Standard Model Physics: from the Tevatron to the LHC

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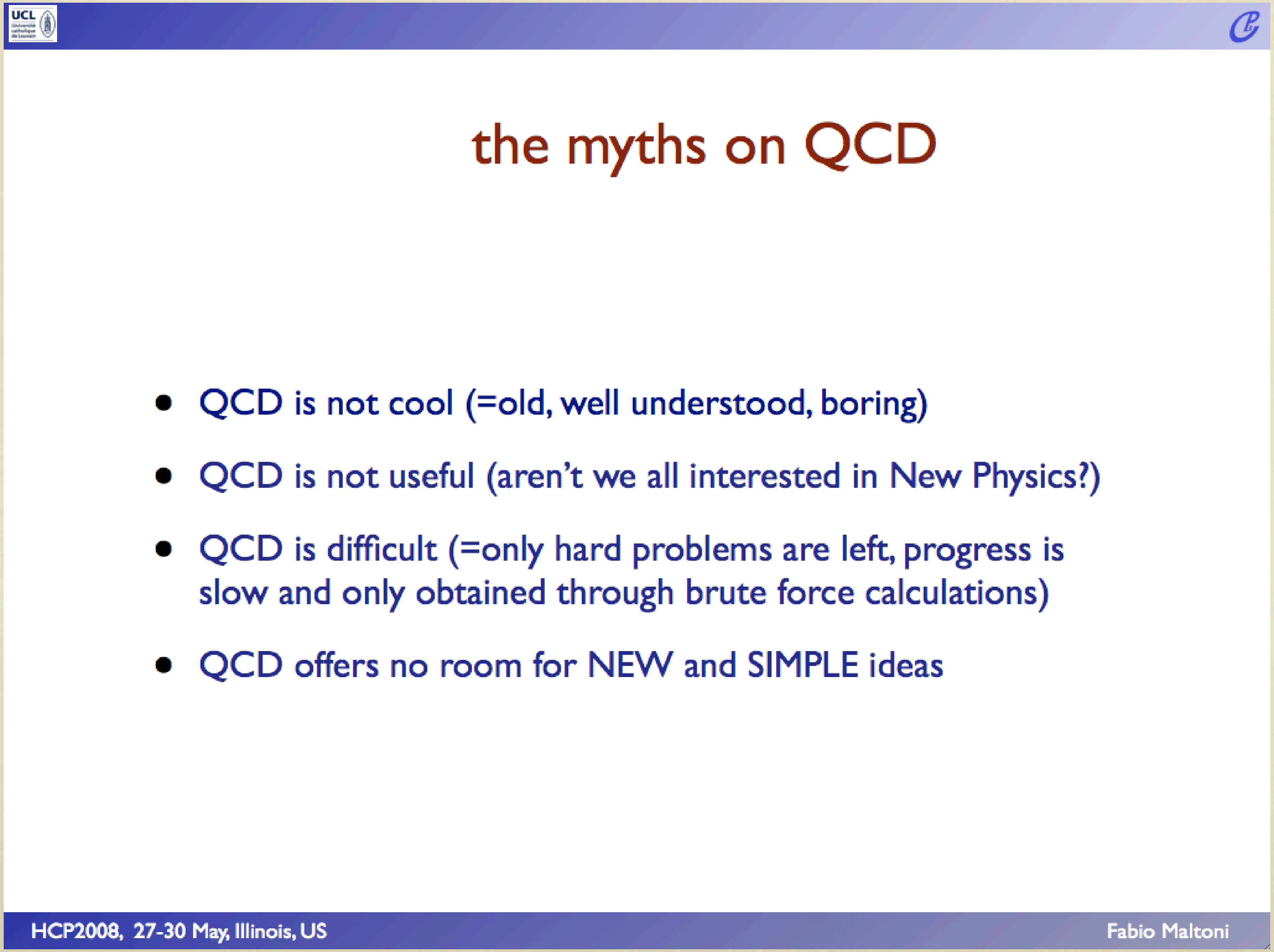
D0 France: Past, Present and Future, Oct. 2008

Setting the stage

- Standard Model physics + hadron colliders = QCD.


UCL

the myths on QCD

- QCD is not cool (=old, well understood, boring)
- QCD is not useful (aren't we all interested in New Physics?)
- QCD is difficult (=only hard problems are left, progress is slow and only obtained through brute force calculations)
- QCD offers no room for NEW and SIMPLE ideas

HCP2008, 27-30 May, Illinois, US   Fabio Maltoni

Setting the stage

Dispelling the myths on QCD

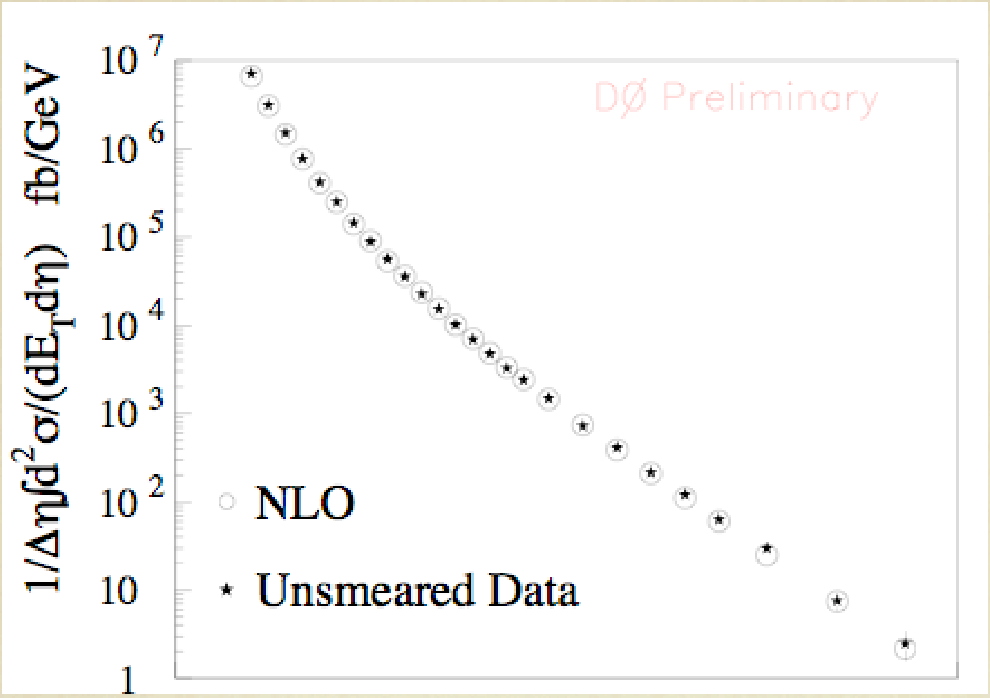
- QCD is ~~not~~ cool (string theorists now publishing on hep-ph)
- QCD is ~~not~~ useful also because we are interested in New Physics
- QCD is difficult because we ask more challenging questions
- QCD ~~no~~ room for NEW and SIMPLE ideas

Outline

- Theory perspective on selected Tevatron results:
  - inclusive jets;
  - vector boson plus jets;
  - single top.
- Prospects at the LHC:
  - PDFs;
  - advances in NLO computations;
- A look back at a solved problem.
- A new problem?
- Conclusions.

Jets - then

- Few surprises from measurements of jets at the Tevatron.



For a long time NLO QCD has given a good description of the observed data.

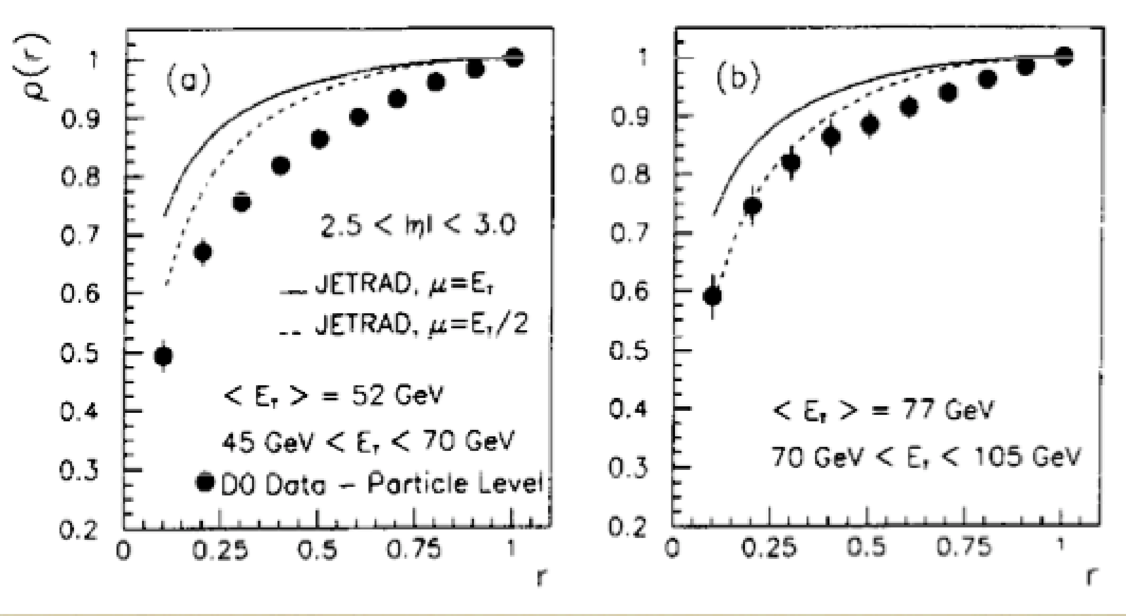
Fermilab-Conf-96/132-E

- Some discrepancies observed in differential observables such as the jet shape. Predictions effectively at LO anyway.

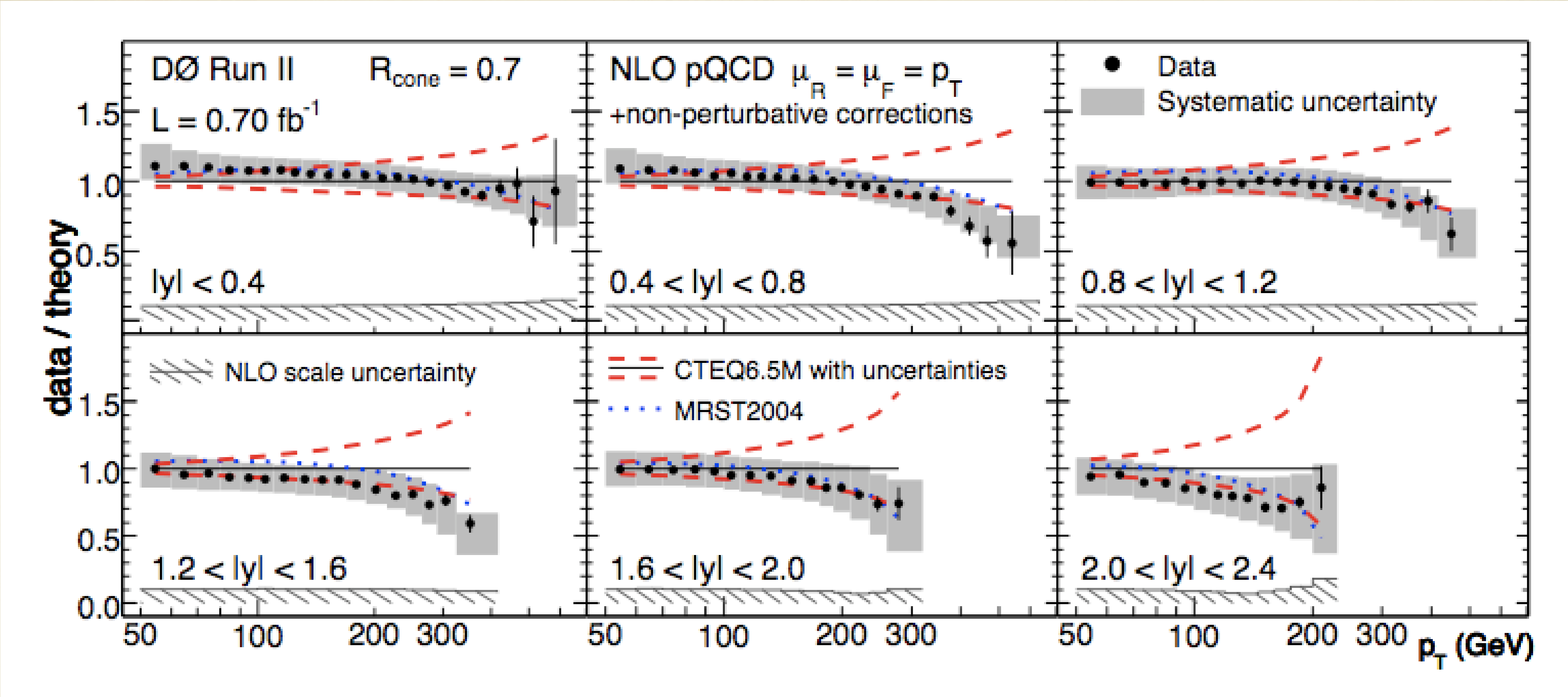
$$\rho(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_T(r)}{E_T(r=1)}$$

NLO jets narrower

PLB 357, 500 (1995)



… AND NOW



Fermilab-pub-08-034-E

- Excellent agreement in all kinematic regions.
- PDF uncertainties now rigorously included in the theory.
- Systematic uncertainty at the same level, providing tight constraints on the form of the PDFs.

