NLO Assistance to LHC Searches with Complex Final States using BlackHat and Sherpa

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for the **BlackHat** collaboration

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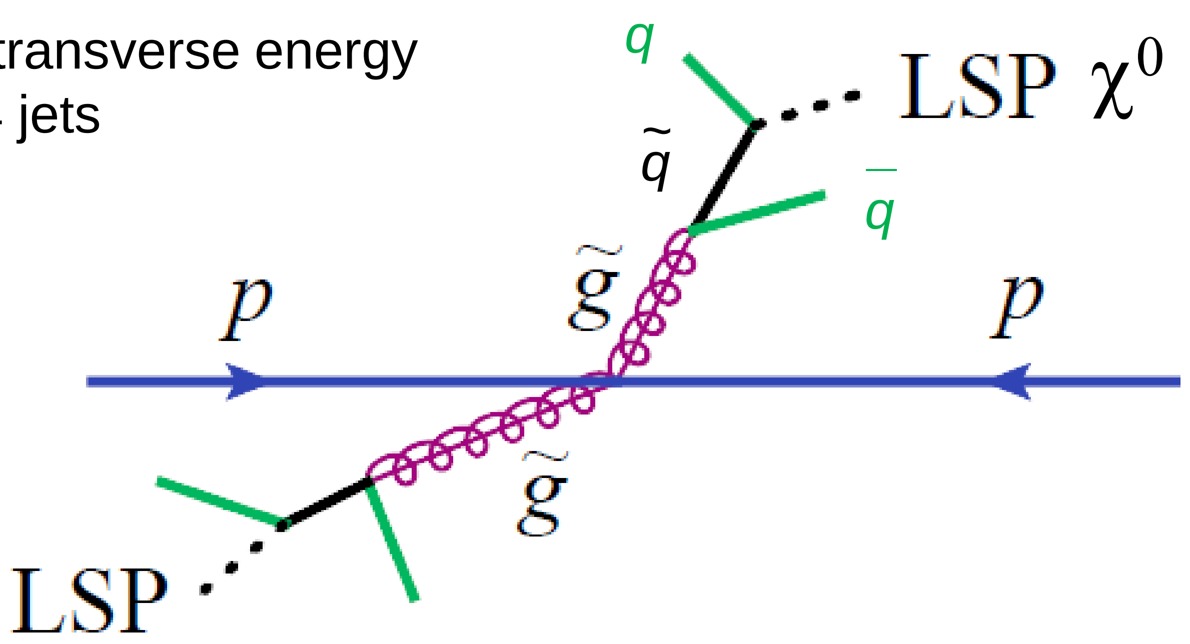
ATLAS EXPERIMENT
http://atlas.ch

Classic SUSY dark matter signature
→ Multiple jets + missing energy (+ lepton(s)?)

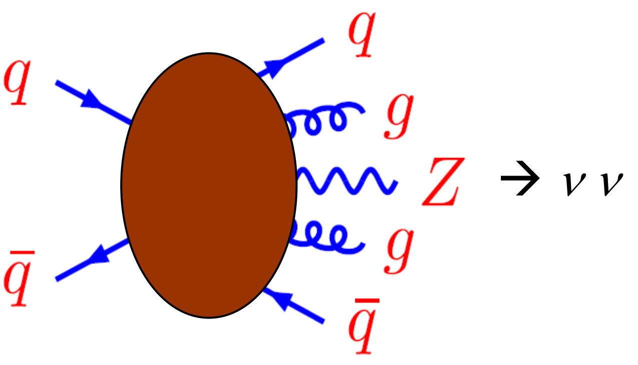
In models such as supersymmetry, heavy produced particles (colored) decay rapidly to stable Weakly Interacting Massive Particle (WIMP) plus jets

→ Missing transverse energy
MET + 4 jets



Irreducible Standard Model Background

- **MET + 4 jets from**
  pp → *Z* + 4 jets,
  Z → $\nu\nu$
- Neutrinos also weakly interacting, escape detector.
- Also large background from
  pp → *W* + 4 jets,
  W → $l\nu$
  (~ 10x *Z* → $\nu\nu$ rate)
  - if you lose the charged lepton
  (- or if you want a lepton)



- Motivates theoretical and experimental study of *V* + n jets at Tevatron and LHC.
- Talks in this session by Strauss, Mesropian, Beauchemin, Lenzi, Ganguli, Kosower, Schönherr

Recent progress on V + jets at NLO

MCFM: *V* + 0,1,2 jets Campbell, Ellis, hep-ph/0202176

Rocket: *W* + 3 jets Ellis, Melnikov, Zanderighi, 0901.4101, 0906.1445

Blackhat+Sherpa: Berger, Bern, LD, Diana, Febres Cordero, Forde, Gleisberg, Höche, Ita, Kosower, Maître, Ozeren

