NLO Theory for SUSY Searches

October 19, 2011

Zvi Bern, UCLA (on behalf of BlackHat)

BlackHat Collaboration current members:
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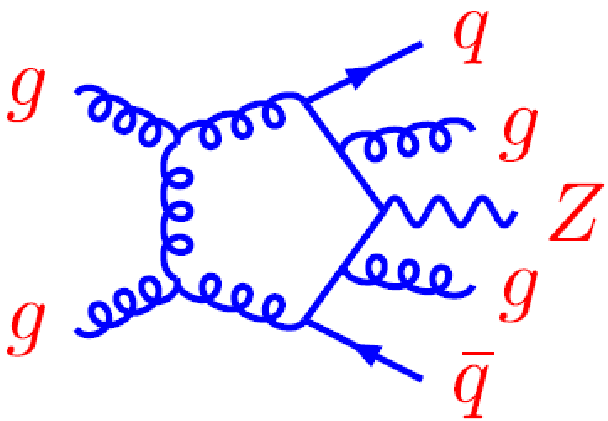
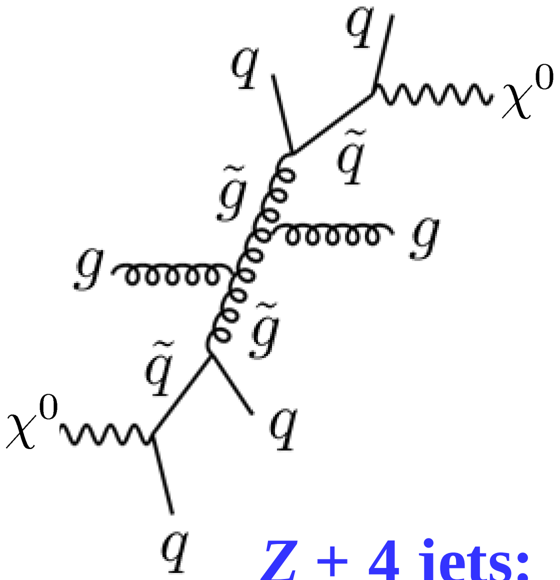
D. Kosower, D. Maitre, K. Ozeren



Outline

- Recent theoretical progress in performing NLO QCD computations.
- Will present *W*, *Z* + 3,4 jets at the LHC as examples.
- Comparison to data.
- Example where NLO QCD has already significantly helped CMS with susy search.
- Prospects for future: Many new NLO calculations are going to be completed in coming years.

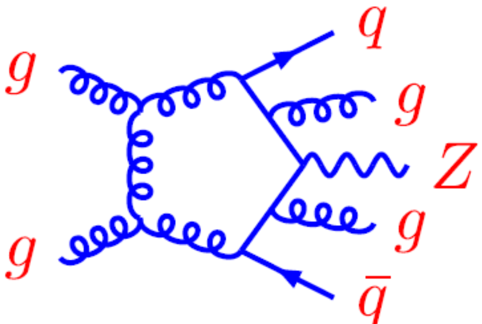
Example: Susy Search



- Cascade from gluino to neutralino (escapes detector)
- Signal: missing energy + 4 jets
- SM background from Z + 4 jets, Z → neutrinos

Z + 4 jets: Standard tools, e.g ALPGEN, based on LO tree amplitudes → normalization still quite uncertain. Questions on shape.

To improve we want $pp \to Z + 4$ jets at NLO



Now done!

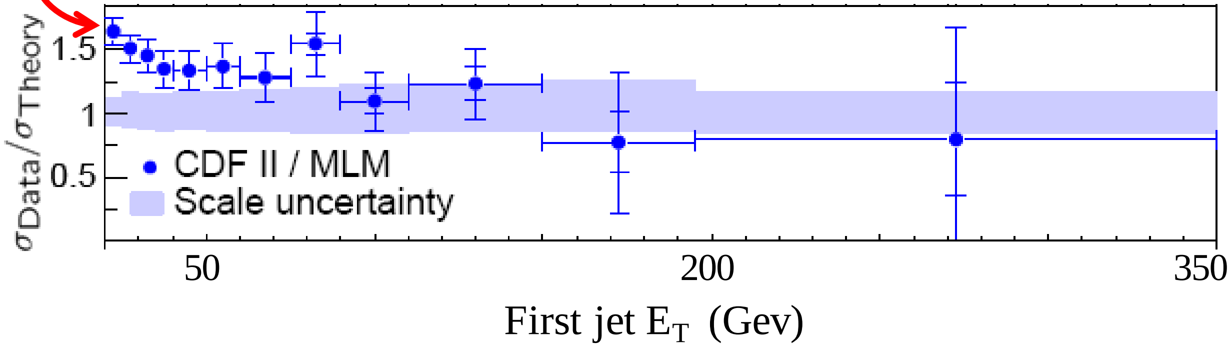
Why we do NLO

CDF collaboration arXiv: 0711.4044

note disagreement

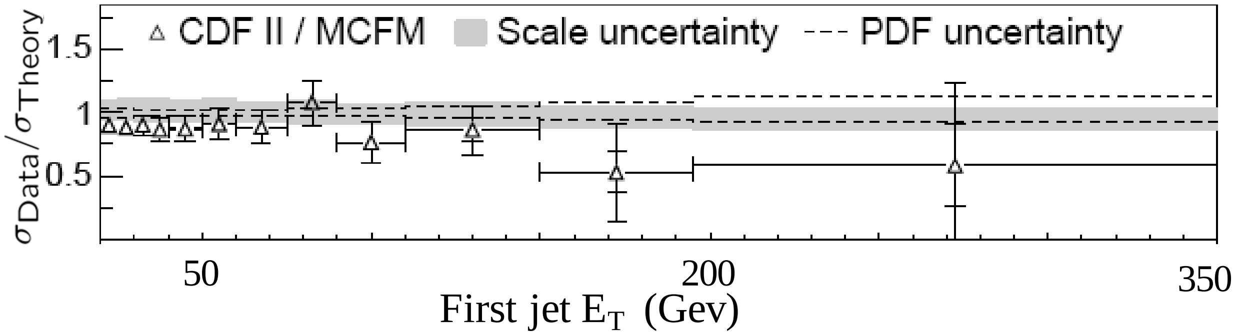
W + 2 jets at the Tevatron

LO



leading order + parton showering

NLO QCD

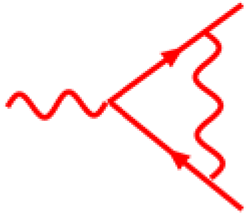


NLO does better, smallest theoretical uncertainty

Want similar studies at the LHC and Tevatron with extra jets.

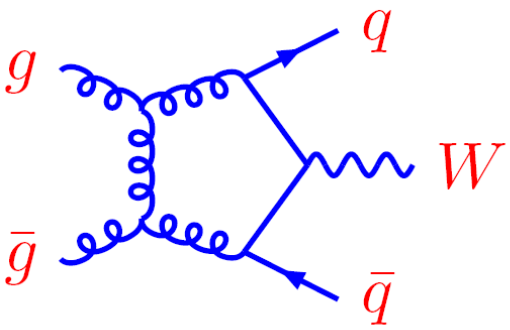
State-of-the-Art NLO Calculations

In 1948 Schwinger computed anomalous magnetic moment of the electron.



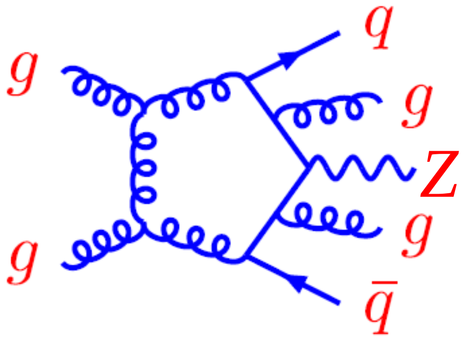
60 years later typical example we can calculate via Feynman diagrams:

$$pp \longrightarrow W, Z + 2 \text{ jets}$$



Only two more legs than Schwinger!

For LHC physics we need also four or more final state objects

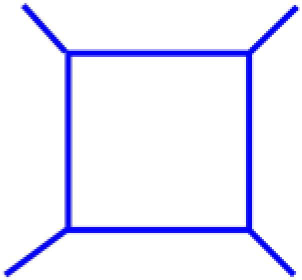


- Z+3,4 jets not yet done via Feynman diagrams.
- Widespread applications to LHC physics.

$$pp \to W, Z + 3, 4 \text{ jets}$$

Example of loop difficulty

Consider a tensor integral:

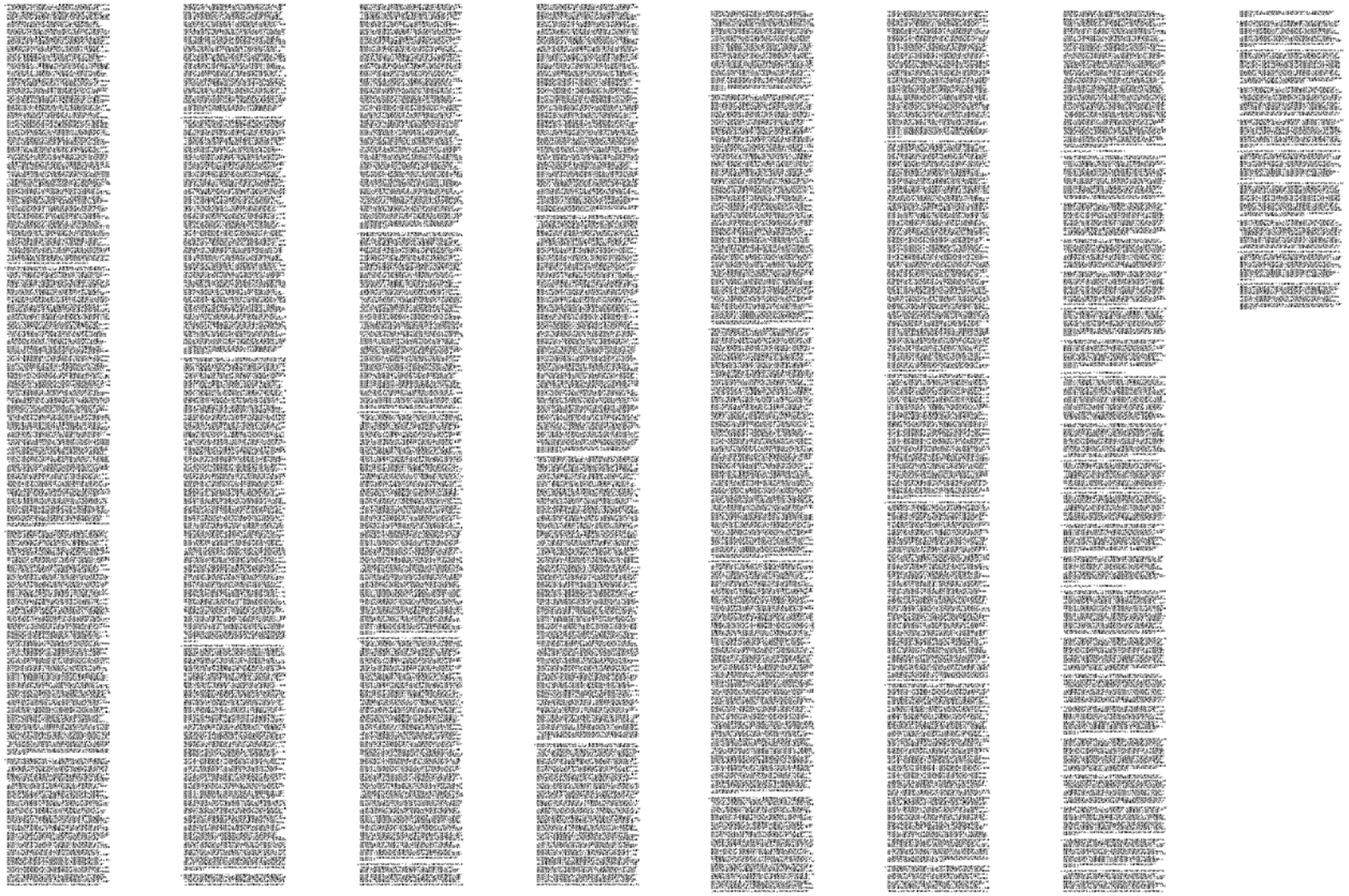


$$\int \frac{d^{4-2\epsilon}\ell}{(2\pi)^{4-\epsilon}} \frac{\ell^\mu\, \ell^\nu\, \ell^\rho\, \ell^\lambda}{\ell^2\, (\ell - k_1)^2\, (\ell - k_1 - k_2)^2\, (\ell + k_4)^2}$$

Note: this is trivial on modern computer. Non-trivial for larger numbers of external particles.

