# QCD Tools and Searches for New Physics

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[1]Many thanks to Lance Dixon for slides on $G^3$ and to Steffen Schumann for slides on Jet scaling

# Outline

- Gluon compositeness
- $W$ polarization
- Jet scaling patterns
- New Monte-Carlo tools

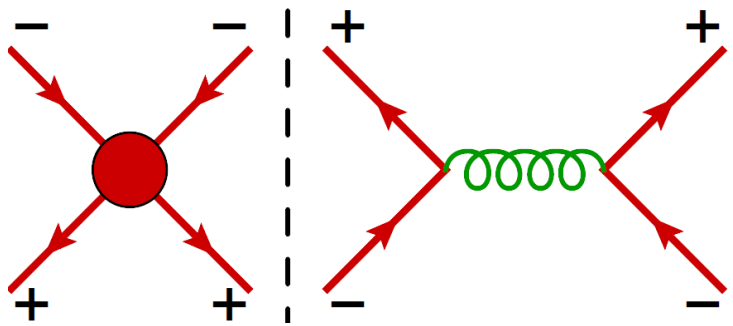
# Quark Compositeness

- Common to search for quark compositeness, or other new physics affecting quarks, by looking in tail of jet pT distribution or di-jet invariant mass spectrum.
- Tests a model in which dimension-6 4-quark operators (contact interactions) have been added:

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD}} + \frac{1}{\Lambda_{4q}^2}\,\bar{q}\gamma^{\mu}q\,\bar{q}\gamma_{\mu}q$$

- Amplitudes produced by operator interfere with QCD amplitudes

  $\rightarrow$ Di-jet cross section altered at order $\frac{1}{\Lambda_{4q}^2}$

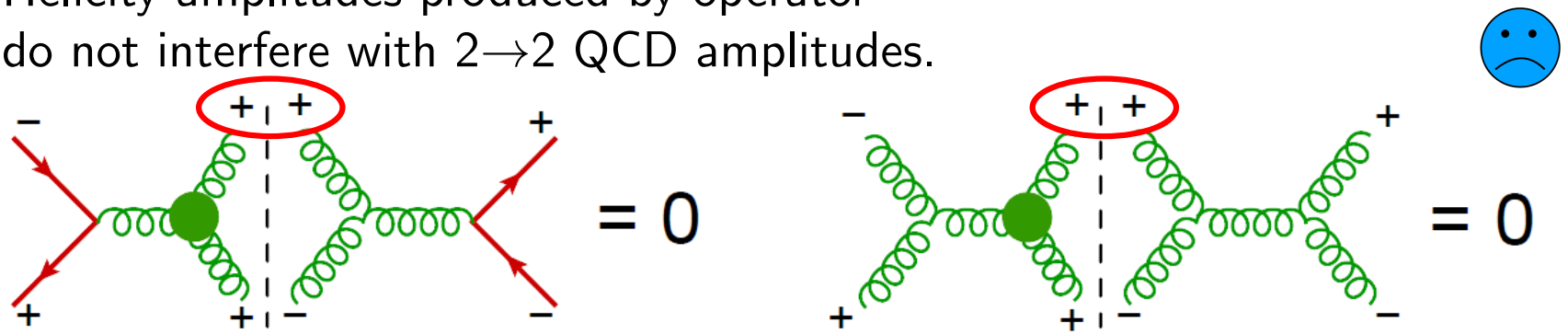


# Gluon Compositeness

- Add dimension-6 three-gluon operator:

$$\mathcal{L} = \mathcal{L}_{\rm QCD} + \frac{1}{\Lambda_{3g}^2} f_{abc} G_\mu^{\nu\, a} G_\nu^{\rho\, b} G_\rho^{\mu\, c}$$

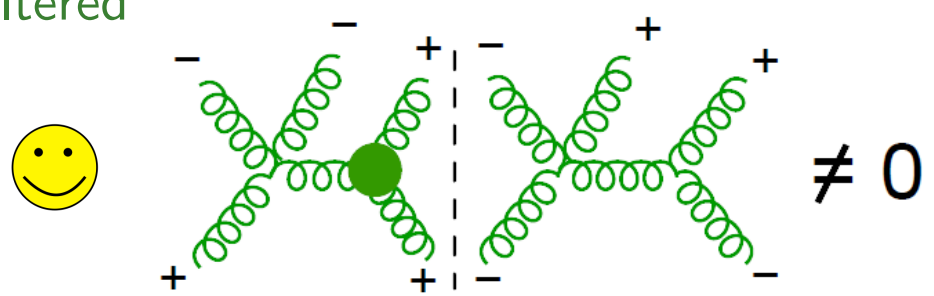
- Helicity amplitudes produced by operator do not interfere with 2→2 QCD amplitudes.



