W/Z+jets theory

Standard Model Benchmarks at the Tevatron and the LHC
November 20, 2010

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Background

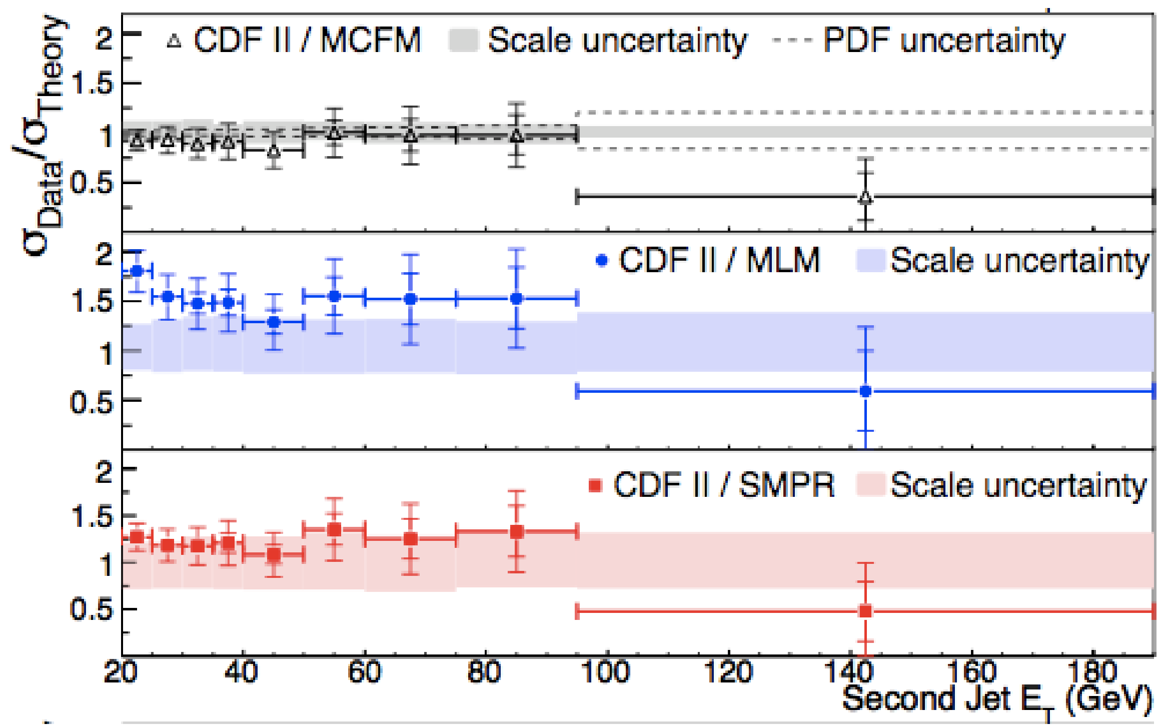
* W/Z production is a classic process:
  * clean experimental signatures with high cross sections;
  * well-defined in perturbation theory.
* Inclusive studies:
  * studies of kinematic properties, e.g. Z transverse momentum;
  * information on pdfs;
  * backgrounds to new physics;
  * paradigm for similar processes, e.g. Higgs production via gluon fusion.
* Identify final-state jets:
  * smaller cross sections, more sensitive to structure of QCD radiation;
  * still well-defined theoretically, but harder to calculate;
  * significant backgrounds to new physics, esp. heavy flavor jets.

Legacy of the Tevatron years

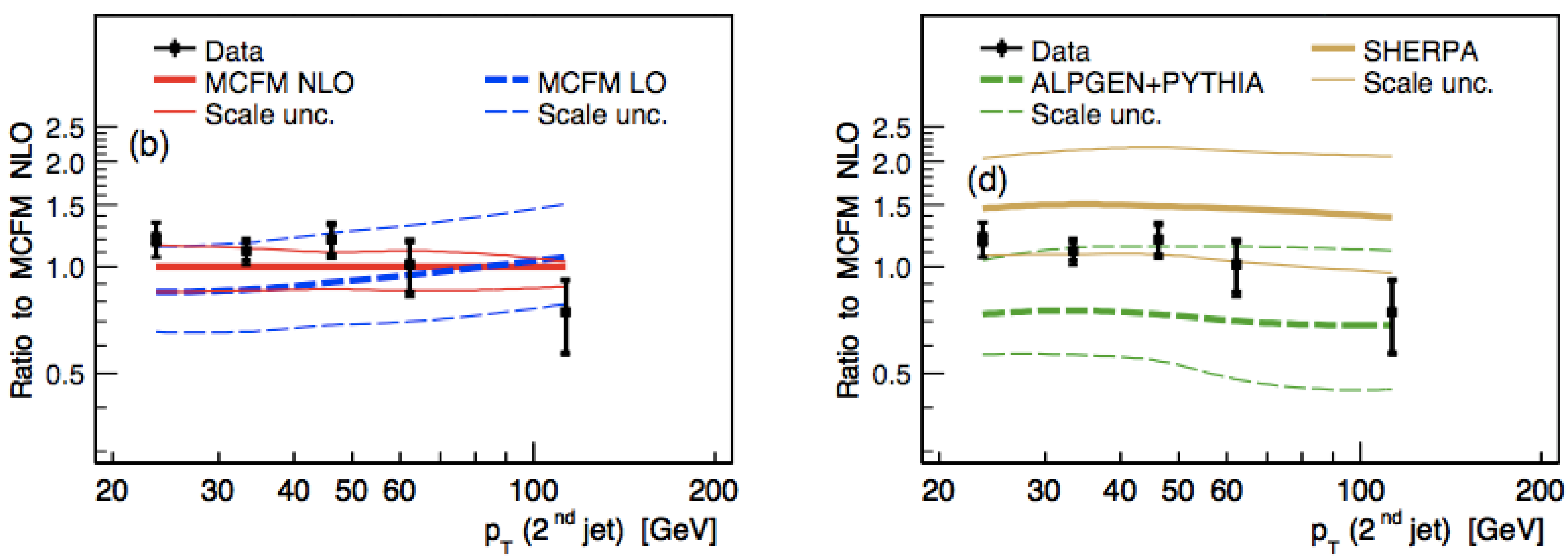
W/Z+ jets

- Has become a benchmark of QCD, with rates and jet spectra well-studied.
- Comparison with NLO now the norm (when available).
- Matched parton shower predictions now available.

Aaltonen et al., arXiv: 0711.4044

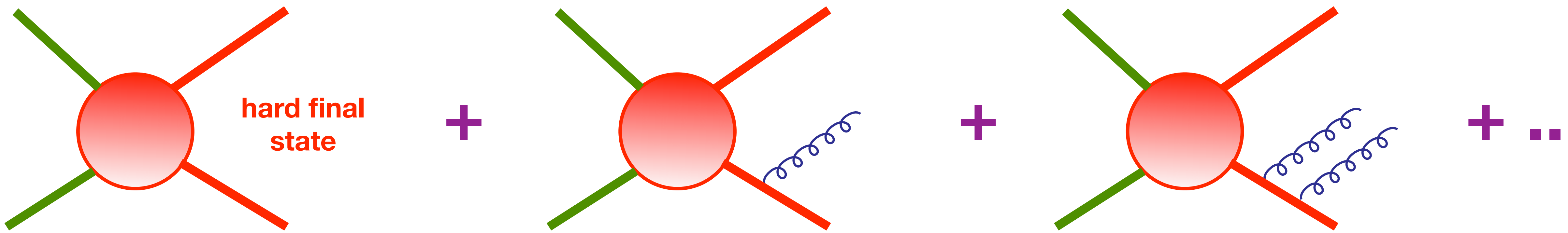


Abazov et al., arXiv: 0903.1748

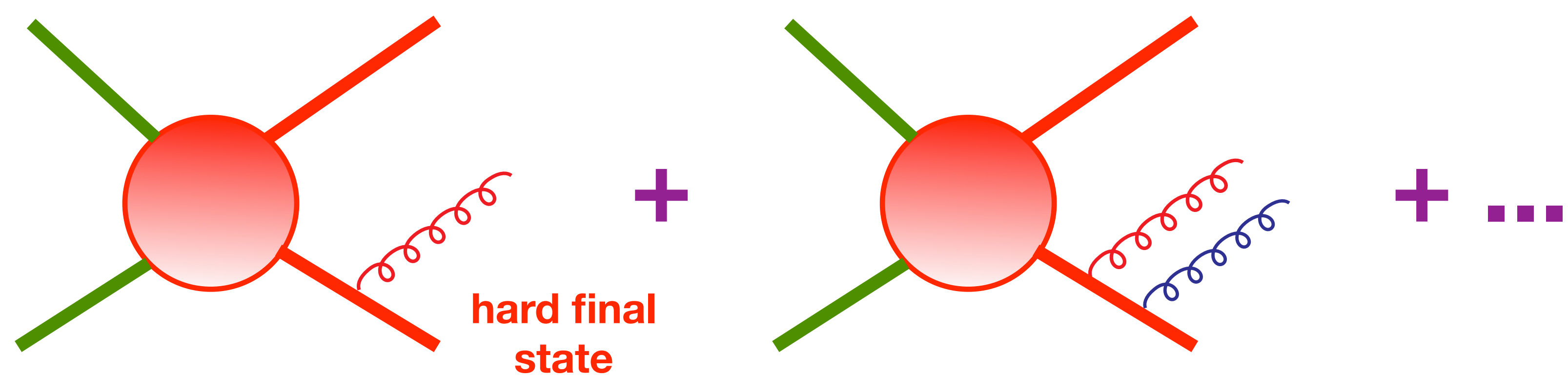


Improved parton showers

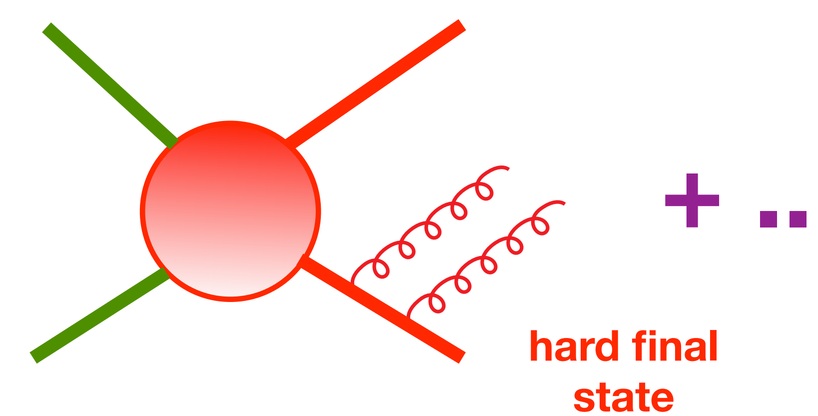
- Matched parton showers: include more hard matrix elements as initial hard scatters, with the trick being to avoid double counting: ME matching/merging.



- A number of different schemes for performing the merging exist, e.g.