W + 3 jets 0902.2760, 0907.1984

Z + 3 jets 1004.1659

W + 4 jets 1009.2338

Z + 4 jets 1108.2229

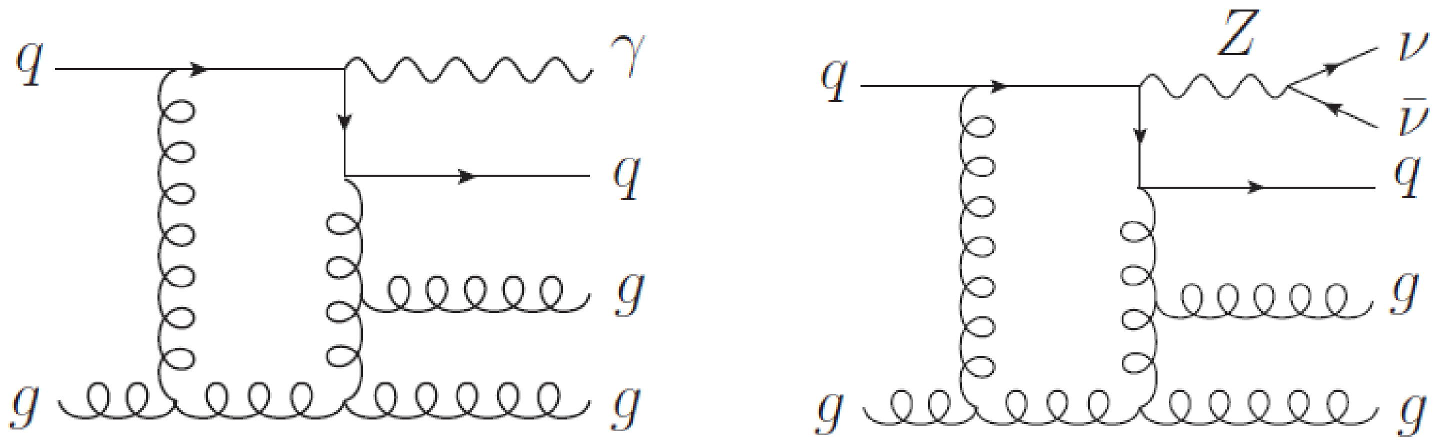
W + 5 jets 12mm.nnnn

- Could try to use such predictions directly for backgrounds to experimental searches.
- However, it is generally safer to use data-driven techniques

Data Driven Techniques

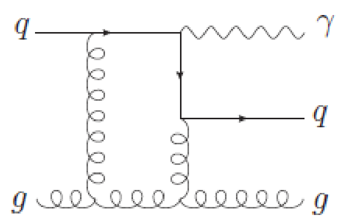
- Measure process "close" to the one you want to estimate. (Possibly the same process in a different kinematic region.)
- Rely on theory only for ratio of desired process to measured one.
- Ratios can be considerably less sensitive to:
  - perturbative uncertainties
  - shower + nonperturbative effects
  - jet energy scale
  - pdf uncertainties
- Nevertheless, useful to have at NLO as well as LO+shower.
- Examples of V + jets ratios:
- [$W + n$ jets]/[$Z + n$ jets]
- [W^+ + n jets]/[W^- + n jets]
- [$\gamma + n$ jets]/[$Z + n$ jets]
- W polarization fractions
- [$V + n$ jets]/[$V + (n$-1) jets]

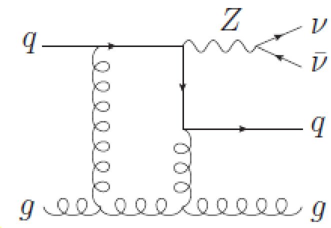
γ + jets for $Z(\rightarrow \nu\nu)$ + n jets



- CMS [CMS PAS SUS-08-002, SUS-10-005, 1106.4503] and ATLAS [1107.2803, 1109.6572] both use γ + jets to "calibrate" Z ($\rightarrow$ $\nu\nu$) + jets SUSY background.
- High rate compared to Z ($\rightarrow$ l^+l^-), relatively clean.
- But: How much does a γ behave like a Z?
- *E.g.*, photon-quark collinear pole is cut off by Z mass in the Z case. Does this make much difference?

NLO (Z + 2 jets)/ (γ + 2 jets)

