W+3 jet production

— *signal or background* —

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W + 3 jets

1. W + 3 jets measured at the Tevaton, but LO varies by more than a factor 2 for reasonable changes in scales

	$W^{\pm}$, TeV	W^{+}, LHC	W^{-}, LHC
σ [pb], $\mu = 40$ GeV	74.0 ± 0.2	783.1 ± 2.7	481.6 ± 1.4
σ [pb], $\mu = 80$ GeV	45.5 ± 0.1	515.1 ± 1.1	316.7 ± 0.7
σ [pb], $\mu = 160$ GeV	29.5 ± 0.1	353.5 ± 0.8	217.5 ± 0.5

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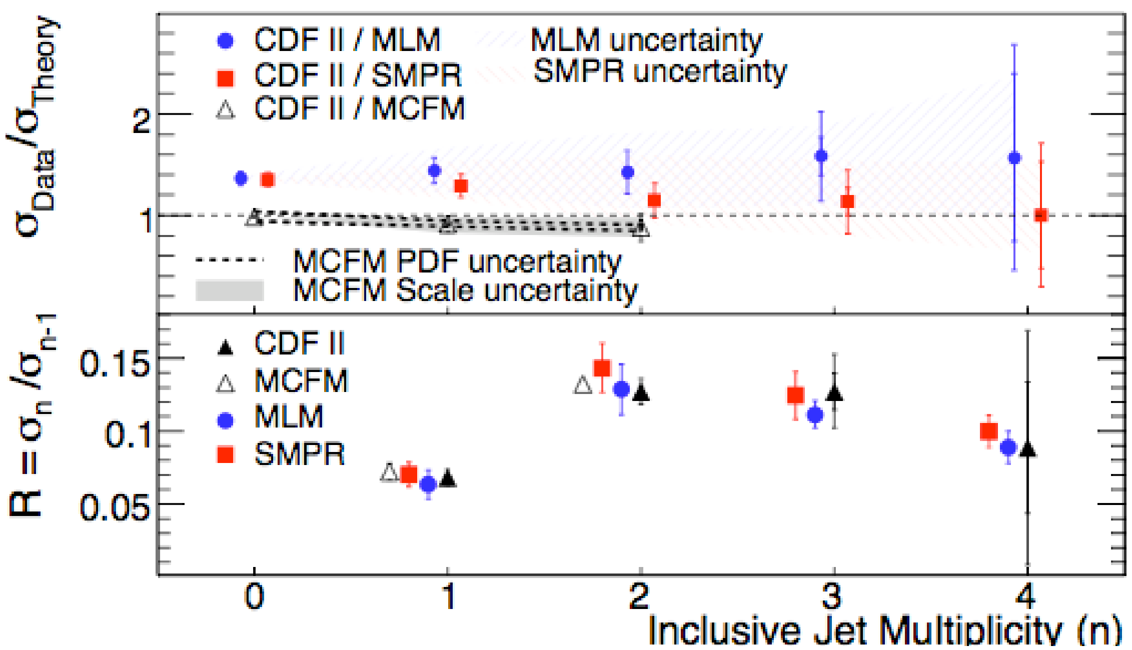
II. CDF data for W + n jets with n=1,2 is described exceptionally well by NLO QCD
$\Rightarrow$ verify this for 3 and more jets



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III. W/Z + 3 jets of interest at the LHC, as one of the backgrounds to model-independent new physics searches using jets + MET

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IV. Calculation highly non-trivial optimal testing ground

$0 \to \bar{u}\, d\, g\, g\, g\, W^+$ → 1203 +104 Feynman diagrams

$0 \to \bar{u}\, d\, \bar{Q}\, Q\, g\, W^+$ → 258 +18 Feynman diagrams

Generalized unitarity

I will not explain the method.
I will concentrate on applications & recent results

References:

- Ellis, Giele, Kunszt '07 — *[Unitarity in D=4]*
- Giele, Kunszt, Melnikov '08 — *[Unitarity in D≠4]*
- Giele & GZ '08 — *[All one-loop N-gluon amplitudes]*
- Ellis, Giele, Melnikov, Kunszt '08 — *[Massive fermions, ttggg amplitudes]*
- Ellis, Giele, Melnikov, Kunszt, GZ '08 — *[W+5p one-loop amplitudes]*
- Ellis, Melnikov, GZ '09, Melnikov & GZ '09 — *[W+3 jets]*

These papers heavily rely on previous work

- Bern, Dixon, Kosower '94 — *[Unitarity, oneloop from trees]*
- Ossola, Pittau, Papadopoulos '06 — *[OPP]*
- Britto, Cachazo, Feng '04 — *[Generalized cuts]*
- *[....]*

The F90 Rocket program

Rocket science!

Eruca sativa =Rocket=roquette=arugula=rucola
Recursive unitarity calculation of one-loop amplitudes

So far computed one-loop amplitudes:

- ✓ N-gluons
- ✓ qq + N-gluons
- ✓ qq + W + N-gluons
- ✓ qq + QQ + W
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NB: N is a parameter in Rocket

In perspective, for gluons:

$N = 6 \Rightarrow$ 10860 diags.

$N = 7 \Rightarrow$ 168925 diags.

Successfully computed up to N=20

Cross-section calculation

- Consider the NLO leading color approximation, keep n_f dependence exact (important for beta function) but neglect $1/N_c^2$ terms

- Real radiation part:
  - leading color tree level W+6 parton amplitudes computed recursively
  - we use Catani-Seymour subtraction terms modified to deal with the minimal set of color structures needed at leading color

- Real + virtual implemented in the MCFM parton level integrator

Full-color NLO calculation done by Berger et al. '09

Leading color adjustment

Define

$$\mathcal{R}_{\mathcal{O}} = \frac{\int \mathcal{O}(p) \mathrm{d}\sigma_{LO}^{\mathrm{FC}}(\mu, p)}{\int \mathcal{O}(p) \mathrm{d}\sigma_{LO}^{\mathrm{LC}}(\mu, p)}$$

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This turns out to be very stable, independent of factorization/renormalization and on the observable (e.g. bin of distribution)

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Leading color adjustment tested in W+1, W+2jets and W+3jets: always OK to 3 %

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<u>Other O(1%) effects neglected:</u>

- CKM set to unity ⇒ ~ -1%
- W treated onshell ⇒~ +1%

CDF cuts

$$p_{\perp,j} > 20\text{GeV} \qquad p_{\perp,e} > 20\text{GeV} \qquad E_{\perp,\text{miss}} > 30\text{GeV}$$

$$|\eta_e| < 1.1 \qquad M_{\perp,W} > 20\text{GeV}$$

$$\mu_0 = \sqrt{p_{\perp,W}^2 + M_W^2} \qquad \mu = \mu_R = \mu_F = [\mu_0/2, 2\mu_0]$$

- PDFs: cteq6l1 and cteq6m
- CDF applies lepton-isolation cuts. This is a O(10%) effect. Lepton-isolation has been corrected for (would not have been needed ...) No lepton isolation applied
- CDF uses JETCLU with R = 0.4, but this is not infrared safe, use a different jet-algorithm

Jet-algorithms

- CDF uses JETCLU which is not infrared safe
- NLO calculation with JETCLU not possible
- use e.g. SISCone and anti-kt algorithm which are IR safe
- can compare Leading order results for these algorithm (even if meaning of LO for JETCLU is questionable ...)

<u>Leading order:</u>

Algorithm	R	$E_\perp^{\text{jet}} > 20$ GeV	$E_\perp^{\text{3rdjet}} > 25$ GeV
JETCLU	0.4	$1.845(2)^{+1.101(3)}_{-0.634(2)}$	$1.008(1)^{+0.614(2)}_{-0.352(1)}$
SIScone	0.4	$1.470(1)^{+0.765(1)}_{-0.560(1)}$	$0.805(1)^{+0.493(1)}_{-0.281(1)}$
anti-$k_\perp$	0.4	$1.850(1)^{+1.105(1)}_{-0.638(1)}$	$1.010(1)^{+0.619(1)}_{-0.351(1)}$

SIScone: Salam & Soyez '07;
anti-kt: Cacciari, Salam, Soyez '08

At LO anti-kt R =0.4 is closer to JETCLU

<u>Moral:</u>
precision comparison with theory require that experiments use IR-safe algorithms

Cross-section at the Tevatron

$$\sigma_{W+3j}(p_{\perp,j} > 25\,\mathrm{GeV}) = (0.84 \pm 0.24)\,\mathrm{pb}$$

CDF

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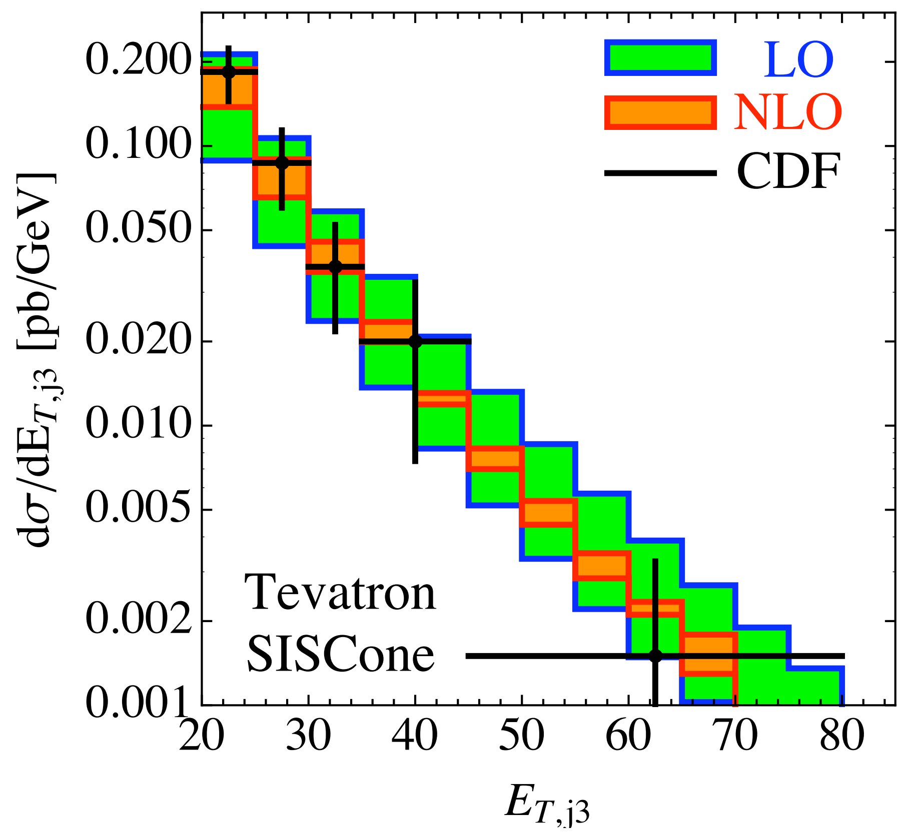
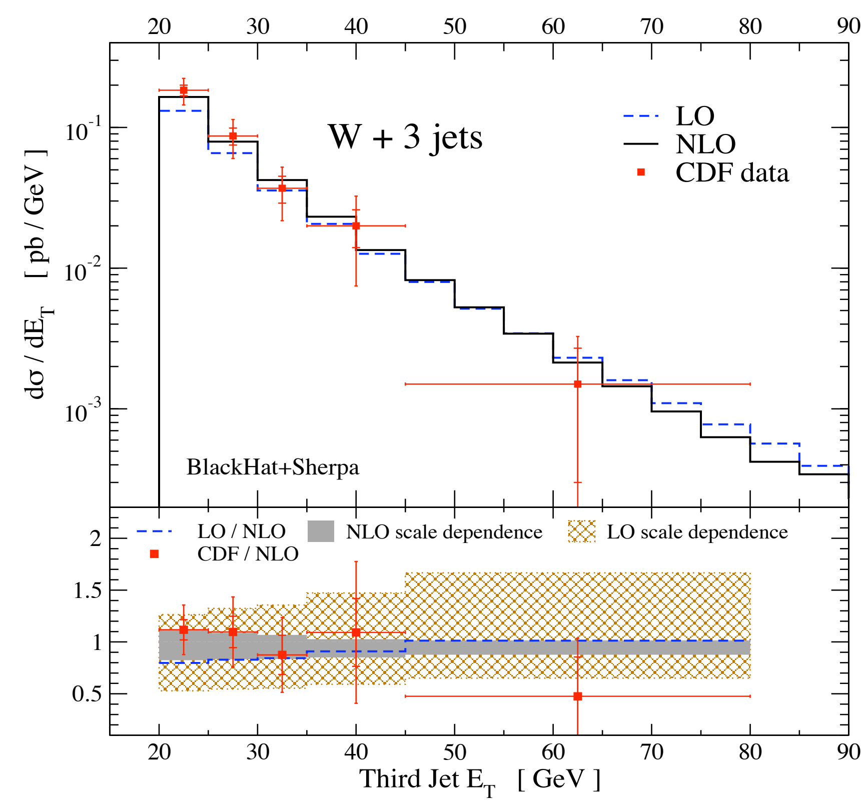
$\Rightarrow$ important (10% or more) differences due to different jet-algorithms.
High precision comparison impossible if using different algorithms