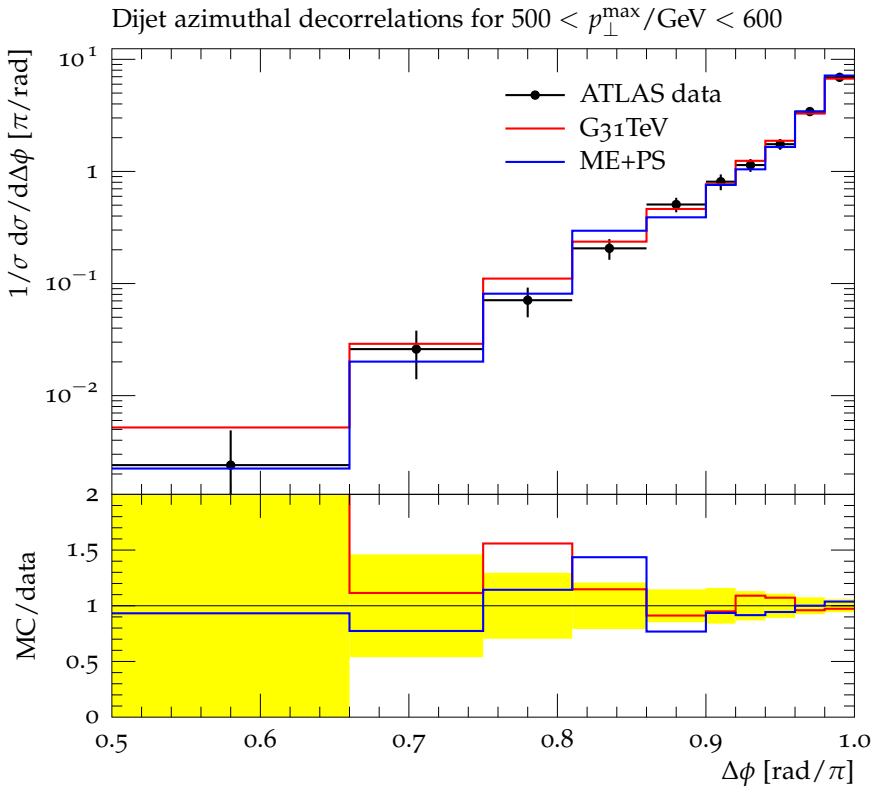

- Di-jet cross section not altered at order $\frac{1}{\Lambda_{3g}^2}$

  However, 3-jet cross section is altered

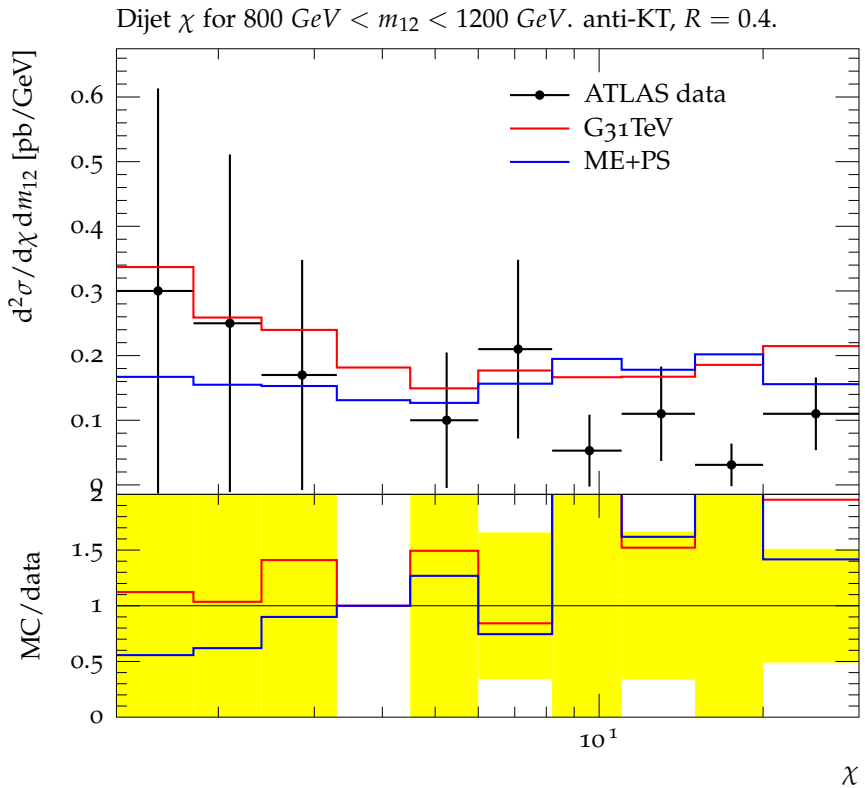
[Dixon,Shadmi] Nucl Phys B423(1994)3



# "G3" matrix elements in BlackHat+Sherpa




Exp. data: [ATLAS] PRL106(2011)172002




Exp. data: [ATLAS] EPJC71(2011)1512

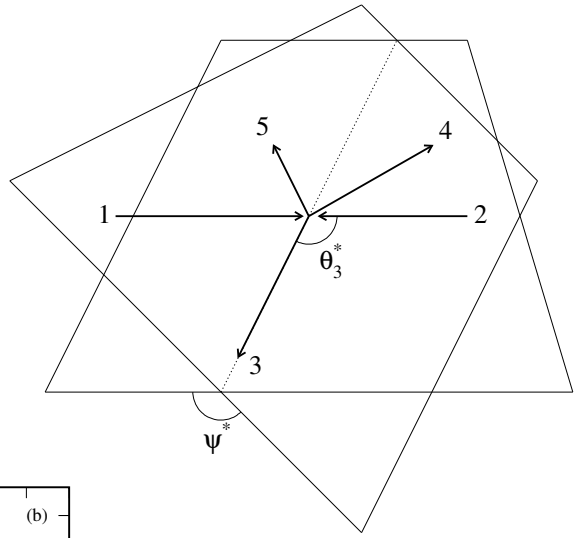
- Including parton shower with ME+PS, at order $1/\Lambda_{3g}^2$
- Distributions for $\Lambda_{3g} = 1$ TeV compared to ATLAS data

# "G3" search strategies?

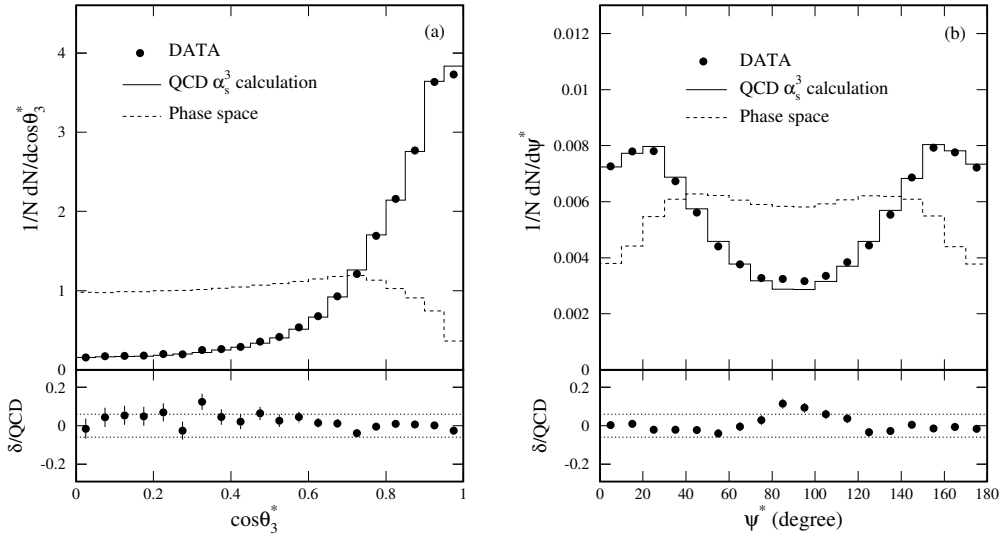
- Could use dedicated experimental analysis to find best distributions
  Set best (and only) bound on $\Lambda_{3g}$
- Potential candidates: 3-/4-jet angles

$$1 + 2 \to 3 + 4 + 5$$

$$\cos\psi^* = \frac{(p_1 \times p_3)(p_4 \times p_5)}{|p_1 \times p_3||p_4 \times p_5|}$$