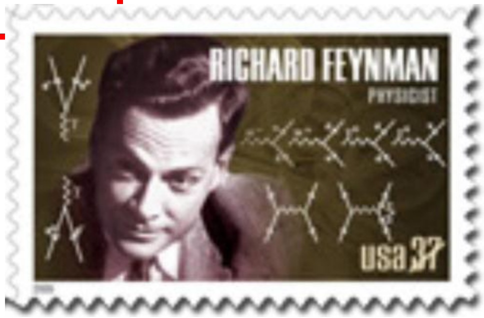
Evaluate this integral via Passarino-Veltman reduction. Result is …

Result of performing the integration

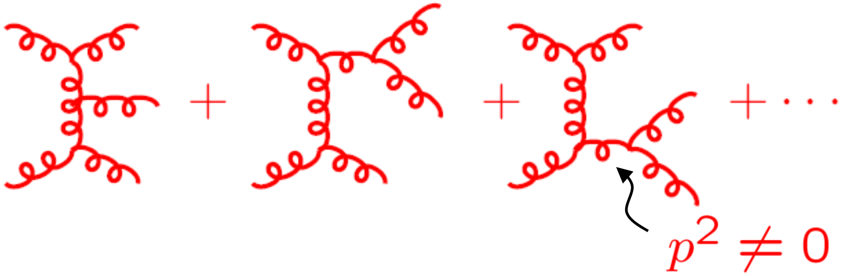


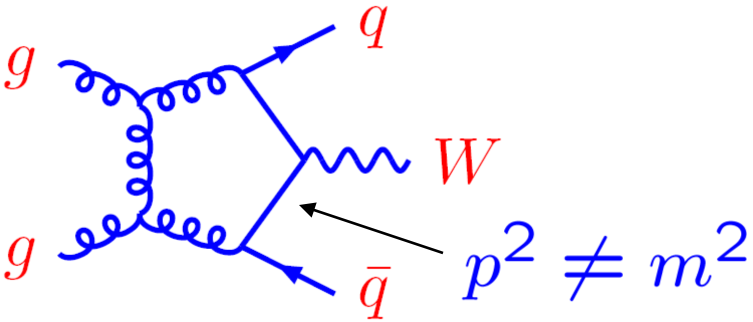
Calculations explode for larger numbers of particles or loops. Clearly, there should be a better way!

Why are Feynman diagrams clumsy for high-loop or multiplicity processes?



- Vertices and propagators involve gauge-dependent off-shell states. Origin of the complexity.

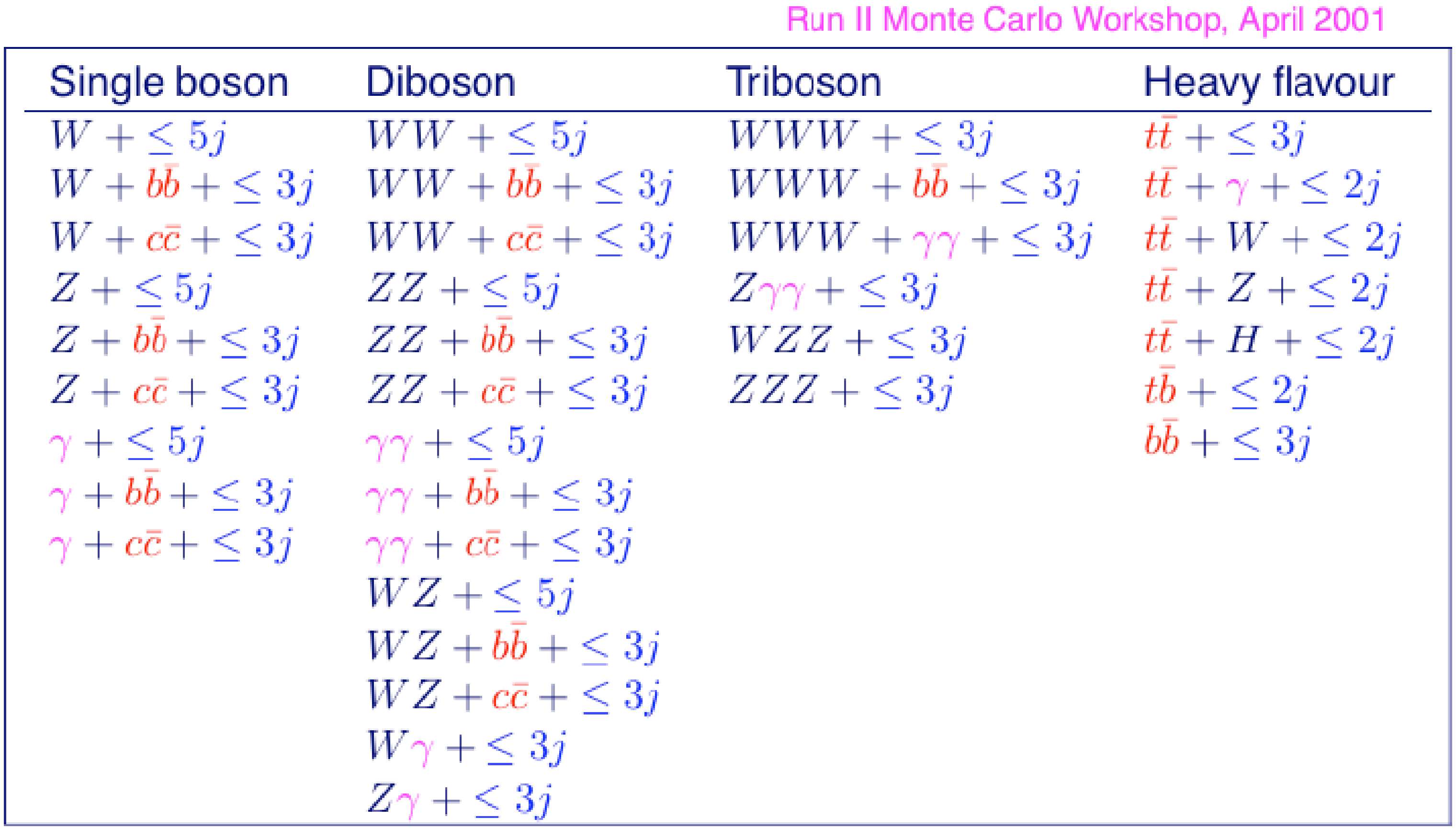




- To get at root cause of the trouble we must rewrite perturbative quantum field theory.

- **All steps should be in terms of gauge invariant on-shell states.** $p^2 = m^2$ **On shell formalism.**
- **Radical rewrite of gauge theory needed.**

Amusing NLO Wish List



Run II Monte Carlo Workshop, April 2001

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

Just about every process of process of interest listed

The Les Houches Wish List (2010)

2010

process wanted at NLO	background to
1. $pp \to VV +$ jet	$t\bar{t}H$, new physics Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi
2. $pp \to H + 2$ jets	H in VBF Campbell, Ellis, Zanderighi; Ciccolini, Denner Dittmaier
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$ Bredenstein, Denner Dittmaier, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$ Bevilacqua, Czakon, Papadopoulos, Worek
5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF $\to H \to VV$ Melia, Melnikov, Rontsch, Zanderighi VBF: Bozzi, Jäger, Oleari, Zeppenfeld
7. $pp \to V + 3$ jets	new physics Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre; Ellis, Melnikov, Zanderighi
8. $pp \to VVV$	SUSY trilepton Lazopoulos, Melnikov, Petriello; Hankele, Zeppenfeld; Binoth, Ossola, Papadopoulos, Pittau
9. $pp \to b\bar{b}b\bar{b}$	Higgs, new physics GOLEM

Feynman diagram methods

now joined by

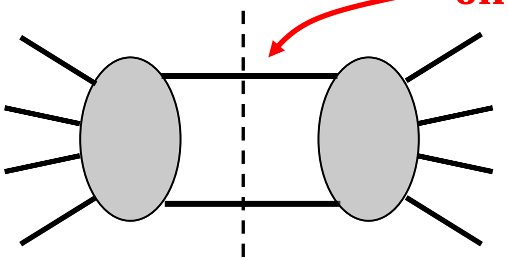
unitarity based methods

2005 list basically done. Want to go beyond this

On-shell Methods

Key idea: Rewrite quantum field theory so only gauge invariant onshell quantities appear in intermediate steps.