Jet algorithms

- Cannot talk about jets without discussing algorithms.
- Everyone knows what an ideal algorithm looks like.

Several important properties that should be met by a jet definition are [3]:

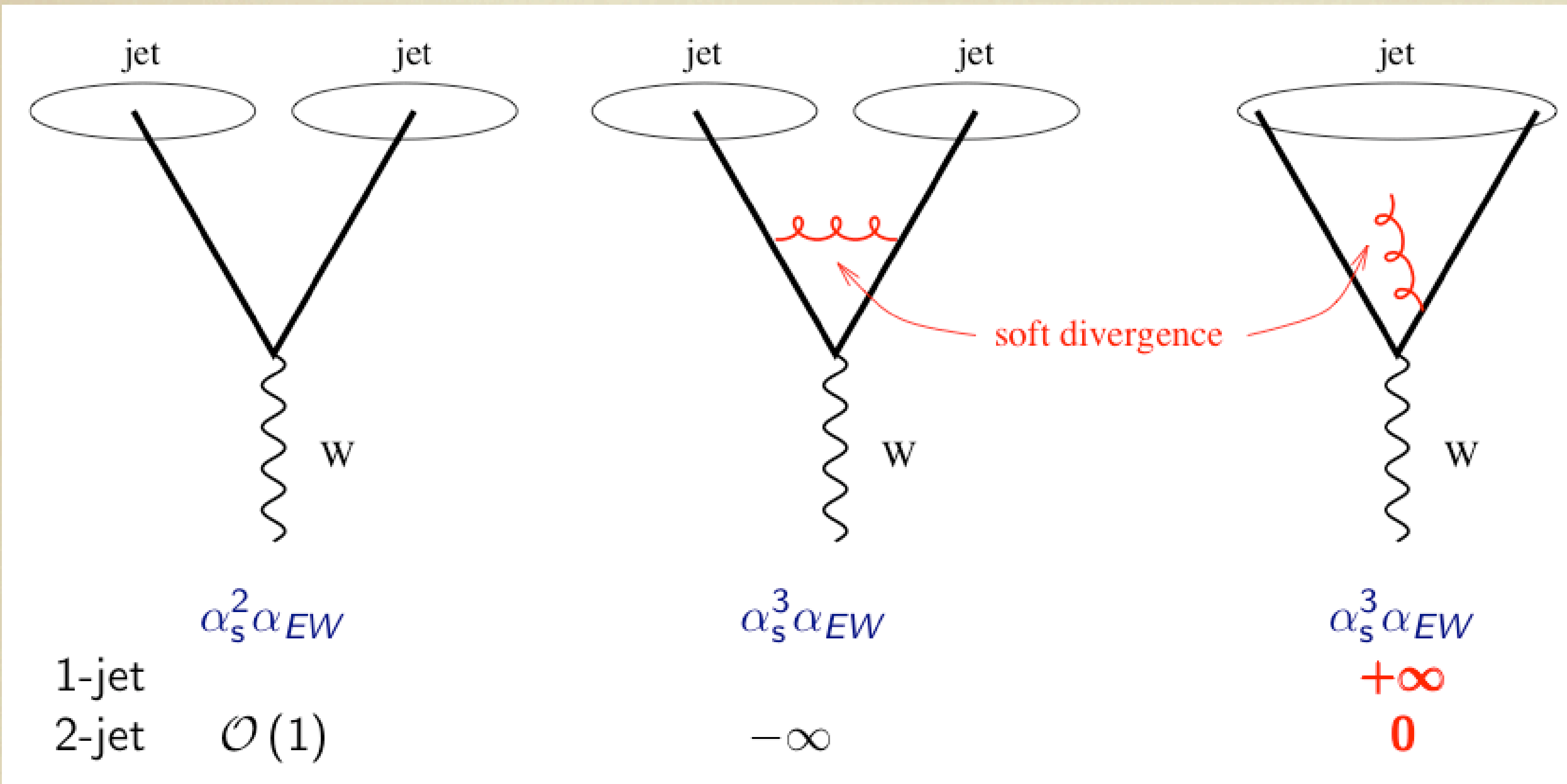
1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

"Snowmass accord"

Fermilab-Conf-90/249-E

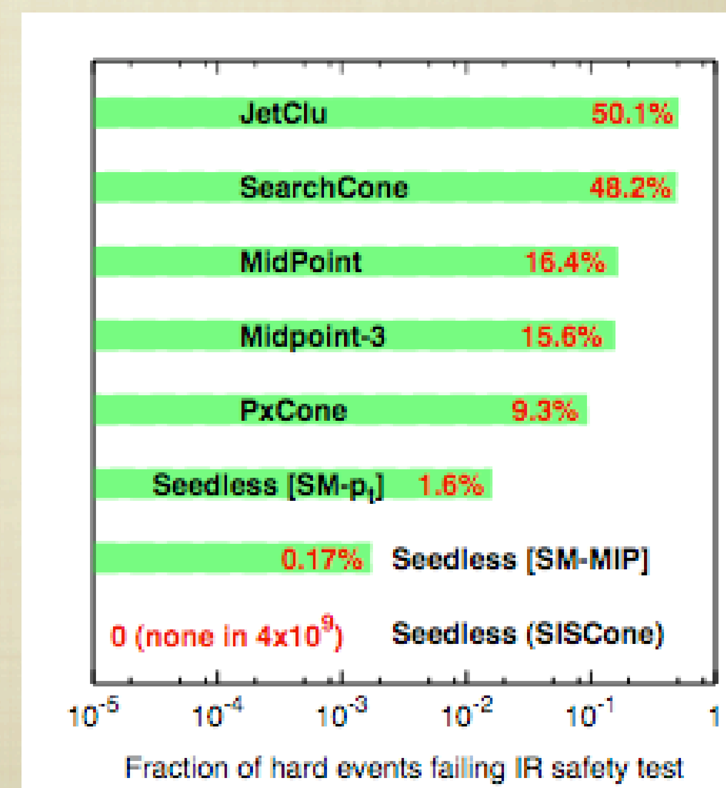
- It is just hard to realise this in practice.
- Protracted debate between cone (exp.) and k_T (theory) proponents as a result of tension between 1. and 4.
- Point 4. fails due to a lack of infrared safety. Typically this only kicks in at higher orders, typically a notional ~1% error.
- Small effect + human inertia leading to adiabatic change.

Infrared safety



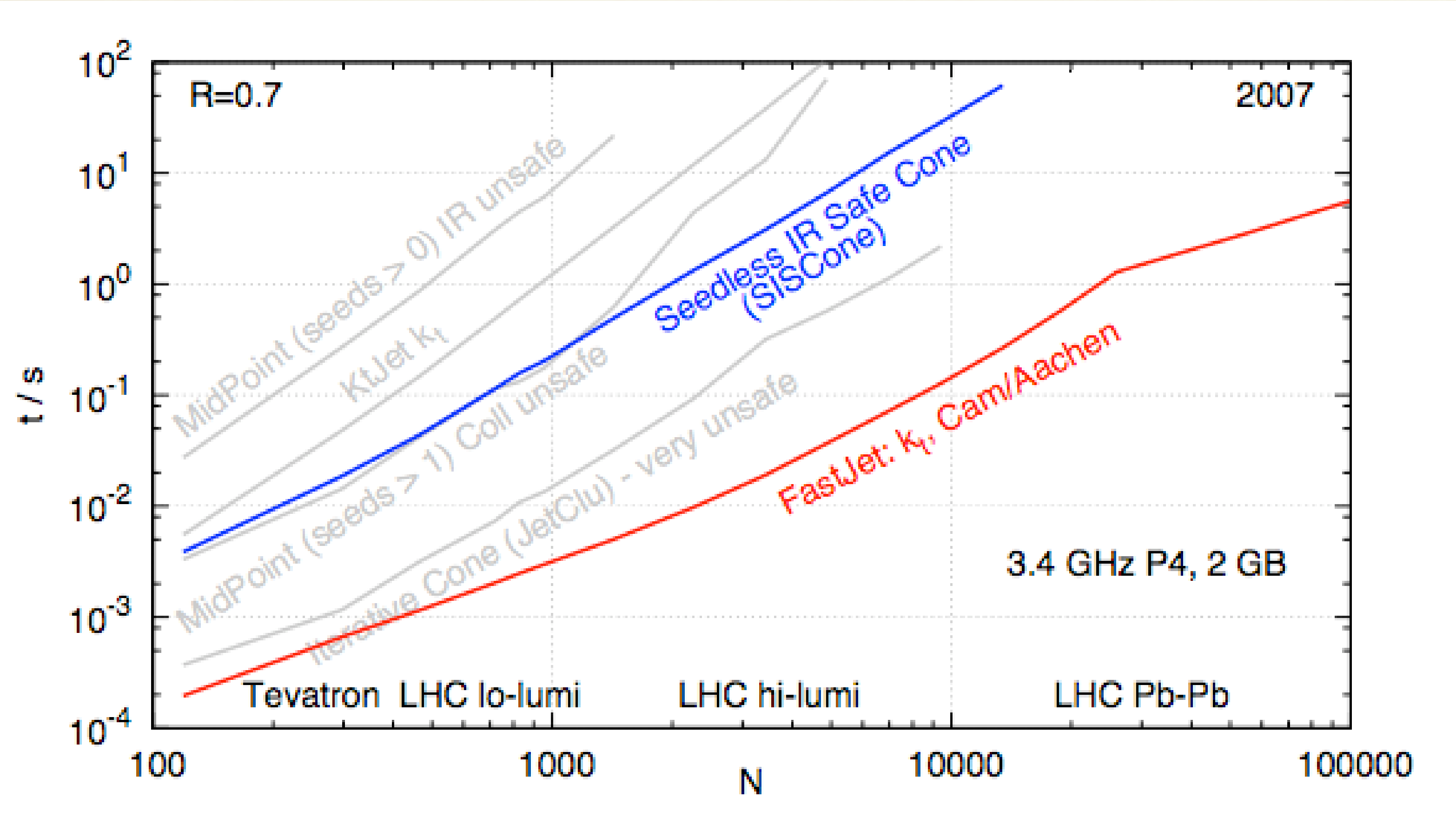
jets at LO and NLO

- Unfortunately, "higher order effect" is in principle a fraction of an infinite contribution.
- Failure rate can be large for the usual algorithms.



New algorithms

- A show-stopper for the k_T algorithm has been its complexity - computationally, $O(N^3)$ for N towers.
- This has now been much reduced to O(N logN) by recasting the problem as one in computational geometry.



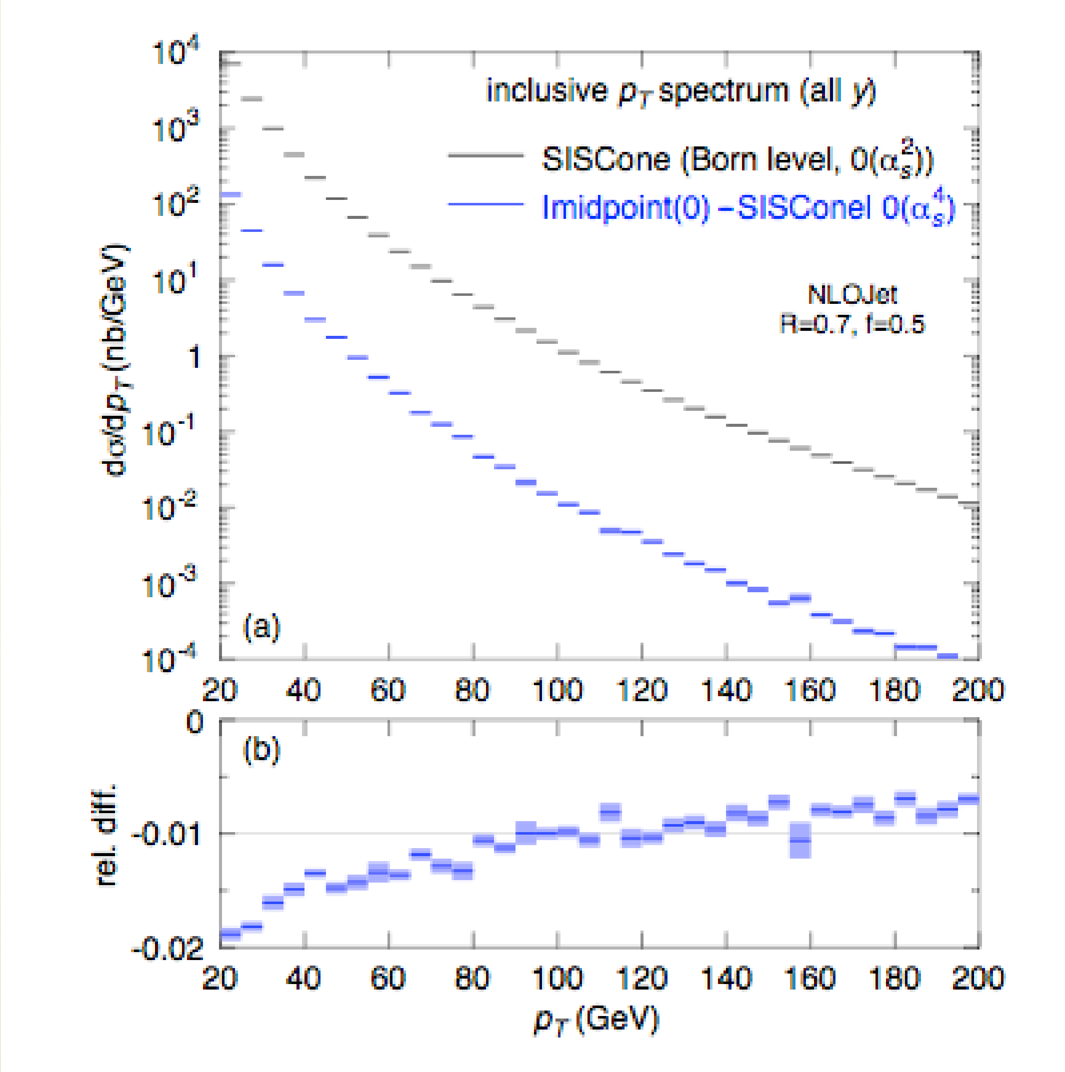
Cacciari, Salam, Soyez

Fast k_T algorithm available as part of the "Fastjet" package

- Now even faster than the (IR unsafe) usual cone algorithm.

