Assisting LHC Searches Using BlackHat & SHERPA

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on behalf of the BlackHat Collaboration
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[1106.1423 & work in progress; 0907.1984 & 1103.5445]

LoopFest XI, Pittsburgh
May 10, 2012

Next-to-Leading Order in QCD

- Precision QCD requires at least NLO

- QCD at LO is not quantitative: large dependence on unphysical renormalization and factorization scales
- NLO: reduced dependence, first quantitative prediction

- Applications to Multi-Jet Processes:
  - Measurements of Standard-Model distributions & cross sections

    ⇒ Kemal Ozeren's talk
  - Estimating backgrounds in Searches
- Having a Mulitple-Jet NLO calculation is the minimal entry fee, but it's not the end of the story

On-Shell Revolution & BLACKHAT

High-multiplic parton ector-boson one-loop amplitudes using

Unitarity applied nu

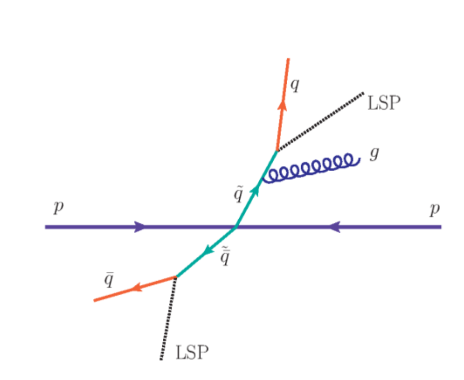
Efficient trees from ecursion, as well as explicit solutions ations in N=4 SUSY (Dixon, Henn, Pl

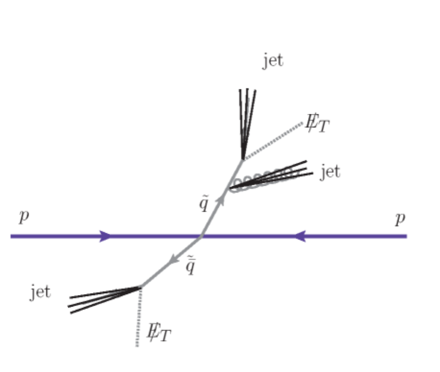
- Numerical implementati of on-shell methods one-loop amplitudes
- Automated implementation ⇒ industrialization
- C++ library: organization of amplitudes, integral basis, spinor products, residue extraction via contour integrals, tree ingredients, caching
- Do algebra numerically, analysis symbolically (“analytically”)
- SHERPA for real subtraction, real emission, phase-space integration, and (optionally) analysis

- Lots of revolutionaries roaming the world
  - BlackHat
  - CutTools+HELAC-NLO: Ossola, Papadopoulos, Pittau, Actis, Bevilacqua, Czakon, Draggiotis, Garzelli, van Hameren, Mastrolia, Worek & their clients
  - Rocket: Ellis, Giele, Kunszt, Lazopoulos, Melnikov, Zanderighi
  - Samurai: Mastrolia, Ossola, Reiter, & Tramontano
  - NGluon: Badger, Biedermann, & Uwer
  - MadLoop: Hirschi, Frederix, Frixione, Garzelli, Maltoni, & Pittau
  - Giele, Kunszt, Stavenga, Winter
- Ongoing analytic work
  - Almeida, Britto, Feng & Mirabella

Dark-Matter Searches

- … in the context of the MSSM





- $Z \to \nu\bar{\nu}$ accompanied by jets $\Rightarrow$ missing ET + jets important background

- Data-driven estimate suggested & pursued by CMS
- ➢ Estimate from W production
- ➢ Estimate from photon production – no $t\bar{t}$, higher rates

- Experimenters don’t care about theory predictions for the ratio – though they ought to
- What they really want are uncertainty estimates
- We’ll provide both

Predicting MET+Jets from γ+Jets

- Define search variables:
  - $|\text{MET}| \equiv |-\sum \boldsymbol{E}_T|$ for all jets with $p_T > 30$ & $|\eta| < 5$
  - H_t^{jets} corresponding to jets with $p_T > 50$ & $|\eta| < 2.5$

- Looking in tails of distributions, force vector p_T to large values
  - Hard cuts: control region 13% of signal, search regions 11 and 5.5%

    Control $H_t^{\text{jets}} > 300$, $|\text{MET}| > 150$; signals $H_t^{\text{jets}} > 300$, $|\text{MET}| > 250$ & $H_t^{\text{jets}} > 500$, $|\text{MET}| > 150$
  - Harder cuts: control region 5.8%, search regions 0.06 to 0.7%

