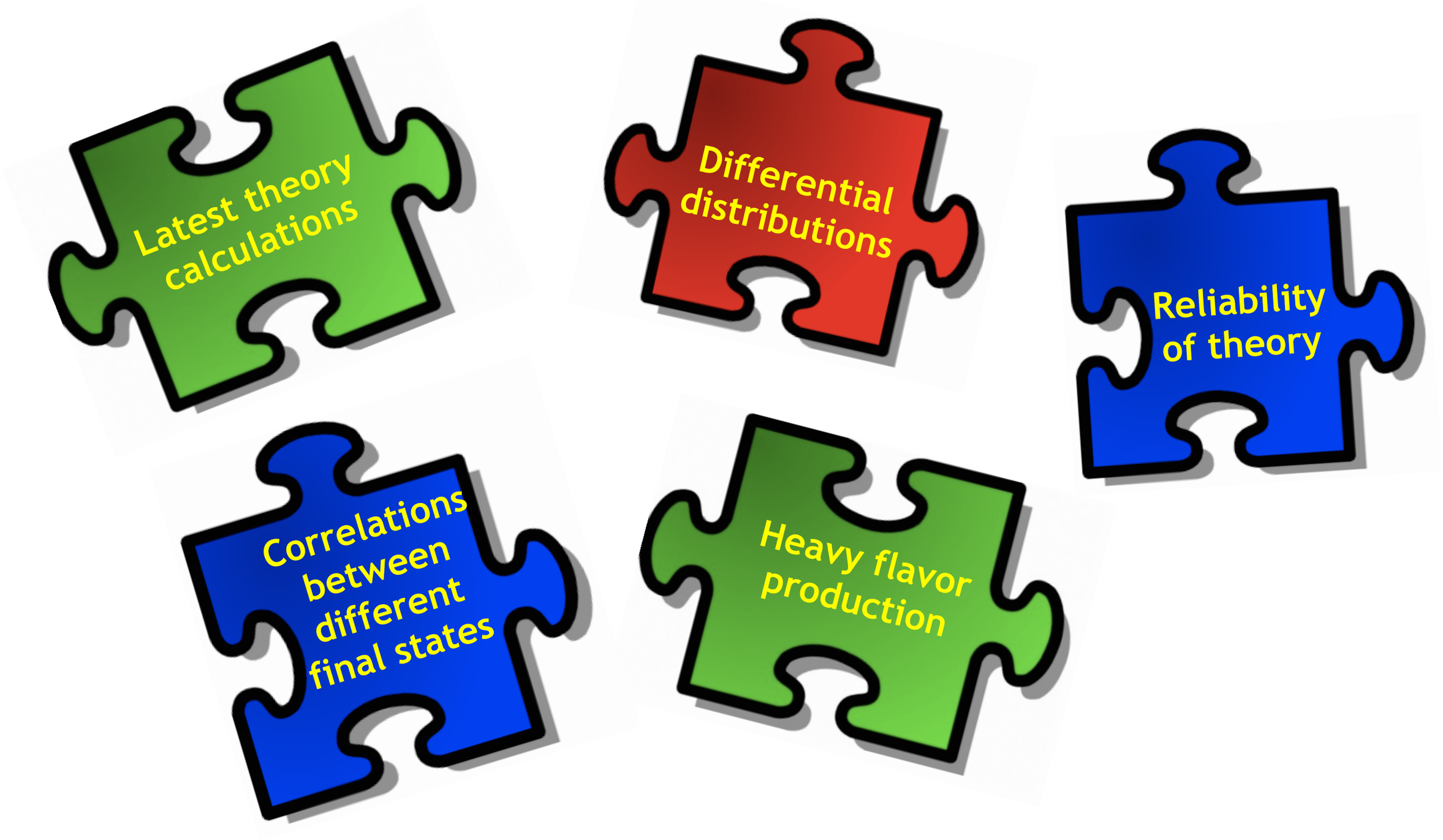
W/Z+jets theory

Higgs Systematics Meeting, May 17-19, 2010

John Campbell, Fermilab

Topics to cover

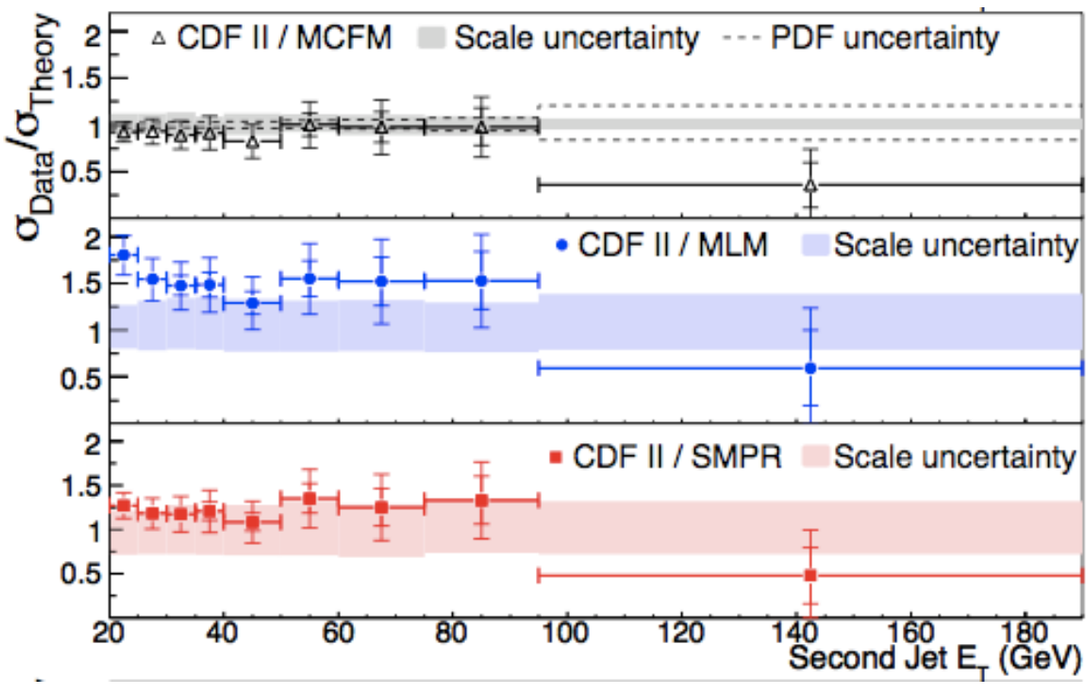


- Probably not many answers to be found within these slides, but hopefully some kindling for useful discussion

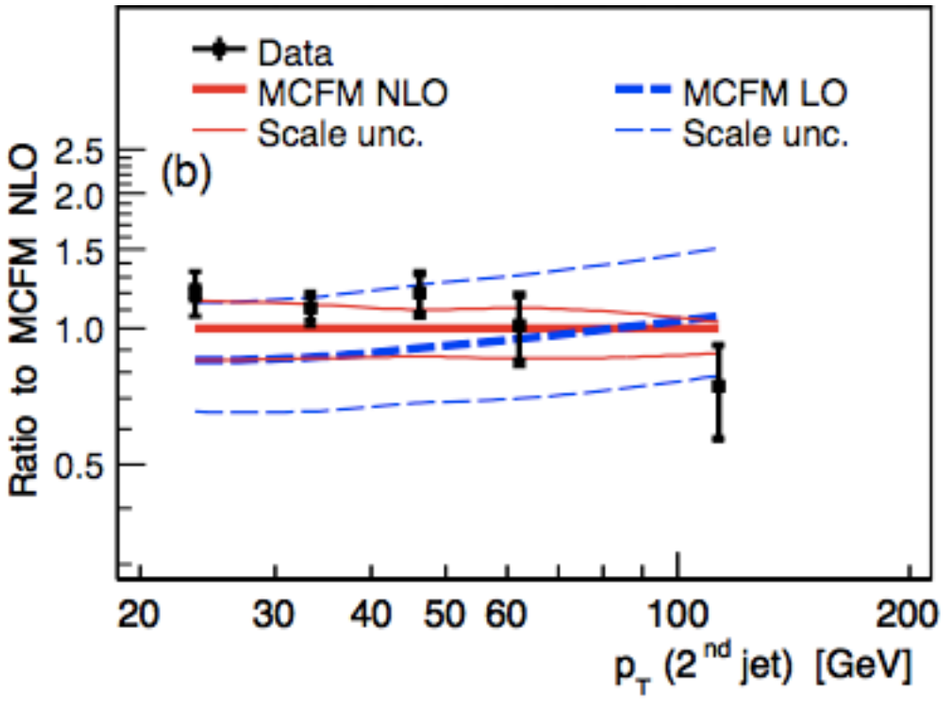
W/Z+light jets

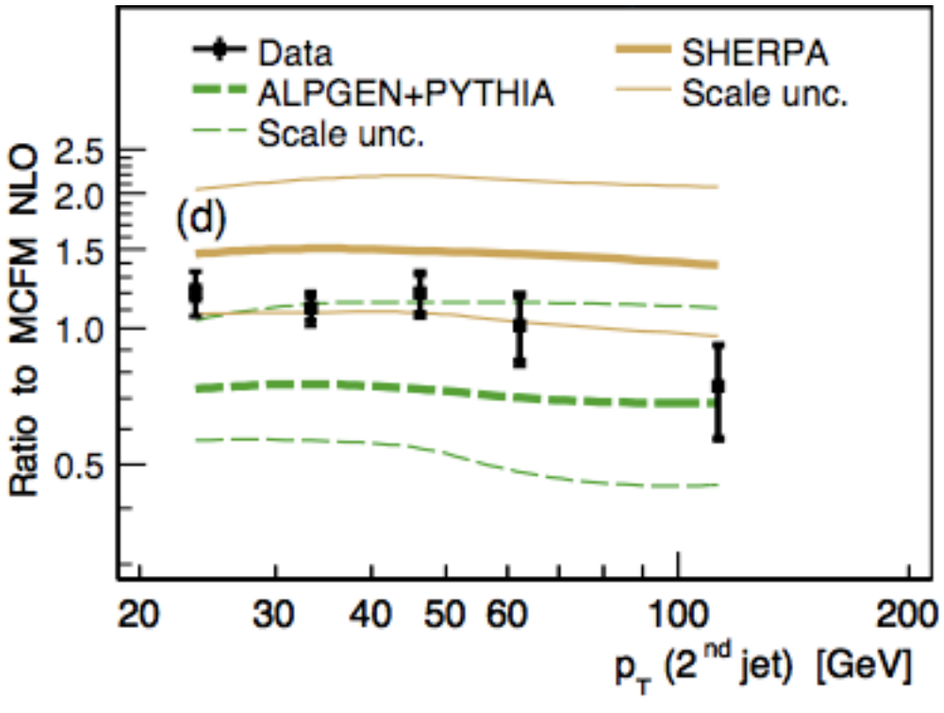
- Has become a benchmark of QCD, with rates and jet spectra well-studied.

