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On QCD+QED corrections

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In collaboration with (1612.06548, 16xx.nnnnn):

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and:

S. Catani

But: what follows is (partly) preliminary, so any mistake is mine and only mine

I shall briefly discuss

- A new approach to the procedures used in fixed-order calculations that involve NLO EW corrections
- Implications for automation (including QCD) and matching to PS
- A case study: NLO corrections to dijet hadroproduction (1612.06548)

My own motivations (before, and on top of, automation)

- I dislike the use of a mixed scheme in NLO EW computations. Eg with l photons in an n-body final state, one has a factor $\alpha(0)^l \alpha_{G_F}^k \alpha(m_Z)^{n-l-k}$ – a mixture of on-shell and $\overline{\mathrm{MS}}$-like renormalisation prescriptions

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- I want to set $m_q = 0$ if need be; this implies that for me an IR-sensitive quantity (dependence on m_q) and an IR-divergent quantity (presence of $1/\epsilon_{\rm IR}$) must be strictly equivalent

(Very rough) IR viewpoint

- The photon splits: IR singularity cancelled by that of self-energy. S-matrix residues are IR-finite in $\overline{\mathrm{MS}}$-like schemes
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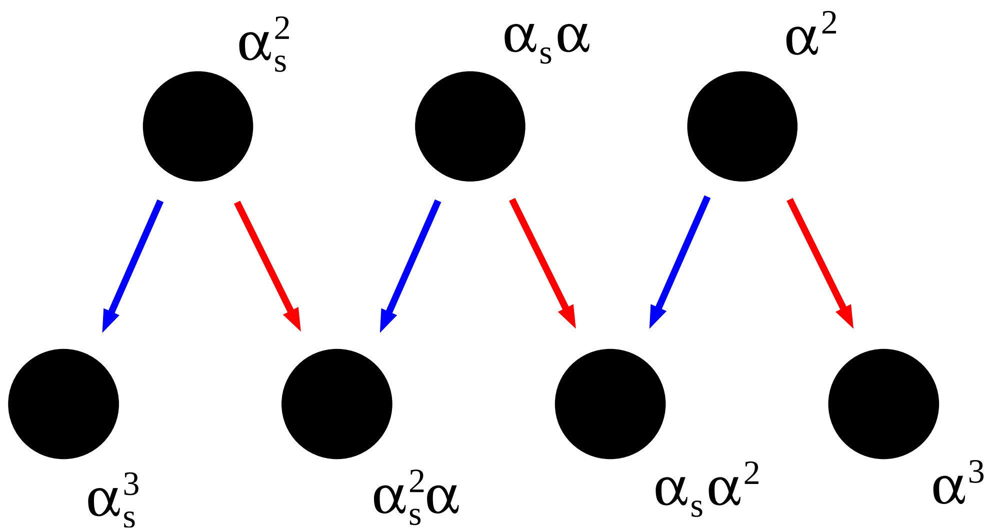
Keeping the above in mind, one can actually rather easily work in $\overline{\mathrm{MS}}$ in all cases of interest

Notation for mixed-coupling expansion

For example in dijet production; Σ is a generic observable

$$\begin{aligned}
\Sigma_{jj}^{(\mathrm{LO})}(\alpha_S, \alpha) &= \alpha_S^2\,\Sigma_{2,0} + \alpha_S\alpha\,\Sigma_{2,1} + \alpha^2\,\Sigma_{2,2} \\
&\equiv \Sigma_{\mathrm{LO},1} + \Sigma_{\mathrm{LO},2} + \Sigma_{\mathrm{LO},3} \\
\Sigma_{jj}^{(\mathrm{NLO})}(\alpha_S, \alpha) &= \alpha_S^3\,\Sigma_{3,0} + \alpha_S^2\alpha\,\Sigma_{3,1} + \alpha_S\alpha^2\,\Sigma_{3,2} + \alpha^3\,\Sigma_{3,3} \\
&\equiv \Sigma_{\mathrm{NLO},1} + \Sigma_{\mathrm{NLO},2} + \Sigma_{\mathrm{NLO},3} + \Sigma_{\mathrm{NLO},4}
\end{aligned}$$

