Vector boson + multi jets at NLO

Harald Ita, UCLA

In collaboration with

C.F. Berger, Z. Bern, L.J. Dixon, F. Febres Cordero, D. Forde, D.A. Kosower, D. Maitre; T. Gleisberg

West Coast Theory Meeting, UCSC – May 21, 2010

Physics Motivation

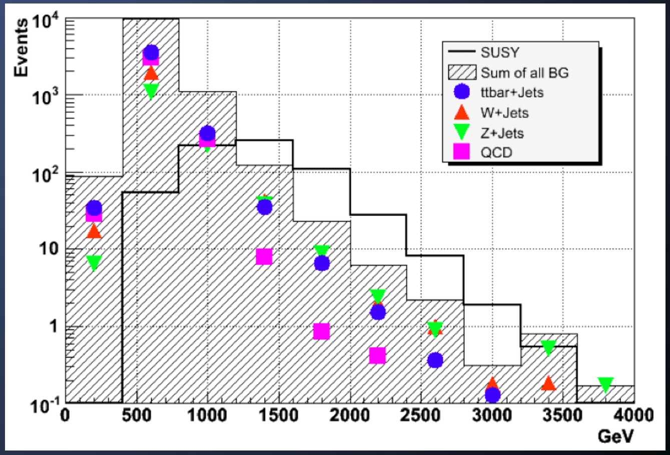
W/Z/γ-processes at the heart of electro-weak symmetry breaking

- As signals
- As backgrounds (Higgs, $t\bar{t}$, single top)
- Luminosity

SUSY missing energy background

- $W \rightarrow e\nu$
- $Z \rightarrow \bar{\nu}\nu$
- $W/Z \rightarrow \bar{q}q$, (missed jet)

M L Mangano



Ws versus Zs ($\rightarrow$ leptons)

W-boson

- Larger cross section
- Less clean signal (neutrino)

Z-boson

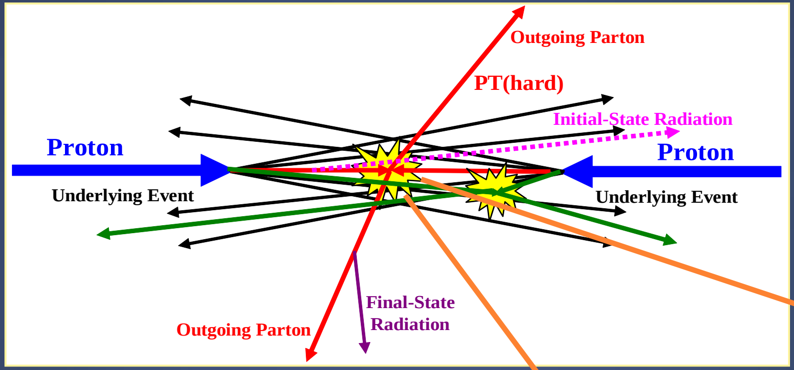
- Cleaner signal in the $Z \rightarrow e\bar{e}/\mu\bar{\mu}$ channel
- Smaller cross section

Similar underlying QCD

- relate $Z \rightarrow e\bar{e}/\mu\mu$ to $W \rightarrow e\nu$ and $Z \rightarrow \nu\bar{\nu}$

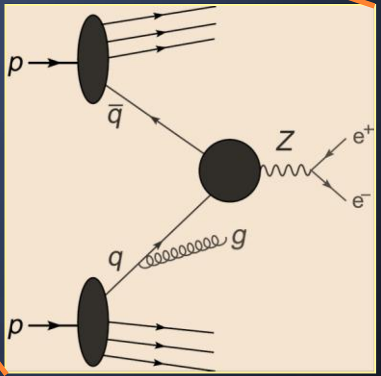
The Simulation

A multi layered problem



Here parton level hard scattering

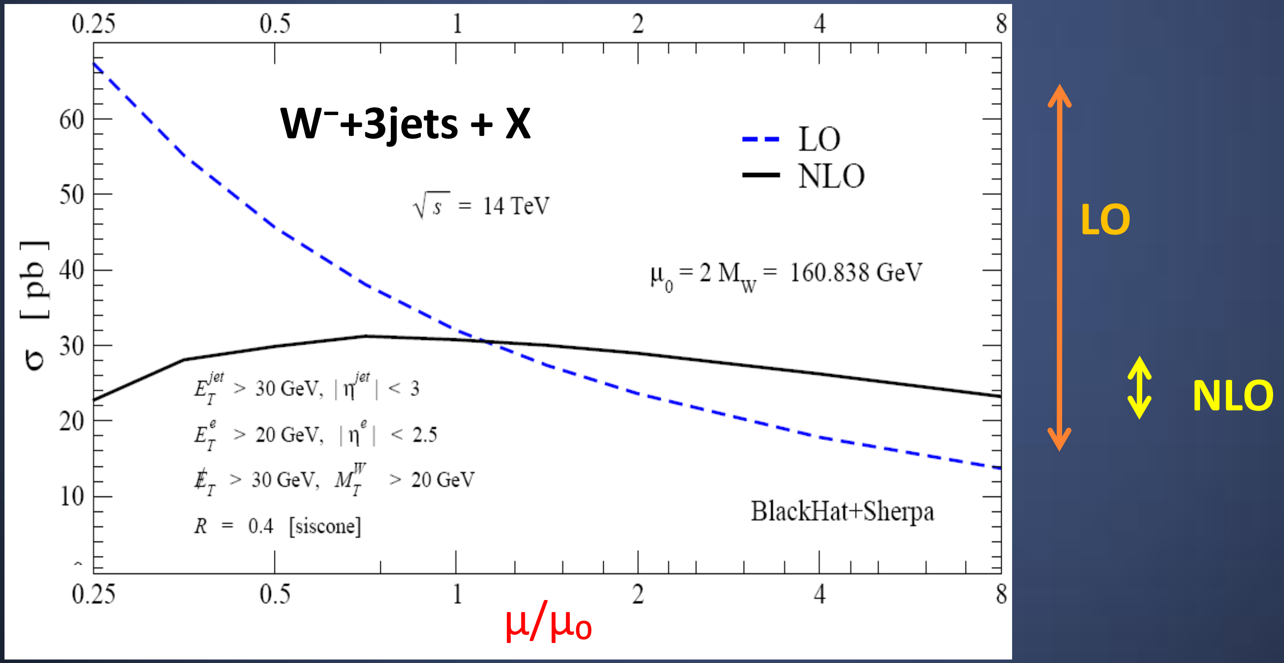
- parton model
- perturbative QCD
- jet algorithms



Scale Dependence

At fixed order renormalization scale dependence through $\alpha_{strong}(\mu)$

BlackHat+Sherpa



Multi-jet QCD at NLO

NLO corrections improve theory predictions:

- Reduce renormalization scale dependence

BlackHat+Sherpa

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

W+jets cross-sections (Tevatron):
Variation for doubling Renormalization and Factorization scale.

