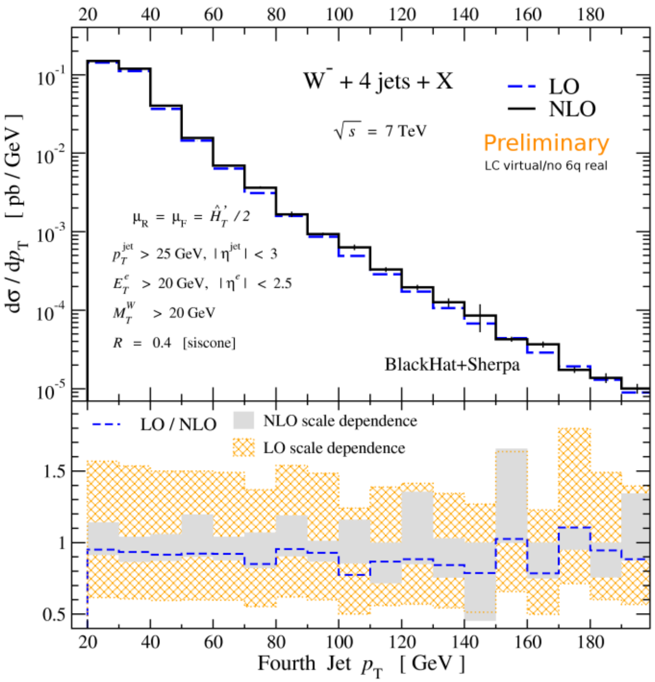
Recent Advances in NLO QCD

(V-boson+jets)



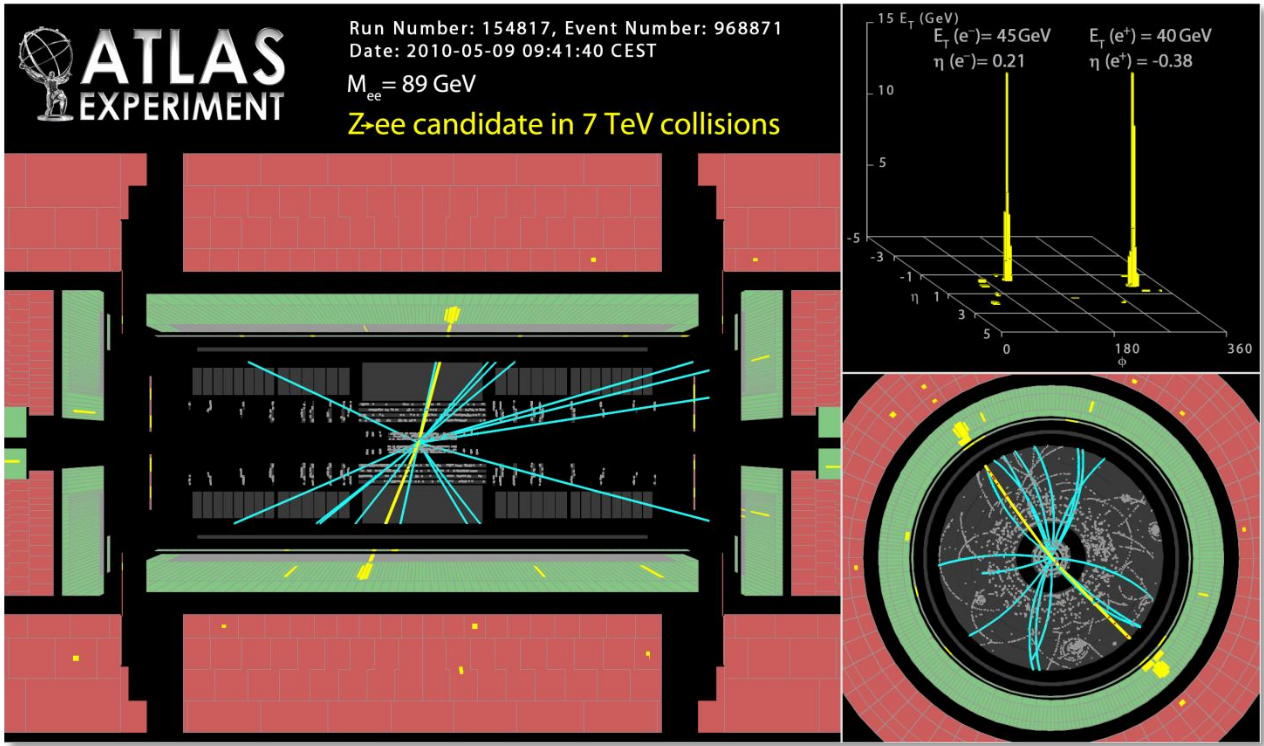
In collaboration with BlackHat: C.F.Berger, Z.Bern, L.J.Dixon, F.Febres Cordero, D.Forde, D.A.Kosower, D.Maitre; +Sherpa: T.Gleisberg

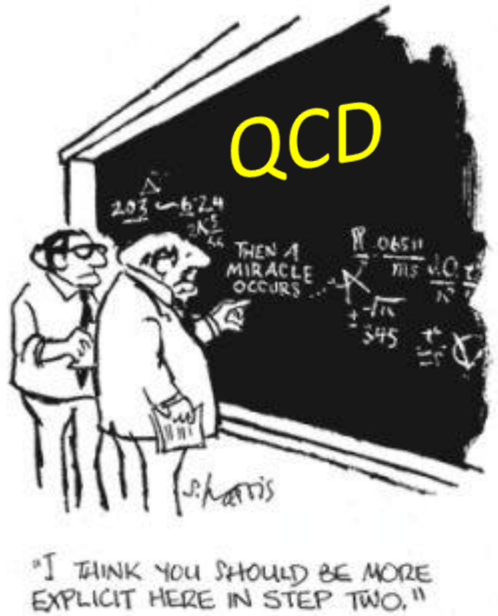
Harald Ita, (UCLA+NSF TI-fellow)

US ATLAS Hadronic Final State Forum

SLAC, Aug 23rd 2010

QCD omnipresent @ the LHC

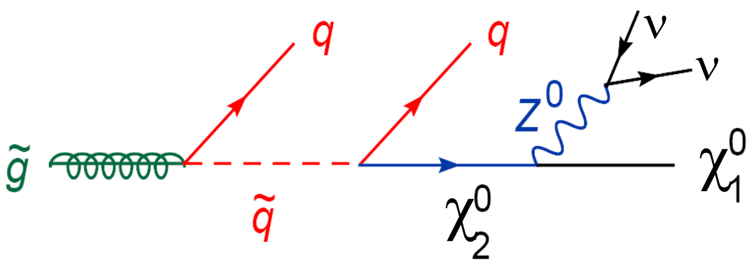




Fundamental stuff:
masses, couplings, fields,
strategies, theories ...

Signals in multi-jet final states

Example: SUSY gluino cascade

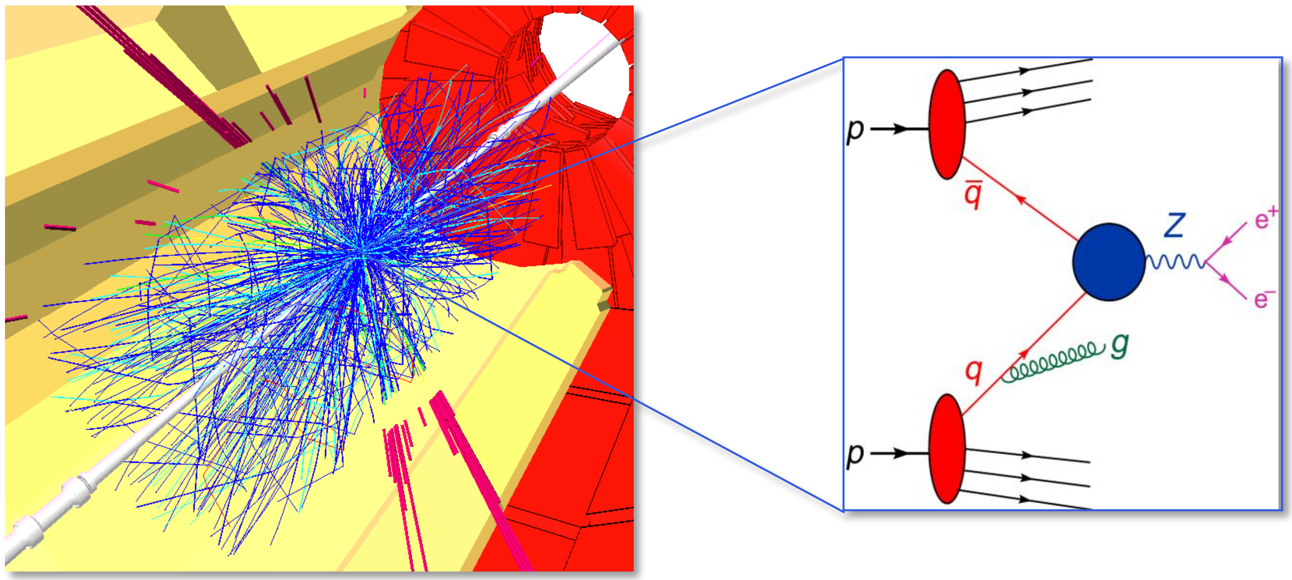


- New particles, e.g. supersymmetry , Higgs boson(s) typically decay through cascades into multi-jet final states

- Kinematic signatures not always clean (*e.g.* mass bumps) if dark matter, neutrinos, or other escaping particles present

Need **precise Standard Model backgrounds** for a variety of processes with multiple jets, to maximize potential for new physics discoveries.

