Theory of W/Z + jets and Heavy Flavor

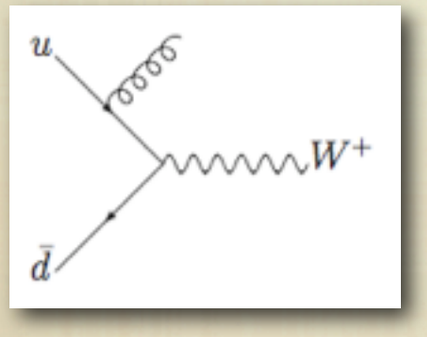
John Campbell

University of Glasgow

19th Hadron Collider Physics Symposium 2008

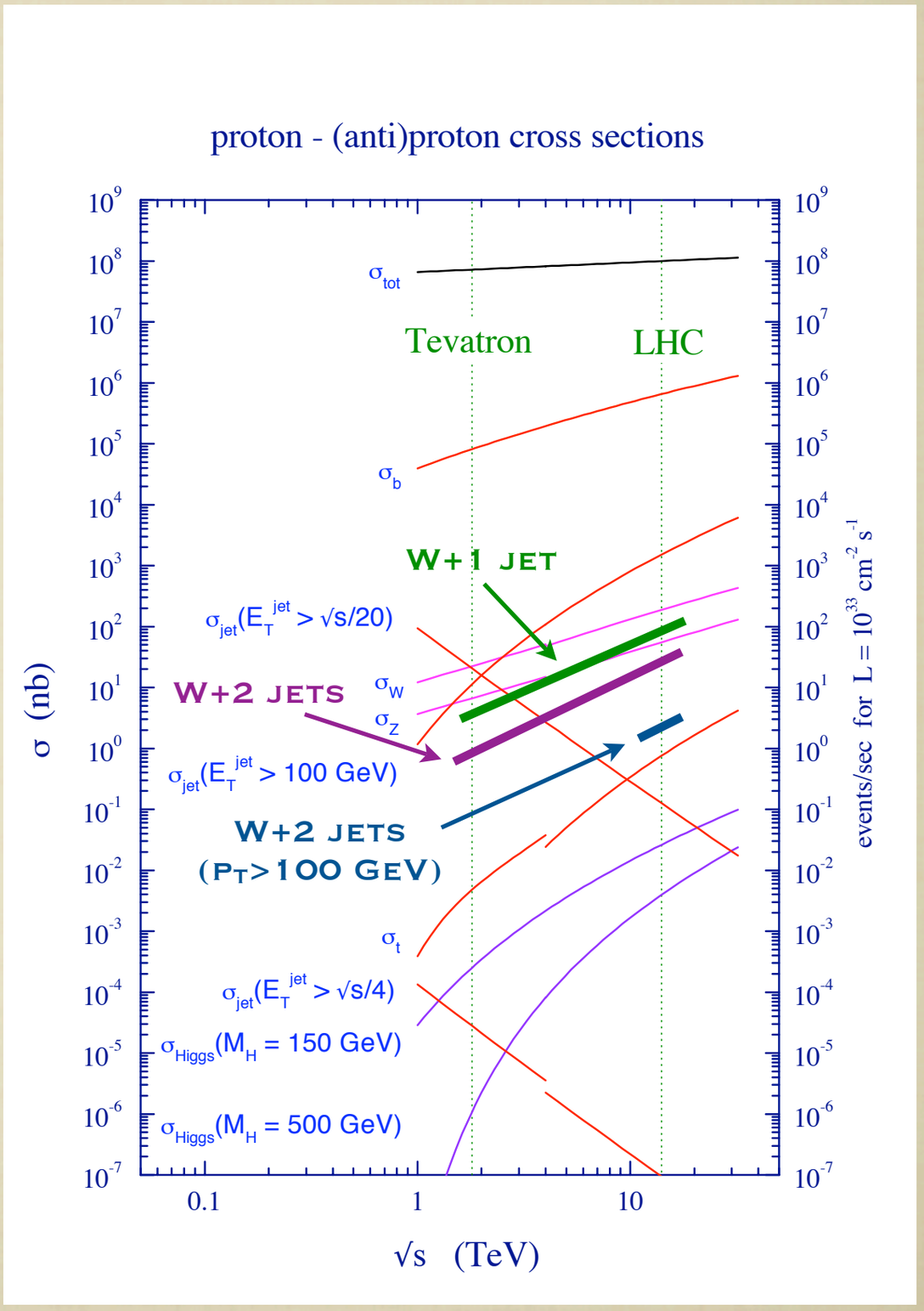
Introduction

- W and Z bosons are produced at an extremely high rate at both the Tevatron and the LHC.
- Such events contain additional radiation, mostly soft.
- Hard radiation is not that expensive; naive estimate of suppression by $\alpha_s(m_W)$ about right.



each extra jet gives one more α_s

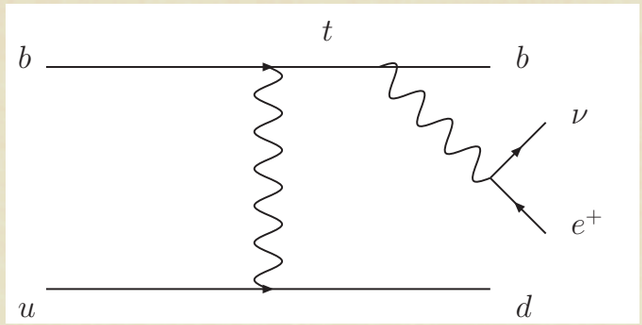
- Plenty of events compared to top and Higgs/NP processes.



Motivation

- Tag W/Z decay→ final state: lepton(s)+(missing energy)+jets; background to many search channels at the Tevatron and LHC.

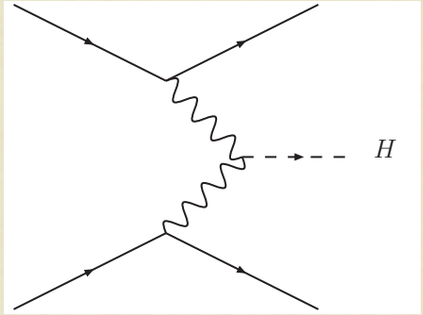
  - top processes



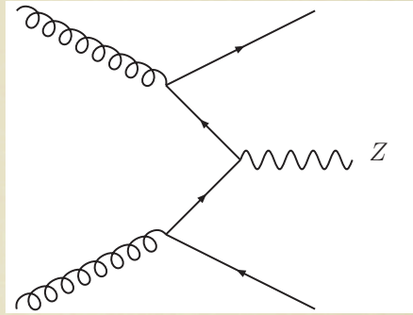
t-channel single top → W+ at least 1 jet (b-tag)

W+2 or more jets for tt

  - Higgs production



background for WBF H→ττ



  - supersymmetry and other models for new physics provide plenty of sources of missing energy and jets.

- Validation of theoretical tools with plenty of data.

