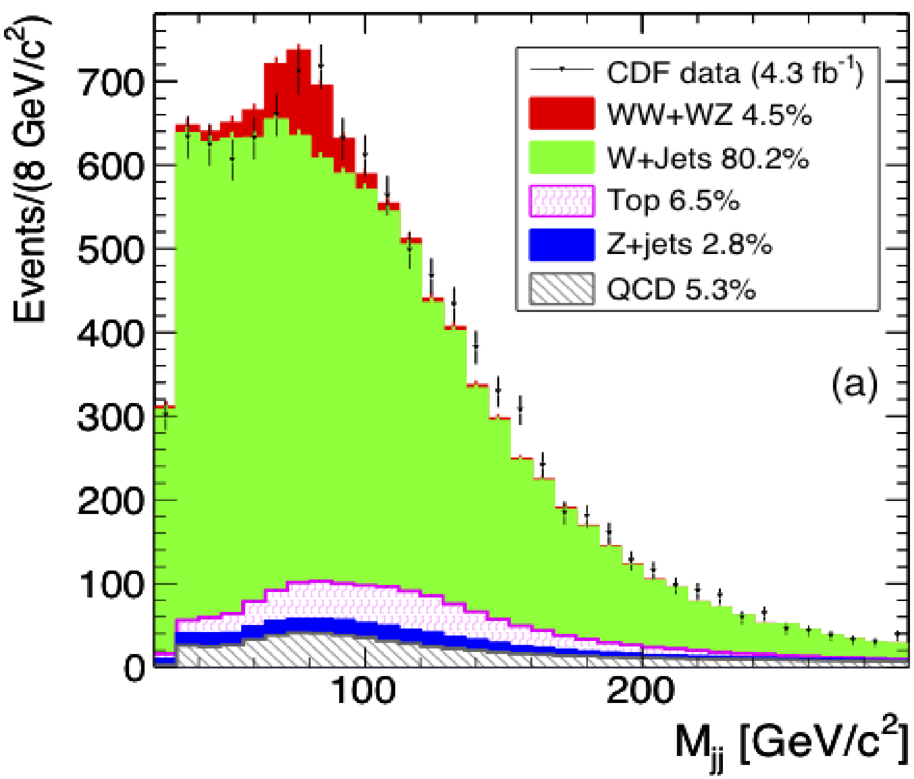
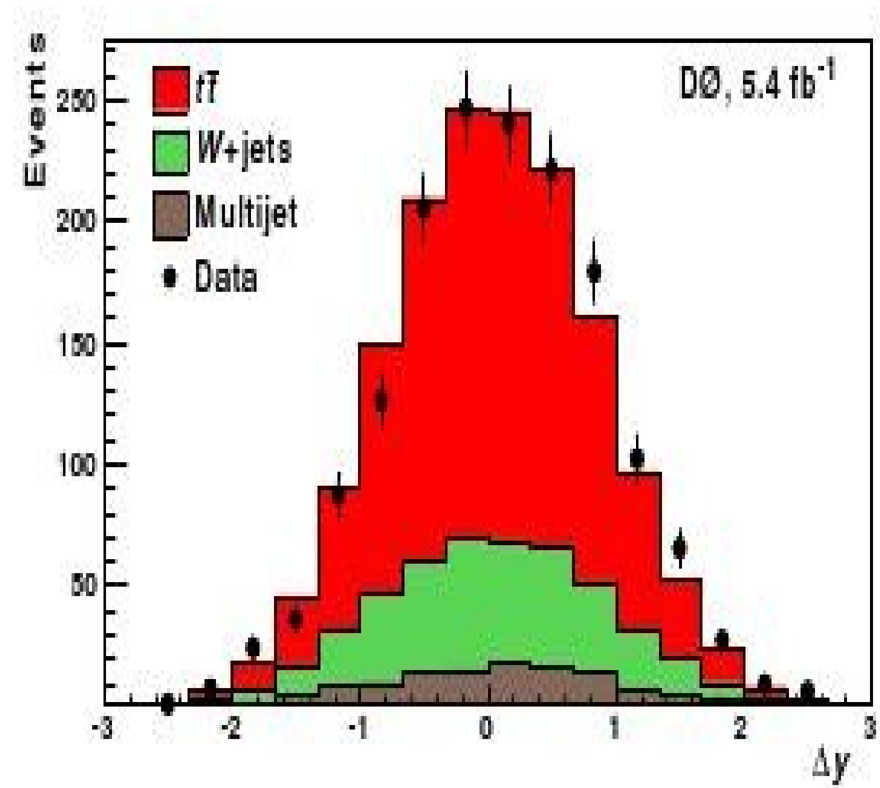
Outline

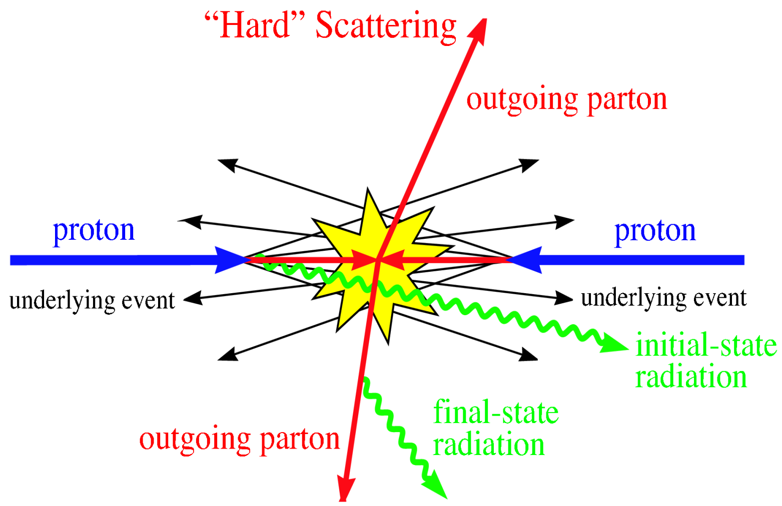
- Anomalies are worth talking about only if the quality of theoretical predictions is good. At hadron colliders, the quality is controlled by our ability to describe a given observable in perturbative QCD – the only systematic, parametric tool available to us

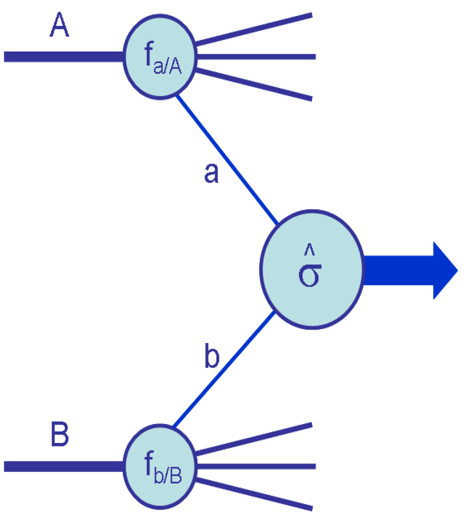




Outline

- The requirements for the ``quality" predictions are clear
  - good theory results have small, quantifiable error bars
  - good theory results address realistic, measurable quantities
- These simple criteria were driving developments of pQCD for hadron collider physics in the past and will continue to do so in the future





$$\langle \mathcal{O} \rangle = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1) f_j(x_2) \; \mathrm{d}\sigma_{ij \to p} \; \mathcal{F}_{p \to \mathcal{O}} + \mathcal{O}(1/Q)$$

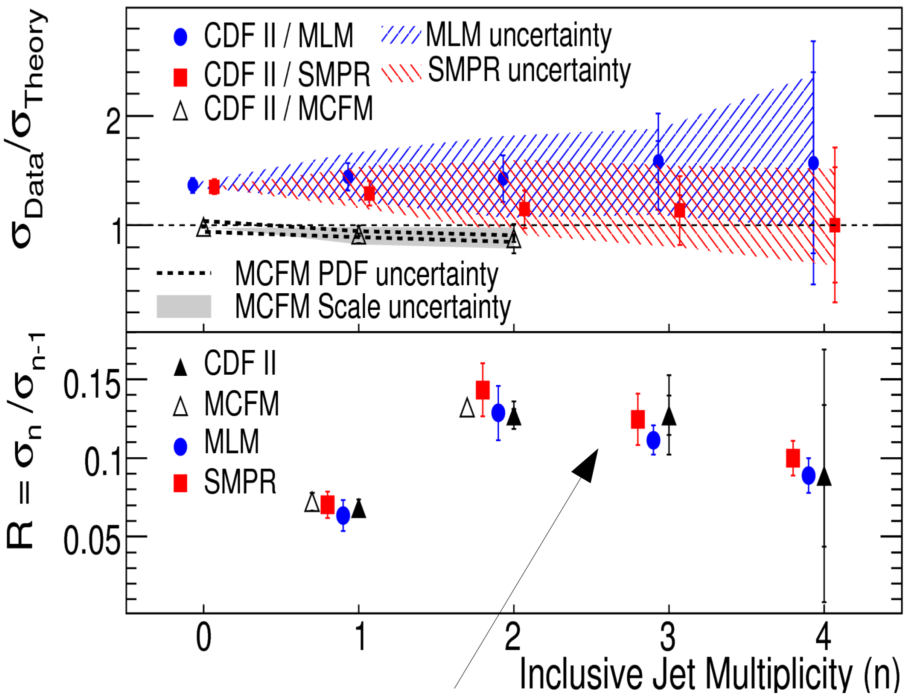
PQCD for hard scattering processes

- To achieve ``quality predictions'' we have learned to
  - apply pQCD to hard scattering processes, use higher-order computations for infra-red safe observables to assess errors
  - perform resummations of dominant perturbative effects
  - use of parton showers in their domain of applicability and matrix elements (leading or next-to-leading order) beyond that
  - accept that parton distributions have legitimate errors
  - use infrared-safe jet algorithms to facilitate theory/experiment comparisons

