Giant K factors

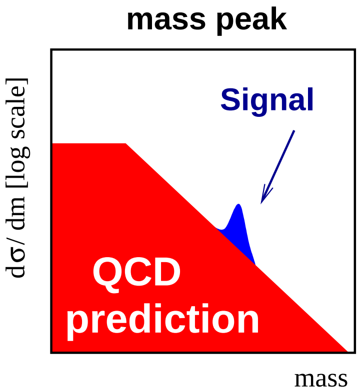
Gavin Salam

CERN, Princeton & LPTHE/CNRS (Paris)

Work performed with Mathieu Rubin and Sebastian Sapeta, arXiv:1006.2144

Fermilab Theory Seminar
19 May 2011

What kinds of searches at colliders?



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- swamp signal
- smear signal

leptonic case easy; hadronic case harder

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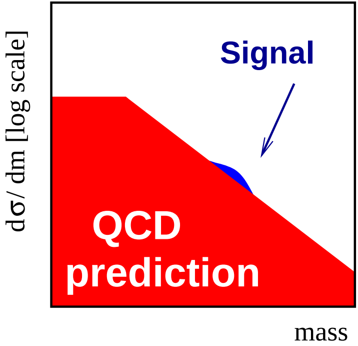

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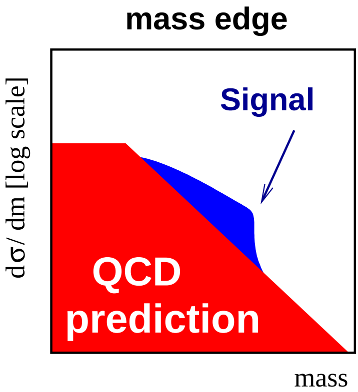

New resonance (e.g. R-parity conserving SUSY), where undetected new stable particle escapes detection.

Reconstruct only *part* of an invariant mass $\rightarrow$ kinematic edge.

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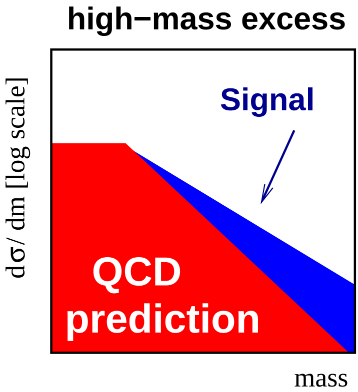
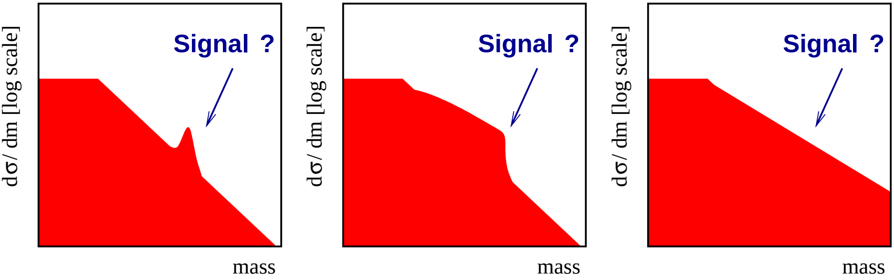


Unreconstructed SUSY cascade. Study *effective* mass (sum of all transverse momenta).

Broad excess at high mass scales.

Knowledge of backgrounds is crucial is declaring discovery.

QCD is *one way* of getting handle on background.


Signal ?
dσ/ dm [log scale]
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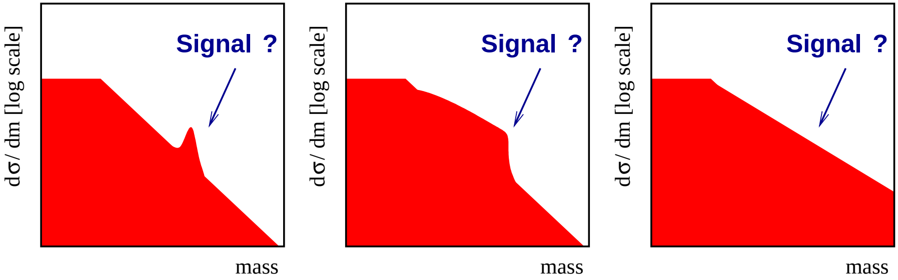
THIS
TALK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THIS TALK

SUSY example: gluino pair production

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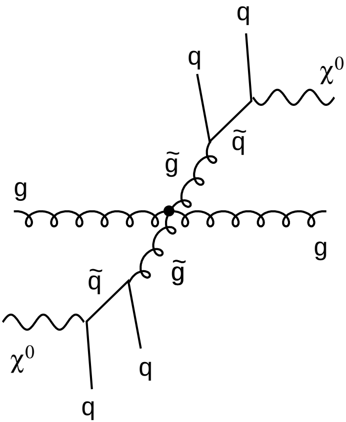

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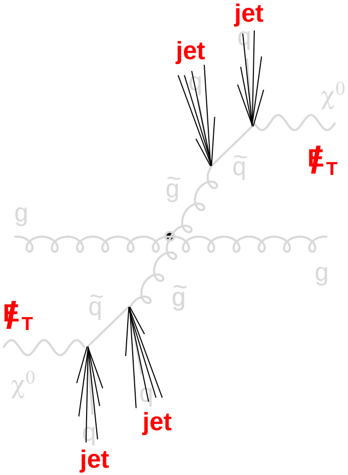

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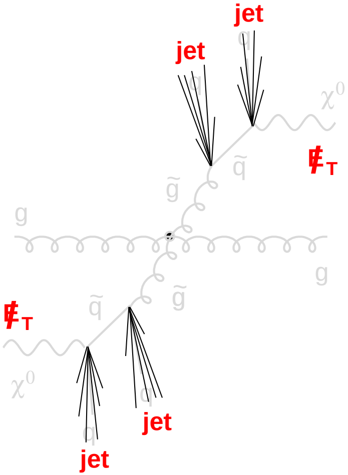
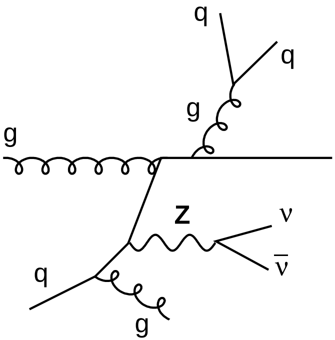


Background



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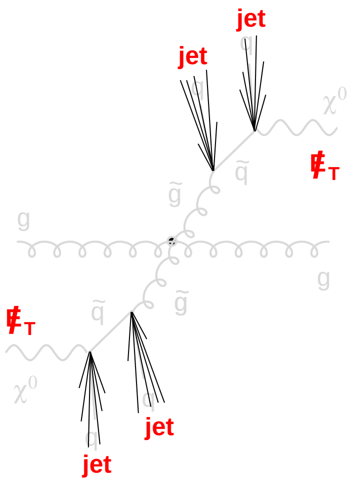

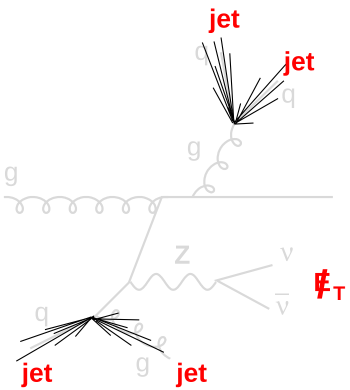

SUSY searches: what excesses?

Atlas selection [all hadronic]

- no lepton
- MET > 100 GeV
- $1^{st}, 2^{nd}$ jet > 100 GeV
- $3^{rd}, 4^{th}$ jet > 50 GeV
- MET / m_{eff} > 20%

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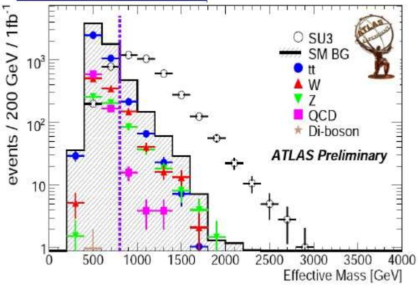

CMS selection [leptonic incl.]

(optimized for 10fb⁻¹, using genetic algorithm)

- 1 muon pT > 30 GeV
- MET > 130 GeV
- $1^{st}, 2^{nd}$ jet > 440 GeV
- 3^{rd} jet > 50 GeV
- $-0.95 < \cos(\mathrm{MET}, 1^{st}\mathrm{jet}) < 0.3$
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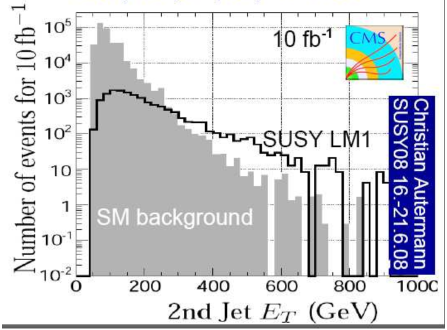

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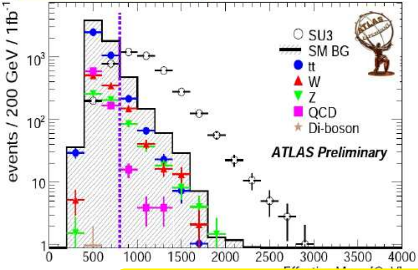

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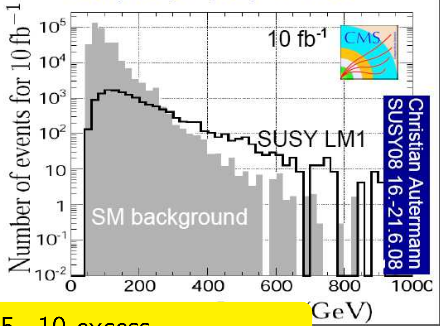

SUSY $\simeq$ factor 5$-$10 excess

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 talk is about an example where these rules fail spectacularly, the lessons we learn, and the solutions we can apply.

