

Lance Test

Edinburgh, June 2026

The Black Hat Project & Phenomenology @ the LHC

FERNANDO FEBRES CORNERO
FLORIDA STATE UNIVERSITY

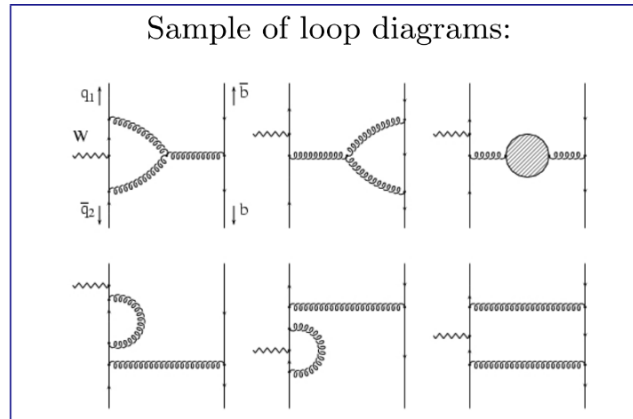
Meeting Lance: LoopFest V @ SLAC



Mass Effects in $W\bar{b}b$ production
 arXiv: hep-ph/0606102 (FFC, REINA, WACKEROTH)

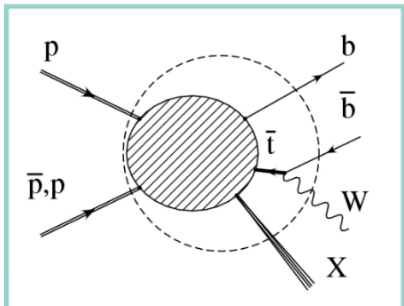
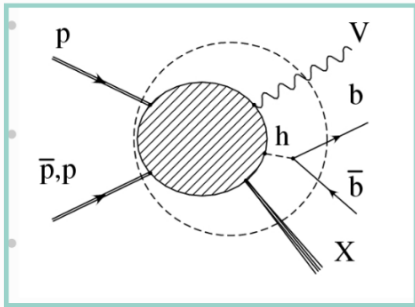
Virtual corrections

Sample of loop diagrams:



- We use dimensional regularization and \overline{MS} renormalization scheme.
- Tensor integrals reduced analytically to scalar integrals and organized to avoid spurious divergences.
- Scalar integrals dealt with standard techniques; two massive boxes not in the literature were calculated analytically.

- After introducing counterterms we obtain UV finite amplitudes.
- Remaining divergences, of IR nature, are proportional to the Born and cancel with Real corrections after convoluting with renormalized PDFs.
- Finite pieces finally are interfered with the Born amplitude.



Joining the BlackHat Project

→ Dec 20, 2006 @ 2:14pm (V3ka)
Email from Zvi Bern

→ Dec 22, 2006 @ 11:08am (V3ka)
My reply

→ Dec 23, 2006 @ 2:40am (V3ka)
Email from Zvi

???

→ Dec 26, 2006 @ 2:01pm (V3ka)
My email to Laura Reina





The BlackHat Project Timeline

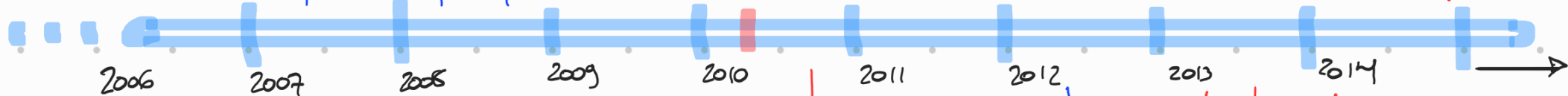
"Hello BlackHat World"

LH Ws @ LHC

Implementation: 8 gluon amplitudes
2q3g2l amplitudes

SUSY 2j BACKGROUNDS
Z+4j @ HCs
4j @ LHC

W+mj ratios (m ≤ 6)



LC W+3j @ NLO
Full W+3j @ HCs
Z+3j @ Tevatron
W+4j @ LHC

Susy 3j BACKGROUNDS
VX+2j @ NLO

W+5j @ LHC

NTuple for NLO



SHERPA

The BlackHat Team (2009 @ SLAC)

CAROLA BERGER (then @ MIT)

ZVI BERN (UCLA)

LANCE (SLAC)

FFC (then @ UCLA)

DARREN FORDE (then @ SLAC)

TANJU GLEISBERG (then @ SLAC)

HARALD ITA (then @ UCLA)

DAVID KOSOWER (SACLAY)

DANIEL MAÎTRE (then @ SLAC)



The BlackHat Team (2011 @ Ferney)

Zvi BERN (UCLA)
GIOVANNI DIANA (then @ SLAC)
LANCE (SLAC)
FFC (then @ USB)
DARREN FORDE (then @ CERN)
STEFAN HÖCHE (then @ SLAC)
HARALD ITA (then @ UCLA)
DAVID KOSOWER (SACLAY)
DANIEL MAÎTRE (then @ CERN)
KEMAL OZEREN (then @ UCLA)



Before 2007

- 90's development of generalized unitarity for loop scatt amplitudes (Bern, Dixon, Dunbar, Kosower, ...)
- BCF, BCFW
- On-shell recursion relations for rational terms (BDK, 2005)
- More amplitudes from on-shell techniques (Berger, Bern, Dixon, de Duca, Forde, Kosower, 2006)
- OPP (2006)
- Forde's Triangle/Sub technique (2007)
- CUT CONSTRUCTIBLE from NUMERICS (Ellis, Giele, Kunszt, 2007)

After 2014

- BLACKHAT to C++ 11
- VV' + jets (ITA, Hofmann 2015)
- Masses (ANGER, FFC, ITA, Sotnikov 2017)
- NTuples beyond 1-loop (MAÎTRE, ...)
- Numerical unitarity at 2 loops (Abreu, Dormans, FFC, ITA, Kraus, Page, Pascual, Ruf, Sotnikov, ... 2017 -)
- HP Floating point from BlackHat for analytics (de Laurentis, MAÎTRE, ...)
- ...

Numeric Trials in the 2000's

- Multiple groups realized the importance of semi-numerical approaches to high multiplicity one-loop amplitudes (Binotti, Dittmar, Denner, Ellis, Giele, Gehrmann, Heinrich, Nagy, Mastrolia, Soper, Zanderighi, ...)
- Major bottlenecks were numerical stability in tensor integral reduction & efficiency of large Feynman diagram expressions
- By mid 2000's impressive 6-pt results had been achieved!

BlackHat : 4-dim Numerical Unitarity ∇

$$A_m = C_m + R_m \rightarrow \text{Rational Part}$$

\downarrow generic n -point scattering amplitude

\downarrow cut-constructible part

$$C_m = \sum_i d_i I_4^i + \sum_i c_i I_3^i + \sum_i b_i I_2^i$$

\downarrow boxes

\downarrow triangles

\downarrow bubbles

- For NLO Phenomenology pentagons are reducible
- Massless internal particles \rightarrow no tadpoles

CUT CONDITIONS

Box : $d_i = \frac{1}{2} \sum_{\sigma=\pm} A_{(1)}^{tree} A_{(2)}^{tree} A_{(3)}^{tree} A_{(4)}^{tree} \Big|_{l_i=l_i^\sigma}$

TRIANGLE : In 4-d a single-parameter on-shell

loop momentum parametrization :

$$l^\mu(t) = \tilde{l}_{(0)}^\mu + t \tilde{l}_{(1)}^\mu + \frac{1}{t} \tilde{l}_{(2)}^\mu \quad (p_k(l^\mu) = 0 \quad k=1,2,3)$$

$$\Rightarrow A_{(1)}^{tree} A_{(2)}^{tree} A_{(3)}^{tree} \Big|_{l=l(t)} = \underbrace{\frac{c_{-3}}{t^3} + \frac{c_{-2}}{t^2} + \frac{c_{-1}}{t} + c_0 + c_1 t + c_2 t^2 + c_3 t^3}_{T_3(t)} + \sum_i \frac{d_i}{f_i(l(t))}$$

DISCRETE FOURIER TRANSFORM :

(See also Mastrolia, Ossola,
Papadopoulos & Pittau)

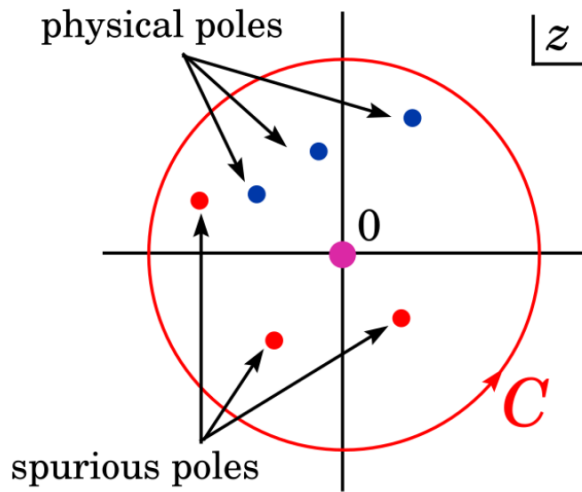
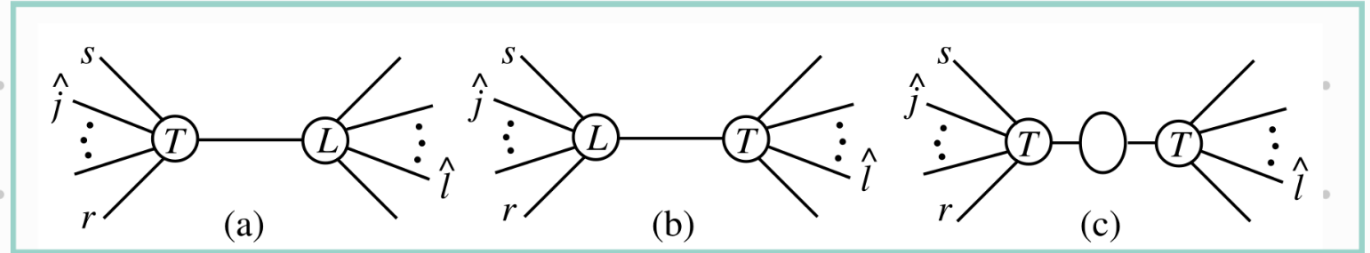
$$C_0 = \frac{1}{2P+1} \sum_{j=-P}^P T_3 \left(t_0 e^{2\pi i j / (2P+1)} \right)$$

↳ and similar for other coefficients!

