W+3 jet production at the LHC

— *signal or background* —

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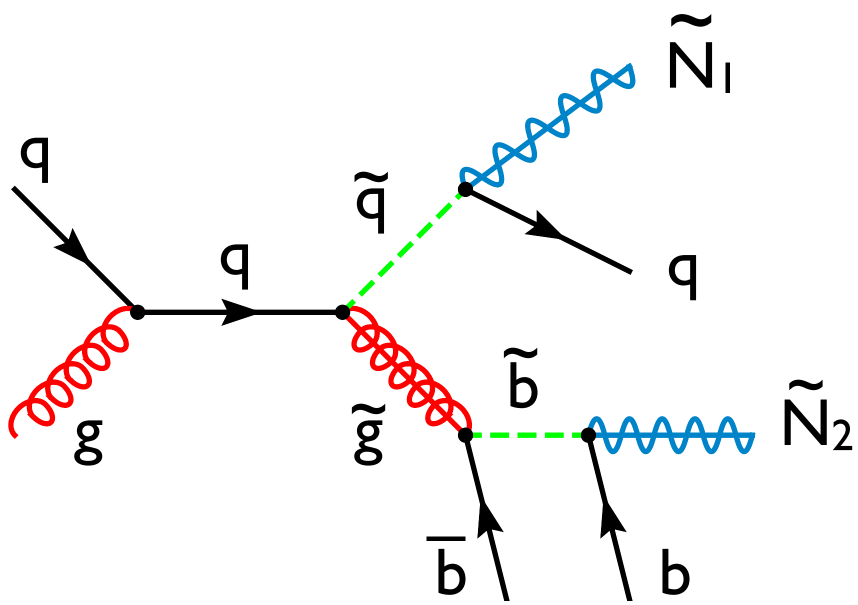
University of Sussex, 1st February 2010

Multiparticle final states

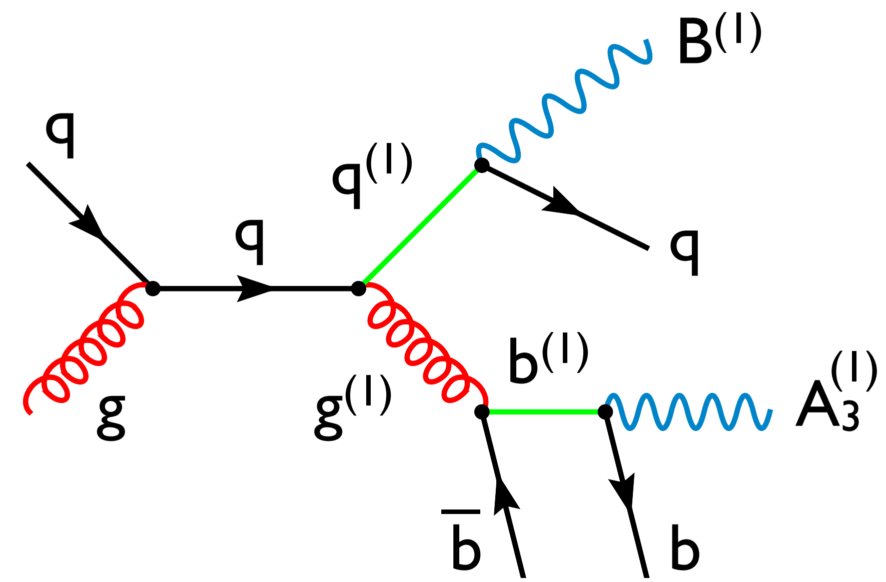
LHC's new regime in energy and luminosity implies that we will have a very large number of high-multiplicity events

- typical SM process is accompanied by radiation multi-jet events
- most signals involve pair-production and subsequent chain decays

SUSY:



UED:



More important than ever to describe high-multiplicity final states

Leading order

Status: fully automated, edge around outgoing 8 particles

Alpgen, CompHEP, CalcHEP, Helac, Madgraph, Helas, Sherpa, Whizard, ...

⇒ amazing progress in the last years [before only parton shower]

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Drawbacks of LO:
large scale dependences, sensitivity to cuts, poor modeling of jets, ...

Example: W+4 jet cross-section $\propto \alpha_s(Q)^4$
Vary $\alpha_s(Q)$ by ±10% via change of Q ⇒ cross-section varies by ±40%

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When and why LO:

- always the fastest option, often the only one
- test quickly new ideas with fully exclusive description
- many working, well-tested approaches
- highly automated, crucial to explore new ground, but *no precision*

Why NLO?

- LO predictions only qualitative, due to poor convergence of perturbative expansion ($\alpha_s \sim 0.1$) $\Rightarrow$ NLO can be 30-100%
- first handle on normalization of cross-sections is at NLO
- less sensitivity to unphysical input scales (renormalization,factorization)
- more physics at NLO
  - parton merging to give structure in jets
  - more species of incoming partons enter at NLO
  - initial state radiation effects
- a prerequisite for more sophisticated calculations which match NLO with parton showers

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⇒ Role of NLO for precision measurement uncontested
What about for discoveries?

The 2007 Les Houches NLO wishlist

NLO multi-leg Working group report '08

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [3]; Campbell/Ellis/Zanderighi [4] and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [5]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [6, 7]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [8] and WWZ by Hankele/Zeppenfeld [9]
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$
5. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
6. $pp \to V\,V\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
7. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [10–12]
8. $pp \to V$+3jets	various new physics signatures
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

} based on Feynman diagrams; private codes only

← '09 with standard techniques (item 4)

← '09 with new techniques (item 8)

+ virtual amplitudes for all 2 → 4 at one point *[van Hameren, Papadopoulos, Pittau]*

NLO: current status

Status of NLO:

☑ $2 \to 2$: all known (or easy) in SM and beyond

☑ $2 \to 3$: very few processes left

[but: often do not include decays, newest codes mostly private]

☐ $2 \to 4$: *the frontier*

- NLO cross-sections available only for two processes at the LHC
  ✓ tt + bb *[Bredenstein et al '08; Bevilacqua et al '09]*
  ✓ W + 3jets *[Berger et al '09; Ellis et al '09 (LC)]*
- Benchmark results for all $2 \to 4$ processes in the Les Houches list at one phase space point *[van Hameren et al '09]*

Generalized unitarity

I will not explain the method in detail, only remind of the main ideas
I will concentrate on applications & recent results

References:

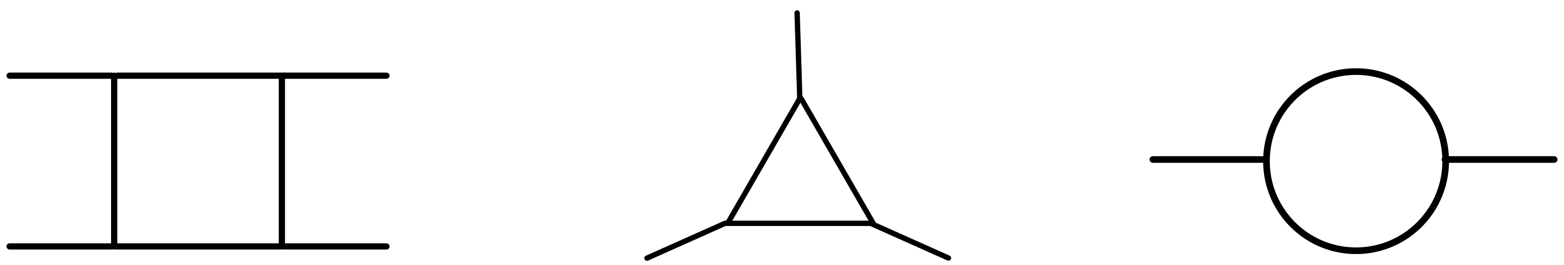
- Ellis, Giele, Kunszt '07 *[Unitarity in D=4]*
- Giele, Kunszt, Melnikov '08 *[Unitarity in D≠4]*
- Giele & GZ '08 *[All one-loop N-gluon amplitudes]*
- Ellis, Giele, Melnikov, Kunszt '08 *[Massive fermions, ttggg amplitudes]*
- Ellis, Giele, Melnikov, Kunszt, GZ '08 *[W+5p one-loop amplitudes]*
- Ellis,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

Decomposition of the one-loop amplitude

$$\mathcal{A}_N^D = \sum_{[i_1|i_4]} d^D_{i_1i_2i_3i_4} I^{(D)}_{i_1i_2i_3i_4} \quad + \quad \sum_{[i_1|i_3]} c^D_{i_1i_2i_3} I^{(D)}_{i_1i_2i_3} + \sum_{[i_1|i_2]} b^D_{i_1i_2} I^{(D)}_{i_1i_2} \;^{*}$$



<u>Remarks:</u>

- higher point function reduced to boxes + vanishing terms
- coefficients depend on D (i.e. on ϵ) $\Rightarrow$ rational part
- box, triangles and bubble integrals all known analytically

['t Hooft & Veltman '79; Bern, Dixon Kosower '93, Duplancic & Nizic '02; Ellis & GZ '08, public code $\Rightarrow$ http://www.qcdloop.fnal.gov]

* if non-vanishing masses: tadpole term; notation: $[i_1|i_m] = 1 \leq i_1 < i_2 \ldots < i_m \leq N$

Cut-constructable part

Start from

$$\mathcal{A}_N^{\text{cut}} = \sum_{[i_1|i_4]} d_{i_1 i_2 i_3 i_4} I^{(D)}_{i_1 i_2 i_3 i_4} + \sum_{[i_1|i_3]} c_{i_1 i_2 i_3} I^{(D)}_{i_1 i_2 i_3} + \sum_{[i_1|i_2]} b_{i_1 i_2} I^{(D)}_{i_1 i_2} = \int \frac{d^D l}{i(\pi)^{D/2}} \mathcal{A}_N^{\text{cut}}(l)$$

with

$$I^D_{i_1 \cdots i_M} = \int \frac{d^D l}{i(\pi)^{D/2}} \frac{1}{d_{i_1} \cdots d_{i_M}}$$

Look at the integrand

$$\mathcal{A}_N^{\text{cut}}(l) = \sum_{[i_1|i_4]} \frac{\bar{d}_{i_1 i_2 i_3 i_4}}{d_{i_1} d_{i_2} d_{i_3} d_{i_4}} + \sum_{[i_1|i_3]} \frac{\bar{c}_{i_1 i_2 i_3}}{d_{i_1} d_{i_2} d_{i_3}} + \sum_{[i_1|i_1]} \frac{\bar{b}_{i_1 i_2}}{d_{i_1} d_{i_2}}$$

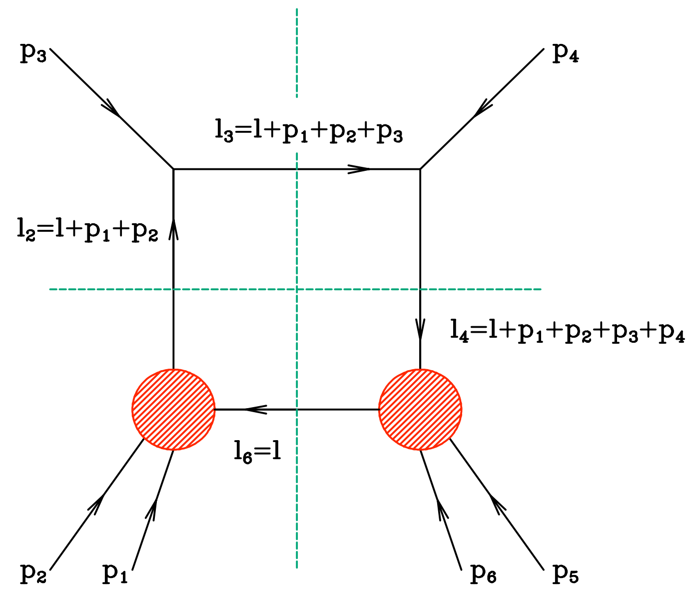
Get cut numerators by taking residues: i.e. set inverse propagator = 0
In D=4 up to 4 constraints on the loop momentum (4 onshell propagators) ⇒ get up to box integrals coefficients