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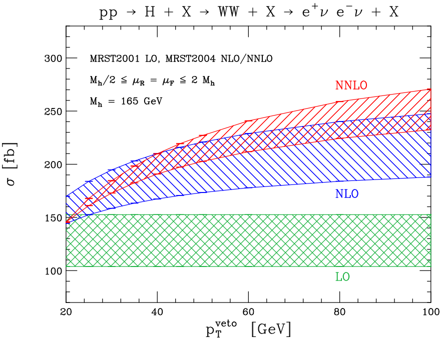

Anastasiou, Melnikov & Petriello '04
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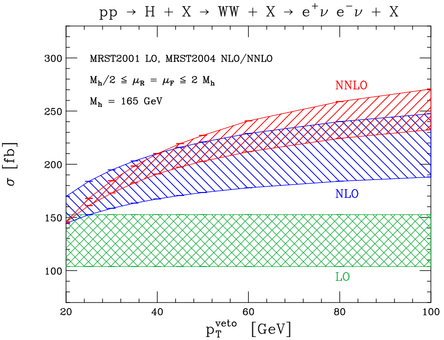

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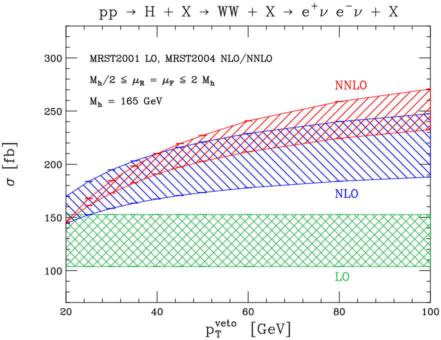

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Control samples

We don't always have NLO for the background (e.g. Z+4 jets, a $2 \to 5$ process).

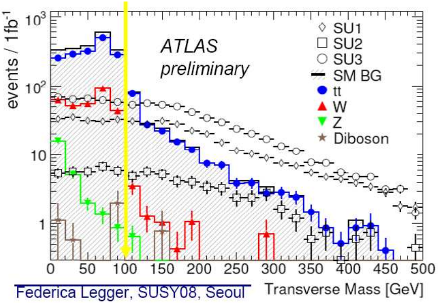
Though amazing recent progress
$2 \to 4$: Blackhat, Rocket, Helac-NLO, BDDP
$2 \to 5$ (W+4j): Blackhat

Must then rely on LO (matched with parton showers). How does one verify it?

Common "data-driven" procedure:

[roughly]

- Get control sample at low p_t
- SUSY should be small(er) contamination there
- Once validated, trust LO prediction at high-p_t



Is this safe?

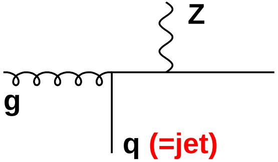
A conservative QCD theory point of view:

It's hard to be sure: since we can't (yet) calculate Z+4 jets beyond LO.

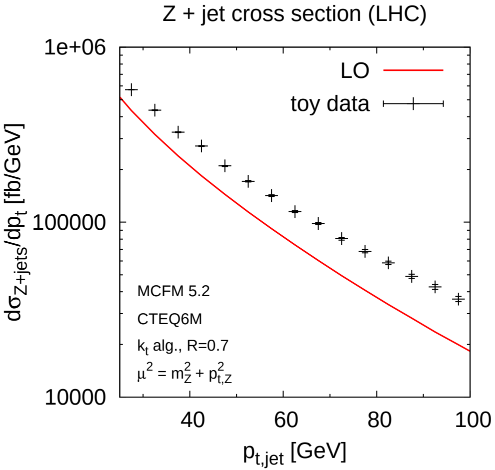
But we would tend to think it is safe, as long as control data are within usual factor of two of LO prediction

Illustrate issues with toy example: Z+jet production

- It's known to NLO — and a candidate for "first" $2 \to 2$ NNLO
  $\sim e^+e^- \to \gamma^*/Z \to 3$ jets, NNLO: Gehrman et al '08, Weinzierl '08
- But let's pretend we only know it to LO, and look at the p_t distribution of the hardest jet (no other cuts — keep it simple)



Toy data, control sample



stage 1: get control sample

Check LO v. data at low p_t

- normalisation off by factor 1.5 (consistent with expectations)

  So renormalise LO by K-fact

- shape OKish

  Don't be too fussy: SUSY could bias higher p_t

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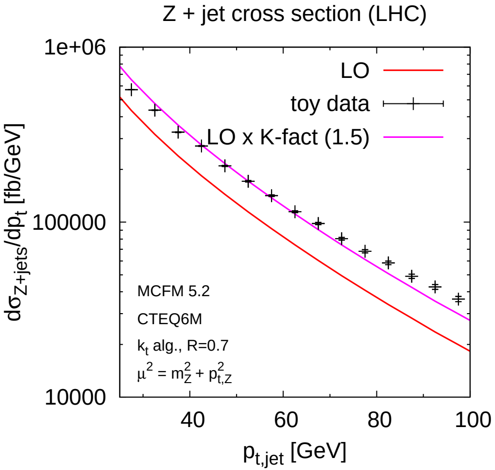

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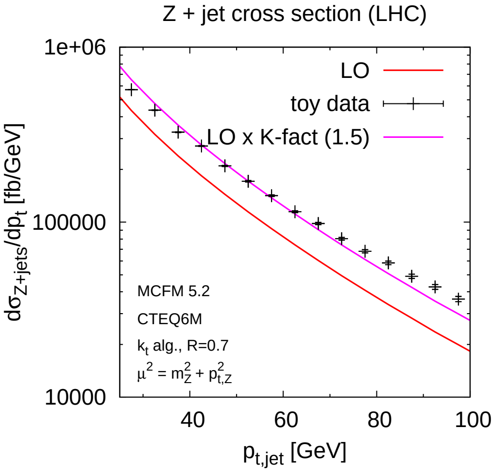

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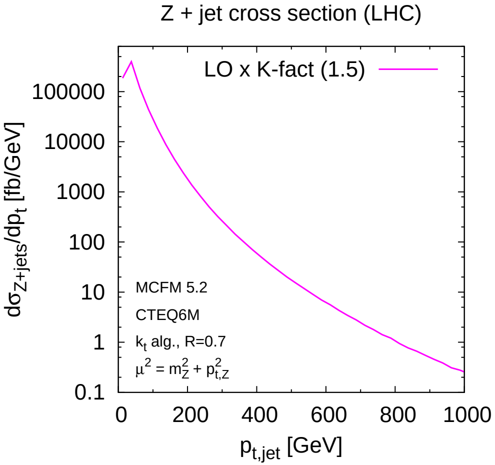

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- good agreement at low p_t, by construction
- excess of factor ~ 10 at high p_t
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[NB: not always done except e.g. Alwall et al. 0706.2569]
still big excess

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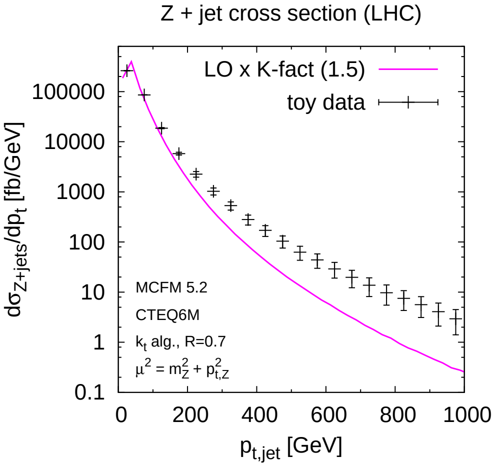

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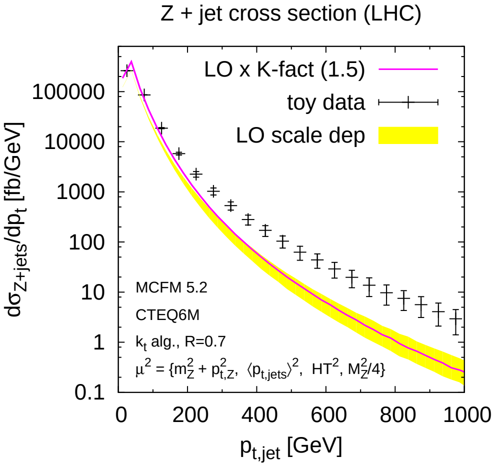

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What's in the toy data?