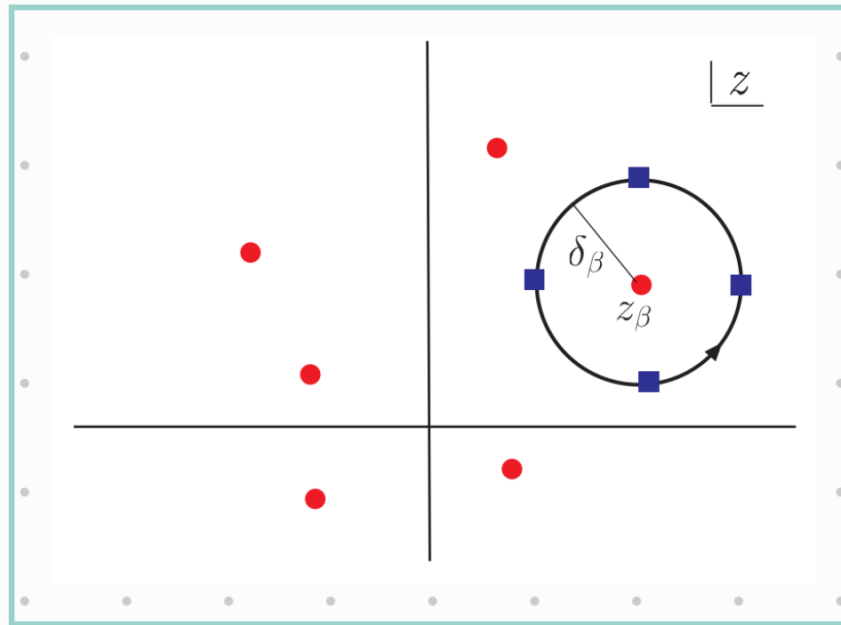
- A similar approach can be done for bubble coeffs → 2-dim discrete Fourier transform
- For bubble a natural connection to spherical harmonics
- **DFT** provided a fast and numerical stable way to solve (related) linear algebra well-condition (perfect?!) linear system!

RATIONAL PIECES :

on-shell recursion relations



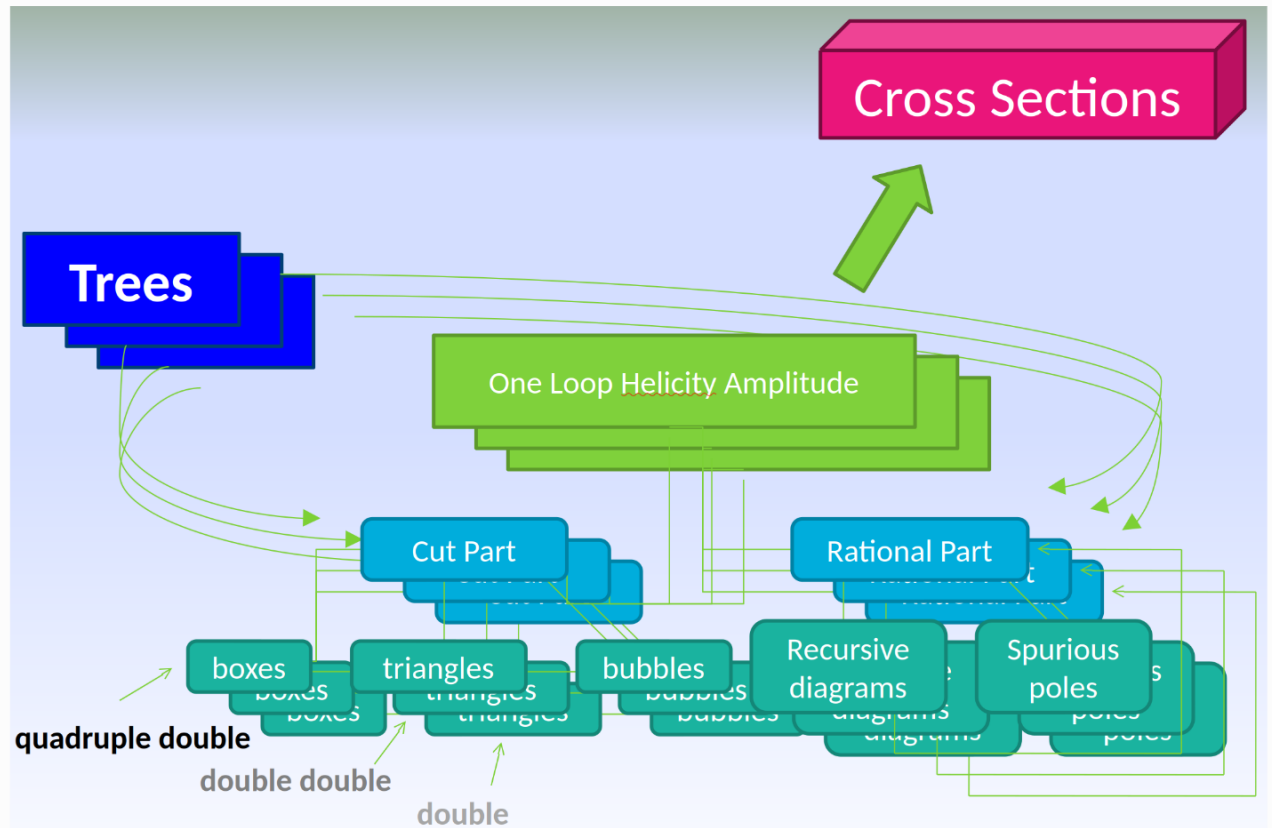
Numerical extraction
from cut-constructible
piece



- EVENTUALLY VARIANTS of D-dim unitarity (GIELE, KUNZT, MENIKOV, 2008) WERE ALSO IMPLEMENTED FOR RATIONAL PART CALCULATIONS

The BlackHat LIBRARY

- Template library
- SAM for C++
(Mastrolia, Hütten))
- 4-D on-shell parametrizations
- on-shell recursion relations (and eventually also off-shell rec. rel.)
- MULTI-PRECISION integral library
- Large library of optimized analytics (trees, 1-loop, rat pieces)
- $(MEs)^2$ assembly



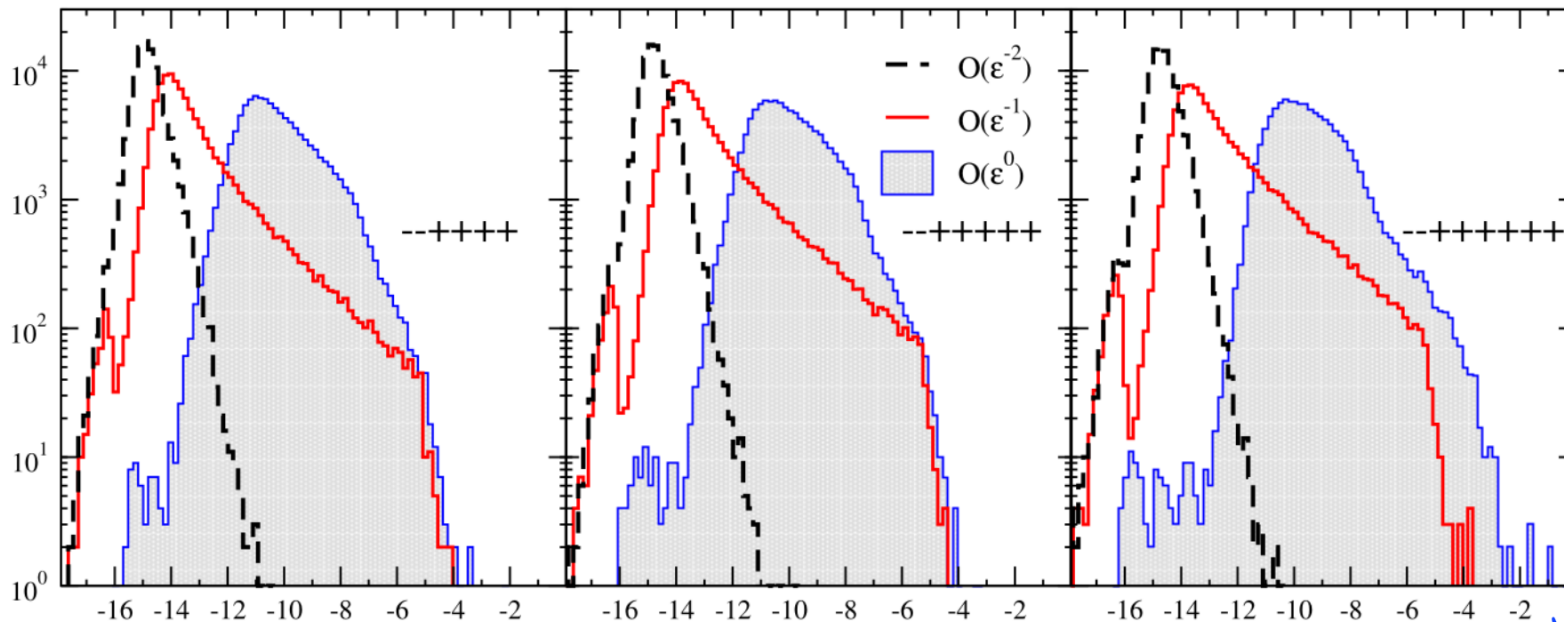
- Large library of optimized analytics (trees, 1-loop, rat pieces)

- $(MEs)^2$ assembly

- Multiple rescue systems for num stability (analytics, ϵ poles, integrand constraints, etc)

READY for the LHC Challenge

→ #events off 10⁵



→ numerical stability

BlackHat, from early on, showed speed and numerical stability!