Construction of the box residue

Four cut propagators are onshell
⇒ the amplitude factorizes into 4 tree-level amplitudes

Residues at the poles [⇒ coefficients at the poles $\bar{d}_{ijkl}(l^{\pm})$]

$$\begin{aligned}\mathrm{Res}_{ijkl}\Big(\mathcal{A}_N(l^{\pm})\Big) &= \mathcal{M}^{(0)}(l_i^{\pm};p_{i+1},\ldots,p_j;-l_j^{\pm})\times\mathcal{M}^{(0)}(l_j^{\pm};p_{j+1},\ldots,p_k;-l_k^{\pm})\\ &\times\ \mathcal{M}^{(0)}(l_k^{\pm};p_{k+1},\ldots,p_l;-l_l^{\pm})\times\mathcal{M}^{(0)}(l_l^{\pm};p_{l+1},\ldots,p_i;-l_i^{\pm})\end{aligned}$$



Need full loop momentum dependence of the coefficients: $\bar{d}_{ijkl}(l)$

Construction of the box residue

p_1, p_2, p_3 span the physical space. The dependence on loop momentum enters only through component in the orthogonal, trivial space (n_1)

$$\overline{d}_{ijkl}(l) \equiv \overline{d}_{ijkl}(n_1 \cdot l)$$

Use

$$(n_1 \cdot l)^2 \sim n_1^2 = 1$$

Then the maximum rank is one and the most general form is

$$\overline{d}_{ijkl}(l) = d^{(0)}_{ijkl} + d^{(1)}_{ijkl}\, l \cdot n_1$$

Using the two solutions of the unitarity constraint one obtains

$$\begin{aligned} d^{(0)}_{ijkl} &= \frac{\mathrm{Res}_{ijkl}\Big(\mathcal{A}_N(l^+)\Big) + \mathrm{Res}_{ijkl}\Big(\mathcal{A}_N(l^-)\Big)}{2} \\ d^{(1)}_{ijkl} &= \frac{\mathrm{Res}_{ijkl}\Big(\mathcal{A}_N(l^+)\Big) - \mathrm{Res}_{ijkl}\Big(\mathcal{A}_N(l^-)\Big)}{2i\sqrt{V_4^2 - m_l^2}} \end{aligned}$$

For triangle, bubble and tadpole coefficients proceed in the same way

Final result: cut-constructable part

Spurious terms integrate to zero

$$\int [d\, l]\ \frac{\overline{d}_{ijk}(l)}{d_i d_j d_k d_l} = d^{(0)}_{ijkl} \int [d\, l]\ \frac{1}{d_i d_j d_k d_l} = d_{ijkl} I_{ijkl}$$

$$\int [d\, l]\ \frac{\overline{c}_{ijk}(l)}{d_i d_j d_k} = c^{(0)}_{ijk} \int [d\, l]\ \frac{1}{d_i d_j d_k} = c_{ijk} I_{ijk}$$

$$\int [d\, l]\ \frac{\overline{b}_{ij}(l)}{d_i d_j} = b^{(0)}_{ijk} \int [d\, l]\ \frac{1}{d_i d_j} = b_{ij} I_{ij}$$

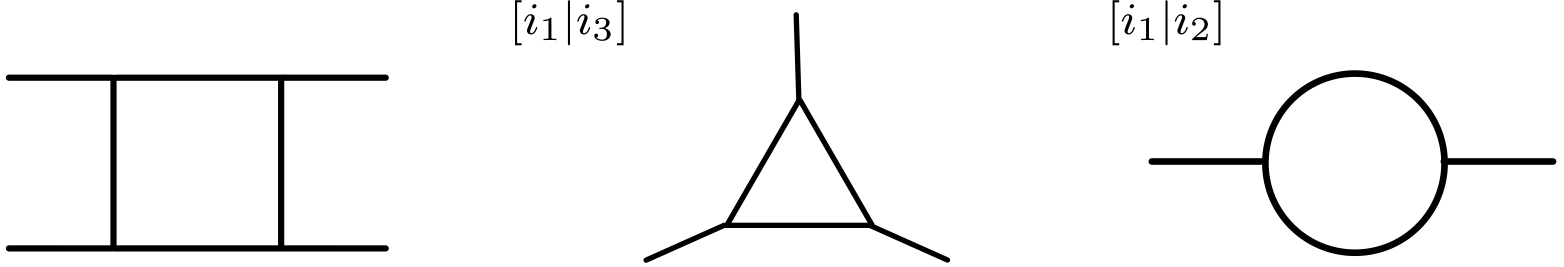
The final result for the cut constructable part then reads

$$\mathcal{A}_N^{\text{cut}} = \sum_{[i_1|i_4]} d^{(0)}_{i_1 i_2 i_3 i_4} I^{(D)}_{i_1 i_2 i_3 i_4} + \sum_{[i_1|i_3]} c^{(0)}_{i_1 i_2 i_3} I^{(D)}_{i_1 i_2 i_3} + \sum_{[i_1|i_2]} b^{(0)}_{i_1 i_2} I^{(D)}_{i_1 i_2}$$

One-loop virtual amplitudes

Cut constructible part can be obtained by taking residues in D=4

$$\mathcal{A}_N = \sum_{[i_1|i_4]} \left(d_{i_1 i_2 i_3 i_4}\ I^{(D)}_{i_1 i_2 i_3 i_4} \right) + \sum_{[i_1|i_3]} \left(c_{i_1 i_2 i_3}\ I^{(D)}_{i_1 i_2 i_3} \right) + \sum_{[i_1|i_2]} \left(b_{i_1 i_2}\ I^{(D)}_{i_1 i_2} \right) + \mathcal{R}$$



Rational part: can be obtained with D ≠ 4

Generic D dependence

Two sources of D dependence

dimensionality of loop momentum D

# of spin eigenstates/ polarization states D_s

Keep D and D_s distinct

$$\mathcal{A}^D \Rightarrow \mathcal{A}^{(D,D_s)}$$

Two key observations

1. External particles in D=4 ⇒ no preferred direction in the extra space

$$\mathcal{N}(l) = \mathcal{N}(l_4, \tilde{l}^2) \qquad \tilde{l}^2 = -\sum_{i=5}^{D} l_i^2$$

$\mathcal{N}$: numerator function

☛ in arbitrary D up to 5 constraints ⇒ get up to pentagon integrals

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$$\mathcal{N}^{D_s}(l) = \mathcal{N}_0(l) + (D_s - 4)\mathcal{N}_1(l)$$

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Choose D_{s1}, D_{s2} integer ⇒ suitable for numerical implementation

[$D_s = 4 - 2\epsilon$ ‘t-Hooft-Veltman scheme, $D_s = 4$ FDH scheme]

In practice

- Start from

$$\frac{\mathcal{N}^{(D_s)}(l)}{d_1 d_2 \cdots d_N} = \sum_{[i_1|i_5]} \frac{\overline{e}^{(D_s)}_{i_1 i_2 i_3 i_4 i_5}(l)}{d_{i_1} d_{i_2} d_{i_3} d_{i_4} d_{i_5}} + \sum_{[i_1|i_4]} \frac{\overline{d}^{(D_s)}_{i_1 i_2 i_3 i_4}(l)}{d_{i_1} d_{i_2} d_{i_3} d_{i_4}} + \sum_{[i_1|i_3]} \frac{\overline{c}^{(D_s)}_{i_1 i_2 i_3}(l)}{d_{i_1} d_{i_2} d_{i_3}} + \sum_{[i_1|i_2]} \frac{\overline{b}^{(D_s)}_{i_1 i_2}(l)}{d_{i_1} d_{i_2}} + \sum_{[i_1|i_1]} \frac{\overline{a}^{(D_s)}_{i_1}(l)}{d_{i_1}}$$

- Use unitarity constraints to determine the coefficients, computed as products of tree-level amplitudes with complex momenta in higher dimensions

- Berends-Giele recursion relations are natural candidates to compute tree level amplitudes: they are very fast for large N and very general (spin, masses, complex momenta)

Berends, Giele '88

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☺ Generalized unitarity: very simple, efficient, general, transparent method, straightforward to implement/automate

Final result

$$\mathcal{A}_{(D)} = \sum_{[i_1|i_5]} e^{(0)}_{i_1 i_2 i_3 i_4 i_5}\; I^{(D)}_{i_1 i_2 i_3 i_4 i_5}$$
$$+ \sum_{[i_1|i_4]} \left(d^{(0)}_{i_1 i_2 i_3 i_4}\; I^{(D)}_{i_1 i_2 i_3 i_4} - \frac{D-4}{2}\, d^{(2)}_{i_1 i_2 i_3 i_4}\; I^{(D+2)}_{i_1 i_2 i_3 i_4} + \frac{(D-4)(D-2)}{4}\, d^{(4)}_{i_1 i_2 i_3 i_4}\; I^{(D+4)}_{i_1 i_2 i_3 i_4} \right)$$
$$+ \sum_{[i_1|i_3]} \left(c^{(0)}_{i_1 i_2 i_3}\; I^{(D)}_{i_1 i_2 i_3} - \frac{D-4}{2} c^{(9)}_{i_1 i_2 i_3}\; I^{(D+2)}_{i_1 i_2 i_3} \right) + \sum_{[i_1|i_2]} \left(b^{(0)}_{i_1 i_2}\; I^{(D)}_{i_1 i_2} - \frac{D-4}{2} b^{(9)}_{i_1 i_2}\; I^{(D+2)}_{i_1 i_2} \right)$$

Cut-constructible part:

$$\mathcal{A}_N^{CC} = \sum_{[i_1|i_4]} d^{(0)}_{i_1 i_2 i_3 i_4}\; I^{(4-2\epsilon)}_{i_1 i_2 i_3 i_4} + \sum_{[i_1|i_3]} c^{(0)}_{i_1 i_2 i_3}\; I^{(4-2\epsilon)}_{i_1 i_2 i_3} + \sum_{[i_1|i_2]} b^{(0)}_{i_1 i_2}\; I^{(4-2\epsilon)}_{i_1 i_2}$$

Rational part:

$$R_N = -\sum_{[i_1|i_4]} \frac{d^{(4)}_{i_1 i_2 i_3 i_4}}{6} + \sum_{[i_1|i_3]} \frac{c^{(9)}_{i_1 i_2 i_3}}{2} - \sum_{[i_1|i_2]} \left(\frac{(q_{i_1} - q_{i_2})^2}{6} - \frac{m_{i_1}^2 + m_{i_2}^2}{2} \right) b^{(9)}_{i_1 i_2}$$

Vanishing contributions: $\mathcal{A} = \mathcal{O}(\epsilon)$

Scalar integrals $I^{(D)}_{i_1 i_2 \ldots}$ all known

't Hooft & Veltman '79; Bern, Dixon Kosower '93, Duplancic & Nizic '02; Ellis & GZ '08, public code ⇒ http://www.qcdloop.fnal.gov

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
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✓ qq + QQ + W
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✓ tt + qq + N-gluons [Schulze]

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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