- Absolute normalizations
- Shape of distributions
- Corrections can be large

Multiplicity Bottleneck

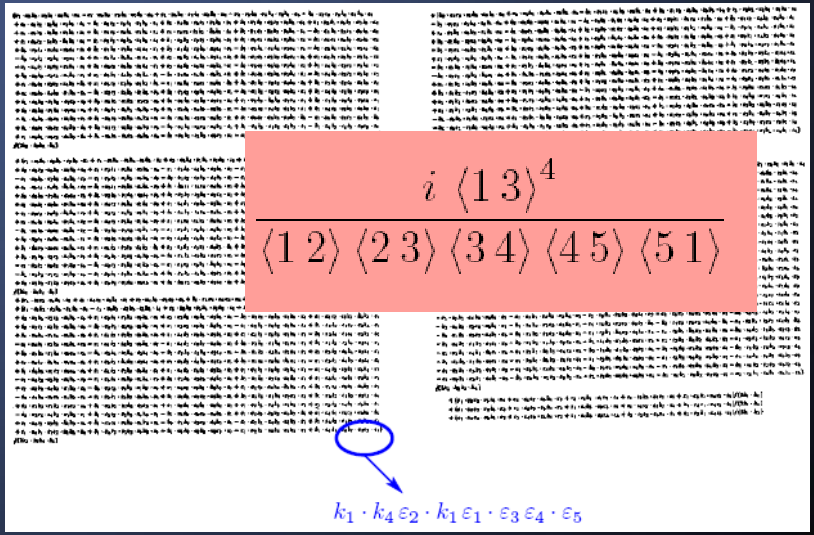
Unitarity and on-shell methods
resolve obstructions in conventional approaches

- Factorial number of Feynman diagram expressions
- Tensor integral reduction

Think off-shell work on-shell

- Park-Taylor amplitude
- Quadruple cut

5-point pure glue amplitude



Multi jet NLO with BlackHat & Sherpa

Berger, Bern Dixon, Febres Cordero, Forde, HI, Kosower, Maitre

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

Sherpa

BlackHat

PDFs + coupling:
CETEQ6M (LO), CETEQ6L1 (NLO)

Sherpa

Gleisberg, Hoeche, Krauss, Schoenherr, Schumann, Siegert, Winter

Event generator providing:

- Phase space integration
- Jet algorithms
- Automated dipoles for real part integration
  (Catani, Seymour; Gleisberg, Krauss)
- Analysis framework

BlackHat

Berger, Bern Dixon, Febres Cordero, Forde, HI, Kosower, Maitre; Gleisberg

Numerical on-shell methods for LO and NLO matrix elements for QCD processes:

- Loops:
  - unitarity method — Bern, Dixon, Kosower, Dunbar
  - and recent extensions — Britto, Cachazo, Feng; Ossola, Papadopoulos, Pittau; Forde; Bern, Morgan; Bern, Dixon, Dunbar, Kosower; Ellis, Giele, Kunszt, Melnikov; Badger
  - one-loop recusions — Berger, Bern, Dixon, Forde, Kosower; Bern, Bjerrum-Bohr, Dunbar, HI
- Input tree amplitudes:
  - on-shell recursions — Britto, Cachazo, Feng, Witten

How good are our tools

Compare to Tevatron studies

- W+jets CDF — Phys.Rev.D 77, 011108 (2008)
- Z+jets D0 — Phys.Lett. B 669, 278 (2008), Phys.Lett. B 678, 45 (2009), Phys.Lett. B 682, 370 (2010)
- Z+jets CDF — Phys.Rev.Lett. 100, 102001 (2008)

CDF W+jets

CDF, Phys. Rev. D 77, 011108 (2008)

data: 320 pb^{-1}, particle level

$$E_T^{jet} > 20\,\mathrm{GeV}\,, \qquad |\eta^{jet}| < 2$$

$$E_T^{e} > 20\,\mathrm{GeV}\,, \qquad |\eta^{e}| < 1.1\,,$$

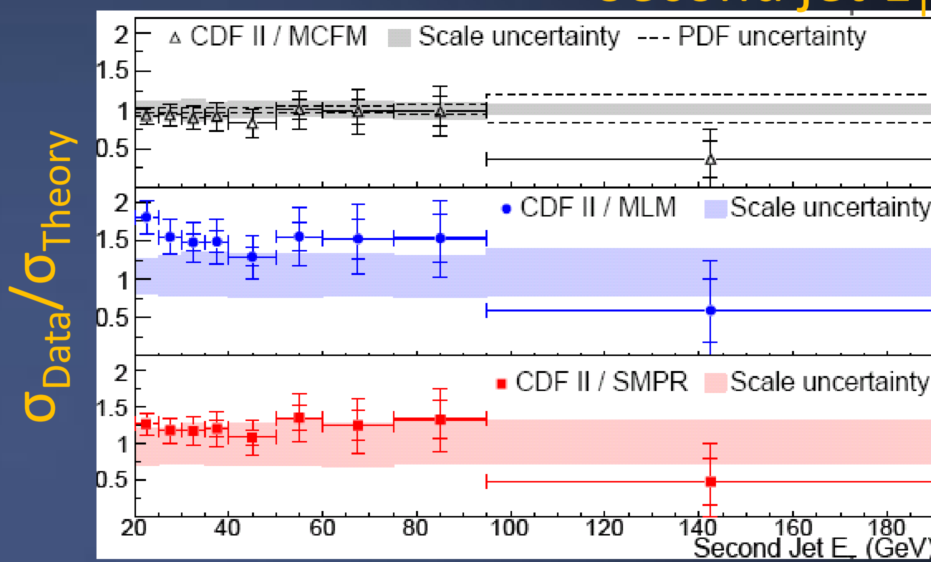
$$\not{E}_T > 30\,\mathrm{GeV}\,, \qquad M_T^W > 20\,\mathrm{GeV}$$

