Reaching beyond the electroweak scale:

Giant *K*-factors, FAT jets and pileup pileup pileup

Gavin Salam

CERN, Princeton & LPTHE/CNRS (Paris)

based on work with Matteo Cacciari, Mathieu Rubin, Sebastian Sapeta & Gregory Soyez

CMS Week
CERN, 30 March 2011

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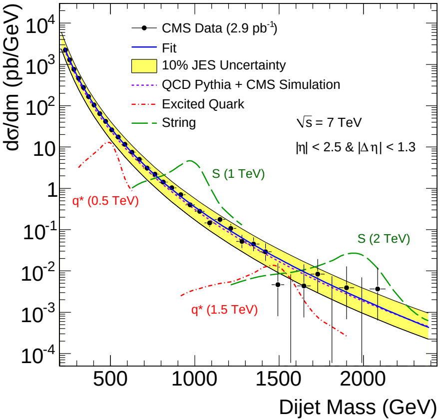
With the forthcoming few fb^{-1}, strongly interacting physics will be taken to the multi-TeV scale and electroweak physics close to the TeV scale.



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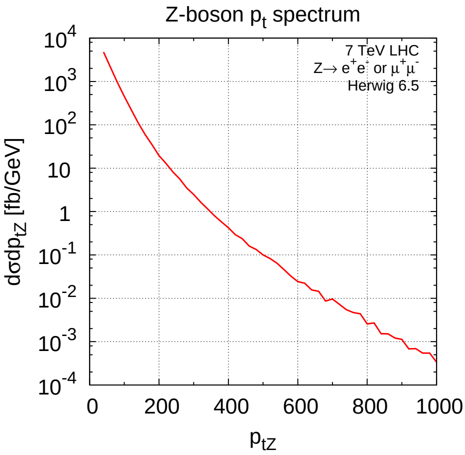

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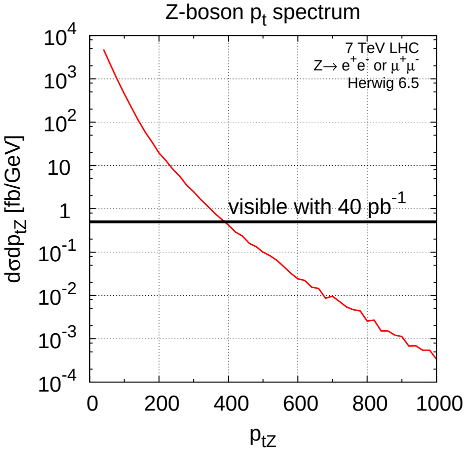

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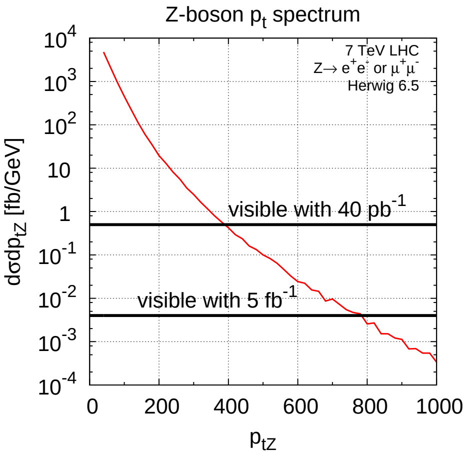

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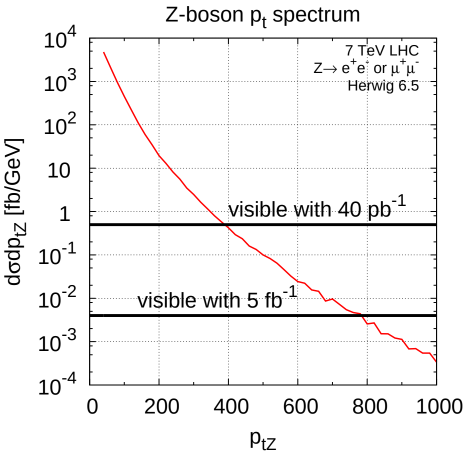

What's characteristically new as we approach the TeV scale with EW-scale objects?

W's, Z's, Higges and even top-quarks all become **light**

Giving $p_t \sim 1$ TeV to a Z-boson is analogous to giving $p_t \sim 50$ GeV to a B-hadron.

This can have implications for:

1. the convergence of perturbative QCD
2. the methods used for reconstruction

And as a side effect of the high luminosities, you need to deal with large amounts of pileup

Giant K factors

How accurate is perturbative QCD?

$$\sigma = c_0 + c_1\alpha_s + c_2\alpha_s^2 + \ldots$$

$$\alpha_s \simeq 0.1$$

That implies LO QCD (just c_0) should be accurate to within 10%

It isn't

Rules of thumb:

LO good to within factor of 2

NLO good to within scale uncertainty

This drives our understanding of accuracy of QCD predictions; e.g. when combining QCD with data-driven background estimates

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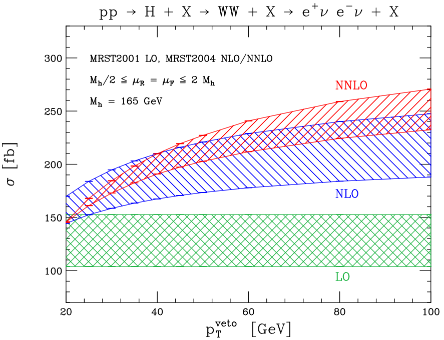

Anastasiou, Melnikov & Petriello '04
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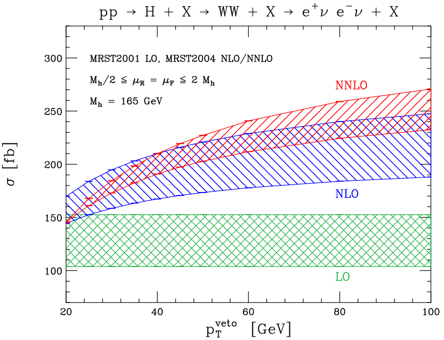

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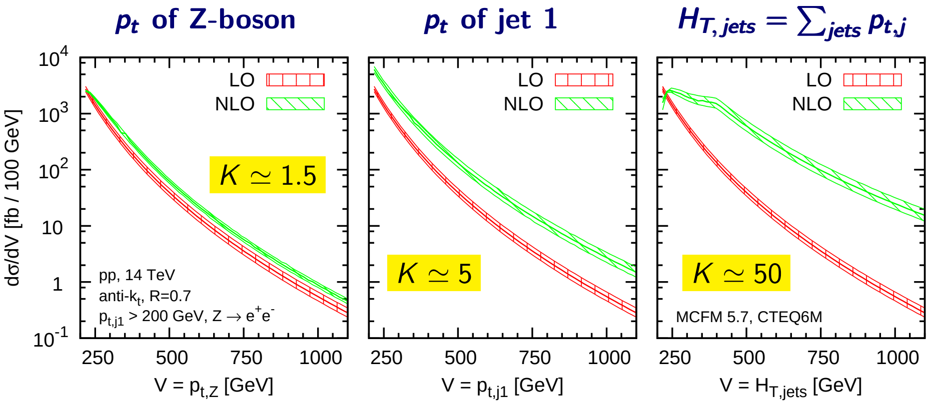
QCD convergence can fail badly — eg. Z+jet



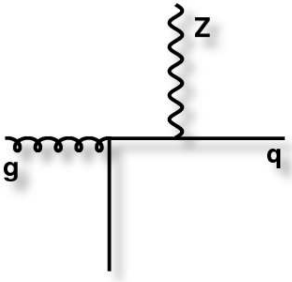
"Giant K-factors"

They're not just large; they often depend on p_t; and they can even have kinks

Butterworth et al '08; Bauer & Lange '09; Denner et al '09; Rubin, GPS & Sapeta '10

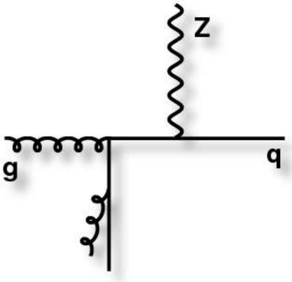
Why the large *K*-factor?

Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order



$\alpha_s^2 \alpha_{EW}$

New logarithmically enhanced topologies appear because EW bosons are light; $M_Z \ll \sqrt{s}$

Also: new partonic channels at NLO, qq scattering with large PDF lumi

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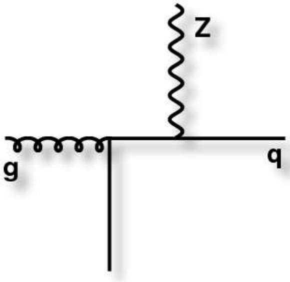

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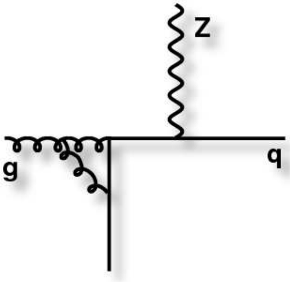

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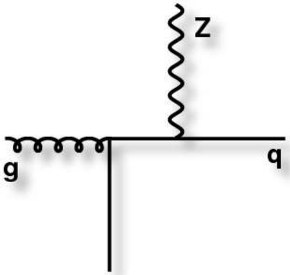

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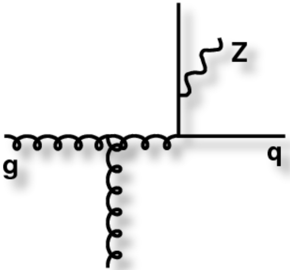

$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$

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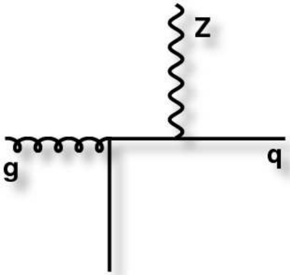

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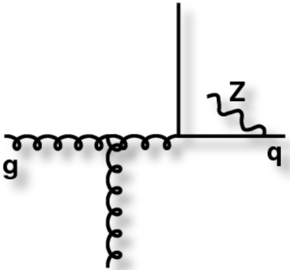

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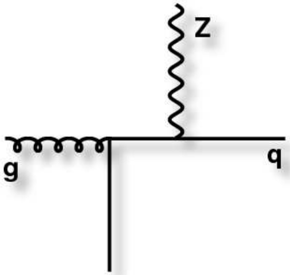

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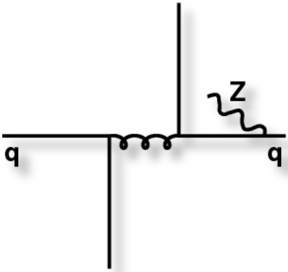

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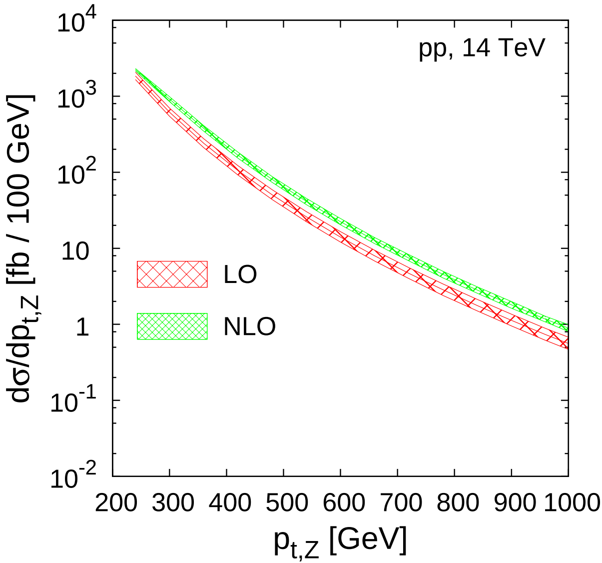
Testing Alpgen + Herwig + MLM Matching

p_t of Z-boson



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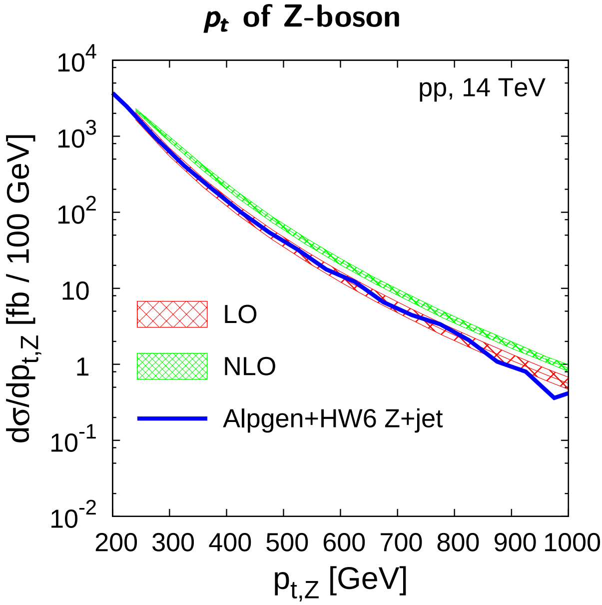

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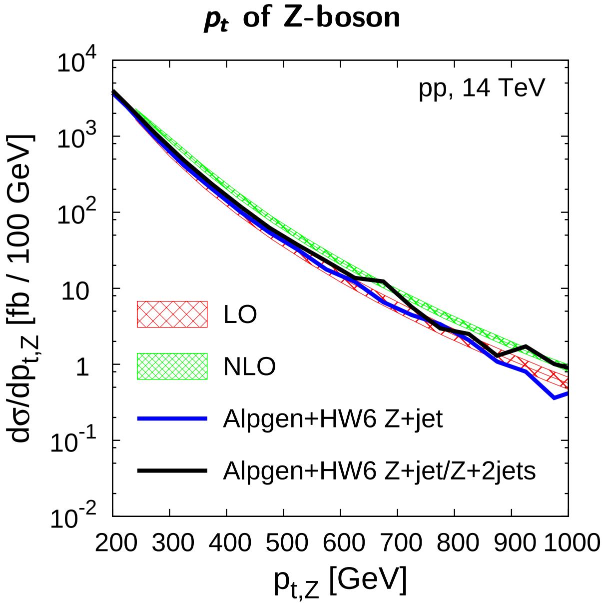
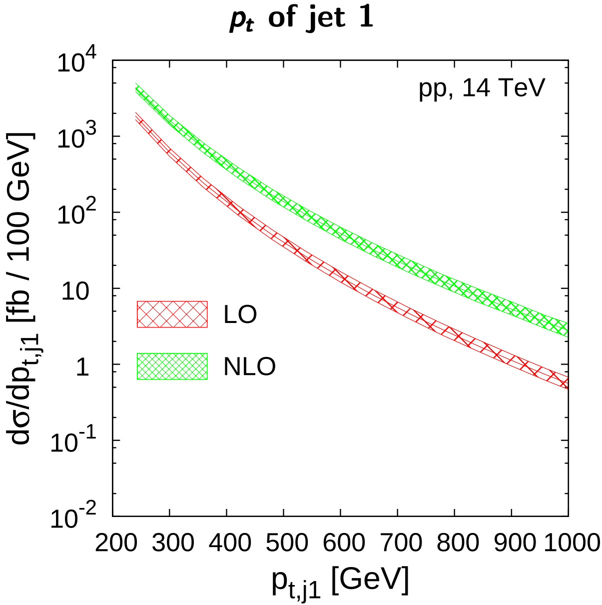