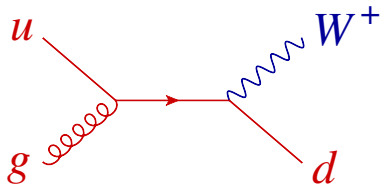


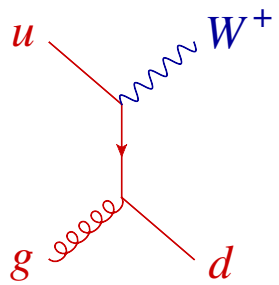

[CDF] PRD53(1996)6000



# $W$ polarization at high $p_T$

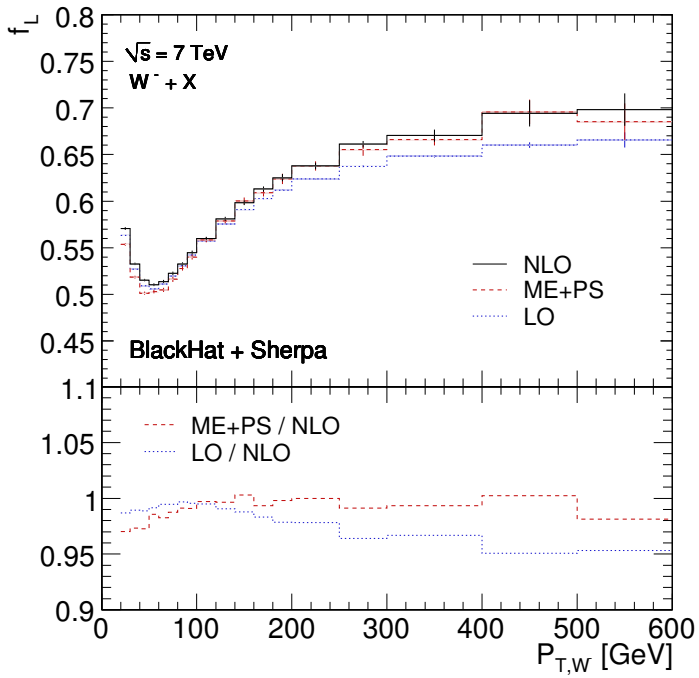
- Leading $W$ production modes at LHC



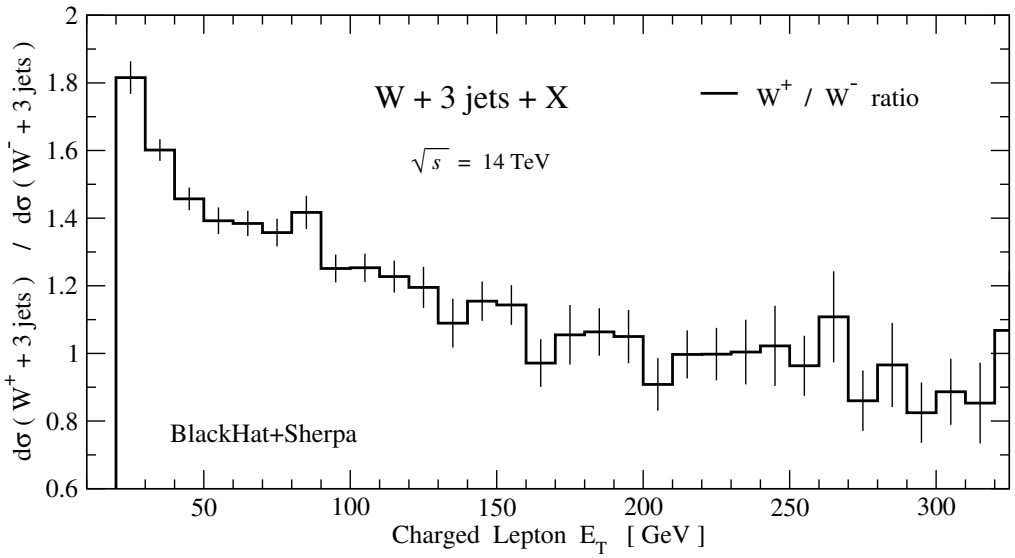

- Angular-momentum conservation in $s$-channel guarantees left-handed $W$
  $t$-channel contributes right-handed $W$ at high $p_T$, but only 1/4 rate
- 100% analyzing power in leptonic decay
- Effects persist at NLO

  [BlackHat] arXiv:0912.4927
  [BlackHat] PRD84(2011)034008



# Distinguishing $W$+jets from top production

- Left-handed polarization in $W$+jets translates into:
  - larger $p_T$ for $\nu_L$ in $W^+$ events
  - larger $p_T$ for $e_L^-$ in $W^-$ events




- $t\bar{t}$ production processes C-invariant

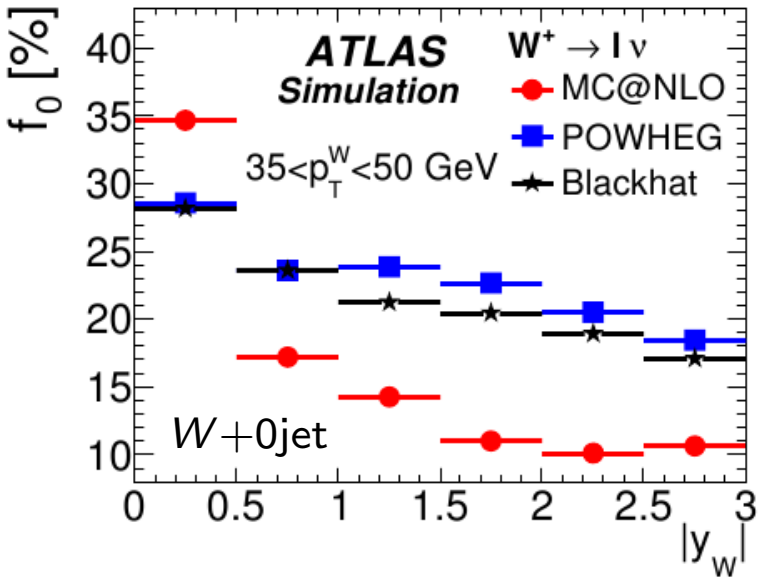
  $gg \to t\bar{t}$ $\quad$ $q\bar{q} \to t\bar{t}$

- $W^+$ from decay same degree right-handed as $W^-$ left-handed
  $\to$ same $p_T$ spectra for electron and positron

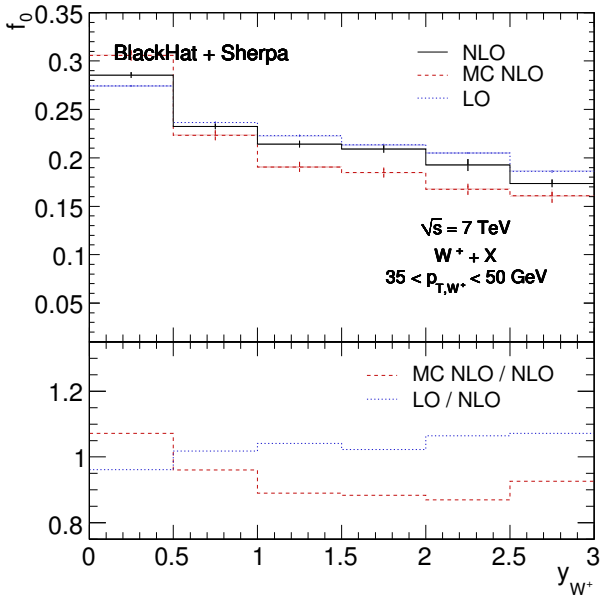
# Predictions at particle level

- Seeming discrepancy between MC@NLO & POWHEG results
- Entirely due to PS/LO prediction of polarization at high $p_T$
- Must use MC@NLO for $W$+jet

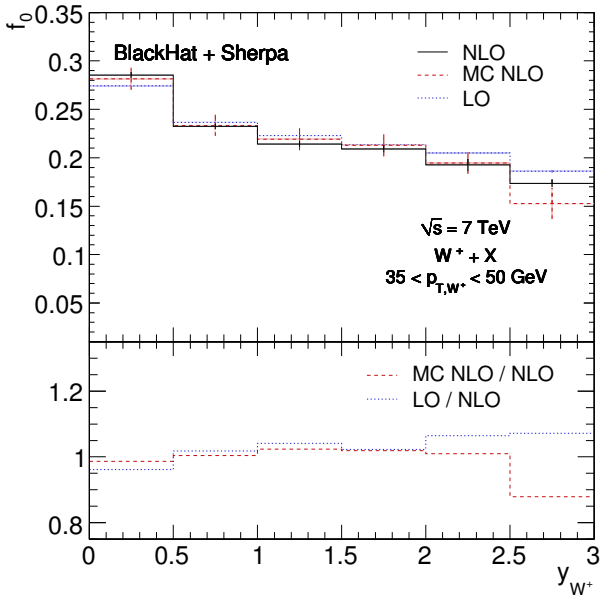
[ATLAS] EPJC72(2012)2001




$W$+0j MC@NLO ✗




$W$+1j MC@NLO ✓



# Jet ratio scaling patterns

- Consider "core" process (e.g. $W$-production) plus $n$ jets
- Cross section ratios
$$R_{(n+1)/n} = \frac{\sigma_{n+1}^{\text{excl}}}{\sigma_n^{\text{excl}}}$$
$\sim$ stable against QCD corrections [Gerwick et al.] JHEP10(2012)162

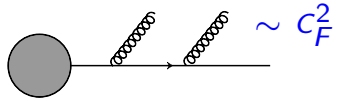
- **Staircase Scaling**:
$$R_{(n+1)/n} = \text{const} \quad \left(\sigma_n = \sigma_0\, R^n\right)$$
- First predicted for $W/Z$+jets
[Berends,Giele,Kuijf] NPB321(1989)39
- Induced by democratic jet cuts

