Weak Vector Boson Production with Jets at the LHC

Precise Predictions with BlackHat

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HP2: High Precision for Hard Processes

Max Planck Institute for Physics, Munich, September 6th, 2012

WEAK BOSONS AND JETS

V's at the LHC, 2,3,4 Jets, V+jets, LH Wishlist

NLO QCD CORRECTIONS FOR V+JETS

Multi leg results, BlackHat+SHERPA, V+1,2,3,4 Jets, NTUPLES

EXPERIMENTAL RESULTS

CMS polarization, ATLAS W/Z plus many Jets

Drell-Yan Precision

→ Inclusive NNLO QCD corrections know for some time
→ Fully exclusive NNLO QCD results available
→ NLO Electroweak and QED corrections
→ Very recent NNLO QCD + NLO EW corrections
→ …

All this leaves the theory uncertainty for Drell-Yan observables at the few percent level!

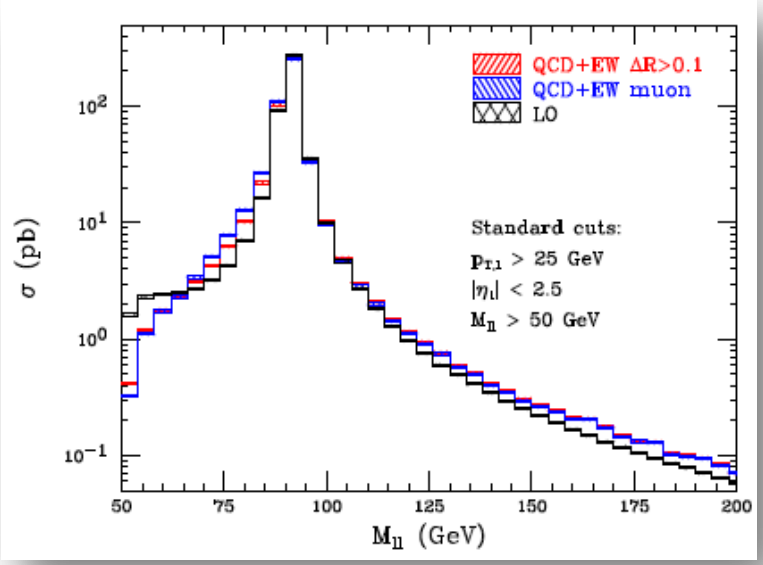
Hamberg, van Neerven, Matsuura (1991)

See for example: Gavin, Li, Petriello, Quackenbush (2012) ; Catani, Cieri, Ferrera, de Florian, Grazzini (2009)

See for example: Baur, Keller, Wackeroth (1999) ; Dittmaier, Kramer (2002) ; Calame, Montagna, Nicrosini (2006)

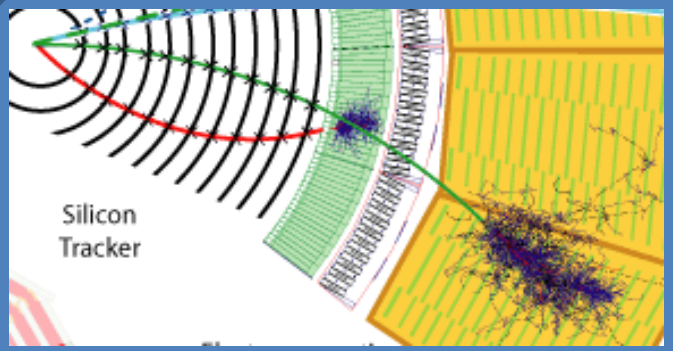
See: Li and Petriello arXiv:1208.5967

http://gate.hep.anl.gov/fpetriello/FEWZ.html

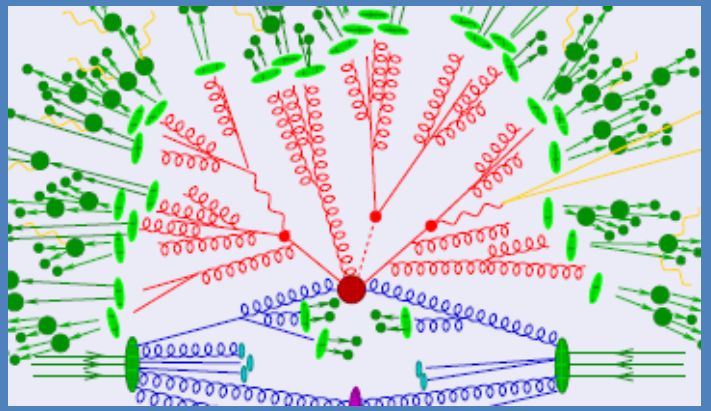


Jets

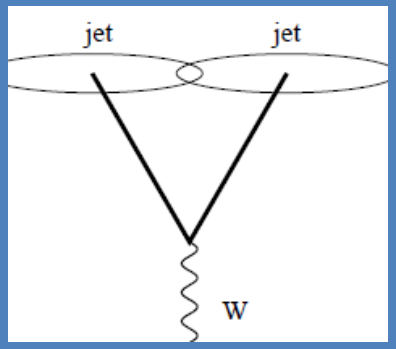
- Definition of complex objects



Detector towers



Shower simulations



Parton level calculations

IR Safe Jet Algorithms

In the past, performance of implementations of IR safe jet algorithms, kept them away from practical use at hadron colliders: for example with the "standard" N^3 scaling of the kt algorithm, or the naive 2^N of seedless cone algorithms

Great progress in recent years:

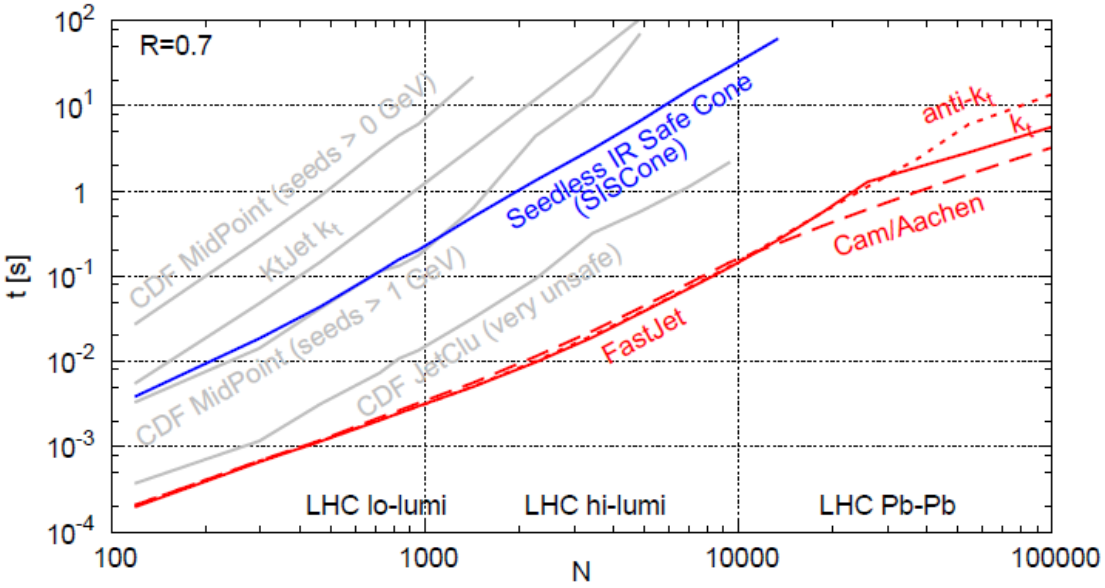
- Sequential recombination algorithms as kt / Cambrige-Aachen / anti-kt have been implemented with *N ln (N)* scaling [Cacciari, Salam hep-ph/0512210]
- A seedless infrared safe cone algorithm, SISCone, has appeared with N^2 *ln (N)* scaling [Salam, Soyez arXiv:0704.0292]

Available within FastJet http://fastjet.fr

Some typical event multiplicities at colliders:

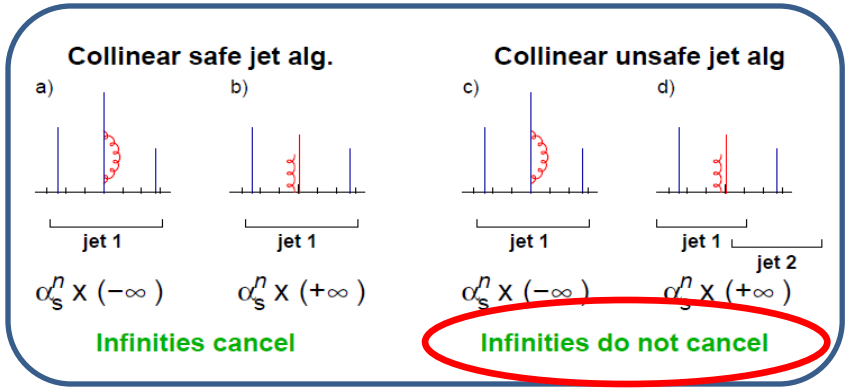
Type of event	N
e^+e^- event on the Z peak	50
Tevatron ($\sqrt{s} = 1.96$ TeV) dijet event	200
LHC ($\sqrt{s} = 14$ TeV) dijet event	500
LHC low-luminosity event (5 pileup collisions)	1000
LHC high-luminosity event (20 pileup collisions)	4000
RHIC Au Au event ($\sqrt{s} = 200$ GeV/nucleon)	3000
LHC Pb Pb event ($\sqrt{s} = 5.5$ TeV/nucleon)	30000

[Salam arXiv:0906.1833]

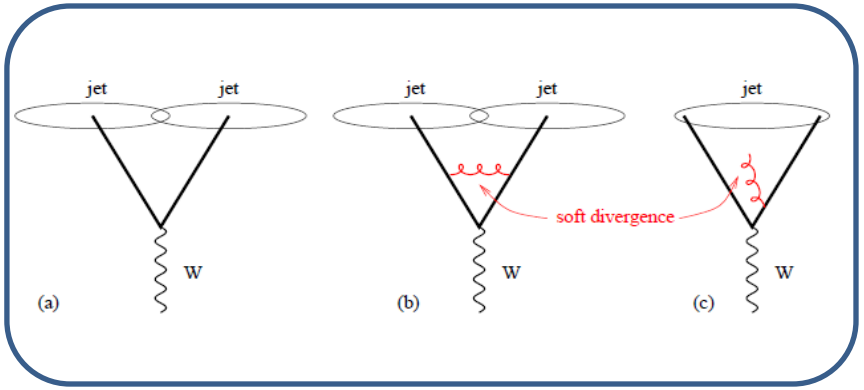


The need of IR safety

Collinear Configuration



Soft Configuration



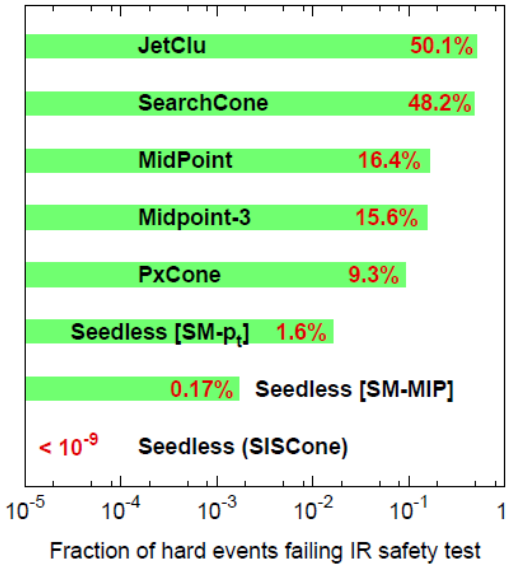
→ IRC unsafety makes data / pertubative calculation comparison hard (if at all meaningful)

→ Indeed, quantum corrections become useless for large enough multiplicity!