Is it:

- QCD + extra signal?
- just QCD? But then where does a K-factor of 10 come from?

Here it's just a toy illustration. Later this year it may be for real:

- Do Nature / Science / PRL accept the paper?

  Discovery of New Physics at the TeV scale

  We report a 5.7σ excess in MET + jets production that is consistent with a signal of new physics . . .

- Do we proceed immediately with a linear collider?

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- At what energy? It would be a shame to be locked in to the wrong energy. . .

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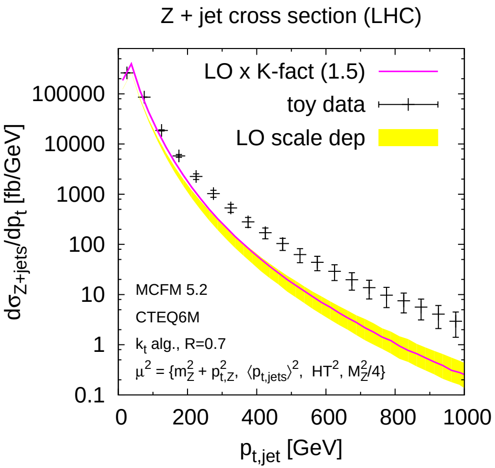

Unlike for SUSY multi-jet searches, in the Z+jet case we do have NLO.

Once NLO is included the excess disappears

The "toy data" were just the upper edge of the NLO band

Example based on background work for Butterworth, Davison, Rubin & GPS '08

Related observations also by Bauer & Lange '09; Denner, Dittmaier, Kasprzik & Muck '09

Hold on a second: how does QCD give a K-factor $\mathcal{O}(5-10)$*?*

NB: DYRAD, MCFM consistent

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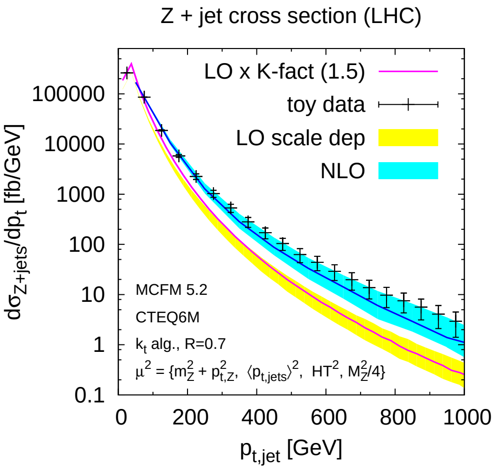

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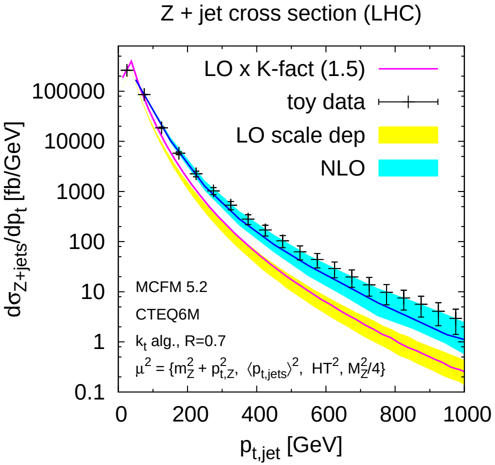

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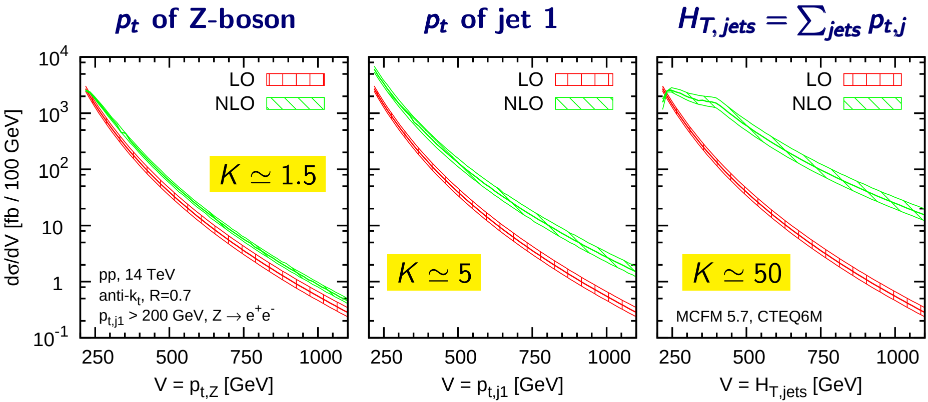
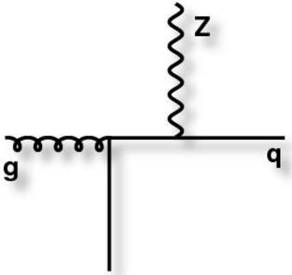
What about other observables?



"Giant K-factors"

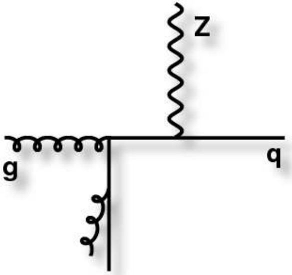
Why the large K-factor?

Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order



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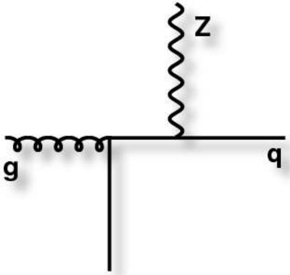

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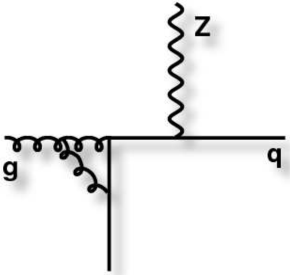

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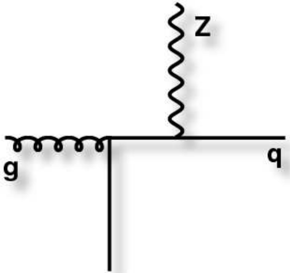

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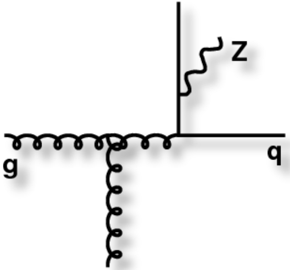

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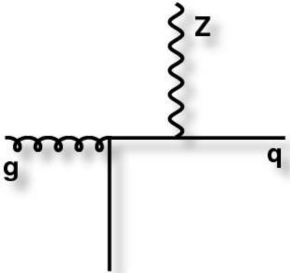

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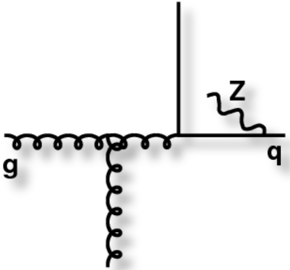

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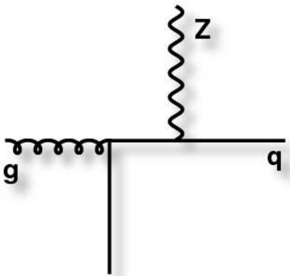

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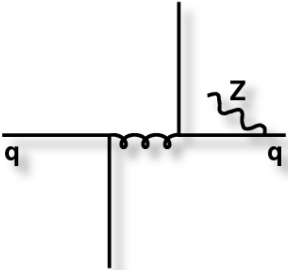

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NLO driven in part by qq parton luminosity: large at pp colliders

Is this example not a little contrived?
After all, experiments would surely notice unexpected event topology such as that here.

We actually first saw the problem in a more complex process: $Wb\bar{b}$ as a background to boosted Higgs searches (with “wrong” cuts). *The more complicated the process, the trickier the diagnosis of the problem.*

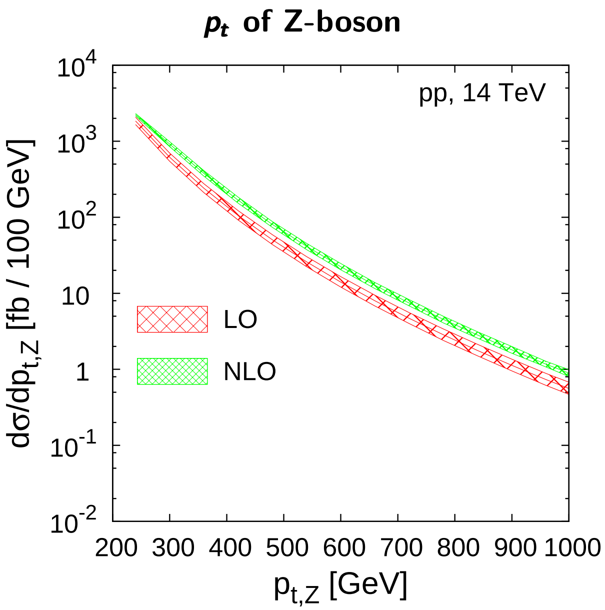
It’s enough to get this wrong once, leading to “unwarranted” press-releases and major subsequent embarassment.

In day-to-day work the experiments don't just use LO.