e.g. CDF W+jets,
Aaltonen et al., arXiv: 0711.4044



e.g. D0 Z+jets,
Abazov et al., arXiv: 0903.1748





Latest theory

- NLO results for W+3 jets available for just over a year.
  - two collaborations, Blackhat (arXiv:0902.2760), Rocket (arXiv:0901.4101).
- New results for Z+3 jets from Blackhat.

C. Berger et al., arXiv: 1004.1659

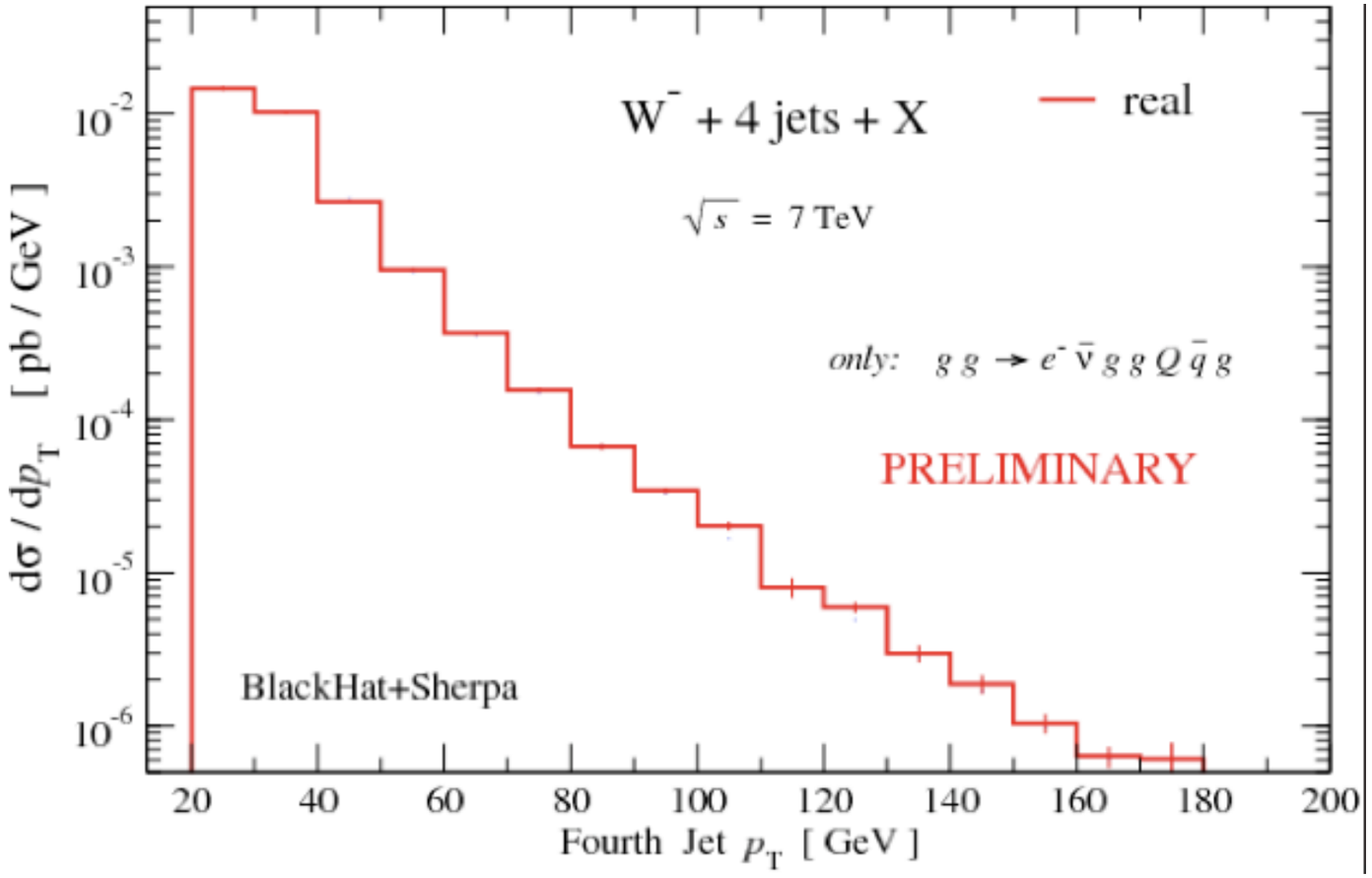
# of jets	CDF midpoint	LO parton SISCone	NLO parton SISCone	LO parton anti-k_T	NLO parton anti-k_T
1	$7003 \pm 146^{+483}_{-470} \pm 406$	$4635(2)^{+928}_{-715}$	$6080(12)^{+354}_{-402}$	$4635(2)^{+928}_{-715}$	$5783(12)^{+257}_{-334}$
2	$695 \pm 37^{+59}_{-60} \pm 40$	$429.8(0.3)^{+171.7}_{-111.4}$	$564(2)^{+59}_{-70}$	$481.2(0.4)^{+191}_{-124}$	$567(2)^{+31}_{-57}$
3	$60 \pm 11^{+8}_{-8} \pm 3.5$	$24.6(0.03)^{+14.5}_{-8.2}$	$35.9(0.9)^{+7.8}_{-7.2}$	$37.88(0.04)^{+22.2}_{-12.6}$	$44.9(0.3)^{+4.7}_{-7.1}$

- Will (try to) not open the jet algorithm can of worms here, but note:
  - Z+2 jets algorithm dependence is relatively large at LO, but insignificant at NLO.
  - Z+3 jets shows a significant difference even at NLO.
  - same story for W+3 jets (see also Hoche et al., arXiv: 1003.1241).

Yet more jets

- Blackhat already on the way to W+4 jets.

Maitre, April 2010

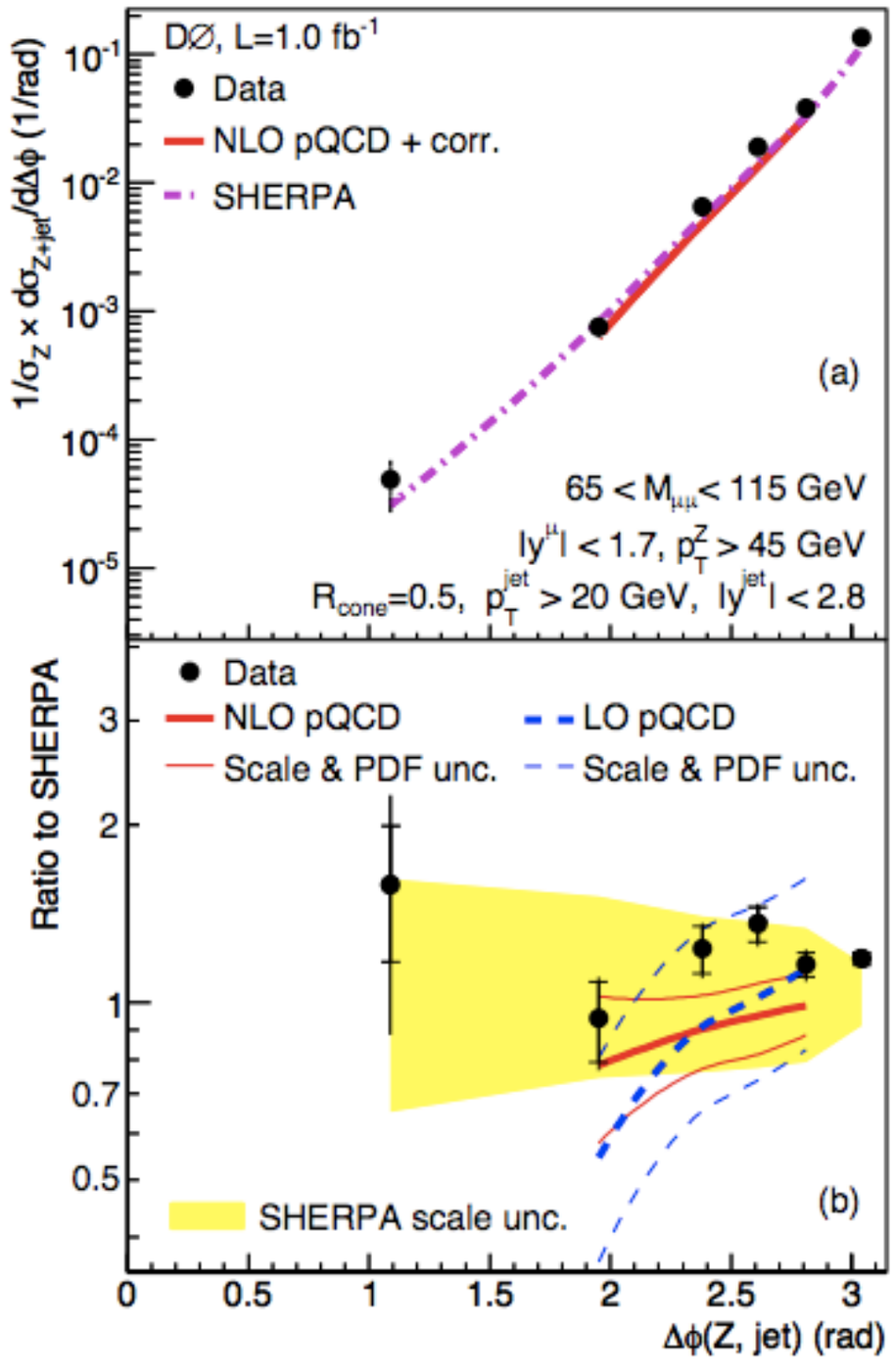


- This many jets not so relevant for the Tevatron (Higgs) analyses, but may teach us more about theory/experiment comparison.
  - e.g. W+3 jets prefers event-by-event QCD scale choice, $\mu \sim H_T/2$ for well-behaved description of differential distributions.

