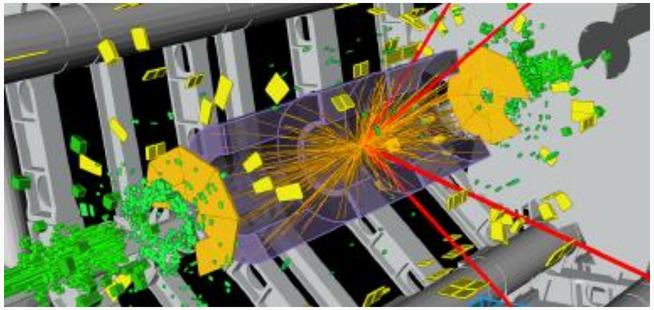
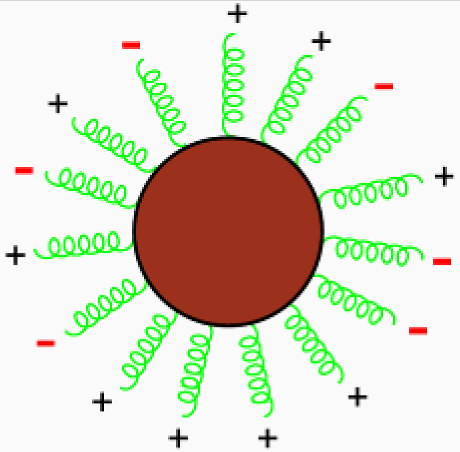


High Multiplicity Processes at NLO: BlackHat+Sherpa

Fernando Febres Cordero

Universidad Simon Bolivar, Caracas, Venezuela



Joint LPNHE & LPTHE Seminar

December 9th 2013, Paris, France

Work in collaboration with Zvi Bern, Lance Dixon, Stefan Hoeche, Harald Ita, David Kosower, Adriano Lo Presti, Daniel Maitre

arXiv:1304.1253 [hep-ph] ; arXiv:1310.7439 [hep-ph] ; arXiv:1312.0592 [hep-ph] ; …

BlackHat 2009

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

BlackHat 2011

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

2013: + N.A. Lo Presti

OVERVIEW

NLO with BlackHat+SHERPA: Basic Setup, Unitarity, QCD

W+5 JETS AT THE LHC

Why Large Multiplicity?, Setup, Results, Fits Beyond 5 Jets

DIPHOTON+2-JET PRODUCTION AT THE LHC

First VV from BH, Basic/VBF/ATLAS, Higgs Physics

BLACKHAT+SHERPA NTUPLES FOR NLO

Distributing NLO results, Store information, BHSntuples, nTupleReader

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

1-loop Amplitudes from Unitarity

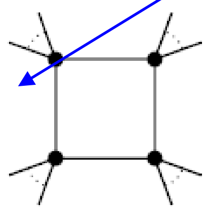
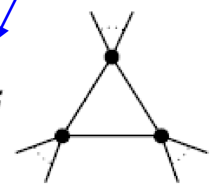
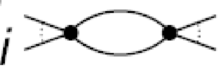
See [Bern, Dixon, Dunbar, Kosower hep-ph/9212308]

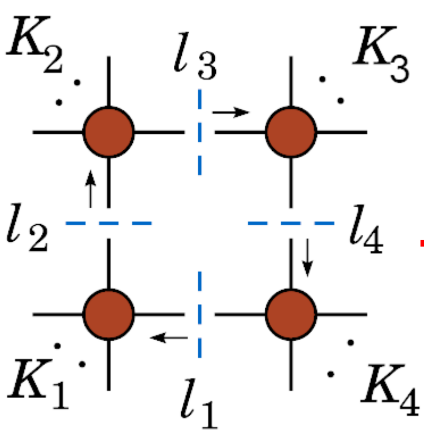
Rational in momenta

Logarithmic in momenta

Process dependent; rational in momenta

$$A = R + C$$

$$C = \sum_i b_i$$  $$+ \sum_i c_i$$  $$+ \sum_i d_i$$ 

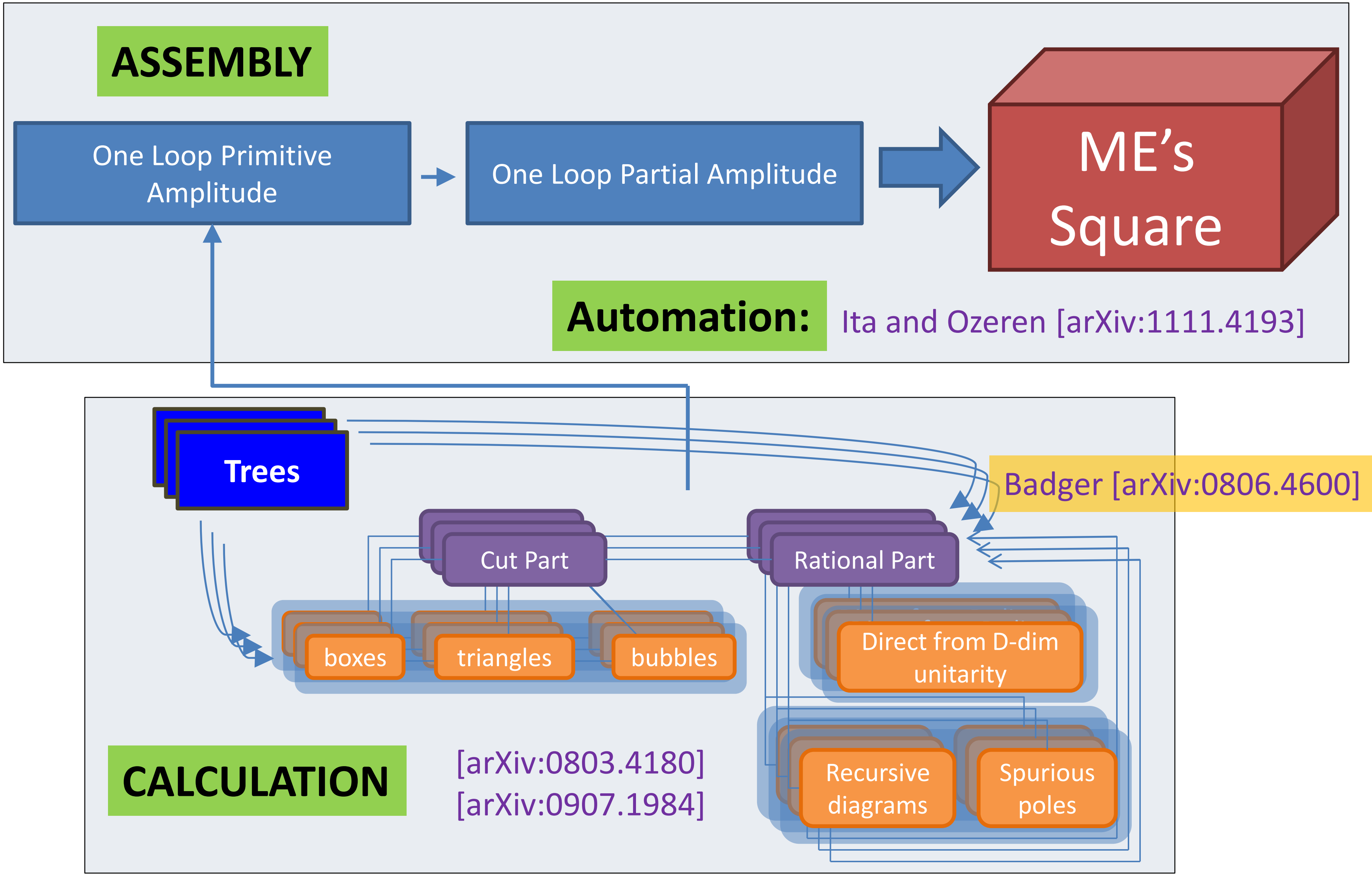


[Britto, Cachazo, Feng hep-th/0412103]

$$b_i = A^{\text{tree}}_{(1)} A^{\text{tree}}_{(2)} A^{\text{tree}}_{(3)} A^{\text{tree}}_{(4)}$$

And then one can extract all coefficients! [Ossola, Papadopoulos, Pittau hep-ph/0609007] [Ellis, Giele, Kunszt arXiv:0708.2398] [Forde arXiv:0704.1835]

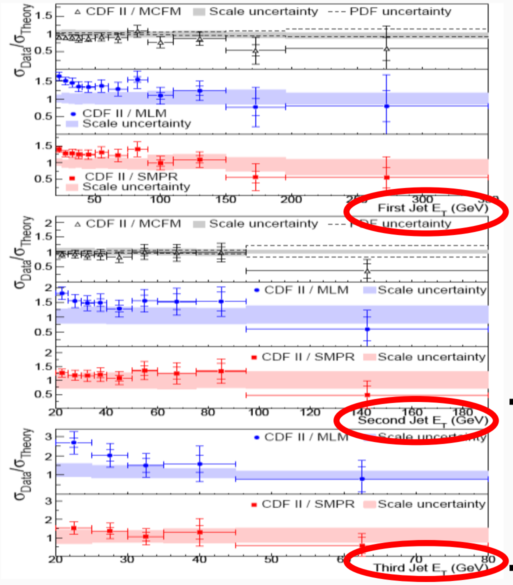
BlackHat: *a snapshot…*



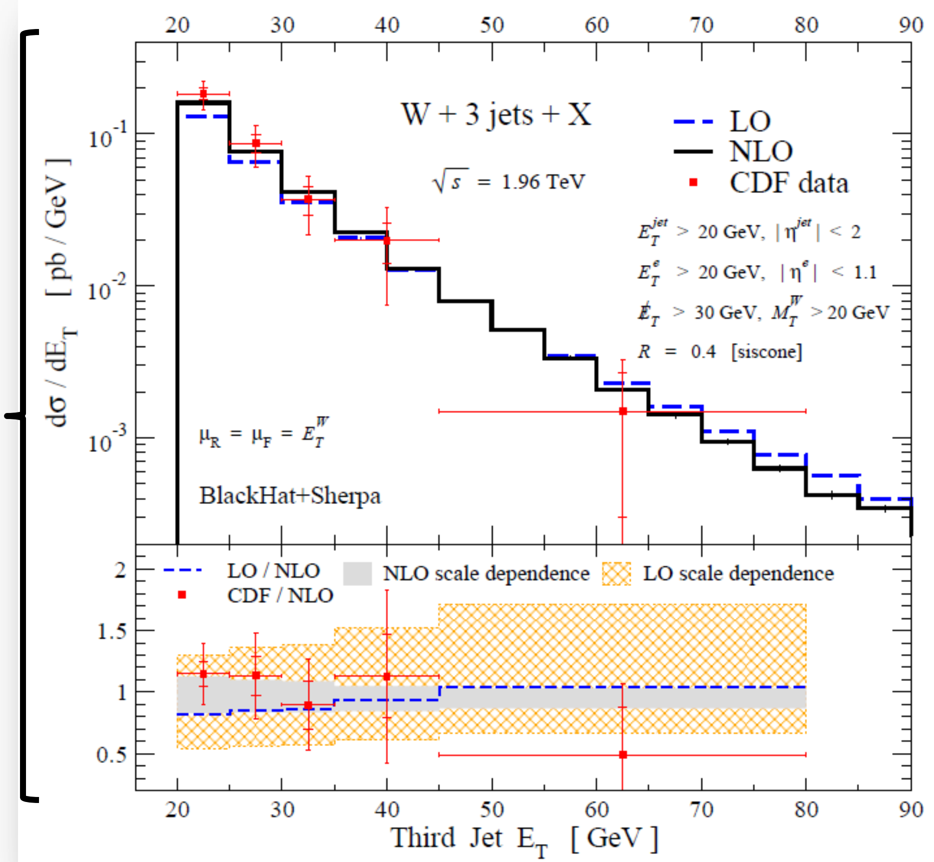
NLO QCD CORRECTIONS TO W + 3 JET

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]



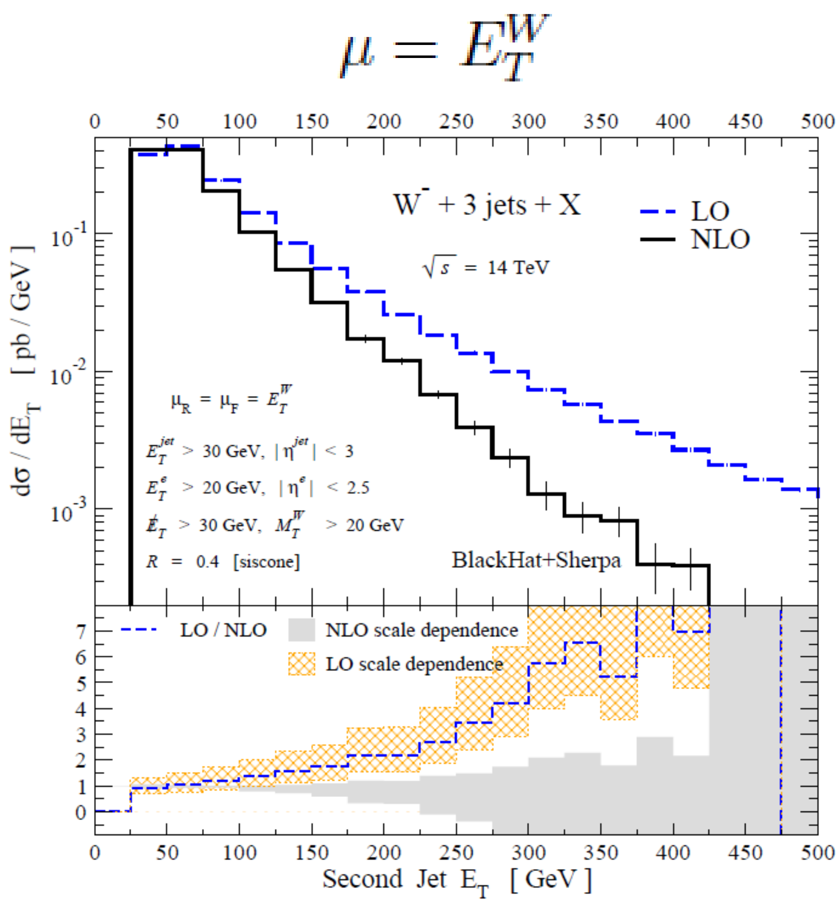
NLO agrees well with W+3 data!

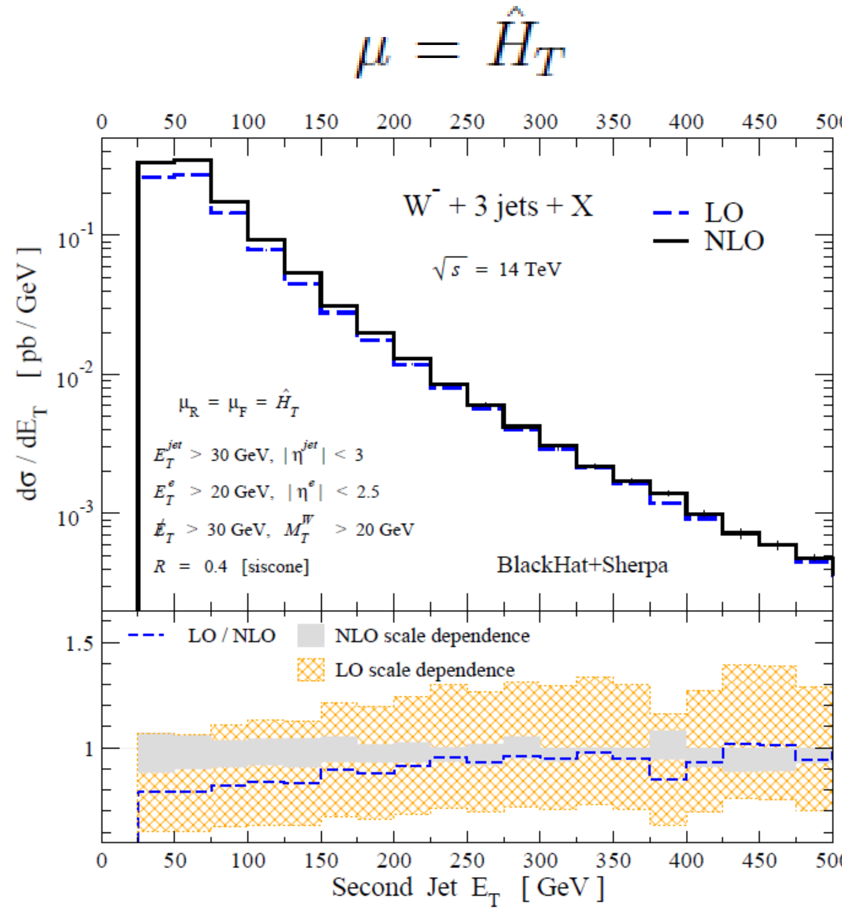
number of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