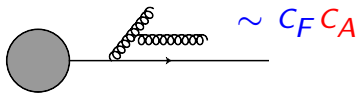
- **Poisson Scaling**:
$$R_{(n+1)/n} = \frac{\bar{n}}{n+1} \quad \left(\sigma_n = \frac{\bar{n}^n e^{-\bar{n}}}{n!}\right)$$
- Independent emission picture
(like soft $\gamma$ radiation in QED)
- Driven by large emission probability

# Theoretical background

- Analytically tractable $\rightarrow$ resummed jet rates [Gerwick et al.] JHEP04(2013)089
- Example: Durham jet rates in $e^+e^-$ collisions [Gerwick et al.] JHEP10(2012)162

$$P_0^{\mathrm{DLA}} = \exp\left[-\frac{aC_F L^2}{2}\right]$$



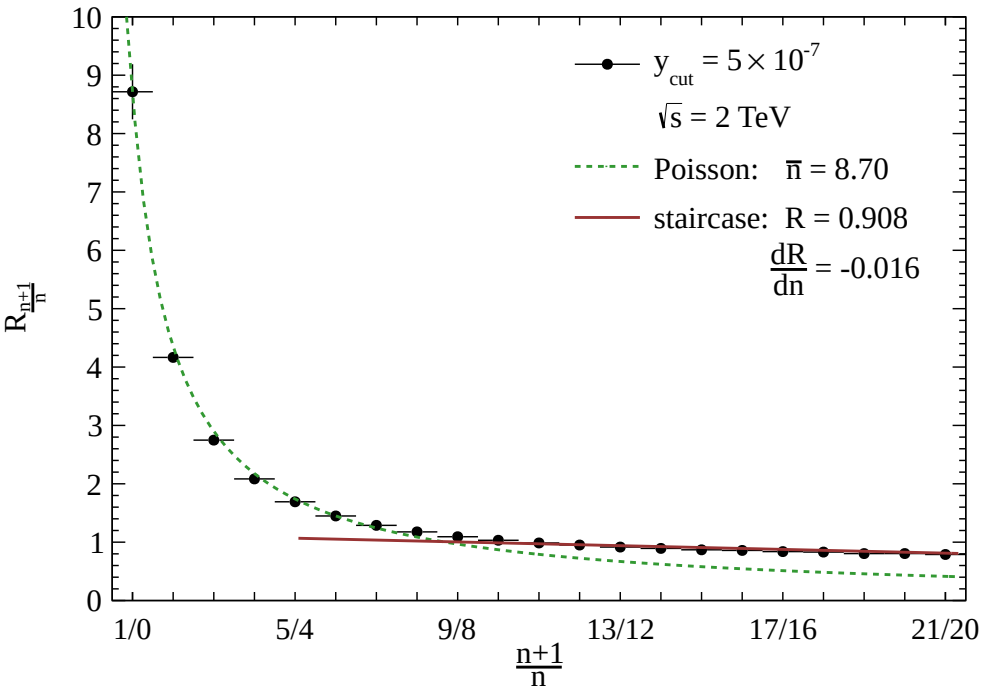

$$P_1^{\mathrm{DLA}} = \left(\frac{aC_F L^2}{2}\right)\exp\left[-\frac{aC_F L^2}{2}\right] - a^2\left(\frac{C_F C_A}{48}\right)L^4 + a^3\left(\frac{C_F^2 C_A}{96} + \frac{C_F C_A^2}{960}\right)L^6 + \ldots$$

$$P_2^{\mathrm{DLA}} = \frac{1}{2!}\left(\frac{aC_F L^2}{2}\right)^2\exp\left[-\frac{aC_F L^2}{2}\right] + a^2\left(\frac{C_F C_A}{48}\right)L^4 - a^3\left(\frac{C_F^2 C_A}{48} + \frac{7C_F C_A^2}{2880}\right)L^6 + \ldots$$

$$P_3^{\mathrm{DLA}} = \ldots$$

- Resummed abelian contributions yield Poisson distribution
  Deviation due to secondary emissions
- Modified by PDF in hadronic collisions, but overall picture remains

# Comparison with Monte-Carlo simulation



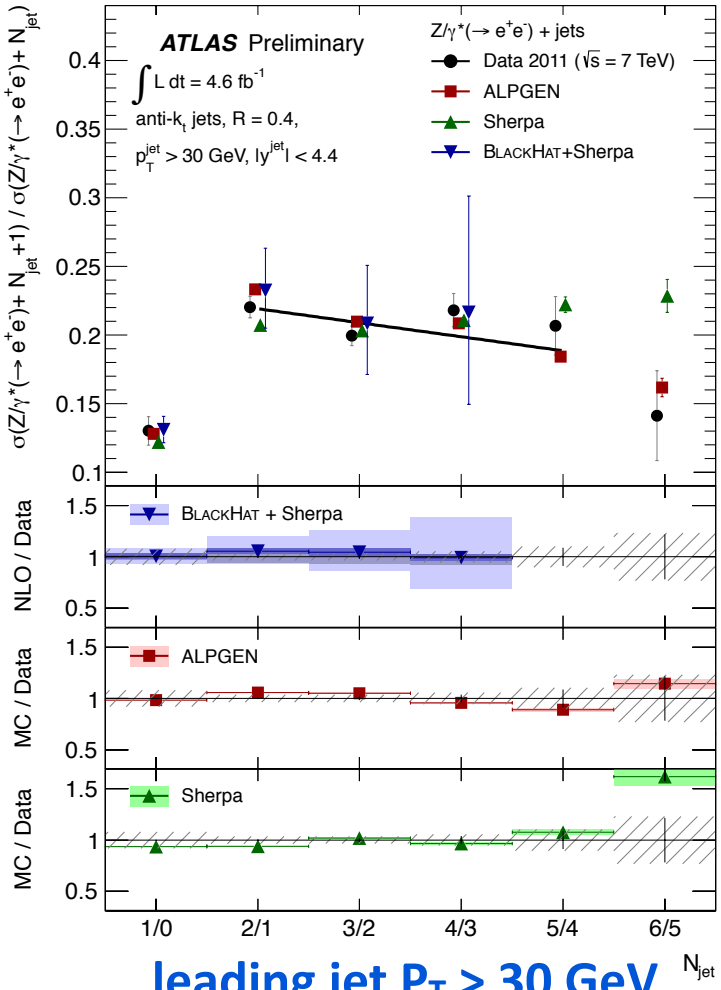

- $e^+e^-$-collider at $\sqrt{s} = 2$ TeV & $y_{\mathrm{cut}} = 5 \cdot 10^{-7}$
- Simulated results from Sherpa parton shower ($g \to q\bar{q}$ off)
- Good fit to a Poisson for low multi, transition to staircase at $\sim n = 8$

