Automated NLO QCD+EW corrections

"open" issues

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Les Houches

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OUTLINE

- Quick overview of **NLO QCD+EW** effort in **MG5_aMC**
- **Skeleton** of mixed corrections
- **Snapshot** of results for dijet

(cherry-picked) issues in EW+QCD

- **Photon definition** for arbitrary processes and corrections.
- Application of the **complex mass scheme**:
  - Implication of setting $|\alpha|$
  - How to handle **unstable particles in the final states**

Mixed NLO QCD+EW
with
MG5_aMC

(See also recent progress made within the SHERPA+RECOLA framework
arXiv:1704.05783, [B. Biedermann, S.Bräuer, A. Denner, M. Pellen, S. Schumann, J. M. Thompson])

UV-Renormalization and Photon-induced IR-divergencies

- Work with massless leptons ($\alpha(M_Z)$ or G_μ scheme)

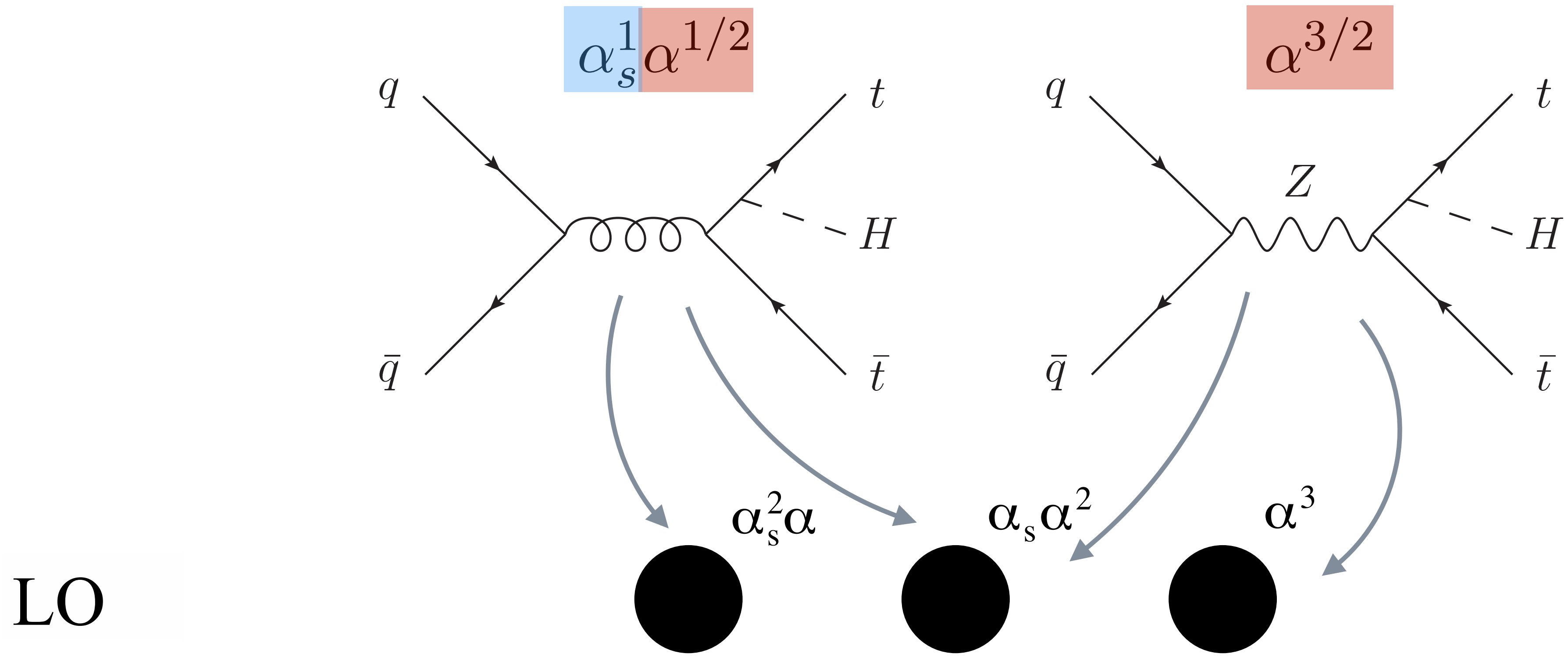
- In mixed EW renormalization schemes, for an $\mathbf{n}$-body process with l-photons in the final states, one typically has: $\alpha(0)^l \alpha(M_Z)^{(n-l)}$
We want to avoid this and work within one scheme throughout.

- Always allow photon splitting, and explicitly cancel the corresponding collinear singularity.

- Use the complex mass scheme whenever a contribution features a resonance (otherwise widths set to 0 is acceptable).

Structure of NLO EW-QCD corrections

The ttH case: S.Frixione, V.Hirschi, D. Pagani, H.-S. Shao, M. Zaro [arXiv:1504.03446]



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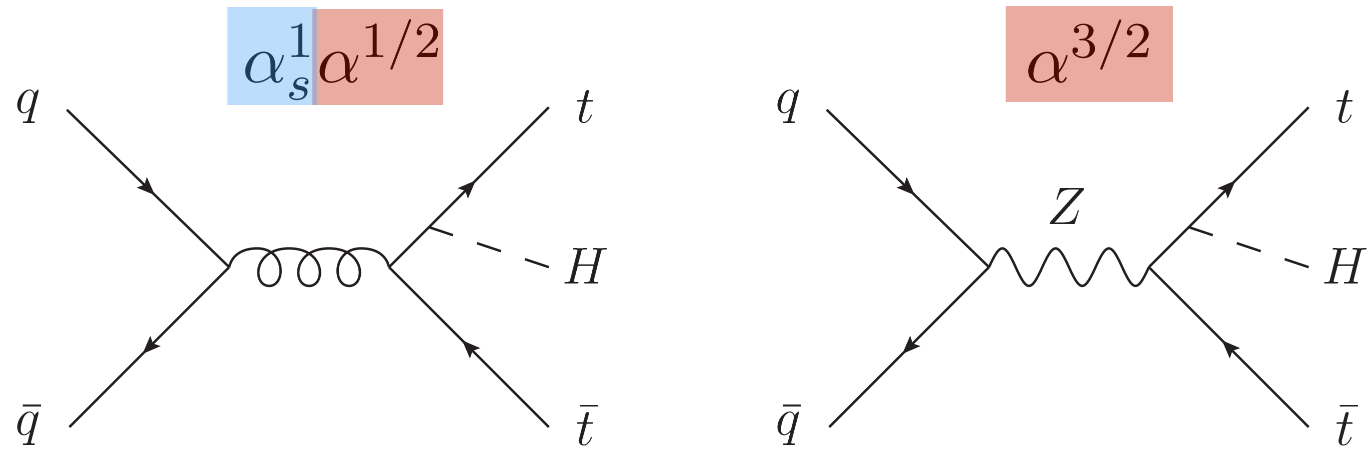

