Automated ElectroWeak Corrections with MadGraph5_aMC@NLO

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Based On Work with
MadGraph5_aMC@NLO Collaboration
And EW SubGroup:
R. Frederix, S. Frixione, V. Hirschi, D. Pagani, M. Zaro

NLO EW AUTOMATION

- Relevance of EW corrections at LHC run II:
  - *Energy reach extends deeper into TeV range*
  - *Integrated luminosity will reach some 100 fb-1*
  - *Planned many high-precision measurements*

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- Possible further enhancement in EW corrections:
  - *Electromagnetic logarithms, e.g. initial-state radiation at LEP* $\alpha \log \frac{M_Z^2}{m_e^2} \sim 3.0\%$
  - *EW Sudakov corrections at high energy* $\frac{\alpha}{2s_w^2} \log^2 \frac{s}{M_W^2} \sim 6.6\% \quad \text{when} \quad \sqrt{s} = 1 \text{ TeV}$
  - *Possible new opened topologies/channels*

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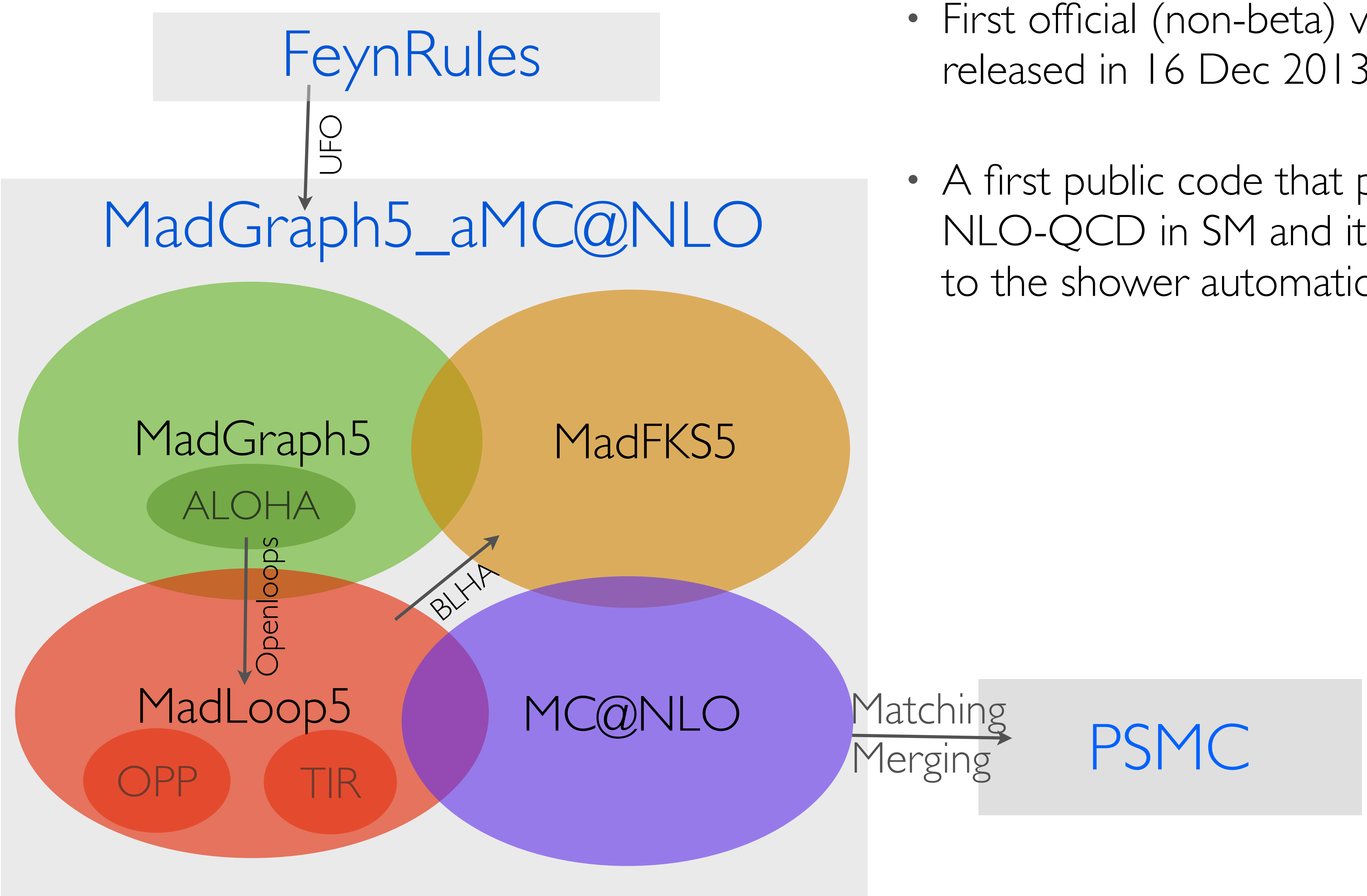
- EWK automation collaborations:

MadGraph5_aMC@NLO, Openloops, Recola, GoSam, ...

