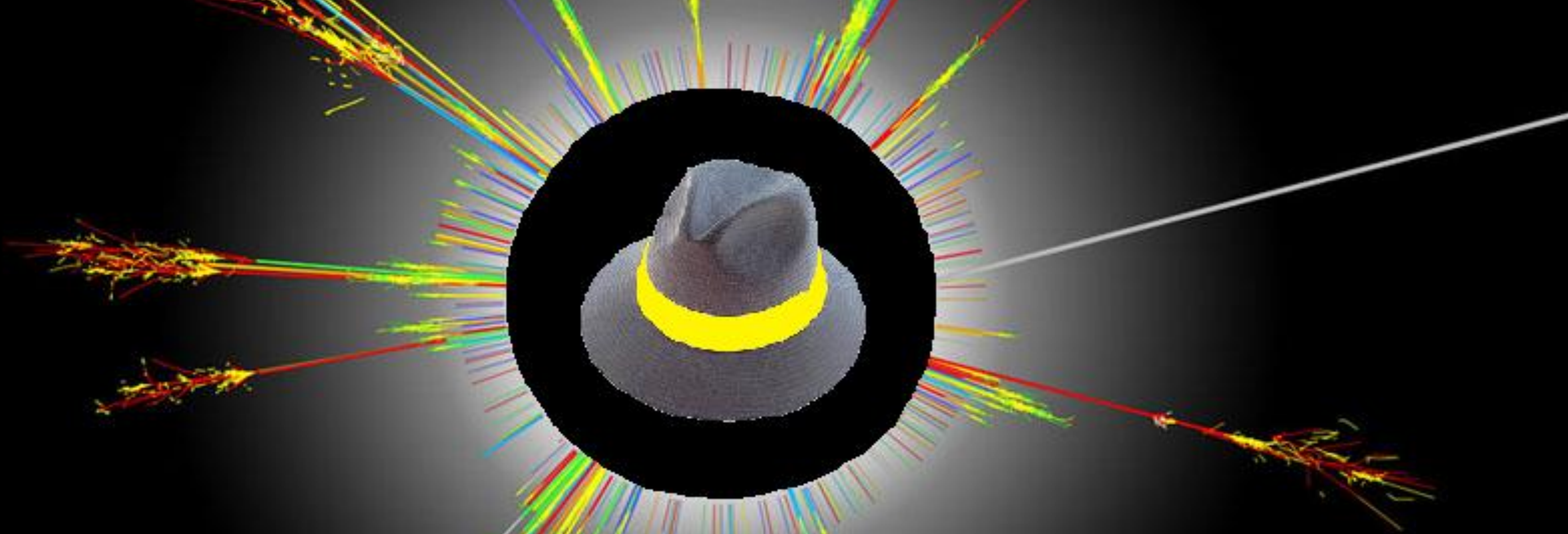
Electroweak Vector Boson Production in Association with Jets at the LHC



Lance Dixon (CERN & SLAC)

for the **BlackHat** collaboration
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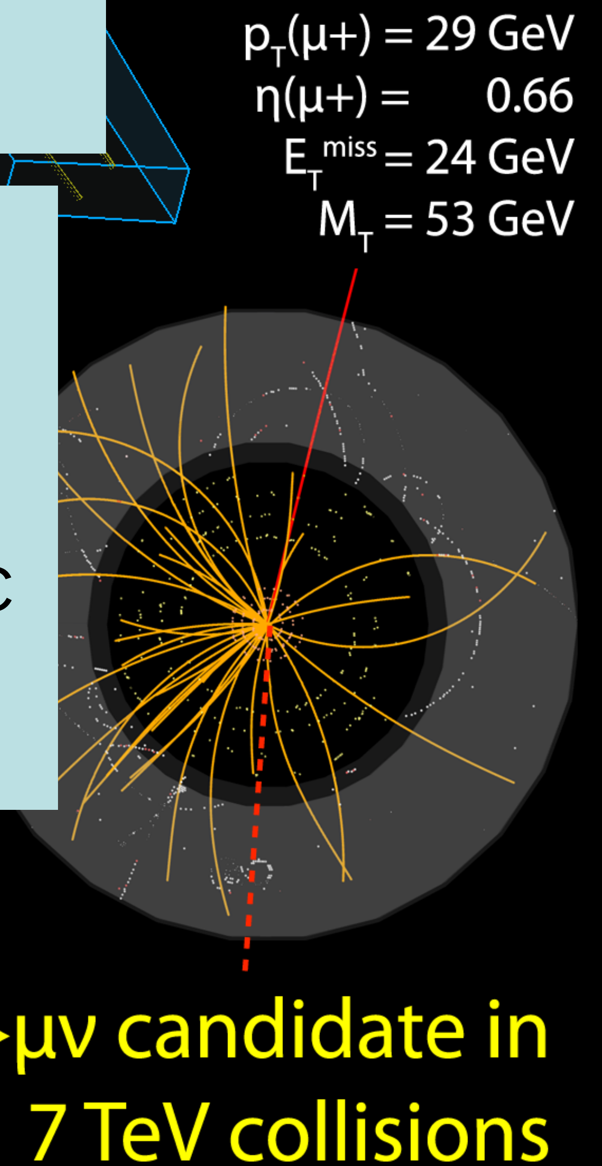
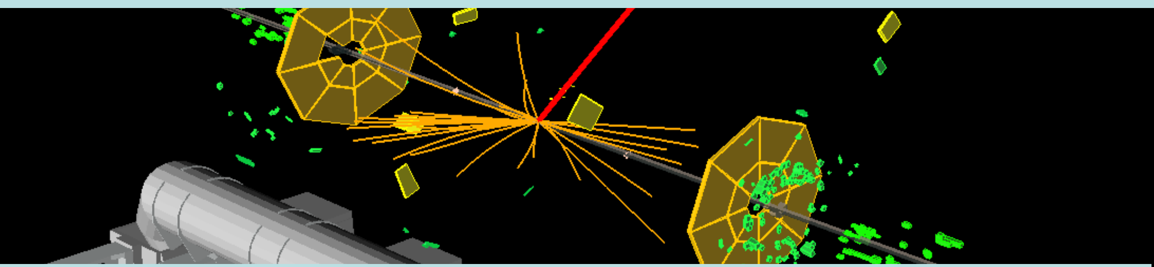
13 June 2011

Outline

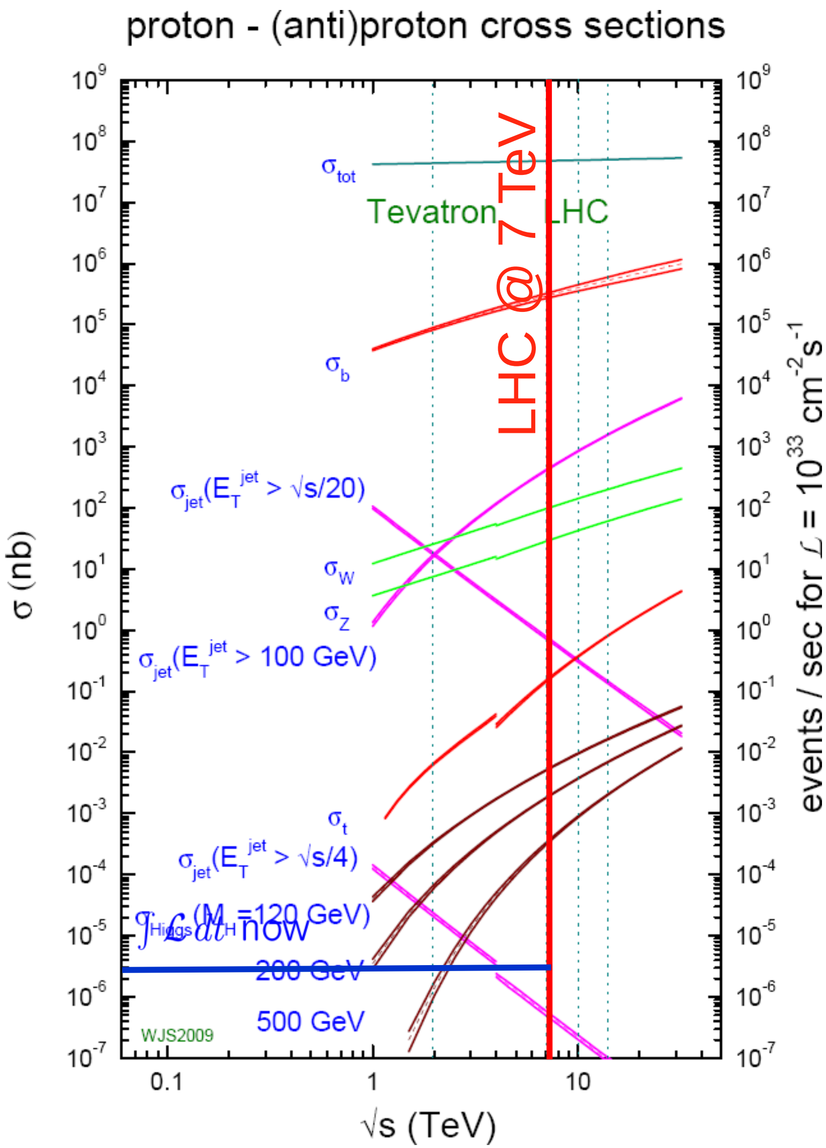
- Motivation
- *W* + 3 jets production at Tevatron & LHC at NLO in QCD
- Lessons about choice of scales
- NLO *W* + 4 jets
- Strong, stable *W* polarization effects at LHC
- NLO (γ + 2 jets) / (*Z* + 2 jets)
- Conclusions





Based on 0803.4180, 0902.2760, 0907.1984, 0912.4927,1004.1659, 1009.2338, 1103.5445, 1106.1423

LHC Data Dominated by Jets



new physics →

Jets come from quarks and gluons.

- q,g from decay of new particles?
- Or from old QCD?

- Every process shown also comes with one more jet at ~ 1/5 the rate
- Should understand Standard Model production of

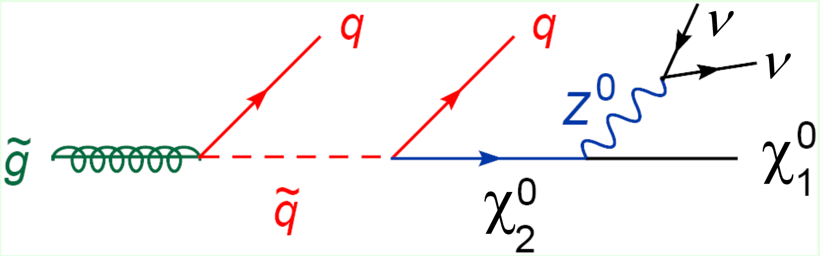
X + 1,2,3,… jets

where

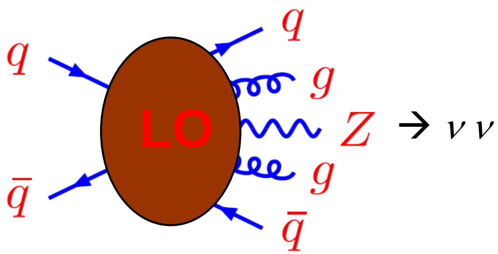
X = W, Z, tt, WW, H, …

Backgrounds to Supersymmetry at LHC

- **Decay from gluino to neutralino** (dark matter, escapes detector)



- **2 gluinos in event →**
  ***Signal:* missing energy (MET) + 4 jets**
- SM background*:* Z + 4 jets, Z → neutrinos

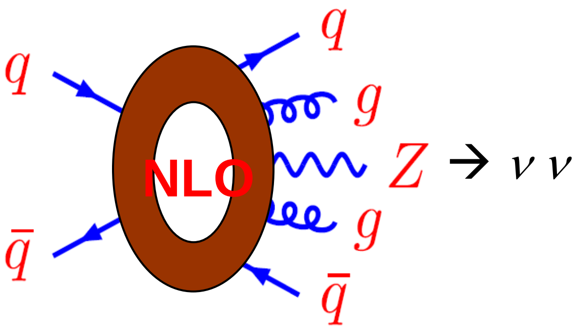


Current state of art for Z + 4 jets based on **LO approximation** → normalization still quite uncertain