We use SISCone; CDF used IR unsafe JETCLU

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

NLO Guidance for Scale Choices

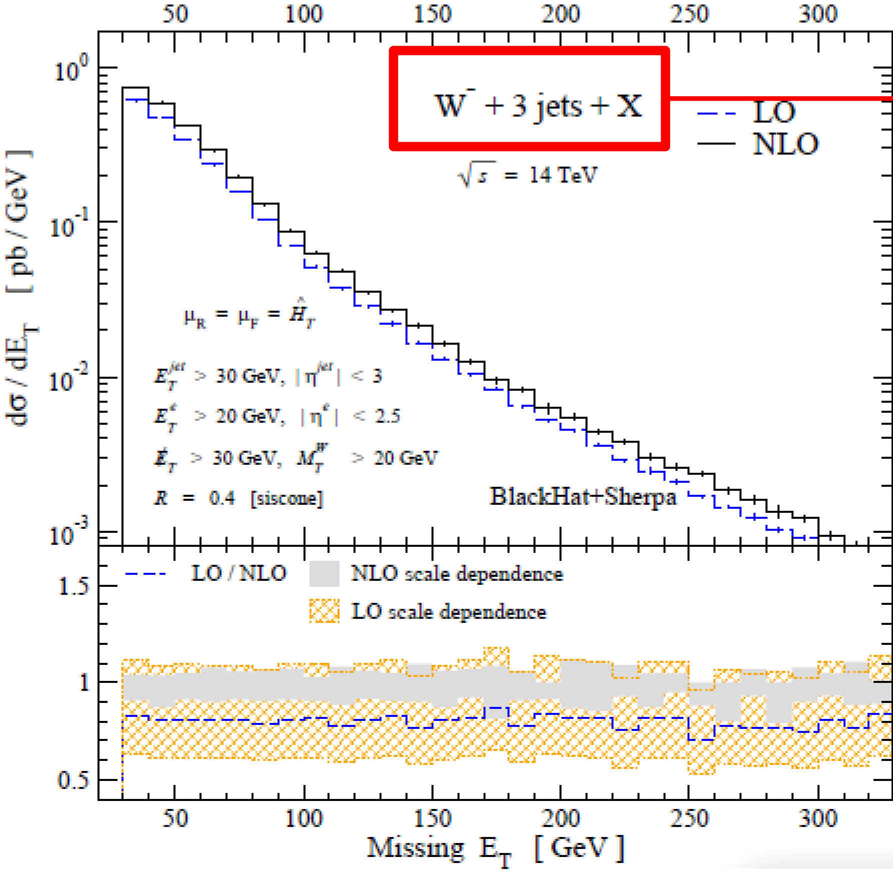


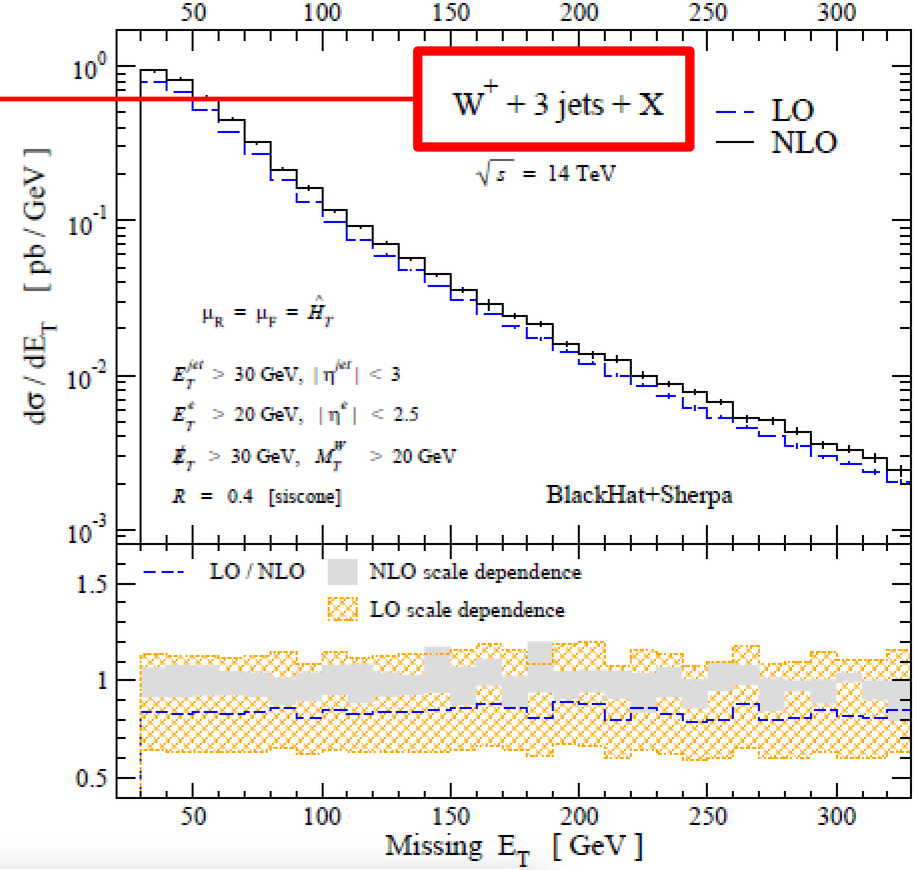


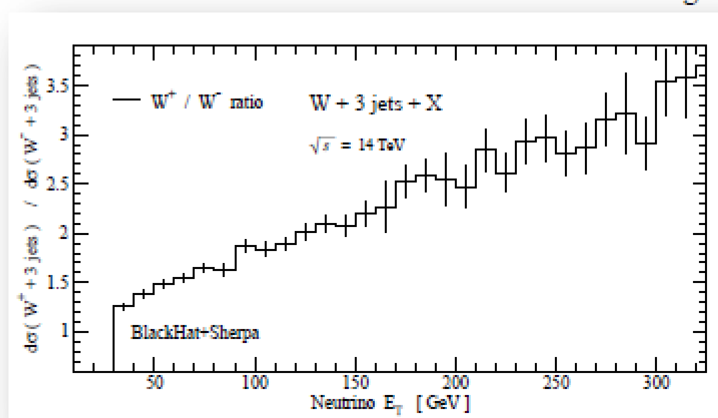
- LO/NLO ratio sensible.
- NLO scale dependence very good.

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

Finding W Polarization In An Odd Place

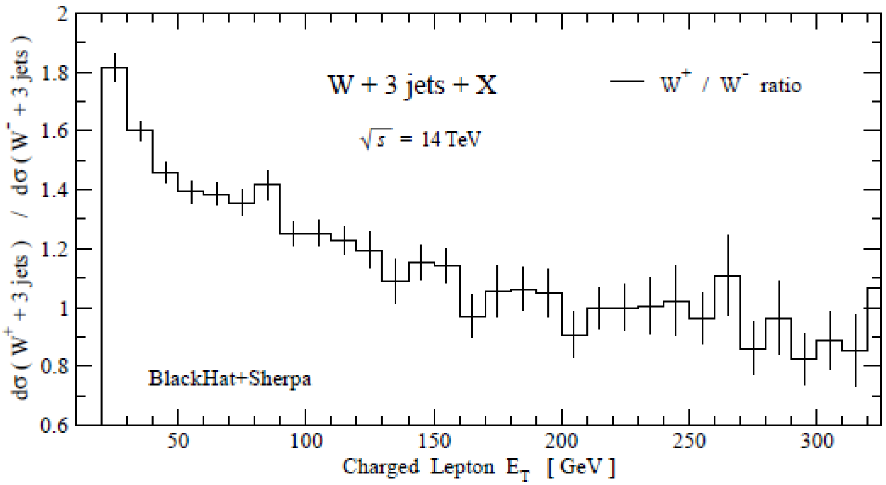


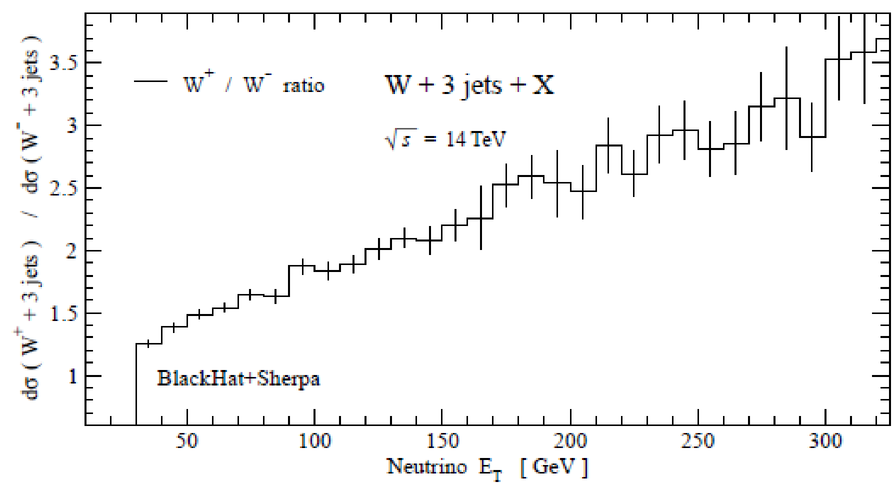




Leptonic E_T in W + 3 jets at LHC

[arXiv:0907.1984] [arXiv:1103.5445]





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

– independent of number of jets

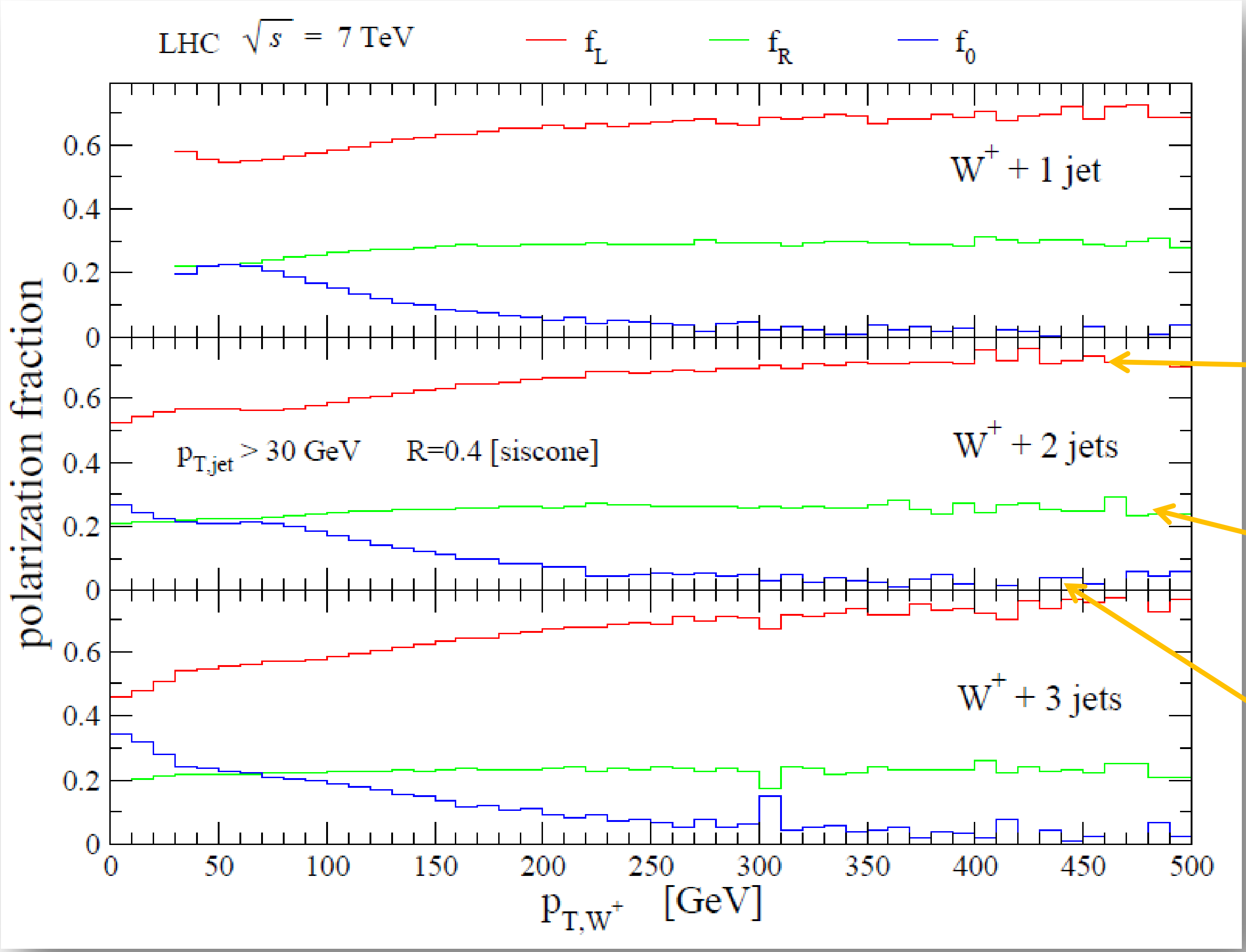
– stable under QCD corrections

– 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

CMS W POLARIZATION MEASUREMENT

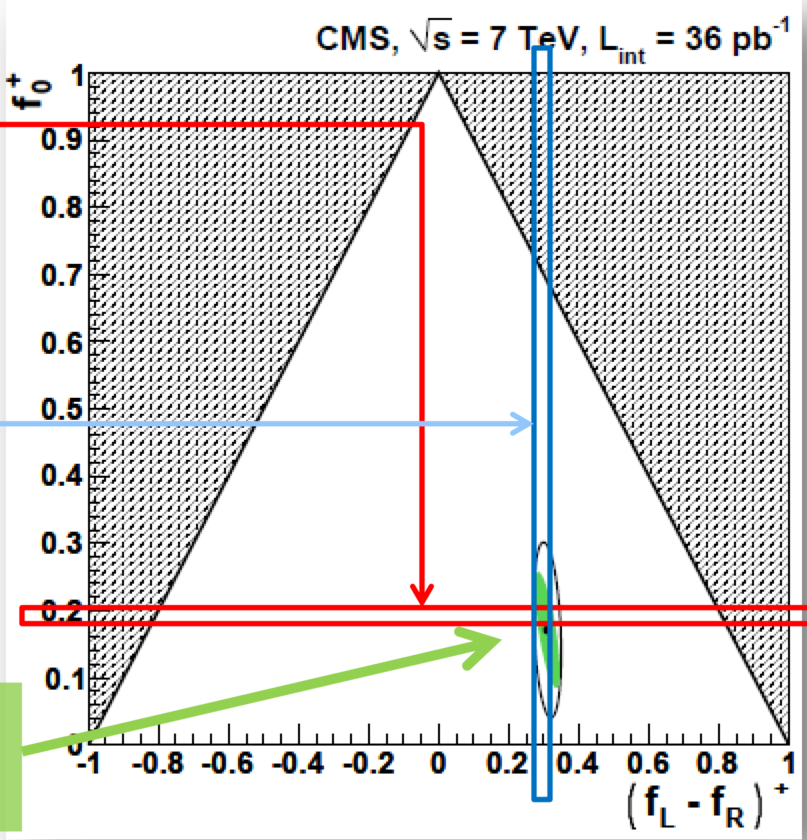
arXiv:1104.3829 [hep-ex]

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

V+JETS ANALYSES AT THE TEVATRON

WITH FINAL DATA SET!!

arXiv:1302.6508 [hep-ex]

Even more…

arXiv:1106.1457 [hep-ex]

D0

hep-ex/9709016

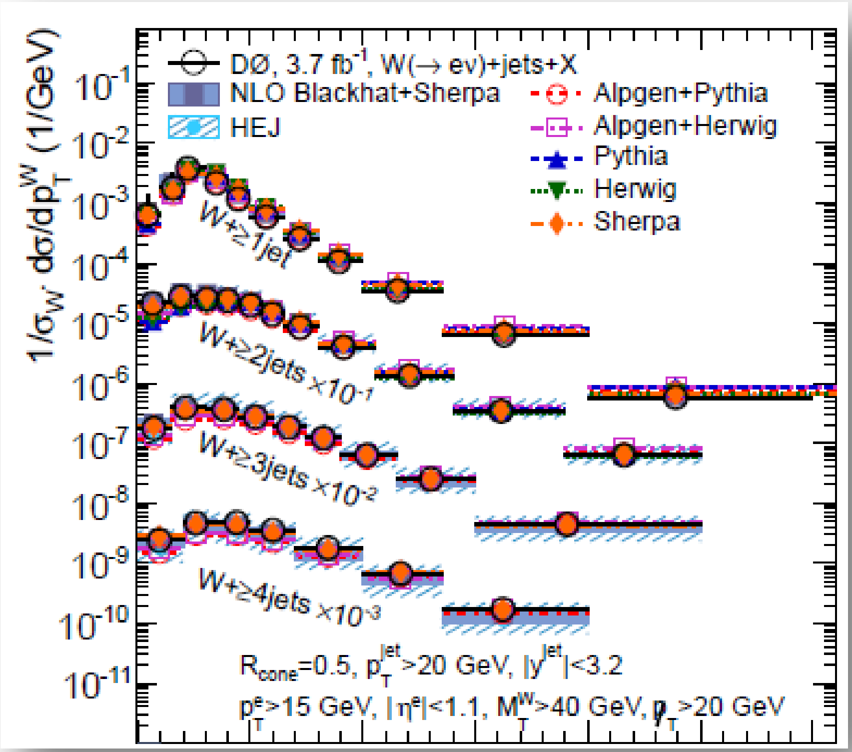
arXiv:0711.4044 [hep-ex]

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

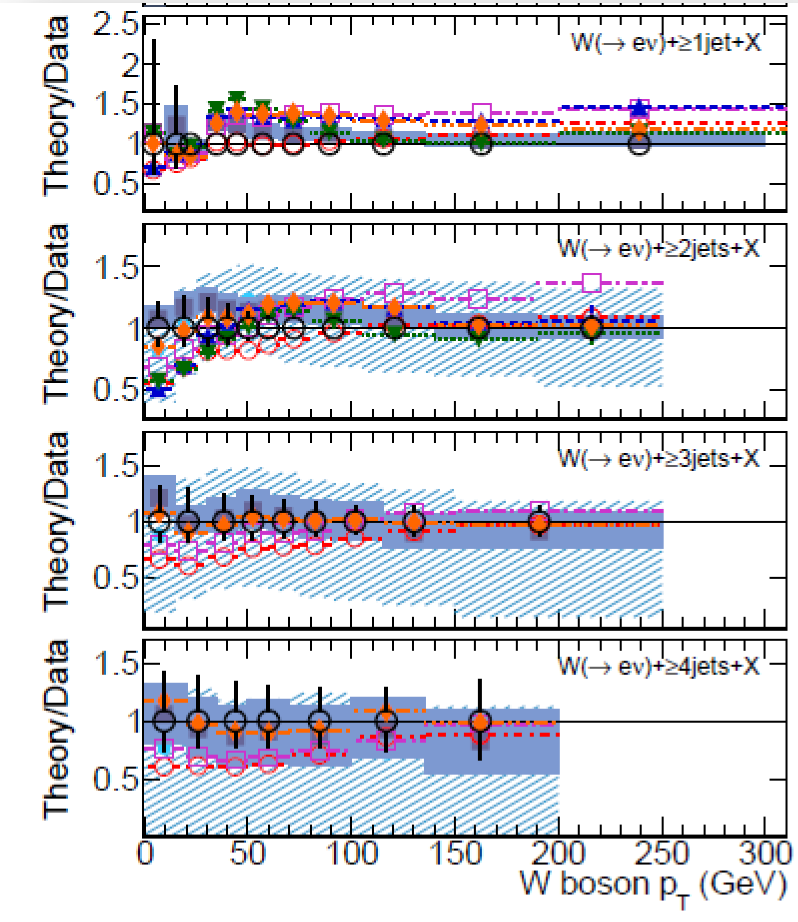
CDF

Final Data Sets from the Tevatron

→ D0 finished and CDF is preparing final V+jets analysis with all data collected until 09 / 2011
→ D0 analized data for W+1,2,3,4 Jet production with 3.8 fb^{-1} of data
→ CDF have shown 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