Tevatron: sample distribution: $E_{t,j3}$

NB: CDF ⇒ JetCLU VERSUS NLO Theory ⇒ SISCone



Ellis et al '09 (LC)



Berger et al '09

- ☺ agreement with CDF data (within currently large errors)
- ☺ small K=1.0-1.1, reduced uncertainty: 50% (LO) → 10% (NLO)
- ☺ first applications of new techniques to 2 → 4 LHC processes

Dual role of SM processes

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- primary signals (apply signal cuts)
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Standard procedure

- study a given process with signal cuts $\Rightarrow$ refine theoretical tools
- once good understanding of the process is achieved with signal cuts (e.g. low p_t region) extrapolate to background cuts region (e.g. high p_t)

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How reliable is this procedure ?

Purpose of background cuts: push into corners of phase-space the SM process, therefore the robustness of the procedure is not assured.
NLO QCD predictions for non-trivial processes can shed light on this.

W^+ + 3 jets at the LHC

In the following: use highly non-trivial NLO calculation of W^++3 jets to illustrate/study this issue

Signal-cut setup (inspired by CMS studies):

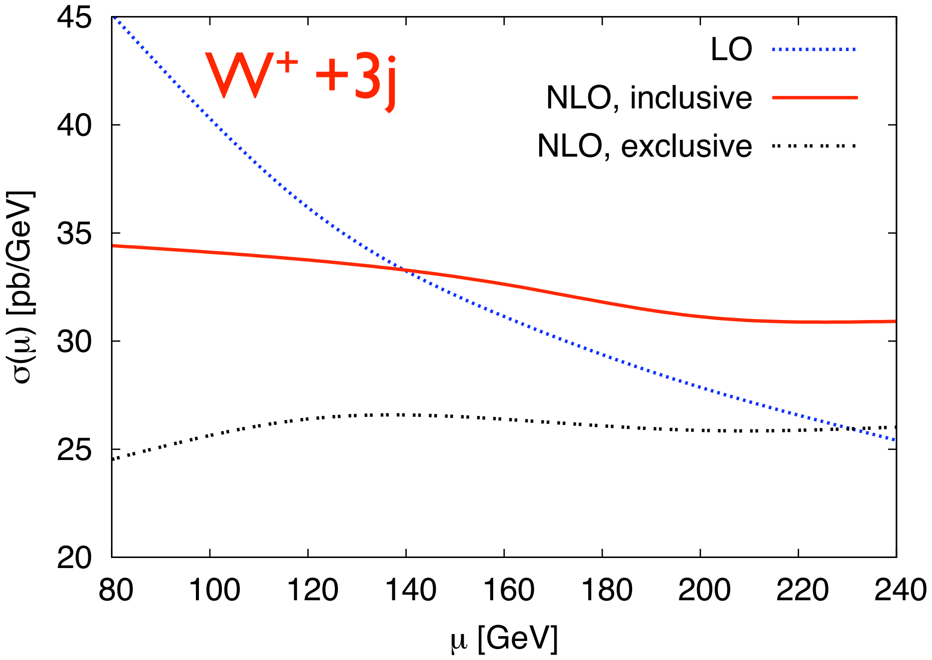
$$E_{\rm CM} = 10\,{\rm TeV} \qquad E_{\perp,{\rm jet}} = 30\,{\rm GeV} \qquad E_{\perp,e} = 20\,{\rm GeV}$$

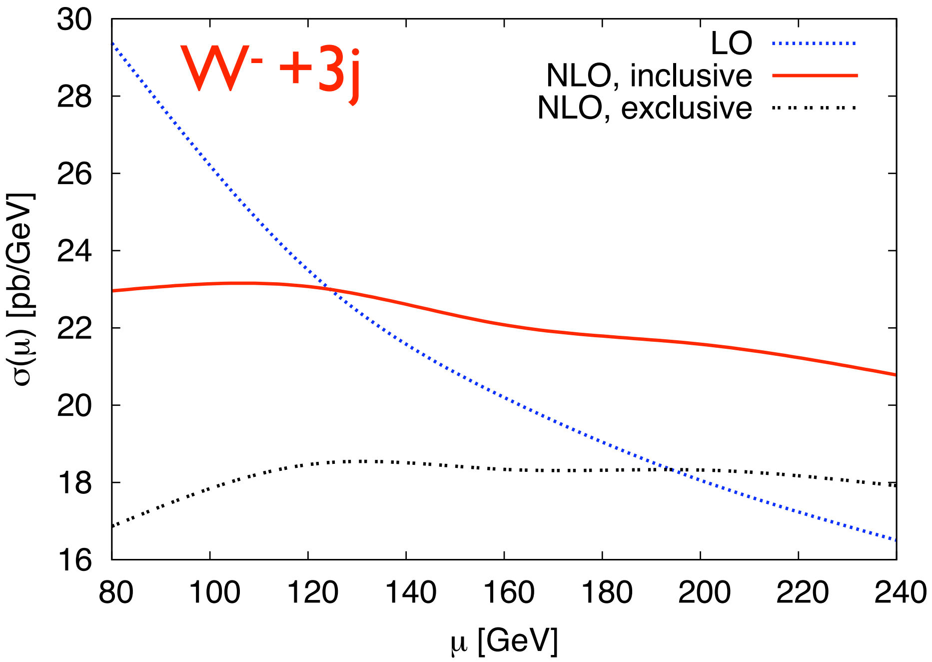
$$E_{\perp,{\rm miss}} = 15\,{\rm GeV} \quad M_{\perp,W} = 30\,{\rm GeV} \quad |\eta_e| < 2.4 \quad |\eta_{\rm jet}| < 3$$

$$\mu_0 = \sqrt{p_{\perp,W}^2 + M_W^2} \qquad \mu = \mu_R = \mu_F = [\mu_0/2, 2\mu_0]$$

Jets: SIScone with R = 0.5; PDFs: cteq6l1/cteq6m

Scale dependence

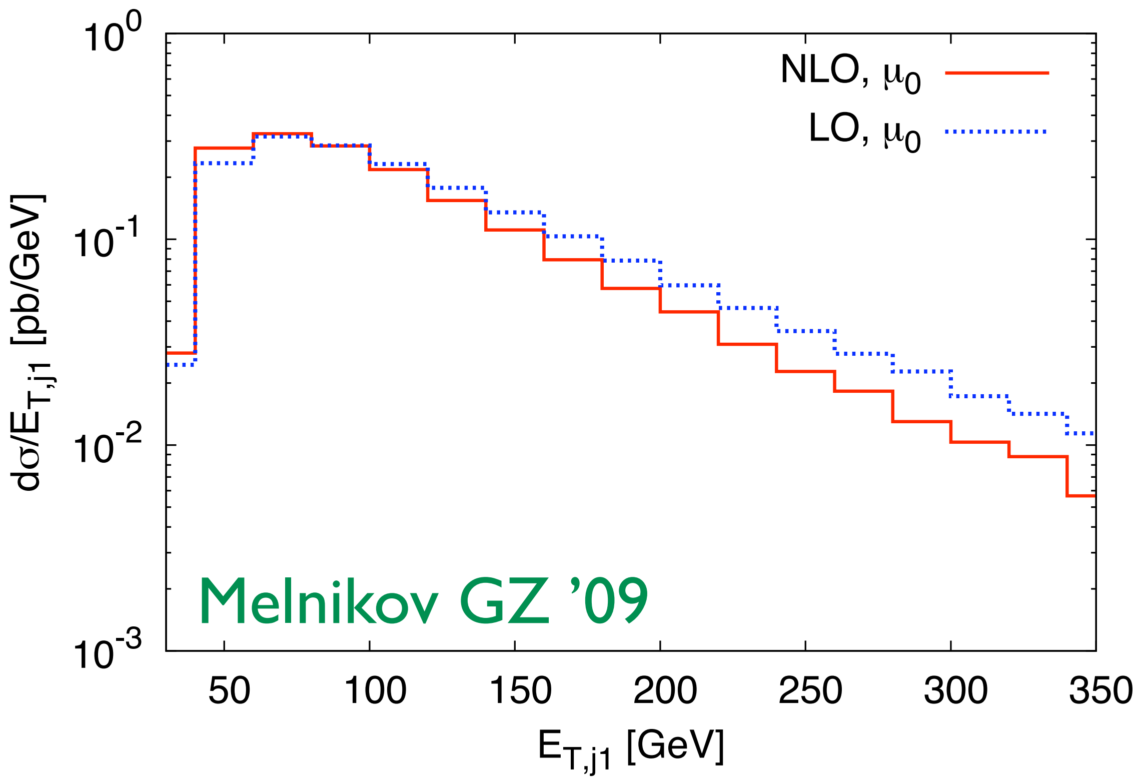




Melnikov & GZ '09

- scale dependence considerably reduced at NLO (both inclusive and exclusive)
- NLO tends to reduce cross-section
- because of very large scale dependence of LO, quoting a K-factor not very meaningful