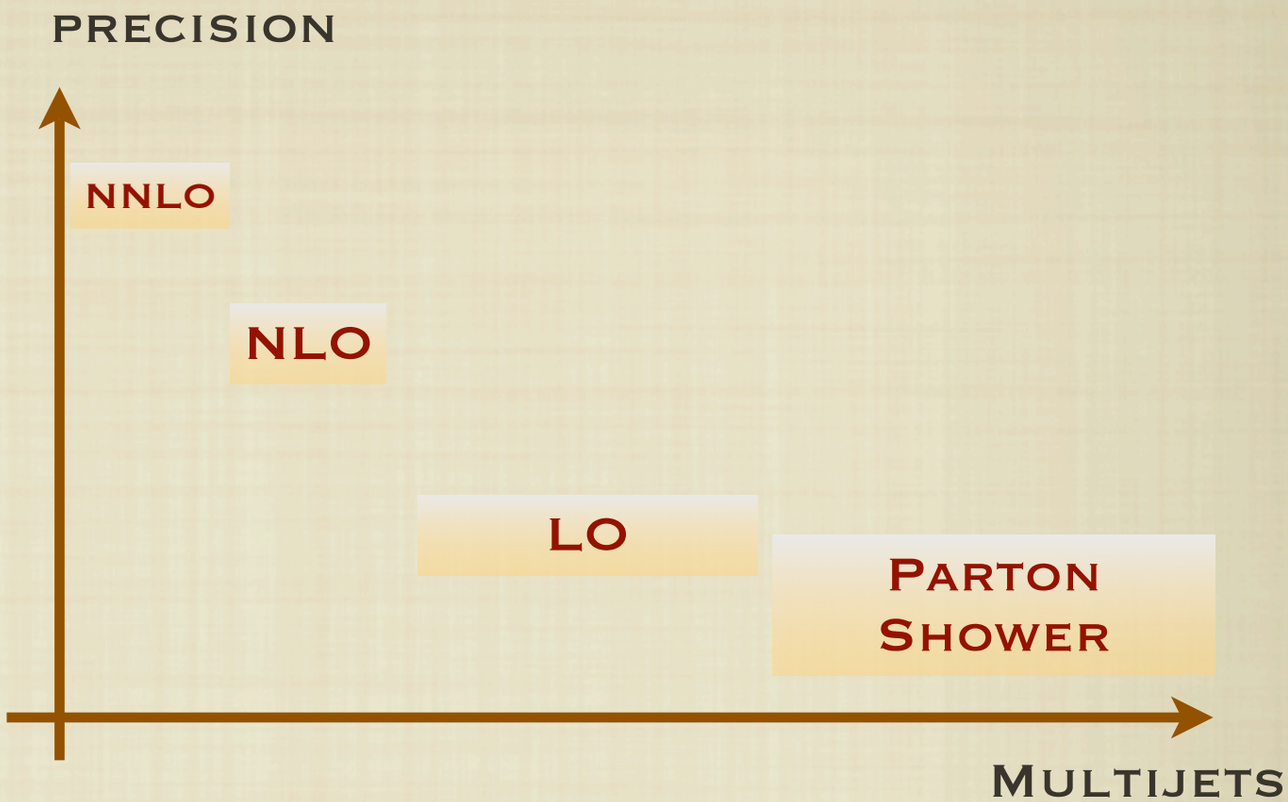
- Benchmark for next round of backgrounds, e.g. top + jets, and hopefully for signals at the LHC too!

Theory approaches

- Theoretical predictions are mostly based on two approaches.
- Fixed order QCD perturbation theory.
  - easy at LO but limited at NLO, almost no-go at NNLO;
  - one parton per jet at LO, possibly two at NLO, ... ;
  - small number of particles in total.
- Parton shower, e.g. Pythia or HERWIG.
  - start with a hard process, additional radiation produced stochastically;
  - any number of particles in total/per jet;
  - effects of soft and collinear particles well-modelled (resummed) but large angle/hard radiation poorly described.

Precision vs. Jets

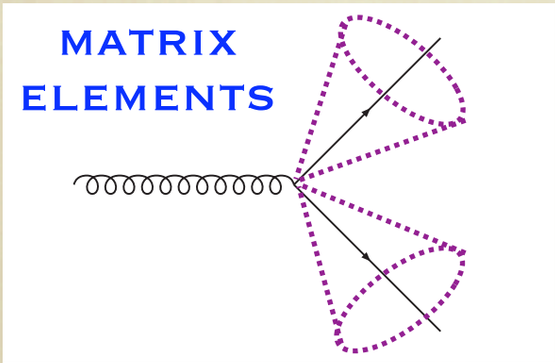
- To describe W+jets data, we need to work in both directions.
- Progress on multiple fronts: primarily more NLO and techniques for improving parton showers.



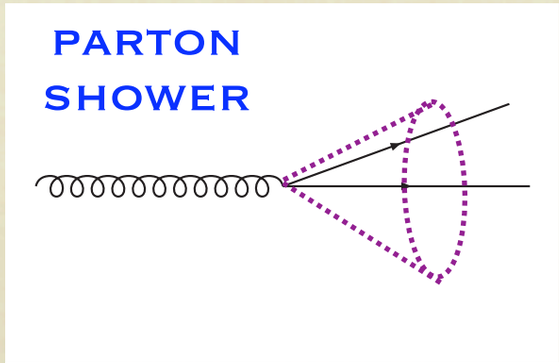
Precision vs. Jets

- To describe W+jets data, we need to work in both directions.
- Progress on multiple fronts: primarily more NLO and techniques for improving parton showers.

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



technical cut dependence

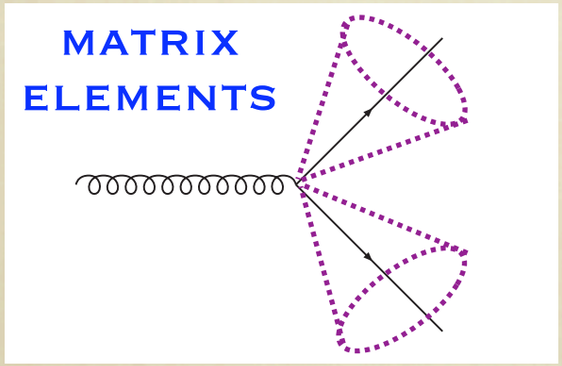


CKKW (Catani, Kuhn, Krauss, Webber)
MLM (Mangano)
SCET (Schwartz)
GenEvA (Bauer, Tackmann, Thaler)

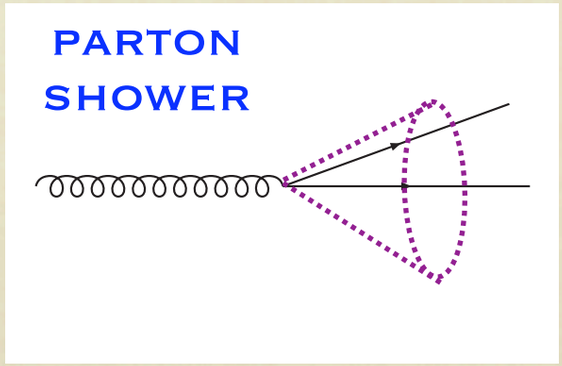
Precision vs. Jets

- To describe W+jets data, we need to work in both directions.
- Progress on multiple fronts: primarily more NLO and techniques for improving parton showers.

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



technical cut dependence



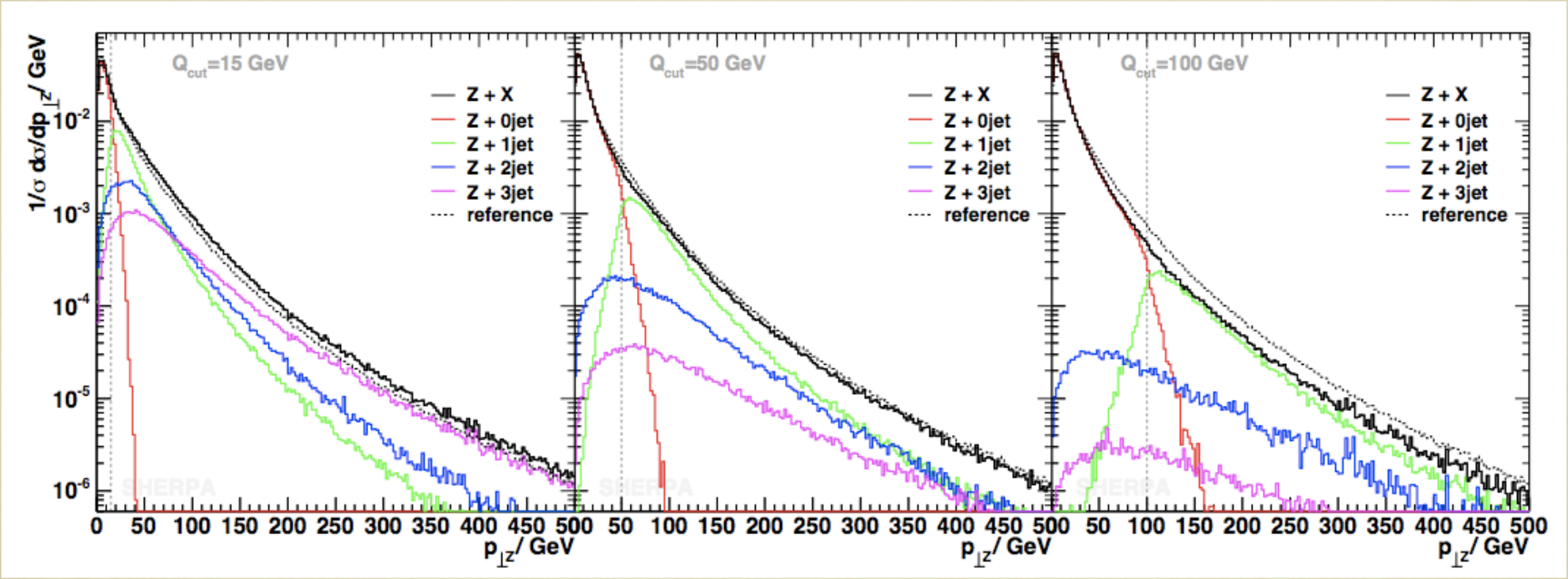
CKKW (Catani, Kuhn, Krauss, Webber)
MLM (Mangano)
SCET (Schwartz)
GenEvA (Bauer, Tackmann, Thaler)

- NLO PS: shower uses NLO MEs, including one real emission, e.g. MC@NLO. Must avoid double counting.