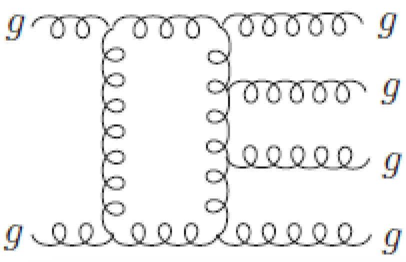


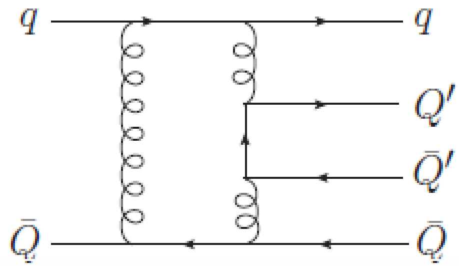
arXiv:1302.6508 [hep-ex]



QCD CORRECTIONS TO 4 JET PRODUCTION

4-Jet Production @ NLO



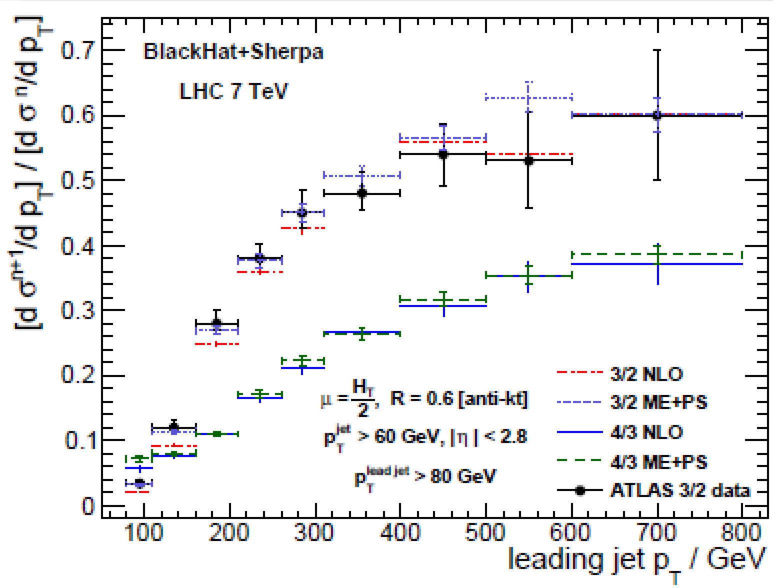


Bern, Diana, Dixon, FFC, Hoeche, Kosower, Ita, Maitre, Ozeren **[arXiv:1112.3940]**

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	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$3.97(0.08)$	$5.54(0.12)^{+0.08}_{-2.44}$	$0.92(0.05)$	$5.11(0.29)^{+0.08}_{-2.32}$

→ Took ten years to go beyond 3-Jet Production at NLO QCD
→ BlackHat+SHERPA presented Postdictions and Predictions for an ATLAS setup
→ Single framework for several multiplicities
→ One of the most complex 2 → 4 NLO QCD calculations

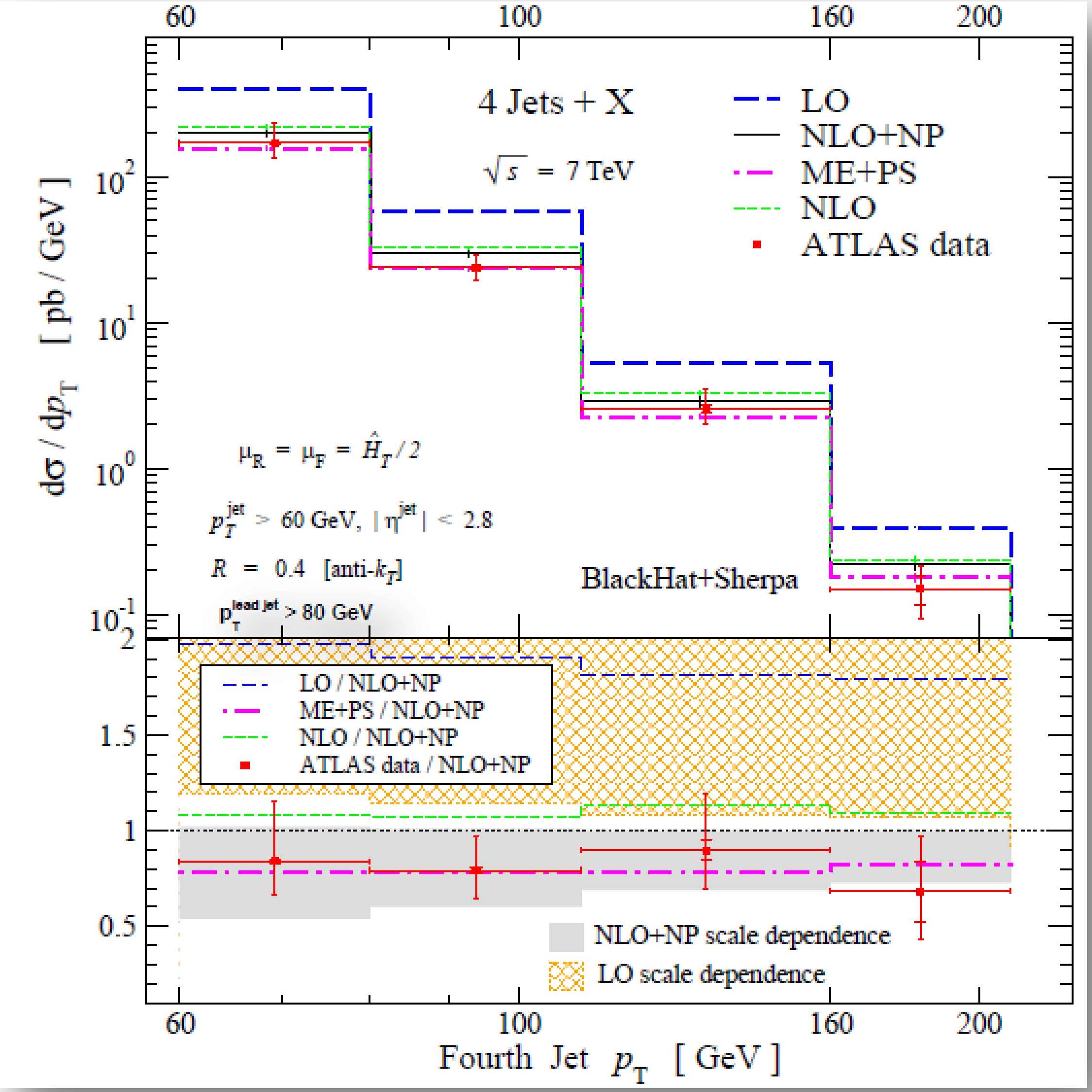


Calculation reproduced by Badger, Biedermann, Uwer and Yudin **[arXiv:1209.0098]**

4-Jet Production @ NLO

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



OVERVIEW

NLO with BlackHat+SHERPA: Basic Setup, Unitarity, QCD

W+5 JETS AT THE LHC

Why Large Multiplicity?, Setup, Results, Fits Beyond 5 Jets

DIPHOTON+2-JET PRODUCTION AT THE LHC

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BLACKHAT+SHERPA NTUPLES FOR NLO

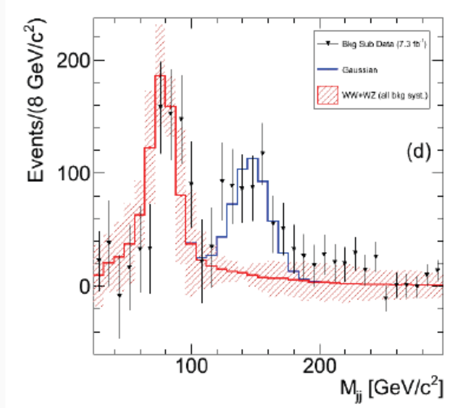
Distributing NLO results, Store information, BHSntuples, nTupleReader

W+5 Jets at the LHC

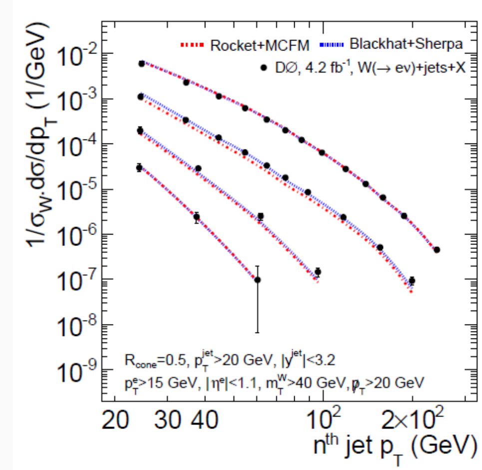
WHY NLO WITH (VERY) LARGE MULTIPLICITY?

arXiv:1304.1253 [hep-ph]

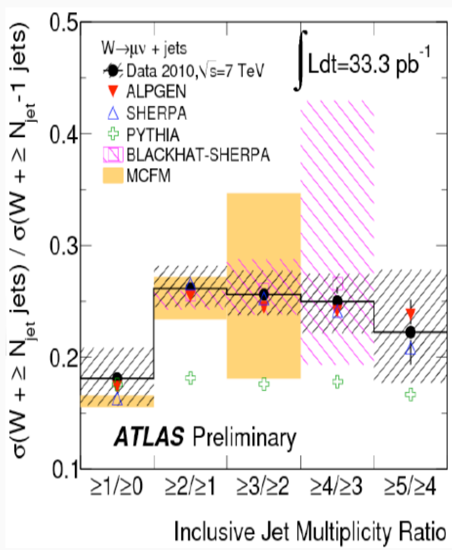
COMBINING V'S AND JETS: A IMPORTANT SIGNAL



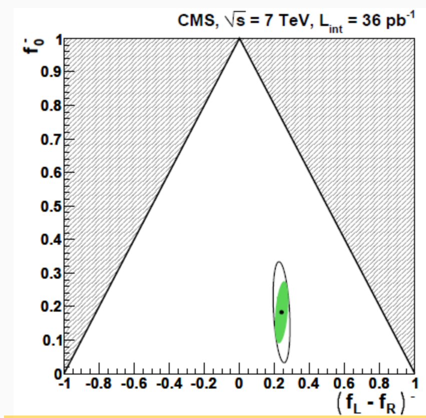
CDF Bump



D0 W+Jets Measurement
arXiv:1302.6508



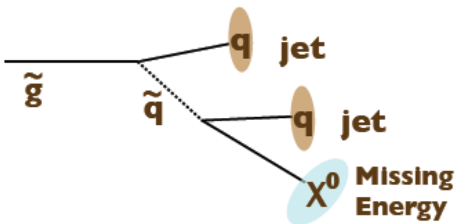
Atlas Jet Ratios



CMS Pol Measurement
arXiv:1104.3829

V + Jets at NLO for SUSY Searches

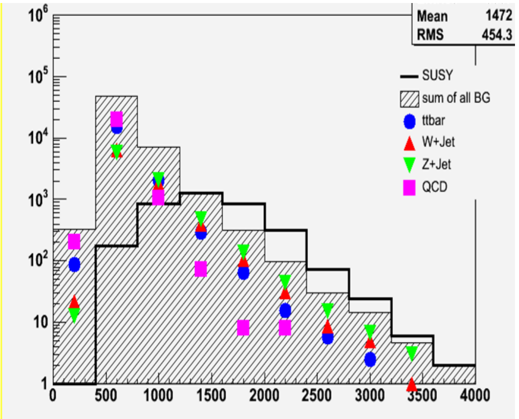
Gluino pair production with:



Mangano [arXiv:0809.1567]

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

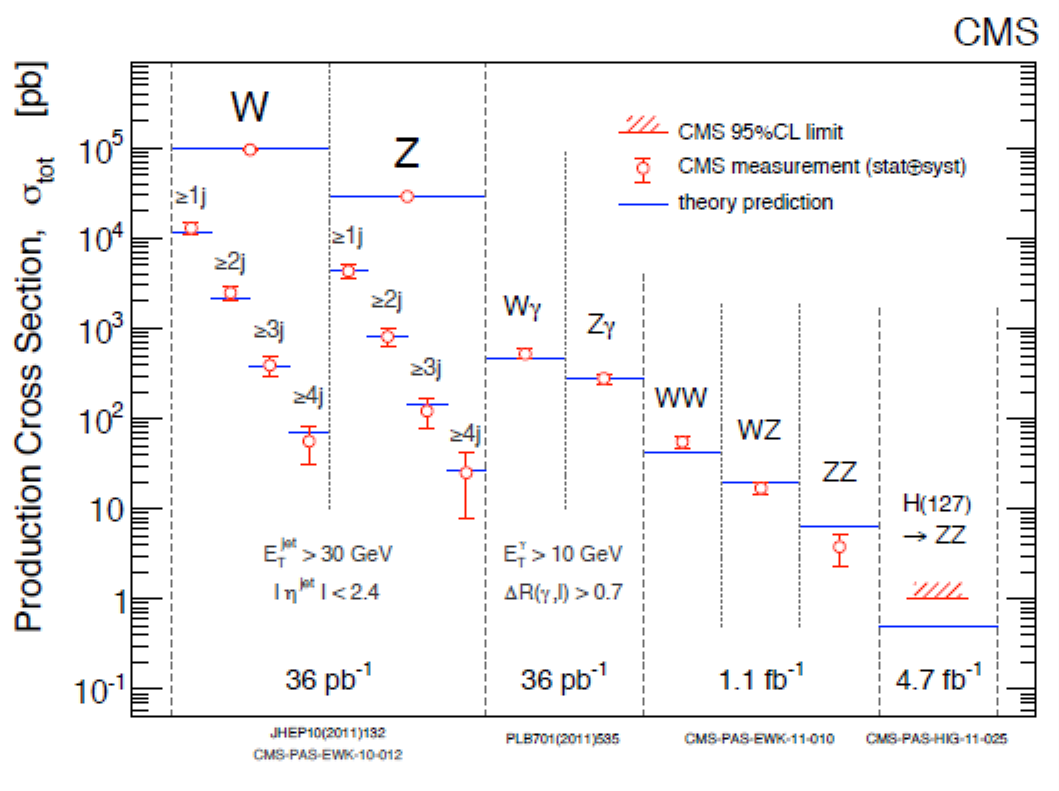
$Z\ +\ 4\ \text{jet}$ followed by: $Z \to \nu\bar{\nu}$



ATLAS simulation for missing ET + Jets signal

WHY NLO WITH (VERY) LARGE MULTIPLICITY?

→ Large Data Sets collected @ LHC
→ The Hope for New Physics @ TeV Scale
→ Reliable and Out-of-the-Box Prediction



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

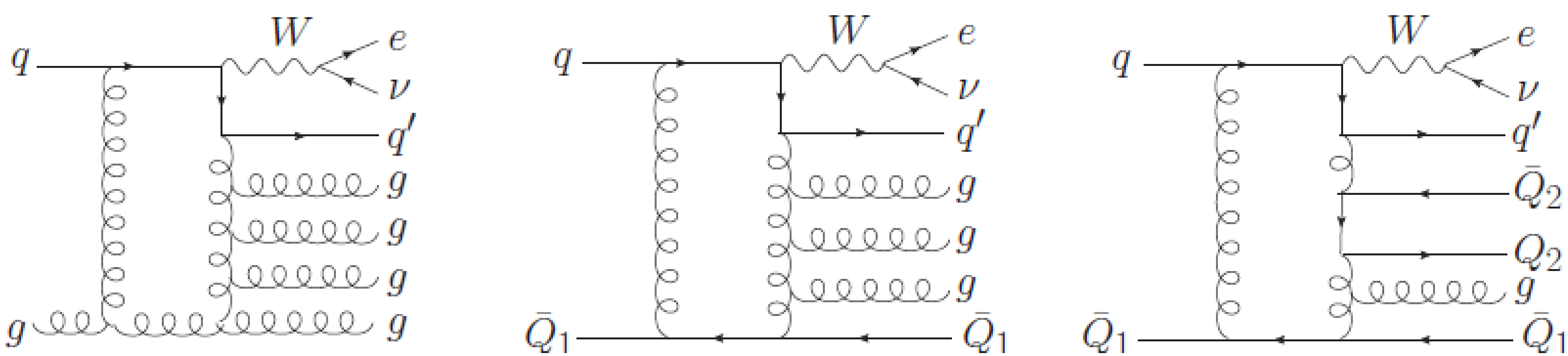
Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t}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