Sample transverse energy distribution



Renormalization and factorization scale set to

$$\mu_0 = \sqrt{p_{T,W}^2 + m_W^2}$$

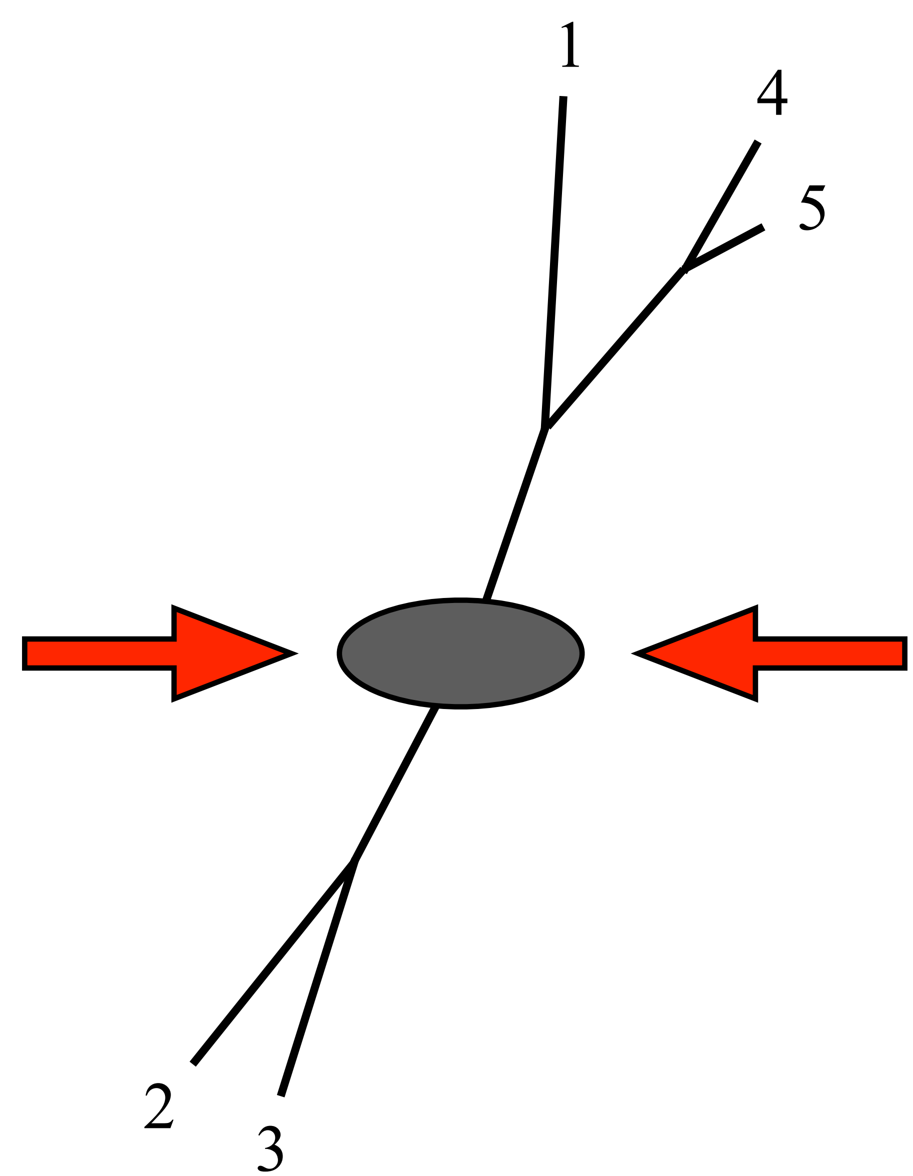
- with scale μ_0: considerable change in shape between LO and NLO (extrapolation of LO from low p_t to high p_t would fail badly)
- but origin of the change in shape well understood: at high E_T, μ_0 is smaller than typical scales of the QCD branching $\Rightarrow$ LO overshoots the result

Can one do a more sophisticated LO calculation?

Local (CKKW) scale

<u>Local scale choice (CKKW):</u>

- given a partonic event reconstruct a branching history: cluster partons into jets using k_t-algorithm
- at each branching the scale in the coupling to set to the relative k_t of the daughter partons
- local scale = CKKW scale choice, but no Sudakov reweighting, no parton shower



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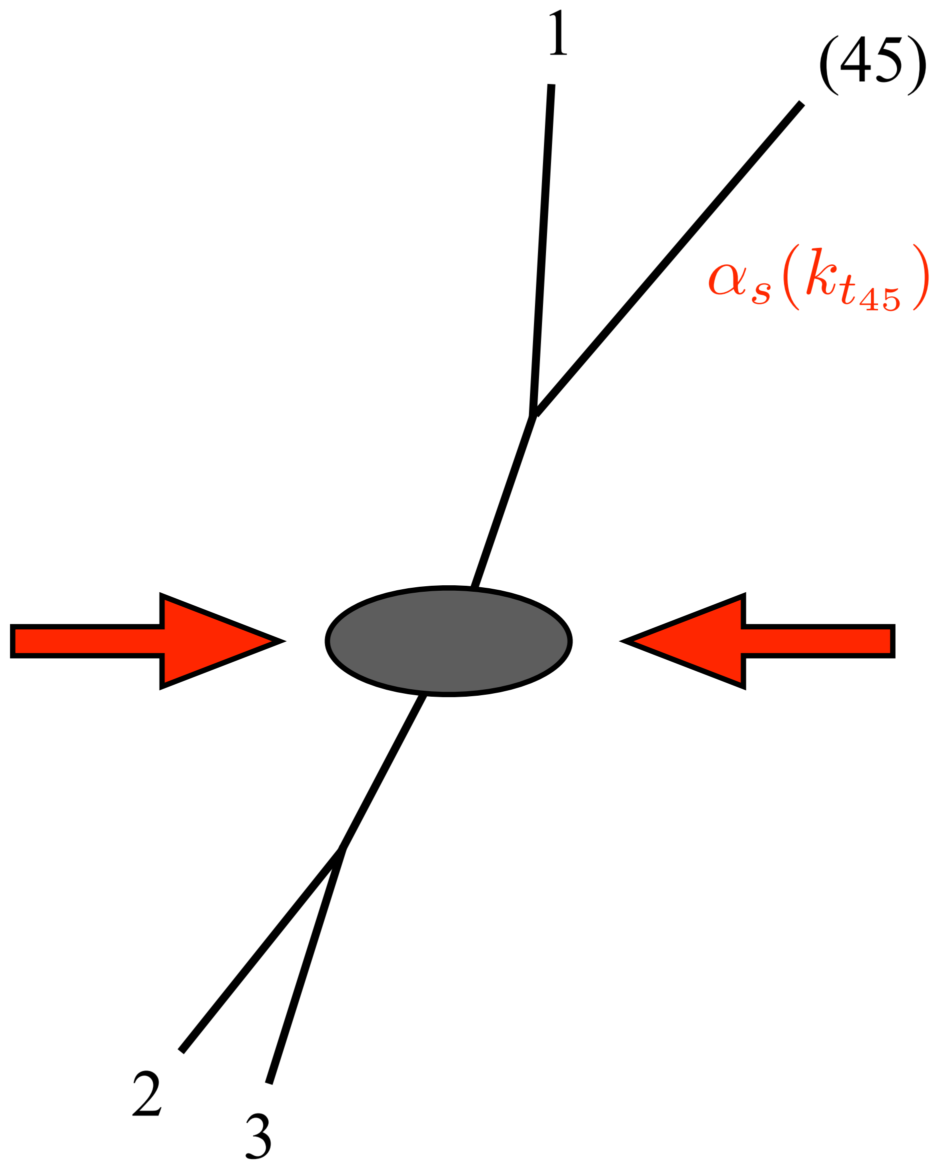

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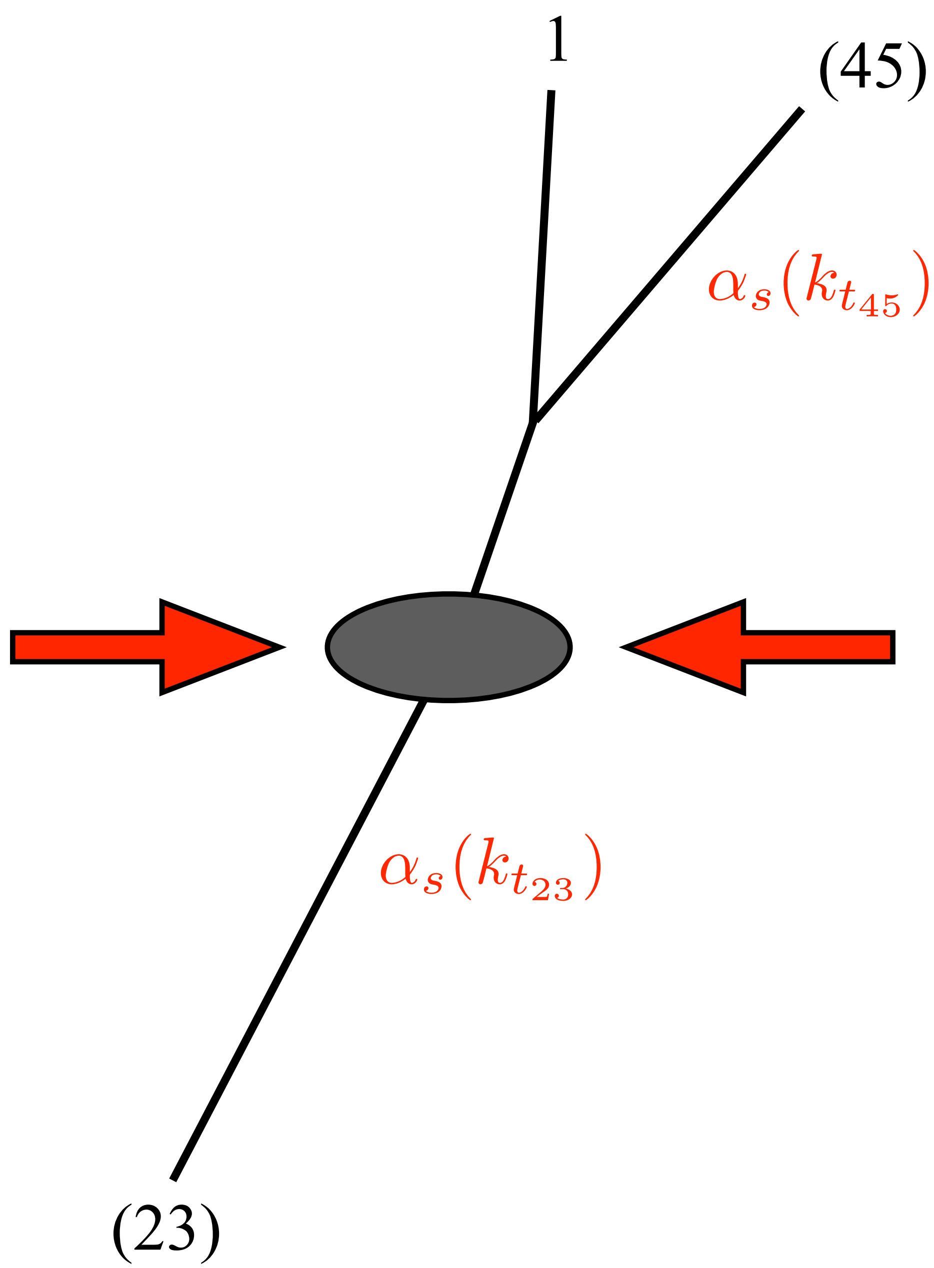