QCD factorization & parton model



Heavy fundamental particles produced in high energy interactions
→ Factorization:

- Protons appear as clouds of point-like partons (quarks + gluons).
- Asymptotic freedom guarantees that hard interactions between partons well described by perturbative QCD.

Quantitative first principle predictions.

How best to control SM backgrounds?

Increasing availability ↑

1. Get the **best theoretical prediction** you can, whether
   – Basic Monte Carlo [PYTHIA, HERWIG, Sherpa, …]
   – LO QCD parton level
   – LO QCD matched to parton showers [MadGraph/MadEvent, ALPGEN/PYTHIA, Sherpa, …]
   – NLO QCD at parton level
   – NLO matched to parton showers [MC@NLO, POWHEG,…]
   – NNLO inclusive at parton level
   – NNLO with flexible cuts at parton level

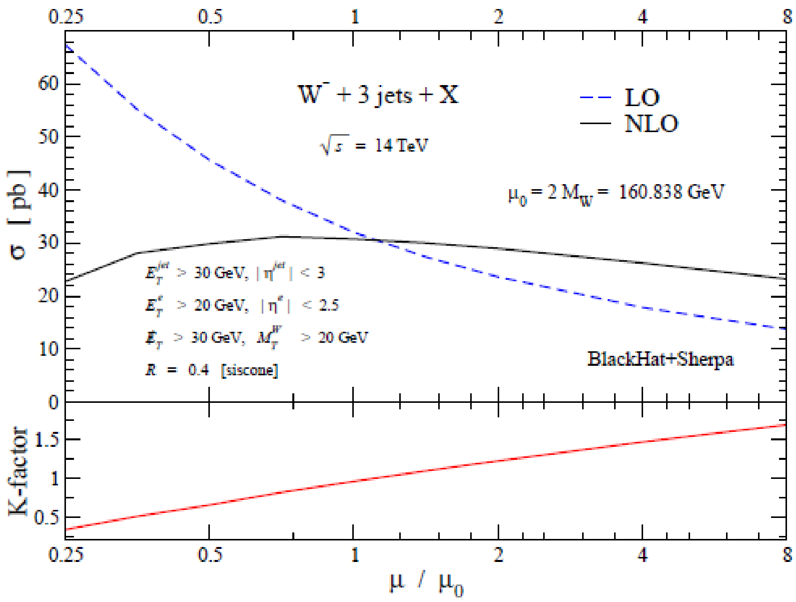
Increasing accuracy ↓

2. Take **ratios** whenever possible
   - QCD effects cancel when event kinematics are similar
   - Closely related to "data driven" strategies

L. Dixon

Want NLO for multi-jets

[BlackHat,0907.1984]



Typical scale variation W+n jets

Number of Jets	LO	NLO
1	16 %	7 %
2	30 %	10 %
3	42 %	12 %

- Reduced dependence on unphysical renormalization and factorization scales.

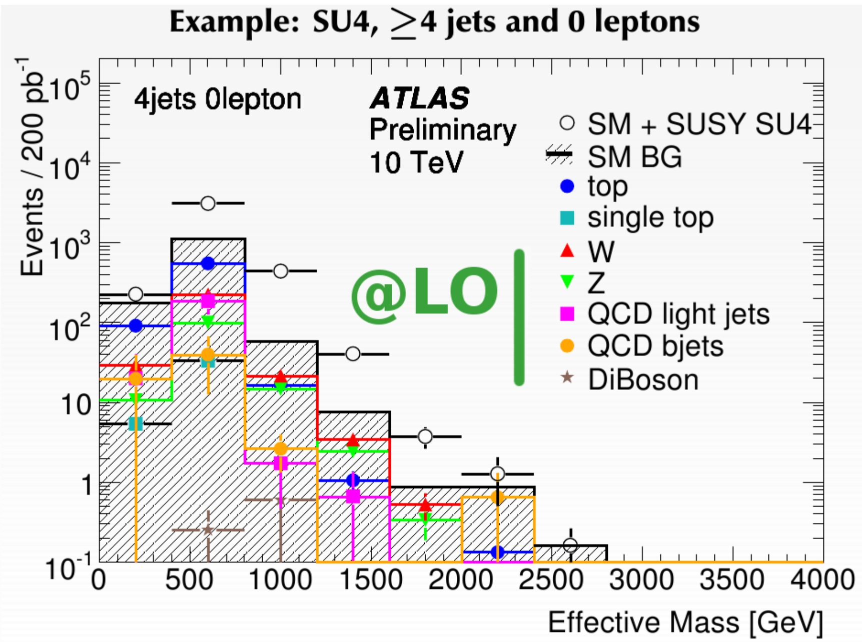
- NLO importance for scale dependence grows with increasing number of jets.

- NLO captures more physics:
  - multiple partons merged to jets
  - initial state radiation
  - more types of initial state partons included

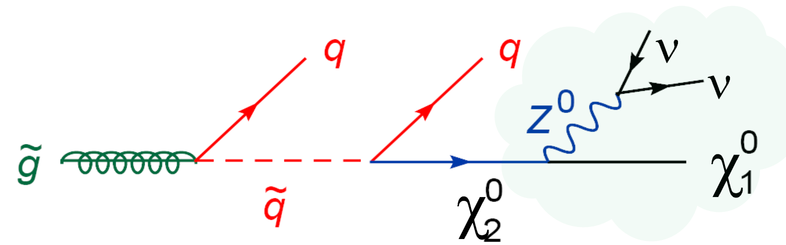
- Shape changes

NLO required for quantitative control of multi-jet final states

NLO motivation from SUSY search



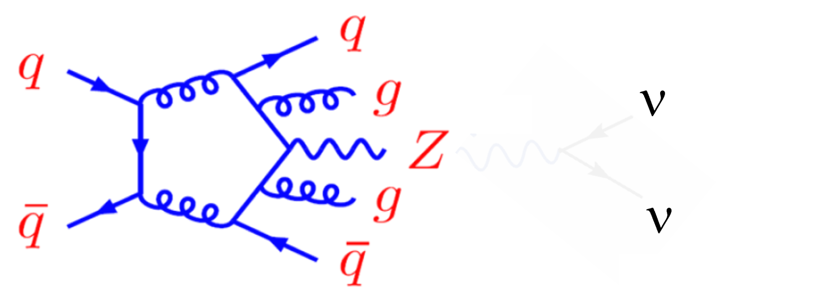
- Signature: multijet + Missing E_T + X



- Irreducible background:
  Z (→ neutrinos) + 4 jets

- Signal excess over LO background with normalization still quite uncertain

Aim for NLO background:
Z (→ neutrinos) + 4 jets



The Les Houches Wish List (2001)

Run II Monte Carlo Workshop, April 2001

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

- Five-particle processes under good control with Feynman diagram based approaches.

- Problem posed for over 10 years. Solution clear only recently!

Les Houches Wish List (2005)

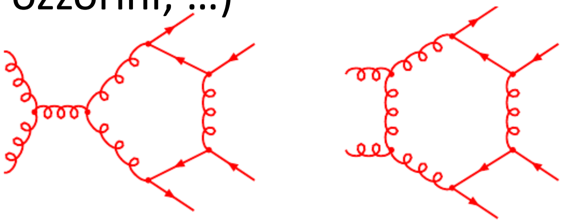
Descope!