- Motivates goal of

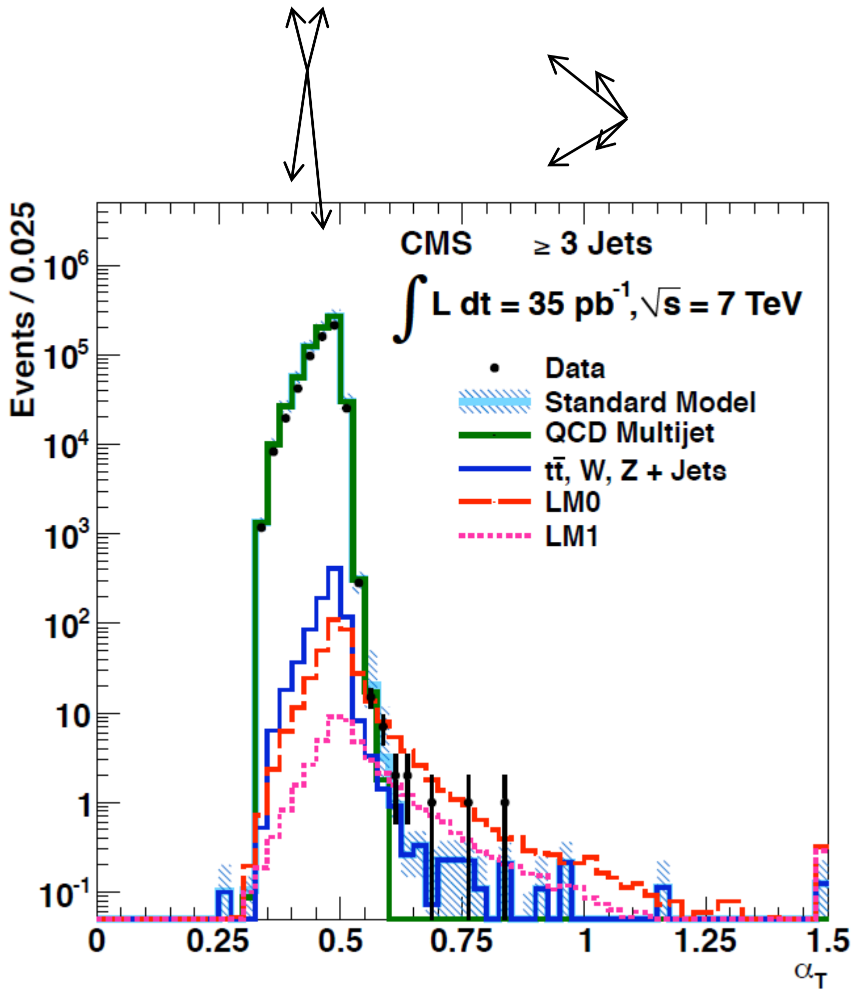
$$pp \to Z + 4 \text{ jets}$$

at NLO in QCD



MET + jets search at LHC

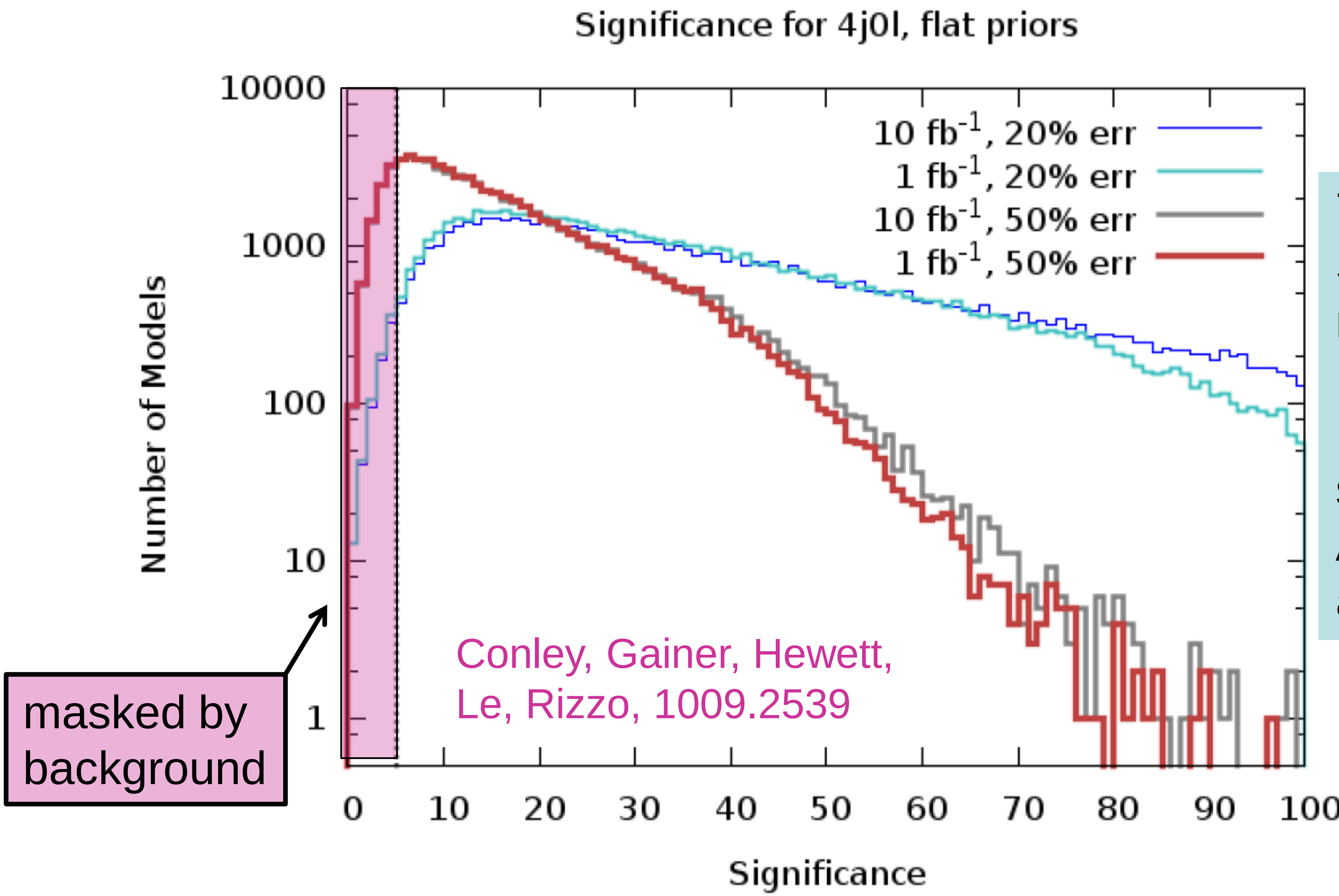
CMS, 1101.1628



Limits on CMSSM version of SUSY already exceed Tevatron's

α_T ~ alignment of MET with main jet axis

Reducing Background Systematics Improves SUSY Search Sensitivity



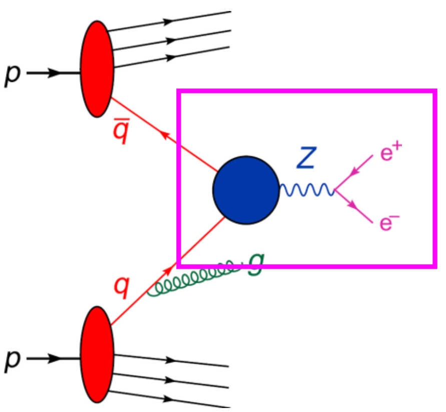
70,000 SUSY models

MET + 4 jet search, ATLAS-style analysis

QCD factorization & parton model

- Asymptotic freedom guarantees that at short distances (large transverse momenta), partons in the proton are almost free
- Sampled "one at a time" in hard collisions

→ QCD-improved parton model:



"suitable" final state

Parton distribution function: prob. of finding parton a in proton 1, carrying fraction x_1 of its momentum

factorization scale ("arbitrary")

$$\sigma^{pp\to X}(s;\alpha_s,\mu_R,\mu_F) = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2\, f_a(x_1,\alpha_s,\mu_F)\, f_b(x_2,\alpha_s,\mu_F) \times \hat{\sigma}^{ab\to X}(sx_1x_2;\alpha_s,\mu_R,\mu_F)$$

Partonic cross section, computable in perturbative QCD

partonic CM energy^2

renormalization scale ("arbitrary")

Short-Distance Cross Section in Perturbation Theory

$$\hat{\sigma}(\alpha_s, \mu_F, \mu_R) \;=\; [\alpha_s(\mu_R)]^{n_\alpha} \left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi} \hat{\sigma}^{(1)}(\mu_F, \mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F, \mu_R) + \cdots \right]$$

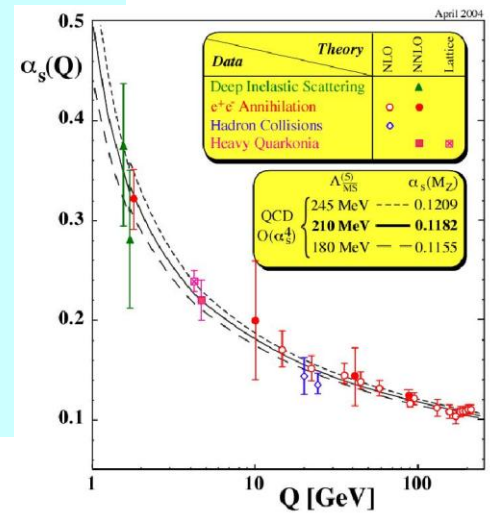
LO NLO NNLO

Problem: Leading-order (LO) predictions only qualitative due to **poor convergence** of expansion in $\alpha_s(\mu)$

- Traditional to estimate "error" bands by varying combined renormalization and factorization scale

$$\mu_R = \mu_F = \mu$$

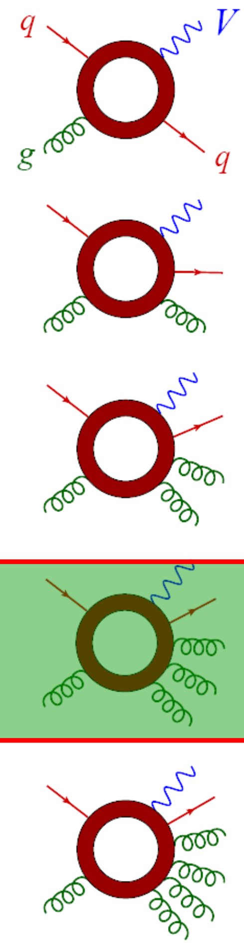
from ½ to 2 times a "typical scale"



Loops get difficult quickly!

For ***pp* → *W* + *n* jets** (just the cases with most gluons)

# of jets	# 1-loop Feynman diagrams
1	11
2	110
3	1,253
4	16,648
5	256,265

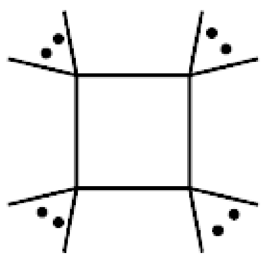
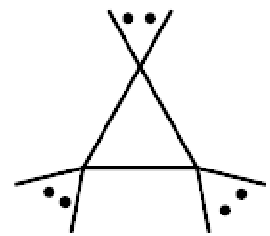


On-shell methods, exploiting **analyticity**, can be more efficient, especially for multi-gluon + quark processes

One-Loop Amplitude Decomposition

When all external momenta are in *D=4*, loop momenta in *D=4-2ε* (dimensional regularization), one can write: BDDK (1994)

coefficients determined algebraically
from products of trees using (generalized) unitarity

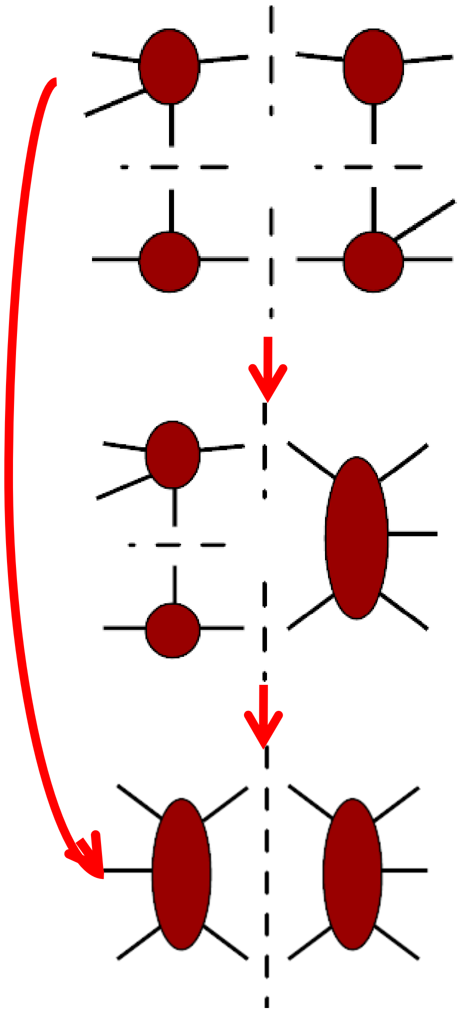
$A^{1-\mathrm{loop}} = \sum_i d_i$  $+ \sum_i c_i$  $+ \sum_i b_i$ 

$+ R + \mathcal{O}(\epsilon)$

rational part

known **scalar** one-loop integrals,
same for all amplitudes

Amplitude determined hierarchically



Britto, Cachazo, Feng, hep-th/0412103

Each box coefficient comes uniquely from 1 “quadruple cut”

Ossola, Papadopolous, Pittau, hep-ph/0609007;
Mastrolia, hep-th/0611091; Forde, 0704.1835;
Ellis, Giele, Kunszt, 0708.2398; Berger et al., 0803.4180;…

Each triangle coefficient from 1 triple cut, but “contaminated” by boxes

Each bubble coefficient from 1 double cut, removing contamination by boxes and triangles

Rational part depends on all of above, whether from D-dimensional unitarity, or rational recursion relations

Automated On-Shell Programs at One Loop

Blackhat: Berger, Bern, LD, Febres Cordero, Forde, T. Gleisberg, H. Ita, D. Kosower, D. Maître 0803.4180, 0808.0941, 0907.1984, 1004.1659, 1009.2338
+ **Sherpa** → NLO W,Z + 3,4 jets

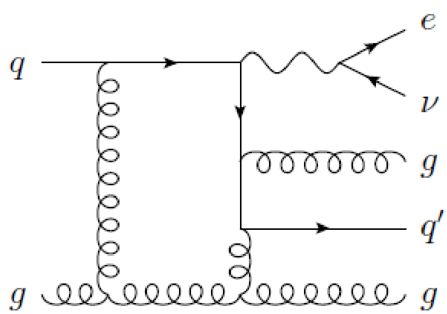
CutTools: Ossola, Papadopolous, Pittau, 0711.3596
NLO *WWW, WWZ, ...* Binoth+OPP, 0804.0350
NLO $t\bar{t}b\bar{b}$, $t\bar{t}$ + 2 jets, …
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek, 0907.4723; 1002.4009
MadLoop: Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau 1103.0621

Rocket: Giele, Zanderighi, 0805.2152
Ellis, Giele, Kunszt, Melnikov, Zanderighi, 0810.2762
NLO W + 3 jets (large N_c) Ellis, Melnikov, Zanderighi, 0901.4101, 0906.1445
$W^+W^\pm$ + 2 jets Melia, Melnikov, Rontsch, Zanderighi, 1007.5313, 1104.2327

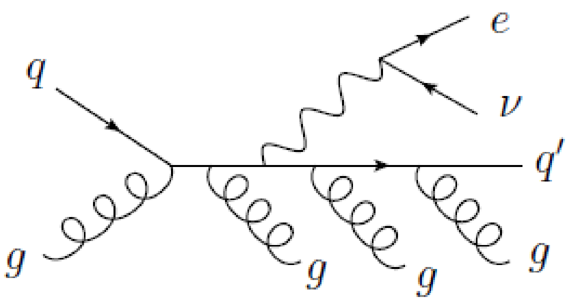
SAMURAI: Mastrolia, Ossola, Reiter, Tramontano, 1006.0710

NGluon: Badger, Biedermann, Uwer, 1011.2900

Real emission terms



Infrared singularities cancel



- General subtraction methods for integrating real-emission contributions developed in mid-1990s

Frixione, Kunszt, Signer, hep-ph/9512328;
Catani, Seymour, hep-ph/9602277, hep-ph/9605323

- Recently automated by several groups

Gleisberg, Krauss, 0709.2881;
Seymour, Tevlin, 0803.2231;
Hasegawa, Moch, Uwer, 0807.3701;
Frederix, Gehrmann, Greiner, 0808.2128;
Czakon, Papadopoulos, Worek, 0905.0883;
Frederix, Frixione, Maltoni, Stelzer, 0908.4272

Disclaimer

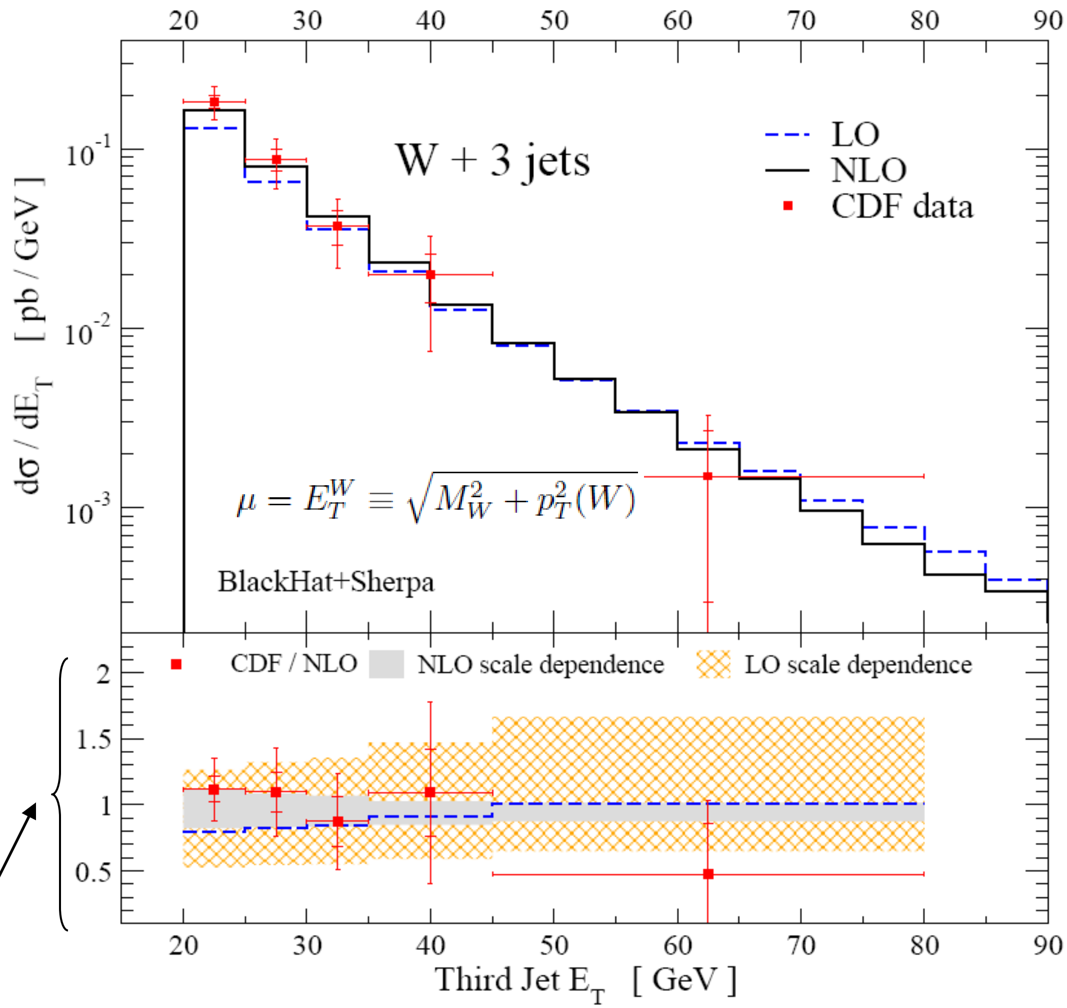
- Results shown today are NLO but fixed-order, parton level: no parton shower, no hadronization, no underlying event.
- Methods for matching NLO parton-level results to parton showers, maintaining NLO accuracy:
  - **MC@NLO** Frixione, Webber (2002), ...
  - **POWHEG** Nason (2004); Frixione, Nason, Oleari (2007)
  - **None implemented for such complex final states, as yet**
- Experimentalists usually use LO-matched shower simulations (ALPGEN/Pythia, MadGraph/Pythia, Sherpa, ...)
- NLO parton-level predictions give best overall normalizations (unless NNLO available!), and some "shapes", away from shower-dominated regions.
- Ratios considerably less sensitive to shower + nonperturbative effects:
- *W* polarization fractions, *W/Z/*γ + jets ratios, ...