JOINT EFFORTS FOR AUTOMATION AT NLO

J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, HSS, T. Stelzer, P. Torrielli, M. Zaro (2014)



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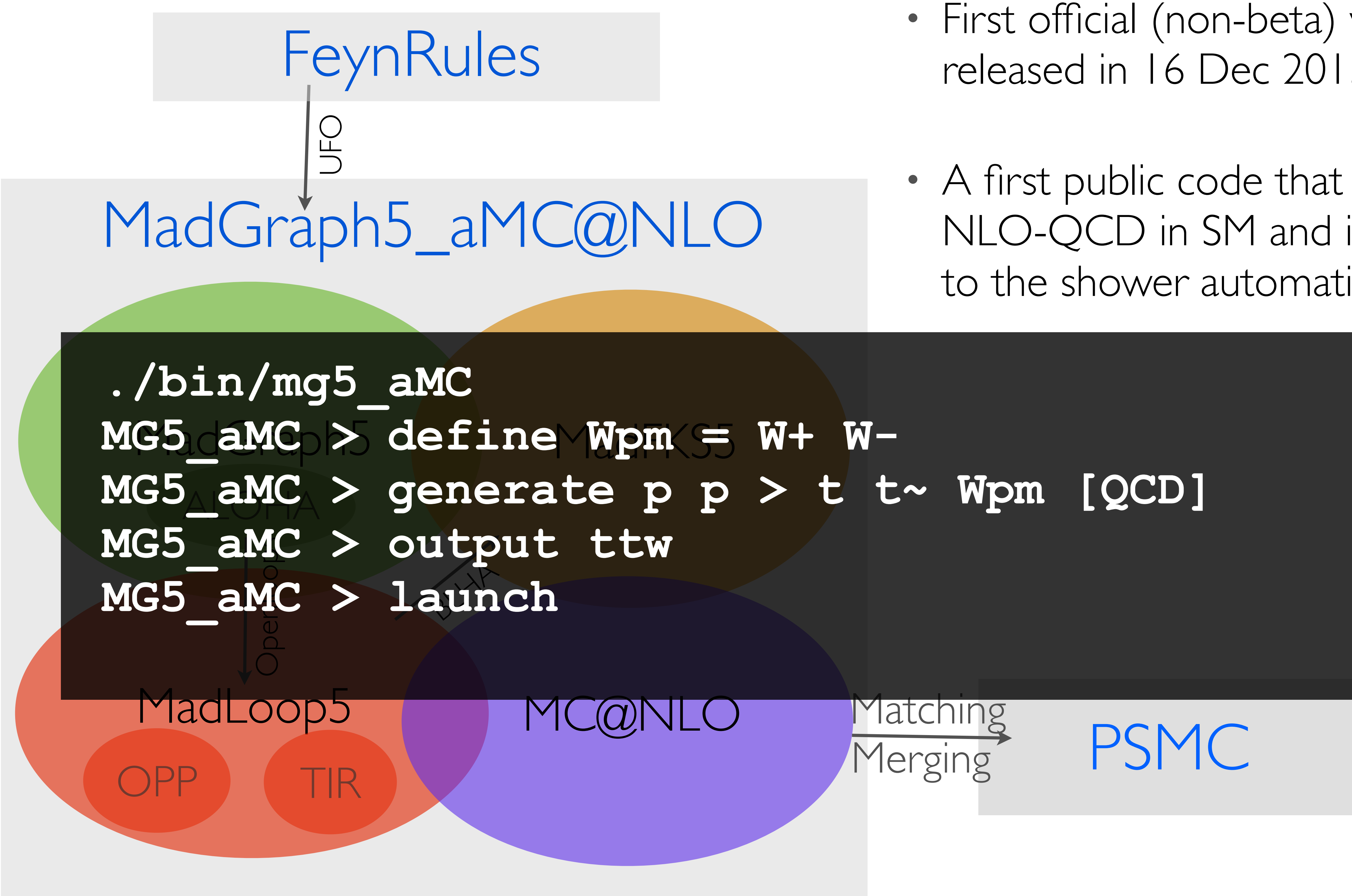

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```
./bin/mg5_aMC
MG5_aMC > define Wpm = W+ W-
MG5_aMC > generate p p > t t~ Wpm [QCD]
MG5_aMC > output ttw
MG5_aMC > launch
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Saturday, January 23, 16