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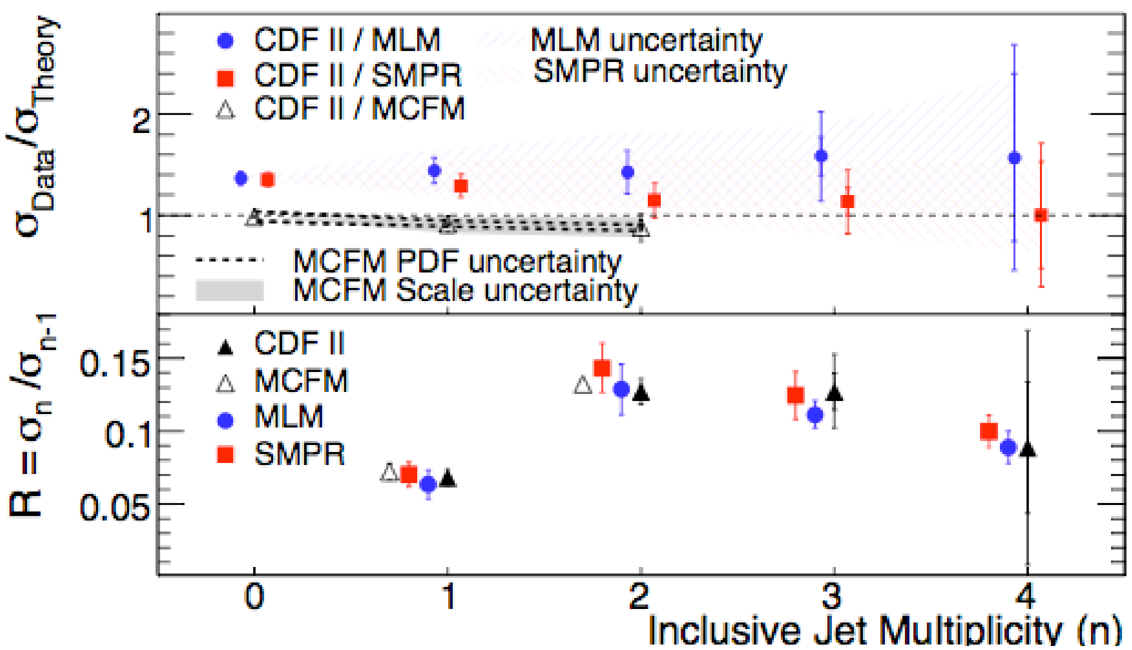
II. CDF data for W + n jets with n=1,2 is described exceptionally well by NLO QCD
$\Rightarrow$ verify this for 3 and more jets



First application: W + 3 jets

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

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)

$$\mathcal{R}_{\mathcal{O}}(\mu) \Rightarrow r$$

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

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Other O(1%) effects neglected:

- 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 ...)

Leading order:

Algorithm	R	$E_\perp^{\rm jet} > 20$ GeV	$E_\perp^{\rm 3rdjet} > 25$ 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

Moral:
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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	LO^{LC}						
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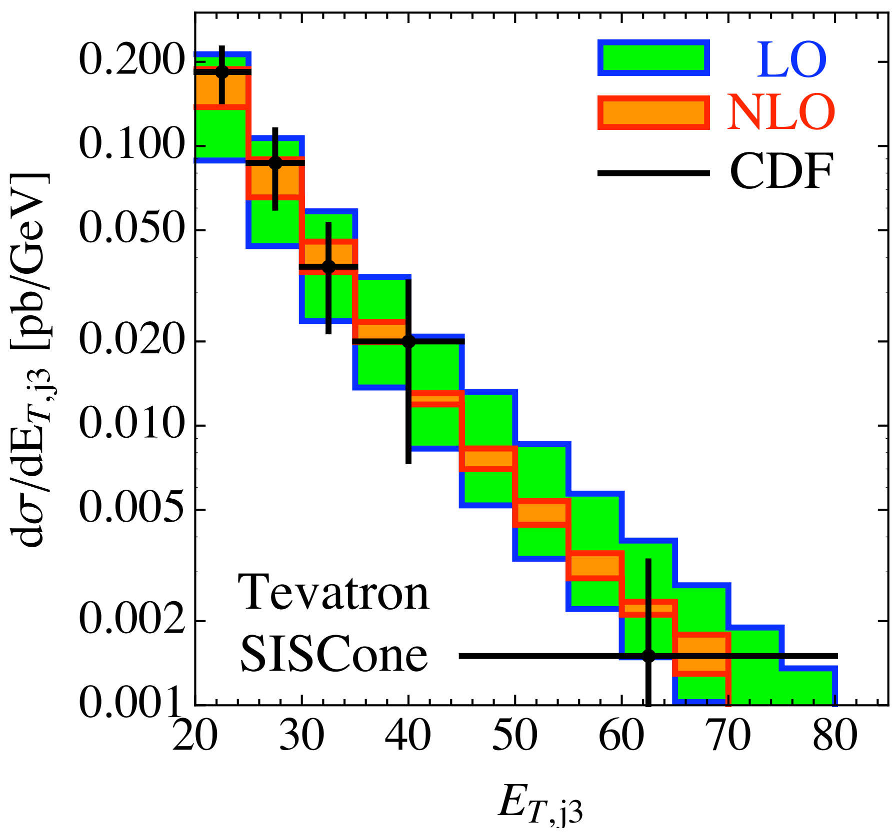
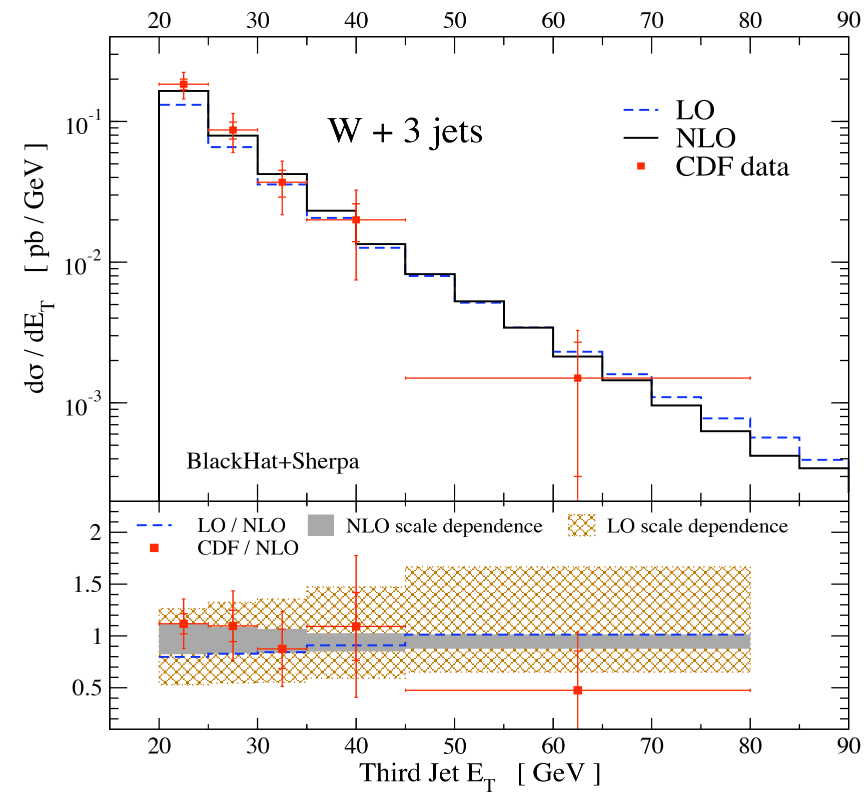
$\Rightarrow$ important (10% or more) differences due to different jet-algorithms.
High precision comparison impossible if using different algorithms

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)
- unwanted background (apply background cuts)

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- study a given process with signal cuts ⇒ refine theoretical tools
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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):

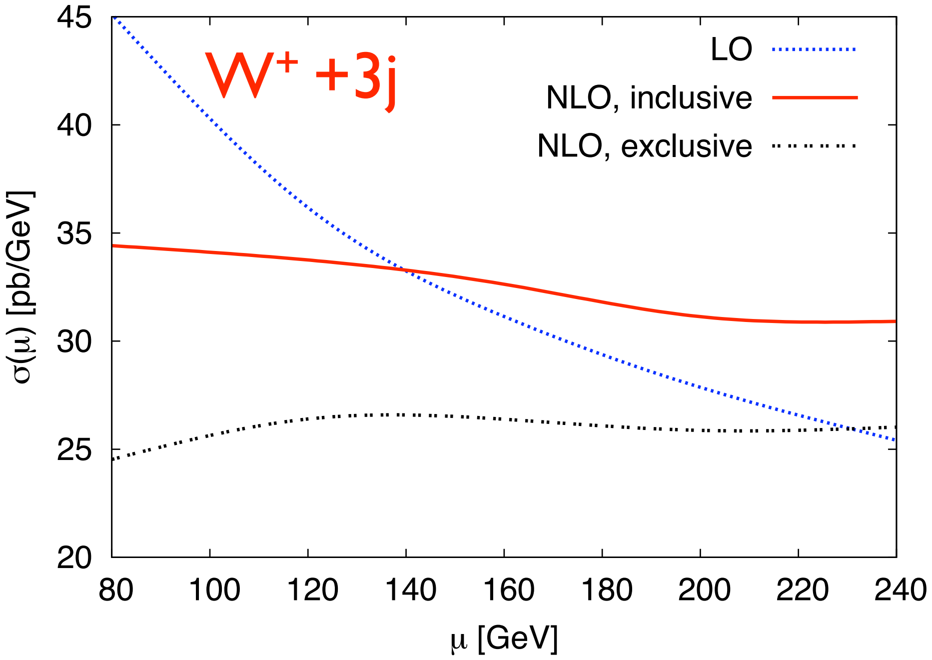
$$E_{\mathrm{CM}} = 10\,\mathrm{TeV} \qquad E_{\perp,\mathrm{jet}} = 30\,\mathrm{GeV} \qquad E_{\perp,e} = 20\,\mathrm{GeV}$$

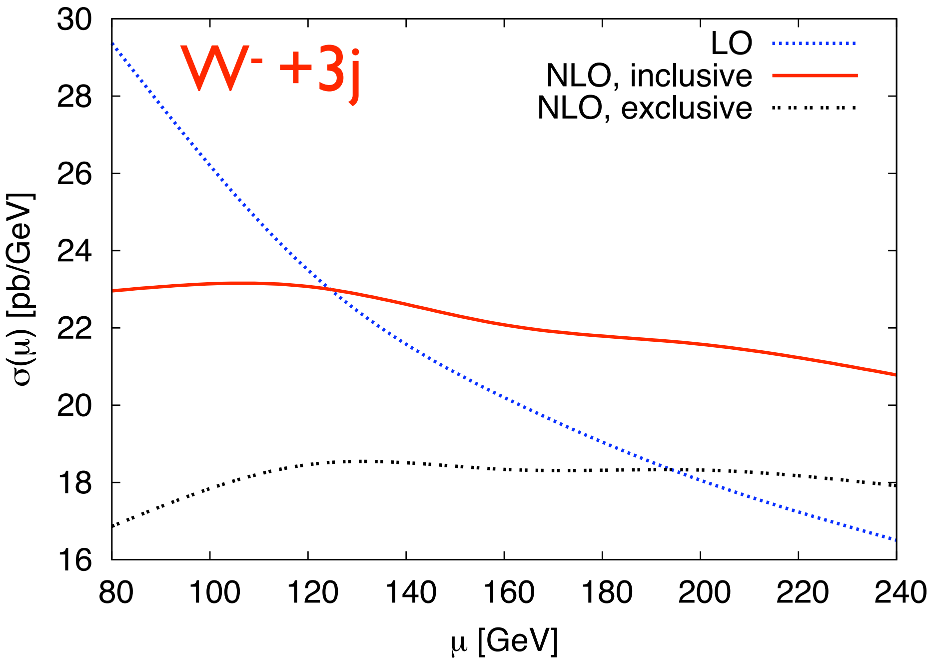
$$E_{\perp,\mathrm{miss}} = 15\,\mathrm{GeV} \quad M_{\perp,W} = 30\,\mathrm{GeV} \quad |\eta_e| < 2.4 \quad |\eta_{\mathrm{jet}}| < 3$$