S.Frixione, B.Webber, hep-ph/0305252

Technical cut

- SHERPA implements the CKKW prescription for matching, with a jet resolution cut Q_{cut} determining the use of ME or PS.
- In principle, algorithm independent of choice (at this order), but in practise should be guided by common sense/data.

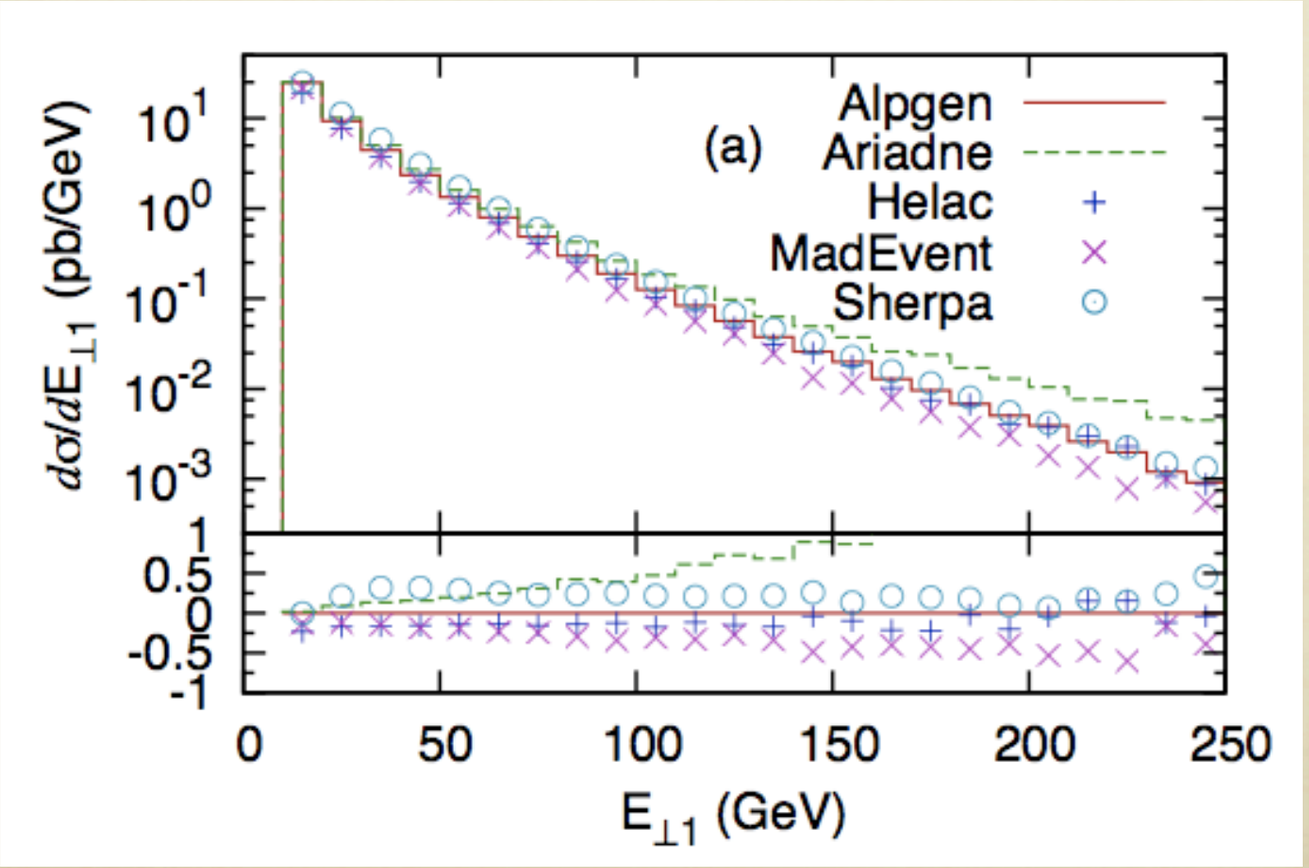


F. Krauss et al., hep-ph/0503280

- Clearly, choosing the cut too hard exposes the inadequacy of the PS that we were trying to avoid. Similar for other methods.

Matching comparison

- Much work has been done to compare different parton shower matching procedures for W+jet predictions.
- Differences in rates and distributions, but ...
  - variations can be accounted for by usual change of scales
  - could tune to Tevatron data and extrapolate to LHC



leading jet p_T in W+jet events at the Tevatron

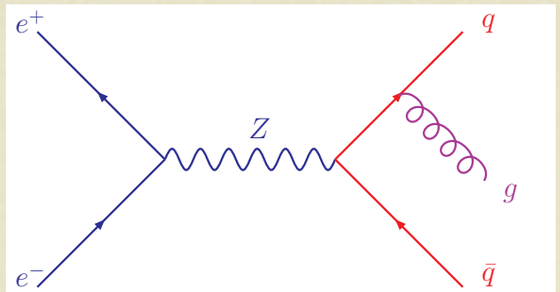
broadly consistent

J. Alwall et al. arXiv:0706.2569

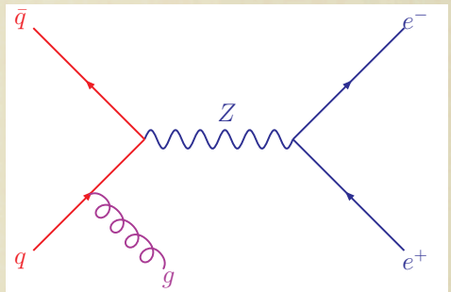
Higher orders

- Inclusive production of W and Z known to NNLO. C. Anastasiou et al. hep-ph/0312266
  - accuracy of a few percent on total rate and distributions.
- W/Z+1 jet known at NLO for a long time, where "jet" means a massless quark or gluon. W. Giele, N. Glover, D. Kosower, hep-ph/9302225
  - related process $e^+e^- \to 3$ jets now known at NNLO

A. Gehrmann-de Ridder et al, arXiv:0711.4711



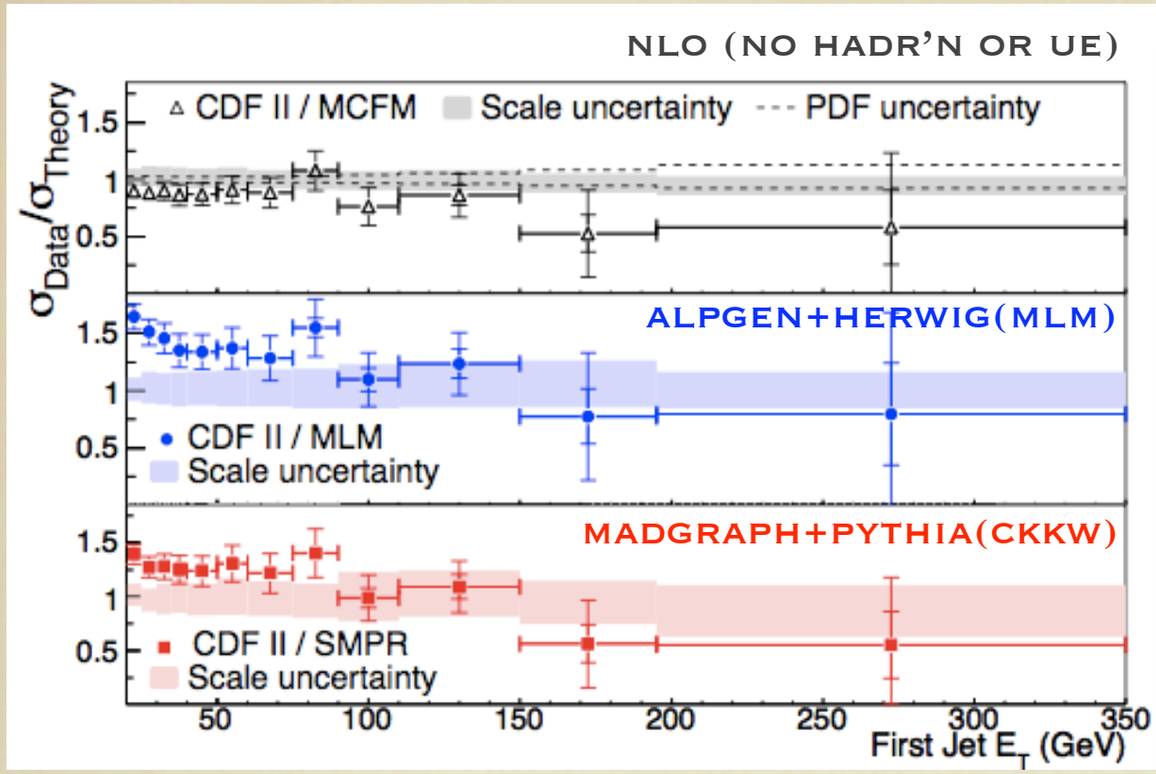
non-trivial work to do crossing to hadron collider