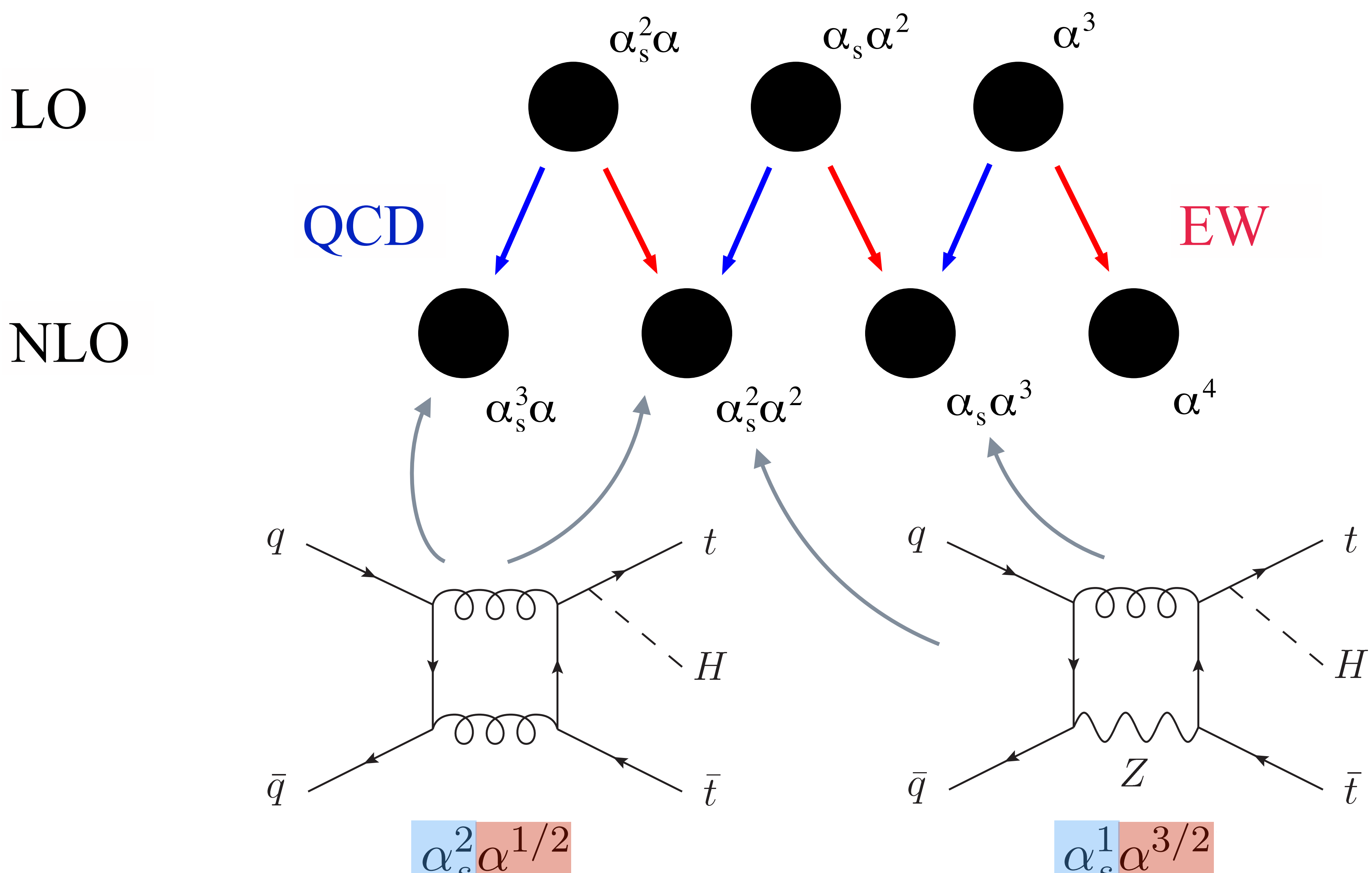

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