    Control $H_t^{\text{jets}} > 350$, $|\text{MET}| > 200$; signals $H_t^{\text{jets}} > 500$, $|\text{MET}| > 350$; & $H_t^{\text{jets}} > 800$, $|\text{MET}| > 150$; & $H_t^{\text{jets}} > 200$, $|\text{MET}| > 500$

Measuring Photons

- Need a theoretical definition
- Must isolate photons from surrounding hadronic radiation: lots of photons inside jets
- But can't isolate too stringently: not infrared safe

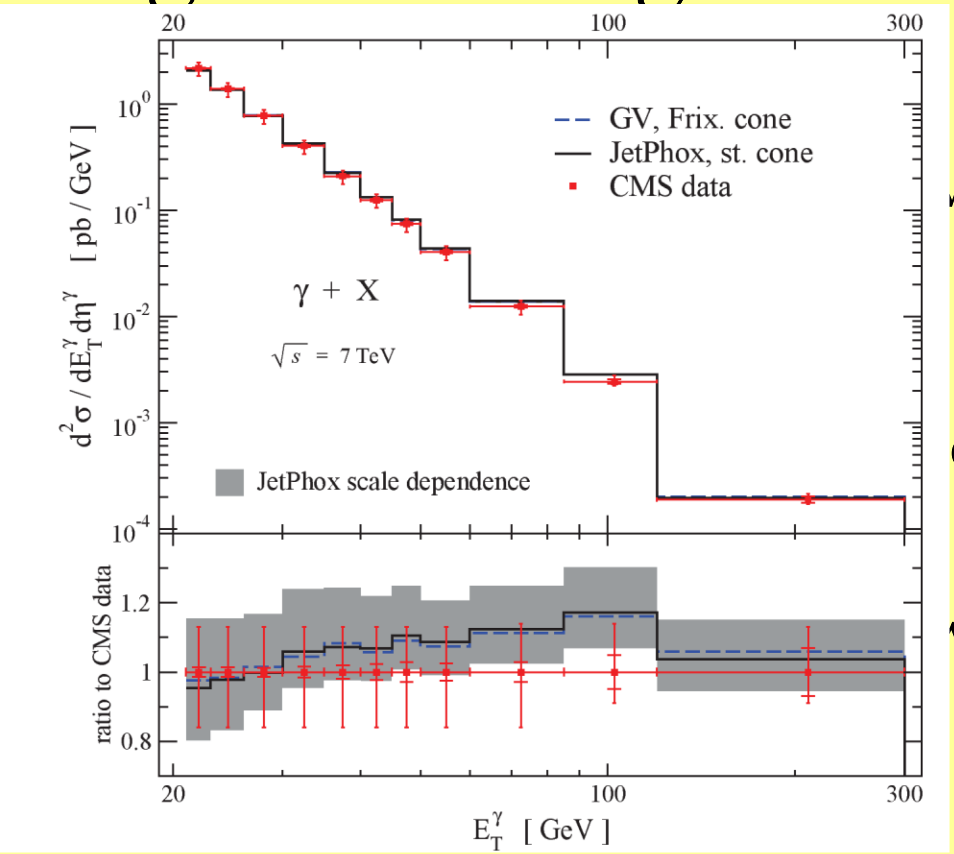
- Experiments use cones, with limit on absolute or fractional hadronic E_T inside the cone
- Requires fragmentation function contribution
  - Additional theoretical headache
  - Fragmentation function contribution must be extracted from data; not that well-known; no error sets available

- Frixione cone has a radially-dependent ET limit
- $\sum_p E_{\mathrm{T}p}\Theta(\delta - R_{p\gamma}) \leq E(\delta)$ with $E(\delta) = E_{\mathrm{T}}^{\gamma}\,\epsilon\left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)^n$
- Eliminates fragmentation function contribution because limit $\rightarrow$ 0 at the center
- But $\rightarrow$ 0 slowly enough to stay infrared safe

- We use the Frixione cone for theoretical calculations (ε = 0.025, δ_0 = 0.3, n = 2; theoretical predictions are not very sensitive to these numbers)

How Much Error Do We Introduce by Using the 'Wrong' Cone?