W + 3 jets at NLO

0902.2760, 0907.1984

- Background to SUSY searches in the "Jets + MET" channel, when the charged lepton in $W \rightarrow l\ \nu_l$ is lost
- Also closely related to Z + 3 jets, another SUSY background when $Z \rightarrow \nu\ \nu$
- Similar to top-quark pair production in semi-leptonic W decay channel, $t\,\bar{t} \rightarrow l\ \nu_l + 4\ \text{jets}$
- **Many different kinematic configurations** can appear in final state – have to be careful to choose renormalization/factorization scale μ correctly to avoid pathologies!

NLO W + 3 jets at Tevatron



CDF 0711.4044

same cuts as CDF

$$E_T^{\rm jet} > 20\,{\rm GeV}\,, \qquad |\eta^{\rm jet}| < 2$$
$$E_T^e > 20\,{\rm GeV}\,, \qquad |\eta^e| < 1.1\,,$$
$$\not{E}_T > 30\,{\rm GeV}\,, \qquad M_T^W > 20\,{\rm GeV}$$
$$M_T^W = \sqrt{2E_T^e E_T^\nu(1-\cos(\Delta\phi_{e\nu}))}$$

Except: we use SISCone ($R = 0.4$); CDF used IR unsafe JETCLU

- Much smaller Uncertainties than at LO.
- Agrees well with data; also with new data from D0 1106.1457

uncertainty bands from varying ren./fact. scale from $\mu/2 \rightarrow 2\mu$

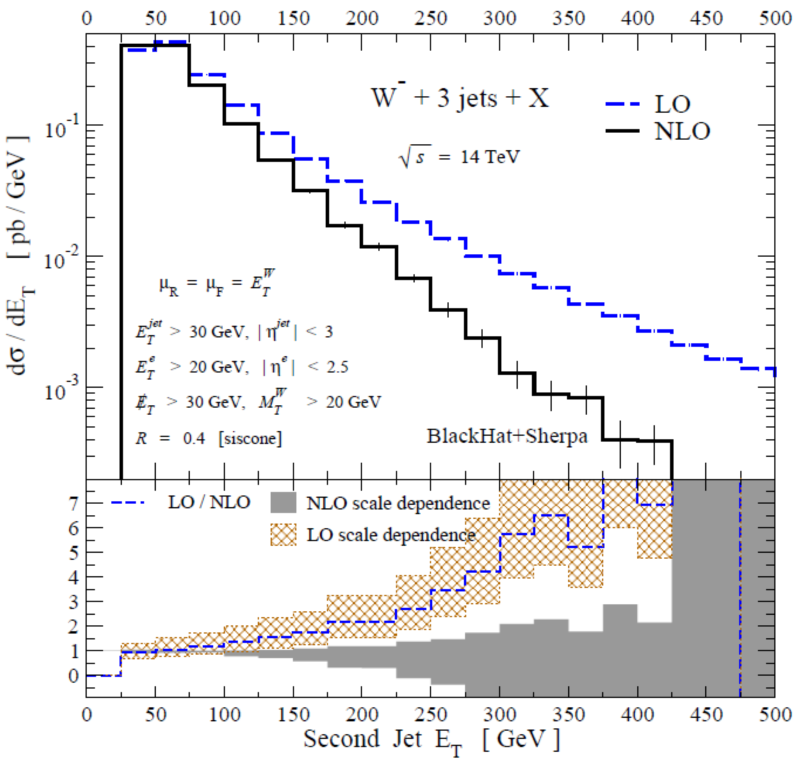
NLO W + 3 jets at LHC

New dynamics at LHC
→ Importance of choosing a reasonable scale

- LHC → much greater dynamic range.
- Events with $E_T^{\text{jet}} >> M_W$.
- Scale we used at the Tevatron,

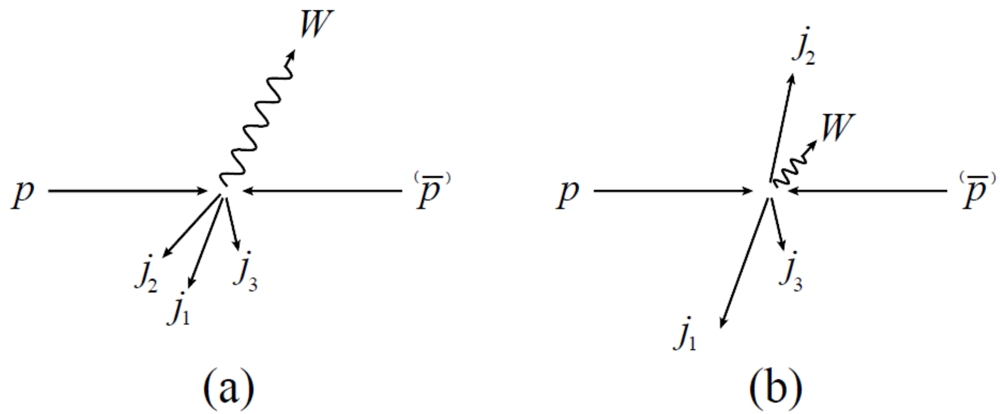
$$\mu = E_T^W \equiv \sqrt{M_W^2 + p_T^2(W)}$$

also used in several other LO studies, is a really bad choice
– NLO cross section can even dive negative! →



Powerful Jets, Wimpy *W*s

What's going on?
Consider these
2 configurations:



• If (a) dominates, then $\mu = E_T^W \equiv \sqrt{M_W^2 + p_T^2(W)}$ is OK

• **But (b) usually dominates, due to soft W emission.**
Then scale ***E_T^W*** **is way too low**.

• Looking at large E_T for the 2nd jet **forces** configuration (b).

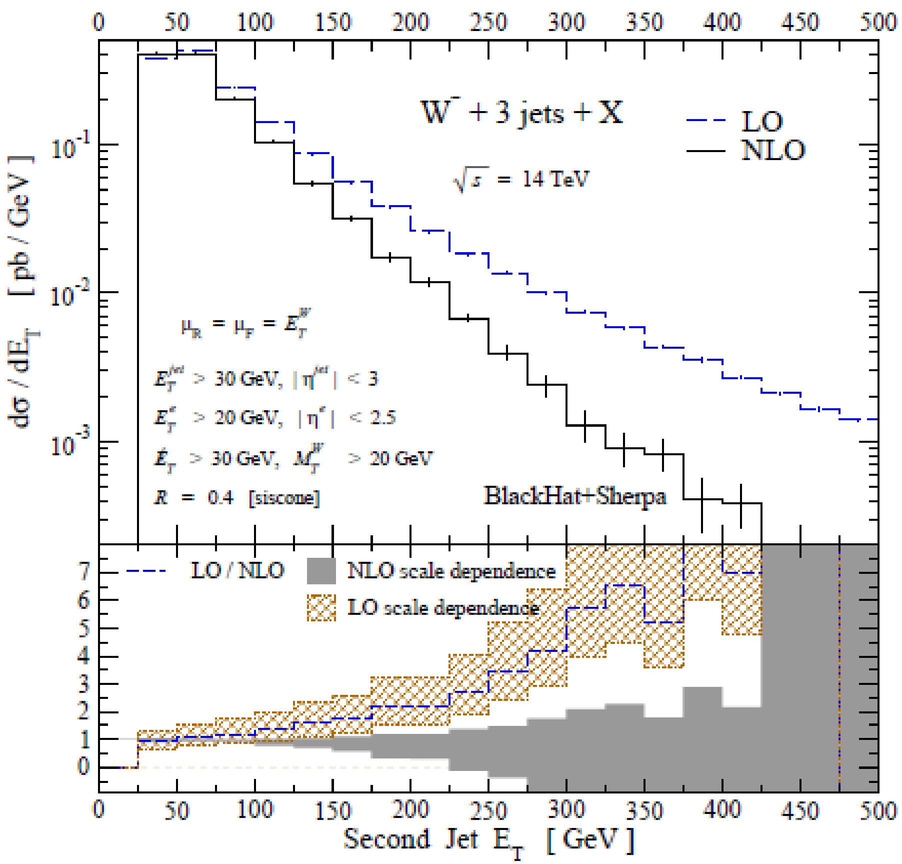
• **Total (partonic) transverse energy** is a **better variable**; gets large properly for both (a) and (b)

$$\hat{H}_T = \sum_p E_T^p + E_T^e + E_T^\nu$$

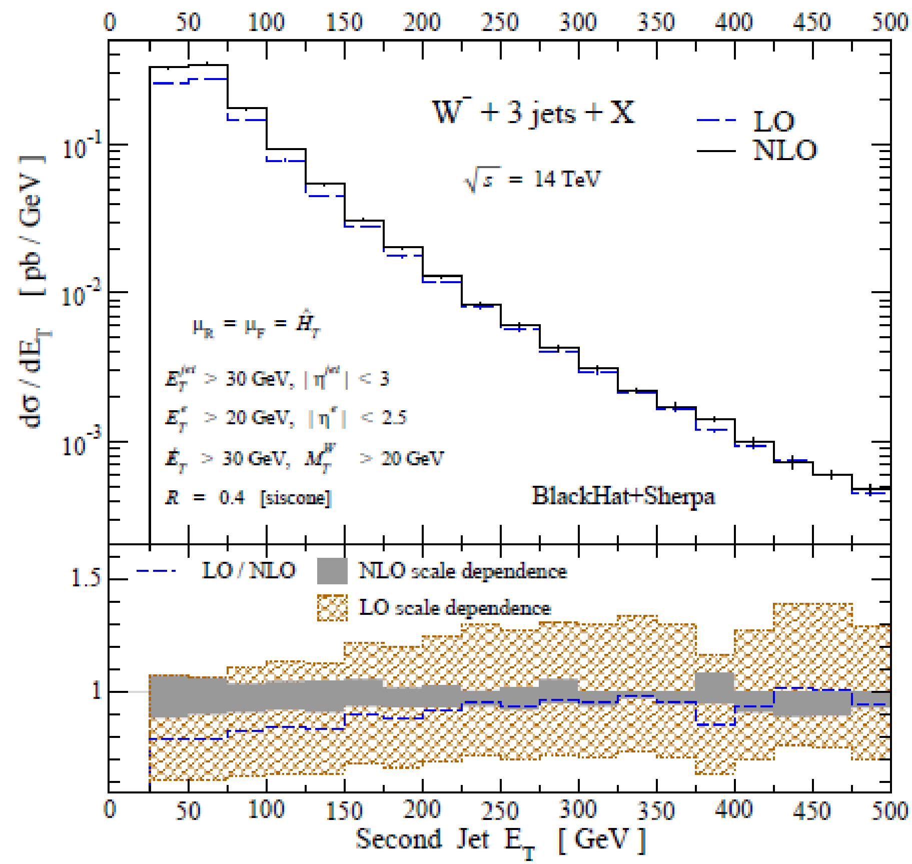
• Many other "reasonable scales", including invariant mass of jets

Bauer, Lange 0905.4739

Compare the Two Scale Choices



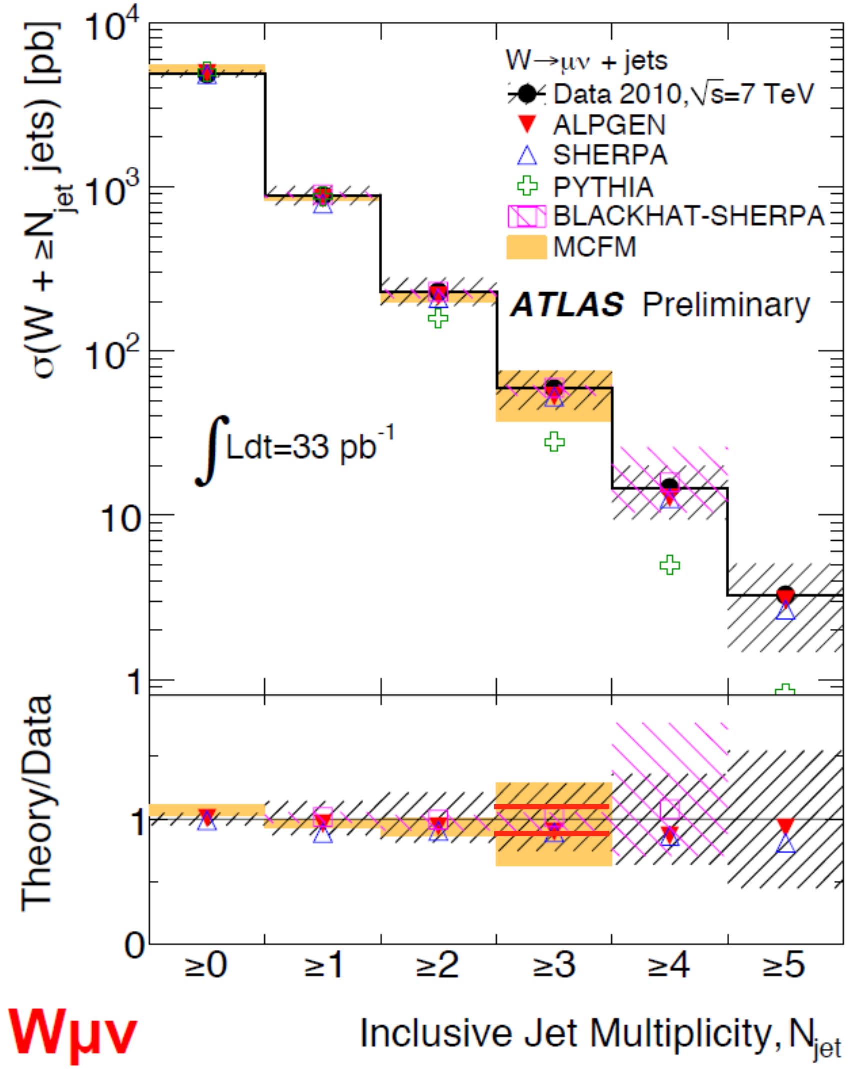
$\mu = E_T^W$ very poor



$\mu = \hat{H}_T$ excellent!