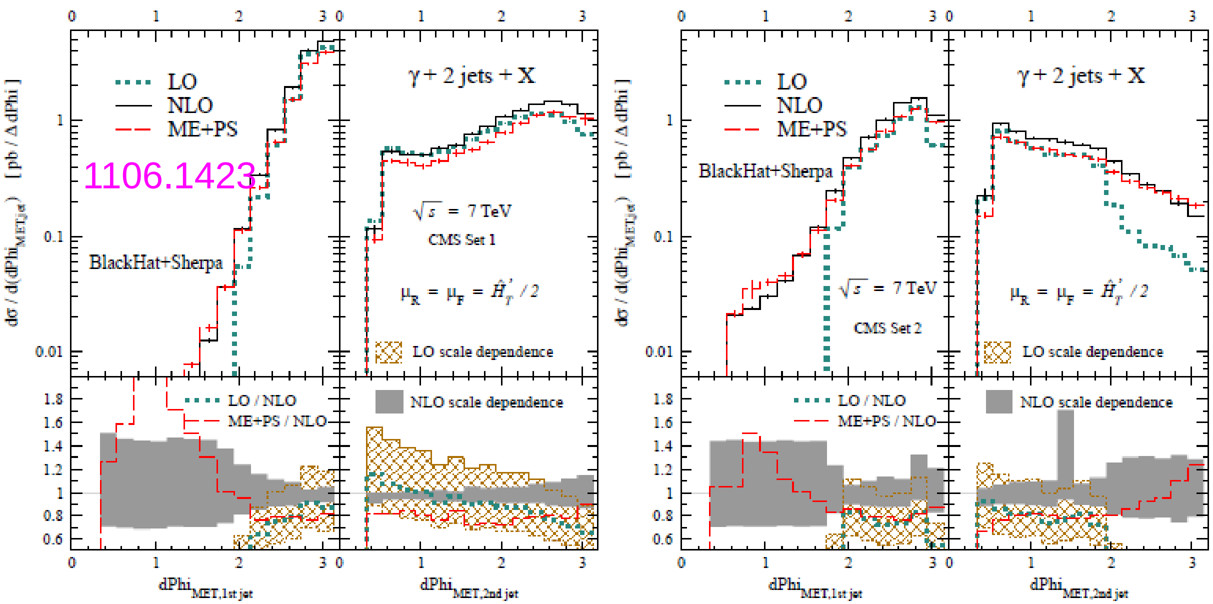




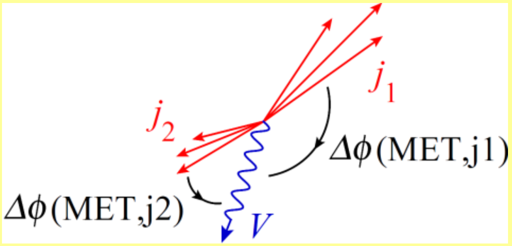
1106.1423

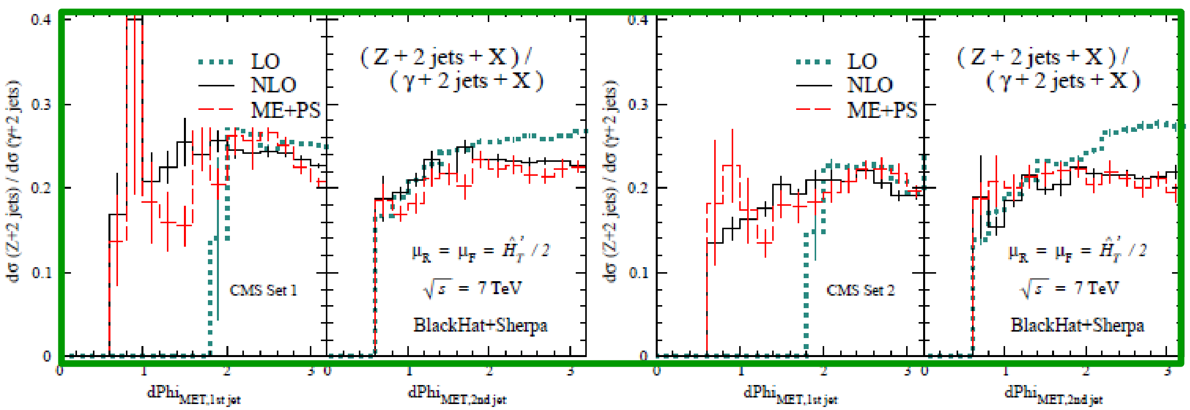
- Computed (Z + 2 jets)/ (γ + 2 jets) as a function of various kinematic variables, 3 different ways:
- LO (just for reference)
- NLO (probably the most reliable)
- LO+shower (ME+PS) – to estimate NLO error, and because it is similar to what CMS/ATLAS rely on.
- Traditional method of varying renormalization and factorization scales does not provide useful uncertainty estimate for ratios of similar quantities
- We used a "Frixione" photon isolation to simplify the NLO theory, but checked that it's within ~1% of CMS's isolation cone

(Z + 2 jets)/ (γ + 2 jets) distributions



- Azimuthal angle distribution, between MET vector and p_T vector of 1st, 2nd jets





- LO distribution wrong – kinematics too restrictive.
NLO and ME+PS agree to within about 10% in Z/γ ratio.

NLO (Z + 3 jets)/ (γ + 3 jets)

- Most events in CMS samples have at least 3 jets
- For 2011 data, new (tighter) kinematic cuts

2010 data
1106.4503

Set 1: $H_T^{\text{jet}} > 300$ GeV, $|\text{MET}| > 250$ GeV

Set 2: $H_T^{\text{jet}} > 500$ GeV, $|\text{MET}| > 150$ GeV

Set 3: $H_T^{\text{jet}} > 300$ GeV, $|\text{MET}| > 150$ GeV

Set 4: $H_T^{\text{jet}} > 350$ GeV, $|\text{MET}| > 200$ GeV

control regions

2011 data

Set 5: $H_T^{\text{jet}} > 500$ GeV, $|\text{MET}| > 350$ GeV

Set 6: $H_T^{\text{jet}} > 800$ GeV, $|\text{MET}| > 200$ GeV

Set 7: $H_T^{\text{jet}} > 800$ GeV, $|\text{MET}| > 500$ GeV

NLO (γ + 3 jets)/ (Z + 3 jets) results

BH+S, 1206.nnnn

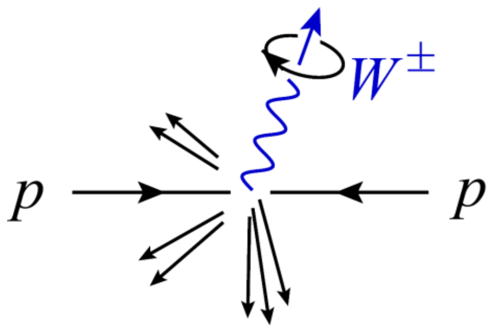
Set	Prediction	Z + 3-jet/γ + 3-jet	Z + 2-jet/γ + 2-jet	ratio
4	LO	0.215(0.001)	0.2336(0.0003)	0.922(0.003)
	ME+PS	0.194(0.003)	0.213(0.002)	0.908(0.01)
	NLO	0.209(0.003)	0.215(0.001)	0.973(0.01)
5	LO	0.245(0.001)	0.257(0.001)	0.952(0.01)
	ME+PS	0.230(0.004)	0.239(0.004)	0.961(0.02)
	NLO	0.242(0.01)	0.246(0.002)	0.981(0.02)
6	LO	0.220(0.002)	0.232(0.001)	0.948(0.01)
	ME+PS	0.218(0.004)	0.232(0.003)	0.940(0.02)
	NLO	0.222(0.01)	0.224(0.002)	0.988(0.03)
7	LO	0.257(0.003)	0.259(0.001)	0.992(0.01)
	ME+PS	0.244(0.01)	0.261(0.003)	0.935(0.02)
	NLO	0.254(0.01)	0.255(0.003)	0.993(0.03)

ME+PS, NLO always within 10%

pdf and other uncertainties 5% or less

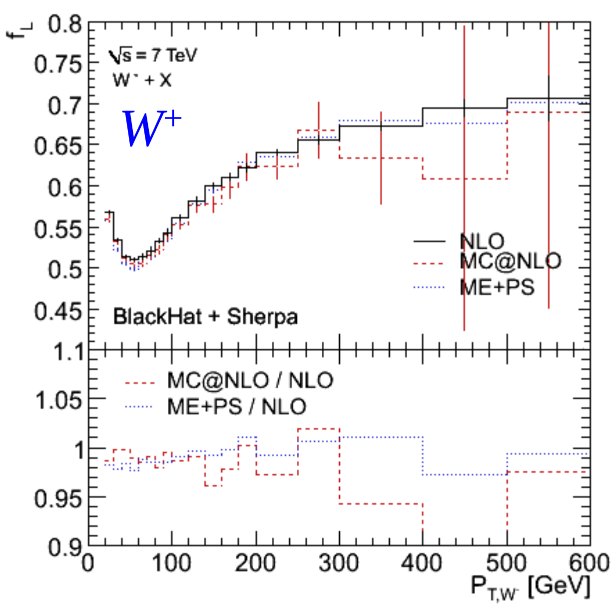
Validates this method of estimating background