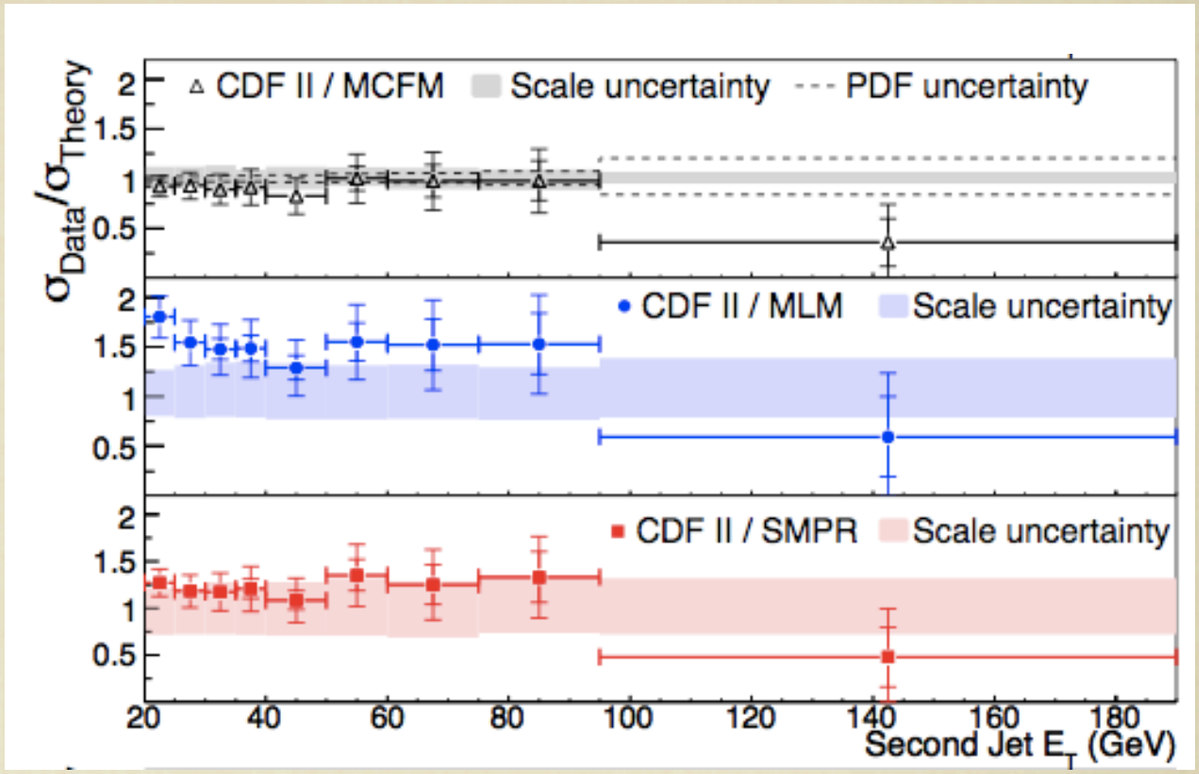


- W/Z + 2 jets known at NLO for some time JC, K. Ellis, hep-ph/0202176
  - barring immense breakthrough, NNLO very unlikely
- The NLO parton shower MC@NLO matches to inclusive W/Z processes. One extra jet not infeasible, but for now must choose either higher orders or parton shower.

CDF comparison

T. Aaltonen et al. (CDF), arXiv:0711.4044

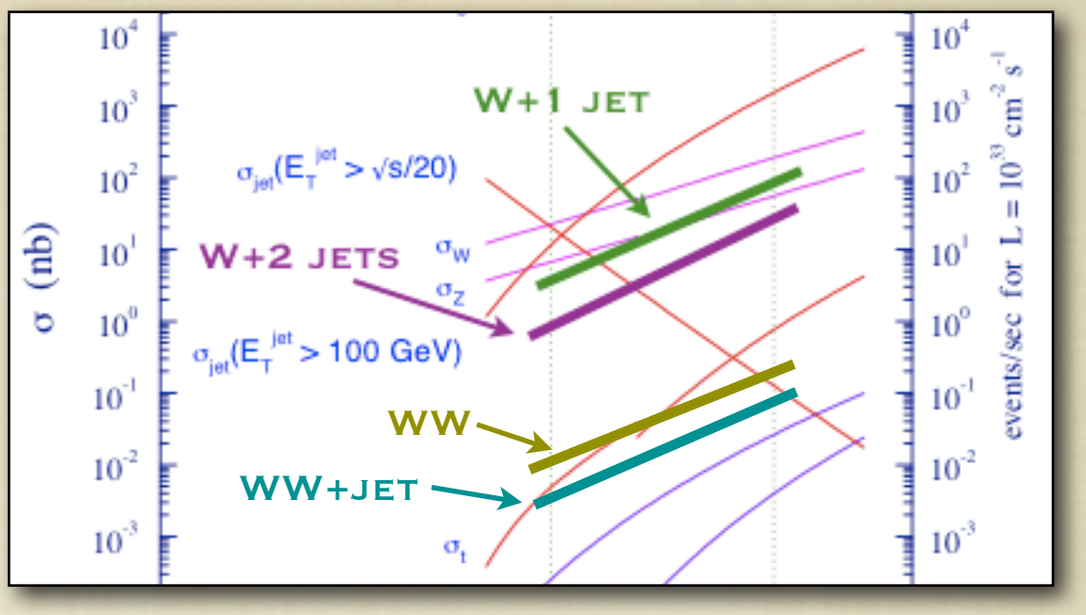




- Open questions:
  - NLO description excels, but agreement "too good".
  - can we extend NLO to higher multiplicities?
  - if not, how do we best estimate rates?
  - how do the approaches fare for distributions?

LHC prospects

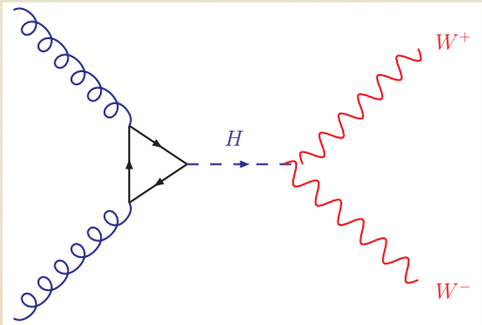
- At the Tevatron, rate for vector boson pairs is just enough to be observable.
- At the LHC there will be plenty of WW+ jets.



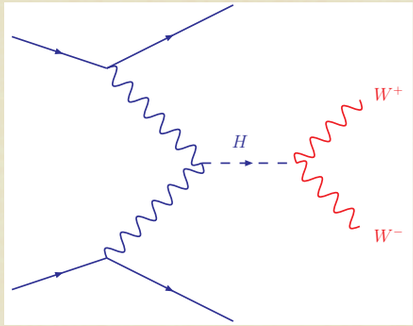
- Need similar studies there, e.g. for probing Higgs sector.

B. Mellado, W. Quayle, S. L. Wu, 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 of WW+jet backgrounds a priority

- ME+PS: extra W means harder to crunch, but much the same.
- Fixed order: WW known at NLO for a long time, WW+jet recently calculated.