Cone reloaded

- IR problems with cone result from the fact that not all possible stable cones are sought. Reason: $O(N\,2^N)$ time.
- "Thinking outside the cone" using geometrical methods reduces this to $O(N^2 \log N)$ and gives the first safe cone algorithm, SISCone.
- Slower than k_T, but same as midpoint. Still feels like the same old cone algorithm but now theor. well-defined.



NOMINAL 1% JUSTIFIED IN P_T SPECTRUM

BIGGER EFFECTS EXPECTED IN MORE EXCLUSIVE OBSERVABLES

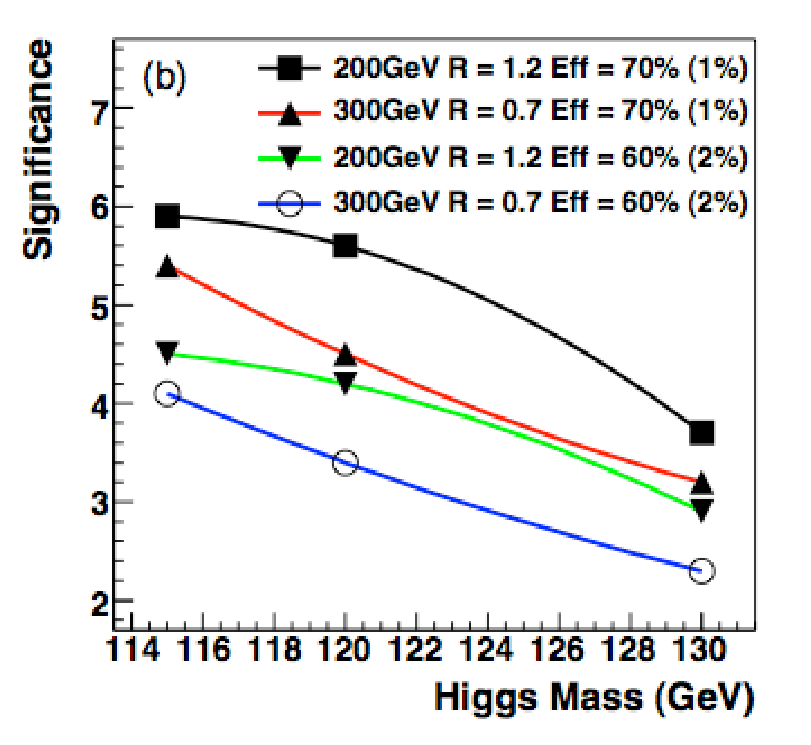
New uses @ LHC

Butterworth et al., PRL 100:242001 (2008)

- Idea: resurrect Higgs search channels that utilize the decay into bottom quarks. Specifically, WH and ZH.
  - use boosted events, $p_T(V)$, $p_T(H) > 200$ GeV;
  - smaller cross sections (~5%) but higher acceptance and much reduced top backgrounds;
  - Higgs candidates produce a fat jet containing two b quarks.
- Identify candidate bottom quarks by undoing steps of the clustering procedure and examining jet substructure.

Signal significance looks promising

LHC should use bigger jets?



Vector boson+jets

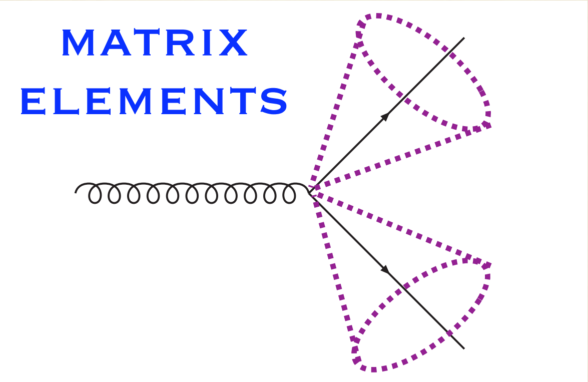
- Playground for pQCD innovation, driven by high importance (backgrounds).
- Challenge: need good precision and multijets.
- Progress on both fronts during lifetime of Tevatron.

- More NLO and techniques for improving parton showers such as Pythia or HERWIG.

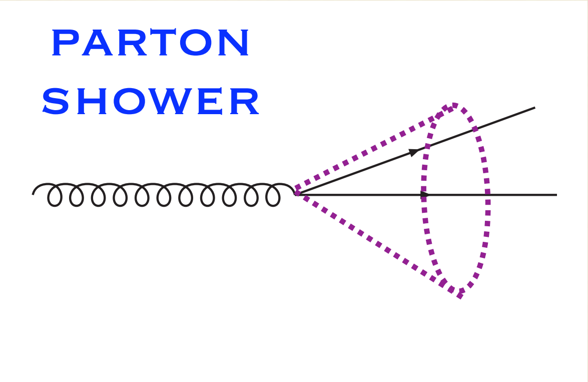
FEATURE	BENEFITS	DRAWBACKS	SOLUTIONS
approximations in matrix elements	any number of particles in total or per jet, resummed Sudakov logs good for soft region	problems at high p_T, large angles	matching prescriptions: MLM, CKKW
stochastic (independent) branchings		no quantum interference, problems with correlations	inclusion of some effects: Nagy, Soper
leading order matrix elements	solved problem	uncertain normalization	NLO parton shower, e.g. MC@NLO, POWHEG

Improved PS

- Matching: use PS shower where it works and LO matrix elements where approximations break down.



technical cut dependence



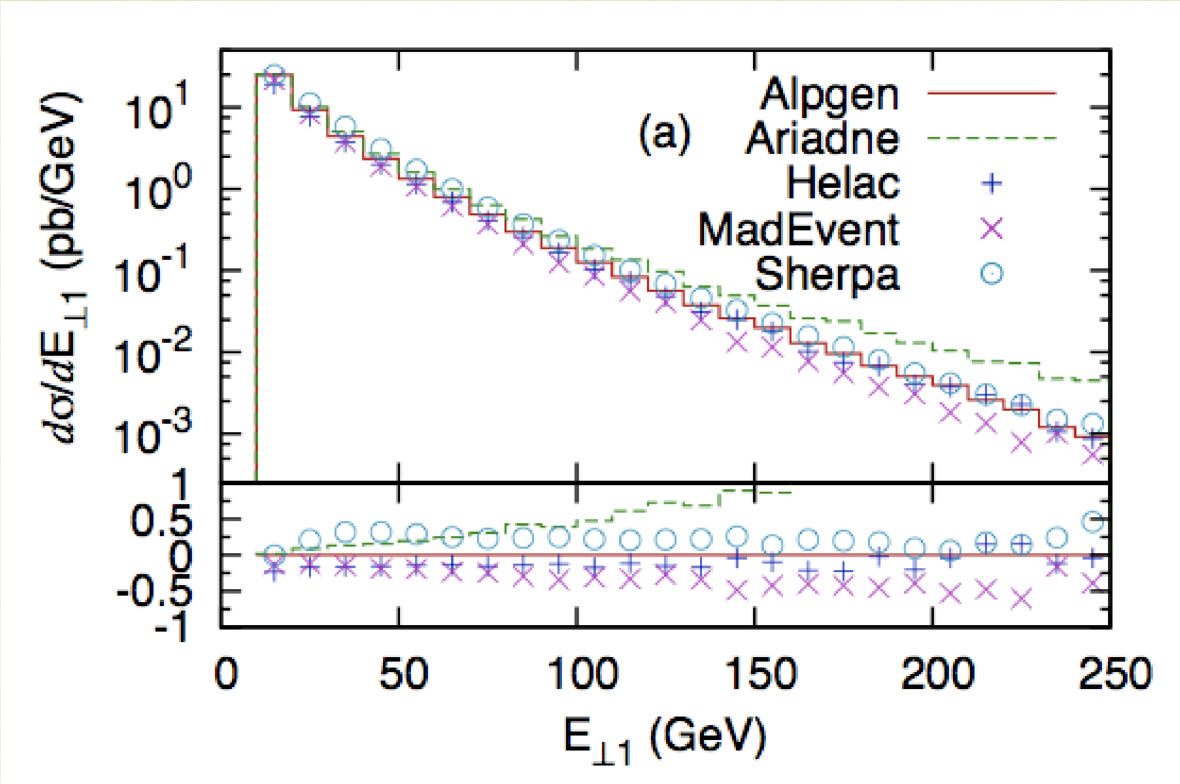
- Formally independent of technical cut, but not in practise. Must use common sense and tuning with data.

- Variety of matching schemes widespread.

CKKW	Catani, Kuhn, Krauss, Webber
MLM	Mangano
SCET	Schwartz
GenEvA	Bauer, Tackmann, Thaler

PS comparison

- Good testing ground for various parton shower approaches:
  - vector boson mass sets a hard scale so pQCD good;
  - plenty of data to compare with over a large kinematic range.



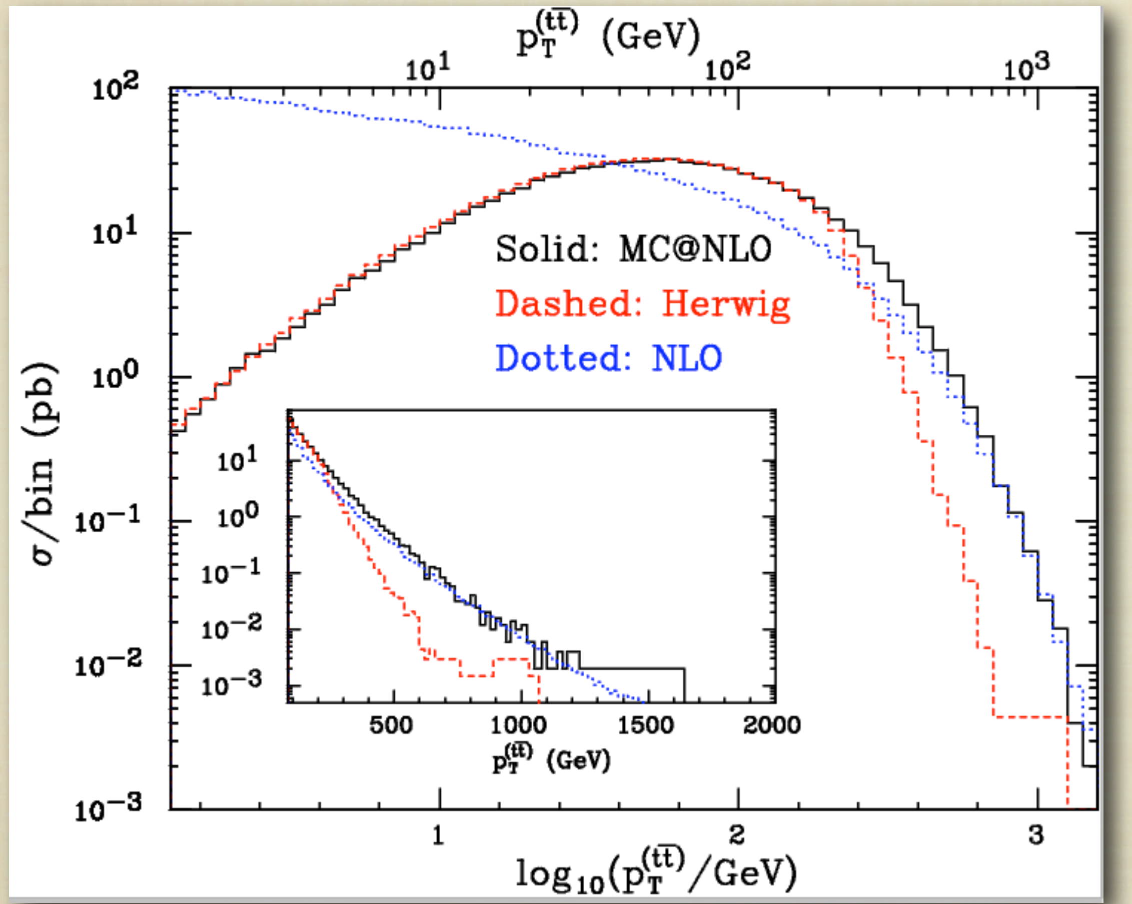
Leading jet P_T in W+jet events at the Tevatron

J. Alwall et al. arXiv:0706.2569

- Differences in rates and distributions, but ...
  - variations can be accounted for by usual change of scales;
  - can tune to Tevatron data and extrapolate to LHC.

PS+NLO

- NLO PS: shower uses NLO matrix elements, including one real emission. Must take care to avoid double counting.
- First real implementation in the wild: MC@NLO.