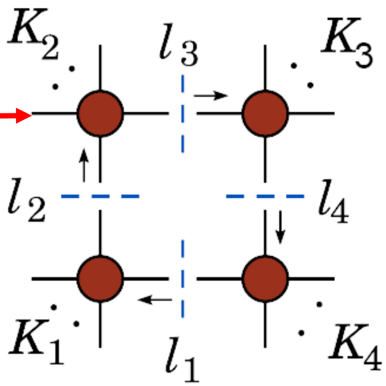
Loops amplitudes constructed from tree amplitudes .


on-shell physical

Unitarity method

Bern, Dixon, Dunbar and Kosower (BDDK)

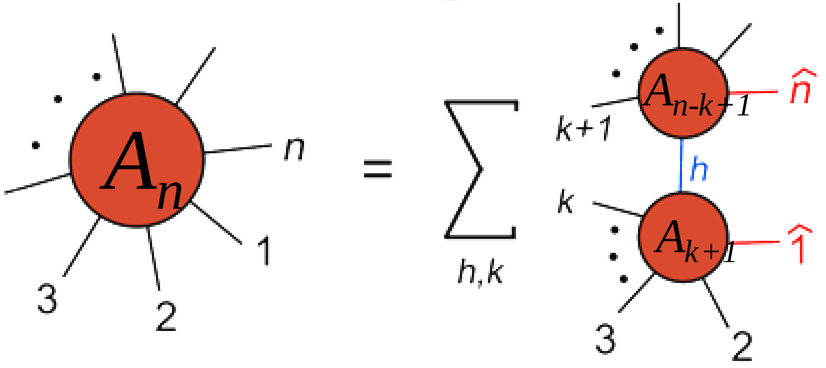
Generalized unitarity as a practical tool:



tree amplitude

Bern, Dixon and Kosower
Britto, Cachazo and Feng,
Ossola, Papadopoulos, Pittau;
Giele, Kunszt and Melnikov
Forde; Badger; Mastrolia

On-shell recursion



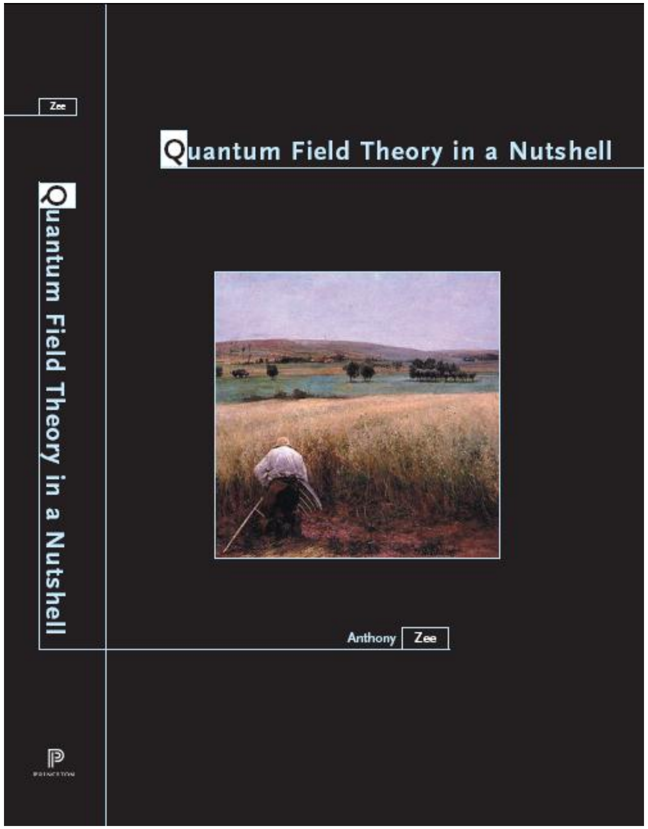
Britto, Cachazo, Feng and Witten (BCFW)

Further Reading

For an introduction to the basic concepts of on-shell methods I recommend:

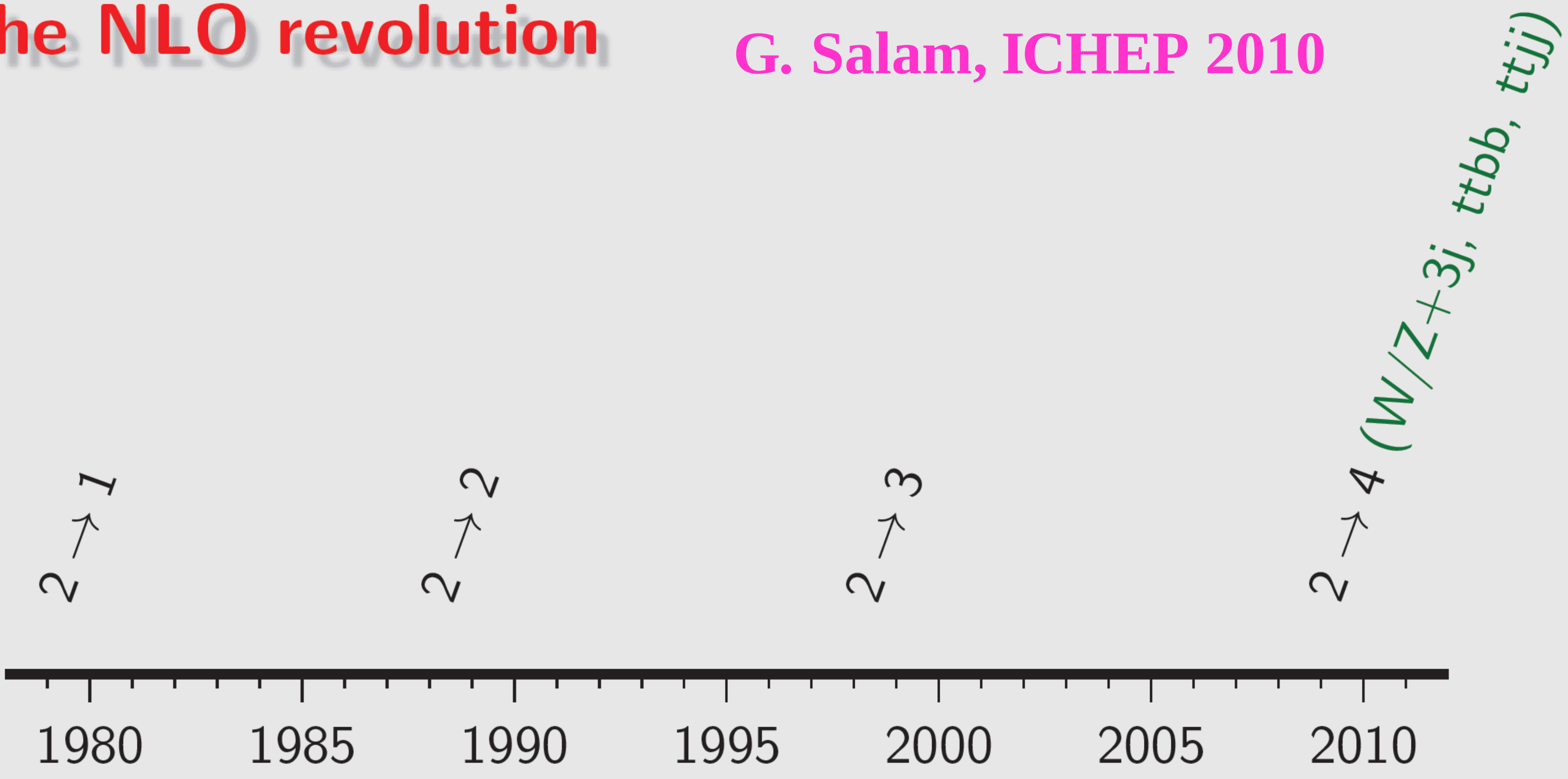
Quantum Field Theory in a Nutshell, **2nd edition, by Tony Zee.**

First textbook to contain modern formulation of scattering and commentary on new developments. Four new chapters compared to first edition.



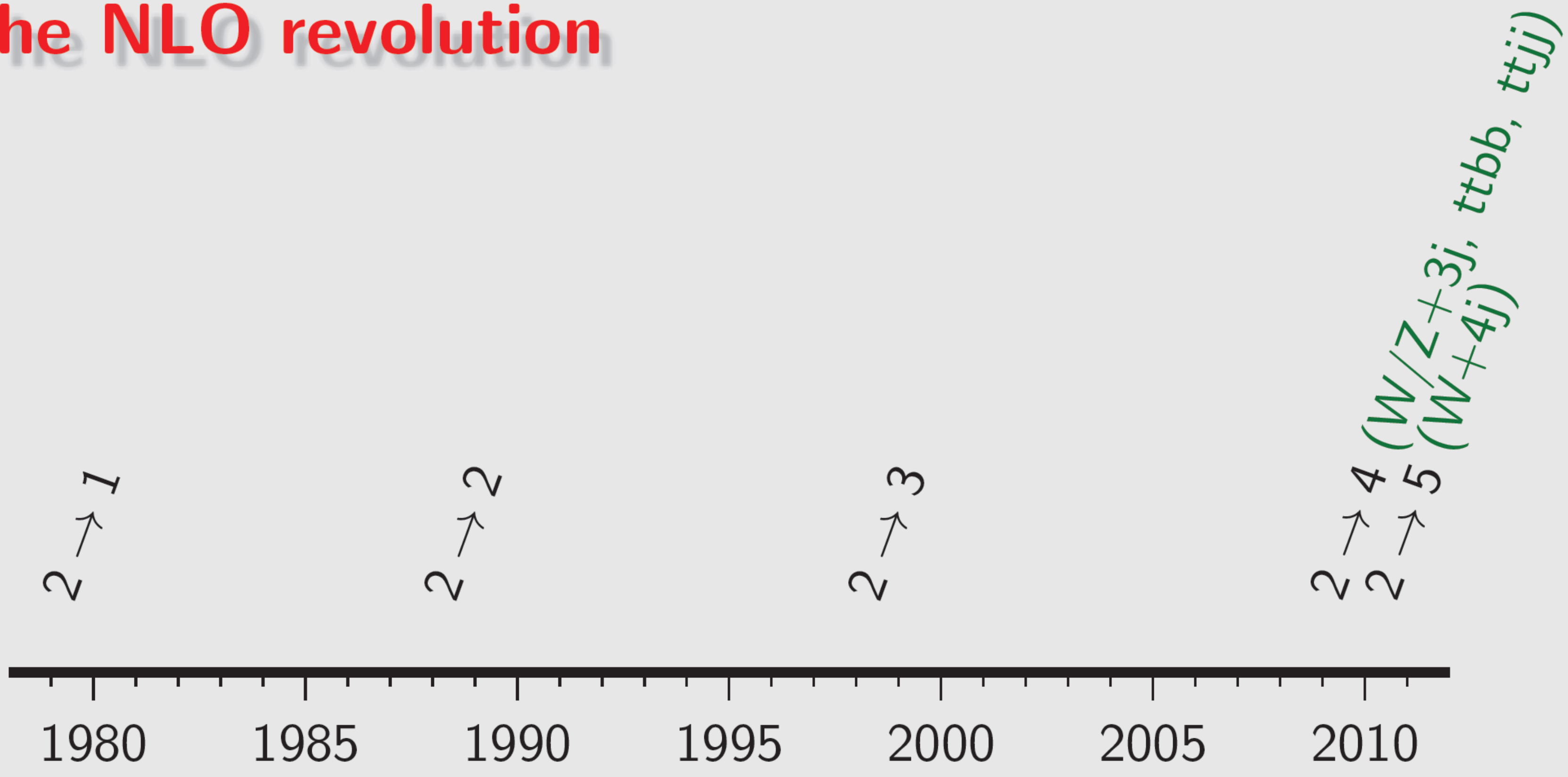
The NLO revolution

G. Salam, ICHEP 2010



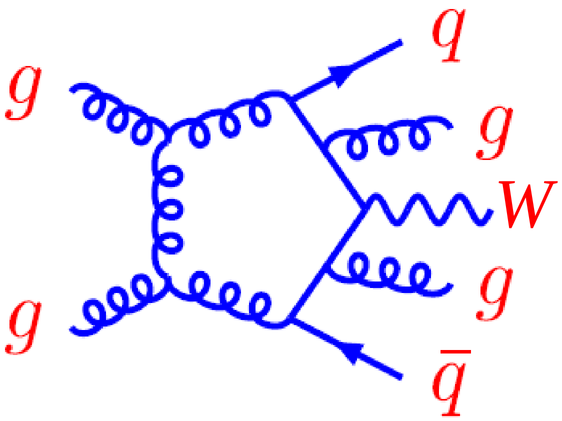
2009: NLO W+3j [Rocket: Ellis, Melnikov & Zanderighi] [unitarity]
2009: NLO W+3j [BlackHat: Berger et al] [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al] [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [Golem: Binoth et al] [traditional]
2010: NLO $t\bar{t}jj$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2010: NLO Z+3j [BlackHat: Berger et al] [unitarity]

The NLO revolution



2010: NLO W+4j [BlackHat: Berger et al, preliminary] [unitarity]

BlackHat



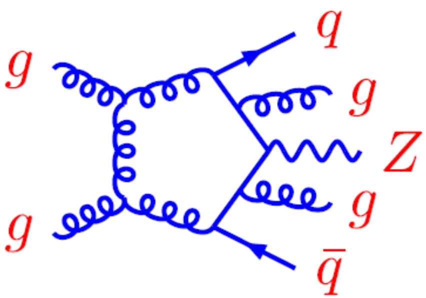
Berger, ZB, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre
New Members (not shown): Diana and Ozeren

BlackHat: C++ implementation of on-shell methods for one-loop amplitudes

Berger, ZB, Dixon, Febres Cordero,
Forde, Gleisberg, Ita, Kosower, Maitre

BlackHat is a C++ package for numerically computing one-loop matrix elements with 6 or more external particles.