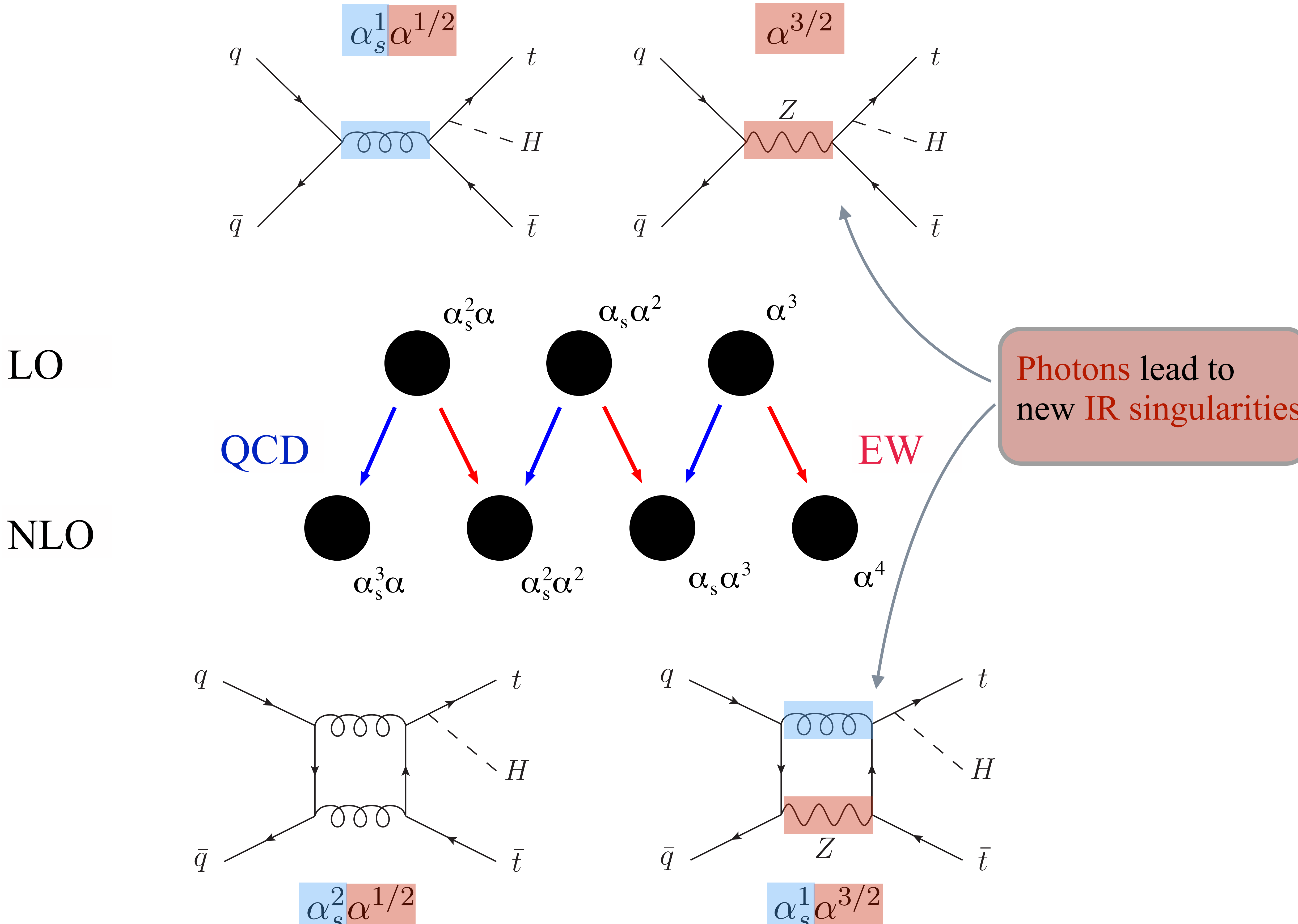
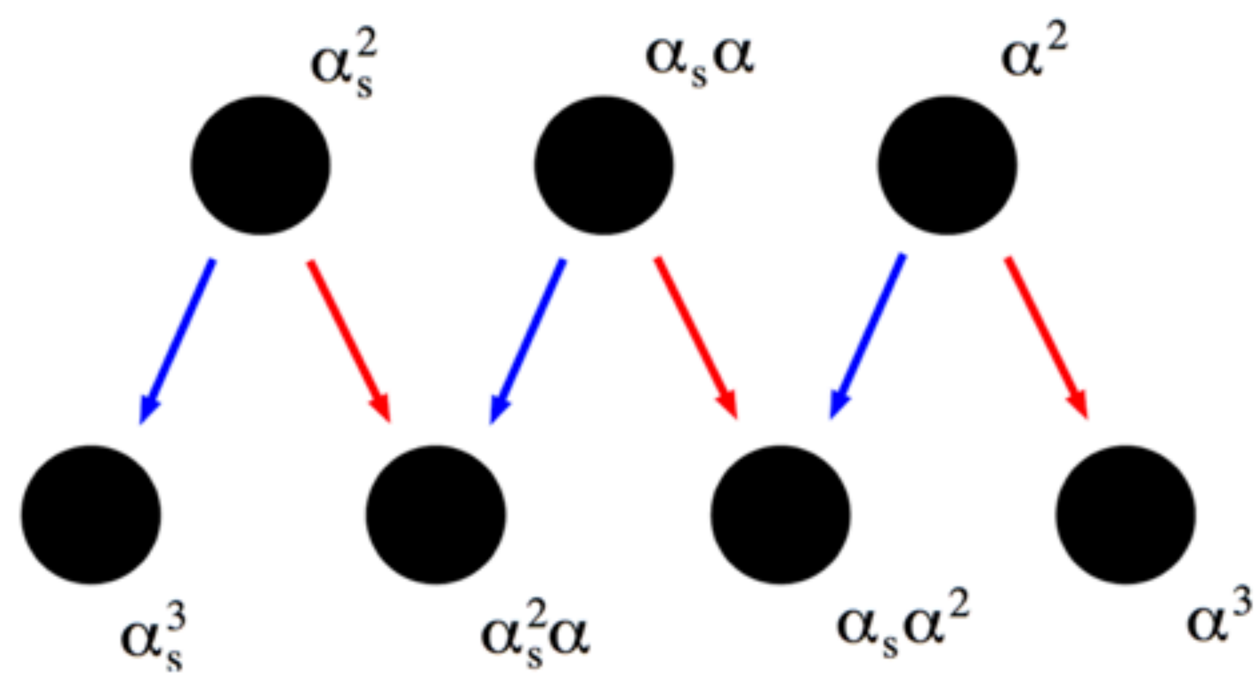