BEST OF BOTH WORLDS:

INFORMATION ON THE NLO NORMALIZATION AND SCALE DEPENDENCE, TOGETHER WITH ALL THE GOODNESS OF A PARTON SHOWER

FRIXIONE AND WEBBER, 2003

- More recently, POWHEG: not tied to a specific PS and easier to use with existing NLO results.

NASON ET AL., 2004, 2007

MC@NLO

S. FRIXIONE

MC@NLO 3.3 [hep-ph/0612272]

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706		7	7	×	$H_1H_2 \to t\bar{t} + X$
–1706		i	j	✓	$H_1H_2 \to (t \to) b l_i^+ \nu_i (\bar{t} \to) \bar{b} l_j^- \bar{\nu}_j + X$
–2000–IC		7		×	$H_1H_2 \to t/\bar{t} + X$
–2000–IC		i		✓	$H_1H_2 \to (t \to) b l_i^+ \nu_i / (\bar{t} \to) \bar{b} l_i^- \bar{\nu}_i + X$
–2001–IC		7		×	$H_1H_2 \to \bar{t} + X$
–2001–IC		i		✓	$H_1H_2 \to (\bar{t} \to) \bar{b} l_i^- \bar{\nu}_i + X$
–2004–IC		7		×	$H_1H_2 \to t + X$
–2004–IC		i		✓	$H_1H_2 \to (t \to) b l_i^+ \nu_i + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0 W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0 (W^+ \to) l_i^+ \nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0 W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0 (W^- \to) l_i^- \bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0 Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0 (Z \to) l_i \bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l_i^+ \nu_i (W^- \to) l_j^- \bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

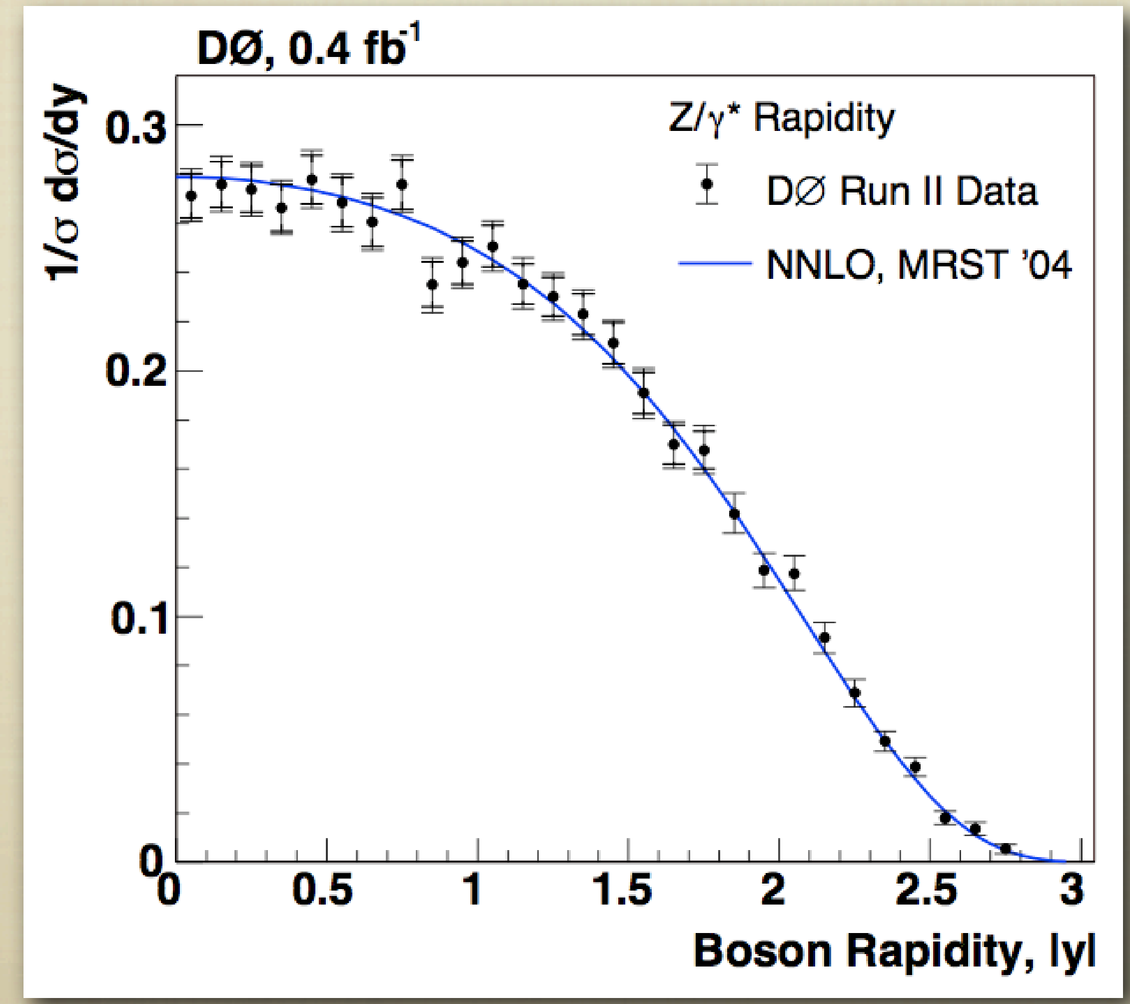
Recent activities:

- Lepton spin correlations in $t\bar{t}$ and single-top production released with v3.3
- Hadron spin correlations in $t\bar{t}$ now into ATLAS and CMS software (v3.31)
- W and Z production with interface to HERWIG++
- Early stage of interface to PYTHIA
- Wt is now completed

- Large catalogue of processes, but regrettably no V+jets.

Higher orders

- During the Tevatron runs, theorists have learned how to perform NNLO calculations.
- Highly non-trivial due to both two-loop diagrams and double infrared singularities in real diagrams.
- Benchmark process: inclusive production of a W or Z.



Accuracy of a few percent on total rate and distributions.

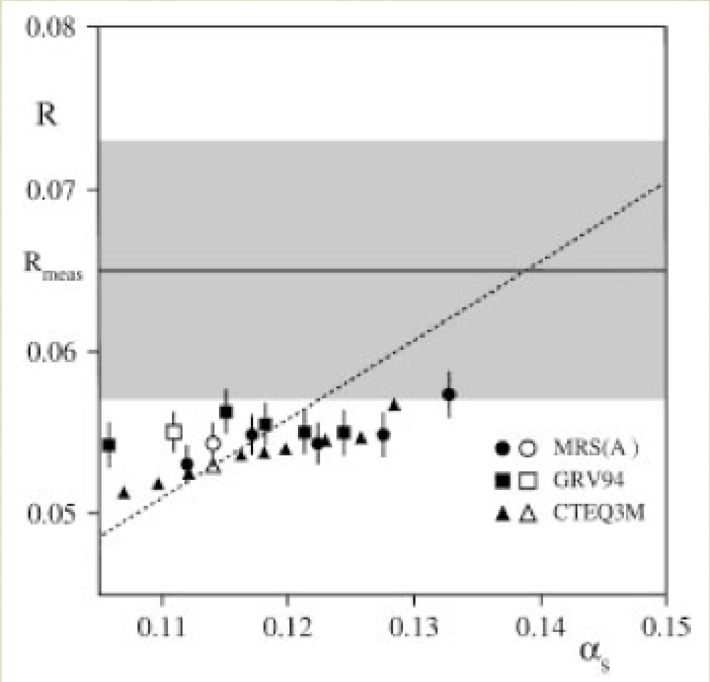
Spectacular agreement with data from D0

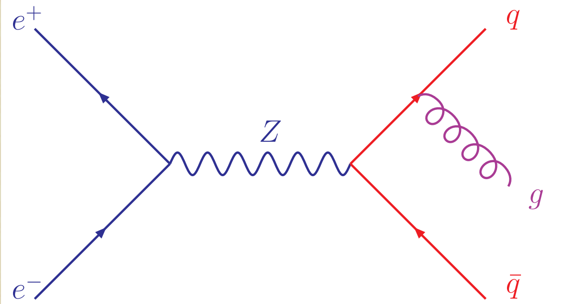
Anastasiou, Dixon, Melnikov, Petriello

W/Z+JETS

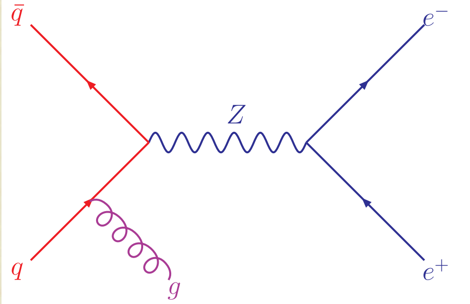
- W/Z+1 jet known at NLO for a long time. GIELE ET AL. HEP-PH/9302225
  - c.f. early measurements of α_s
  - related process $e^+e^- \to 3$ jets now known at NNLO.

PRL 75, 18 (1995)



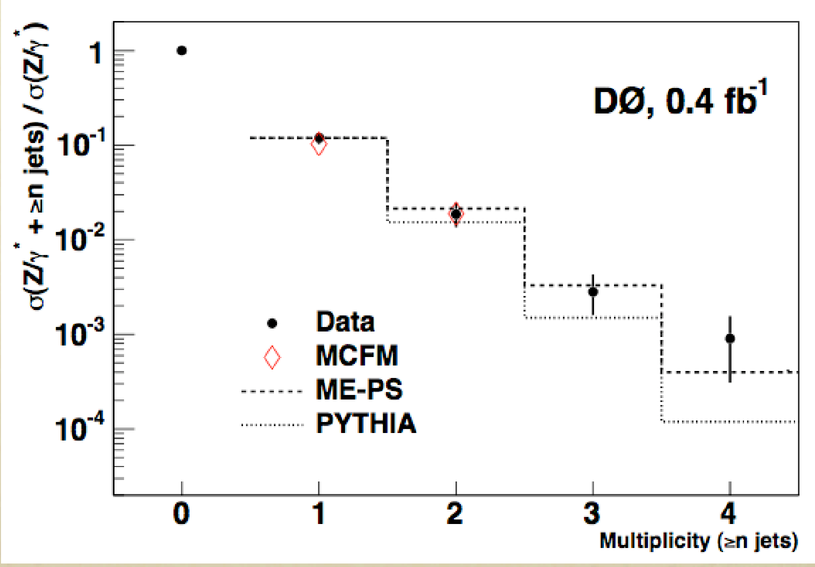


non-trivial work to do crossing to hadron collider



A. GEHRMANN-DE RIDDER ET AL, ARXIV:0711.4711

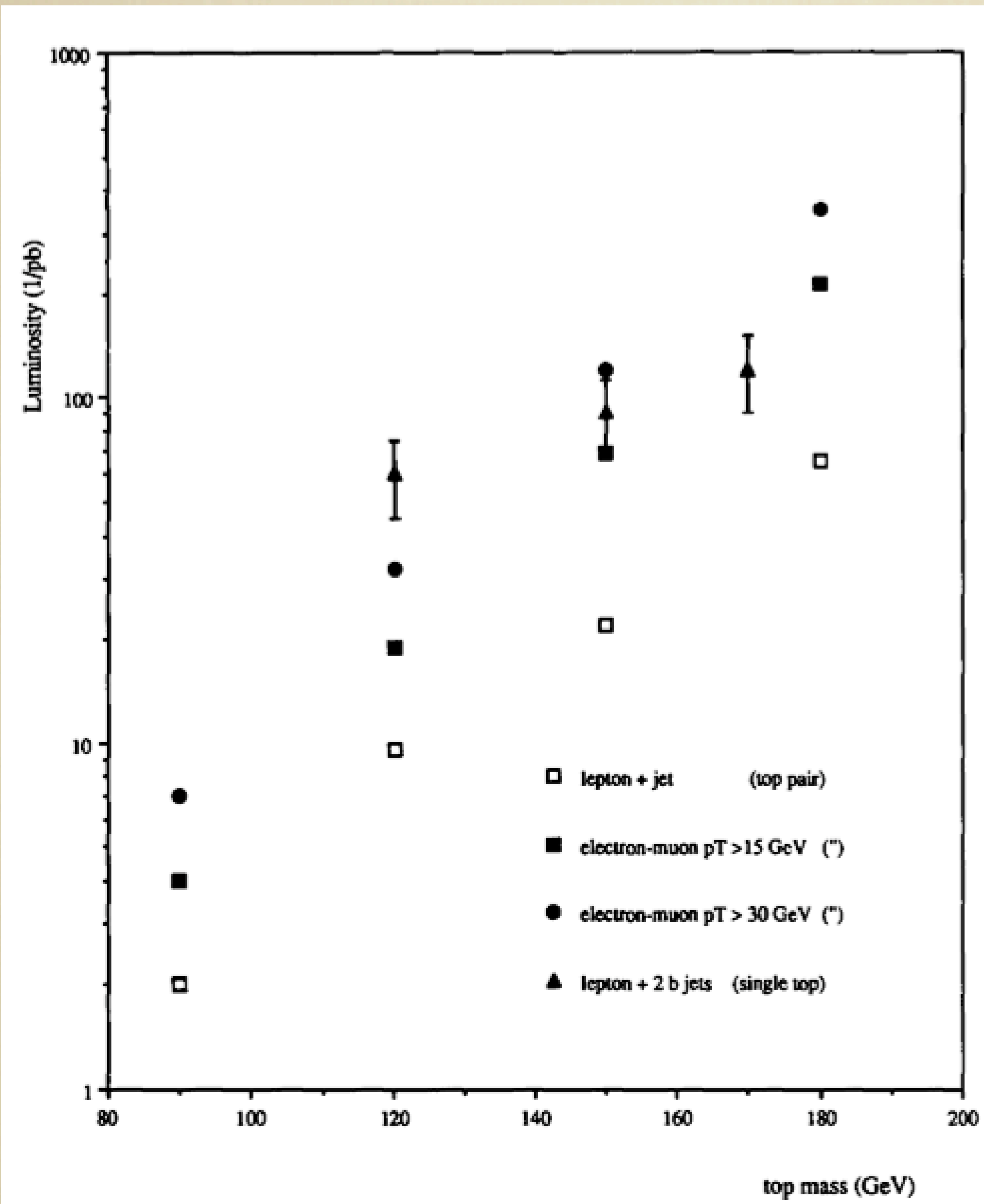
- W/Z + 2 jets known at NLO for some time.
  JC, K. ELLIS, HEP-PH/0202176
  - barring immense breakthrough, NNLO very unlikely.