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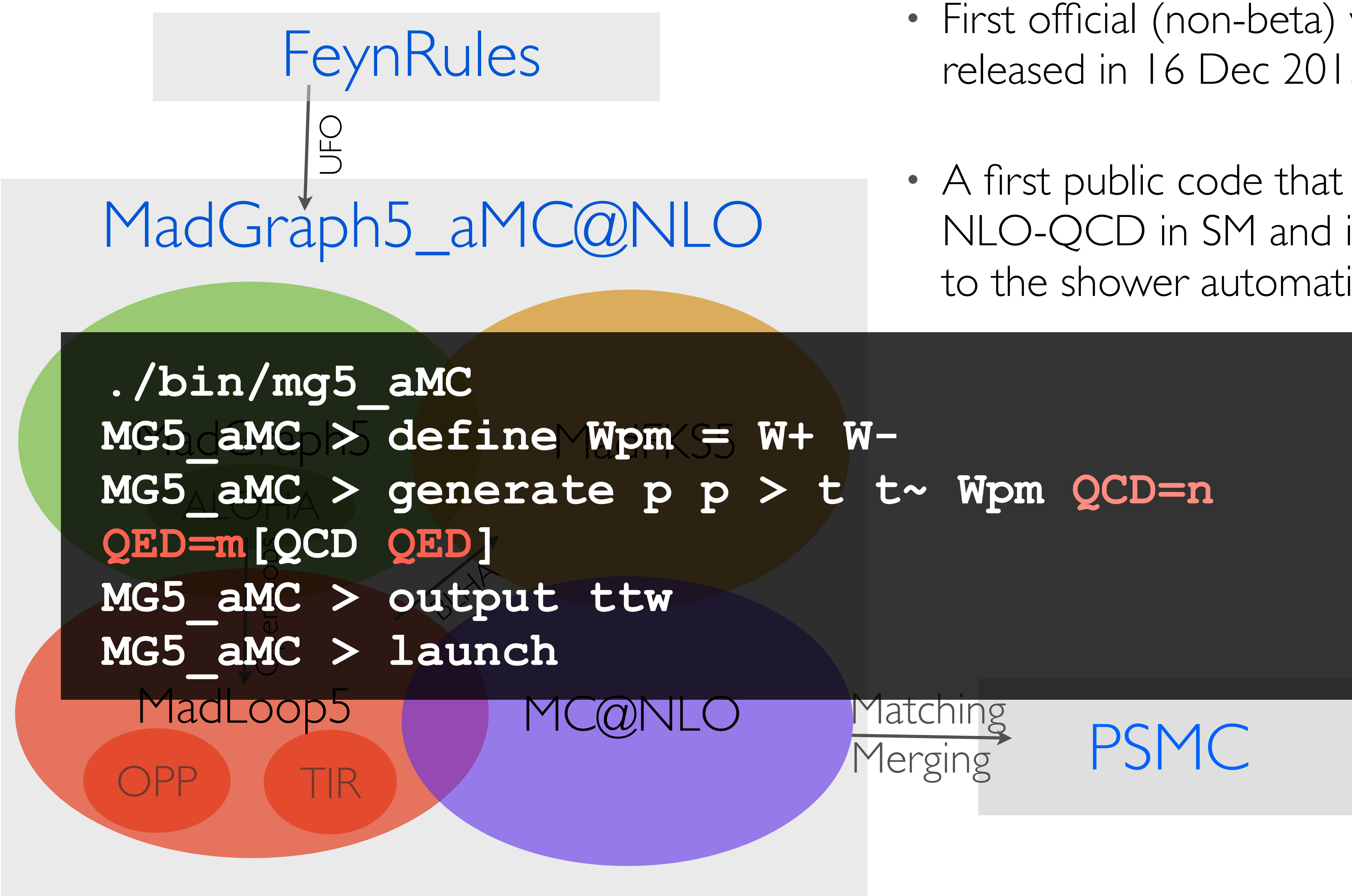


```
./bin/mg5_aMC
MG5_aMC > define Wpm = W+ W-
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QED=m[QCD QED]
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```

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- Expand the cross-section as a series in the perturbative couplings:

$$d\sigma = d\sigma_0[1 + \frac{\alpha_s}{2\pi}\Delta_1 + \left(\frac{\alpha_s}{2\pi}\right)^2\Delta_2 + \ldots$$

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QCD

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$$\alpha \sim 0.01 = 0.1^2 \sim \alpha_s^2$$

- Necessary for the the precision test and especially in the EW Sudakov region.

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QCD

```
tMass_UV = CTParameter(name = 'tMass_UV',
                       type = 'complex',
                       value = {-1:'cond(MT,0.0,complex(0,1)*((G**2)/(16.0*cmath.pi**2))*3.0*CF*MT)',
                       0:'cond(MT,0.0,complex(0,1)*((G**2)/(16.0*cmath.pi**2))*CF*(4.0-3.0*reglog(MT**2/MU_R**2\
))*MT)'
                       },
                       texname = '\delta m_t')
```

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EW