First entry from the 2001 LH Wish List filled by BlackHat+SHERPA calculation

W+5 Jets Calculation Setup

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

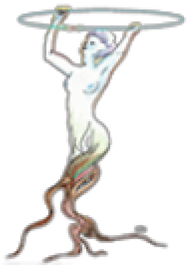
Sample of Loop Parent Diagrams



W+5 Jets Calculation Setup

From K. Ozeren at HP2/2012

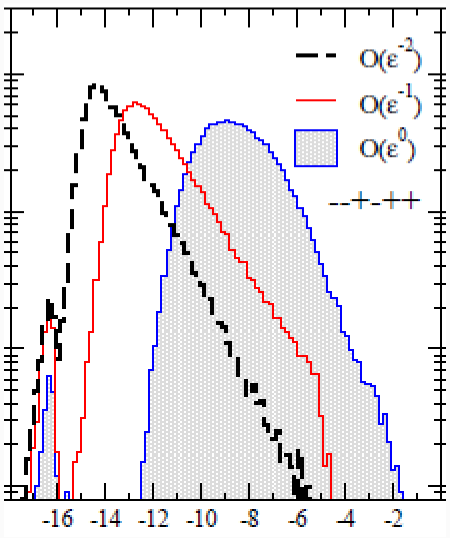
Theoretical Tools



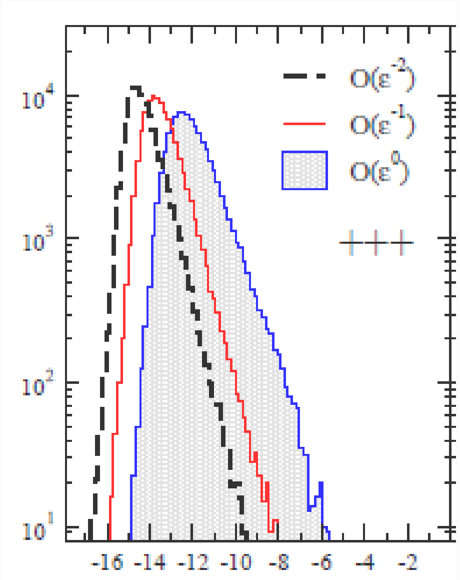
- BlackHat for virtual part [Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, KJO]
- COMIX (part of Sherpa) for real emission [Hoeche]
- Sherpa - organizational framework [Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Winter]
- LHAPDF for parton distributions [Whalley, Bourilkov, Group]
- FASTJET for jet clustering [Cacciari, Salam, Soyez]
- ROOT for analysis and storing events [see later]

Loop Calculation Numerical Stability

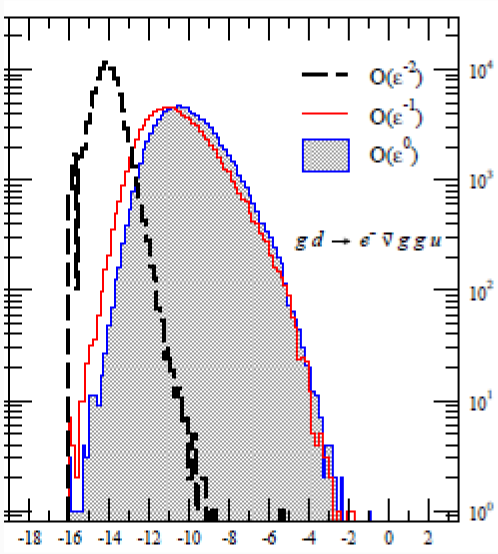
→ Traditional Feynman Diagram Calculations suffer from numerical instabilities when leg multiplicity is large. Any new algorithm or calculation must be checked to prove its numerical behavior



6 gluon primitive amplitudes
[arXiv:0803.4180]



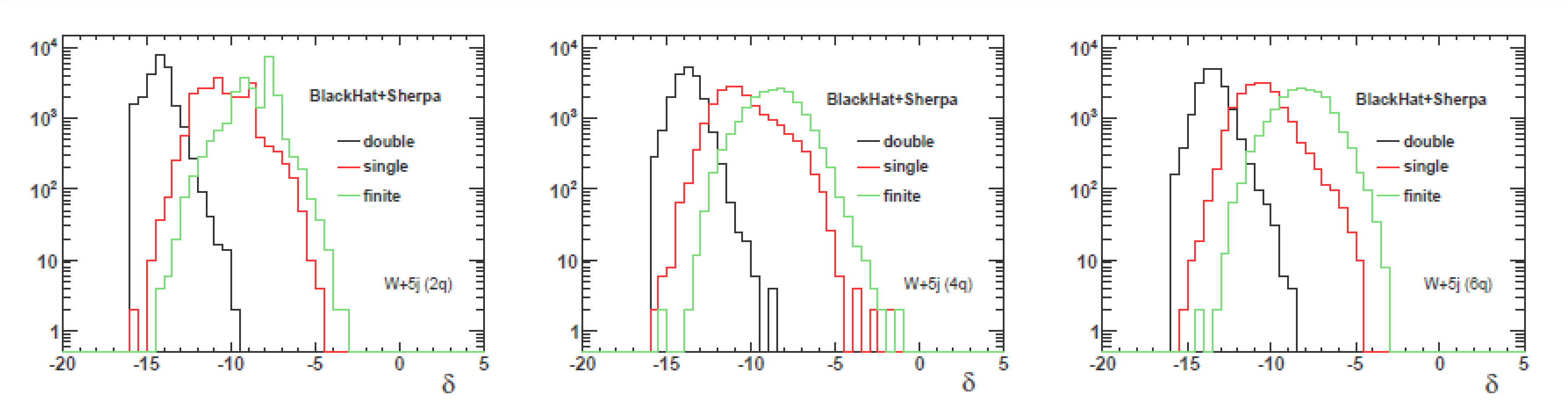
2q3g2l primitive amplitudes
[arXiv:0808.0941]



Sample W+3 Jet X-Sec Stability
[arXiv:0907.1984]

W+5 Jet Numerical Stability

→ Traditional Feynman Diagram Calculations suffer from numerical instabilities when leg multiplicity is large. Any new algorithm or calculation must be checked to prove its numerical behavior



Sample W+5 Jet X-Sec Stability, for each Type of Subprocess
[arXiv:1304.1253]

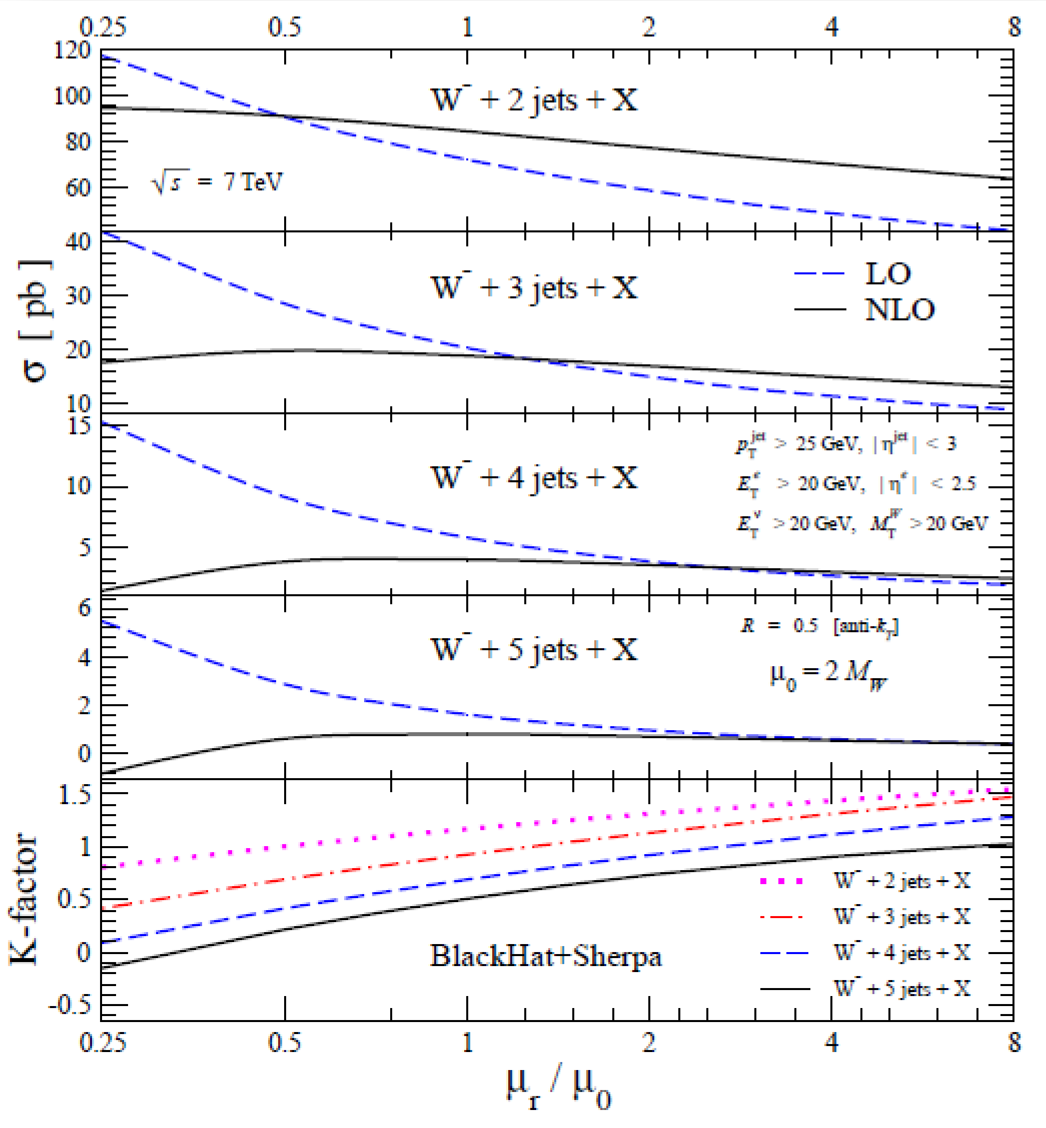
W+5 Jet Experimental Setup – LHC 7 TeV

Kinematical Cuts	$E_T^e > 20$ GeV, $\quad |\eta^e| < 2.5$, $\quad \not{E}_T > 20$ GeV, $p_T^{\mathrm{jet}} > 25$ GeV, $\quad |\eta^{\mathrm{jet}}| < 3$, $\quad M_T^W > 20$ GeV.
Main Jet-Alg (other available)	anti-k_T $\quad R = 0.5$
Dynamical R & F Scales	$\hat{H}'_T \equiv \sum_m p_T^m + E_T^W$
Set of PDFs employed	MSTW2008 LO and NLO PDFs

RENORMALIZATION SCALE DEPENDENCE FOR W+*N* JETS

→ Reduction on the unphysical scale at NLO
→ Factorization scale is kept fixed
→ NLO corrections ever more important with number of jets

arXiv:1304.1253 [hep-ph]



TOTAL CROSS SECTIONS FOR W+N JETS

Jets	W^- LO	W^- NLO	W^+ LO	W^+ NLO
1	$284.0(0.1)^{+26.2}_{-24.6}$	$351.2(0.9)^{+16.8}_{-14.0}$	$416.8(0.6)^{+38.0}_{-35.5}$	$516(3)^{+29.}_{-23}$
2	$83.76(0.09)^{+25.45}_{-18.20}$	$83.5(0.3)^{+1.6}_{-5.2}$	$130.0(0.1)^{+39.3}_{-28.1}$	$125.1(0.8)^{+1.8}_{-7.4}$
3	$21.03(0.03)^{+10.66}_{-6.55}$	$18.3(0.1)^{+0.3}_{-1.8}$	$34.72(0.05)^{+17.44}_{-10.75}$	$29.5(0.2)^{+0.4}_{-2.8}$
4	$4.93(0.02)^{+3.49}_{-1.90}$	$3.87(0.06)^{+0.14}_{-0.62}$	$8.65(0.01)^{+6.06}_{-3.31}$	$6.63(0.07)^{+0.21}_{-1.03}$
5	$1.076(0.003)^{+0.985}_{-0.480}$	$0.77(0.02)^{+0.07}_{-0.19}$	$2.005(0.006)^{+1.815}_{-0.888}$	$1.45(0.04)^{+0.12}_{-0.34}$

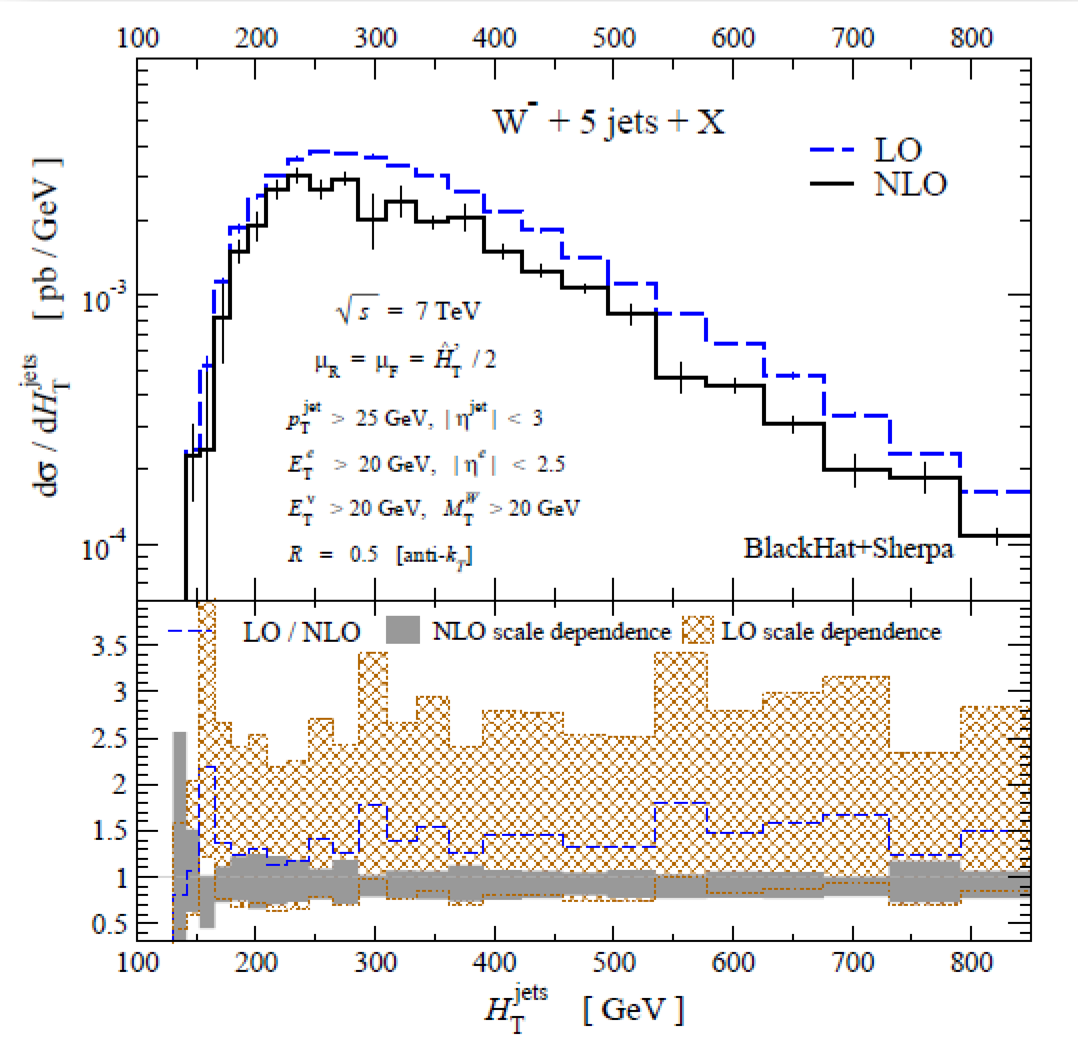
arXiv:1304.1253 [hep-ph]

→ Upper and lower values from factors of two in scale choice
→ Difficult to keep under 1% relative integration error for W+5 Jet
→ Regularity with increasing number of jets

→ Charge asymmetry ratios
→ Jet ratios

Jets	W^+/W^-		$\frac{W^- + n}{W^- + (n-1)}$		$\frac{W^+ + n}{W^+ + (n-1)}$	
	LO	NLO	LO	NLO	LO	NLO
1	1.467(0.002)	1.47(0.01)	—	—	—	—
2	1.552(0.002)	1.50(0.01)	0.2949(0.0003)	0.238(0.001)	0.3119(0.0005)	0.242(0.002)
3	1.651(0.003)	1.61(0.01)	0.2511(0.0005)	0.220(0.001)	0.2671(0.0004)	0.235(0.002)
4	1.753(0.006)	1.72(0.03)	0.2345(0.0008)	0.211(0.003)	0.2490(0.0005)	0.225(0.003)
5	1.864(0.008)	1.87(0.06)	0.218(0.001)	0.200(0.006)	0.2319(0.0008)	0.218(0.006)

W+5 JET CROSS SECTIONS VERSUS JET HT



arXiv:1304.1253 [hep-ph]

→ Good control over integration errors for general observables
→ Scale choice performs well over PS
→ Relatively flat LO/NLO ratio
→ Scale dependence down from ~70% at LO to ~ 20% at NLO

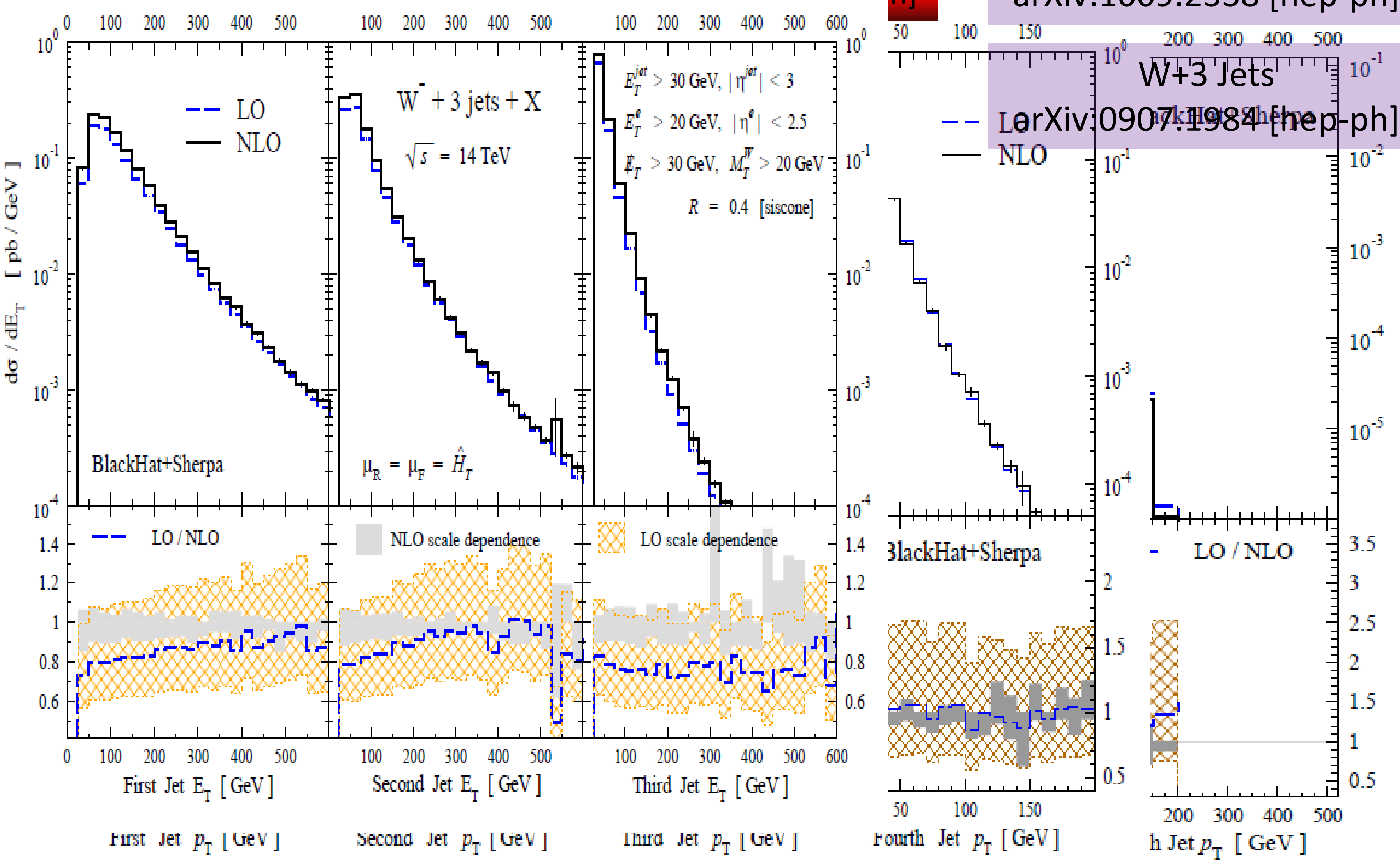
JET PT SPECTRA

W+5 Jets
arXiv:1304.1253 [hep-ph]