Differential distributions

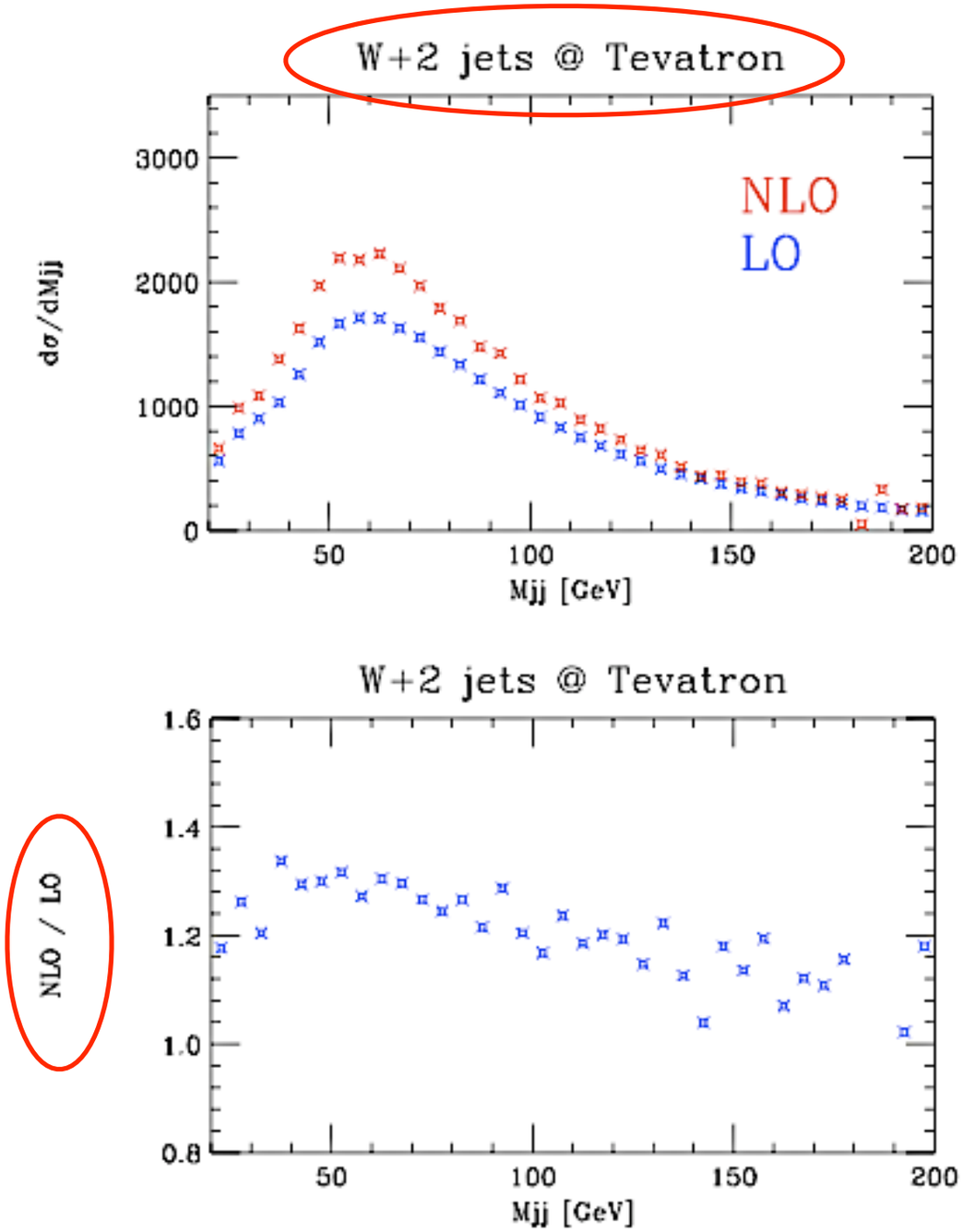
- For Higgs analyses, require control of more than just jet spectra.
- More theory/data comparison required outside the established benchmark distributions.
- A good example comes from recent Z+jet analysis from D0.
  - beware region where parton level calculation is unreliable (here, $\Delta\Phi \rightarrow \pi$).
  - indication that further tuning of the parton shower may be required for best description.