PLB 658, 112 (2008)

Single top

- Tantalizing prospect since the inception of Run I.



W-gluon fusion/
T-channel
Yuan, PRD 41 (1990)

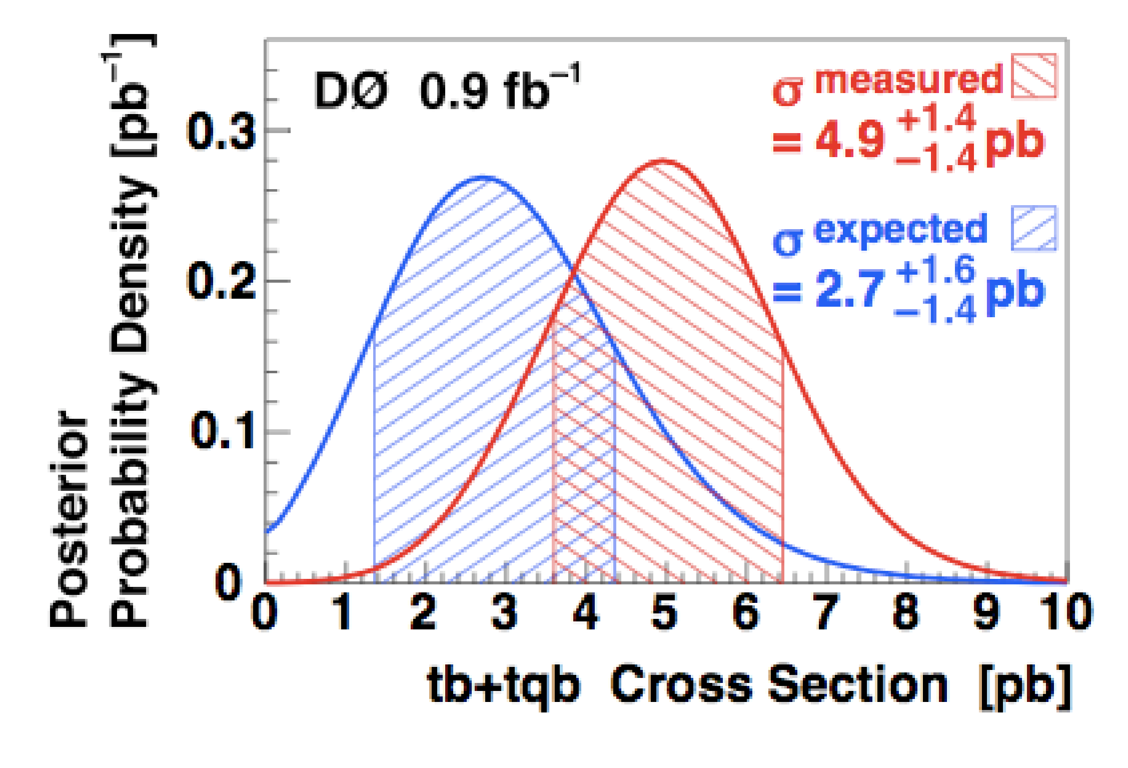
On the basis of the unique transverse momentum P_T and rapidity Y distributions of the spectator quark which emitted the W-boson for W-gluon fusion which produces a heavy top quark, we conclude that the W-gluon fusion process is most useful for detecting a heavy top quark at the upgraded Tevatron with $\sqrt{S}=2$ TeV and integrated luminosity 100 pb^{-1}. In this paper, we have focused on the example of a 180-GeV top quark and conclude that a 5-GeV mass resolution of $M^{e\nu b}$ would be desired at the upgraded Tevatron for its detection. Also, more than one year of integrated luminosity is needed. To gain a factor

s-channel
Cortese & Petronzio, PLB 253 (1991)

- Usual theorist optimism kept reasonably in check.

Reality is tough

- Top mass is large → kinematic suppression.
- Slight shortfall in energy in Run II significant for single top.
- Backgrounds are large and b-tagging is difficult.
  - exp: many W+(hf) jets, top pair events survive cuts;
  - theory: (K-factors for bkgs) > (K-factors for signals).
- First evidence based on long history of analyses.
- Culminates with advanced techniques at the interface of experiment and theory: decision trees with NLO input.



Fermilab-Pub-06/475-E

To the LHC: PDFs

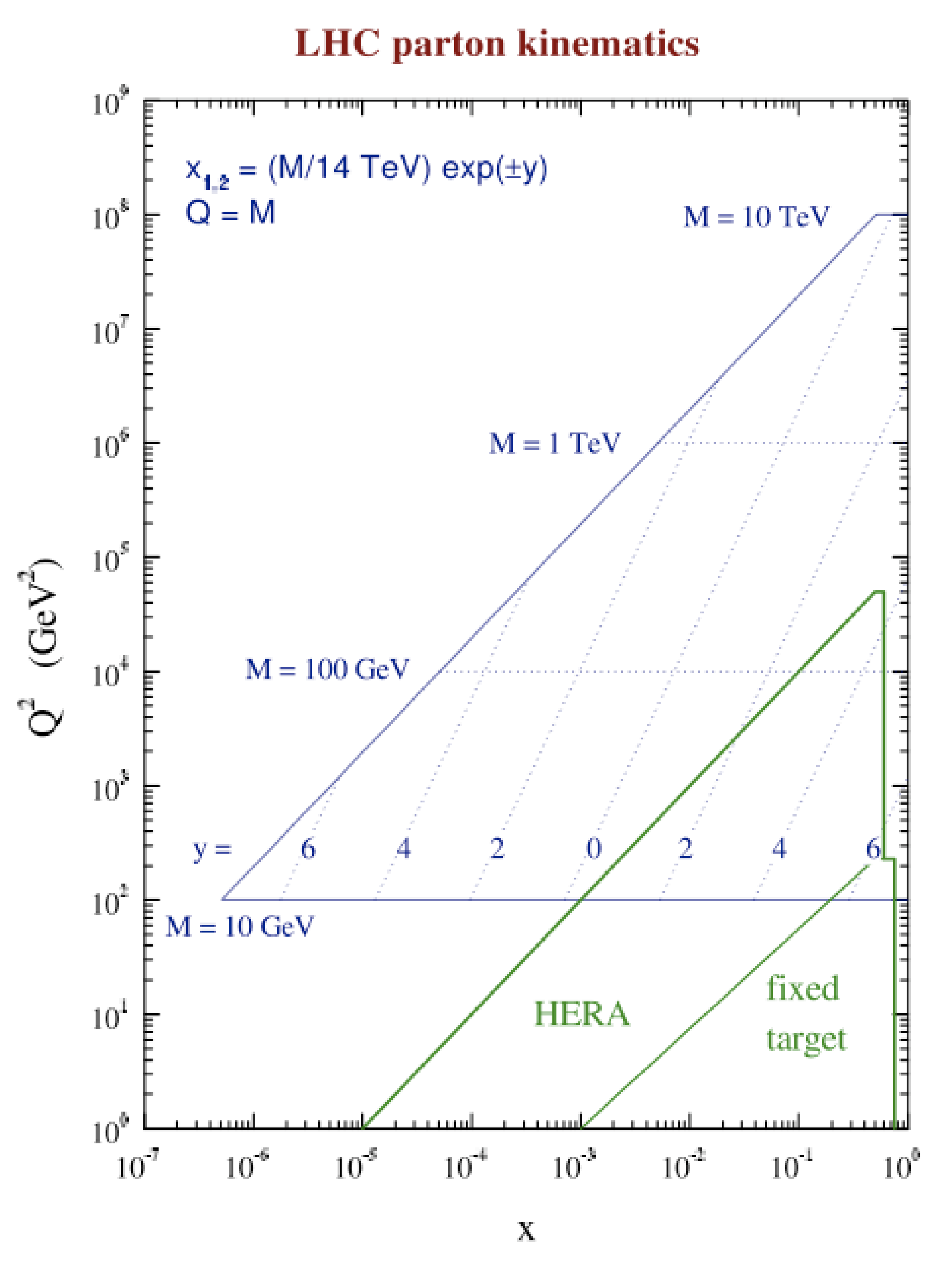
- Two prerequisites for higher precision: determination of matrix elements and PDFs to higher orders in α_S.

- Reliance on pQCD in extraction (fit to a perturbative calculation) and in evolution (must be calculated to required precision).

- Central production of SM and new particles relatively well-determined. Total cross-sections less so.

- We are of course reliant on the evolution to the new regime of (x,Q^2) probed by the LHC.

- No reason to expect surprises, but must bear it in mind.

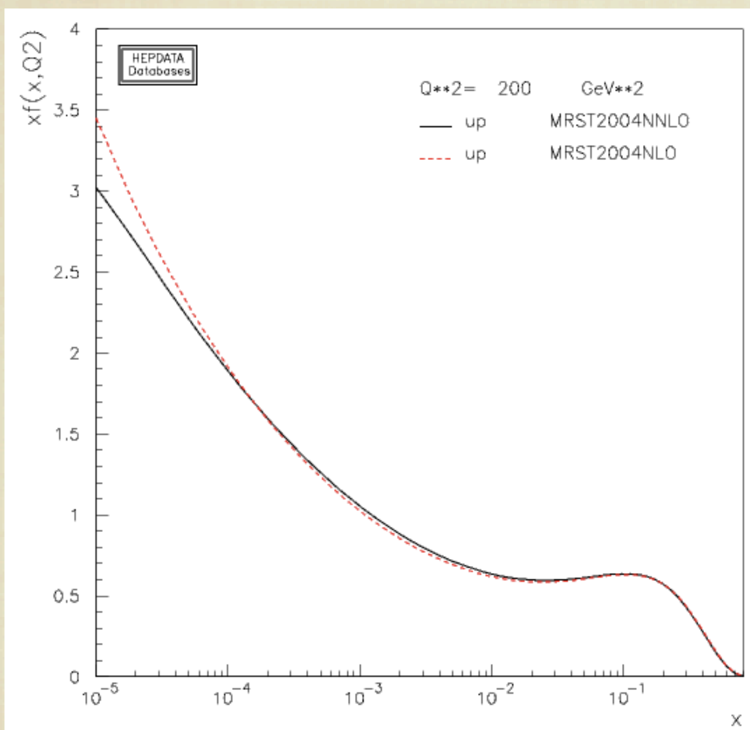


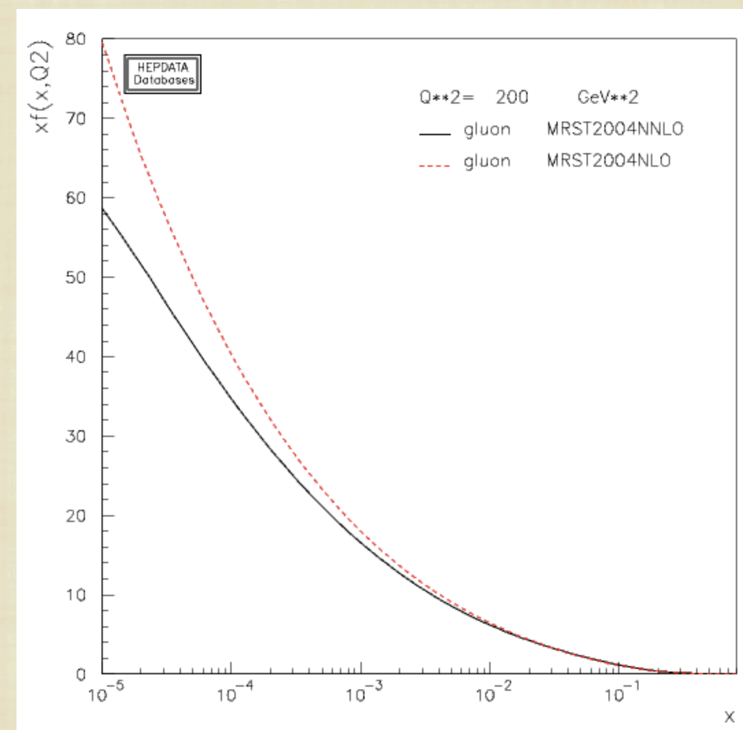
NNLO and more

- Fits including NNLO running are now available, a vital component of improved predictions in pQCD.

  Moch, Vermaseren and Vogt

- Changes wrt. NLO can be significant (beyond α_s reduction).





- For truly NNLO global PDF fit, need MEs to the same order. Missing inclusive jets, although doable on LHC timescale.