- Almost No
- In the high [...]wo predictions
- Additional [...]clusion
- Also suppo[...]ver calculation



V+3 Jet Cross Sections

Search
Search
Search
Search
Control
Control
Control
Search
Search
Search

Set	Prediction	$Z+$ 3-jet	$\gamma+$ 3-jet
1	LO	$0.200(0.001)^{+0.105}_{-0.064}$	$0.856(0.002)^{+0.446}_{-0.273}$
	ME+PS	0.157(0.001)	0.772(0.009)
	NLO	$0.184(0.002)^{+0.006}_{-0.022}$	$0.812(0.006)^{+0.038}_{-0.102}$
2	LO	$0.179(0.000)^{+0.095}_{-0.058}$	$0.913(0.002)^{+0.479}_{-0.292}$
	ME+PS	0.160(0.002)	0.844(0.009)
	NLO	$0.171(0.002)^{+0.008}_{-0.022}$	$0.871(0.008)^{+0.038}_{-0.107}$
3	LO	$0.664(0.001)^{+0.346}_{-0.211}$	$3.460(0.01)^{+1.780}_{-1.090}$
	ME+PS	0.533(0.006)	3.090(0.04)
	NLO	$0.616(0.005)^{+0.020}_{-0.074}$	$3.220(0.02)^{+0.105}_{-0.376}$

Preliminary

Set	Prediction	$Z+$ 2-jet	$\gamma+$ 2-jet
1	LO	$0.512(0.001)^{+0.188}_{-0.128}$	$2.050(0.00)^{+0.745}_{-0.508}$
	ME+PS	0.432(0.002)	1.930(0.02)
	NLO	$0.540(0.002)^{+0.020}_{-0.048}$	$2.370(0.02)^{+0.186}_{-0.256}$
2	LO	$0.200(0.000)^{+0.075}_{-0.051}$	$0.933(0.001)^{+0.346}_{-0.235}$
	ME+PS	0.236(0.002)	1.140(0.01)
	NLO	$0.266(0.001)^{+0.035}_{-0.036}$	$1.340(0.01)^{+0.207}_{-0.196}$
3	LO	$1.230(0.00)^{+0.445}_{-0.304}$	$5.780(0.00)^{+2.050}_{-1.410}$
	ME+PS	1.160(0.01)	6.120(0.04)
	NLO	$1.410(0.00)^{+0.091}_{-0.144}$	$7.290(0.03)^{+0.782}_{-0.876}$

Preliminary

5	ME+PS	0.0284(0.0003)	0.124(0.002)
	NLO	$0.0315(0.0004)^{+0.0012}_{-0.0040}$	$0.133(0.002)^{+0.007}_{-0.018}$
	ME+PS	0.0173(0.0002)	0.0795(0.0010)
	NLO	$0.0175(0.0007)^{+0.0012}_{-0.0024}$	$0.0837(0.0010)^{+0.0072}_{-0.0123}$
	LO	$0.00275(0.00002)^{+0.00152}_{-0.00091}$	$0.0107(0.0001)^{+0.0059}_{-0.0035}$
	ME+PS	0.00245(0.00003)	0.0100(0.0002)
	NLO	$0.00269(0.00005)^{+0.00027}_{-0.00043}$	$0.0104(0.0002)^{+0.0008}_{-0.0016}$

Three different theoretical predictions: noticeable corrections from LO to NLO & ME+PS to NLO; don't expect absolute normalization to be correct
Scale variation shrinks from LO to NLO

Let's look at various ratios, also vs V+2 jet cross sections, where LO→NLO shows bigger shift

How Should We Estimate the Uncertainty in the Ratio?

- Only truly honest way within fixed order is comparing to NNLO – but that's a ways off