# Experimental observation

- First measurement by ATLAS in $Z$+jets

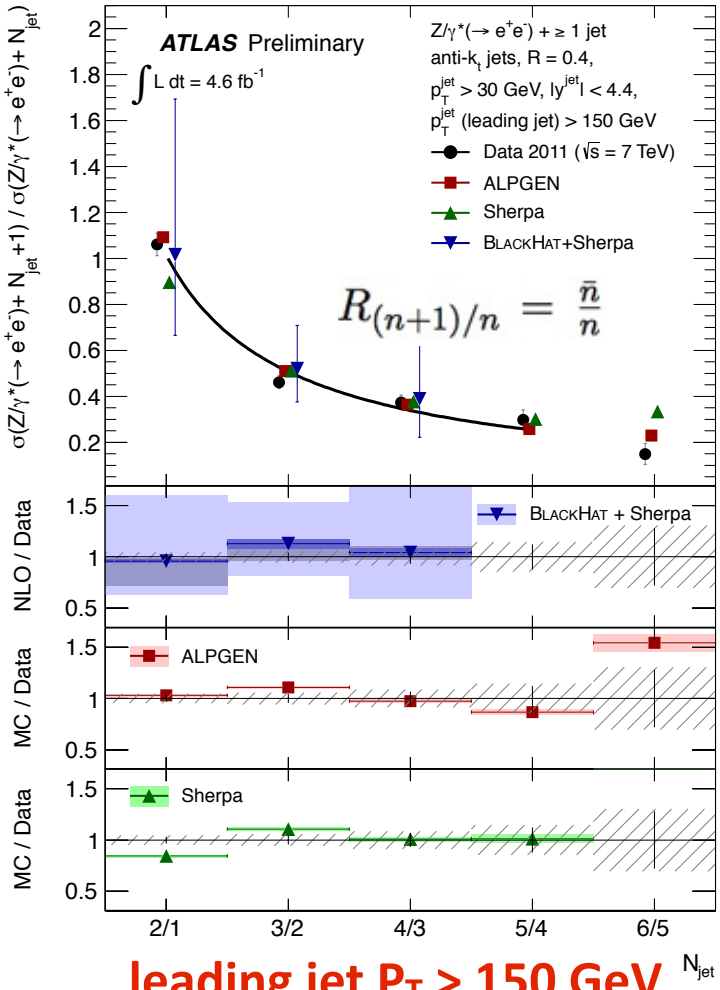
[ATLAS] arXiv:1304.7098

Staircase scaling




leading jet $P_T$ > 30 GeV

Poisson scaling




leading jet $P_T$ > 150 GeV

# NLO predictions

[BlackHat] arXiv:1304.1253

- $W$+jets at 7 TeV, $E_T^e > 20\ \mathrm{GeV}$ , $|\eta^e| < 2.5$ , $\not{E}_T > 20\ \mathrm{GeV}$
  $p_T^j > 25\ \mathrm{GeV}$ , $|\eta^j| < 3$ , $M_T^W > 20\ \mathrm{GeV}$

| Jets | $\frac{W^- + (n+1)}{W^- + n}$ | | $\frac{W^+ + (n+1)}{W^+ + n}$ | |
|---|---|---|---|---|
| | LO | NLO | LO | NLO |
| 1 | 0.2949(0.0003) | 0.238(0.001) | 0.3119(0.0005) | 0.242(0.002) |
| 2 | 0.2511(0.0005) | 0.220(0.001) | 0.2671(0.0004) | 0.235(0.002) |
| 3 | 0.2345(0.0008) | 0.211(0.003) | 0.2490(0.0005) | 0.225(0.003) |
| 4 | 0.218(0.001) | 0.200(0.006) | 0.2319(0.0008) | 0.218(0.006) |