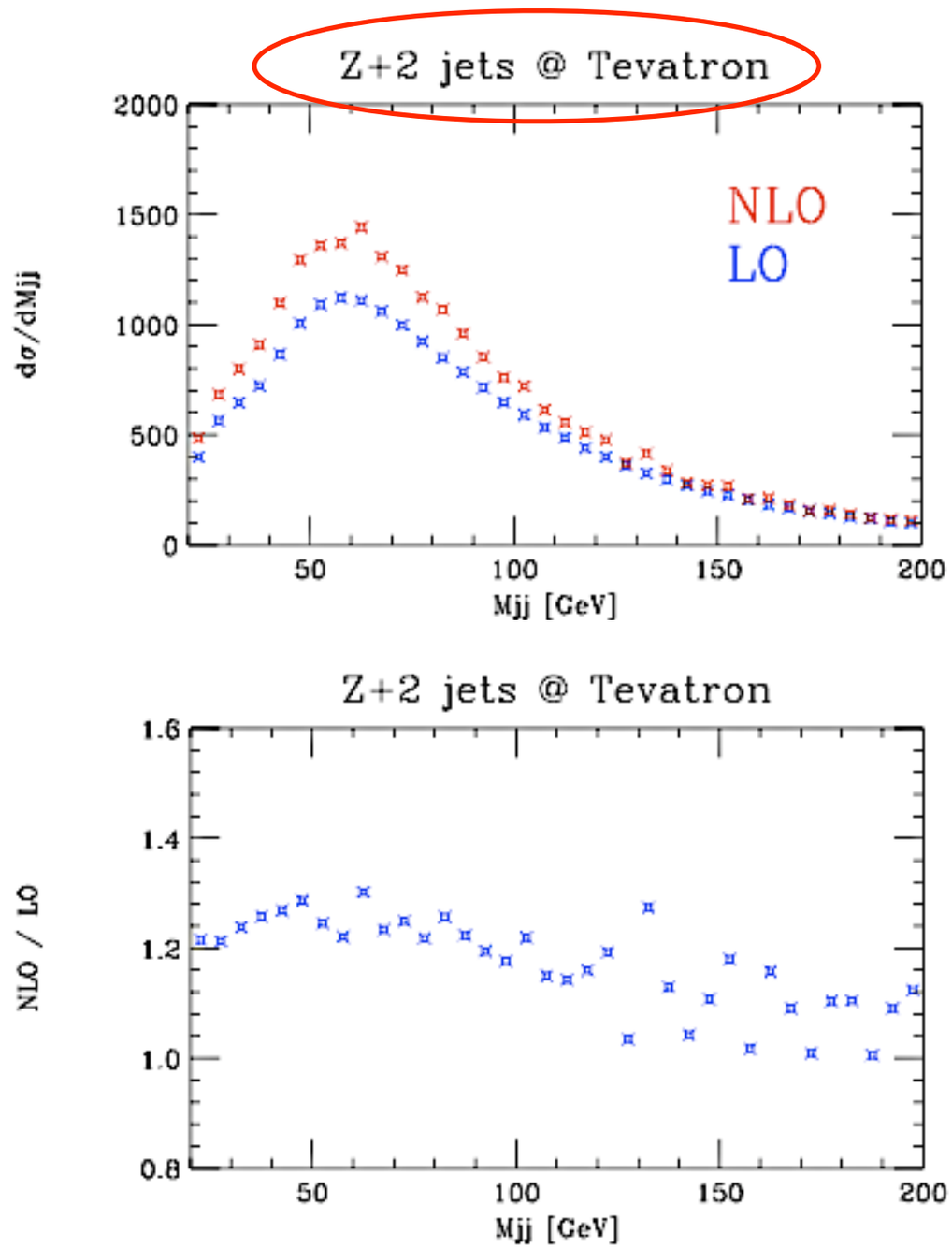
Abazov et al., arXiv: 0907.4286



Dijet invariant mass

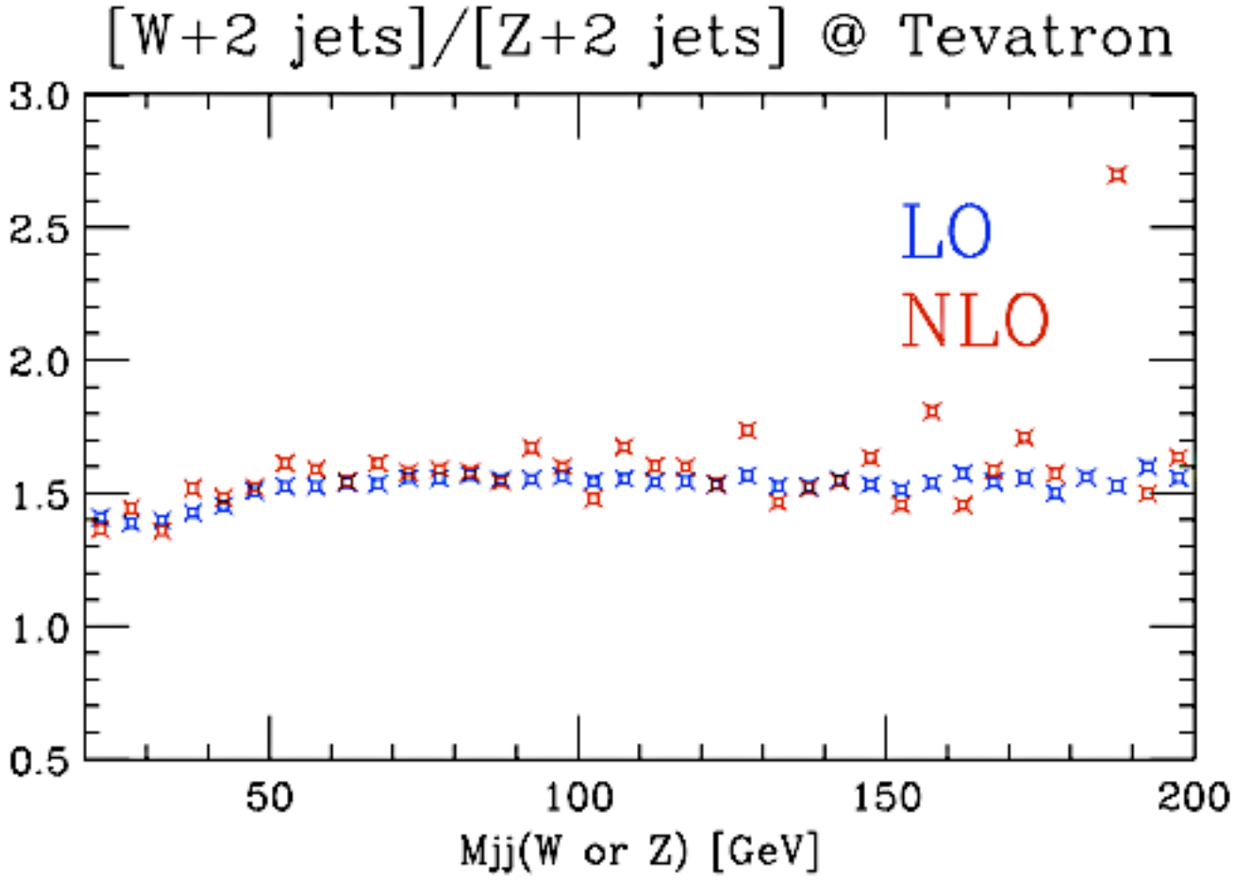
- Particularly relevant for associated production. Typical Tevatron cuts.





W/Z dijet mass comparison

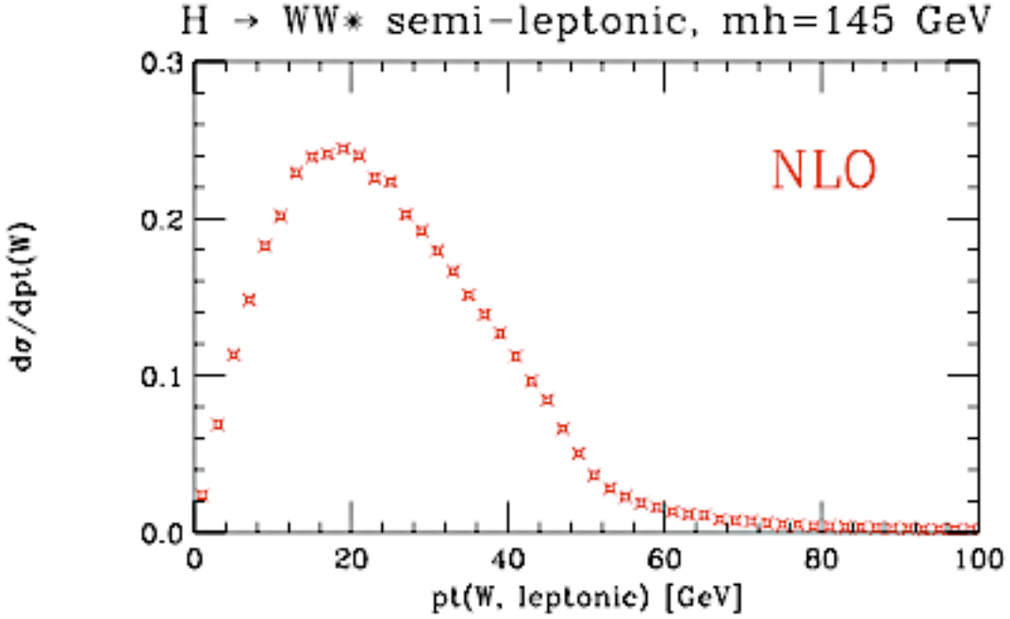
- In principle these two processes are slightly different - not only M_W vs. M_Z but also through couplings leading to different dependence on PDFs.
- In practice, these effects are very small.



- NLO statistics need some work, but:
  - usefulness of this ratio confirmed through NLO; practically just an overall rescaling.
  - simulations based on LO matrix elements should be reliable.

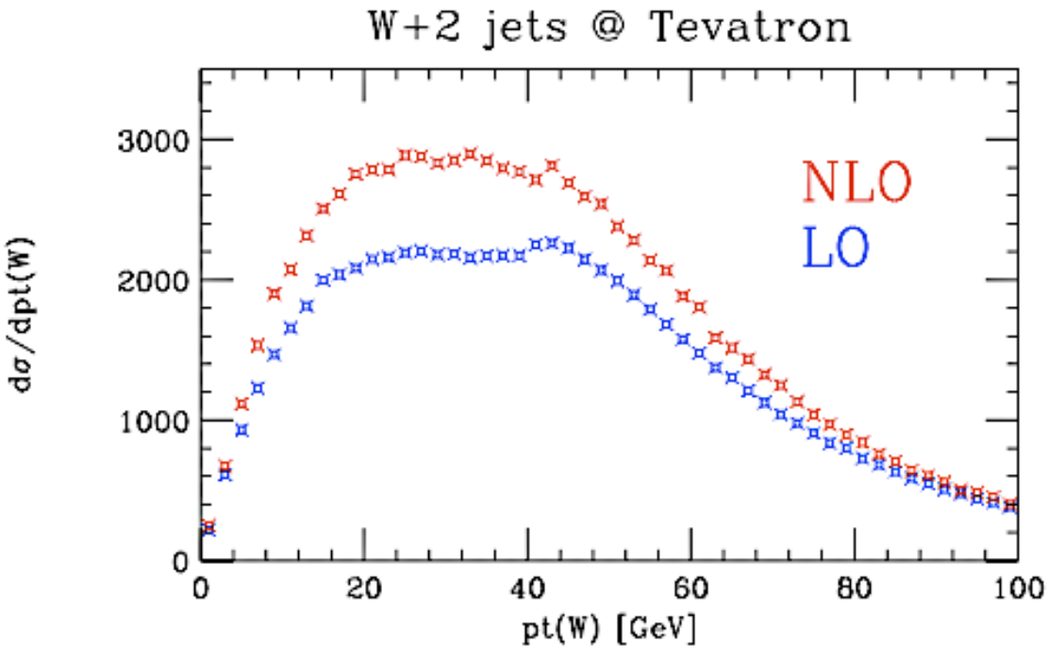
W/Z transverse momentum

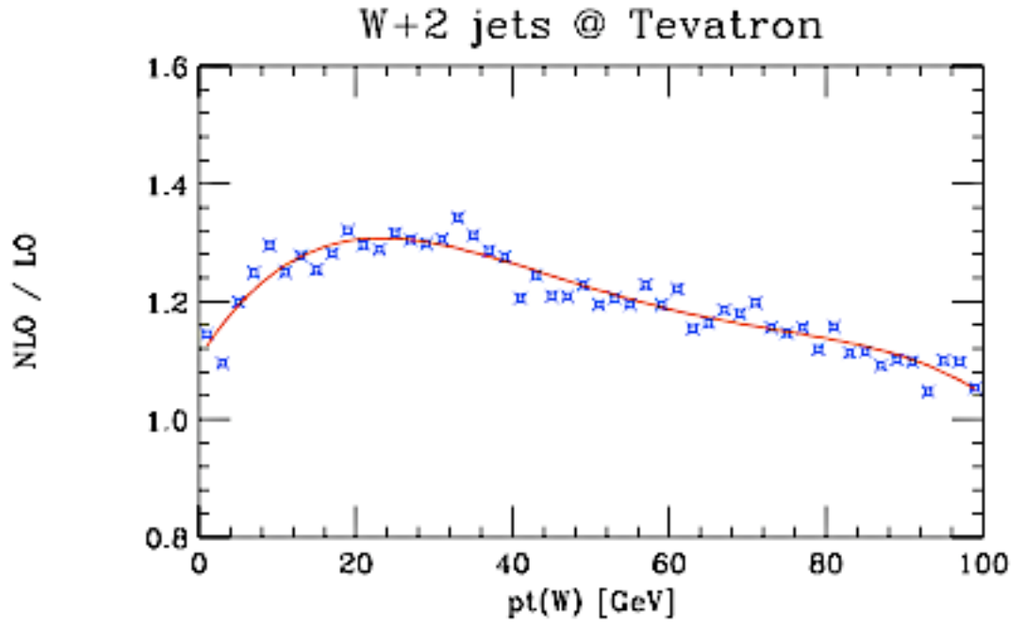
- Well-studied in the inclusive sample.
  - pQCD reliable at high p_T, resummation/parton shower important for modelling the bulk of the cross section at low p_T .
- Semi-leptonic H→WW* decays (i.e. below 160 GeV) produce a W with low transverse momentum, but in the presence of two jets.