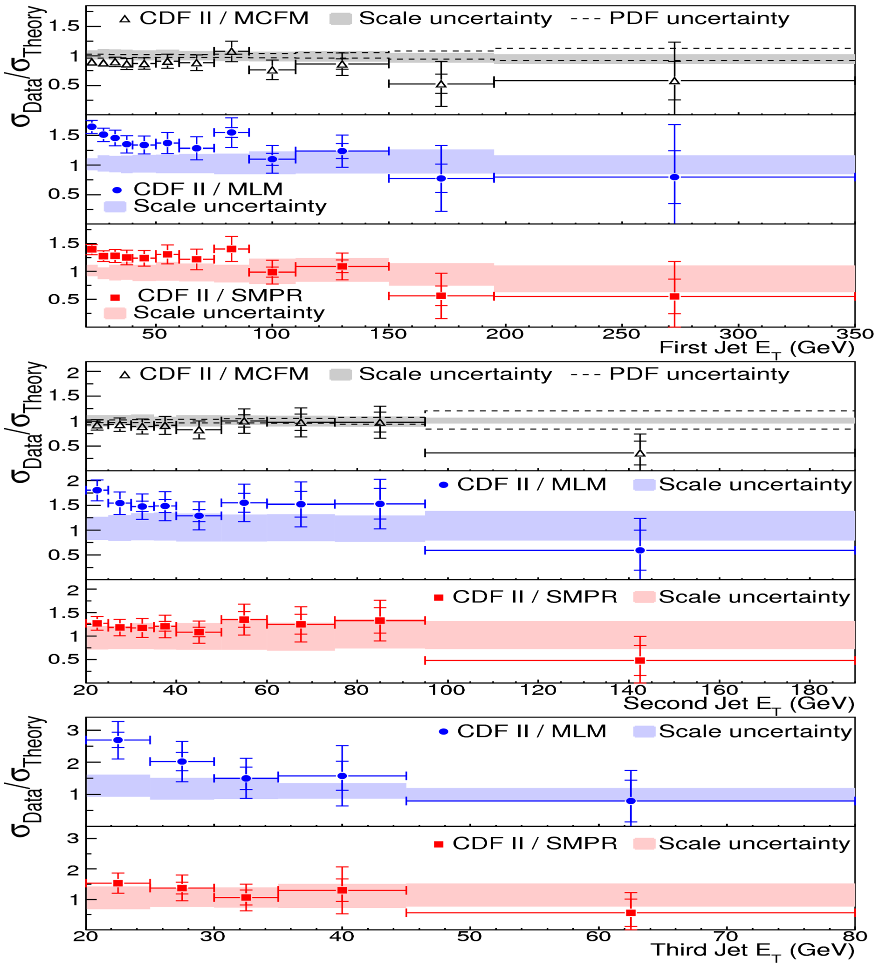
- PQCD toolkit
  - leading order computations with up to 7-8 particles in the final state are fully automated, matched to parton showers (CKKW)
  - next-to-leading order computations with up to 4 (5!) particles in the final state; first indications that automation at NLO is within reach
  - NLO matched to parton showers (MC@NLO, POWHEG)
  - differential NNLO ($pp \to W, Z, H$, di-photons)
  - CTEQ, MSTW, NNPDF parton distributions

W+ jets at the Tevatron

- W+jets is a background to everything that contains missing energy and jets. In 2007 CDF collaboration published their 320 pb-1 results, where W+jets cross-sections are measured within 10-20 percent precision.

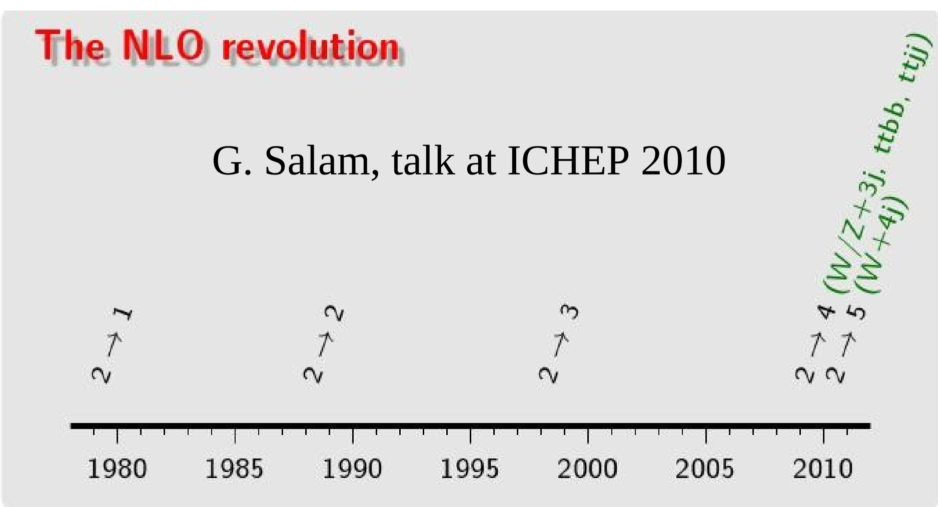


No MCFM result for W+3jets at that time because it used to be too complicated



Progress with NLO computations

- Lack of W+3 jets NLO computation just three years ago is an illustration of a general problem – it was not know how to perform 2 → 4 NLO computations. On the other hand, the LHC physics is high-multiplicity physics, so it is essential to go to 2->4 or even 2-> 5 processes
- As an example, typical searches for supersymmetry require 4 jets and misssing energy, so Z+4 jets is an irreducible background. A NLO prediction for Z+4 jets was absolutely impossible until very recently



G. Salam, talk at ICHEP 2010

In recent three to four years new technology for NLO computations appeared that allowed us to take on 2->4 and 2 → 5 computations

April 2001

An experimenter's wishlist

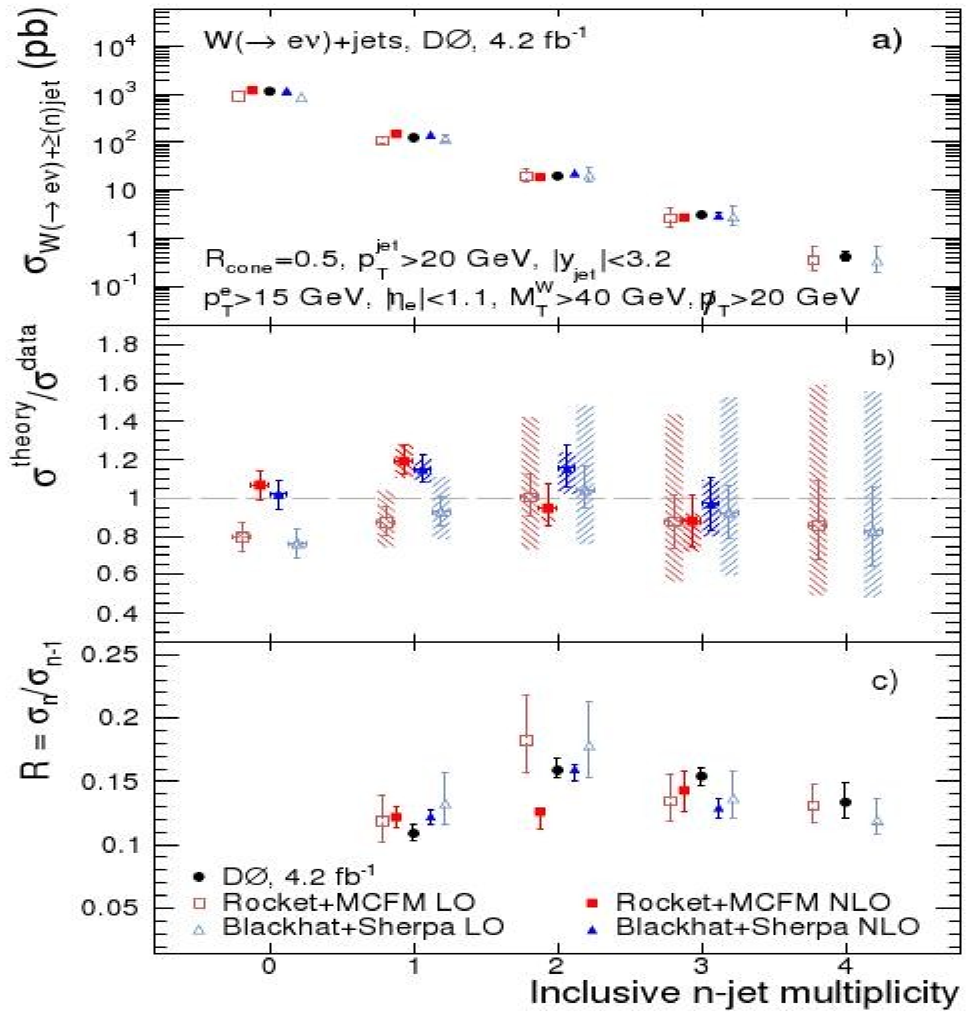
- Hadron collider cross-sections one would like to know at NLO