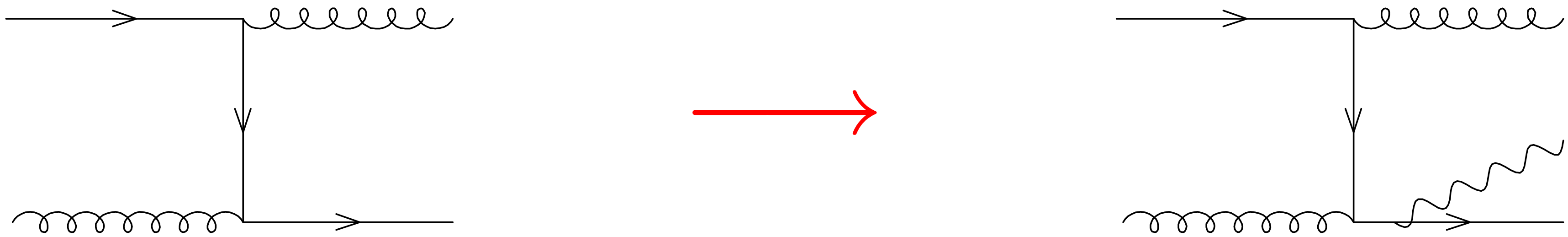
Usually, $\Sigma_{\mathrm{NLO},1}$=NLO QCD, $\Sigma_{\mathrm{NLO},2}$=NLO EW (weak+QED)



- Key point: to be able to compute *all* $\Sigma_{\mathrm{LO},i}$ and $\Sigma_{\mathrm{NLO},i}$ terms
- This requires work both at the conceptual level and on the (automated) code (bookkeeping, subtraction, integration)
- Note: “NLO EW” for $\Sigma_{\mathrm{NLO},2}$ not really an appropriate name

QED corrections to jets: potential issues

Need to compute "QED corrections": then, include photon emission



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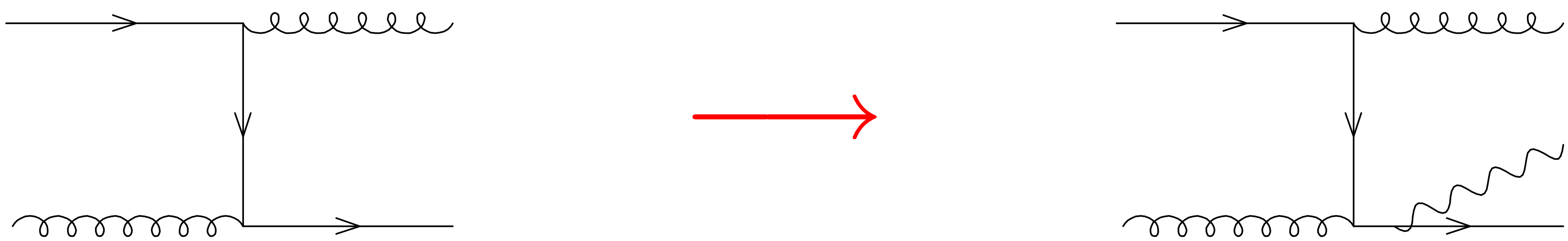

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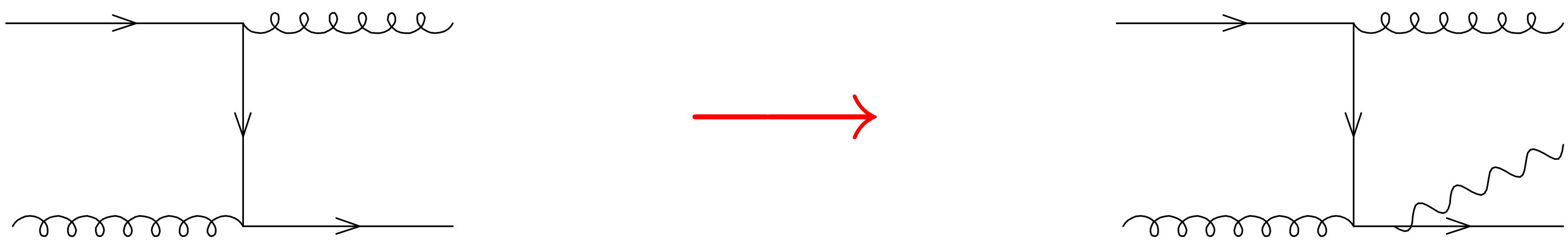

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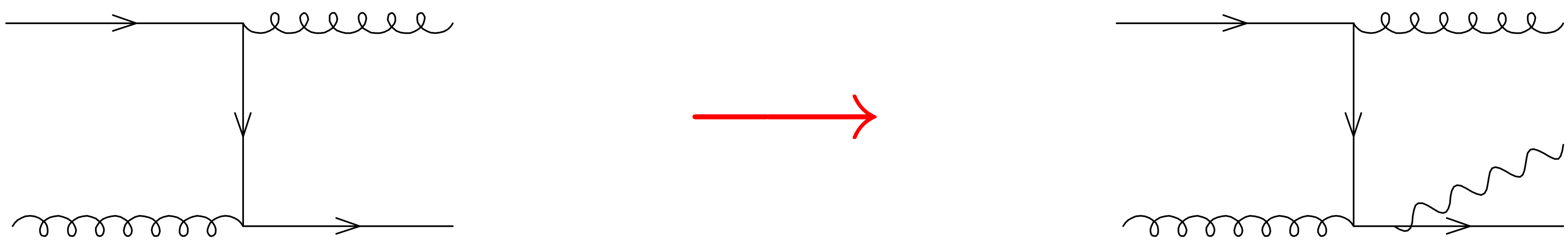