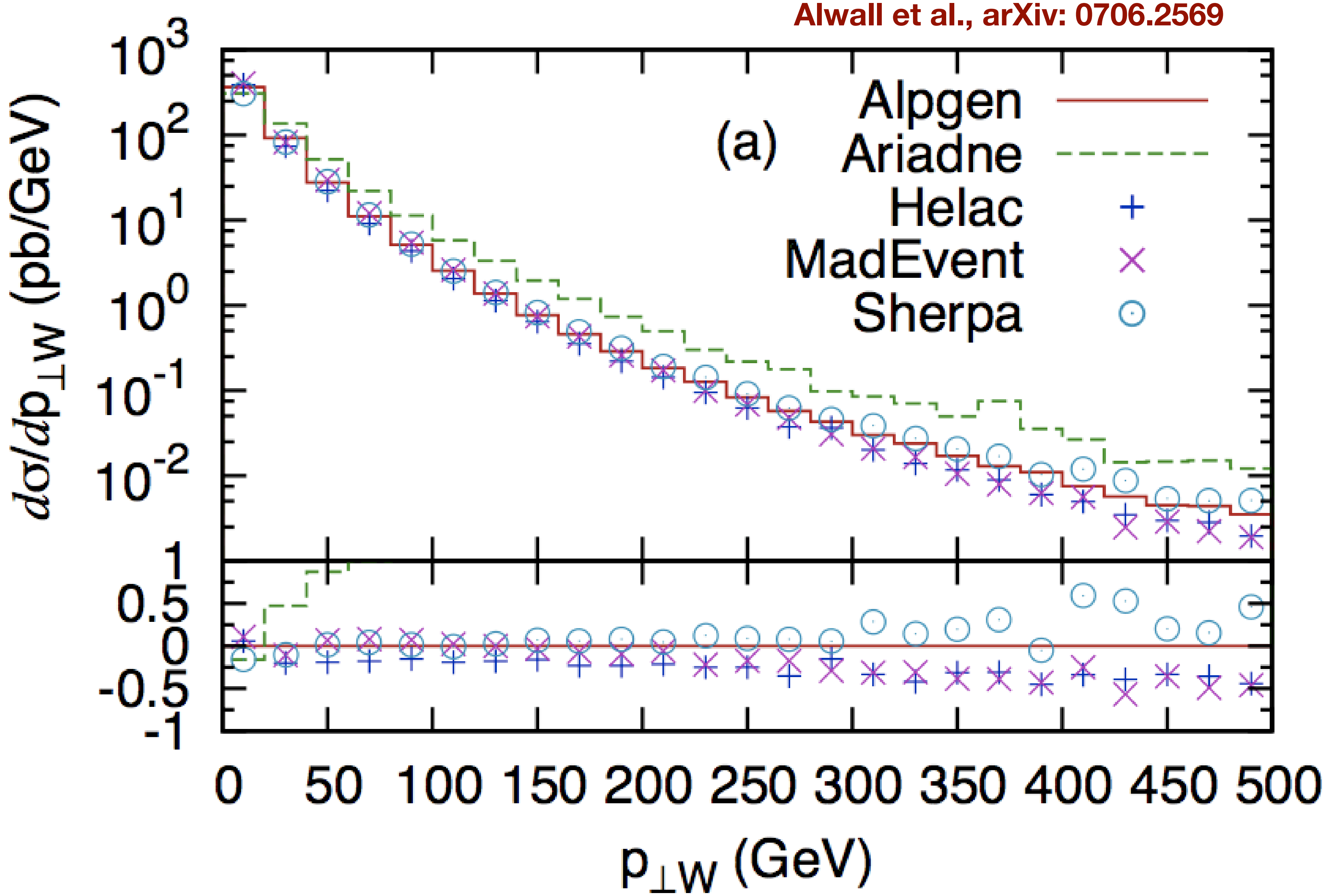
MLM } ALPGEN
CKKW
ME&TS } SHERPA
("matrix element+truncated shower")



Tuning

- Huge effort to validate/tune the range of different Monte Carlos against each other and Tevatron data.
- Aim: cross-check at Tevatron and extrapolate to LHC.

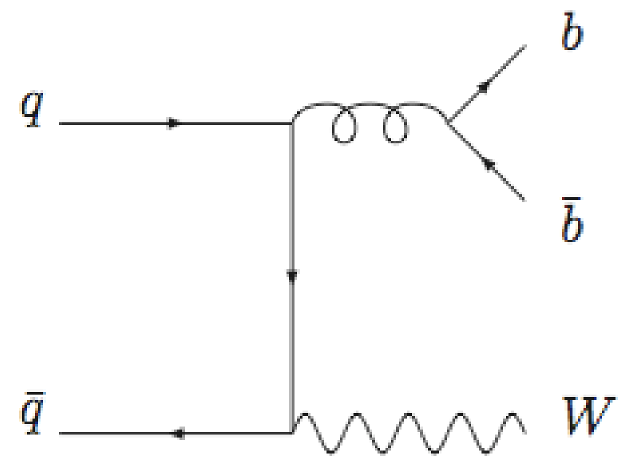
Alwall et al., arXiv: 0706.2569

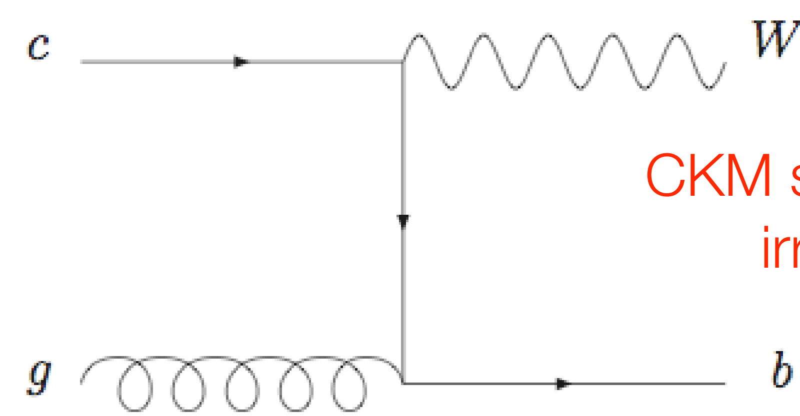


14 TeV LHC

W+b jet production

- At first sight, heavy flavor jets should be well described (large single top, H bkgds). Dominant contribution is a subset of diagrams for light jet production.





CKM suppressed, irrelevant

CDF, arXiv: 0909.1505

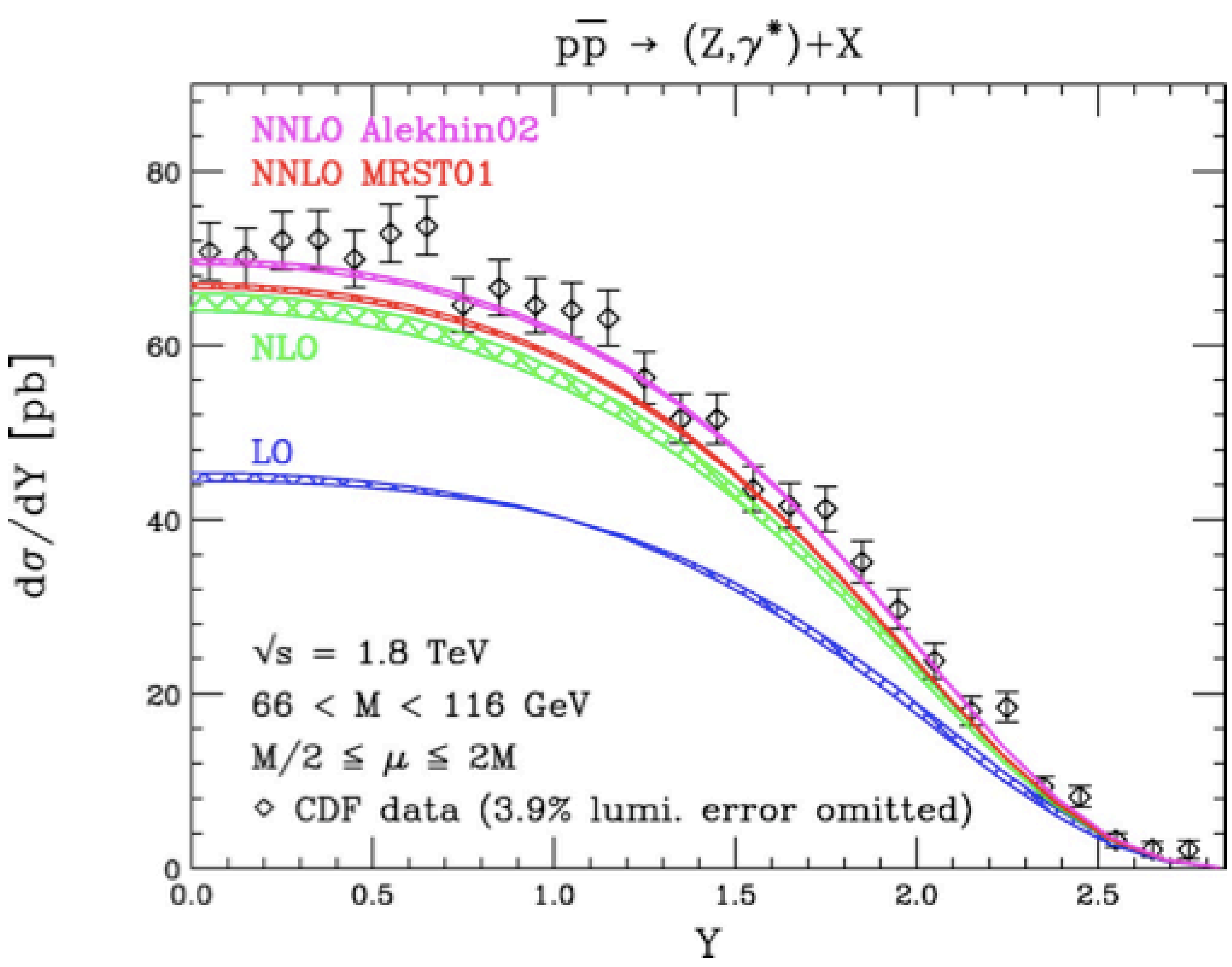
CDF	**2.74** ±0.27 (stat) ±0.42 (syst) pb
ALPGEN	**0.78** pb
PYTHIA	**1.10** pb
NLO	**1.22** ±0.14(scale) pb

Overall: comparison of pQCD predictions for W/Z+heavy flavour with Tevatron data not as satisfactory as for light jets

Percent precision

* NNLO corrections to inclusive cross section known since 1991 (Hamberg et al.).
* Similar level in distributions much more recently.