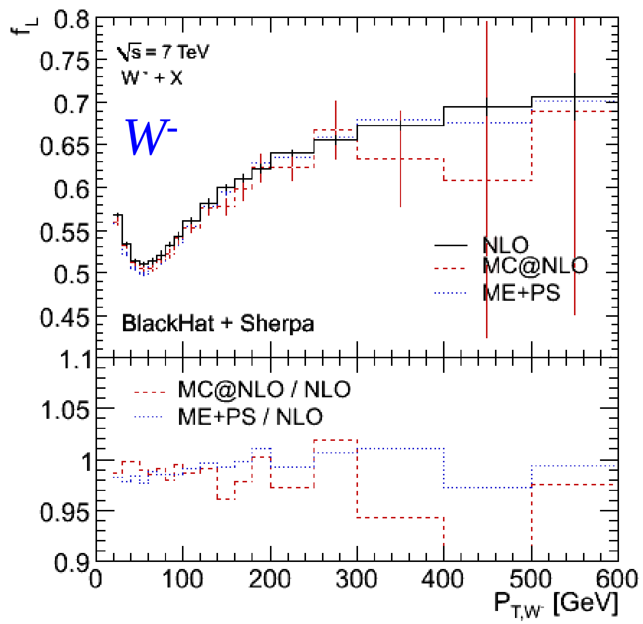
W^+ and W^- "differ" at LHC: polarized same way [left-handed]



Helicity frame:

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

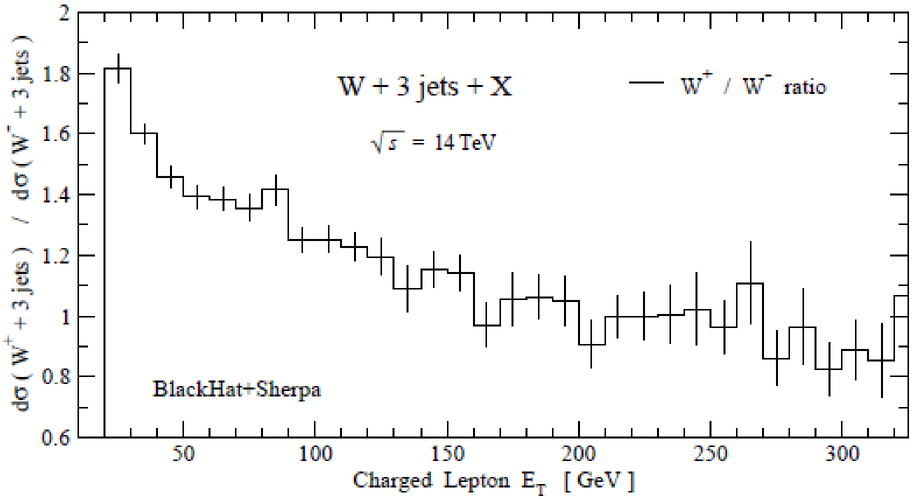


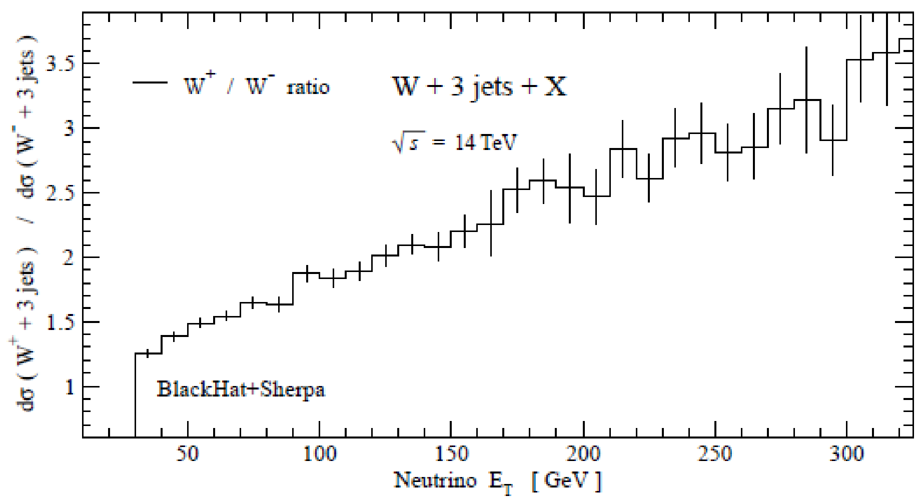


1103.5445

Leptonic E_T in $W^{\pm}$ + 3 jets

0907.1984

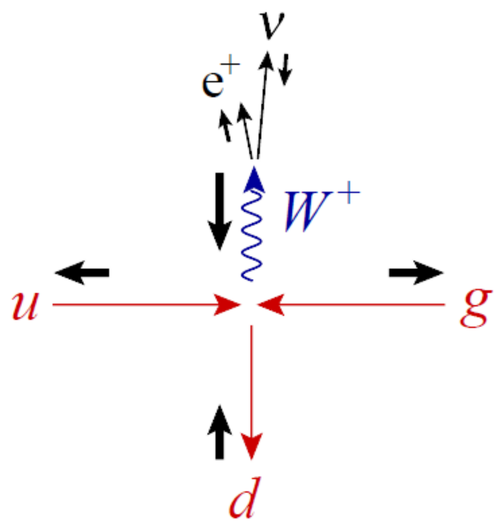


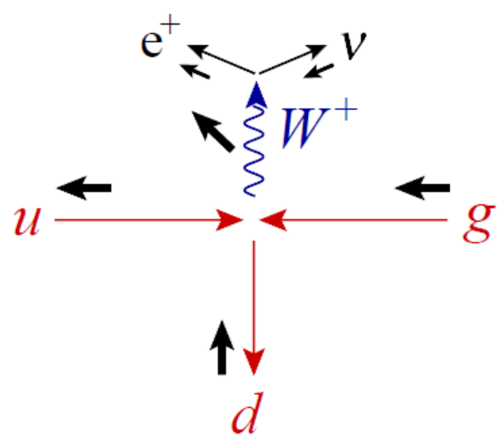


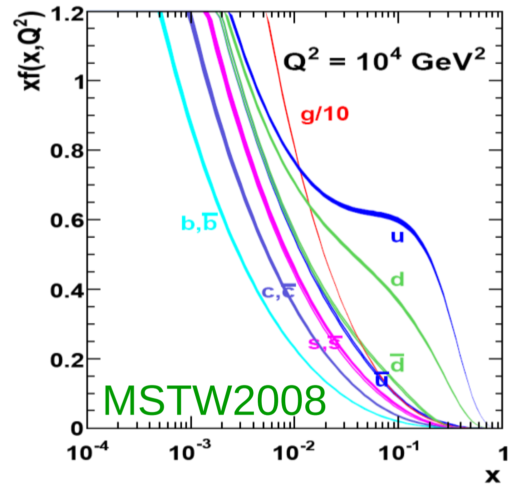
W^+/W^- transverse lepton ratios are skewed because they are analyzing a large left-handed W polarization at large $p_T(W)$