[Salam, Soyez arXiv:0704.0292]

Observable	1st miss cones at	Last meaningful order
Inclusive jet cross section	NNLO	NLO
$W/Z/H + 1$ jet cross section	NNLO	NLO
3 jet cross section	NLO	LO
$W/Z/H + 2$ jet cross section	NLO	LO
jet masses in 3 jets, $W/Z/H + 2$ jets	LO	none

Testing IR safety of some commonly used cone algorithms



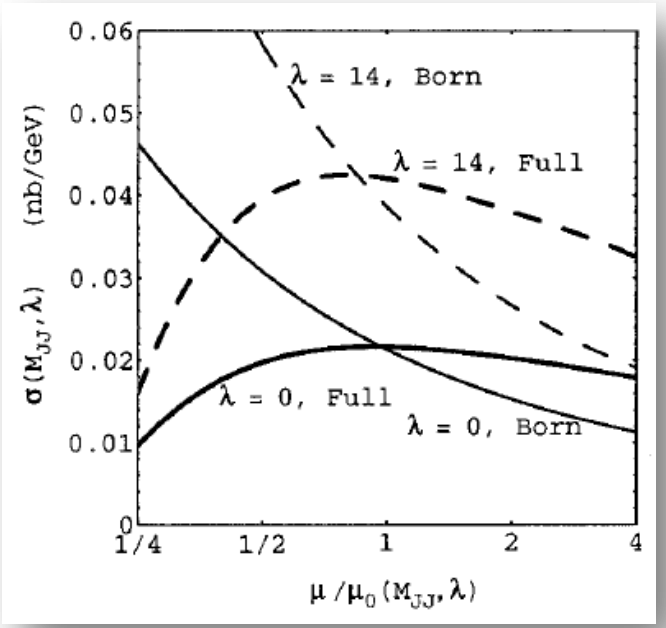
Both ATLAS and CMS use IR safe algorithms in their analyses!

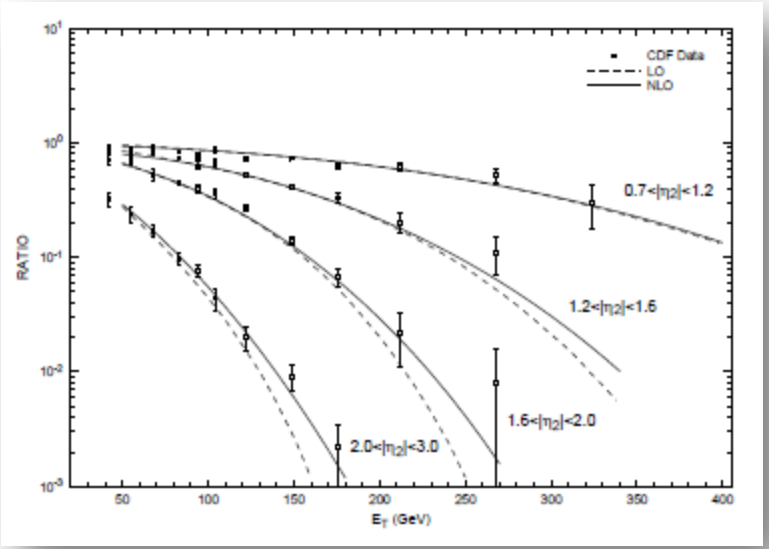
QCD CORRECTIONS TO JET PRODUCTION

Inclusive and Two Jet Production

First single-jet inclusive NLO QCD calculations performed in the early 90's

S.D. Ellis, Z. Kunszt and D.E. Soper 1990 & 1992





Fully exclusive NLO QCD results two-jet production, compared to CDF data

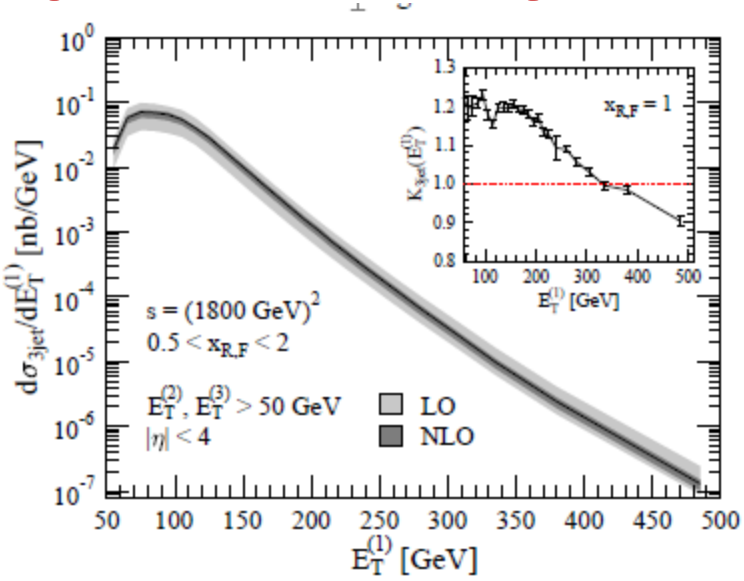
W.T. Giele, E.W.N. Glover and D.A. Kosower 1993 & 1994

Results implemented into the MC program JETRAD

http://vircol.fnal.gov/MCdownload/jetrad.html

3-Jet Production (NLOJet++)

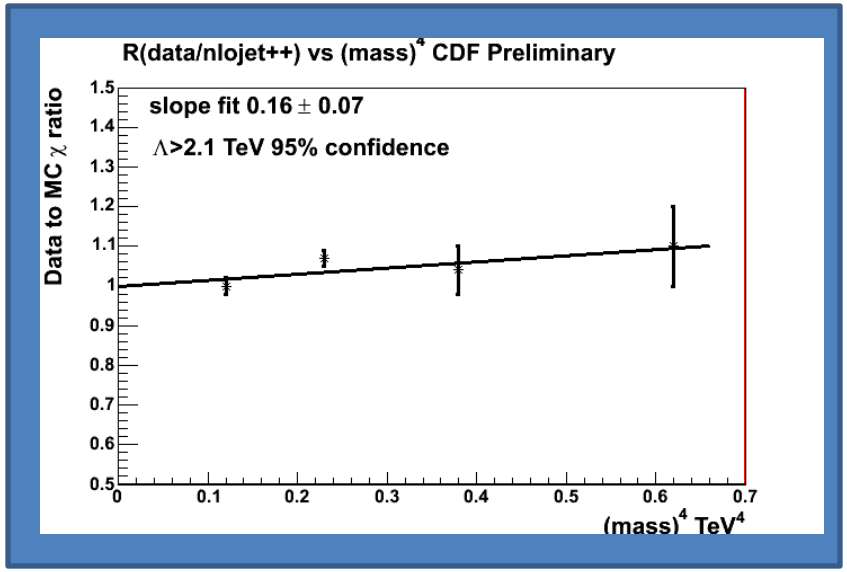
→ It would take about ten years to obtains first NLO QCD results to 3-Jet production
→ Kilgore and Giele present complete results in 2000
→ Nagy also obtains result in 2001(2003) and releases NLOJET++
→ One of the most complex 2 → 3 NLO QCD calculations



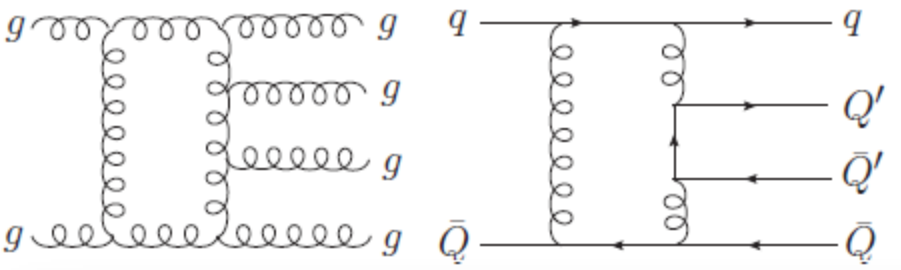
Results implemented into the C++ program NLOJET++

http://www.desy.de/~znagy/Site/NLOJet++.html

Code employed by multiple analyses of Tevatron and LHC collaborations!



4-Jet Production @ NLO (BlackHat+SHERPA)



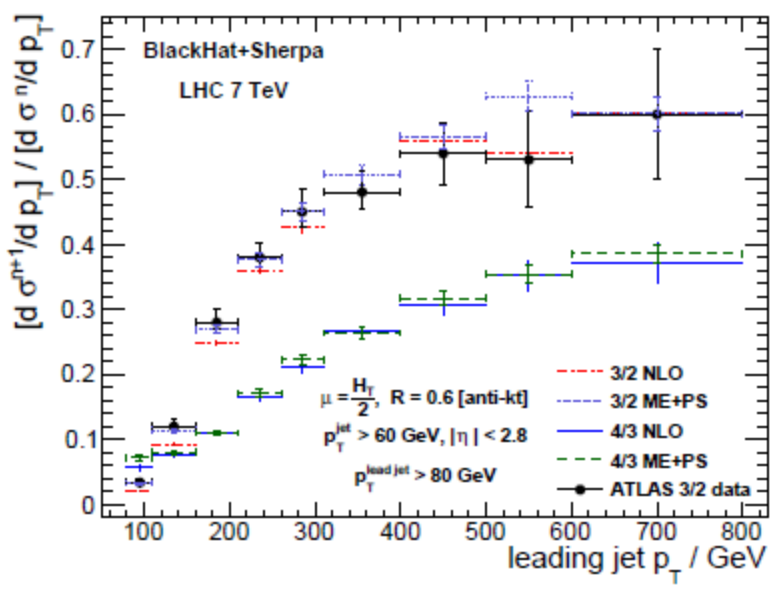
Bern, Diana, Dixon, FFC, Hoeche, Kosower, Ita, Maitre, Ozeren **[arXiv:1112.3940]**

Automated Calculation (On-Shell Techniques) of Loop ME's and Real Pieces (CS Dipoles)

no. jets	ATLAS	LO	ME+PS	NLO	NP factor	NLO+NP
≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	559(5)	$1193(3)^{+130}_{-135}$	0.95(0.02)	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	39.7(0.9)	$54.5(0.5)^{+2.2}_{-19.9}$	0.92(0.04)	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	3.97(0.08)	$5.54(0.12)^{+0.08}_{-2.44}$	0.92(0.05)	$5.11(0.29)^{+0.08}_{-2.32}$

→ Ten more years to obtain first NLO QCD results for 4-Jet Production
→ Computed by the BlackHat Collaboration
→ Postdictions and Predictions for an ATLAS setup
→ Single framework for several multiplicities
→ One of the most complex 2 → 4 NLO QCD calculations

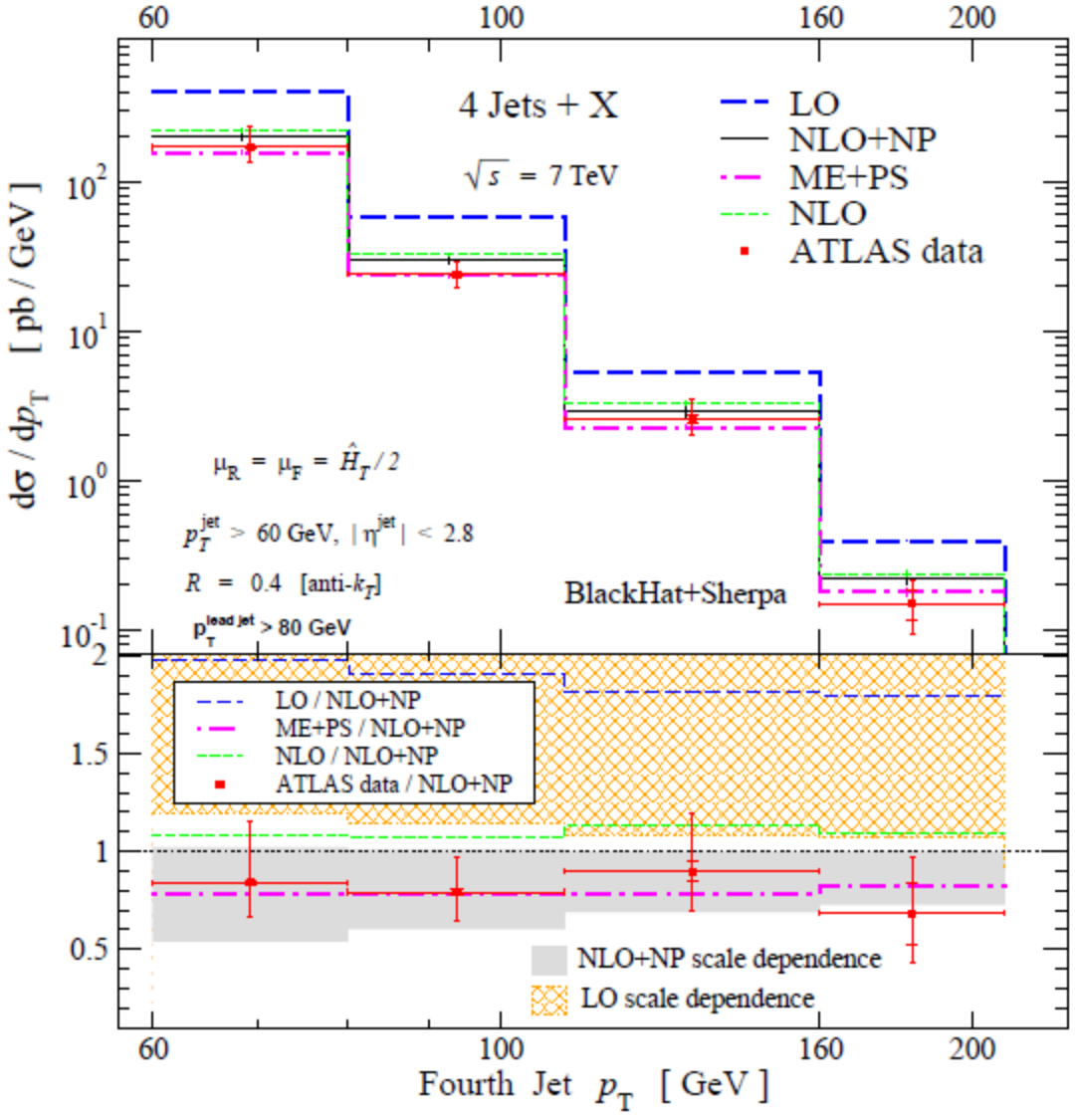
Calculation reproduced very recently by Badger, Biedermann, Uwer and Yudin **[arXiv:1209.0098]**