All predictions similar and stable

Testing Alpgen + Herwig + MLM Matching



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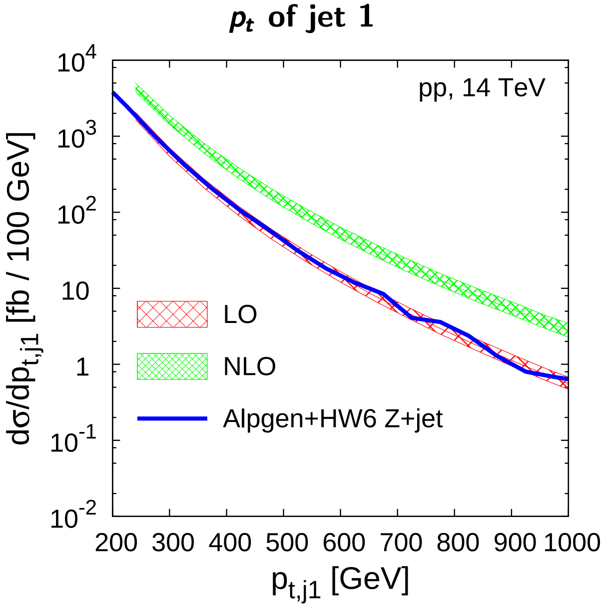

Showered Z+j $\simeq$ LO

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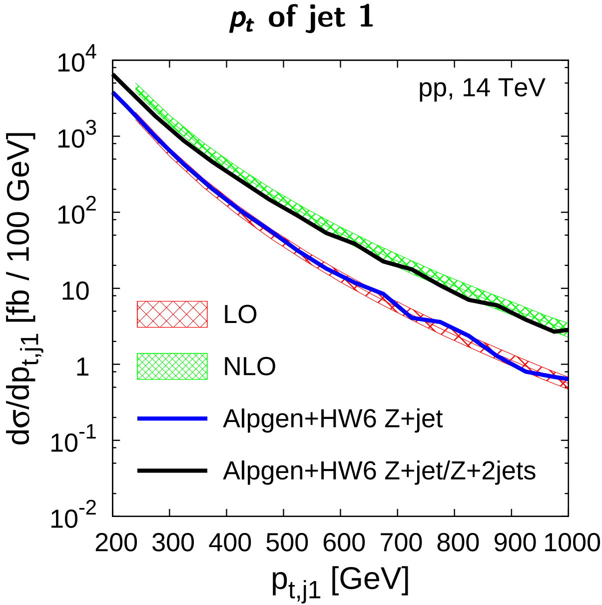

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Showered Z+j/Z+2j $\simeq$ NLO

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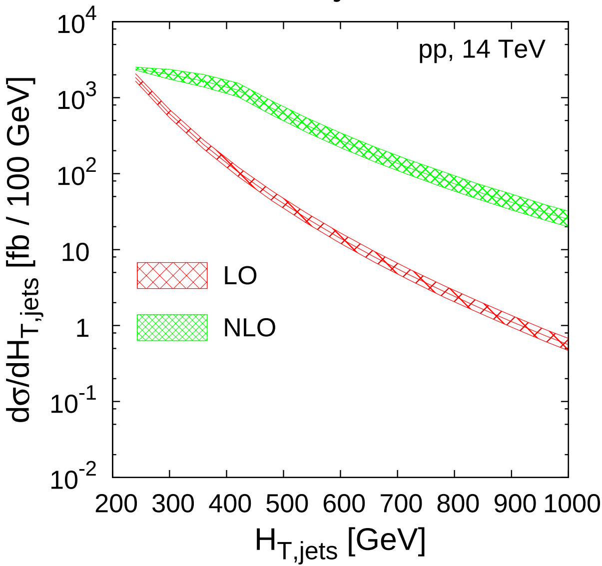
$$H_{T,jets} = \sum_{jets} p_{t,j}$$



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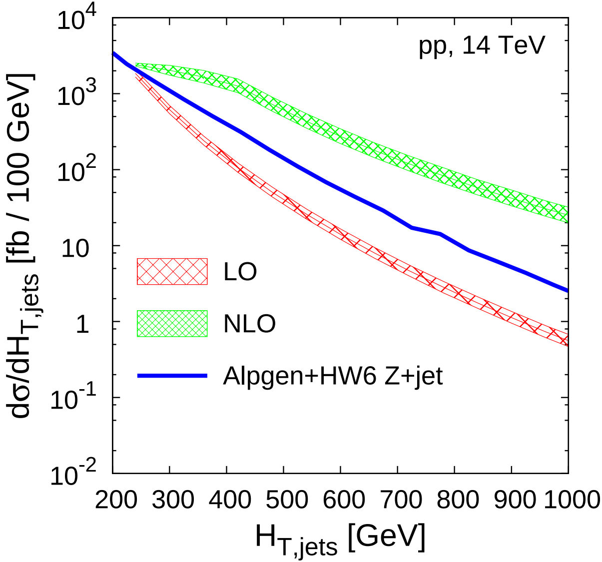

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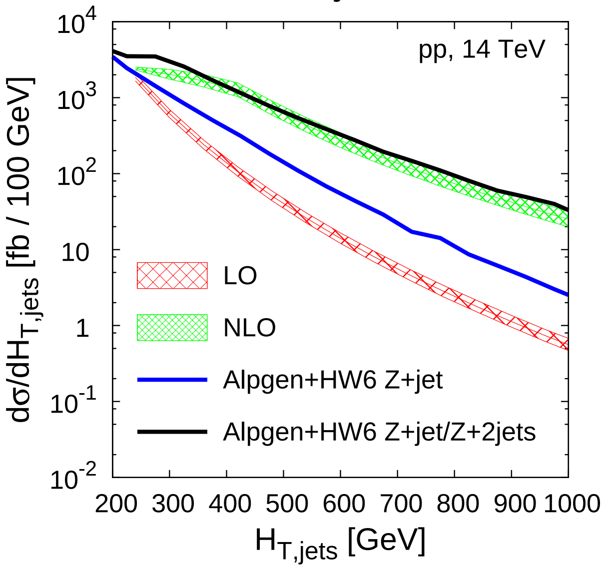

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Showered Z+j/Z+2j $\simeq$ NLO

1st lesson:

If you figure out the "leading" process
[Z + jet @ LO]

and add in process with one extra jet through
MLM/CKKW matching.
[i.e. include Z + 2 jets @ LO]

impact of new large topologies will often show up
This might be called "Pauper's NLO"

It's reassuring that **suitable use** of Alpgen/Madgraph/... catches this.
[cf. also de Aquino et al '11]

Is it always being used "suitably" (i.e. with extra jets)?
How do you get NLO normalisation for these samples?

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Beyond NLO

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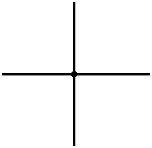
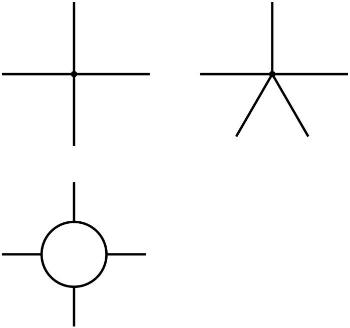


Beyond NLO

NLO



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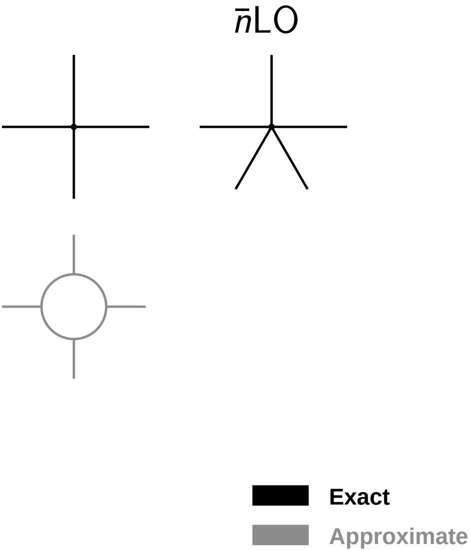


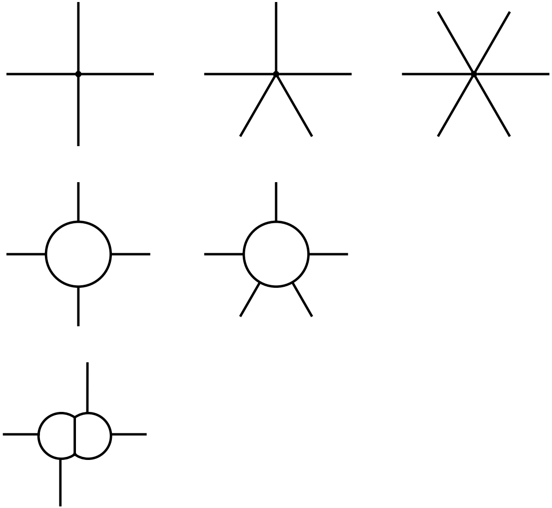
MLM matching keeps the tree-level parts of NLO, but approximates the loops.