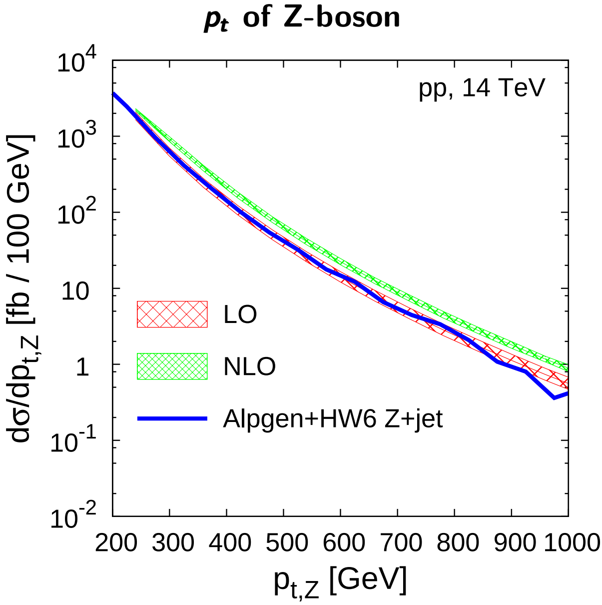
Instead, they

- Take Z + jet, Z + 2 jet samples, etc.,
- Attach a parton shower to each of them
- and combine with procedures such as MLM matching or CKKW matching.