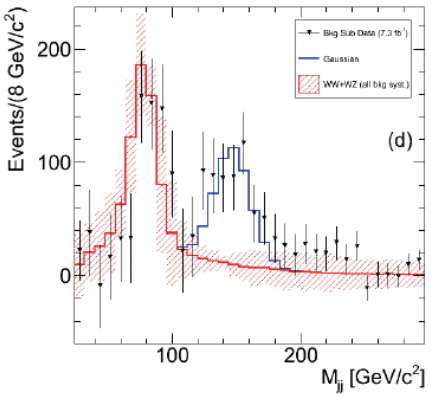
4-Jet Production @ NLO (BlackHat+SHERPA)

Bern, Diana, Dixon, FFC, Hoeche, Kosower, Ita, Maitre, Ozeren
[arXiv:1112.3940]

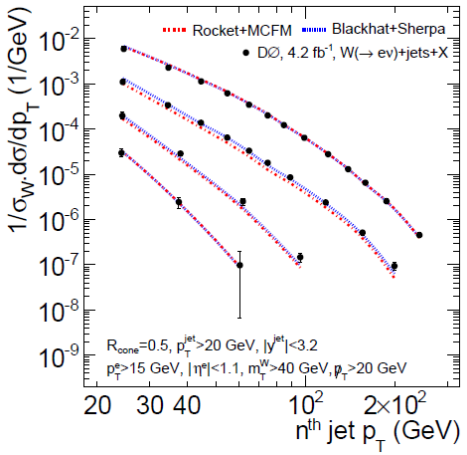
→ Fourth Jet p_T spectrum
→ NLO corrections large (reducing NLO cross section)
→ Comparison to ATLAS 2.4 pb^{-1} data shows good agreement
→ Relatively small (~10%) non-perturbative corrections



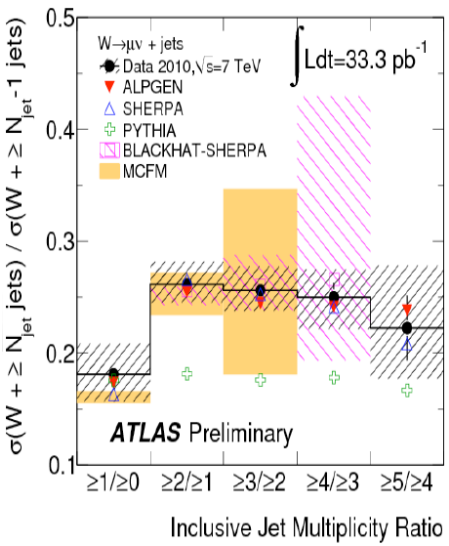
COMBINING V'S AND JETS: A IMPORTANT SIGNAL



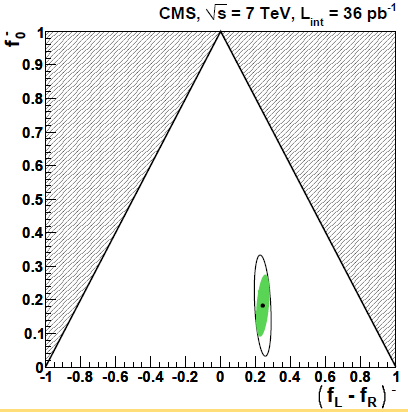
CDF Bump



D0 W+Jets Measurement
arXiv:1106.1457



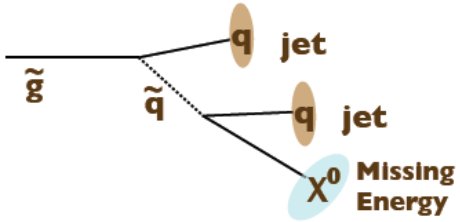
Atlas Jet Ratios



CMS Pol Measurement
arXiv:1104.3829

V + Jets at NLO for SUSY Searches

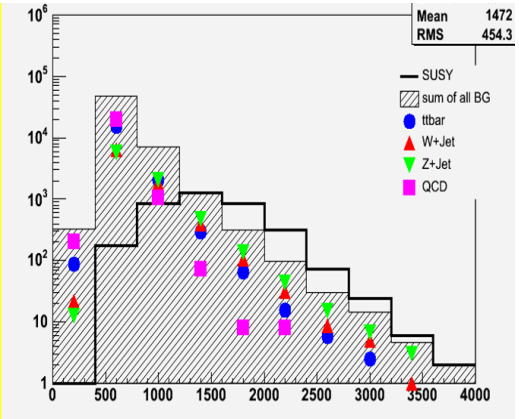
Gluino pair production with:



Mangano [arXiv:0809.1567]

$W^+ + 3$ jet followed by: $W^+ \rightarrow \bar{\tau}\nu_\tau \rightarrow \bar{\nu}_\tau\nu_\tau + \text{hadrons}$

Z + 4 jet followed by: $Z \rightarrow \nu\bar{\nu}$



ATLAS simulation for missing ET + Jets signal

Must Match Experimental Needs!

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

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

First entry filled by BlackHat+SHERPA calculation (See K. Ozeren's Talk!)

Campbell

WEAK BOSONS AND JETS

V's at the LHC, 2,3,4 Jets, V+jets, LH Wishlist

NLO QCD CORRECTIONS FOR V+JETS

Multi leg results, BlackHat+SHERPA, V+1,2,3,4 Jets, NTUPLES

EXPERIMENTAL RESULTS

CMS polarization, ATLAS W/Z plus many Jets

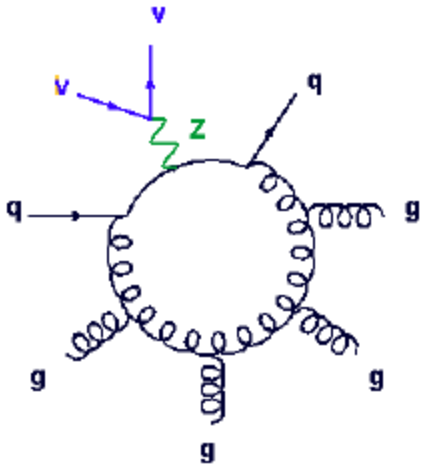
BlackHat 2009

Berger, Bern, Dixon, FFC, Forde, Gleisberg, Ita, Kosower, Maitre

BlackHat 2011

Bern, Diana, Dixon, FFC, Forde, Höche, Ita, Kosower, Maitre, Ozeren

NLO with BlackHat+SHERPA



2 → 4 Processes

- pp → W + 3 Jets [2009]
- pp → Z + 3 Jets [2010]
- pp → 4 Jets [2011]

2 → 5 Processes

- pp → W + 4 Jets [2010] *(leading color)*
- pp → Z + 4 Jets [2011] *(leading color)*
- pp → W + 4 Jets [Ita and Ozeren, 2011] *(full color)*

2 → 6 Processes (PRELIMINARY)

- pp → W + 5 Jets [2012] *(leading color)*

See K. Ozeren's talk!

NLO with BlackHat+SHERPA

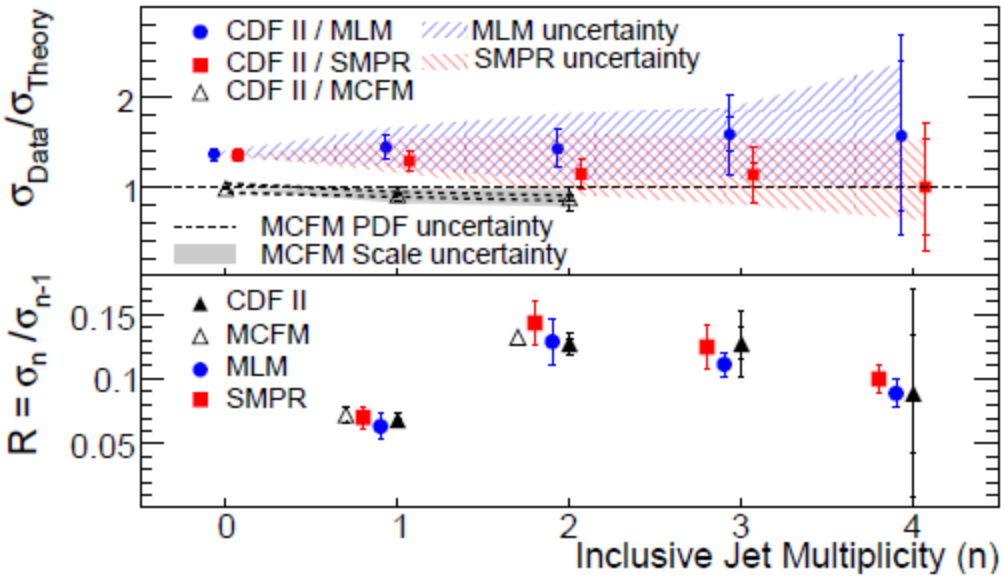
$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

High level of automation and optimization for pure QCD and V+Jet processes

Loop amplitudes based on Generalized Unitarity

NLO Success Describing W+jets Data

Tevatron: W + n jets Data. (CDF, arXiv:0711.4044) data from $320 pb^{-1}$



NLO:

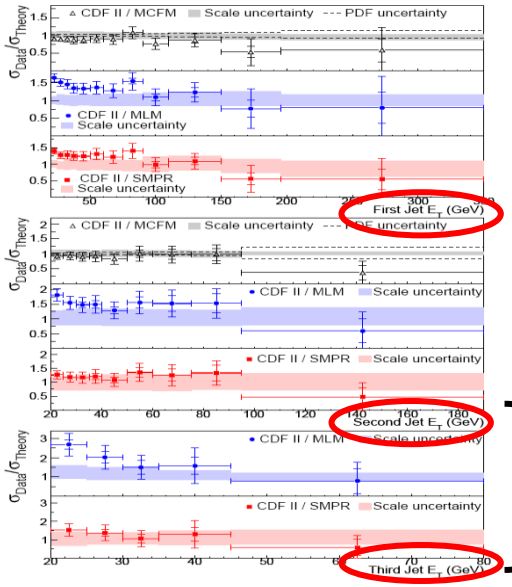
MCFM; parton level;
including Bern, Dixon, Kosower and Weinzierl
W+2 1-loop matrix elements;
Full NLO by Campbell and Ellis.

LO matched to parton shower:

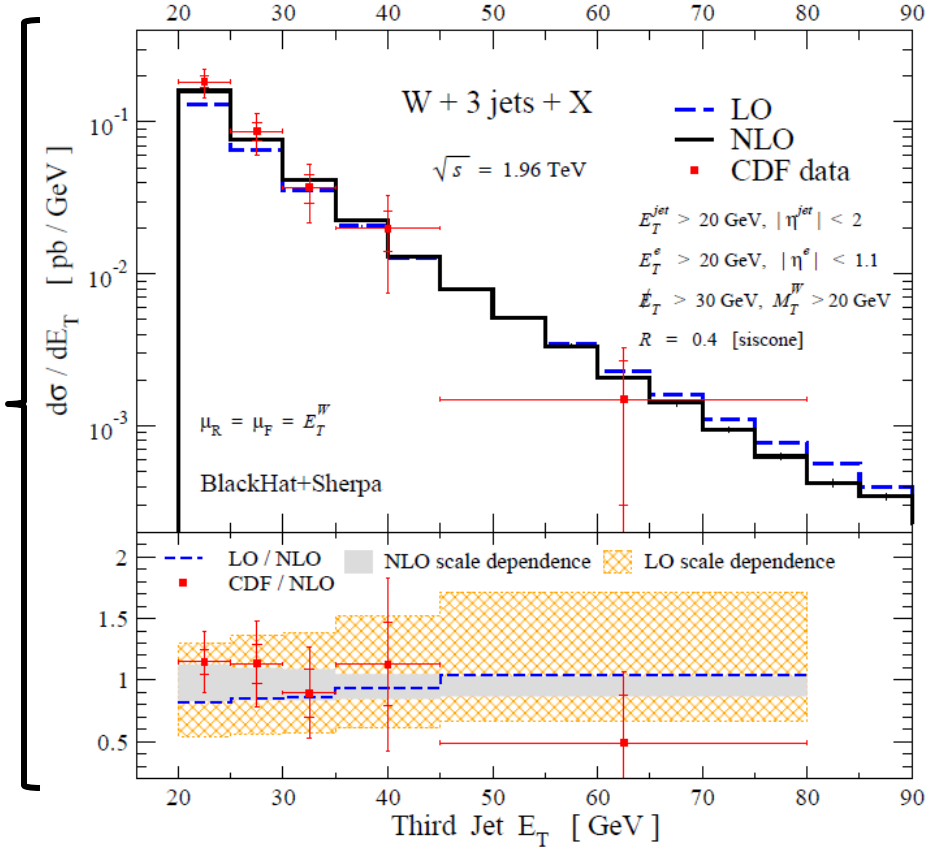
- MLM-model: Alpgen+Herwig.
- SMPR-model: Madgraph+Pythia

QCD corrections to W+3 Jets at the Tevatron

[Berger, Bern, Dixon, Forde, FFC, Gleisberg, Ita, Kosower, Maître arXiv:0902.2760; arXiv:0907.1984]



[CDF arXiv:0711.4044]



NLO agrees well with W+3 data!