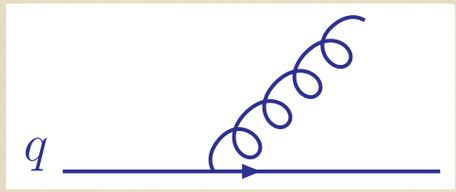
S. Dittmaier, S. Kallweit, P. Uwer, arXiv:0710.1577

JC, K. Ellis, G. Zanderighi, arXiv:0710.1832

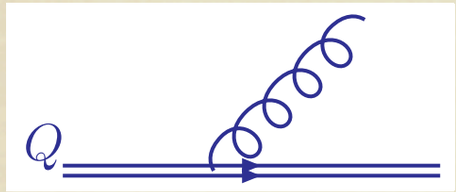
T. Binoth et al., arXiv:0803.0494

Heavy flavors

- Heavy quarks are different: the mass regulates the collinear pole in the matrix elements so that e.g. $p_T(Q) \to 0$ limit is safe.

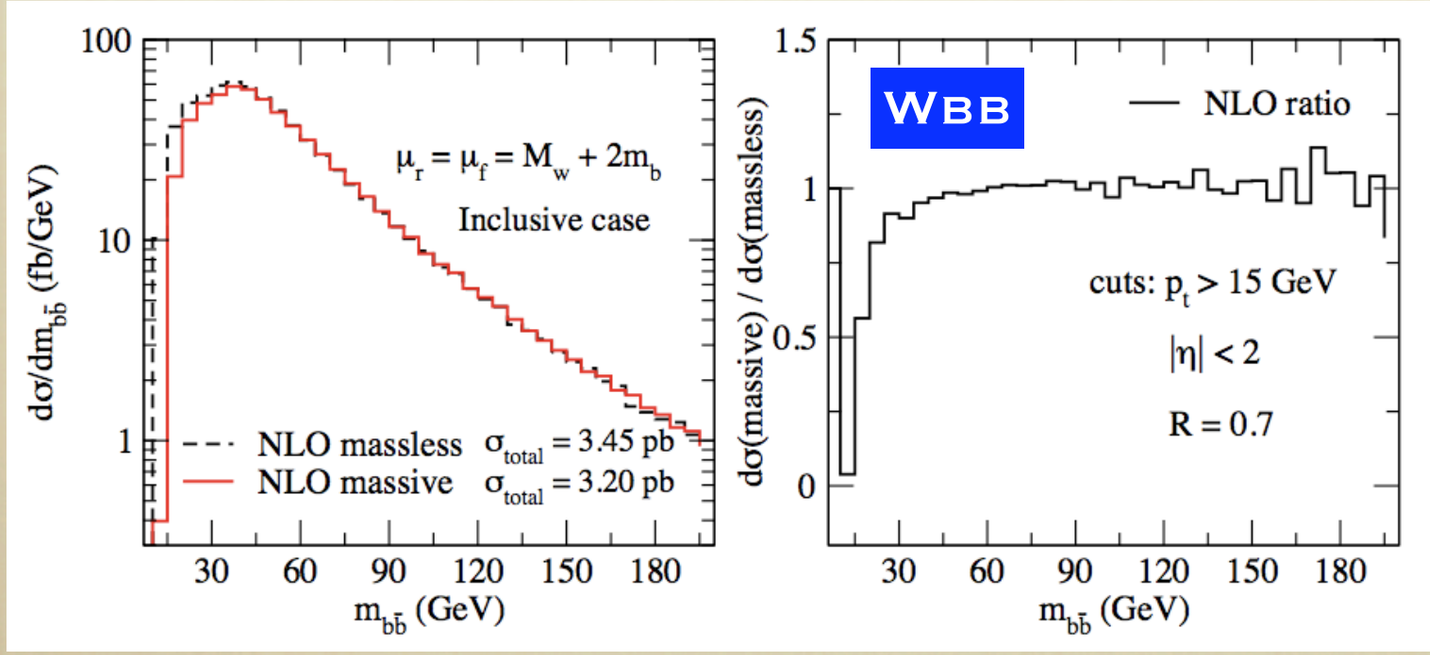


- massless quark
- predictions diverge as $p_T(Q) \to 0$
- must impose min. p_T and jet separation



- massive quark
- divergence regulated, behaves as $\log(m^2)$
- no cuts necessary, can calculate inclusively

- Sometimes we are not interested in the low p_T behaviour and want to treat the heavy quark as just another ordinary jet.



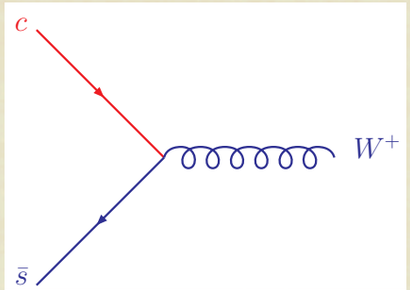
- The effect of the mass is $O(m^2/Q^2)$ but large around threshold.
- Neglect → easier theory.

F. Febres Cordero et al., hep-ph/0606102

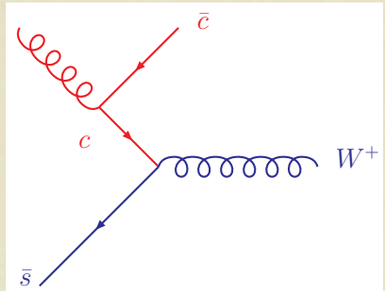
HQ approaches

- For very high c.o.m. energies we are sensitive to the heavy quark content of the proton sea
- We are used to this description already for charm, but not as familiar with the bottom quark - more important at LHC.

about 5% of the inclusive W cross section at the LHC



"variable flavor scheme" (VFS)

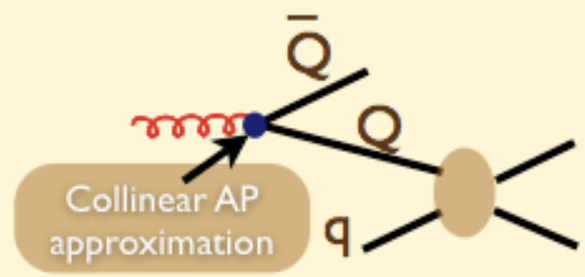
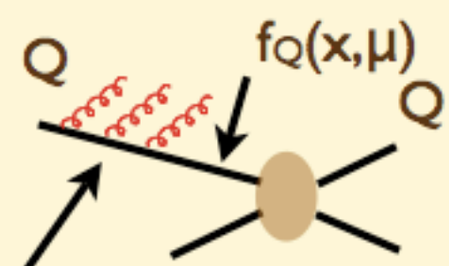
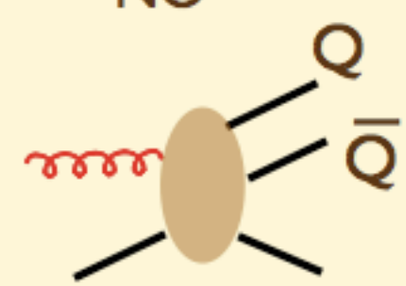


no heavy quark PDF "fixed flavor scheme" (FFS)

- The PDF represents the production of a heavy quark from a gluon splitting, together with an (unobserved) antiquark.
  - could have included splitting explicitly and integrated out.
- 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. Parton shower typically uses FFS.