$$\mu = E_T^W \equiv \sqrt{M_W^2 + p_T^2(W)}$$

JETCLU, R=0.4, f=0.75

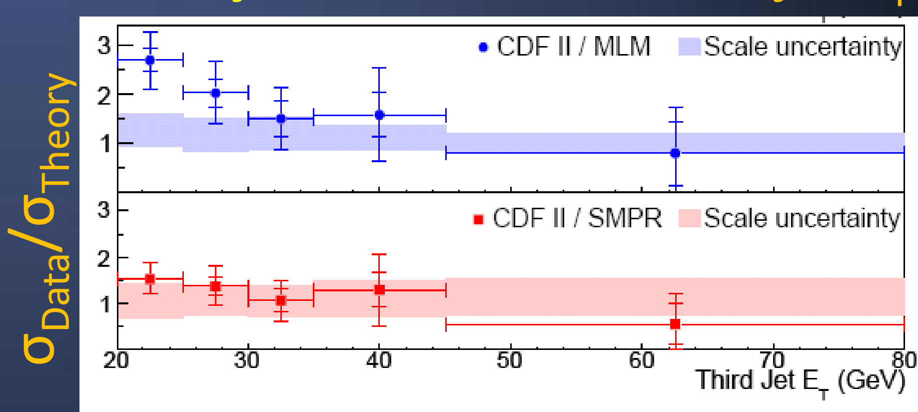
W+2 jets

Second jet E_T



W+3 jets

Third jet E_T



Comparison:

- MCFM (NLO parton)
- MLM (LO Alpgen+Herwig)
- SMPR (LO Madgraph+Pythia)

W+3 jets

CDF, Phys. Rev. D 77, 011108 (2008)

Jet algorithms:

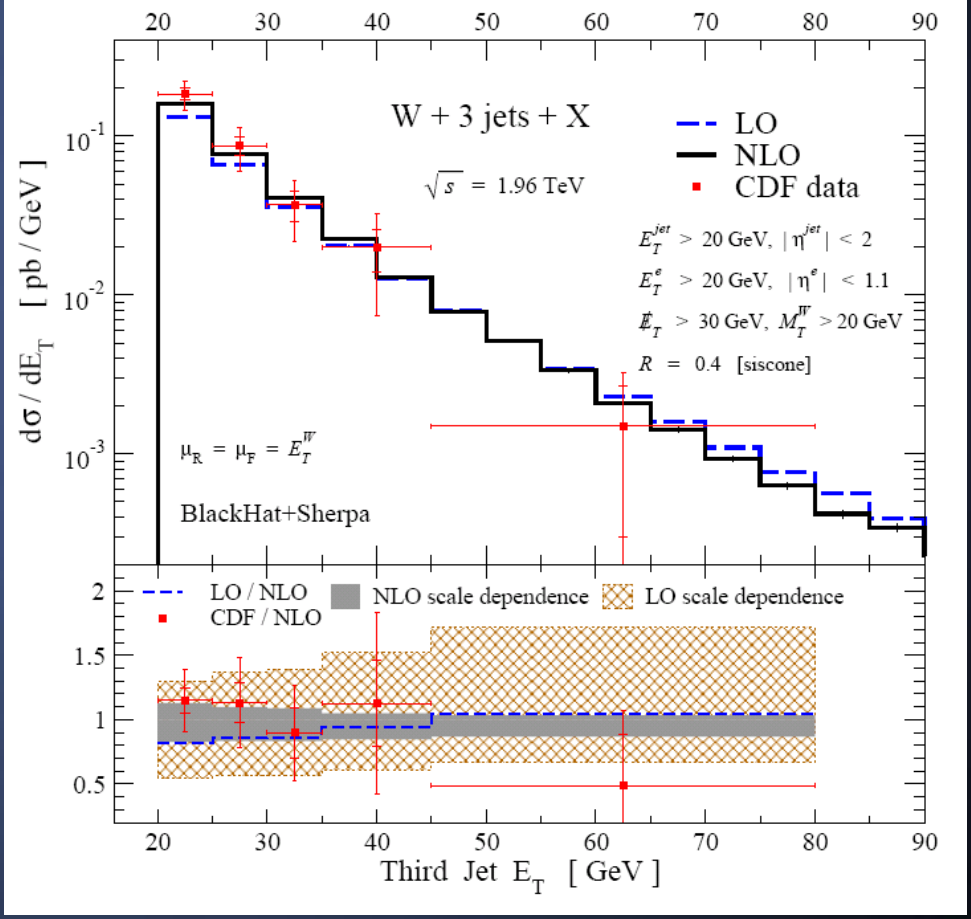
- SISCone R=0.4, f=0.5

  Salam, Soyez

- CDF: JETCLU R=0.4, f=0.75

Third jet E_T

BlackHat: 0907.1984



D0 Z+3jets

BlackHat: 1004.1659

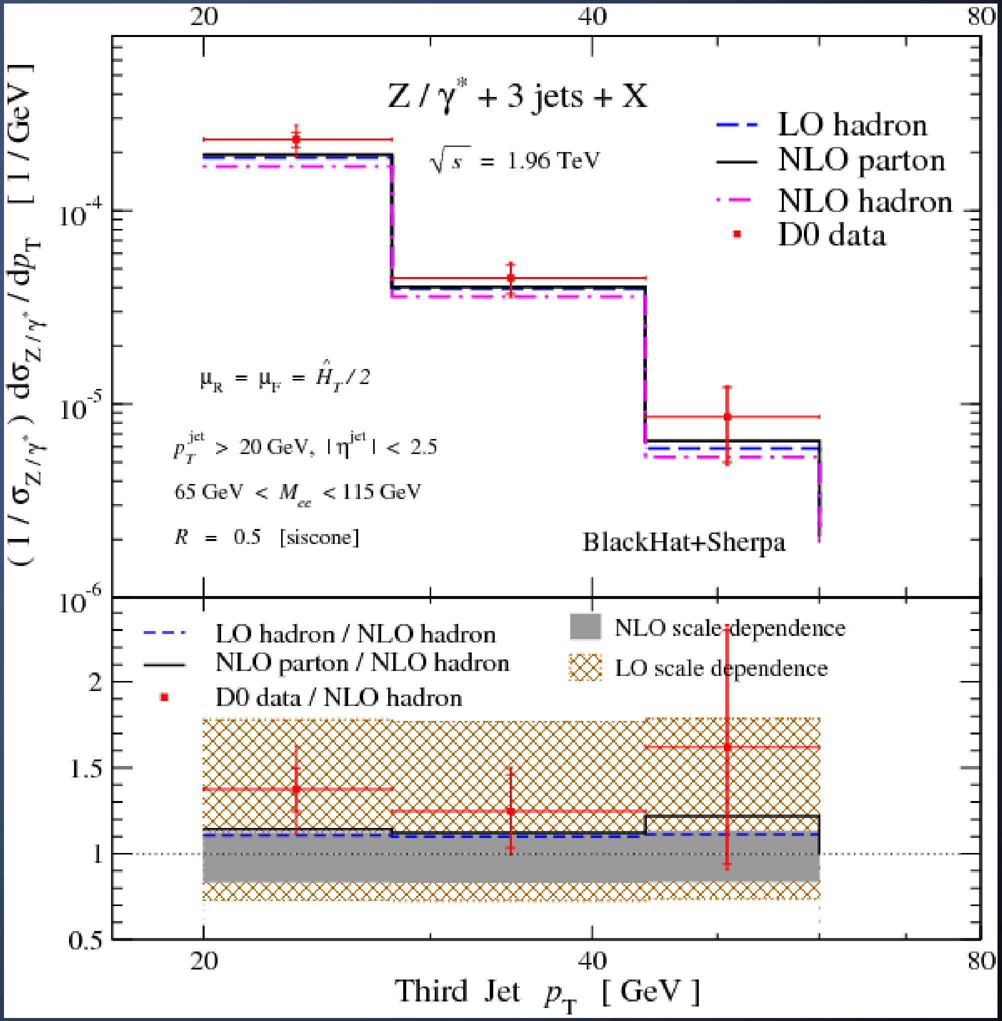
Good Agreement up to

- Non-perturabtive aspects
- Jet-algorithms

Jet algorithms

- SISCone R=0.5, f=0.5
- D0 Run II Midpoint, R=0.5, f=0.5; not IR safe

Our scale choice μ=$\hat{H}_T/2$



Choosing renormalization scales

Have to choose scale