Notation for an observable Σ

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

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

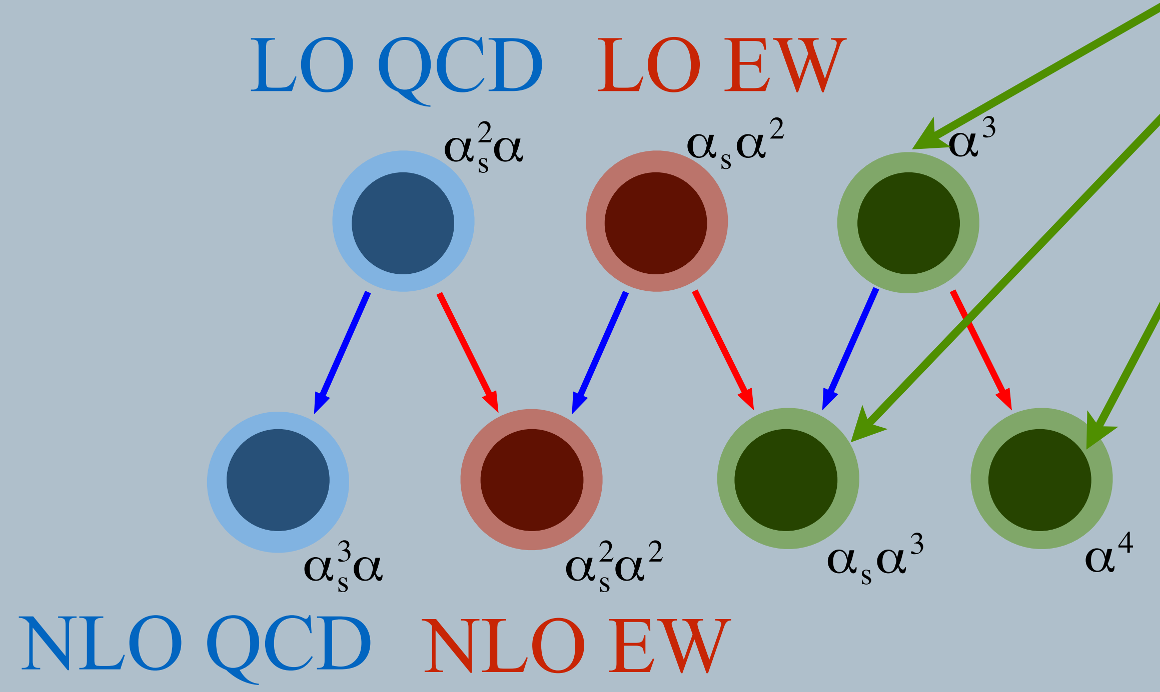


AUTOMATED NLO EW+QCD COMPUTATIONS

The ttH case: S.Frixione, V.Hirschi, D. Pagani, H.-S. Shao, M. Zaro [arXiv:1504.03446]

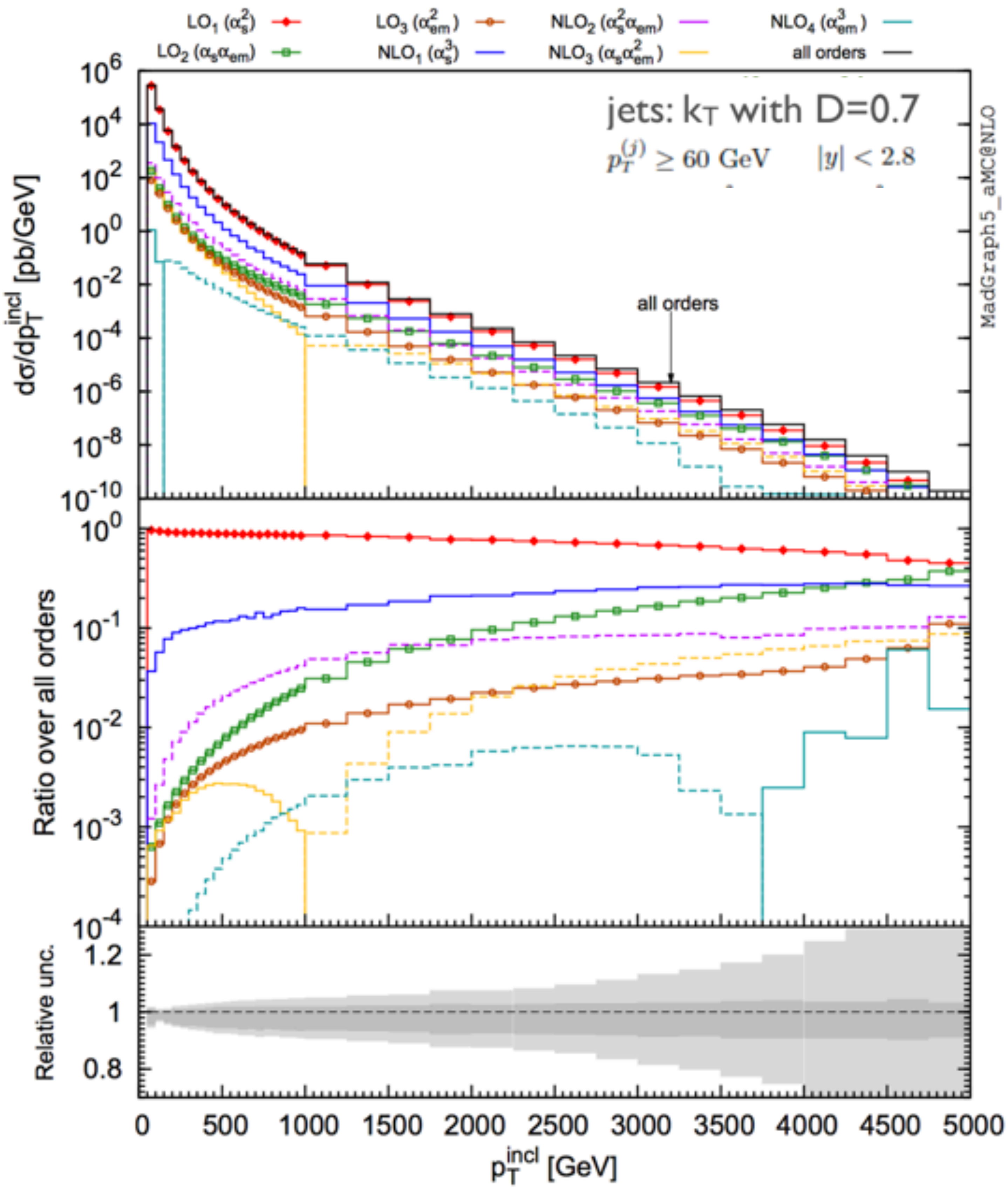
```
MG5_aMC> define p = p b b~ a
MG5_aMC> generate p p > t t~ h [QCD QED]
MG5_aMC> output ttbarh_QCD_QED
MG5_aMC> launch
```