Pros and Cons

M. Mangano, LBNL workshop, March 2008

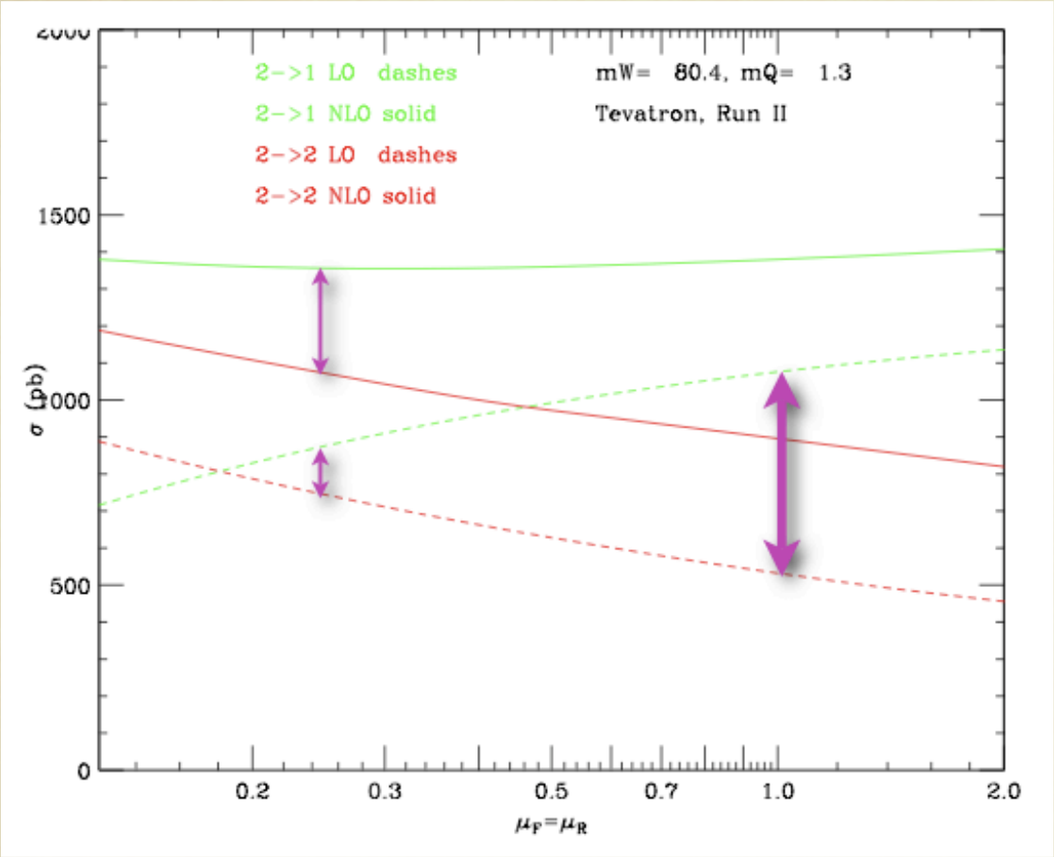
Features:	Massless PDF approach	Massive ME approach
Exact massive kinematics and phase-space onset	NO	YES
Description of recoiling hvq		Full ME
Availability/easiness of NLO results	V	–
Accuracy w.r.t. possibly large higher-order logs	YES 	NO 

$$\frac{d f_Q(x,\mu)}{d \log \mu^2} = \frac{\alpha_s}{2\pi} \left[P_{Qg} \otimes g(\mu) + P_{QQ} \otimes f_Q(\mu) \right]$$

Prototype process

- W+c: simplest possible case. Analyzed by Berger et al. (1989).
- NLO predictions known in both schemes.

W. Giele, S. Keller, E. Laenen, hep-ph/9511449



JC, F. Maltoni, M. Mangano, F. Tramontano

large difference at LO reduced at NLO

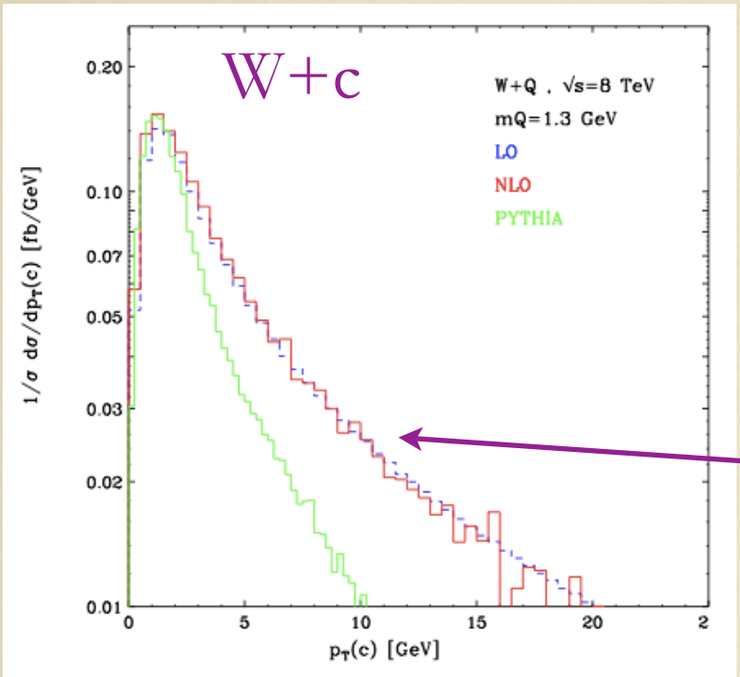
agreement at 20% level for small scale choice, which is well-motivated theoretically

good stability wrt scale variation for 2→1

- Real phenomenology: differences of this size bring into question claims of few % accuracy in inclusive W cross-section.

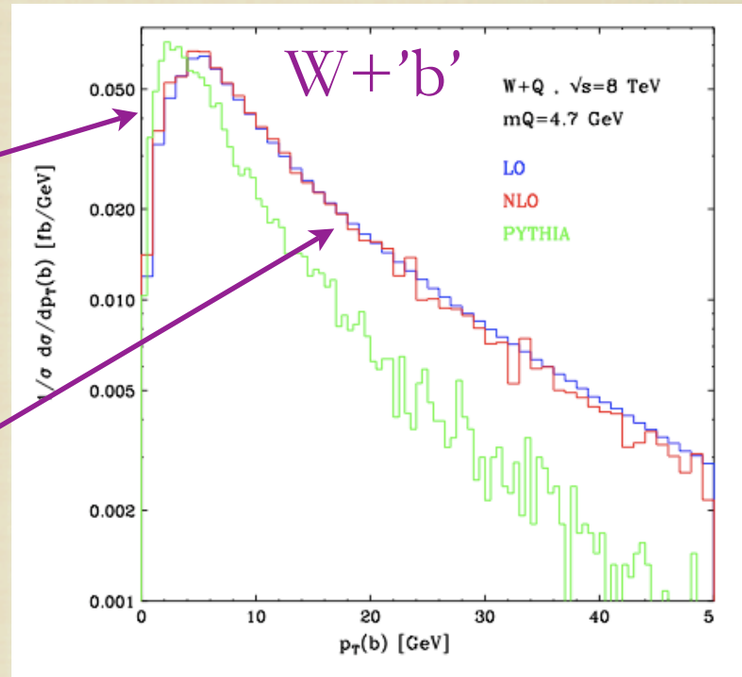
Distributions

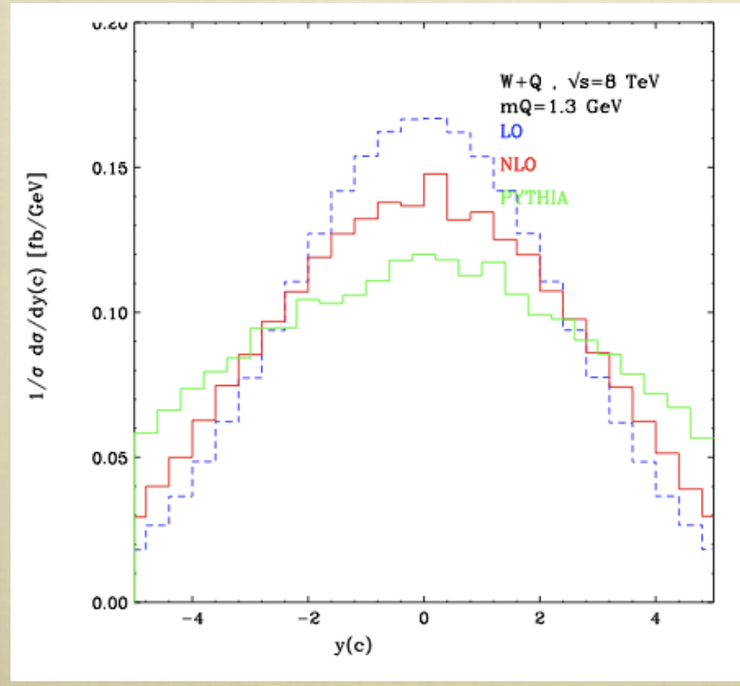
- More important: how do distributions compare with parton shower approaches used in many analyses?



Pythia of course lacks hard radiation, but not good for low $p_T(b)$

LO≈NLO everywhere, so no sign of large logs (motivation for VFS)





- Some features of NLO reflected in Pythia prediction - not all bad?
- Lots of room for improvement:
  - further comparison of approaches.
  - more use of PS/ME merging.

