Perturbative QCD and the LHC physics

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CERN TH colloquium

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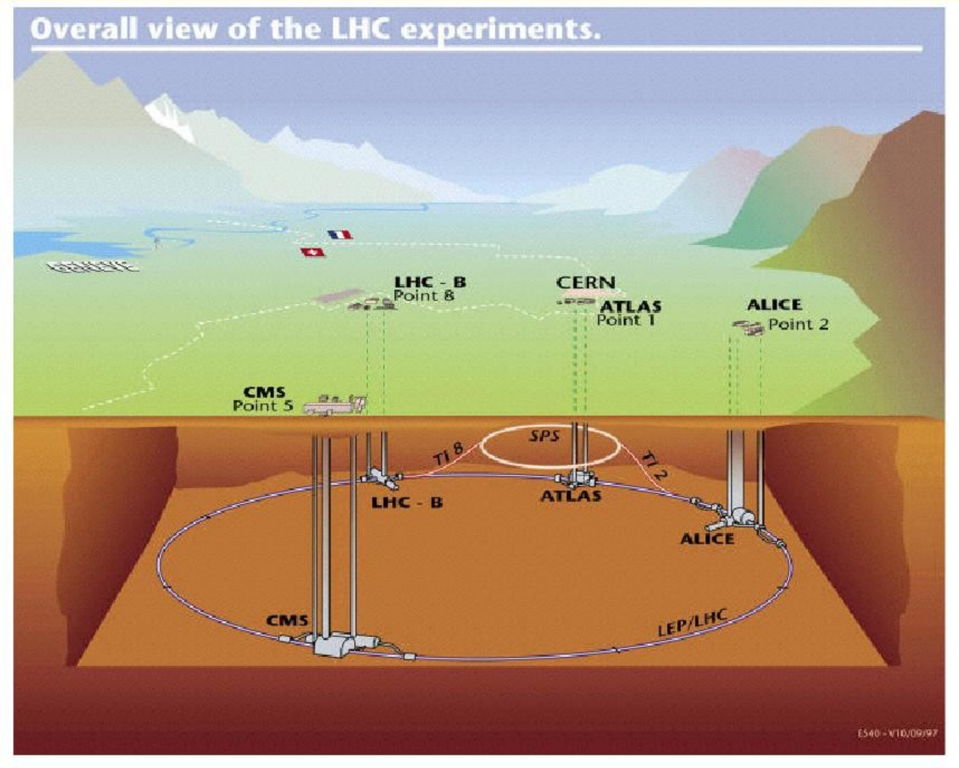
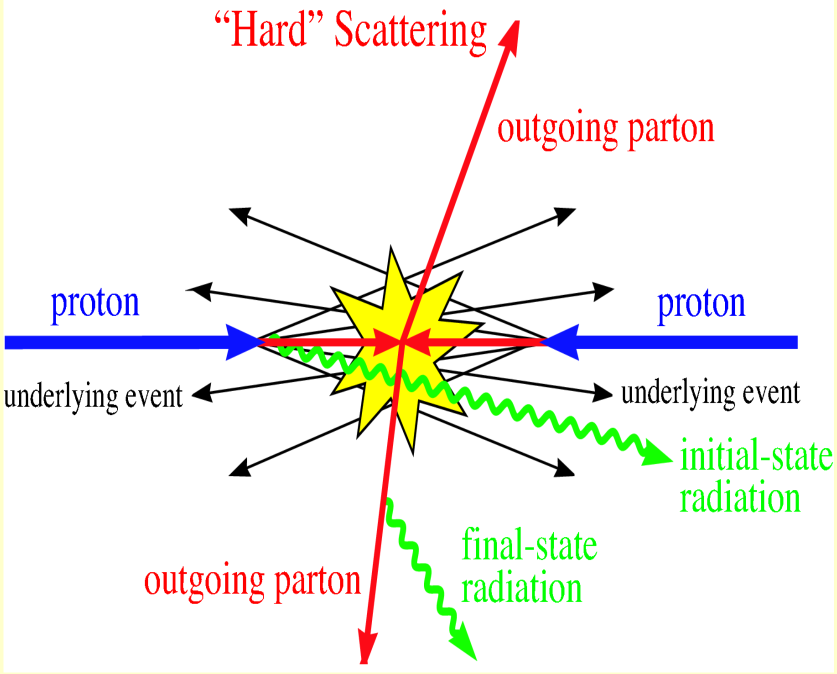
The LHC

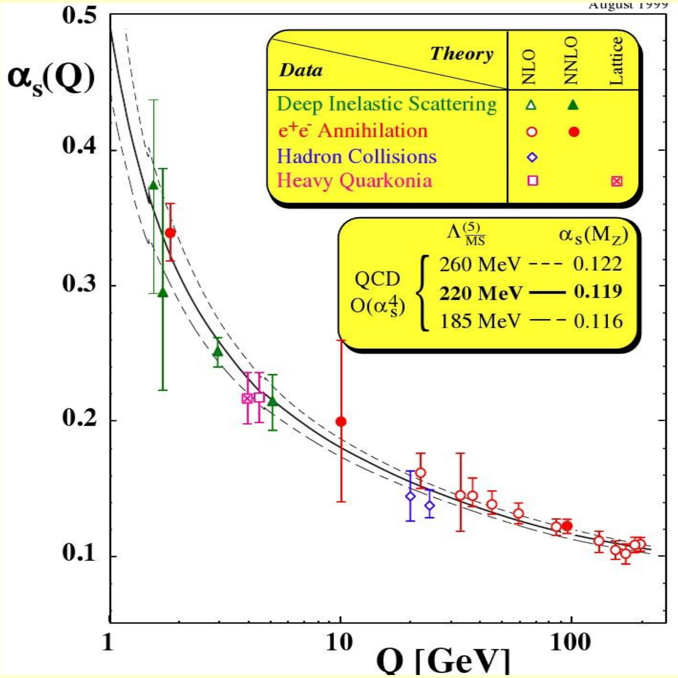
- *Next decade of high-energy physics will be decade of the LHC, the proton proton collider here at CERN*



Colliding hadrons

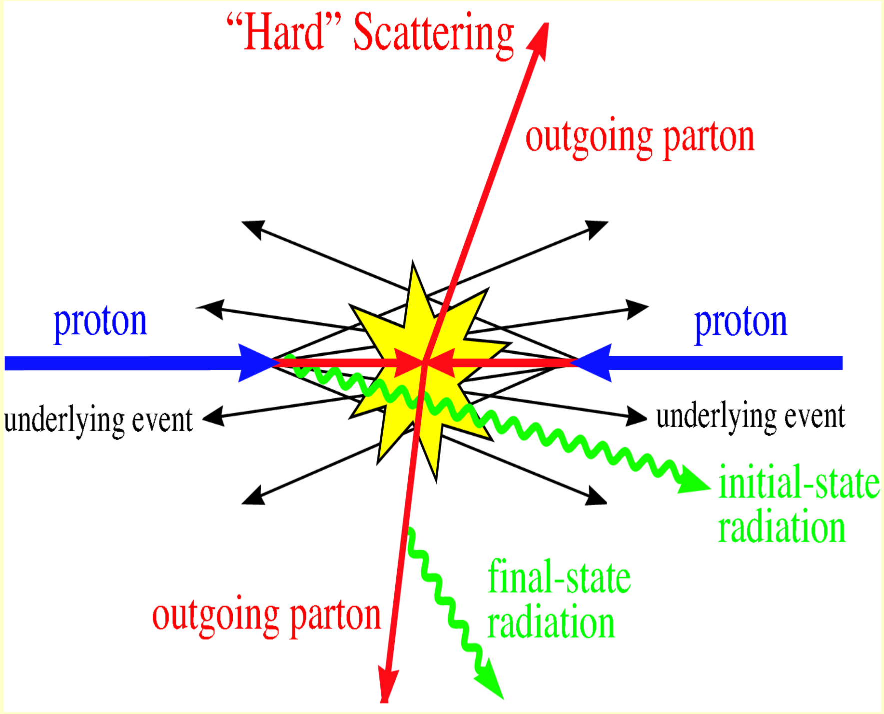
- Description of hadron collisions requires QCD. To search for "heavy BSM physics", need description of hard QCD processes where protons desintegrate.
- These processes are responsible for a tiny fraction of proton proton scattering cross-section

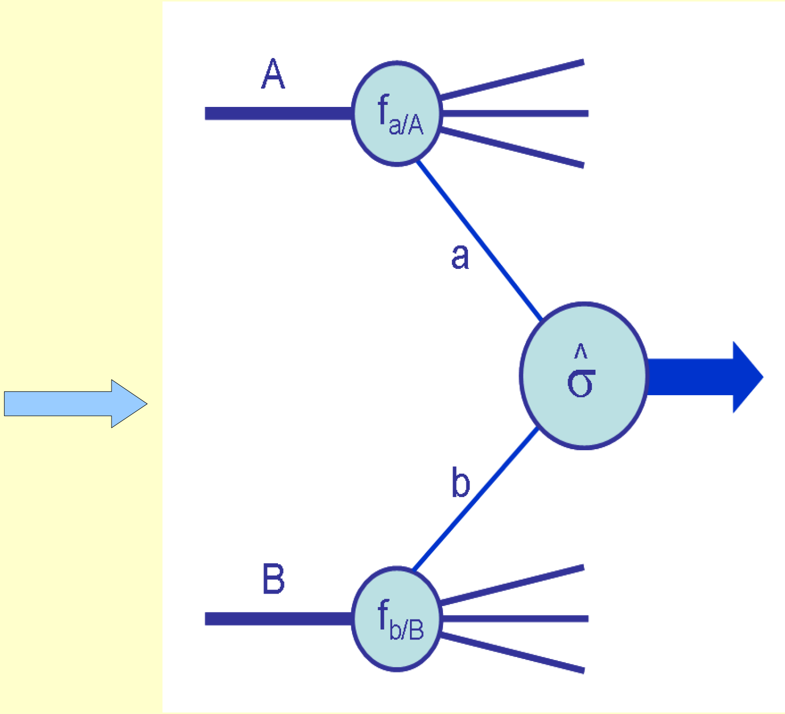




Perturbative QCD

- These rare processes are "double-deep-inelastic" and the formalism to describe them is similar





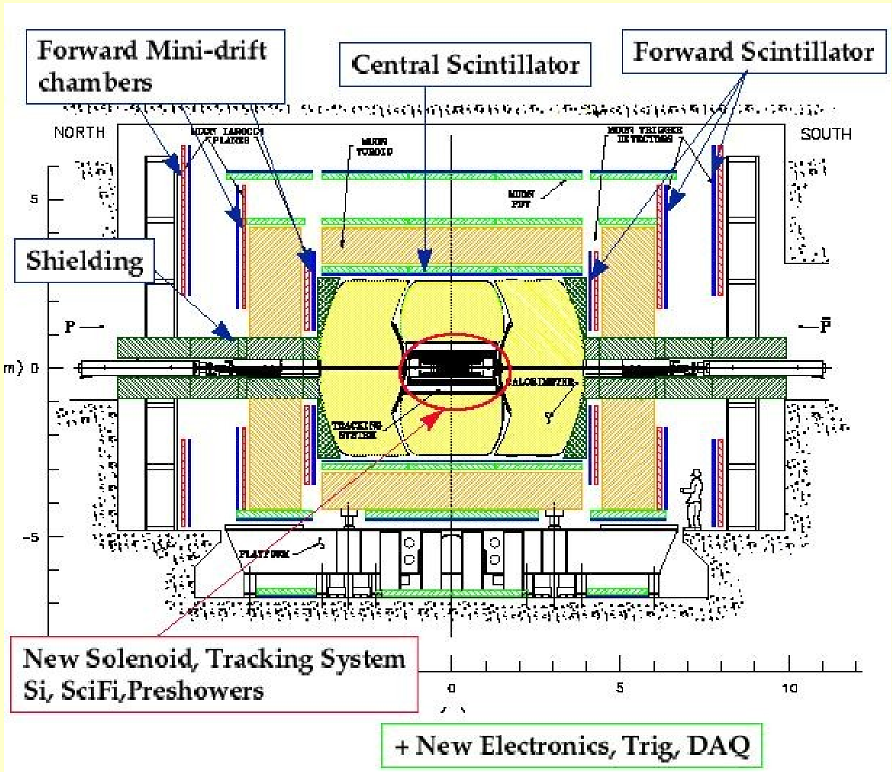
$$\langle \mathcal{O} \rangle = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1) f_j(x_2) \; \mathrm{d}\sigma_{ij \to p} \; \mathcal{F}_{p \to \mathcal{O}} + \mathcal{O}(1/Q)$$

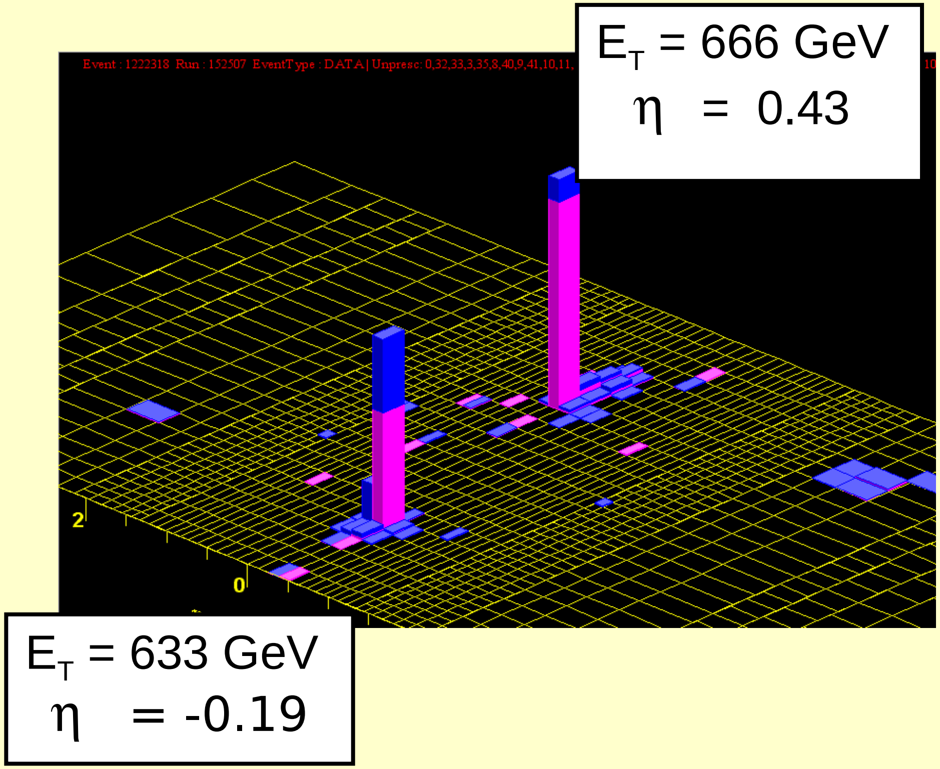
The pQCD menu

- Perturbative QCD is an expansion in the strong coupling constant that leads to a large variety of approximations
  - Leading order matrix elements
  - Next-to-leading order matrix elements
  - Next-to-next-to-leading order matrix elements
  - Resummations
  - Parton showers
  - Parton showers merged with leading order matrix elements
  - Parton showers matched to next-to-leading order matrix elements

What would you like for your next project?