We denote this **$\bar{n}$LO**

Can be a good approx. to NLO

Beyond NLO

NNLO



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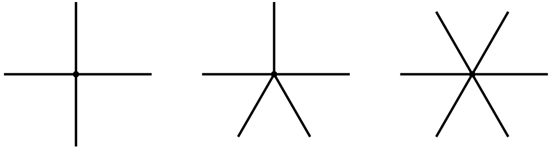
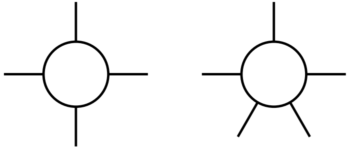
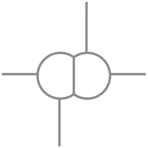
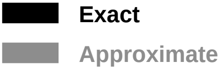








MLM matching keeps the tree-level parts of NLO, but approximates the loops.

We denote this **$\bar{n}$LO**

Can be a good approx. to NLO

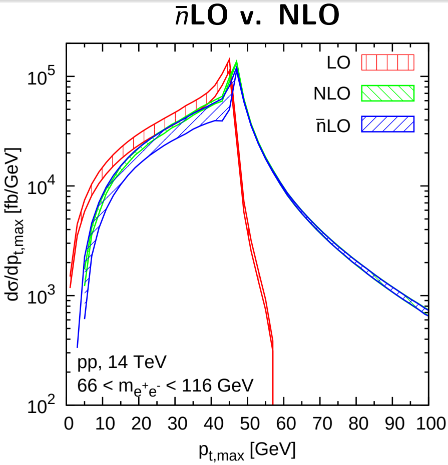
To approximate NNLO, take tree-level and 1-loop pieces (from NLO Z+j & Z+2j) and approximate 2-loop part.

$\bar{n}$NLO, using “LoopSim”

NB: pure partonic; no shower MC

Rubin, GPS & Sapeta ’10

Validation: Drell-Yan lepton p_t, $\bar{n}$NLO v. NNLO



Z (i.e. DY) with Z+j from MCFM & LoopSim

For $p_{t,\ell} \gtrsim \frac{1}{2} M_Z + \Gamma_Z$ (giant K-factor!) it had to work
For $p_{t,\ell} \lesssim \frac{1}{2} M_Z + \Gamma_Z$ it's remarkable that it still works

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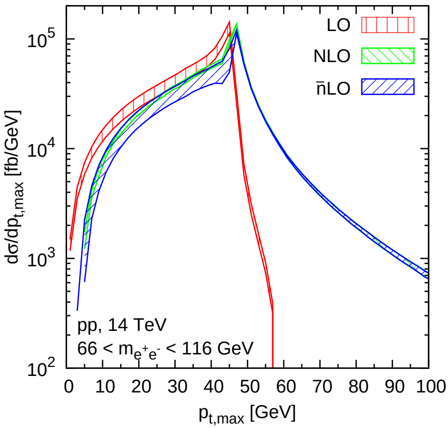
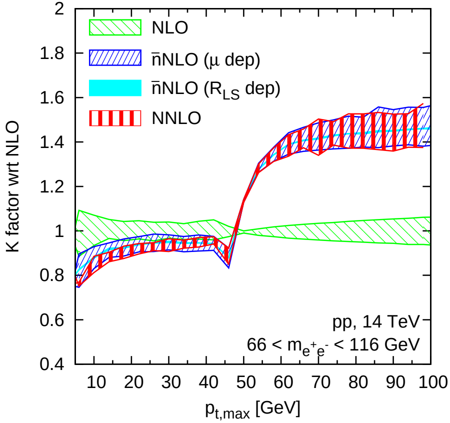
$\bar{n}$LO v. NLO



$\bar{n}$NLO v. NNLO



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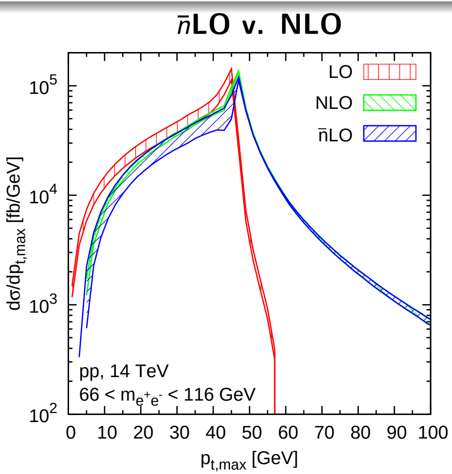

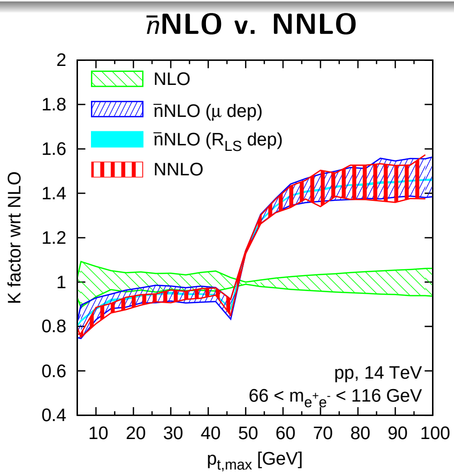

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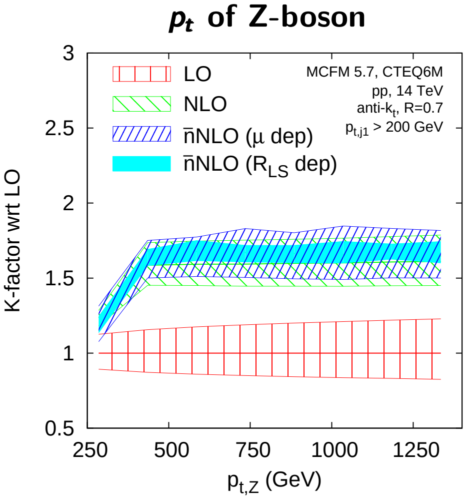
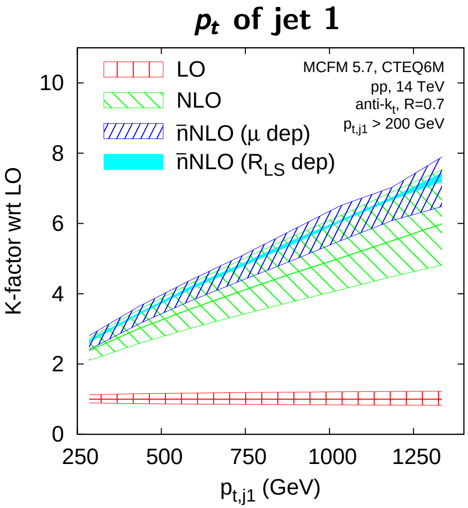
$\bar{n}$NLO for Z+j observables



- p_{tZ} distribution didn't have giant K-factors.
- $\bar{n}$NLO brings no benefit

  To get improvement you would need exact 2-loop terms

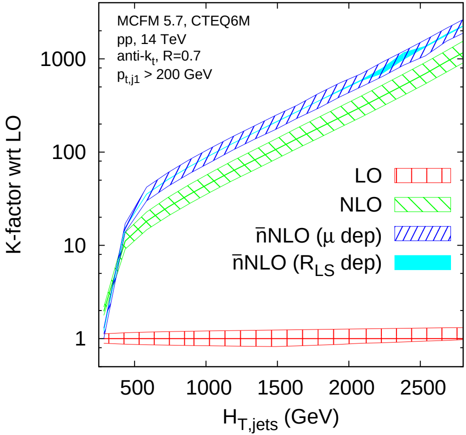
$\bar{n}$NLO for Z+j observables



- p_{tj} distribution seems to converge at $\bar{n}$NLO
- scale uncertainties reduced by $\sim$ factor 2