W+4 Jets
arXiv:1009.2338 [hep-ph]

W+3 Jets
arXiv:0907.1984 [hep-ph]

W+4 Jet Full Color Computed by
Ita & Ozeren arXiv:1111.4193 [hep-ph]



EXTRAPOLATING TO W+6,… JET PRODUCTION

arXiv:1304.1253 [hep-ph]

Jets	W^+/W^-		$\frac{W^- + n}{W^- + (n-1)}$		$\frac{W^+ + n}{W^+ + (n-1)}$	
	LO	NLO	LO	NLO	LO	NLO
1	1.467(0.002)	1.47(0.01)	—	—	—	—
2	1.552(0.002)	1.50(0.01)	0.2949(0.0003)	0.238(0.001)	0.3119(0.0005)	0.242(0.002)
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4	1.753(0.006)	1.72(0.03)	0.2345(0.0008)	0.211(0.003)	0.2490(0.0005)	0.225(0.003)
5	1.864(0.008)	1.87(0.06)	0.218(0.001)	0.200(0.006)	0.2319(0.0008)	0.218(0.006)

→ Ratios are sensitive to new physics
→ They change quite linearly as function of jet multiplicity
→ Fits produced from pseudo data sets

RATIO FITS

$$R^{\mathrm{NLO}}_{W^+/W^-} = 1.27 \pm 0.03 + (0.11 \pm 0.01)\, n$$

$$R^{\mathrm{NLO},\,W^-}_{n/(n-1)} = 0.248 \pm 0.008 - (0.009 \pm 0.002)\, n$$

$$R^{\mathrm{NLO},\,W^+}_{n/(n-1)} = 0.263 \pm 0.009 - (0.009 \pm 0.003)\, n$$

EXTRAPOLATION

$$\boxed{1.94 \pm 0.08}$$

$W^- + 6$ jets : 0.15 ± 0.01 pb

$W^+ + 6$ jets : 0.30 ± 0.03 pb

$$\boxed{2.0 \pm 0.3}$$

OVERVIEW

NLO with BlackHat+SHERPA: Basic Setup, Unitarity, QCD

W+5 JETS AT THE LHC

Why Large Multiplicity?, Setup, Results, Fits Beyond 5 Jets

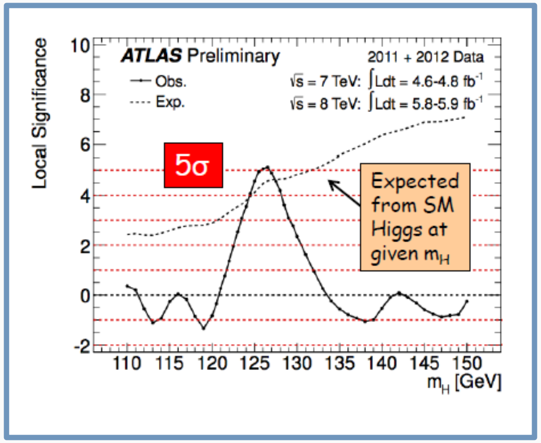
DIPHOTON+2-JET PRODUCTION AT THE LHC

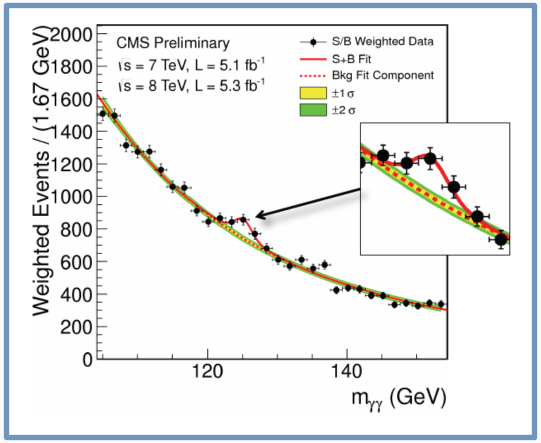
First VV from BH, Basic/VBF/ATLAS, Higgs Physics

BLACKHAT+SHERPA NTUPLES FOR NLO

Distributing NLO results, Store information, BHSntuples, nTupleReader

DIPHOTON+*X* PRODUCTION AT THE LHC





On July 4th, 2012, the ATLAS and CMS experiments at the CERN laboratories announced the discovery of a new boson, very much alike to the SM Higgs Boson

DIPHOTON+2-JET PRODUCTION AT THE LHC

- Photon pairs are one of the key decay channels for detecting the Higgs-like boson announced in 2012
- Good understanding of prompt photon-pair production is important for exploring deviations from SM expectations
- When produced in association with two jets, relevant to VBF production
- NLO is necessary to obtain quantitatively reliable predictions in perturbation theory
- Recently another NLO calculation for this process appeared, performed by Gehrmann, Greiner and Heinrich [arXiv:1308.3660]

arXiv:1312.0592 [hep-ph]

DIPHOTON+2-JET PRODUCTION AT THE LHC

- New type of process for the BlackHat library: vector boson pairs
- Checks performed based on:
  - Collinear and factorization properties
  - PS points for $\gamma\gamma$+0-jet with HELAC & MCFM
  - PS points for $\gamma\gamma$+1-jet with GoSam and 2q1g2y analytic result by Bern, Dixon and Kosower [hep-ph/9409393]
  - Given helicity $\gamma\gamma$+4-parton amplitudes against GoSam
  - Integrated level against MCFM for $\gamma\gamma$+0-jet and against Gehrmann, Greiner and Heinrich[arXiv:1303.0824] for $\gamma\gamma$+1-jet

arXiv:1312.0592 [hep-ph]

KINEMATICS FOR SEARCHES

BASIC

$$p_T^{\gamma_1} > 50\text{ GeV}, \quad p_T^{\gamma_2} > 25\text{ GeV},$$
$$p_T^{\text{jet}_1} > 40\text{ GeV}, \quad p_T^{\text{jet}_2} > 25\text{ GeV},$$
$$|\eta^\gamma| < 2.5, \quad |\eta^{\text{jet}}| < 4.5, \quad R_{\gamma,\text{jet}} > 0.4$$

VBF

BASIC+

$$M_{jj} > 400\text{ GeV}, \quad |\Delta\eta_{jj}| > 2.8$$

ATLAS inspired

$$p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}, \quad p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma},$$
$$p_T^{\text{jet}} > 30\text{ GeV}, \quad R_{\gamma,\text{jet}} > 0.4,$$
$$|y^\gamma| < 2.37, \quad |y^{\text{jet}}| < 4.4, \quad 122 \le m_{\gamma\gamma} \le 130$$

Thanks to Joey Huston for input

Cuts	LO	NLO	$\boxed{gg \to \gamma\gamma gg}$
Basic	$2.678(0.003)^{+0.808}_{-0.577}$	$3.23(0.03)^{+0.31}_{-0.36}$	$0.0509(0.0007)$
VBF	$0.1398(0.0003)^{+0.0541}_{-0.0359}$	$0.159(0.002)^{+0.016}_{-0.021}$	$0.004(0.001)$
ATLAS	$0.0886(0.0005)^{+0.0264}_{-0.0189}$	$0.099(0.002)^{+0.007}_{-0.010}$	$0.00157(0.00003)$
ATLAS VBF	$0.00392(0.00004)^{+0.00153}_{-0.00101}$	$0.0046(0.0001)^{+0.0006}_{-0.0006}$	$8.9(0.4)\cdot 10^{-5}$

Formally NNLO contribution, but relevant at the LHC

arXiv:1312.0592 [hep-ph]

FEW SETUP DETAILS

PHOTON ISOLATION:

- Experimentally, a photon needs to be isolated from hadronic radiation
- Formally, one needs to allow some radiation to ensure IR safety

We use the Frixione Isolation cone, which depends on the radius:

$$\delta = [(\phi - \phi_\gamma)^2 + (\eta - \eta_\gamma)^2]^{1/2}$$

With this, the transverse energy allowed inside a cone around the photon is:

$$\sum_p E_{\mathrm{T}p}\theta(\delta - R_{p\gamma}) \leq E(\delta) \quad \text{with} \qquad E(\delta) = E_{\mathrm{T}}^{\gamma}\varepsilon\left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)^n$$

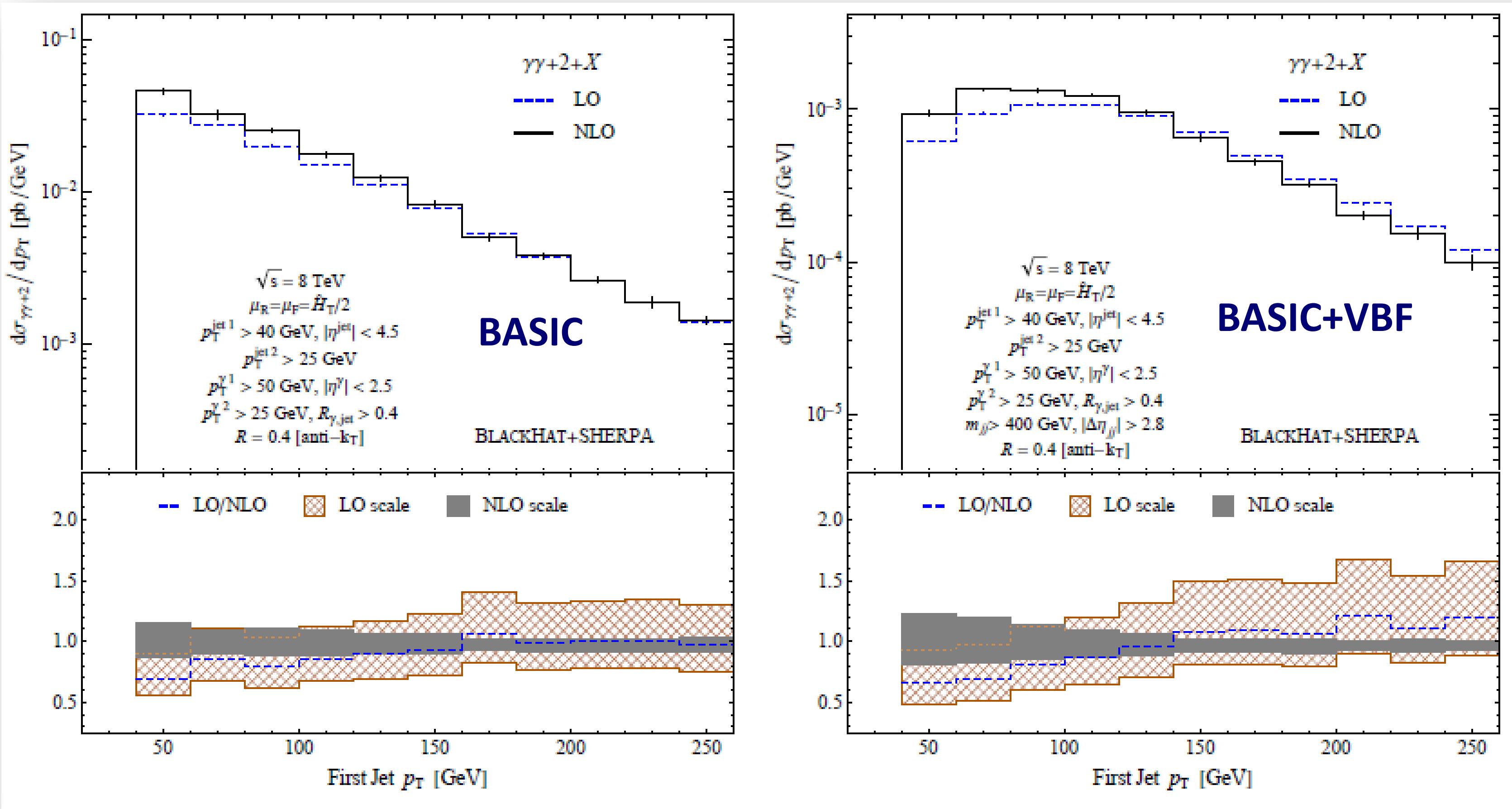
We used $\varepsilon = 0.5$, $\delta_0 = 0.4$ and $n = 1$

DYNAMICAL SCALE:

- As a factorization and renormalization scale, we choose the following dynamical (PS point by PS point) scale:

$$\mu_R = \mu_F = \hat{H}_{\mathrm{T}}/2, \text{ where} \qquad \hat{H}_{\mathrm{T}} \equiv p_{\mathrm{T}}^{\gamma_1} + p_{\mathrm{T}}^{\gamma_2} + \sum_m p_{\mathrm{T}}^m$$

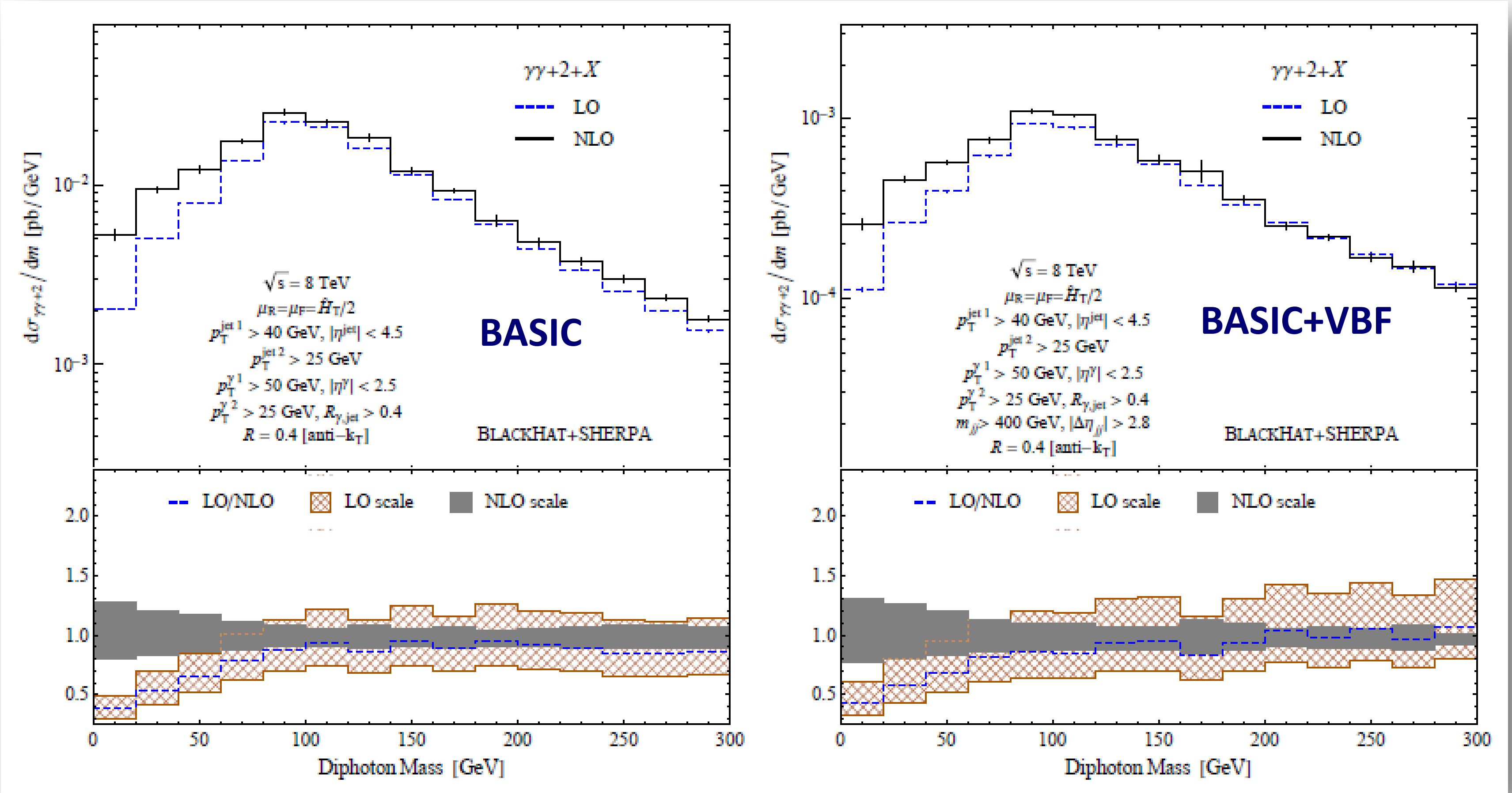
DIPHOTON+2-JET @ NLO: LEADING JET PT



•Steeper NLO for leading jet PT
•Scale band narrowed at NLO, specially at large jet PT

• Overall, NLO corrections are modest to this observable
• Similar feature to observed in V+jets production