Testing Alpgen + Herwig + MLM Matching

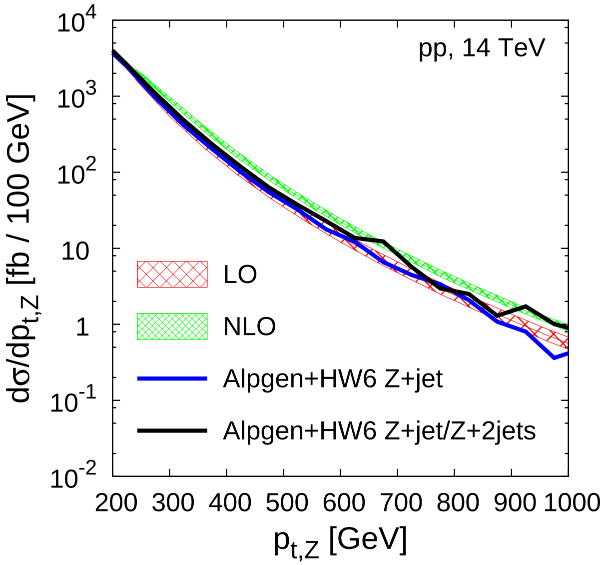


Testing Alpgen + Herwig + MLM Matching



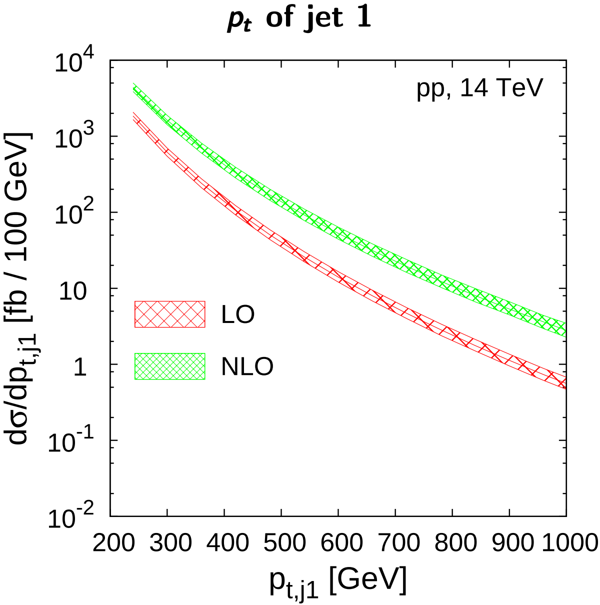
Testing Alpgen + Herwig + MLM Matching

p_t of Z-boson

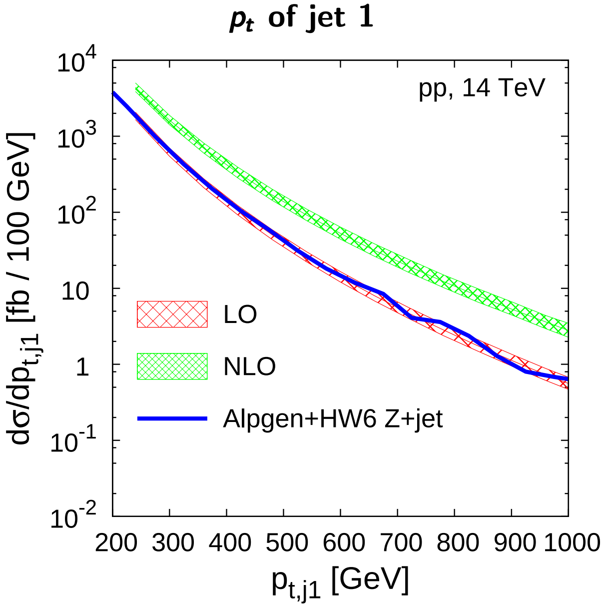


All predictions similar and stable

Testing Alpgen + Herwig + MLM Matching

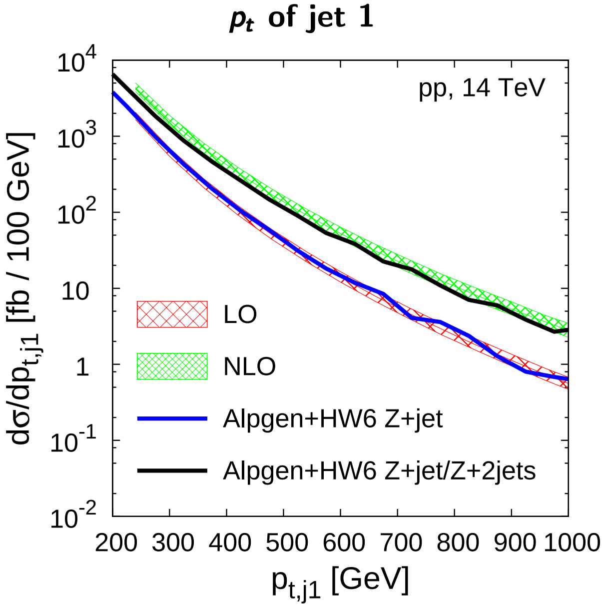


Testing Alpgen + Herwig + MLM Matching



Showered Z+j $\simeq$ LO

Testing Alpgen + Herwig + MLM Matching

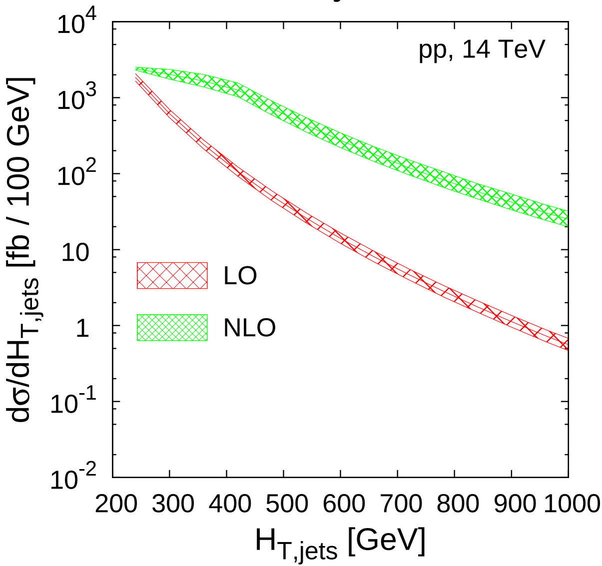


Showered Z+j $\simeq$ LO

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

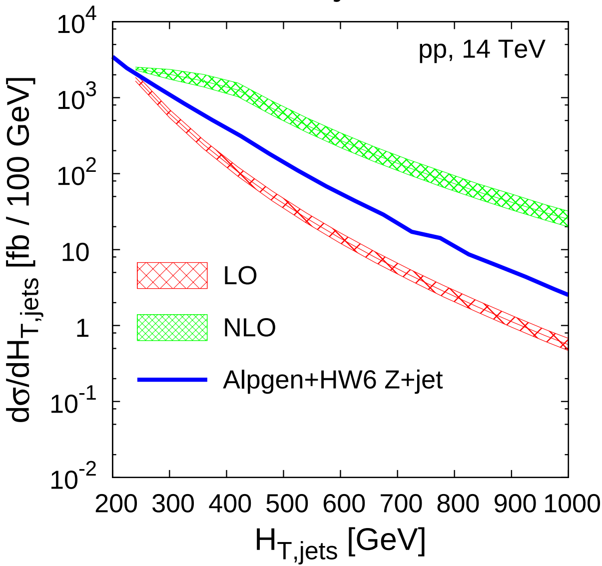
Testing Alpgen + Herwig + MLM Matching

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



Testing Alpgen + Herwig + MLM Matching

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

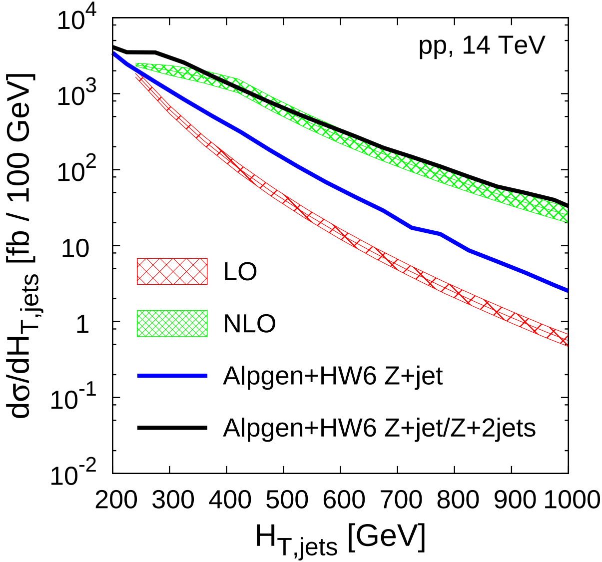


Showered Z+j $\neq$ LO

cf. also de Aquino, Hagiwara, Li & Maltoni '11

Testing Alpgen + Herwig + MLM Matching

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



Showered Z+j $\neq$ LO

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

cf. also de Aquino, Hagiwara, Li & Maltoni '11

It's great that (the widely-used) MLM/CKKW matching procedure correctly approximates the NLO giant K-factor.

But what happens at NNLO?

a natural question when LO $\rightarrow$ NLO convergence is poor

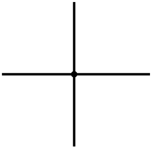
Despite 10 years' calculation, the answer is not yet known

Our strategy: get an *approximation* to NNLO

specifically, we will approximate a subset of the loop contributions, with a method dubbed "LoopSim"

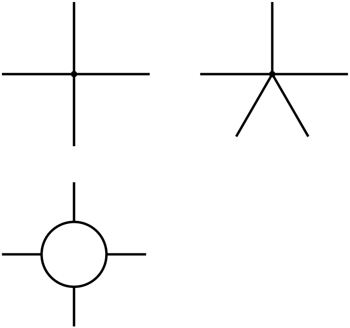
Ingredients of (N)NLO

LO



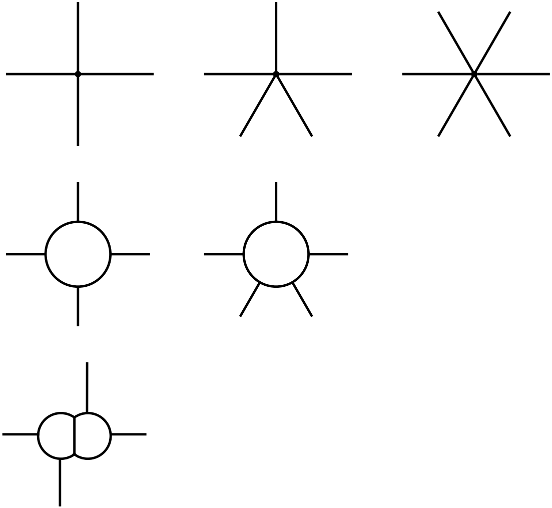
Ingredients of (N)NLO

NLO



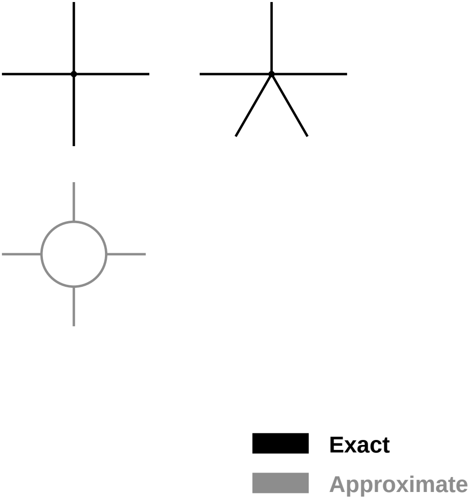
Ingredients of (N)NLO

NNLO



Approximations to (N)NLO

$\bar{n}$LO

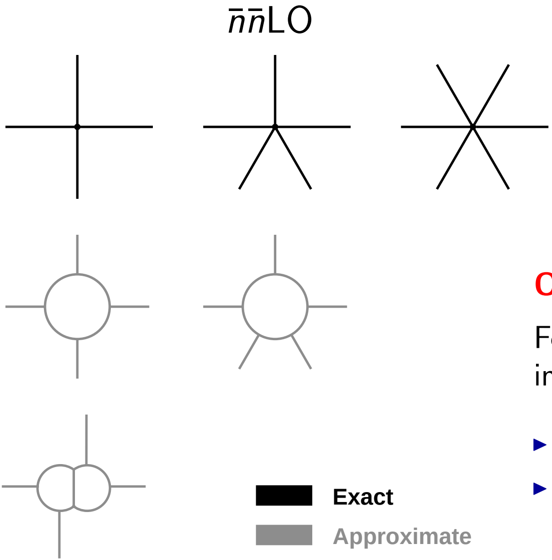


Our naming scheme:

For each loop that we approximate, replace N $\rightarrow \bar{n}$

- $\bar{n}$LO: approx 1-loop diagrams

Approximations to (N)NLO



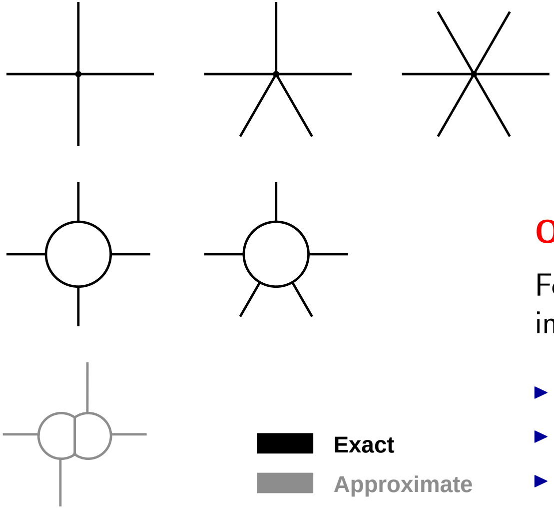
Our naming scheme:

For each loop that we approximate, replace N $\rightarrow \bar{n}$

- $\bar{n}$LO: approx 1-loop diagrams
- $\bar{n}\bar{n}$LO: approx 1- and 2-loops

Approximations to (N)NLO

$\bar{n}$NLO



Our naming scheme:

For each loop that we approximate, replace N $\to$ $\bar{n}$

- $\bar{n}$LO: approx 1-loop diagrams
- $\bar{n}\bar{n}$LO: approx 1- and 2-loops
- $\bar{n}$NLO: approx 2-loop only

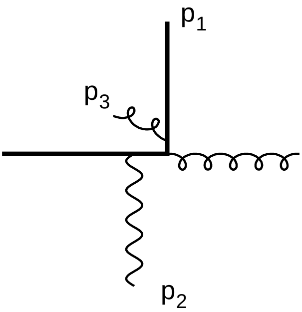
First try Z + jet @ $\bar{n}$LO:

Take the "leading" process
[Z + jet @ LO]

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

approximate the 1-loop Z+jet term, by requiring cancellation of all divergences
[those from singly unresolved limit of Z + 2 jets]

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

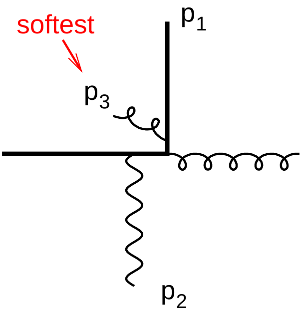


Z + 2 partons

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

- 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

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



Z + 2 partons

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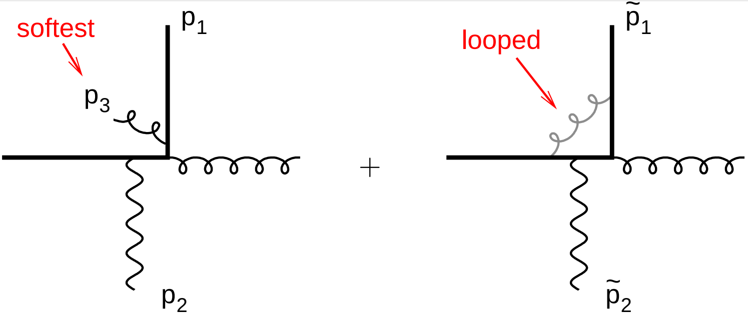
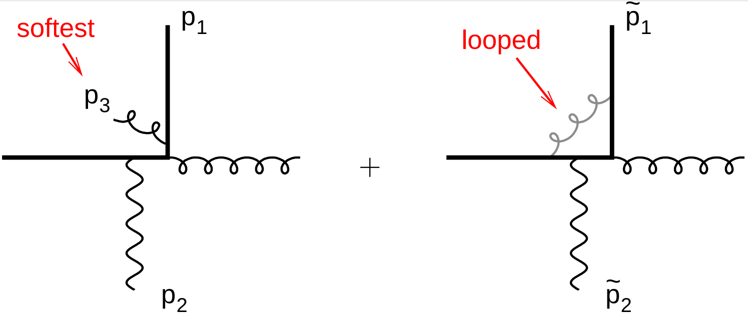
The LoopSim idea: $\bar{n}$LO