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Solution: sum over all configurations

However: (QCD) IR safety demands $E_{gluon} \to 0$ to be a smooth limit.
This implies a $q\gamma$ final state must exist at the Born level.
That's OK: treat q's, g's and γ's democratically

Most theorists* do not like this (jet $\equiv$ photon)

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This is a problem only at $\Sigma_{\rm NLO,3}$ and beyond (at least two EW couplings are needed): in principle it can be ignored at NLO EW.

Still, it is much cleaner to devise a solution which is universally valid

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Our proposal:

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Thus:

- A fragmentation function (FF) $D_\gamma^{(a)}$ must be introduced for each possible $a \to \gamma$ "hadronisation", with a any "parton"
- Key: this includes $D_\gamma^{(\gamma)}$ for $\gamma \to \gamma$ (turns a short-distance photon into a taggable photon)
- Note: $D_\gamma^{(q)}$ is necessary already at NLO EW when applying an E_γ cut

From the purely perturbative FF evolution:

$$D_{\gamma}^{(\gamma)}(z,\mu) = \frac{\alpha(0)}{\alpha(\mu)}\delta(1-z) + \cdots$$

which allows one to recover immediately all known pQCD results

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Problem: even with FFs, one cannot introduce wee-photon jets:
FFs are not well defined for $z \to 0$

Solution: define cross sections for hard-photon jets, and subtract them from the democratic-jet cross section

$$d\sigma_{X;nj}^{(\mathrm{antitag})} = d\sigma_{X;nj}^{(\mathrm{dem})} - \sum_{k=1}^{n} d\sigma_{X+k\gamma;\,nj}$$

This eliminates jet $\equiv$ photon contributions (and others)

Bottom line

- One can work in $\overline{\mathrm{MS}}$-like schemes, regardless of the nature of the final state
- Treat all light particles democratically, and insert FFs if an observable object must be searched for
- In a parton-level generator, fragmented and un-fragmented cross sections might be integrated simultaneously
- Collinear counterterms associated with FFs solve the IR problem
- Note: what's above applies to *light leptons* as well

The work on including these ideas into the automated code MG5_aMC@NLO is well advanced

From the formal viewpoint, this has required the extension of the FKS subtraction method in two different directions, to deal with:

- Mixed-coupling expansion
- Presence of fragmentation functions

The final formulae are a bit more involved than the QCD ones, but the key features of FKS are unchanged

Usage of MG5_aMC@NLO

Current syntax (leading terms, i.e. NLO QCD)

```
MG5_aMC> generate a b > c d e f [QCD]
```

Will become (or something similar):

```
MG5_aMC> generate a b > c d e f QCD=n QED=m [QCD QED]
```

in order to include in the computation all the terms that factorise:

$$\begin{array}{lllll} \text{LO} & \alpha_S^k \alpha^p\,, & k \leq n\,, & p \leq m\,, & k+p=b \\ \text{NLO} & \alpha_S^k \alpha^p\,, & k \leq n+1\,, & p \leq m+1\,, & k+p=b+1 \end{array}$$

For dijets, we have executed:

```
MG5_aMC> set complex_mass_scheme True
MG5_aMC> import model loop_qcd_qed_sm_Gmu
MG5_aMC> define p = p a l+ l- ta+ ta-
MG5_aMC> define j = p
MG5_aMC> generate p p > j j QCD=2 QED=2 [QCD QED]
```

Notable run parameters:

$$1/\alpha = 132.507\,, \qquad \mu_0 = H_T/2\,, \qquad \mu_0/2 \le \mu_R, \mu_F \le 2\mu_0$$

Massless leptons, five-flavour scheme

NNPDF2.3QED ("maximises" impact of photon PDF)