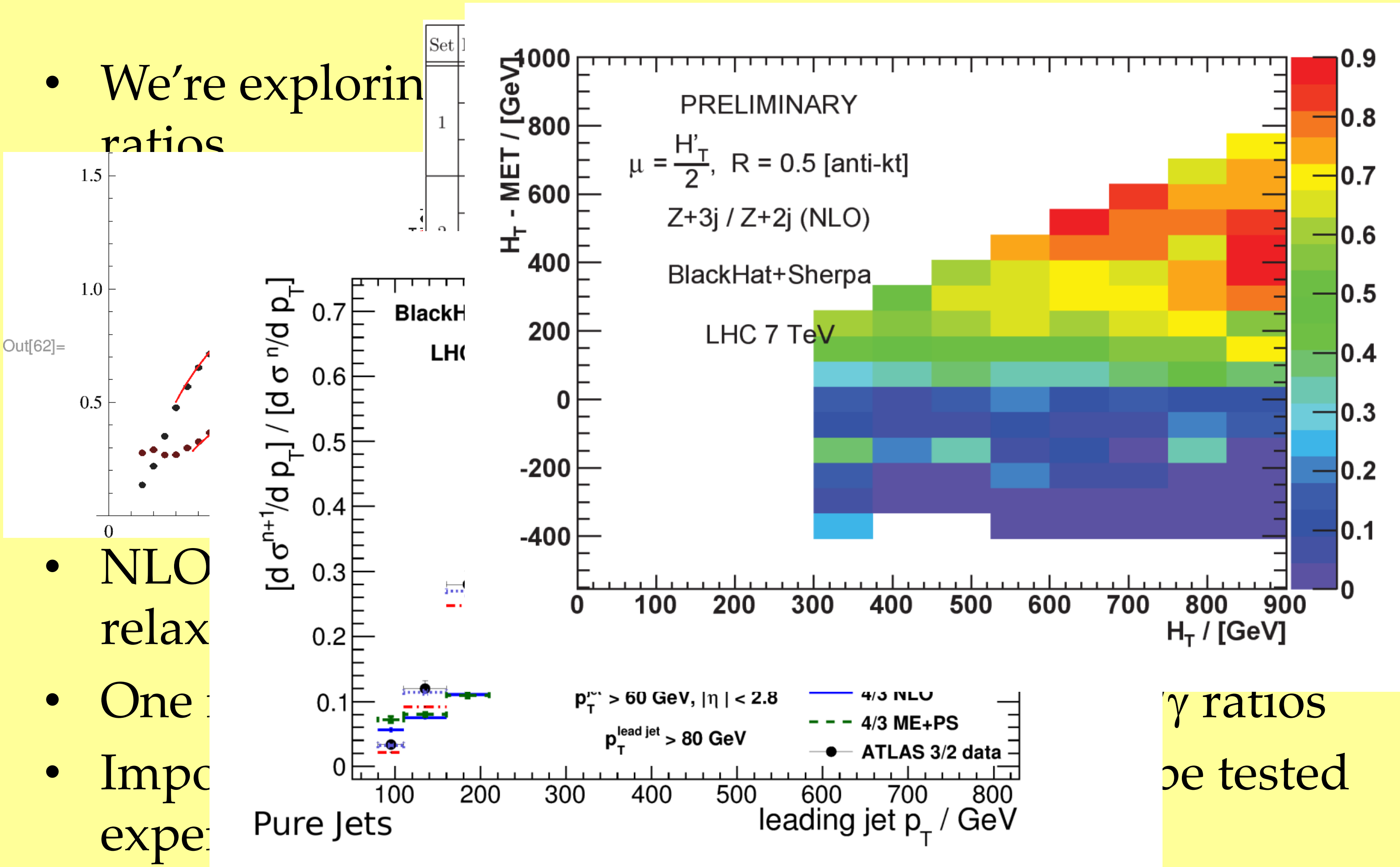
- Scale variation is typically used as a proxy

- But here, [correlated] scale variations in the ratio are tiny, $< 0.5\%$
  - Good, because it makes the prediction more robust
  - But means that the scale variation clearly underestimates the remaining uncertainties

- Need a second theoretical calculation: parton shower matched to LO matrix elements (ME+PS), using SHERPA & CKKW-style matching

How Stable is the Fixed-Order Prediction?

- We're explorin
  ratios
- NLO
  relax
- One γ ratios
- Impo be tested
  expe



Peering into the ME+PS Calculation

- Can't use off-the-shelf SHERPA
- Important to ensure that treatment of Z and γ is same in matched shower
- Matching in SHERPA requires CKKW-type clustering of matrix element configurations back to shower initiators
  - For massive bosons, helicity information to do this exactly isn't available
  - Code clusters neutrinos on same footing as other decay products, leading to a bias in treatment of radiation for $pT < M_Z$
- Use custom version with Z decay products preclustered

Z/γ Ratios in Search Regions

- Last year, a … using Z+2/γ+2 ratio
- Here, exten …

Preliminary

Set	Prediction	Z + 3-jet/γ + 3-jet	Z + 2-jet/γ + 2-jet	ratio
1	LO	0.233(0.001)	0.250(0.000)	0.933(0.004)
	ME+PS	0.204(0.003)	0.224(0.002)	0.913(0.020)
	NLO	0.226(0.003)	0.228(0.002)	0.992(0.020)
2	LO	0.196(0.001)	0.215(0.000)	0.914(0.004)
	ME+PS	0.190(0.003)	0.207(0.002)	0.916(0.020)
	NLO	0.196(0.003)	0.199(0.001)	0.986(0.010)
3	LO	0.192(0.001)	0.213(0.000)	0.899(0.003)
	ME+PS	0.173(0.003)	0.190(0.001)	0.908(0.020)
	NLO	0.191(0.002)	0.193(0.001)	0.990(0.010)

- NLO prediction is extremely stable (<4.5%) under addition of one jet
- LO & ME+PS vary by up to 10%