Anastasiou et al. (2003); Melnikov and Petriello (2006), Catani et al. (2009)

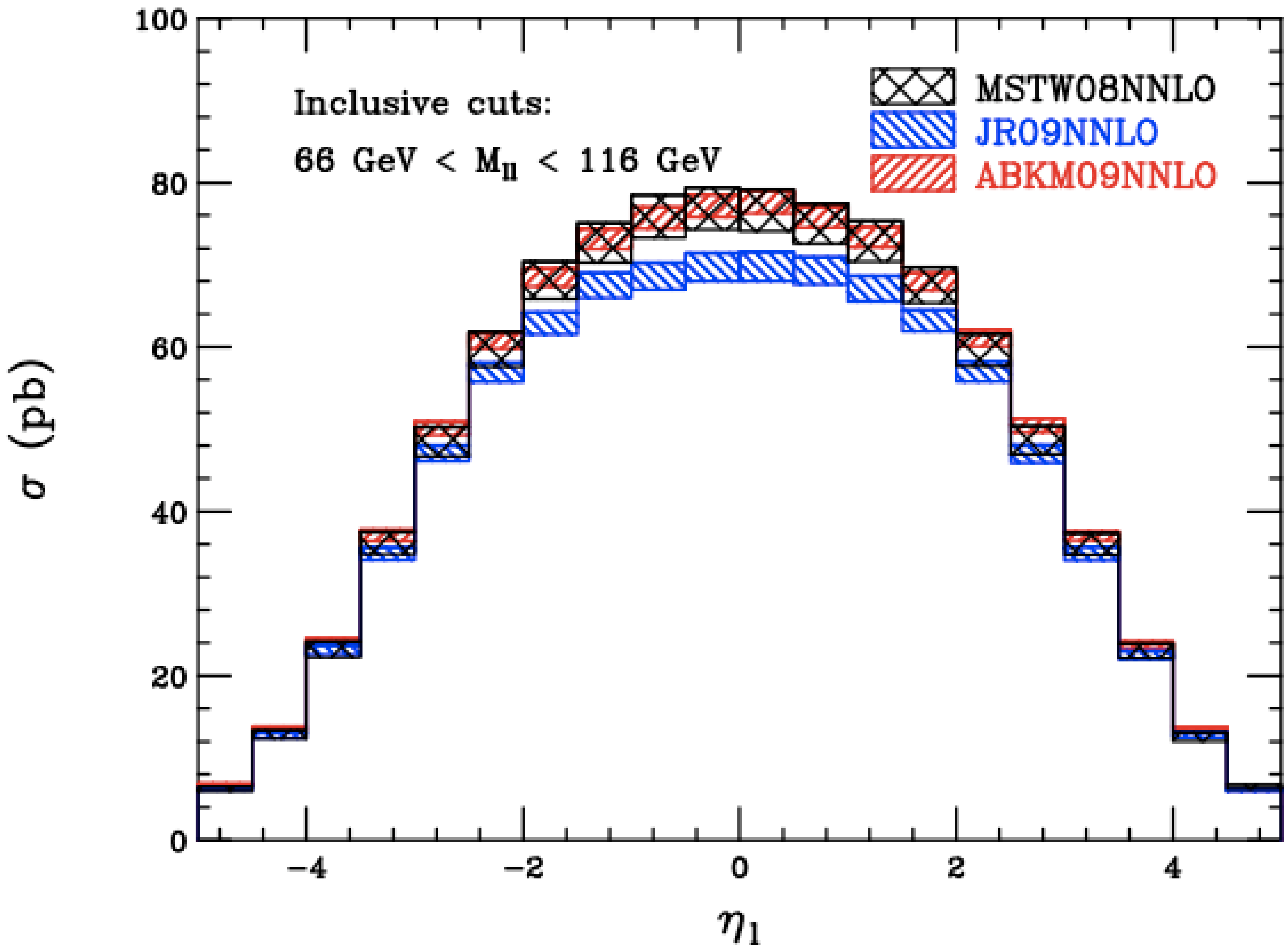


Technological breakthrough for NNLO calculations

Allows matching of experimental cuts and detailed kinematic comparisons

FEWZ 2.0

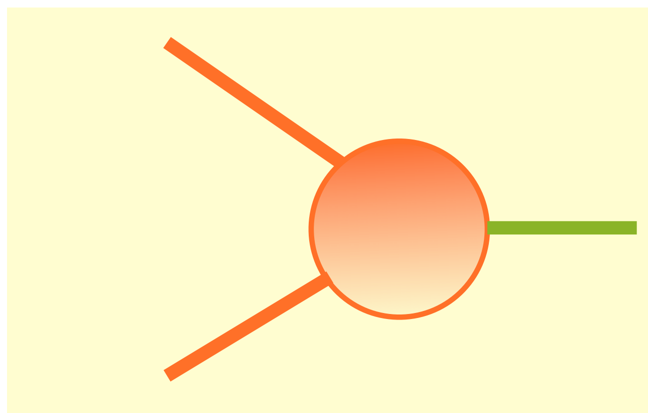
- Fully Exclusive W and Z Production. **Gavin, Li, Petriello, Quackenbush, arXiv:1011.3540**
- Improved version of previous code: customization and speed (x12 speed-up).



Inclusive/exclusive comparison

- Orders of calculation populate different jet bins at differing orders of accuracy.

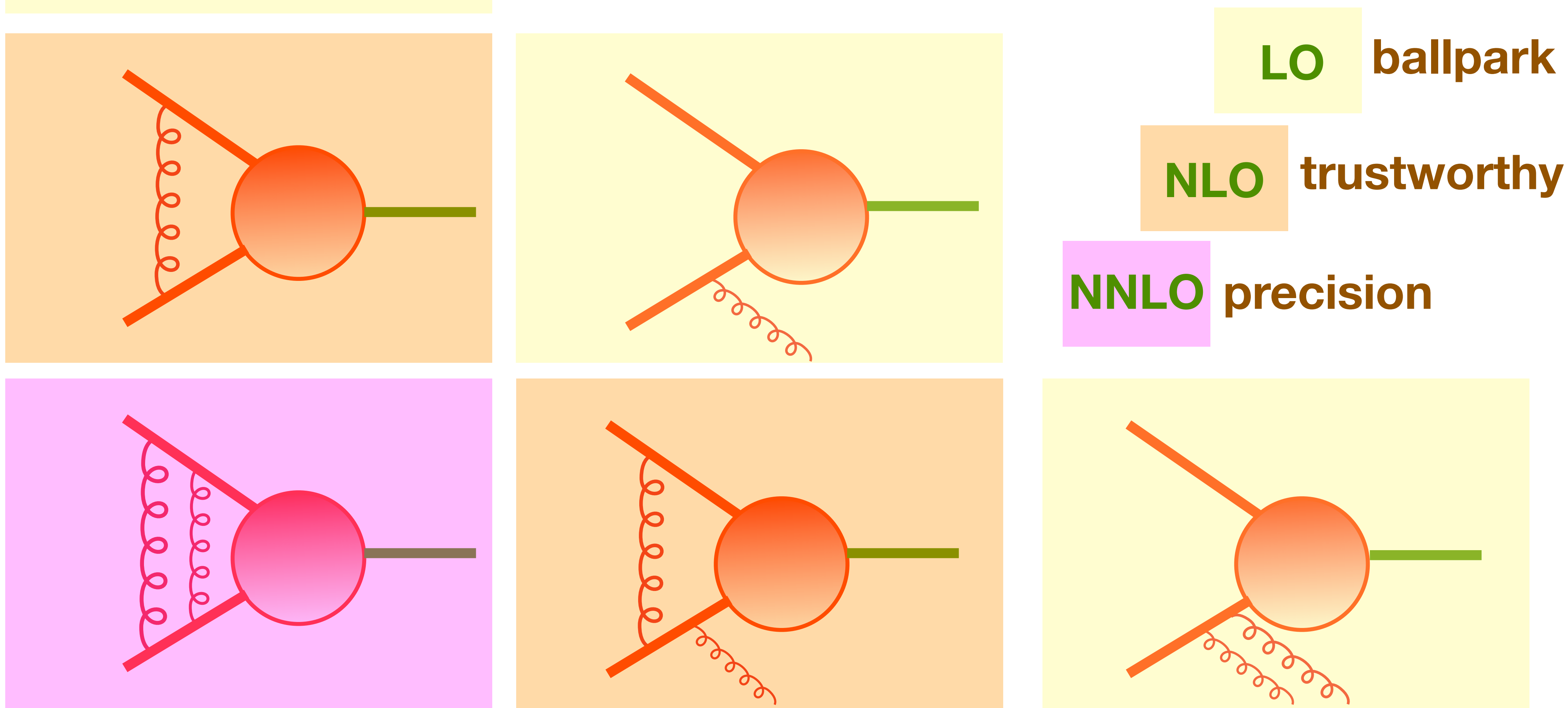
LO W production



- When moving beyond normalizing a total cross section, better to think of order of **observable** rather than **calculation**.

NLO W inclusive

NNLO W inclusive



0-jet kinematics **1-jet** **2-jet**

Tools for the LHC

Recent NLO results

- Access to new NLO results for high-multiplicity final states thanks to generalized unitarity and ease of automation of such algorithms → vital for LHC.
- NLO results for W+3 jets available for just over a year.
  - two groups, Blackhat+Sherpa (arXiv:0902.2760), Rocket (arXiv:0901.4101).
- New results for Z+3 jets from Blackhat+Sherpa.