k_T jets $D = 0.7$

Keep in mind

$$\Sigma_{jj}^{(\mathrm{NLO})}(\alpha_S,\alpha) = \alpha_S^3\,\Sigma_{3,0} + \alpha_S^2\alpha\,\Sigma_{3,1} + \alpha_S\alpha^2\,\Sigma_{3,2} + \alpha^3\,\Sigma_{3,3}$$
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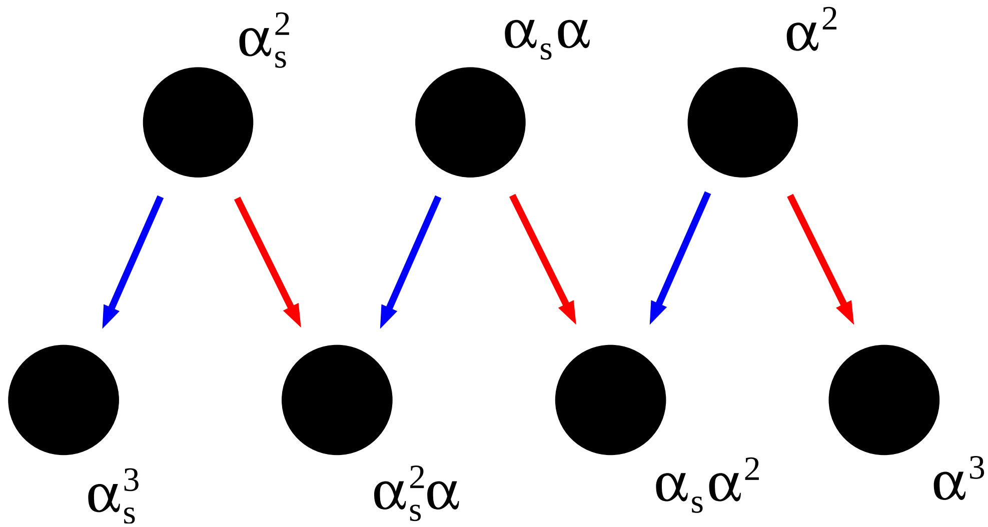


- $\Sigma_{\mathrm{NLO},2}$ weak: Dittmaier, Huss, Speckner 2012
- $\Sigma_{\mathrm{NLO},2}(\mathrm{QED}) + \Sigma_{\mathrm{NLO},3} + \Sigma_{\mathrm{NLO},4}$: new (1612.06548)

Note: beyond the dominant $\gamma \to \gamma$ FF term, one deals with very small effects. Furthermore, FFs are so far poorly determined. Thus, a more pragmatic solution for the time being:

- find jets democratically;
- find isolated photons, using smooth isolation;
- loop over those photons: if a photon belongs to a jet, and it carries more than 90% of the p_T of that jet, then flag the jet as a candidate photon jet;
- candidate photon jets are considered as proper photon jets if and only if:
  - there is exactly one isolated photon, and one computes either $\Sigma_{\rm LO,2}$ or $\Sigma_{\rm NLO,2}$;
  - there are exactly two isolated photons, and one computes either $\Sigma_{\rm LO,3}$ or $\Sigma_{\rm NLO,3}$;
- each photon jet gives an entry to the histograms relevant to single-inclusive observables. For dijet correlations, there is an histogram entry for each pair of jets, at least one of which is a photon jet.

This still eliminates jet $\equiv$ photon contributions

All jets must be central:

$$\left|y^{(j)}\right| < 2.8$$

Single inclusive:

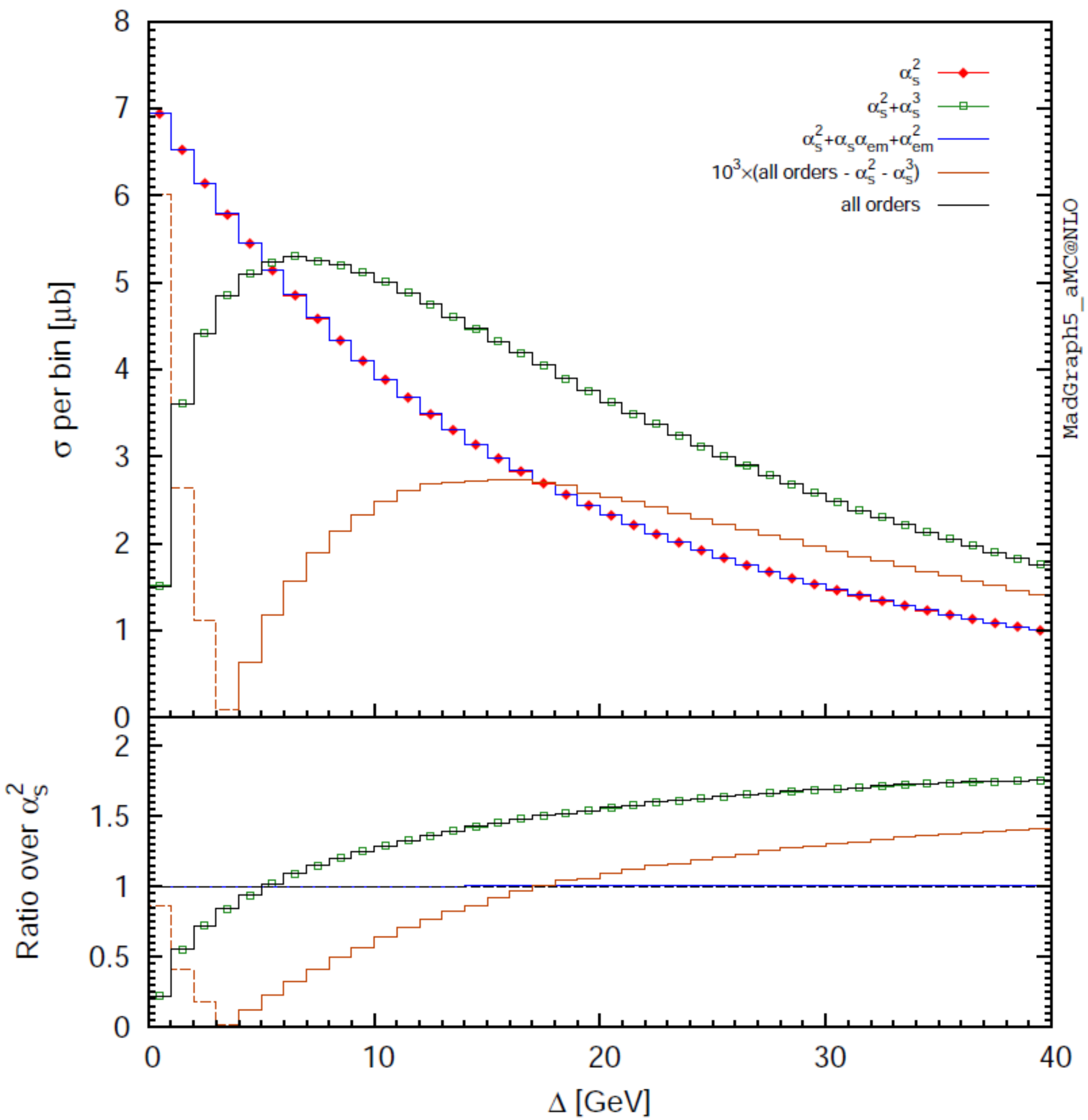
$$p_T^{(j)} \geq 60 \text{ GeV}$$

Correlations:

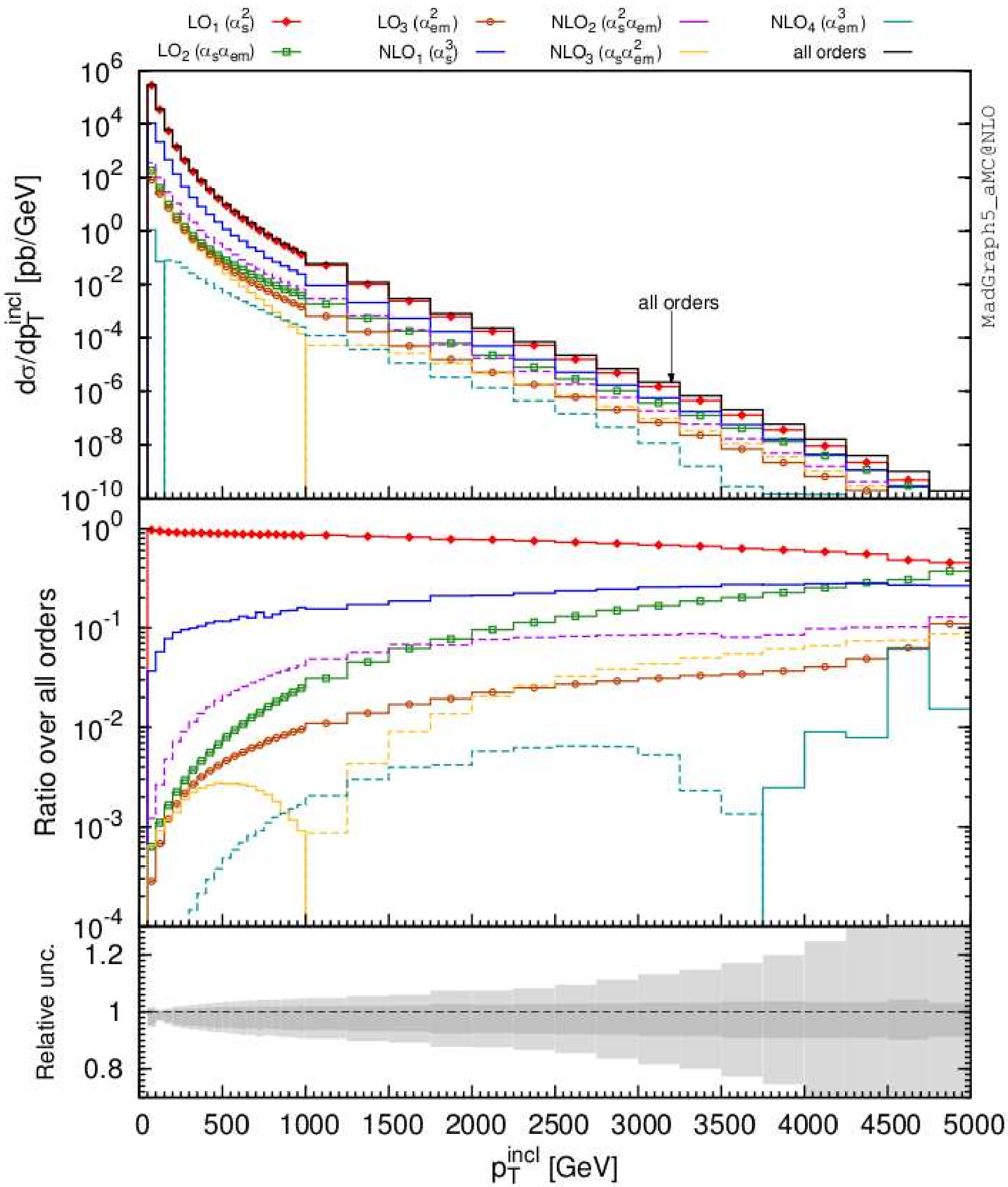
$$p_T^{(j_1)} \geq 80 \text{ GeV}\,, \qquad p_T^{(j_2)} \geq 60 \text{ GeV}$$