↳ Similar test up to $W+5j$ 1-loop squared MEs!



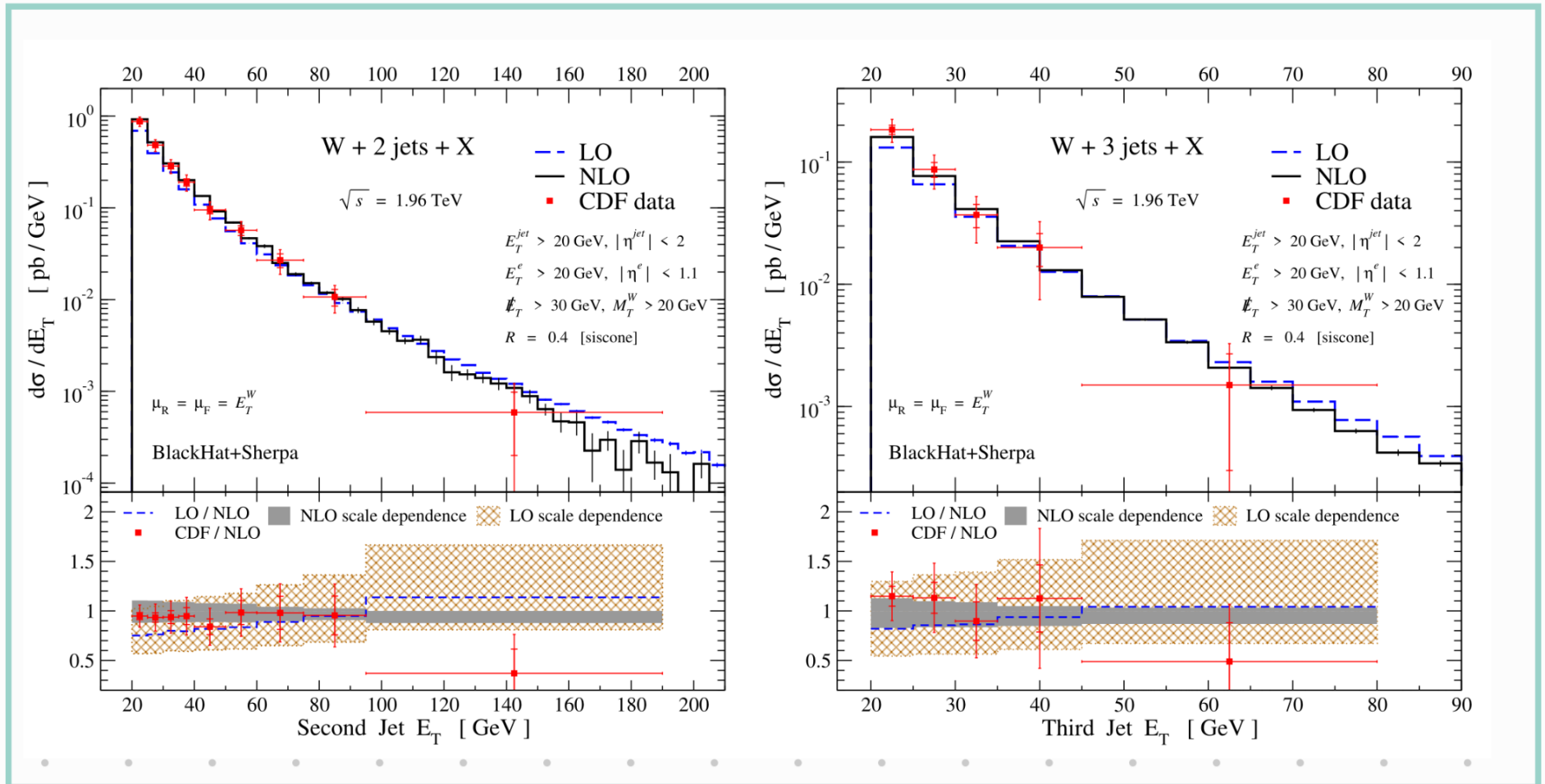
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BLACKHAT + SHERPA for

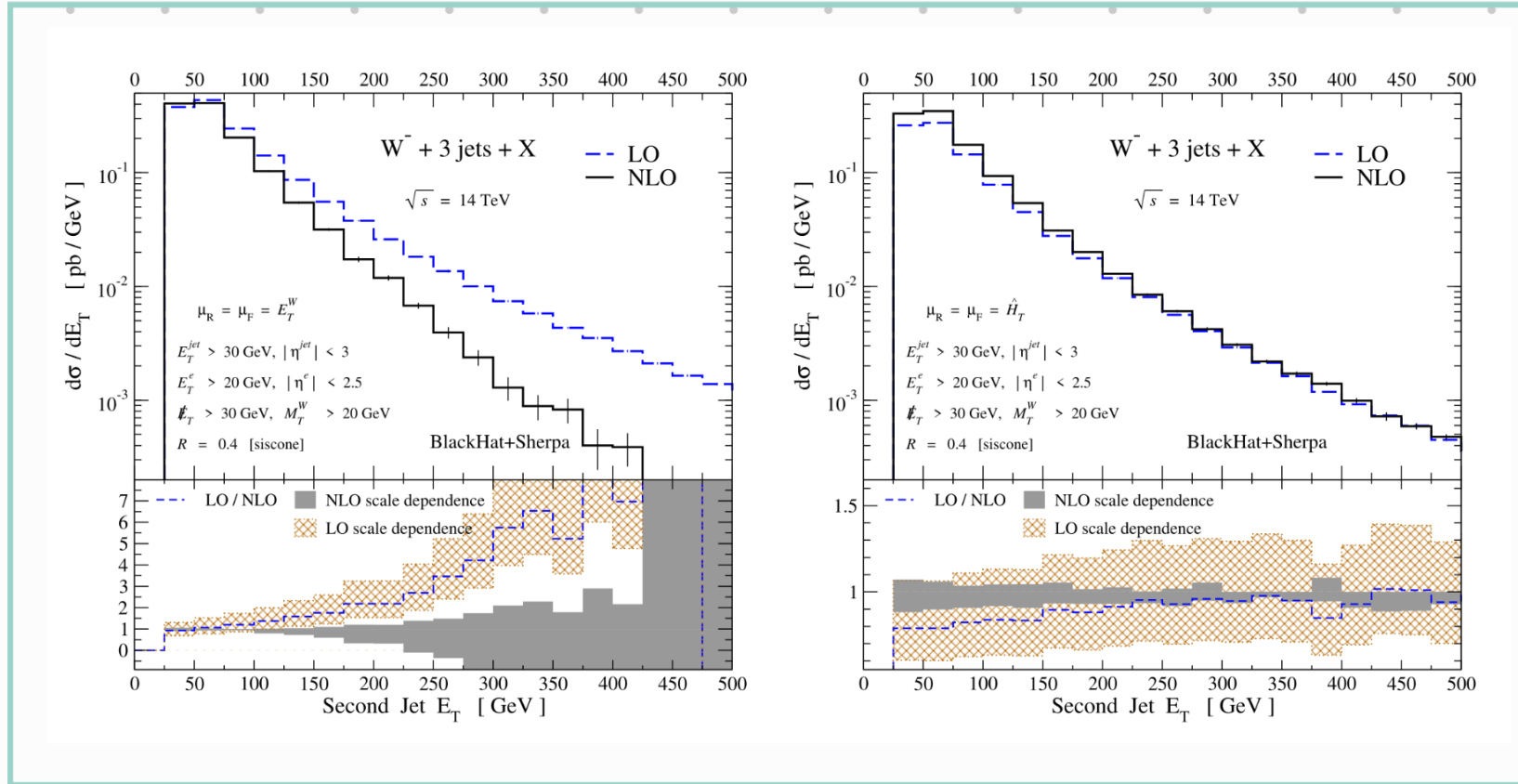
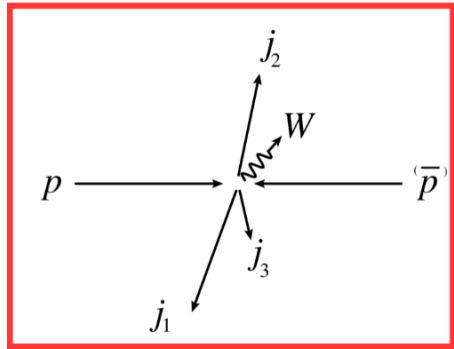
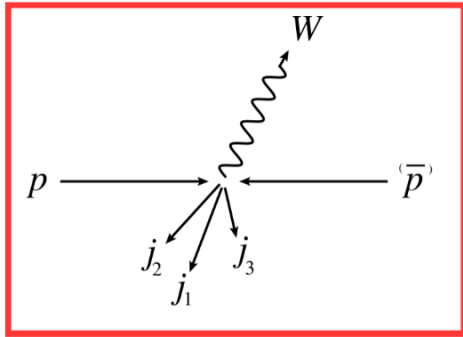
HANBON COLLIDER Phenomenology!

$W + 3j$ @ NLO QCD : Tevatron Data



Early comparisons to CDF data
(Jet physics hampered @ Tevatron!)