Origin of *W* polarization at LHC at large $p_T(W)$

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







1103.5445

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

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

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

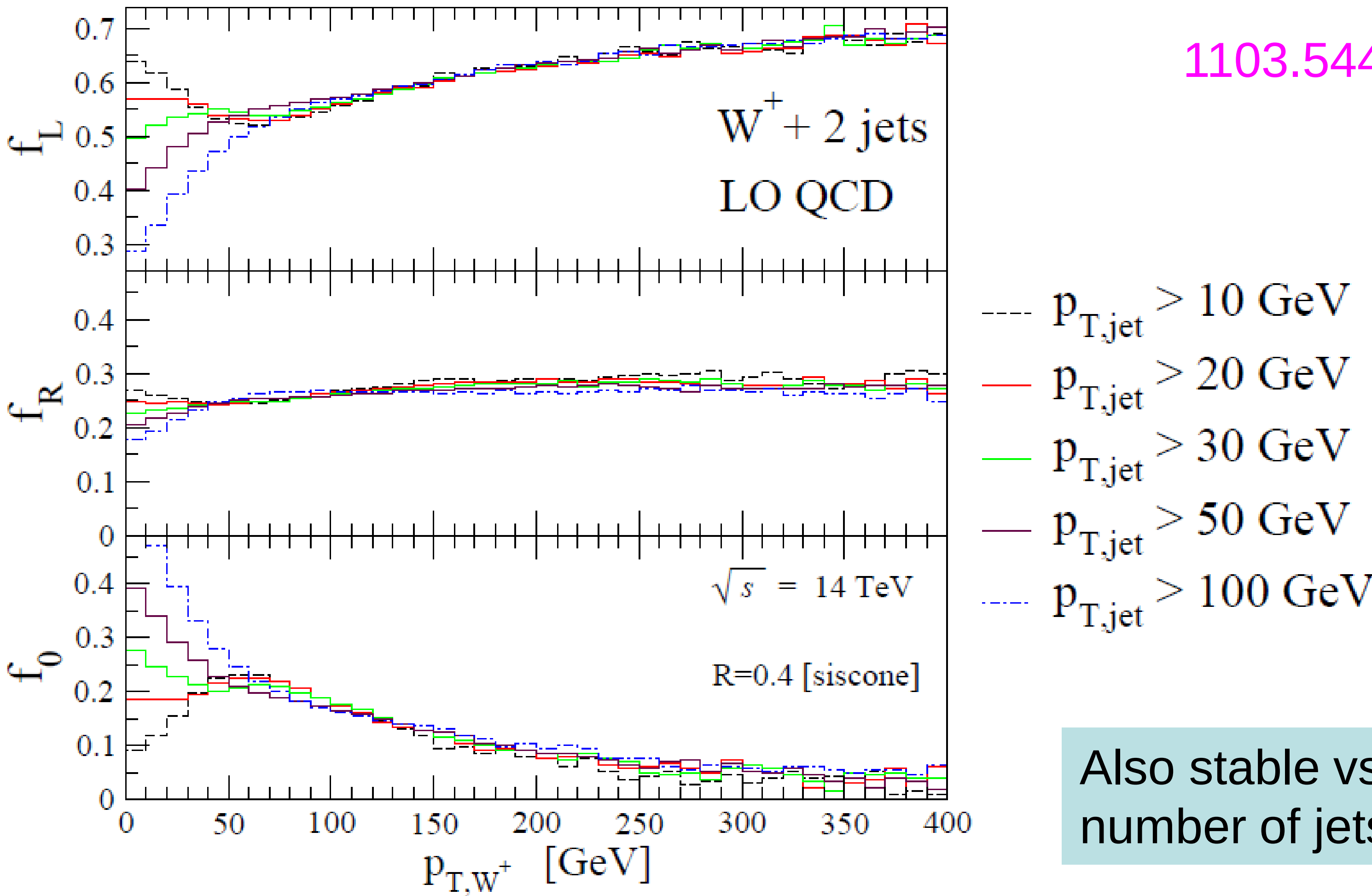
$$d\sigma \propto (k_u \cdot k_e)^2$$

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



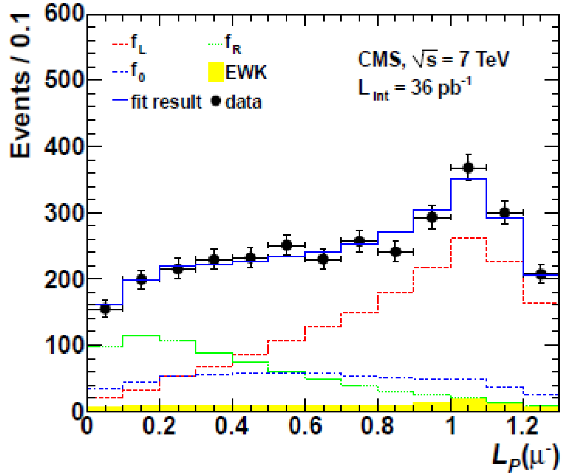
Also stable vs. number of jets

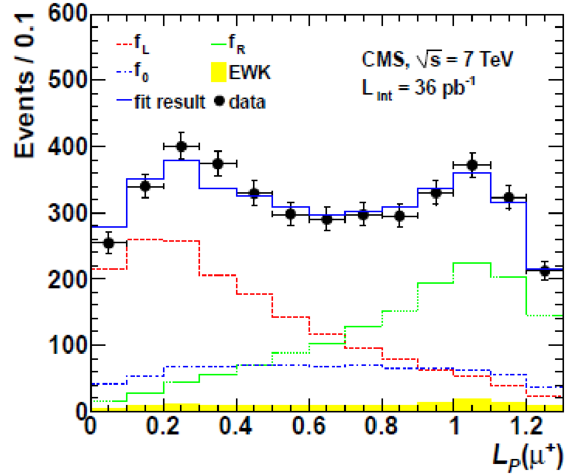
CMS measurement – no explicit jet cuts

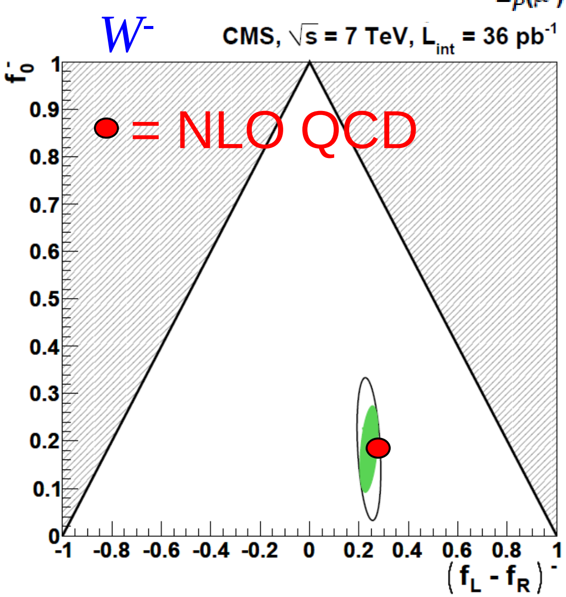
1104.3829

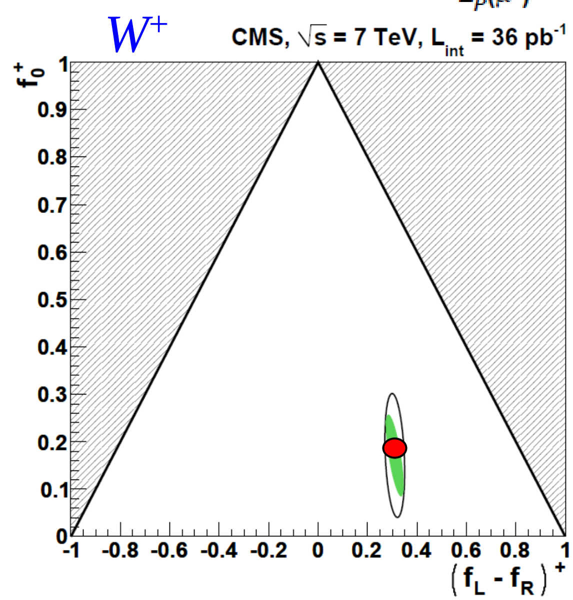
$p_T(W) > 50$ GeV

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









Also ATLAS measurement (smaller uncertainties) using

$$\cos\theta_{2D} = \frac{\vec{p}_T^{\,\ell*} \cdot \vec{p}_T^{\,W}}{|\vec{p}_T^{\,\ell*}|\,|\vec{p}_T^{\,W}|}$$

1203.2165

Conclusions

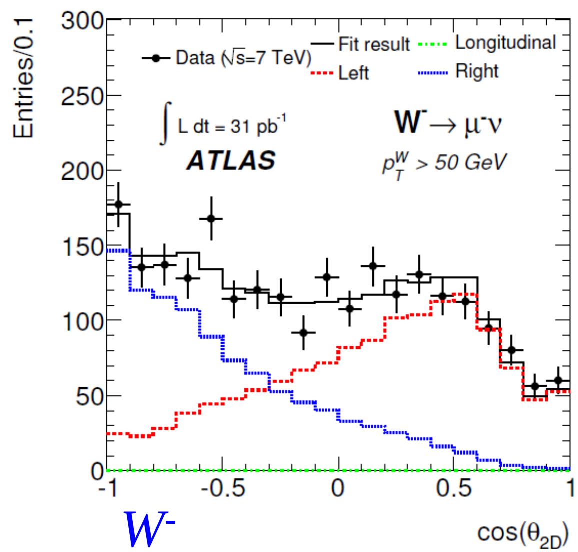
- We compared γ + 2,3 jets to *Z* + 2,3 jets for cuts relevant for CMS SUSY searches with 2010 and 2011 data.
- We found very similar results for the ratio, between NLO and ME+PS approximations,
- This validates the data-driven method of using γ + jets to calibrate the *Z* + jets background to the MET + jets SUSY searches.