- Input is on-shell tree-level amplitudes.
- Output is numerical on-shell one-loop amplitudes.

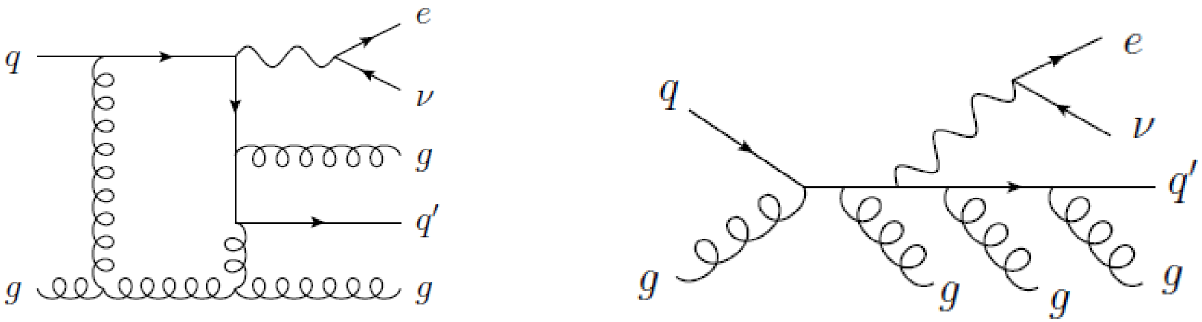


On-shell methods used to achieve the speed and stability required for LHC phenomenology at NLO.

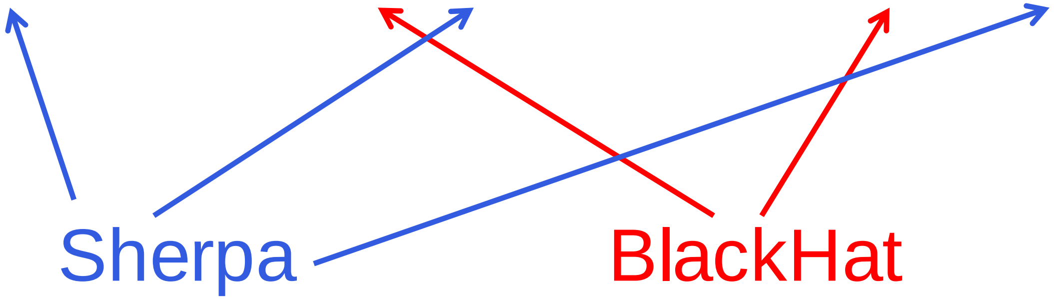
Other (semi) on-shell packages under construction

- **Helac-1loop:** Bevilacqua, Czakon, Ossola, Papadopoulos, Pittau, Worek
- **Rocket:** Ellis, Giele, Kunszt, Melnikov, Zanderighi
- **SAMURAI:** Mastrolia, Ossola, Reiter, Tramontano
- **MadLoop:** Hirchi, Maltoni, Frixione, Frederix, Garzelli, Pittau

BlackHat + Sherpa



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



Sherpa

BlackHat

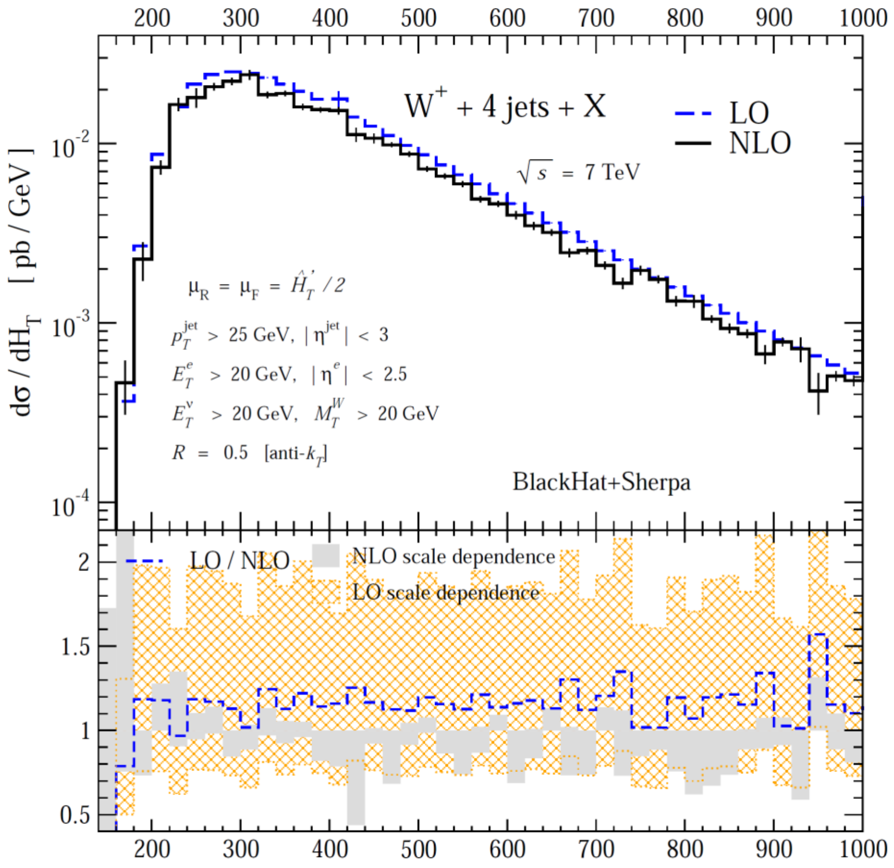
Sherpa integrates phase space.
Uses Catani-Seymour dipole formalism
for IR singularities, automated in Amegic package.

Gleisberg and Krauss

First NLO calculation of *W* + 4 jets

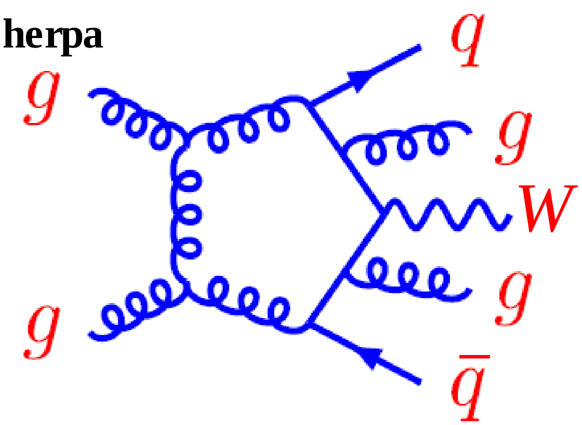
Berger, ZB, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre [BlackHat collaboration]

W+4 jets H_T distribution



H_T [GeV] –total transverse energy

BlackHat + Sherpa



NLO QCD provides the *best* available theoretical predictions. Leptonic decays of *W* and *Z*'s give missing energy.

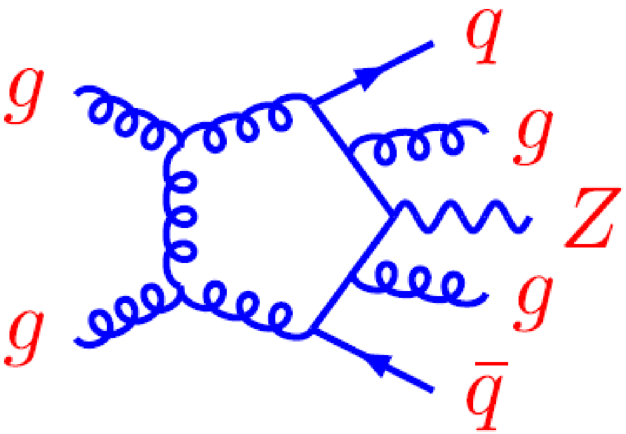
- **On-shell methods really work!**
- **2 legs beyond Feynman diagrams!**

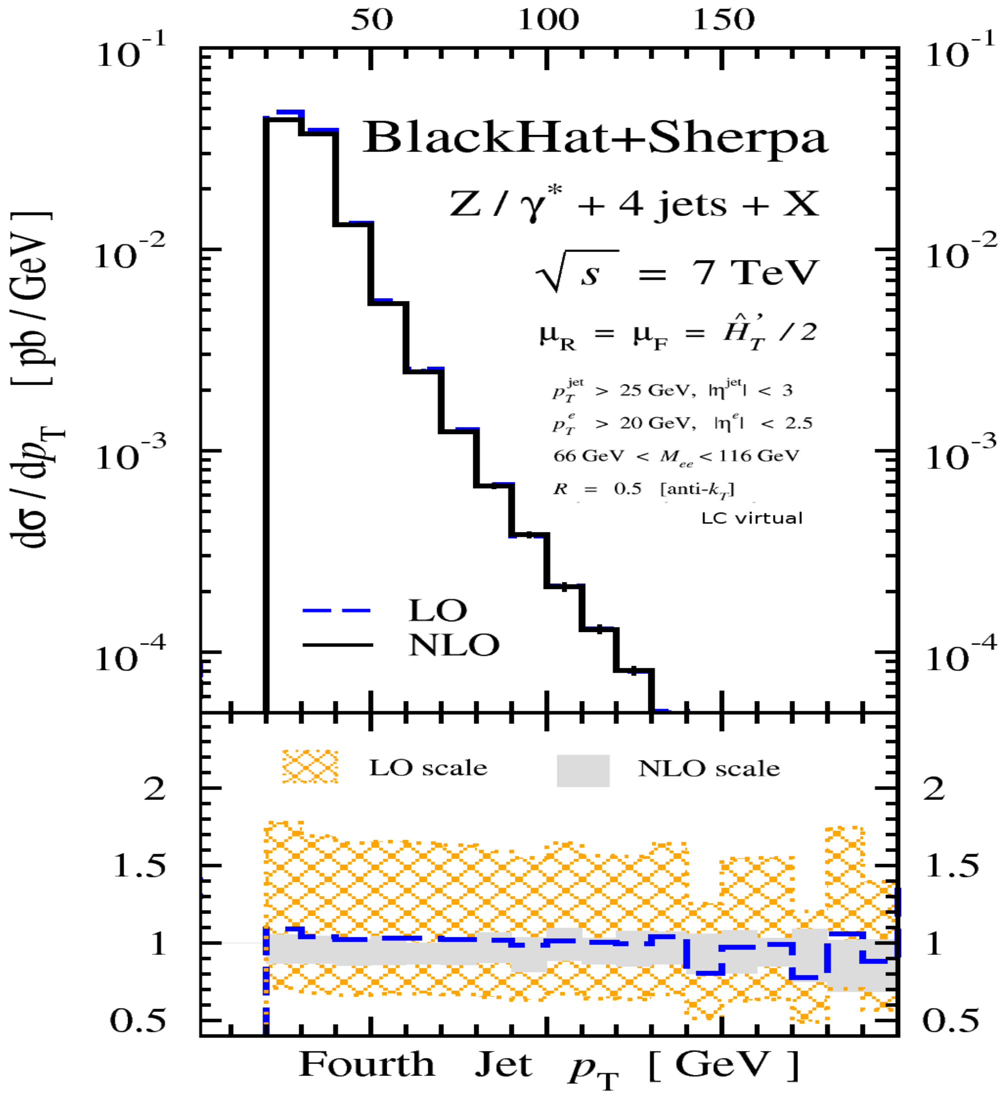
Uses leading color approx good to ~ 3 percent