Electroweak Sudakovs & Real Corrections

- In addition to QCD corrections, there are electroweak corrections arising from exchange of virtual EW bosons, or real emissions of them
- Detailed calculation of virtual corrections is supposed to be straightforward in SCET formalism
- Estimates based on Maina, Moretti, Ross & Kuhn, Kulesza, Pozzorini & Schulze suggest 5–15% corrections for hard to hardest cuts
- Estimate of leading EW real-emission corrections (W emission producing the jet pair) suggests corrections are small (3–4%)

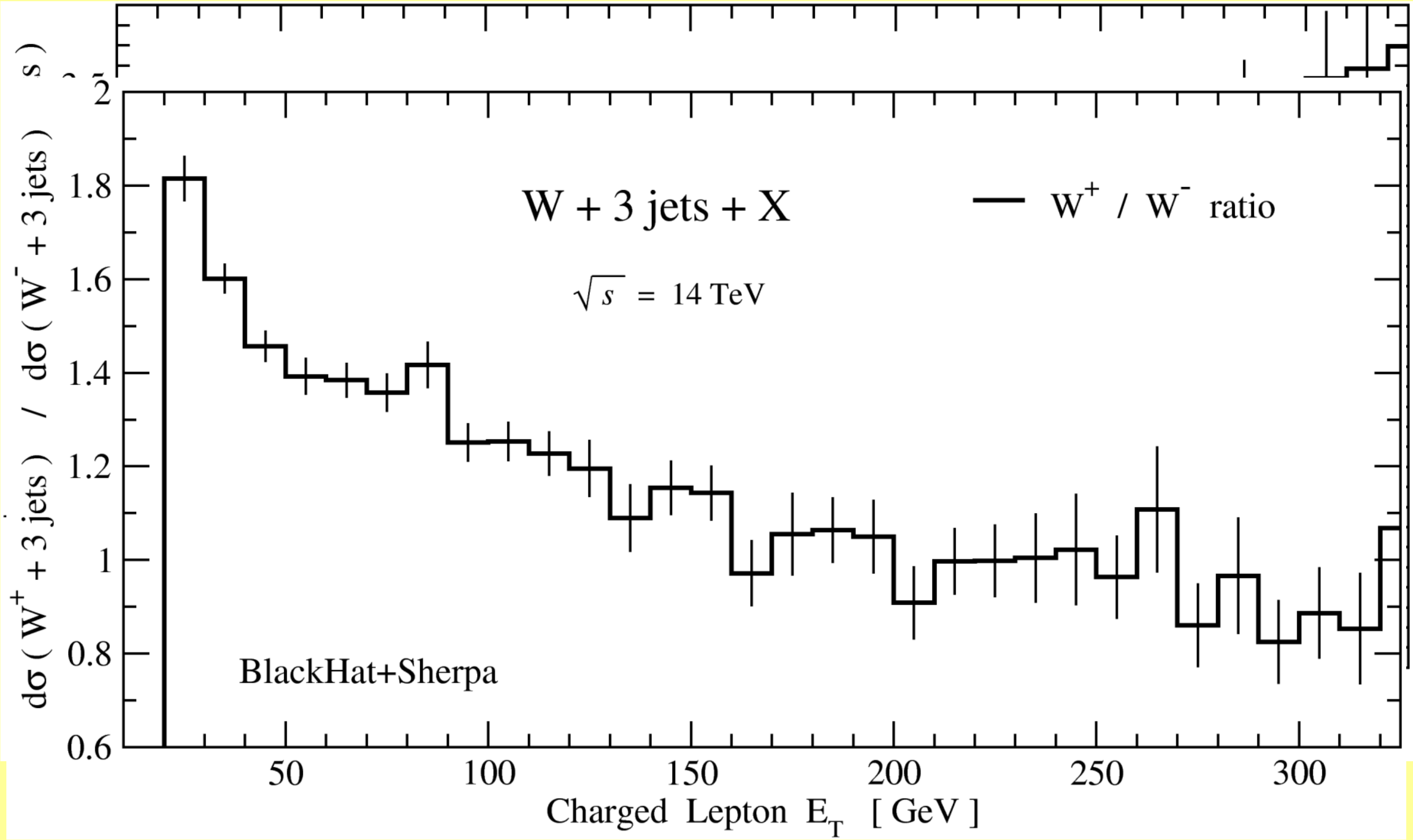
QCD Uncertainty Estimates

Source \ Set	1	2	3	4	5	6	7
perturbative	0.0981	0.0320	0.0952	0.0980	0.0292	0.0431	0.0571
PDF	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400
photon-cone	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
total	0.106	0.0522	0.104	0.106	0.0505	0.0597	0.0704