The asymmetry on the leading jet p_T's stems from studying:

$$\sigma(\Delta) = \sigma\left(p_T^{(j_1)} \geq 60 \text{ GeV} + \Delta,\; p_T^{(j_2)} \geq 60 \text{ GeV}\right)$$

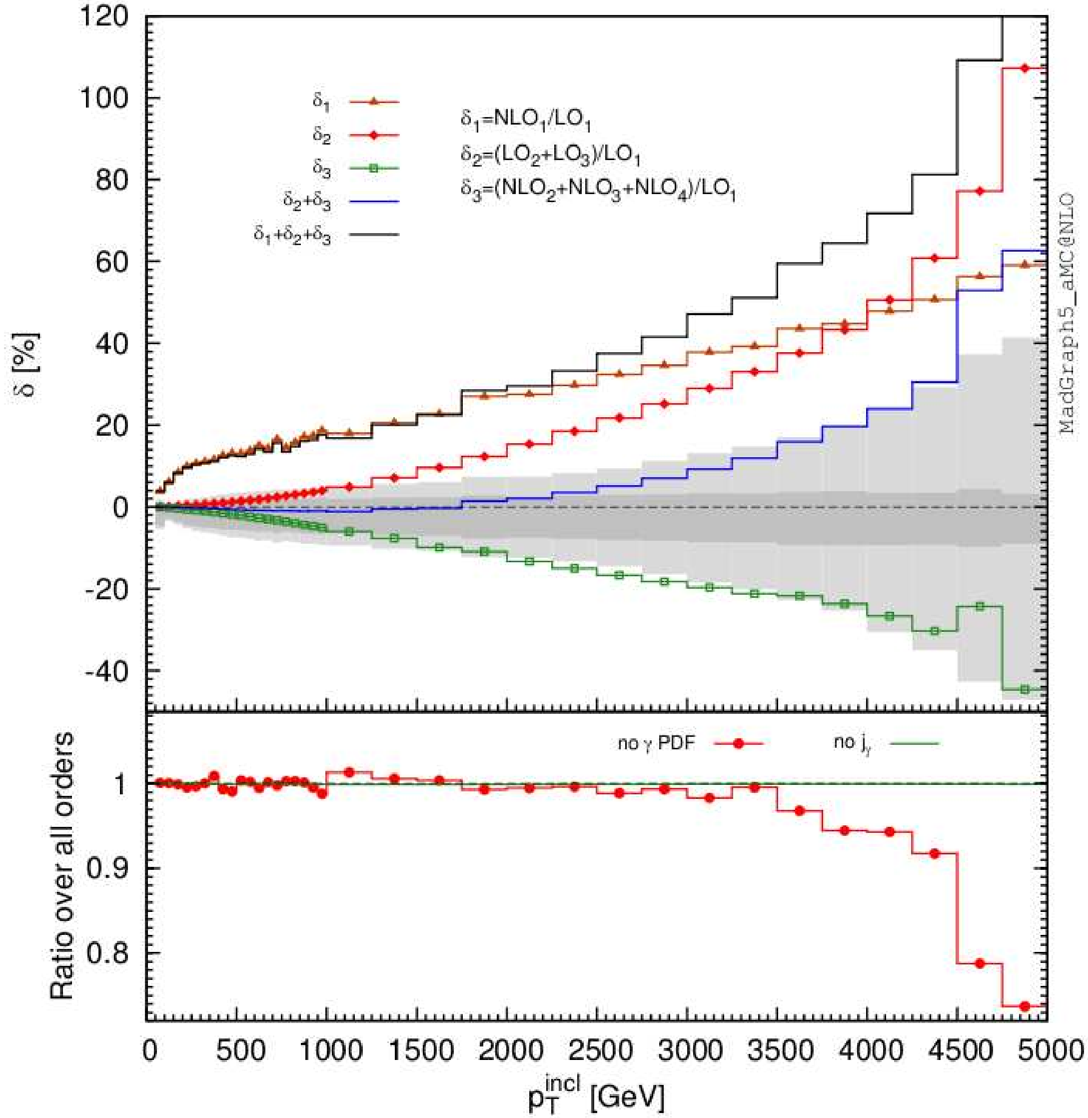


- $\Delta = 0$ pathological at fixed order
- Dashed $\equiv$ negative Σ
- *Extremely* small subleading contributions (these are total rates)