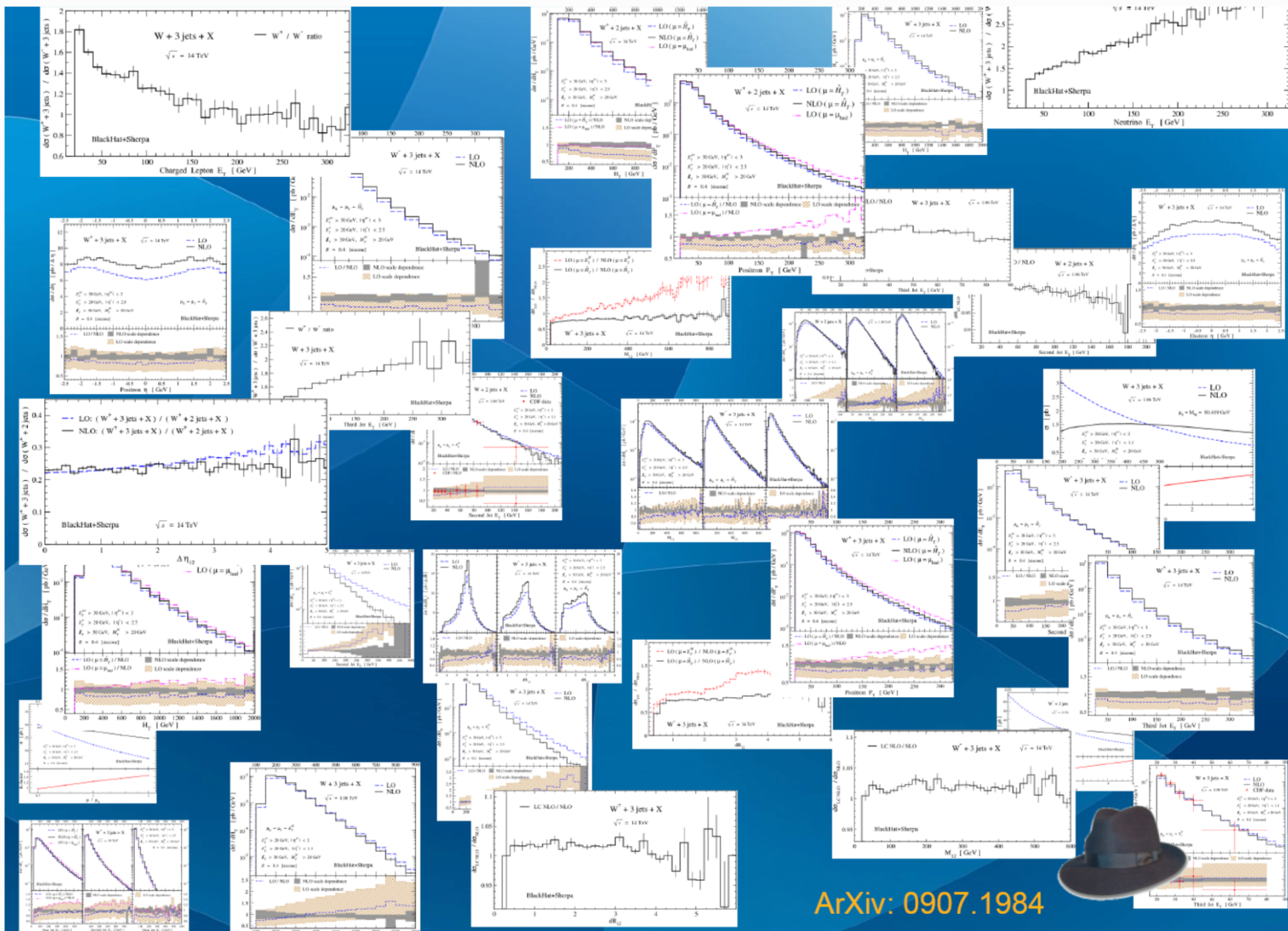
There are no "RIGHT Scales": but certainly there are "Bad" ones



- A common choice of renormalization & factorization scale at the Tevatron clearly broke down at the more energetic LHC!

One of many exciting
stories in studying
LHC physics ...

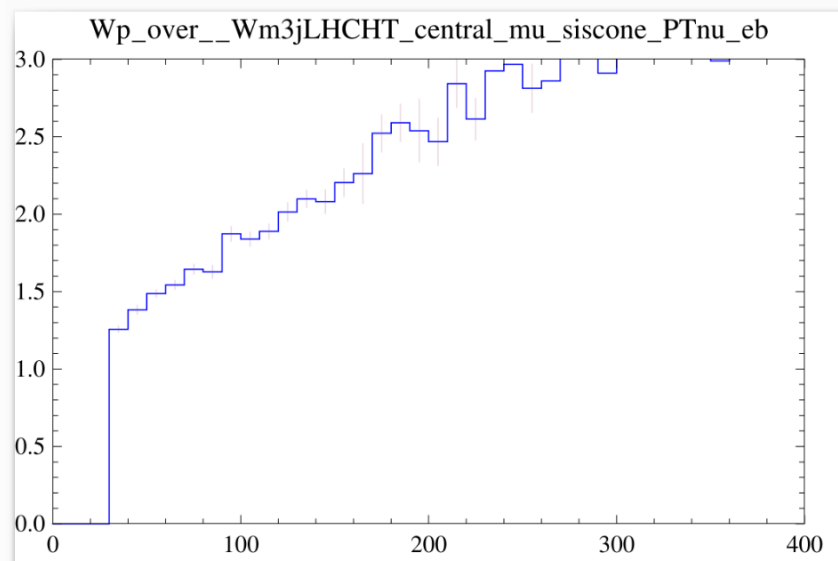
L.H. W's in an odd place ...



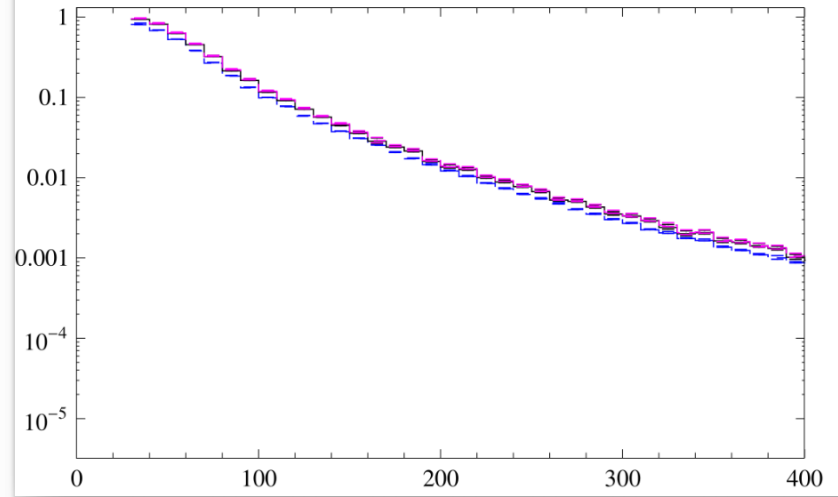
ArXiv: 0907.1984



The flood of plots!



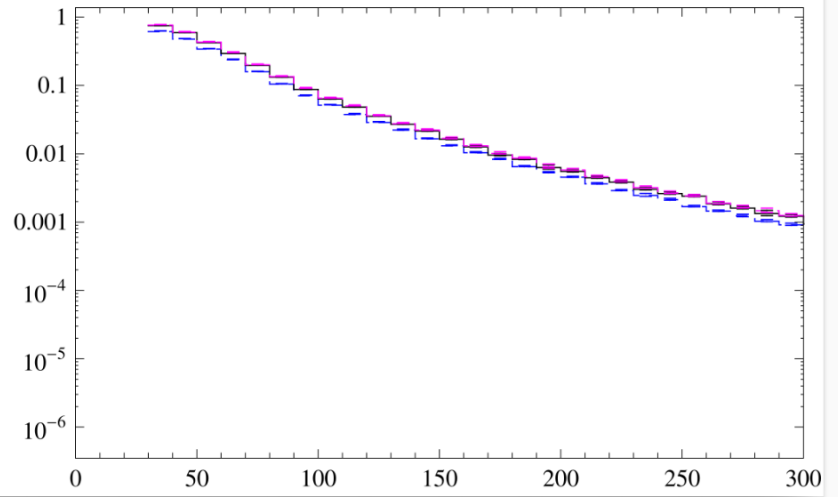
PTnu_e
 NLO: 41.452 st. err 1.6308%
 NLO_lc: 42.0673 st. err 1.5341%
 LO: 34.9035 st. err 0.993018%



..

BUT ONE PARTICULAR
 ASYMMETRY KEPT
 BORDERING!

PTnu_eb
 NLO: 27.4903 st. err 1.2902%
 NLO_lc: 28.1074 st. err 1.1869%
 LO: 22.2786 st. err 0.587821%



A NEW POLARIZATION EFFECT

→ Jul 2, 2009 @ 11:58 am (LA)
to Lance

Hi Lance,

a bit of something that has been bothering me a bit. Figure 20 shows the ratio of W^+ / W^- over the distribution of the PT of the charged lepton. I wrote that maybe it goes to 1 due to a PDF effect. But compare this two:

```
~plots/Wp_over_Wm3jLHCHT_central_mu_siscone_PTe-.pdf  
~plots/Wp_over_Wm3jLHCHT_central_mu_siscone_PTnu_eb.pdf
```

I don't understand why the trend is so different. The latter is a similar plot, but of the neutrino PT. It could be that the difference is coming due to the constraints on the charged lepton eta cut, but I have not convinced myself of a reason.

→ Jul 2, 2009 @ 12:39 pm (LA)

Hi Fernando,

...

I missed this plot completely before, because it was added after my last printed version, and there is nothing in the text about it. But I believe I understand it, as an electroweak polarization effect.