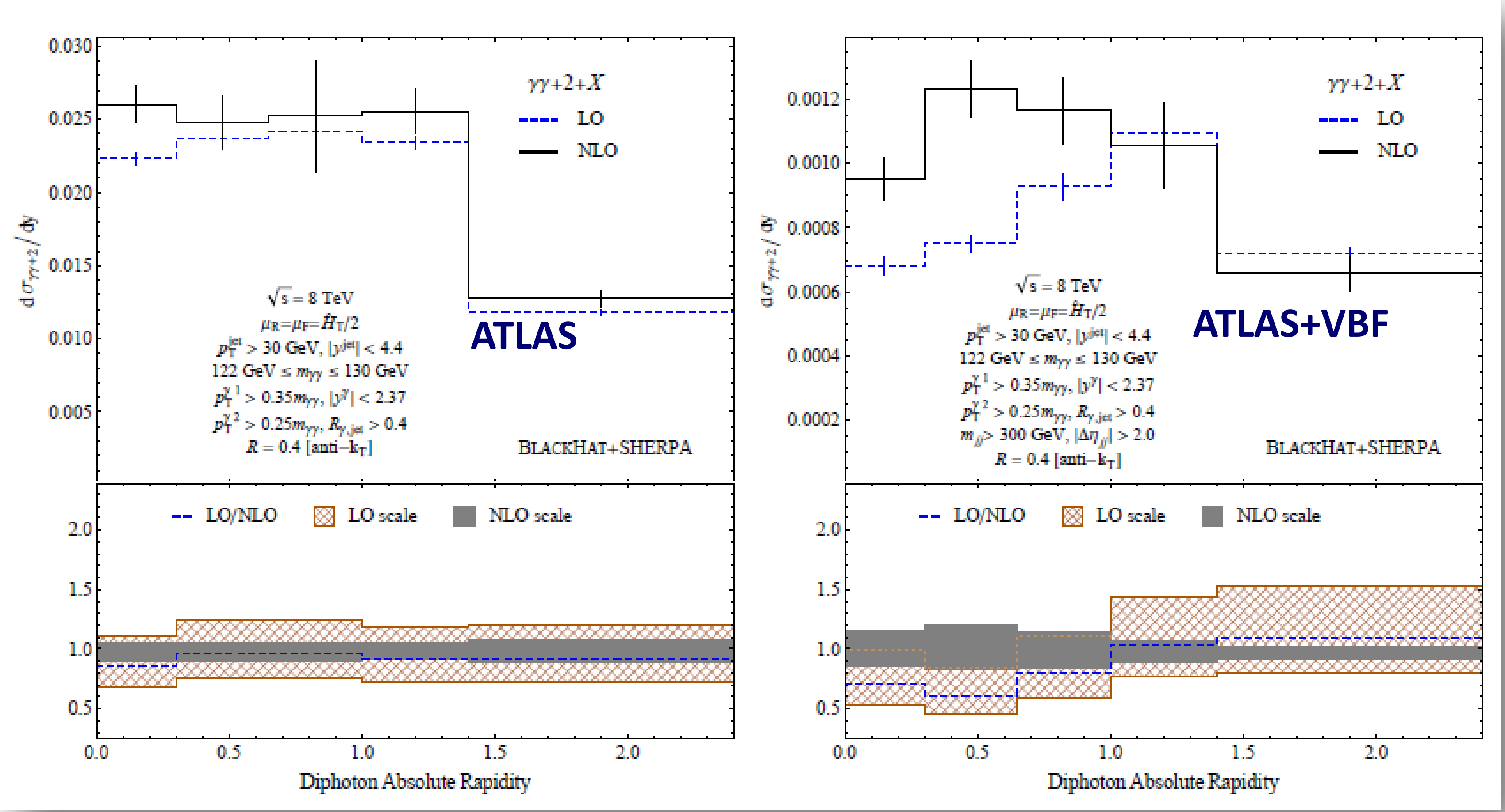
DIPHOTON+2-JET @ NLO: $M_{\gamma\gamma}$



- Sizable NLO corrections for low $M_{\gamma\gamma}$
- Real contributions -> relaxation of kinematical constrains

- NLO bands widens accordingly
- Dynamical scale produces good LO shapes at large $M_{\gamma\gamma}$

DIPHOTON+2-JET @ NLO: | $\eta_{\gamma\gamma}$ |



- Clear impact on correction with VBF cuts
- The larger corrections with VBF cuts produces an increase in NLO band (larger real contribution in that reagion)
- Still, a noticeable decrease on scale uncertainty occurs at NLO

arXiv:1312.0592 [hep-ph]

DIPHOTON+2-JET PRODUCTION AT THE LHC

- Good control over theoretical uncertainty achieved. Scale dependence reduced from ~40% at LO to ~15-20% at NLO
- Improvements can be made with interfacing with NLO parton showers
- Future analyses based on Ntuples produced will be shown for other experimental setup
- We expect, depending on needs, to study ever more exclusive associated processes
- We look forward to help studies for the Higgs-like boson properties

OVERVIEW

NLO with BlackHat+SHERPA: Basic Setup, Unitarity, QCD

W+5 JETS AT THE LHC

Why Large Multiplicity?, Setup, Results, Fits Beyond 5 Jets

DIPHOTON+2-JET PRODUCTION AT THE LHC

First VV from BH, Basic/VBF/ATLAS, Higgs Physics

BLACKHAT+SHERPA NTUPLES FOR NLO

Distributing NLO results, Store information, BHSntuples, nTupleReader

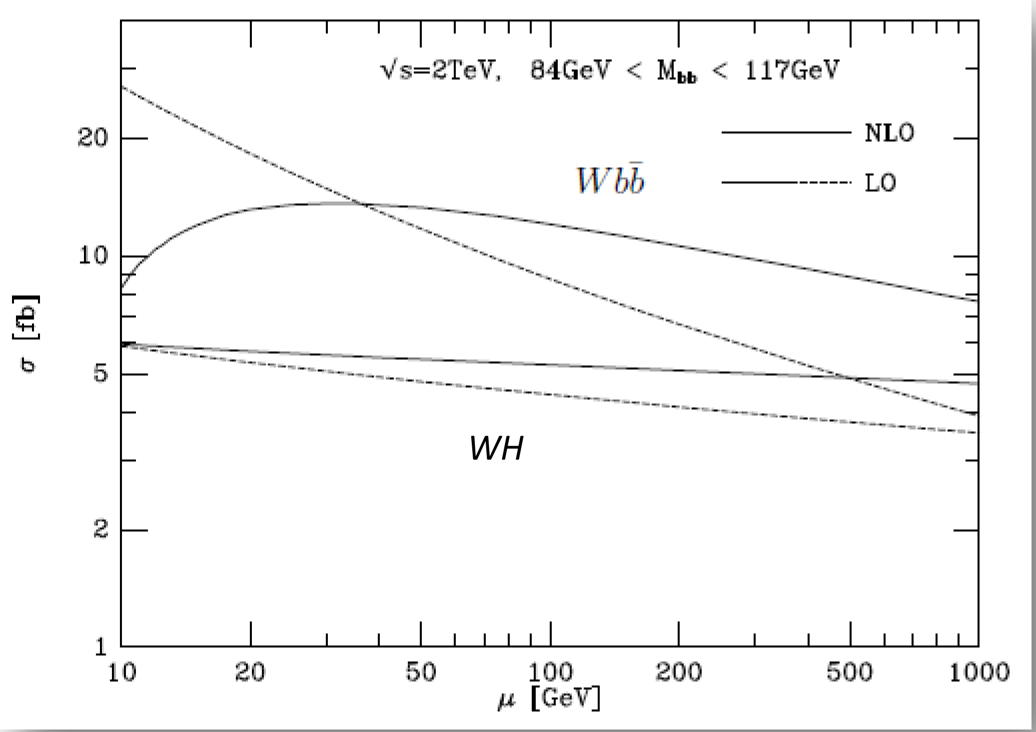
THE (N)NLO BUSINESS…

Let’s have a quick look at what’s on the market!

MCFM v1

John Campbell, Keith Ellis

→ FORTRAN based Parton Level NLO Montecarlo
→ First released in 2000, with a compilation of analytically computed NLO QCD corrections
→ Originally included a handful of processes (W/Z production, W/Z+jet, W/Z+bb, Weak Vector Boson Pairs and Higgstrahlung processes)
→ Meant to make available important calculations to the larger experimental and theory community
→ Easy access to multiple observables

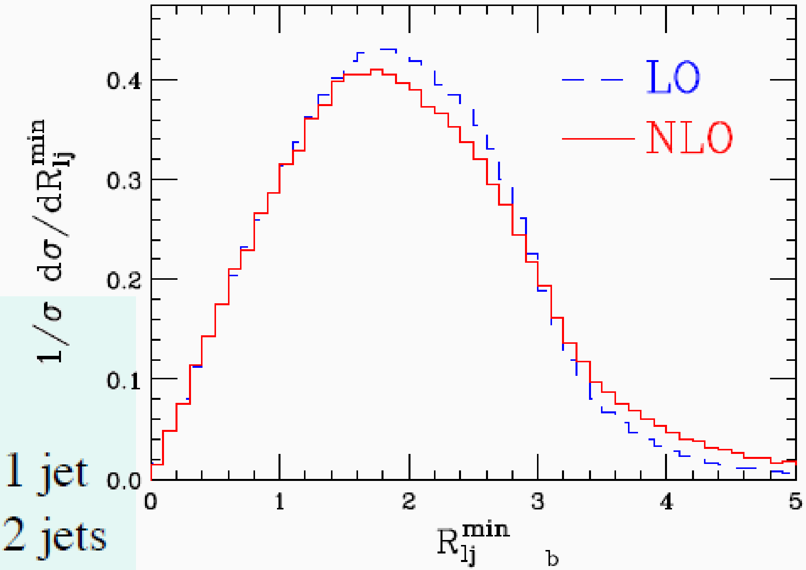


MCFM v6.7

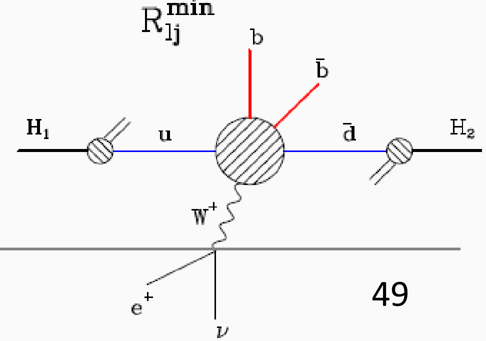
John Campbell, Keith Ellis, Ciaran Williams

http://mcfm.fnal.gov/ arXiv:1208.0566 [hep-ph], arXiv:1107.5569 [hep-ph], arXiv:1105.0020 [hep-ph], arXiv:1011.6647 [hep-ph] …

→ Widely used by experimental collaborations and theorist
→ Instrumental in the computation of recent state of the art calculations (like W+3 jets with Rocket)
→ Large amount of procceses included. Still analytical *handmade* calculations



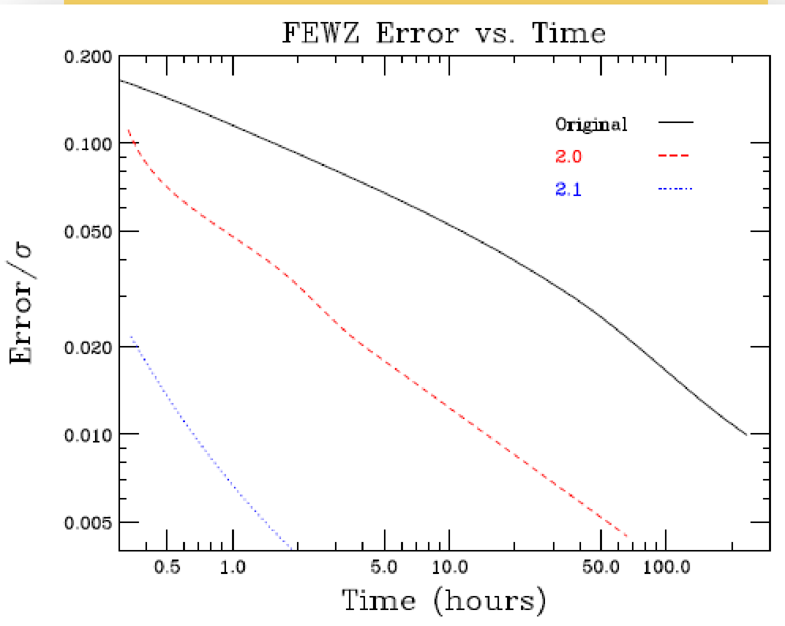
- pp → W/Z
- pp → W+Z, WW, ZZ
- pp → W/Z + 1 jet
- pp → W/Z +2 jets
- pp → t W
- pp → tX (s&t channel)
- pp → tt
- pp → W/Z+H
- pp (gg) → H
- pp→(gg) → H + 1 jet
- pp→(gg) → H + 2 jets
- pp(VV) → H +2 jets
- pp → W/Z +b , W+c
- pp → W/Z +bb



and more…

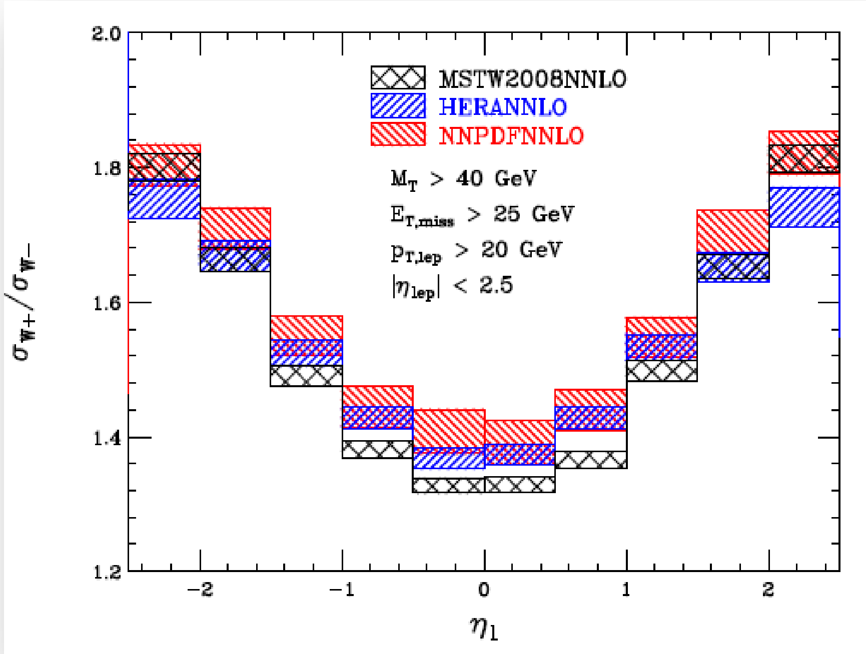
FEWZ v2.1

→ Parton Level Montecarlo of fully exclusive NNLO QCD calculation of W/Z production (including decaying products)
→ Reference for Drell-Yan studies at Hadron Colliders
→ Important recent improvements on convergence of numerical integration for observables



Frank Petriello, Seth Quackenbush, Ryan Gavin, Ye Li

http://gate.hep.anl.gov/fpetriello/FEWZ.html
arXiv:1201.5896 [hep-ph] arXiv:1011.3540 [hep-ph]
…



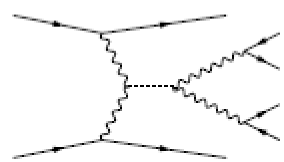
Recently Catani, Cieri, Ferrara, de Florian and Grazzini have presented a similar/alternative code (see for example arXiv:0903.2120 [hep-ph]) which should be made public soon.