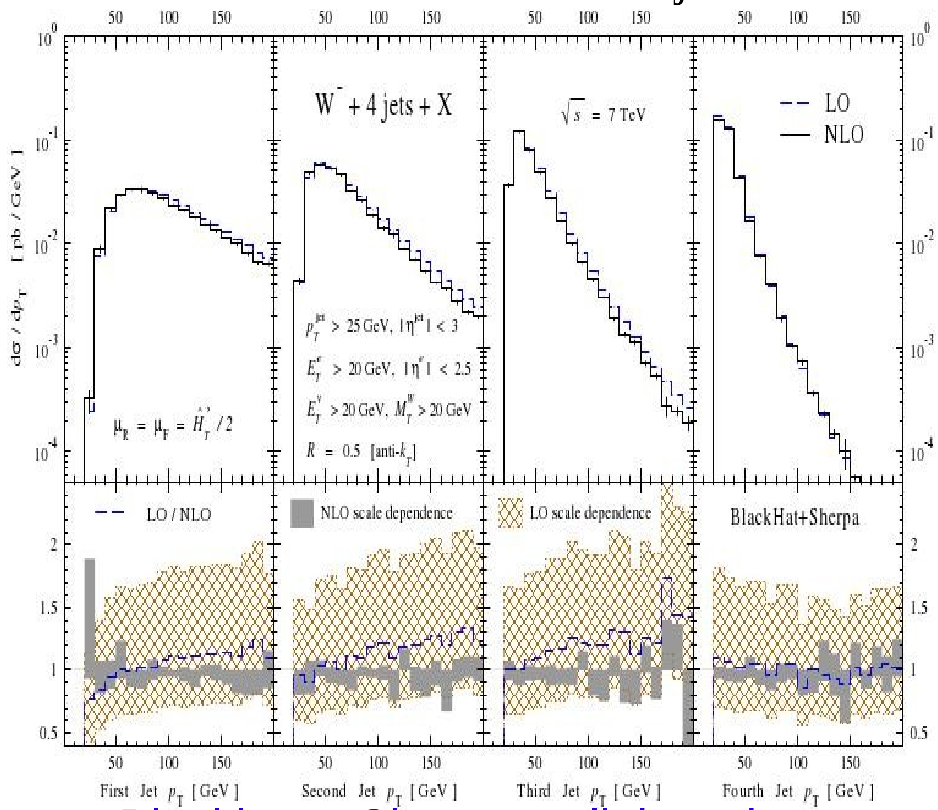
Run II Monte Carlo Workshop, April 2001

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

W/Z + jets @ NLO

- D0 compares W+jets spectra with NLO QCD predictions due to Blackhat/Sherpa and MCFM/Rocket
- Predictions for W+4jets at the LHC; transverse momenta distributions of four jets





Blackhat + Sherpa collaboration

A computation of that complexity was unthinkable, just a few years ago

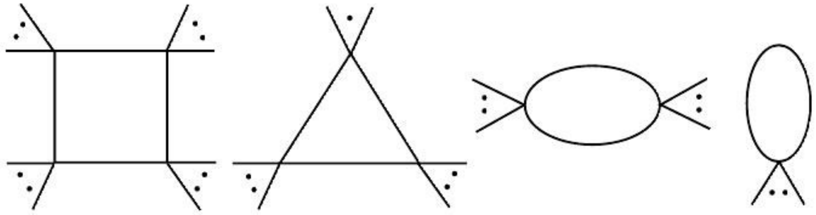
The change in the paradigm

- The remarkable progress illustrated on previous slides occurred (at least partially) due to development of a radically new method for one-loop computations
- Instead of computing scattering amplitudes from Feynman diagrams, we construct them from on-shell gauge invariant tree-level scattering amplitudes
- The trick is a generalization of the old idea of unitarity where imaginary parts of scattering amplitudes are reconstructed from the unitarity cuts

$$i\left(T_{ij} - T^{+}_{ij}\right) = \sum T_{in} T^{+}_{nj}$$

- Exploit the fact that large fraction of any c

$$\mathcal{A}^{1-\mathrm{loop}} = \sum c_j I_j \qquad I_j =$$



$$\mathrm{Im}\left(\mathcal{A}^{1-\mathrm{loop}}\right) \propto \sum \left|\mathcal{A}^{\mathrm{tree}}\right|^2 \qquad \sum c_j \mathrm{Im}(I_j) \propto \sum \left|\mathcal{A}^{\mathrm{tree}}\right|^2$$

In the past few years, a procedure appeared that allows computation of the reduction coefficients directly from on-shell scattering amplitudes by-passing Feynman diagrams.

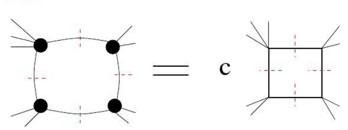
Modern unitarity techniques

- Unitarity techniques in the contemporary context were introduced by Bern, Dixon and Kosower in 1990s and used for a number of high-profile computations (pp → W+2 jets, ee → 4 jets)

- Solid computational method emerged in the past four years
  - Quadrupole cuts freeze loop momentum and give box reduction coefficient directly in terms of tree amplitudes — Britto, Cachazo, Feng
  - The OPP tensor integral reduction technique; — Ossola, Pittau, Papadopoulos
  - The OPP procedure meshes well with unitarity; — Ellis, Giele, Kunszt
  - Generalized D-dimensional unitarity — Giele, Kunszt, Melnikov

Box Coefficients from Quadruple Cuts

(RB, Cachazo, Feng)



Generalized Unitarity: Try replacing all four propagators by delta functions.

This operation isolates any given box.

In four dimensions, these four delta functions localize the integral completely. This computation is very easy!

The loop momentum solution

The box coefficients computed from quadruple cuts are given by

$$c = \frac{1}{2}\sum_{\mathcal{S}} A_1^{\text{tree}} A_2^{\text{tree}} A_3^{\text{tree}} A_4^{\text{tree}}$$

$\mathcal{S}$ is the set of all solutions of the on-shell conditions for the internal lines.

$$\mathcal{S} = \{\, \ell \mid \ell^2 = 0, \quad (\ell - K_1)^2 = 0, \quad (\ell - K_1 - K_2)^2 = 0, \quad (\ell + K_4)^2 = 0 \}$$

Can these equations always be solved?

In complexified momentum space, there are exactly 2 solutions.

(Note: nonvanishing 3-point amplitudes.)

From R. Britto talk, LoopFest 2008

Automation and craftsmanship

- It appears that new paradigm for NLO calculations makes the automation@NLO possible

	Process	μ	n_{lf}	Cross section (pb) LO	Cross section (pb) NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+\, j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ\, j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

Table 2: Results for total rates, possibly within cuts, at the 7 TeV LHC, obtained with MadFKS and MadLoop. The errors are due to the statistical uncertainty of Monte Carlo integration. See the text for details.

MadLoop, Hirshi, et al

Madgraph to generate diagrams and OPP reduction procedure

Automatic construction of Frixione-Kunszt-Signer subtractions for real emission processes

Parton shower (MC@NLO) is automatic

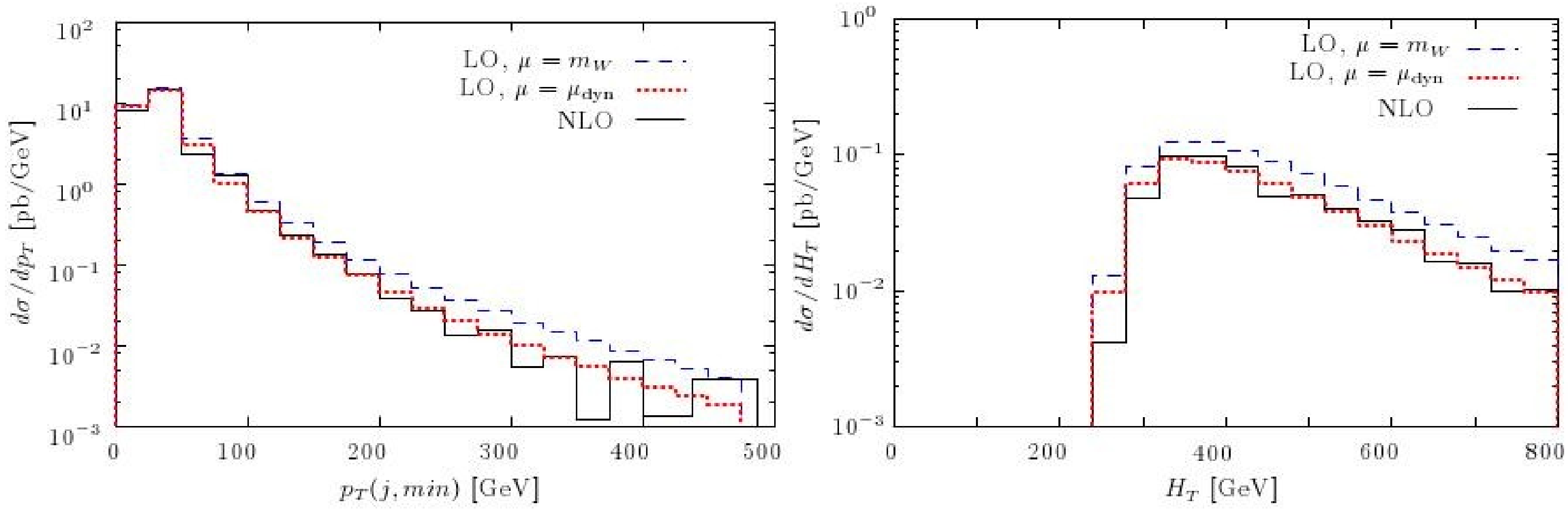
Craftsmanship still required to deal with highest multiplciity processes and processes with unusual features

$$pp \to t\bar{t}b\bar{b} \qquad pp \to W(Z) + 3j$$
$$pp \to t\bar{t}jj \qquad pp \to W^+W^-b\bar{b}$$
$$pp \to W(Z) + 4j \quad pp \to W^+W^+jj$$