Les Houches 2005

process wanted at NLO ($V \in \{Z, W, \gamma\}$)	background to
1. $pp \to VV +$ jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF $\to H \to VV$
7. $pp \to V + 3$ jets	new physics
8. $pp \to VVV$	SUSY trilepton

NLO bottleneck: loops

state of the art: $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$
(Bredenstein, Denner, Dittmaier, Pozzorini; ...)



114 pentagons 40 hexagons

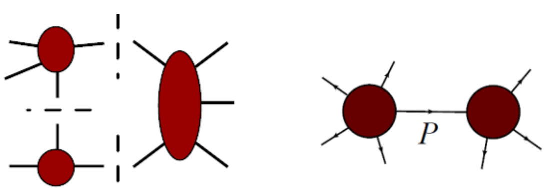
- Traditional methods:

Simplify loop-level Feynman diagrams analytically.

Reduce tensor integrals.

Factorial growth of number of diagrams with multiplicity.
Intricate tensor reductions.

Bern, Dixon & Kosower
Britto, Cachazo & Feng
Ossola, Pittau & Papadopoulos
Giele, Kunszt & Melnikov



- Recursive & on-shell/unitarity methods:

Use unitarity and factorization properties to assemble amplitudes from (on-shell) tree amplitudes numerically.

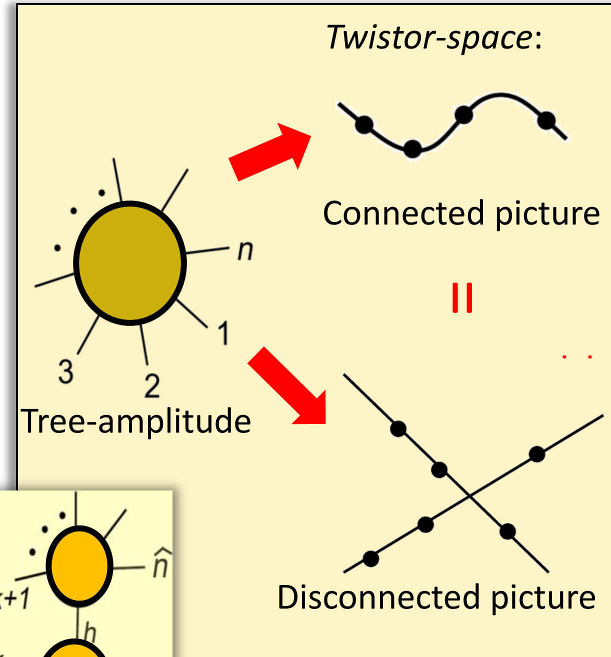
Efficiently drops unphysical parts (ghosts,...).
Automatable for many processes.

Example: new insights

twistor string [Witten 03']:

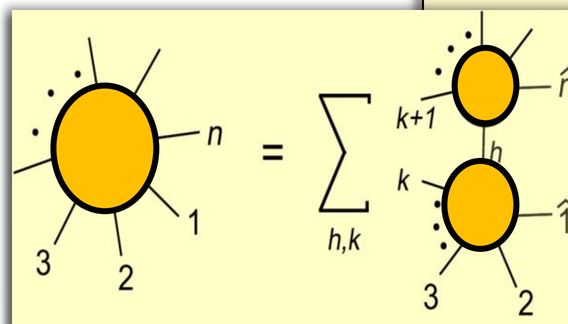
- Remarkable simplicity: Tree amplitudes supported on lines in twistor space.

Obscure from *Feynman diagrams*!



- Tree recursions: [Britto, Cachazo, Feng, Witten 05']

Fast QCD tree amplitudes from lower point on-shell amplitudes.

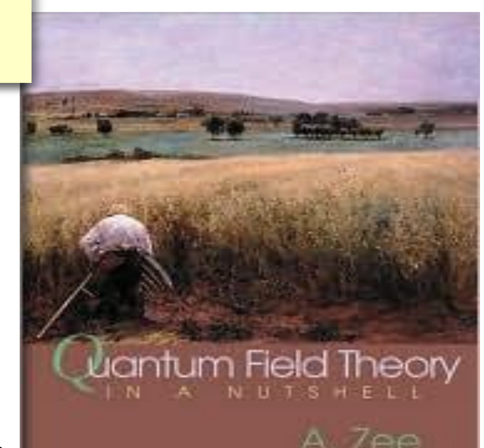


- Loop recursions: [Bern, Dixon, Kosower 05']

Most efficient for parts of loop amplitudes (rational terms).

Leads to *rewriting of and rethinking* about perturbative QFT.

New textbook QFT



4 new chapters in 2nd edition!

05’ Wishlist 2→4 processes

- **pp → $t\bar{t}b\bar{b}$:**
  - 09’ Bredenstein, Denner, Dittmaier and Possorini [traditional]
  - 09’ Bevilacqua, Czakon, Papadopoulos, Pittau and Worek [unitarity]
- **pp → W+3 jets:**
  - 09’ Ellis, Melnikov and Zanderighi (leading color approx) [unitarity]
  - 09’ BlackHat [unitarity]
- **pp → Z+3 jets:**
  - 10’ BlackHat [unitarity]
- **pp → $b\bar{b}b\bar{b}$** ($q\bar{q}$-channel):
  - 09’ Binoth, Greiner, Guffanti, Reuter, Guillet and Reiter [traditional]
- **pp → $t\bar{t}jj$:**
  - 10’ Bevilacqua, Czakon, Papadopoulos and Worek [unitarity]
- **pp → W^+W^++2 jets:**
  - 10’ Melia, Melnikov, Rontsch, Zanderighi [unitarity]

Selected recent NLO

- **pp → WWW, WWZ, … ZZZ:**
  - 08' Binotha, Ossola, Papadopoulos, Pittau [unitarity]
- **pp → H+2 jets:**
  - 09'+10' Campbell, Ellis, Zanderighi, Badger, Williams; Dixon, Sofianatos [unitarity]
- **pp → $t\bar{t}$+1 jet:**
  - 07' Dittmaier, Uwer, Weinzierl [traditional]
  - 10' Melnikov, Schulze [unitarity]

The Les Houches Wish List (2010)

2010

process wanted at NLO	background to
1. $pp \to VV +$ jet	$t\bar{t}H$, new physics Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi
2. $pp \to H + 2$ jets	H in VBF Campbell, Ellis, Zanderighi; Ciccolini, Denner Dittmaier
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$ Bredenstein, Denner Dittmaier, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$ Bevilacqua, Czakon, Papadopoulos, Worek
5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF $\to H \to VV$ Melia, Melnikov, Rontsch, Zanderighi VBF: Bozzi, Jäger, Oleari, Zeppenfeld
7. $pp \to V + 3$ jets	new physics Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre; Ellis, Melnikov, Zanderighi
8. $pp \to VVV$	SUSY trilepton Lazopoulos, Melnikov, Petriello; Hankele, Zeppenfeld; Binoth, Ossola, Papadopoulos, Pittau
9. $pp \to b\bar{b}b\bar{b}$	Higgs, new physics GOLEM

Feynman diagram methods

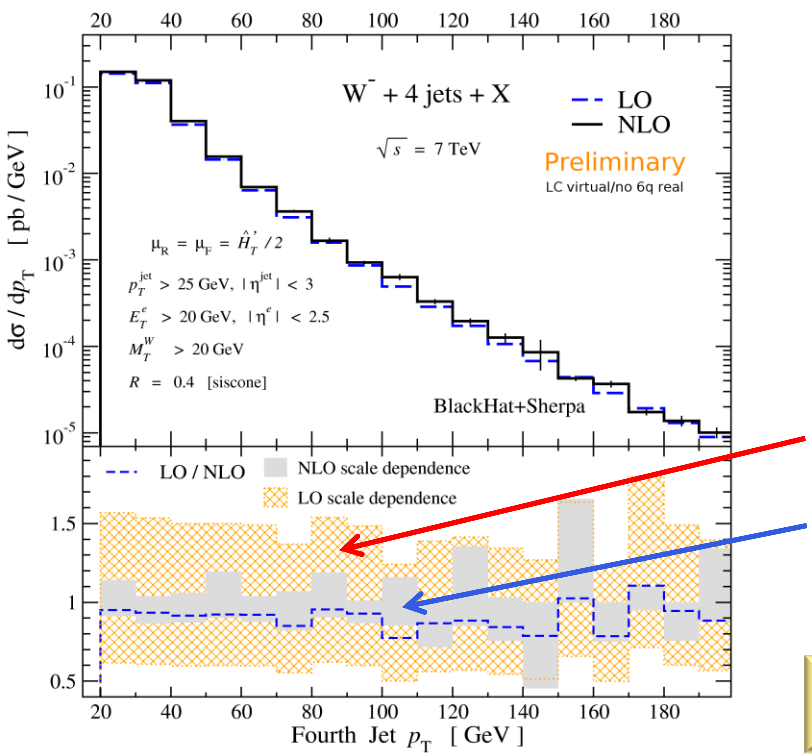
now joined by

unitarity based methods

C. Berger, L. Dixon

First 2→5 process

- **pp → W+4 jets:**
  - 10’ BlackHat (leading color, preliminary) [unitarity]



- First 2→5 NLO computation as needed for SUSY background
- Background to top quark studies

Back on the earlier 2001 wishlist!