$\bar{n}$NLO for Z+j observables

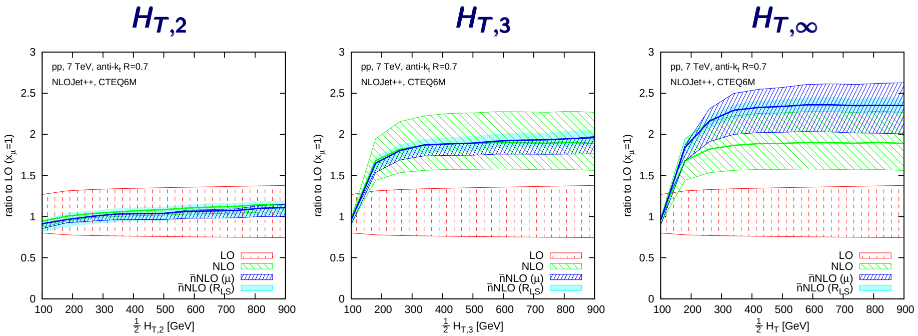
$$H_{T,jets} = \sum_{jets} p_{t,j}$$



- Signficiant further enhancement for $H_{T,jets}$
- $\bar{n}$NLO brings clear message:

$H_{T,jets}$ is not a good observable!

$H_{T,n}$ in (di)jet events



A clear message:

for a process with n objects at lowest order, use $H_{T,n}$

Do you know what gets used in your experiment's searches?
Many writers of LHC SUSY proceedings didn't...

LoopSim status

LoopSim, as it stands, should work for processes with zero or one vector bosons and any number of jets. Not yet public:

- Interfaces to MCFM and NLOJet++ required more (or less) hacking

  and then very long run times
- Let us (Sebastian Sapeta, GPS) know if you need predictions

Giant K factors are present in many contexts beyond those shown here, and may be directly relevant in searches

e.g. with $V\gamma$ backgrounds

- You can check for giant K factors, by comparing LO & NLO
- Watch out for how H_T is defined in searches:

  Rule of thumb(?): H_T should sum over all non-jet objects and at most as many jets as are present in the signal

Another “side-effect” of having $\sqrt{s} \gg M_{EW}$:

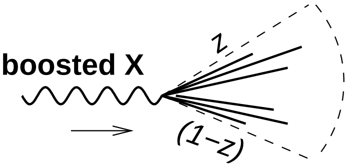
Hadronically decaying boosted Z/W/H/tops
a.k.a. Fat Jets

What’s new?

a number of recent papers — more than can be reviewed here

Boosted massive particles, e.g.: EW bosons

Hadronically decaying EW boson at high $p_t \neq$ two jets

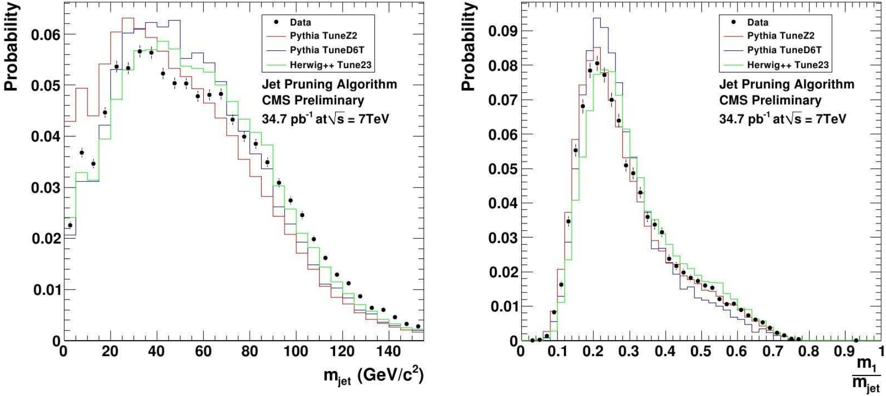


$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

Rules of thumb: $m = 100$ GeV, $p_t = 500$ GeV

- $R < \dfrac{2m}{p_t}$: always resolve **two** jets $R < 0.4$
- $R \gtrsim \dfrac{3m}{p_t}$: resolve **one** jet in 75% of cases $(\frac{1}{8} < z < \frac{7}{8})$ $R \gtrsim 0.6$

Part of the news is from CMS



Important: confirms general MC reliability for background predictions in this hitherto relatively untested region.

Interesting Herwig++ does remarkably well

Part of the news is from CDF / Eshel et al.

Looking for 2 “top” jets:

- each with $130 < m < 210$ GeV
- leading one with $p_t > 400$ GeV

Expected $t\bar{t}$	3 ± 0.8
Expected background	11 ± 4.6
Observed	30

CDF also sees an excess
in tri-jet mass for 6-jet events

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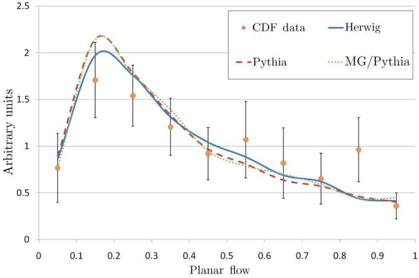
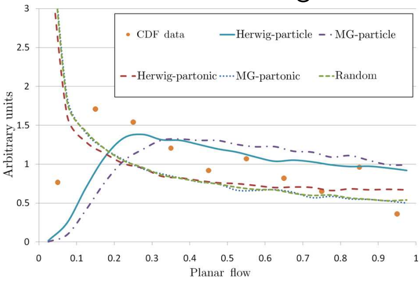
Diagnostic: a jet shape variable, **planar flow**

Planar flow data v. QCD



Planar flow data v. gluino



Other work → improving the methods

- Using matrix-element methods for the substructure Done analytically
  Soper & Spannowsky '11
  Most "physically interesting"

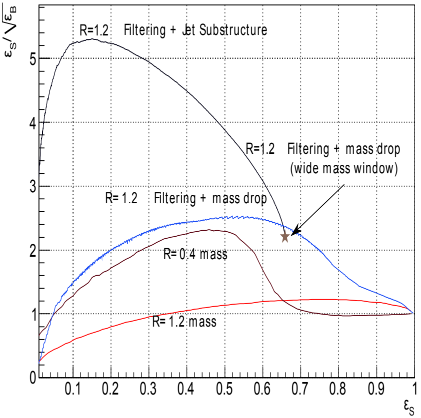
- Using jet shapes. E.g. subjettiness: break a jet into subjets $1, 2, \ldots N$

$$S_N = \frac{1}{p_t} \sum_i p_{ti} \min(\delta R_{i1}, \ldots \delta R_{iN})$$

J-H Kim '10; Thaler & Van Tilburg '10

- Using boosted decision trees
  Cui, Han & Schwartz '10; seems powerful

Cui et al BDT v. BRDS



Biggest improvements are to be had at moderate signal efficiencies

Conclusion from Boost 2010 comparison study of top taggers
The method to be adopted depends on the signal efficiency you want

Pileup

high p_t → requires high lumi → high pileup

28/03/2011 LHC 8:30 meeting

2011 Records

3.5 TeV

Items in red are records set in the past week

Peak Stable Luminosity Delivered	2.49×10^{32}	Fill 1645	11/03/22, 17:12
Maximum Peak Events per Bunch Crossing	13.08	Fill 1644	11/03/22, 02:20
Maximum Average Events per Bunch Crossing	8.93	Fill 1644	11/03/22, 02:20