– LO/NLO quite flat, and also for many other observables

NLO *W* + 3 jets vs. new ATLAS data



Jet and Lepton Cuts:

anti-k_T , R = 0.4

p_T^{jets} > 20 GeV, $|y^{jets}|$ < 2.8

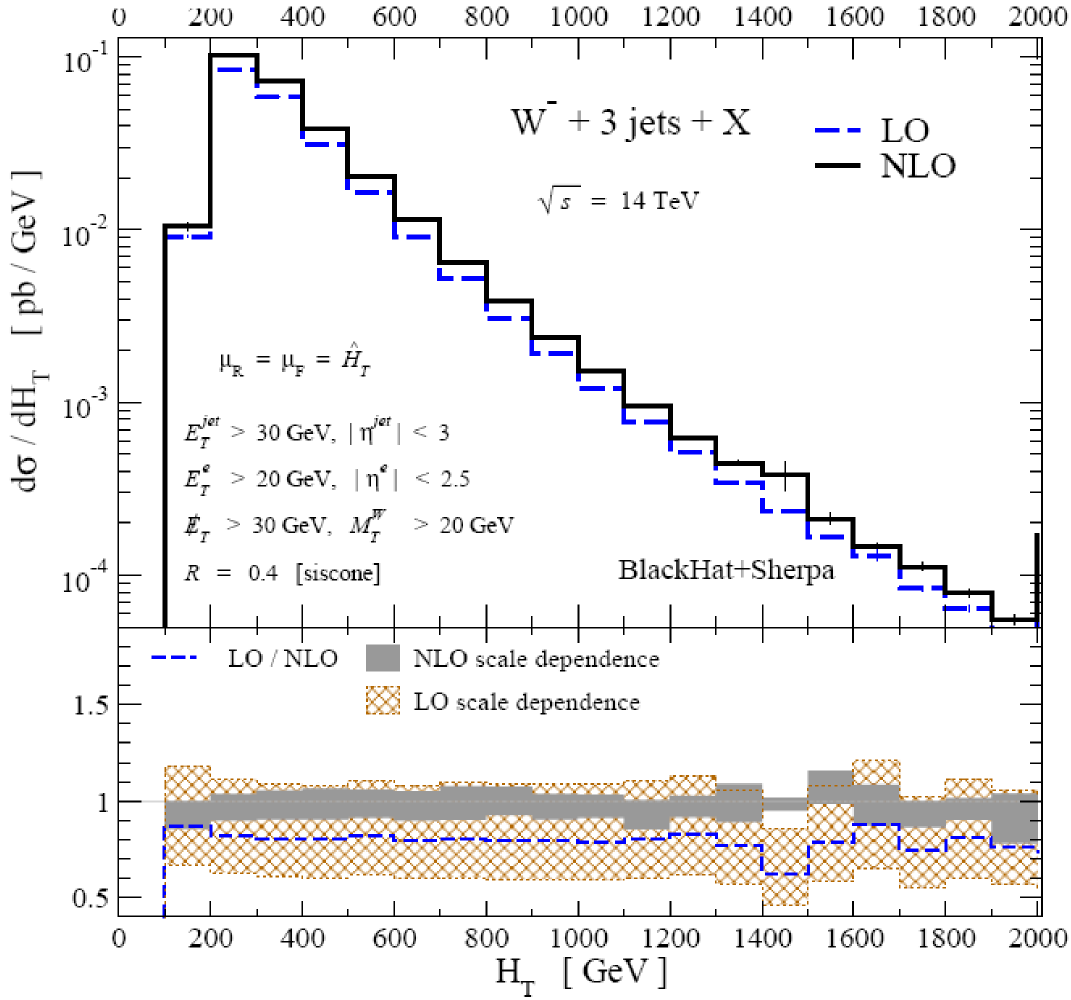
p_T^{μ} > 20 GeV, $|\eta^{\mu}|$ < 2.4

MET > 25 GeV, M_W^T > 40 GeV

Total Transverse Energy H_T at LHC

$$H_T = \sum_j E_{T,j}^{\rm jet} + E_T^e + E_T^\nu$$

often used in supersymmetry searches

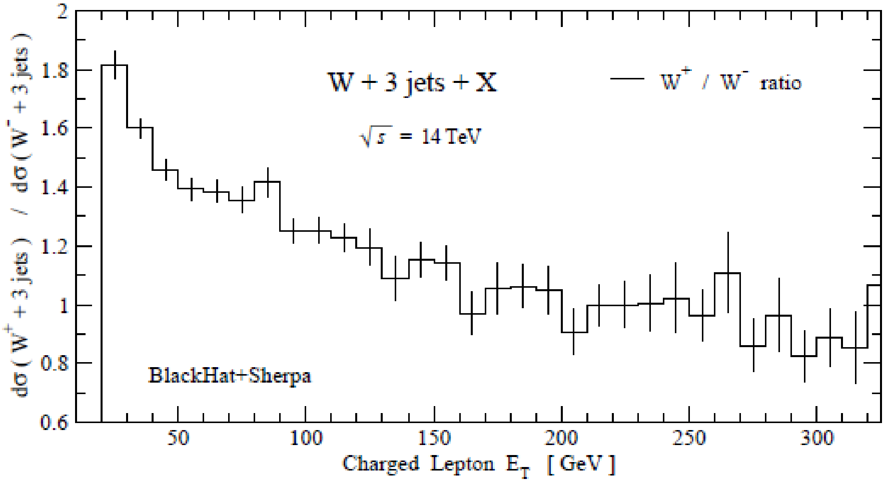


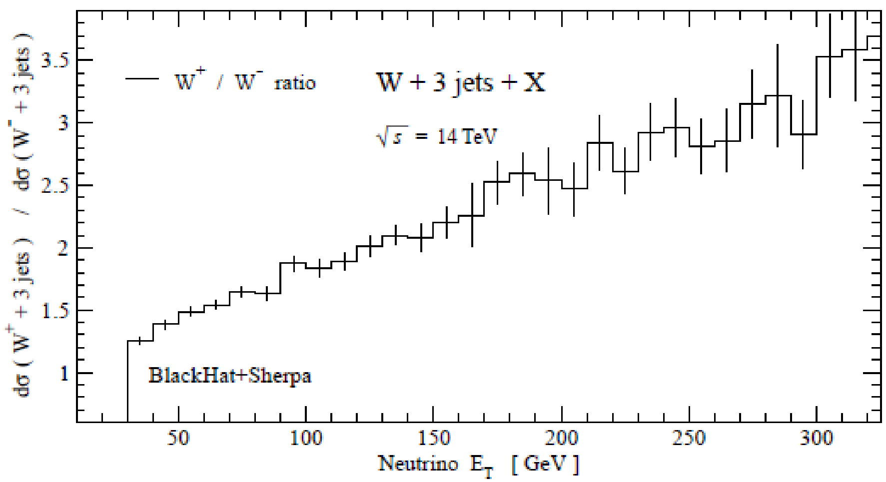
0907.1984

flat LO/NLO ratio due to good choice of scale $\mu = H_T$

Leptonic E_T in *W* + 3 jets at LHC

0907.1984

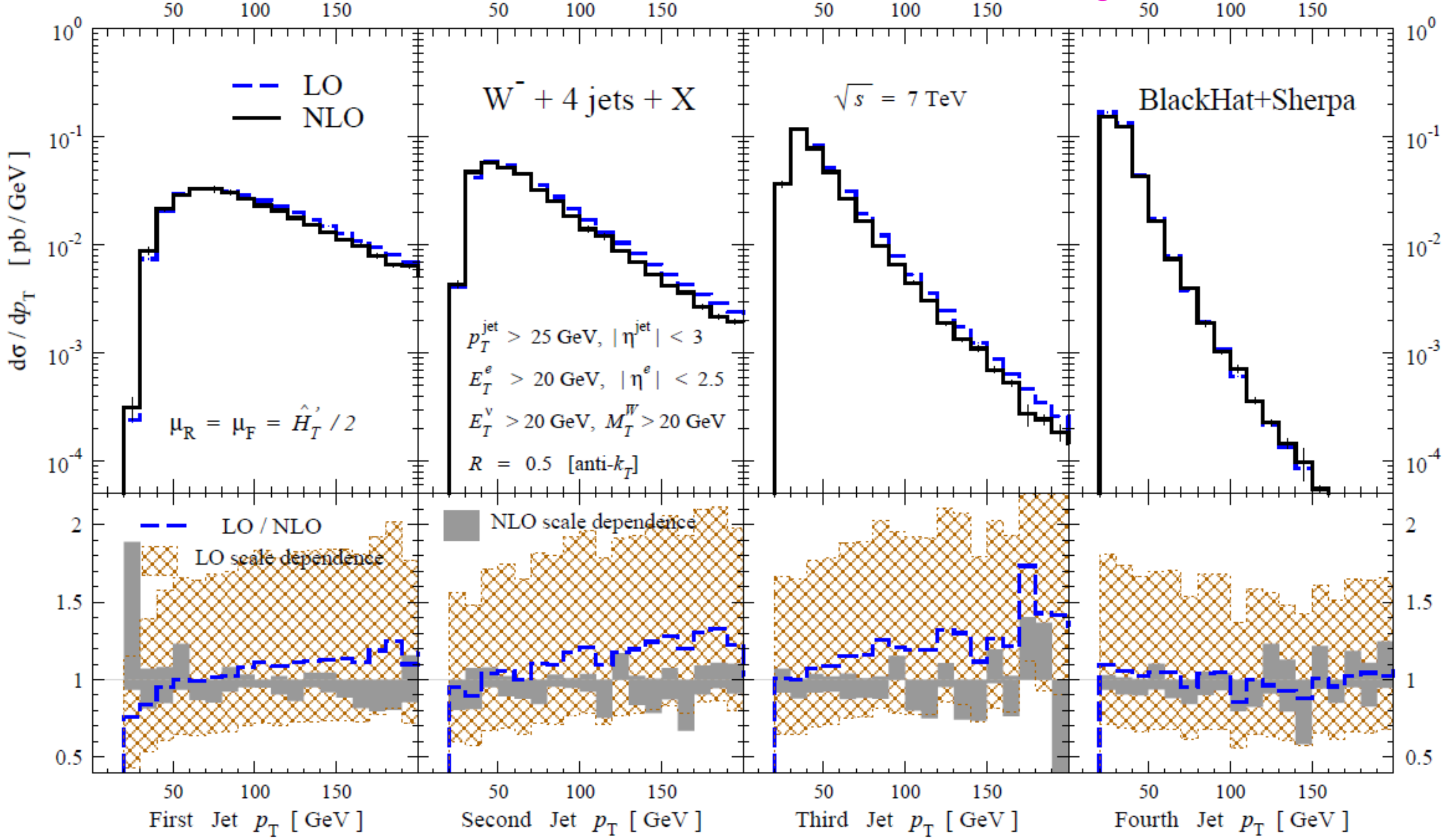




W^+/W^- transverse lepton ratios trace a remarkably large and stable left-handed *W* polarization at large $p_T(W)$
– independent of number of jets
– will be useful to separate *W* + n jets from top, maybe also from new physics

NLO $pp \rightarrow W + 4$ jets

Berger et al., 1009.2338



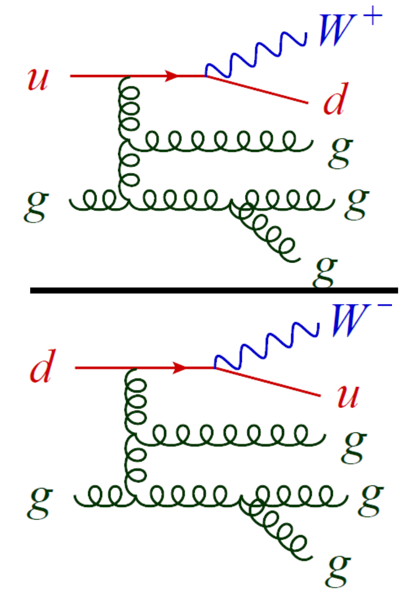
First hadron collider process known at NLO with 5 objects in final state. Also important SUSY background.

Simple yet robust ratio: W^+ to W^-

Kom, Stirling, 1004.3404.

$$R^{\pm}(n) \equiv \frac{\sigma(W^+ + n \text{ jets})}{\sigma(W^- + n \text{ jets})}$$

n	QQ	Qg	gg
0	100	0	0
1	18	82	0
2	21	73	6
3	23	70	7
4	25	67	8



- Very small experimental systematics
- NLO QCD corrections quite small, 2% or less
- → Intrinsic theoretical uncertainty very small.
- PDF uncertainty also ~1-2%. Driven by PDF ratio

  $u(x)/d(x)$

  in well-measured valence region of moderate x.
- Sensitive to new physics (or Higgs, or top quark pairs) that produces $W^{\pm}$ symmetrically
- Fraction of new physics in sample is:

$$f_{\text{NP}} = \frac{2(R^{\pm}_{\text{SM}} - R^{\pm}_{\text{exp.}})}{(R^{\pm}_{\text{SM}} + 1)(R^{\pm}_{\text{exp.}} - 1)}$$

W^+ to W^- ratio at NLO

no. jets	W^- LO	W^- NLO	W^+/W^- LO	W^+/W^- NLO
0	$1614.0(0.5)^{+208.5}_{-235.2}$	$2077(2)^{+40}_{-31}$	1.656(0.001)	1.580(0.004)
1	$264.4(0.2)^{+22.6}_{-21.4}$	$331(1)^{+15}_{-12}$	1.507(0.002)	1.498(0.009)
2	$73.14(0.09)^{+20.81}_{-14.92}$	$78.1(0.5)^{+1.5}_{-4.1}$	1.596(0.003)	1.57(0.02)
3	$17.22(0.03)^{+8.07}_{-4.95}$	$16.9(0.1)^{+0.2}_{-1.3}$	1.694(0.005)	1.66(0.02)
4	$3.81(0.01)^{+2.44}_{-1.34}$	$3.55(0.04)^{+0.08}_{-0.30}$	1.812(0.001)	1.73(0.03)

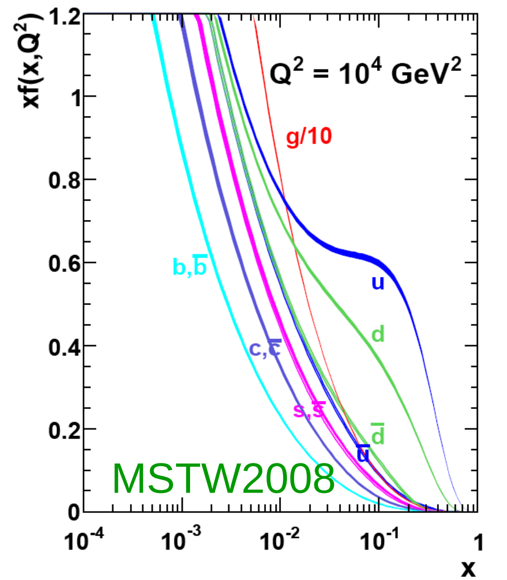
$p_T^{\rm jet} > 25$ GeV, $|\eta^{\rm jet}| < 3$