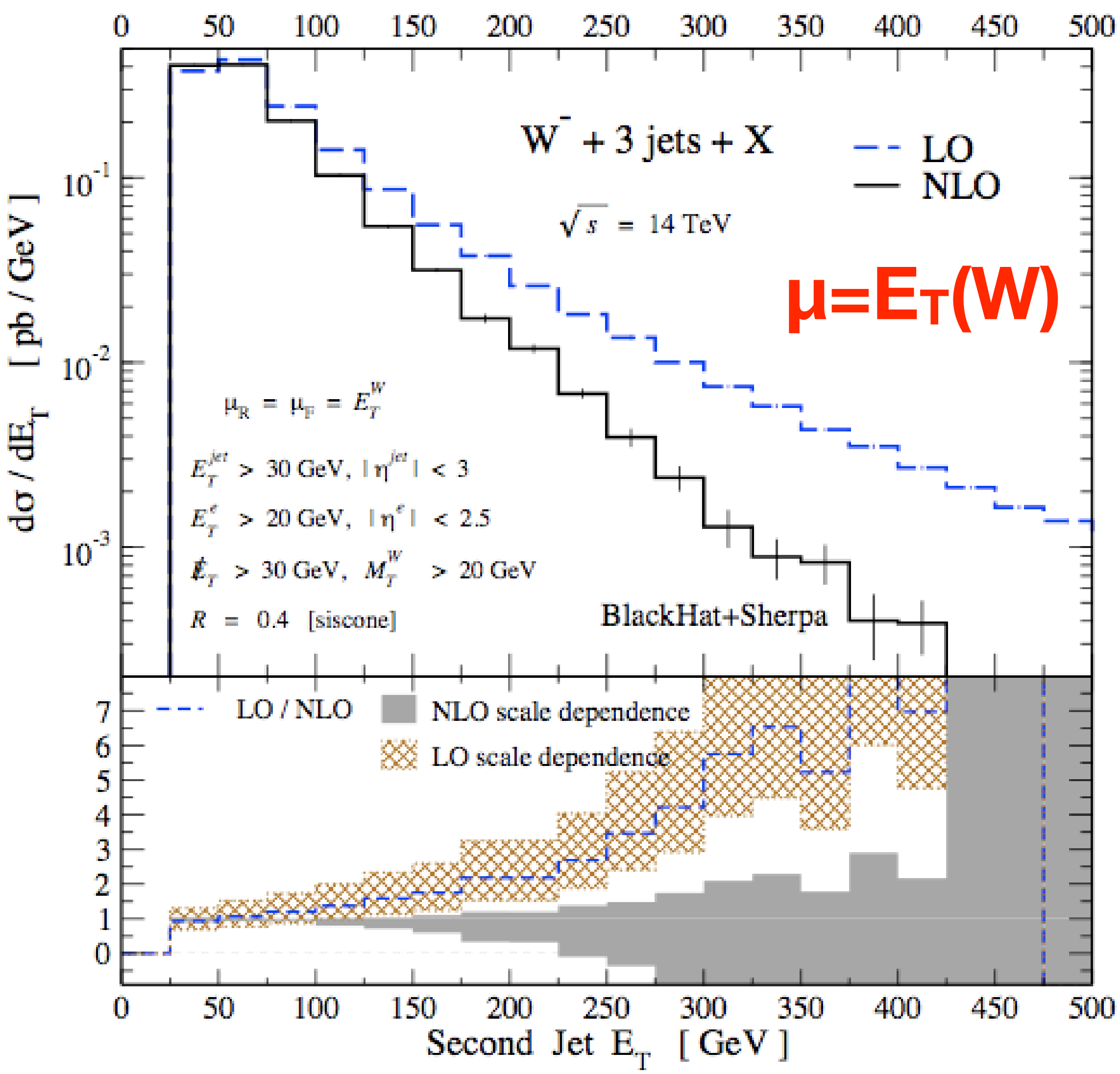
C. Berger et al., arXiv: 1004.1659

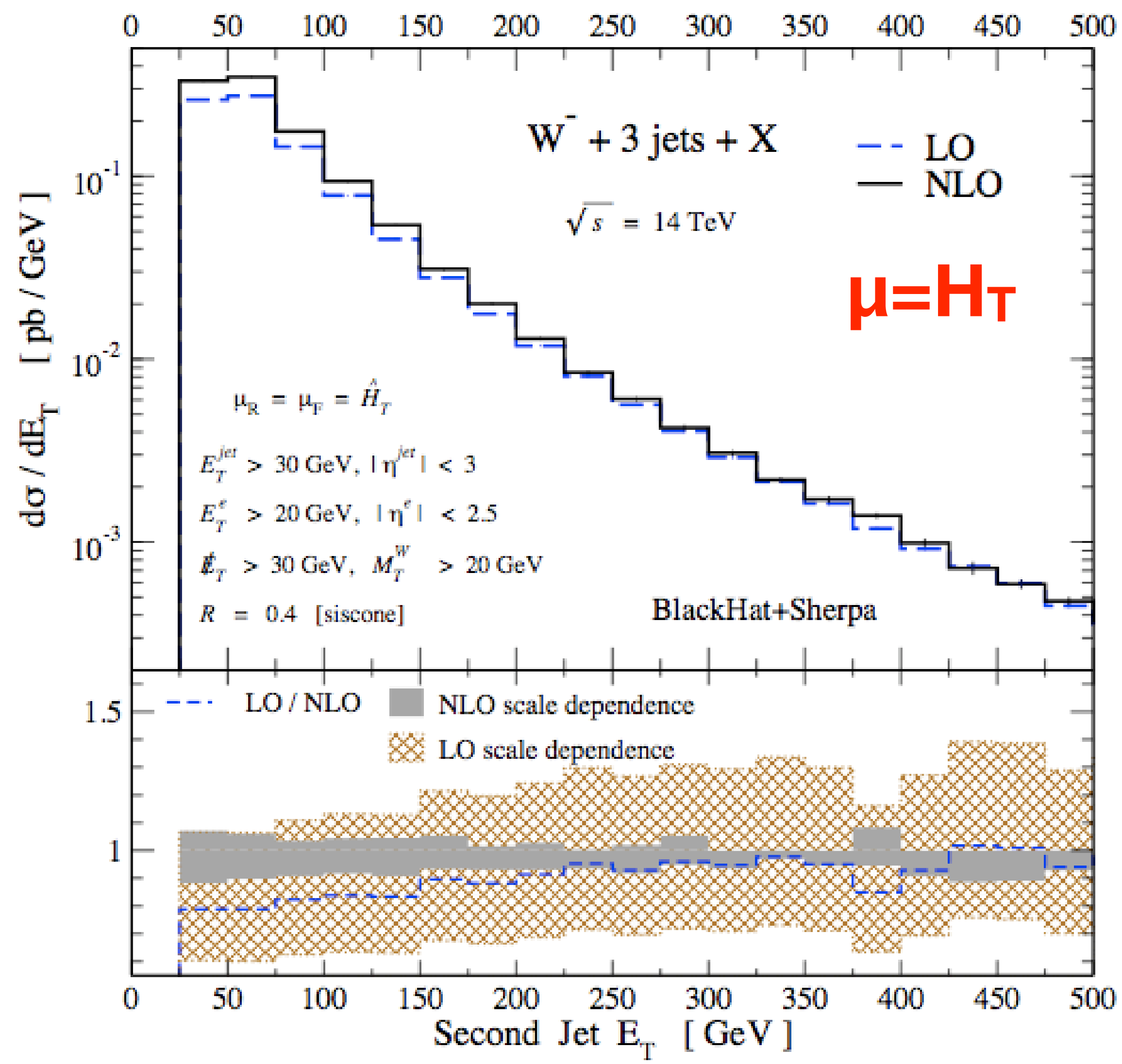
# of jets	CDF midpoint	LO parton SISCone	NLO parton SISCone	LO parton anti-k_T	NLO parton anti-k_T
1	$7003 \pm 146^{+483}_{-470} \pm 406$	$4635(2)^{+928}_{-715}$	$6080(12)^{+354}_{-402}$	$4635(2)^{+928}_{-715}$	$5783(12)^{+257}_{-334}$
2	$695 \pm 37^{+59}_{-60} \pm 40$	$429.8(0.3)^{+171.7}_{-111.4}$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

- As the number of jets increases details of the jet algorithm become more important. CDF analysis: midpoint, R=0.7, so large hadronization corrections.
  - much closer for W+3 jets where R=0.4 (see Hoche et al., arXiv: 1003.1241).
- W+4 jet results just released (C. Berger et al., arXiv: 1009.2338).

New insight

- Not just more predictions with which to compare, but better understanding of features of perturbative calculations.
  - e.g. choices of scale leading to good perturbative behaviour.

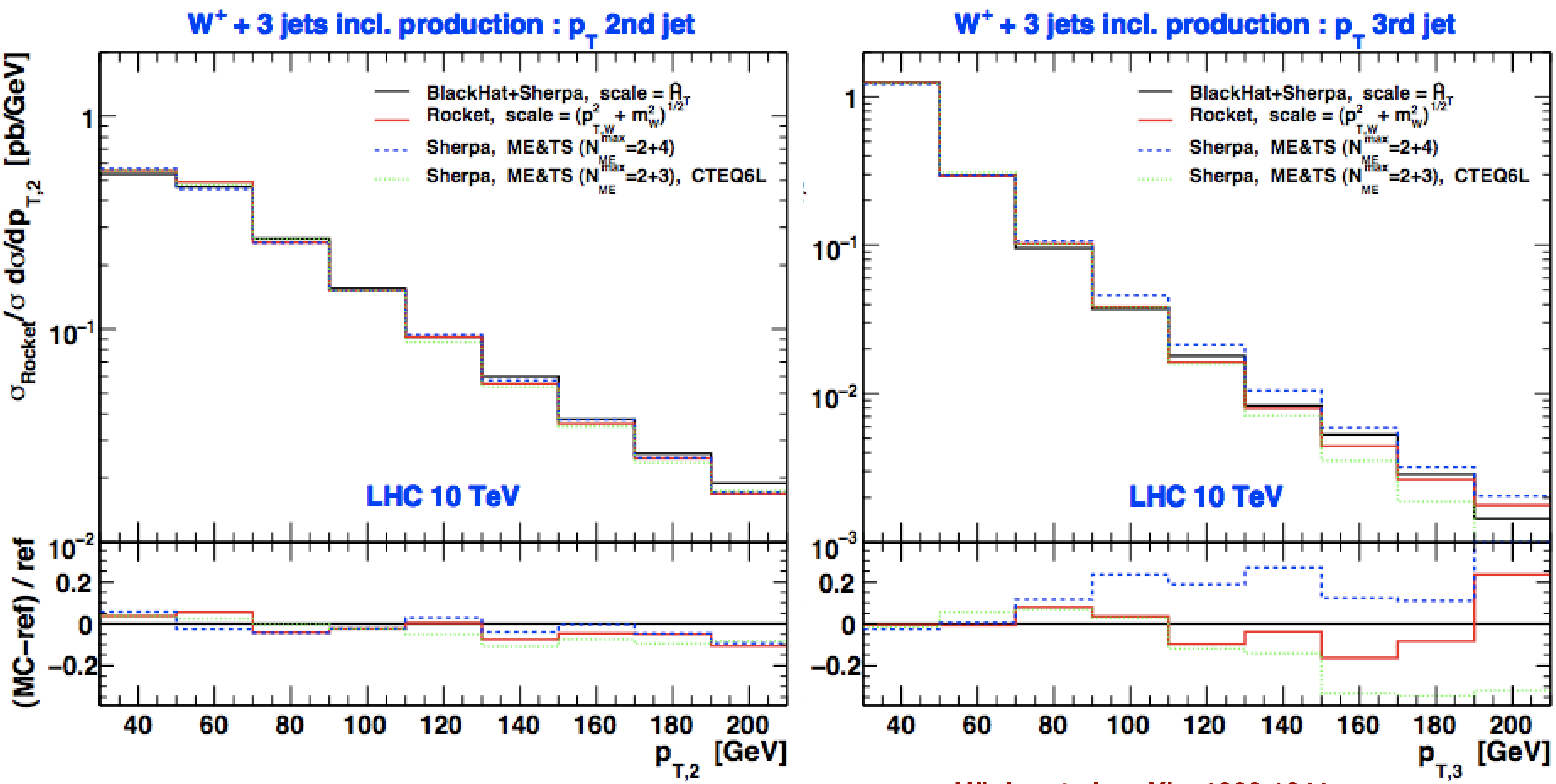




Moral: at large E_T, properties of W are not important

NLO vs. parton shower

- Systematic comparisons now possible at high jet multiplicities.
- In absence of NLO+PS, essential for making the most out of NLO results.