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

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

Scale dependence

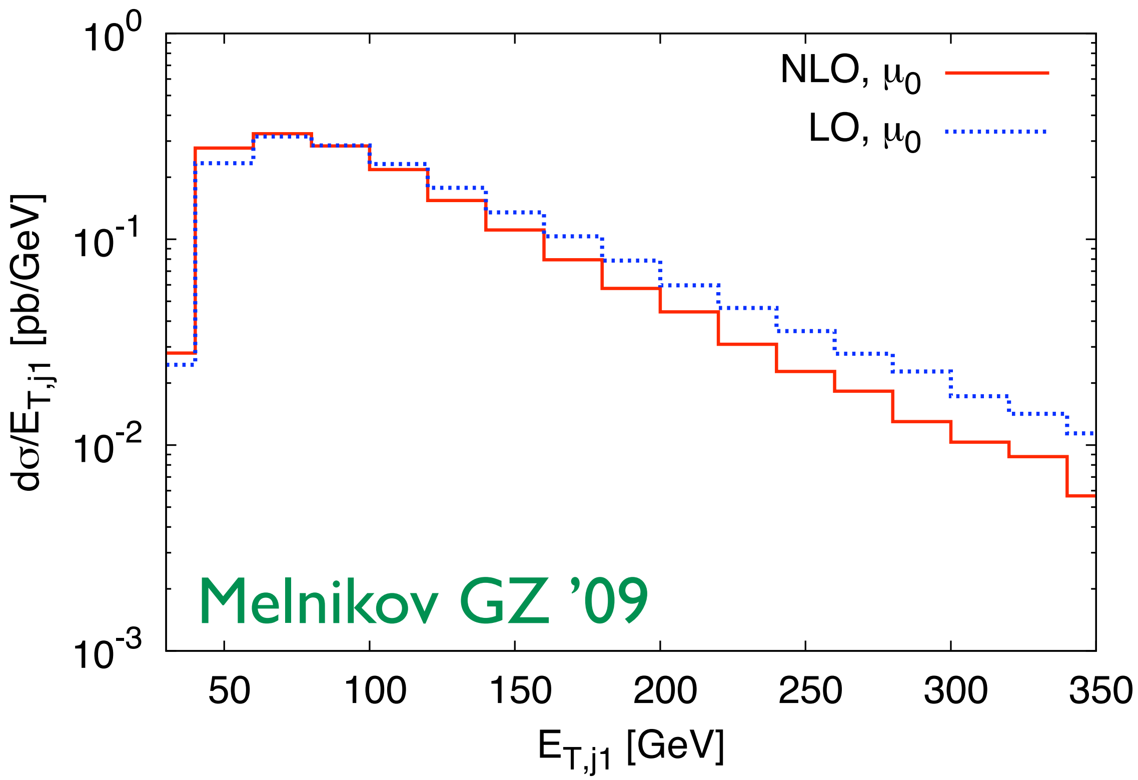




Melnikov & GZ '09

- 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?

Scale choice in V + jets

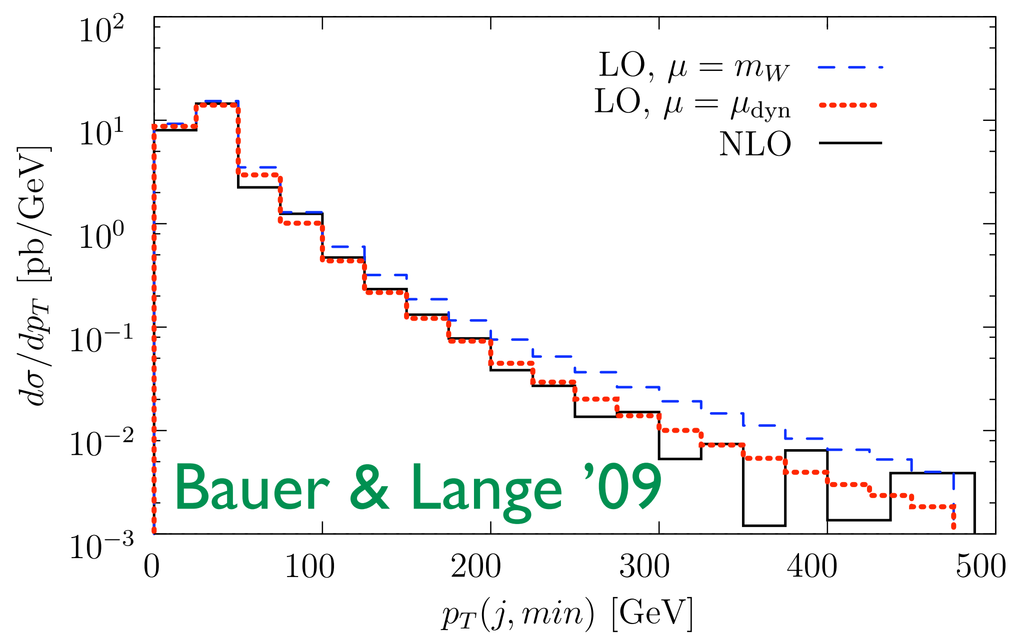
In a slightly different context, Bauer & Lange ('09) suggest that using a dynamical scale *LO results do reproduce the NLO shapes*

For W+2 jets they suggest

$$\mu^2 = M_W^2 + (m_{\mathrm{hadr}}/2)^2$$

Similarly Berger et al ('09) suggest

$$\mu = \hat{H}_T = \sum_i p_{ti} \qquad \text{(i = any parton)}$$



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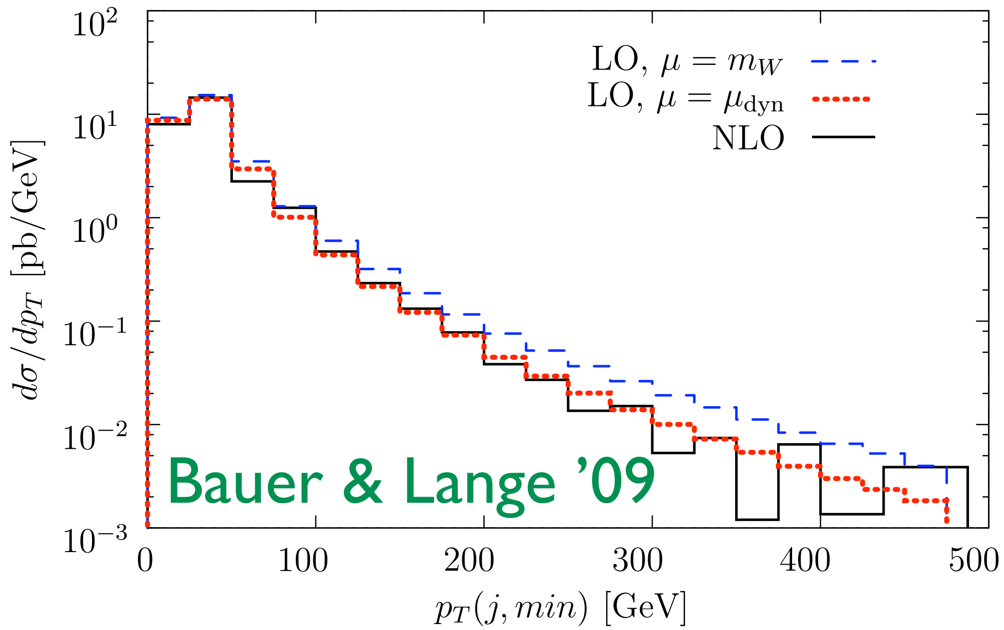

The idea of using dynamical scales is not new, it is implemented in all matrix element generators (CKKW local scales).
Useful to compare NLO to those state-of-the art LO calculations.

Same transverse energy distribution

Local scale choice (CKKW):

- 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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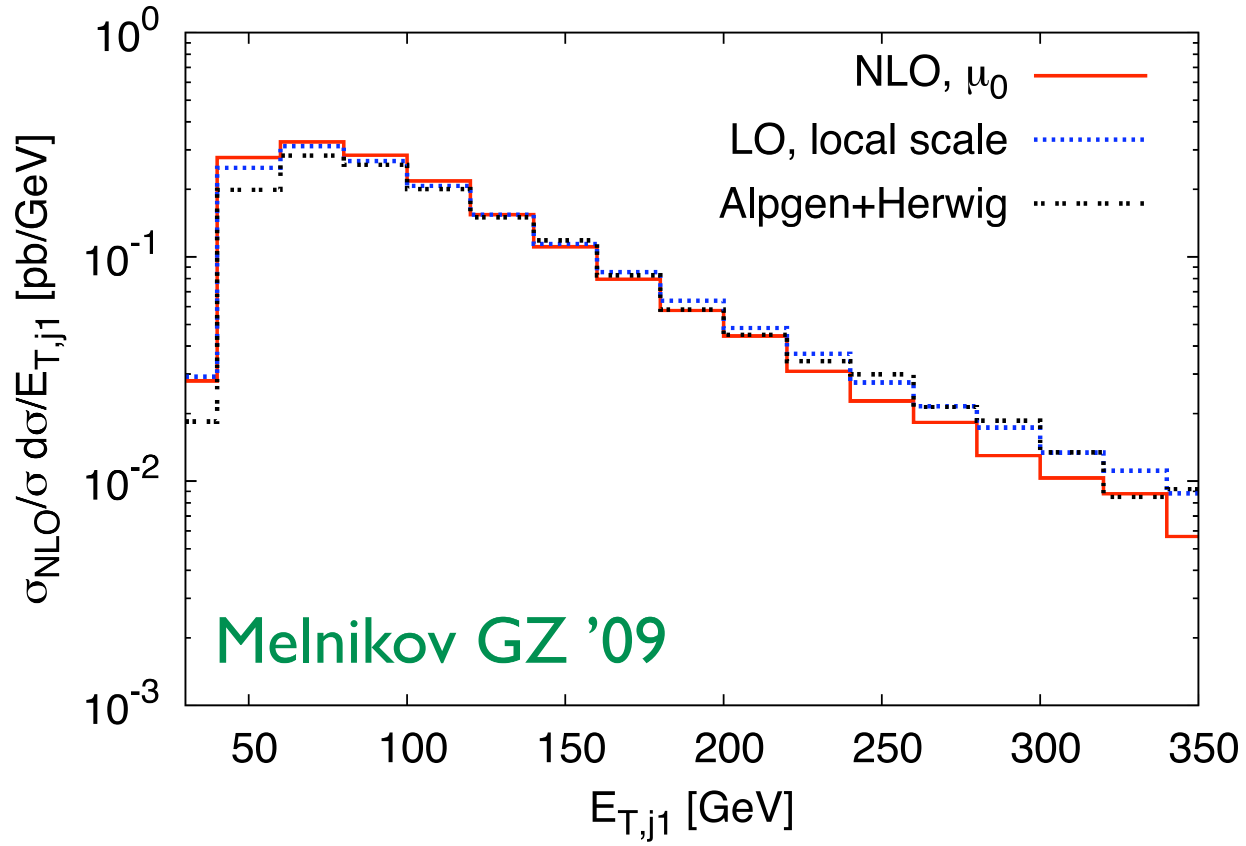