$E_T^e > 20$ GeV, $|\eta^e| < 2.5$

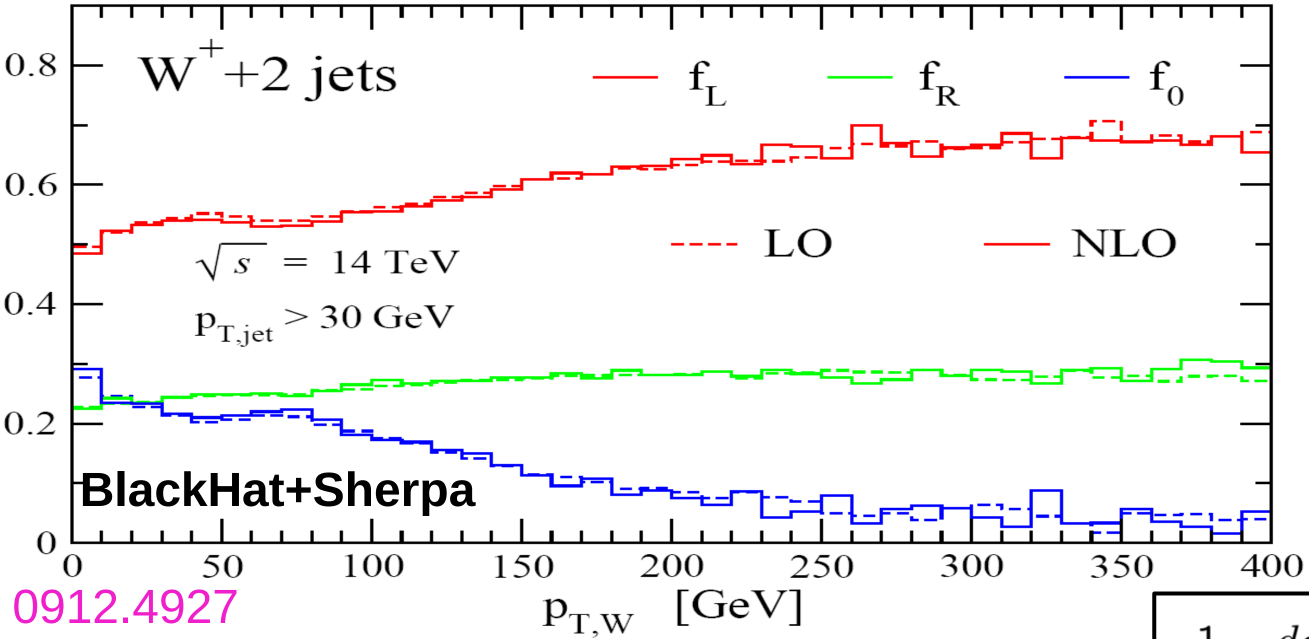
$E_T^\nu > 20$ GeV, $M_T^W > 20$ GeV

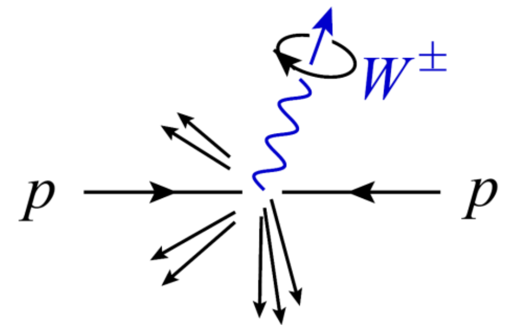
$R = 0.5$ [anti-k_T]

- Huge scale dependence at LO cancels in ratio
- Small corrections from LO → NLO
- Increases with n due to increasing x



Another stable ratio:
W polarization at nonzero p_T





Helicity frame

0912.4927

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}(1 \mp \cos\theta^*)^2 f_L + \frac{3}{8}(1 \pm \cos\theta^*)^2 f_R + \frac{3}{4}\sin^2\theta^* f_0$$

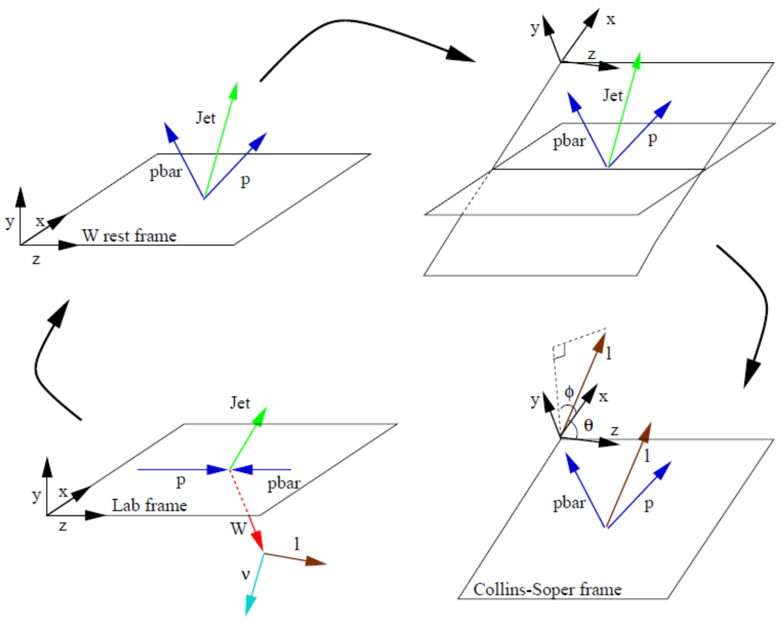
- **Strong left-handed polarization for W^+ and W^-**
- Increases slowly with W boson p_T and with number of jets, due to increasing parton x
- Also stable against QCD corrections

Transverse spin can be confusing

talk by W. Vogelsang

Previous studies of *W* polarization at nonzero p_T used Collins-Soper frame

Collins, Soper PRD16, 2219 (1977); Lam, Tung, PRD21, 2712 (1980);
Mirkes NPB387, 3 (1992); Mirkes, Ohnemus, PRD50, 5692 (1994), PRD51, 4891 (1995);
Hagiwara, Hikasa, Kai, PRL52, 1076 (1984);
CDF Run I, PRD73, 052002 (2005); CDF Run II, 1103.5699 (Z)

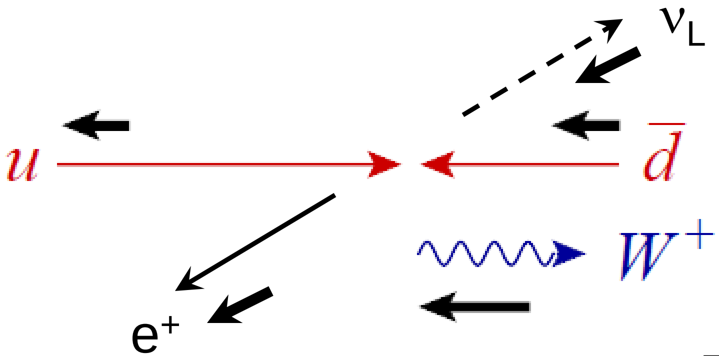


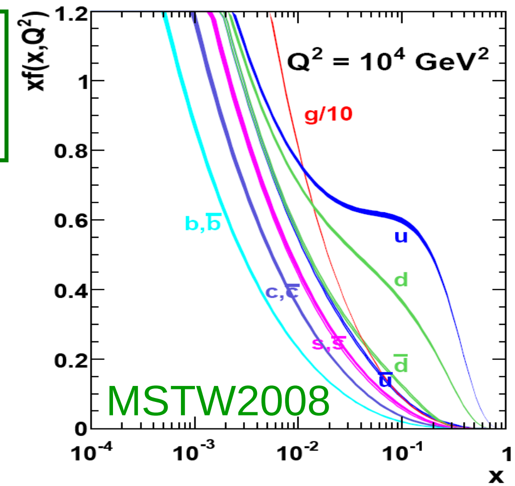
$$
\begin{aligned}
\frac{d\sigma}{d(p_T^W)^2 dy\, d\cos\theta\, d\phi} &= \frac{3}{16\pi}\frac{d\sigma^u}{d(p_T^W)^2 dy}[(1+\cos^2\theta) \\
&+ \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi \\
&+ \frac{1}{2}A_2 \sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \\
&+ A_4\cos\theta + A_5\sin^2\theta\sin 2\phi \\
&+ A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi]
\end{aligned}
$$

Advantage: Some coefficients can be measured with no ambiguity
Disadvantage: Large left-handed polarization in helicity frame obscured

W polarization along beamline (inclusive)

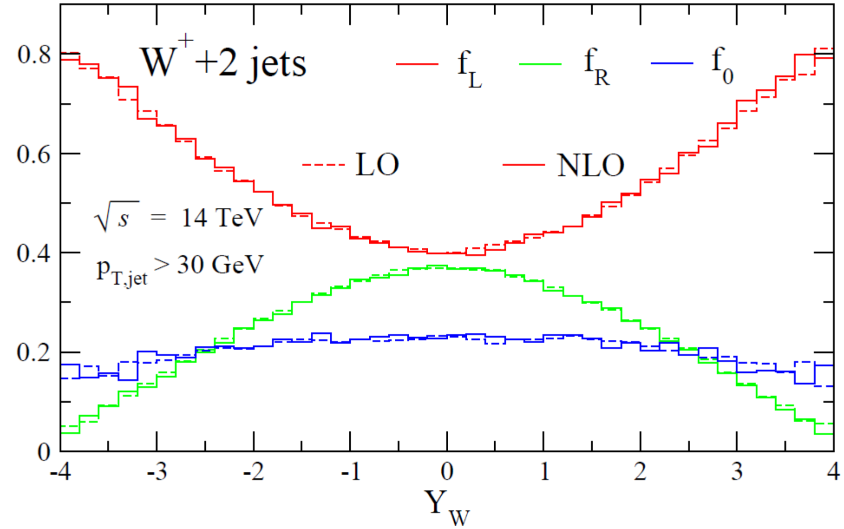
W bosons are left-handed by $SU(2)_L$,
plus stiffness of valence quark pdfs vs. anti-quarks





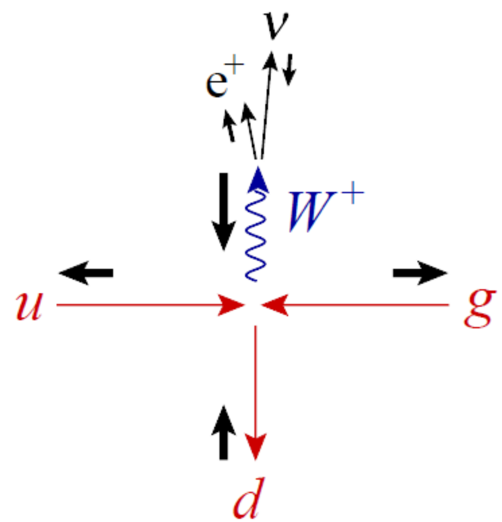
Left-handed W^+ decay puts ν_L forward, e^+_R backward

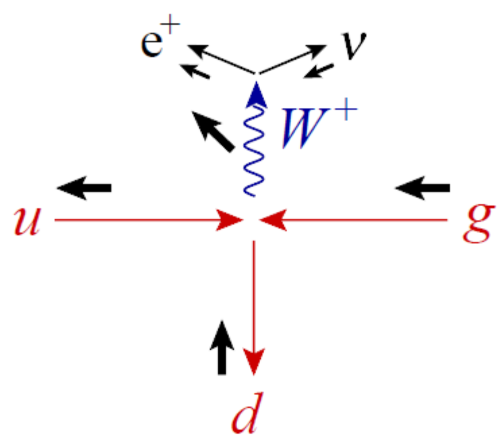
Left-handed W^- decay puts e^-_L forward, $\bar{\nu}_R$ backward

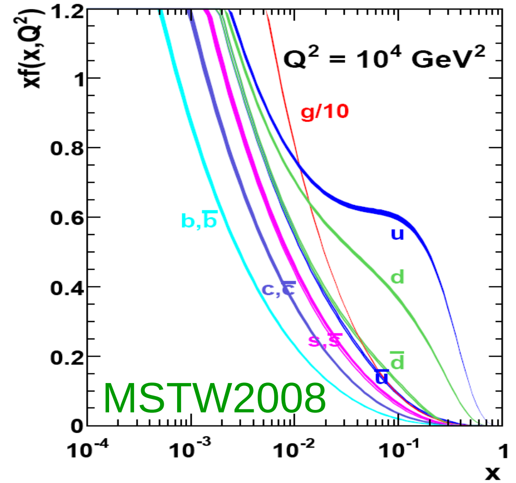


Origin of *W* polarization at LHC in LO *W* + 1 jet

ug → W^+d dominates due to pdfs at a pp machine.
Only 2 relevant helicity configurations:







1103.5445

$$A^{\text{tree}} \propto \frac{\langle d\,\nu\rangle^2}{\langle u\,g\rangle\langle g\,d\rangle}$$

$$d\sigma \propto (k_d \cdot k_\nu)^2$$

$$A^{\text{tree}} \propto \frac{[u\,e]^2}{[u\,g][g\,d]}$$

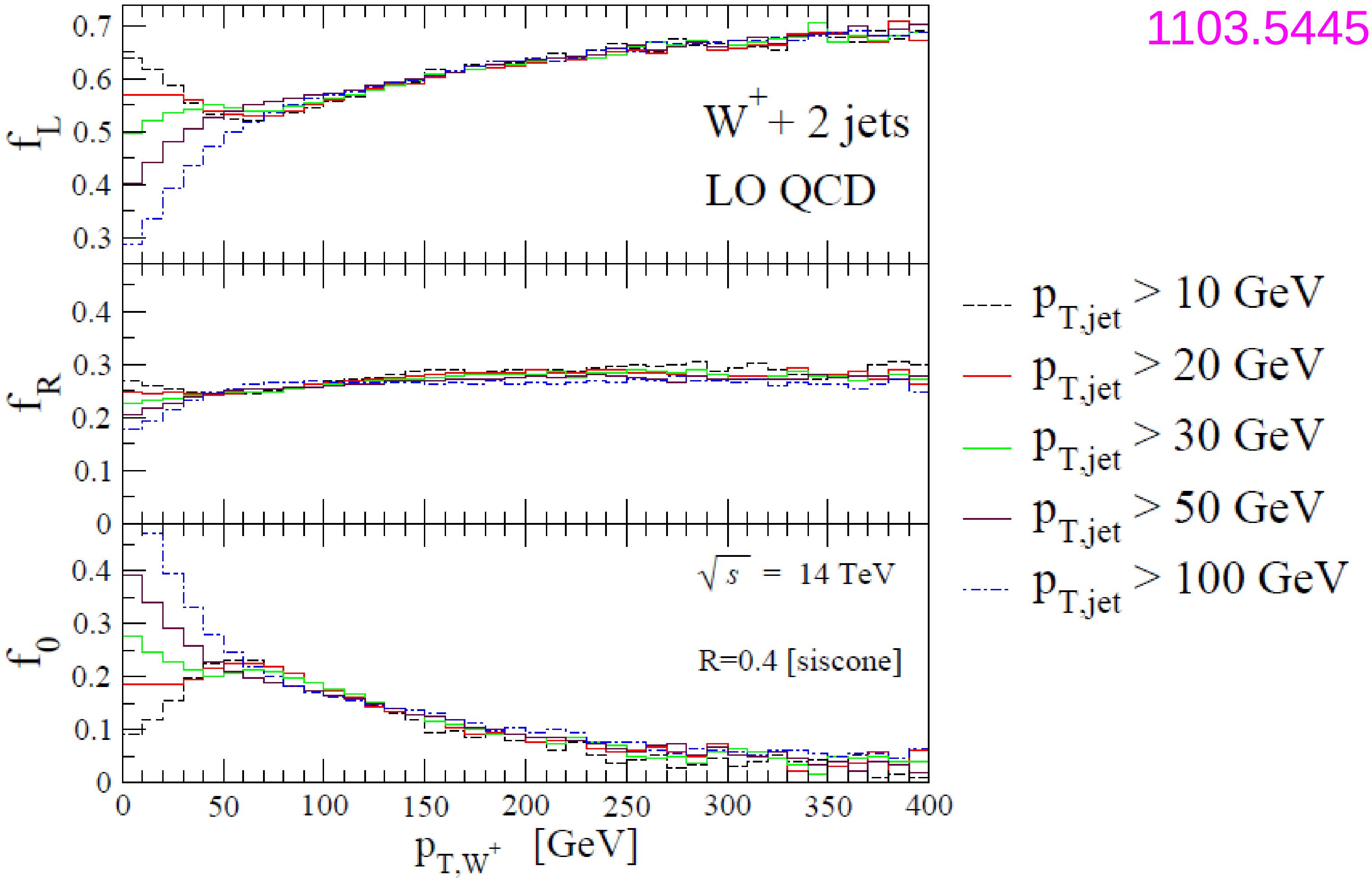
$$d\sigma \propto (k_u \cdot k_e)^2$$

100% left-handed
(in partonic CM frame)