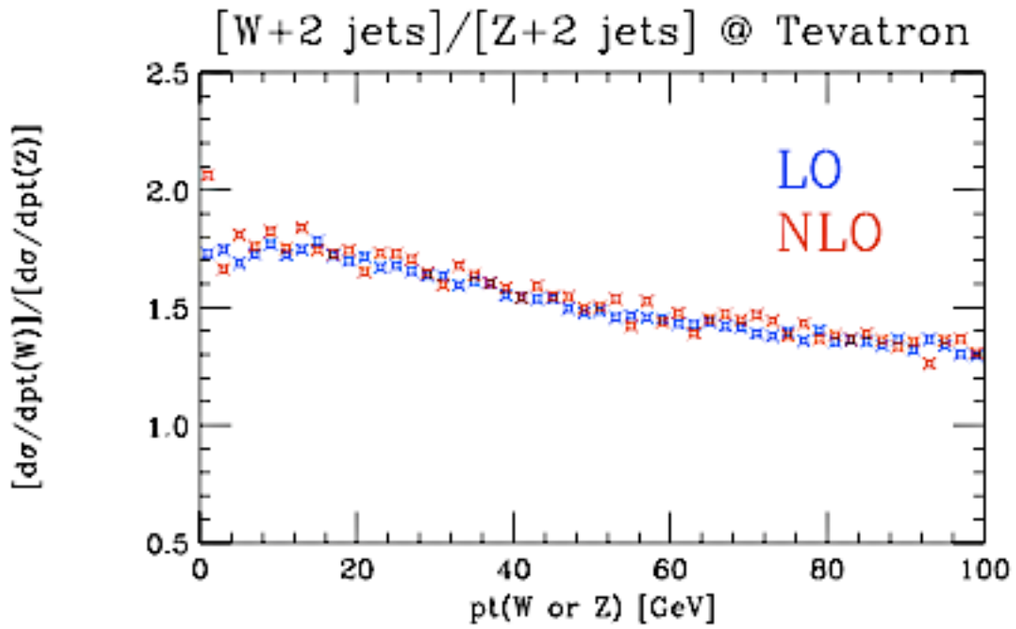


- So, a very different kinematic regime to inclusive W events.
- Requiring two hard jets enforces perturbative reliability even as $p_T(W)\rightarrow 0$.

W/Z transverse momentum comparison





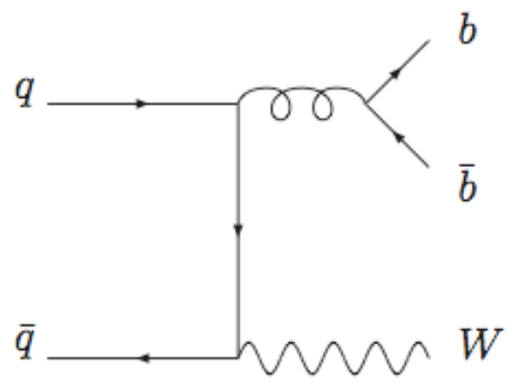


- Much the same story as dijet mass.
- W/Z ratio has more of a shape this time, but prediction is essentially the same at LO and NLO.

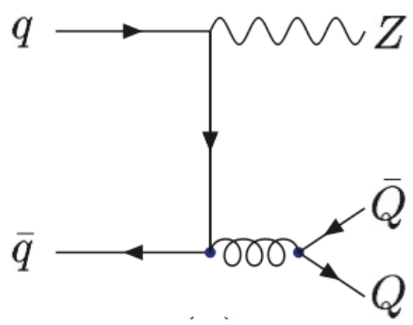
Heavy flavor

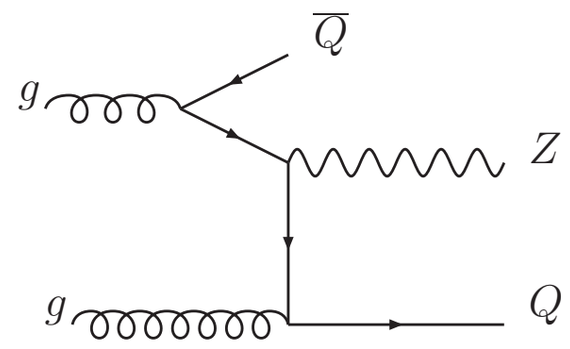
- Identifying heavy flavor component more important for associated production.
- Naively, very similar final states but:
  - smaller cross sections, less data, less studies.
  - harder theory: importance (or not) of mass effects, 4F vs 5F (more later).
- Stick with simplest case for now: two heavy flavor tags.
- Already differences between the two cases.