Next step: compute all blobs

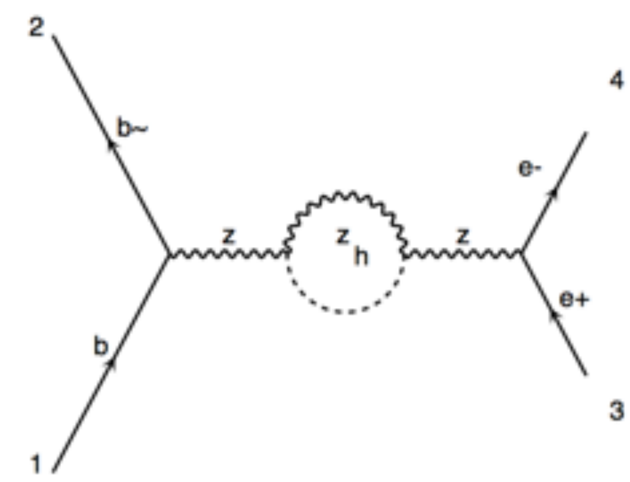


COMPLETE DIJET QCD+EW NLO CORRECTIONS

R. Frederix, S. Frixione, V. H., D. Pagani, H-S.Shao, M.Zaro [arXiv:1612.06548]

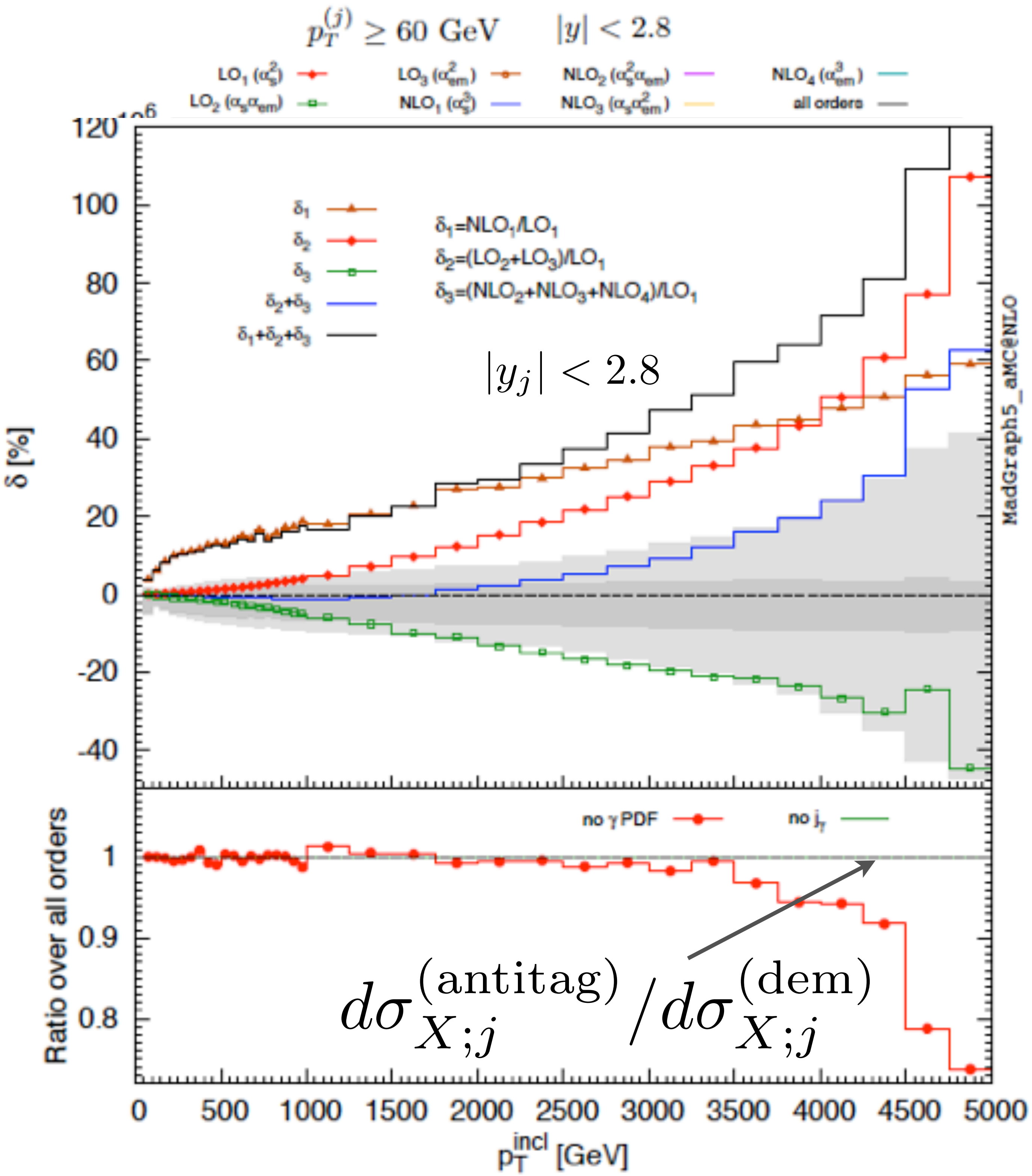


- All $\mathcal{O}(\alpha_s^m, \alpha^n), m+n=2,3$ contributions to dijet. Use G_μ-scheme
- Use democratic jets and proposed a novel definition of (anti-)tagged photons
- Necessitated large computing resources, 219 subprocesses
- This process involves the whole particle spectrum of the SM. Yes, even the Higgs!