$\gtrsim$ 10 events per bunch crossing

$\mathcal{O}\,(10\text{ GeV})$ of extra p_t per jet, with large fluctuations

Subtracting noise from jets

$$p_{t,jet}^{\text{subtracted}} = p_{t,jet} - \rho \times A_{jet}$$

Cacciari, GPS & Soyez '08

$$A_{jet} = \text{jet area}$$

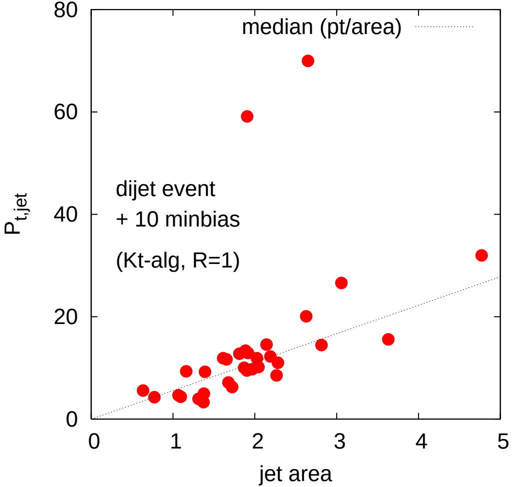
$\rho = p_t$ per unit area from pileup
(or "background")

This procedure is intended to be common to pp ($\rho \sim 1-2$ GeV), pp with pileup ($\rho \sim 2-15$ GeV) and Heavy-Ion collisions ($\rho \sim 100-300$ GeV)

As proposed so far: jet-by-jet area determination,
event-by-event ρ determination

Event-by-event ρ (background) estimation

IN A SINGLE EVENT



Most jets in event are "background"

Their p_t is correlated with their area.

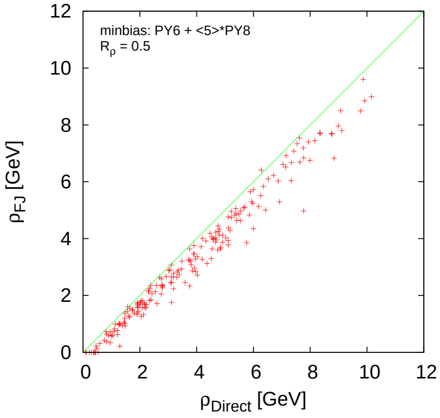
Estimate ρ:

$$\rho \simeq \underset{\{jets\}}{\text{median}} \left[\frac{p_{t,jet}}{A_{jet}} \right]$$

Median limits bias from hard jets
Cacciari & GPS '07

Comparing pileup estimation methods

Compare FastJet median ρ to Monte Carlo truth (ρ_{Direct})



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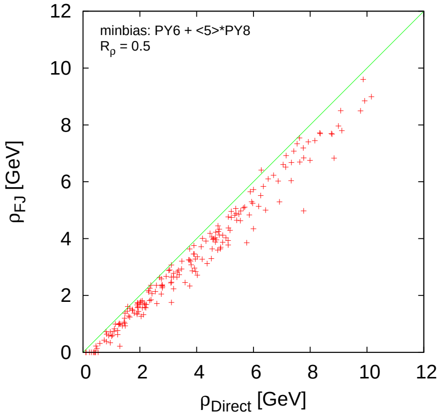
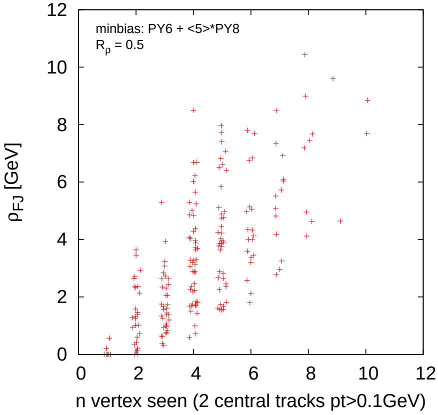


Works much better than counting primary vertices



A non-trivial issue: rapidity dependence

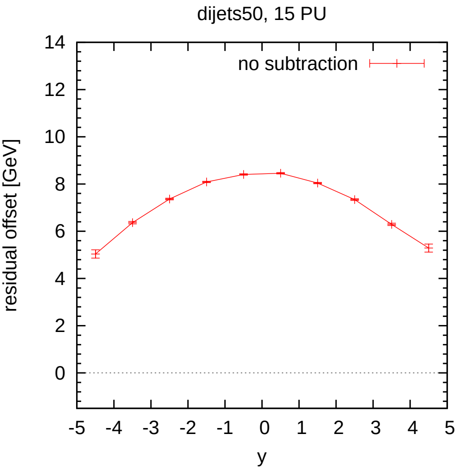
The original method assumed rapidity dependence was small

- In some sense it is, $\lesssim 1.5$ GeV
- Measure ρ globally, and include a rapidity-dependent rescaling

$$p_t^{sub} = p_t - f(y)\rho A$$

determine $f(y)$ from min-bias

- Measure ρ "locally" in strips of $|\Delta y| < 1.5$



Conclusion: global ρ determination with fixed rapidity-dependent rescaling is probably the most effective choice

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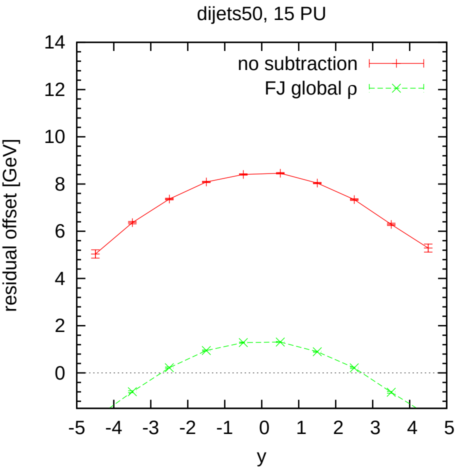

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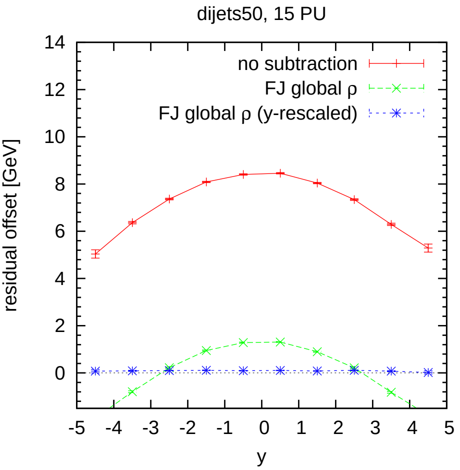

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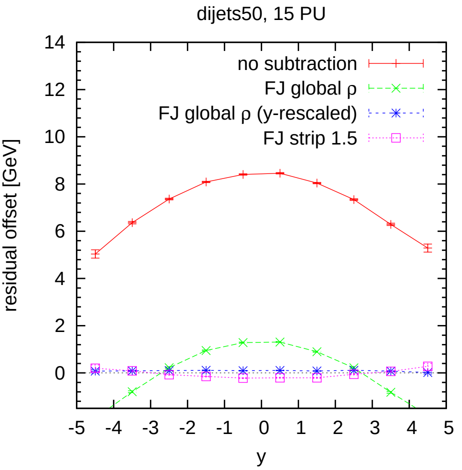

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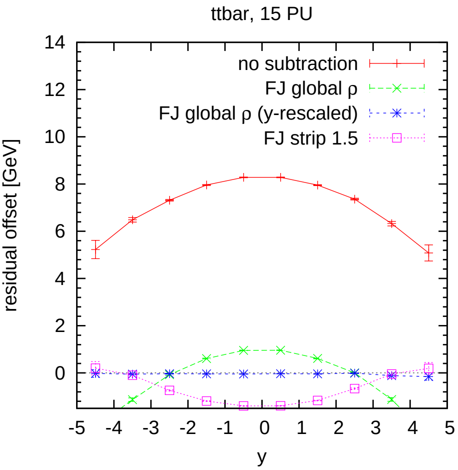

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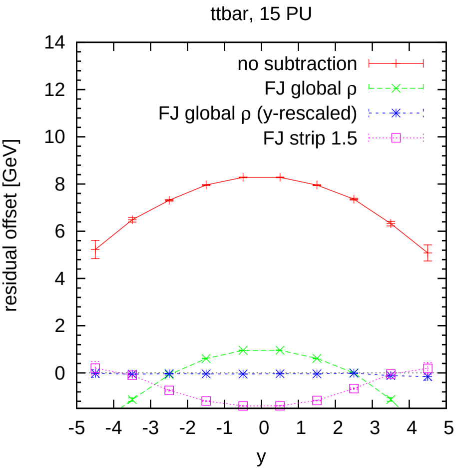