If you were to plot the W_{E_T} the ratio W^+/W^- would just keep increasing at larger and larger E_T , because x would increase and $u(x)/d(x)$ just keeps getting larger. But let's assume the W 's are still being radiated off final state valence quarks (not anti-quarks)

...

→ And highlight curiosity of this happening @ $W+3jets$ and strength of Polarization

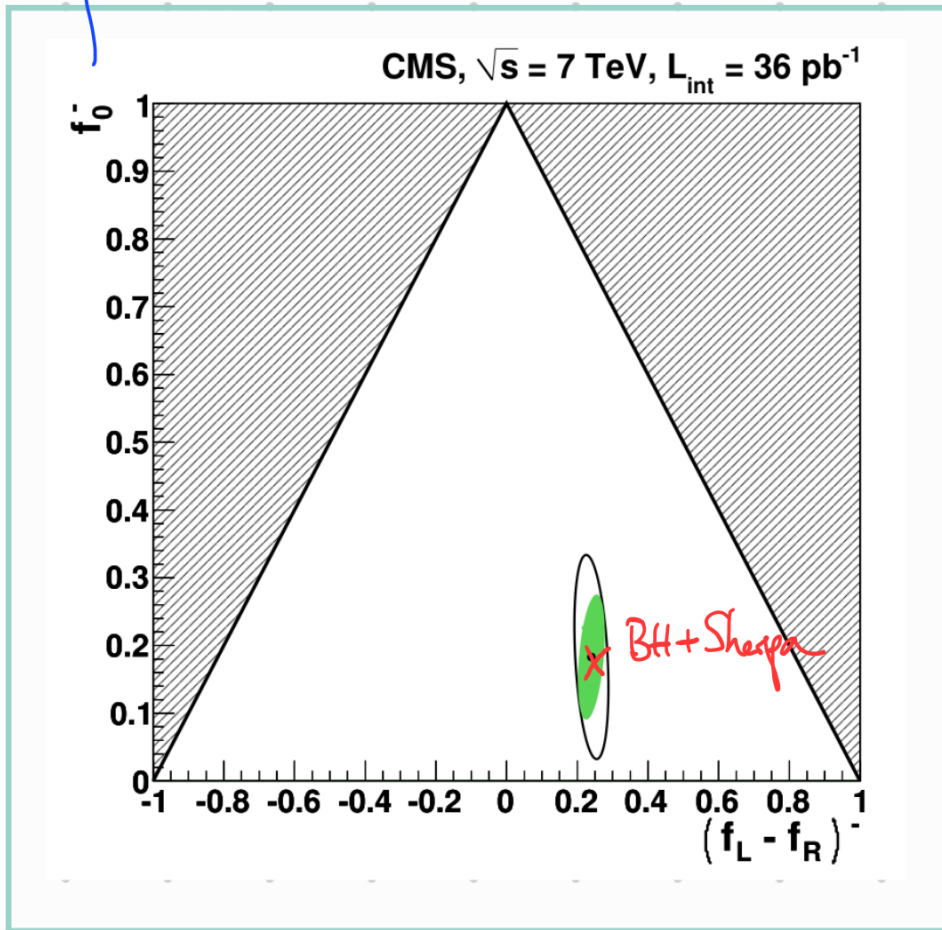
- In a dedicated study [arXiv:1103.5445](https://arxiv.org/abs/1103.5445) we showed how partonic channel distribution, tree-level helicity effects and left-handed nature of W bosons induced this effect in $W + 1 \text{ jet}$ production @ the LHC.

→ AND THE EFFECTS WERE ROBUST UNDER QUANTUM CORRECTIONS

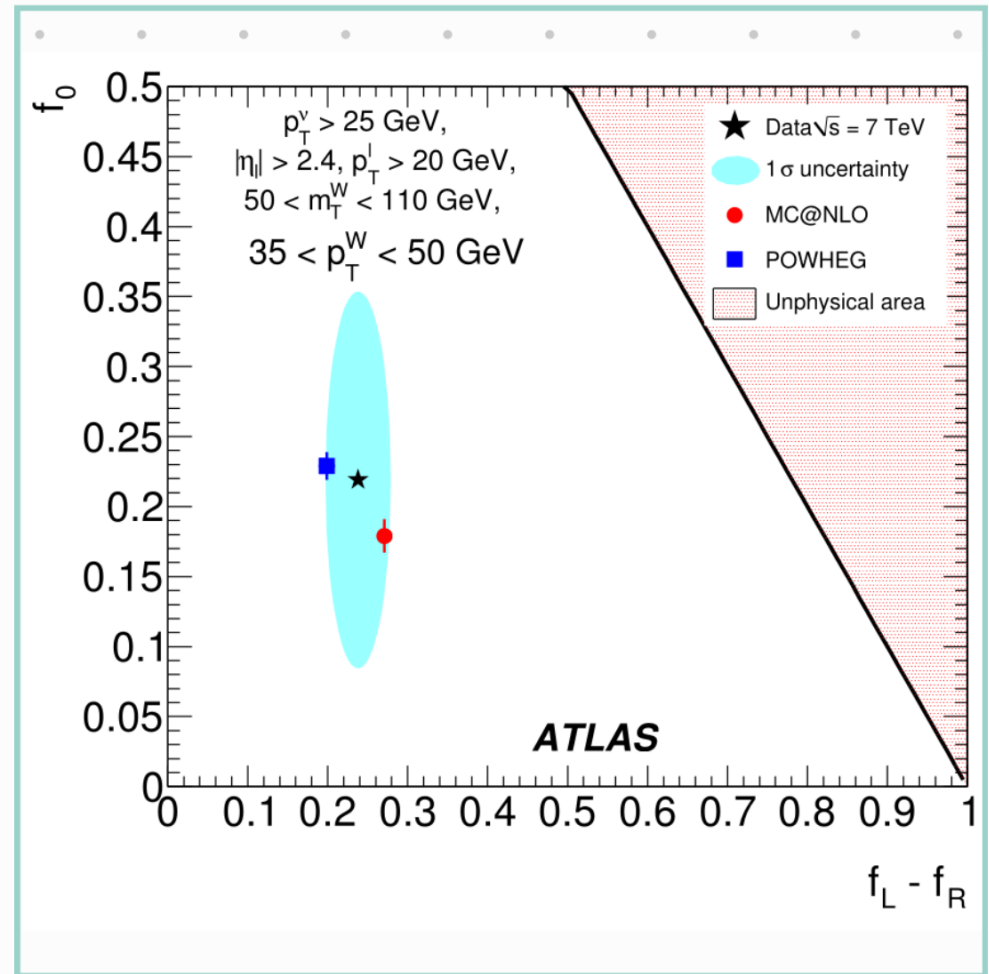
→ AND PRESERVED BY FACTORIZATION in the $W + 2 \text{ jet}$ & $W + 3 \text{ jet}$ PROCESSES!