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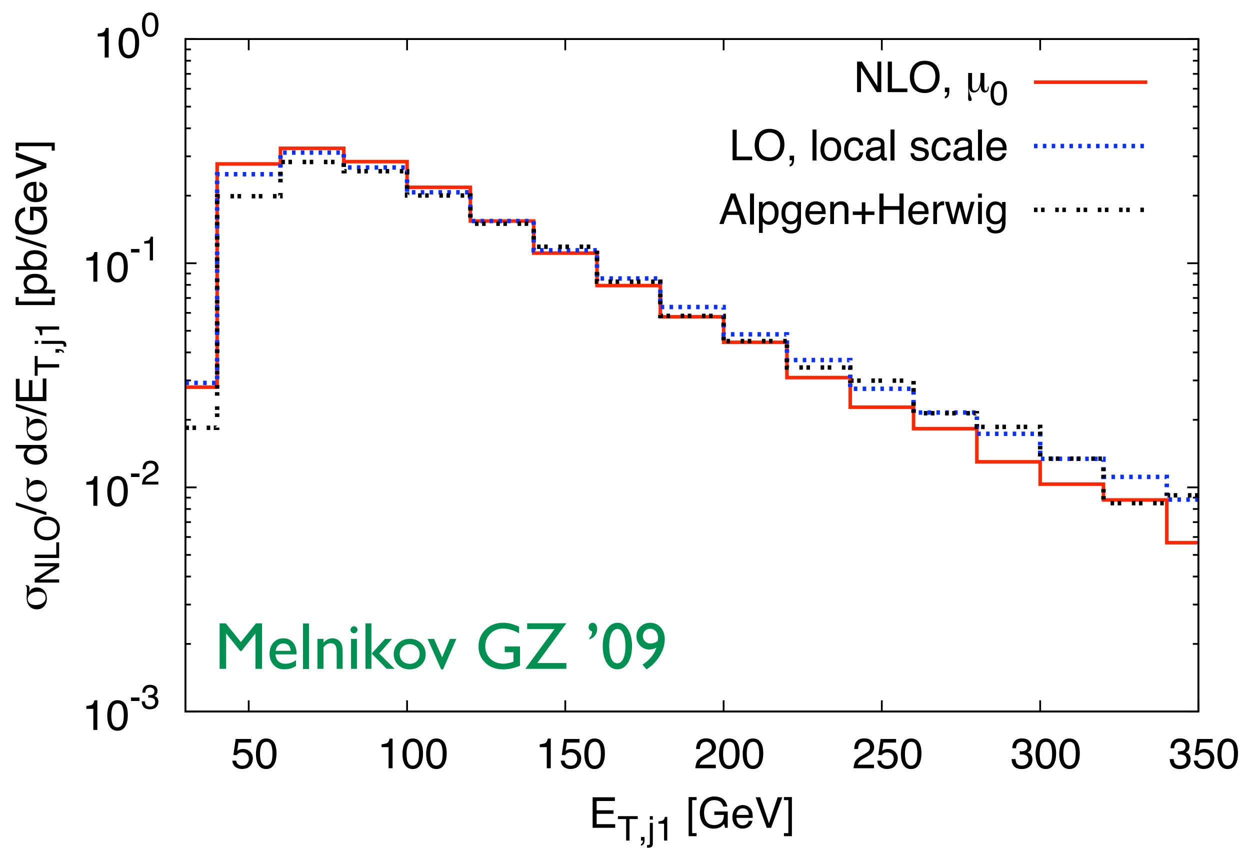
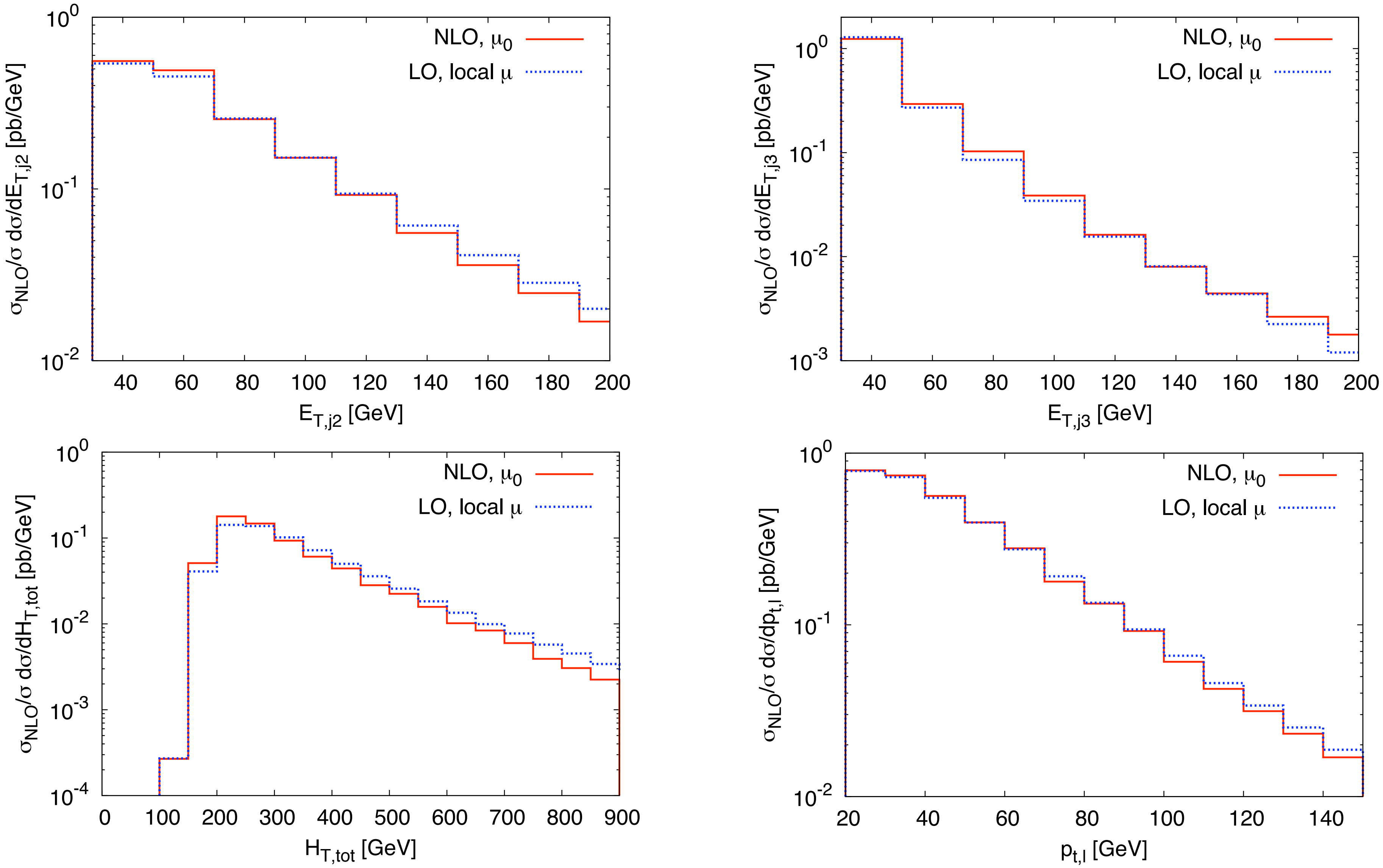


☛ difference between "LO, local scale" and full Alpgen+Herwig indicative of importance of parton shower

☛ local scale choice very close to Alpgen+Herwig which reproduces the NLO shape reasonably well

Other hadronic distributions



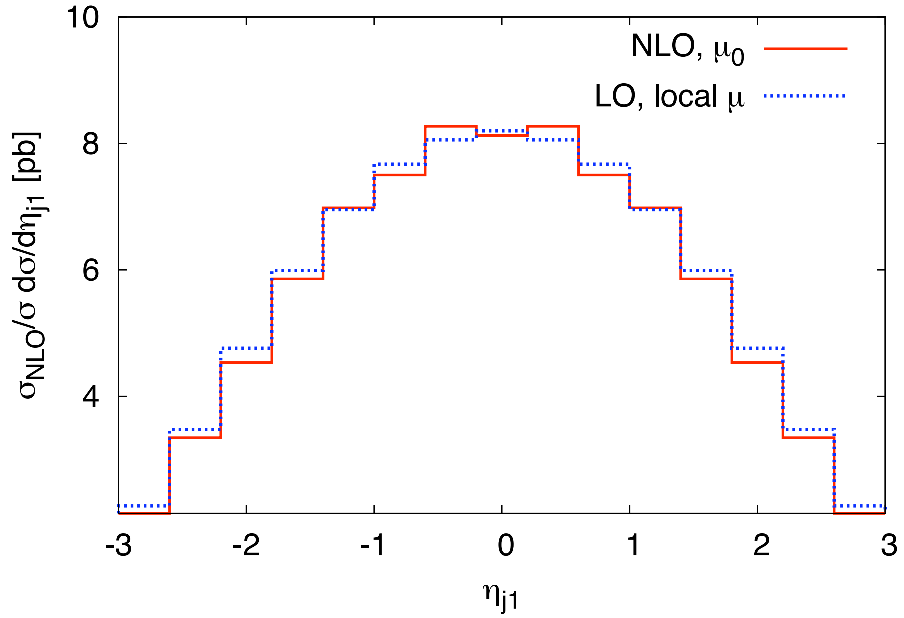
Melnikov GZ '09

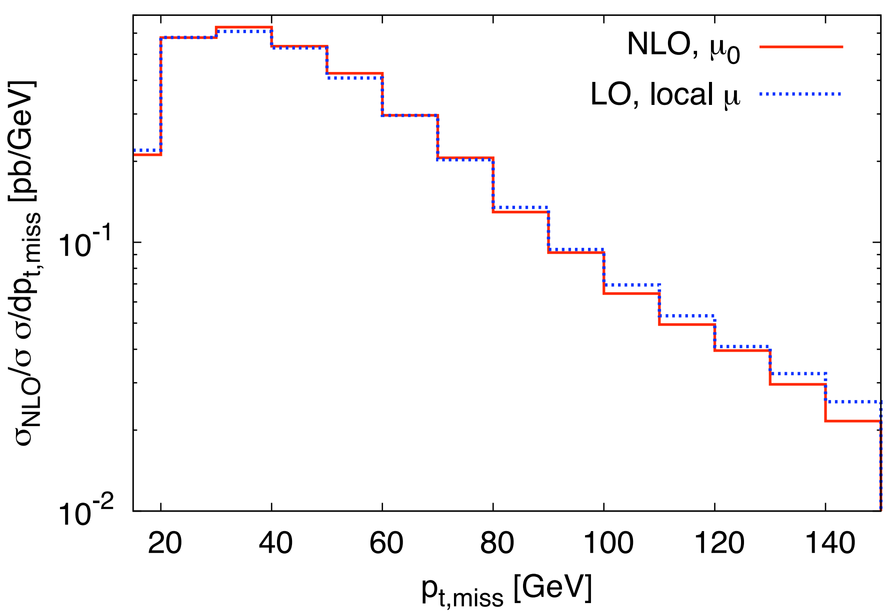
☛ LO with local scale does a very reasonable job in reproducing shapes

NB:

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

Leptonic distributions





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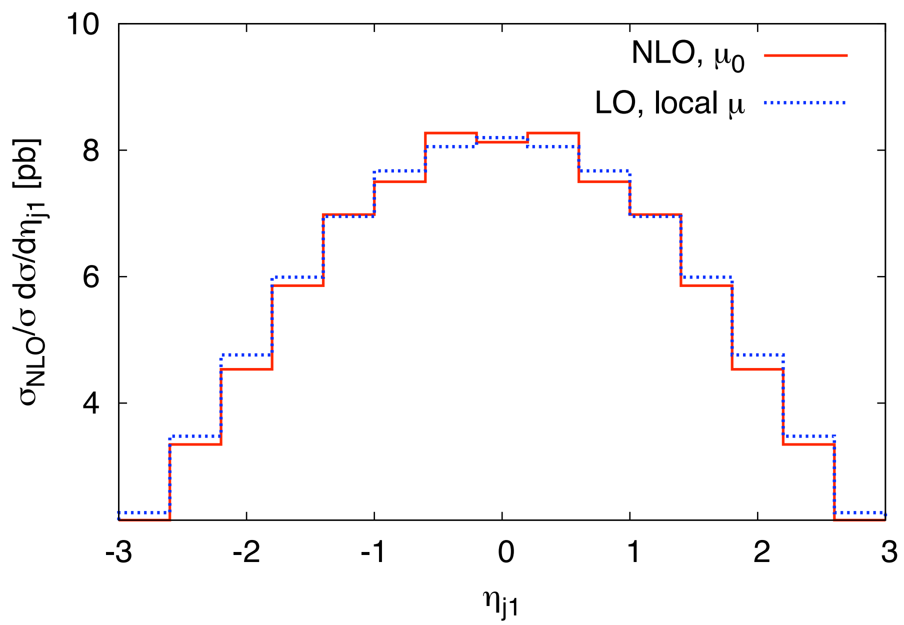
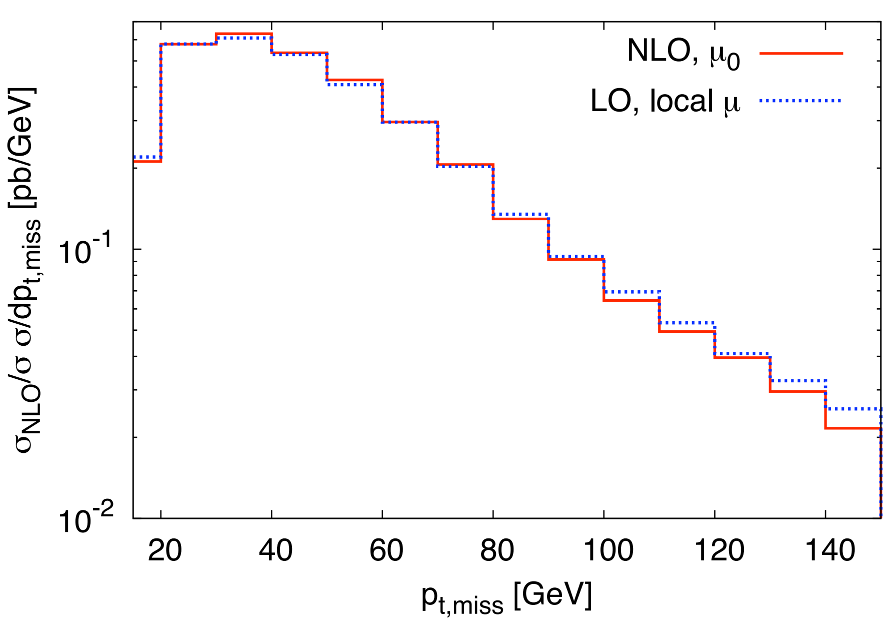
Leptonic distributions





Melnikov GZ ’09

- same conclusion holds for leptonic distributions

How solid (cut-independent) is this statement ?

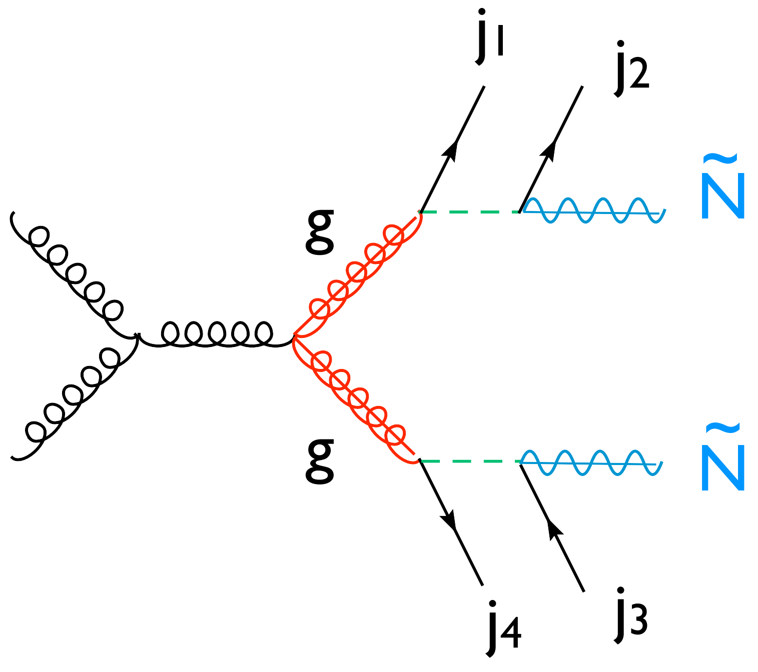
See what happens with different cuts.

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

SUSY signature

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

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



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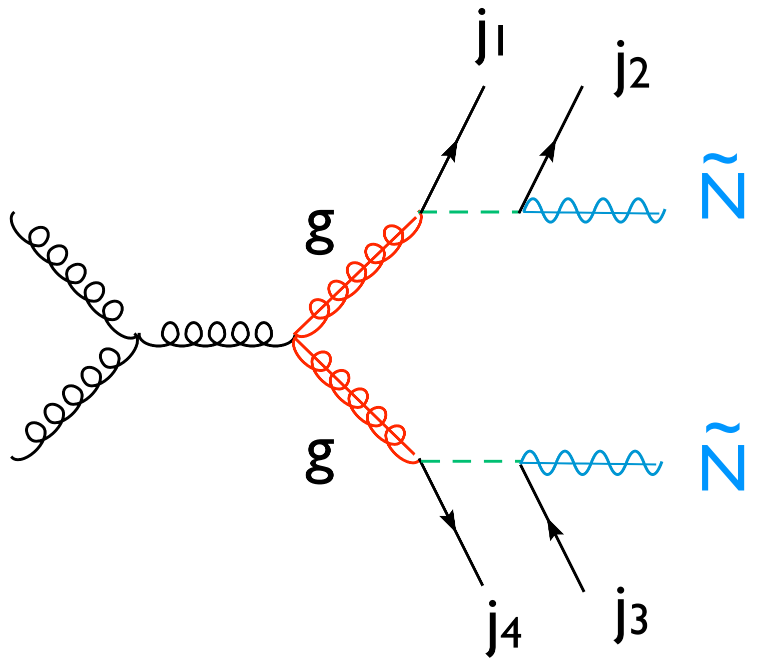

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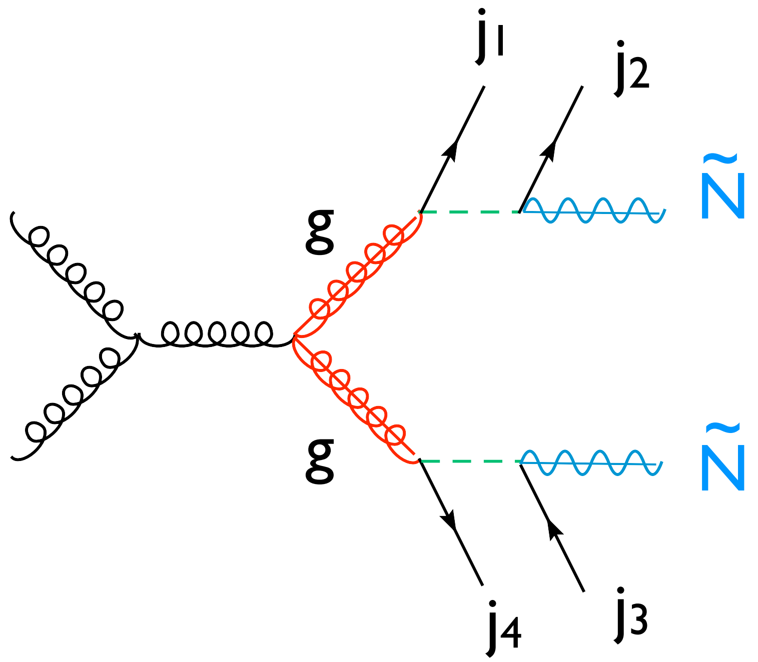

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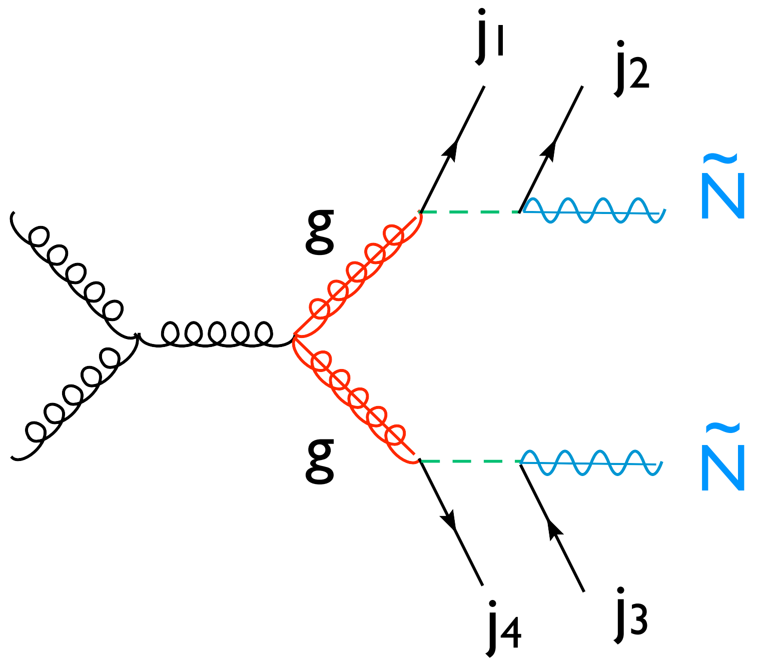

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1) limited efficiency for identifying τ-decays

2) σ(W +3 j) ~ 100 σ(Z + 4j)

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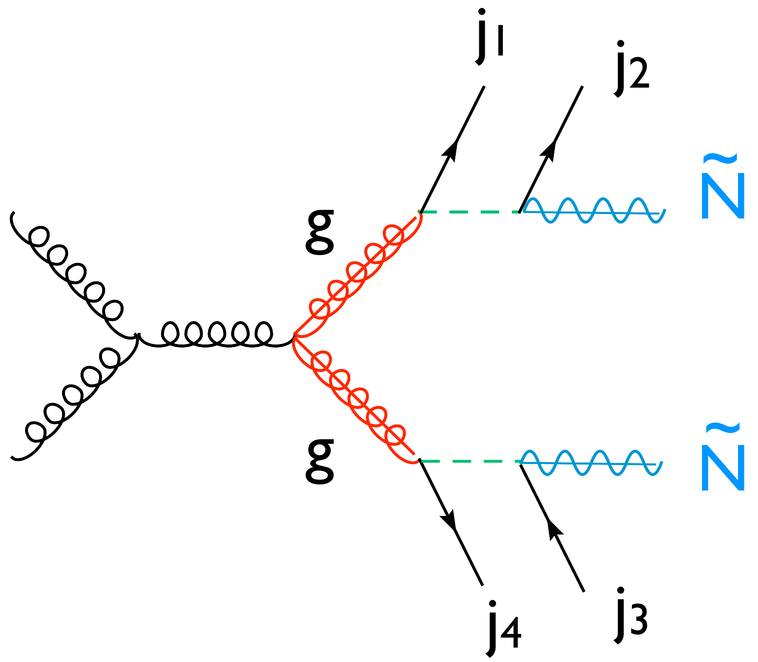

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1) limited efficiency for identifying τ-decays

2) σ(W +3 j) ~ 100 σ(Z + 4j)

$\Rightarrow$ 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
Yamamoto [ATLAS Col.] 0710.3953