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Hints from charged tracks

Dispersion of offset gives another measure of the subtraction "quality"

- several GeV without subtraction
- only partially reduced with FJ subtraction
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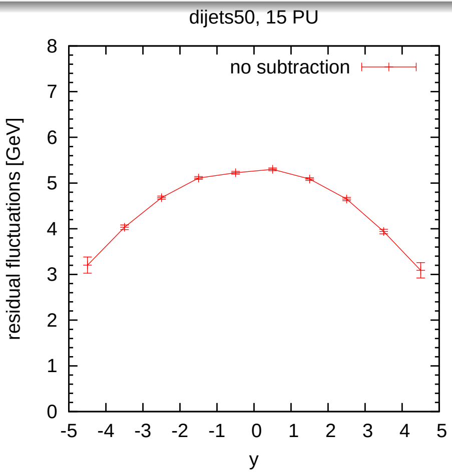
  if PU is in-time
  - scaling PU charged track in the jet to correct also for neutrals



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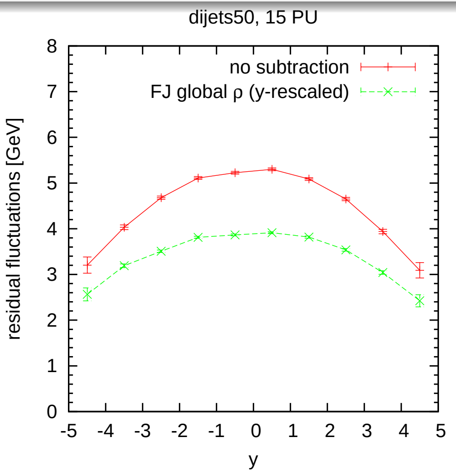

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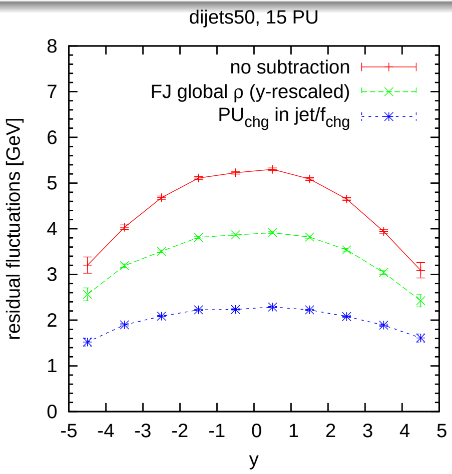

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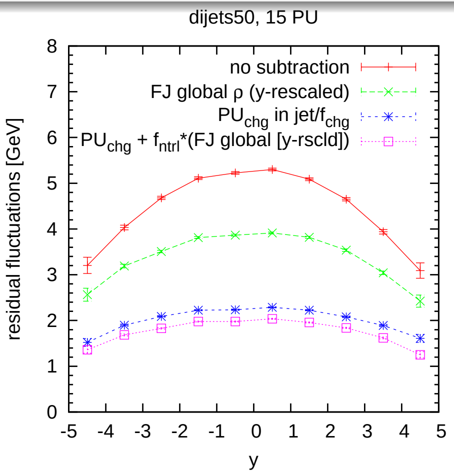

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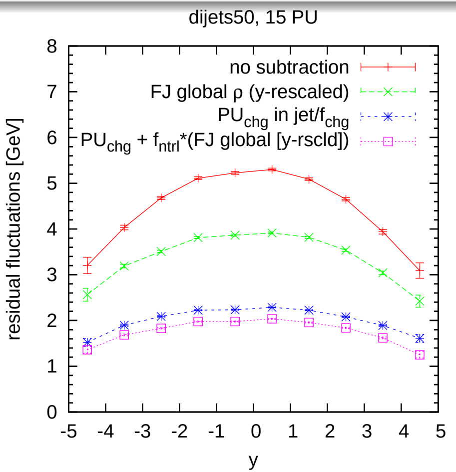

Direct knowledge of PU from tracks can be beneficial

Detector impact harder to judge

Jet masses etc.?

Fat-jet studies need more than just the jet p_t. E.g. **jet mass**

There are methods to limit PU sensitivity of jet masses.

Filtering: Butterworth et al '08
Pruning: Ellis et al '09
Trimming: Thaler et al '09

4-vector subtraction can also help

$$p_\mu^{(sub)} = p_\mu - f(y)\rho A_\mu$$

"Automatically" corrects mass
as long as hadron masses set to zero

Many more things can be corrected for PU beyond jet p_t
Tests are still in v. early stages / drawing board

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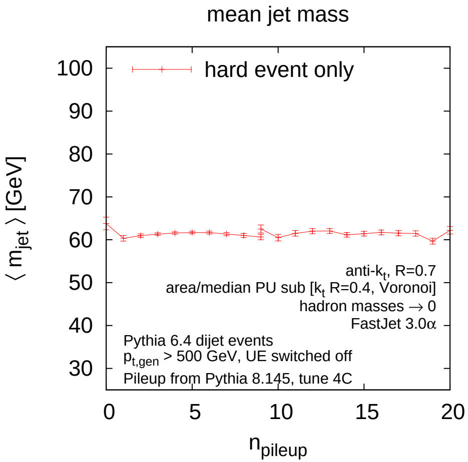

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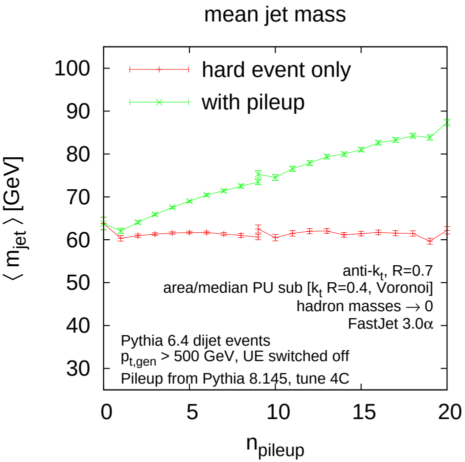

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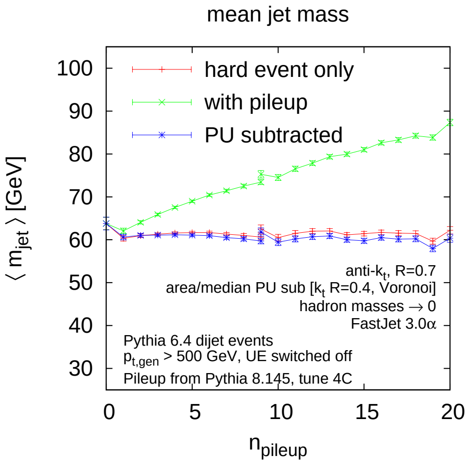

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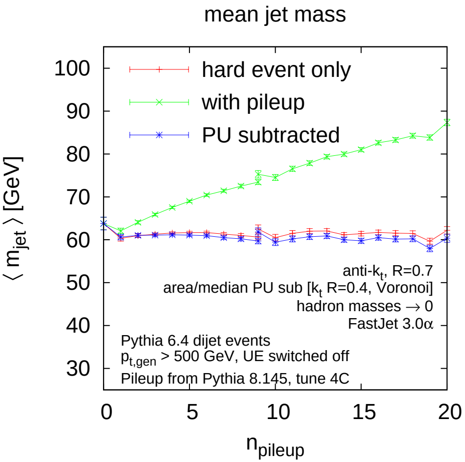

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Conclusions

As we (you!) explore beyond the electroweak scale, our way of thinking about W/Z/H/top needs to evolve