```
tMass_UV_EW = CTParameter(name = 'tMass_UV_EW',
                          type = 'complex',
                          value = {-1:'recms(CMSParam==1.0 and WT != 0,(ee**2*MT*(MW**2*(3 + 24*sw**2 - 32*sw**4) + cw**2*(9*MT**2 + 2*MW**2*(3 - 16*sw**2\
))))/(384.*cw**2*MW**2*cmath.pi**2*sw**2))'+'+'+dMB_tMass_UV_EW.value[-1],
                          0:'recms(CMSParam==1.0  and WT != 0,-(ee**2*(9*cw**2*MH**2*MT**2 - 72*cw**2*MT**4 - 18*MT**2*MW**2 - 9*cw**2*MT**2*MW**2 + 18*cw\
**2*MW**4 + 9*cw**2*MT**2*MZ**2 + 9*MW**2*MZ**2 - 96*MT**2*MW**2*sw**2 + 128*cw**2*MT**2*MW**2*sw**2 - 24*MW**2*MZ**2*sw**2 + 128*MT**2*MW**2*sw**4 + 32*M\
W**2*MZ**2*sw**4 - 9*cw**2*MT**4*reglog(16) + 9*cw**2*MT**4*reglog(1/(4.*cmath.pi)) + 9*MT**2*MW**2*reglog(1/(4.*cmath.pi)) - 24*MT**2*MW**2*sw**2*reglog(\
1/(4.*cmath.pi)) + 16*MT**2*MW**2*sw**4*reglog(1/(4.*cmath.pi)) - 18*cw**2*MT**4*reglog(cmath.pi) + 96*MT**2*MW**2*sw**2*reglog(cmath.pi) - 112*cw**2*MT**\
2*MW**2*sw**2*reglog(cmath.pi) - 128*MT**2*MW**2*sw**4*reglog(cmath.pi) - 192*MT**2*MW**2*sw**2*reglog(2*cmath.pi) + 224*cw**2*MT**2*MW**2*sw**2*reglog(2*\
cmath.pi) + 256*MT**2*MW**2*sw**4*reglog(2*cmath.pi) + 27*cw**2*MT**4*reglog(4*cmath.pi) + 9*MT**2*MW**2*reglog(4*cmath.pi) + 72*MT**2*MW**2*sw**2*reglog(\
4*cmath.pi) - 112*cw**2*MT**2*MW**2*sw**2*reglog(4*cmath.pi) - 112*MT**2*MW**2*sw**4*reglog(4*cmath.pi)))/(1152.*cw**2*MT*MW**2*cmath.pi**2*sw**2) + (ee**\
2*MH**2*MT*reglog(MU_R**2/MH**2))/(128.*MW**2*cmath.pi**2*sw**2) - (ee**2*MT*(18*cw**2*MT**2 + 9*MW**2 - 24*MW**2*sw**2 + 96*cw**2*MW**2*sw**2 + 32*MW**2*\
sw**4)*reglog(MU_R**2/MT**2))/(1152.*cw**2*MW**2*cmath.pi**2*sw**2) + (ee**2*MT*(MT**2 + 2*MW**2)*reglog(MU_R**2/MW**2))/(128.*MW**2*cmath.pi**2*sw**2) + \
(ee**2*MZ**2*(9*cw**2*MT**2 + 9*MW**2 - 24*MW**2*sw**2 + 32*MW**2*sw**4)*reglog(MU_R**2/MZ**2))/(1152.*cw**2*MT*MW**2*cmath.pi**2*sw**2) - (ee**2*(-9*cw**\
2*MH**2*MT**2 + 36*cw**2*MT**4 + 18*MT**2*MW**2 - 9*cw**2*MT**2*MZ**2 - 9*MW**2*MZ**2 + 48*MT**2*MW**2*sw**2 + 24*MW**2*MZ**2*sw**2 - 64*MT**2*MW**2*sw**4\
 - 32*MW**2*MZ**2*sw**4)*reglog((MT**2 + vep*complex(0,-1))/MU_R**2))/(1152.*cw**2*MT*MW**2*cmath.pi**2*sw**2) - (ee**2*(MT - MW)**2*(MT + MW)**2*(MT**2 +\
 2*MW**2)*reglogm((-MT**2 + MW**2 + vep*complex(0,-1))/MW**2))/(128.*MT**3*MW**2*cmath.pi**2*sw**2) + (ee**2*(-18*MT**2*MW**2 + 9*cw**2*MT**2*MZ**2 + 9*MW\
**2*MZ**2 - 48*MT**2*MW**2*sw**2 - 24*MW**2*MZ**2*sw**2 + 64*MT**2*MW**2*sw**4 + 32*MW**2*MZ**2*sw**4)*reglog((-MZ**2 - cmath.sqrt(MZ**4 - 4*MT**2*(MZ**2 \
+ vep*complex(0,-1))))/(2.*MT**2)))/(1152.*cw**2*MT*MW**2*cmath.pi**2*sw**2) + (ee**2*(-18*MT**2*MW**2 + 9*cw**2*MT**2*MZ**2 + 9*MW**2*MZ**2 - 48*MT**2*MW\
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**2*sw**2 + 64*MT**2*MW**2*sw**4 + 32*MW**2*MZ**2*sw**4)*(2*MT**2 - MZ**2 + cmath.sqrt(-4*MT**2*MZ**2 + MZ**4 + MT**2*vep*complex(0,4)))*reglog((-MZ**2 + \
cmath.sqrt(MZ**4 - 4*MT**2*(MZ**2 + vep*complex(0,-1))))/(2*MT**2 - MZ**2 + cmath.sqrt(MZ**4 - 4*MT**2*(MZ**2 + vep*complex(0,-1))))))/(2304.*cw**2*MT**3*\
MW**2*cmath.pi**2*sw**2) - (ee**2*(-18*MT**2*MW**2 + 9*cw**2*MT**2*MZ**2 + 9*MW**2*MZ**2 - 48*MT**2*MW**2*sw**2 - 24*MW**2*MZ**2*sw**2 + 64*MT**2*MW**2*sw\
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**2 + vep*complex(0,-1))))/(-2*MT**2 + MZ**2 + cmath.sqrt(MZ**4 - 4*MT**2*(MZ**2 + vep*complex(0,-1))))))/(2304.*cw**2*MT**3*MW**2*cmath.pi**2*sw**2) - (e\
e**2*MT*(-MH + 2*MT)*(MH + 2*MT)*reglog(-1 + (MH**2 - cmath.sqrt(MH**4 - 4*MT**2*(MH**2 + vep*complex(0,-1))))/(2.*MT**2)))/(128.*MW**2*cmath.pi**2*sw**2)\
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4*MH**2*MT**2 + MT**2*vep*complex(0,4)))/(MH**2 + cmath.sqrt(MH**4 - 4*MH**2*MT**2 + MT**2*vep*complex(0,4)))))/(256.*MT*MW**2*cmath.pi**2*sw**2) + (ee**2\
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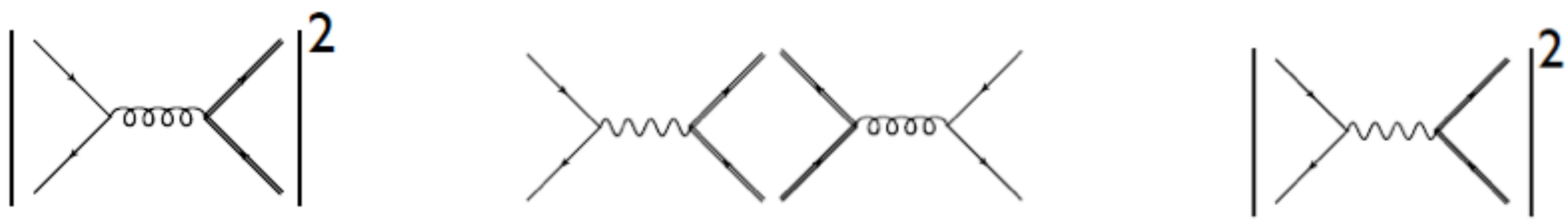