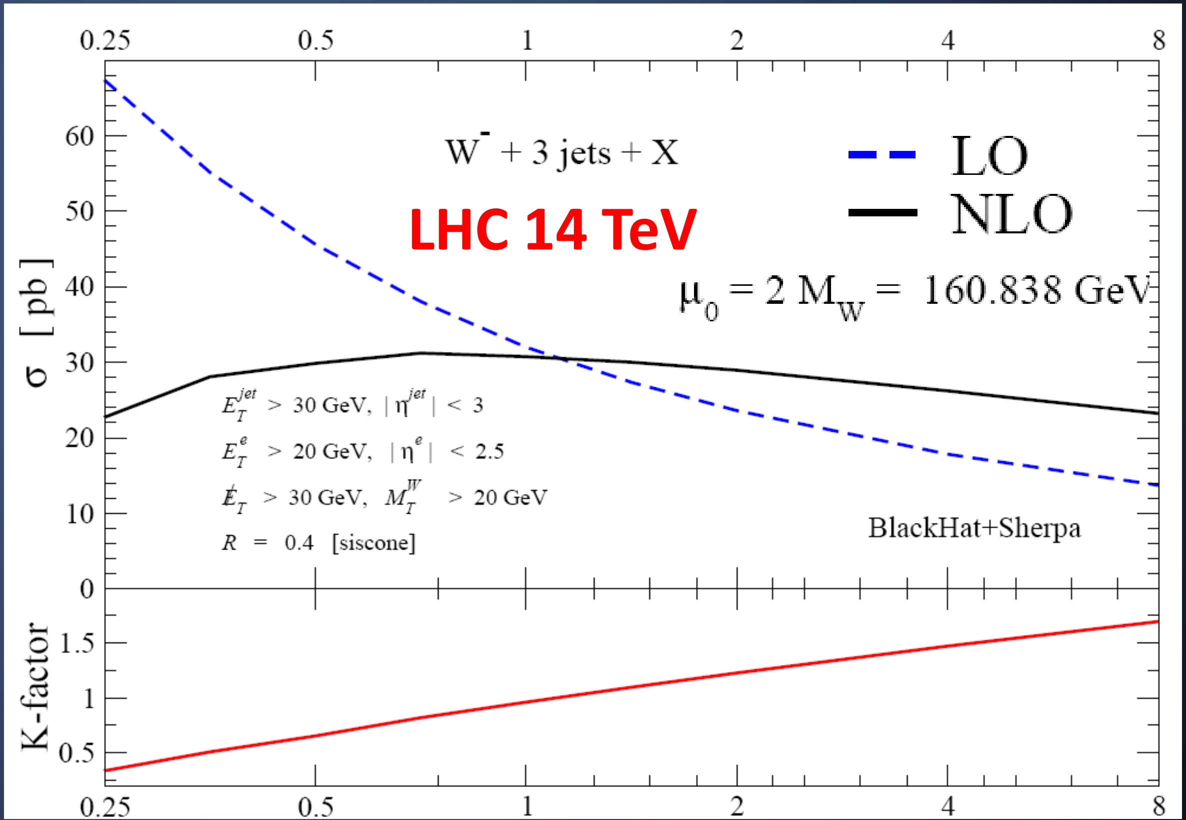
Total cross section

- fixed scales works well

Distributions

- Dynamical scale

BlackHat 0903.1984

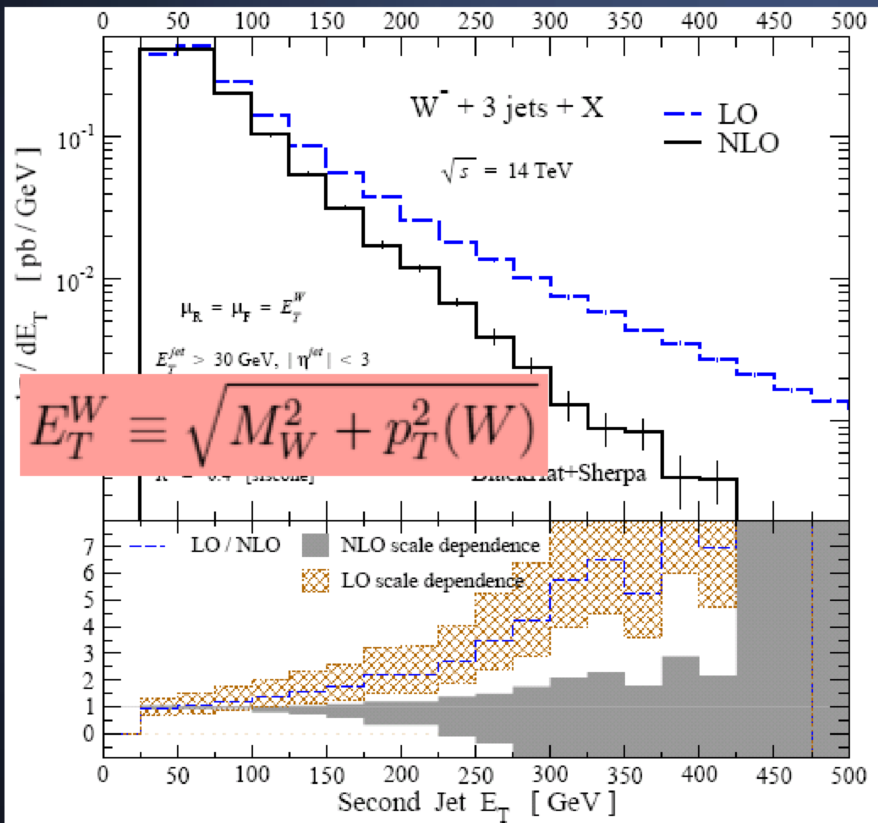


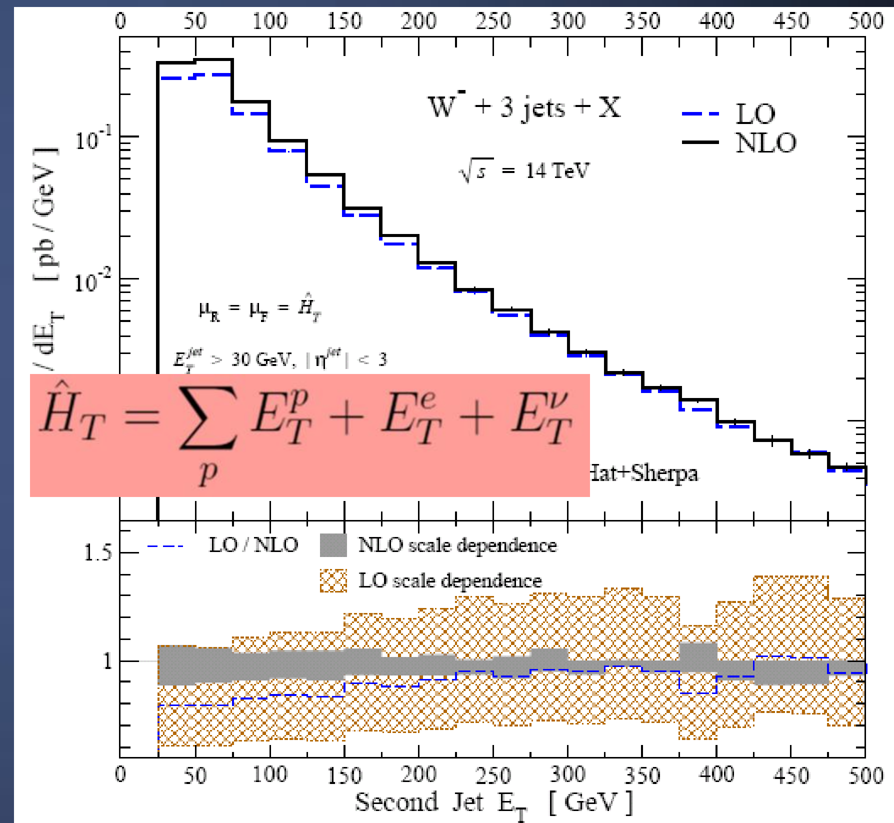
μ/μ_0

Bad scale choice Good scale choice

LHC 14 TeV

BlackHat 0903.1984



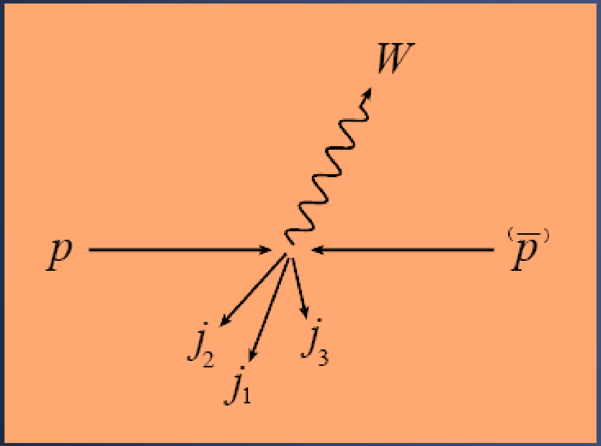


Transverse energy of W boson $\mu = E_{TW}$

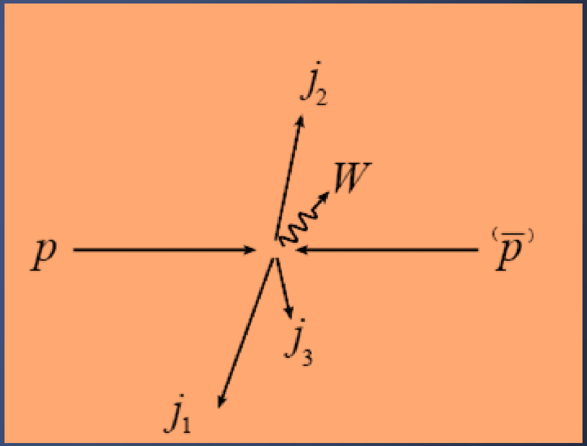
Total transverse partonic energy $\mu = \hat{H}_T$