Preliminary

- In agreement with earlier analysis suggesting 10%

W+3 jets at the LHC: W^+/W^- Ratio



W Polarization

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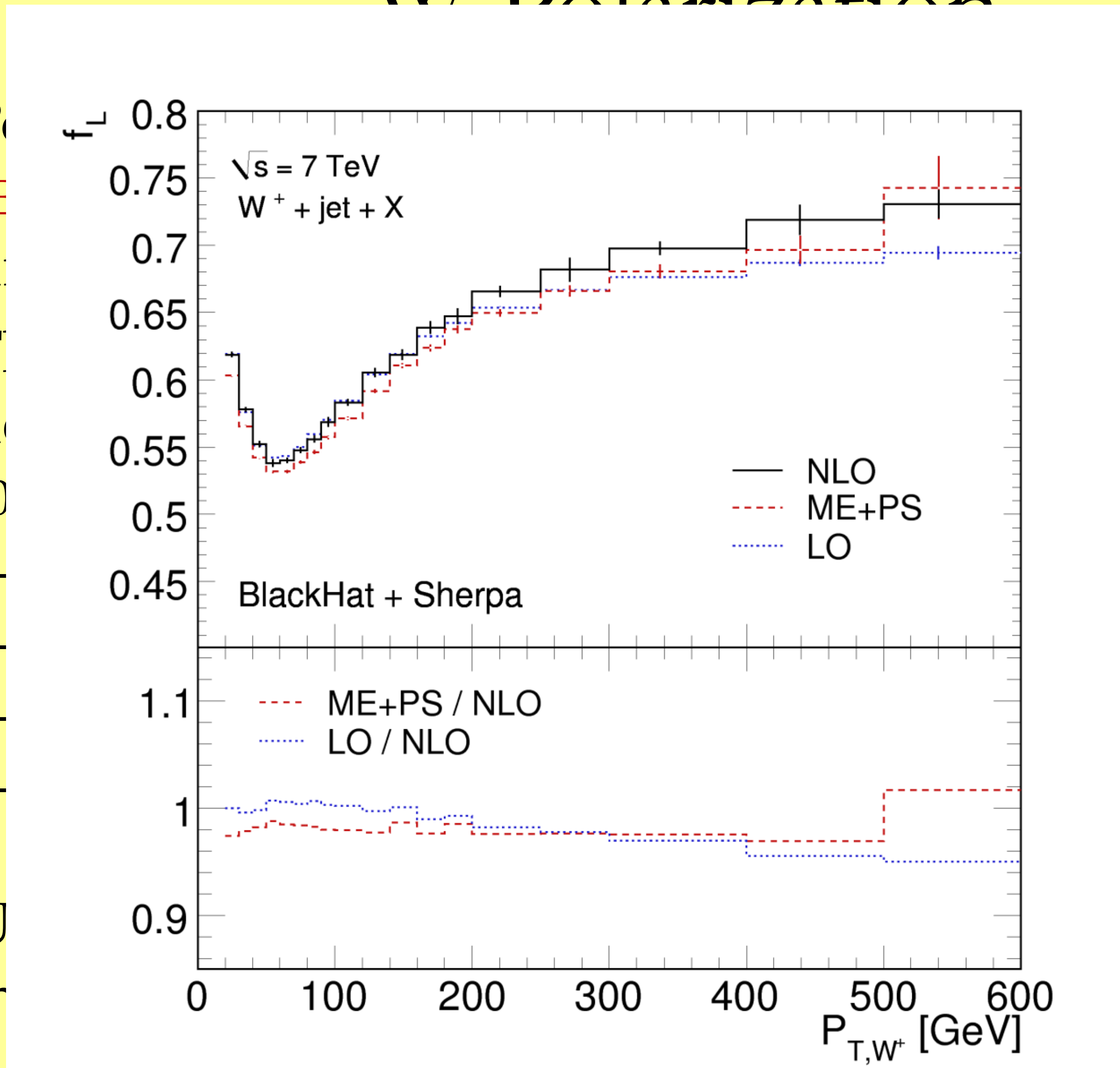