Z + 2 partons	**Z + 1 parton + 1 sim. loop**
$\lvert M^2(p_1, p_2, p_3)\rvert$	$-\lvert M^2(p_1, p_2, p_3)\rvert$

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

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



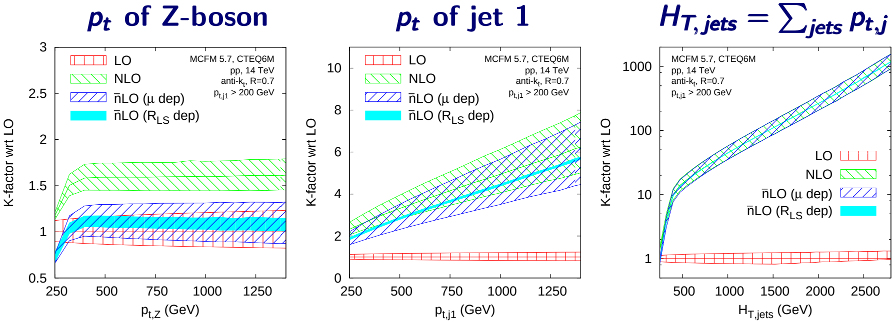
Z + 2 partons — $|M^2(p_1, p_2, p_3)|$

Z + 1 parton + 1 sim. loop — $-|M^2(p_1, p_2, p_3)|$

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

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

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



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

Works with similar “quality” to MLM matching

MLM/CKKW matching also effectively provide $\bar{n}$LO type accuracy

How dooes LoopSim compare to MLM/CKKW?

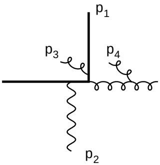
1. Does not rely on shower (✓: simplicity; ✗: not easily integrated with shower MCs)

2. Does not need arbitrary separation of Z+1/Z+2/etc. samples with (hard-to-choose) momentum cutoff

3. Can easily be extended beyond LO matching

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

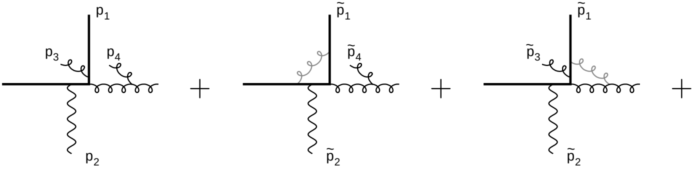
add tree-level Z+3,
cancel divergences in single + doubly unresolved limits: **$\bar{n}\bar{n}$LO**



$$|M^2(p_1, p_2, p_3, p_4)|$$

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**

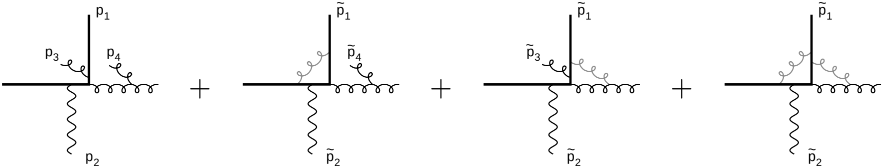


$$|M^2(p_1, p_2, p_3, p_4)| \qquad -|M^2(p_1, p_2, p_3, p_4)| \qquad -|M^2(p_1, p_2, p_3, p_4)|$$

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

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**

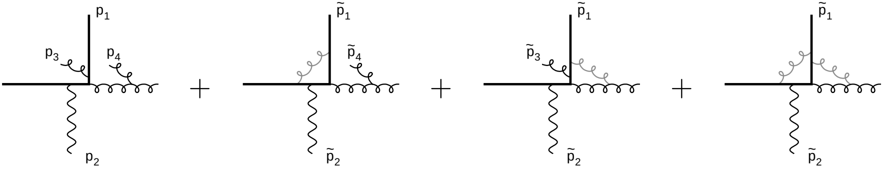


$|M^2(p_1, p_2, p_3, p_4)| \qquad -|M^2(p_1, p_2, p_3, p_4)| \qquad -|M^2(p_1, p_2, p_3, p_4)| \qquad +|M^2(p_1, p_2, p_3, p_4)|$

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,
cancel divergences in single + doubly unresolved limits: **$\bar{n}\bar{n}$LO**



$$|M^2(p_1, p_2, p_3, p_4)| \quad -|M^2(p_1, p_2, p_3, p_4)| \quad -|M^2(p_1, p_2, p_3, p_4)| \quad +|M^2(p_1, p_2, p_3, p_4)|$$

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

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.

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

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

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.

Testing $\bar{n}$NLO, in 3 processes

[making use of existing NLO calculations]

1. Z@NLO and Z+j@NLO $\rightarrow$ Z@$\bar{n}$NLO

   with MCFM; compare to exact NNLO from DYNNLO

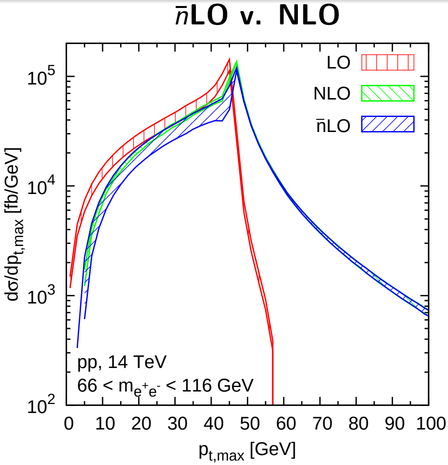
2. Z+j@NLO and Z+2j@NLO $\rightarrow$ Z+j@$\bar{n}$NLO

   with MCFM

3. 2j@NLO and 3j@NLO $\rightarrow$ 2j@$\bar{n}$NLO

   with NLOjet++

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

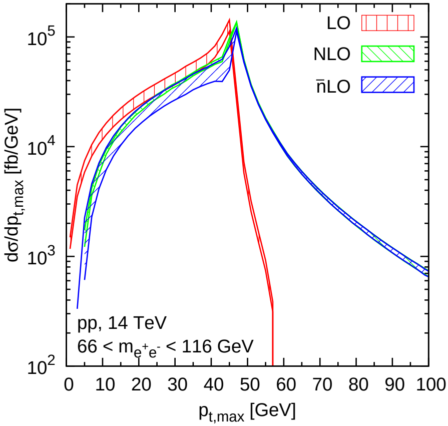


Z (i.e. DY) with Z+j from MCFM & LoopSim

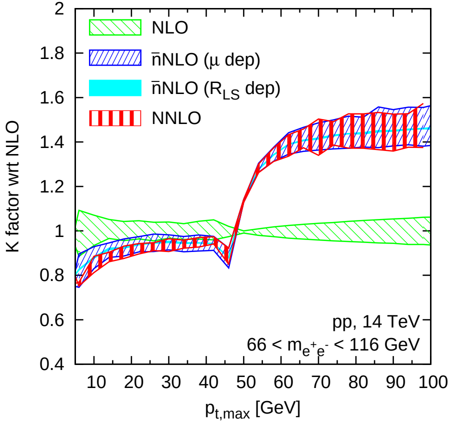
For $p_{t\,ell} \gtrsim \frac{1}{2}M_Z + \Gamma_Z$ (giant K-factor!) it had to work
For $p_{t,\ell} \lesssim \frac{1}{2}M_Z + \Gamma_Z$ it's remarkable that it still works

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

$\bar{n}$LO v. NLO



$\bar{n}$NLO v. NNLO

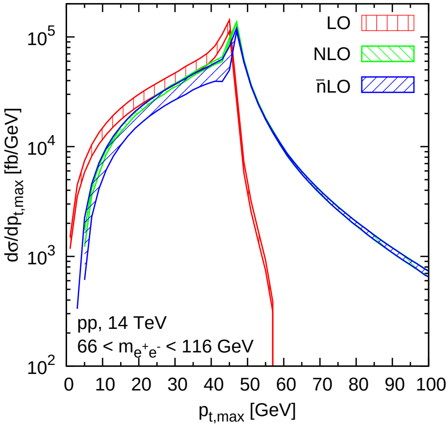


NNLO from DYNNLO, Z (i.e. DY) with Z+j from MCFM & LoopSim

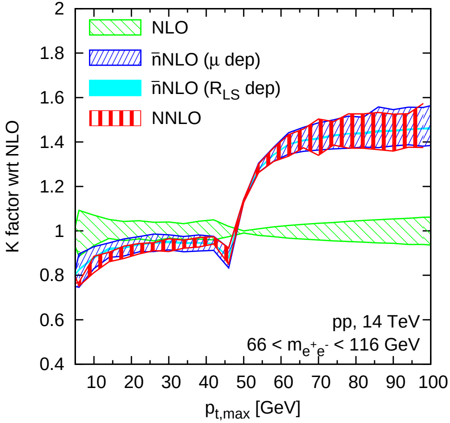
For $p_{t\,ell} \gtrsim \frac{1}{2}M_Z + \Gamma_Z$ (giant K-factor!) it had to work
For $p_{t,\ell} \lesssim \frac{1}{2}M_Z + \Gamma_Z$ it's remarkable that it still works