- Fit to straight line for $W + n$ jets gives $(n \geq 2)$

$$R^{\mathrm{NLO},\,W^-}_{n/(n-1)} = 0.248 \pm 0.008 - (0.009 \pm 0.002)\, n$$

$$R^{\mathrm{NLO},\,W^+}_{n/(n-1)} = 0.263 \pm 0.009 - (0.009 \pm 0.003)\, n$$

- Extrapolate to six jets

$W^- + 6$ jets : $0.15 \pm 0.01$ pb

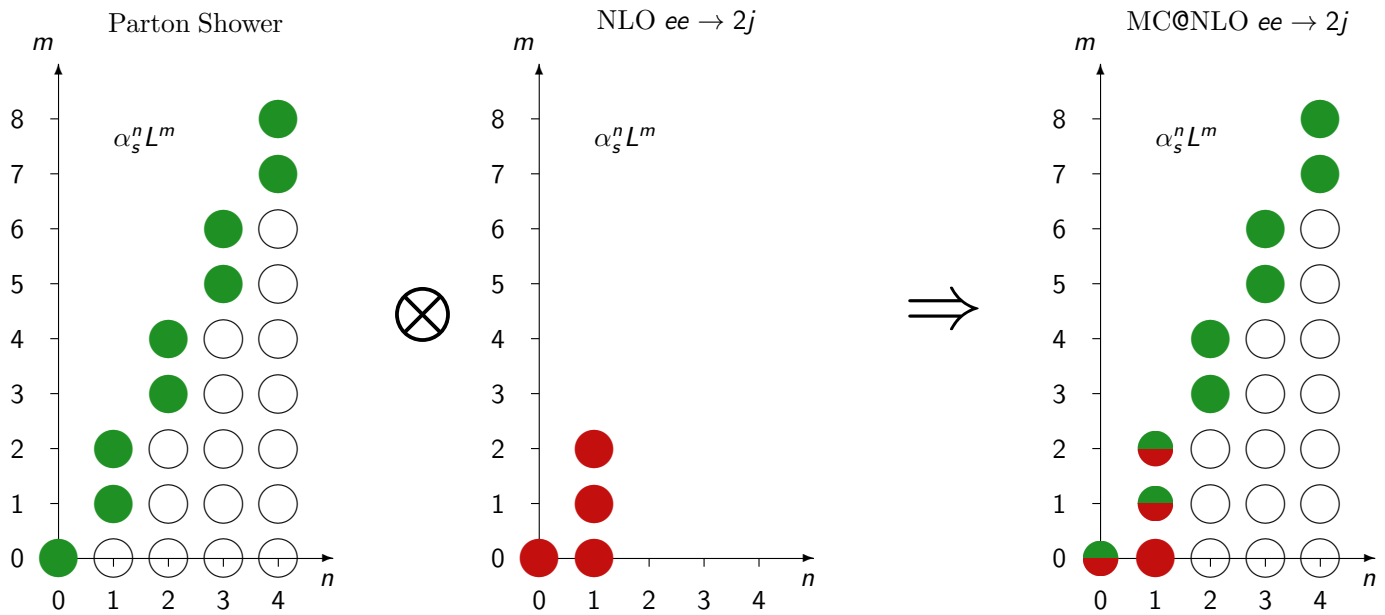
$W^+ + 6$ jets : $0.30 \pm 0.03$ pb

# Matching NLO calculations and parton showers

[Frixione,Webber] JHEP06(2002)029
[Nason] JHEP11(2004)040

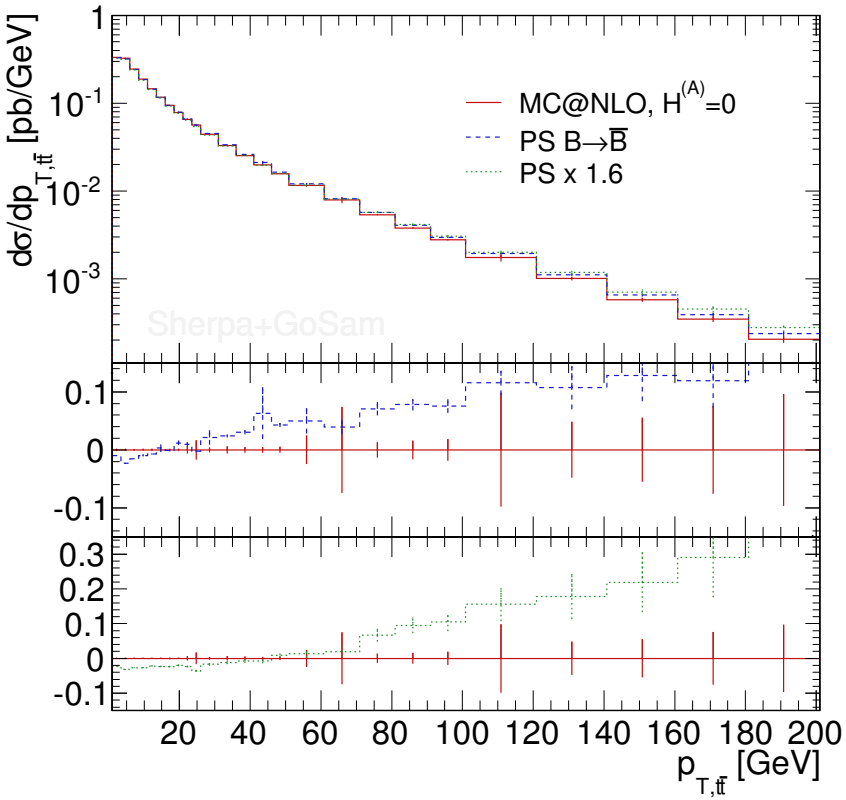
## Objective

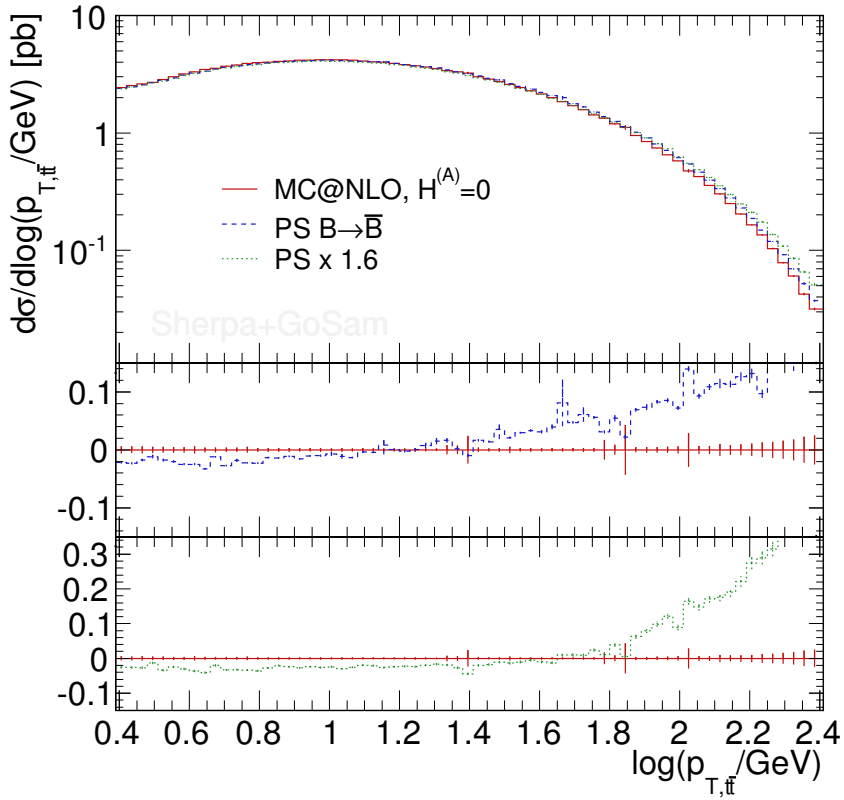
- NLO accurate parton-level prediction for $n$-jet process
- Combined with resummation encoded in parton shower




Example: $e^+e^- \to$hadrons

# Example: Top-pair production



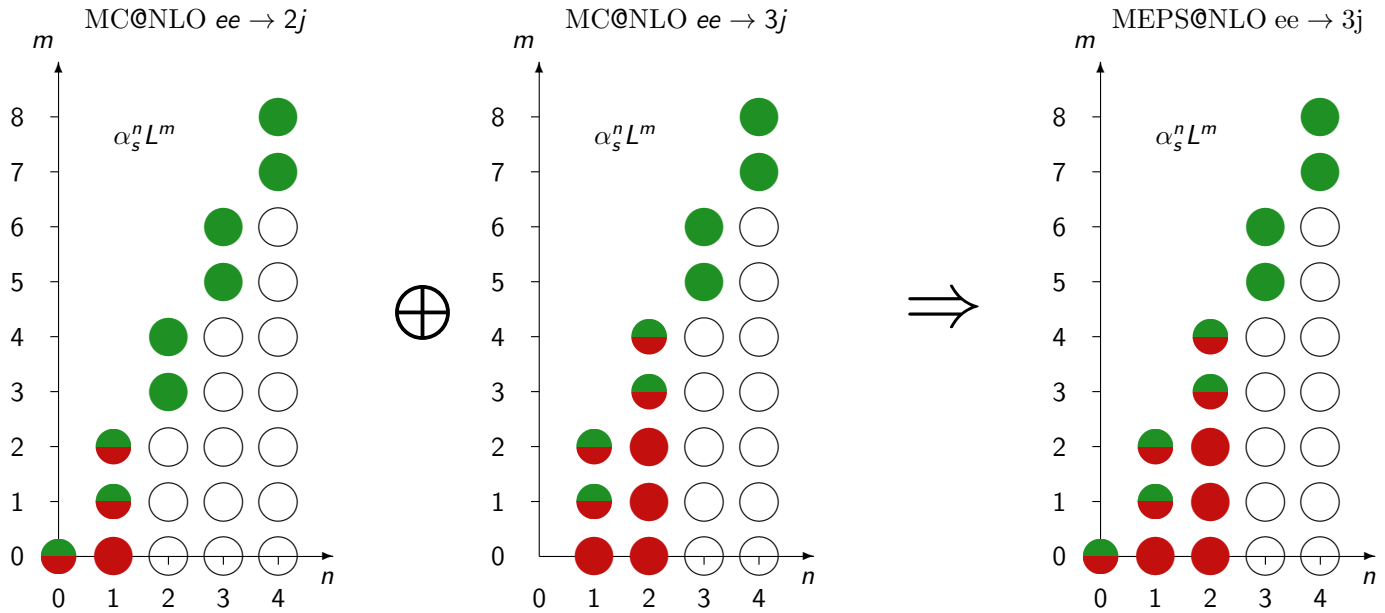

- Simulation includes sub-leading color terms in MC@NLO
- Small impact here, but also small shape difference LO↔NLO