The Tevatron legacy





$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G^{a}_{\mu\nu} G^{a,\mu\nu} + \sum_{i=1}^{n_f} \bar{\psi}_i \left(i\hat{D} - m_i \right) \psi_i$$

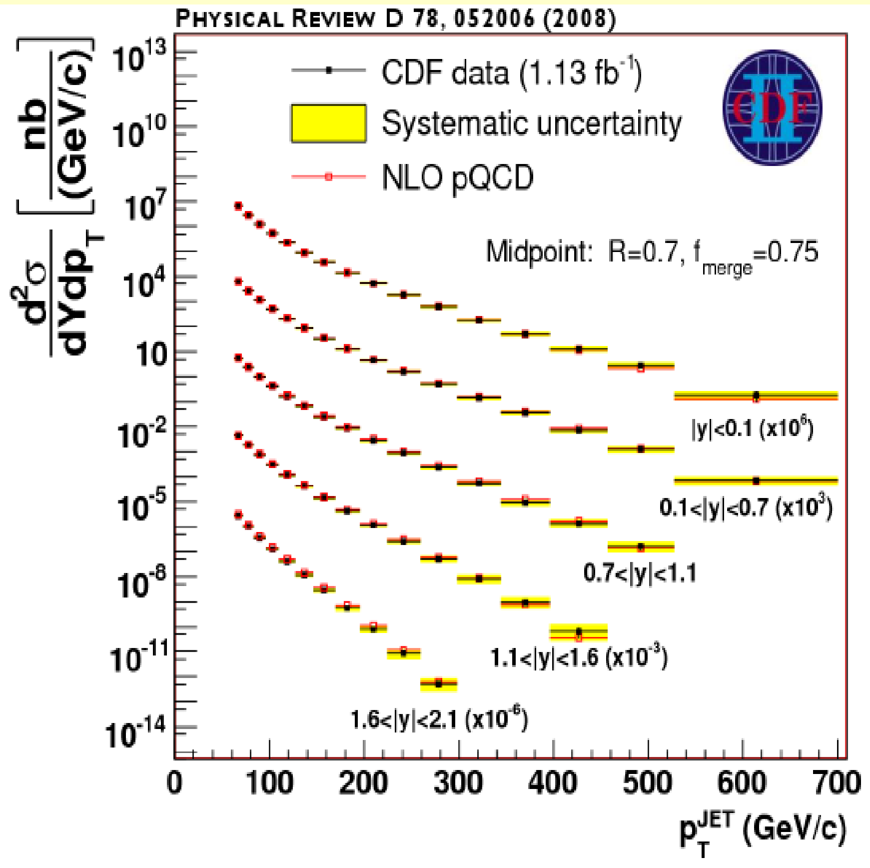
The Tevatron experiments confirmed that we know how to connect events registered in a detector and the QCD Lagrangian. Perturbation theory works.

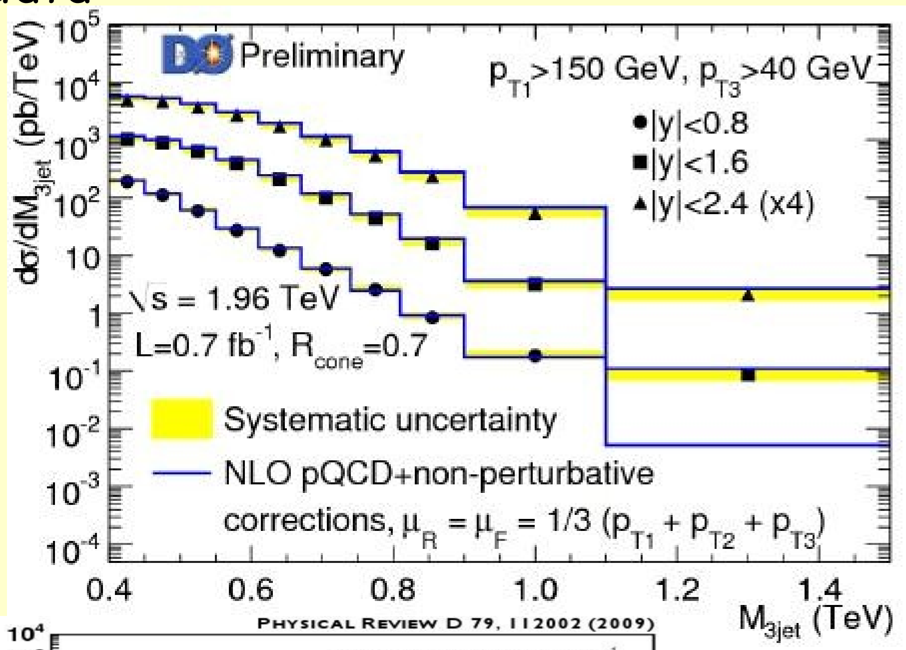
What have we learned

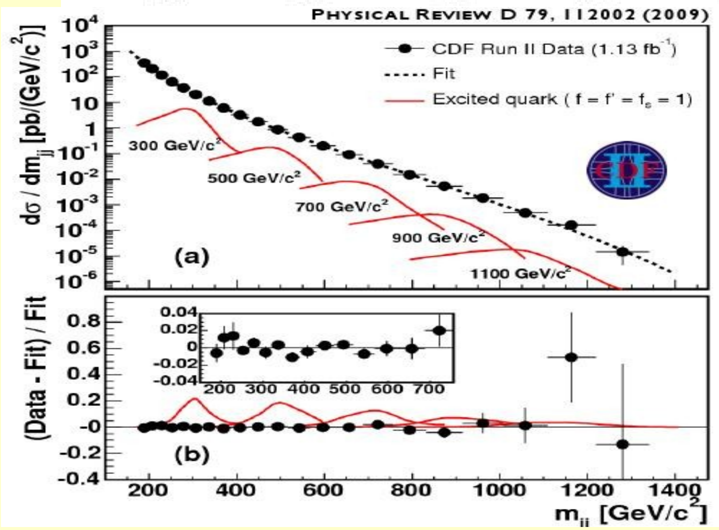
- Tevatron allowed us to
  - verify the quality of various approximations
  - confirm that 20 GeV is indeed the "large momentum transfer"
- A clear message from the Tevatron is that all approximations work, most of the time. However,
  - LO/parton showers work if we choose input parameters carefully
  - NLO out-of-the-box works even if we choose input parameters carelessly (most of the times)
  - Matrix elements merged with parton showers (CKKW,MLM) work reasonably well for shapes;
  - CKKW tells us which scales are good; this has important effect on shapes of various distributions

Perturbative QCD at the Tevatron

- Detailed studies of jet properties at the Tevatron show good agreement between pQCD and data

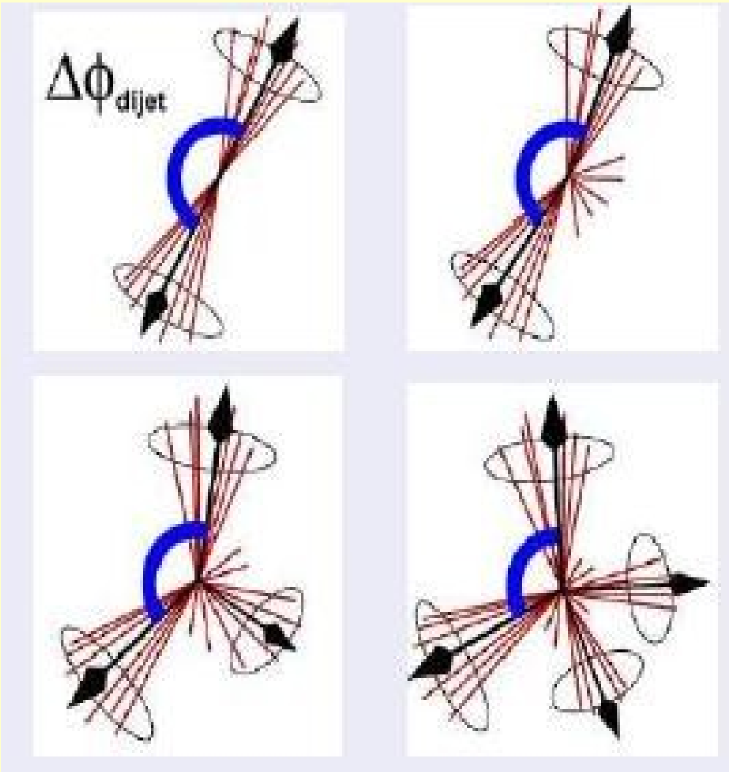


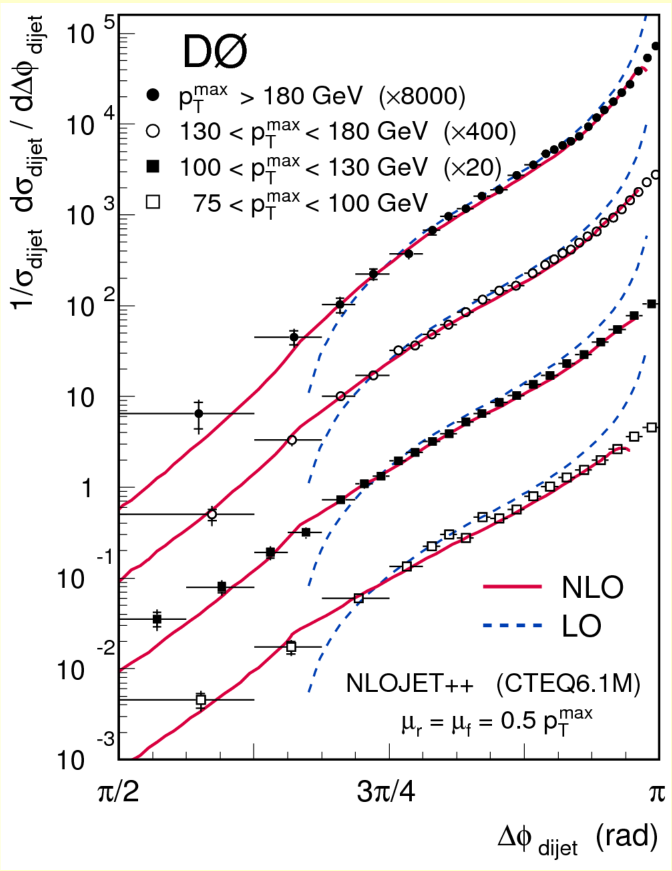


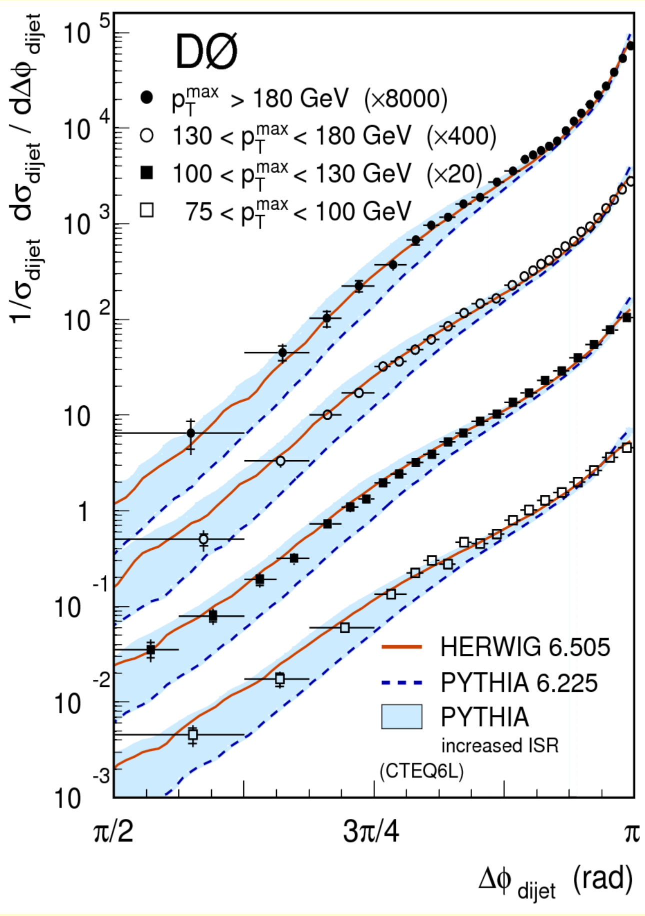


Perturbative QCD at the Tevatron

- *Jet angular correlations allow us to trace how things work when additional jets are being created in the hard process*