Bern, Dixon, Kosower, Berger, Forde, Maitre, Febres-Cordero, Gleisberg, Papadopoulos, Ossola, Pittau, Czakon, Worek, Bevilacqua, Ellis, Kunszt, Giele, Zanderighi, Melia, Rountsh, Denner, Dittmaier, Pozzorini, Kallweit

W/Z+jets at NLO : scales

- When NLO computations are available, it is good to use them. But can we learn – from existing computations – if leading order results can be improved in an approximate manner to catch the main features of NLO?
- The important issue is the question of renormalization and factorization scales; choosing them is always a trouble. A few years ago, Bauer and Lange showed that such choices can have important consequences – when scales are properly chosen, shapes of leading and next-to-leading order kinematic distributions match quite well



Bauer, Lange, 14 TeV LHC, W+2jets

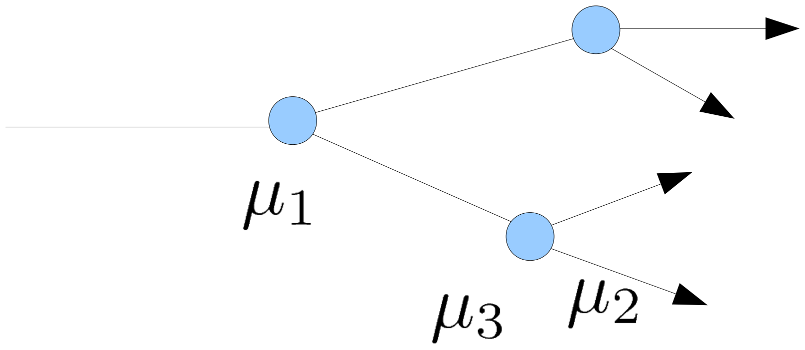
$$\mu_{\rm dyn} = \sqrt{\left(\frac{m_{JJ}}{2}\right)^2 + m_W^2}$$

Learning from the parton shower

- The Bauer-Lange analysis works well because it respects a well-known feature of QCD partons branchings

$$\mathrm{Prob}(a \to bc) \sim \alpha_s(p_\perp)$$

- The CKKW/MLM procedure respects this choice and, in fact, does more careful scale adjustment. The scales are chosen on an event-by-event basis by identifying most probable ``history" of an event
    - iteratively cluster particles that are closest according to some measure (usually, $k_\perp$ algorithm is used).
    - for each node, choose the relative momentum of the daughters as the scale for the strong coupling constant – this is the parton shower choice.

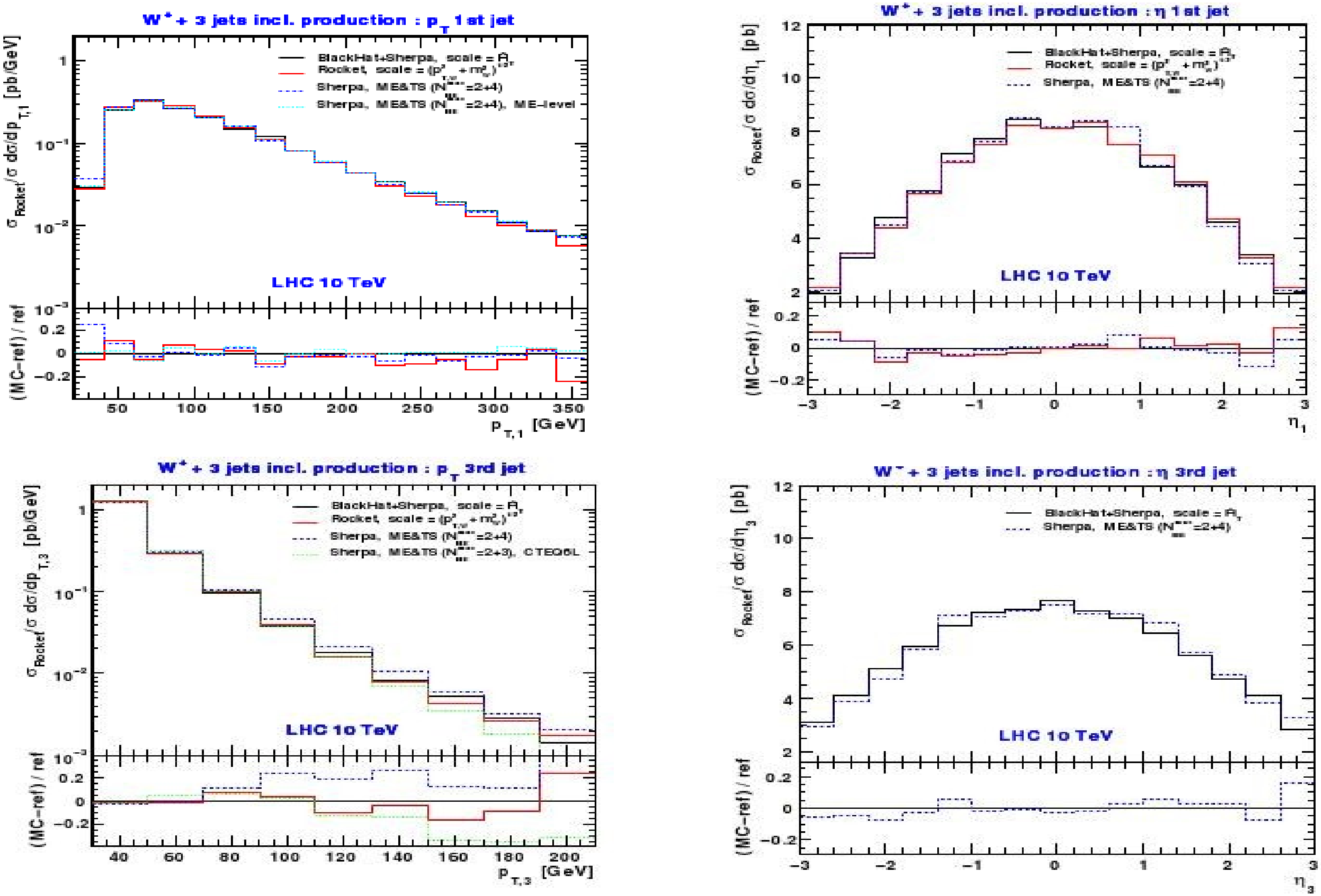


$$|\mathcal{M}|^2 \sim \prod_{i=1}^{N_{\mathrm{part}}} \alpha_s(\mu_i)$$

Catani, Krauss, Kuhn, Webber

Scale setting and W+3 jets at NLO

- CKKW/MLM procedure does a very good jobs in describing NLO shapes

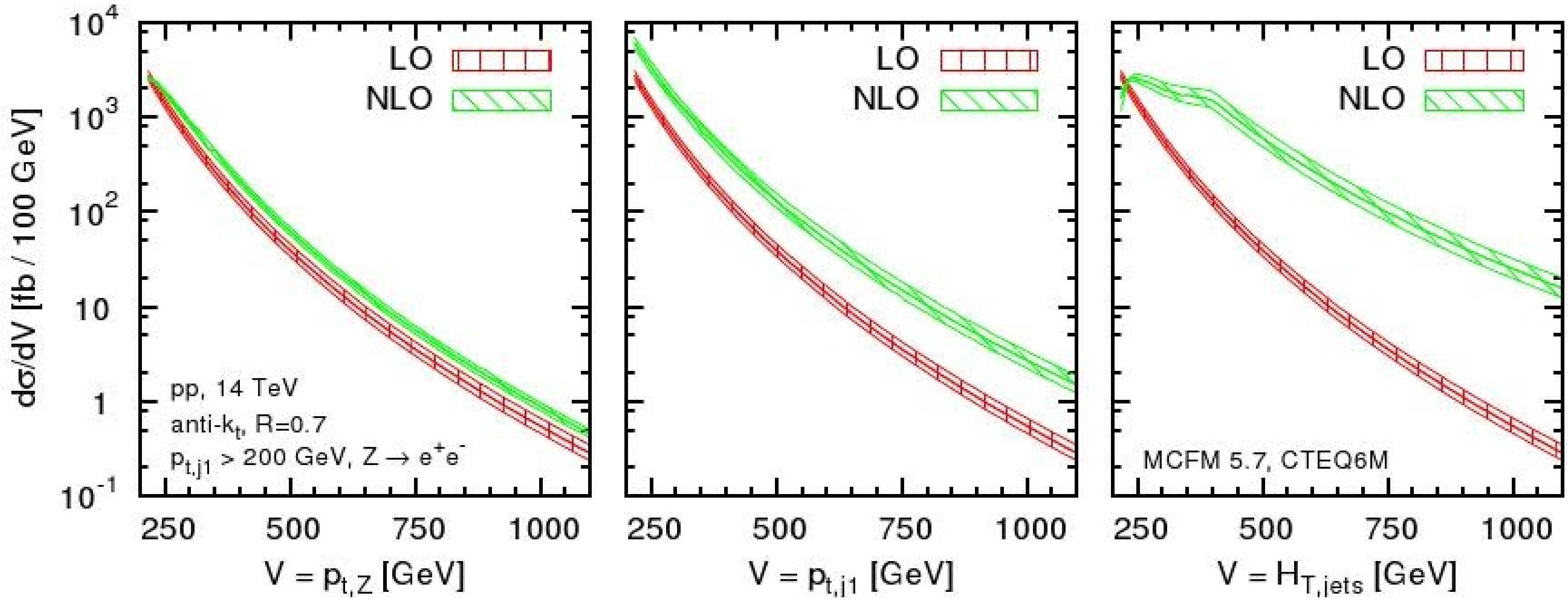


Blackhat/Rocket/Sherpa comparison

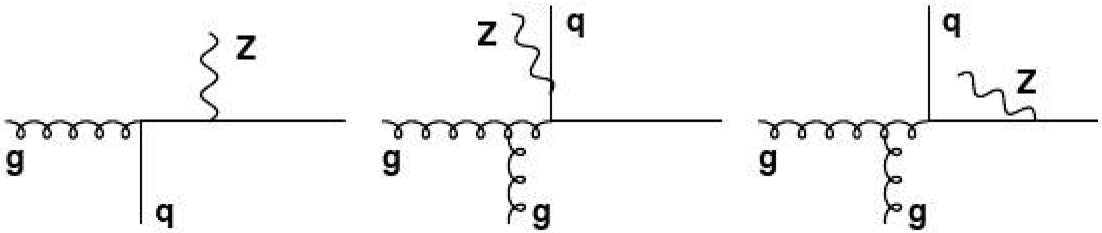
S. Hoche, J. Huston, D. Maitre, J. Winter, G. Zanderighi