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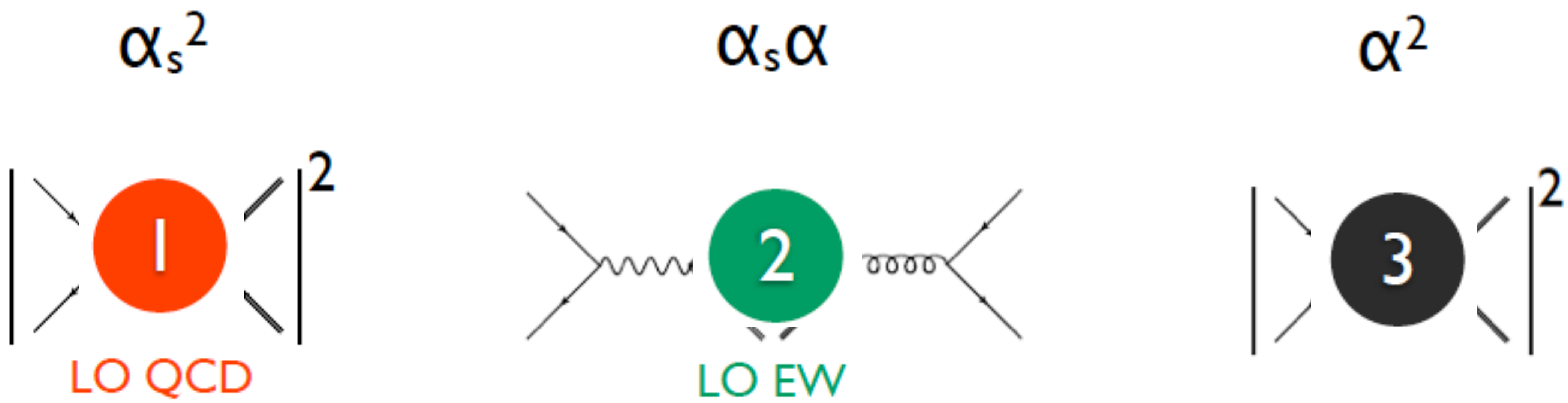