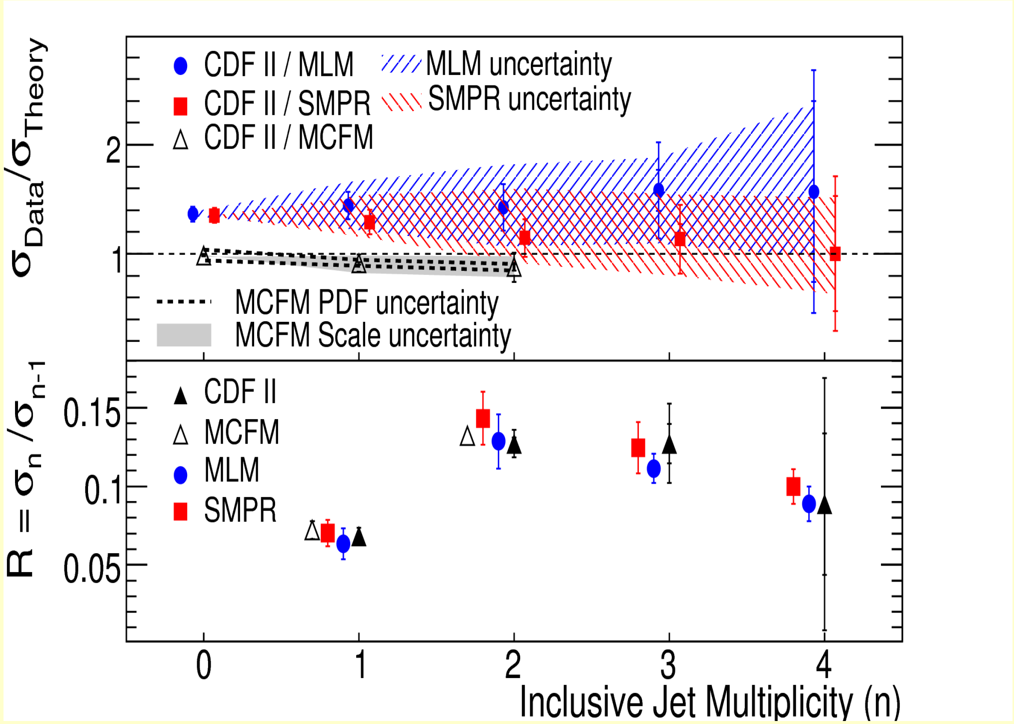






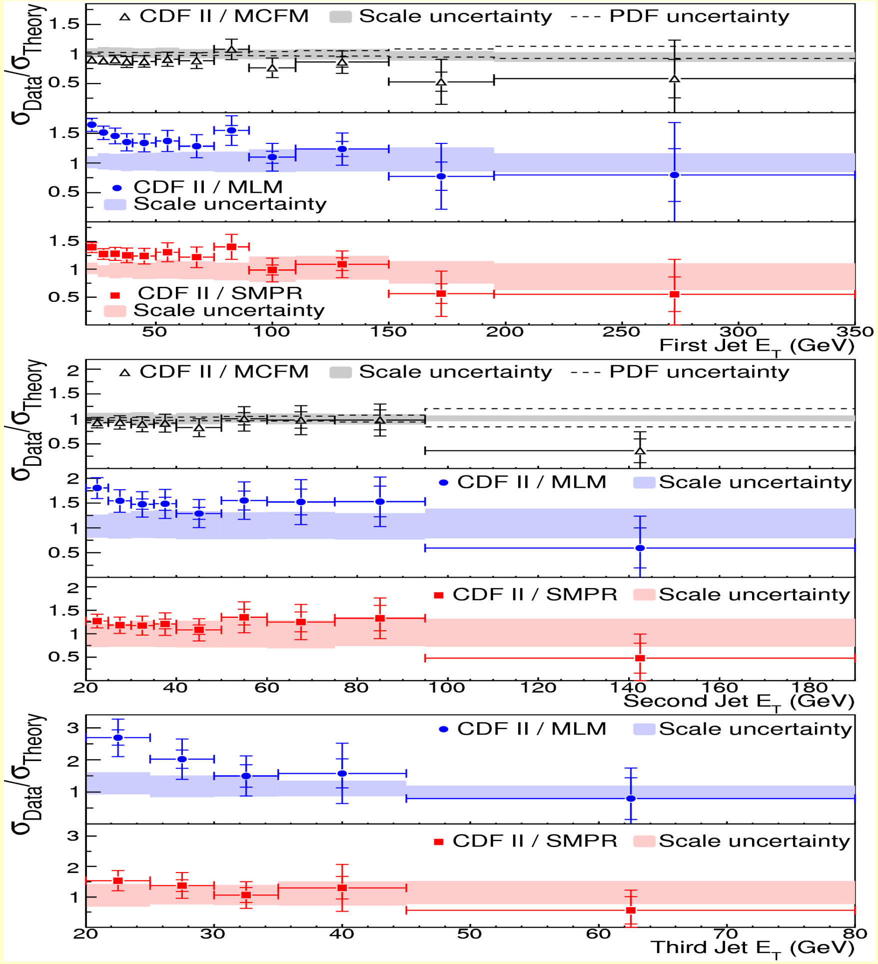
Perturbative QCD at the Tevatron

- *Production of W bosons in association with jets*



number of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

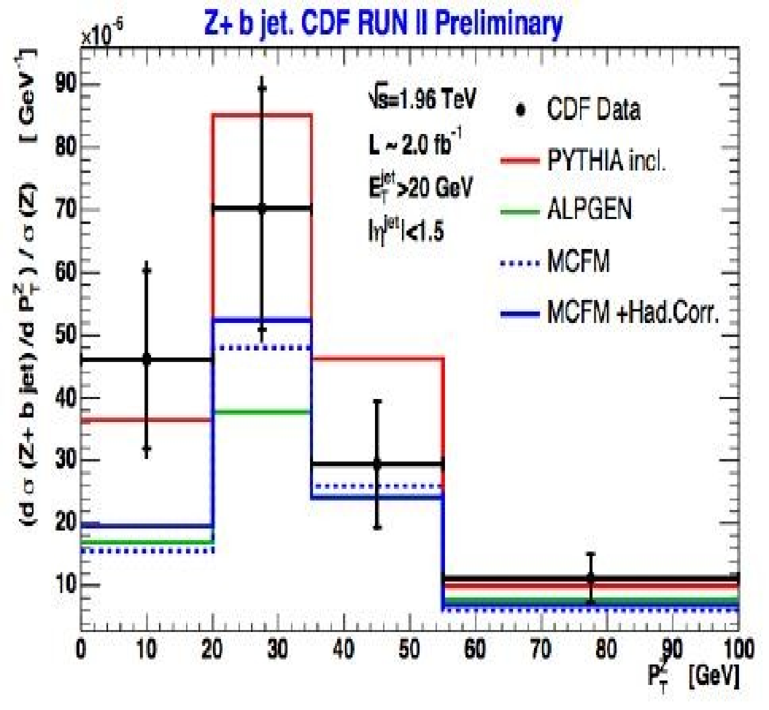
Blackhat/Sherpa collaborations



Interesting issues related to the consistency of theoretical and experimental jet algorithms

Perturbative QCD at the Tevatron

- *But sometimes the situation is very puzzling – for example when b-quarks are involved*



CDF	2.74 ±0.27 (stat) ±0.42 (syst) pb
ALPGEN	0.78 pb
PYTHIA	1.10 pb
MCFM (combined 4F+5F)	1.22 ±0.14(scale) pb

There is not much of a difference between Z+b and W+b production theoretically, so it is hard to understand why one works reasonably and the other fails badly

pQCD: from the Tevatron to the LHC

- NLO QCD works very well for hard collisions at the Tevatron; similar predictions for the LHC background processes will be very useful.
- Because first NLO QED computations appeared nearly 50 years ago, it looked like an easy task but it turned out to be highly non-trivial.

- First computations of processes from the wishlist with 4 final state particles had to wait until 2009 when pp → W+3j and pp → tt bb were computed through NLO in pQCD.

An experimenter's wishlist April 2001

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

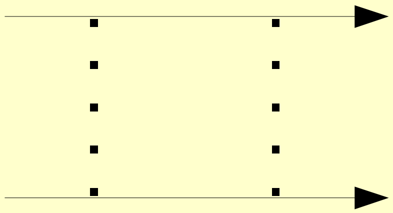
Run II Monte Carlo Workshop, April 2001

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

A new way of computing one-loop graphs

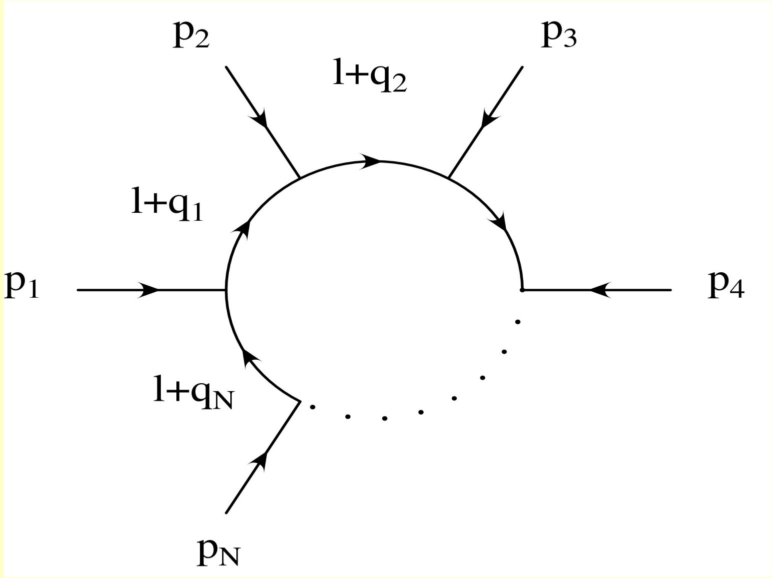
- What do we need to know to compute one-loop amplitudes in arbitrary renormalizable quantum field theory?
  - Traditional (and still viable) answer; Feynman diagrams;
  - New answer: on-shell leading order amplitudes for complex (!) on-shell momenta in two space-times with integer dimensionality higher than 4.
- Higher-dimensional space-times address the issue of divergences
- Complex momenta make the Coulomb field "propagate"

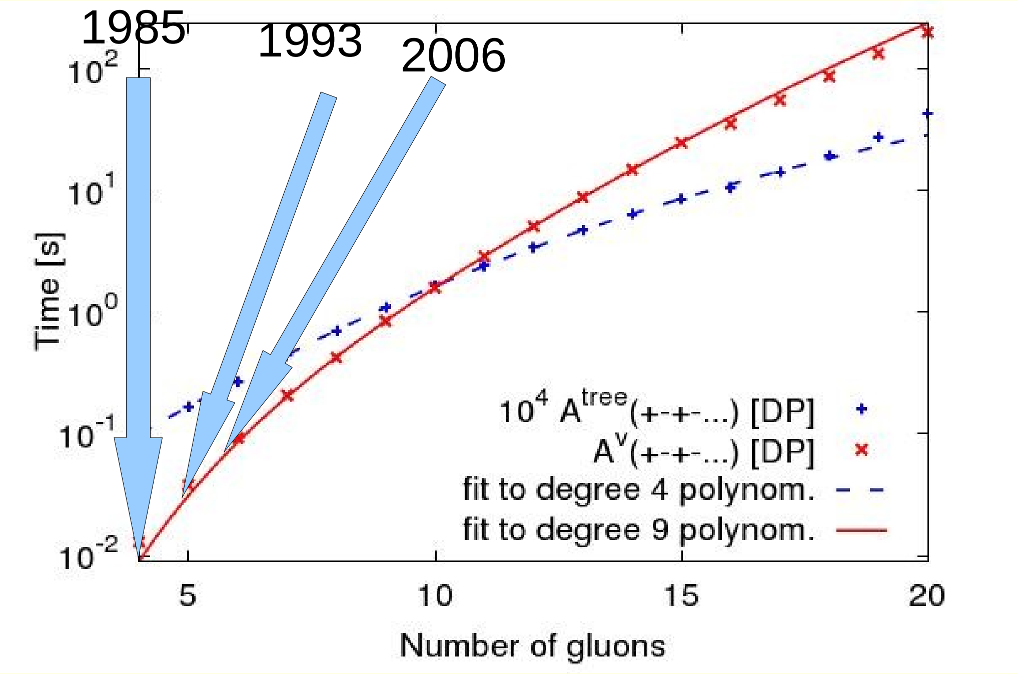
$$D_{00} = \frac{i}{\vec{q}^2}, \quad D_{ij} = \frac{-i}{q^2}\left(\delta_{ij} - \frac{q_i q_j}{\vec{q}^2}\right).$$



The power of unitarity: N-gluon amplitudes

$$20! \approx 2.4 \times 10^{18}$$ ⟷ 100 years of calculating





Giele, Zanderighi

N-gluon amplitudes can be calculated for arbitrary N. Explicit numerical results available for N through 20. Factorial growth in the number of Feynman diagrams makes this computation impossible with traditional methods.