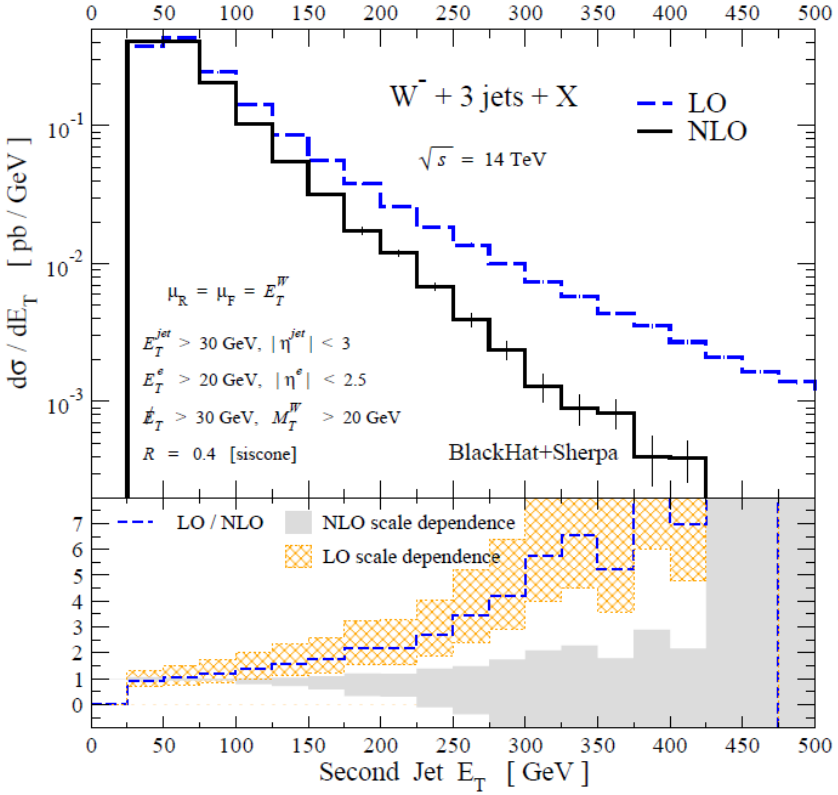
number of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

We use SISCone; CDF used IR unsafe JETCLU

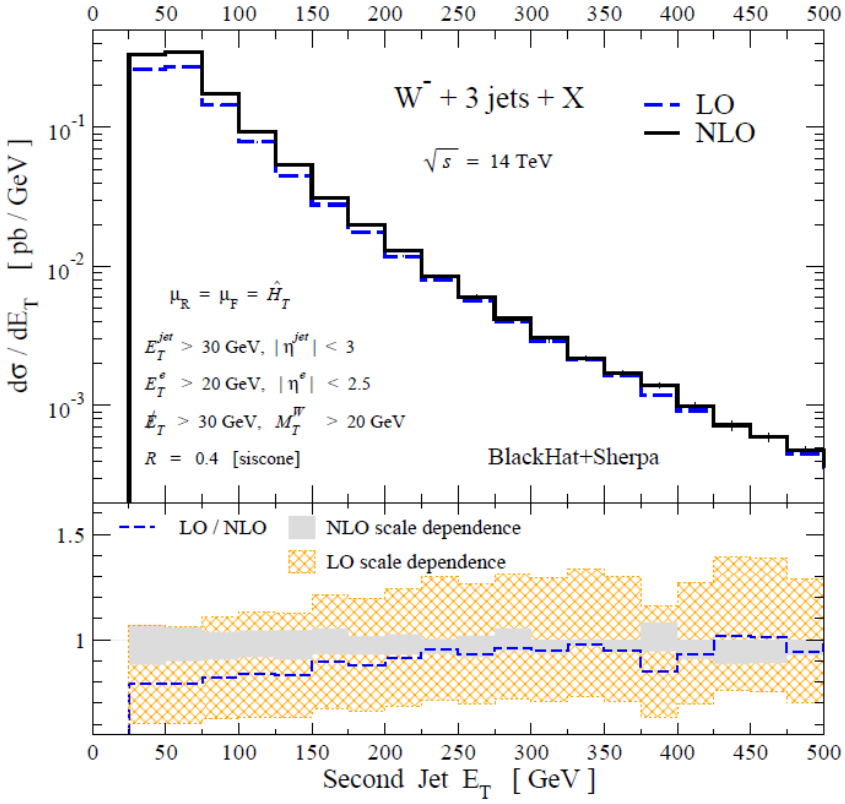
Difference below 20% From comparing to Other IR safe algorithms [Ellis, Melnikov, Zanderighi arXiv:0906.1445]

Compare Two Scale Choices

$\mu = E_T^W$



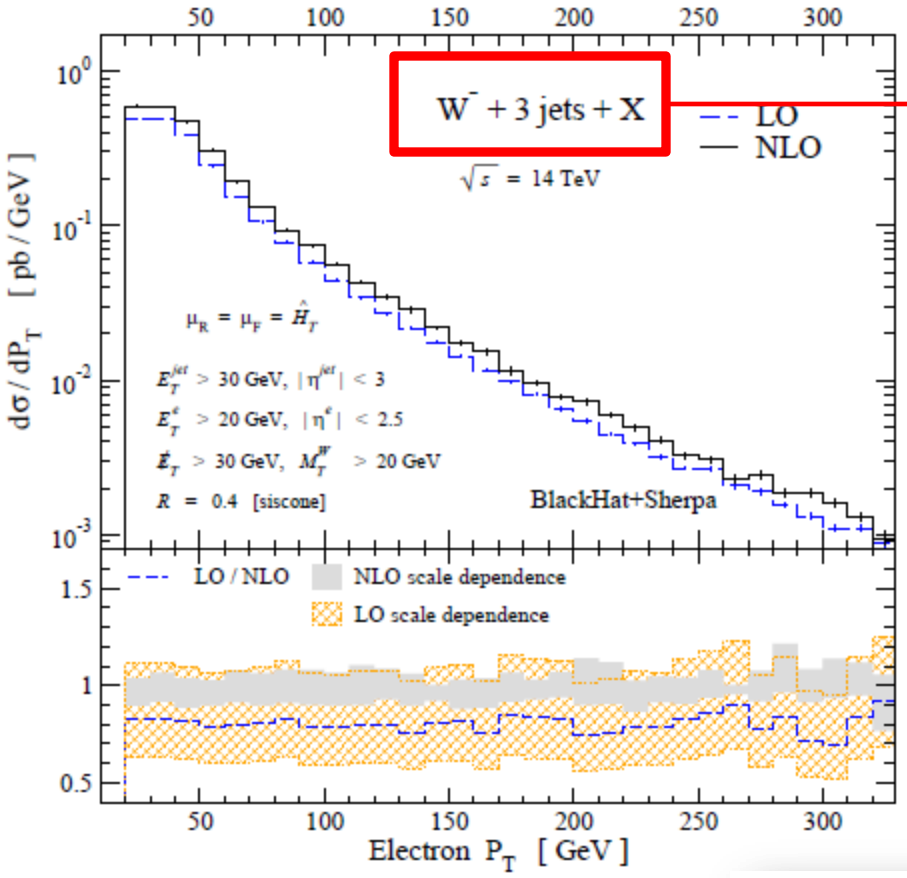
$\mu = \hat{H}_T$

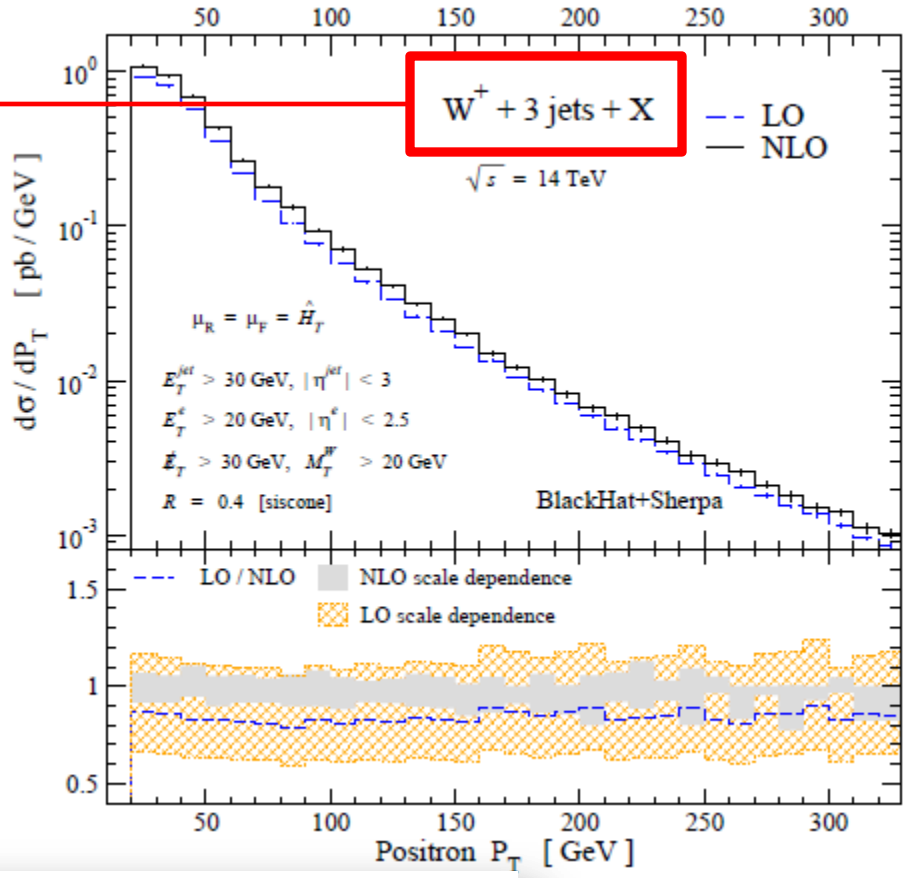


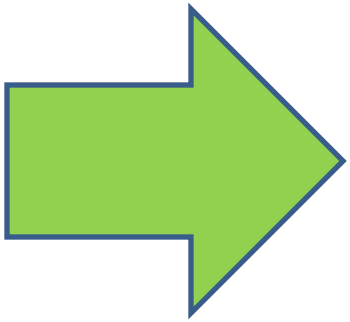
Message: Do not use $\mu = E_T^W$

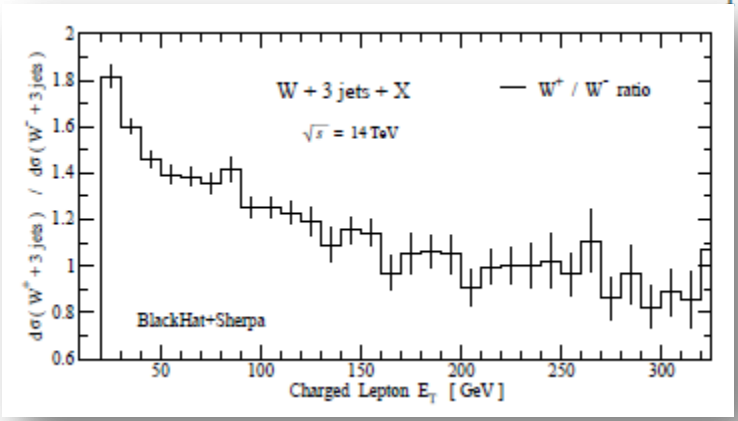
- LO/NLO ratio sensible.
- NLO scale dependence very good.