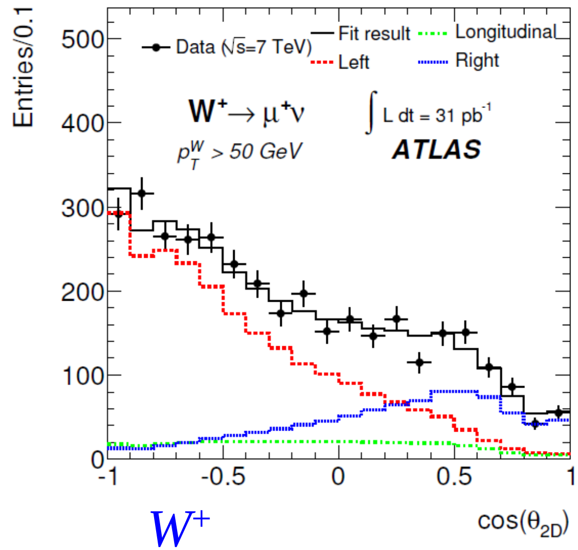
- Left-handed *W* polarization can provide another handle on *W* + jets backgrounds, due to the charge asymmetries it induces.
- In fact, CMS [1107.1870] has used the measured lepton p_T spectrum in *W* + jets, plus the predicted *W* polarization to infer the MET distribution in *W* + jets backgrounds to SUSY.

- Many other ratios out there to study and exploit!

Extra slides

ATLAS measurement – no explicit jet cuts

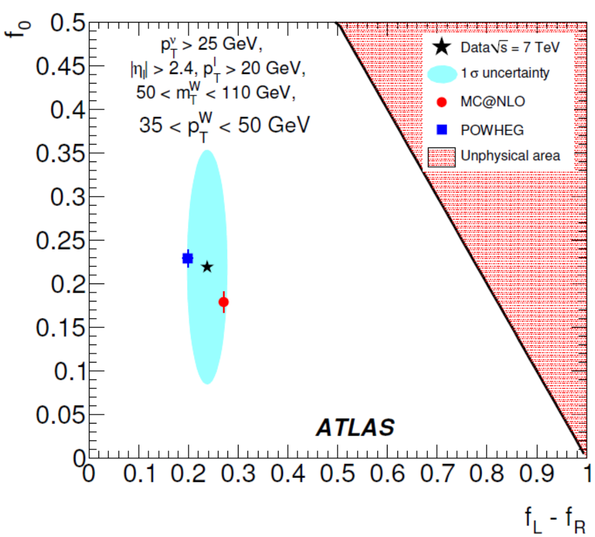


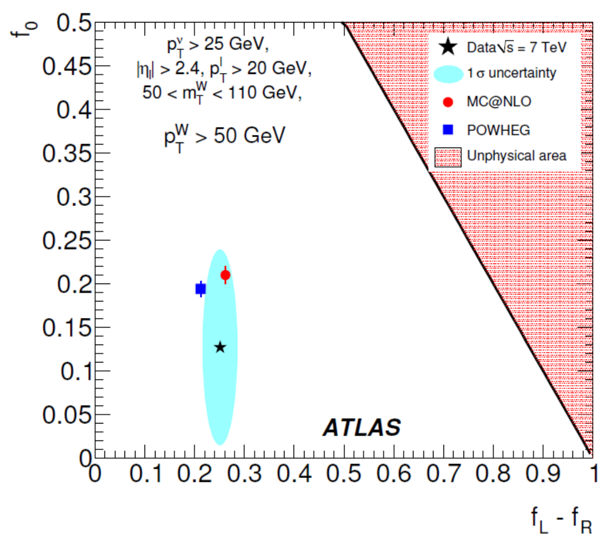


1203.2165

$p_T(W)$ > 50 GeV

$$\cos\theta_{2D} = \frac{\vec{p}_T^{\,\ell*} \cdot \vec{p}_T^{\,W}}{|\vec{p}_T^{\,\ell*}|\,|\vec{p}_T^{\,W}|}$$

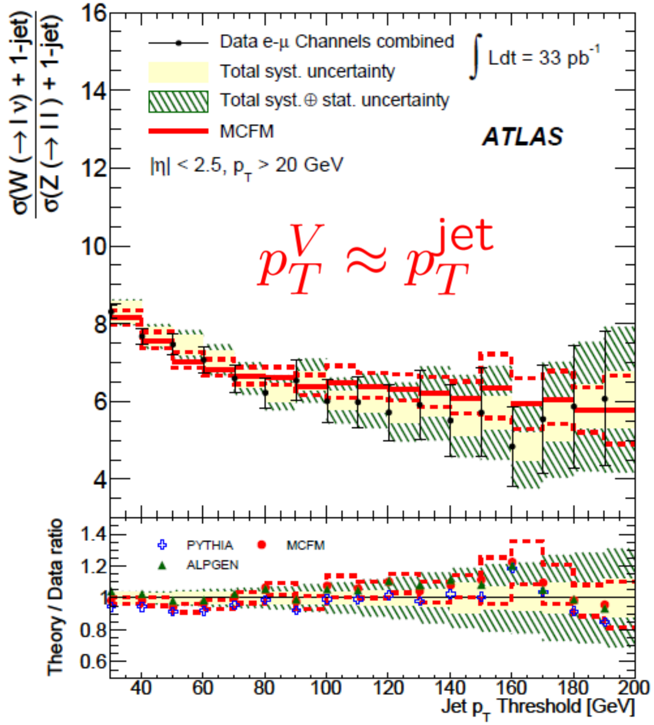


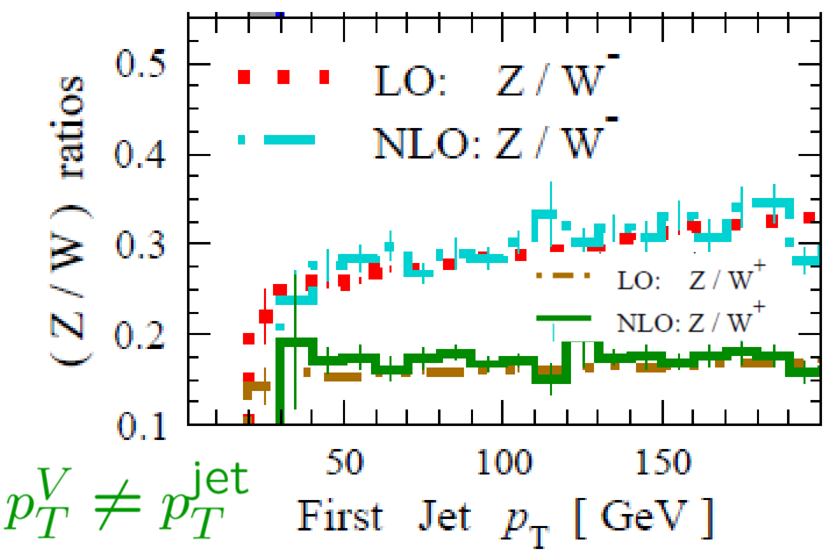


Different dynamics for W/Z + jets ratios for 1 jet, versus more jets

Recent ATLAS measurement of W/Z + exactly 1 jet ratio 1108.4908 – strong dependence on jet p_T