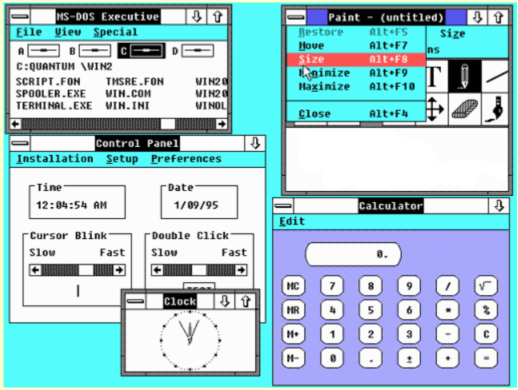
The recent progress

- $pp \to ttbb$ Bredenstein, Denner, Dittmaier, Pozzorini
  Bevilacqua, Czakon, Papadopoulos, Worek
- $pp \to tt$+2jets Bevilacqua, ,Czakon, Papadopoulos, Worek
- $pp \to W$+3 jets Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre
  R.K.Ellis, G.Zanderighi, K.M.
- $pp \to Z$ +3 jets Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre
- Many important $2 \to 3$ processes such as $pp \to VV$ + jet, $pp \to H$ + 2j, $pp \to VVV$, $pp \to V$+ bb, $pp \to tt$ + jet became known/refined in recent years
  Kallweit, Uwer, Campbell, Binoth, Karg, Kauer, Sanguinetti, Ciccolini, Badger, Glover, Mastrolia, Williams, Lazopoulos, Petriello, Camparano, Hankele, Zeppenfeld, Ossola, Pittau, Wackeroth, Reina, Weinzierl, Schulze

The recent progress could not have happened without the OPP procedure, due to Ossola, Pittau, Papadopoulos

December 1987

- NASA awards contracts to build the space station Freedom
- First intifada in Gaza Stip and West bank
- Japanese rock band BOOWY announces their breakup
- Cosmonaut Yuri Romaneko of USSR returns to Earth after 326 days in space
- Microsoft releases Windows 2



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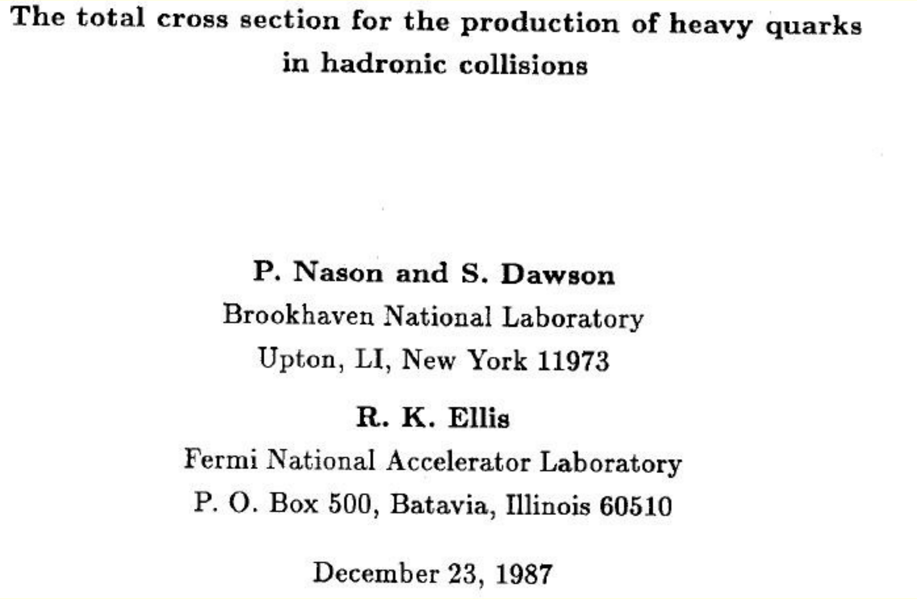
- *Microsoft releases Windows 2*
- *S. Dawson, K. Ellis and P. Nason complete computation of NLO QCD corrections to heavy quark pair production*

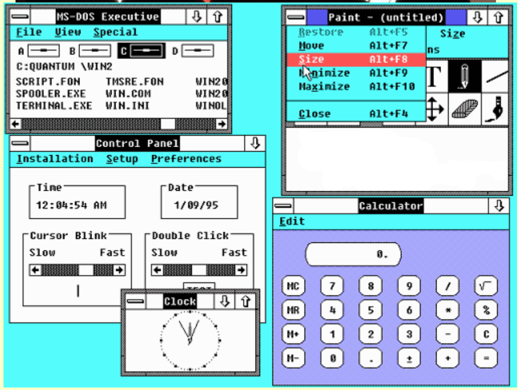


The total cross section for the production of heavy quarks in hadronic collisions

P. Nason and S. Dawson
Brookhaven National Laboratory
Upton, LI, New York 11973

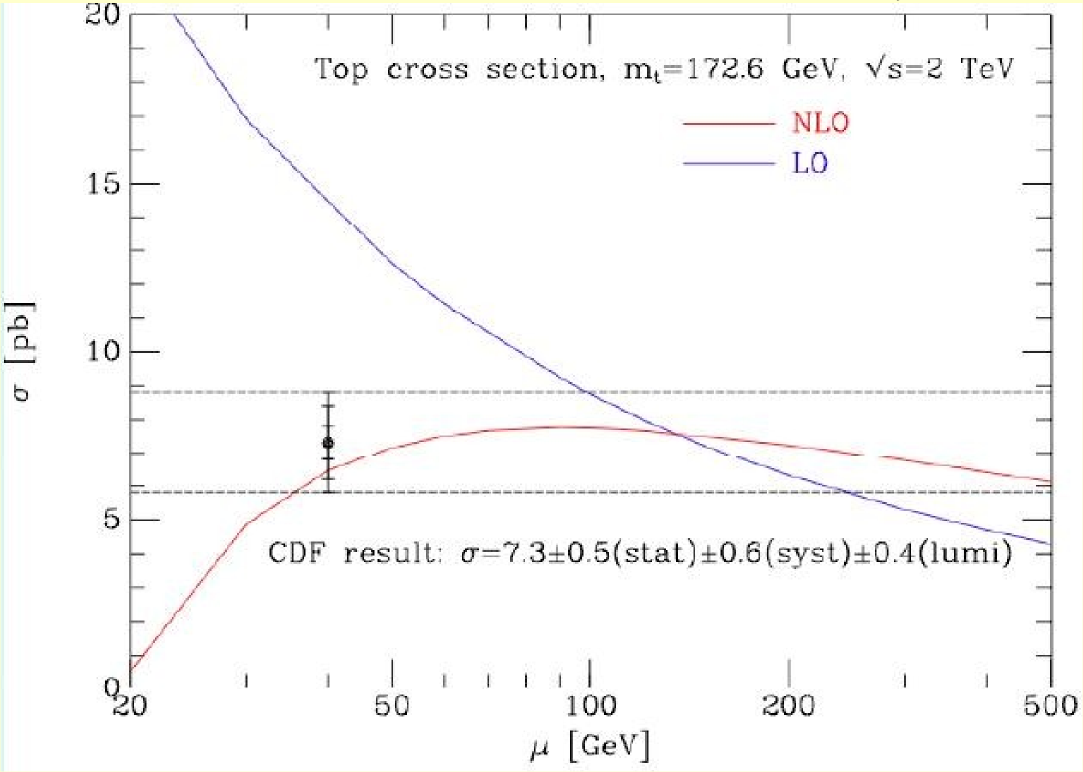
R. K. Ellis
Fermi National Accelerator Laboratory
P. O. Box 500, Batavia, Illinois 60510

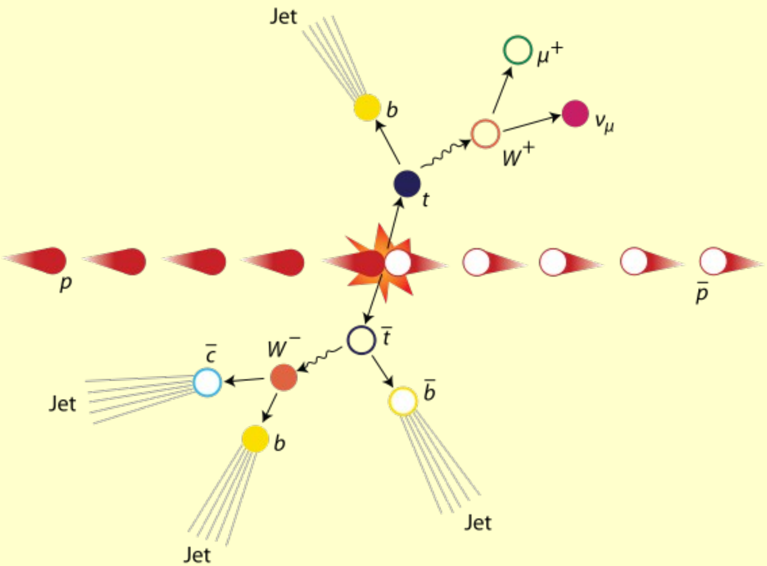
December 23, 1987



Top quarks are not stable

- It is hard to believe but we still their NLO QCD result! It is peculiar perseverance because back in 1990, it was sensible to treat heavy quarks as stable..
- But we know by now that top quarks decay !



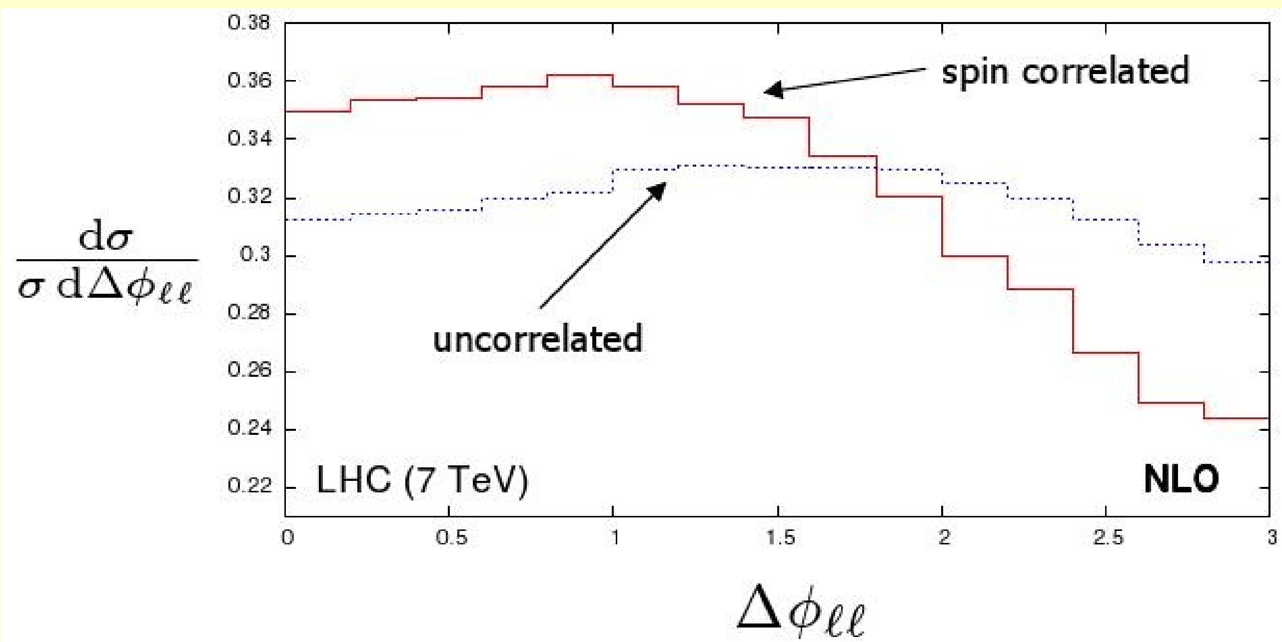


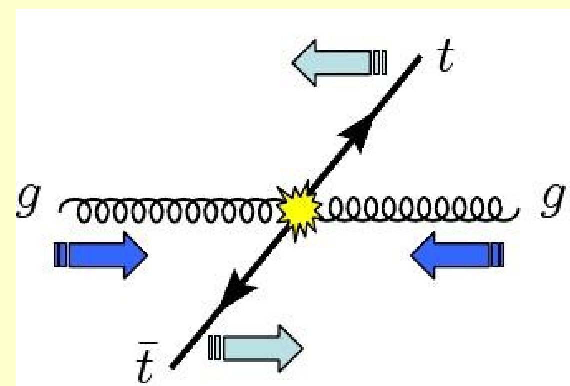
R.K.Ellis, MCFM

Top quarks are not stable

- Top quark decay products are observed in experiment
- Kinematics of top quark decay products is affected by top quark spin correlations – a unique feature of top quark pair production!
- Until 2009, no NLO QCD calculation included spin correlations, corrections to top decay and allowed arbitrary cuts on hadronic and leptonic final states.