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Run II Monte Carlo Workshop, April 2001

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$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
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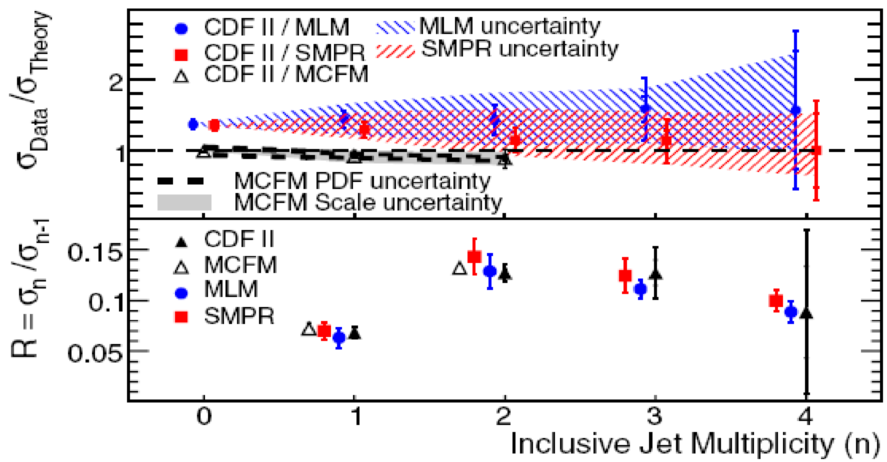
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

Comparing tools

T. Aaltonenet al. [CDF Collaboration], data: 320 pb^{-1}
arXiv:0711.4044



LO+shower:

•SMPR-model: Madgraph+Pythia

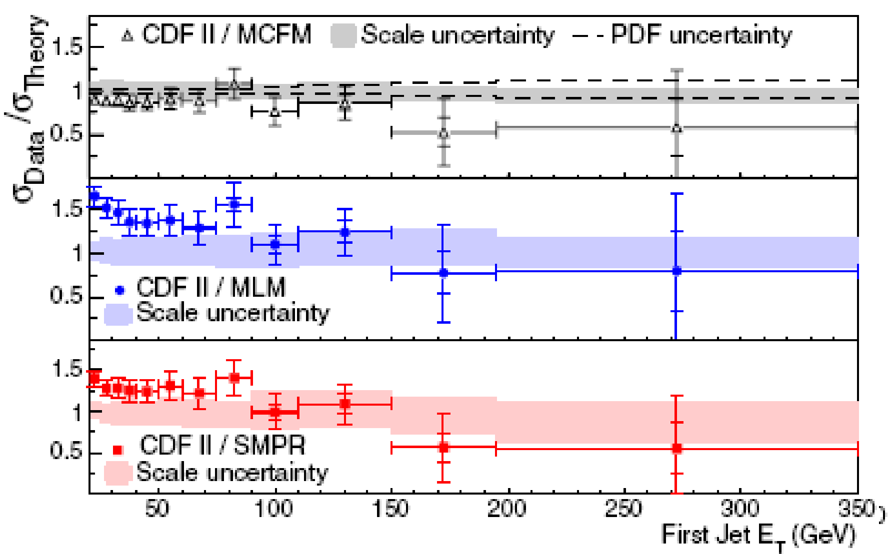
•MLM-model: Alpgen+Herwig

NLO-parton level (MCFM)

CDF: JETCLU R=0.4, f=0.75 (IR unsafe)

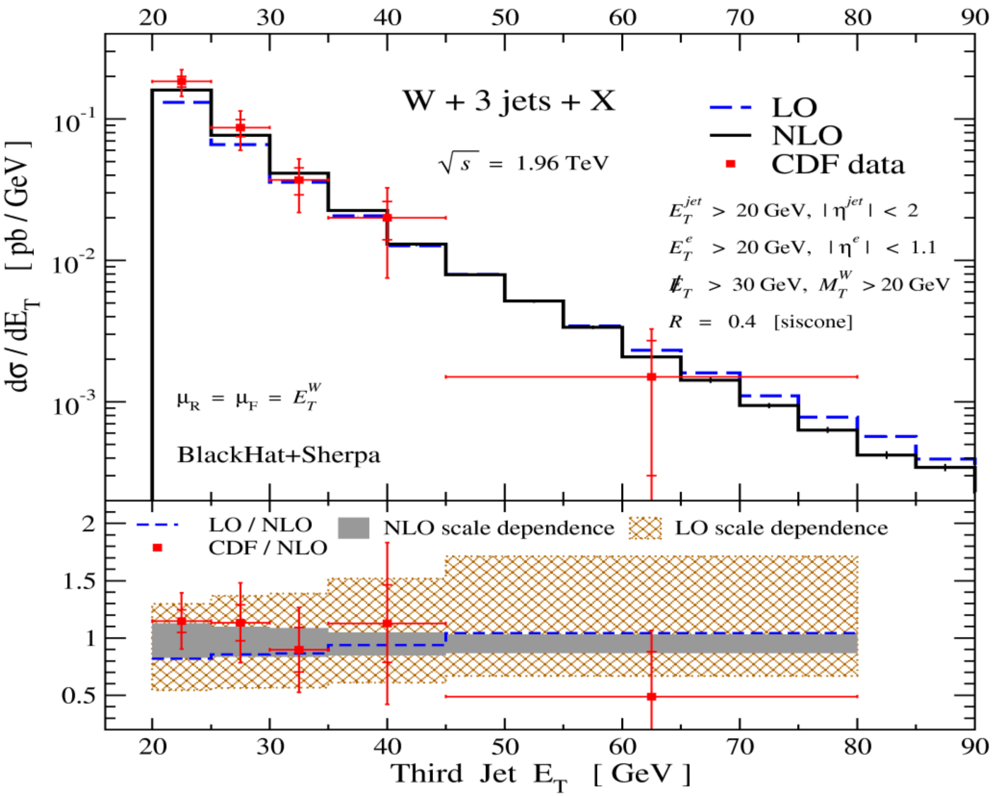
NLO: SISCone: R=0.4, f=0.5

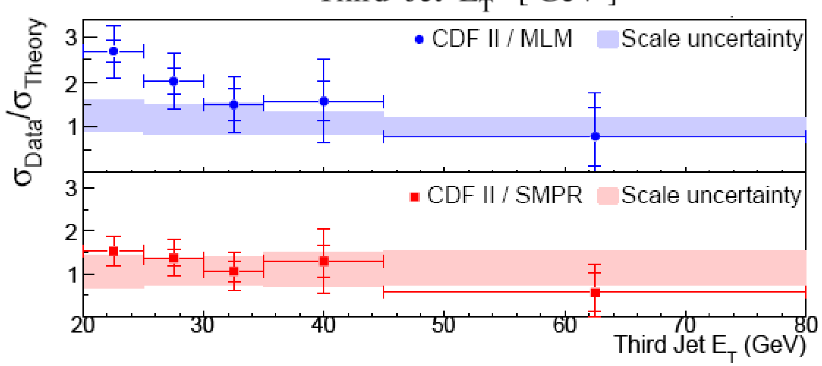
Second jet in W+2 jets



NLO has smallest uncertainties on distributions.
NLO deviation of Data/Theory smaller than other calculations.