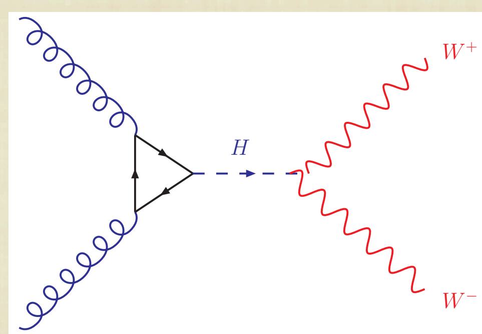
- Faster turn-around: data → fits → predictions on the way, e.g. FastNLO and Carli et al.

Multijets at the LHC

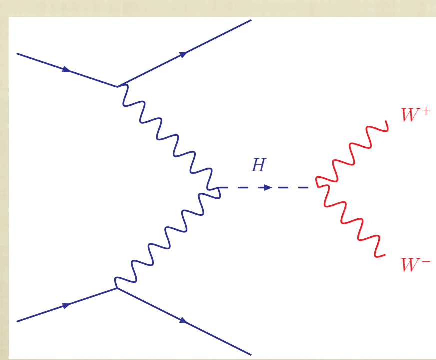
- Multijet rates become more of an issue, even for high p_T jets.
- Use Tevatron W+jets studies as a template for top+jets and diboson+jets analyses.
- Useful for e.g. Higgs search.

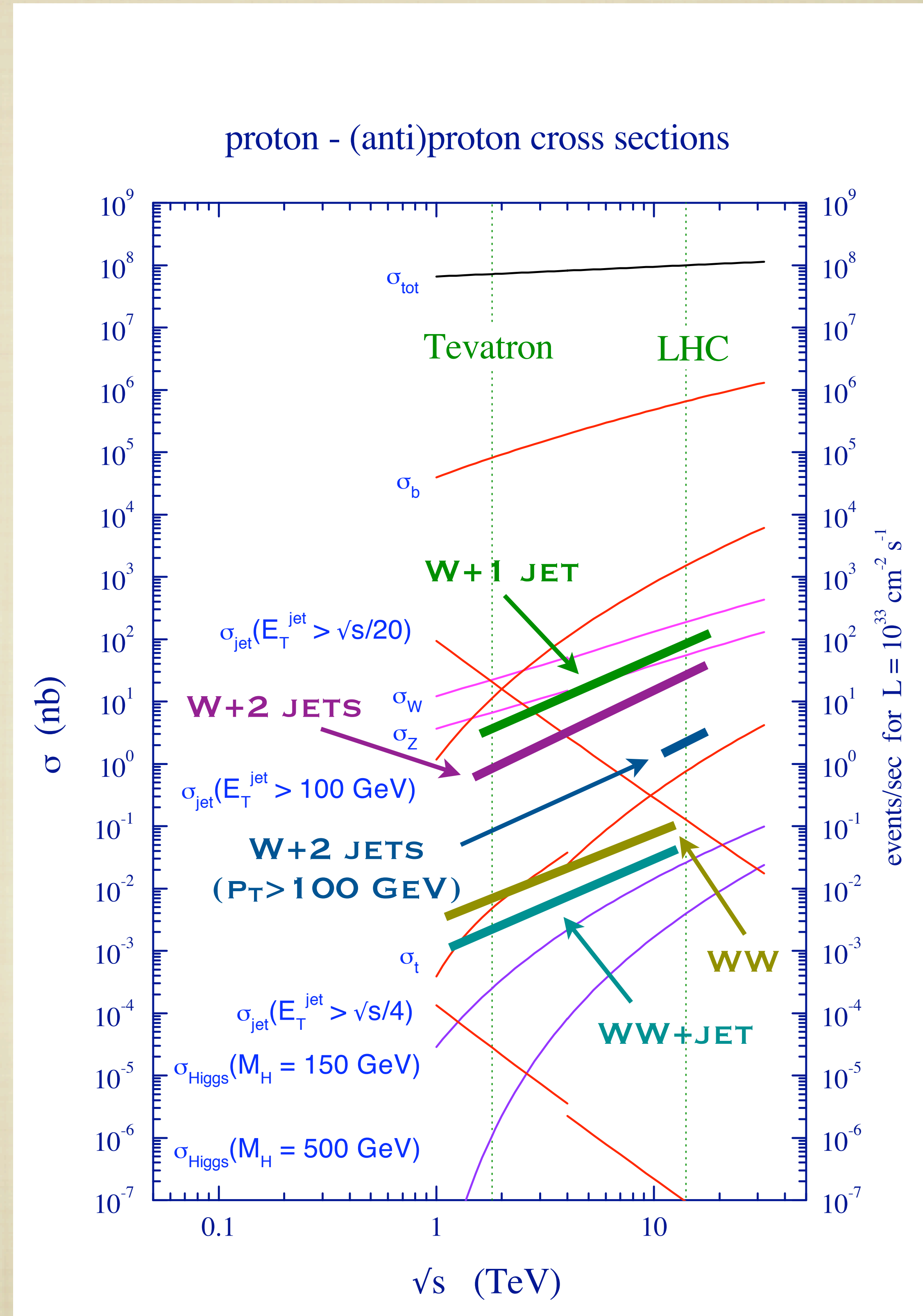
Mellado et al., arXiv:0708.2507

gluon fusion → 0 jets (veto); radiation → 1 or more jets



WBF → two forward jets, one of which may be lost



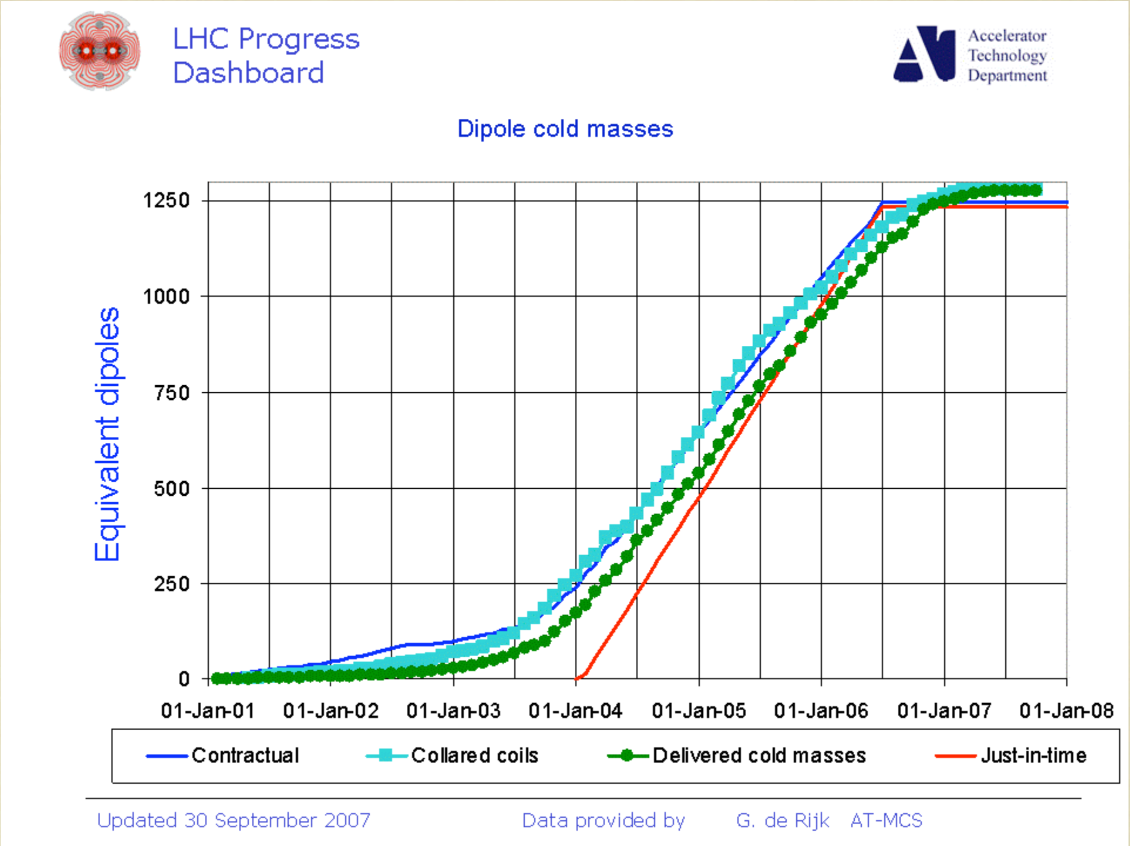


- Systematic study a priority.

Towards the LHC

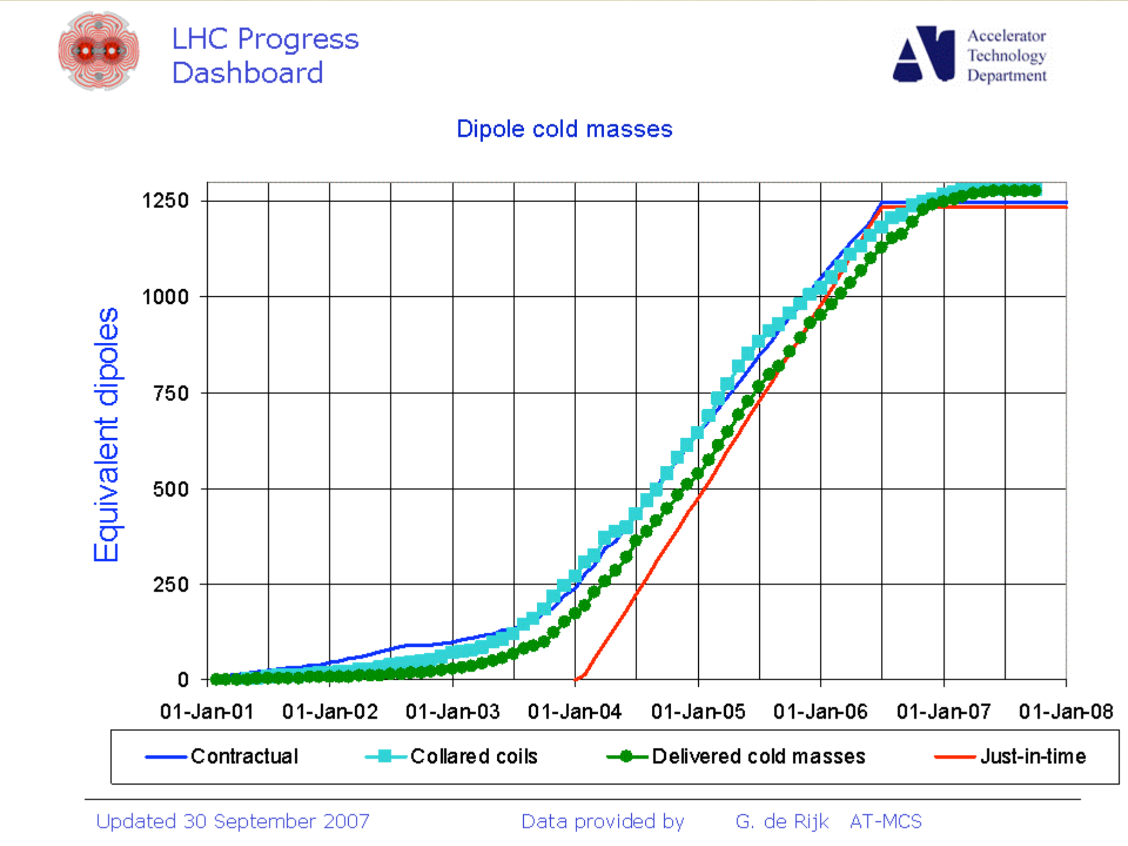
Towards the LHC

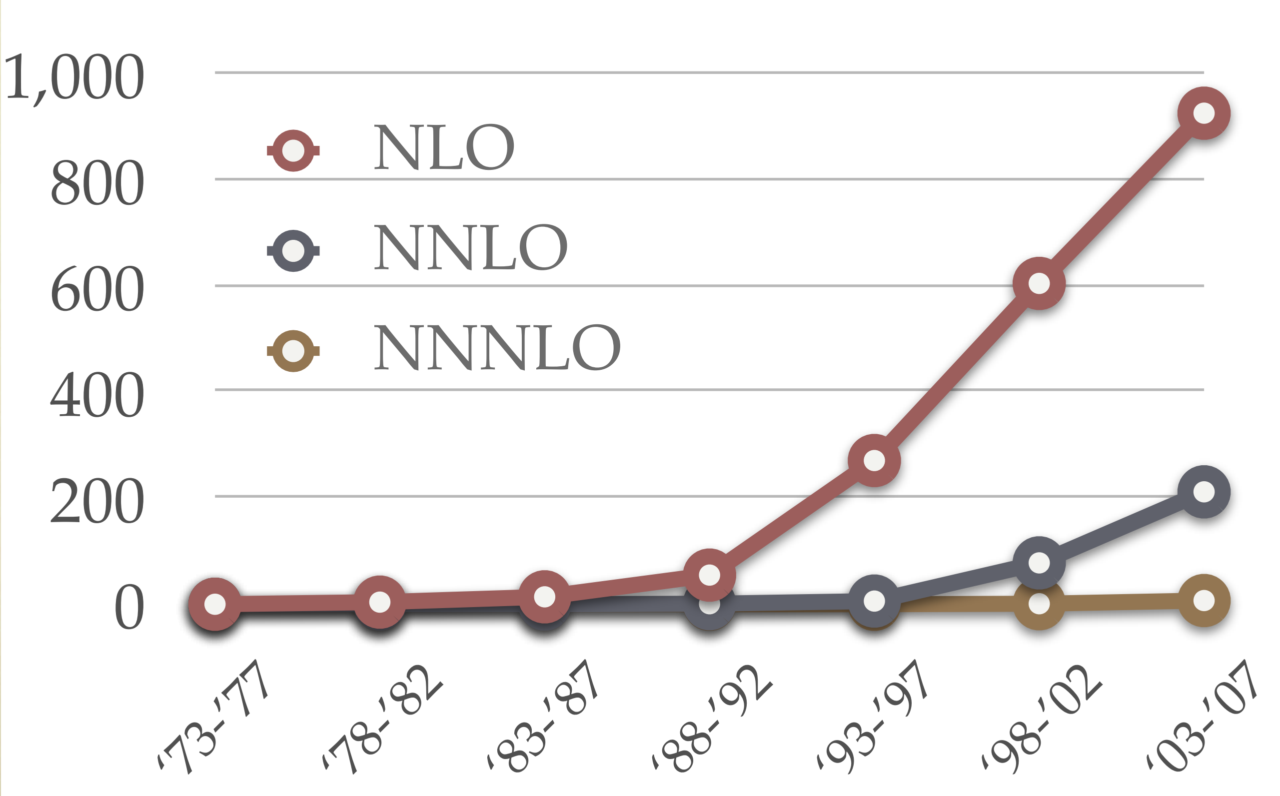
- Impressive installation success at CERN (events since notwithstanding!).
- Similar physics achievements no doubt forthcoming.