$$pp \to t\bar{t} \to b l^+ \nu_l + \bar{b} l \bar{\nu}_l$$





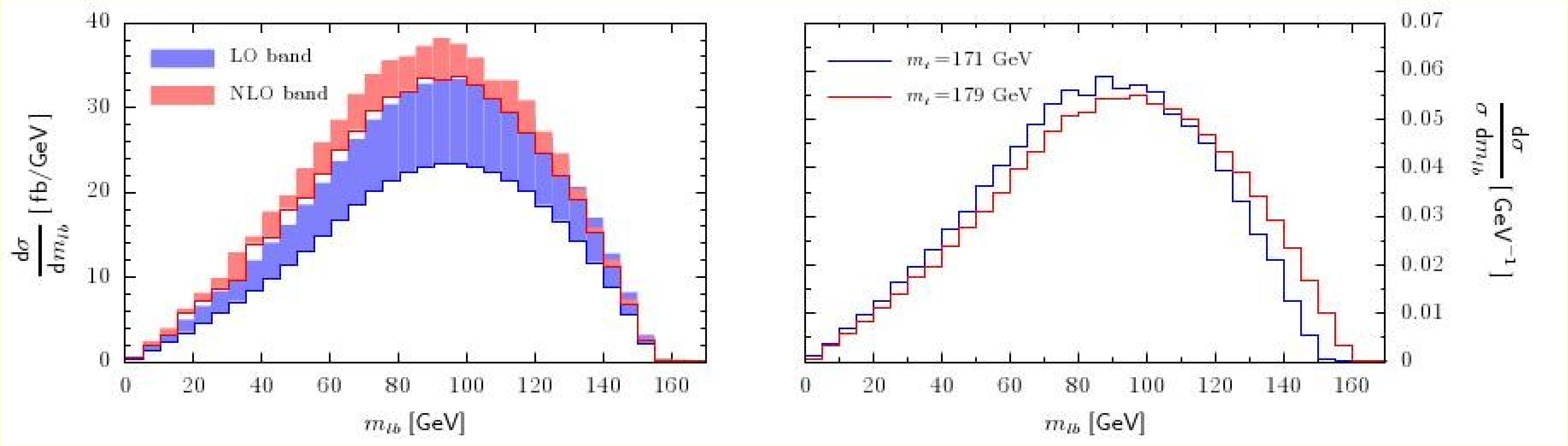
$$m_{l^+l^-} < 100 \text{ GeV}$$

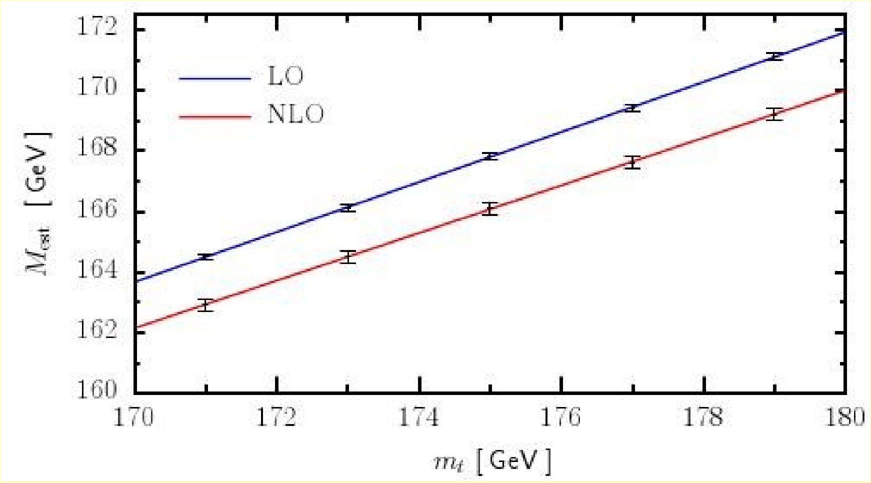
$$p_{\perp,l} < 50 \text{ GeV}$$

Schulze, K.M.

Top quarks are not stable

- Kinematics of top quark decay products is correlated with the top quark mass. Correlations always evaluated with PYTHIA!





Biswas, Schulze, K.M.

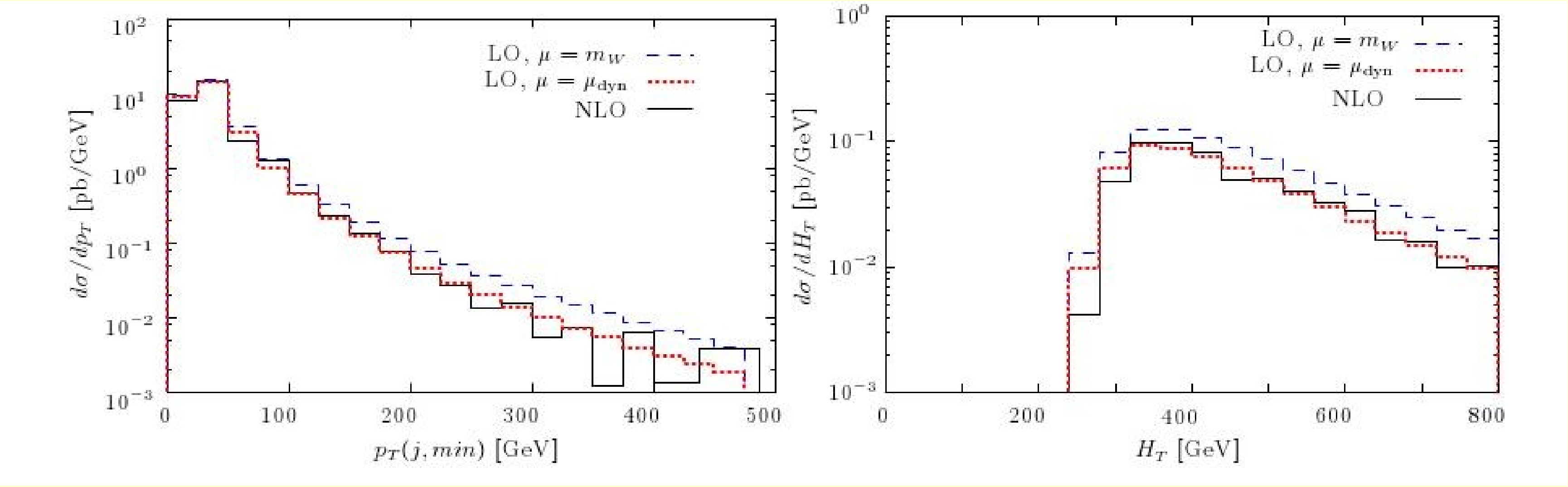
$$M_{\rm est}^2 = m_W^2 + \frac{2\langle m_{lb}^2\rangle}{1-\langle\cos\theta_{lb}\rangle}$$

$$M_{\rm est}^{\rm LO} = 0.8262 m_t + 23.22 \text{ GeV}$$

$$M_{\rm est}^{\rm NLO} = 0.7850 m_t + 28.70 \text{ GeV}$$

NLO calculations: choices of scales

- Bauer and Lange showed that the choice of the renormalization scale of the strong coupling constant leads to important effects for kinematic distributions.
- Properly chosen, dynamical renormalization/factorization scales in LO reproduce shapes of NLO computations



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

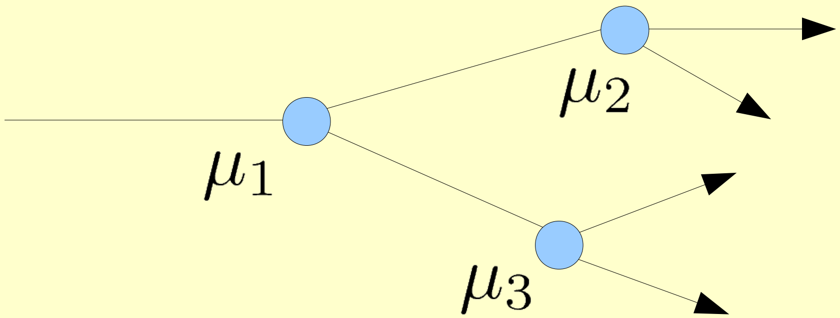
Bauer, Lange

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.

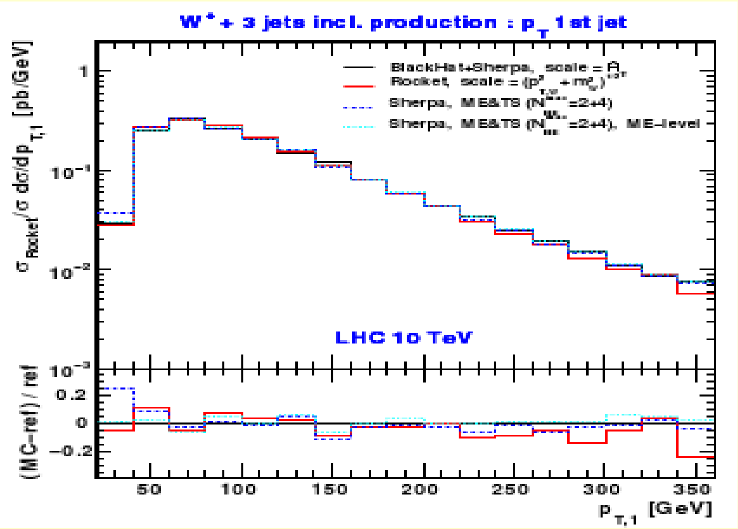


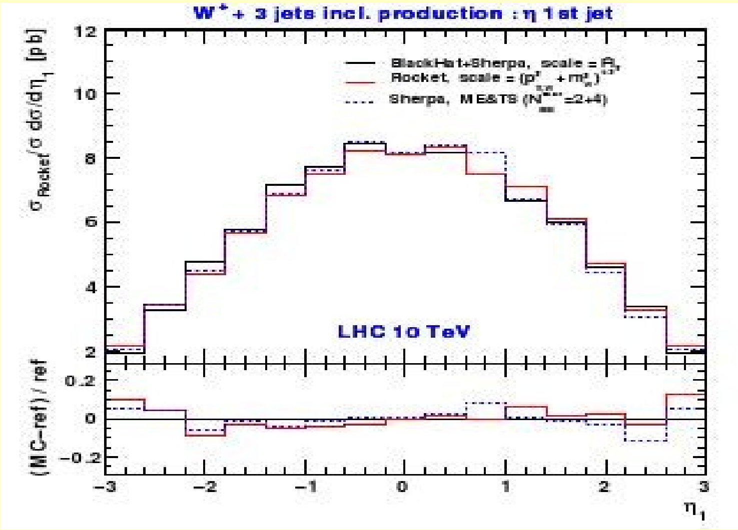
$$|\mathcal{M}|^2 \sim \prod_{i=1}^{N_{\rm part}} \alpha_s(\mu_i)$$

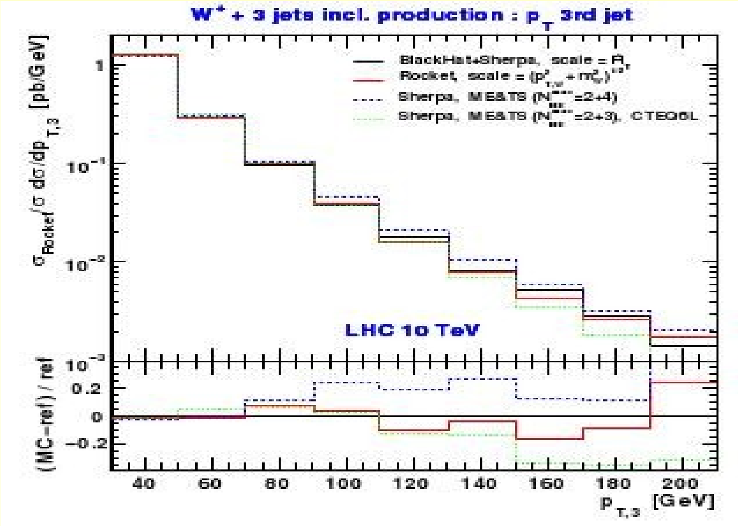
Catani, Krauss, Kuhn, Webber

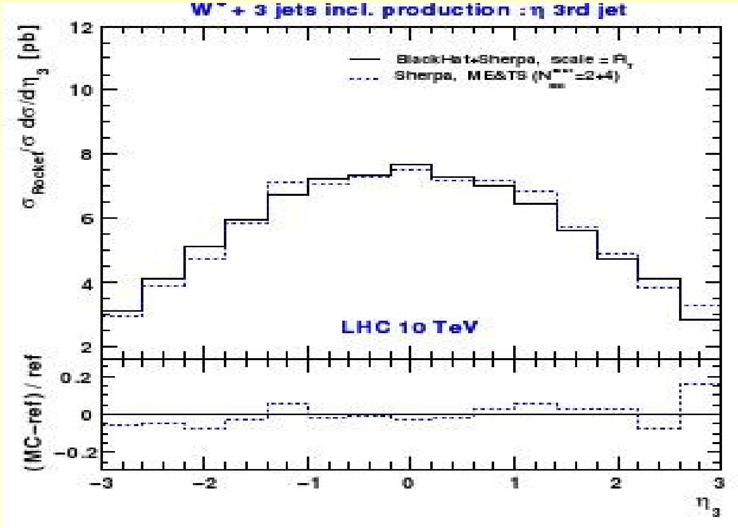
Scale setting and W+3 jets at NLO

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









Blackhat/Rocket/Sherpa comparison S. Hoche, J. Huston, D. Maitre, J. Winter, G. Zanderighi