Single-jet inclusive

jets: k_T with D=0.7

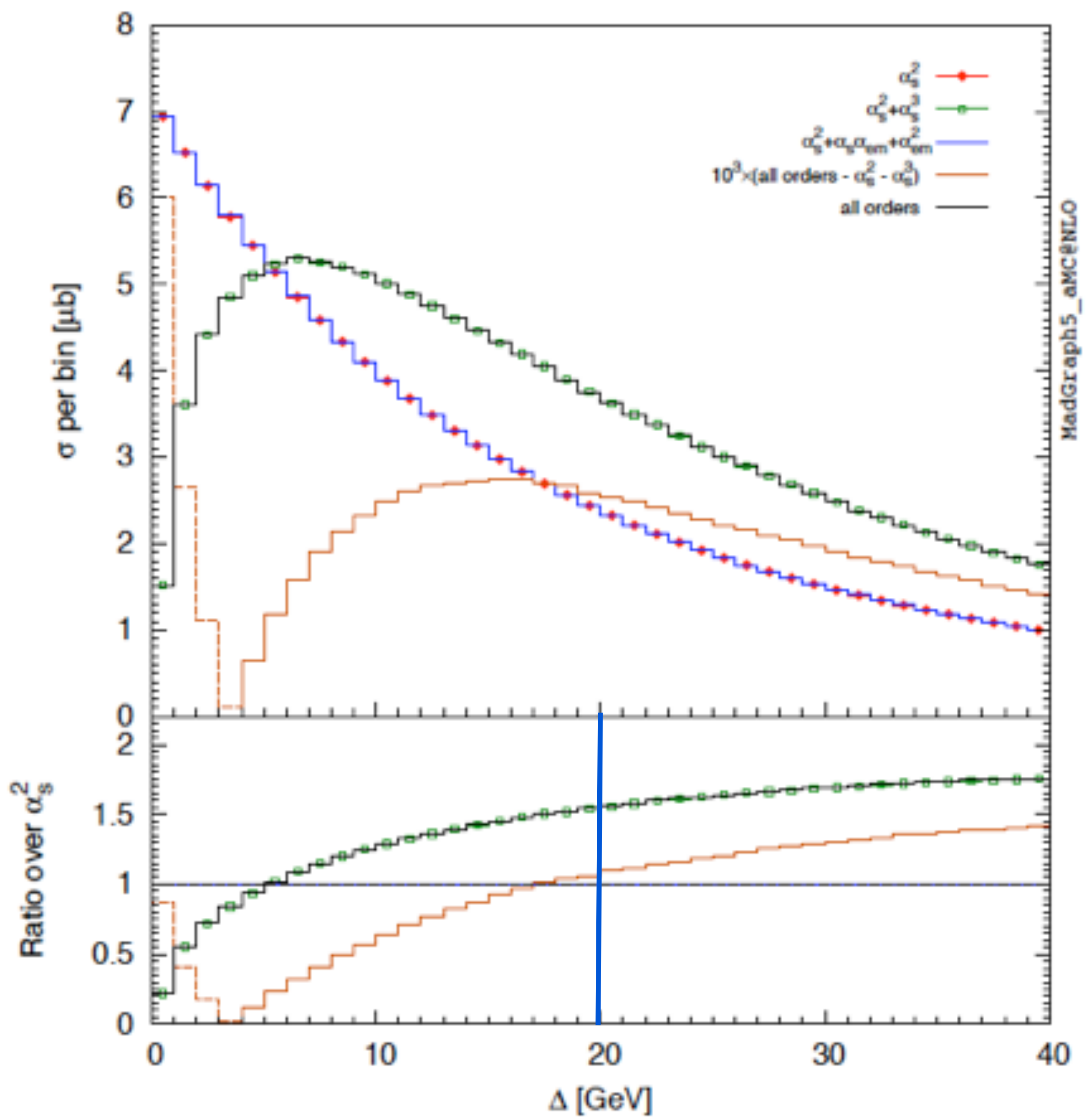


- **EWC (LO_2) is important in the tail**
- **Orders hierarchy respected**
- **In the tail, photon PDF is important**
- **Photon jet is very rare in general**

DIJET-OBSERVABLES

- Fixed-order dijet cross section: a pathological behaviour

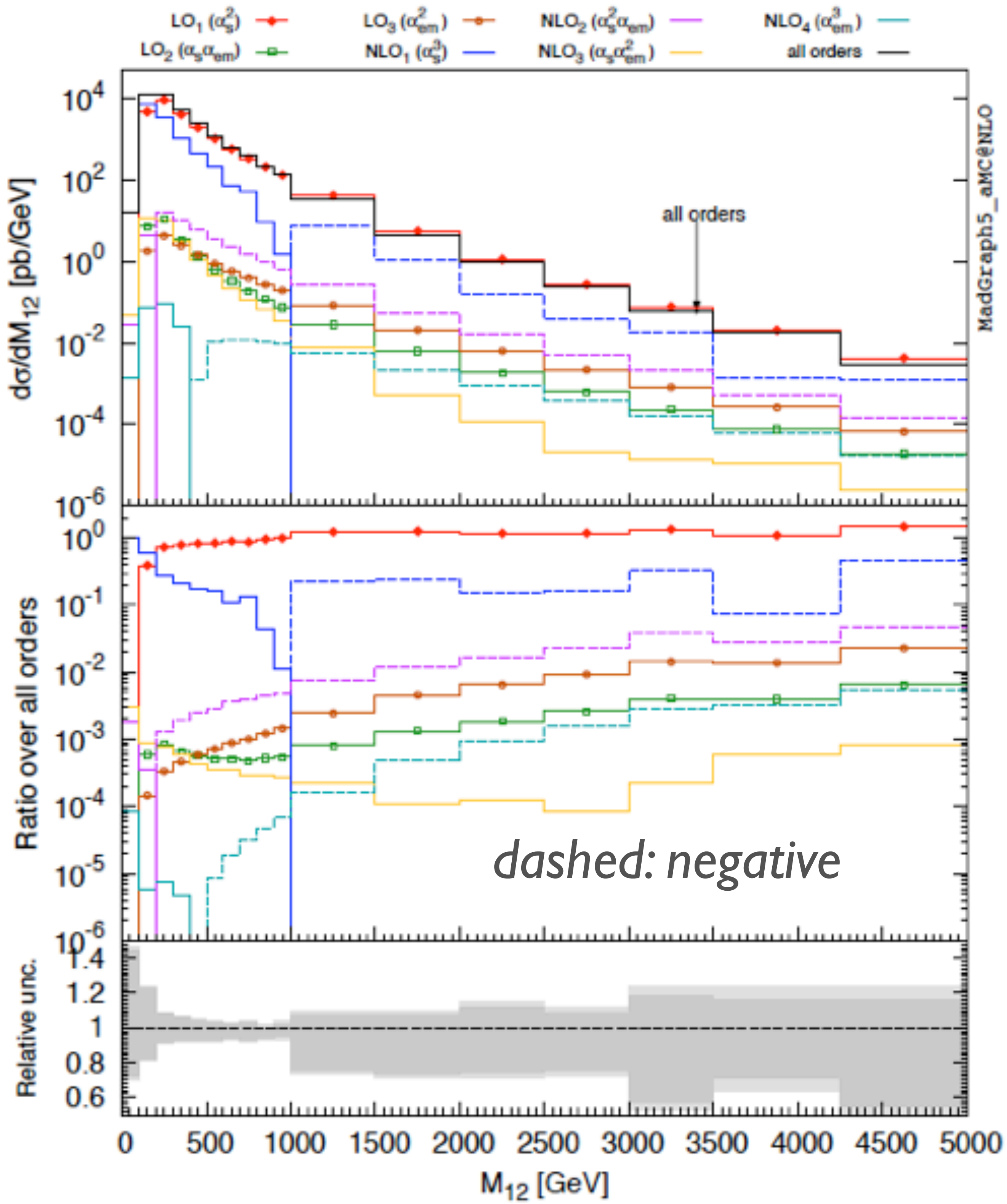
$$\sigma(\Delta) = \sigma\left(p_T^{(j1)} \geq 60\ \mathrm{GeV} + \Delta,\ p_T^{(j2)} \geq 60\ \mathrm{GeV}\right)$$