Z+4 Jets at NLO

Ita, ZB, Febres Cordero, Dixon, Kosower, Maitre

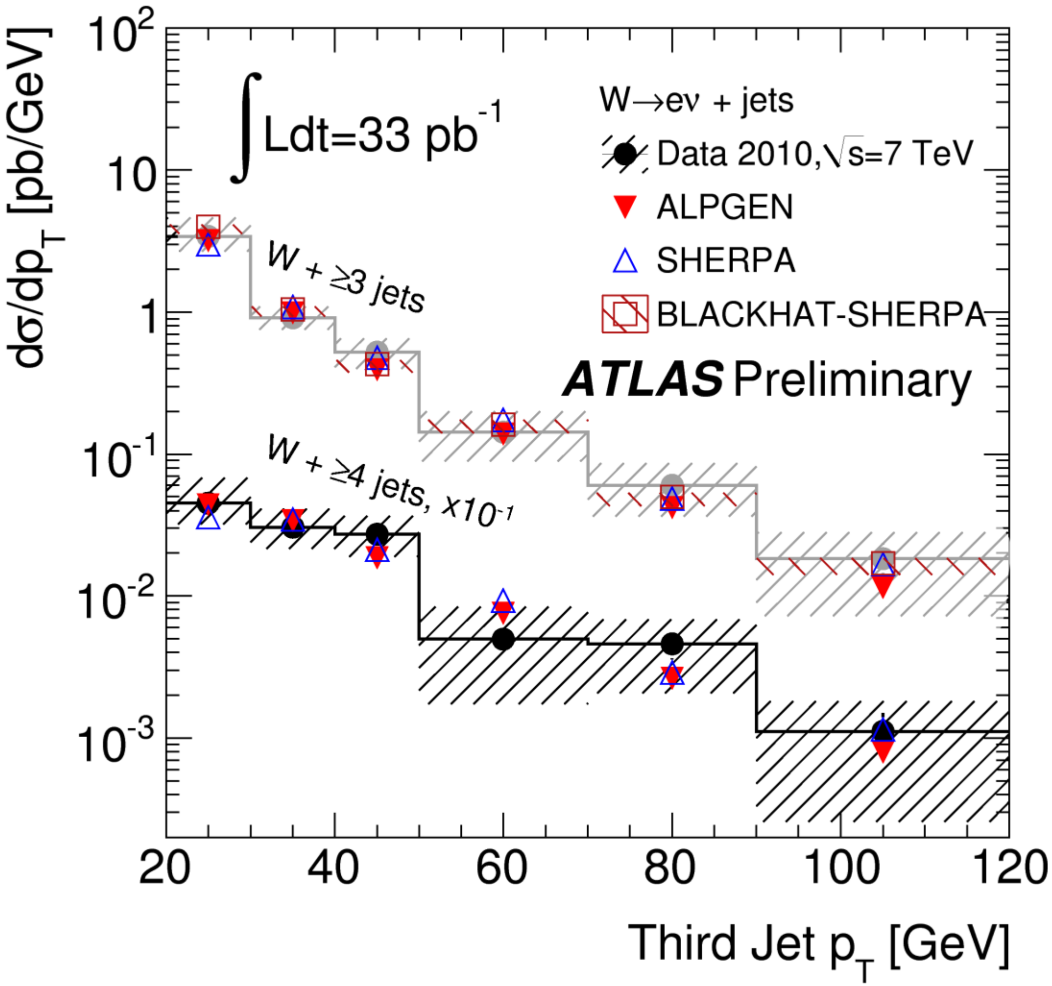
- Big improvement in scale stability
- Numerical reliability





Comparison to LHC Data

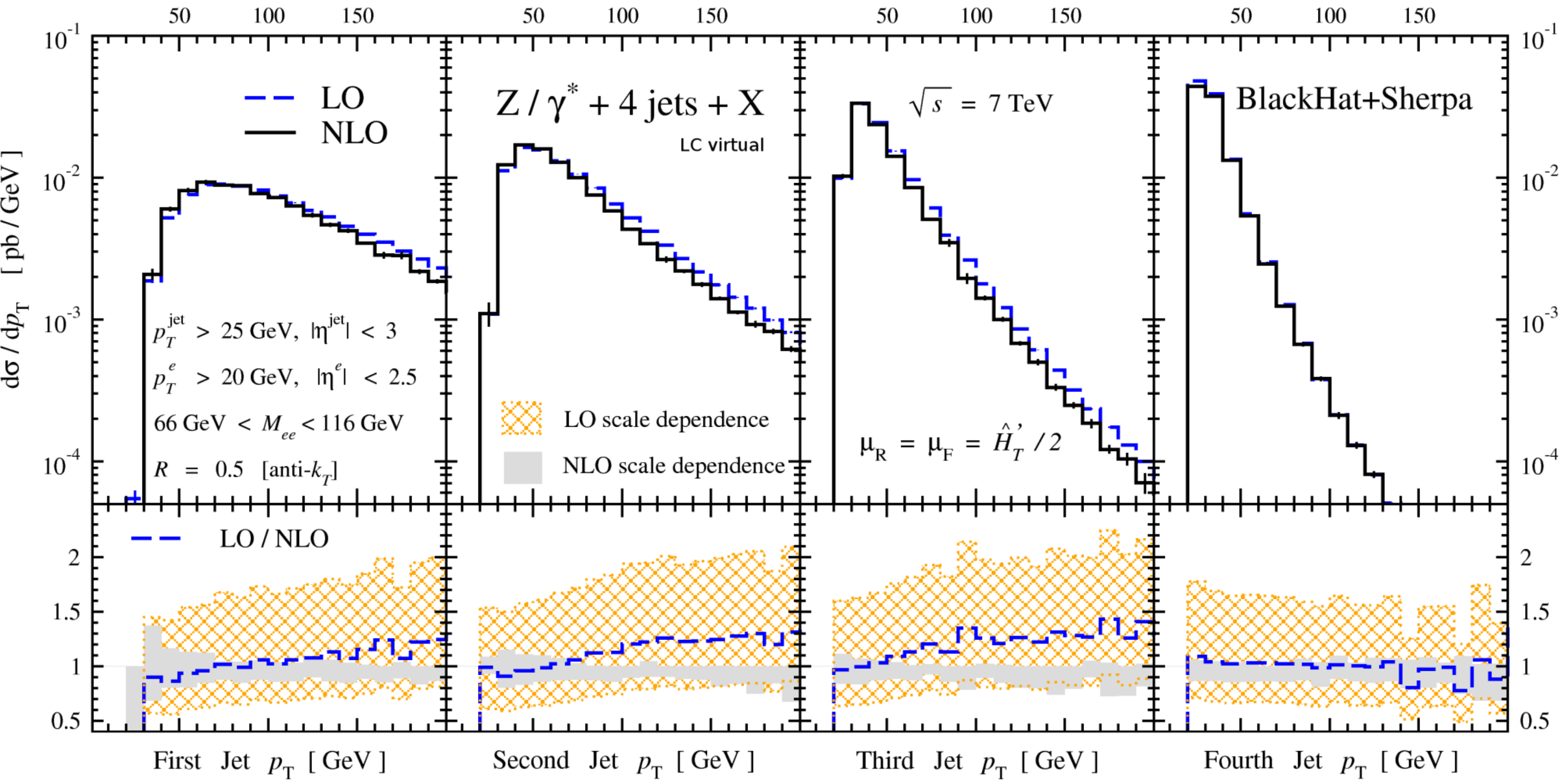
- **Fresh from ATLAS at the EPS conference.**
- **3^{rd} jet p_T in *W*+jets [ATLAS-CONF-2011-060].**
- **Small scale variation at NLO, good agreement with data.**
- **Much more to come including four jets!**

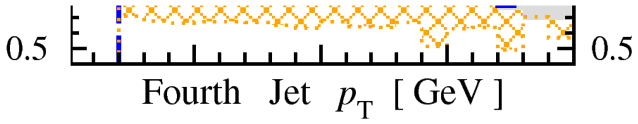


Ntuples give experiments the ability to use BlackHat results without needing to master the program.

Z+4 Jets at NLO

Ita, ZB, Febres Cordero, Dixon, Kosower, Maitre (2011)



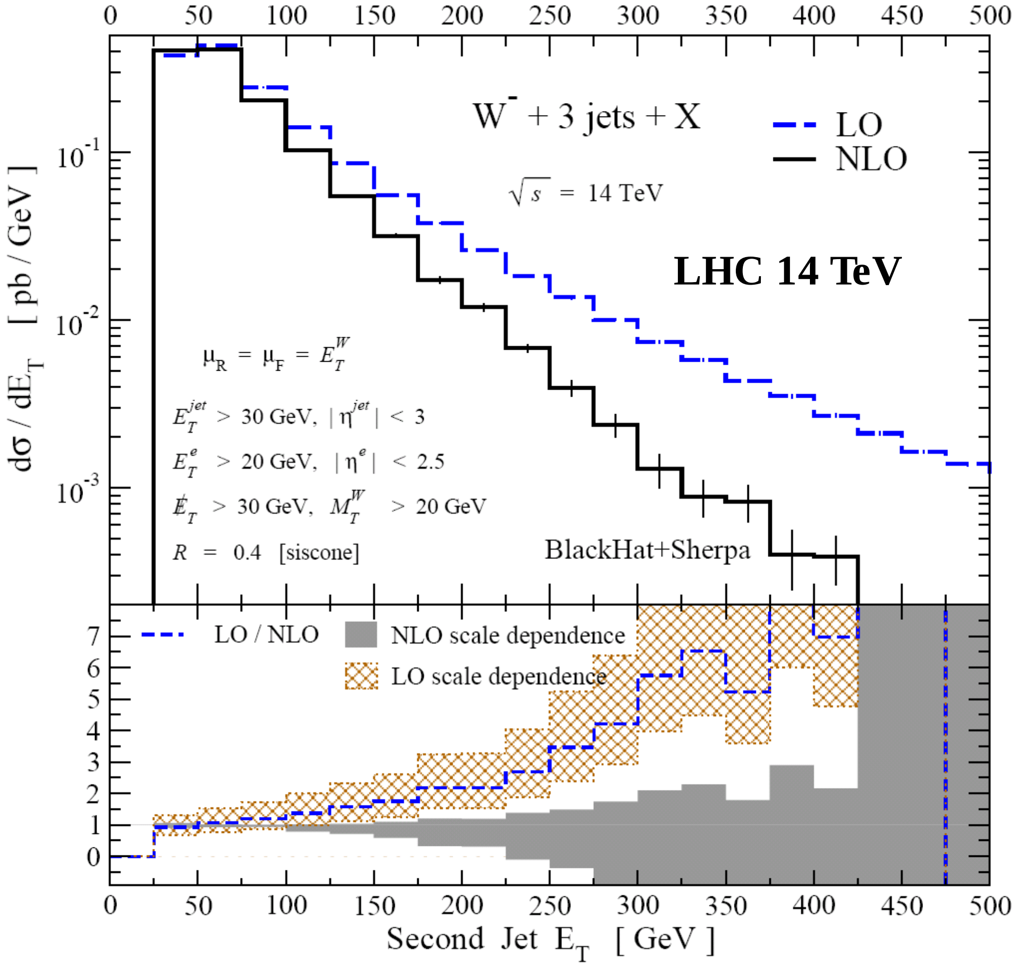


- …but for leading three jet p_Ts, shape changes

Importance of Sensible Scale Choices

BlackHat, arXiv:0902.2760

2nd jet E_T in W^- + 3 jet production



For Tevatron $\mu = E_T^W$ was a common renormalization scale choice.