Comparing tools





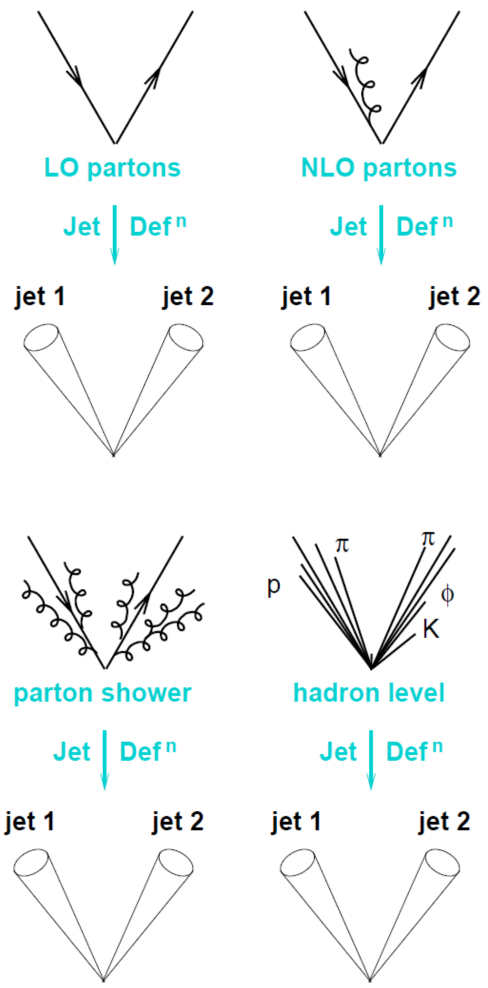
Third jet in W+3 jets

[BlackHat,0907.1984]

- Reduced scale dependence at NLO
- Shape change small compared to LO scale variation

NLO + Shower MCs

Projection to jets provides "universal" view of event



Salam ICHEP 2010

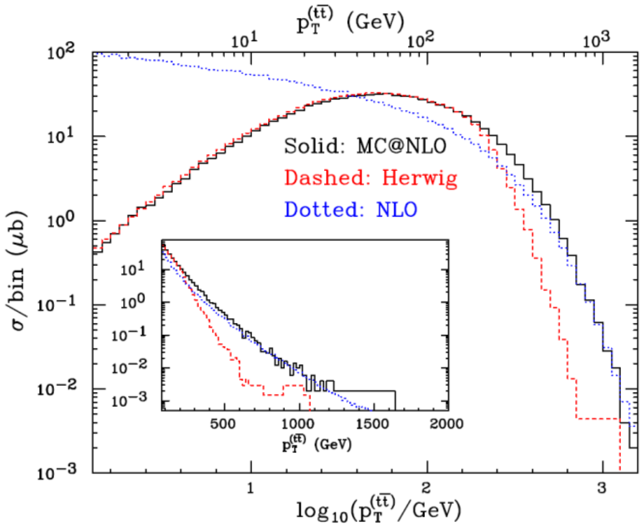
- Recent NLO progress (2→4,5) at parton level:
  no parton shower, no hadronization, no underlying event.
- Methods for matching NLO parton-level results to parton showers:
  - **MC@NLO** [Frixione, Webber 02', …]
  - **POWHEG** [Nason 04'; Frixione, Nason, Oleari 07';…]
  - **GenEvA** [Bauer, Tackmann, Thaler 08']
  - **ME NLO PS** [Gehrmann, Höche, Krauss, Schönherr; Hamilton, Nason; Alioli, Nason, Oleari, Re 10']
- Technical status:
  - no complex multi-jet NLO included yet
  - E.g.: NLO: Z, LO: Z+1/2/3/. . .+ parton shower
    Hamilton & Nason '10; SHERPA, prelim;
    NLO: Z & Z+j + parton shower, Alioli et al, prelim

Meanwhile:

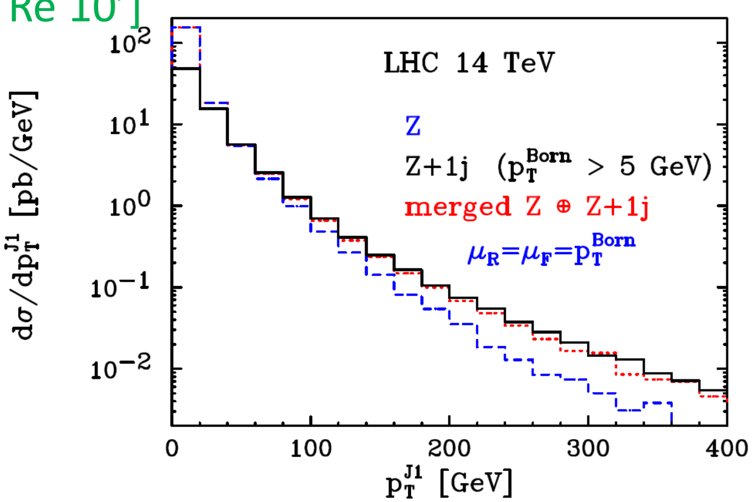
- NLO parton-level gives best normalizations away from shower-dominated regions.
- Ratios will be considerably less sensitive to shower + nonperturbative effects.

NLO + Shower MCs: samples

MC@NLO [Frixione,Webber 02']



Merged Z and Z +1 jet events [Alioli, Nason, Oleari, Re 10']

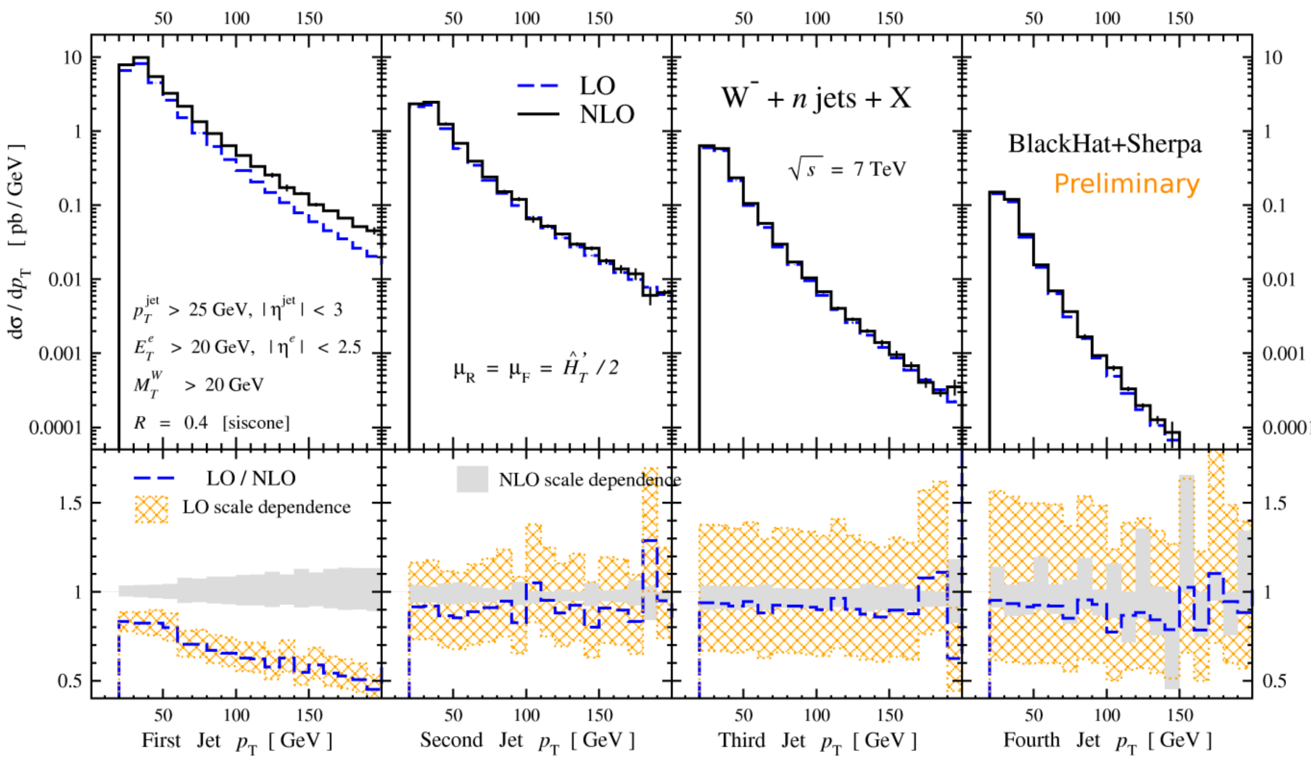


Some LHC processes available, but see above references more complete account.