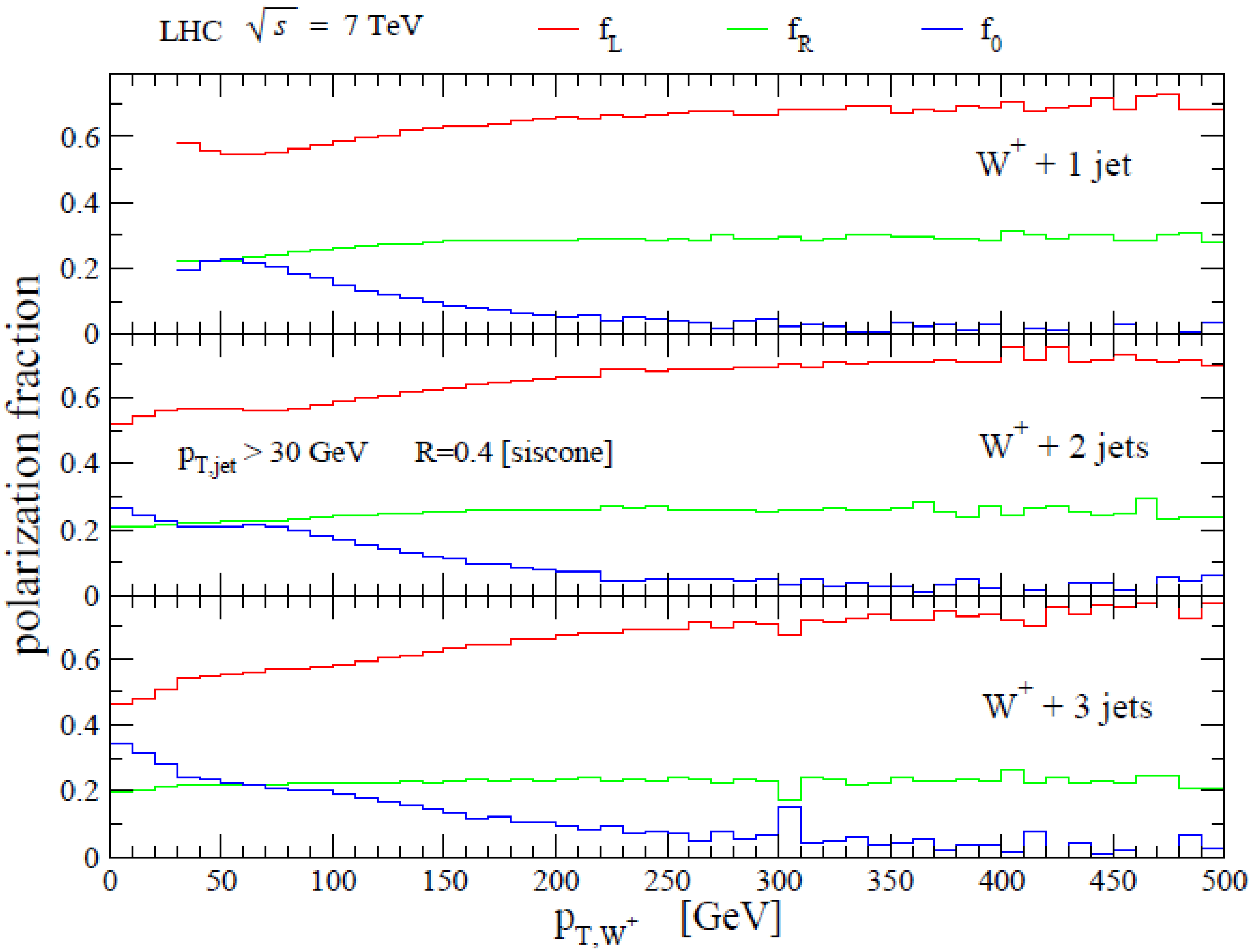
Mixture of polarizations
→ 100% right-handed, but only ¼ the size

Stable W polarization: W + 2 jets, vs. Jet p_T cut

1103.5445



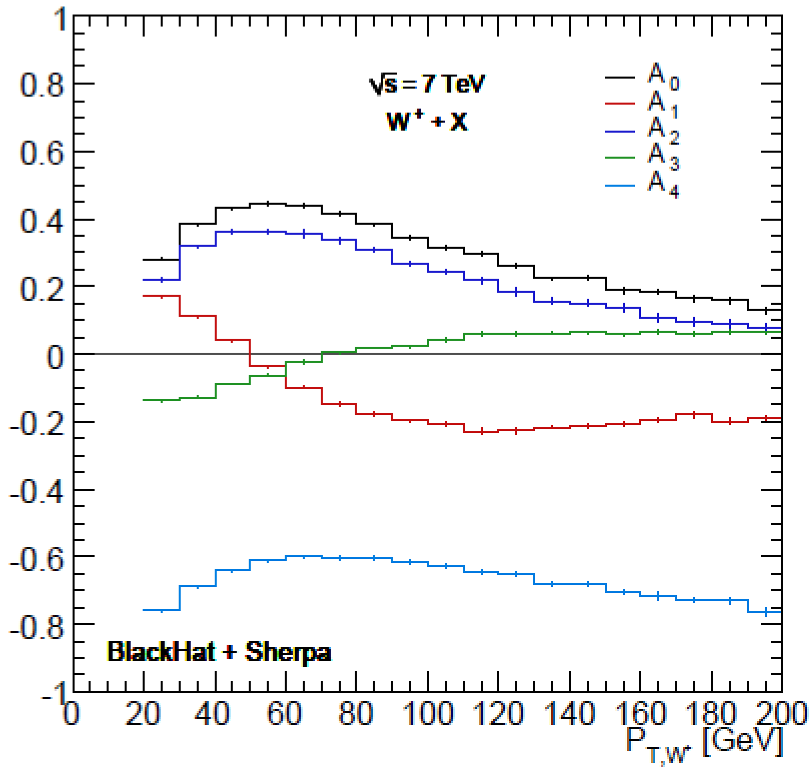
Stable *W* polarization vs. number of jets

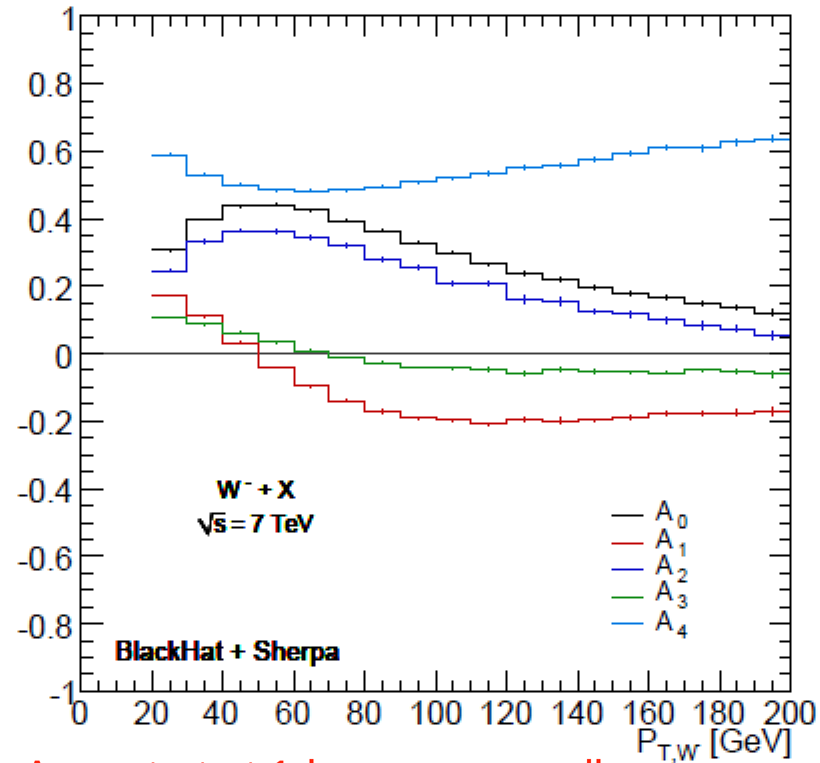


LO

Full NLO density matrix for pp → *W* + X

1103.5445

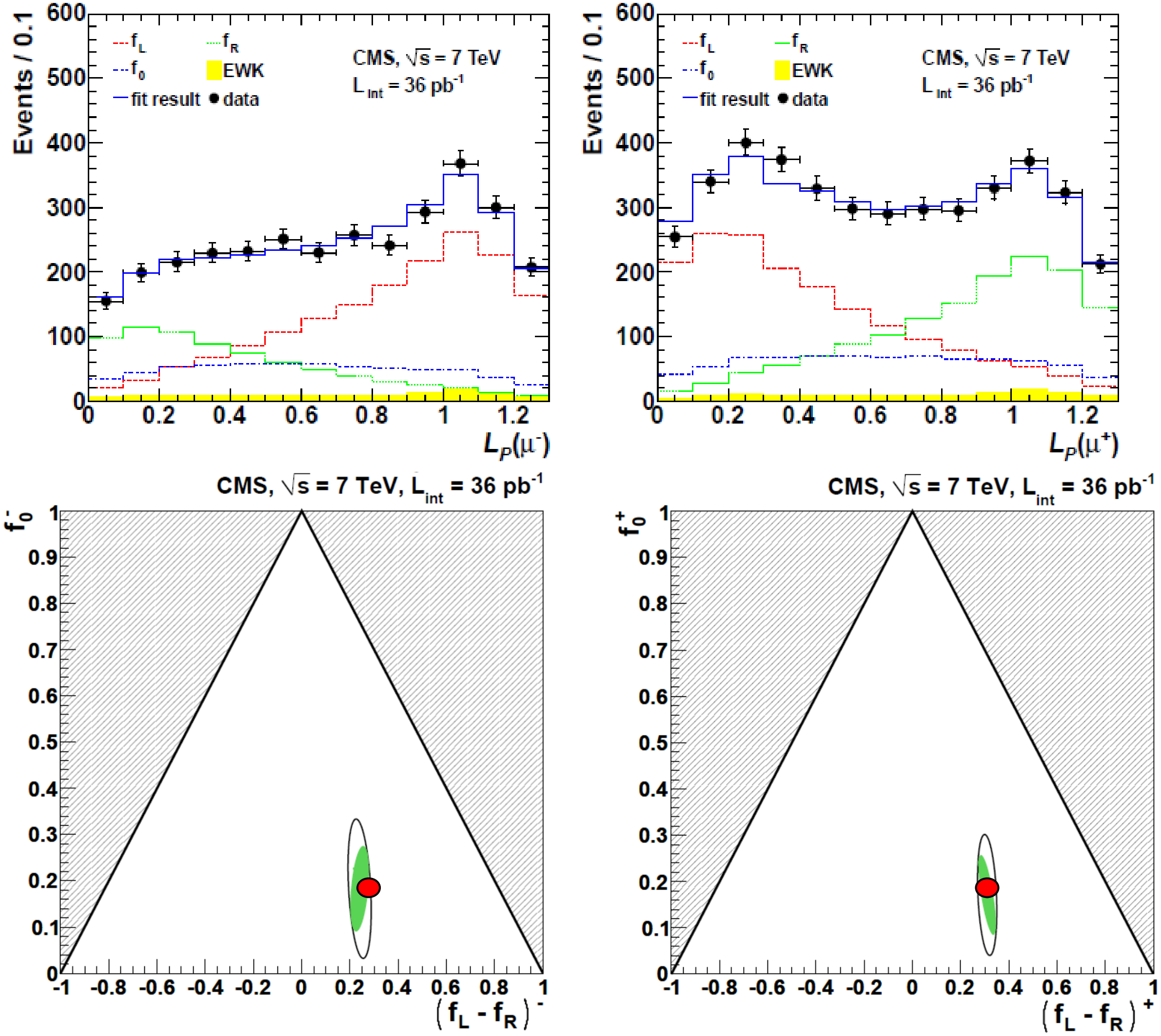




$A_{5,6,7}$ start at 1-loop; very small

$A_{1,2,3}$ used by CMS in their recent measurement of W polarization at LHC: $A_0 \sim f_0$, $A_4 \sim f_L - f_R$

CMS measurement



1104.3829

$$L_P = \frac{\vec{p}_T(\ell)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

NLO QCD

Top quark pairs very different

Main production channels are C invariant:

$$gg \to t\bar{t} \qquad q\bar{q} \to t\bar{t}$$

Semi-leptonic decay involves (partially) left-handed W^+

$$t\bar{t} \to bW^+\bar{b}W^- \to b\,e^+\nu\,\bar{b}jj$$

But charge conjugate decay involves (same degree) right-handed W^-

$$t\bar{t} \to bW^+\bar{b}W^- \to bjj\,\bar{b}\,e^-\bar{\nu}$$

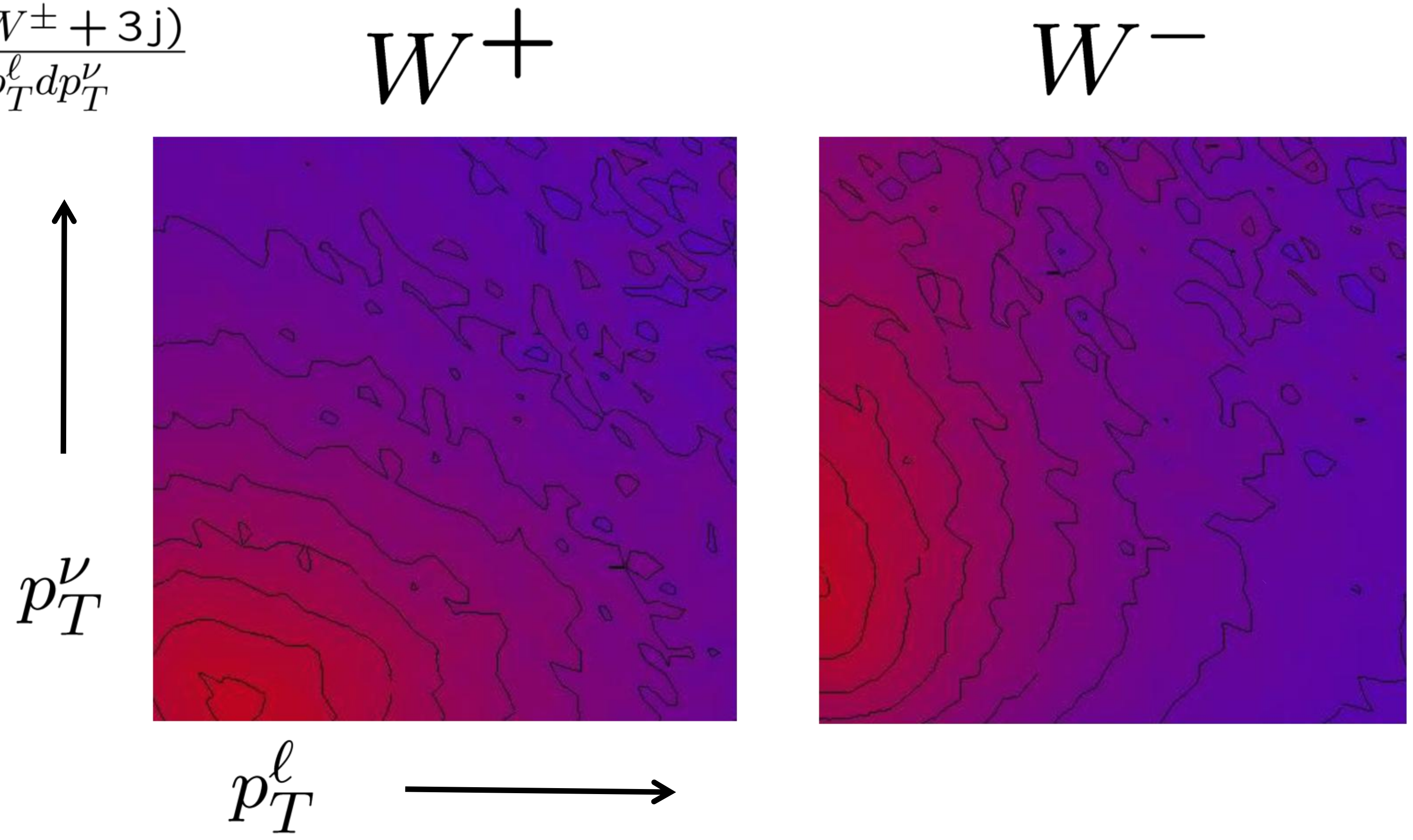
→ electron and positron have almost identical p_T distributions