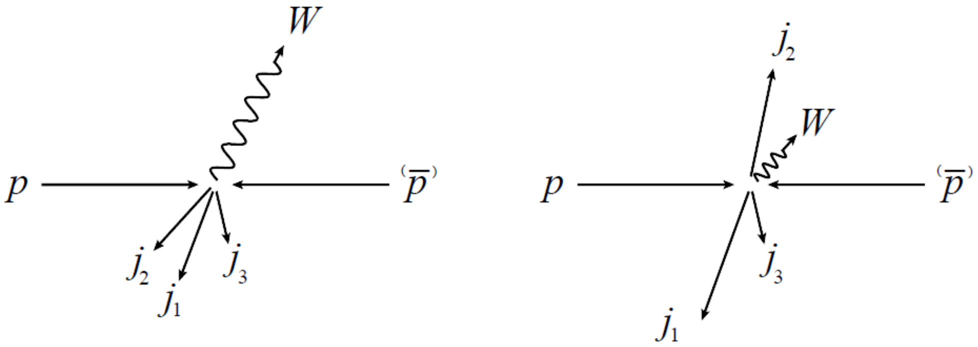
For LHC this is a very poor choice. Does not set the correct scale for the jets.

- **LO/NLO ratio goes haywire.**
- **NLO scale dependence is large at high ET.**
- **NLO cross-section becomes negative!**

Energy of *W* boson does not represent typical jet energy

Better Scale Choices

What is happening? Consider two configurations



(a) (b)

- **If (a) dominates $\mu = E_T^W \equiv \sqrt{M_W^2 + p_T^2(W)}$ is a fine choice**
- **But if (b) dominates then E_T^W too low a scale**
- **Looking at large E_T of 2nd jets forces (b) to dominate**

  - **The total (partonic) transverse energy is a better variable; gets large properly for both (a) and (b)**

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

BlackHat

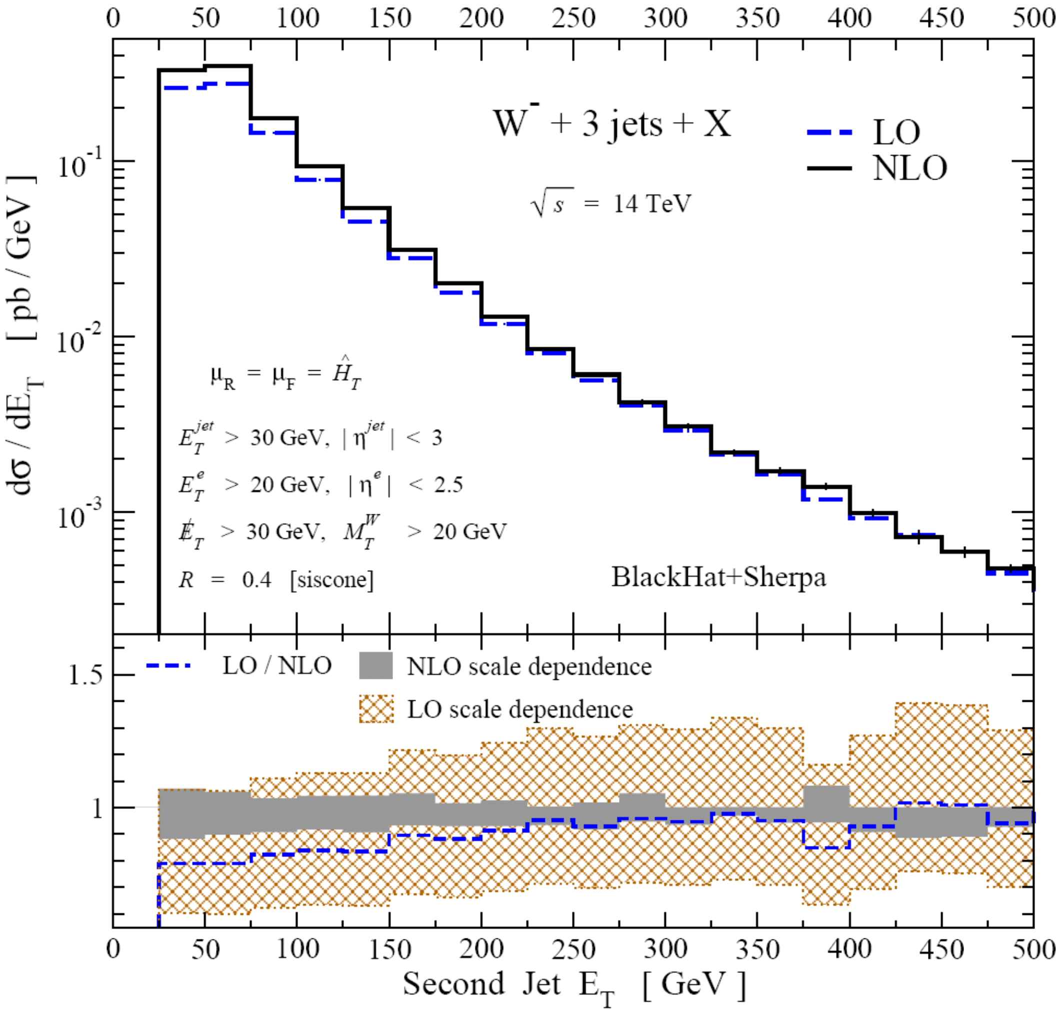
  - **Other reasonable scales are possible.**

Bauer and Lange; Melnikov and Zanderighi

Importance of Sensible Scale Choices

BlackHat, arXiv:0902.2760

2^{nd} jet E_T in W^- + 3 jet production



A much better scale choice is the total partonic transverse energy $\mu = \hat{H}_T$

- LO/NLO ratio sensible.
- NLO scale dependence very good.
- NLO cross sections positive.

Scale choice $\mu = E_T^W$ can cause trouble

NLO Application: Data Driven Background Estimation

CMS uses photons to estimate *Z* background to susy searches.

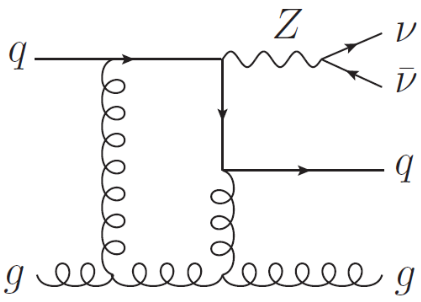
CMS PAS SUS-08-002; CMS PAS SUS-10-005

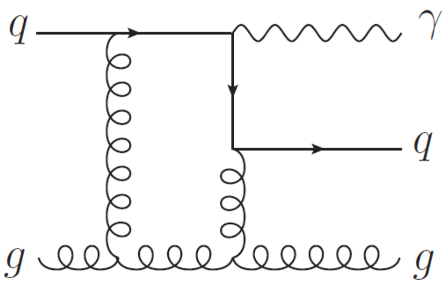
$$\sigma(pp \to Z(\to \nu\bar{\nu}) + \mathrm{jets}) = \sigma(pp \to \gamma + \mathrm{jets}) \times R_{Z/\gamma}$$

irreducible background

measure this

theory input





Has better statistics than $Z \to \mu\bar{\mu}$

Our task was to theoretically understand conversion and give theoretical uncertainty to CMS.

See also recent LO paper from Stirling et al.

CMS Setup

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

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

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

H_T = ' $_j$ E_T^j MET = ¡ ˙ $_j$ p_j

¢(Á)(MET; jet) > 0:5 **to suppress QCD multijet background**

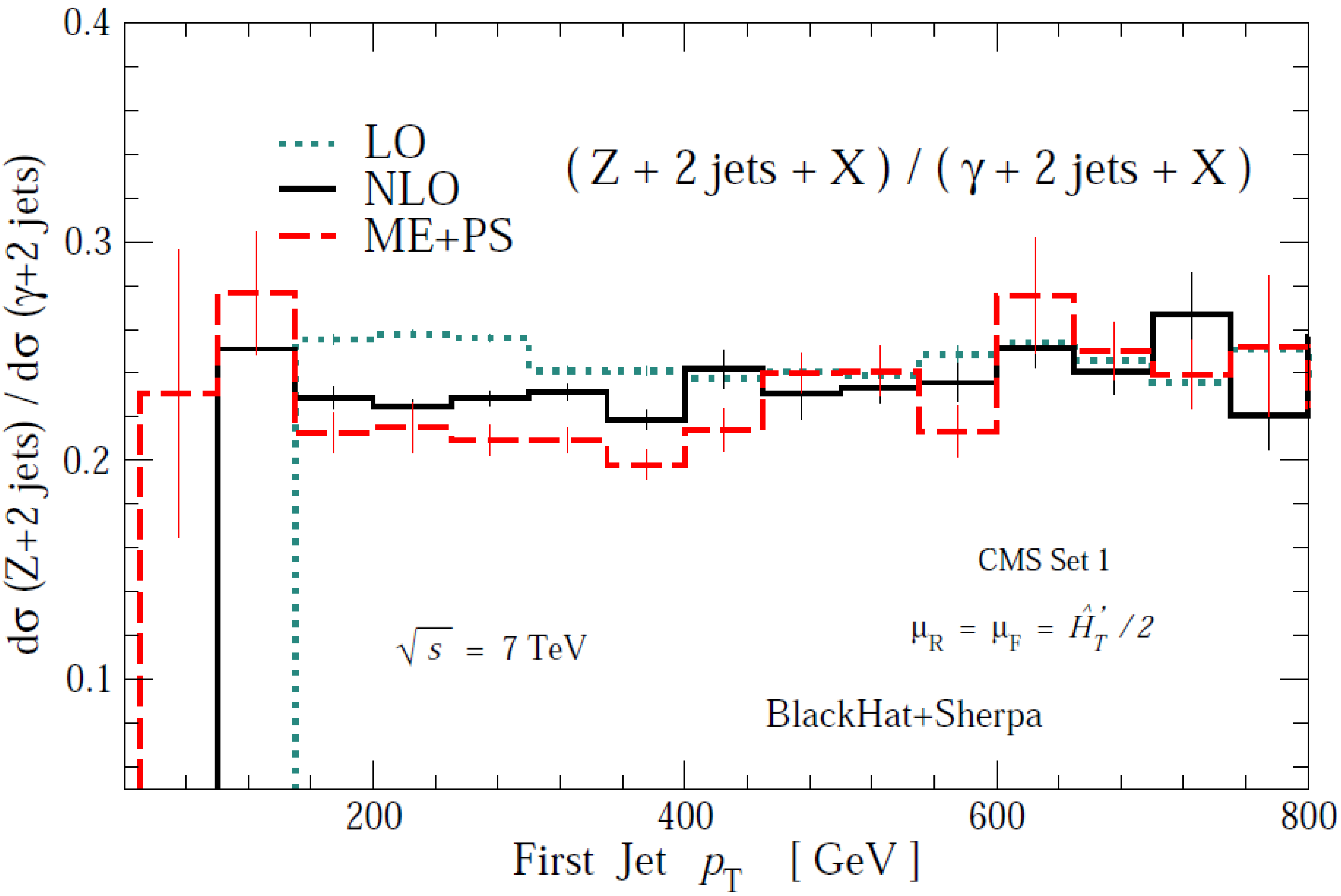
Used Frixone photon isolation $\sum_i E_{iT}\,\Theta\left(\delta - R_{i\gamma}\right) \le \mathcal{H}(\delta)$ ± < $±_0$

$$\epsilon = 0.025,\ \delta_0 = 0.3 \text{ and } n = 2 \qquad \mathcal{H}(\delta) = E_T^\gamma\,\epsilon\left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)^n$$

Technical Aside: Experiments use cone photon isolation. Confirmed via JetPhox (Binoth et al) and Vogelsang's code, that difference very small with this setup.