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

$\bar{n}$LO v. NLO



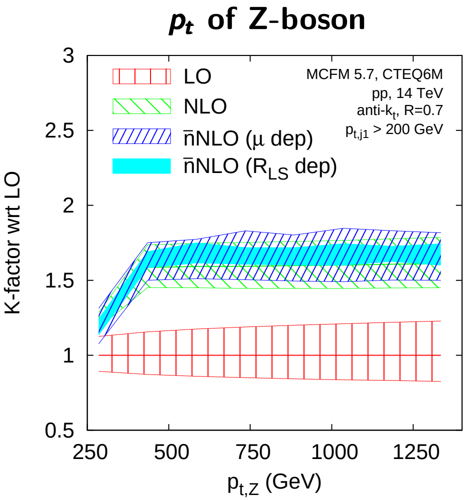
$\bar{n}$NLO v. NNLO



NNLO from DYNNLO, 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

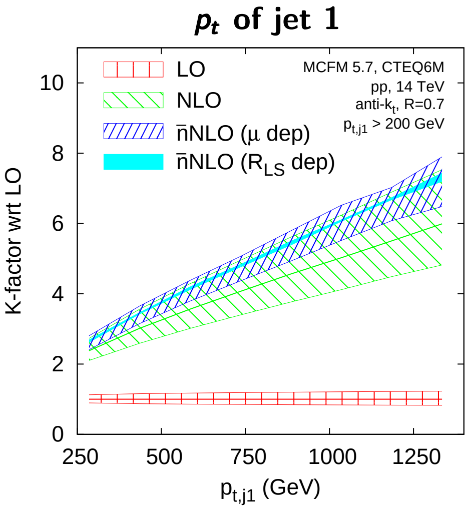
$\bar{n}$NLO for Z+j observables



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

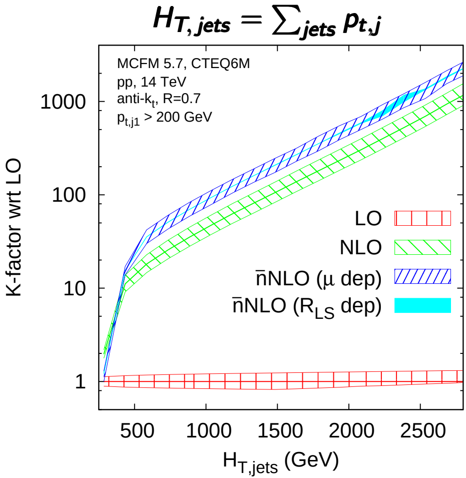
  To get improvement you would need exact 2-loop terms

$\bar{n}$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



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

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

What's the problem with H_T?

H_T (effective mass) type observables are widely used in searches

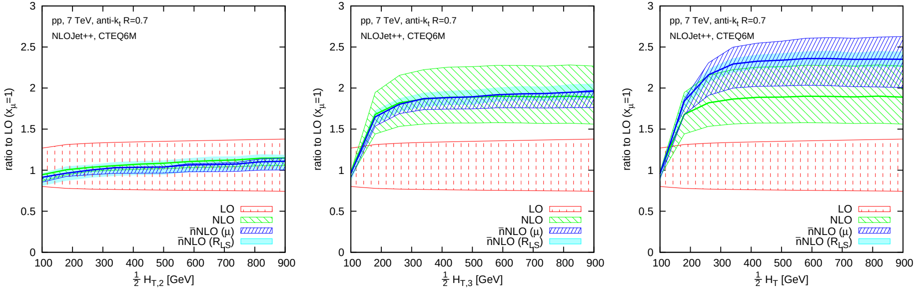
- H_T has a steeply falling distribution (like p_{tj}, p_{tZ})
- At each order (NLO, NNLO), an extra (soft) jet contributes to the H_T sum e.g. from ISR
- That shifts H_T up, which translates to a substantial increase in the cross section

We can test this hypothesis for plain jet events, using a truncated sum,

$$H_{T,n} = \sum_{i=1}^{n} p_{t,\text{jet}\,i}$$

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

$H_{T,2}$ **$H_{T,3}$** **$H_{T,\infty}$**



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?

Some take-home messages

Be aware that giant K-factors exist

Always look one order beyond the leading order, for example with MLM/CKKW matching

New tool to get good predictions in such cases: **LoopSim**

Basically an "operator" to generate approximations to unknown loops

Combine Z+j@NLO, Z+2j@NLO to get "$\bar{n}$NLO" Z+jet

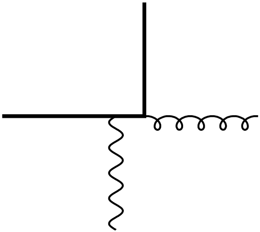
It sometimes works even beyond "giant-K-factor" regions

Watch out for H_T

Even for simple processes, it converges very poorly unless you define it carefully (limit number of objects in sum)