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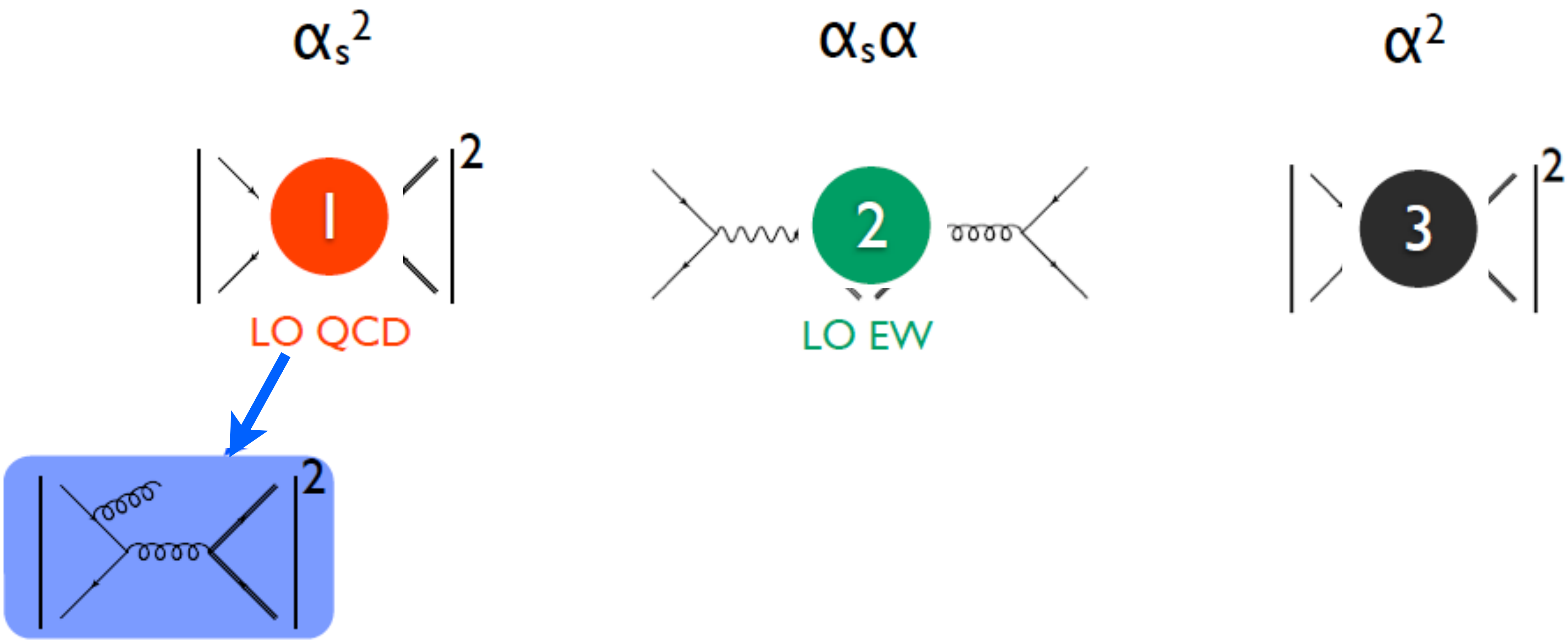