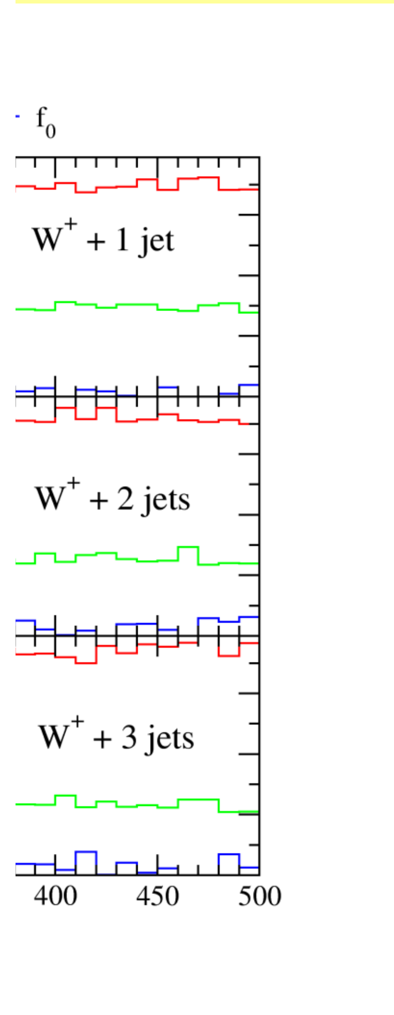

- U... in...
- Measurements by CMS and Atlas

CMS W Polarization Measurement

- Use lepton projection variable $L_P = \frac{\vec{p}_\mathrm{T}(\ell)\cdot\vec{p}_\mathrm{T}(W)}{|\vec{p}_\mathrm{T}(W)|^2}$ and maximum likelihood fit to determine $f_L - f_R$, f_0

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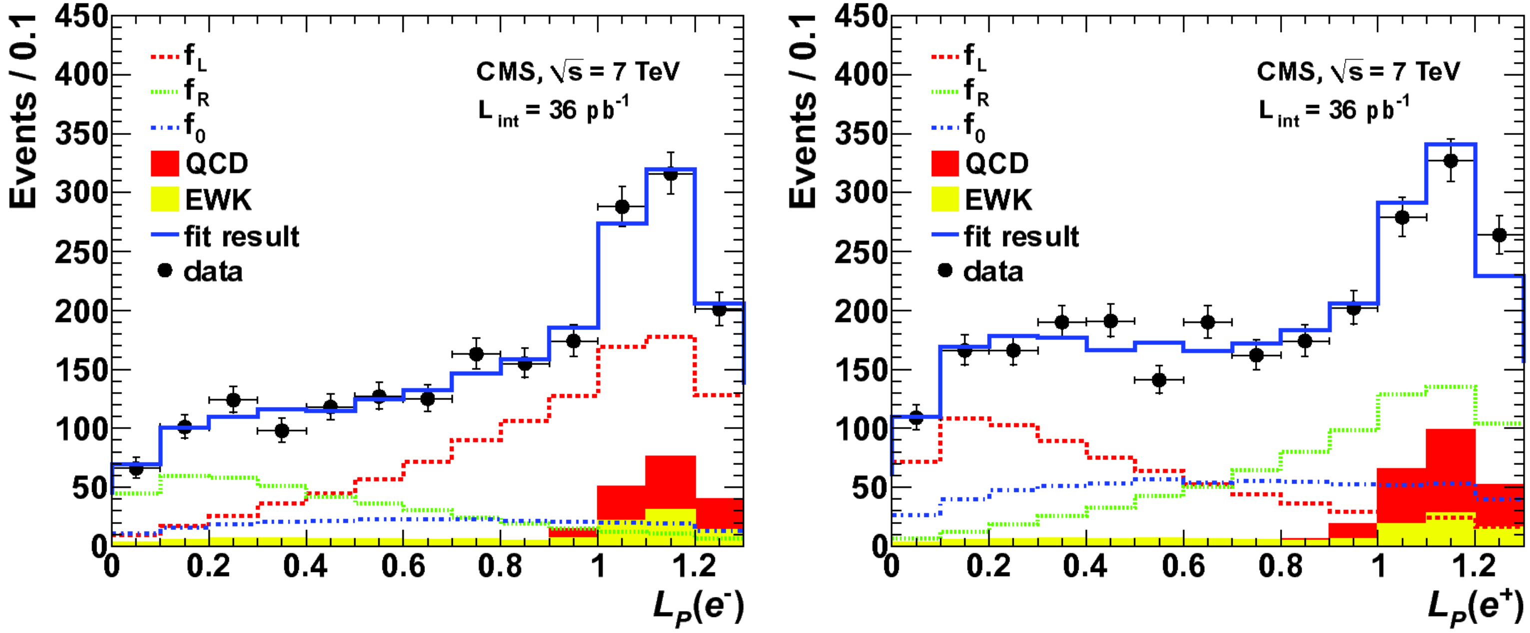
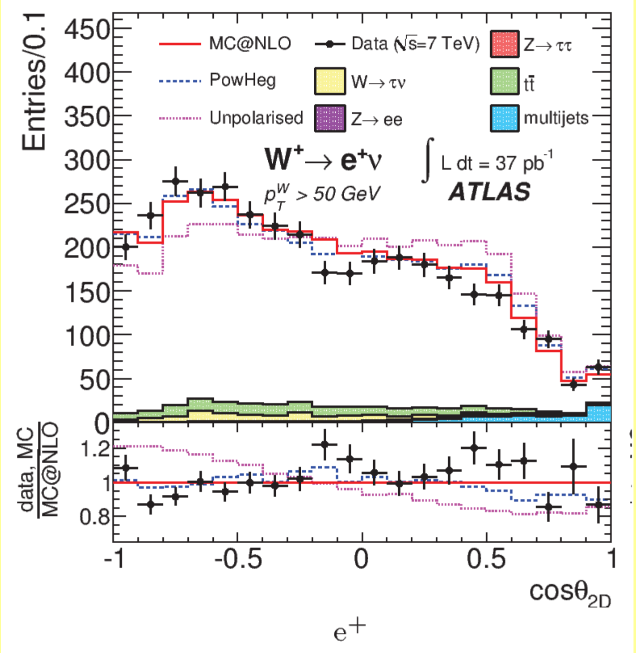