- *W/Z production*
- Higgs production
- *Z + 1 jet*
- vector boson pairs
- heavy quark pairs
- single top
- lepton pairs
- Higgs bosons in association with a W or Z

Multi-jet systematics: W+n jets.

W^-+n jet+X softest jet p_T spectrum
[BlackHat, preliminary]



- Reduction of cross-section by power of strong coupling for each added jet.
- Jets prefer lowerst p_T.
- Growth of LO scale variation and NLO reduction.
- Complete input for MC@NLO approaches for W+4 jets

Multi-jet systematics: jet-algorithms Z+n jets.

CDF: Phys. Rev. Lett. 100, 102001 (2008)
[BlackHat: 0912.4927, 1004.1659]
See also talk by J. Huston

σ in [fb]

# of jets	LO parton SISCone	NLO parton SISCone	LO parton anti-k_T	NLO parton anti-k_T	Non-pert correction
1	$4635(2)^{+928}_{-715}$	$6080(12)^{+354}_{-402}$	$4635(2)^{+928}_{-715}$	$5783(12)^{+257}_{-334}$	~1.1
2	$429.8(0.3)^{+171.7}_{-111.4}$	$564(2)^{+59}_{-70}$	$481.2(0.4)^{+191}_{-124}$	$567(2)^{+31}_{-57}$	~1.2
3	$24.6(0.03)^{+14.5}_{-8.2}$	$35.9(0.9)^{+7.8}_{-7.2}$	$37.88(0.04)^{+22.2}_{-12.6}$	$44.9(0.3)^{+4.7}_{-7.1}$	~1.4

σ (stat) ± scale var

# of jets	CDF
1	7003 ±
2	695
3	60 ±

σ ± stat ± sys ± lum

Need non-perturbative corrections to

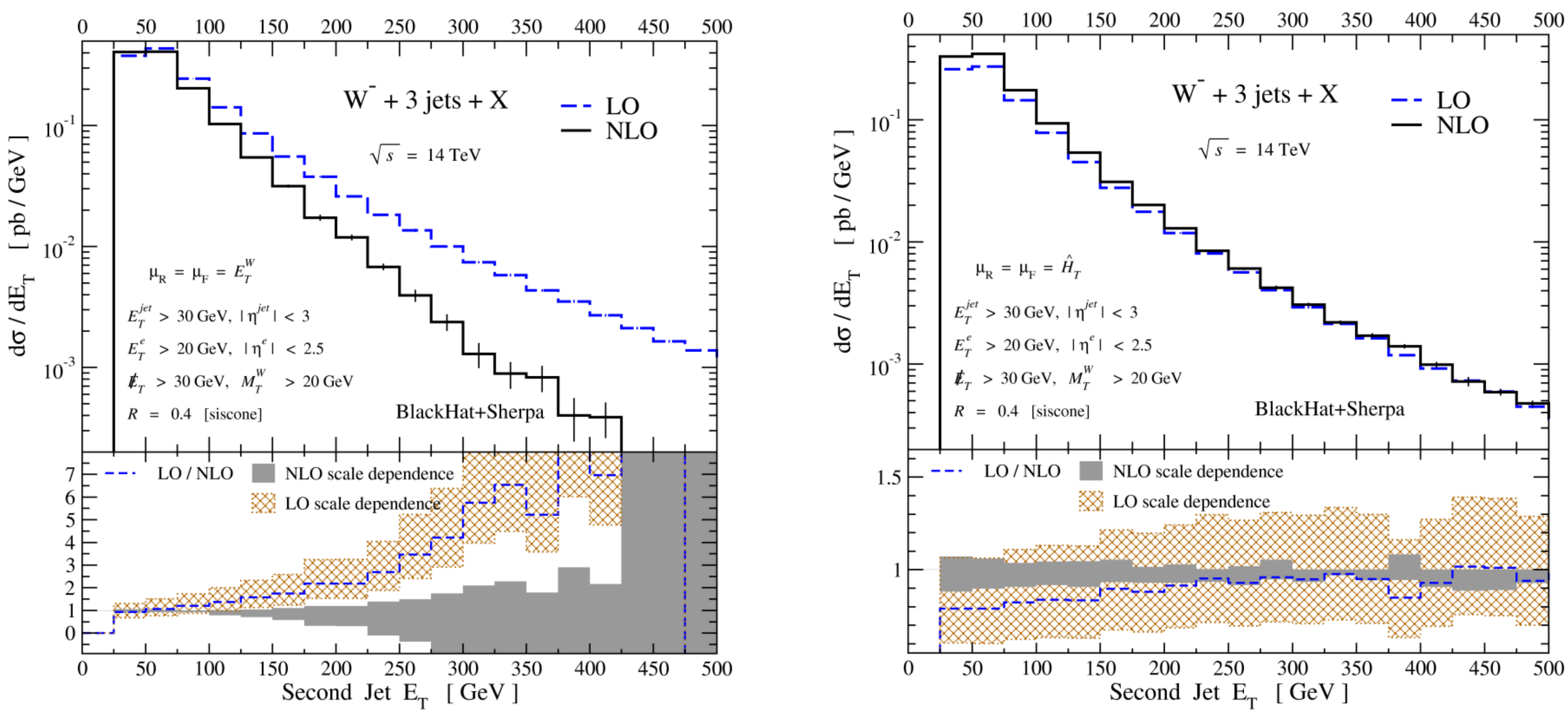
Is there a best value for R?

study	Jet alg R	Non-pert corr
CDF: W+n jets	R=0.4	<10%
CDF: Z+n jets	R=0.7	10-40%

Scale Choices

- Need to choose scales event-by-event
- Functional form of scale choice is also important

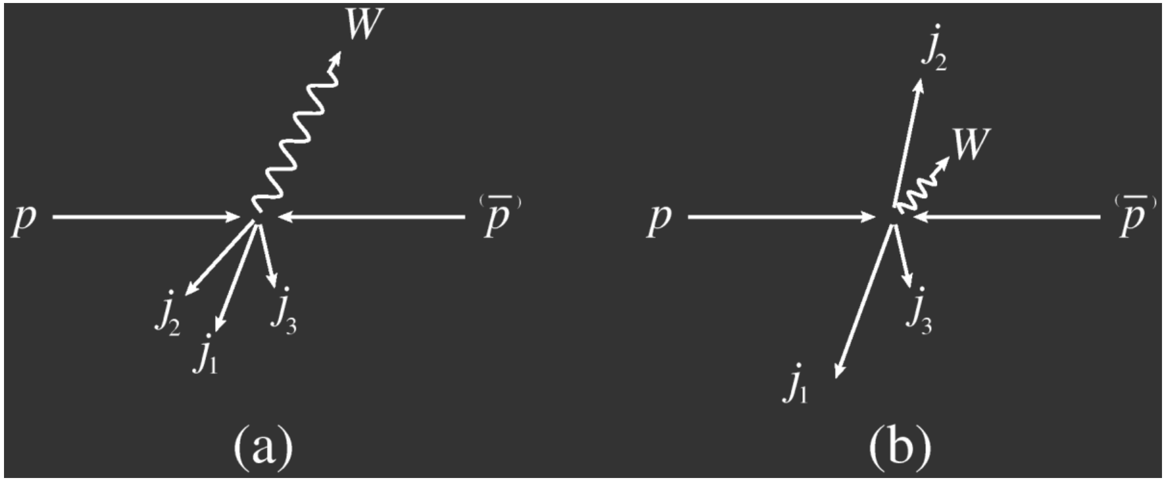
Bauer, Lange 09';
BlackHat 09'