# ME+PS merging at NLO

[Lavesson,Lönnblad] JHEP12(2008)070
[Krauss et al.] JHEP04(2013)027

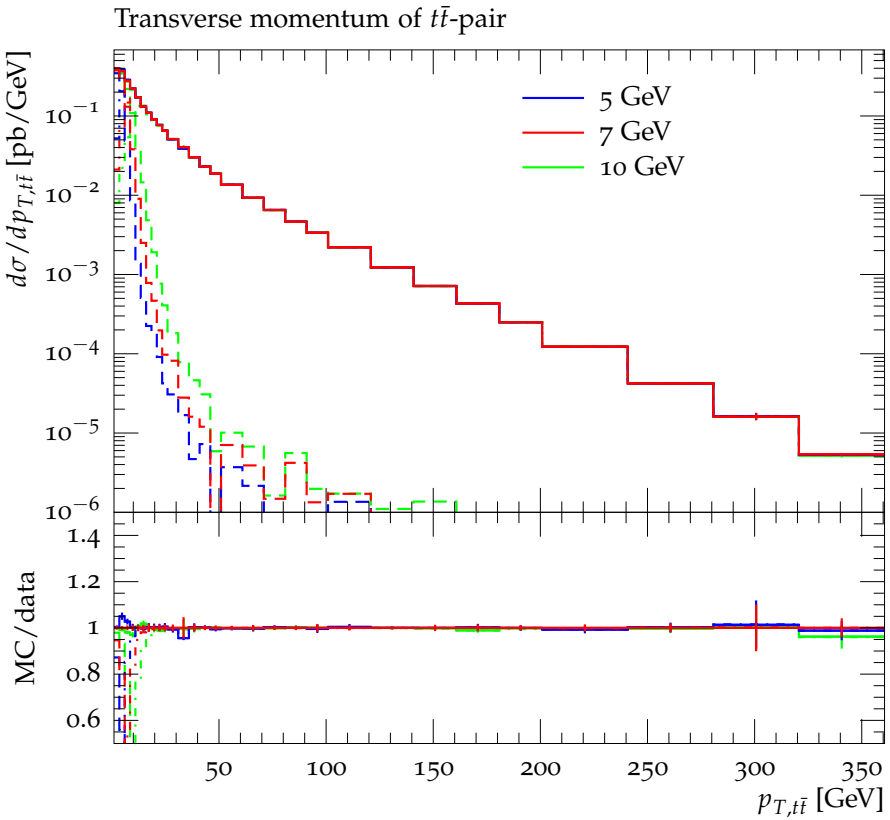
## Objectives

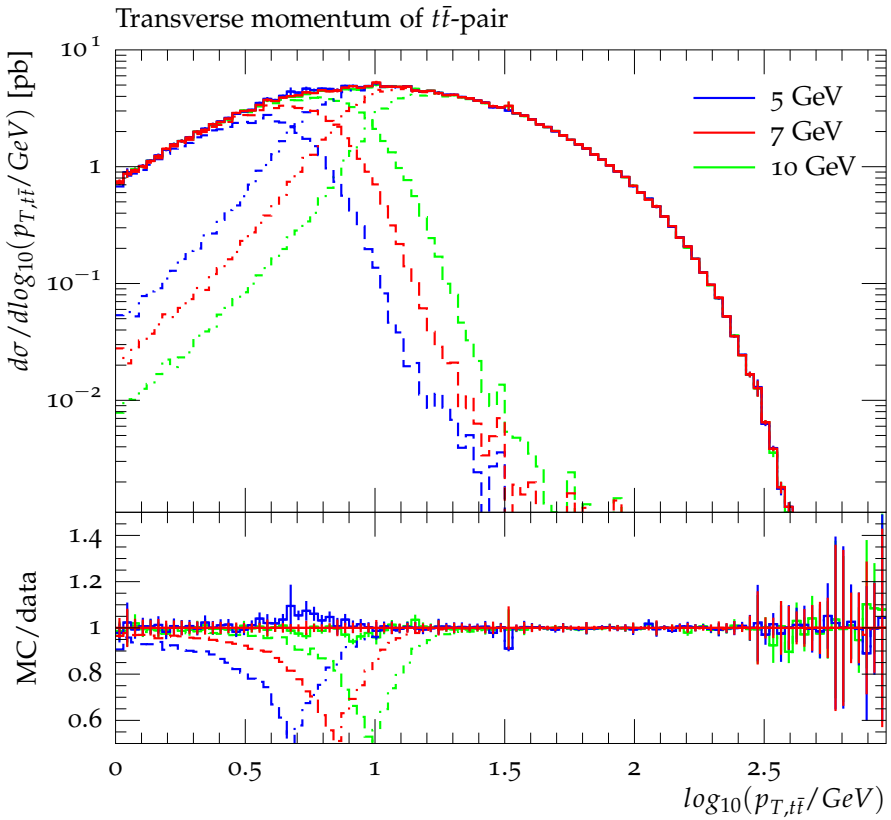
- NLO accurate predictions for $k_{T,j} > k_{T,\mathrm{cut}}$ and variable $n$
- Logarithmic accuracy of PS throughout




Example: $e^+e^-$ →hadrons

# Top pair production at the Tevatron

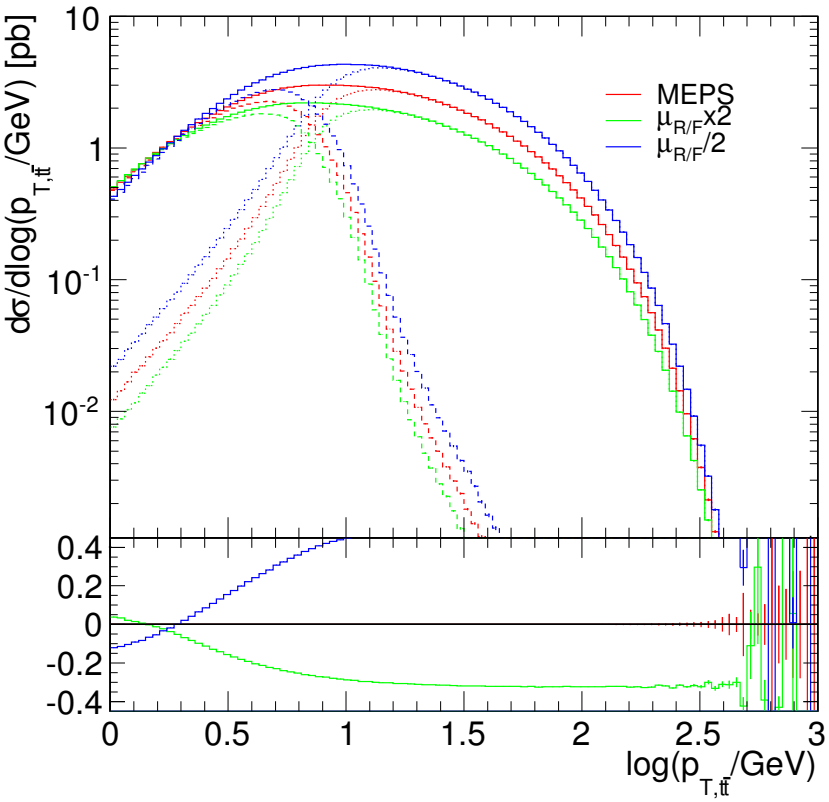


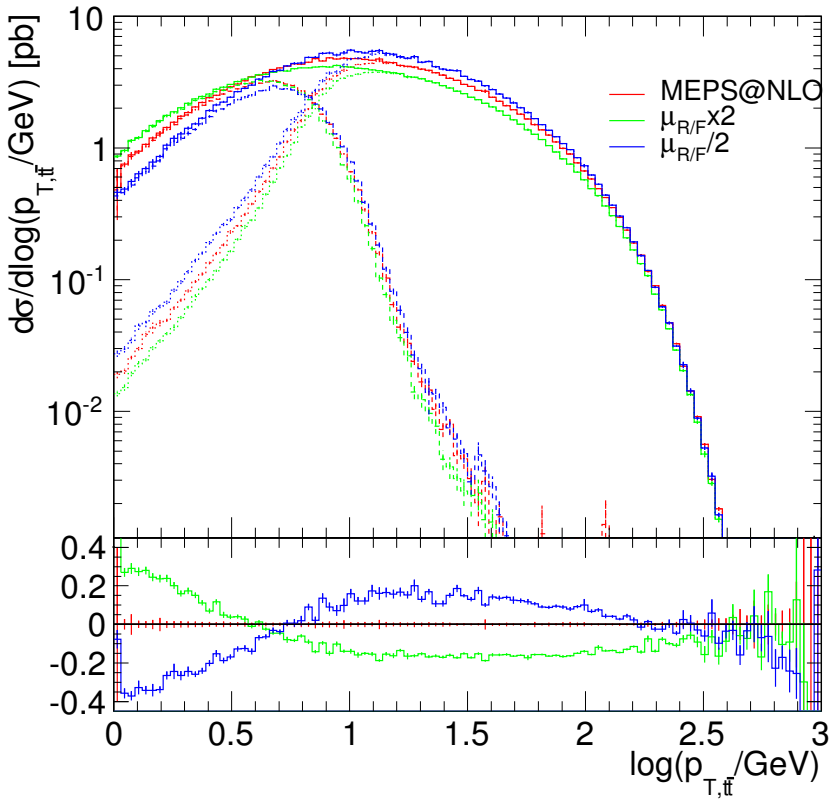

- Consistency check: Variation of phase-space separation cut $Q_{cut}$

# Top pair production at the Tevatron

LO merging




NLO merging




- Renormalization/factorization scale variation
- Central scale according to [Marchesini,Webber] NPB310(1988)461