No giant K-factors with CKKW/MLM

- Giant K-factors are absent if leading order predictions are defined in accord with CKKW/ MLM procedures



Rubin, Salam, Sapeta

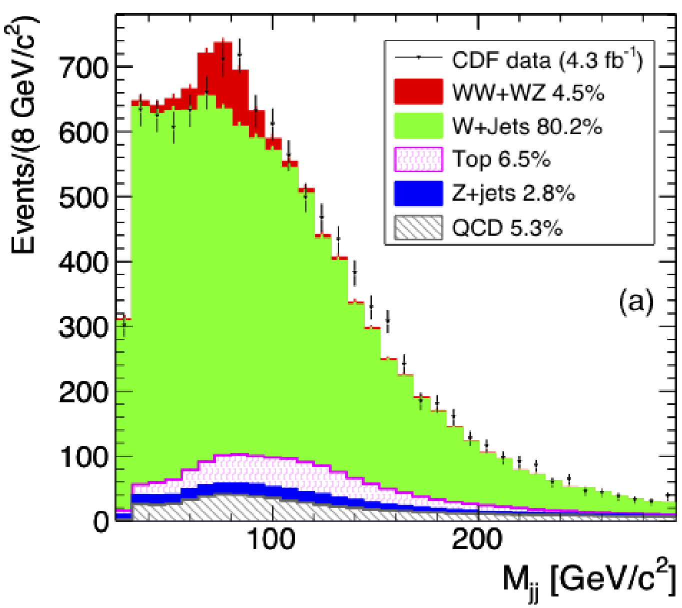


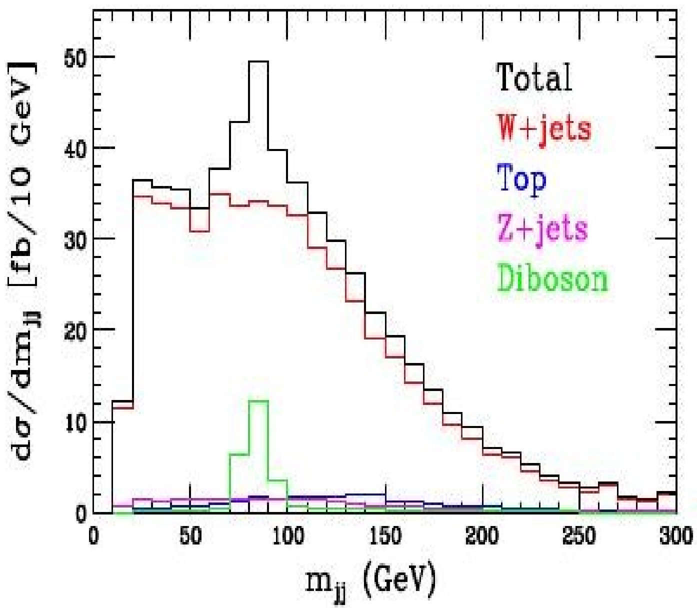
$$\frac{\delta\sigma}{\sigma} \sim \alpha_s \log^2 \frac{p_{\perp,j}}{M_Z}$$

Wjj anomaly

- Existing NLO QCD computations (W+2jets, top pair, single top) allow us to investigate the sensitivity of the CDF Wjj result to radiative corrections. Note that in original CDF analysis the exclusive dijet sample was studied (changed since then) which is not ideal from perturbative stability point of view
- It was pointed out that the explanation for the excess may be related to observed single-top deficit at CDF or to mis-modeling normalization of WW and top backgrounds

Menon, Sullivan; Plehn, Takeuchi

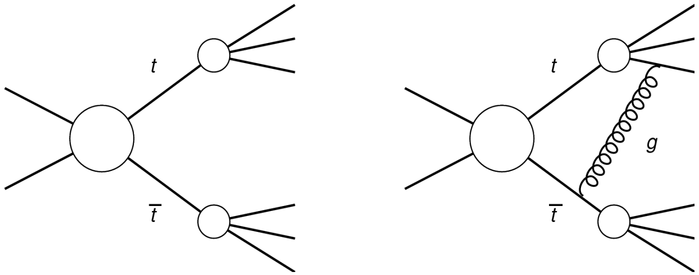




Campbell, Martin, Williams

Top quarks: precision and confusion

- Top quark physics is an interesting example of a potential confusion. NLO QCD corrections known for more than 25 years, but only for stable top quarks
- But top quarks decay, so if we ask for the NLO accuracy, should we include description of decays at NLO as well?
  - how spin-correlations are treated?
  - how radiation in decays is treated?
- It is remarkable that standard codes which are used to treat top quark physics at NLO (MCFM, POWHEG, MC@NLO) do not include these effects in a systematic fashion even for top quarks produced on shell.
- When top quarks decay, non-factorizable corrections appear. How important are they, for acceptances, mass measurements, asymmetries?
- All these questions can be repeated with an obvious replacement NLO $\rightarrow$ NNLO...



Top quark forward-backward asymmetry

- In proton anti-proton collisions, top quarks are produced with forward-backward asymmetry

$$A_{\rm lab}(t\bar{t}) = \frac{N_t(y>0) - N_t(y<0)}{N(y_t>0) + N_{(}y_t<0)} \qquad A_{\rm rest}(t\bar{t}) = \frac{N_t(\Delta y>0) - N_t(\Delta y<0)}{N(\Delta y>0) + N_{(}\Delta<0)}$$

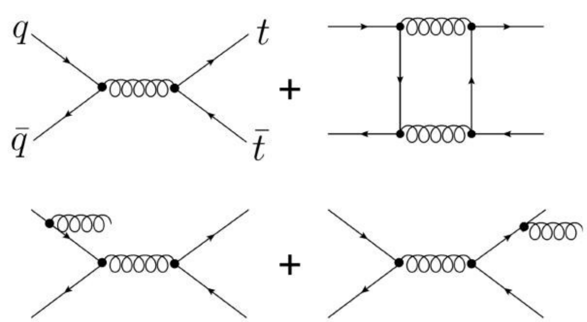
- The asymmetry only appears at one-loop in QCD

$$A^{\rm theory}_{\rm rest} = 0.05 \pm 0.006$$

$$A_{\rm rest} = 0.15 \pm 0.05 \quad {\rm CDF}$$

$$A_{\rm rest} = 0.196 \pm 0.065, \quad {\rm D0}$$

Kuhn, Rodrigo

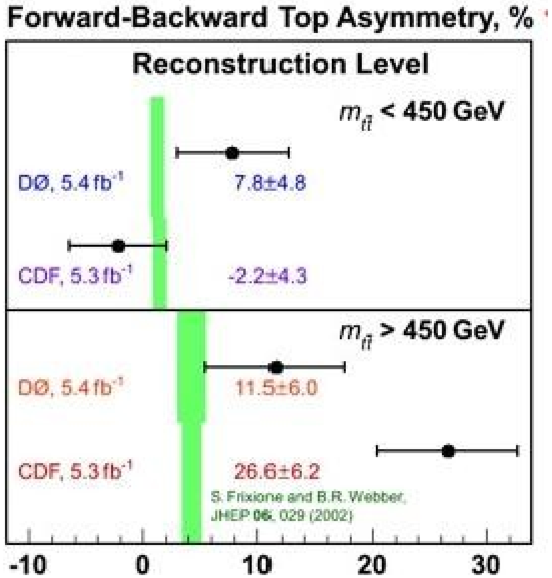


The discrepancy with the SM prediction is about two standard deviations.

CDF finds larger asymmetries/discrepancy at large invariant masses and large rapidities

D0 does not confirm that finding

Many BSM interpretations of this result, some already ruled out by the LHC



QCD predictions for asymmetry are robust

- NLO QCD corrections to top quark pair production give rise to ``leading order " asymmetry, so our knowledge is limited – need NNLO.
- One can imagine two types of effects – ``higher order effects" for stable tops and ``acceptance effects" for top quark decay products
- Theoretical predictions for the asymmetries are found to be stable against
  - inclusion of (approximate) higher order corrections to top quark pair production

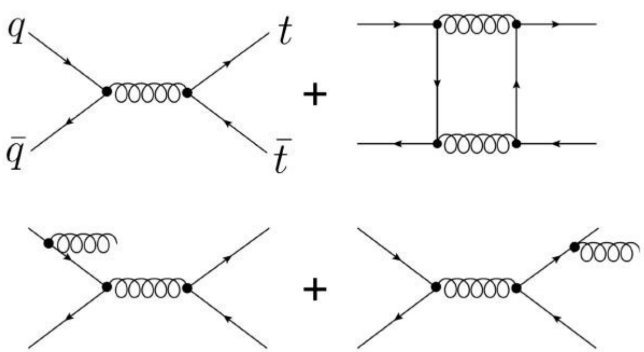
    Almeida, Sterman, Vogelsang
    Ahrens, Ferroglia, Neubert, Pecjak, Yang
  - allowing top quarks to decay and calculating asymmetries for realistic acceptances

    K.M., Schulze, Bernreuther, Si, Bevilacqua, Czakon, van Hammeren, Papadopoulos, Worek
  - off-shell effects, non-factorizable corrections and the interference with non-resonance backgrounds Bevilacqua, Czakon, van Hammeren, Papadopoulos, Worek
  - mixed QCD/QED effects

    Kuhn, Rodrigo
    Bernreuther, Si
    Hollik, Pagani

Asymmetries and additional QCD radiation

- The dependence of the asymmetry on additional hard QCD radiation is strong: QCD prediction for the asymmetry is positive – for the inclusive tt and negative – for the tt+jet.