DIJET-OBSERVABLES

jets: k_T with D=0.7

$p_T^{(j_1)} \geq 80$ GeV , $p_T^{(j_2)} \geq 60$ GeV $|y| < 2.8$



- **NLO$_1$(=NLO QCD) is dominant in NLO**
- **NLO$_1$ changes sign at $M_{12} \sim 1$ TeV**
- **NLO$_2$ (=NLO EW) reduces XS**
- **Scale uncer. is dominant uncer.**
- **Subleading contri. are extremely small**

Need for democratic jets

[Slides onwards from S.Frixione]

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

But: soft photons induce singularities; one must treat them inclusively

Solution: sum over all configurations

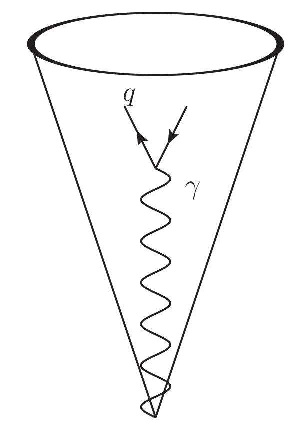
However: (QCD) IR safety demands $E_{gluon} \to 0$ to be a smooth limit.
This implies a $q\gamma$ final state must exist at the Born level.
That's OK: treat q's, g's and γ's democratically

Issues with democratic jets

But experimentalists typically do not consider photon-jets as jets.

Solution: cluster democratically, but discard jets where $E_\gamma > z_{cut} E_{jet}$

However: E_γ is not a well-defined quantity in pQED $(\gamma \rightarrow q\bar{q})$



This is a problem only at $\Sigma_{\mathrm{NLO},3}$ 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

Introducing Fragmentation Functions

Our proposal:

A photon is taggable (i.e. can be subject to physical cuts) only if it emerges from a fragmentation process

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

Introducing Fragmentation Functions

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

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)

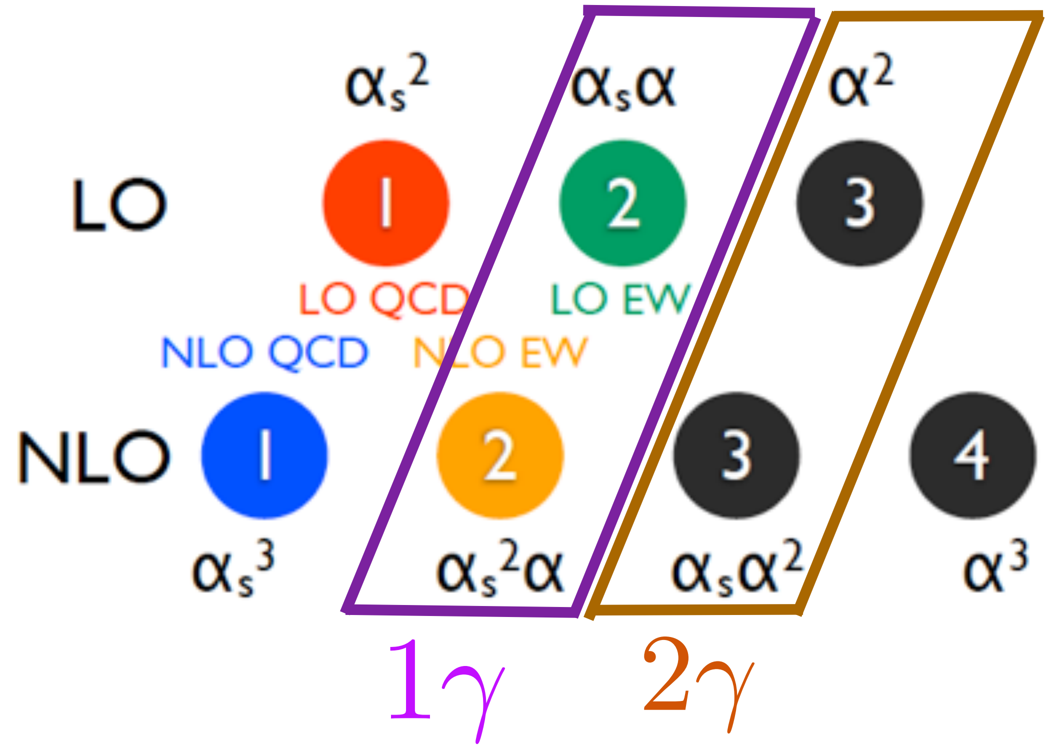
Photon-Jet conclusions

- 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

PRACTICAL SOLUTION IN THE CASE OF DIJET

[SLIDE FROM H-S.SHAO]

- Define photon-jet XSs only where the introduction of FF is **not needed** (no $\gamma \to q\bar{q}$)
- Asses the numerical importance of photon-jet contributions Frixione, '98
- Photon-isolation in this case follows Frixione-type criterion



- Algorithm:
  - find jets democratically
  - find isolated photons via Frixione-type criterion
  - photon jet candidate: a photon belongs to a jet and carries more than 90% p_T
  - photon jet: exactly one (two) isolated photon(s) in $\mathcal{O}(\alpha_s\alpha + \alpha_s^2\alpha)$ $(\mathcal{O}(\alpha^2 + \alpha_s\alpha^2))$
  - For single inclusive observables, each photon jet gives an entry
  - For dijet correlations, each pair of jets with at least one photon jet gives an entry

Complex mass scheme issues

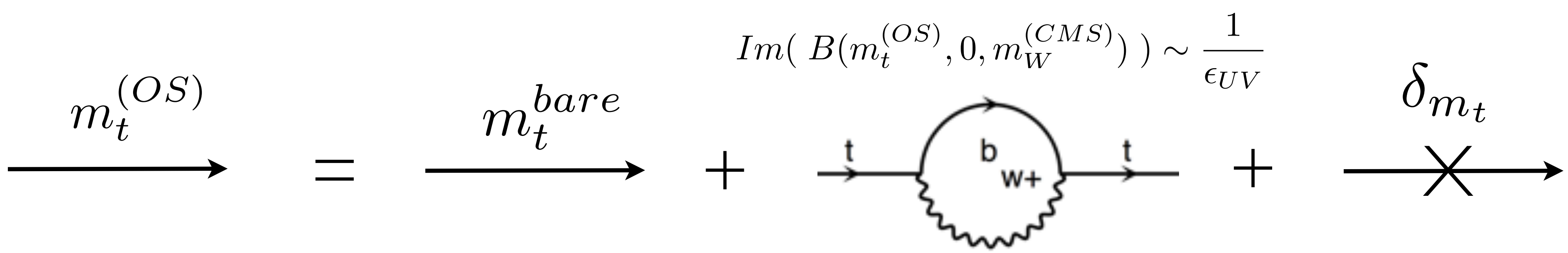
- Is there anyway to salvage the CMS with unstable final states?