# Summary

- It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so. [Mark Twain]
- QCD still full of surprises
- But sometimes also simple ($\rightarrow$ jet scaling)
- New Monte-Carlo tools help fill in the details

# MCatNLO in Sherpa

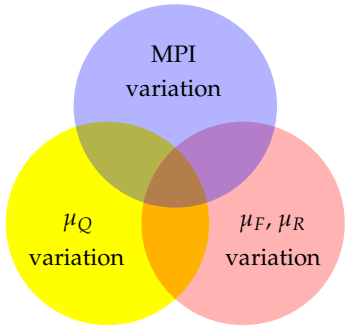
- Automated using CS subtraction

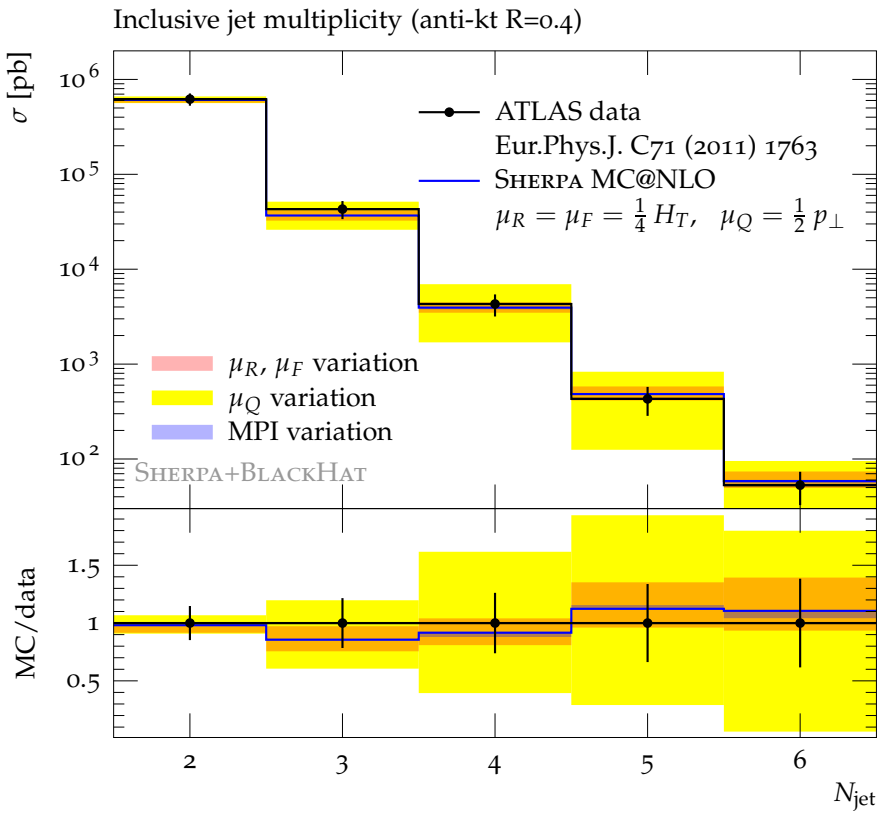
  [Catani,Seymour] NPB485(1997)291
  [Gleisberg,Krauss] EPJC53(2008)501
  [Schumann,Krauss] JHEP03(2008)038

- Validated in QCD jets production
  - CT10, $\alpha_s(M_Z) = 0.118$
  - Full hadron level, incl. MPI
  - Virtual corrections $\rightarrow$ BlackHat

    [Berger et al.] PRD78(2008)036003
    [Giele,Glover,Kosower] NPB403(1993)633
  - $p_{T,j1} > 20$ GeV, $p_{T,j2} > 10$ GeV
  - $\mu_{R/F} = H_T/4$, $\mu_Q = p_T/2$

- Implementation allows to assess renormalization/factorization and resummation scale uncertainty

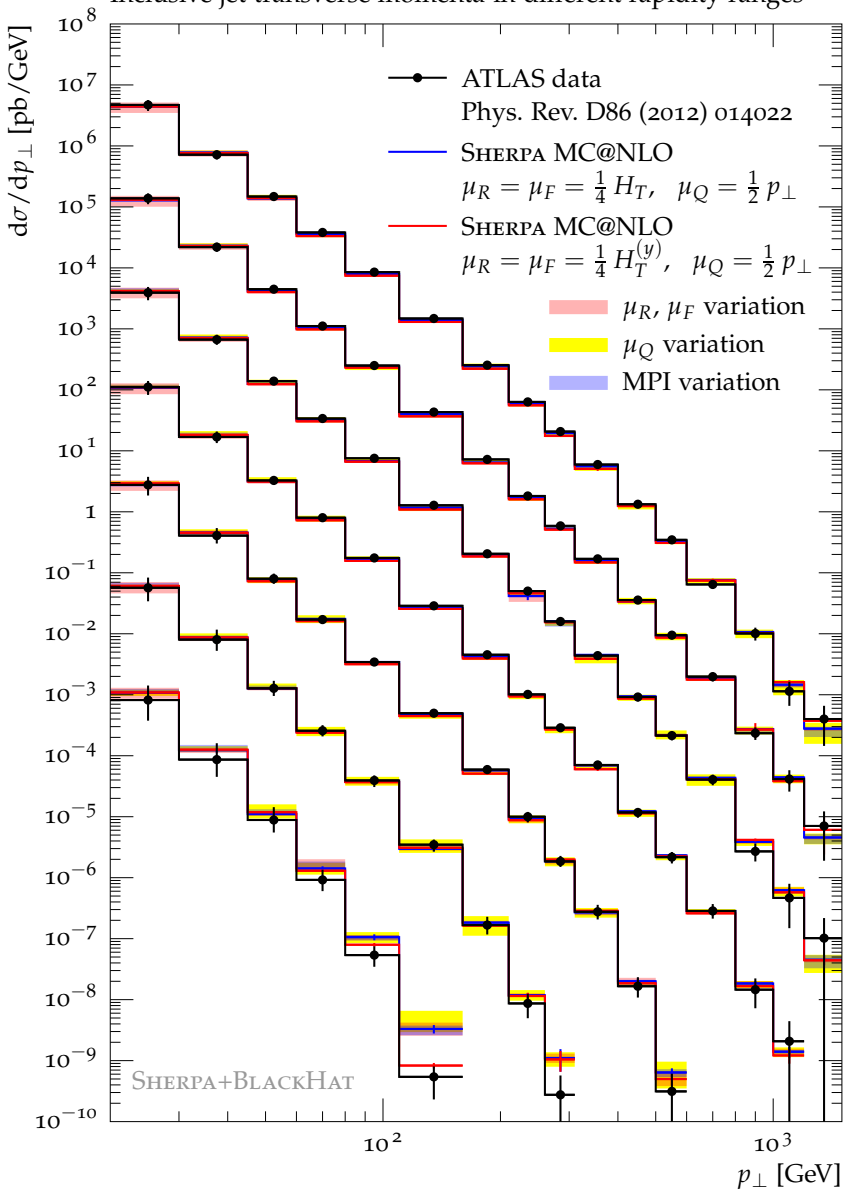



[Schönherr,SH] PRD86(2012)094042

# Inclusive jet production at the LHC

Inclusive jet transverse momenta in different rapidity ranges




Dijet invariant mass spectra in different rapidity ranges