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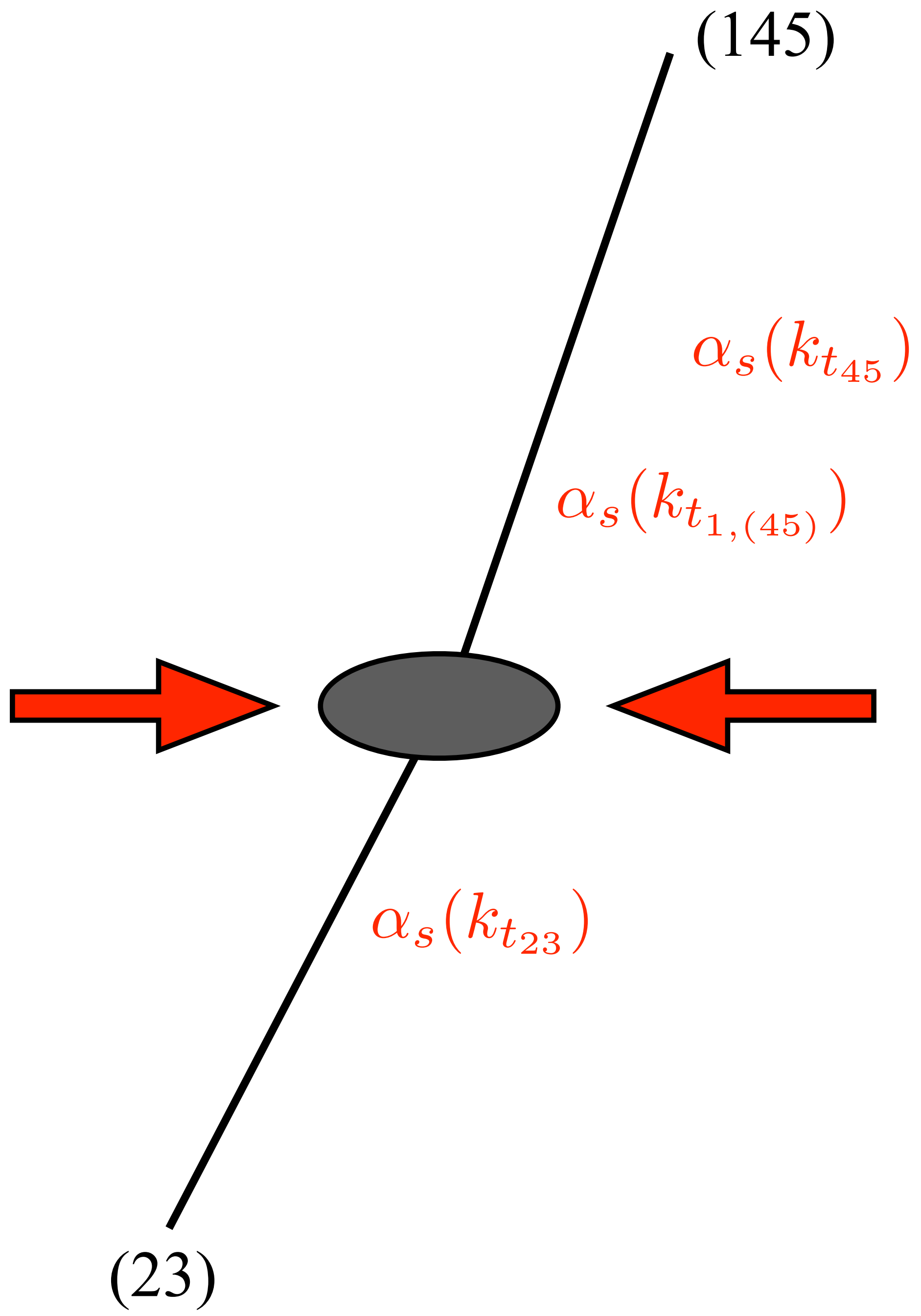

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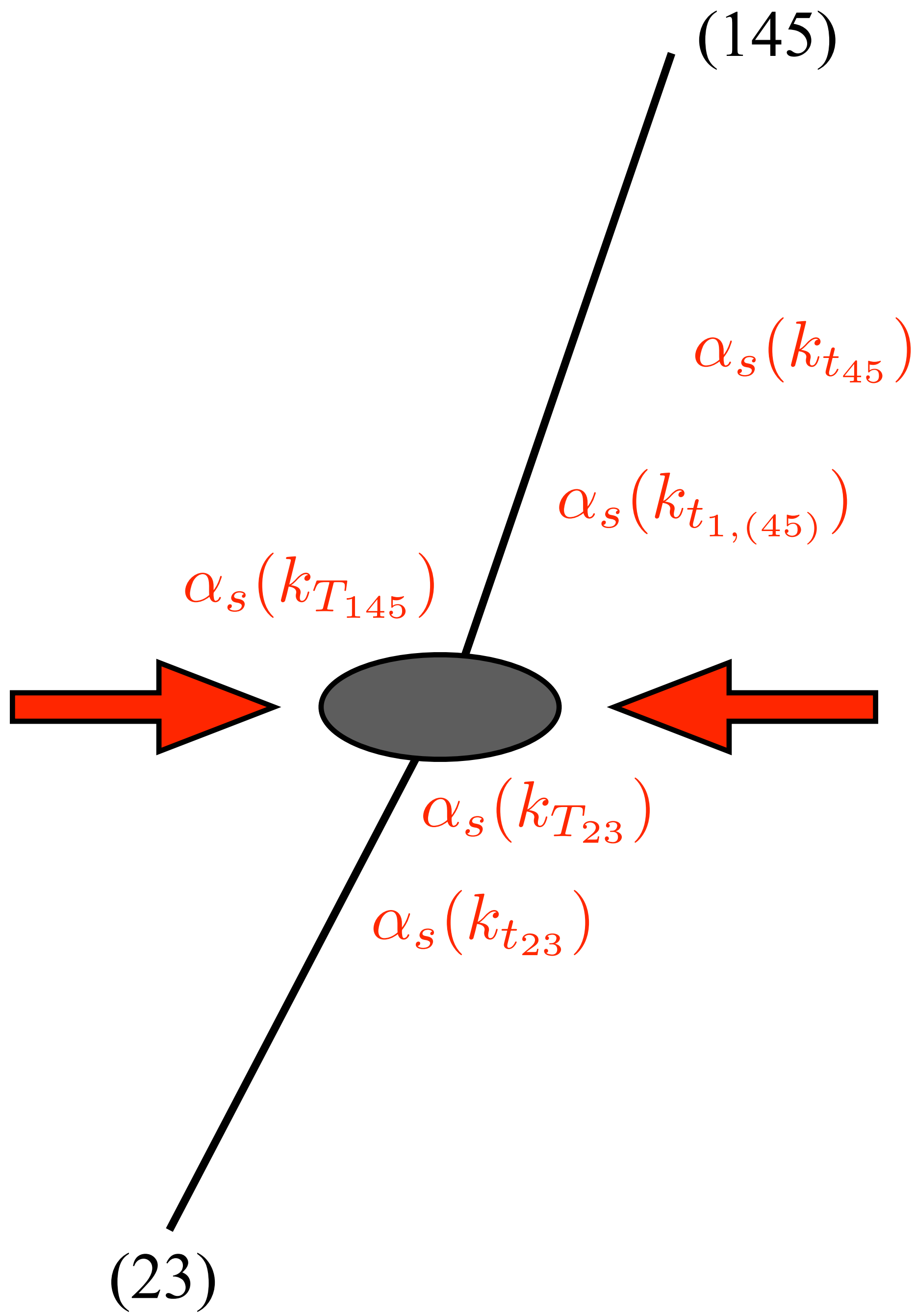