A RUN BY CMS & ATLAS

→ Longitudinal pol fraction



arXiv: 1104.3829

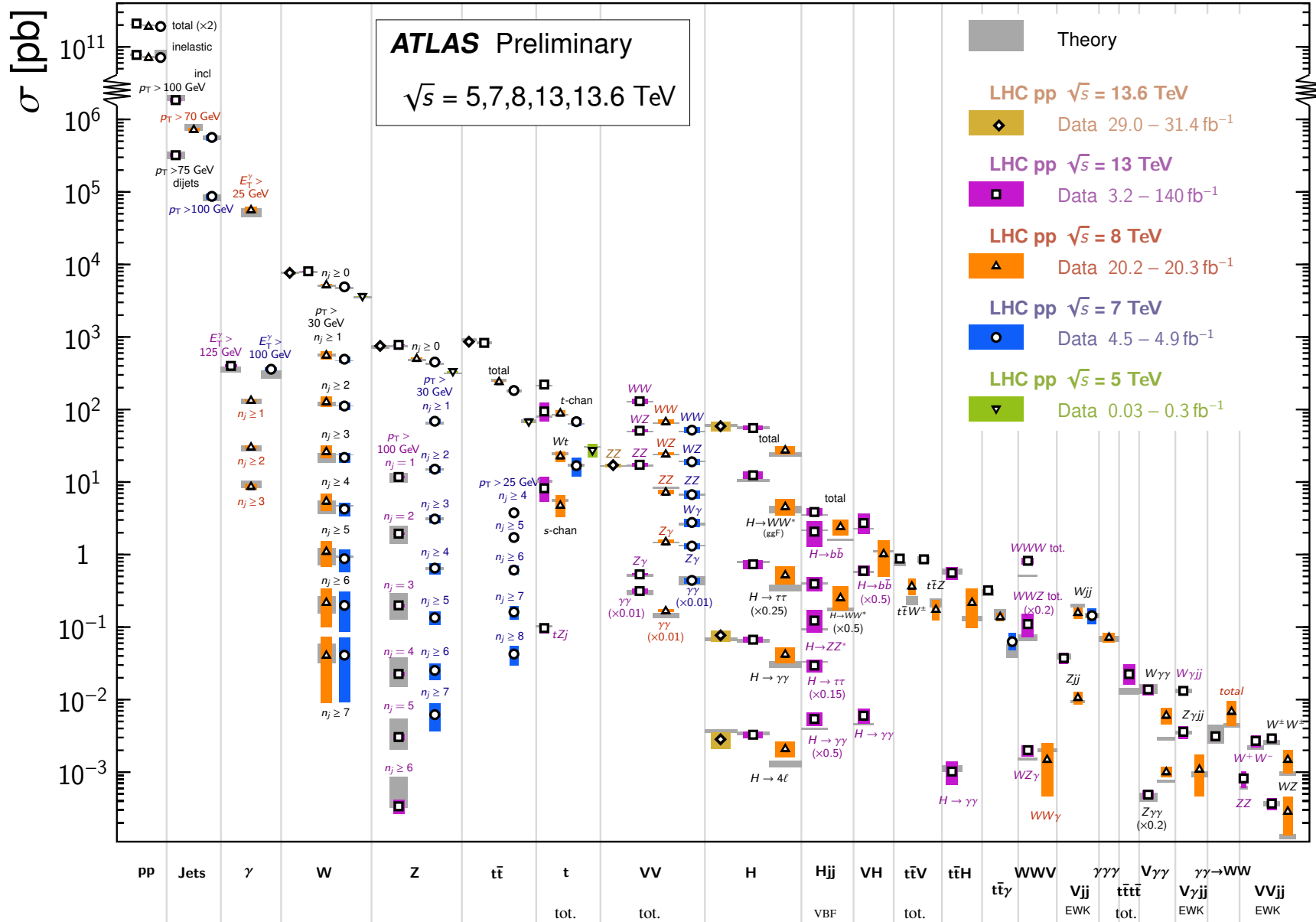


→ left, right pol fractions

arXiv: 1203.2165

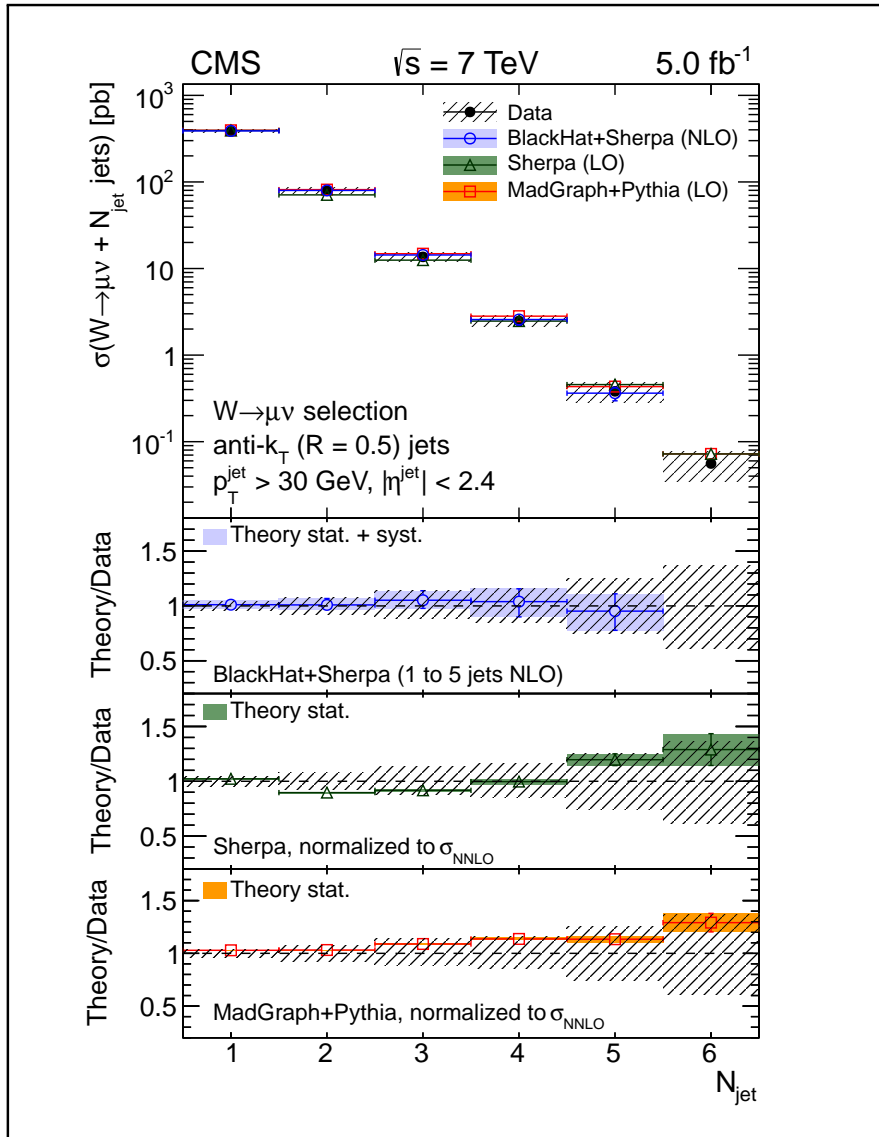
Standard Model Production Cross Section Measurements

Status: June 2024



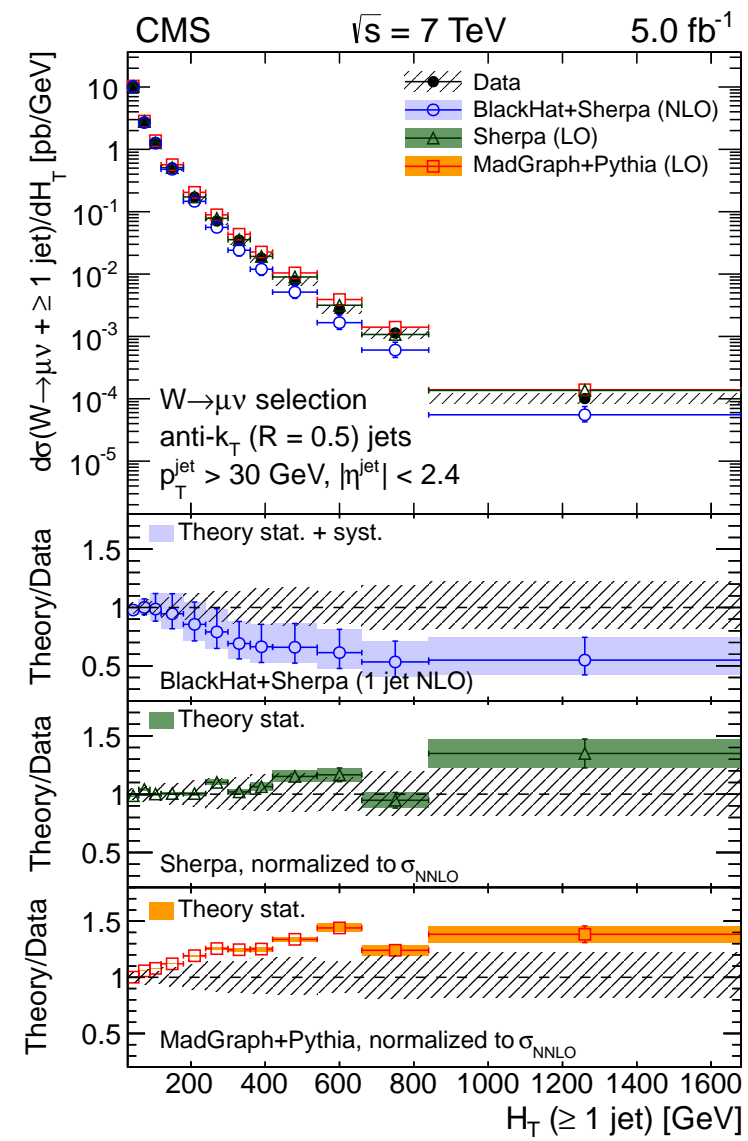
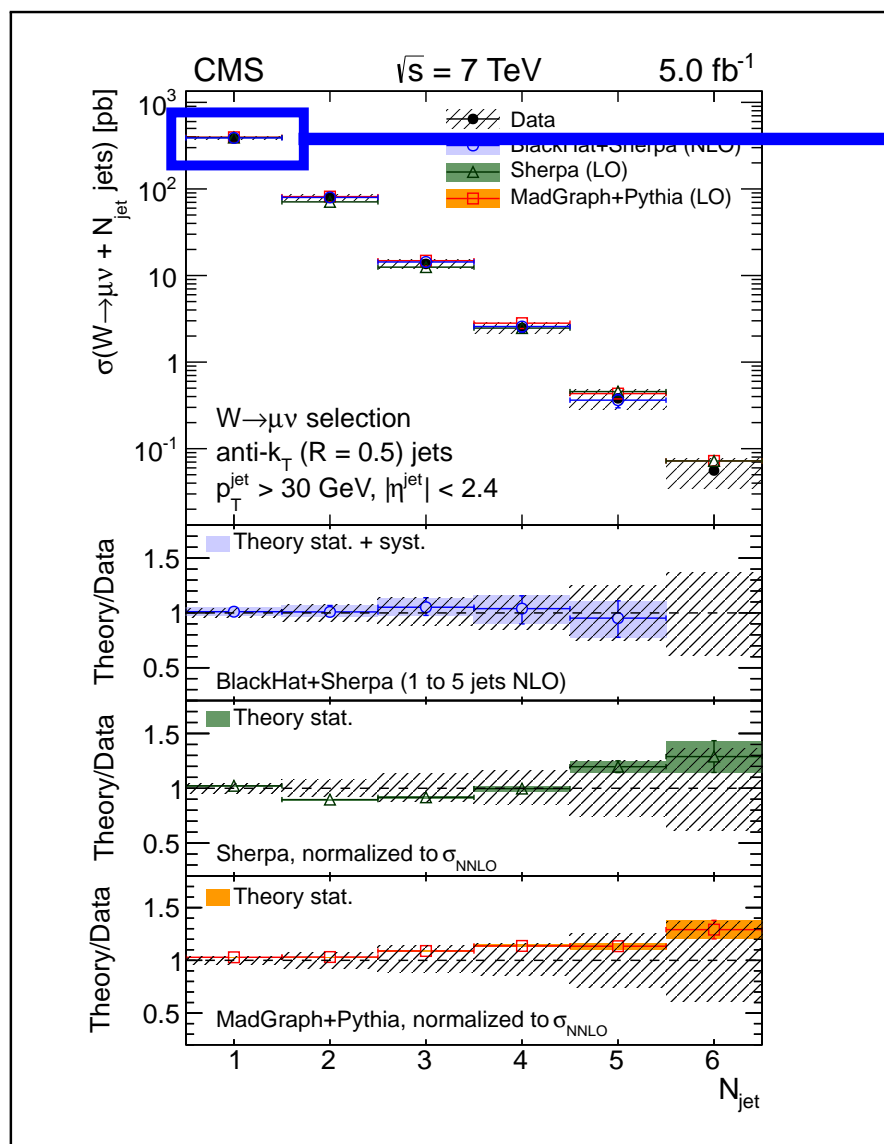
W + n jets @ CMS