Wbb



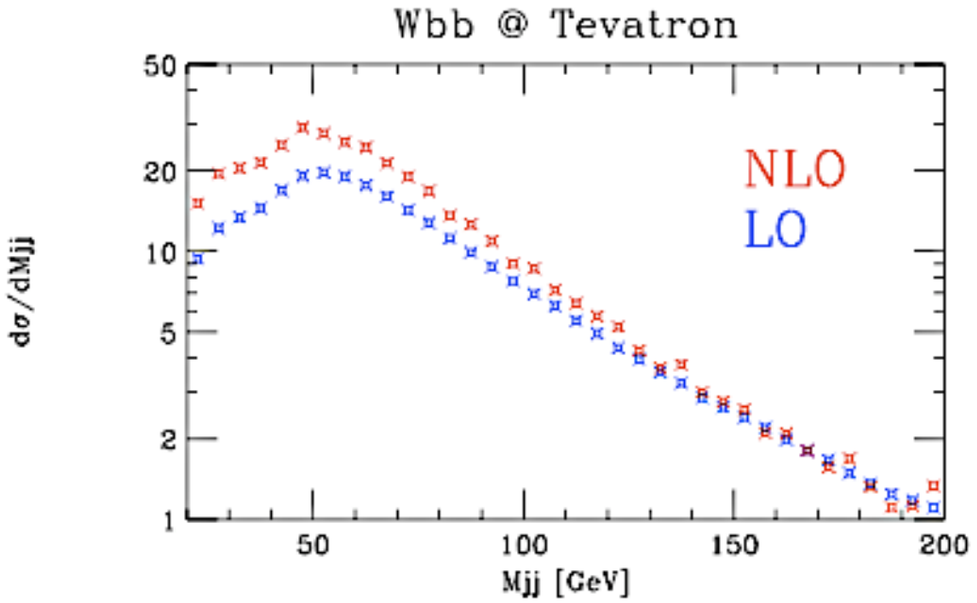
Zbb

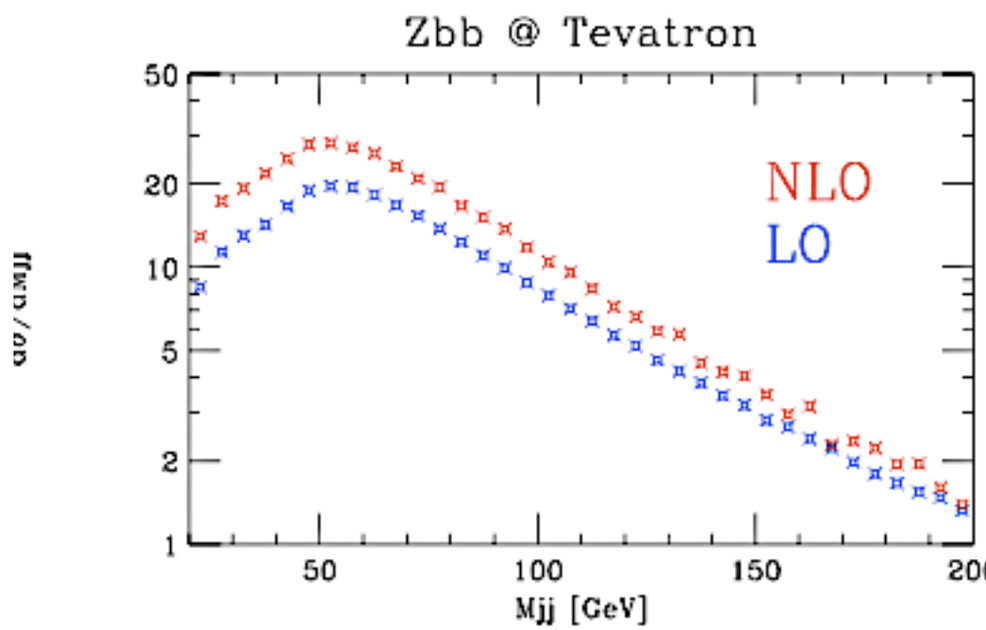


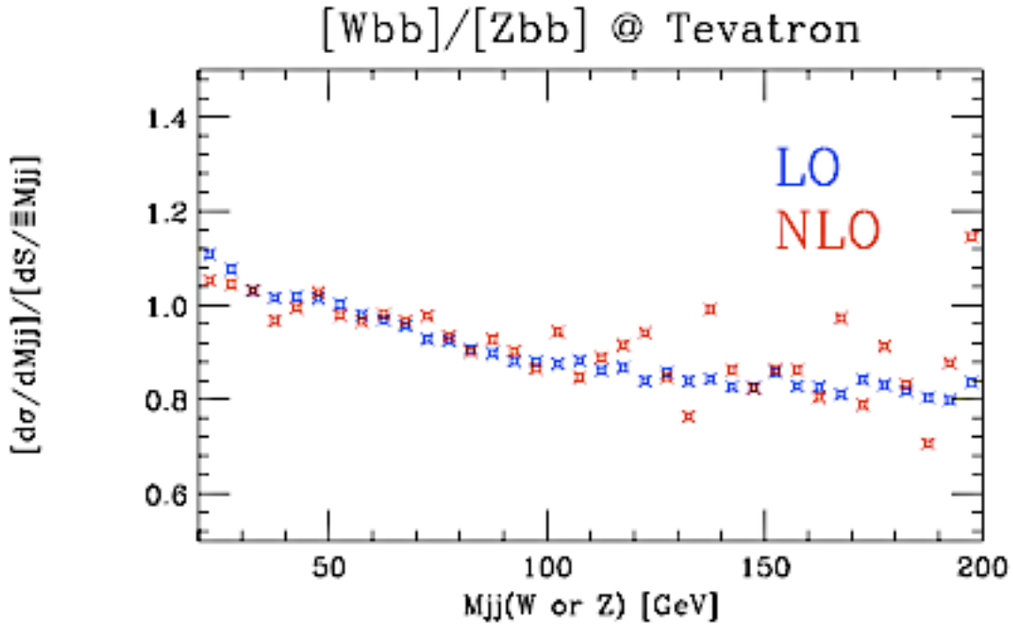


~30%

W/Z tagged dijet mass comparison





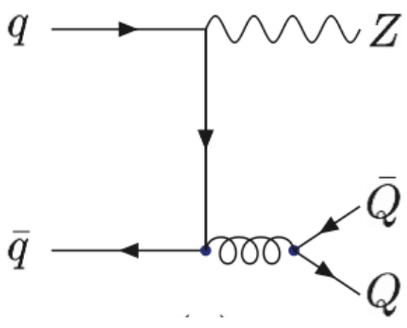


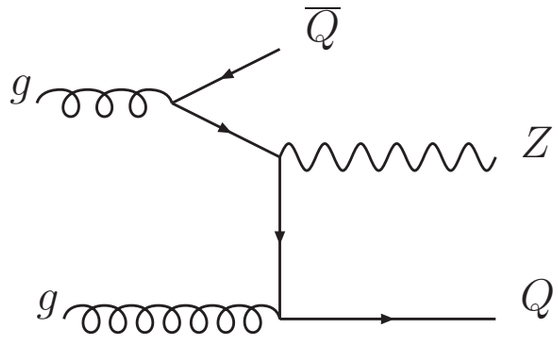
- Difference in production subprocesses appears to have only small effect.
- Again, ratio is stable from LO to NLO.
- Ratios to untagged sample should also be similar.

Dropping a tag

- Highly desirable in order to increase # of candidate events, but more complicated theoretical description.
- Particularly muddled situation in light of Tevatron results so far.

- Easiest to understand theory complications by looking at production of a Z boson and one or more jets, demanding one b-tag, i.e. Z+b.
- First approach: use the same diagrams as before and just integrate out a b-quark so that only one is explicitly observed.



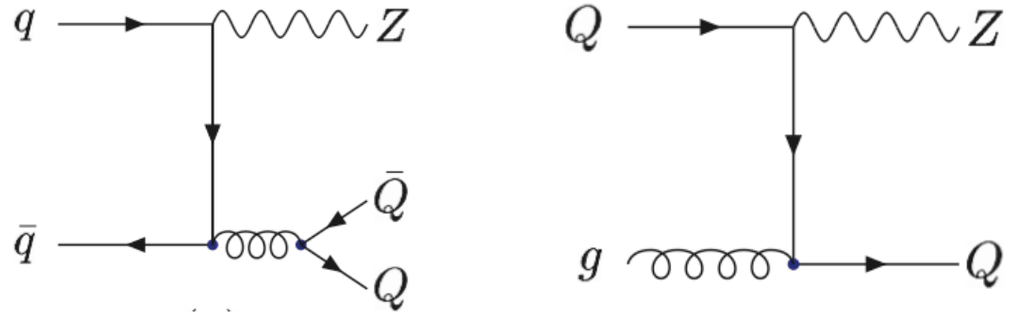


4-flavour scheme:
bottom quark confined
to the final state

- Performing this integration gives a term ~ $\log(m_b^2)$, so calculation must account for real b-quark mass: more difficult. **Febres Cordero, Reina, Wackeroth**

Alternative approach to Z+b

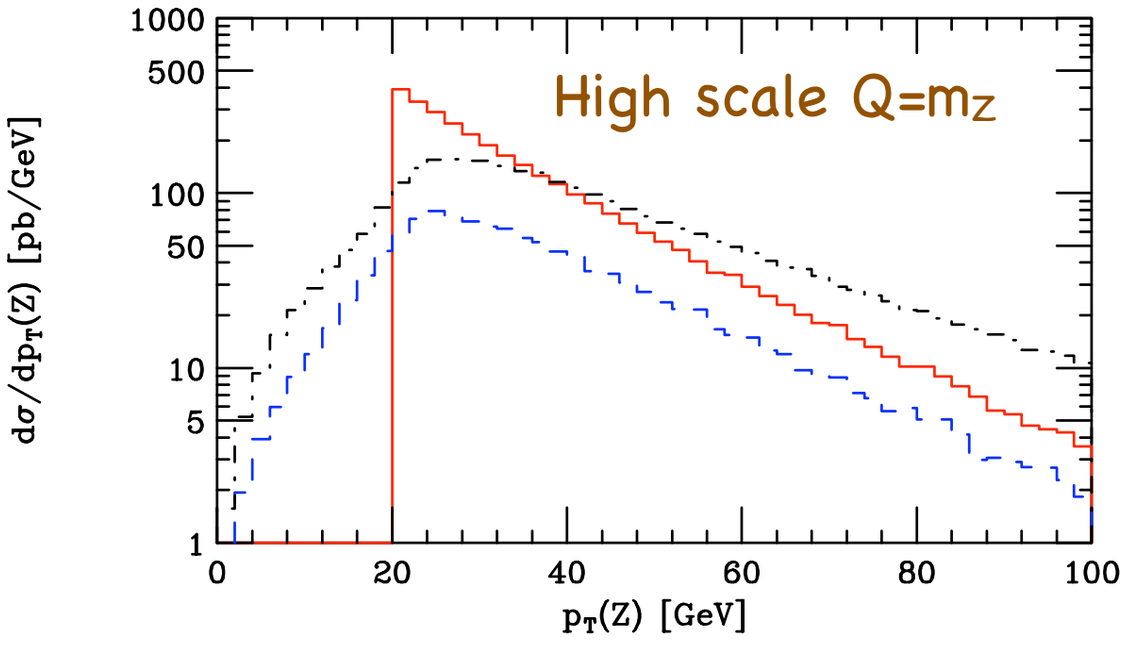
- Or: start from class of diagrams that produces only one b-quark to begin with.

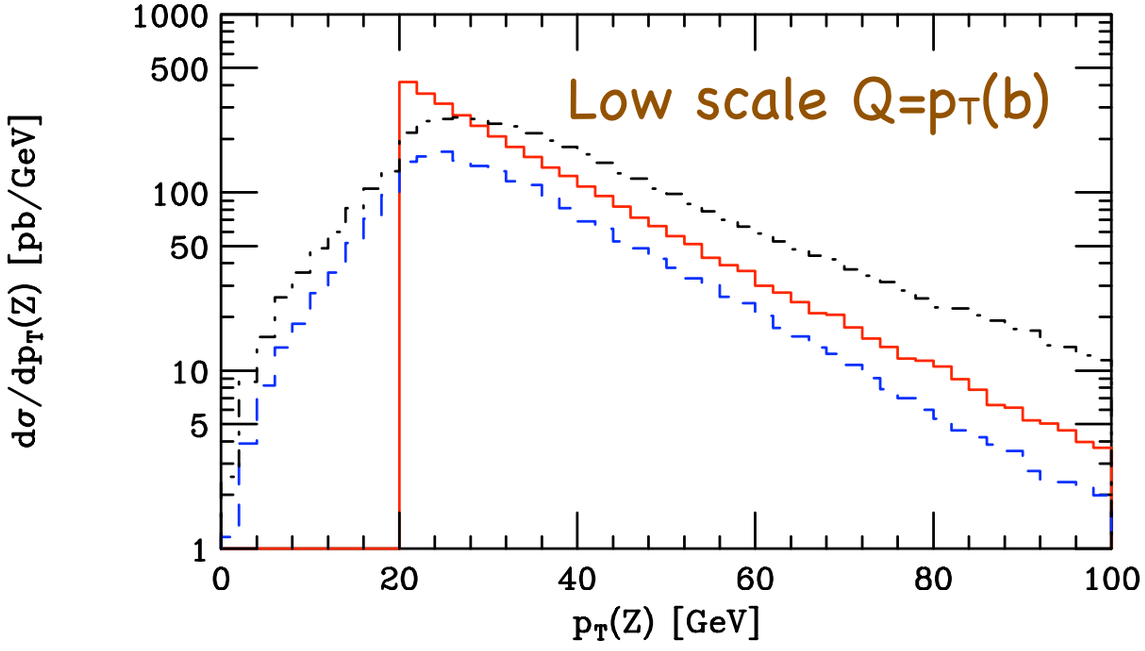


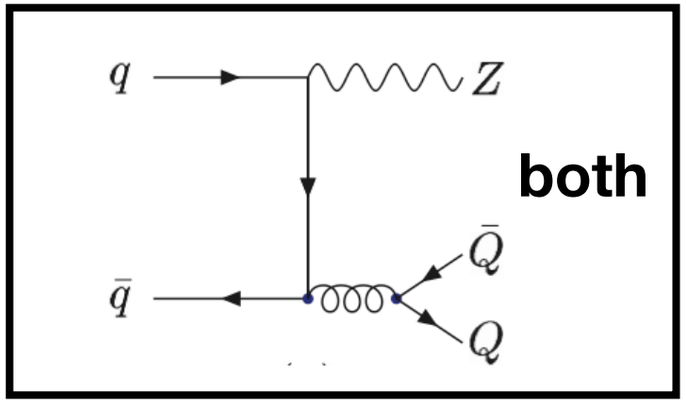
5-flavour scheme: diagrams contain bottom quark in the initial state