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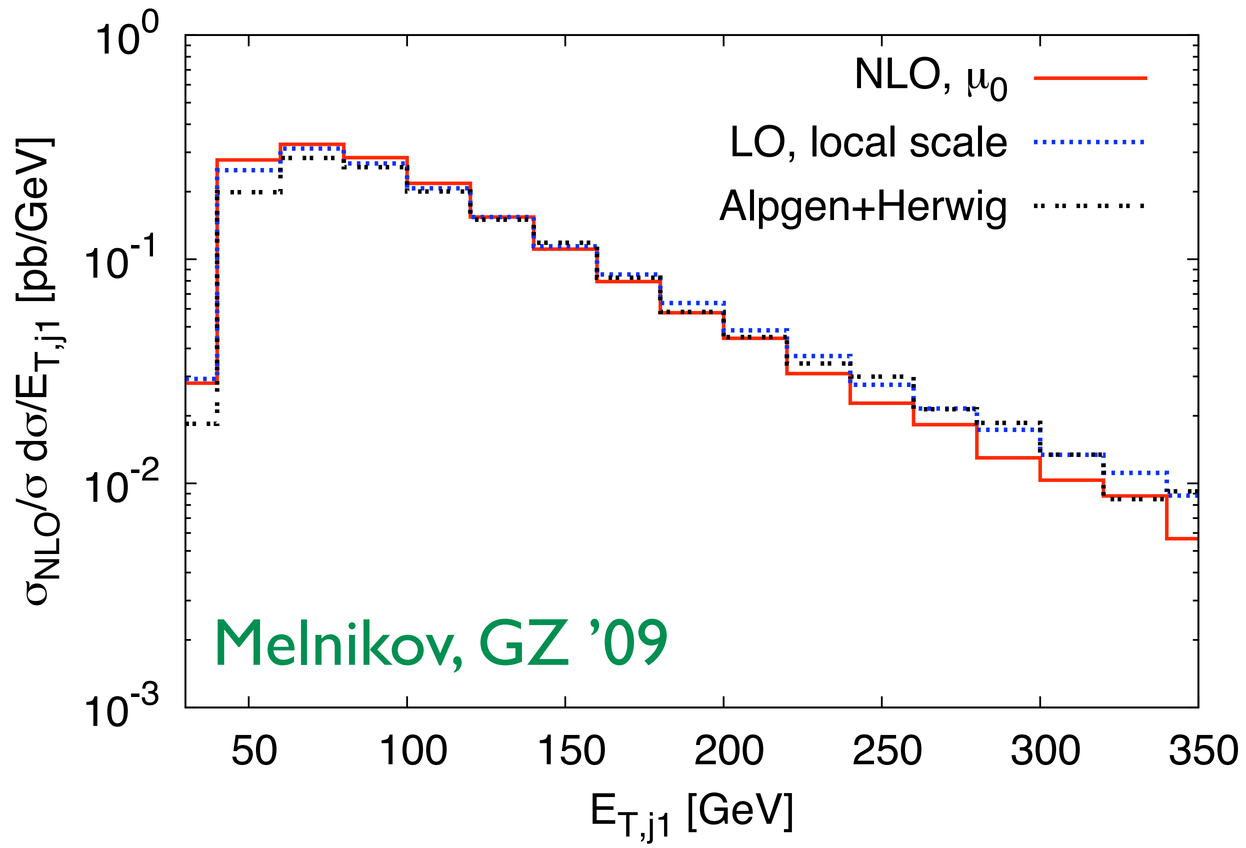
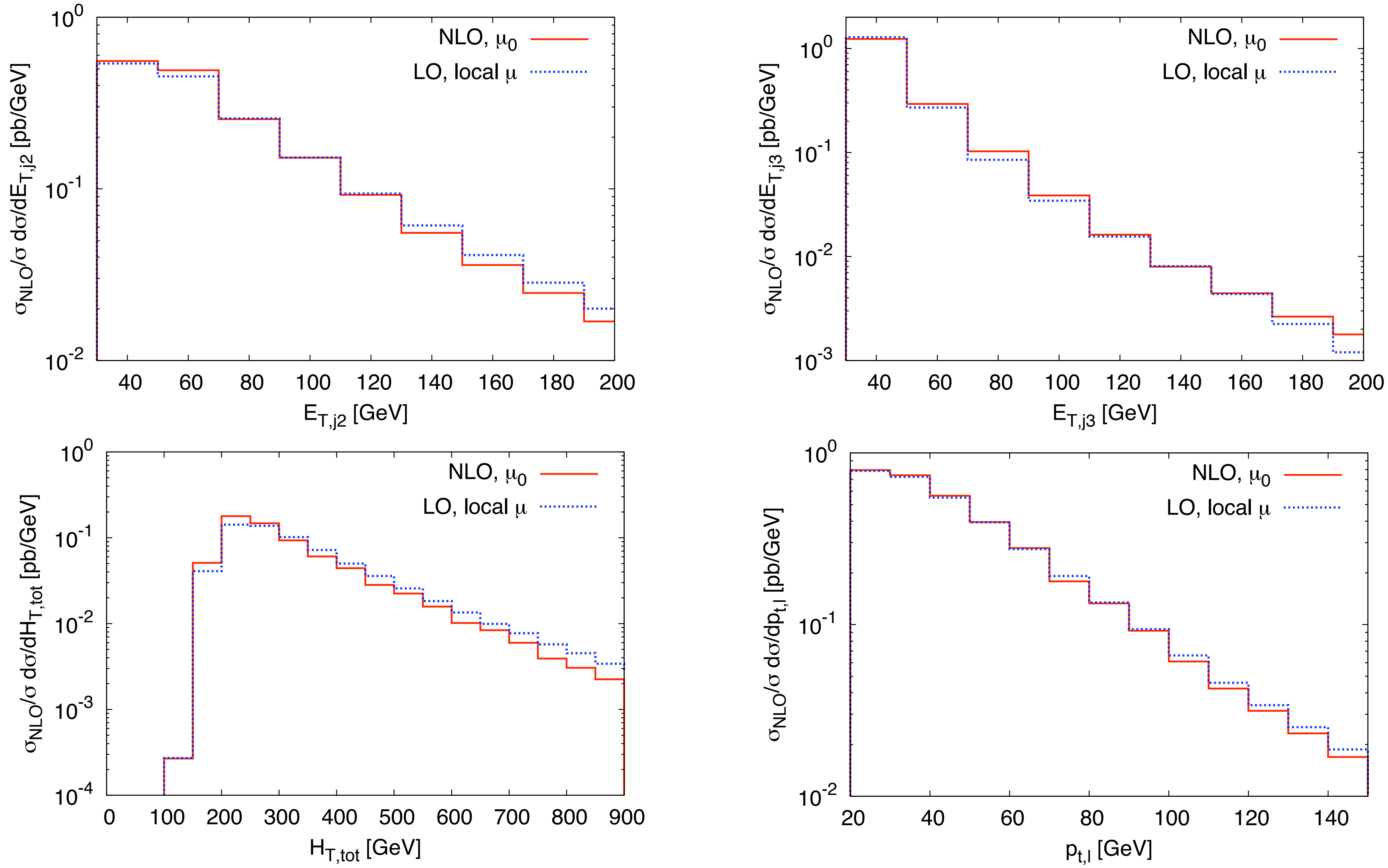


☛ local scale choice reproduces the shape of the NLO distribution well

☛ the difference between LO with local scale and full Alpgen+Herwig indicative of the importance of the parton shower

Other hadronic distributions



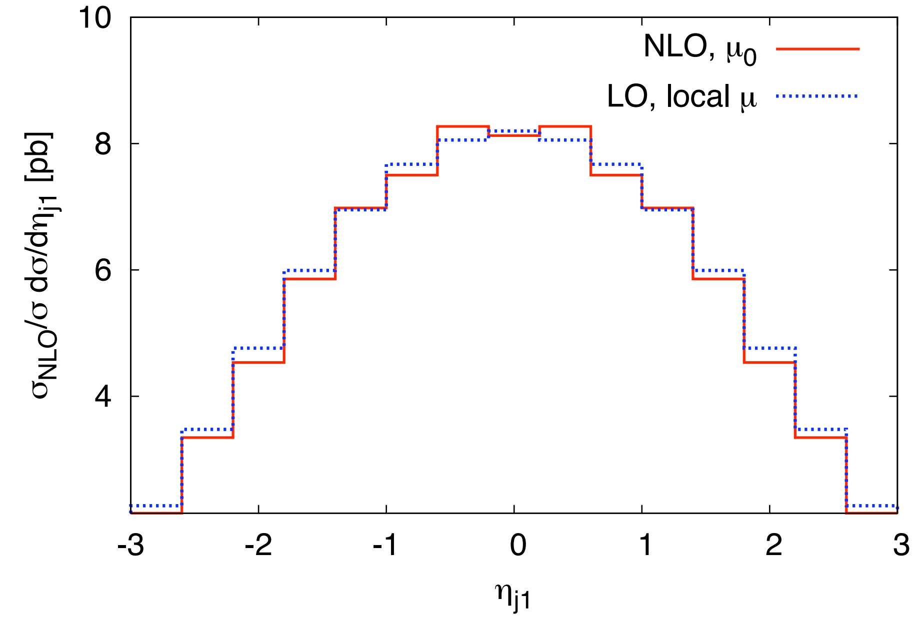
Melnikov GZ '09

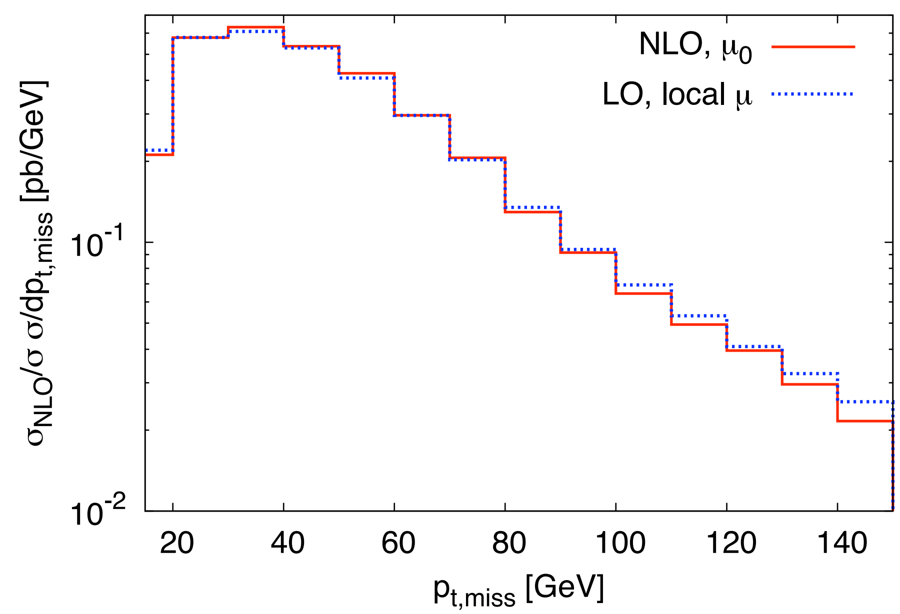
☛ LO with local scale does a very reasonable job in reproducing shapes

<u>NB:</u>

normalization of LO remains out of control. LO is normalized to NLO in above plots

Leptonic distributions





Melnikov GZ ’09

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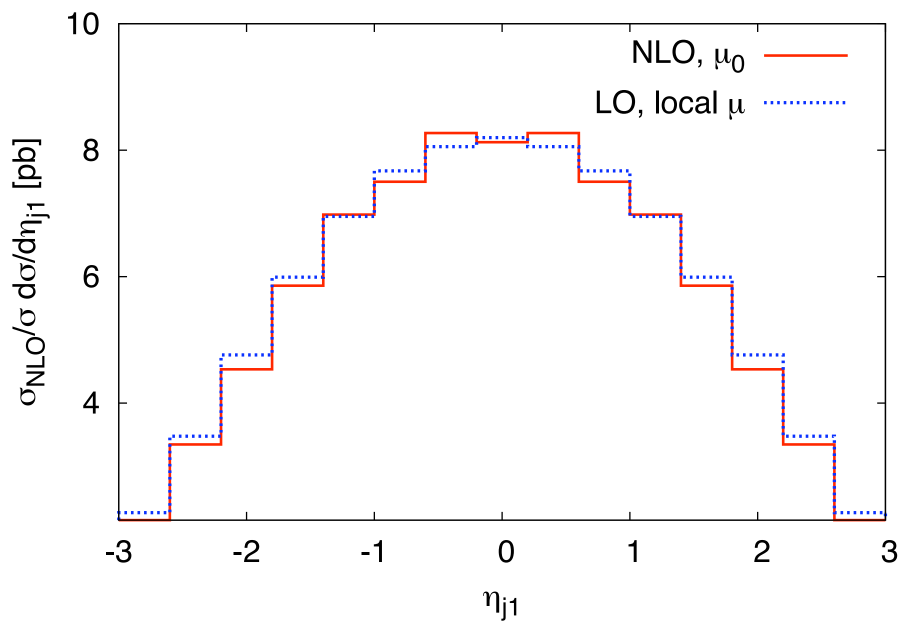

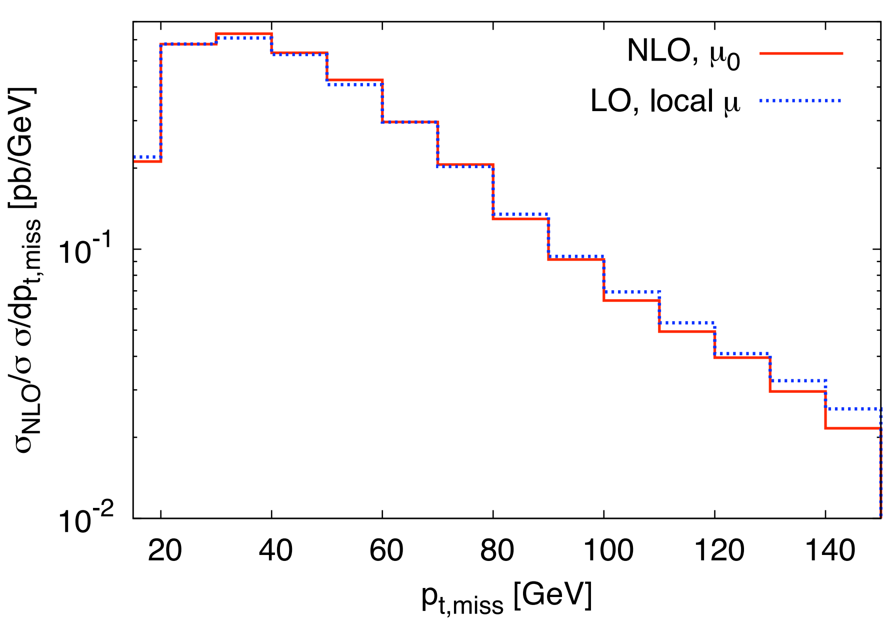

Melnikov GZ '09

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How solid (cut-independent) is this statement ?