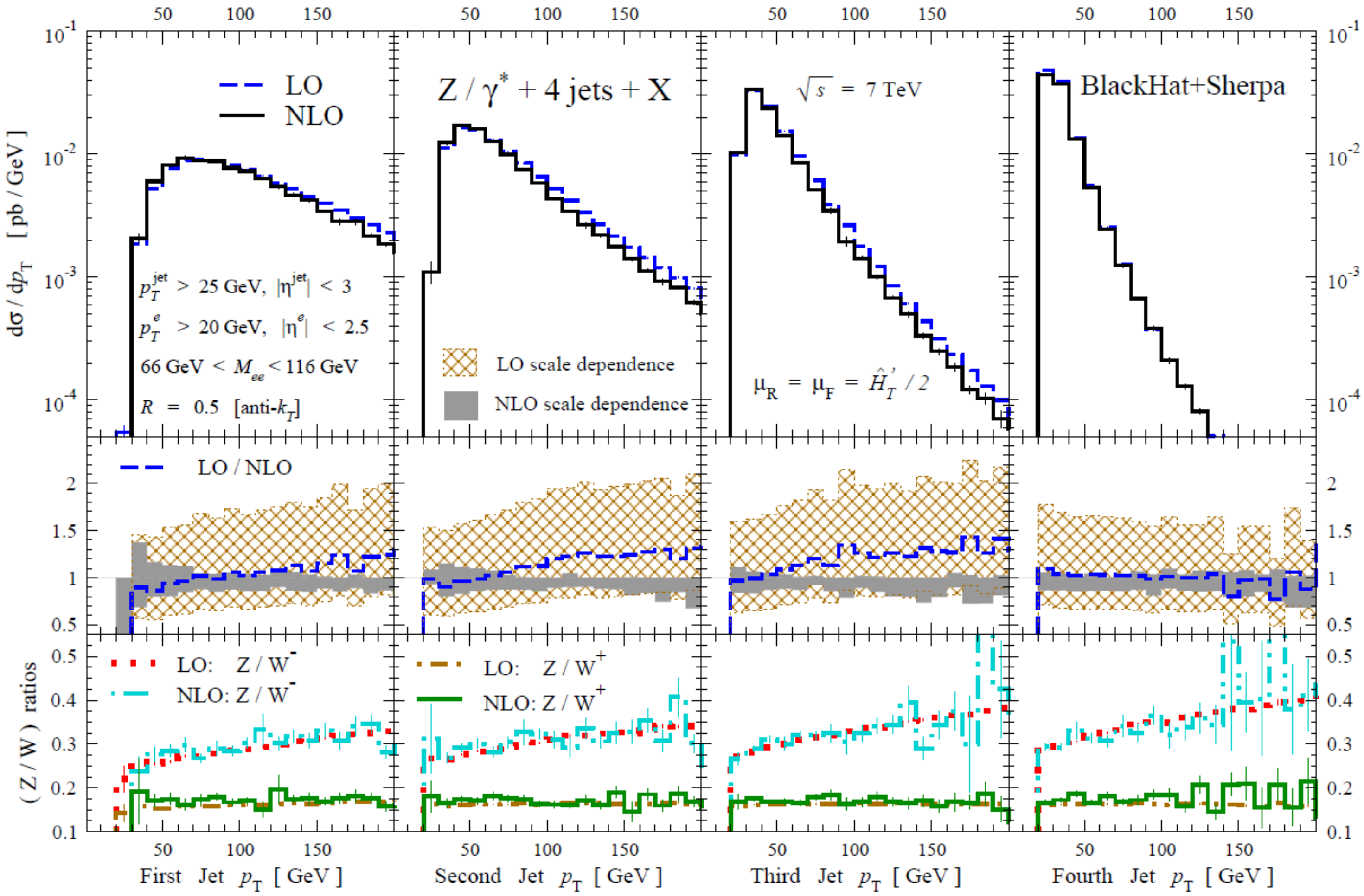
First jet in W/Z + 4 jet ratio: ~ flat in jet p_T





- Would be nice to measure with 2,3,4 jets!
- Also, why not separate W^+ from W^-?

NLO $pp \to Z + 4$ jets, and ratio to $W^{\pm}$



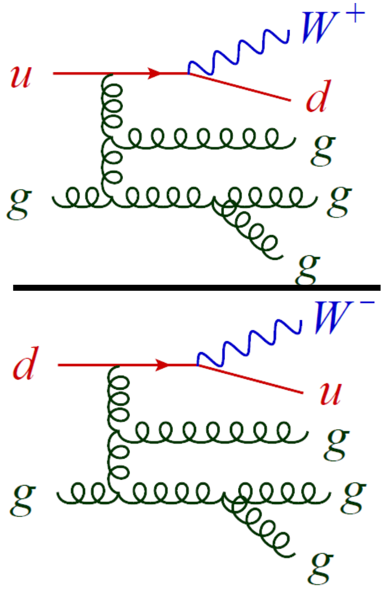
Ita et al.
1108.2229

Ratio of W^+ to W^- rates with jets

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^- ratios at NLO

BH+S, 1009.2338

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