Two typical kinematic configurations

E_{TW} characteristic scale



E_{TW} too soft



Careful

Causes bad tails

Many scale choices

Important to pick well

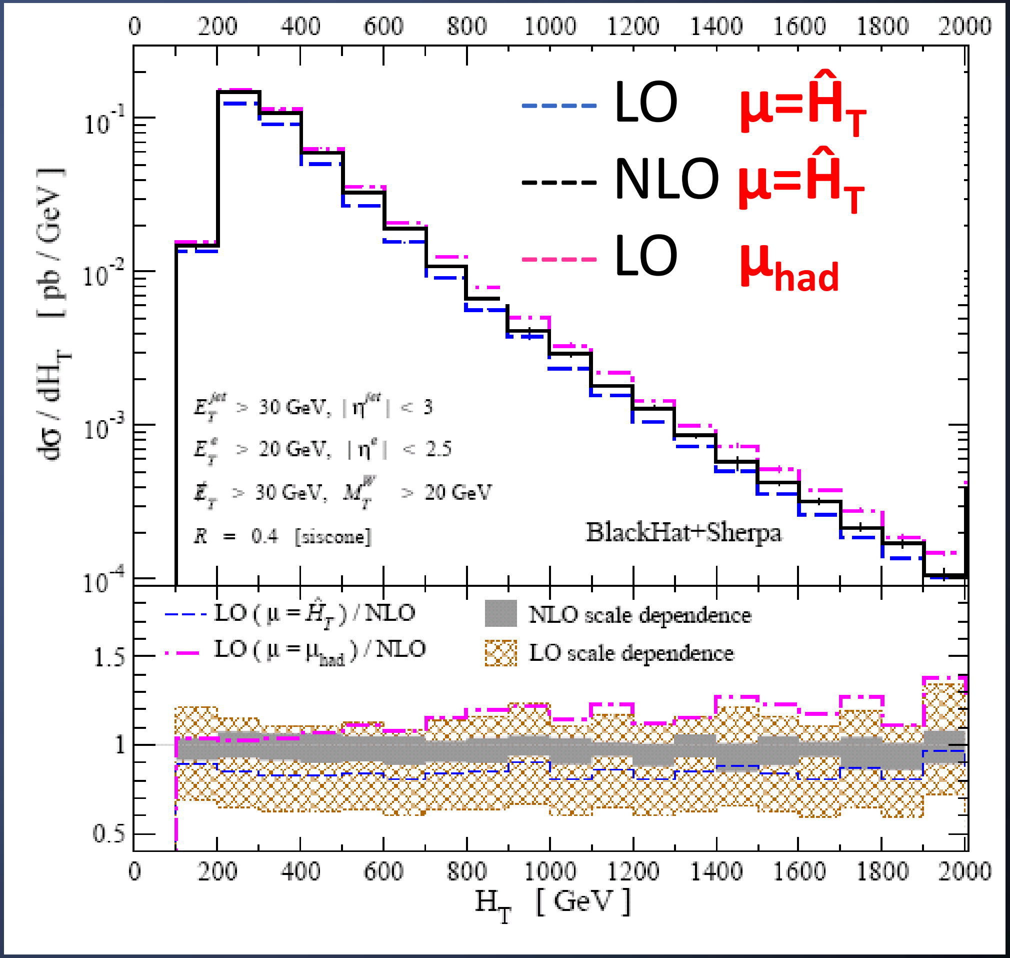
Some suitable choices

- $\mu=\hat{H}_T$
- $\mu^2_{had} = 1/4\ M^2_{had} + M^2_W$

Bauer, Lange

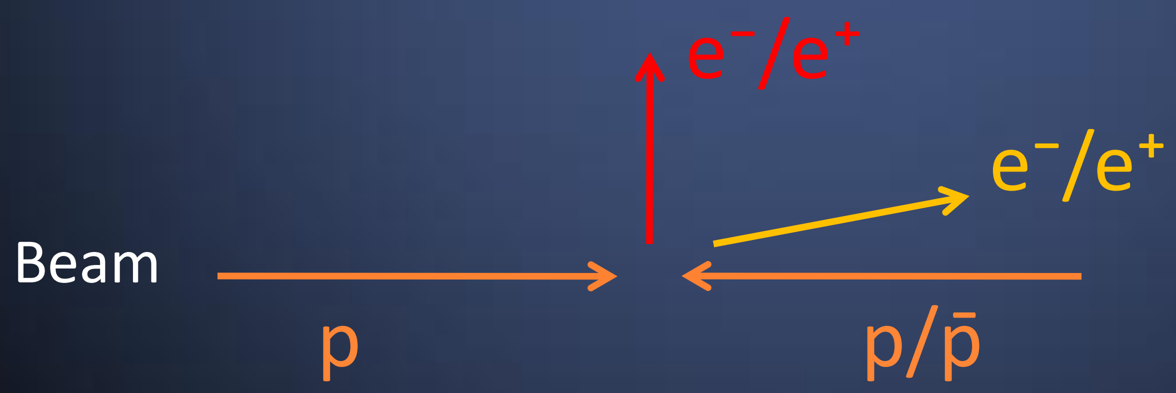
To judge need to look at NLO distributions