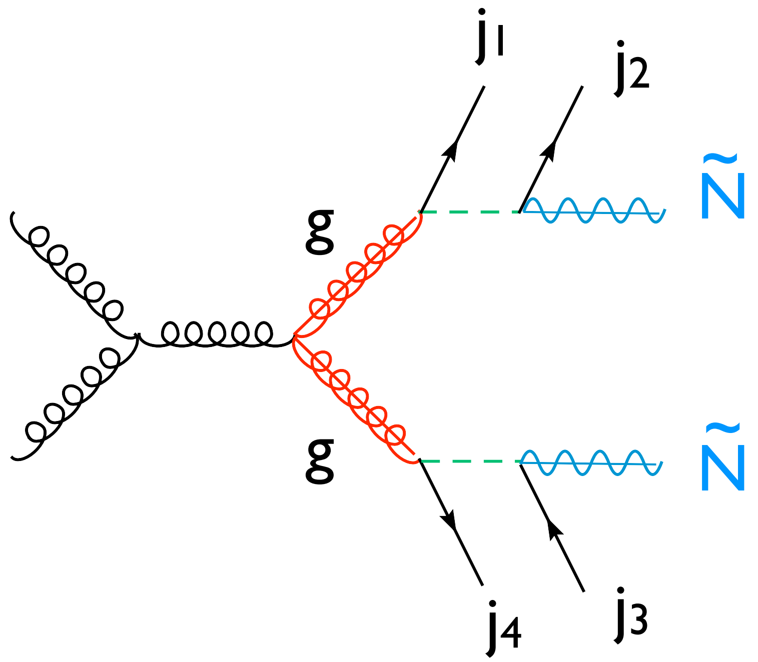
See what happens with different cuts.

Consider two sets of cuts where W+3jet plays the role of unwanted background

SUSY signature

SUSY with R-parity: e.g. gluino pair production, each decays into 2 jets and neutralino

Typical signature: *4 jets and MET (no lepton)*



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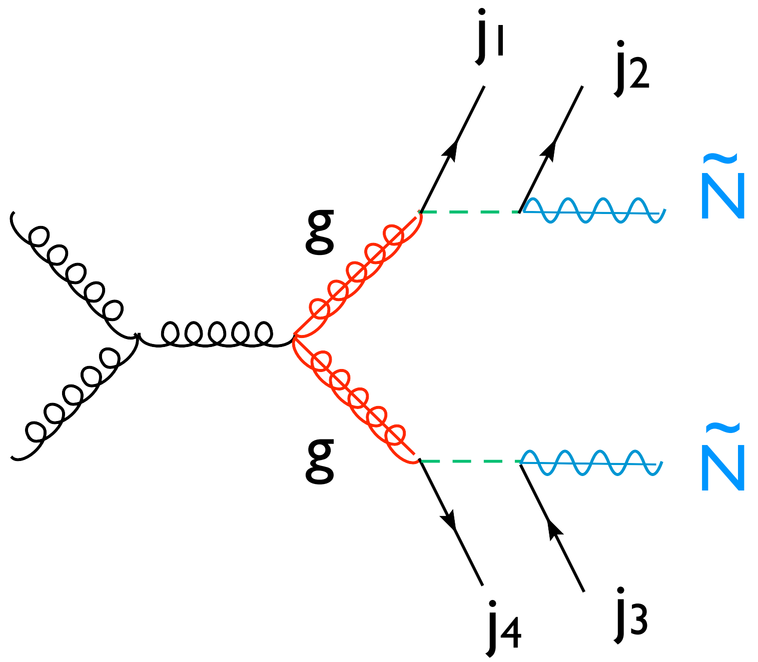

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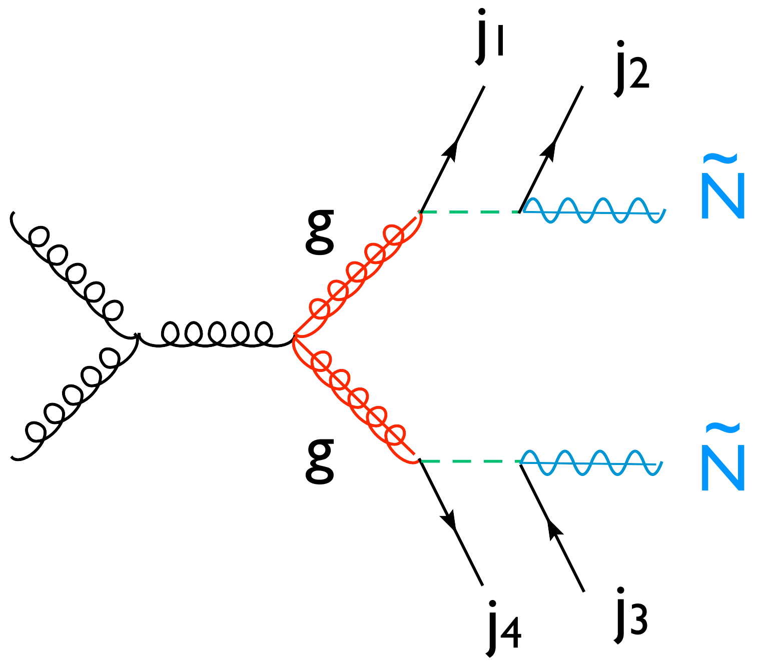

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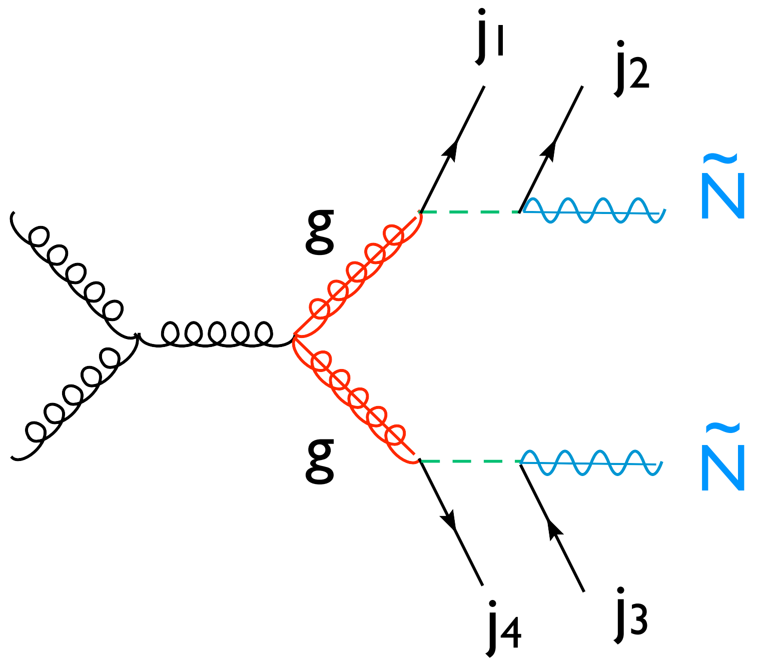

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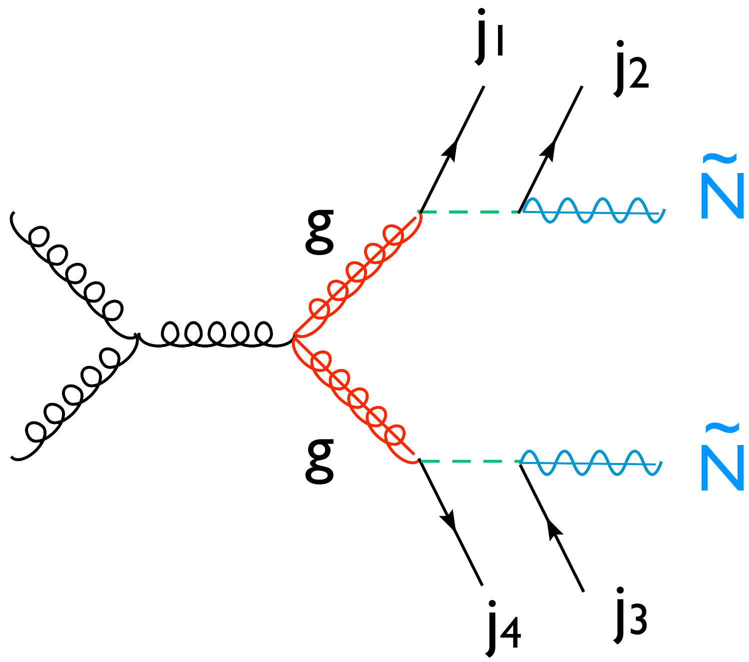

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⇒ important to consider this source of background as well

Atlas setup

Cuts designed by ATLAS to suppress W+3j background

$$p_{T,j} > 50\,\mathrm{GeV} \qquad p_{T,j1} > 100\,\mathrm{GeV} \qquad p_{tl} < 20\,\mathrm{GeV}$$

$$E_{\mathrm{T,miss}} > \max(100\mathrm{GeV}, 0.2 H_T) \qquad H_T = \sum_j p_{T,j} + E_{\mathrm{T,miss}}$$

$$S_T > 0.2 \qquad |\eta_j| < 3$$

Yamazaki [ATLAS and CMS Col.] 0805.3883
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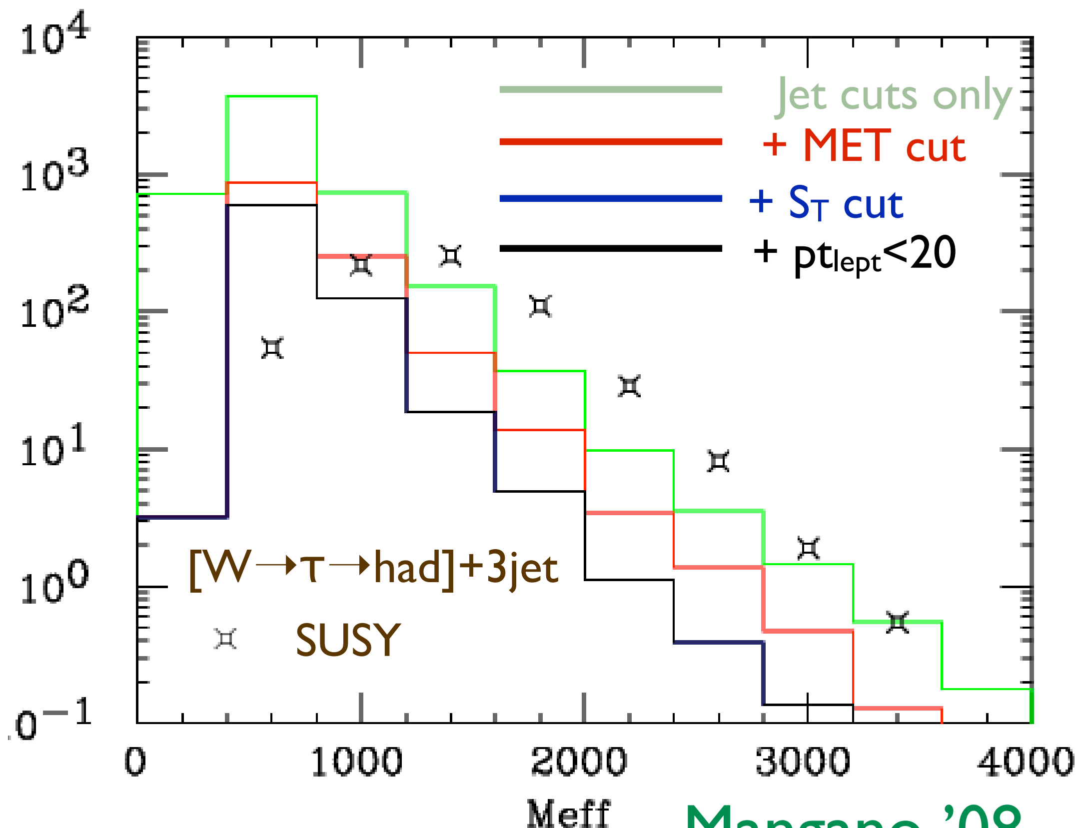