→ Nice handle on separating W + jets from top

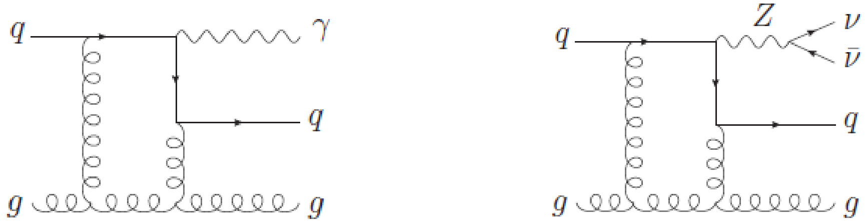
Supersymmetry may be like top – or not – depends on $qg \to \tilde{q}\tilde{g}$

Semi-leptonic tops vs. $W + 3$ jets

$$\frac{\dfrac{d^2\sigma(t\bar{t}\to W^\pm + 3\,\mathrm{j} + X)}{dp_T^\ell dp_T^\nu}}{\dfrac{d^2\sigma(W^\pm + 3\,\mathrm{j})}{dp_T^\ell dp_T^\nu}}$$



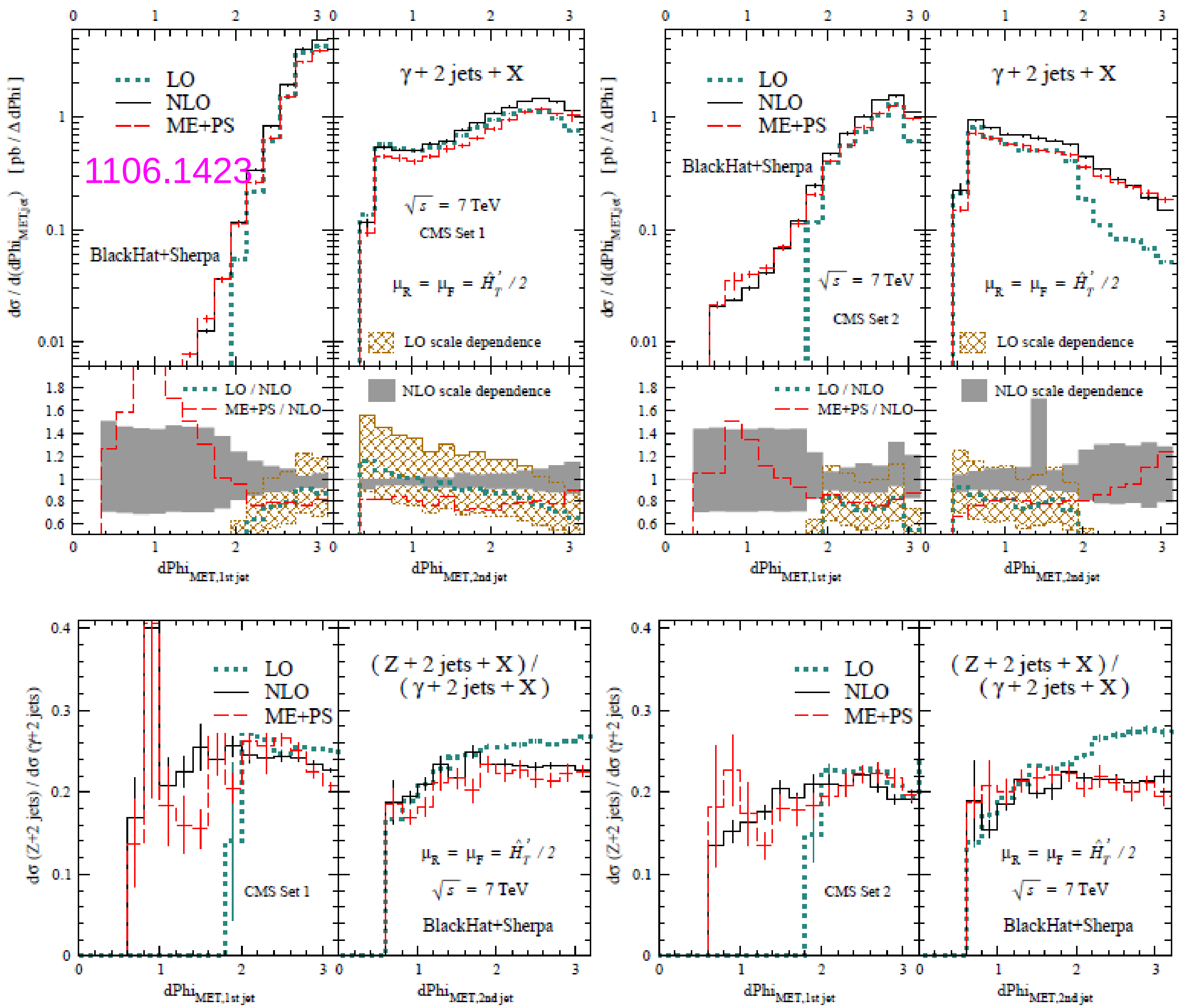
NLO (γ + 2 jets)/ (Z + 2 jets)



1106.1423

- CMS uses γ + jets to "calibrate" Z (→ $\nu\nu$) + jets SUSY background. High rate, relatively clean.
- How much does a photon behave like a Z boson in this sample?
- For example, the photon-quark collinear pole is cut off by the Z mass in the Z case. Does this make much difference?
- Assess this by computing (γ + 2 jets)/ (Z + 2 jets) as a function of various kinematic variables, at LO (just for reference), NLO and ME+PS.

NLO (γ + 2 jets)/ (Z + 2 jets) (cont.)



- Most structure seen in distribution in azimuthal angle between MET vector and p_T vector of 1^{st} and 2^{nd} jets.
- LO distribution wrong because kinematics is too restrictive. However, NLO and ME+PS agree to within about 10% in the Z/γ ratio.

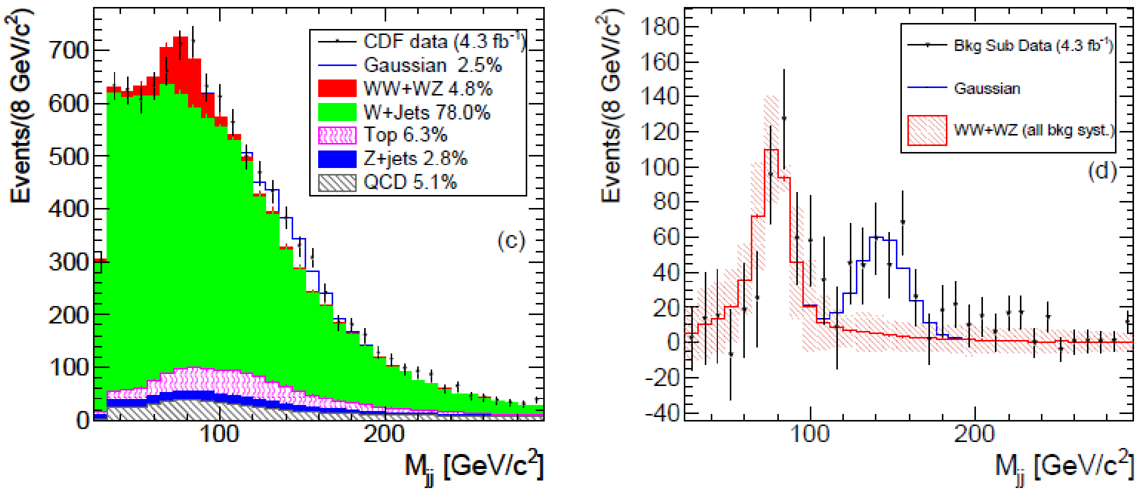
Conclusions

- New and efficient computational approaches to one-loop QCD amplitudes, exploiting analyticity, are now producing results for important LHC backgrounds
  - implemented numerically in C++ program **BlackHat**, as well as **CutTools, MadLoop, Rocket, …**
- NLO *W* + 3 jets agrees well with Tevatron and initial LHC data
- LHC kinematics and pp initial state ➔ new effects
- Valuable lessons already learned about scales and *W* polarization
- First NLO *Z* + 3 jets results now available too [for Tevatron]
- Compared γ + 2 jets vs. *Z* + 2 jets for CMS SUSY search
- *W* + 4 jets also done; *Z* + 4 jets feasible
- Other groups have produced NLO results for several other processes using similar methods (*VVV*, $t\,\bar{t}\,b\,\bar{b}$, *WWjj*, …)
- So far, these NLO results are only at parton level, not yet embedded in a full Monte Carlo, like MC@NLO or POWHEG.
- Still, they will be essential to optimally exploit LHC data.