Z/γ ratio

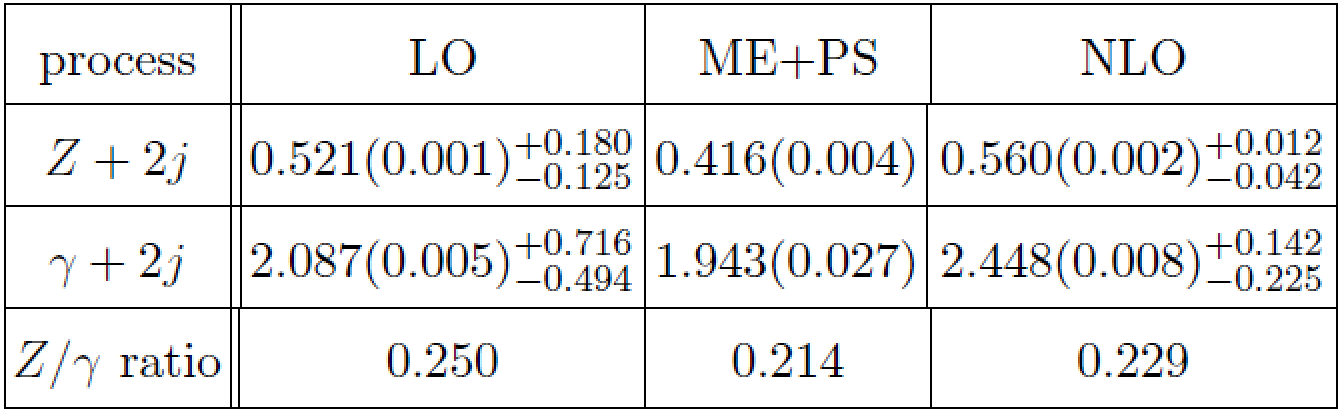
ZB, L. Dixon, F. Febres Cordero, G. Diana, S. Hoeche, H. Ita, D. Kosower, D. Maitre, K. Ozeren



Different theoretical predictions track each other. This conversion directly used by CMS in their estimate of theory uncertainty.

Data Driven Background Estimation

Set 1



process	LO	ME+PS	NLO
$Z + 2j$	$0.521(0.001)^{+0.180}_{-0.125}$	$0.416(0.004)$	$0.560(0.002)^{+0.012}_{-0.042}$
$\gamma + 2j$	$2.087(0.005)^{+0.716}_{-0.494}$	$1.943(0.027)$	$2.448(0.008)^{+0.142}_{-0.225}$
Z/γ ratio	0.250	0.214	0.229

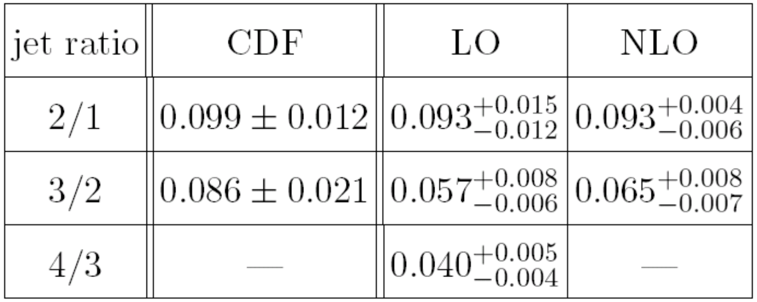
Differences between ME+PS and NLO small in the ratio.

Based on this study we assured CMS that theoretical uncertainty is under 10%. (Quite nontrivial)

Jet production ratios in *Z* + *n* jets

Ellis, Kleiss, Stirling; Berends, Giele, Kuijf, Kliess, Stirling; Berends, Giele, Kuijf , Tausk

Also called 'Berends' or 'staircase' ratio.

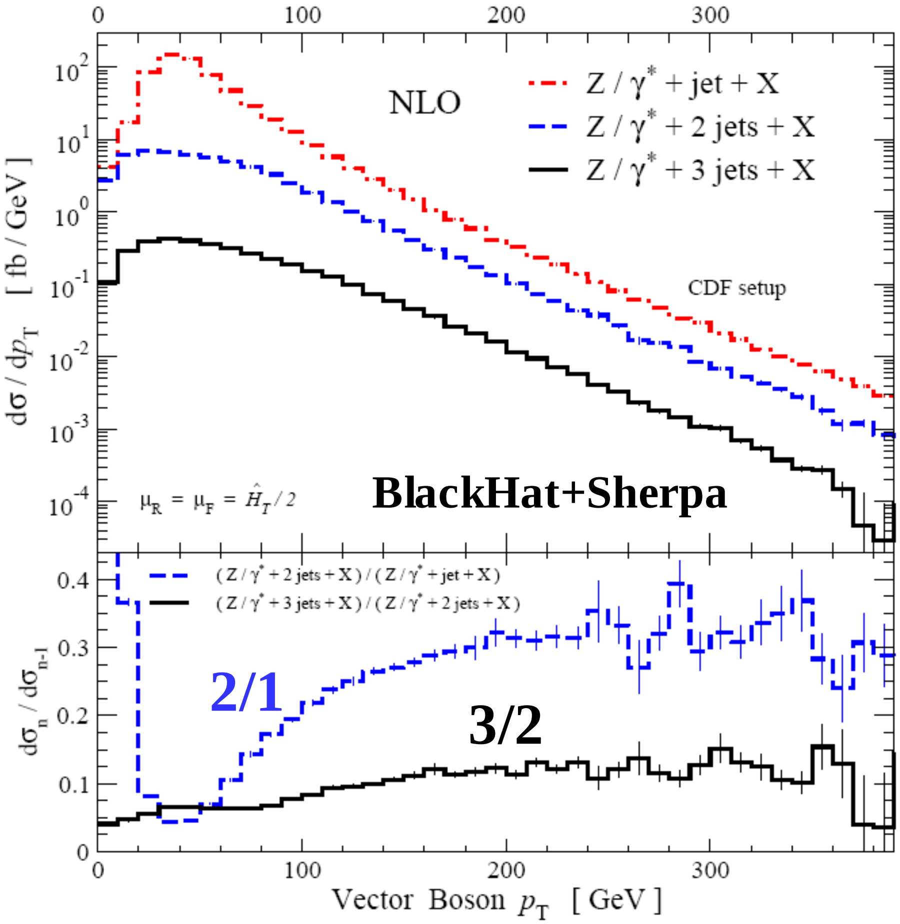


jet ratio	CDF	LO	NLO
2/1	0.099 ± 0.012	$0.093^{+0.015}_{-0.012}$	$0.093^{+0.004}_{-0.006}$
3/2	0.086 ± 0.021	$0.057^{+0.008}_{-0.006}$	$0.065^{+0.008}_{-0.007}$
4/3	—	$0.040^{+0.005}_{-0.004}$	—

- **Ratios should mitigate dependence on e.g.: jet energy scales, pdfs, nonperturbative effects, etc**

- **Strong dependence on kinematics and cuts.**
- **Note: Lore that *n*/(*n*+1) jet ratio independent of *n* is not really right, depends on cuts.** Berger et al (BlackHat)

Z+1, 2, 3 jets with CDF setup



Differential ratios in $p_{T,Z}$

Longer Term Prospects

- **More automation needed to allow any process. BlackHat is investing into this, as are other groups.**

- **Upcoming Gold Standard: NLO + parton showering (+ non-perturbative)**

  Multiple groups working on this:

  MC@NLO, POWHEG, SHERPA, VINCHIA, GenEvA

  ***WW*+ dijets is current state-of-the art example but expect larger numbers of jets in the coming years. NLO programs can provide the needed virtual and real emission contributions.**

Frixione and Webber; Alioli, Nason, Oleari, Re; Hoche, Krauss, Shonherr, Siegert;
Giele, Kosower, and Skands; Bauer, Tackman, Thaler et al,
Melia, Nason, Rontch, Zanderighi, etc.

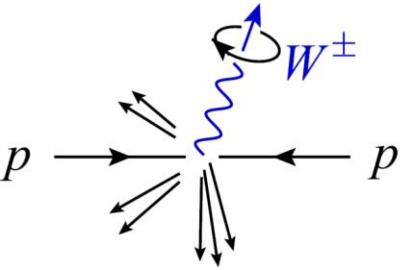
Summary

- On-shell formulation of quantum field theory leads to powerful new ways to compute quantities extremely difficult to obtain via Feynman diagrams.