Towards the LHC

- Impressive installation success at CERN (events since notwithstanding!).
- Similar physics achievements no doubt forthcoming.
- There has been comparable progress in tackling higher orders in pQCD.
- Cumulative no. of papers appearing in SPIRES with the corresponding keyword.
- NLO should be the standard for LHC, with more NNLO eventually.





NLO advances

- Revolution in performing loop calculations for ~ 5 years.
- Initially, "twistor inspired" recursion relations with buzzwords such as MHV, CSW, BCFW.
- Basic idea: break loop amplitudes into smaller pieces (i.e. tree level amplitudes) that are easily and efficiently computed analytically.
- Helicity amplitudes for all-gluon processes in SUSY are simplest.
- Now a viable method in the SM and with quarks.

The Six Gluon one-loop amplitude

	$N=4$	$N=1$	scalar C	scalar R
$A(++++++)$	-	-	-	93
$A(-+++++)$	-	-	-	93
$A(--++++)$	94	94	94	06
$A(-+-+++)$	94	94	05	06
$A(-++-++)$	94	94	05	06
$A(---+++)$	94	05	05	06
$A(--+-++)$	94	05	06	06
$A(-+-+-+)$	94	05	06	06

~14 papers

81% \`B'

Berger, Bern, Dixon, Forde, Kosower

Bern, Dixon, Dunbar, Kosower

Britto, Buchbinder, Cachazo, Feng

Bidder, Bjerrum-Bohr, Dixon, Dunbar

Bern, Chalmers, Dixon, Kosower

Bedford, Brandhuber, Travaglini, Spence

Forde, Kosower

Xiao,Yang, Zhu

Bern, Bjerrum-Bohr, Dunbar, Ita

D Dunbar, IOP, Durham 08

Britto, Feng, Mastriolia

Mahlon

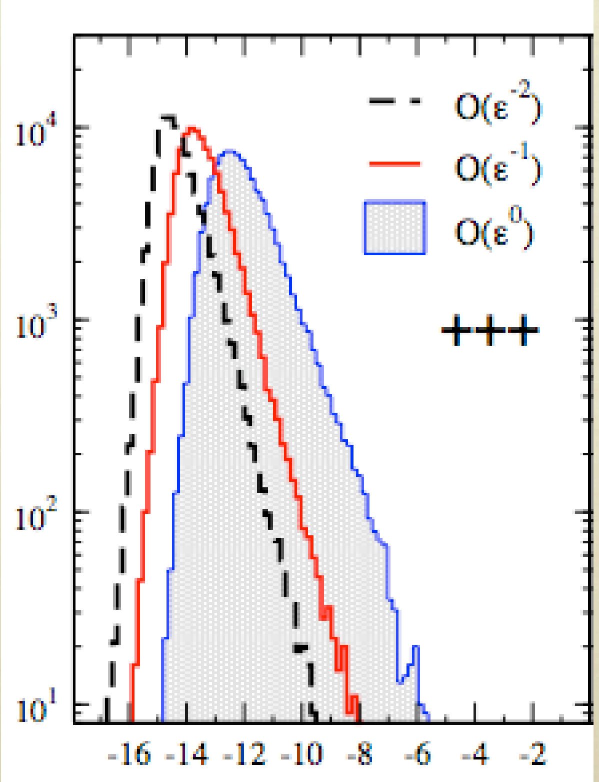
24/25

Recent progress

$$\mathcal{M} = \sum_i a_i(4)\,\text{Boxes}_i + \sum_i b_i(4)\,\text{Triangles}_i + \sum_i c_i(4)\,\text{Bubbles}_i + \sum_i d_i(4)\,\text{Tadpoles}_i + R$$

- These methods have recently been supplemented by recursion relations for amplitudes that are implemented numerically.
- Recurrence on a computer $\longrightarrow$ general solution to NLO?
  - ☑ method scales well with no. of legs, so real leap possible;
  - ? possible issues with numerical stability? A new paradigm.
- First results for W+3 jet leading colour amplitudes presented earlier this year.

BLACKHAT
C. Berger et al.



Test stability by looking at poles (prop. to Born) - looks fine

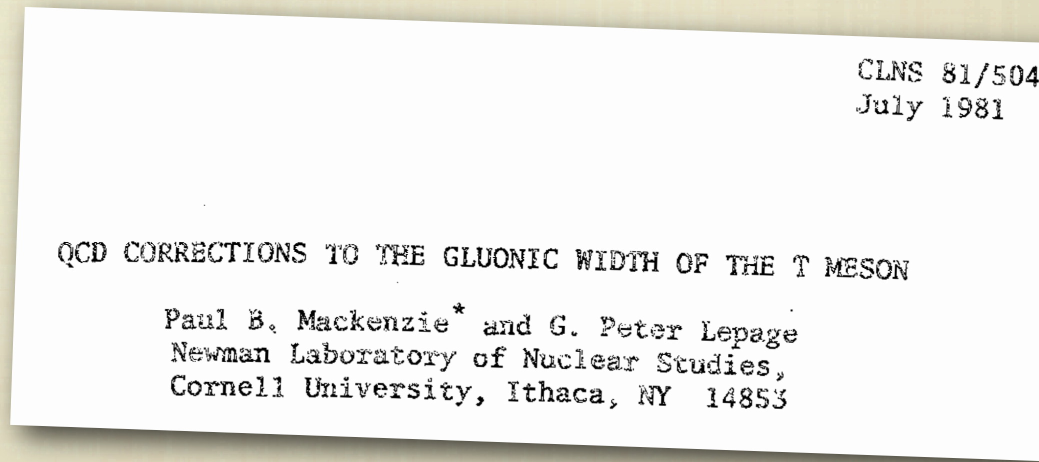
Wrapping it up

- The less-discussed half of NLO calculations also requires automation - subtracting all soft and collinear divergences.
- At least one algorithm known for a long time
  - "dipole subtraction". Catani and Seymour, 1996
- Three automated implementations to date, building on expertise in LO calculations. Gleisberg and Krauss, 2007

  Frederix, Gehrmann and Greiner, 2008

  Seymour and Tevlin, 2008

"The ideal would be the creation of a master program which for any desired process would generate the graphs, assign the momenta in the loops, evaluate the gamma matrix traces and colour algebra, and perform the integrals."


CLNS 81/504
July 1981

QCD CORRECTIONS TO THE GLUONIC WIDTH OF THE Υ MESON

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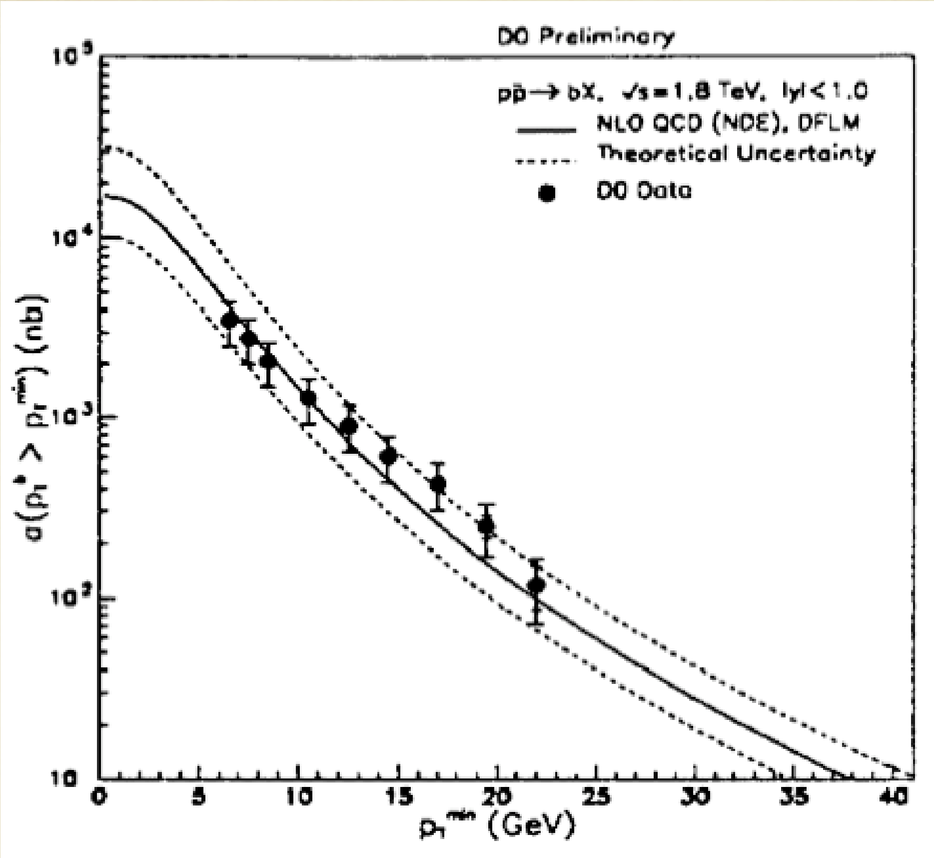
Newman Laboratory of Nuclear Studies,
Cornell University, Ithaca, NY 14853

- Goal from the UA1 era finally in reach!
- Soon do even better - NLO+PS+matching.

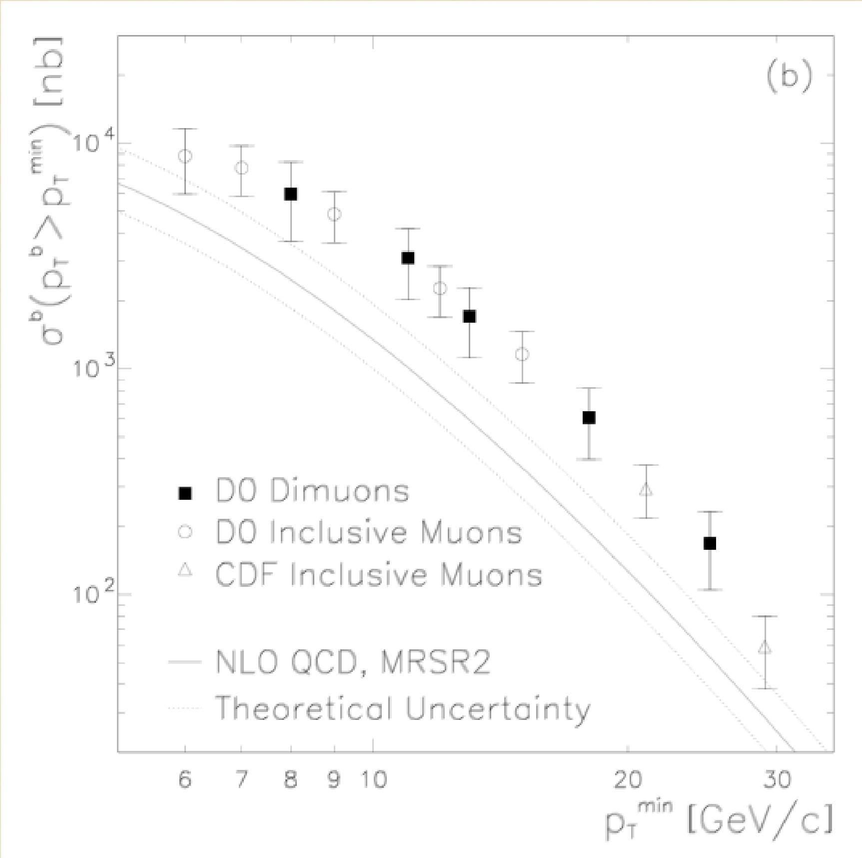
Giele et al.
Schumann, Krauss
Nagy, Soper

The B-quark Saga

- The difficulty of confronting data and theory can be highlighted by tracing the evolution of this comparison.