- Suggests subleading Σ's more affected by $\log \Delta$ than QCD



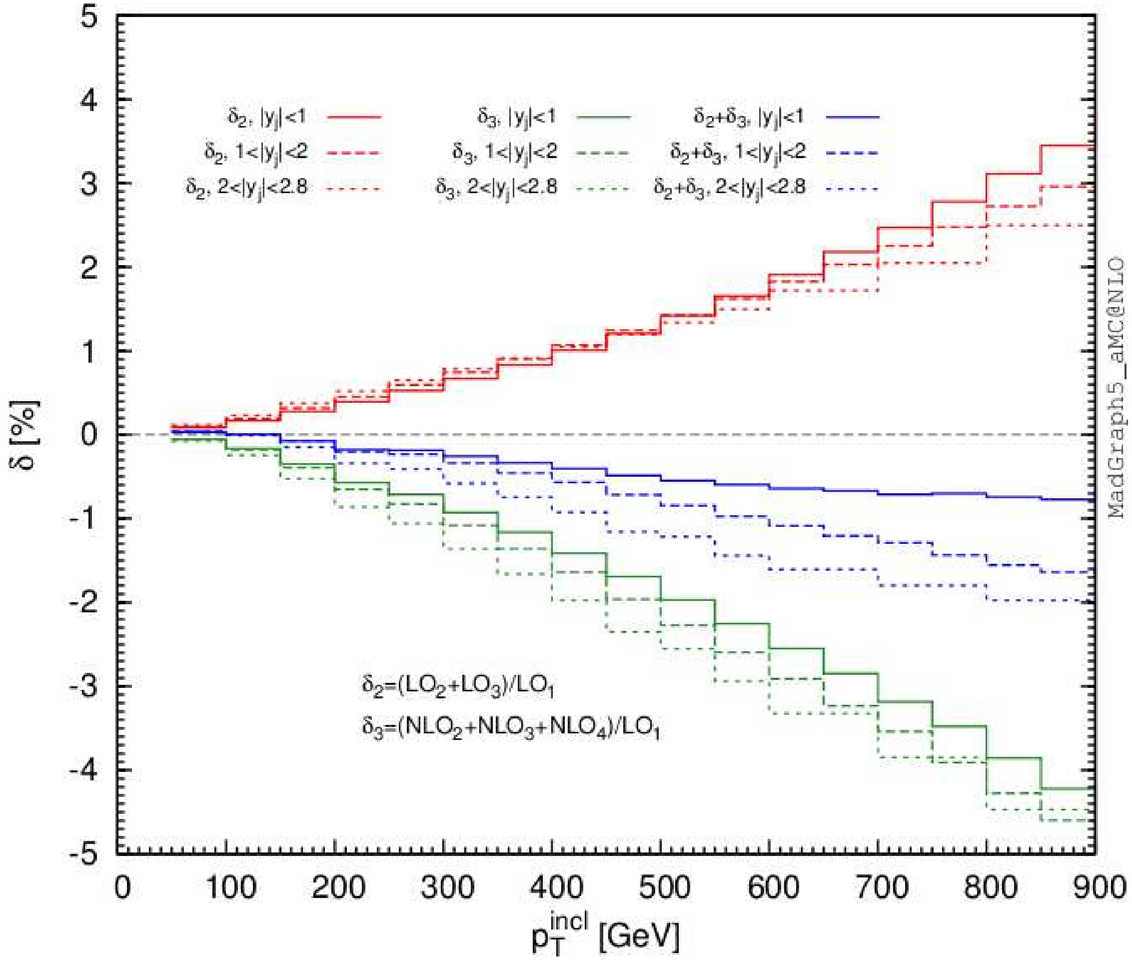
Inclusive p_T

- Subleading LO and NLO have opposite signs. Eventually LO's grow faster than NLO's
- Owing to cancellations, both LO and NLO are necessary
- Significance of non-QCD effects increases with p_T
- So does PDF uncertainty – impact of photon is large but not dominant