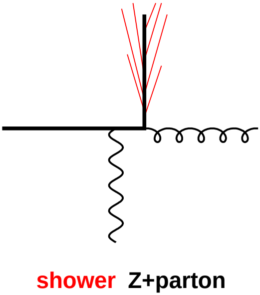
EXTRAS

Add Z+1jet, Z+2jet + shower

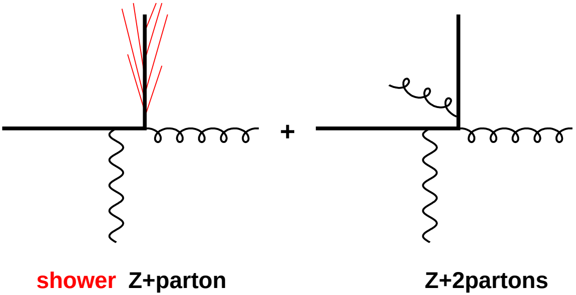


Z+parton

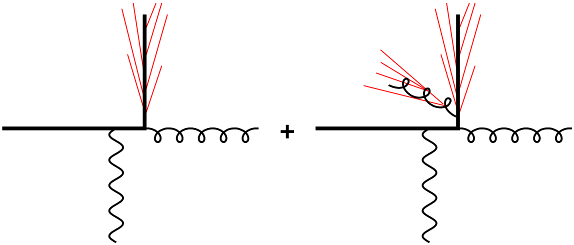
Add Z+1jet, Z+2jet + shower



Add Z+1jet, Z+2jet + shower

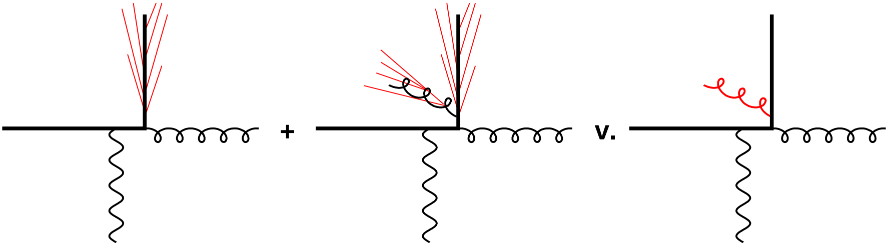


Add Z+1jet, Z+2jet + shower



shower Z+parton **shower Z+2partons**

Add Z+1jet, Z+2jet + shower

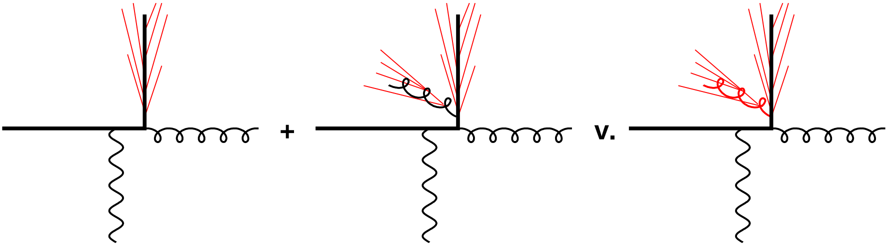


shower Z+parton

shower Z+2partons

shower of Z+parton generates hard gluon

Add Z+1jet, Z+2jet + shower

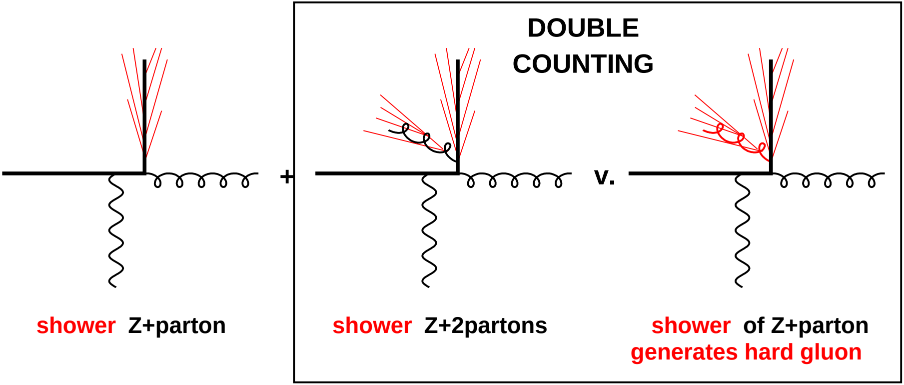


shower Z+parton

shower Z+2partons

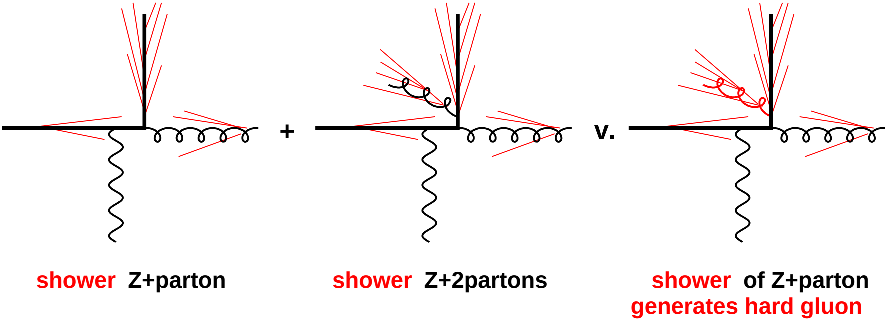
shower of Z+parton
generates hard gluon

Add Z+1jet, Z+2jet + shower



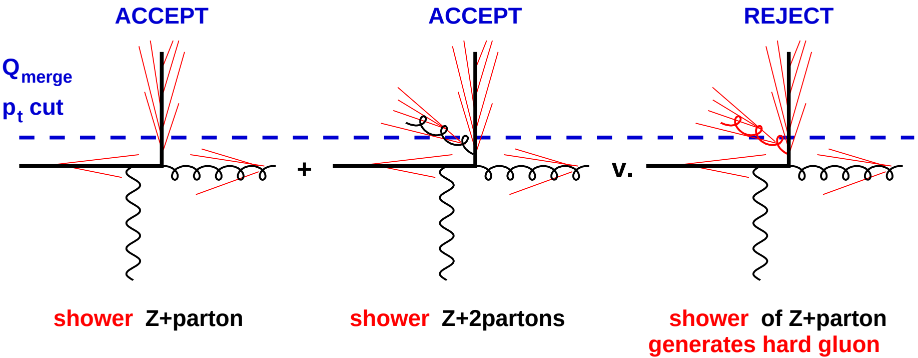
Z + parton implicitly includes part of Z + 2 partons
It's just that the 2nd parton isn't always explicitly "visible"

cartoon of MLM merging of Z+j and Z+2j



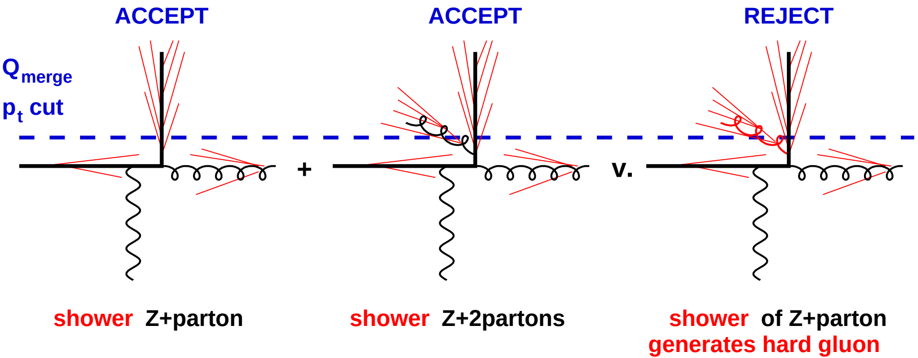
- MLM merging relies on parton shower to help figure out what fraction of Z + parton is really Z + 2 partons.
- In a few slides, we will try to do that without the parton shower

cartoon of MLM merging of Z+j and Z+2j



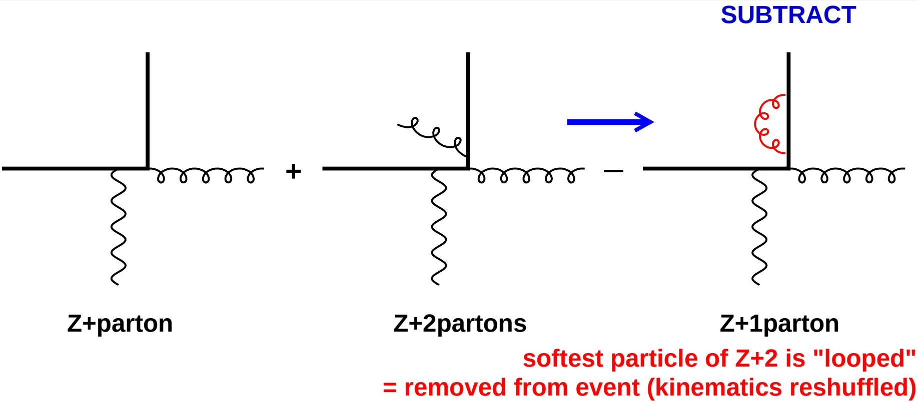
- MLM merging relies on parton shower to help figure out what fraction of Z + parton is really Z + 2 partons.
- In a few slides, we will try to do that without the parton shower

cartoon of MLM merging of Z+j and Z+2j



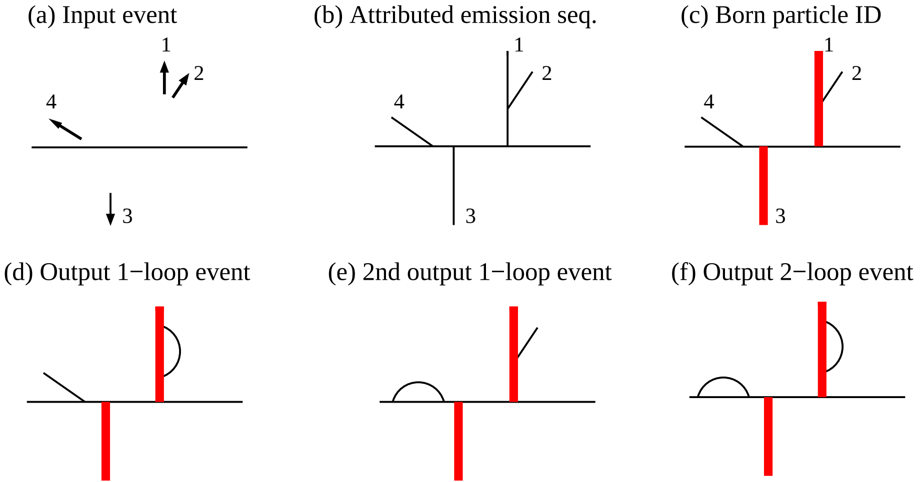
- MLM merging relies on parton shower to help figure out what fraction of Z + parton is really Z + 2 partons.
- In a few slides, we will try to do that without the parton shower

cartoon of the LoopSim idea



- For every $Z + 2$ parton ($2 \to 3$) event, figure out what what $2 \to 2$ event it would really have come from
  "Loop" the softest parton
  [Don't actually explicitly calculate any loop diagrams: simulate the loops]
- Subtract that $2 \to 2$ event
  Unlike MLM, no cutoffs on $2 \to 3$ events
  If done properly, divergences will cancel

cartoon of LoopSim "looping" procedure



- Use jet algorithm to assign a branching structure to event — à la CKKW
- The particles that are softest are the ones that will be "looped"

Define operators:

$$U_\ell(\text{event E}) \equiv \text{all simulated } \ell\text{-loop events from E}$$

$$U_\forall(\text{event}) \equiv \sum_{\ell=0} U_\ell(\text{event})$$

"U" stands for unitarisation (cancellation of all divergences)
sum of all diagrams (essentially) adds up to zero

To combine Z+j with Z+2j take

$$\text{Z+j@}\bar{n}\text{LO} \equiv \text{Z+j@LO} + U_\forall(\text{Z+2j@LO})$$

we use "$\bar{n}$LO" to emphasize that this is a crude approximation
to an actual NLO calculation — the exact loops are missing
NB: $U_\forall$ here includes $\ell = 0, 1$

$\bar{n}$NLO: merging Z+j and Z+2j, both @NLO

Just replace simulated loops with exact loops
Apply LoopSim to exact 1-loop to get (e.g.) simulated 2-loop terms

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$E_{n,\ell} \equiv$ event with n partons and ℓ exact loops
$U_{\forall,\ell} \equiv$ operator to apply when ℓ exact loops known

$$U_{\forall,1}(E_{n,0}) = U_{\forall}(E_{n,0}) - U_{\forall}\left(U_1(E_{n,0})\right)$$
$$U_{\forall,1}(E_{n,1}) = U_{\forall}(E_{n,1})$$

$$\text{Z+j@}\bar{n}\text{NLO} = \text{Z+j@NLO} + U_{\forall,1}(\text{Z+2j@NLO}_{\text{only}})$$

Extension to NLO, NNLO, multi-leg, etc. is almost trivial in LoopSim

Not the case in methods that merge with parton showers too