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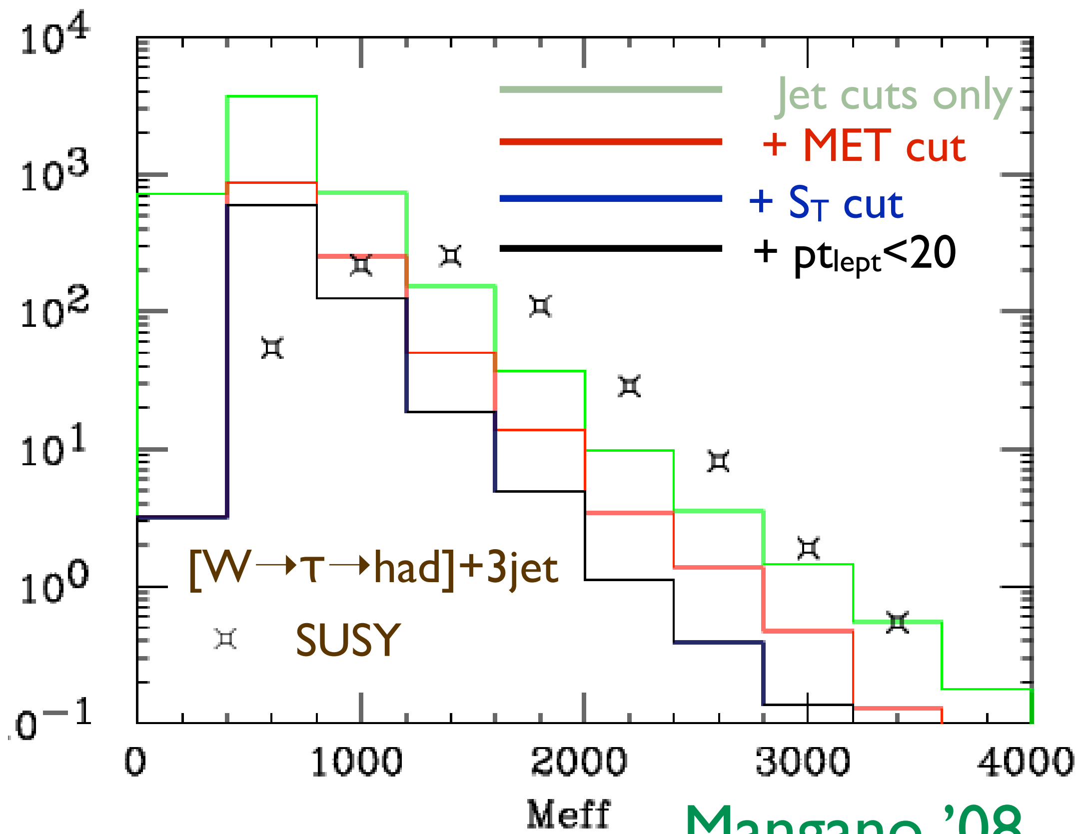


Mangano '08

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

SM background from W+3 jets

Our calculation includes only the leptonic decay of the W (in e, μ or τ) but not the hadronic subsequent decay of τ. However

SM background from W+3 jets

Our calculation includes only the leptonic decay of the W (in e, μ or τ) but not the hadronic subsequent decay of τ. However

➡ kinematic cuts force τ to be highly boosted $\Rightarrow$ τ-decay highly collimated

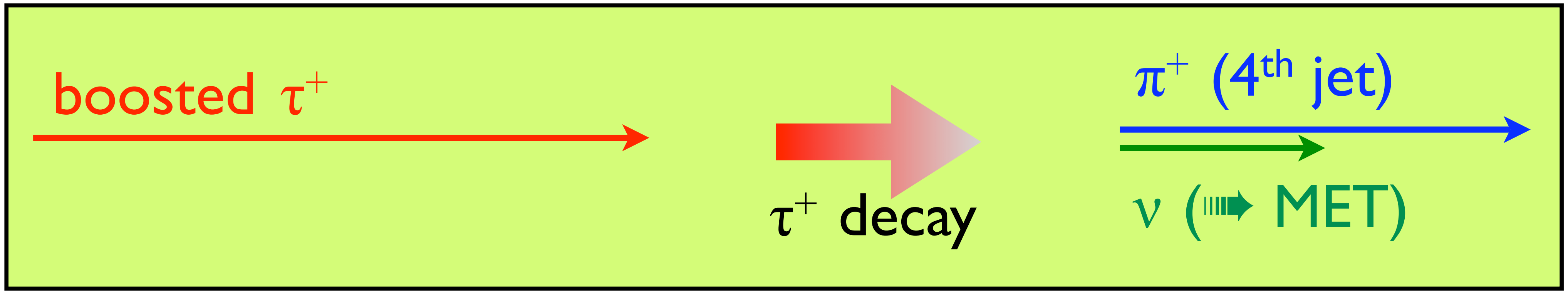
➡ τ^+ essentially decays only into π^+(2/3 of energy) and ν (1/3 of energy)

SM background from W+3 jets

Our calculation includes only the leptonic decay of the W (in e, μ or τ) but not the hadronic subsequent decay of τ. However

➡ kinematic cuts force τ to be highly boosted $\Rightarrow$ τ-decay highly collimated

➡ τ^+ essentially decays only into π^+(2/3 of energy) and ν (1/3 of energy)



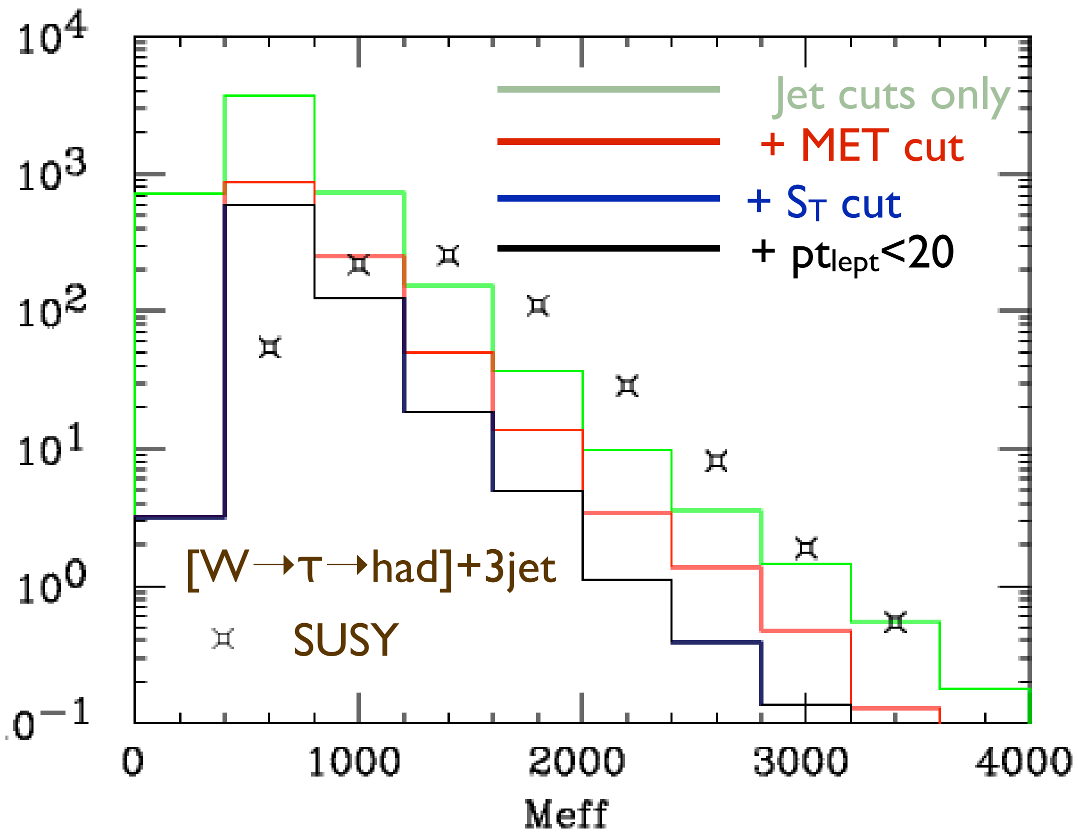
Theoretical robust approximation:

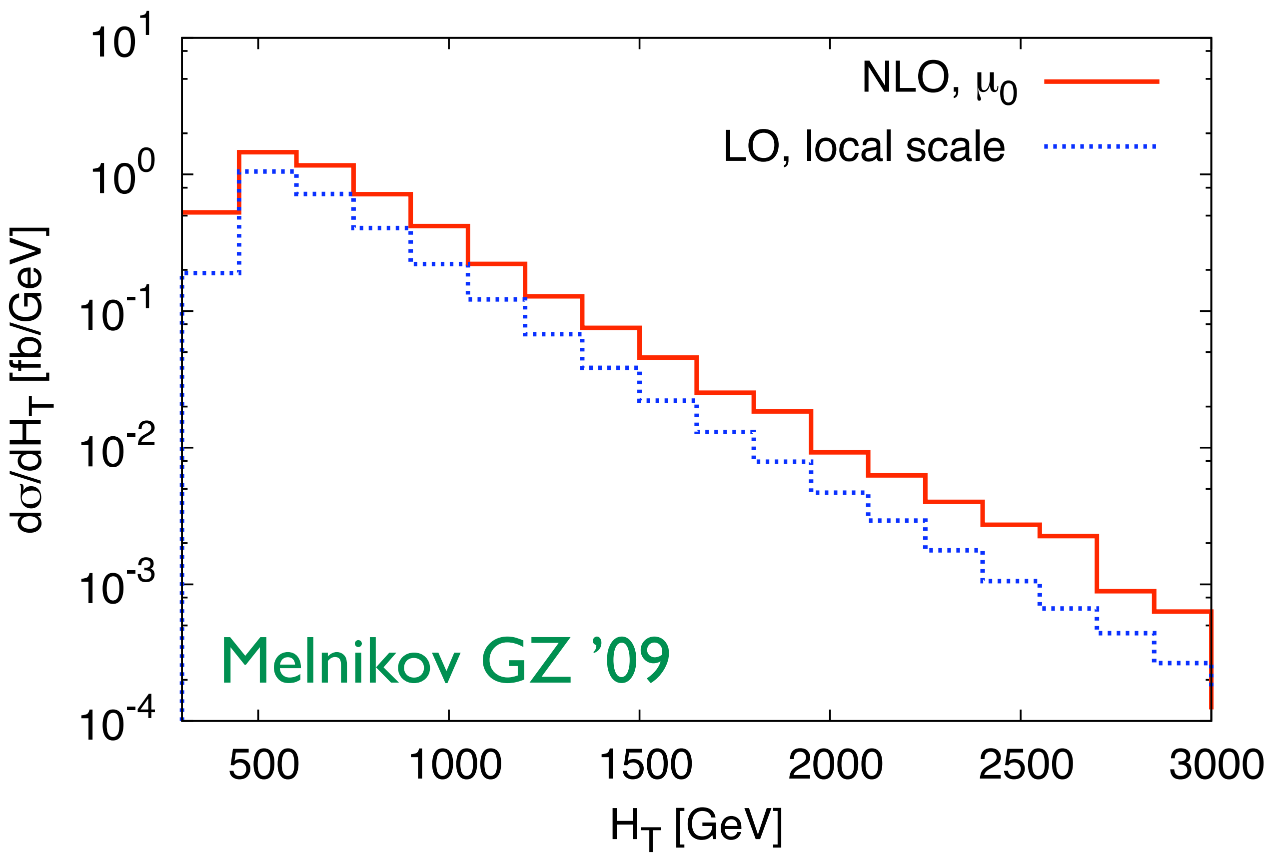
simulate the W decay as a perfect collinear branching with momentum fractions 2/3 (π^+) and 1/3 (ν)