Mangano '08

- each cut suppresses background by factor ~ 3 without modifying the shape
- cut on collinear unsafe sphericity S_T not applied in the following study

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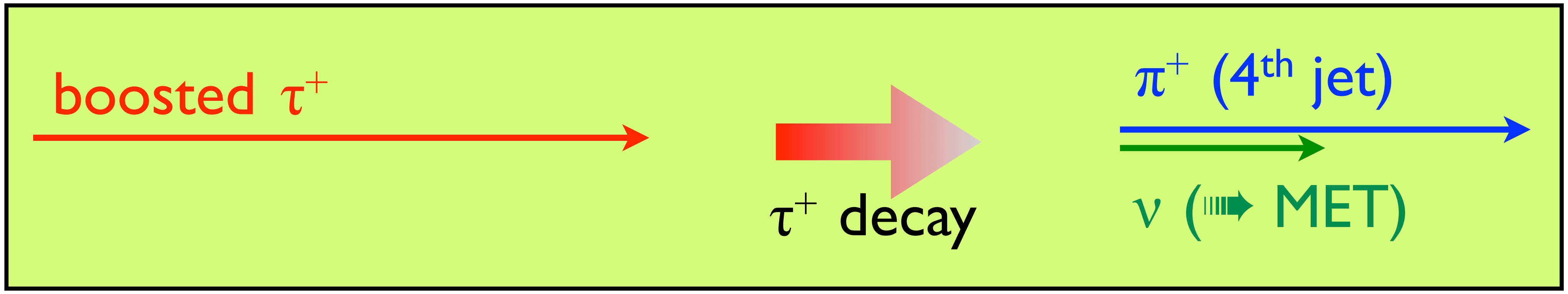


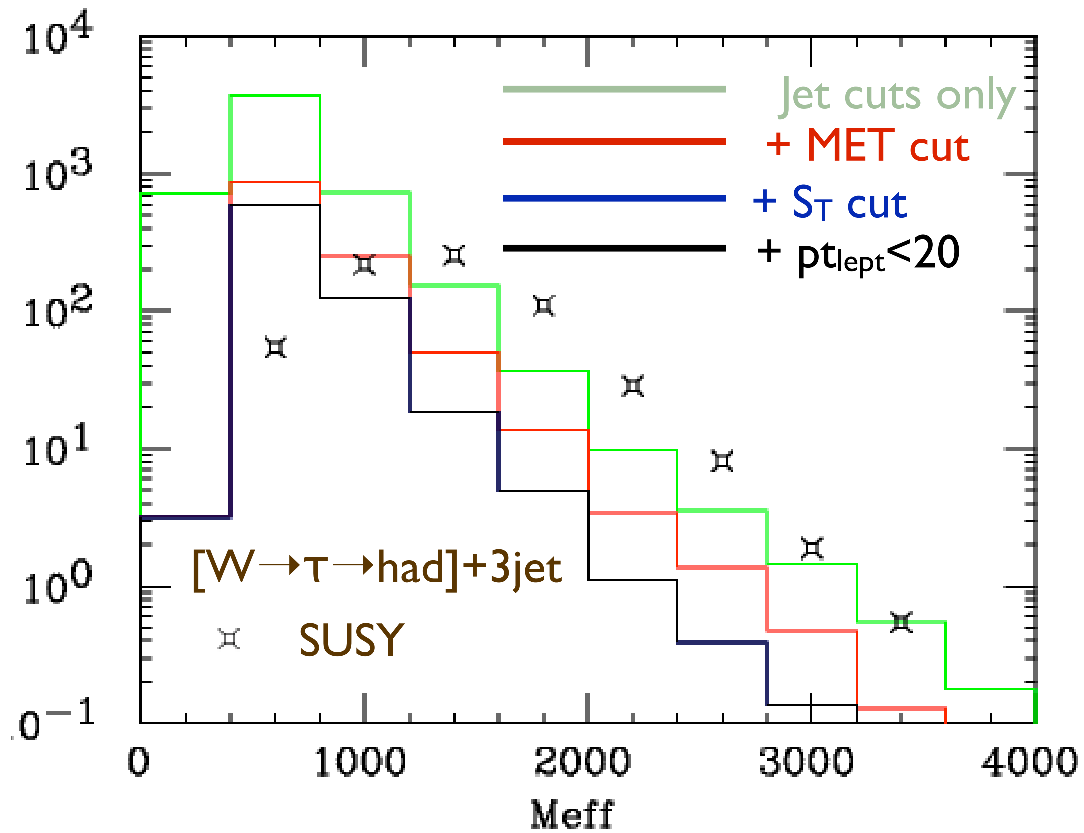
Theoretical robust approximation:

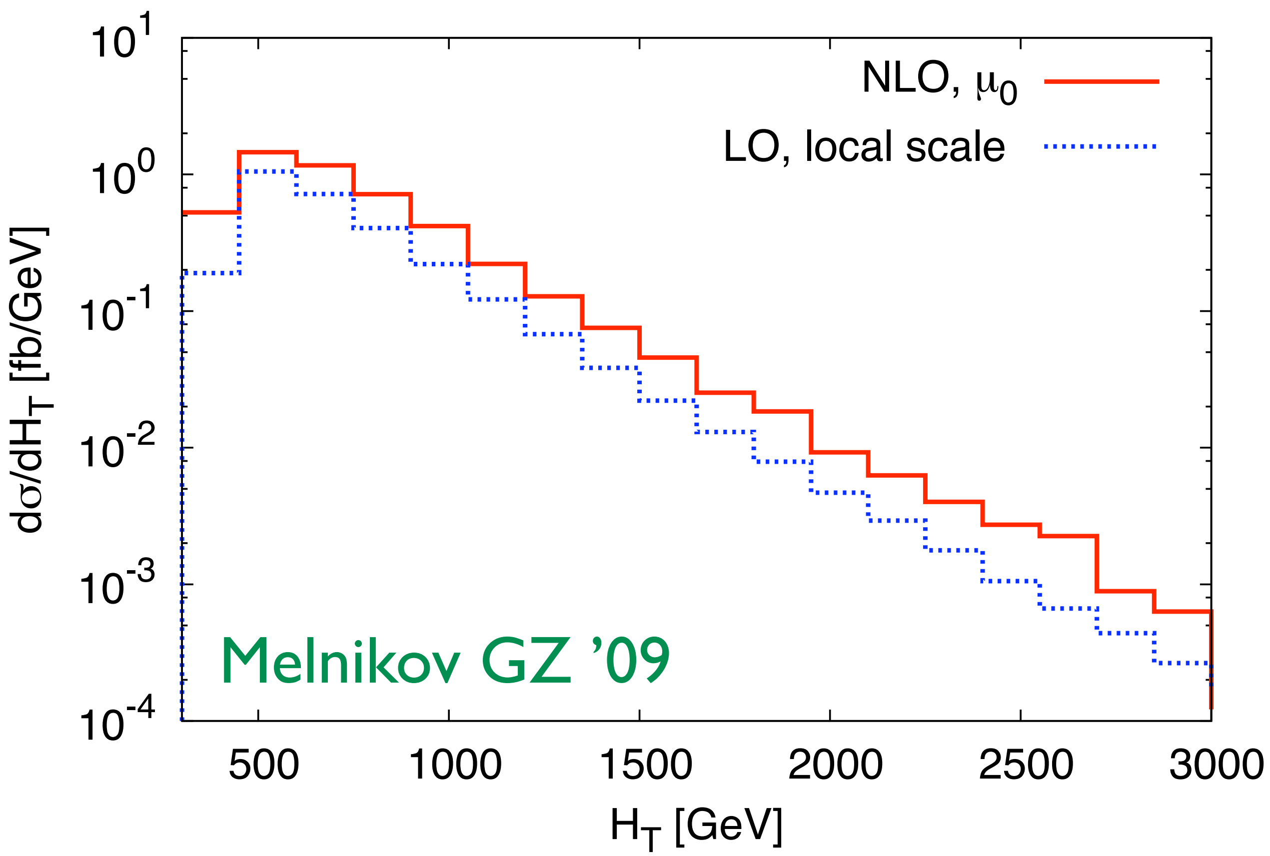
simulate the W decay as a perfect collinear branching with momentum fractions 2/3 (π^+) and 1/3 (ν)