Polarization In An Odd Place









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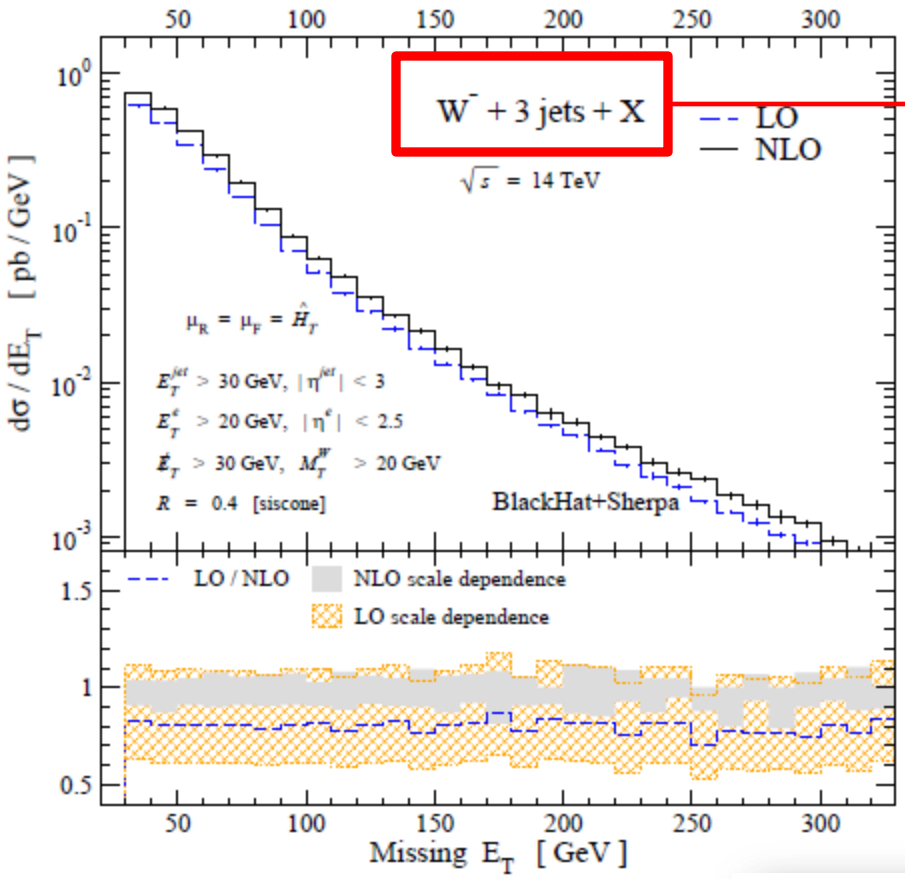
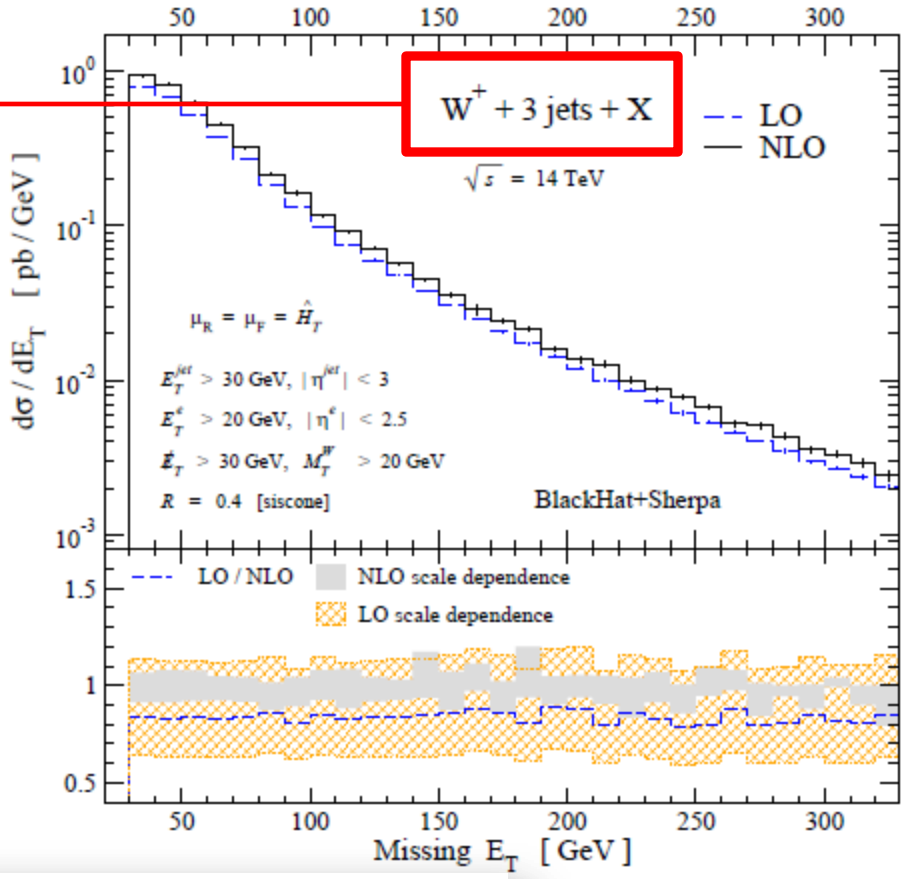
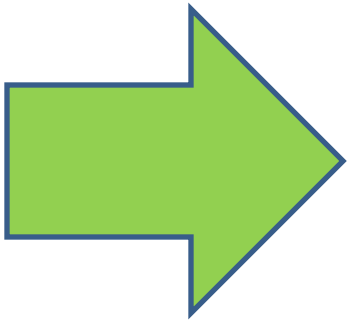
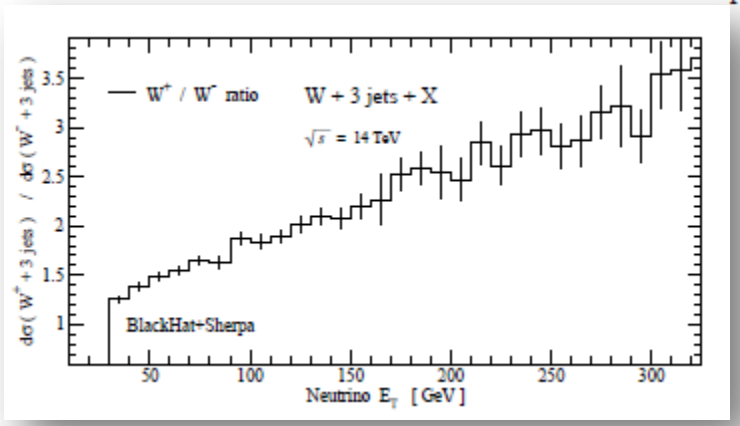


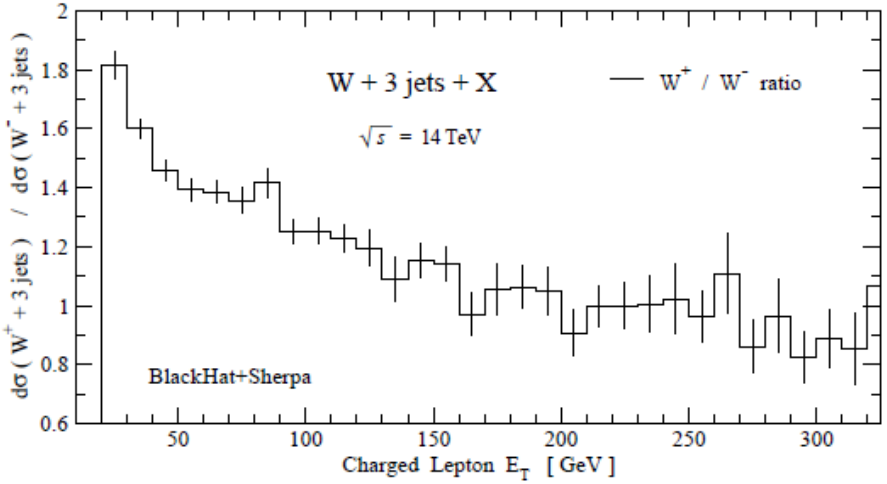


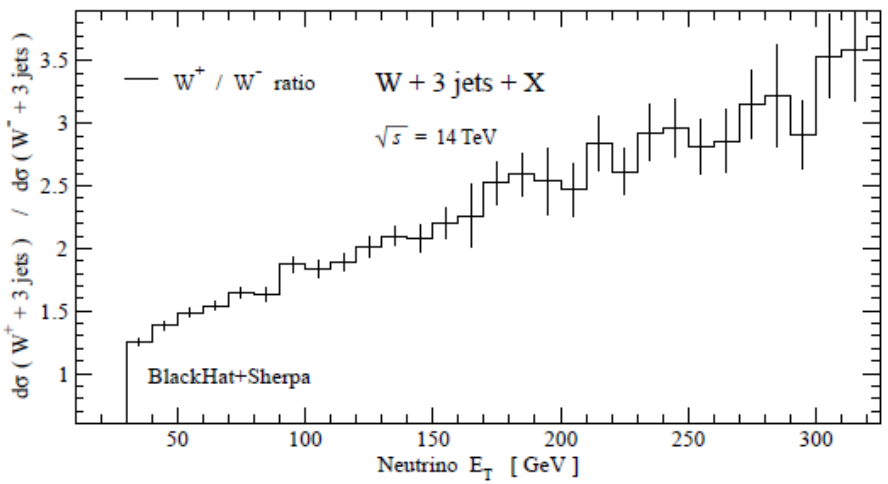




Leptonic E_T in W + 3 jets at LHC

[Berger, et al arXiv:0907.1984]





– W^+/W^- transverse lepton ratios trace a remarkably large left-handed W polarization at large $p_T(W)$

– independent of number of jets

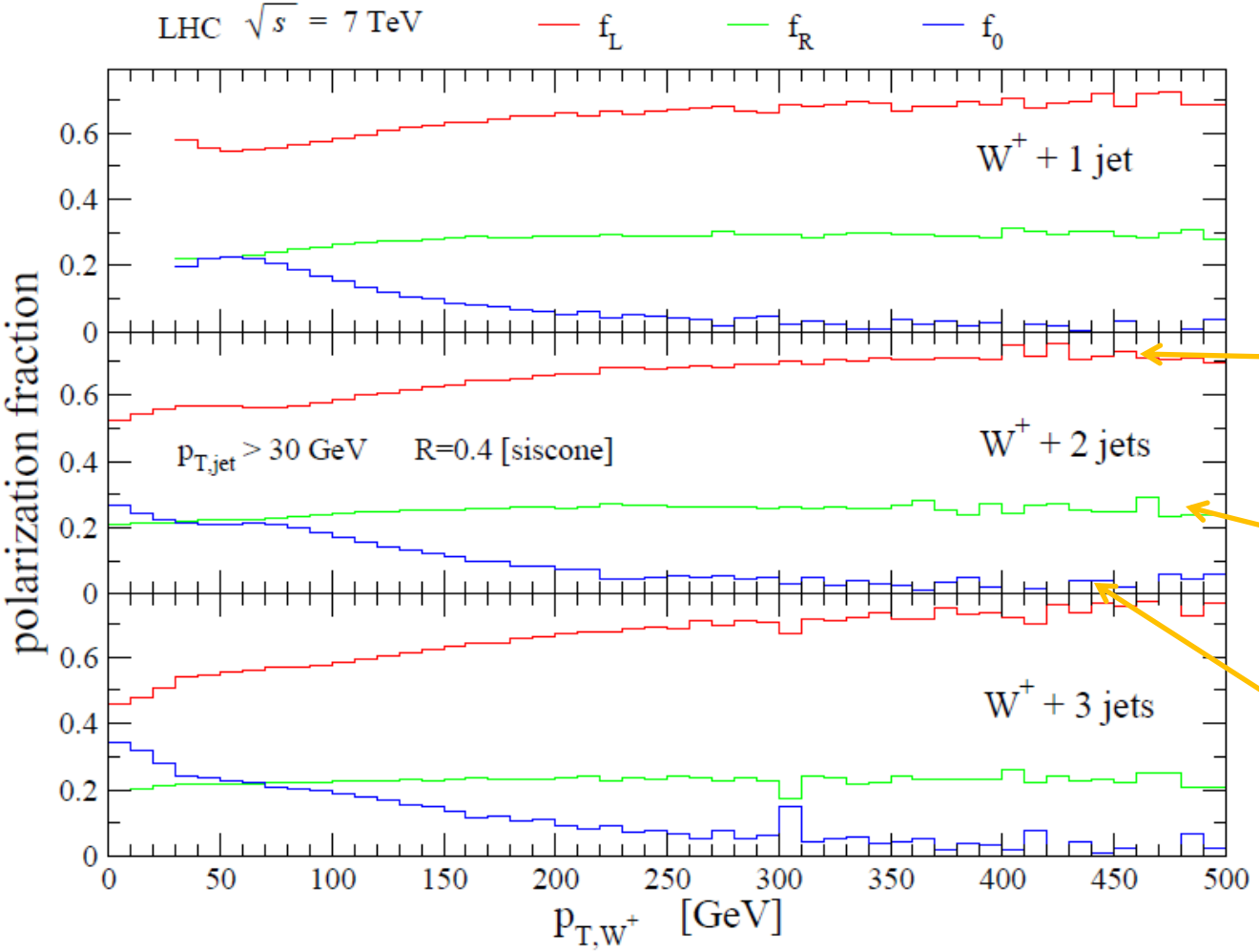
– stable under QCD corrections

– will be useful to separate W + n jets from top, maybe also from new physics

BlackHat: **[arXiv:1103.5445]**

Actual W polarization

BlackHat: [arXiv:1103.5445]