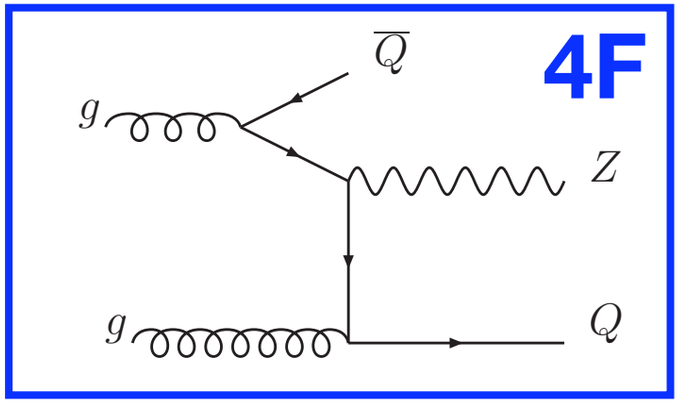
- In this approach the effects of the unobserved b-quark in the second diagram are swept into the bottom-quark PDF.
  - potentially large logarithms are resummed.
- The 4F and 5F approaches are equivalent at sufficiently high order.
- The 5F approach certainly presents an easier calculation but theorists will argue at length about the pros and cons of each scheme.
  - ultimately, data must be the judge.
  - kinematics of the two approaches are quite different.

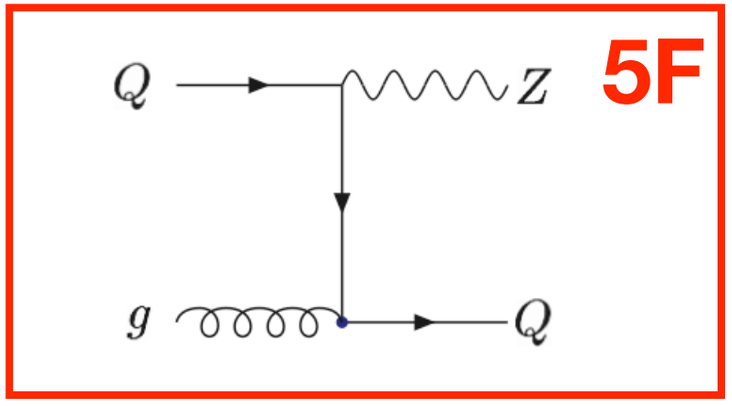
5F vs. 4F: Z p_T distribution in Z+b







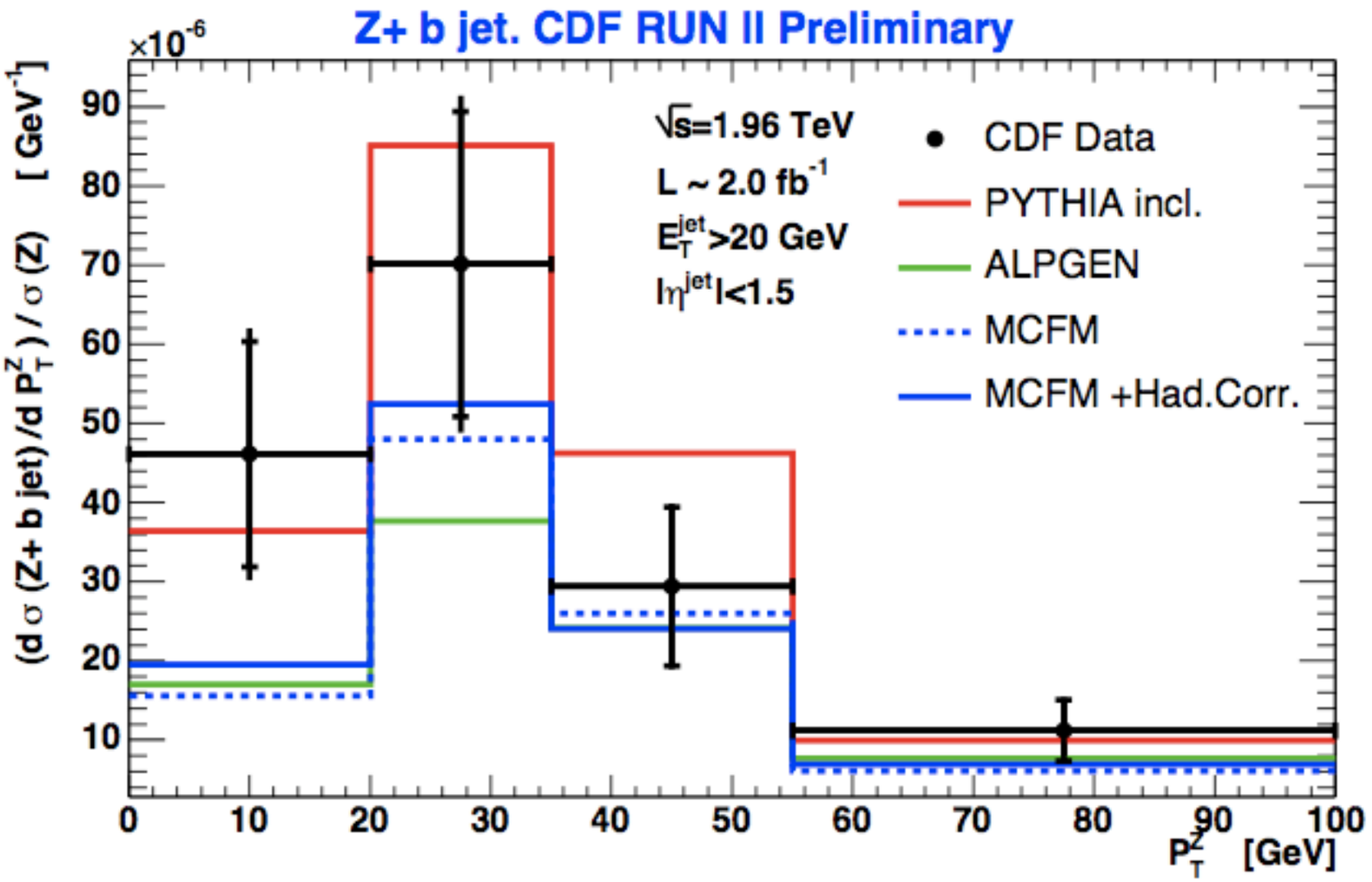




- Many scheme differences (as here) masked by larger qq→Zbb component at the Tevatron. Thus expect good overall modelling whichever scheme is used.
- Less inclusive predictions are harder, e.g. # of events with 2 jets, only 1 b-tag.

Current state of play: Z+b

- Rate of Z+b appears to be well understood (at least in ratio with Z - CDF, or with Z+jet - D0).
- Would be nice to understand more of the kinematic details, but (just) too early to say at the moment.



Aaltonen et al., arXiv: 0812.4458

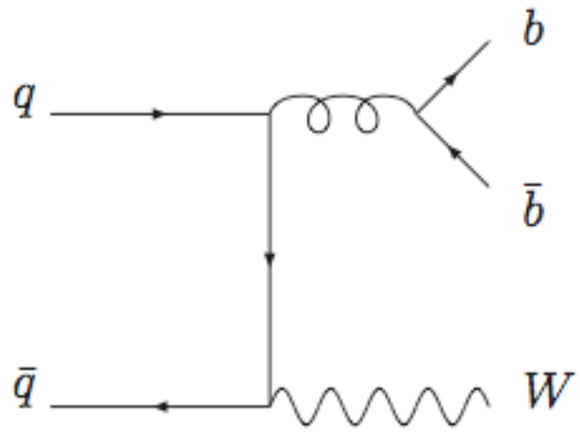
Well understood, or not?

Shape not great for any of the predictions.

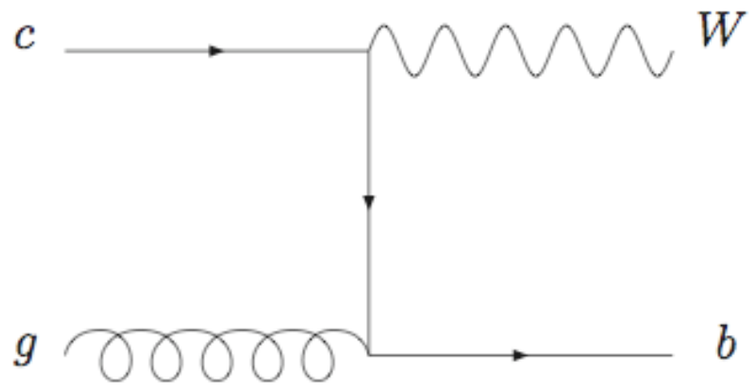
W+b

- Direct analog for W+b? Not quite.