Positive asymmetry

Negative asymmetry

But, in reality both are infinite and can not be treated independently from each other

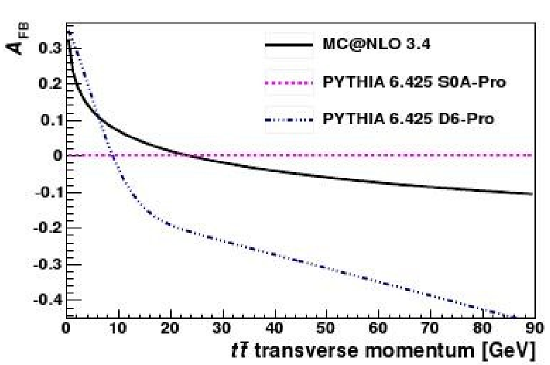
- Although it does not make sense to talk about the two contributions separately, the asymmetry may change significantly, if stringent cuts on additional radiation are imposed. A known story (jet veto, etc.) but perhaps in a new setting

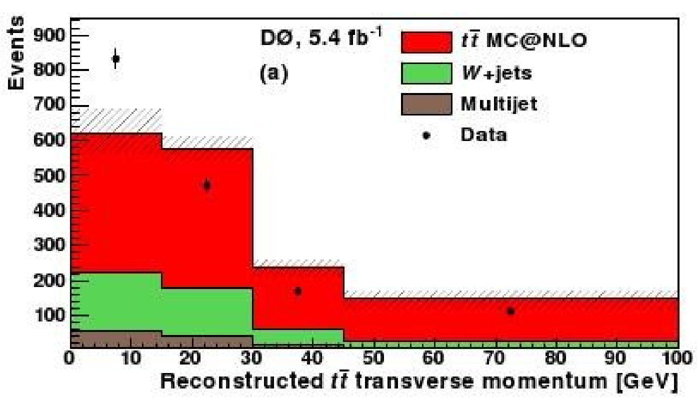
- The importance of soft radiation in an inclusive asymmetry is marginal, as follows from results on gluon resummation

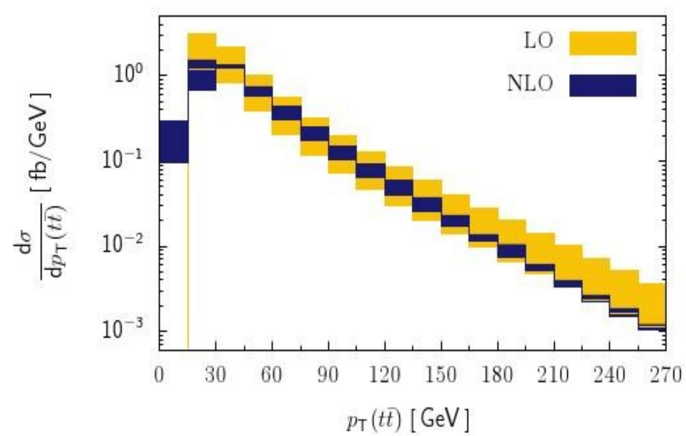
Almeida, Sterman, Vogelsang
Ahrens, Ferroglia, Neubert, Pecjak, Yang

Asymmetries and additional QCD radiation

- D0 shows that the measured transverse momentum distribution of the ttbar pairs does not agree with MC@NLO prediction. It is important to know if the LHC experiments confirm that (qq vs. gg)
- Asymmetry is a strong function of the transverse momentum of the ttbar system – mis-modeling of such distribution may lead to incorrect asymmetry measurement
- The pt-spectrum of the ttbar pair is known at NLO QCD; effects are moderate, no drastic re-shaping (but interesting bins are not shown)   Dittmaier, Uwer, Weinzierl
  K.M., Sharf, Schulze
- Note that forcing color coherence in PYTHIA introduces large negative asymmetries at high ptt. Herwig (MC@NLO base) is angular-ordered, so similar effect should be expected. Can it be trusted?
- Recall that asymmetry is a large-angle emission effect – color coherence is supposed to improve treating large angle emissions correctly in parton showers







Top asymmetries: is there a problem?

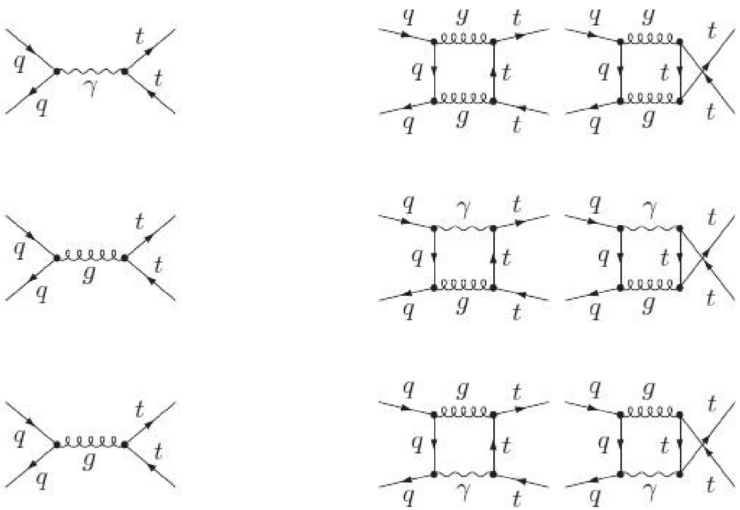
- MC@NLO predictions for the asymmetry seem to be low when compared to data
- PQCD predictions increase quite a bit if normalized to LO, rather than NLO cross-section (default option for presenting MC@NLO results in experimental papers)

$$A_{\rm rest}^{\rm MC@NLO} = 0.05 \pm 0.006$$

$$A_{\rm rest}^{\rm NLO\ \ QCD} = 0.07 \pm 0.01$$

$$A_{\rm rest}^{\rm QCD+EW} = 0.09 \pm 0.01$$

Kuhn, Rodrigo
Bernreuther, Si
Hollik, Pagani



-

Estimates of errors should be taken with the grain of salt. It is quite plausible that NNLO corrections to the asymmetry change it by 20 – 30 %, typical for NLO QCD corrections. The discrepancy can become less than 1 sigma, if a couple of things move in the right direction

$$A_{\rm rest} = 0.15 \pm 0.05 \quad {\rm CDF} \qquad\qquad A_{\rm rest} = 0.196 \pm 0.065, \quad {\rm D0}$$

Asymmetry for top decay products

- It has been customary to talk about asymmetry in top production, but this quantity requires ``reconstruction to the production level". This step changes asymmetry by almost a factor of two and it is inherent to experimental analysis

- We do not need this step – we should compare physical, measured quantities! Lepton asymmetry in lepton + jets sample is an example of such an observable: if top decays are properly treated, this observable can be computed at NLO without a problem

- Lepton asymmetry is slightly smaller than top asymmetry in QCD (it is about 3 percent), but it does not seem to decrease that much in the D0 analysis.

- Lepton asymmetries – theoretically clean and easy-to-measure experimentally – show disagreement between theory and experiment that seems to be very significant

TABLE VI. Lepton-based asymmetries.

	$A^{l}_{\rm FB}$ (%) Reconstruction level	Production level
Data	14.2 ± 3.8	15.2 ± 4.0
MC@NLO	0.8 ± 0.6	2.1 ± 0.1

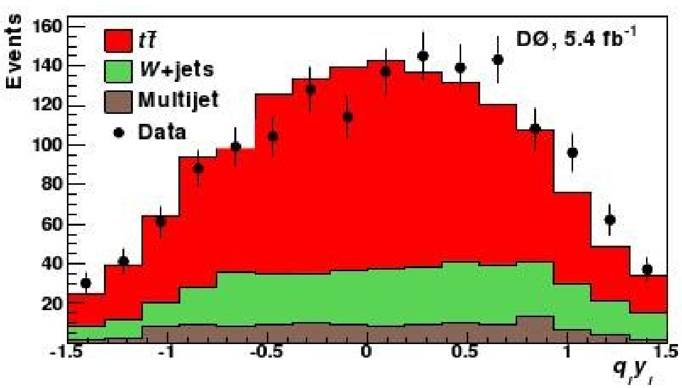
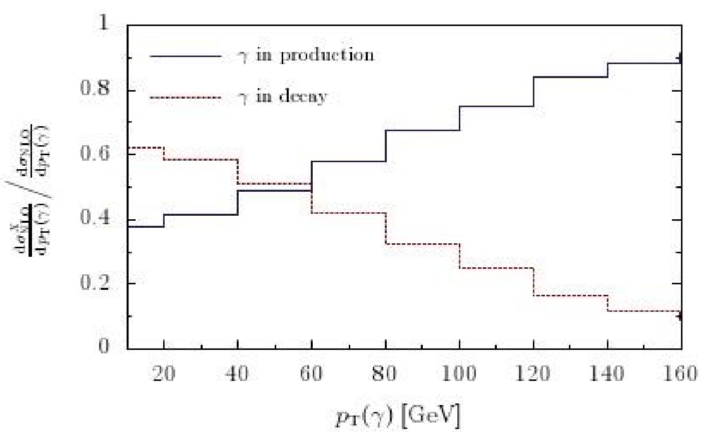


FIG. 4. The reconstructed charge-signed lepton rapidity.