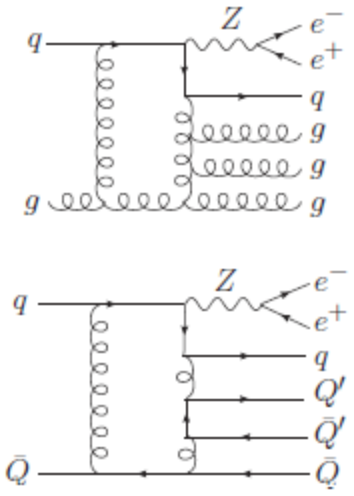
Left handed component

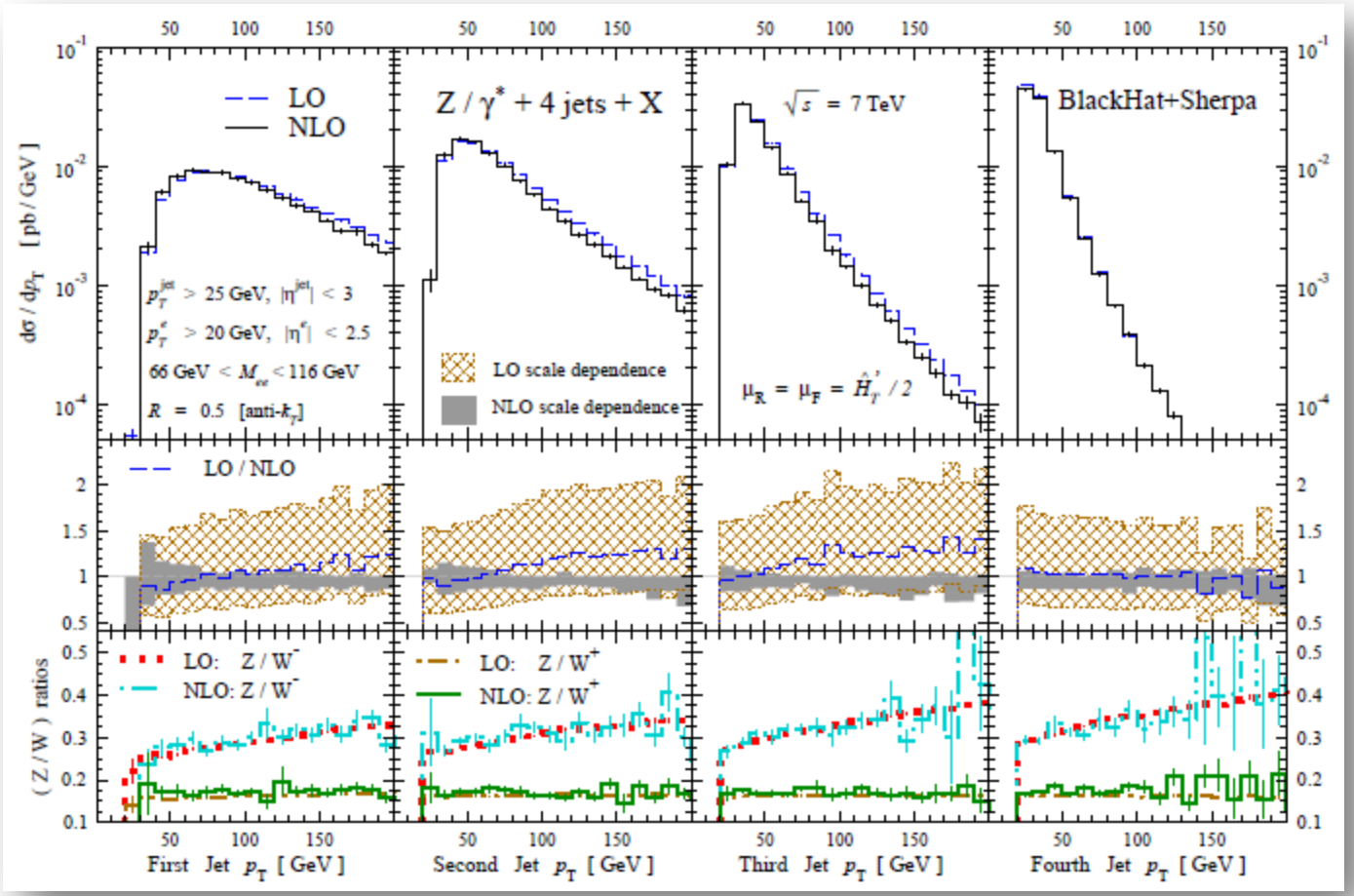
Right handed component

Scalar component

Detailed Studies of Distributions and Ratios

no. jets	Z LO	Z NLO	Z/W^+ LO	Z/W^+ NLO	$Zn/(n-1)$ LO	$Zn/(n-1)$ NLO
0	$323.1(0.1)^{+39.3}_{-44.3}$	$428.6(0.3)^{+6.2}_{-4.1}$	0.1209(0.0001)	0.1306(0.0003)	—	—
1	$66.69(0.04)^{+5.59}_{-5.30}$	$82.1(0.1)^{+3.3}_{-2.6}$	0.1674(0.0002)	0.166(0.001)	0.2064(0.0001)	0.1915(0.0004)
2	$19.10(0.02)^{+5.32}_{-3.82}$	$20.25(0.07)^{+0.31}_{-1.02}$	0.1636(0.0003)	0.166(0.002)	0.2864(0.0003)	0.247(0.001)
3	$4.76(0.01)^{+2.18}_{-1.35}$	$4.73(0.03)^{+0.05}_{-0.35}$	0.1634(0.0004)	0.169(0.002)	0.2494(0.0004)	0.234(0.002)
4	$1.116(0.002)^{+0.695}_{-0.390}$	$1.06(0.01)^{+0.05}_{-0.14}$	0.1618(0.0003)	0.172(0.002)	0.2343(0.0005)	0.223(0.002)





Sharing Complex Calculations

→ High Precision for Hard Processes calculations are most valuable if made available to larger ex/ph/th community

→ Many codes, like MCFM, exist that provide direct access to ME's and integration tools for variety of observables

→ Although efficiency of modern NLO codes for large multiplicities has greatly improved over the last few years, still very computer intensive

→ A solution: Store as many information as possible from your calculation, *the ntuple way…*

BlackHat+SHERPA NTUPLES

- Files containing
  - Kinematic Information
  - Information needed to change factorization and renormalization scales and PDFs
  - Information for multiple jet algorithms (different R's, f-parameters, etc)
- Publically available
  - C++ library to read and handle them
- W/Z+0,1,2,3,4(,5) jets at the LHC
  - Already used by LHC's collaborations!

WEAK BOSONS AND JETS

V's at the LHC, 2,3,4 Jets, V+jets, LH Wishlist

NLO QCD CORRECTIONS FOR V+JETS

Multi leg results, BlackHat+SHERPA, V+1,2,3,4 Jets, NTUPLES

EXPERIMENTAL RESULTS

CMS polarization, ATLAS W/Z plus many Jets

CMS W POLARIZATION MEASUREMENT

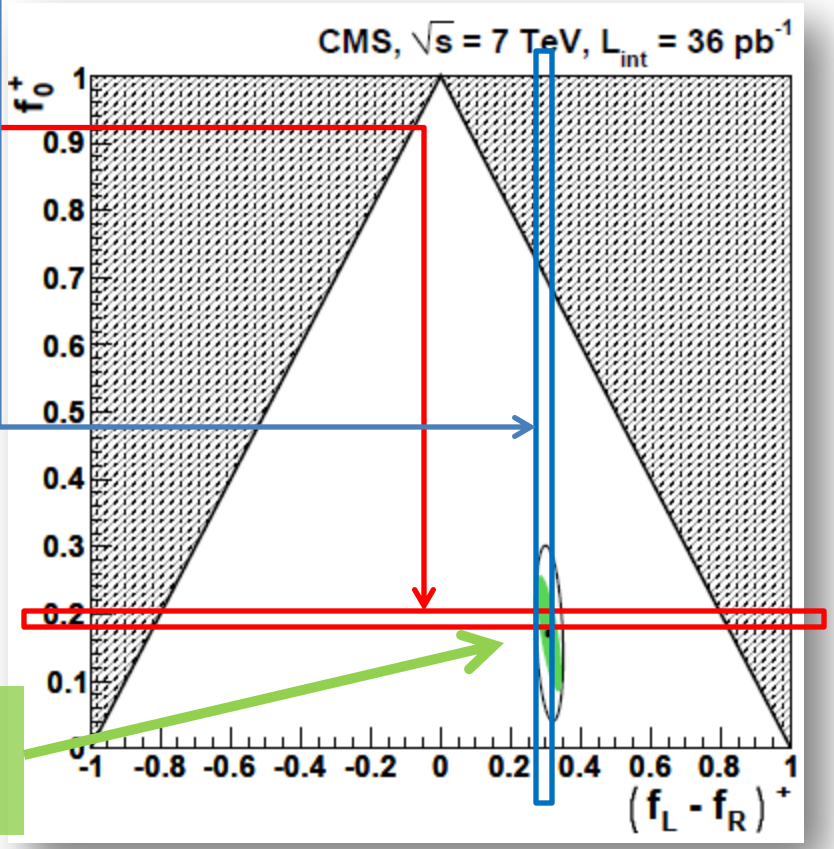
arXiv:1104.3829 [hep-ex]

Polarized W's at CMS

	W^+ NLO	W^+ ME+PS	W^+ LO
f_L	0.554	0.548	0.556
f_R	0.246	0.265	0.246
f_0	0.200	0.187	0.198

Theory predictions by BlackHat+SHERPA collaboration **arXiv:1103.5445 [hep-ph]**

→ In **arXiv:1104.3829 [hep-ex]** CMS reports finding left handed polarized *W*'s
→ Employs 36 pb^{-1} of data collected in 2010
→ Data published in the plane (f_L - f_R) *vs.* f_0
→ Results agree with BlackHat's prediction
→ Results shown here for W^+, but similar results for W^-



Excellent theory/experiment agreement within both statistical and total uncertainties

Z+JETS AT ATLAS: TOTAL XS & DISTRIBUTIONS

arXiv:1111.2690 [hep-ex]

Z+Jets @ ATLAS

→ In **arXiv:1111.2690 [hep-ex]** ATLAS presented a thorough study of associated Z and Jet production at 7 TeV

→ Employs 36 pb^{-1} of data collected in 2010

→ Data shown including up to four jets

→ Comparisons to NLO QCD results with BlackHat+SHERPA Ntuples and with the MC generators SHERPA / ALPGEN / Pythia