(just like Z+b 4F)



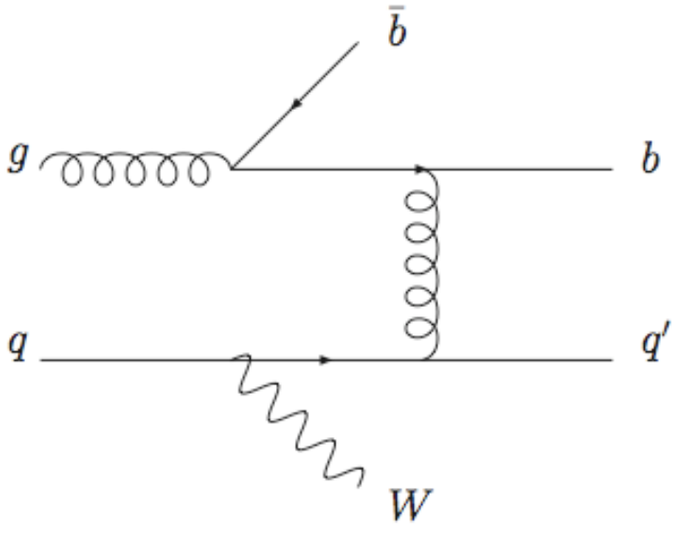
CKM suppressed, irrelevant

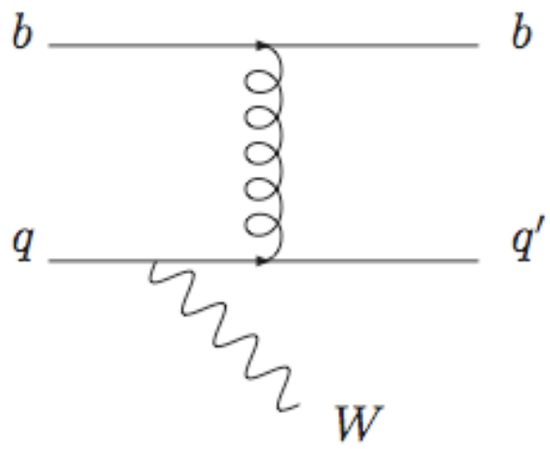


(analog of Z+b 5F)

- Slight wrinkle from next order in perturbation theory. Once again obtain a contribution that could be calculated in either scheme.

(NLO in 4F scheme)





(equivalent in 5F scheme)

- Gluon luminosity at Tevatron again saves us: this contribution is only ~ 10%.

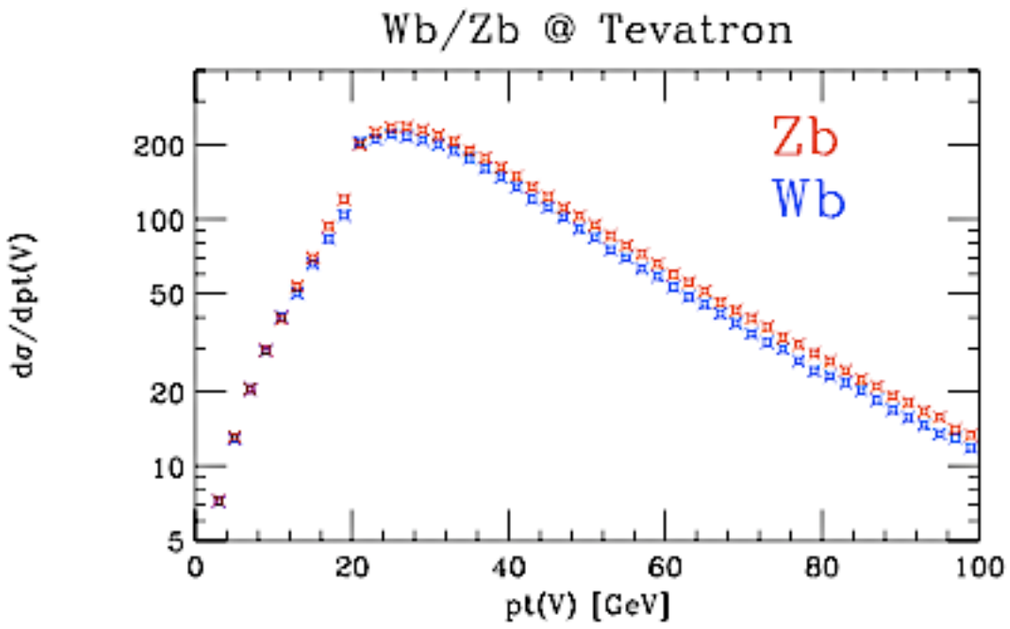
W+b from CDF

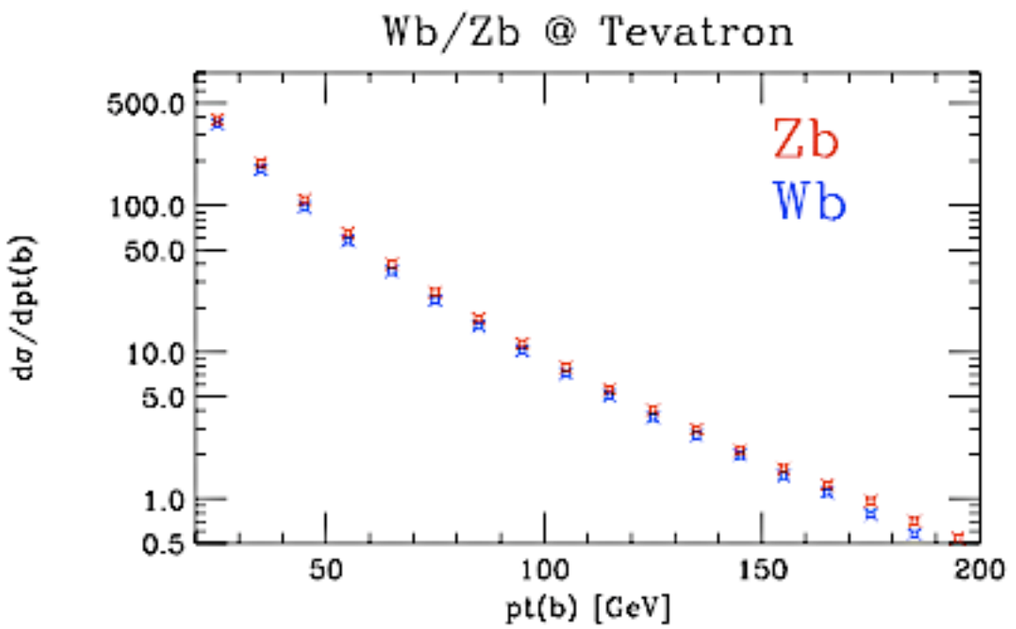
arXiv: 0909.1505

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

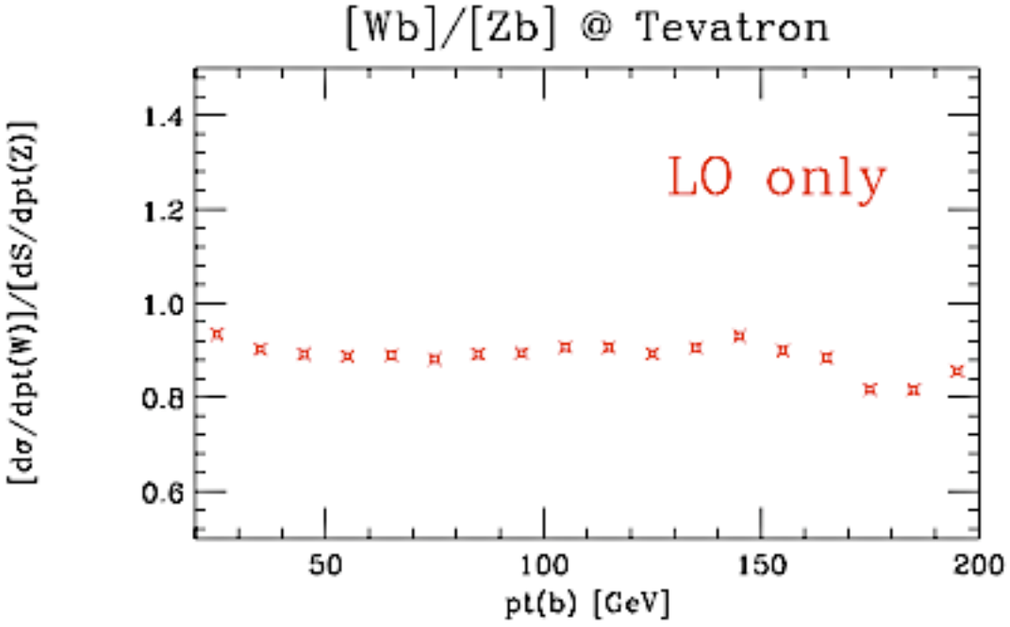
- MCFM calculation includes some 5F effects, but the bulk of the prediction is simply 4F at NLO.
  - enhancement about a factor of 1.35 over LO.
- Whoever you are, your preferred calculation is off by a factor of 2-3.

Wb/Zb comparison





- Behaviour very similar to double-tag case.
- No evidence for big impact of gluon-initiated Zbb process, e.g. pt(b) ratio almost flat.
- Hard to reconcile expected similarity with very different conclusions from Z+b and W+b studies.



Closing thoughts

- W+jets and Z+jets backgrounds appear to be under good theoretical control as long as we don't ask any questions about flavour.
    - ... but it would be nice to have a bit more direct evidence in the case of distributions that are of importance for Higgs searches.
- There is a high degree of similarity between many kinematic distributions for W+jets, Z+jets, whether or not jets are tagged (more than I might have guessed).
    - shapes of many ratios seem to be unchanged going from LO to NLO.
    - may be usefully exploited to get a better handle on some backgrounds.
- Comparisons with b-jet data are still confusing.
    - more kinematic distributions this summer (hopefully) should help to resolve this puzzle.