Top quarks and radiation in decays: pp → tt gamma example

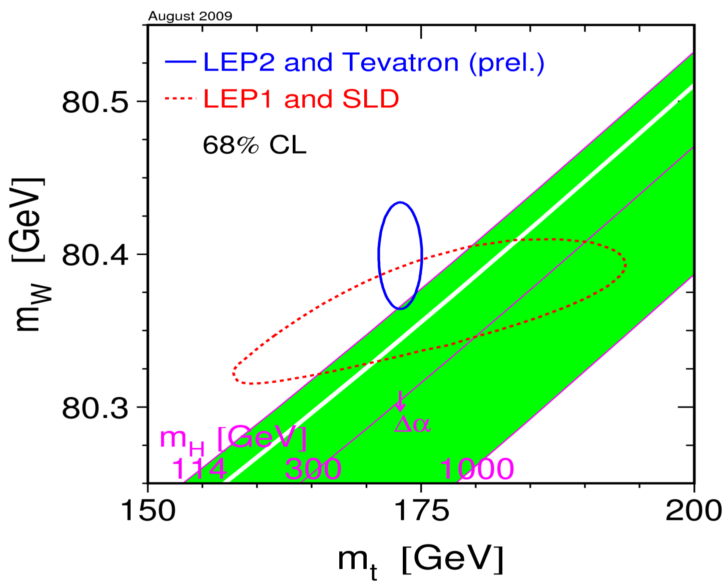
- The reaction pp → tt + gamma is interesting for several reasons; its cross-section was measured by the CDF collaboration recently and (at least) ATLAS measurement is underway
- NLO QCD corrections for stable top quarks were used in experimental analysis
- However, with CDF cuts, in about 50% (!) of all tt + gamma events photon is radiated in the decay of top quarks; moreover top radiation in decays dominates top radiation in production for photon transverse momentum below 60 GeV (!).
- QCD corrections to tt+gamma and QCD corrections to radiative top decays are unrelated – totally misleading to use the K-factor from stable top quark computation...
- Similar story should be true for the production of the top pair in associated with jet (recall the asymmetry problem). It remains be seen if the QCD radiation in top quark decays has significant impact on tt+jet signal for various physics cases



Melnikov, Schulze, Scharf

Precision physics at the LHC era

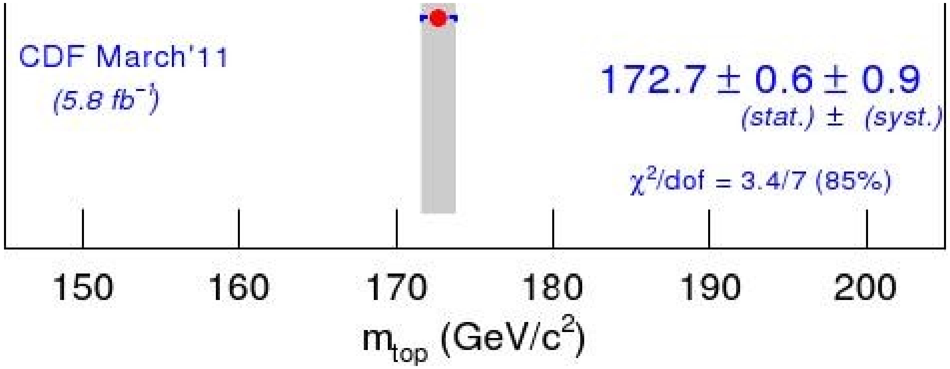
- Because the Standard Model is renormalizable theory, it is over-constrained. We are getting rather close to putting a definite point on this Mt-Mw-Mh plot
- When this happens, the conclusions will be far-reaching
- The hadron collider physics contributes to this endeavor by
  - Measurement of the W mass to 15 MeV
  - Measurement of the top quark mass to better than 1 GeV
  - Discovery the Higgs boson and measurement of its mass



The top quark mass

- Quarks can not be isolated from QCD fields → mass can not be assigned to them → in QCD, quark masses are renormalization -dependent parameters of the Lagrangian, similar to various couplings
- It is very precisely measured by the CDF and D0 (and soon CMS/Atlas) collaborations and used as the ``pole mass" in electroweak fits but .. what exactly is it?
- The difference between the pole mass and the MS mass is large, O(10 GeV)

$$m_t^{\rm pole} = \bar{m}_t(\bar{m}_t)\left(1 + \frac{4\alpha_s}{3\pi} + ..\right) \approx (170 + 7 + ..)\ {\rm GeV}$$

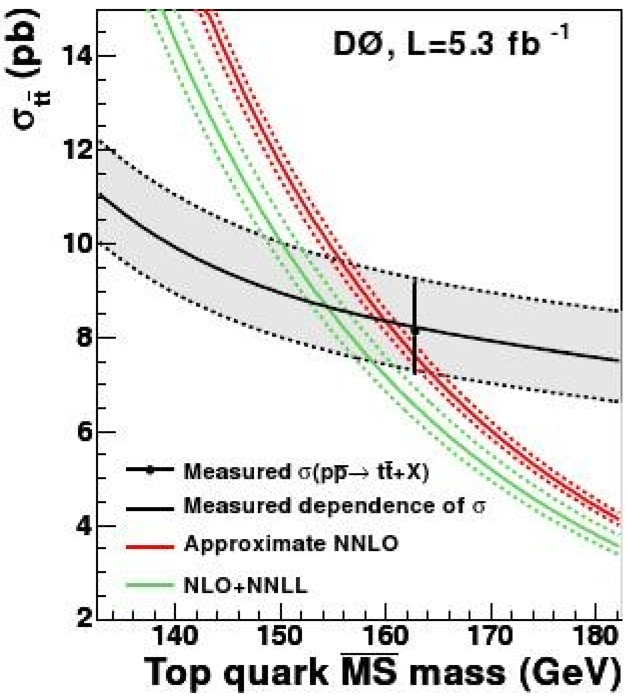


The top quark mass

- The philosophy seems to be that any feature that can beat down the error on the top quark mass can be used in the analysis
- Possible, as any philosophy, but it ignores the following issues
  - not each observable is short-distance (i.e. can be described by perturbative QCD)
  - parton shower technology is not an exact science to handle non-perturbative physics
- It is important to have extraction of top quark masses from quantities that can be described by perturbative QCD (short-distance) because in this case we can switch between different renormalization schemes for the top quark mass
- Note that it is not clear how to combine the most popular and precise methods for the top mass extraction – the ``matrix element method" and its various cousins – with perturbative QCD computations
- Methods that make use of well-defined short distance quantities do not have that high precision on the top quark mass, unfortunately.

Top quark mass measurements

- D0 collaboration extracts the top quark mass from the total cross-section



Theoretical prediction	$m_t^{\overline{\rm MS}}$ (GeV)	$\Delta m_t^{\overline{\rm MS}}$ (GeV)
MC mass assumption	$m_t^{\rm MC} = m_t^{\rm pole}$	$m_t^{\rm MC} = m_t^{\overline{\rm MS}}$
NLO+NNLL [14]	$154.5^{+5.0}_{-4.3}$	-2.9
Approximate NNLO [15]	$160.0^{+4.8}_{-4.3}$	-2.6

Note differences in resulting top mass under different approximate estimates of higher-order terms !

Note changes in the top quark under different assumptions about the mass in the MC

	$m(m)$ [GeV$/c^2$]	m_t [GeV$/c^2$]
LO	$159.2^{+3.5}_{-3.4}$	$159.2^{+3.5}_{-3.4}$
NLO	$159.8^{+3.3}_{-3.3}$	$165.8^{+3.5}_{-3.5}$
NNLO	$160.0^{+3.3}_{-3.2}$	$168.2^{+3.6}_{-3.5}$

The MS-mass from precision electroweak fit is 161.3 GeV

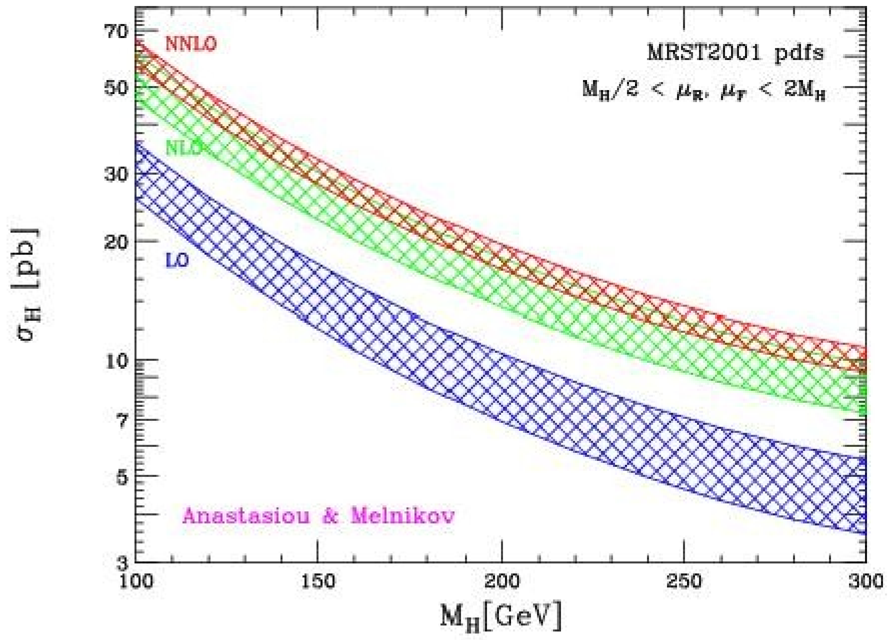
It will be instructive to see the D0 result for the MS mass as a function of order in PT