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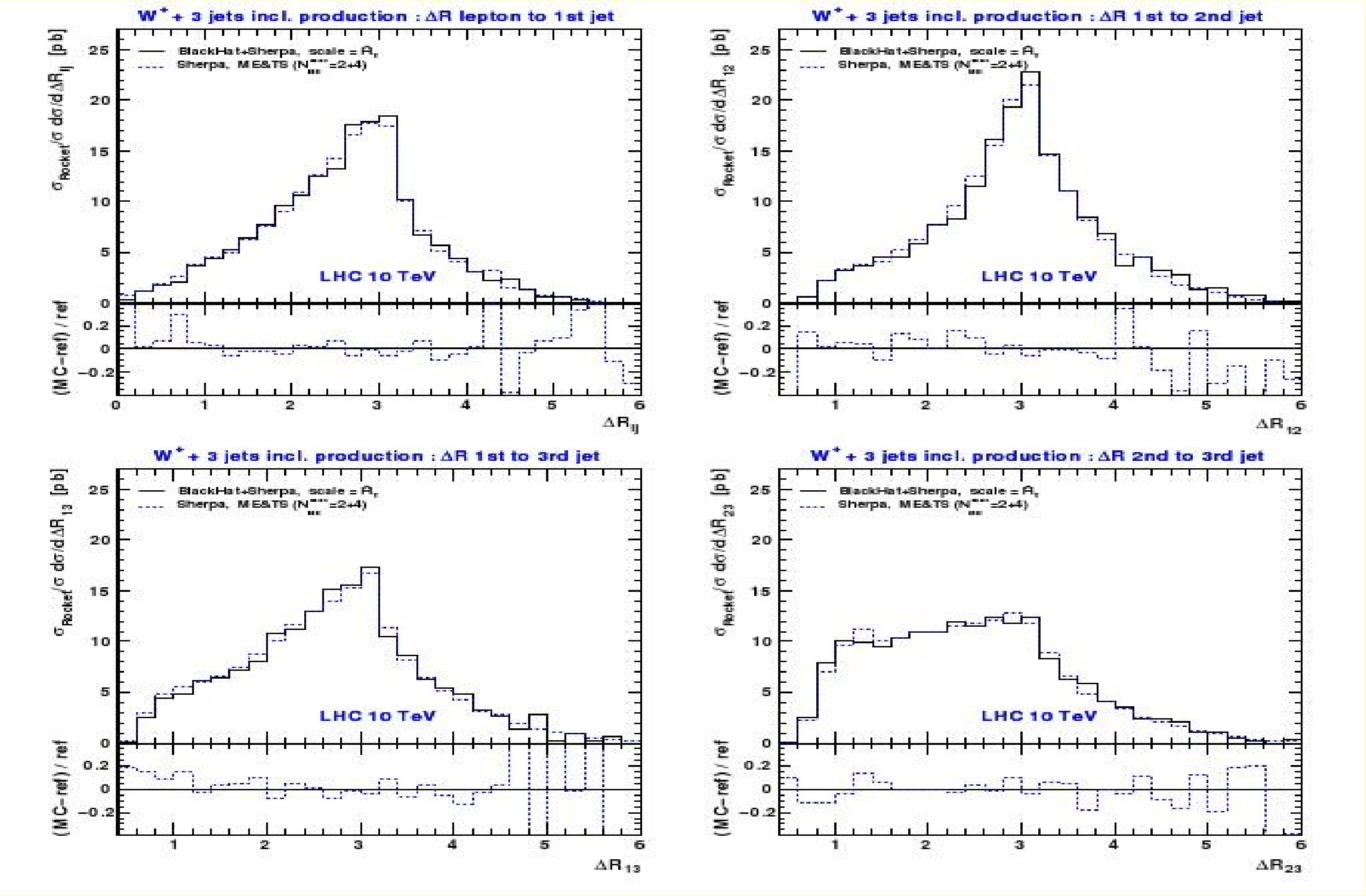
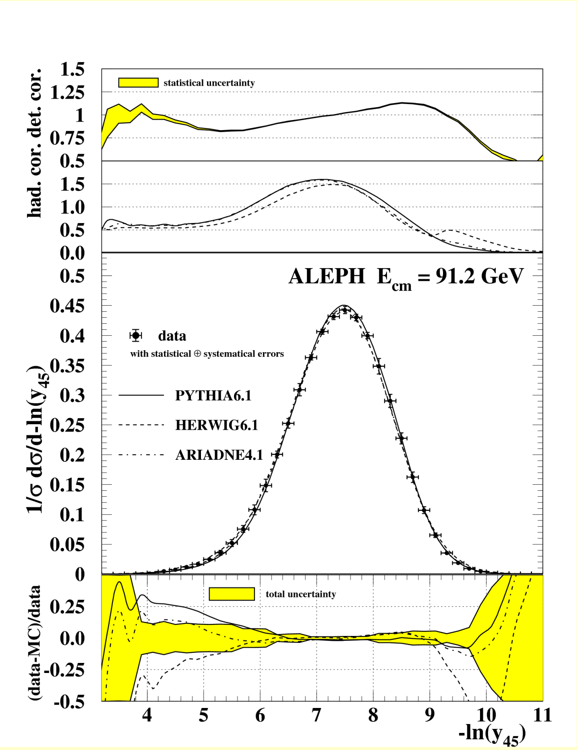
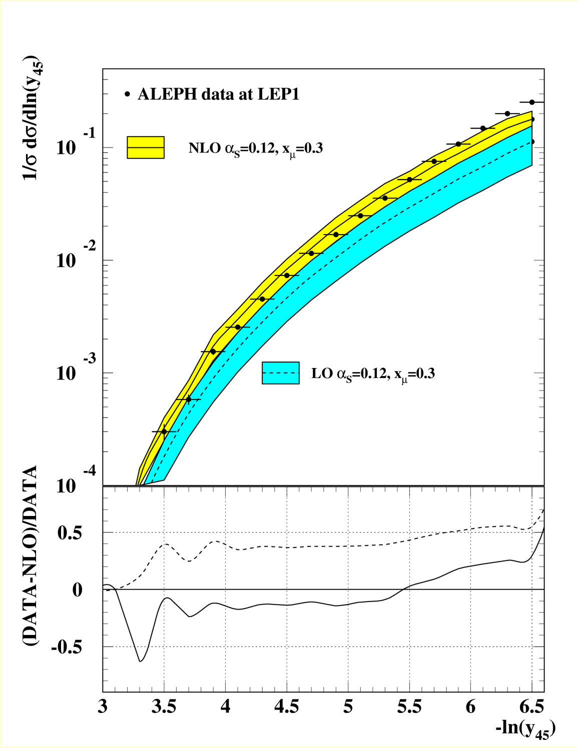


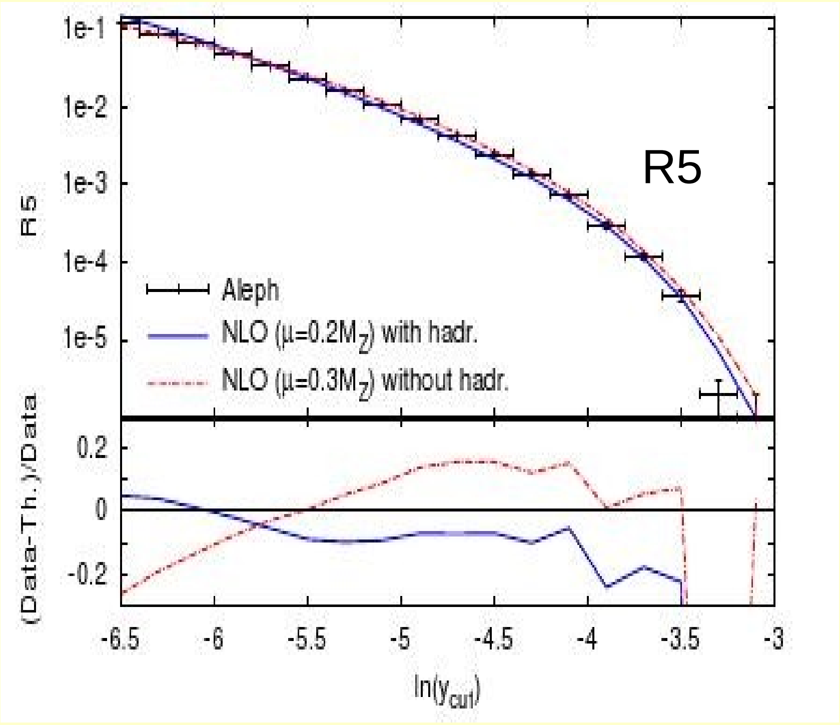
Blackhat/Sherpa comparison *S. Hoche, J. Huston, D. Maitre, J. Winter, G. Zanderighi*

"Perturbative" hadronization

- LHC will be a jetty place – will we know what we are doing? Look at the highest exclusive jet multiplicity studied at LEP – five jets !





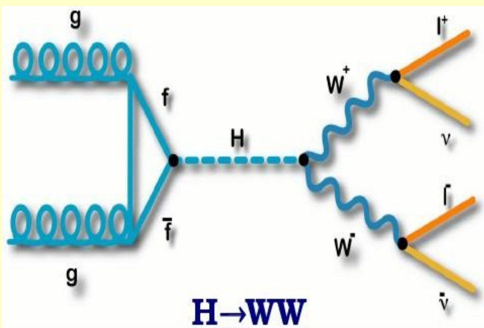


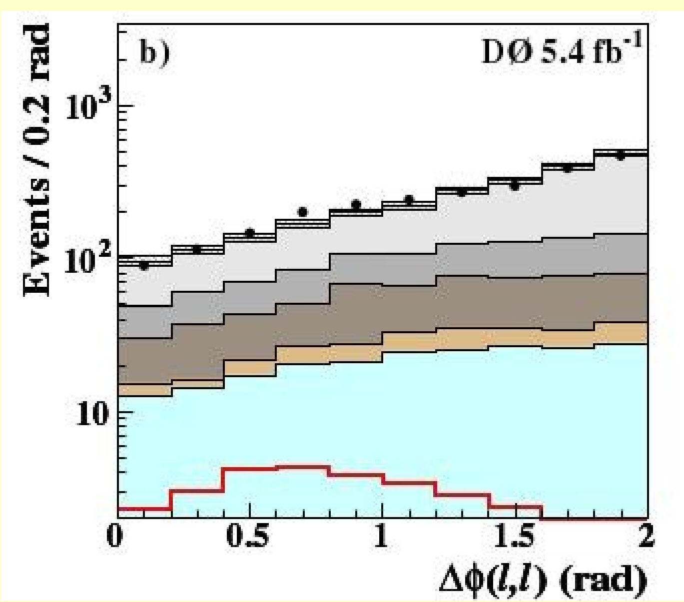
Frederix, Frixione, Zanderighi, K.M., Stenzel

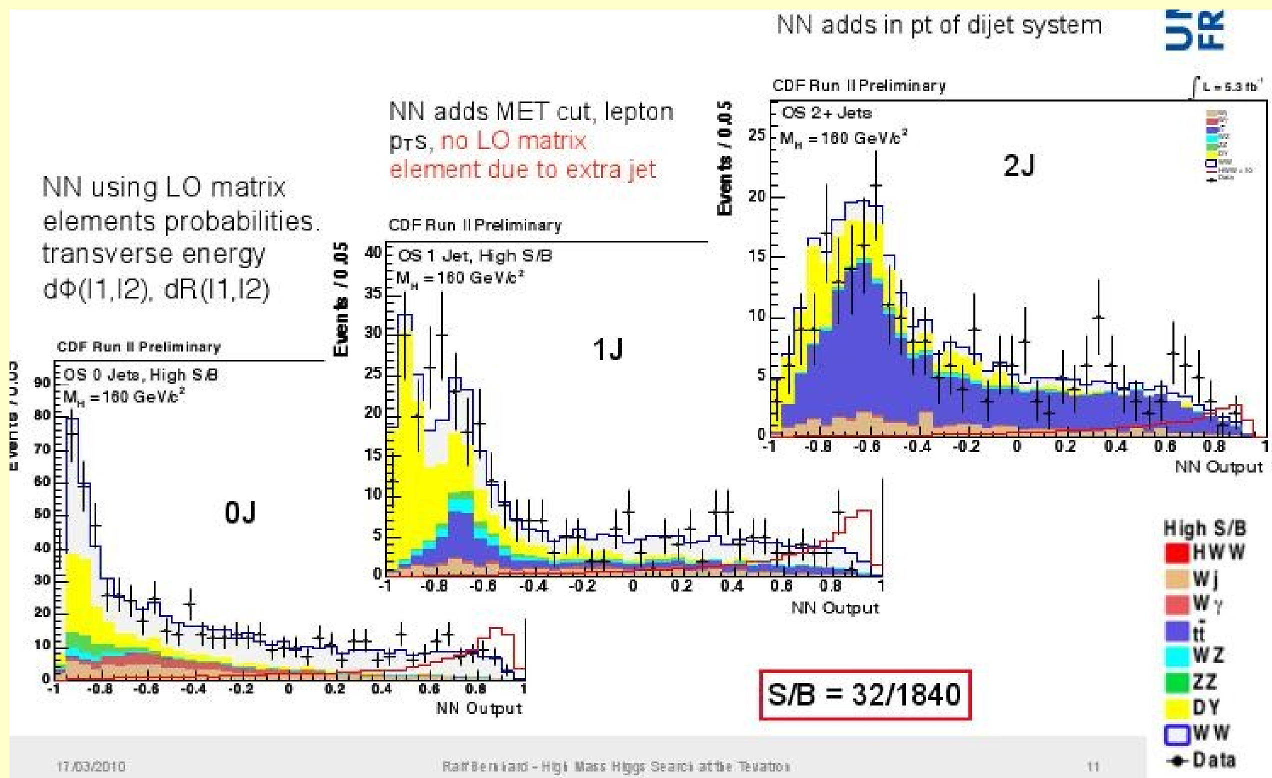
Hadronization corrections and perturbative corrections become entangled for high jet multiplicity

NLO QCD and "correct variables"

- The high-mass Higgs search at the Tevatron is a neural net festival. Can one calculate the neural net variable distributions at NLO?