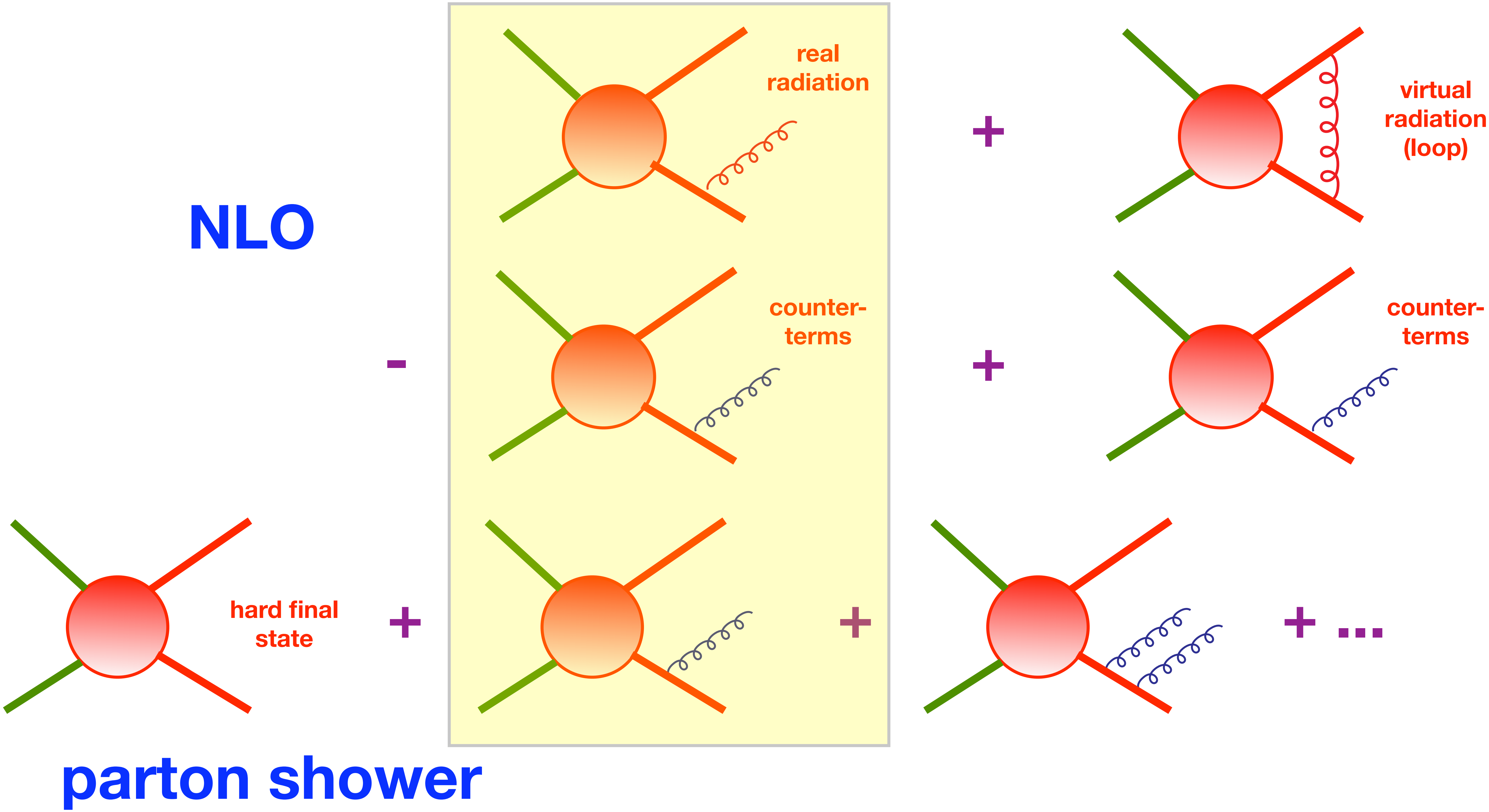


Höche et al., arXiv: 1003.1241

NLO(μ₁) vs. NLO(μ₂) vs. PS (SHERPA)

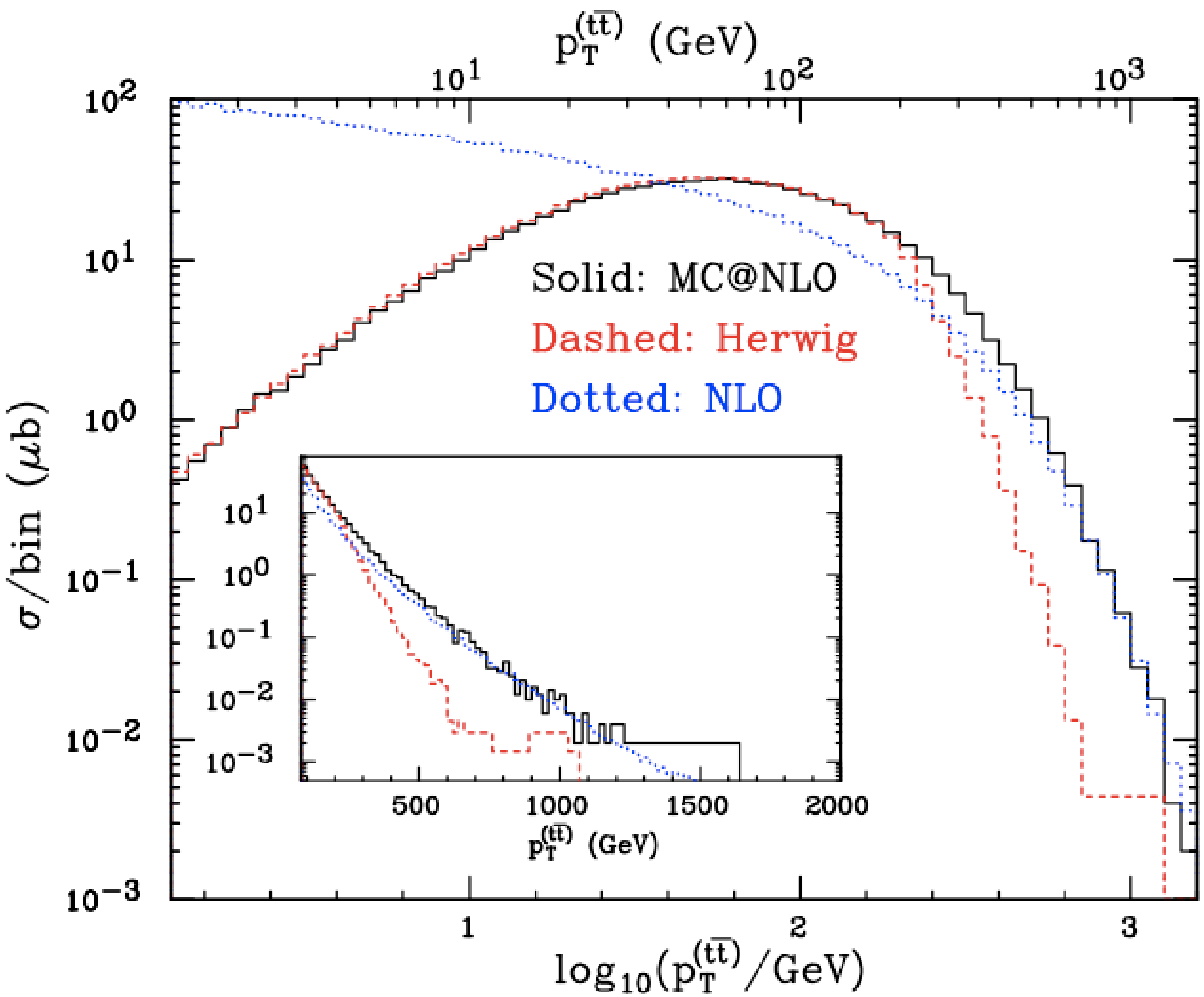
NLO + parton shower

- Problem is relatively easy to state but much harder to solve.



NLO + PS: MC@NLO

* First real matching of a parton shower (HERWIG) onto a NLO calculation.



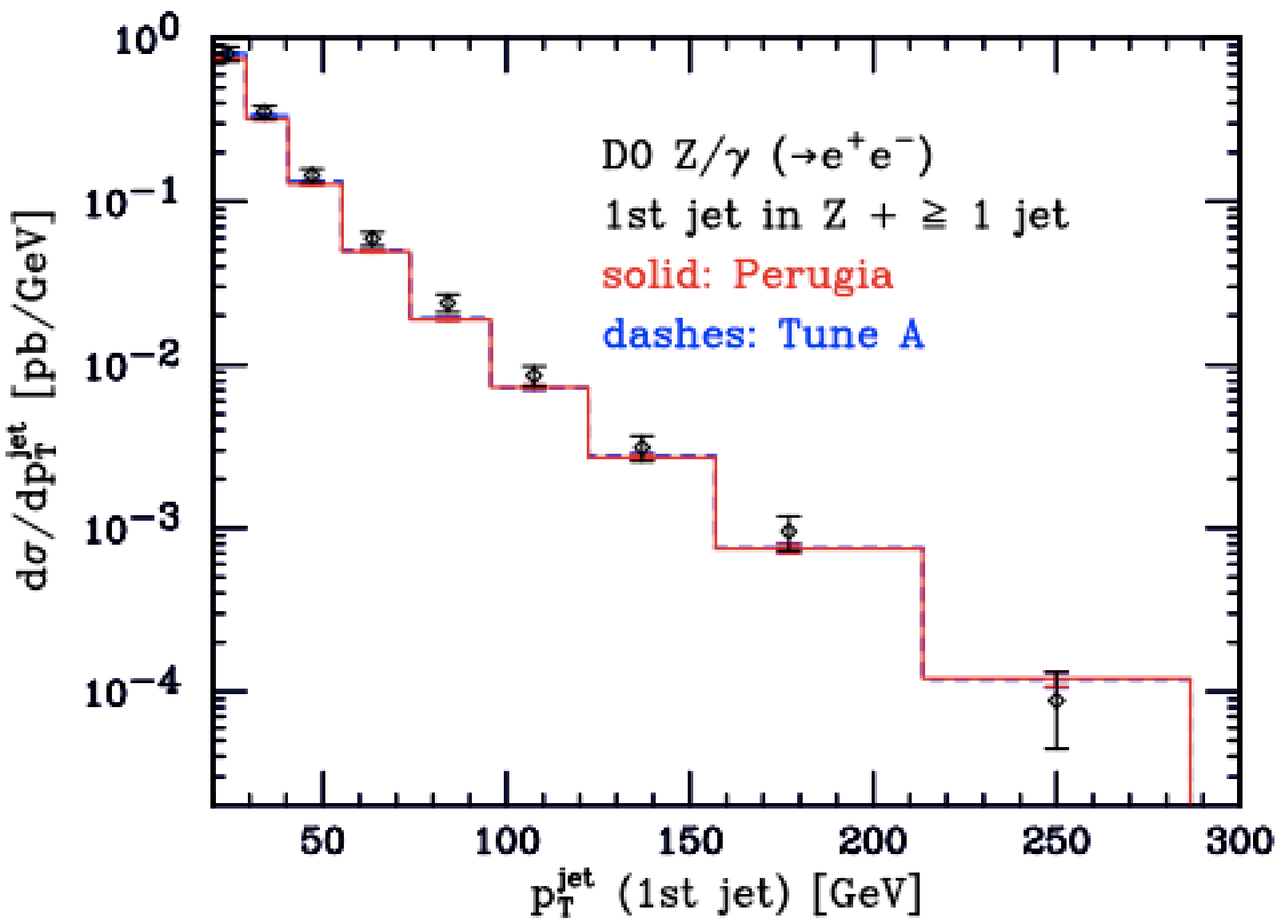
Frixione & Webber (2003)