arXiv: 1406.7533



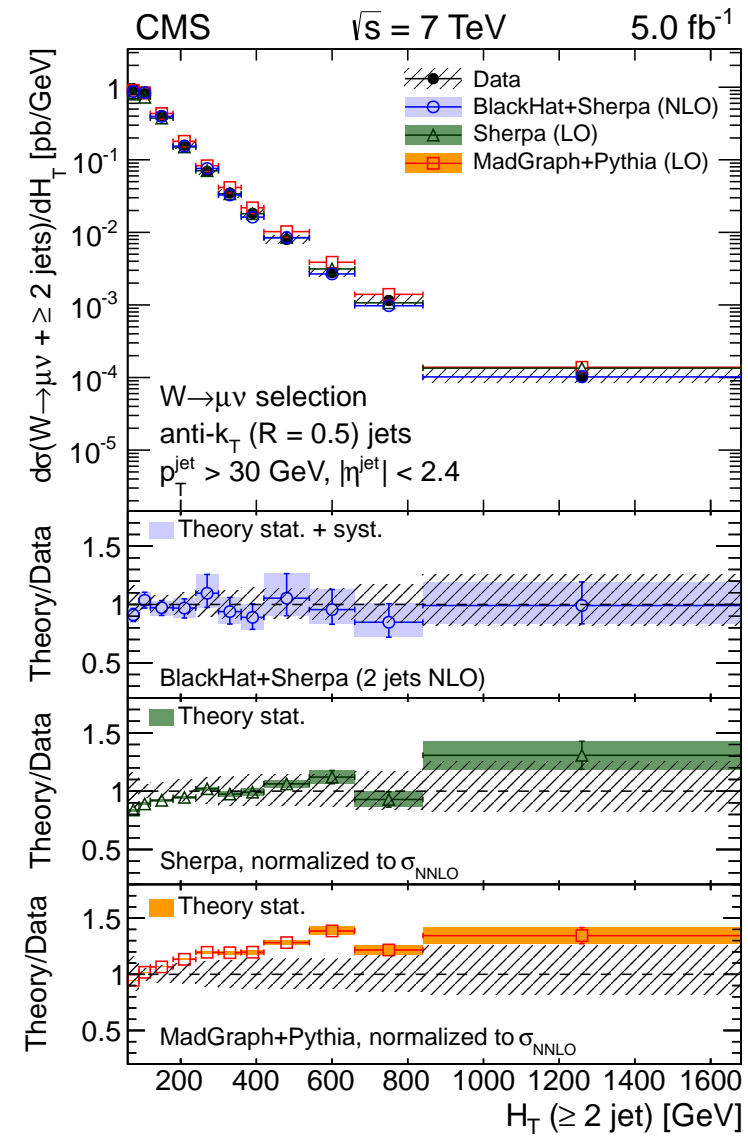
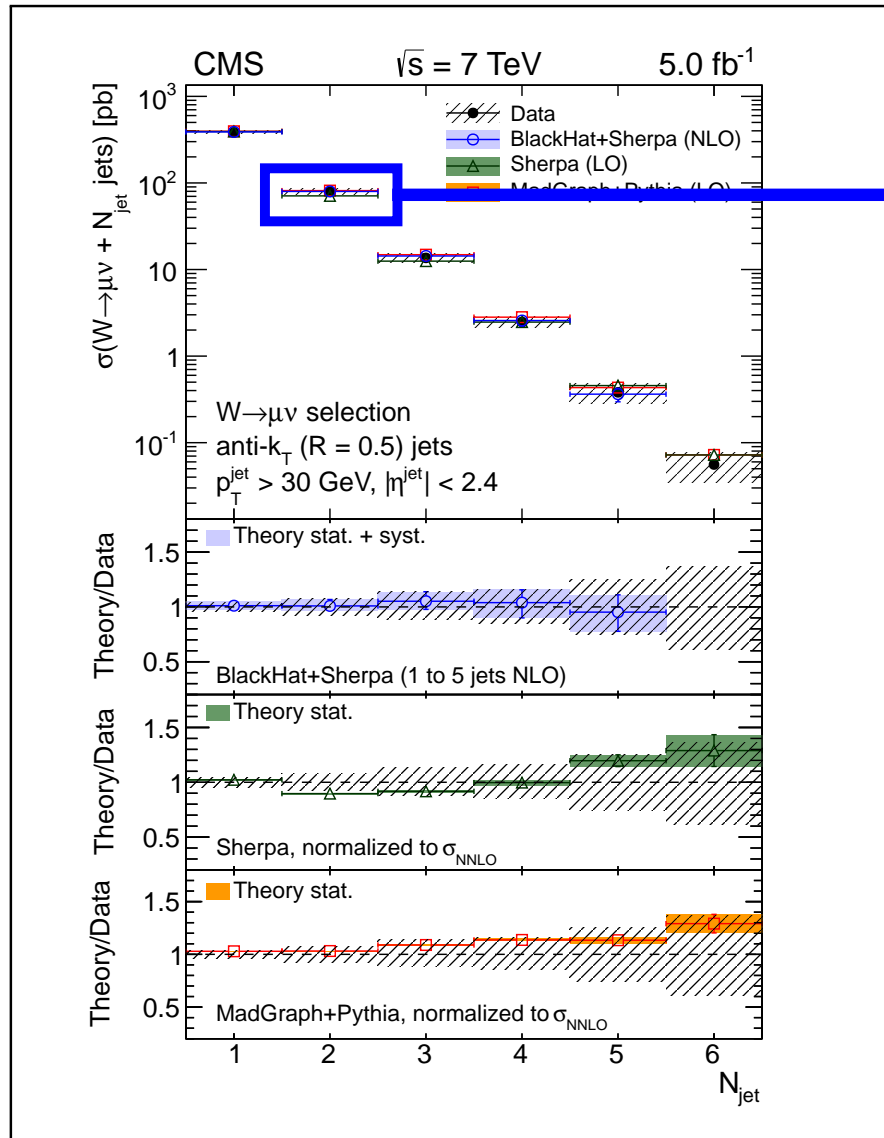
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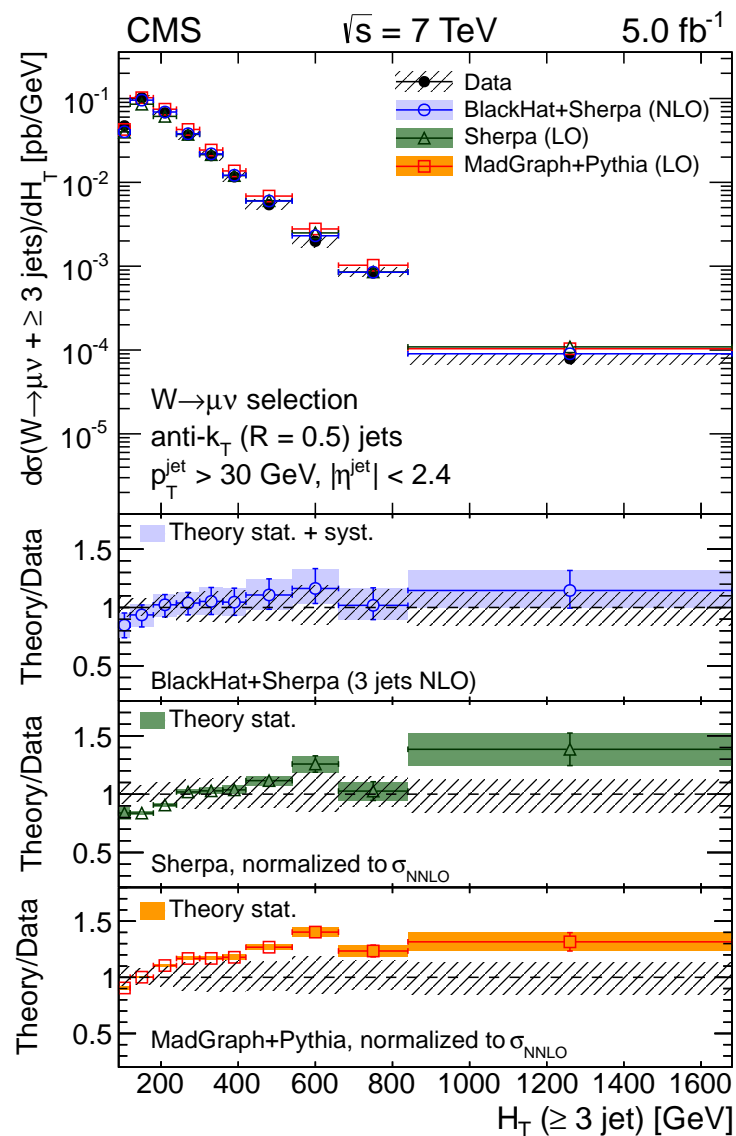
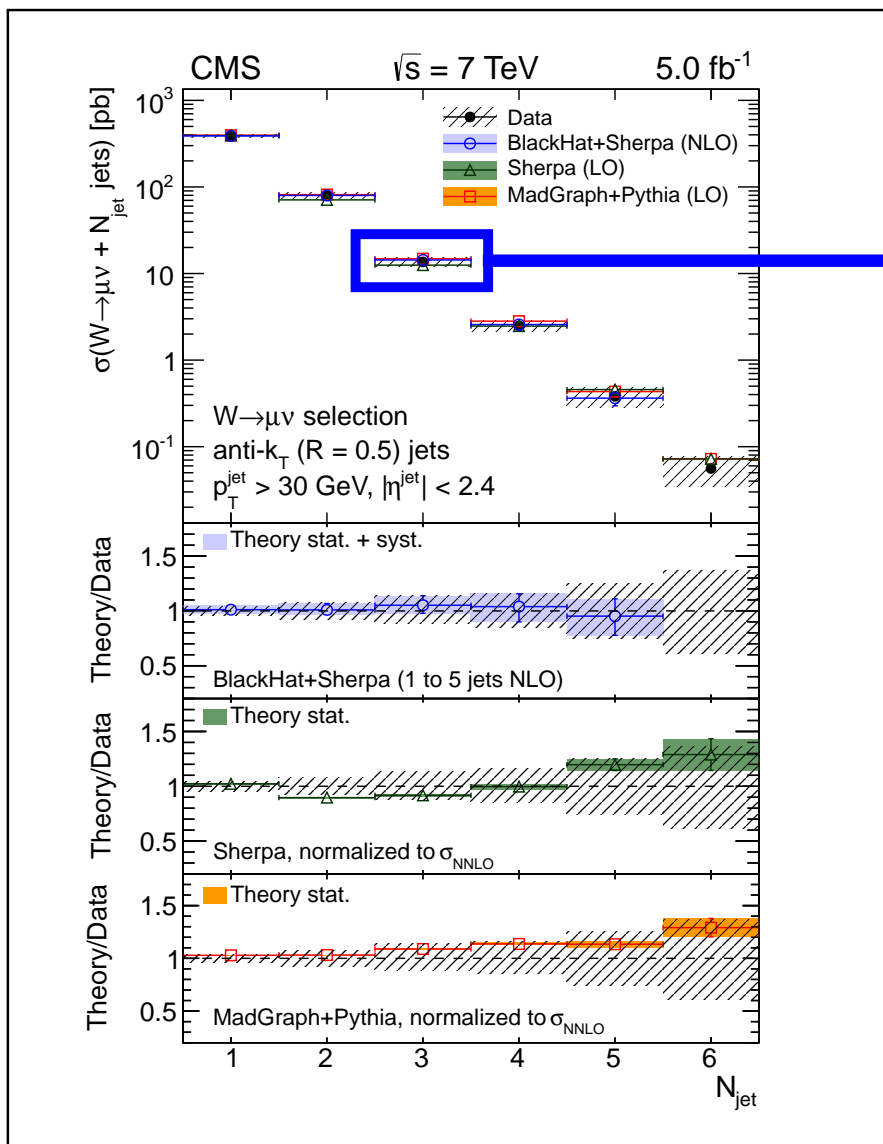
W + n jets @ CMS