R. Bernard, Talk at QCD Moriond 2010

Beyond the NLO: NNLO

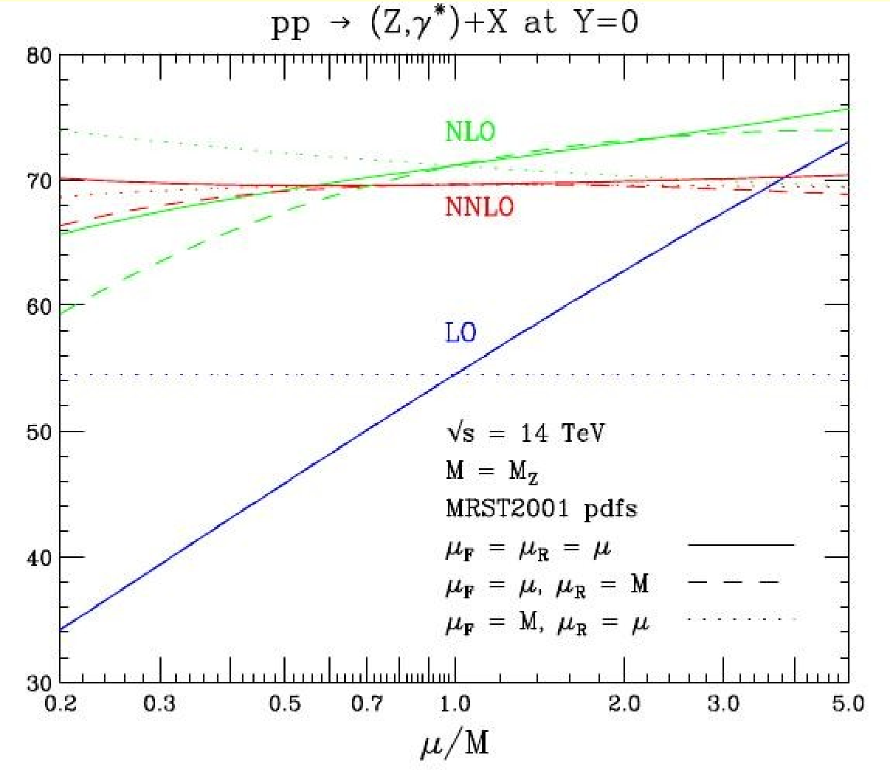
- There are attempts to extend fixed order perturbative computations beyond the NLO.
- Useful for extraordinary clean or important hard processes
- NNLO calculations are in their infancy, and our abilities are very limited. Realistic results for collider processes are available for
  - $e^+e^- \to 3j$ → the value of the strong coupling constant

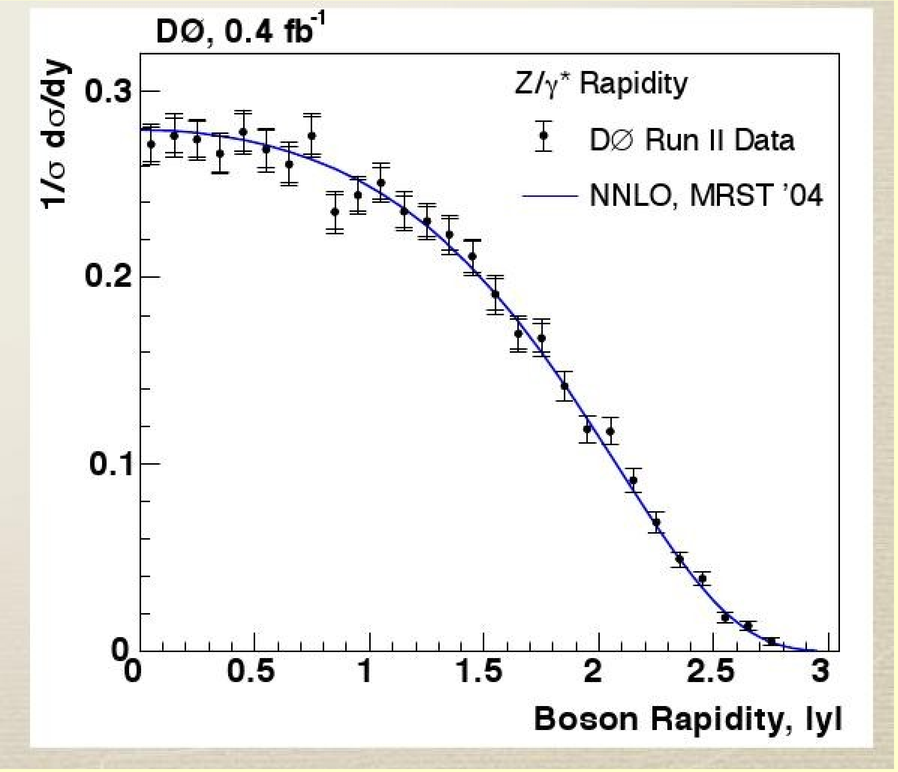
    Gehrmann-De Ridder, Gehrmann, Glover, Heinrich; Weinzierl
  - pp → W, Z, H; the W-mass, parton distributions, Higgs boson exclusion limits at the Tevatron

    Anastasiou, Petriello, K.M., ; Catani, Grazzini, Cieri, De Florian,

NNLO: the ultimate goal

- The rapidity distribution of the Z-boson is known through NNLO and shows all the benefits of going to that high an order in pQCD

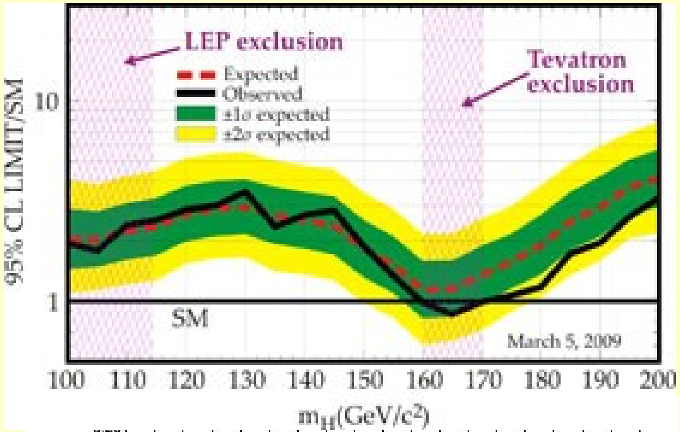


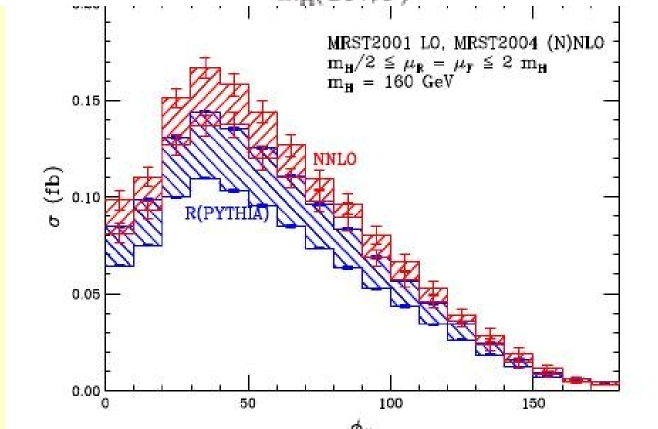


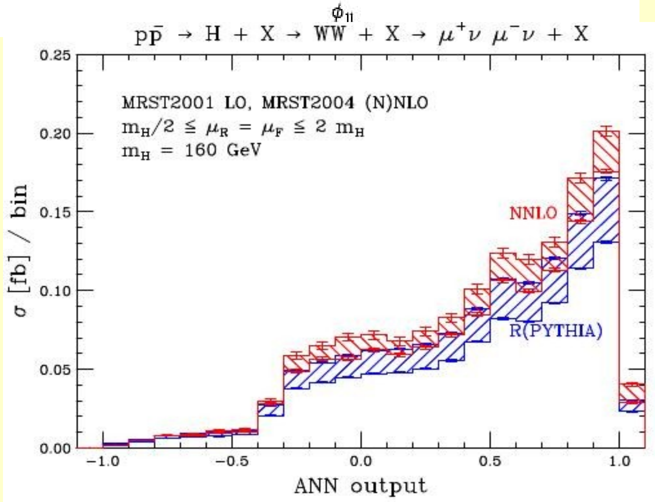
Anastasiou, Dixon, Petriello, K.M.,

Excluding the SM Higgs in $H \to W^+W^- \to l^+l^-\nu\bar{\nu}$

- *CDF and D0 exclude the existence of the SM Higgs boson with the mass around 160 GeV.*
- *Good understanding of the Higgs signal is imperative. But – done with PYTHIA!*
- *Comparison of the NNLO computation with PYTHIA predictions shows that PYTHIA acceptances are lower.*





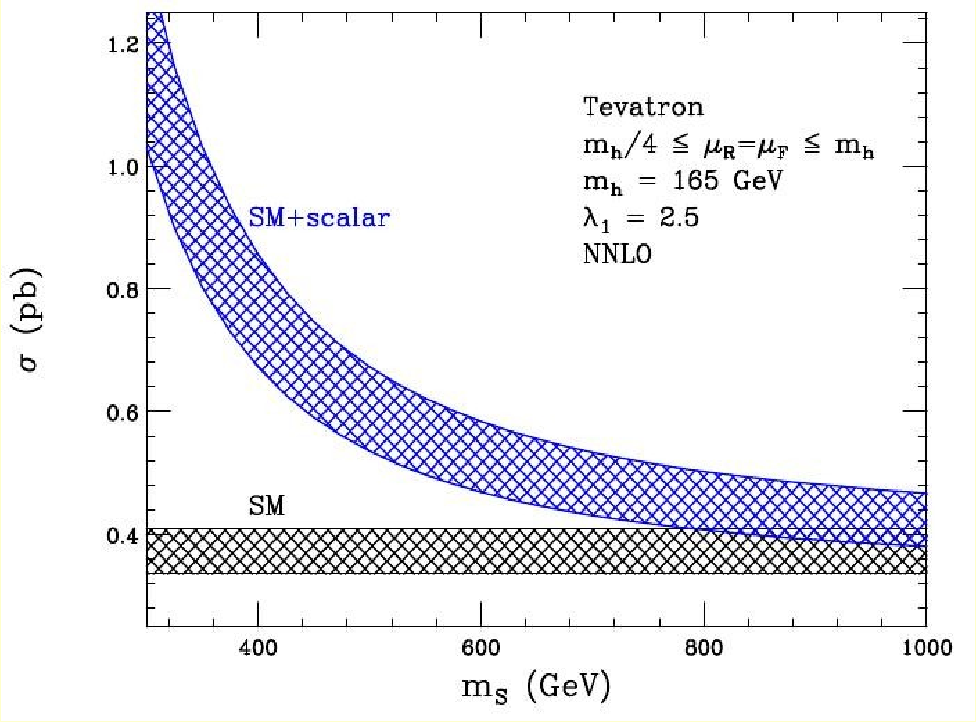


$\sigma_{acc}/\sigma_{incl}$	Trigger	+ Jet-Veto	+ Isolation	All Cuts
NNLO ($\mu = m_H/2$)	44.7%	39.4% (88.1%)	36.8% (93.4%)	27.8% (75.5%)
NNLO ($\mu = 2\,m_H$)	44.9%	41.8% (93.1%)	40.7% (97.4%)	31.0% (76.2%)
MC@NLO ($\mu = m_H/2$)	44.4%	38.1% (85.8%)	35.3% (92.5%)	26.5% (75.2%)
MC@NLO ($\mu = 2\,m_H$)	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