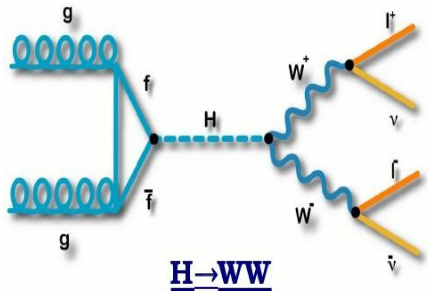
Mass entering MC is definitely not the MS mass. More likely – one of the so-called short-distance low scale masses

Moch, Uwer, Langefeld

The search for the Higgs boson: pp → H → WW

- NNLO QCD corrections to this process, in the large top mass approximation, were computed nearly ten years ago. Both NLO and NNLO QCD effects are large.
- Usefulness of corrections to the total cross-section unclear
  - experimental searches are divided into 0-jet, 1-jet, 2-jet bins
  - a cut on the transverse mass of the W-bosons is introduced to suppress the background, including its interference with the signal
  - spin correlations of leptons are used to discriminate against the background

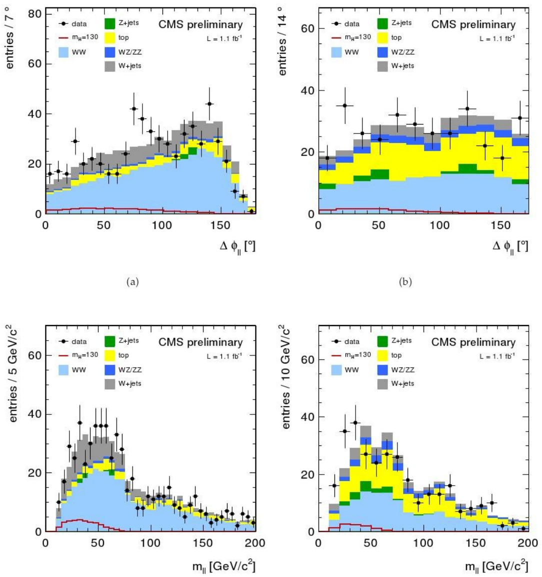




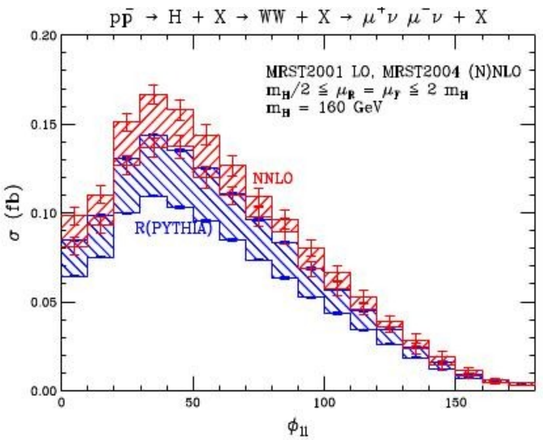
NNLO computations for unintegrated kinematics of the final state are required

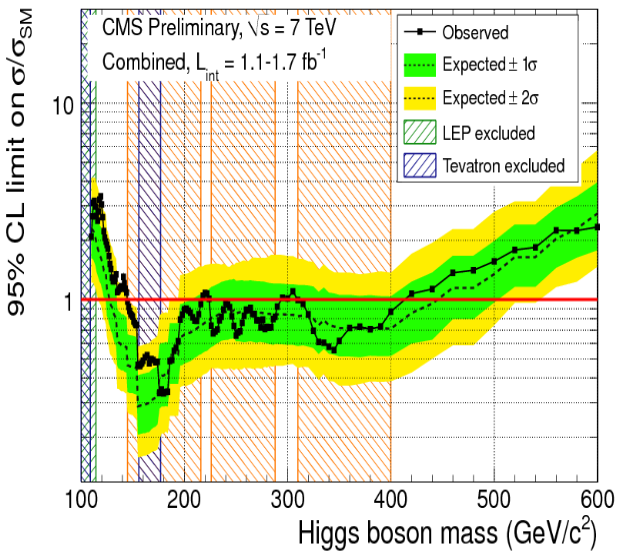
The search for Higgs boson : pp → H → WW

- Such computations have been done; the results are used in the experimental analysis and allows us to draw serious conclusions (bump significance)



$\sigma_{\rm acc}/\sigma_{\rm incl}$	Trigger	+ Jet-Veto	+ Isolation	All Cuts
NNLO ($\mu = m_{\rm H}/2$)	44.7%	39.4% (88.1%)	36.8% (93.4%)	27.8% (75.5%)
NNLO ($\mu = 2\ m_{\rm H}$)	44.9%	41.8% (93.1%)	40.7% (97.4%)	31.0% (76.2%)
MC@NLO ($\mu = m_{\rm H}/2$)	44.4%	38.1% (85.8%)	35.3% (92.5%)	26.5% (75.2%)
MC@NLO ($\mu = 2\ m_{\rm H}$)	44.8%	38.8% (86.7%)	35.9% (92.5%)	27.0% (75.2%)
HERWIG	46.7%	40.8% (87.4%)	37.8% (92.7%)	28.6% (75.7%)
PYTHIA	46.6%	37.9% (81.3%)	32.2% (85.0%)	24.4% (75.8%)

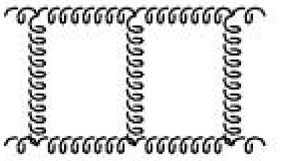


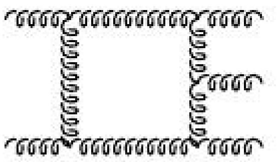


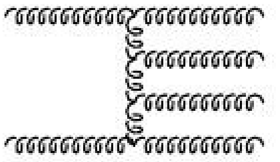
Anastasiou, Dissertori, Grazzini, Stoeckli, Webber

Anatomy of NNLO

- We have flexible tools to describe 2 → 1 processes (pp → W, pp → H) through NNLO in perturbative QCD. We would like to extend those results to cover 2 → 2 processes as well.
- For a variety of reasons, we may be interested in pp → jj, pp → tt, pp → Zj, pp → Hj etc.
- Some 2 → 2 processes, such as pp → W+W- and pp → gamma gamma do not require the full power of the NNLO technology
- How far are we from first physics results on 2 → 2 scattering @ NNLO ?
- For 2 → 2 @ NNLO we require
  - 2 → 2 scattering amplitudes for at two loops
  - 2 → 3 scattering amplitudes @ one-loop, integrated over the phase-space of the unresolved parton
  - 2 → 4 scattering amplitude integrated over the phase-space of two unresolved partons







Large number of 2 → 2 scattering amplitudes at two-loops is available since 2001, we definitely can compute 2 → 3 amplitudes at NLO and clearly 2 → 4 scattering amplitudes for most basic processes are well-known – so what is the problem ?

Why NNLO is non-trivial if loop contributions are known?

- The reason we have not put all these pieces together are infra-red / collinear divergences

$$\mathrm{d}\sigma \sim \mathrm{d}\sigma_{VV} + \mathrm{d}\sigma_{RV} + \mathrm{d}\sigma_{RR}$$

- Each of these contributions leave in a different phase-space and each is infra-red divergent. They must be combined before numerical integration is attempted, but how to do this efficiently is unknown – it is a matter of active research

- Two main lines of thought

Subtractions;

NLO analog: Catani-Seymour

Applied at NNLO to e+e- $\rightarrow$ 3j

Sector decomposition

NLO analog: Frixione-Kunszt-Signer

Applied to pp $\rightarrow$ H, pp $\rightarrow$ W,Z

- Subtractions terms are (still) very difficult to construct

- Sector decomposition – difficult to keep phase-space parametrization ``local", i.e. original applications of sector decompositions attempted to find nice global parametrization of the final state particles phase-space

Sector decomposition and FKS

- The approach to NLO computations by Frixione, Kunszt and Signer (FKS) is an efficient procedure to deal with infra-red divergences at NLO. It is based on two simple observations
  - a phase-space for N+1 final states particles that contributes to a N-jet observable can be partitioned into sectors in such a way that, at any sector, one and only one identified particle can become soft or at most two identified particles can become collinear;
  - for each such sector, a natural phase-space parametrization in terms of soft gluon energy and angles is the one that factors out the singularities

- A recent suggestion to apply similar considerations to NNLO computations seems very promising ! Czakon
  - pre-partitioning of the phase-space
  - choice of a suitable parametrization in each of the pre-sectors
  - sector decomposition and the extraction of singular limits

Conclusions

- During the past ten years the field of pQCD – and its applications to hadron collider physics – went through a remarkable development
- Powerful theoretical tools appeared that improve our ability to describe all stages of hadron collisions from parton distributions in the proton, to hard parton scattering cross-sections, to evolution of partons to final state hadrons
- Using these tools, we establish general consistency of perturbative QCD predictions with the Tevatron and the LHC data, with a healthy fraction of less-than-three sigma deviations
- In the future, theoretical progress in the field will come from
  - re-summations for exclusive realistic (jetty) observables
  - CKKW@NLO
  - general scheme for NNLO and its verification on multi-particle processes
  - automation of NLO (Madgraph@NLO, Alpgen@NLO etc.)

Conclusions

- Top quark FB asymmetry
- Feature in Wjj
- Demise of the CKM
- Proton charge radius in muonic hydrogen
- Muon anomalous magnetic moment