BlackHat 0903.1984



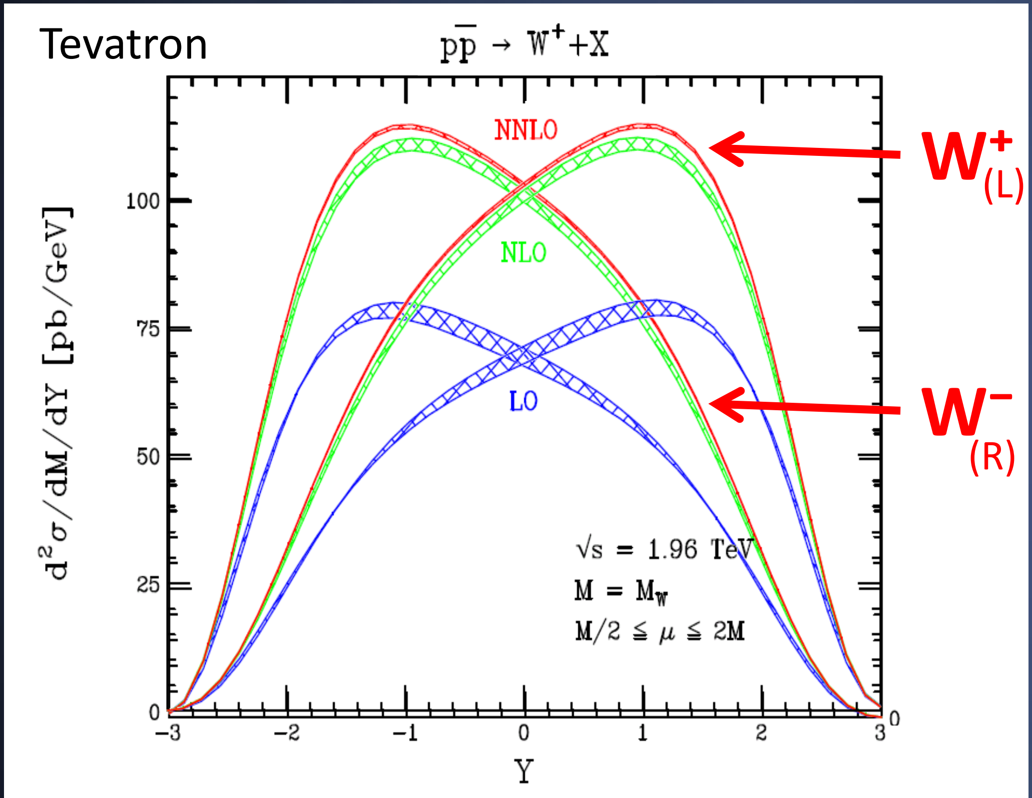
W-Polarization

- Known at large rapidity — see Ellis, Stirling, Webber; recent: Catani, Ferrera, Grazzini
- New at large transverse momentum — BlackHat 0907.1984



At large rapidity

Anastasiou, Dixon, Melnikov, Petriello;
CDF, Aaltonen et al., Phys.Rev.Lett.102(2009)

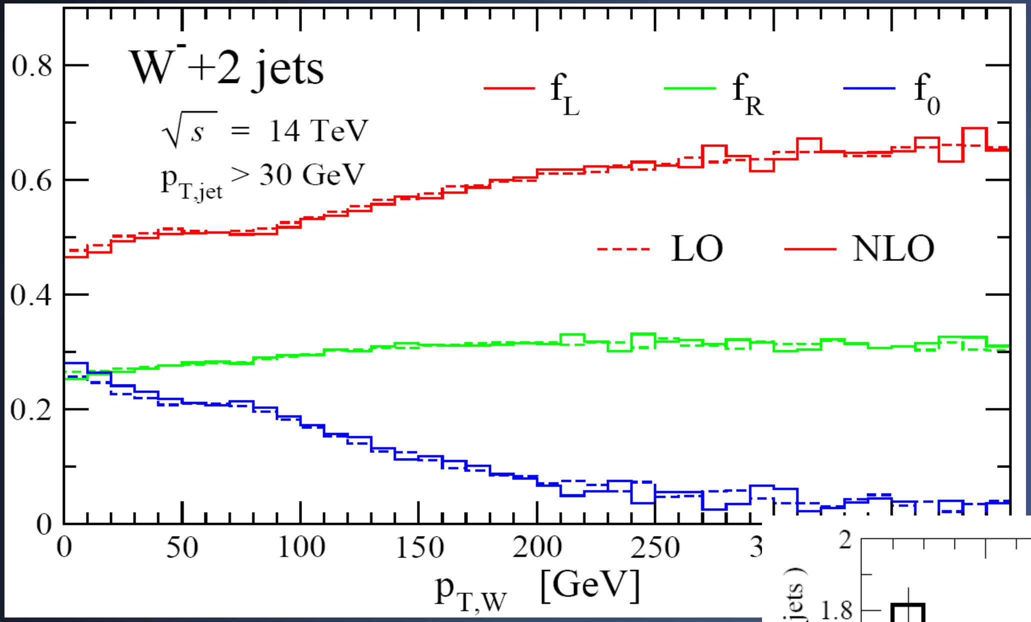


W charge asymmetry

Daughter lepton (charge) asymmetry diluted due to W-polarization. CDF, F.Abe et al., Phys.Rev.Lett.74 (1995)

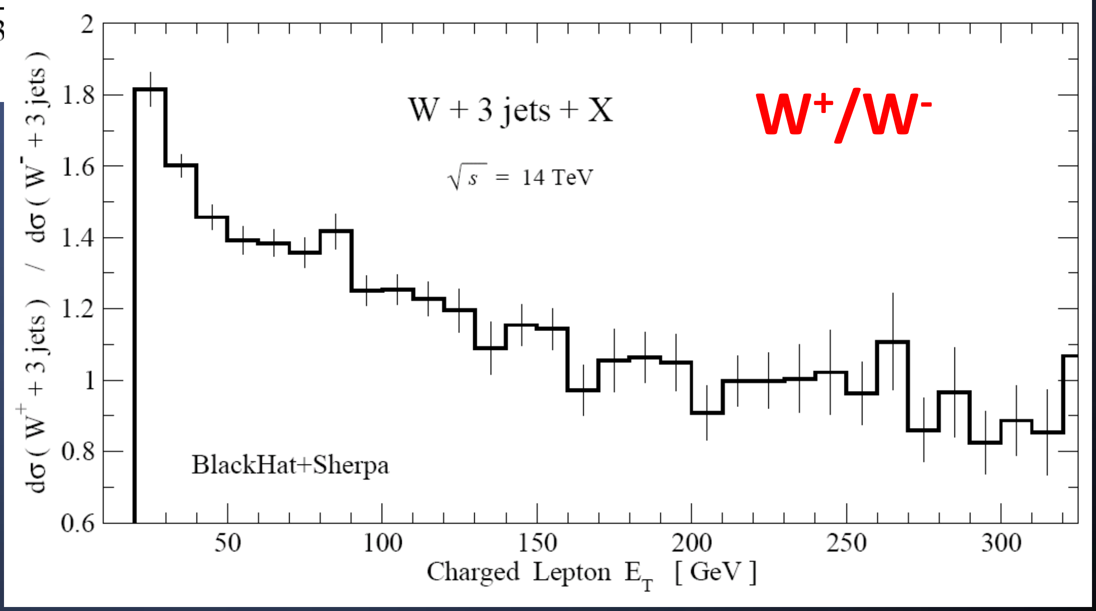
At large transverse momentum

BlackHat 0912.4927



Both W^- and W^+ left-handed at high P_T (similar plot for W^+)

BlackHat 0907.1984



Preferential

- forward e^-_L
- backward e^+_R

Physics application

- Polarization effect largely absent in W-production from decays of tops
- Can be used to separate Ws produced from light quarks and from $t\bar{t}$
- Under study by CMS

Towards W+4 jets

Simplify problem
- Start with leading color approximation

Check
- Check Matrix elements (UV&IR poles, collinear factorization, absence of spurious poles)
- Check numerical stability
- Check integration of real part