→ Both electron and muon decay channels analyzed

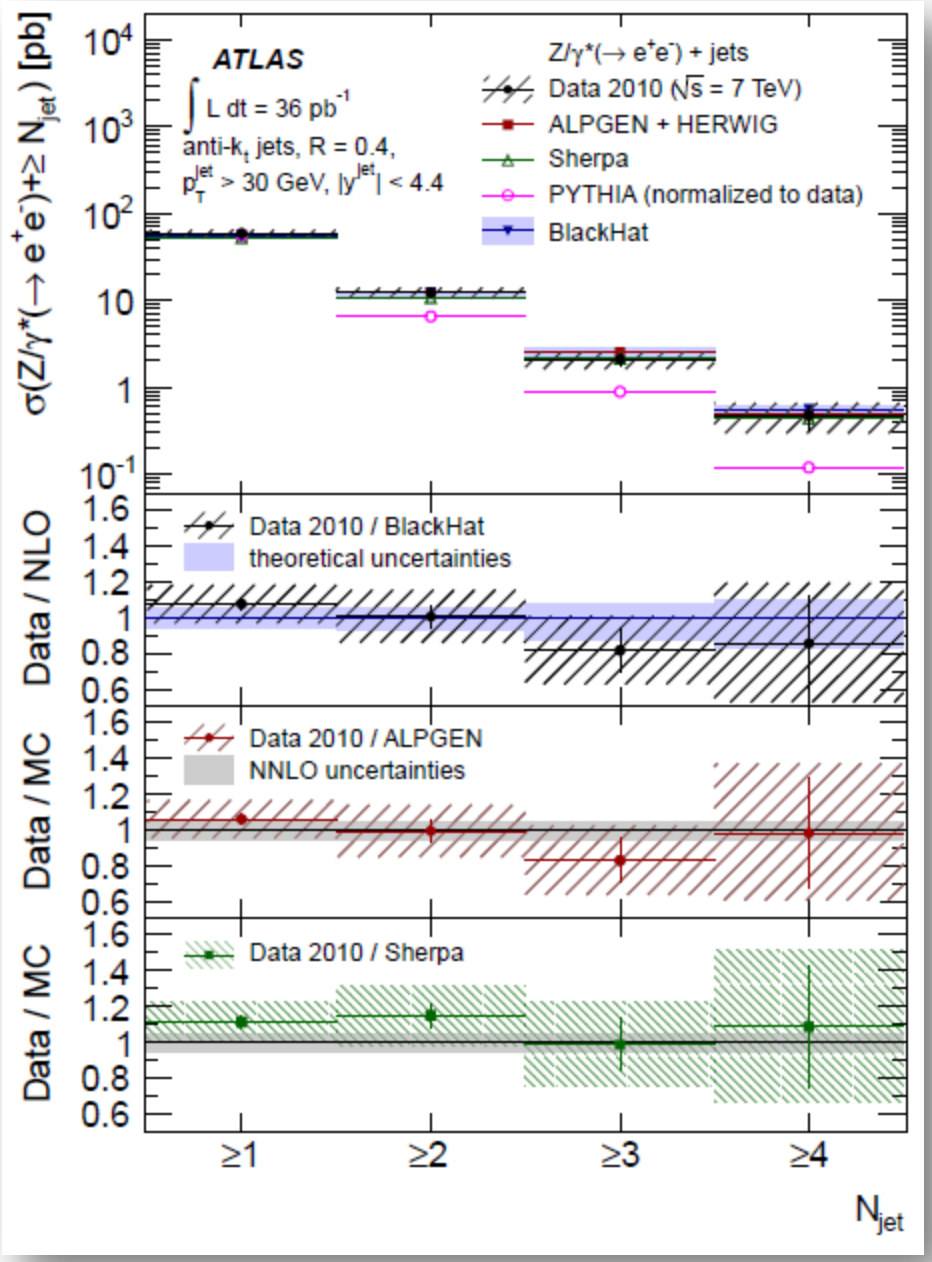
Kinematical cuts:

anti-k_t jets, R = 0.4,

$p_T^{jet} > 30$ GeV, $|y^{jet}| < 4.4$

Z+Jets @ ATLAS

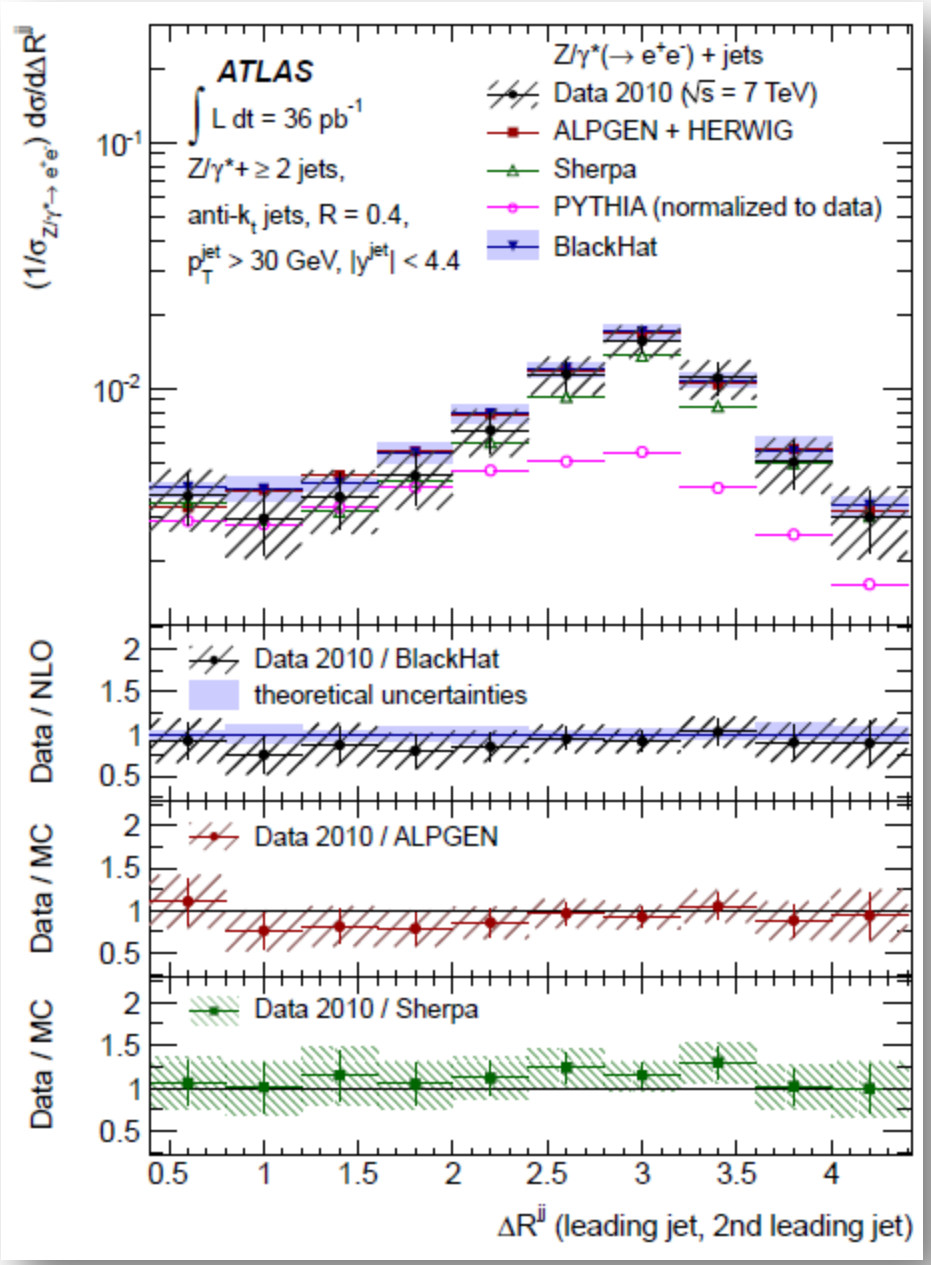
→ 36 pb^{-1}
→ Inclusive cross section for each multiplicity
→Good agreement with NLO results
→ Four Jet bin error expected to be halved with more statistics
→ Electron channel shown



arXiv:1111.2690 [hep-ex]

Z+Jets @ ATLAS

→ 36 pb^{-1}
→ R separation between leading p_T jets
→ Good shape predictions from theory (except for Pythia)
→ Electron channel shown



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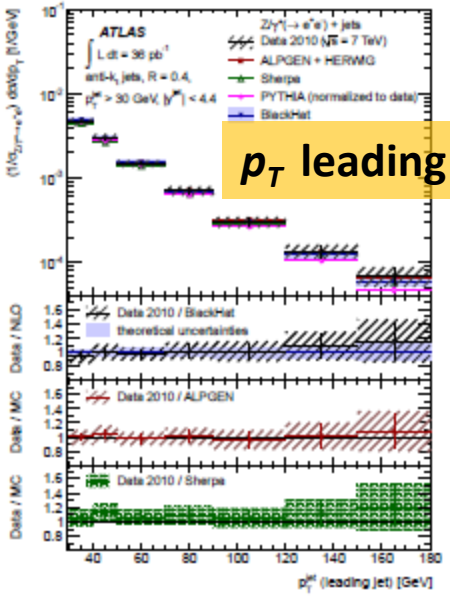
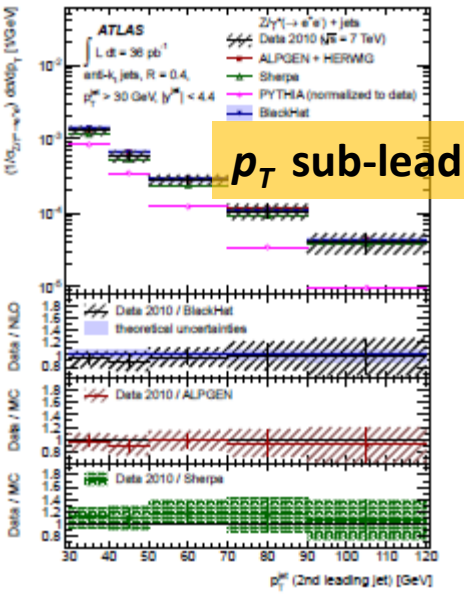
Z+Jets @ ATLAS

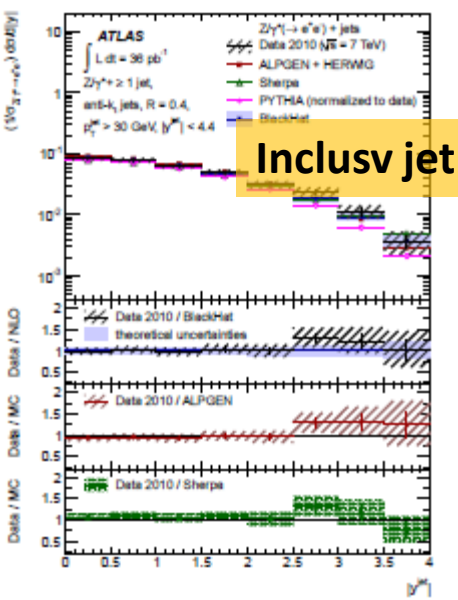
arXiv:1111.2690 [hep-ex]