NLO QCD is α_s correction to LO QCD

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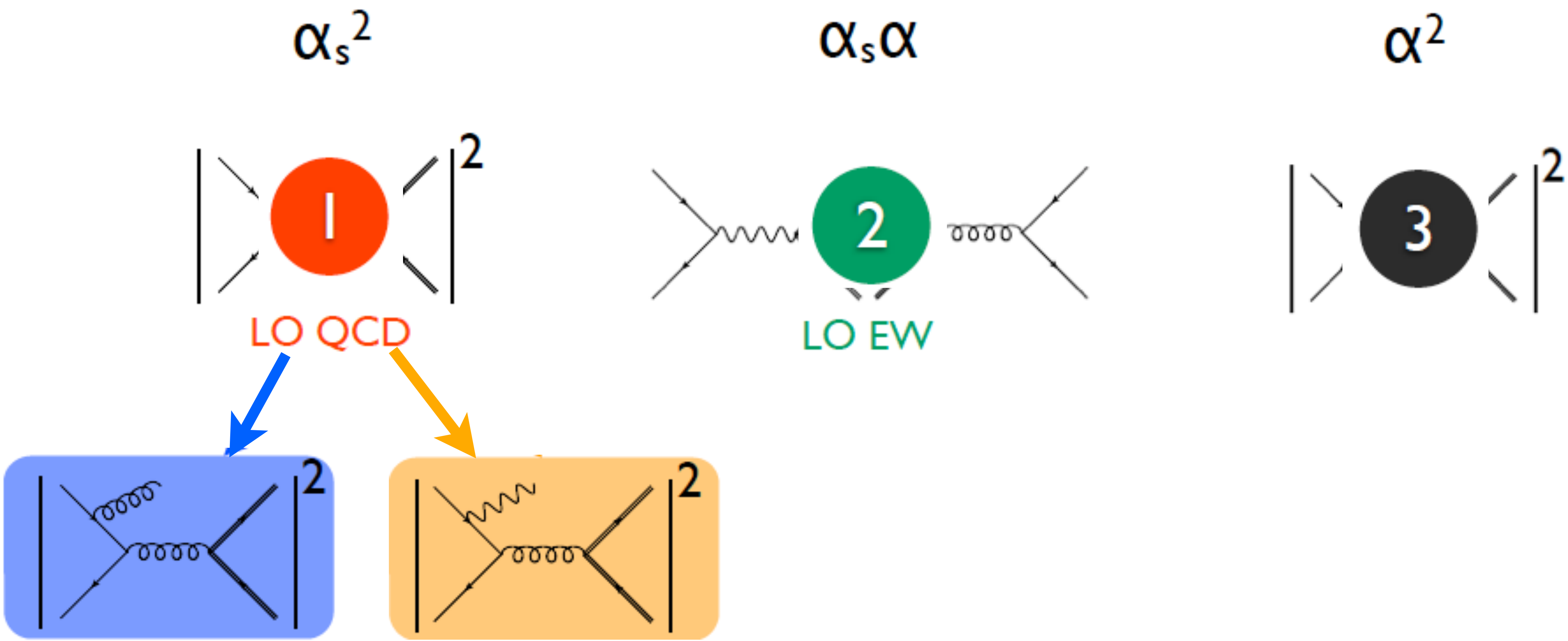

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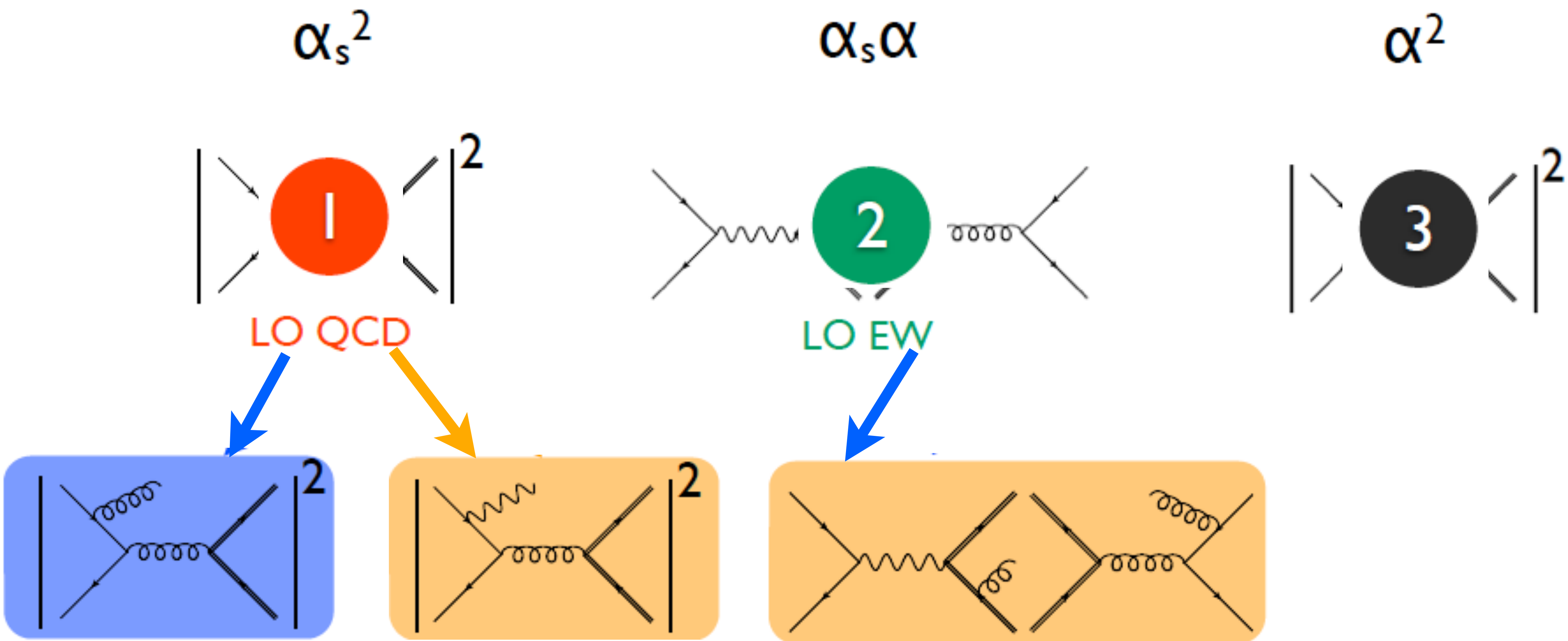