Integrate

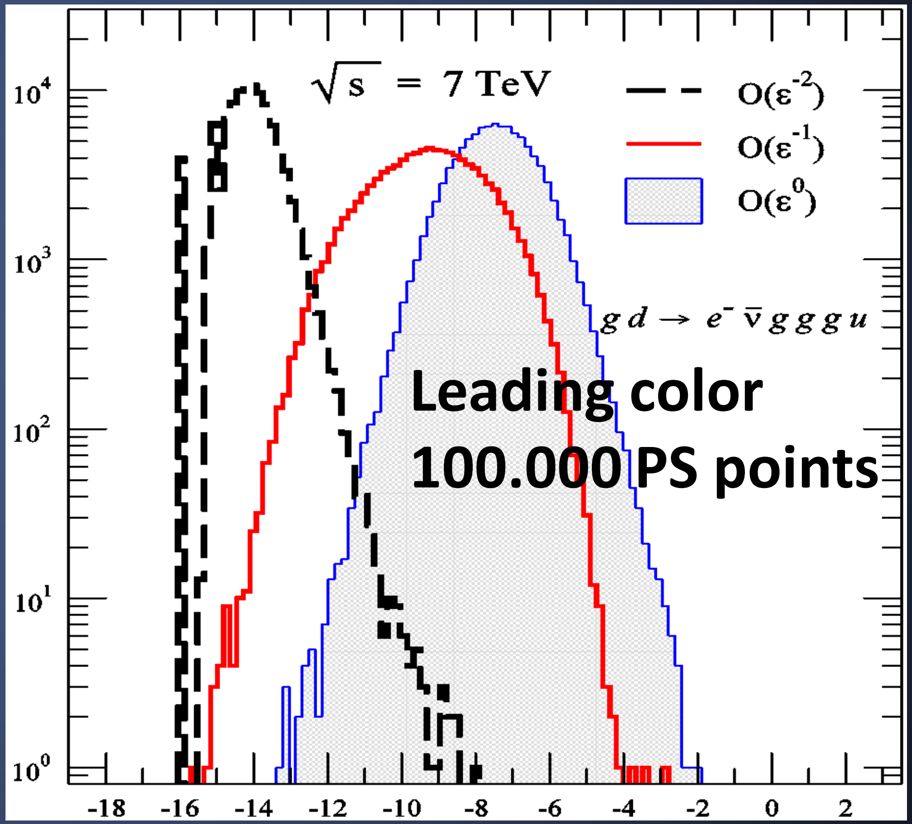
New: Stability plot W+4 jets

BlackHat 1005.3728

Ready to integrate

- Virtual contribution
- gd→e⁻ ν̄gggu
- Physical phase space

Shows BlackHat matrix elements are stable



$$\log_{10}\left(\frac{|d\sigma_V^{\mathrm{BH}} - d\sigma_V^{\mathrm{target}}|}{|d\sigma_V^{\mathrm{target}}|}\right)$$

Real contribution

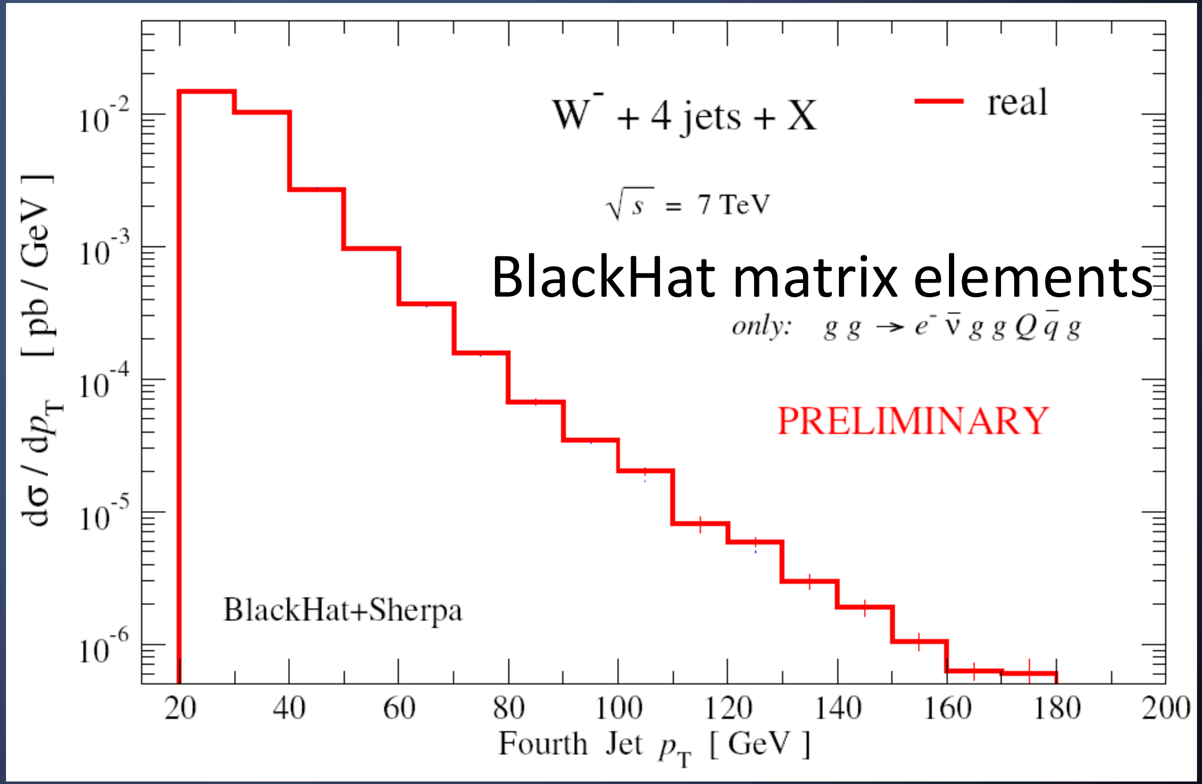
Proof of principle

BlackHat: presented at Loops & Legs 2010
1005.3728

$$\int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

BlackHat Sherpa

- control over integration accuracy
- numerical stability



200 million PS points

Summary

- W/Z + 3 jets at NLO with BlackHat + Sherpa
- Comparison of NLO W/Z+ 3 jets with Tevatron data
- New W-polarization effect at LHC
- Progress towards NLO results for W+4 jets

Future

- Public version of BlackHat
- W+4 jets
- Towards process automation
- Merging with parton shower
- NLO as the standard theory prediction at the LHC