- $E_T{}^W$ is not suitable; $\hat{H}_T$ is

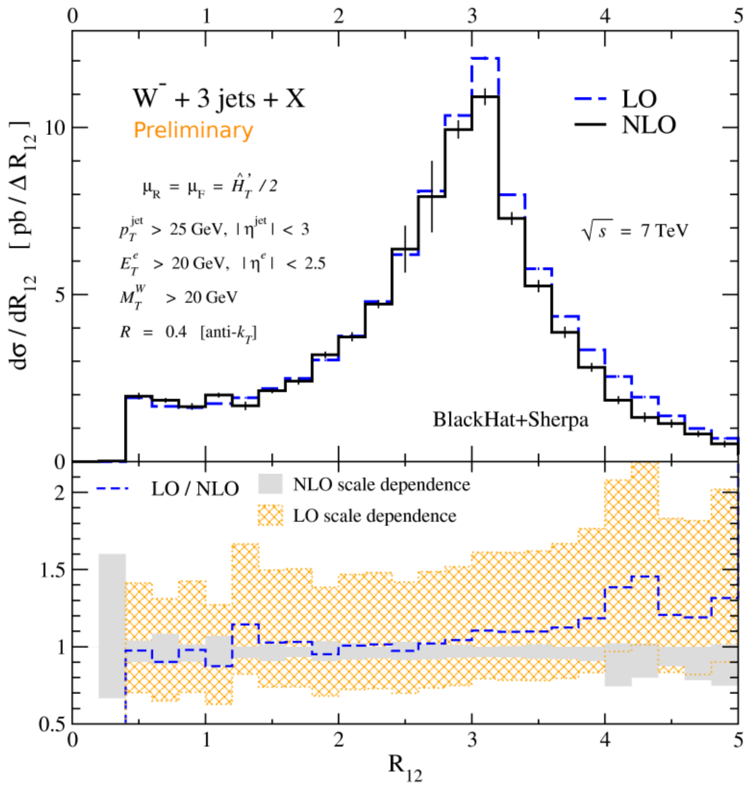
Scale Choices

- $E_T{}^W$ is not suitable; $\hat{H}_T$ is



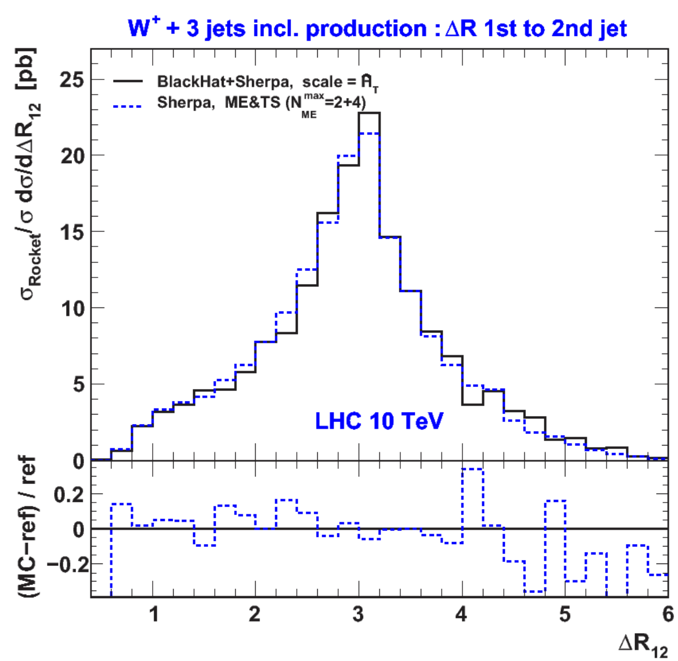
- NLO calculation is self-diagnosing, LO isn't
- In the absence of an NLO calculation, should use a scale like $\hat{H}_T$

Shape change: W+3jets.



- ΔR(1st,2nd) jet
- Physics of leading jets not modeled well at LO: additional radiation allows jets to move closer

⇒ Shapes can change!

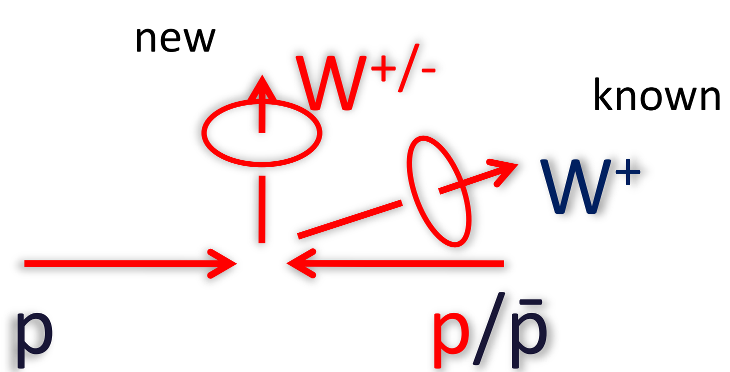


- compare: Les Houches study [Hoche, Huston, Maitre, Winter, Zanderighi , 10'] comparing to SHERPA with ME matching & showering

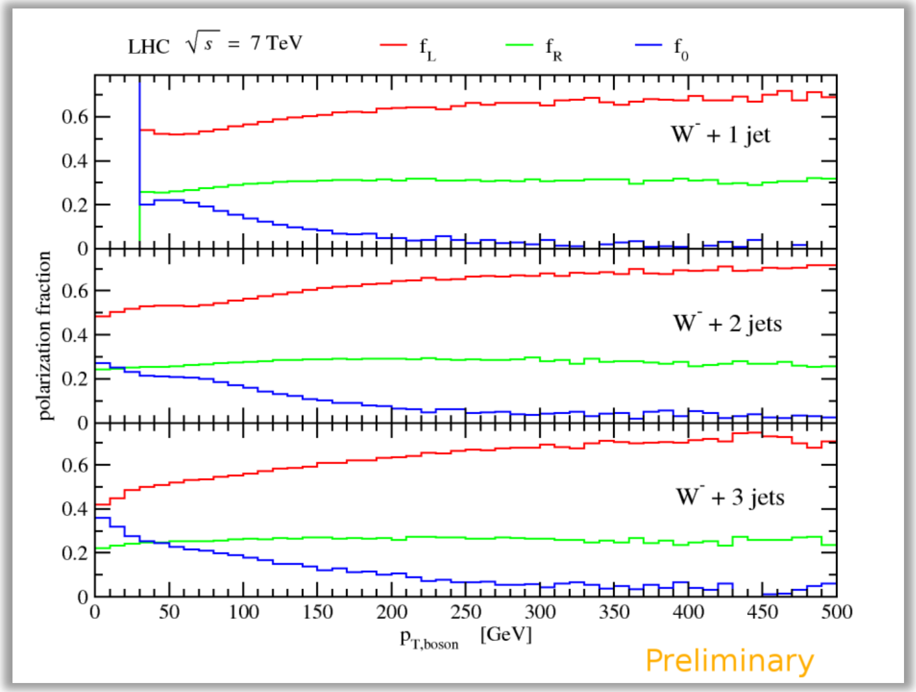
High-E_T W Polarization

- Polarization of low-p_T, longitudinal, *W*s is textbook material [Ellis, Stirling & Webber] $\Rightarrow$ dilution in charged-lepton rapidity distribution asymmetry at Tevatron

- This is a *different* effect! *W*s are also polarized at high p_T
- Universal:
  - Present at LO
  - Present for fewer jets too

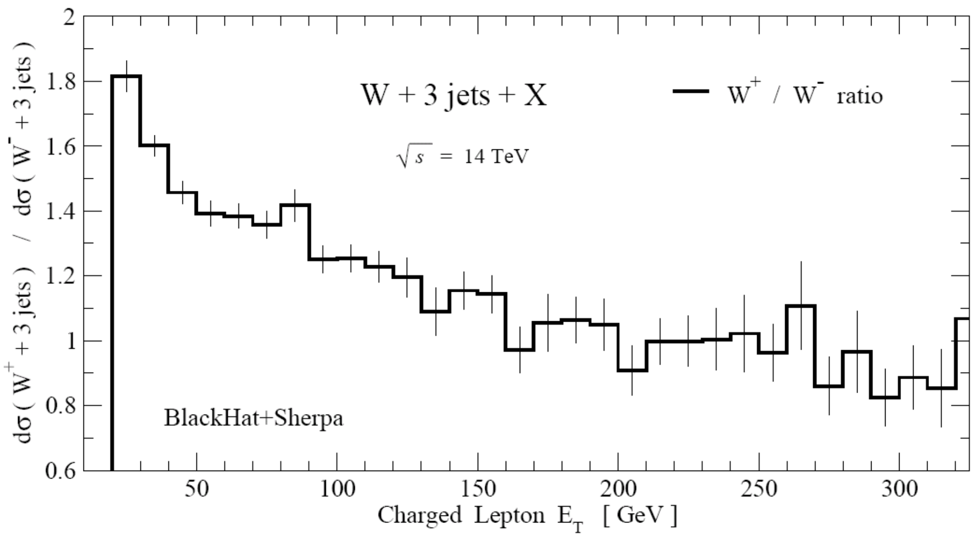


[BlackHat 09',10']