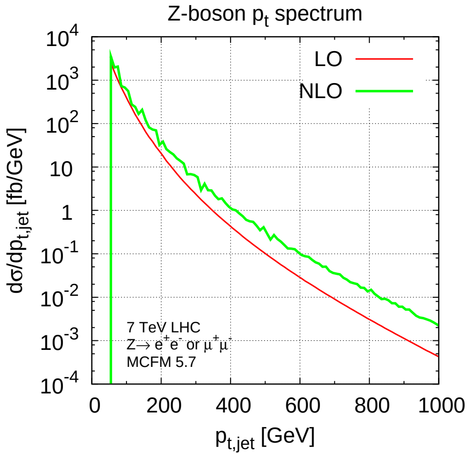
Particles that used to be heavy suddenly become light — EW symmetry is almost restored

As a result W/Z/H/top are easier to produce
And their decays look almost like QCD jets

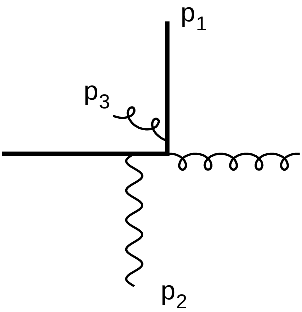
Yet even at the TeV scale, GeV-scale pileup physics matters, but can be corrected for

EXTRAS

giant K-factor at $\sqrt{s} = 7$ TeV



The LoopSim idea: $\bar{n}$LO



Z + 2 partons

$$|M^2(p_1, p_2, p_3)|$$

- Identify softest or most collinear parton [with help of a jet algorithm]
- "Loop" it ≡ remove it from event, reshuffle other momenta; weight of looped event is $(-1)\times$ weight of tree-level event

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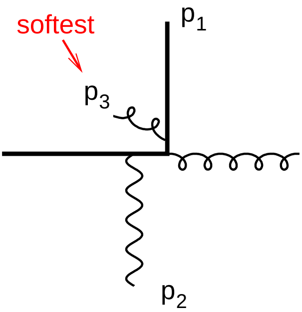

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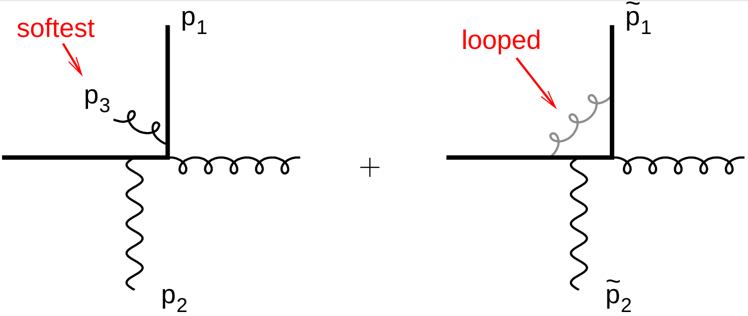

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Z + 1 parton + 1 sim. loop

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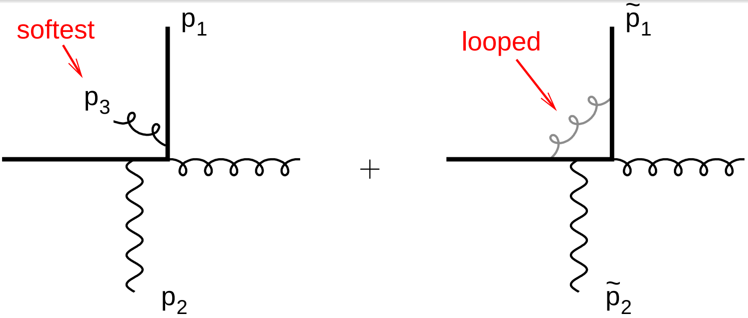

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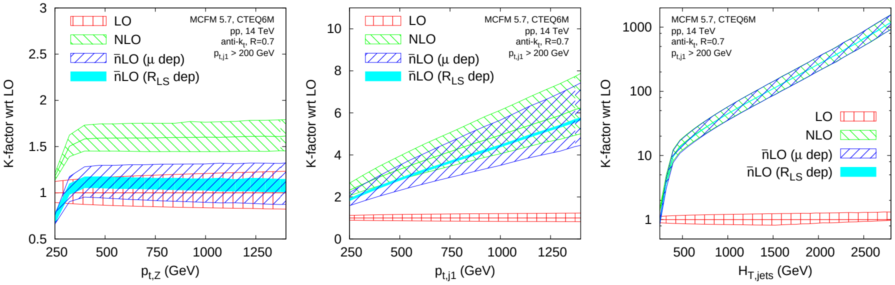
This cancels all the "single-unresolved" divergences in the Z+2 events

$\bar{n}$LO results (K-factors, normalised to LO)

p_t of Z-boson | p_t of jet 1 | $H_{T,jets} = \sum_{jets} p_{t,j}$

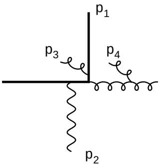


When the K-factors are large, $\bar{n}$LO agrees well with NLO

MLM matching also does a similar job
cf. de Aquino, Hagiwara, Li & Maltoni '11

LoopSim at $\bar{n}\bar{n}$LO and $\bar{n}$NLO

add tree-level Z+3,
cancel divergences in single + doubly unresolved limits: **$\bar{n}\bar{n}$LO**



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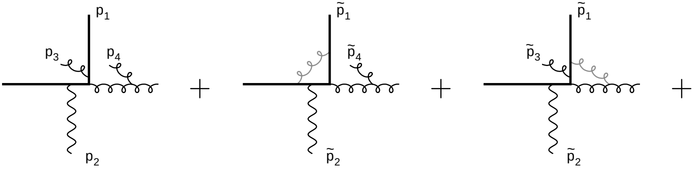

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Separately loop either of the 2 softest emissions: provides approx of 1-loop

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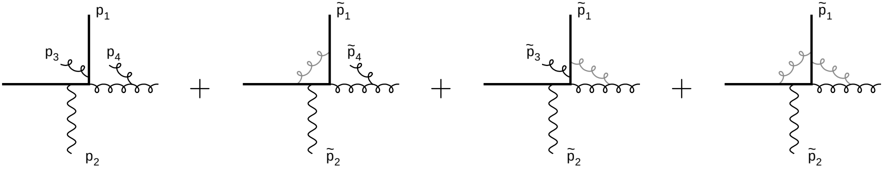

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Simultaneously loop each of the 2 softest emissions: provides approx of 2-loop
Total of tree plus approx 1- and 2-loop pieces gives zero

LoopSim at $\bar{n}\bar{n}$LO and $\bar{n}$NLO

add tree-level Z+3,
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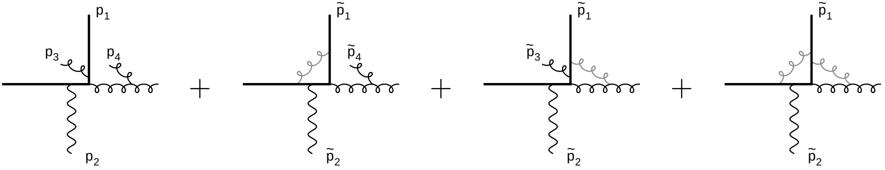

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Total of tree plus approx 1- and 2-loop pieces gives zero

add in (exact Z+2 @ 1-loop) − (approximate Z+2 @ 1-loop)
+ extra simulated 2-loop piece to cancel new Z+2@1-loop divergences
This is $\bar{n}$NLO

Expected accuracy of $\bar{n}$NLO

The 2-loop piece has the topology of the LO diagram.

The "mistake" we make in approximating it should therefore be a "pure" $\mathcal{O}(\alpha_s^2)$ correction, without any large enhancements from new NLO type topologies.

$$\sigma_{\bar{n}\text{NLO}} = \sigma_{NNLO} + \mathcal{O}\left(\alpha_s^2 \sigma_{LO}\right)$$
$$= \sigma_{\text{NNLO}} \left(1 + \mathcal{O}\left(\frac{\alpha_s^2}{K_{\text{NNLO}}}\right)\right)$$

$$K_{\text{NNLO}} = \frac{\sigma_{\text{NNLO}}}{\sigma_{\text{LO}}} \sim K_{\text{NLO}} \gg 1$$

The *relative* contribution of the neglected piece is suppressed by the large K-factor.

$\bar{n}$NLO should be a good approximation to NNLO when the K-factor is large and due to new higher-order topologies.