Comparison with data

- CDF result (non-inclusive): $p_T(c) > 20$ GeV, $|\eta(c)|<1.5$.

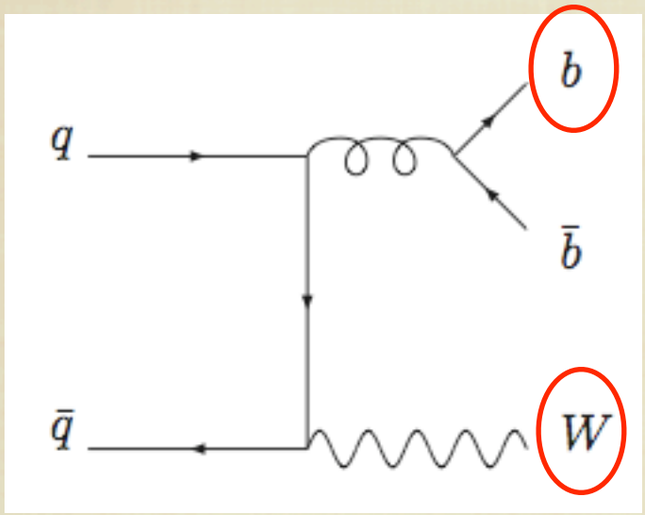
	$\sigma \times BR(W \to e\nu)$ [pb]
CDF T. Aaltonen et al., arXiv:0711.2901	9.8 ± 3.2
LO - $Q^2=m_W^2+p_T^2$	6.8
LO - $Q^2=p_T^2$	8.8
NLO - $Q^2=(40\ \text{GeV})^2$	11.0 (+1.4,-3.0)

variation over wide scale range and multiple PDF sets → large residual uncertainty

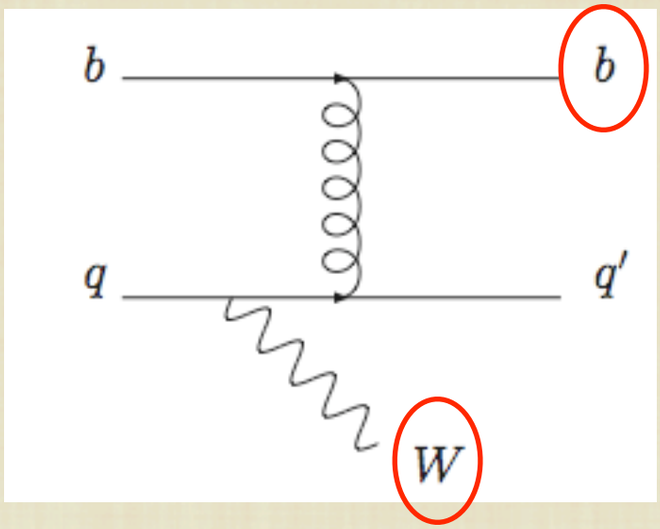
Good agreement

W+bottom

- No direct analogue with W+charm (CKM). Require hard b.
- Two mechanisms for producing W+b+(another unseen jet):



- no b in initial state
- inclusive of second b
  → need massive ME



- use bottom PDF
- inclusive of light quark
  (protected by W mass)

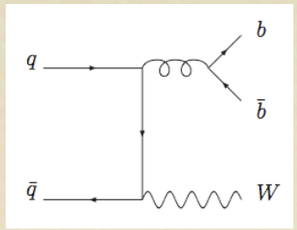
- Goal: combine both calculations at NLO for best prediction. Cannot do all in FFS since Wbbj not known at NLO.

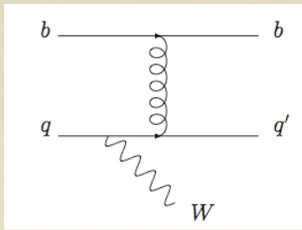
F. Febres Cordero et al. + F. Maltoni et al. (ongoing)

- The calculations have some overlap at NLO, so some care must be taken not to double count.

Preliminary results

Rates for W+b+X [pb]





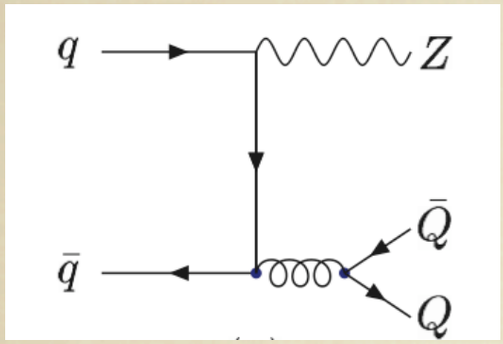
SUM

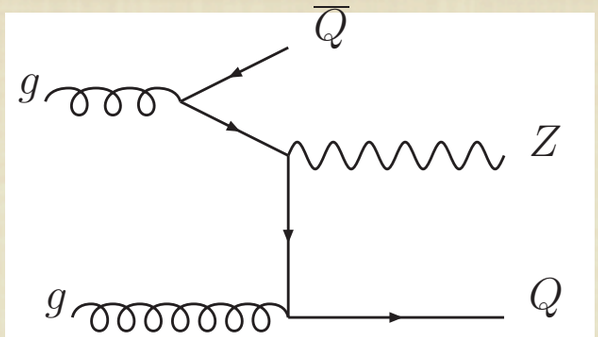
Tevatron p_T>15 GeV $\lvert\eta\rvert$<2	LO	10.22	1.81	12.03
	NLO	15.94	2.78	18.72
		relative importance of the two processes reversed		K-factor ≈ 1.5 at both
LHC p_T>25 GeV $\lvert\eta\rvert$<2.5	LO	97.9	173.0	270.9
	NLO	136.8	283.8	420.6

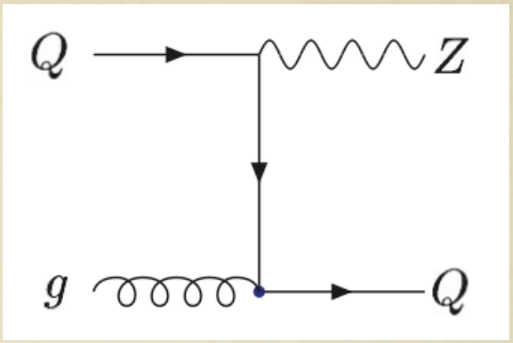
- Preliminary results from CDF (p_T>20 GeV, $\lvert\eta\rvert$<2) indicate data is above LO theory by factor of 3-4, but distns are OK.
  - NLO result might help somewhat but still a puzzle.

Z+HEAVY QUARK

- Similar to W+b, except that there is also a gg $O(\alpha_s^2)$ process.