Inclusive p_T

- Upper frame: as before, but some contributions summed for ease of reading
- Photon-jet subtraction irrelevant on physical Σ (up to 30% for $\Sigma_{\mathrm{LO},2}$ for $p_T < 0.5$ TeV)
- Significant impact of photon PDFs at large p_T's (remember: likely a worst-case scenario)



Inclusive p_T in y slices

- This is of interest for PDF fits (different y's probe different Bjorken x's)
- The pattern of subleading corrections is non trivial

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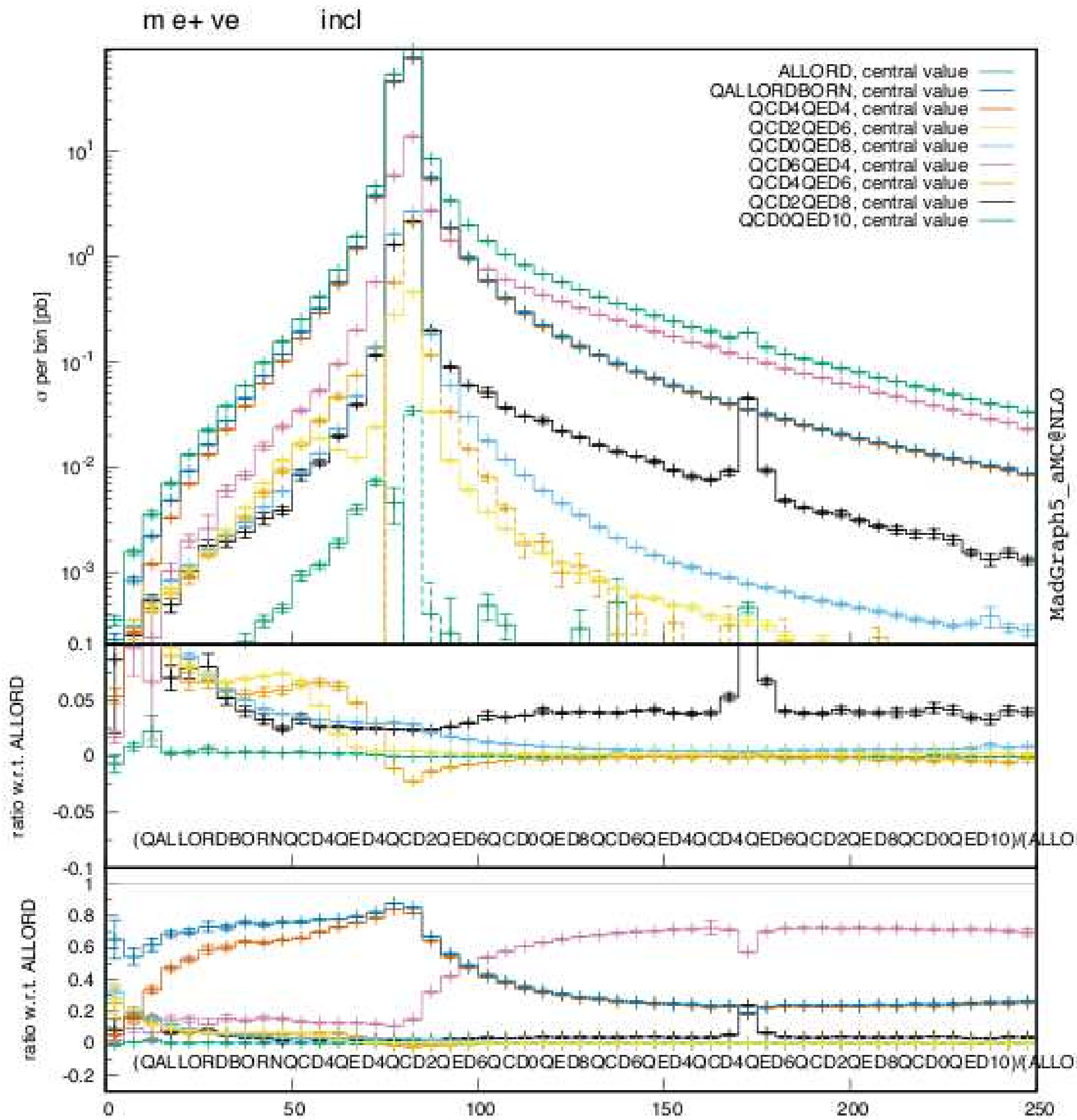
Preliminary: $W(\to e\nu_e)jj$ production



We are stress testing the code with many different processes, analogously to what was done for QCD corrections

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- Full automation under way: dijet hadroproduction a case study

  introduced an IR-safe procedure to all $\alpha_S^n \alpha^m$ orders

  computed all subleading contributions for the first time

  hierarchy suggested by couplings largely respected

  subtraction of photon jets has negligible impact

  EW corrections are small but with a non-trivial pattern

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- This approach should simplify matching to PS