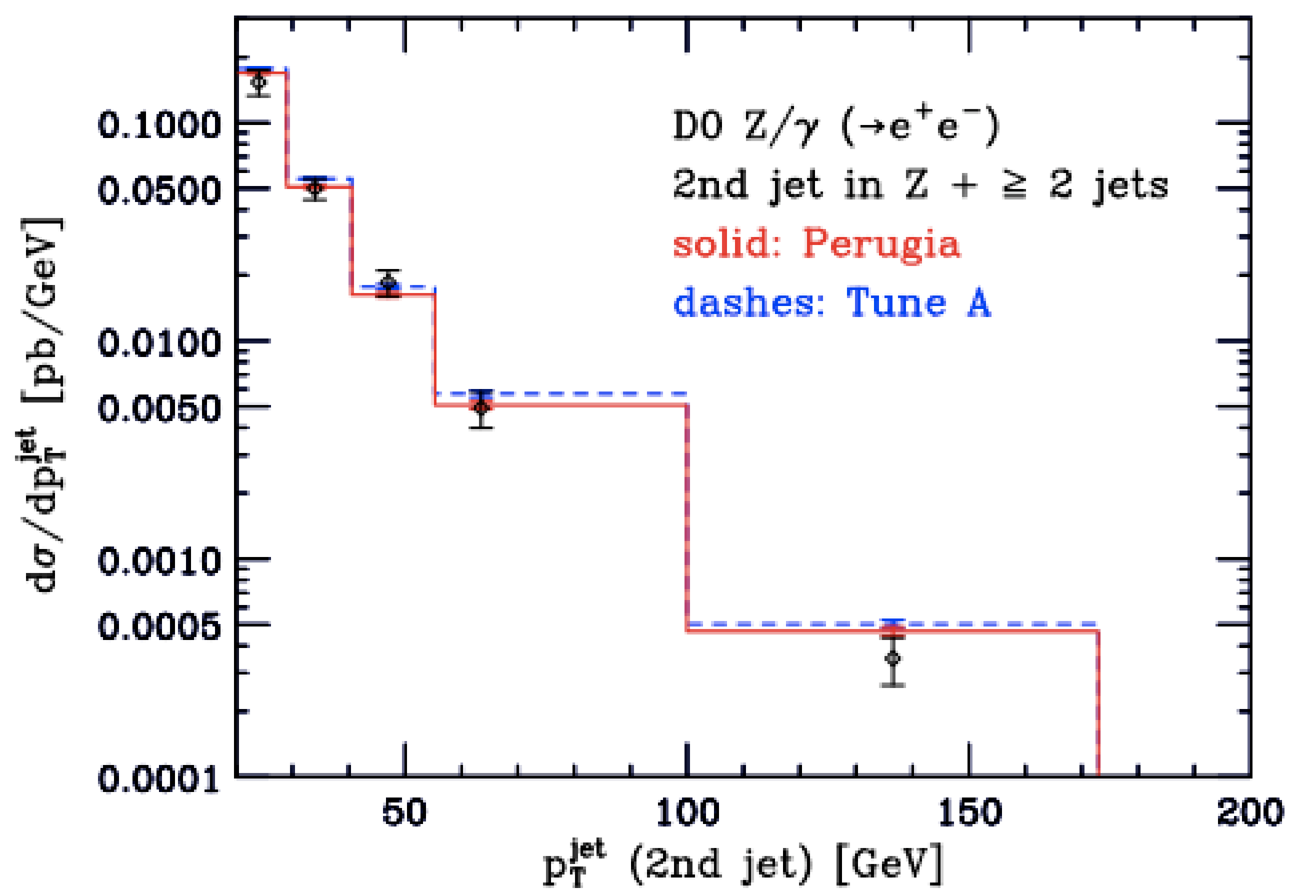
A number of processes since this but no W/Z+jets.

POWHEG

- More recent implementation of NLO+PS than MC@NLO, promising simpler procedure through which to incorporate parton-level NLO calculations.
- First results for Z+jet NLO+PS.

Alioli, Nason, Oleari, Re, arXiv: 1009.5594

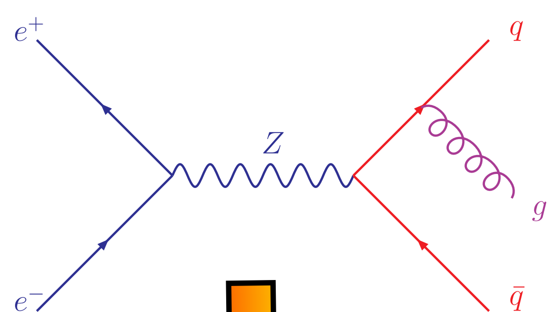


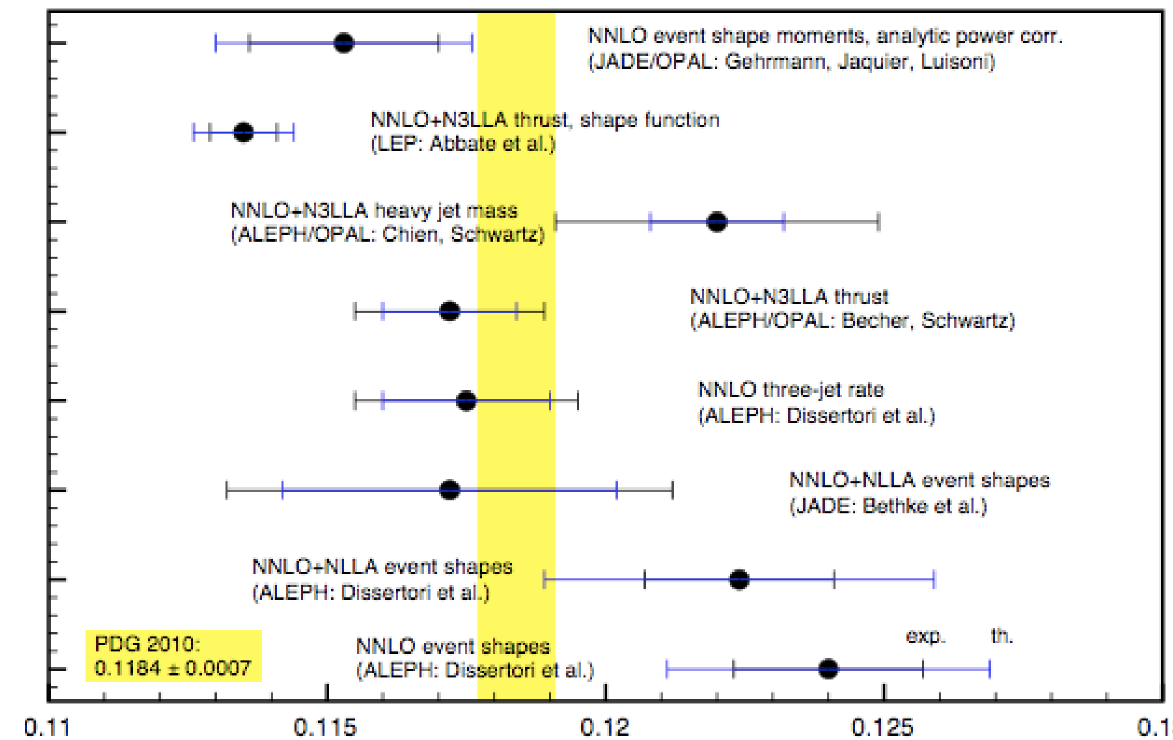


NNLO W/Z+jet?

- Existing NNLO predictions for hadron colliders exploit color singlet final state. Very difficult to extend current approaches beyond that.
- Much NNLO progress recently in jet production in e^+e^- annihilation.

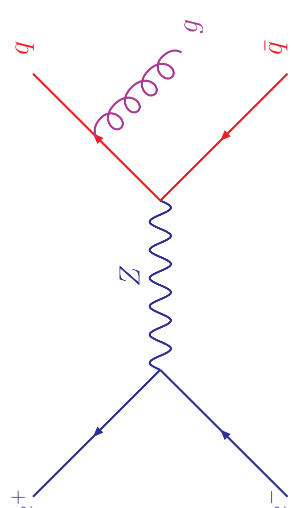
$e^+e^- \to$ 3 jets

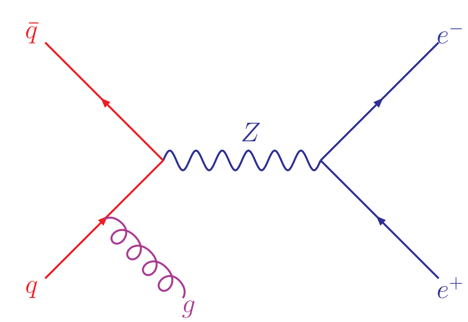




$e^- p \to$ (2+1) jets

(underway → strong coupling and pdfs)