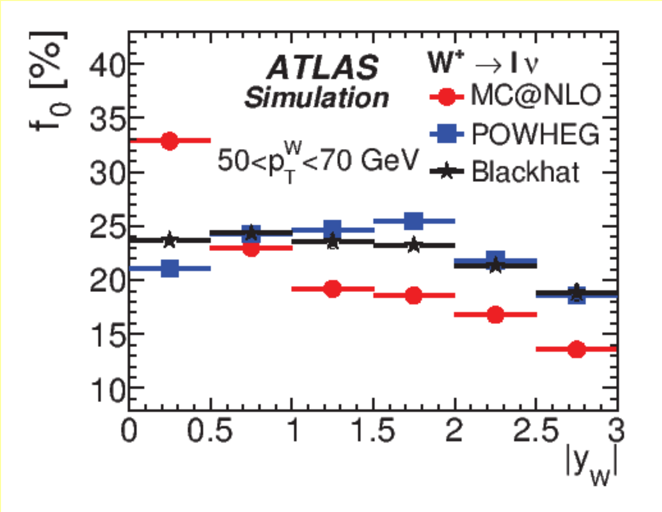
Combined (e^-,μ^-): $f_L - f_R = 0.226 \pm 0.031$ (stat.) $\pm\, 0.050$ (syst.)

Combined (e^+,μ^+): $f_L - f_R = 0.300 \pm 0.031$ (stat.) $\pm\, 0.034$ (syst.)

Atlas Measurement

- Fit templates to angular distribution projected onto transverse plane



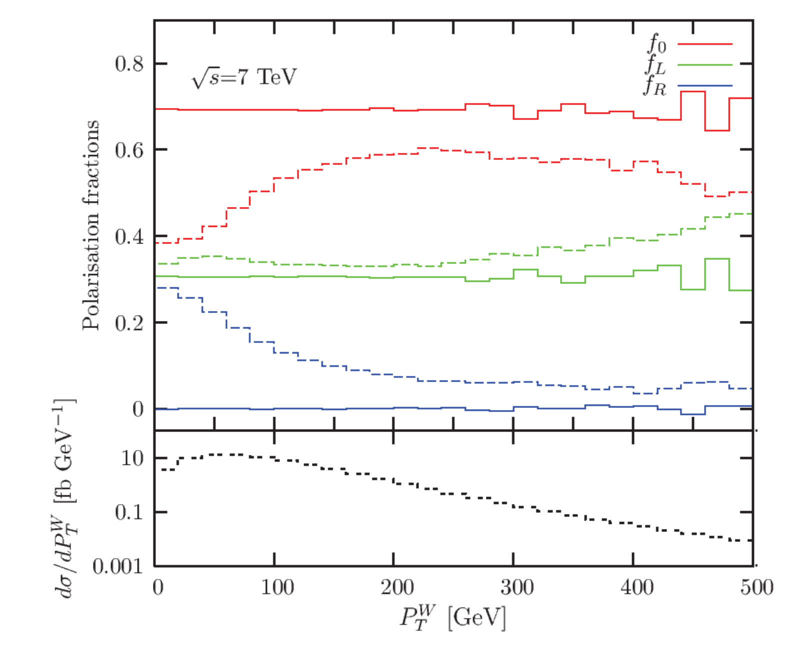


- Transverse polarization agrees nicely between different codes… longitudinal doesn't

Polarization of Non-Prompt W

Stirling & Vryonidou

Differs widely for different processes



Example: W+ from top decay (top rest & lab frames)

Summary

- On-shell methods are maturing into the method of choice for QCD calculations for colliders

- Applications to LHC searches
  - Data-driven estimates of backgrounds to MET+jets in CMS susy search
  - Developing W polarization as a tool