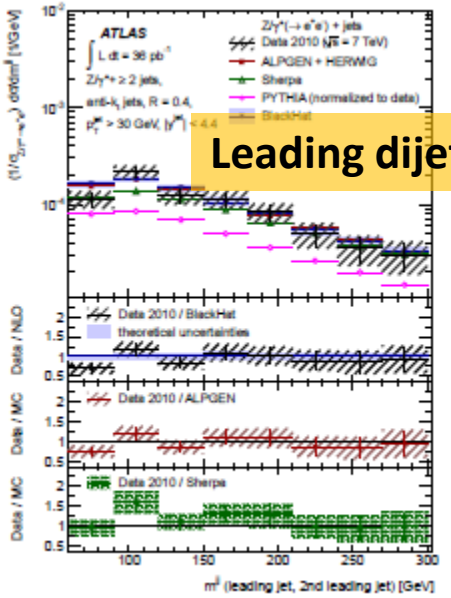
p_T leading



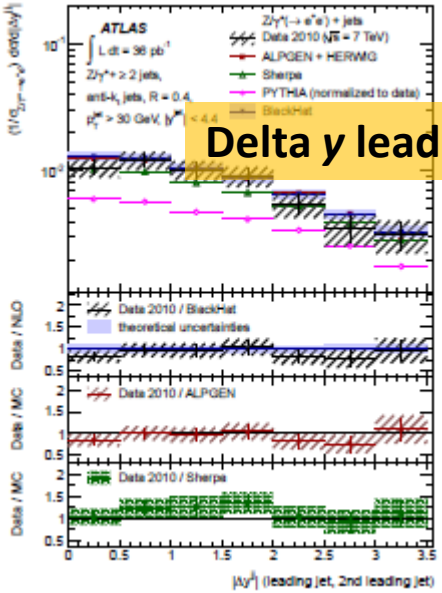
p_T sub-leading



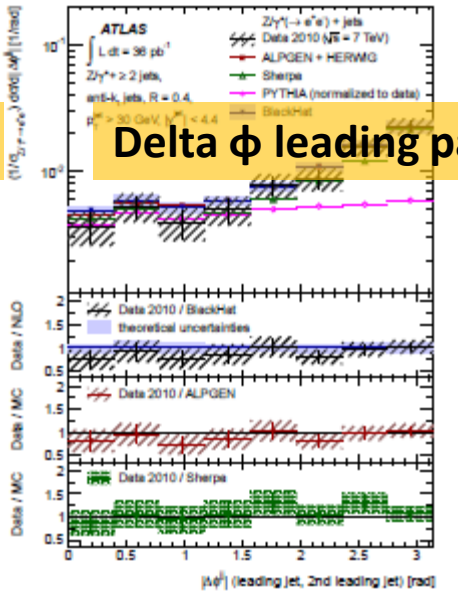
Inclusv jet $|y|$



Leading dijet mass



Delta *y* leading pair

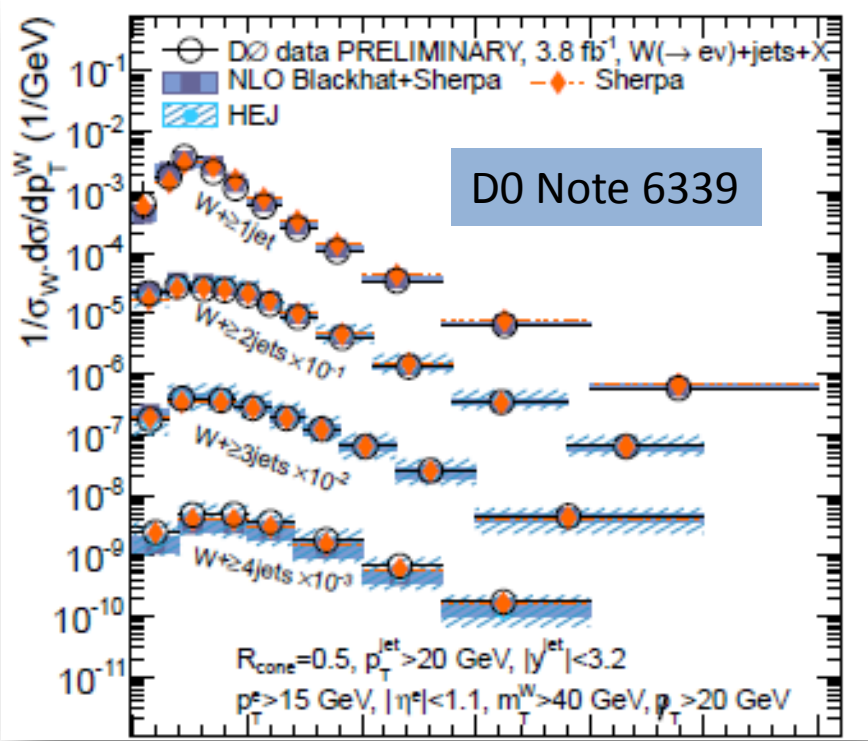


Delta ϕ leading pair

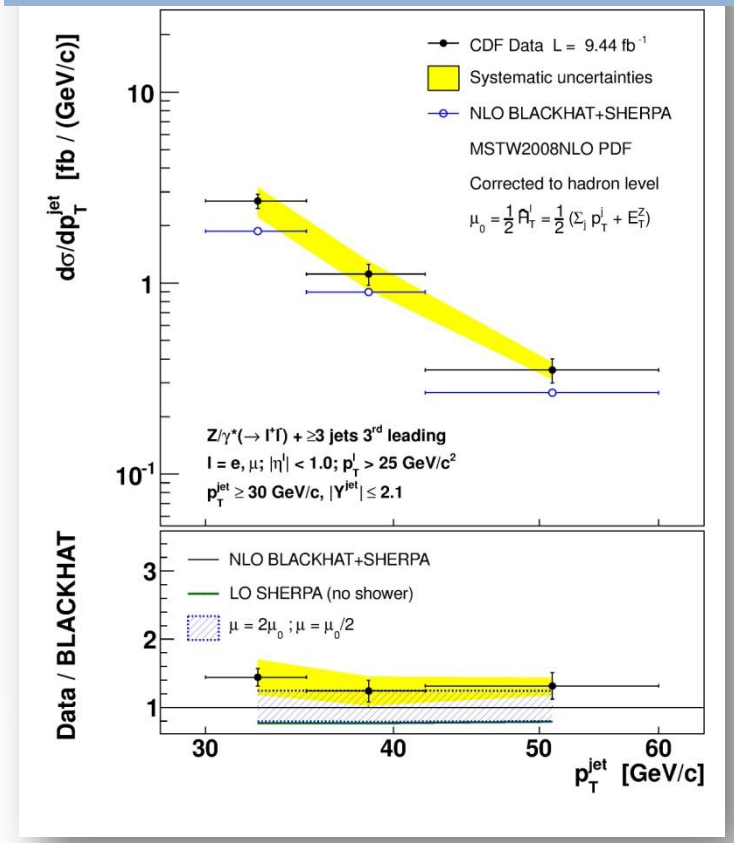
FINAL ANALYSES AT THE TEVATRON

Final Data Sets from the Tevatron

→ Both D0 and CDF are preparing final V+jets analysis with all data collected until September 2011
→ D0 already have shown preliminary results for W+1,2,3,4 Jets production with 3.8 fb^{-1} of data
→ CDF have shown also preliminary results Z+1,2,3 Jets with a 9.44 fb^{-1} data set
→ BlackHat+SHERPA have provided parton level NLO QCD corrections for comparisons
→ We look forward to final and complete studies



www-cdf.fnal.gov/physics/new/qcd/zjets10fb

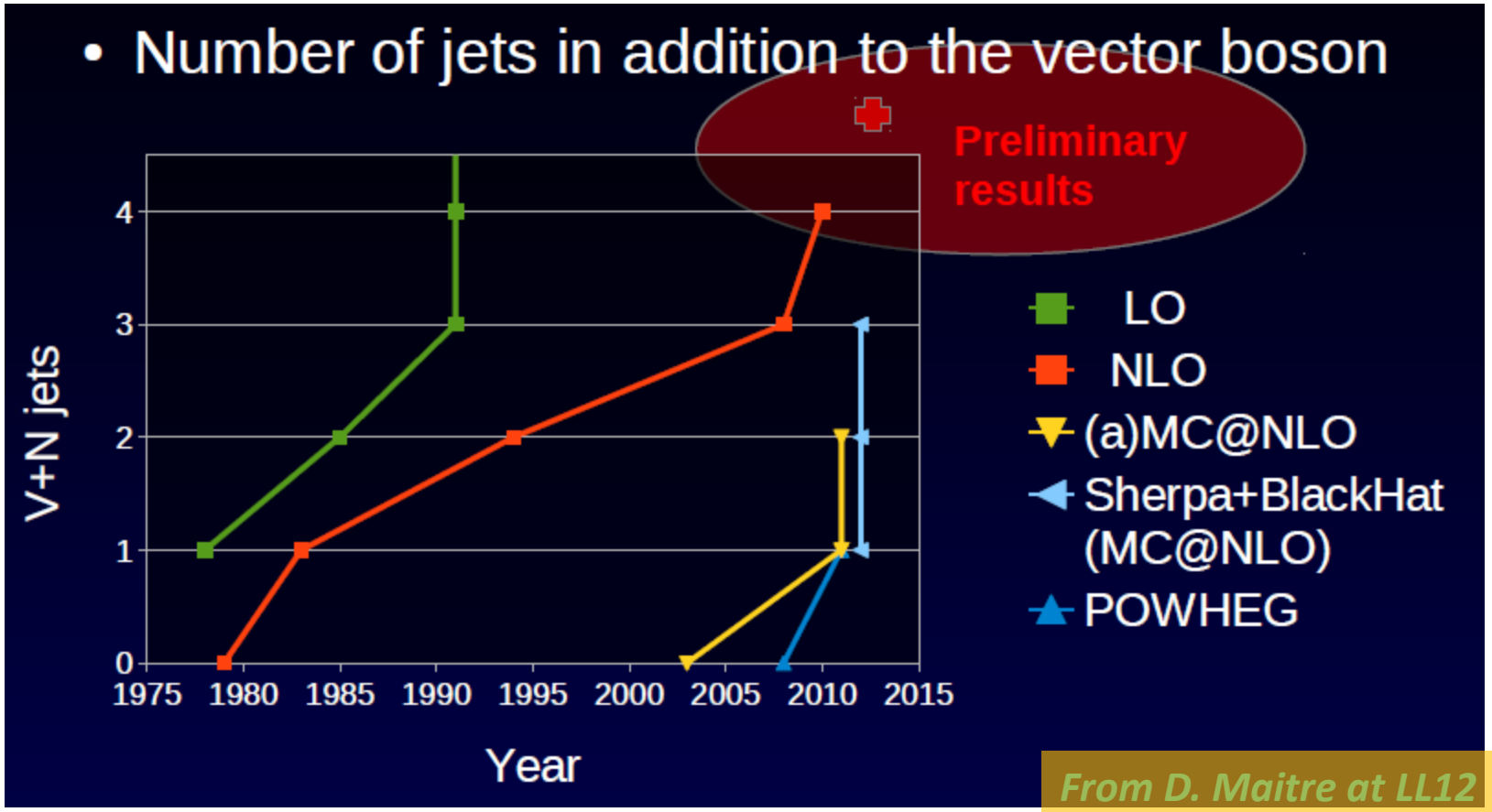


PRELIMINARY!

Outlook

- We showed first results for **4 Jet Production at NLO QCD** using BlackHat+SHERPA
- We showed results for **V+1,2,3,4 Jets at NLO QCD**, including results for polarizations of W bosons
- Good agreement is found with **ATLAS / CMS / CDF / D0 data**! Giving confidence in new measurements and searches to come
- Both ATLAS and CMS are now using **BlackHat's Ntuples** as an efficient way to directly access complex NLO results
- → Recent advancements make now feasible the access to **automated NLO showers** through standard software frameworks of the main experimental collaborations

The New NLO Standard!



From D. Maitre at LL12

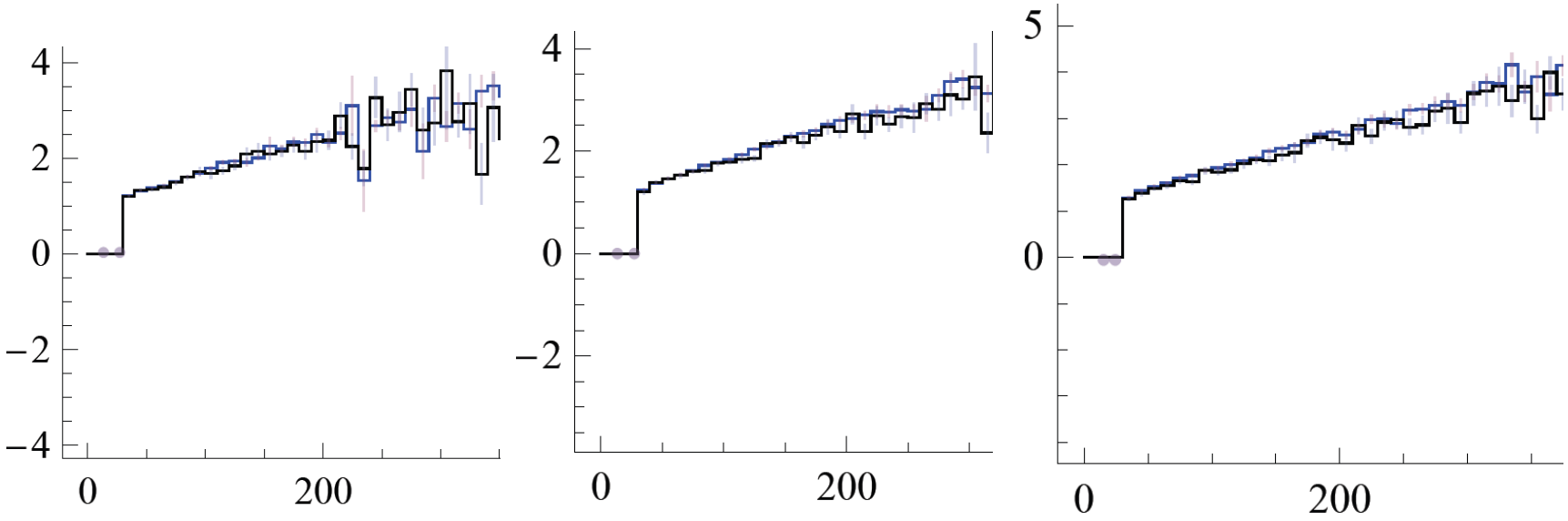
NLO Montecarlo for Standard Experimental Analyses…

Backup slides….

$W^{+/-}$ + n jets: Neutrino E_T

NLO LO

BlackHat: [arXiv:1103.5445]



1 jet 2 jets 3 jets

Effect independent of multiplicity! Almost no difference from NLO and LO!

Similarly for charged lepton E_T