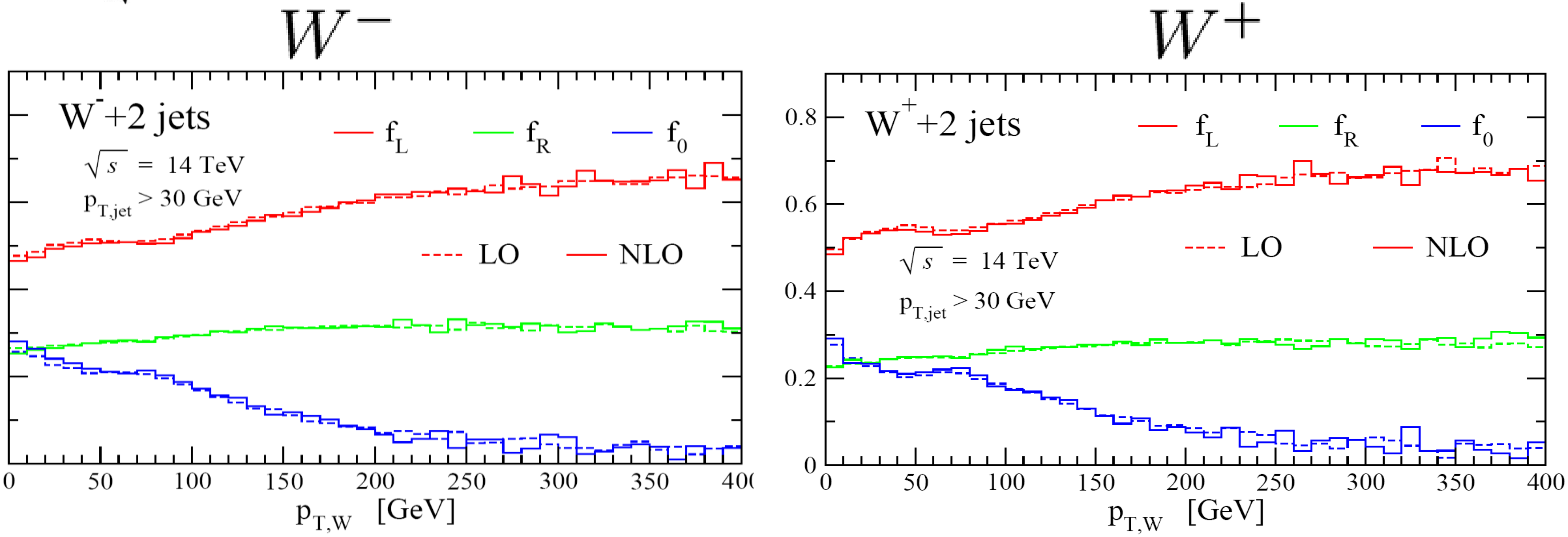
- Huge advance in NLO QCD. For multijet process these are currently the *best* available theoretical predictions.
- Many new processes, W,Z + 3,4 jets and many more on their way.
- NLO QCD has aided CMS in putting constraints on susy by providing reliable estimates of theoretical uncertainty.
- BlackHat stands ready to help experimental groups with their studies. Ntuples allows experimenters to compare NLO theory and experiment.

Extra Transparancies

New *W* Polarization Effect



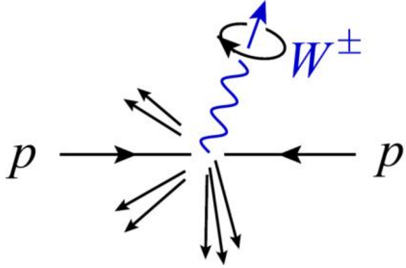
ZB, Diana, Dixon, Febres Cordero, Forde, Gleisberg, Hoeche, Ita, Kosower, Maitre, Ozeren [BlackHat Collaboration] arXiv:0902.2760 , 1103.5445



W-polarization fraction at large $p_{T,W}$

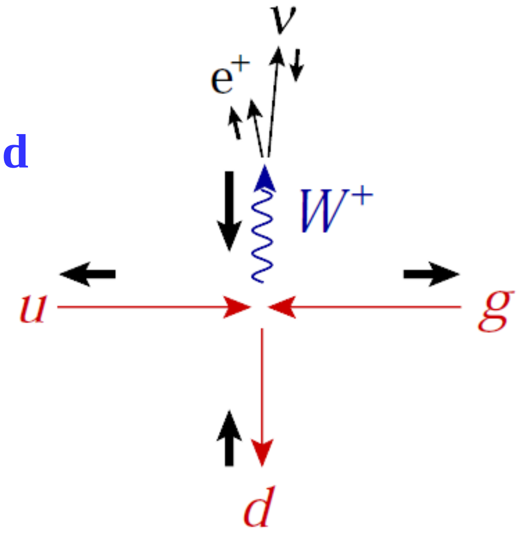
- **Both W^- and W^+ predominantly left-handed at high $p_{T,W}$**
- **Stable under QCD-corrections and number of jets!**
- **Not to be confused with well known longitudinal polarization effect.**

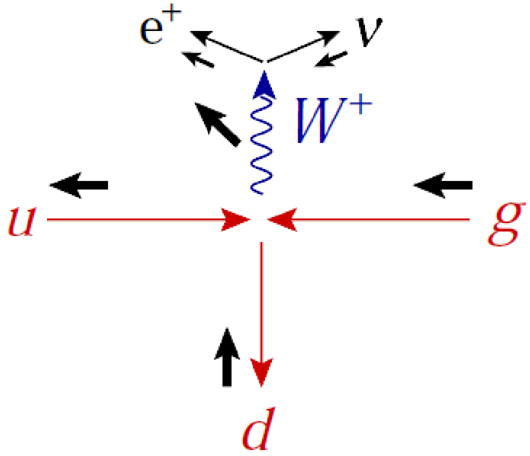
Polarization Effects of *W*'s



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

left-handed gluon





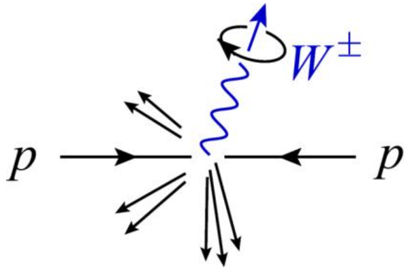
right-handed gluon

100% left handed

mostly right handed
but 1/4 the weight.

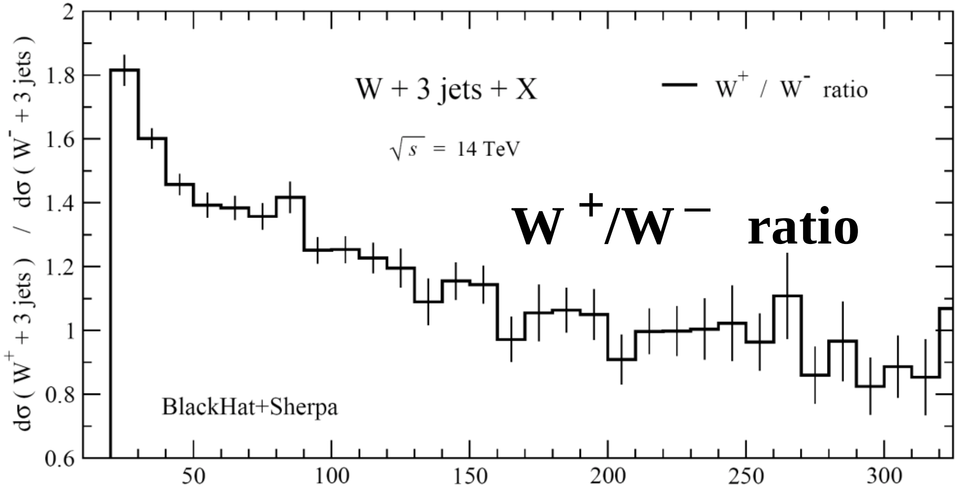
Effect is non-trivial, depending on a unobvious property of the matrix elements.
Up to 80 percent left-handed polarization.
Polarization remains as number jets increases.

Polarization Effects of *W*'s



W^+ gives factor of 3 higher missing E_T than W^- in the tail.

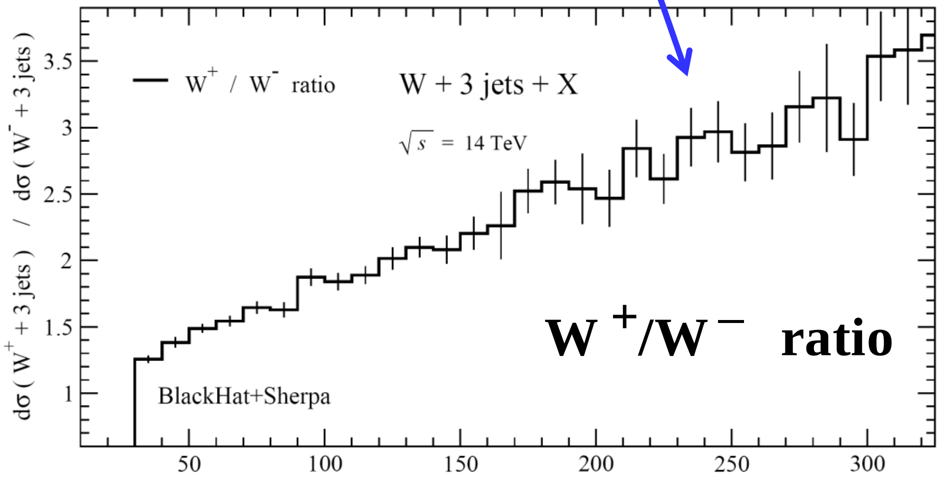
W + 3 jets + X



W^+/W^- ratio

Charged lepton E_T [Gev]

W + 3 jets + X

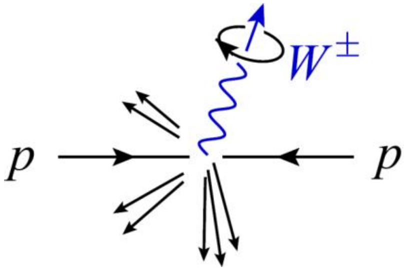


W^+/W^- ratio

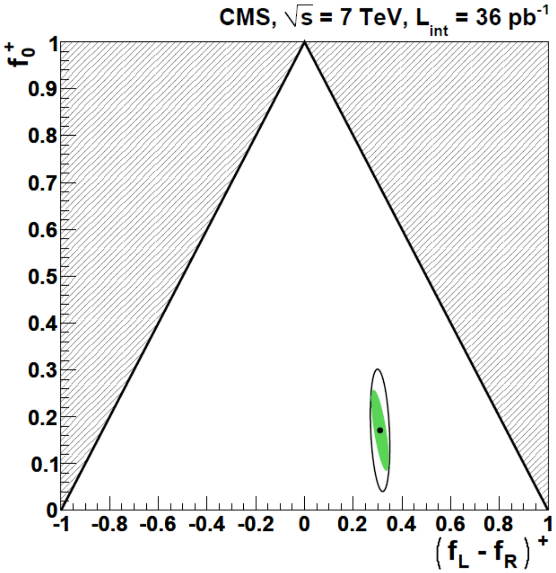
Neutrino E_T [Gev]

The shapes are due to a preference for both *W* bosons to be left handed at high transverse energies.

Measurement by CMS



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



Recent CMS measurement agrees perfectly with theoretical prediction!

***W* polarization may be usable to separate out prompt *W*'s from ones from top (or perhaps new physics). Under study by CMS.**

Recent Applications of Unitarity Method

On-shell methods applied in a variety of problems:

- ***N*** **= 4 super-Yang-Mills ansatz for planar 4,5 point amplitudes to *all* loop orders. Non-trivial place to study AdS/CFT duality.**

Anastasiou, ZB, Dixon, Kosower;
ZB, Dixon, Smirnov; Alday and Maldacena
Drummond, Henn, Korchemsky, Sokatchev
Brandhuber, Heslop, Travaglini; Arkani-Hamed, Cachazo, etc.

- **Applications to gravity.**

Direct challenge to accepted wisdom on impossibility of constructing point-like UV finite theories of quantum gravity.

ZB, Bjerrum-Bohr and Dunbar;
Bjerrum-Bohr, Dunbar, Ita, Perkins, Risager;
ZB, Dixon and Roiban;
ZB, Carrasco, Dixon, Johanson, Kosower, Roiban;
etc.

- **NLO computations for LHC physics.**

Anastasiou, Badger, Bedford, Berger, ZB, Bernicot, Brandhuber, Britto, Buchbinder, Cachazo, Del Duca, Dixon, Dunbar, Ellis, Feng, Febres Cordero, Forde, Giele, Glover, Guillet, Ita, Kilgore, Kosower, Kunszt; Lazopolous, Mastrolia; Maitre, Melnikov, Spence, Travaglini; Ossola, Papadopoulos, Pittau, Risager, Yang; Zanderighi, etc