SM background from W+3 jets

Primary observable is H_T (previously called M_{eff}) which 'measures' the SUSY scale:

$$H_T = \sum_j p_{T,j} + E_{\mathrm{T,miss}}$$





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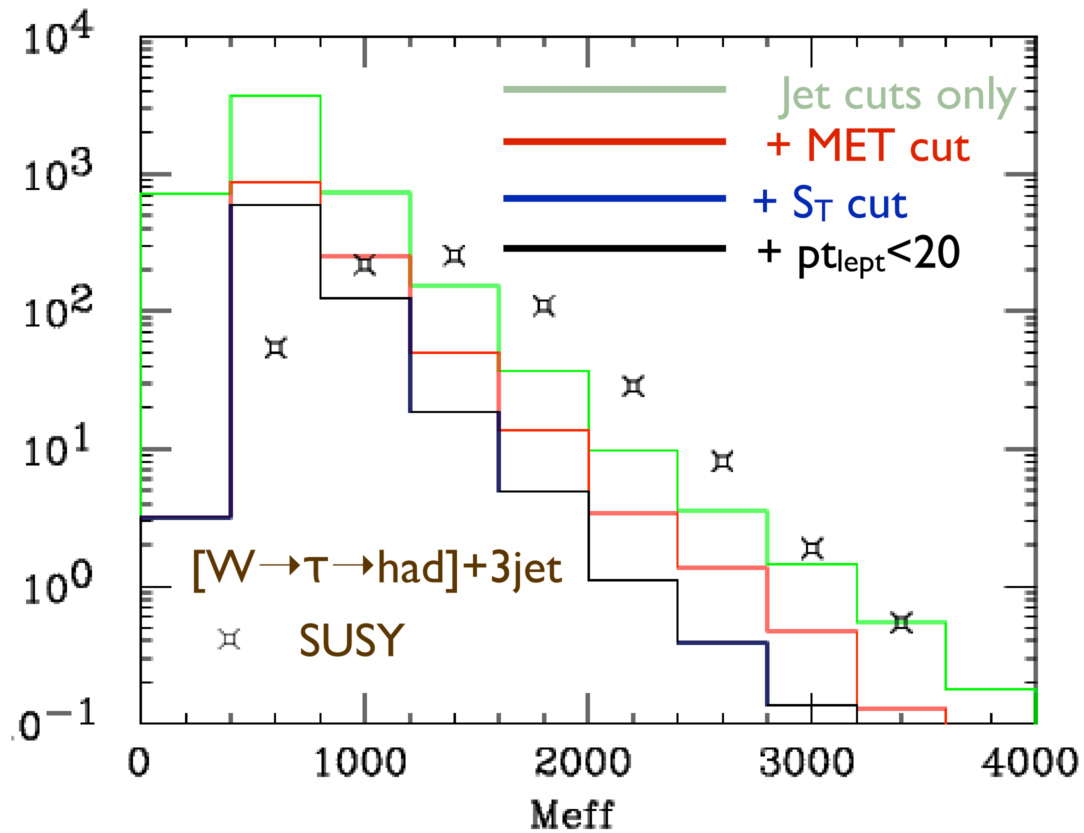

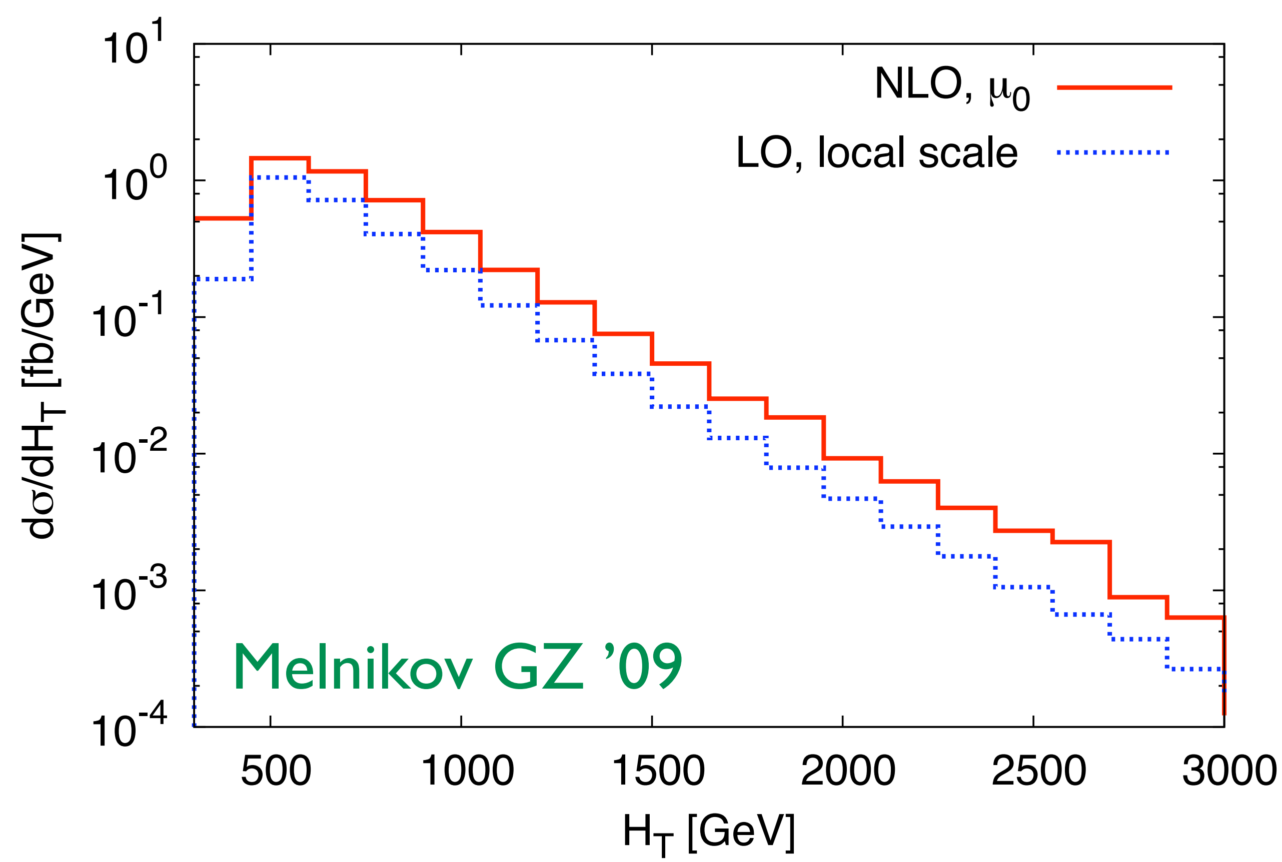

- universal enhancement (K-factor ~3) of LO without distorting the shape
  NB: *same observable* with cuts as shown before had K-factor ~ 1
- NLO effect similar to that of cuts but *works in opposite direction*

CMS style indirect lepton veto cut

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Indirect lepton veto = no explicit lepton veto, but other cuts force contribution from W+jets to become naturally small

$$p_{\mathrm{T,j}} > 30\mathrm{GeV} \quad p_{\mathrm{T,j1}} > 180\mathrm{GeV} \quad p_{\mathrm{T,j2}} > 110\mathrm{GeV} \quad E_{\mathrm{T,miss}} > 200\mathrm{GeV}$$

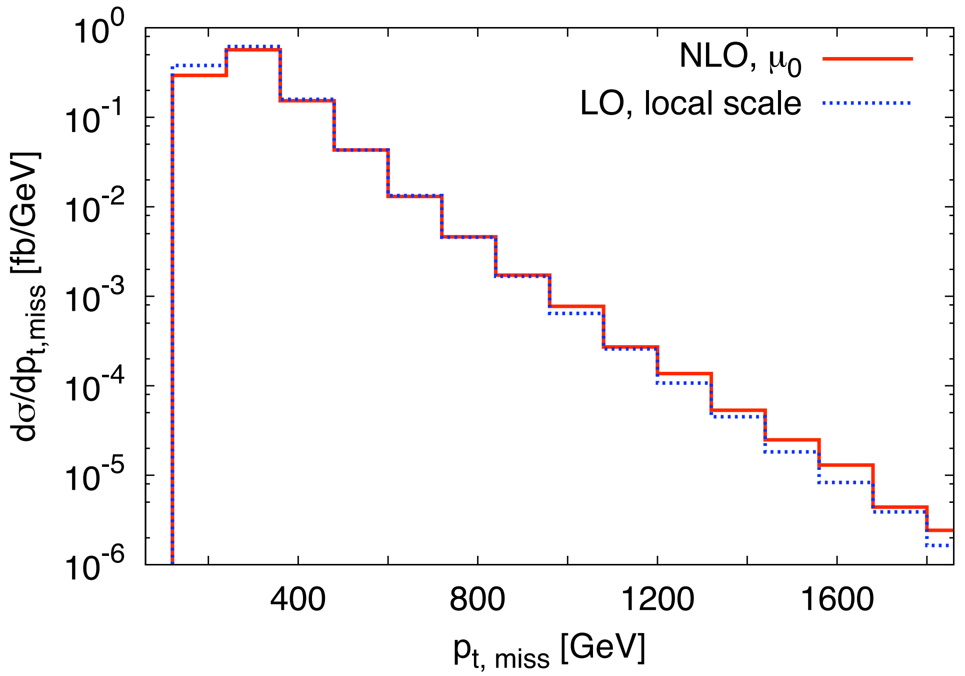
$$|\eta_{\mathrm{lead\ jet}}| < 1.7 \quad |\eta_{\mathrm{other\,jets}}| < 3 \quad H_{\mathrm{T,24}} = \sum_{j=2}^{4} p_{\mathrm{T,j}} + E_{\mathrm{T,miss}} > 500\mathrm{GeV}$$

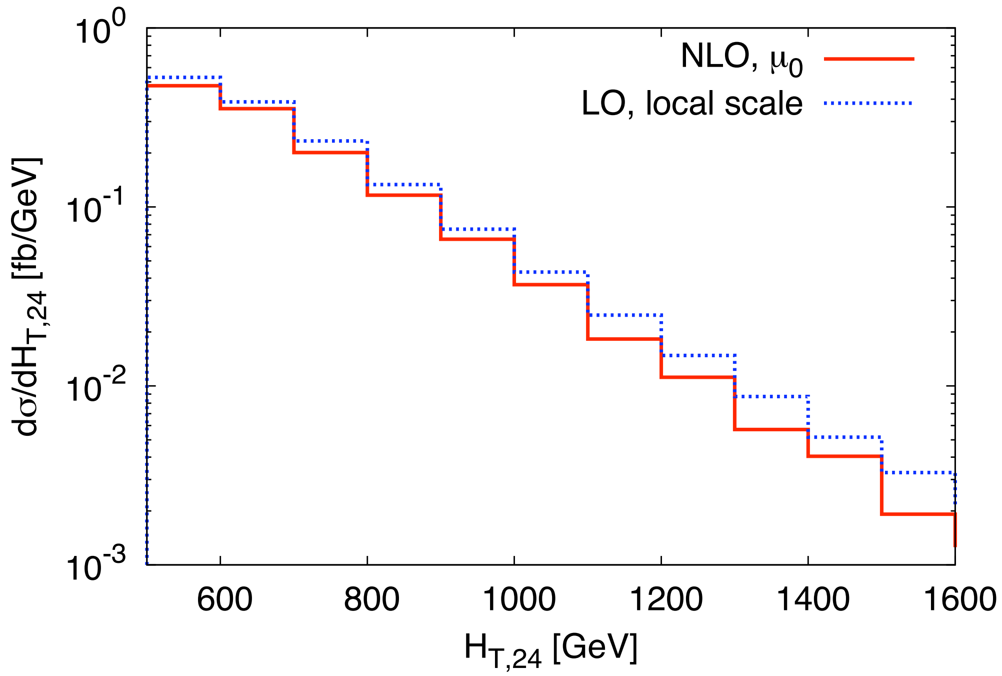
CMS Collaboration Journal Phys. G: Nucl. Part. Phys. 34 (2007) 995

CMS style indirect lepton veto cut

<u>Primary search observables</u>

distribution in transverse missing energy and total effective mass $H_{T,24}$





- NLO correction to cross-section small, K-factor ~ 1
- shapes of LO mostly OK, but moderate shape distortion at high $H_{T,24}$

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- all this emphasizes the need to extend NLO corrections to other processes (Z+3j, W+4j ...)