Relevant case: p p > t t~ (+jets)

p p > t t~ : Can set all widths to zero, so OK.

p p > t t~ j : Must retain the weak bosons width. Is **WT=0** ok?

Probably not! Because the following bubble has an imaginary residue of UV pole that remains uncancelled:



Any easy solution within the CMS? Or is one forced to always consider fully decayed particles?
Notice that the top width offshell effect ($\mathcal{O}(\Gamma_t/m_t)$) are anyway of the same order.

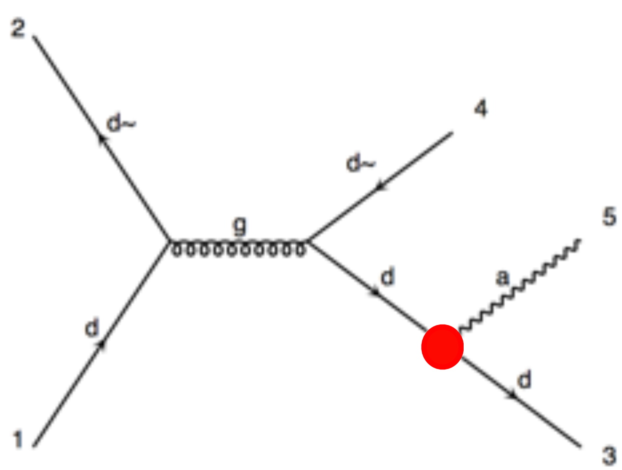
How to handle the complex phase of α ?

- In the G_μ-scheme for example, **α** is defined as:

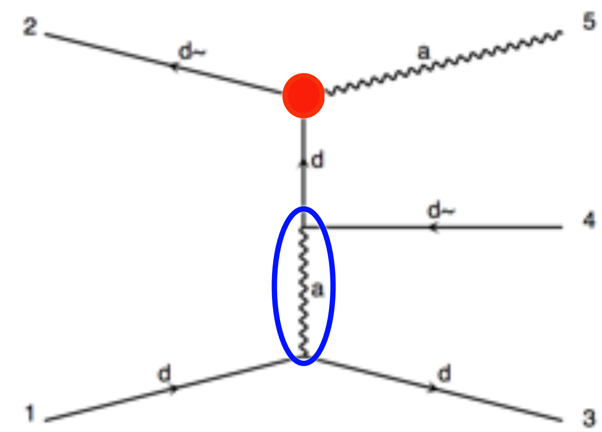
$$\alpha^{(CMS,G_\mu)} = \frac{\sqrt{2}G_f}{\pi}\frac{M_W^{(CMS)2} - M_W^{(CMS)4}}{M_Z^{(CMS)2}} \longrightarrow \text{Should be complex!}$$

- In practice the complex phase is irrelevant because the matrix elements factorize |α|. However, in subleading blobs, one can have:

Reals:



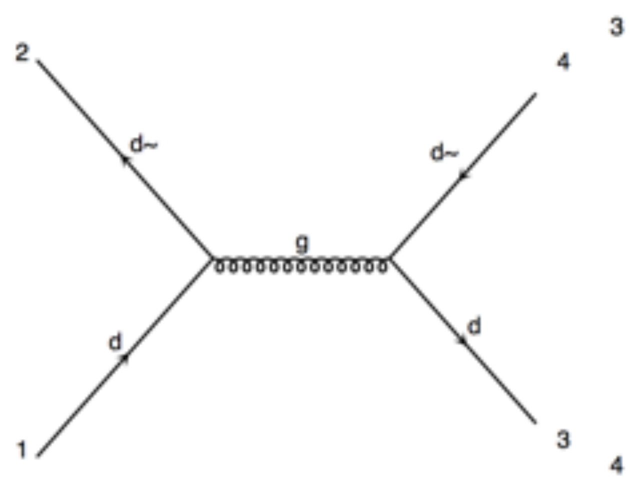
X



$\sim |\alpha|\, Re(\alpha)$

$\neq$

Virtuals:



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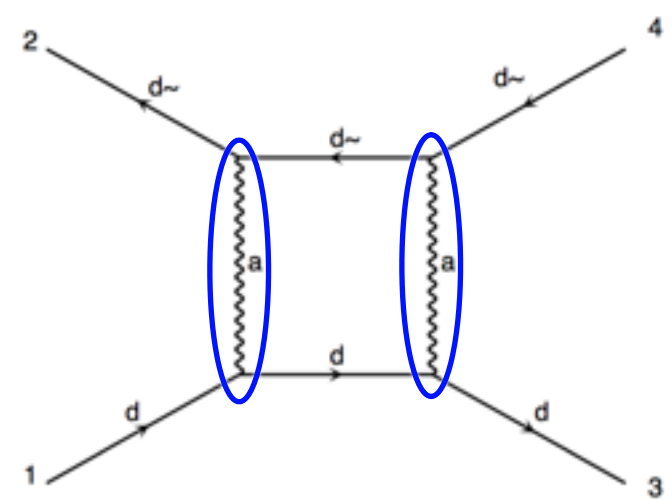

$\sim |\alpha|^2$ $\sim Re(\alpha)^2$

How to handle the complex phase of α ?

- So we must set α→|α| to setup IR factorization and KLN cancel.
  - → This induces **gauge violations** whenever sensitive to complex phase of α (?)
  - → And correspondingly, a potential **dependance** on how one writes EW couplings.

- This typically does not affect **leading** NLO EW corrections, but what is the **best course of actions** for **subleading** NLO ones?

- It is always possible to assign a phase to G_μ so as to make α real (this is what is effectively don in the $\alpha(M_Z)$ scheme) but both cannot be real at the same time.

MIC DROP