PRELIM. (MORIOND, 1994)

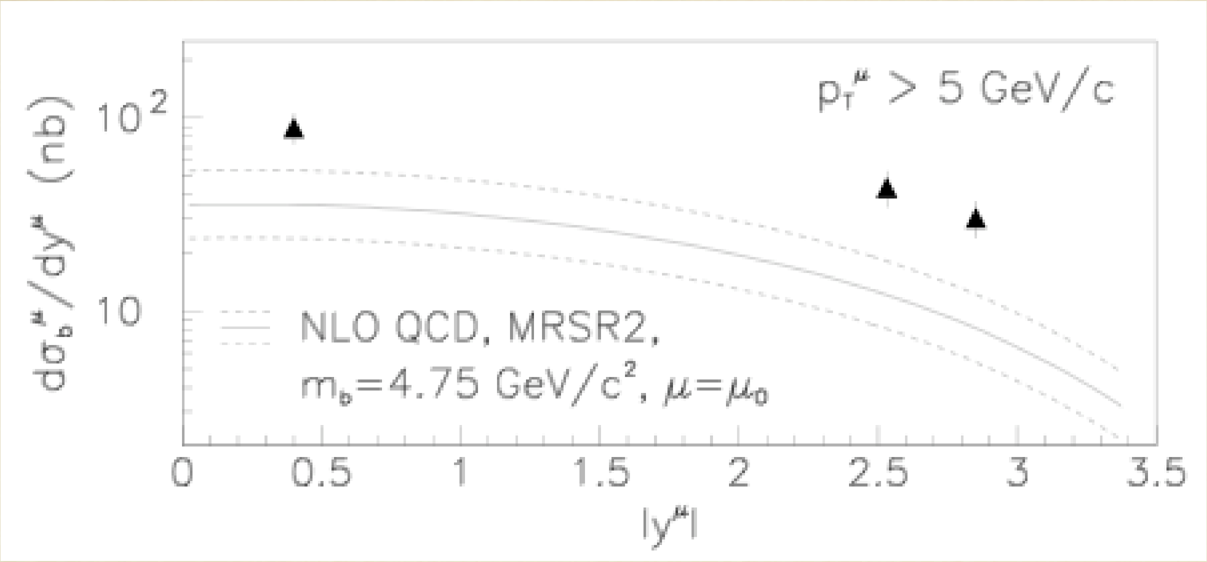


PLB 487, 264 (2000)

- Problems with both data and theory:
    - pollution with other production modes;
    - changes in the gluon PDF and α_s (thanks HERA!)

Key DO input

- Key additional info from D0: cross-section at large rapidity.



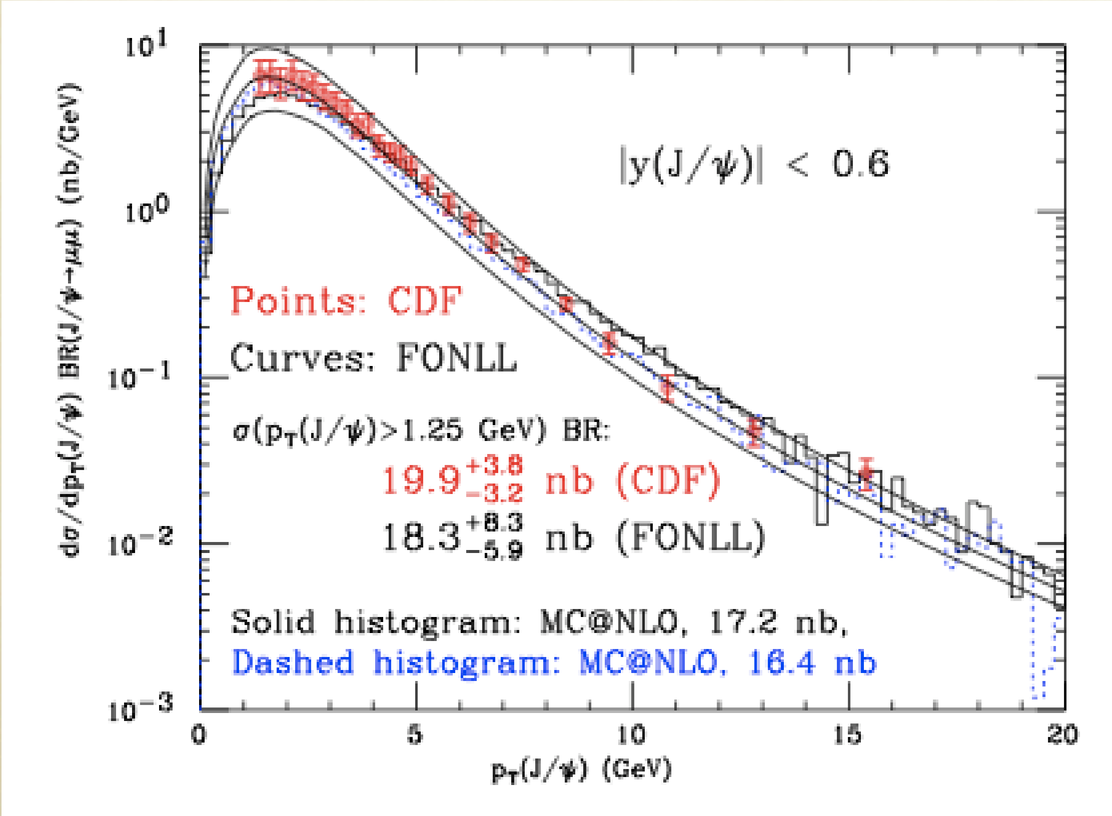
PRL 84, 5478 (2000)

Excess in the forward region larger than in central result

- Theory origin?
  - No reason for pQCD to fail (from phase space or PDF).
  - NP input coming from fragmentation function b → B?
- In fact, frag. function probed in more detail at a hadron collider than in e^+e^- collisions, from which it was extracted.
- This idea was vindicated by further D0 results on b-jets.

Resolution

- This led to a reanalysis of the frag. function using the latest fixed order (NLO) and NLL results - "FONLL". Forward discrepancy solved by a combination of ~20% effects.
- All results then off by about a factor of two.
- Remaining difference vanishes in Run II, where data is smaller than expected and new PDFs reduce theory slightly.



Cacciari et al., JHEP 0407:033,2004

New tool MC@NLO not significantly different in this case (but good for other things!)

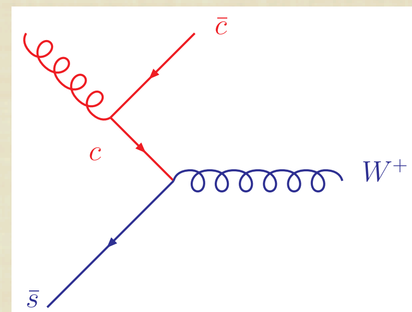
Brief observations

- Early comparisons were not upheld by later studies.
  - Improvements in both theory and exp. understanding.
- The biggest leaps forward involved a synergy of both: updated theory based on experimental inputs (PDF, FF).
- History is not always a guide guide: evolution from Run I to Run II was not a consistent story.
  - In particular, yield in Run II was small compared to extrapolations from Run I.
  - Big initial difference was ultimately explained by the sum of many small changes.

New problems?

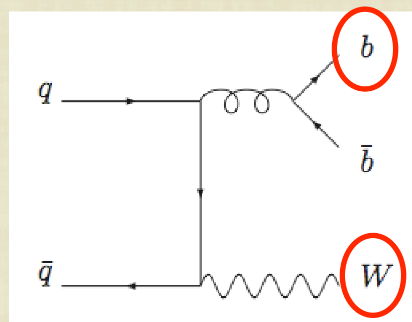
- Tevatron results on vector bosons + heavy flavour jets are hard to interpret at the moment.

W+c



CDF data and NLO consistent

W+b+X



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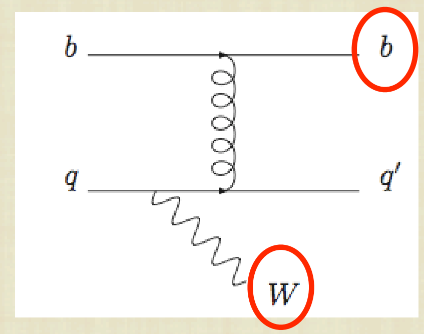
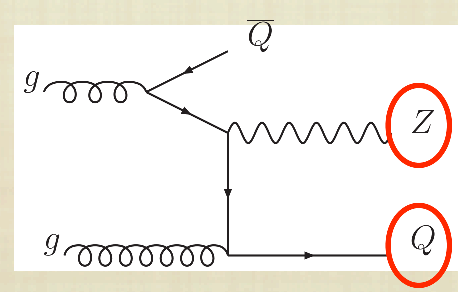


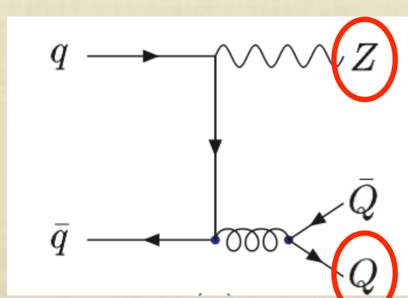
CDF data ~ (3-4) x NLO

(No clues from distributions)



D0 data and NLO consistent

Z+b+X



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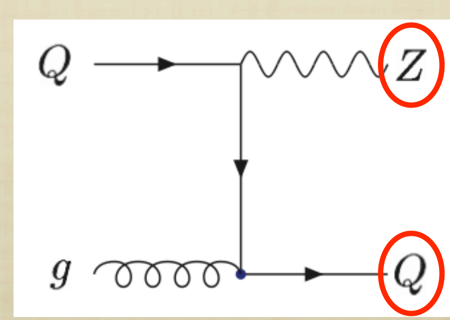
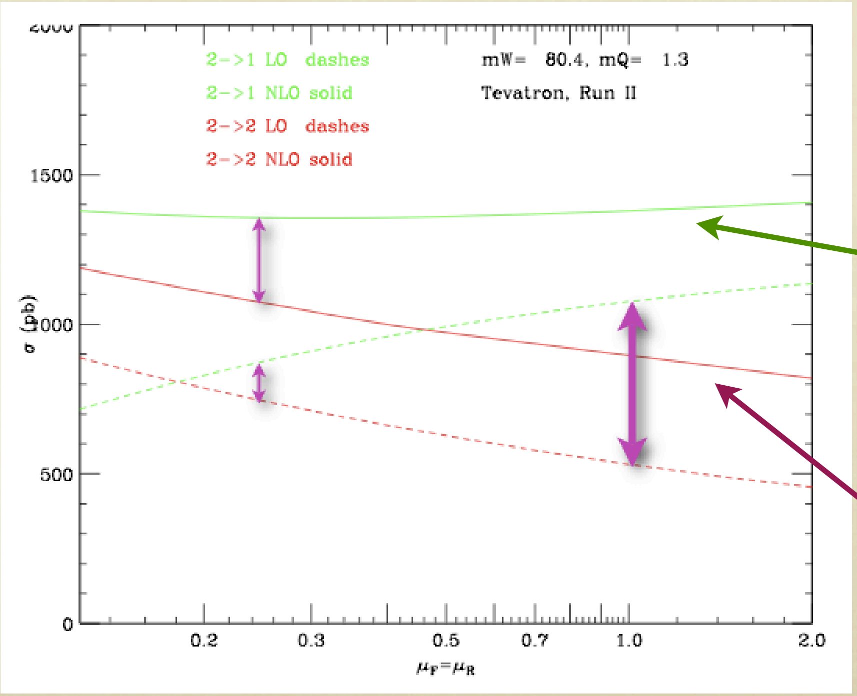
or



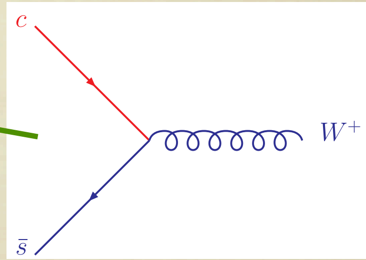
BUT the two different theory approaches give very different $p_T(Z)$ distributions

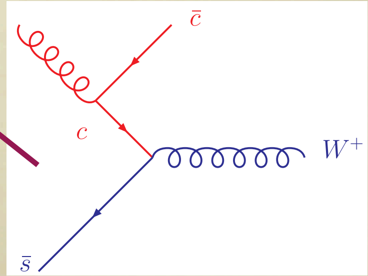
Heavy Quark PDFs

- The two theory approaches are based on either:
  - keeping all heavy quarks explicit in the final state;
  - moving a splitting g→QQ from the ME and into the PDF.
- The two approaches are of course exactly equivalent in the full theory; at a given order of PT, it might not be the case.
- Important to understand what differences exist and if/when one approach is superior. Especially compared to PS.
- Just becoming sensitive to this at the Tevatron (c.f. t-channel single top).
- Differences at the level of claimed accuracy in σ(W).
- LHC will be a real test.



~ 5% of σ(W) at the LHC





Conclusions

- For the most part, the Standard Model - and in particular, QCD - has held up well to scrutiny at the Tevatron.
- Measurements have taught us about the applicability of our theoretical tools and their limitations.
- They have also inspired both a new generation of physicists and a new way of doing business.
- You can teach an old dog new tricks: jet algorithms can be better behaved (IR safety) and do more for you (NP searches).
- Many of the dustier corners of pQCD, which the Tevatron is only beginning to probe, will be under scrutiny at the LHC.
- In many cases, the biggest gains have resulted from the experimental and theoretical communities continually challenging one another. Long may that continue!