NNLO: constraining BSM

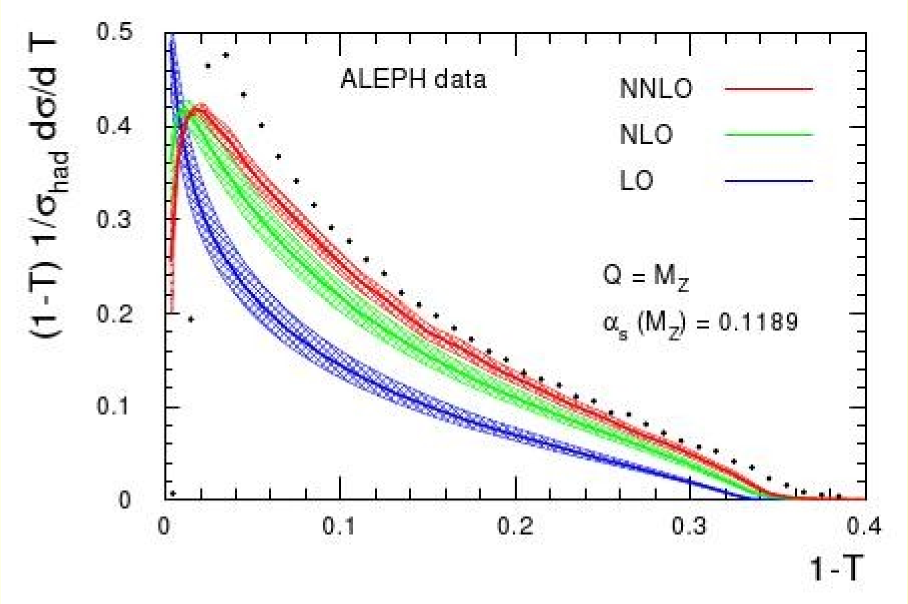
- One can use limits on Higgs boson production cross-section to constrain physics beyond the Standard Model
  - supersymmetry — Anastasiou, Beerli, Daleo;; Muhlleitner, Rzehak, Spira
  - color octet scalars — Boughezal, Petriello
  - additional heavy fermions — Anastasiou, Boughezal, Furlan



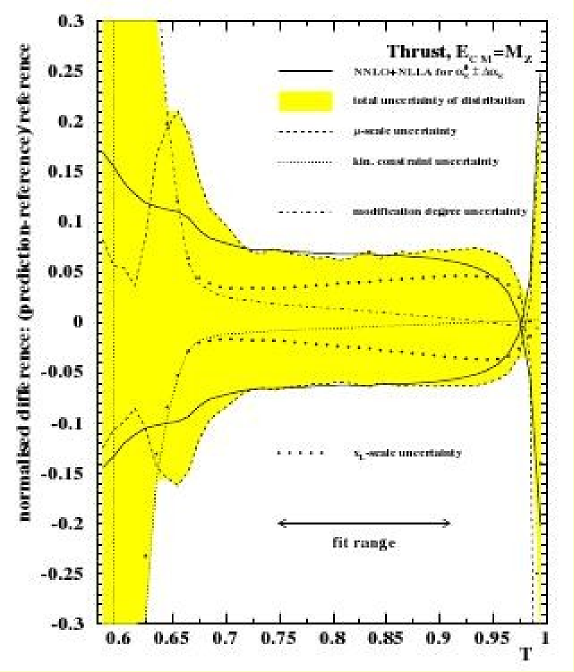
Boughezal, Petriello

NNLO: the strong coupling constant

- Calculation of the NNLO QCD corrections to 3 jet production at LEP is one of the most heroic computations in high-energy physics
- Lead to active re-investigation of the value of the strong coupling constant



Gehrmann-De Ridder, Gehrmann, Glover, Heinrich



+ Dissertori, Luisoni

$$\alpha_s(M_Z) = 0.1224 \pm 0.0039$$

NNLO + SCET = weak(er) coupling

- Traditional determinations of the strong coupling constant from thrust distribution can be critisized on two occasions
  - resummations are limited to NLL
  - non-perturbative corrections are typically taken from parton showers
- SCET improves on both of these things - N^3LL resummations for thrust and self-consistent definition of non-perturbative soft function

  Becher, Schwartz, Hoang,, Stewart

- Simultaneous fit for the strong coupling and the non-perturbative power corrections leads to a smaller value of $\alpha_s(M_z)$

$$\alpha_s(M_z) = 0.1135 \pm 0.001$$

Abbate, Fickinger, Hoang, Mateu, Stewart

It seems that whenever the hadronization effects are fitted together with the strong coupling constant, the results for $\alpha_s(M_z)$ are lower.

NNLO for more difficult processes

- A NNLO computation to hadroproduction of N particles involves
  - Two-loop virtual corrections to $2 \to N$ matrix element, integrated over N-particles phase-space;
  - One-loop virtual corrections to $2 \to N+1$ matrix element, integrated over (N+1)-particles phase-space;
  - $2 \to N+2$ matrix element, integrated over (N+2)-particle phase-space.
- Each of these items lives in a different phase-space but, since they all diverge when integrated separately, they must be combined (and divergences extracted and canceled) before the integration.
- How this can be done efficiently is a matter of active research.

Note that a large number of two-loop amplitudes for $2 \to 2$ scattering processes are known for almost ten years, already.

NNLO: double real emission

- Two main lines of thought
  - subtraction techniques (e+e- → 3j)
  - sector-decomposition for real emission (pp → W,Z,H)
- The NLO analogs exist for both
  - subtraction techniques → Catani-Seymour dipole formalism
  - sector-decomposition → Frixione-Kunszt-Signer technique
- The FKS technique is the result of a simple observation
  - lets partition the phase-space for final state particles so that at any sector one definite particle can be soft or two definite particles can be collinear;
  - in all such sectors, optimal choices of variables and singularities of matrix elements are obvious.

NNLO: from sector decomposition to CzFKS

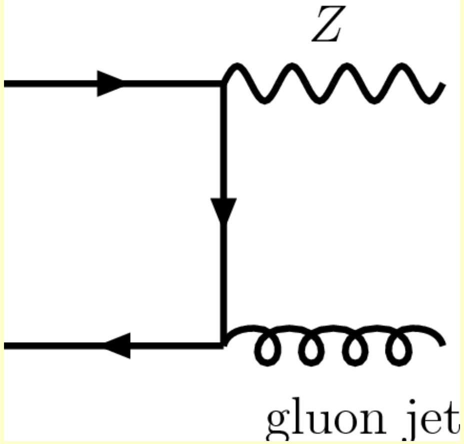
- Sector decomposition at NNLO attempts to construct global changes of variables, looking at various types of Feynman diagrams;
- This worked for $pp \to W,Z,H$; would have trivially worked for $pp \to t$ or $pp \to tt$ but not for something more difficult
- However, it is clear that this limitation is not necessary and that partition of phase-space should exist such that for every sector one can clearly identify two or three partons that become unresolved
- It is harder to deal with such three unresolved partons; but since we have done pp-> W,Z,H, we know how to do this and what kind of sector decomposition needs to be employed.

A combination of FKS ideas and sector decomposition is a very promising suggestion to develop generic NNLO "subtraction" technique

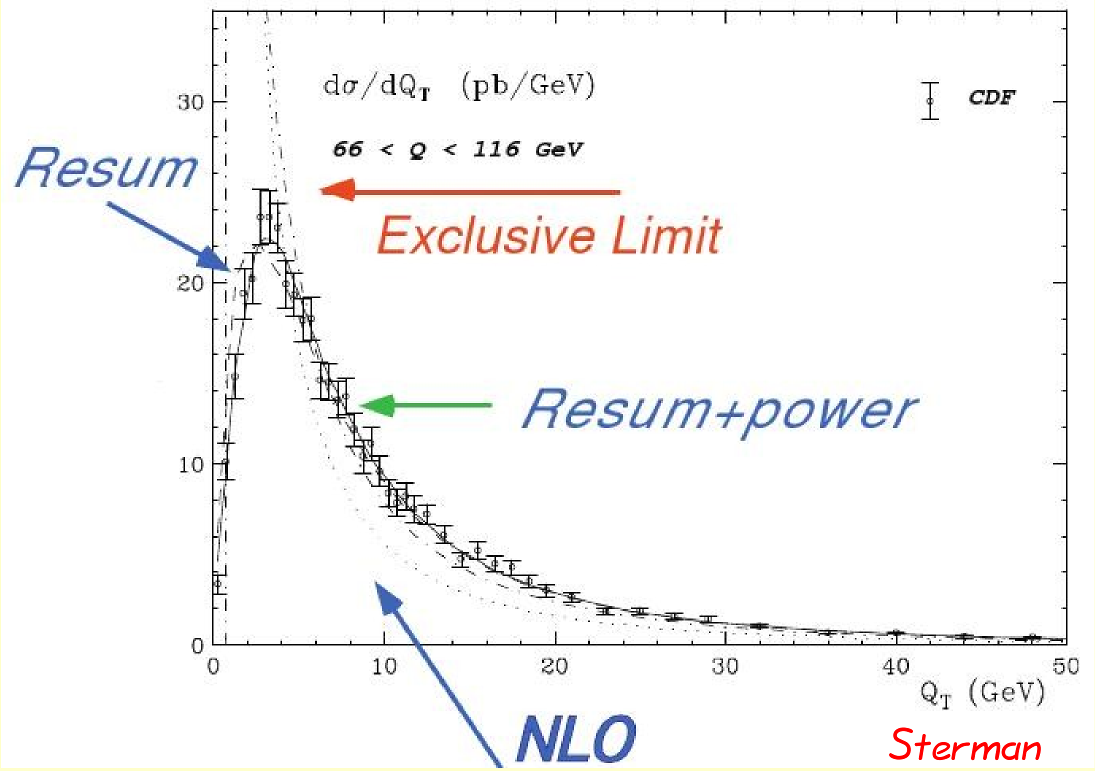
M. Czakon

Resummations

- One way to go beyond NLO/NNLO/… is to use resummed calculations.. Classic example – transverse momentum distribution of Z or W boson



When the gluon "jet" is soft, we need to sum up multiple emissions to produce sensible results



Resummations: EFT

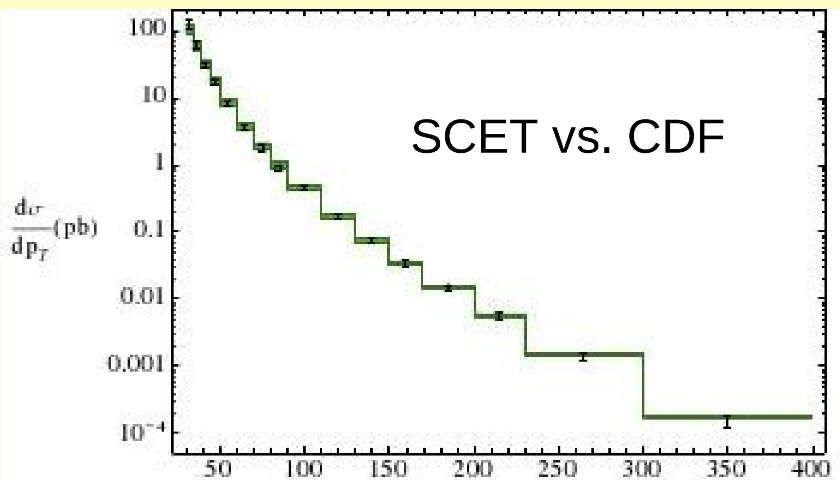
- *General basis for resummations is the factorization formula*

$$\mathcal{M} = H(\mu) \otimes J(\mu) \otimes S(\mu)$$

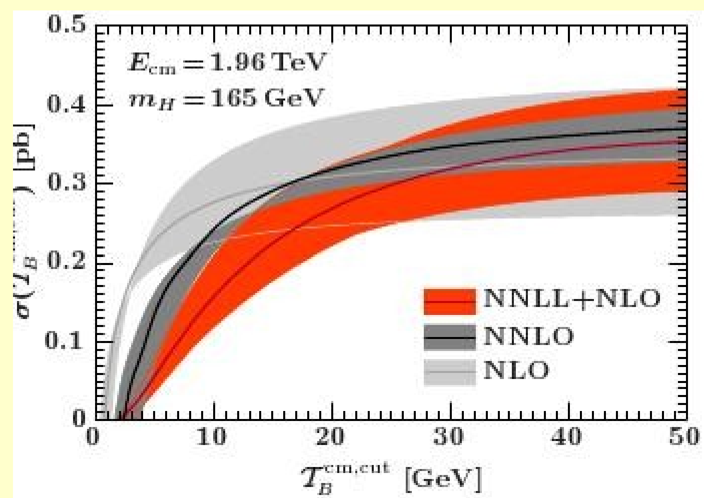
Collins, Soper; Sterman

- *Effective field theory (SCET) → factorization → resummation*

$$\mu \frac{\mathrm{d}H}{\mathrm{d}\mu} = \gamma \otimes H(\mu)$$



Becher and Schwartz



SCET vs. FEHIP

Berger, Waalewijn, Marcatonini, Stewart, Tackmann

What is next?

- Further technical developments related to
  - one-loop computations (MadGraph@NLO)
  - two-loop computations – complicated processes, fully differentially
- Realistic treatment of complicated background and signal processes (large number of jets, decays, spin-correlations, observables)
- Merging fixed order perturbative computations for differential jet production cross-sections with resummations, in a controlled fashion.
- Parton showers with quantum interferences
- Scale-setting prescriptions at NLO (CKKW@NLO)

Conclusion

- Discovering New Physics at the LHC is notpossible without working theory of hadron collisions.
- "Practical" theory of hadron collisions is in good shape
- The theory of hadron collisions went through rapid development in the past ten years
  - new theoretical ideas
  - new computational techniques
  - better appreciation of what works and what does not
- Spectacular agreement with the Tevatron data over wide range of energies
- Every reason to believe that (practical) theory of hadron collisions -- as we have it now – is up to the task that we face at the LHC