arXiv: 1406.7533



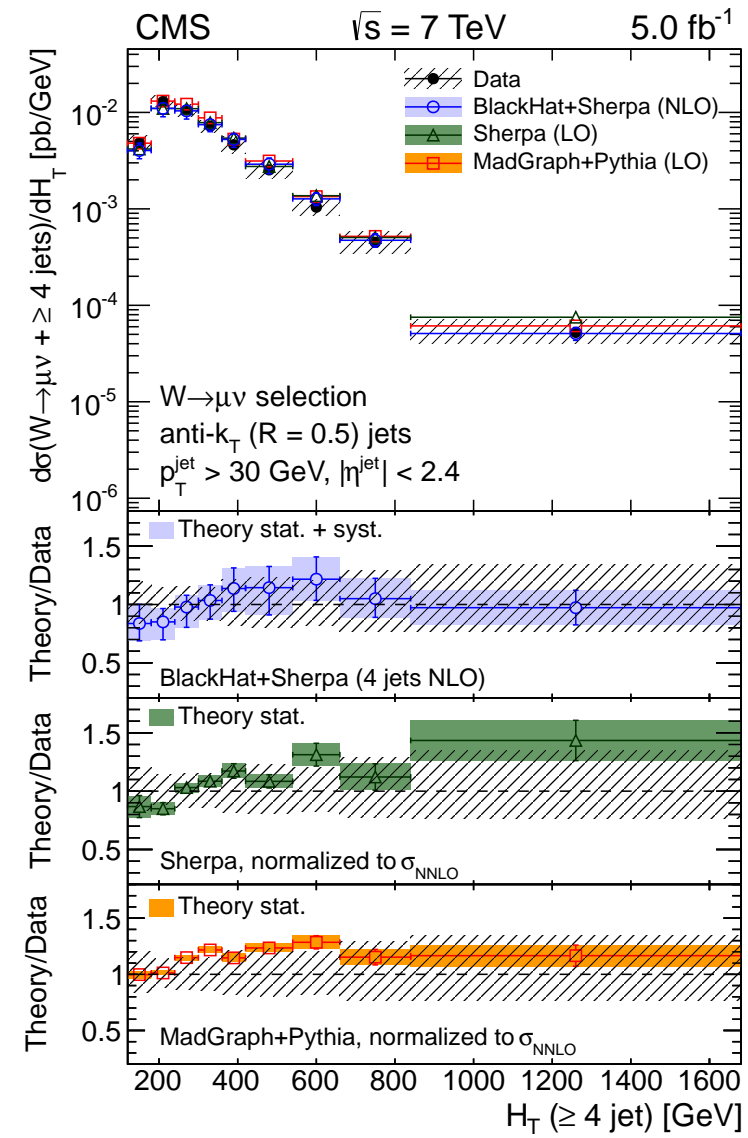
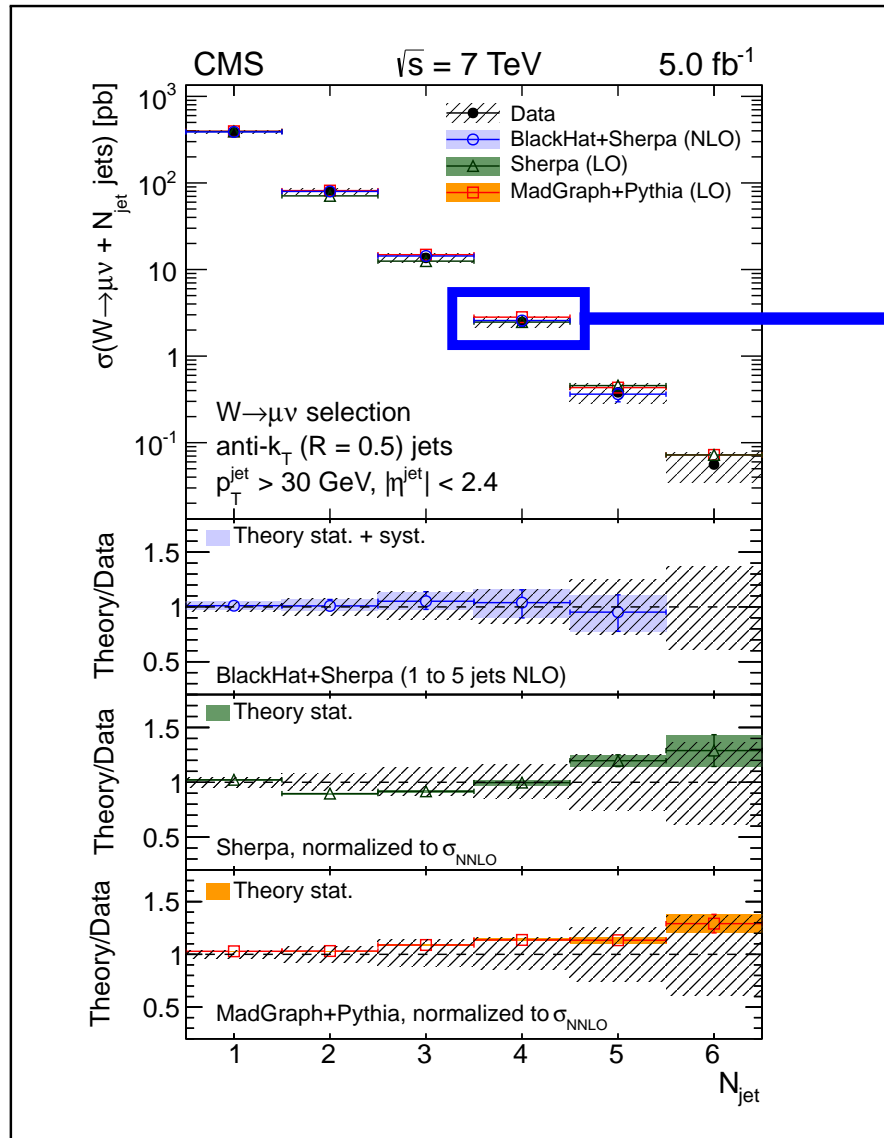
W + n jets @ CMS

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W + n jets @ CMS

arXiv: 1406.7533



Collider Phenomenology Today

A personal view...

- Multiple **event generation** frameworks for general physics analysis with full NLO matching (to MEs) and merging (jet multiplicity), realistic *signatures*
- Standard subtraction methods for **NNLO up to 2 → 2 phenomenology**
- Major progress in **NNLO QCD corrections** for 2 → 3 processes
- Several key processes (**Higgs and Drell Yan production**) computed to N³LO QCD, even including differential information
- Wide variety of analytic and numerical tools to compute **multi-loop master integrals**
- Major progress in our **understanding of the analytic structure of scattering amplitudes** in generic QFTs to high perturbative orders
- Spread-out **ML algorithms** to fully exploit the physics potential of collider datasets
- Robust **jet substructure** techniques for physics analysis

↳ & the BlackHat project contributed decisively!

- Thanks for the opportunity to talk at
this **Lance Fest** celebration!

- Thanks to all **Black Hat** collaborators!