+ { 

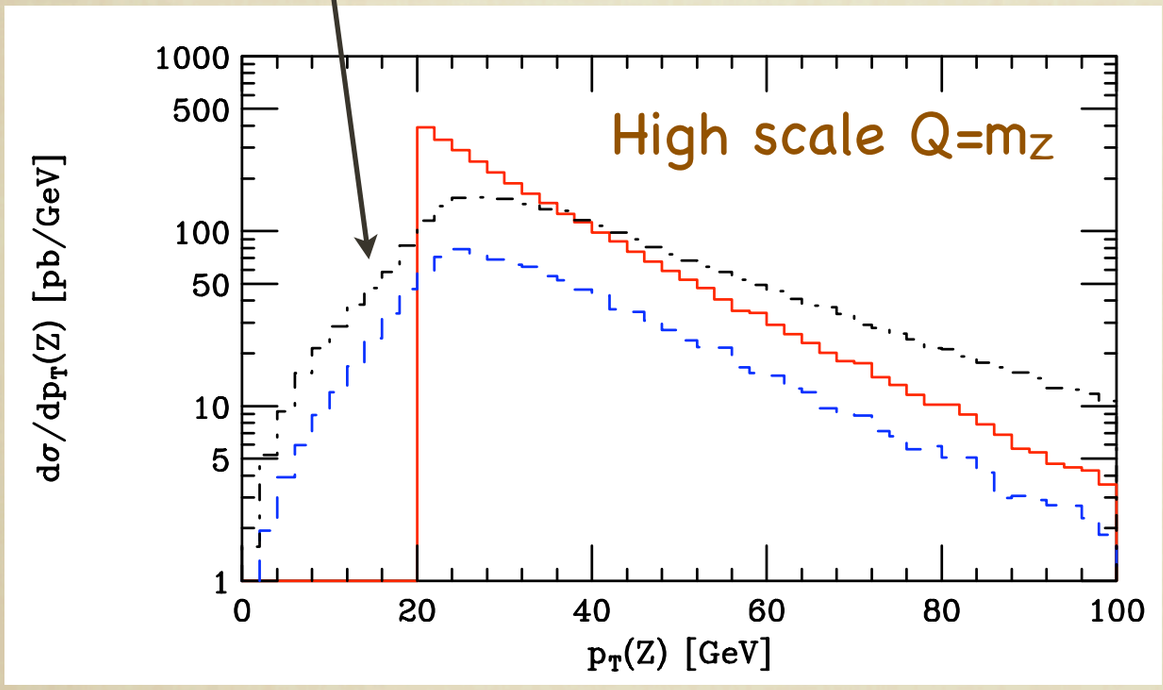
OR 

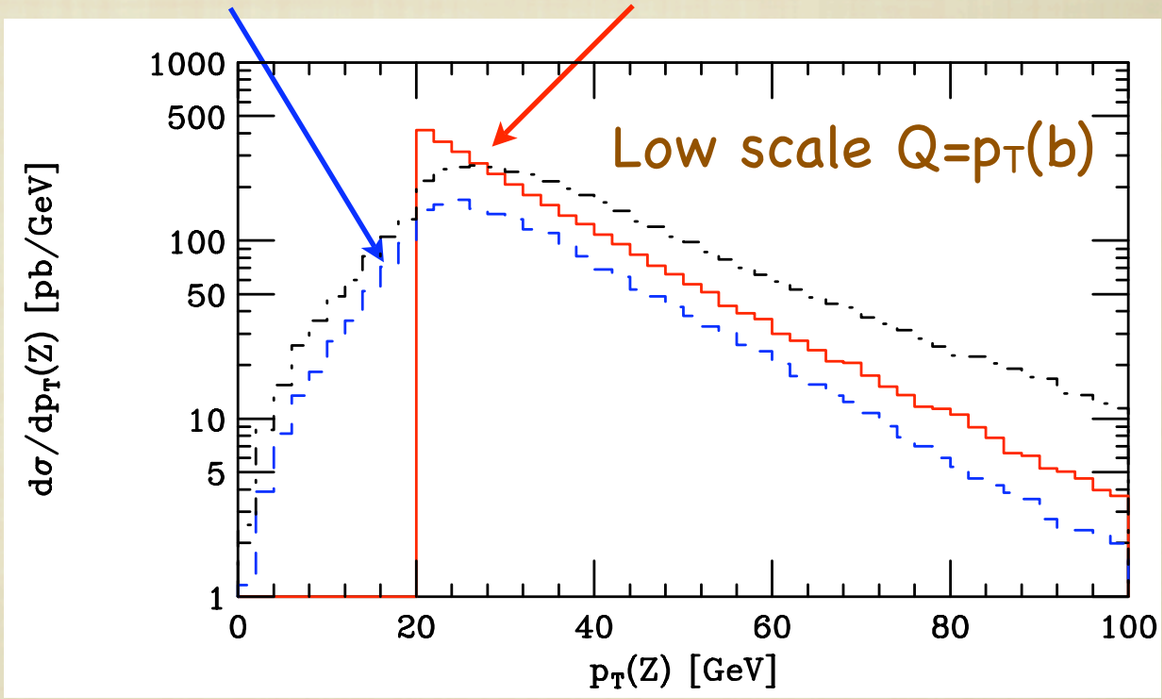
}

analogue of W+b+X

gg initial state, FFS; recently calculated at NLO

absorb into Q-pdf; known at NLO



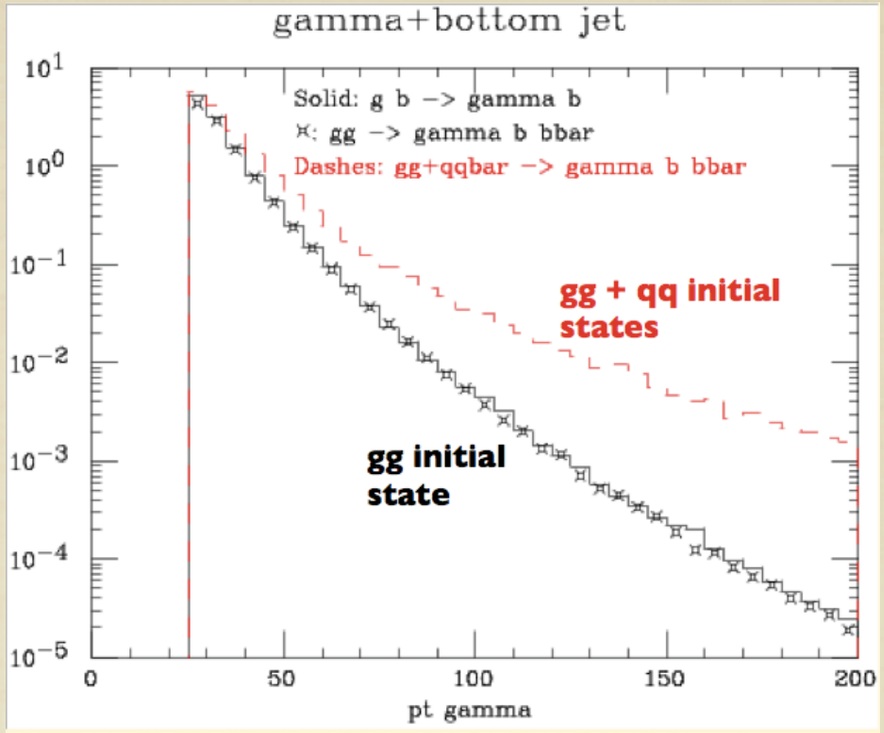


LO comparison: Tevatron, $p_T(b)>20$ GeV, $|\eta(b)|<2.5$

- Large discrepancy, but less for smaller scales. Rigorous study at NLO (like for W+c) necessary for real understanding.

Discrepancy

M. Mangano,
LBNL workshop, March 2008



- The discrepancy is in marked contrast to photon+b process.
- Here photon p_T naturally sets the scale.
- Works well already at LO; how about NLO? Partly known.
  E. Berger, L. Gordon, hep-ph/9512343
- Also, discrepancy is masked by the large qq contribution (>= gg) when comparing with data on the integrated rate.

$$\left[\frac{\sigma(Z+b-\text{jet})}{\sigma(Z+\text{jet})}\right]_{\text{exp}} = 0.021 \pm 0.004$$

V. Abazov et al. (D0), hep-ex/0410078

$$\left[\frac{\sigma(Z+b-\text{jet})}{\sigma(Z+\text{jet})}\right]_{\text{th.}} = \begin{cases} 0.018 \pm 0.004 & \text{NLO VFS} \\ 0.015 - 0.023 & \text{LO FFS} \end{cases}$$

How do we interpret this apparent agreement?

- Comparison of p_T distribution below ~40 GeV essential to understanding theory and learning lessons for LHC.

State of play

- Active field in preparation for upcoming tests at the LHC.

	1 c-tag	1 b-tag	2 c-tag	2 b-tag
W+1 jet	FF NLO (GKL 96, CET 05)	FF+HVQ NLO (FRW+CEMW 08)	N/A	N/A
W+2 jets	LO only	HVQ NLO (CEMW 07)	FF NLO (FRW 07)	
Z+1 jet	FF NLO (FRW 08) HVQ NLO (CEMW 03)		N/A	N/A
Z+2 jets	HVQ NLO (CEMW 06)		FF NLO (FRW 08)	

- 2 jets with one tag → HVQ only
- Beyond 2 jets uncalculated at NLO.

GKL = Giele, Keller, Laenen
CET = JC, Ellis, Tramontano
FRW = Febres Cordero, Reina, Wackeroth
CEMW = JC, Ellis, Maltoni, Willenbrock

Summary

- In absence of heavy quarks, situation is quite encouraging.
  - good agreement between data and theory;
  - PS/ME matching mature, just need more to tune with;
  - NLO works well (up to 2 jets), new automated multi-leg approaches may get us further in the near future.

- For heavy quarks, picture is not so clear.
  - in some cases, no agreement at all - elsewhere, only patchy;
  - latest Tevatron data is confronting the two theoretical approaches → real chance to understand tools;
  - systematic evaluation of theory underway.