VBFNLO v2.6.3

Arnold, Bellm, Bozzi, Campanario, Englert, Feigl, Frank, Figy, Jäger, Kerner, Kubocz, Oleari, Palmer, Rauch, Rzehak, Schissler, Schlimpert, Spannowsky, Zeppenfeld

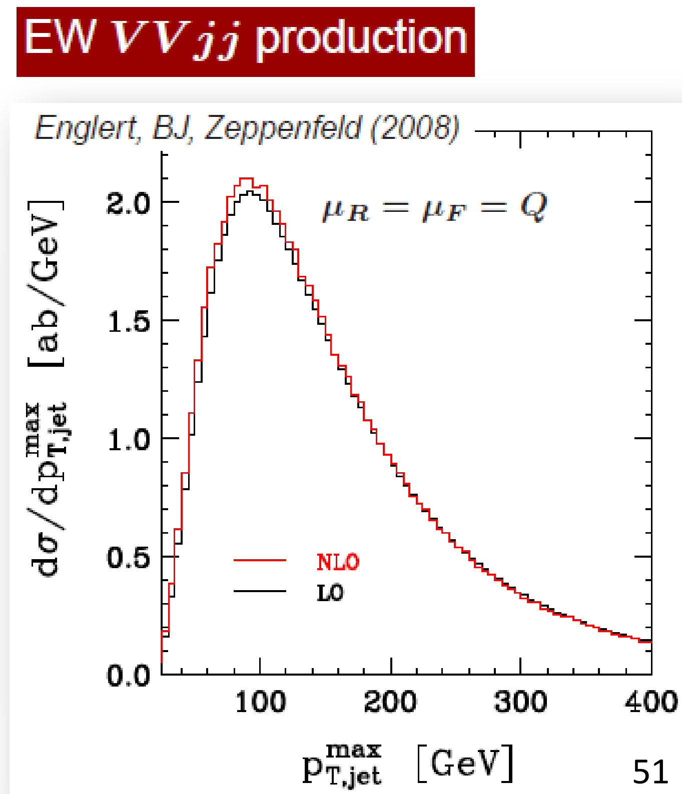
→Flexible Parton Level Montecarlo at NLO-QCD
→ Meant for processes with EW bosons
→ Includes calculations for CP-odd and CP-even Higgs boson production

http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/
arXiv:1207.4975 [hep-ph] arXiv:1107.3149 [hep-ph]
arXiv:1106.4009 [hep-ph] …



it can simulate:

- various weak vector boson fusion processes
- double and triple weak boson production processes
- double weak boson production processes in association with a hard jet
- Higgs production via gluon fusion in association with two jets

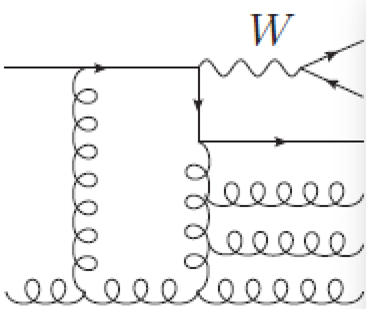


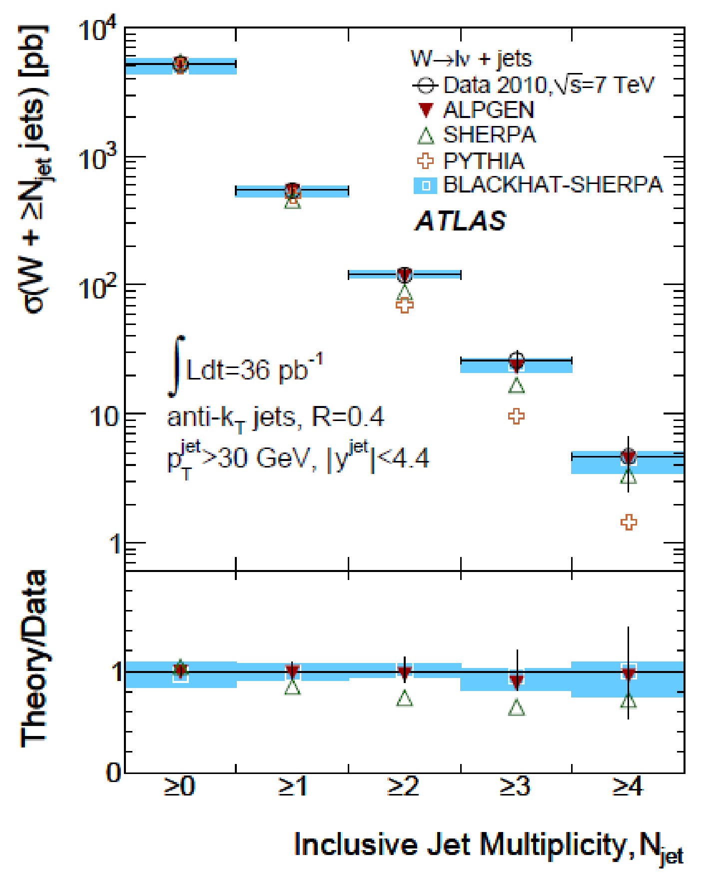
BlackHat + SHERPA

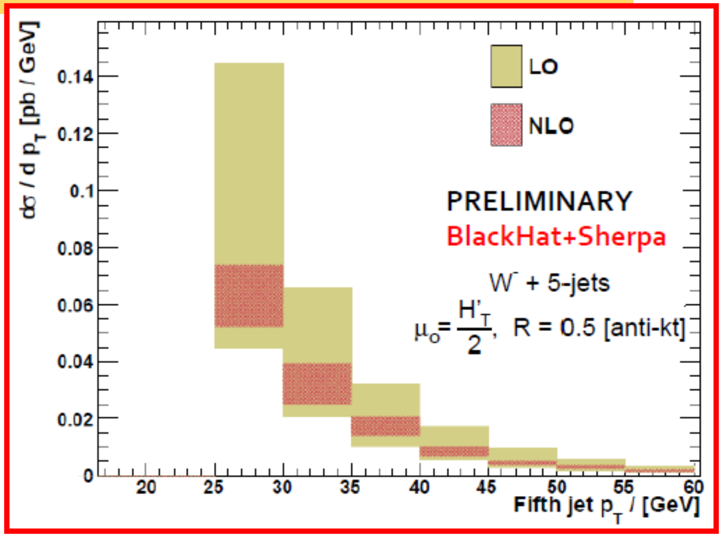
Bern, Dixon, FFC, Hoeche, Ita, Kosower, Maitre, Ozeren

→Automated implementation of on-shell and unitarity techniques to NLO QCD computations
→ Focus on state of the art processes with large amount of jets (V+1,2,3,4,5 jets, pure QCD 2,3,4 jet production)
→ Access to calculations through **NTUPLES**: Flexible to allow user defined scale variations, change of PDFs, extract any IR safe observable, etc

http://blackhat.hepforge.org/ ("private" distribution)
http://sherpa.hepforge.org/trac/wiki
arXiv:1206.6064 [hep-ph], arXiv:1112.3940 [hep-ph], arXiv:1108.2229 [hep-ph] …





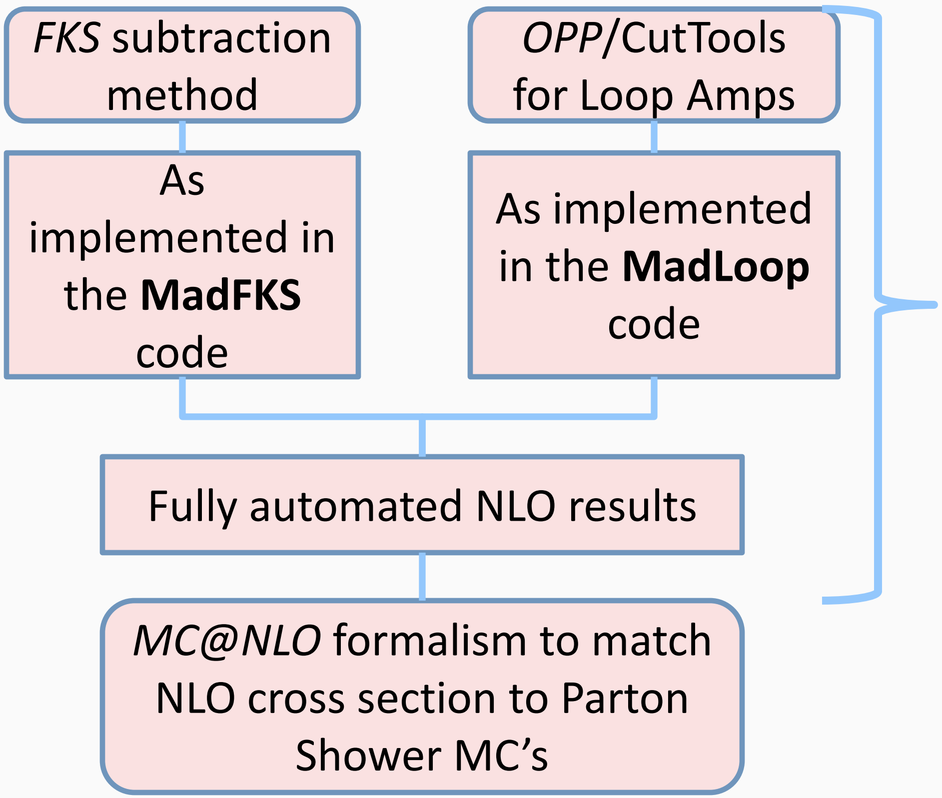


The aMC@NLO Framework

→ Collaborative Project for public automated MC tools for event generators with NLO precision for the LHC (built around MadGraph)

Alwall, Artoisenet, Frederix, Frixione, Fuks, Hirschi, Maltoni, Mattelaer, Pittau, Serret, Stelzer, Torrielli, Zaro

http://amcatnlo.web.cern.ch/ arXiv:1110.5502 [hep-ph] arXiv:1010.0568 [hep-ph] …



NLO all in *one go*…

	Process	μ	n_{lf}	Cross section (pb) LO	Cross section (pb) NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+\, j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ\, j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

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http://amcatnlo.web.cern.ch/ arXiv:1110.5502 [hep-ph] arXiv:1010.0568 [hep-ph] …

FKS subtraction method

As implemented in the **MadFKS** code

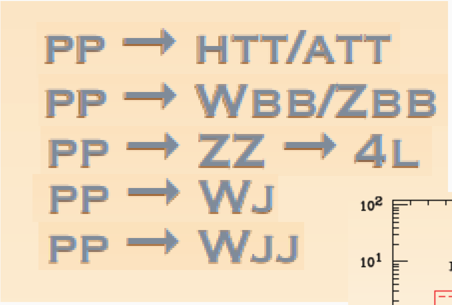
OPP/CutTools for Loop Amps

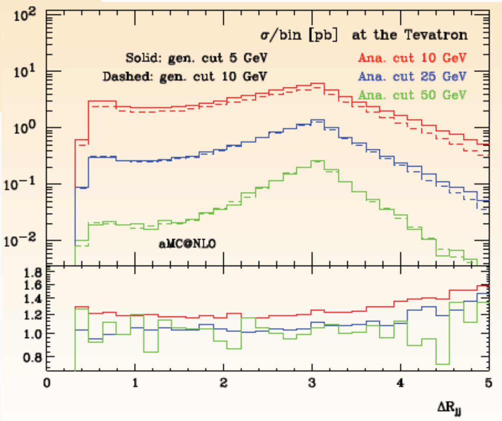
As implemented in the **MadLoop** code

Fully automated NLO results

MC@NLO formalism to match NLO cross section to Parton Shower MC's

NLO+PS also all in *one go…*





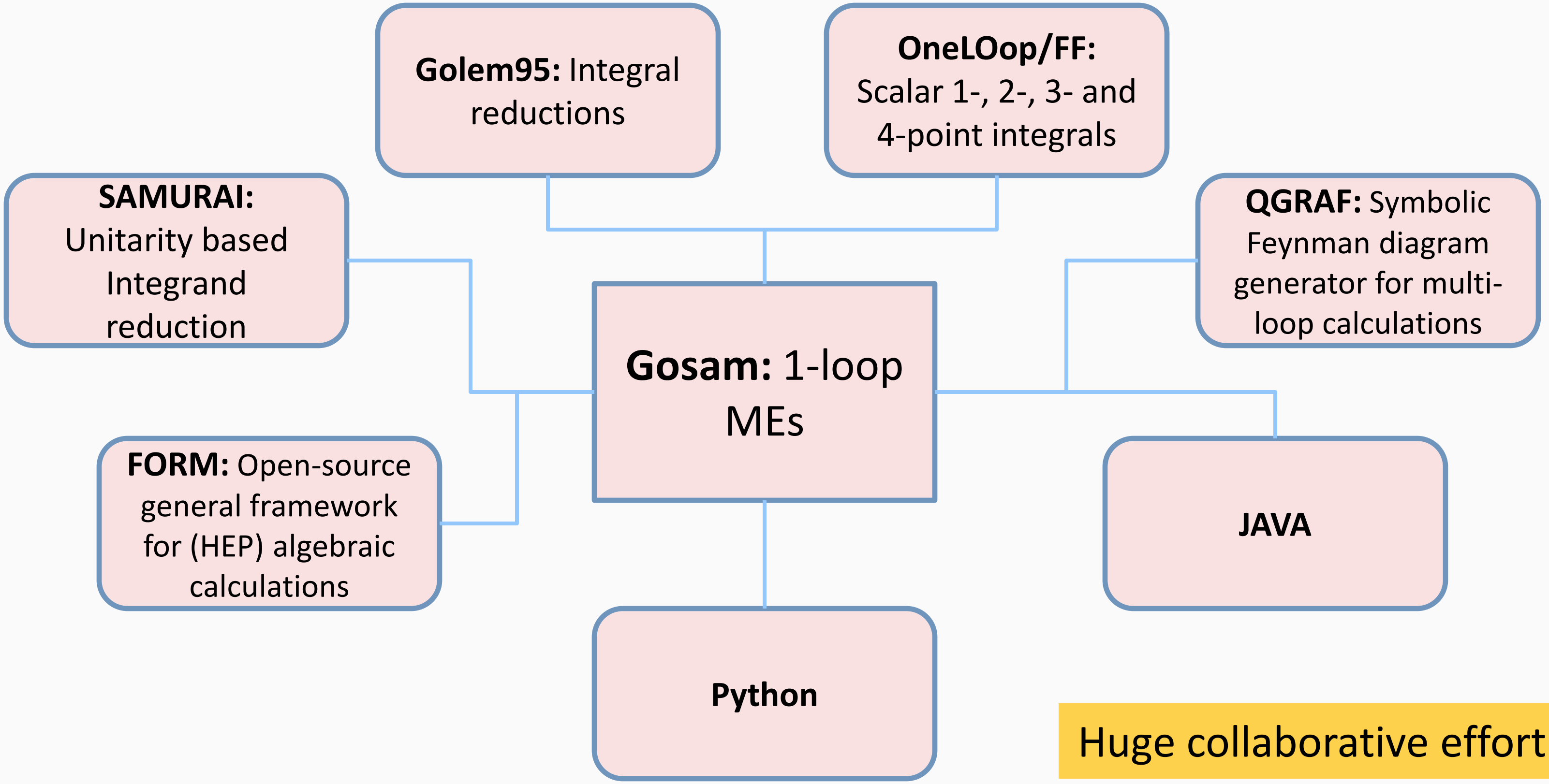
Watch out for similar progress within the **POWHEG BOX** and **SHERPA** frameworks!!! The later already includes matching of loop ME's for several jet multiplicities (see arXiv:1207.5030 [hep-ph])

GoSam Machinery

→ Automated package for extracting one-loop amplitudes for multi-particle processes. It is a wide framework for computing Feynman diagrams employing D-dimensional unitarity

Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano

https://gosam.hepforge.org/ arXiv:1111.2034 [hep-ph] arXiv:1307.8437 [hep-ph] …



Huge collaborative effort!

And much (much) more…

→ **HRes** (de Florian, Ferrera, Grazzini, Tommasini) *NNLO and NNLL gg fusion production of Higgs (with decay modes!)*

→ **NLOJET++** (Nagy) *C++ library to compute jet cross sections in lepton colliders, DIS and hadron colliders*

→ **FastNLO** (Kluge, Rabbertz, Wobisch) *provides computer codes and tables of pre-computed perturbative coefficients for various observables at hadron colliders*

→ **The PHOX family** (Aurenche, Binoth, Fontannaz, Guillet, Heinrich, Pilon, Werlen) *provides NLO corrections to processes involving Photons, hadrons and jets*

→ …

→ **ROCKET** (Ellis, Melnikov, Zanderighi) *Private F90 program for automated loop calculations using D-dimensional Unitarity*

→ **Open Loops** (Cascioli, Maierhoefer, Pozzorini) *Feynman diagram based with powerful recursive offshell technique for reducing multi-process calculation*

→ **NJet** (Badger, Biedermann, Uwer, Yundin) *Multi-parton 1-loop massless QCD, based on generalized unitarity*

→ **CutTools** (Pittau) *Automated approach to loop amps/integrals using OPP algorithm*

→ …

CHECK OUT http://www.hepforge.org/downloads/ for a large amount of available programs for High Energy Physics!

BLACKHAT+SHERPA NTUPLES FOR NLO

Storing detailed NLO calculations

arXiv:1310.7439 [hep-ph]

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
→ Also, computational setups can be cumbersome

BLACKHAT+SHERPA (BHS) NTUPLES FOR NLO

+

→ Store as many information as possible from your calculation to retain all the power of NLO results

BHS NTUPLES in BRIEF

- 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!

The Anatomy of a LO Calculation

The differential cross section at LO in a given observable $\mathcal{O}$ is written:

$$\frac{d\sigma^{\mathrm{LO}}}{dv} = \int d\hat{\sigma}_n \, \delta_v \quad = \int dx_1 dx_2 \int \mathrm{dLIPS}_n \, f_1(x_1) f_2(x_2) \, \hat{\sigma}_n \, \delta\big(v - \mathcal{O}(\{k\}_n)\big)$$

PS integral

PDFs (μ_F dependence)

Hard XS (homogeneus μ_R dependence)

- The PS integral is typically performed numerical with (improved) Monte-Carlo techniques
- One can store the set of random PS points together with the corresponding weights, and then re-evaluate any other observable employing the same calculation setup
- In order to change renormalization scale, one just needs to store the μ_R value used and the power of α_s appearing in the hard XS
- Similarly to change factorization scale and/or PDF set

The Anatomy of an NLO Calculation

At NLO we have:

$$\frac{d\sigma^{\mathrm{NLO}}}{dv} = \int \left(\underbrace{d\hat{\sigma}_n^{\mathrm{Born}}}_{\text{Born piece}} + \underbrace{d\hat{\sigma}_n^{\mathrm{virt}}}_{\text{Virtual (loop, renormalized) piece}}\right) \delta_v + \int \underbrace{d\hat{\sigma}_{n+1}^{\mathrm{real}}}_{\text{Real emission piece}} \, \delta_v$$

- Virtual and Real pieces are separately (IR) divergent
- To deal with this divergences, we employ dimensional regularization and use the Catani-Seymour subtraction approach:

$$\frac{d\sigma^{\mathrm{NLO}}}{dv} = \int d\hat{\sigma}_n^{\mathrm{Born}} \, \delta_v + \int \left(d\hat{\sigma}_n^{\mathrm{virt}} + d\hat{\sigma}_n^{\mathrm{int}}\right) \delta_v + \int \left(d\hat{\sigma}_{n+1}^{\mathrm{real}} - d\hat{\sigma}_{n+1}^{\mathrm{sub}}\right) \delta_v$$

- The structure of the subtraction is chosen such that the integration over the 1-particle PS can be carried out analytically in *D=4-2ε* dimensions, and similarly for the virtual piece
- Their divergences cancel out, and then we can only keep the finite pieces. We end up with:

$$\frac{d\sigma^{\mathrm{NLO}}}{dv} = \underbrace{\int d\hat{\sigma}_n^{\mathrm{Born}} \, \delta_v}_{\mathbf{B}} + \underbrace{\int d\hat{\sigma}_n^{\mathrm{fin.\ virt}} \, \delta_v}_{\mathbf{V}} + \underbrace{\int d\hat{\sigma}_n^{\mathrm{fin.\ int}} \, \delta_v}_{\mathbf{I}} + \underbrace{\int \left(d\hat{\sigma}_{n+1}^{\mathrm{real}} - d\hat{\sigma}_{n+1}^{\mathrm{sub}}\right) \delta_v}_{\mathbf{RS}}$$