pp → Z+1 jet

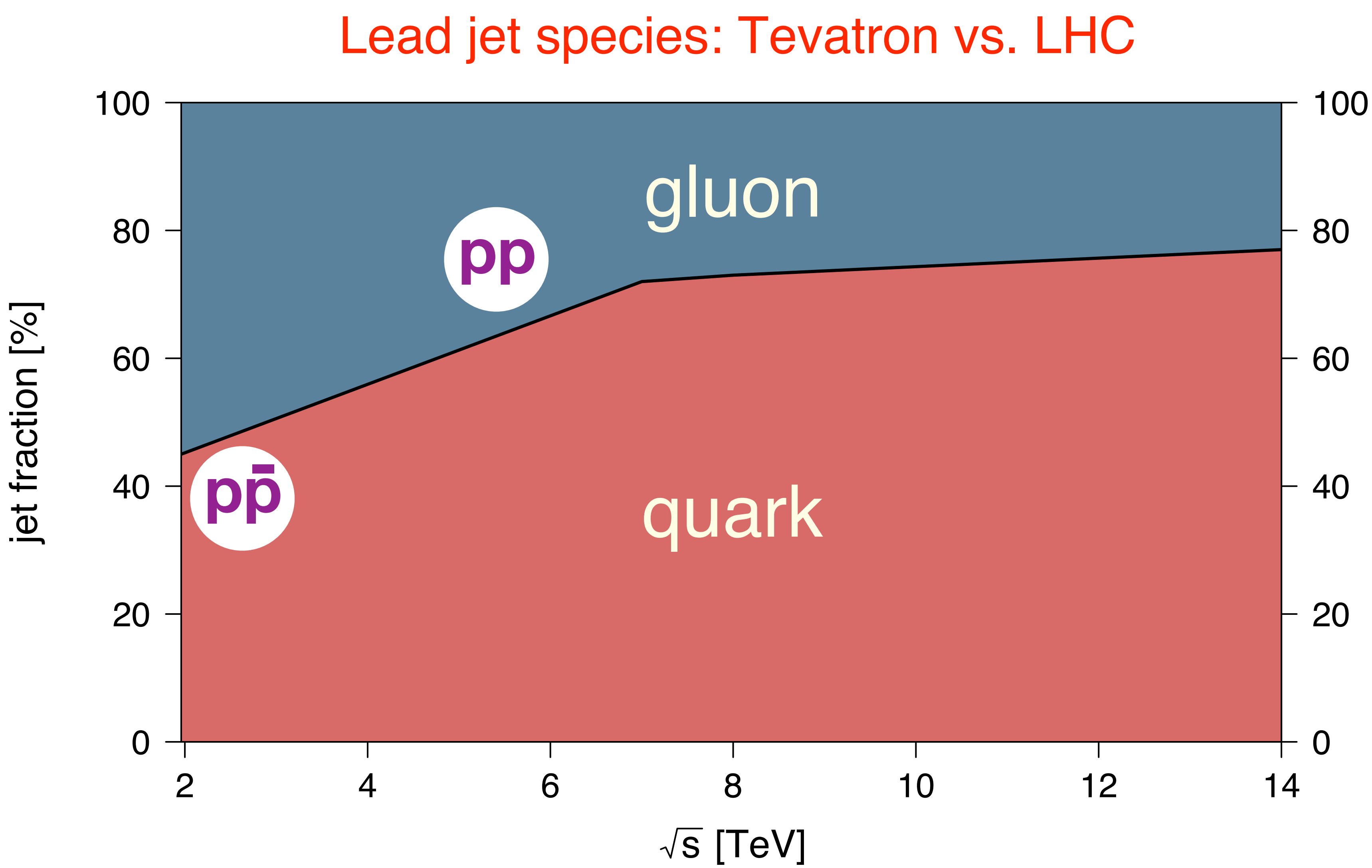
(what we want for LHC)

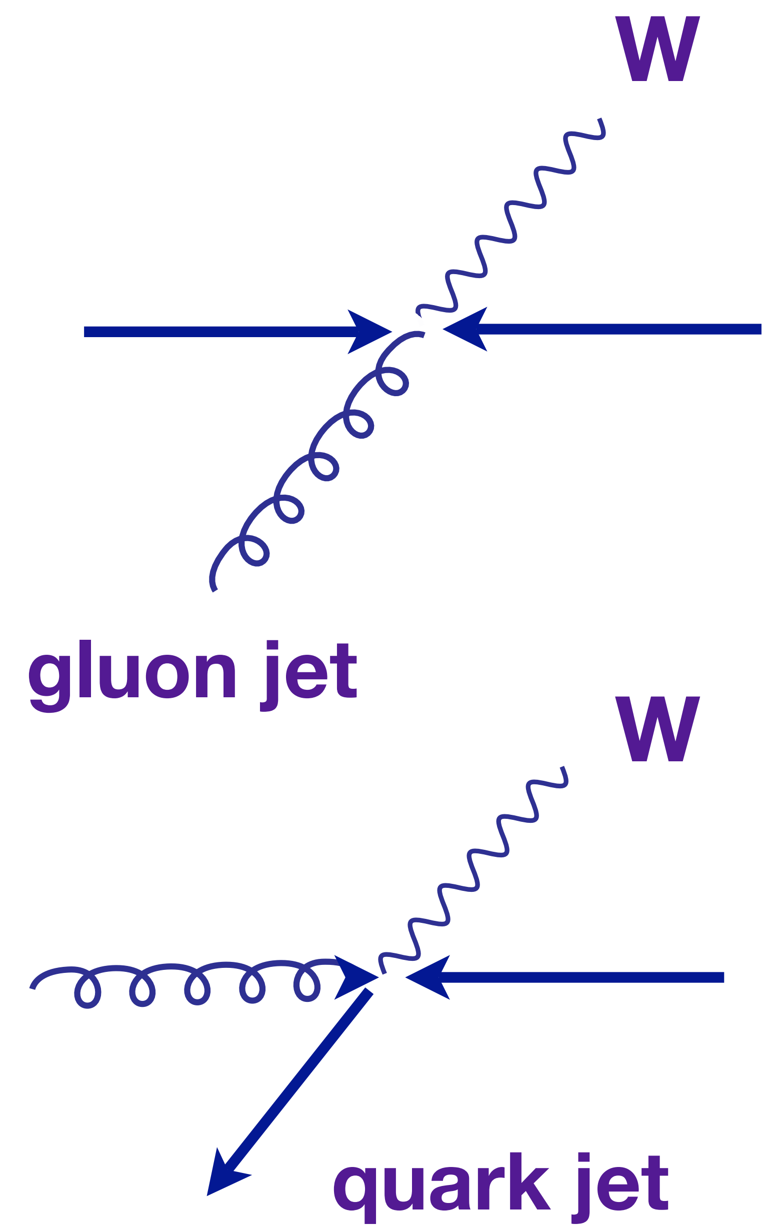
- Similar timescale for inclusive jets at NNLO.

some recent progress: Glover, Pires (2010)

LHC phenomenology

Jet composition





- Leading order estimate only.
- Roughly equal mix at Tevatron, mostly quark jets at LHC ($\approx$ independent of $\sqrt{s}$).
- Possible issues for tuned comparisons with parton showers.

W^+/ W^- differences

* Not the same (c.f. Tevatron)! Significant rate difference.

C. Berger et al., arXiv: 1009.2338

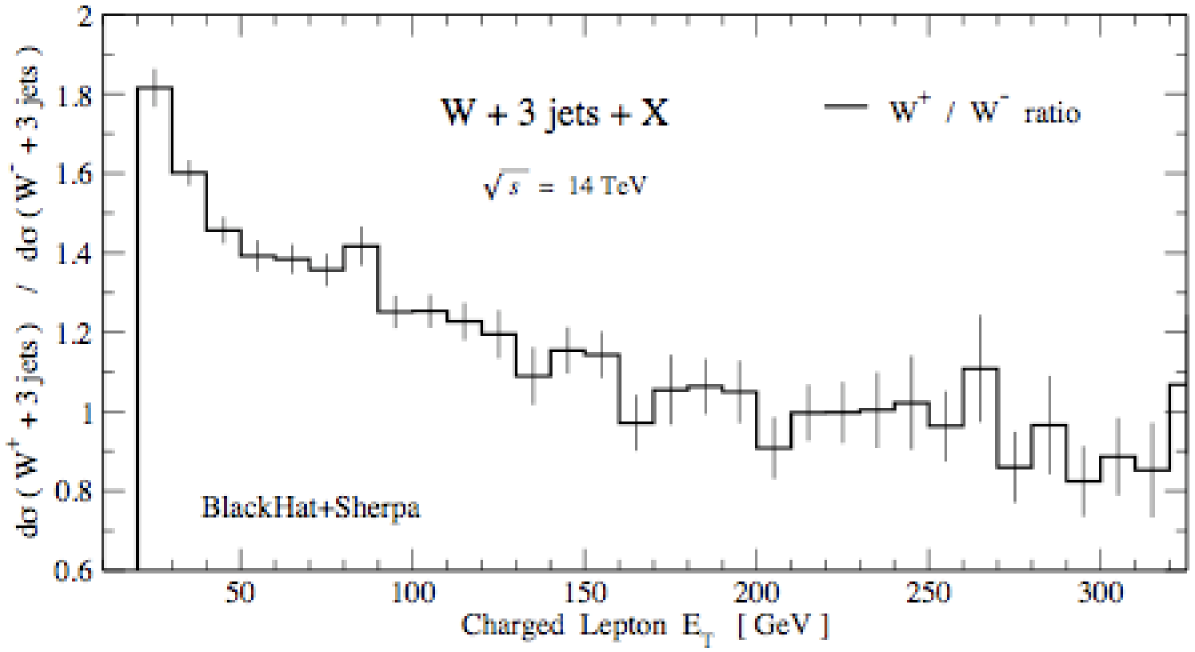
no. jets	W^- LO	W^- NLO	W^+/W^- LO	W^+/W^- NLO
0	$1614.0(0.5)^{+208.5}_{-235.2}$	$2077(2)^{+40}_{-31}$	1.656(0.001)	1.580(0.004)
1	$264.4(0.2)^{+22.6}_{-21.4}$	$331(1)^{+15}_{-12}$	1.507(0.002)	1.498(0.009)
2	$73.14(0.09)^{+20.81}_{-14.92}$	$78.1(0.5)^{+1.5}_{-4.1}$	1.596(0.003)	1.57(0.02)
3	$17.22(0.03)^{+8.07}_{-4.95}$	$16.9(0.1)^{+0.2}_{-1.3}$	1.694(0.005)	1.66(0.02)
4	$3.81(0.01)^{+2.44}_{-1.34}$	$3.56(0.03)^{+0.08}_{-0.30}$	1.817(0.003)	—

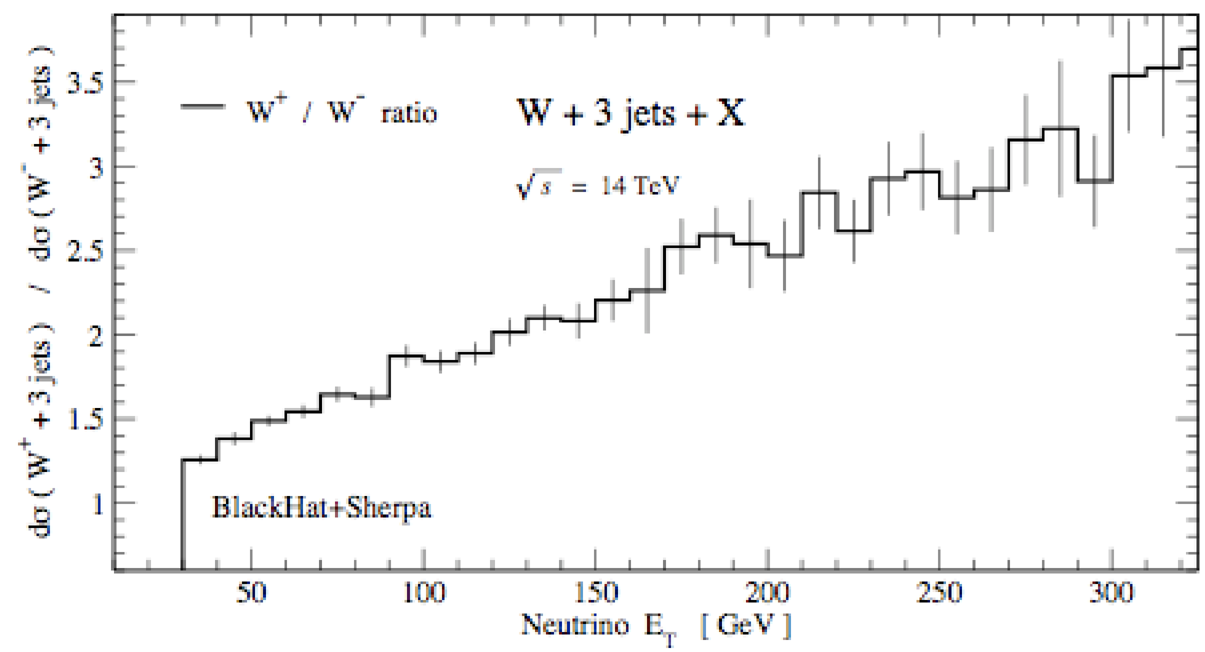
* Ratio sensitive to any physics that produces W^+ and W^- equally.