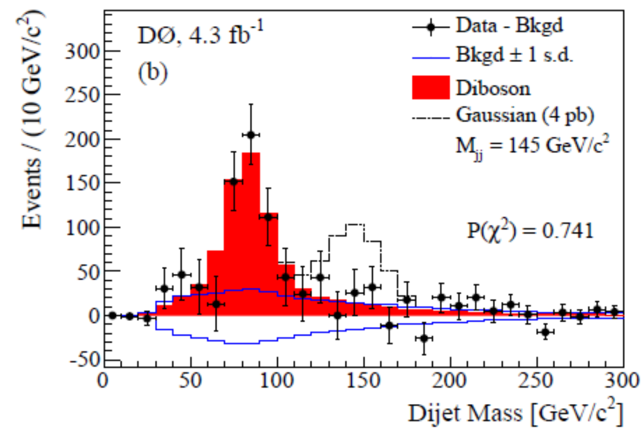
Extra slides

CDF "bump" in $W + 2$ jets

CDF, 1104.0699

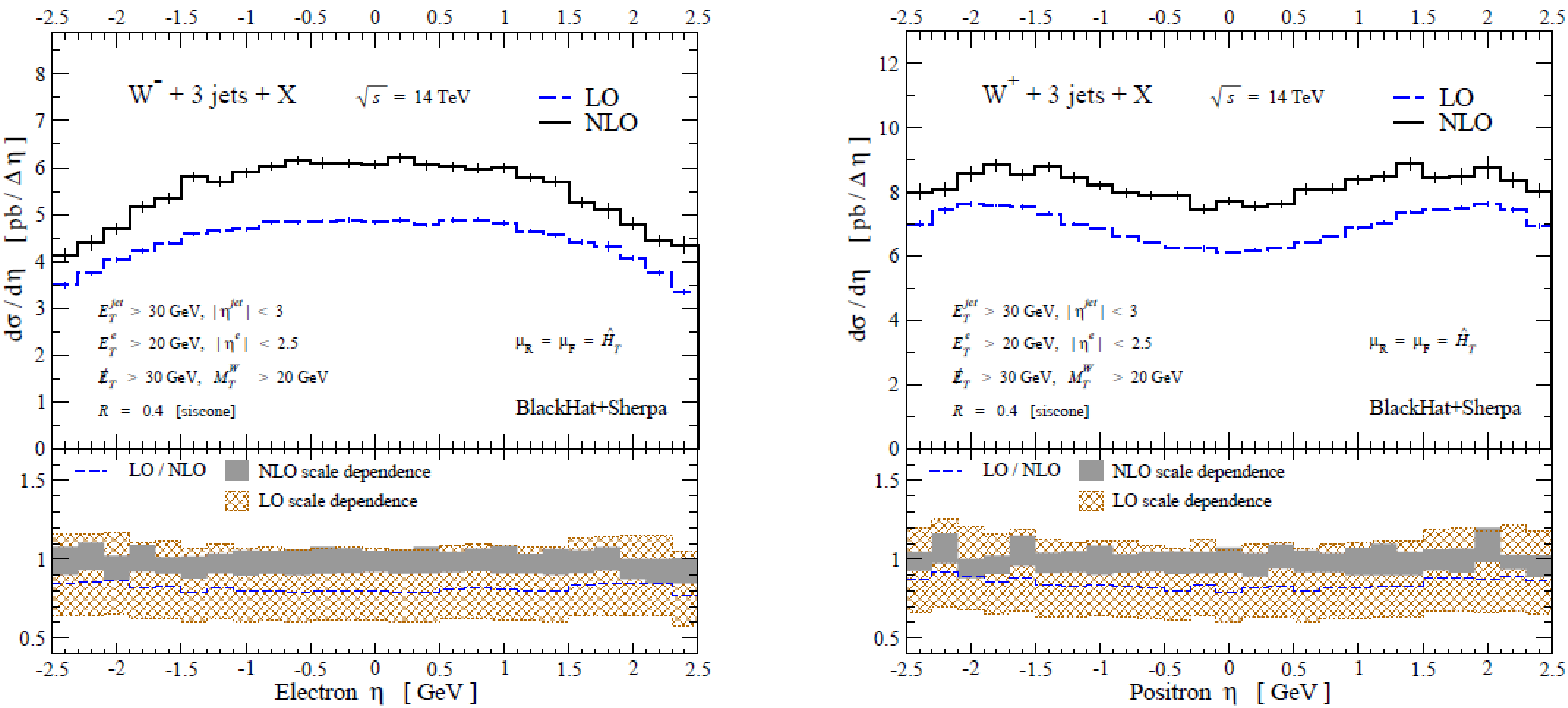


D0, 1106.1921



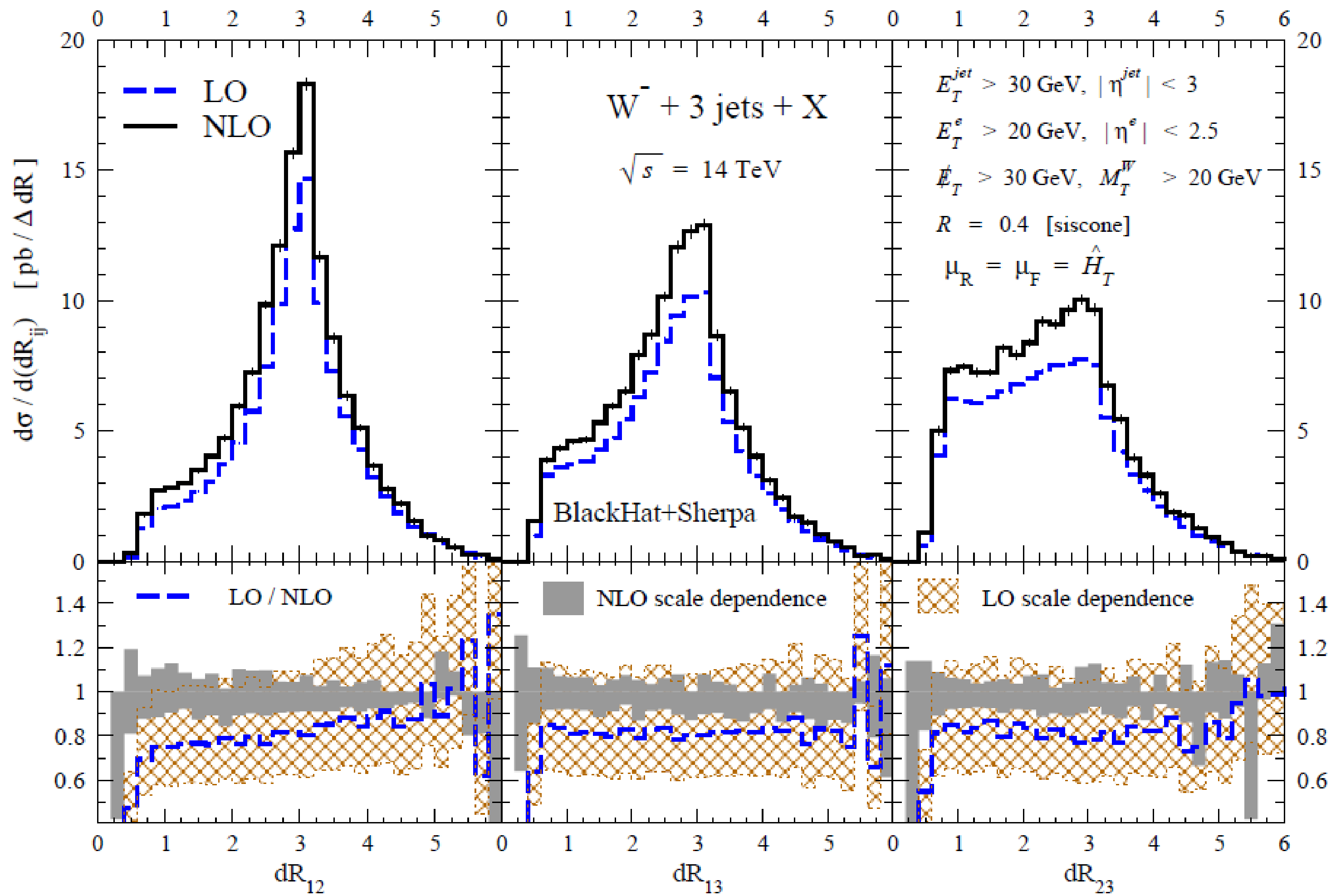
- Significance depends on estimated W + jets background.
- Main estimate uses LO+shower ALPGEN/PYTHIA, normalized by data.
- CDF also checked with NLO parton-level MCFM, for one scale choice, slightly different (IR safe) jet algorithm (JETCLU → midpoint).
- Now D0 has weighed in too – and they don't see it!

Lepton Rapidity in *W* + 3 jets at LHC



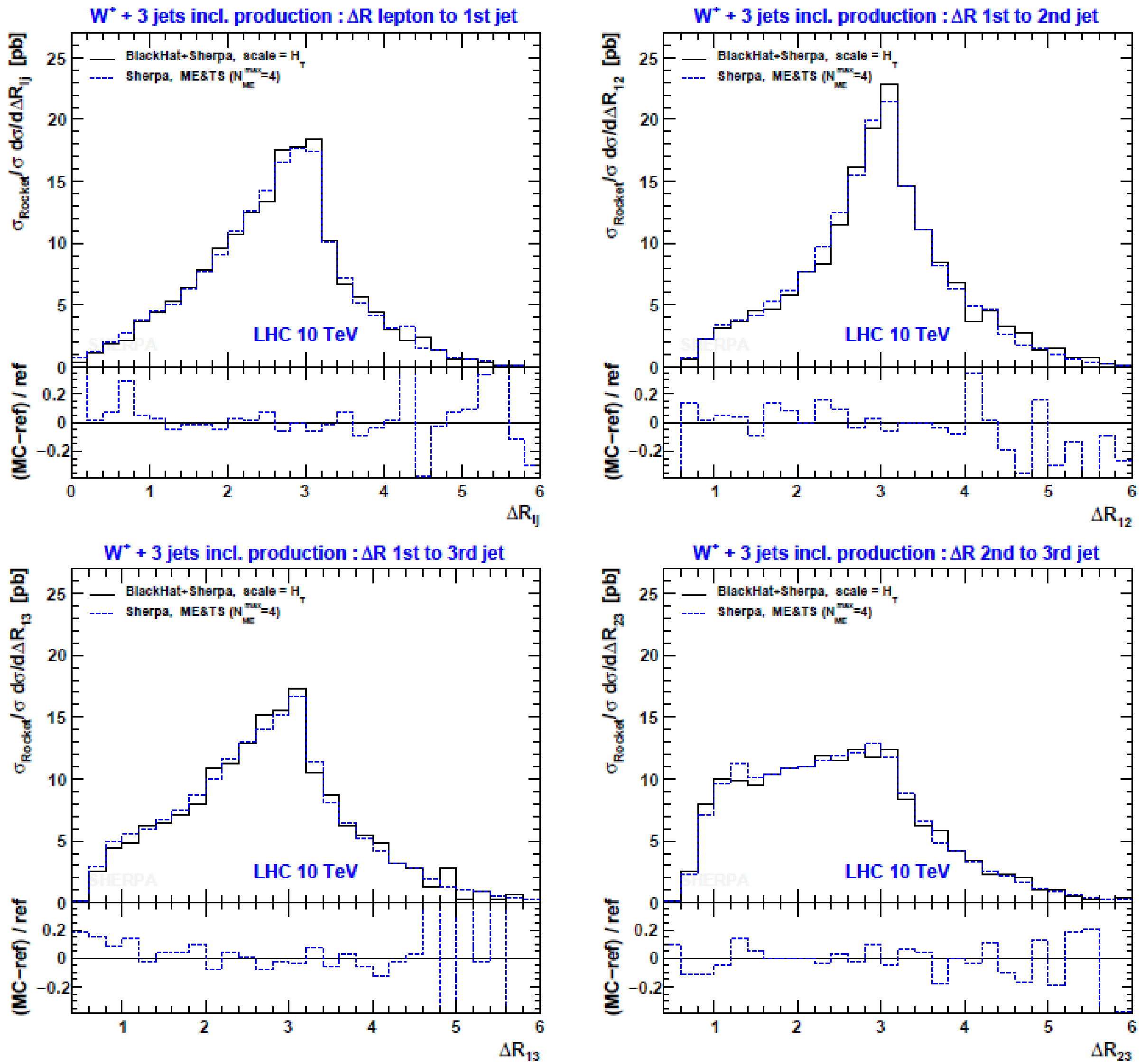
Rapidity distributions "remember" that $u(x)/d(x)$ gets very large as $x \rightarrow 1$

Jet Separations $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$



Pretty well modeled by LO, except for first 2 jets

Jet Separations: NLO vs. Sherpa shower



W polarization: CMS data vs. theory

	CMS	NLO	ME+PS	LO
$W^+ \ (f_L - f_R)$	$0.300 \pm 0.031 \pm 0.034$	0.308	0.283	0.309
$W^- \ (f_L - f_R)$	$0.226 \pm 0.031 \pm 0.050$	0.248	0.222	0.235
$W^+ \ f_0$	$0.192 \pm 0.075 \pm 0.089$	0.200	0.187	0.198
$W^- \ f_0$	$0.162 \pm 0.078 \pm 0.136$	0.193	0.179	0.190

Numbers of $V + \text{jets}$ events at 7 TeV

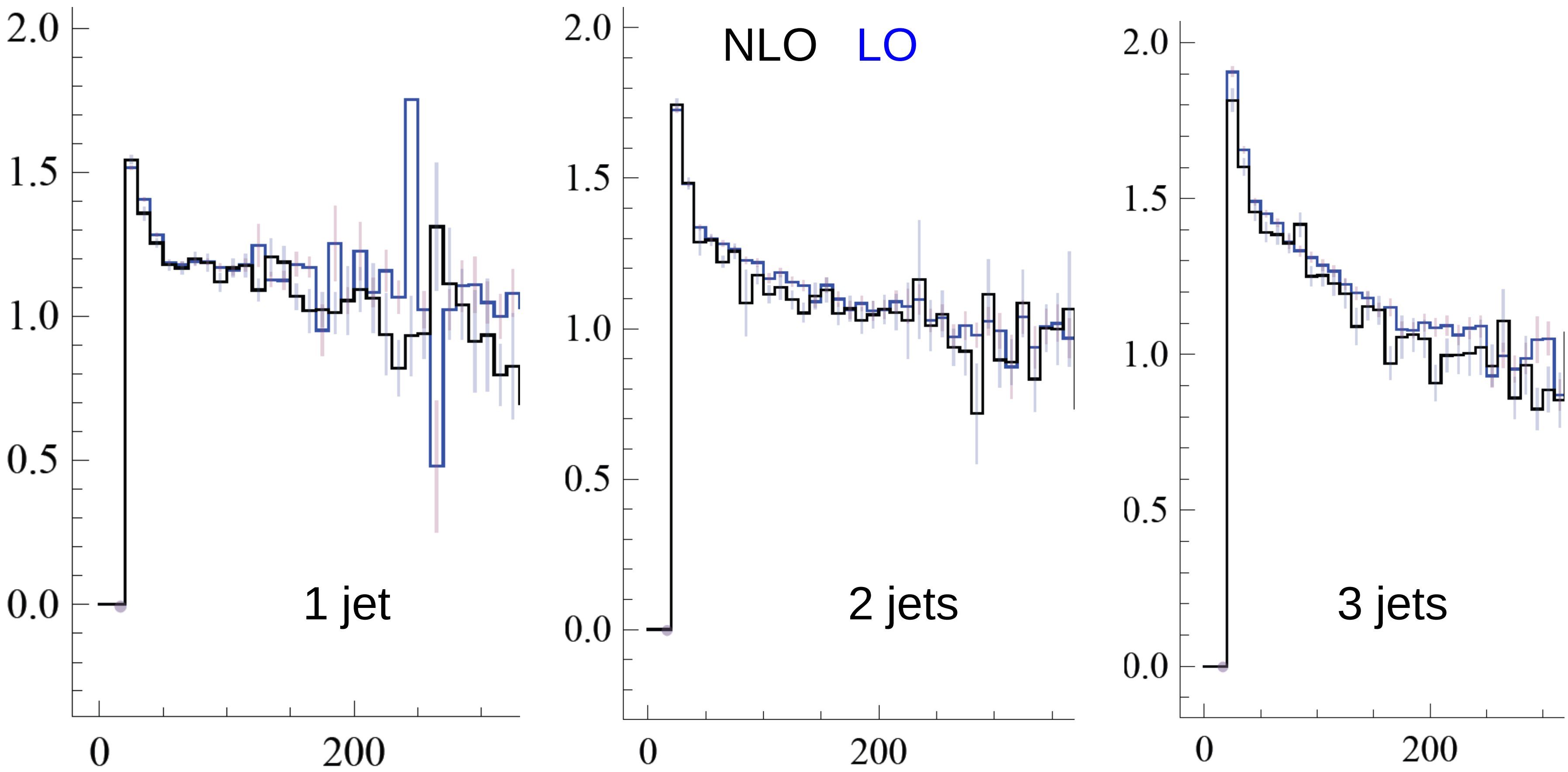
$E_T^{\text{n}^{\text{th}}\text{ jet}} > 25\text{ GeV}$

plus standard cuts on jet (anti-k_T, R=0.4) rapidity, lepton, missing E_T

$W^\pm \to e^\pm\nu$ or $\mu^\pm\nu$ $\quad\quad$ $Z^0 \to e^+e^-$ or $\mu^+\mu^-$

$\int \mathcal{L}\,dt =$	40 pb^{-1}	2 fb^{-1}
$\sigma(W^\pm j) \approx 800\text{ pb}$	32,000	1,600,000
$\sigma(W^\pm jj) \approx 200\text{ pb}$	8,000	400,000
$\sigma(W^\pm jjj) \approx 45\text{ pb}$	1,800	90,000
$\sigma(Zj) \approx 80\text{ pb}$	3,200	160,000
$\sigma(Zjj) \approx 20\text{ pb}$	800	40,000
$\sigma(Zjjj) \approx 4.8\text{ pb}$	192	9,600

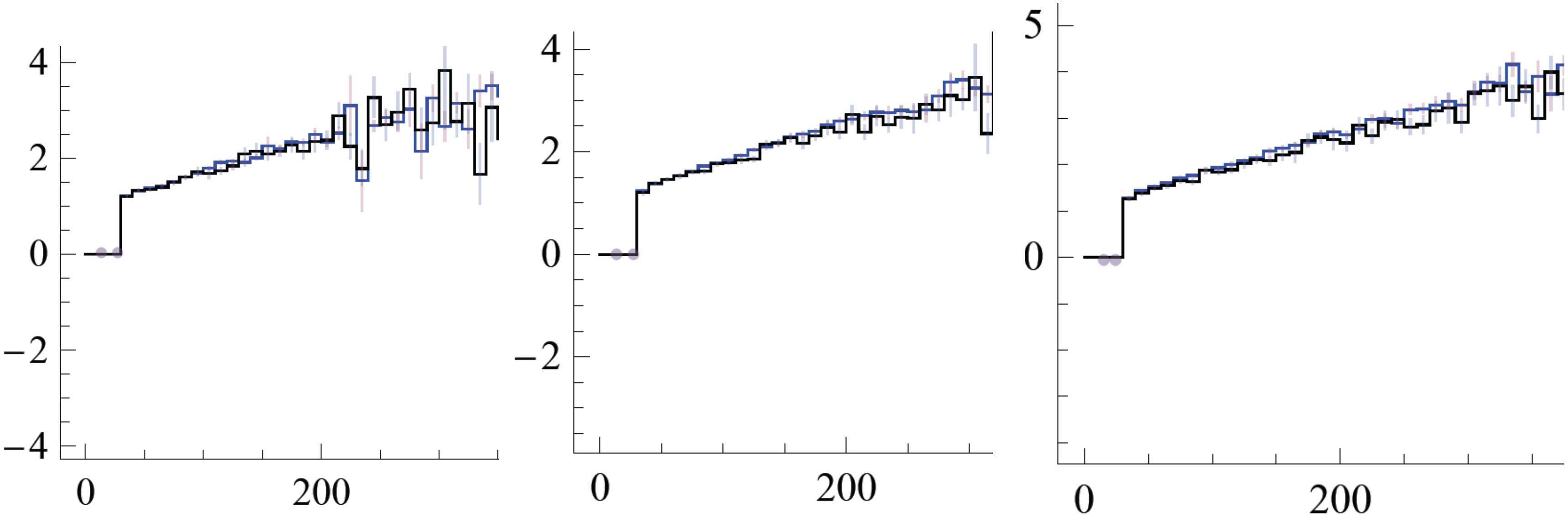
$W^{+/-}$ + n jets: e^+/e^- E_T ratio



- LO → NLO hardly affects ratios

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

NLO   LO



1 jet   2 jets   3 jets