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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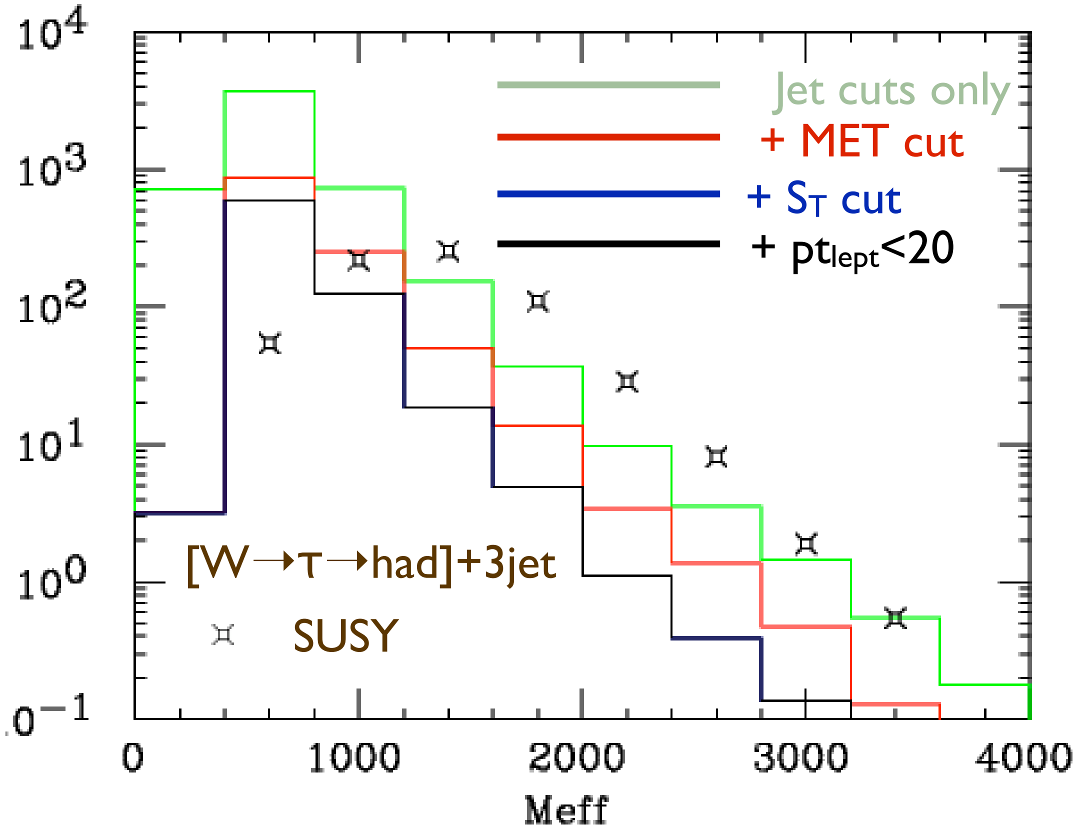

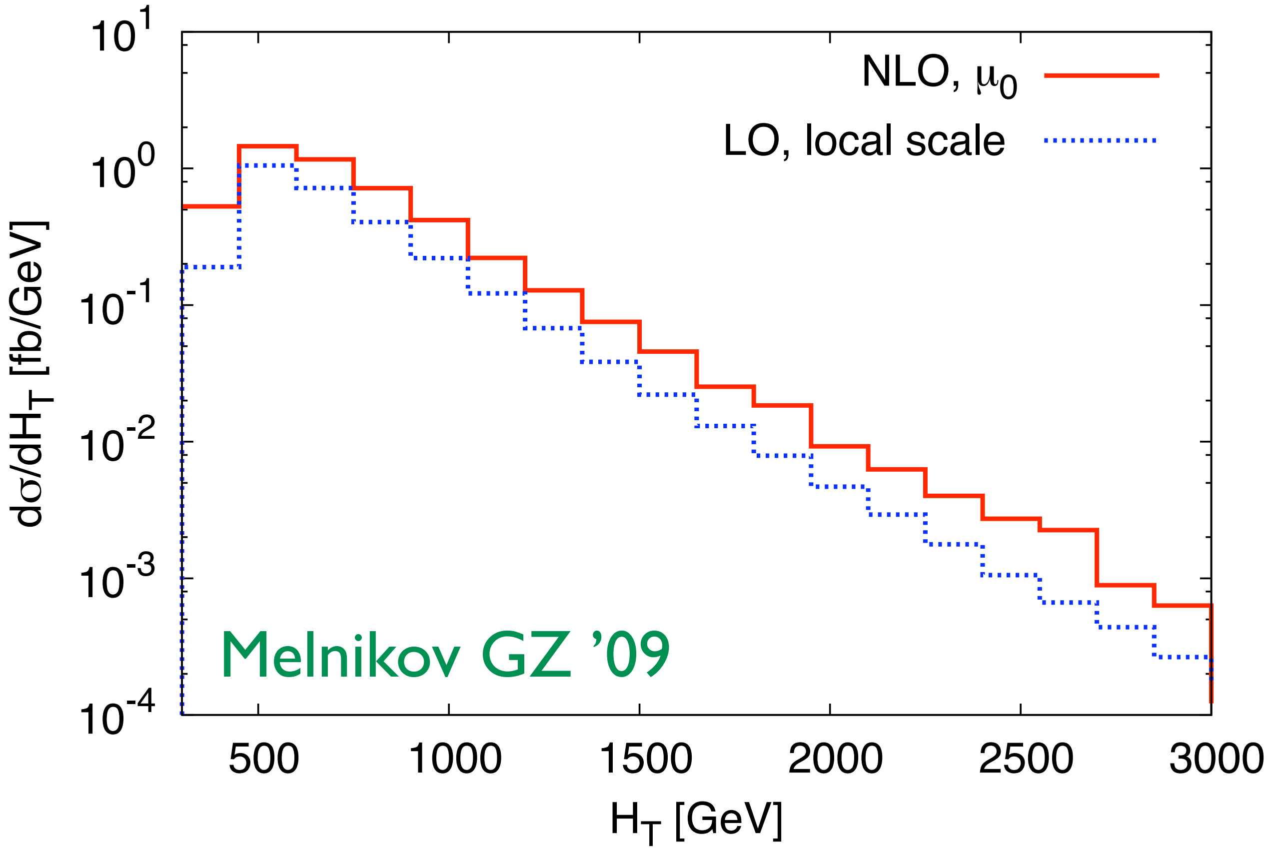

- universal enhancement (K-factor ~3) of LO without distorting the shape

  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

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

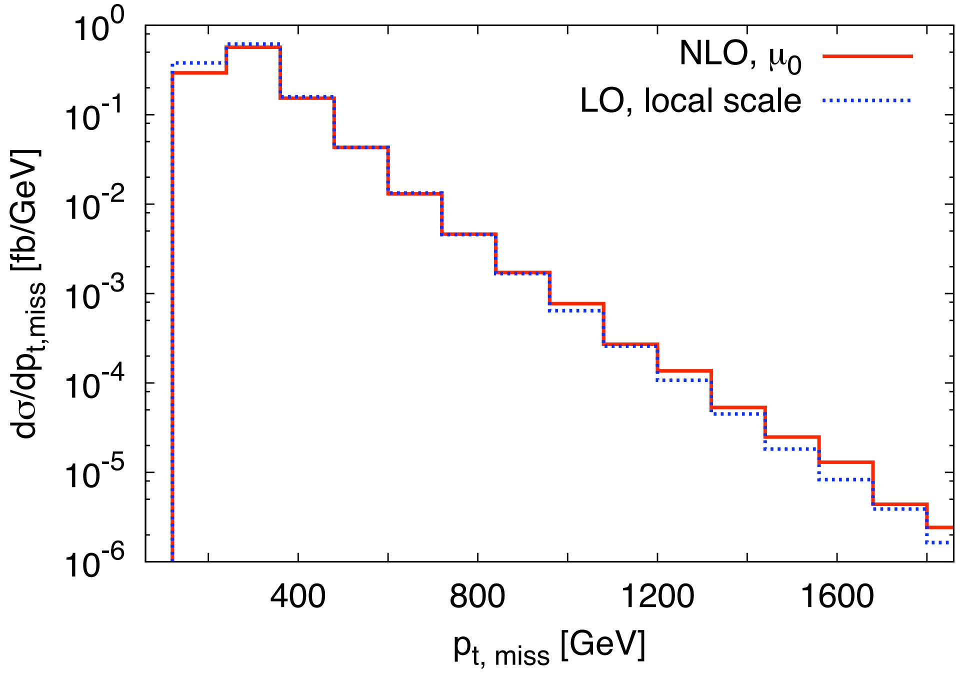
$$|\eta_{\mathrm{lead\ jet}}| < 1.7 \quad |\eta_{\mathrm{other\,jets}}| < 3 \quad H_{\mathrm{T,24}} = \sum_{j=2}^{4} p_{\mathrm{T,j}} + E_{\mathrm{T,miss}} > 500\mathrm{GeV}$$

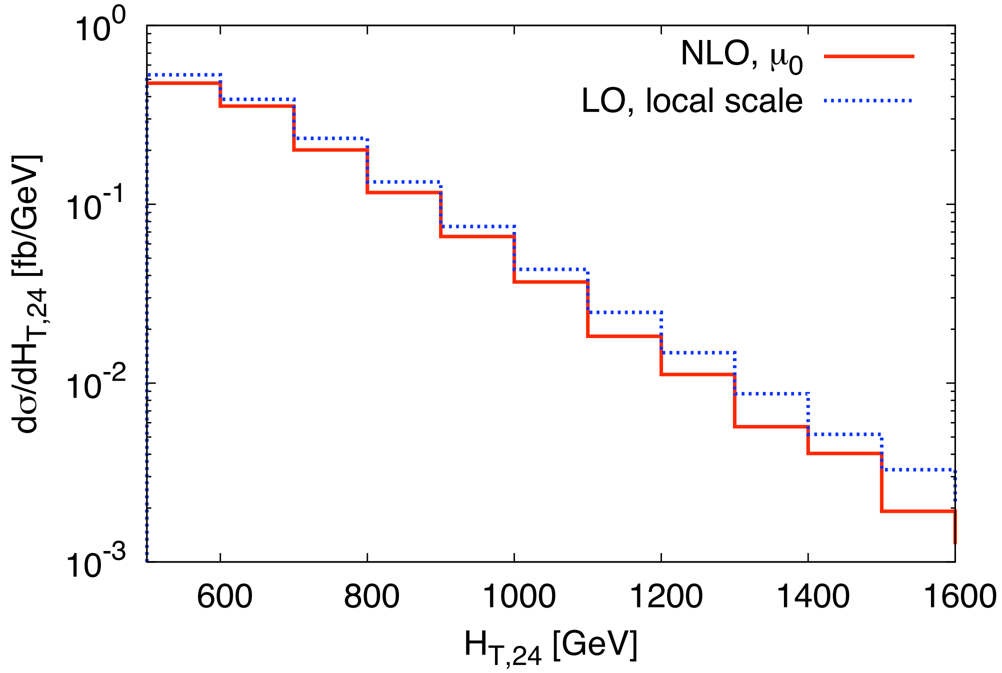
CMS Collaboration Journal Phys. G: Nucl. Part. Phys. 34 (2007) 995

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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- large (~100%) corrections for ATLAS setup, small corrections (~10%) for CMS cuts *despite the fact that the cuts are designed for the same purpose*
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- all this emphasizes the need to extend NLO corrections to other processes (Z+3j, W+4j ...)

Conclusions

A lot of physics to be learned from NLO QCD. Very fast evolving field, impressive progress in the last years, mainly driven by

- various inspiring/enlightening ideas
- hard work: several techniques developed, implemented, tested
- many competitive groups (cross-checks/tuned comparisons) & more efficient computers

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NLO QCD will provide solid basis for a successful program at the LHC