Kom and Stirling, arXiv: 1004.3404

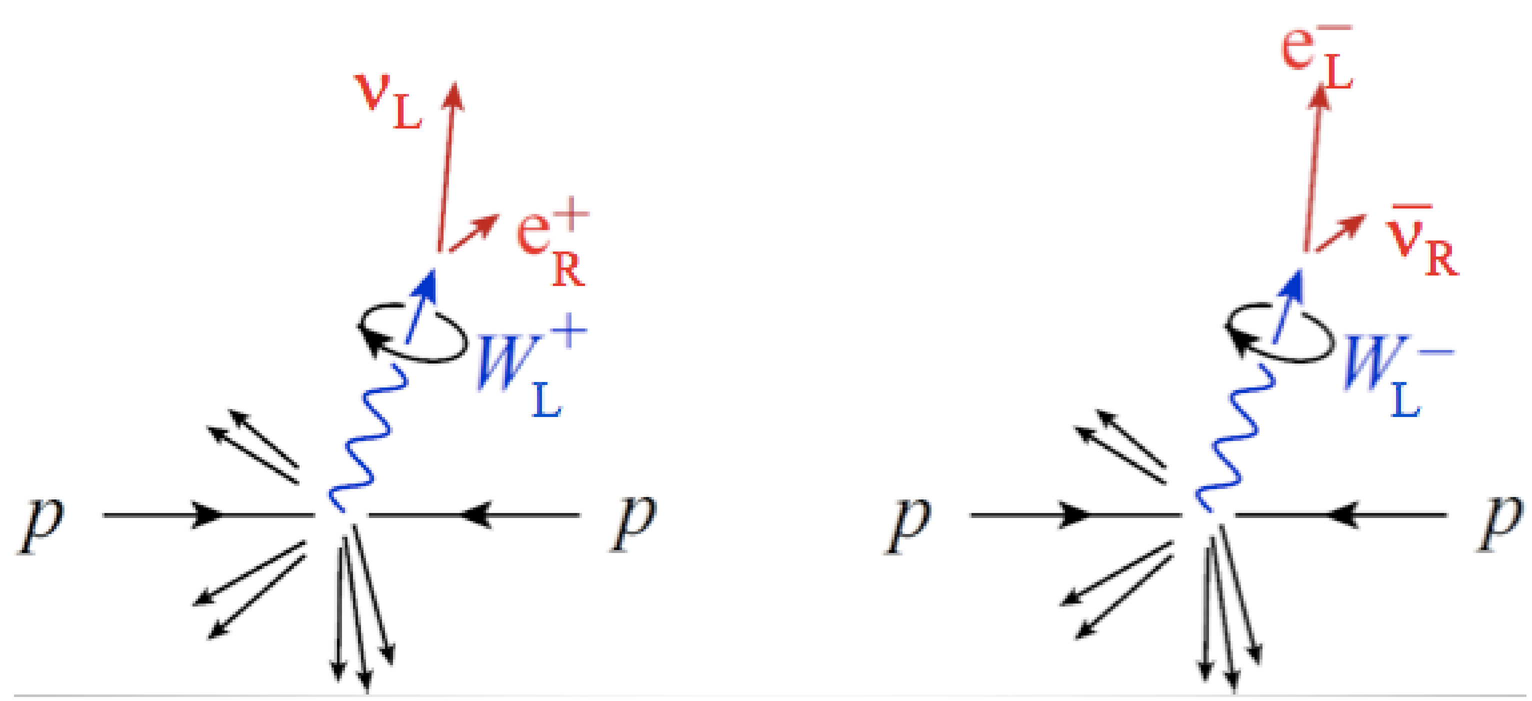
  * e.g. W+4 jet bin at 14 TeV sensitive to semi-leptonic top decays, reduces W^+/W^- ratio by about 30% for typical cuts.
  * equally valuable for Higgs/new physics searches.

Lepton transverse momenta





- Universal in W+n jets.
- Stems from mostly left-handed W polarization.
- Top pairs again produce symmetric final states, so no difference between electron and positron.
  - another discriminant.



Other ratios

- Ratios of W and Z cross sections.
  - theoretically just as good as W^+/W^-.
  - experimentally, different acceptances and backgrounds may dilute power.
  - could use to calibrate MET+jets using high statistics W sample.
- σ(W+ n jets) / σ(W + (n-1) jets) "Berends Scaling"
  - ratio ~ α_s ; empirically a constant factor only after tuning jet cuts
  - not as well-motivated or perturbatively well-behaved as other ratios.

- For more details on these ratios, see talk by L. Dixon at Trento ("QCD at the LHC")

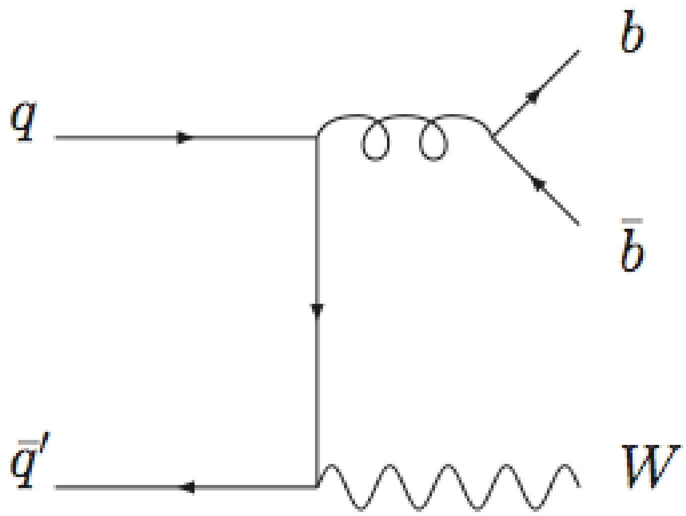
  http://indico.cern.ch/conferenceDisplay.py?confId=93790

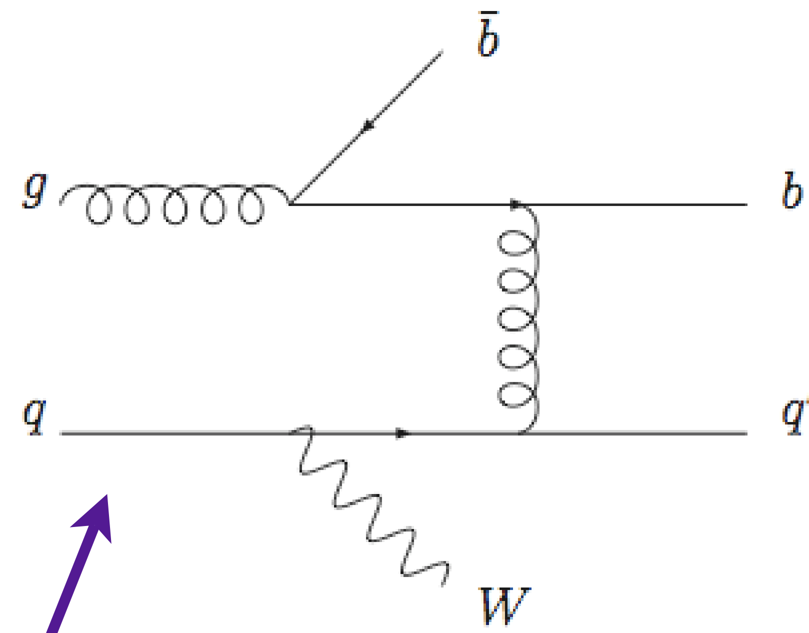
Vector bosons+heavy flavour

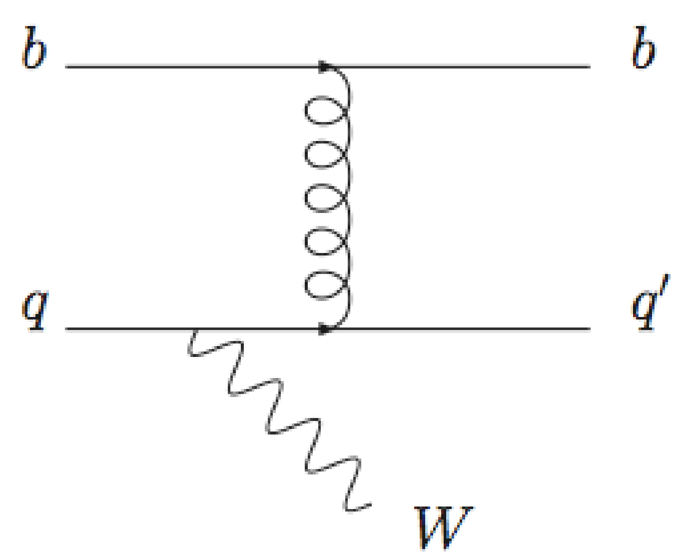
* Slightly different game at the LHC, e.g. demand W+one b-tagged jet.

Tevatron **90%** **10%**

14 TeV LHC **70%** **30%**







Sensitivity to whether or not theory should include b-quark in PDF

Closing thoughts

- W+jets and Z+jets backgrounds appear to be under good theoretical control.
    - predictions for W/Z+3,4, ... jets increasingly available.
    - variety of parton shower + matching/merging predictions.
    - parton shower + NLO (for one jet) recently calculated.
- W/Z + heavy flavor may be a different story.
    - would be nice to have measurements of some of these processes as part of search analyses (e.g. single top and Higgs at the Tevatron).

- Asymmetry between W^+ and W^- at the LHC useful in various contexts.
    - ratio sensitive to other SM (esp. top) and New Physics.