Each integral is finite in *D=4*

The Anatomy of an NLO Calculation

$$\frac{d\sigma^{\mathrm{NLO}}}{dv} = \underbrace{\int d\hat{\sigma}_n^{\mathrm{Born}}\,\delta_v}_{\mathbf{B}} + \underbrace{\int d\hat{\sigma}_n^{\mathrm{fin.\ virt}}\,\delta_v}_{\mathbf{V}} + \underbrace{\int d\hat{\sigma}_n^{\mathrm{fin.\ int}}\,\delta_v}_{\mathbf{I}} + \underbrace{\int \left(d\hat{\sigma}_{n+1}^{\mathrm{real}} - d\hat{\sigma}_{n+1}^{\mathrm{sub}}\right)\delta_v}_{\mathbf{RS}}$$

- Each of the B, V, I and RS pieces are integrated (and stored) independently. In cases, even finer subdivision appear, which we call types.
- All corresponding information, as in the LO case, should be stored. This suffices for the B and RS pieces to change scales and PDFs, but not for V and I pieces
- The V piece for example has a dependence on a polynomial of degree 2 in logs of the scales. Also the I pieces, together with a (convolution) dependence of related PDFs
- In order to store and be able to compute general observables (including statistical errors), the full set of information of the following table is needed

The *n*-Tuple Files

arXiv:1310.7439 [hep-ph]

Each piece and type of contribution is split in a number of ROOT *n*-Tuple files for convinience. Each file contains a set of events, information about the file contents and a sample histogram for cross checks. Information on the entries of the file is stored in a ROOT tree called BHSntuples. Its branches are:

Branch name	Type	Notes
`id`	I	ID of the event. Real-emission entries and their associated counterterms share the same ID.
`nparticle`	I	number of particles in the final state
`px`, `py`, `pz`	F[`nparticle`]	array of p_x, p_y, p_z respectively, for final-state particles
`E`	F[`nparticle`]	array of energies E for final-state particles
`kf`	I[`nparticle`]	PDG codes of the final-state particles
`weight`	D	total weight of the entry
`weight2`	D	secondary or correlated weight used to compute the subtracted real-emission's statistical errors. Identical to `weight` for the B, V, and I contributions; the normalization differs for the R contribution
`me_wgt`	D	coefficient of the product of parton-distribution functions in `weight`. For the B, V, and R contributions, this is the squared matrix element multiplied by the phase-space measure and the Jacobian from SHERPA's phase-space mapping
`me_wgt2`	D	coefficient of the product of parton-distribution functions in `weight2`

The *n*-Tuple Files

arXiv:1310.7439 [hep-ph]

`x1, x2`	D	fraction of hadron momentum carried by the first and second incoming partons, respectively
`x1p,x2p`	D	secondary momentum fractions $x'_{1,2}$ used in integrated subtraction entries [9]
`id1, id2`	I	PDG codes of the first and second incoming partons respectively
`fac_scale`	D	factorization scale used ($\mu_{F,0}$)
`ren_scale`	D	renormalization scale used ($\mu_{R,0}$)
`nuwgt`	I	number of additional weights
`usr_wgts`	D[`nuwgt`]	additional weights needed to recompute the entry's weight for a different scale or pdf choices
`part`	C	type of contribution: B, V, I, or R
`alphas_power`	S	power of the coupling
`alphas`	D	α_s value used for this entry

With this information all strengths of an NLO calculation can be extracted as long as the following conditions are met:

1. One of the jet algorithms used to generate the files is applied
2. Kinematical cuts of the study are tighter than the ones used to generate the *n*-tuples
3. The numbers of jets passing the algorithm and kinematical cuts is at least *n* for an *n*-jet process
4. All cuts are defined in terms of jets and no in terms of partons

BHSntuples (publicly) Available

Process	n-tuple file sets
$W^{\pm}(\to e^{\pm}\overset{(-)}{\nu}) + 0, 1, 2$ jets	B001, I001, R001, V001
$W^{\pm}(\to e^{\pm}\overset{(-)}{\nu}) + 3$ jets	B001, I001, R001, V001–V002
$W^{-}(\to e^{-}\bar{\nu}) + 4$ jets	B001, I001, R001, V001
$W^{+}(\to e^{+}\nu) + 4$ jets	B001, I001, R001–R005, V001
$Z(\to e^{+}e^{-}) + 0, 1, 2$ jets	B001, I001, R001, V001
$Z(\to e^{+}e^{-}) + 3$ jets	B001, I001, R001, V001–V002
$Z(\to e^{+}e^{-}) + 4$ jets	B001, I001–I003, R001–R006, V001–V006
n jets $(n = 1, 2, 3, 4)$	B001, I001, R001, V001

Which you can access/download from:

From the web:
https://blackhat.hepforge.org/trac/wiki/Availability
From CASTOR:
/castor/cern.ch/d/dmaitre/BHSNtuples/PROCESS/ENERGY/PART
From the LHC Grid:
/grid/pheno/BHSNtuples/PROCESS/ENERGY/PART

nTupleReader: A Utility to Use BHSntuples

We have provided a C++ library, *nTupleReader*, which provides an easy-to-use interface to the *n*-tuple files provided by BlackHat+SHERPA

- Program to extract information from *n*-tuple files
- Utilities to change scales and PDFs consistently for all pieces of the NLO results
- Consistent treatment of statistical uncertainties, to obtain reliable estimates for all pieces
- Python interface included

Download from
http://www.hepforge.org/archive/blackhat/ntuplereader-1.0.tar.gz

BHSntuples AT WORK: Z+Jets @ ATLAS

arXiv:1304.7098 [hep-ex]

Z+Jets @ ATLAS

→ In **arXiv:1304.7098 [hep-ex]** ATLAS presented a thorough study of associated Z and Jet production at 7 TeV
→ Employs 4.6 fb^{-1} of data collected until 2011
→ Data shown including up to six jets
→ Comparisons to NLO QCD results with BlackHat+SHERPA Ntuples and with the MC generators SHERPA / ALPGEN / (MC@NLO, Pythia)
→ Both electron and muon decay channels analyzed

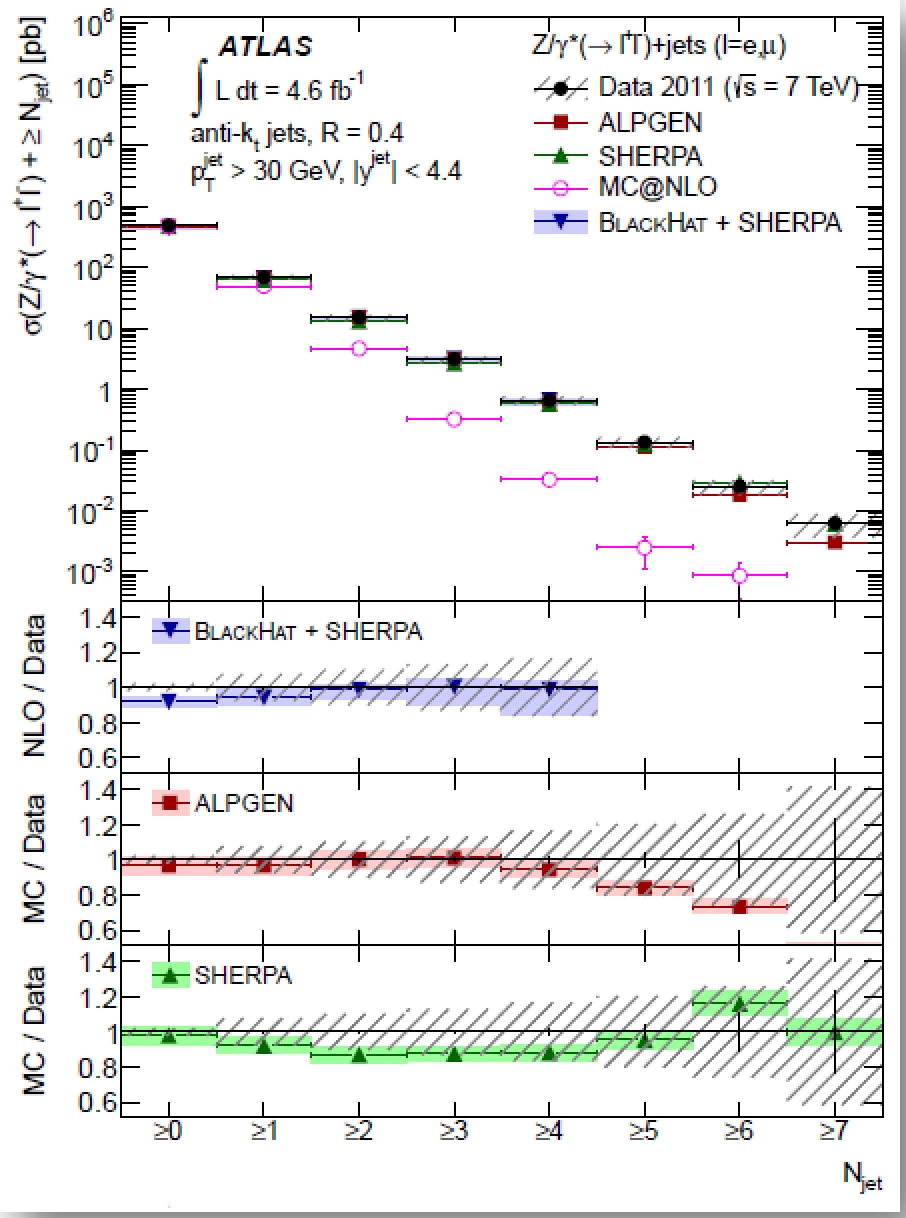
Kinematical cuts:

anti-k_t jets, $R = 0.4$,
$p_T^{jet} > 30$ GeV, $|y^{jet}| < 4.4$

Z+Jets @ ATLAS

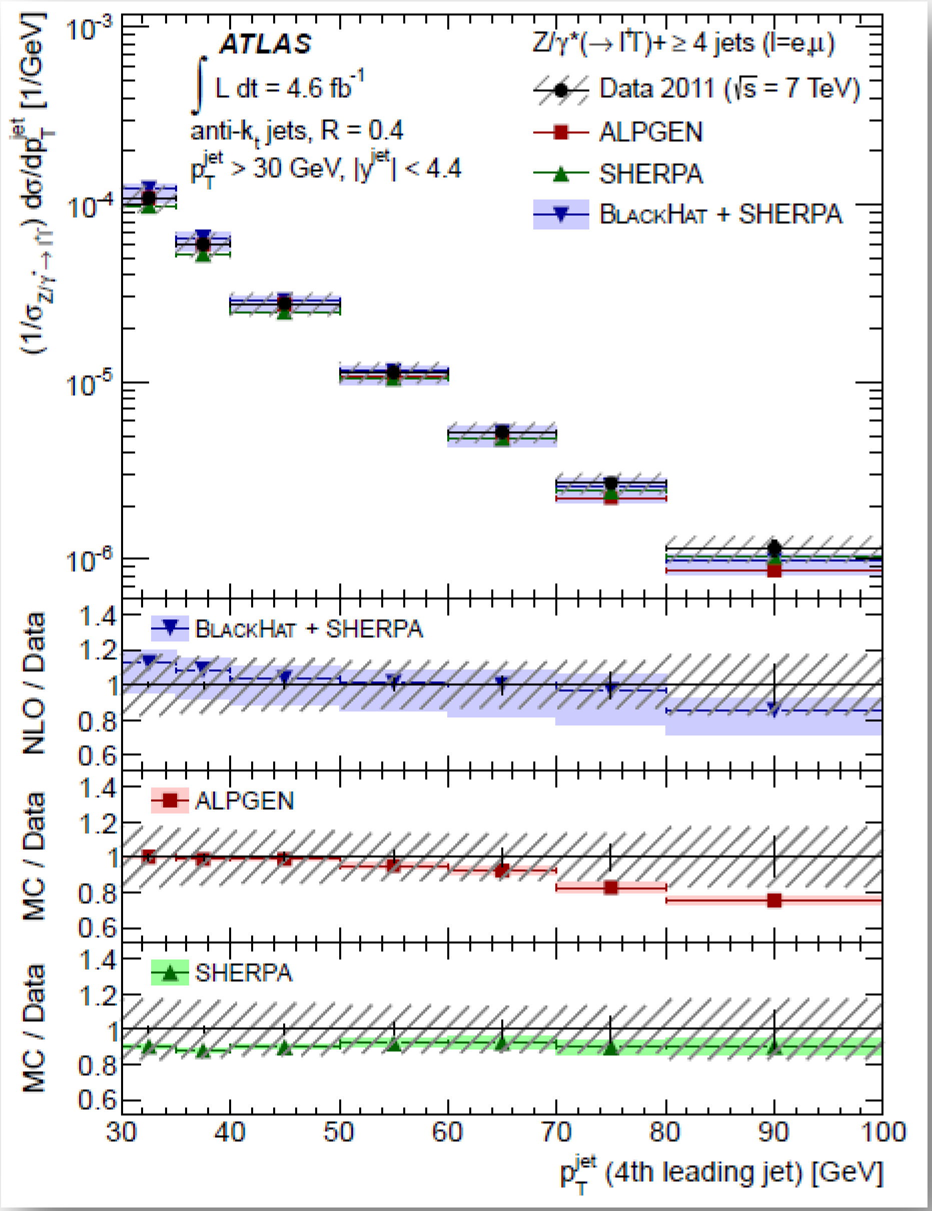
→ 4.6 fb^{-1}
→ Inclusive cross section for each multiplicity
→Good agreement with NLO results
→ Good statistical error control for six jet events
→ Electron/muon channel shown

arXiv:1304.7098 [hep-ex]



Z+Jets @ ATLAS

→ 4.6 fb^{-1}
→ Fourth jet p_T spectrum
→ Good shape predictions from theory (although ALPGEN seem to have a deficit at large p_T)
→ Electron/muon channel shown



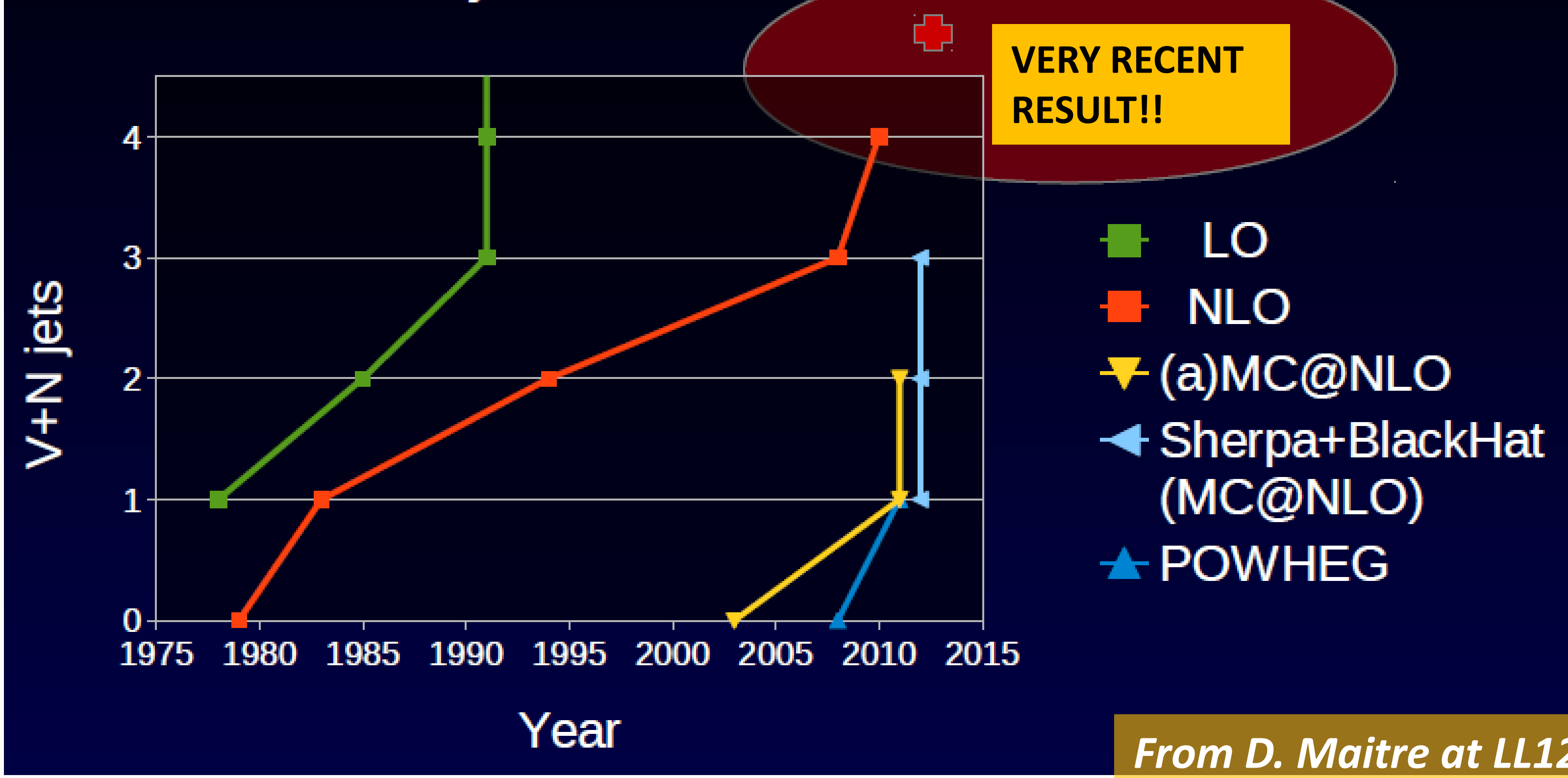
arXiv:1304.7098 [hep-ex]

Summary

- **BlackHat+SHERPA** has made important contributions to the NLO revolution of the last few years
- We showed the first NLO QCD results for a 2 → 6 process at a hadron collider, that of **W+5 Jet Production**
- Also available results for **V+1,2,3,4 Jets at NLO QCD**, and **2,3,4 Jet Production at NLO QCD**
- Recent results on **Diphoton + 2-Jet** shown. We expect comparisons with data and future large multiplicity analyses
- **BlackHat's Ntuples** show a great potential to efficiently distribute NLO calculations. We show an application by ATLAS in Z+Jets production

The New NLO Standard!

• Number of jets in addition to the vector boson



From D. Maitre at LL12

NLO Montecarlo for Standard Experimental Analyses…

Backup slides….