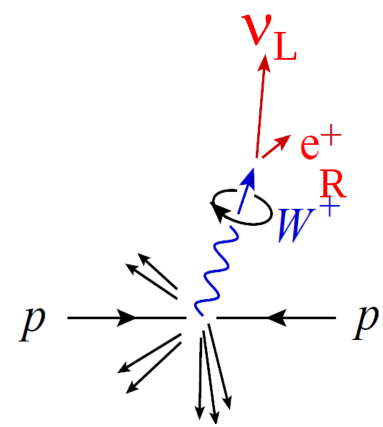


High-E_T *W* Polarization: analyzed by leptons

Ratio: E_T of e^+ over E_T of e^- [BlackHat 09']



- *W* Polarization analyzed by leptons:

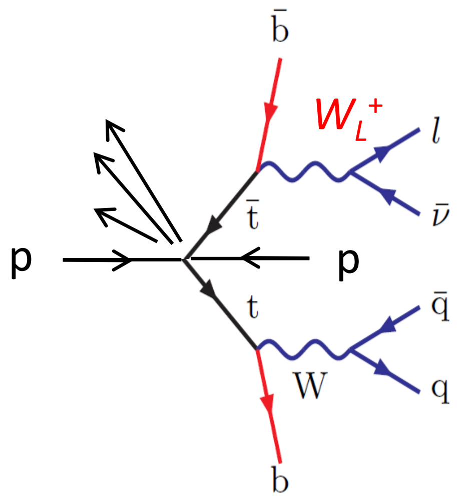


$\Rightarrow$ E_T dependence of e^+/e^- ratio and missing E_T in W^+/W^- at LHC.

- Useful for distinguishing "prompt" *W*s from daughter *W*s in top decay (or new heavy-particle decays)!

High-E_T *W* Polarization

Semi-leptonic $t\bar{t}$-decay



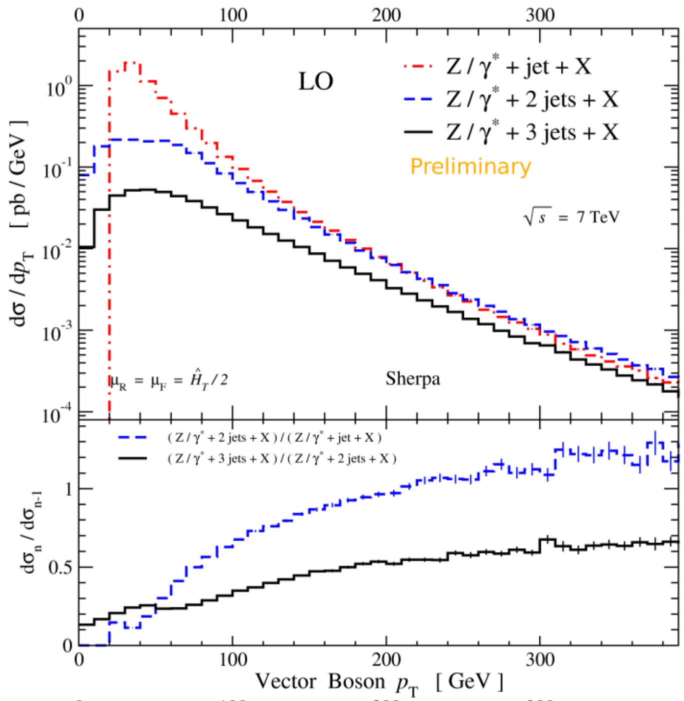
+ **charge conjugate decay**

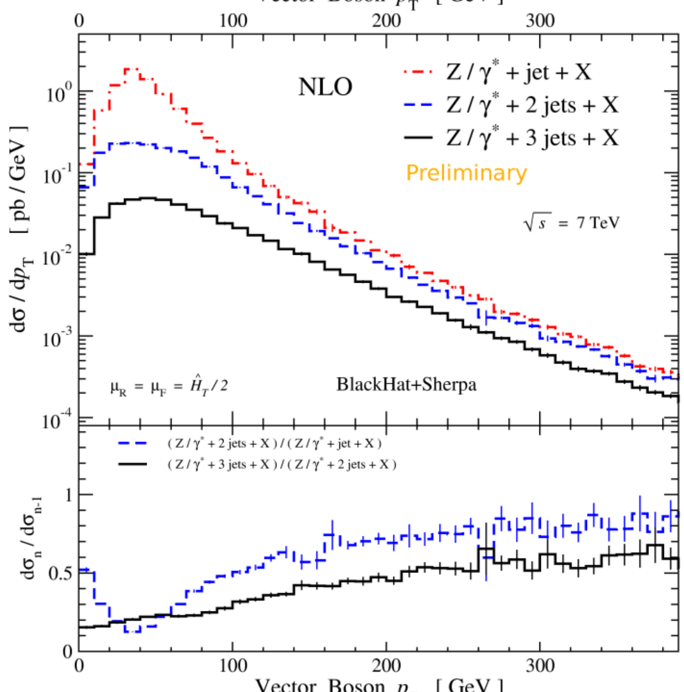
- Semi-leptonic top decay involves left-handed W^+
- But charge conjugate top decay involves right-handed W^-

$\Rightarrow$ Electron and positron have almost identical p_T distributions.

Nice handle on separating *W* + jets from semi-leptonic top pairs.

Jet-Production Ratios: Z+jets.





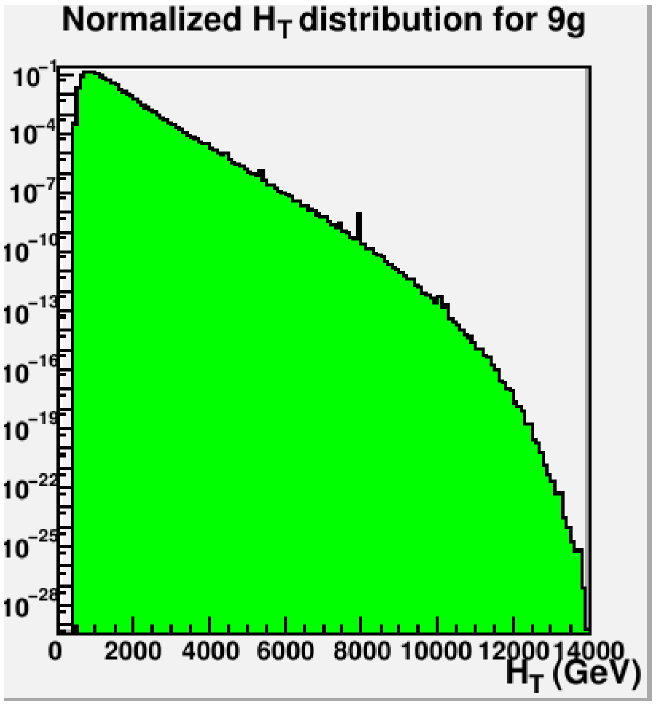
- Ratios of jet cross sections should be less sensitive jet energy scale and non-pert corrections

- Ratios are stable LO→NLO

- But hide a lot of structure in differential distributions:
  - Kinematic constraints at low p_T in 2/1
  - Factorization & IR $\ln(p_T / p_{T\,min})$s at intermediate p_T
  - Phase-space & pdf suppression at higher p_T.

Interesting developments

J. Winter and W. Giele 09';
Here LO; total NLO in progress



Multi-jet computation time-consuming:

- need to integrate over multi particle phase space
- amplitudes themselves take longer to evaluate

Or get efficiency gain from graphics cards?
[Hagiwara et al '09, Giele, Stavenga & Winter '09-10]

Generation of ROOT tuples: [Huston,…; BlackHat in progress]

- Re-analysis possible
- Distribute distributions
- Flexibility for studying scale variations
- Flexibility for computing error estimates associated with PDFs

Conclusions

- NLO calculations required for reliable QCD predictions at the Tevatron and LHC
- New efficient computational approaches to one-loop QCD amplitudes, exploiting unitarity & factorization properties, are now method of choice for important LHC backgrounds.
- Many new processes: *W/Z* + 1,2,3,4 jets, *tt* + 1,2 jets, VV+1,2 jets,... now known at NLO!

- Most complex NLO results are still at parton level and not embedded in a full Monte Carlo. Best use of these results may sometimes be via **ratios** – as aids to data-driven analysis of backgrounds. Interesting recent progress from NLO parton-shower approaches.

- Discussed some new understanding from multi-jet NLO for V+n jets: scale choices, jet-algorithms,...
- Left-handed *W* polarization large and universal and allows to, leading to further charge-asymmetric effects in *W* + *n* jets.

Thanks.