NLO EW can also be α_s correction to LO EW

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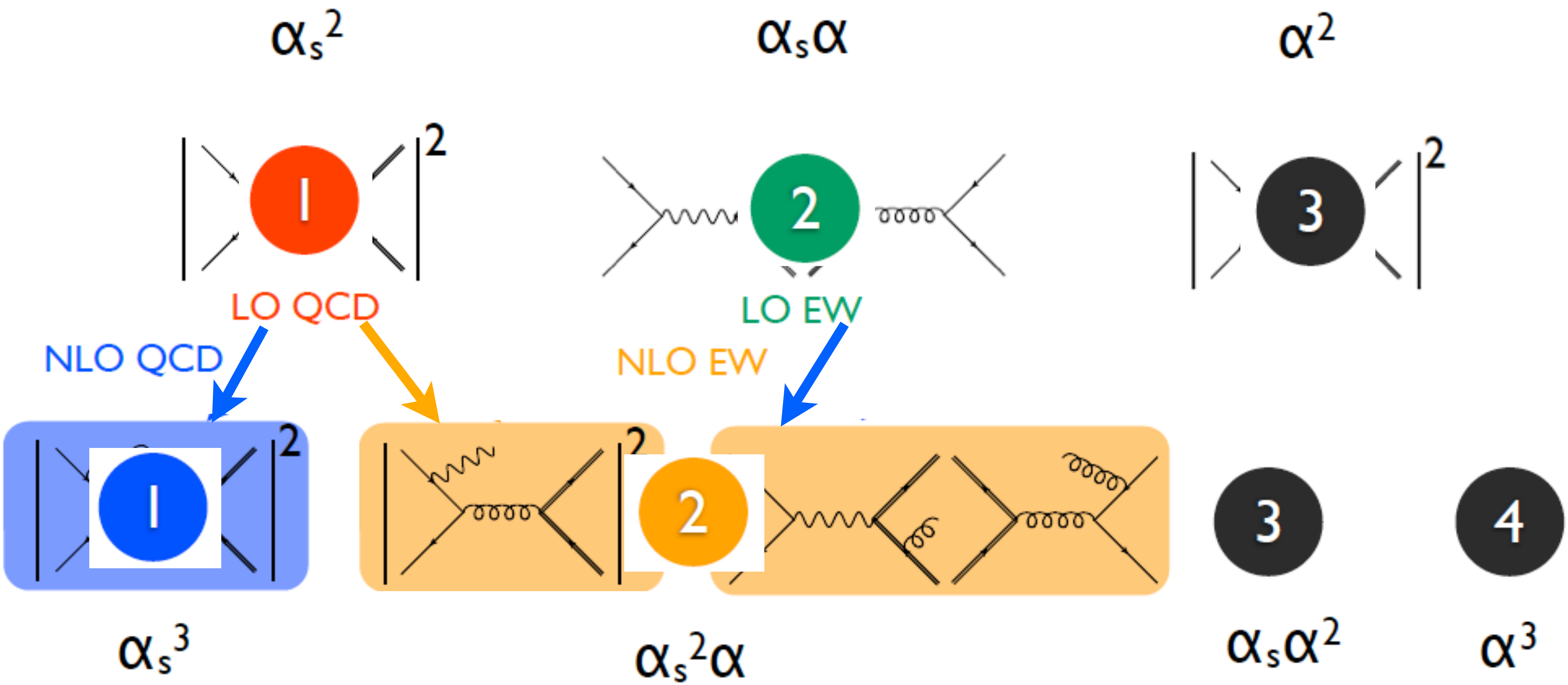

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- Loop computation: MadLoop V. Hirschi et al. (2011);J. Alwall et al. (2014)
  - OPP: CutTools G. Ossola et al. (2006,2007)
  - or TIR:
    - Golem95 T. Binoth et al. (2008), PJFry++ V. Yundin (2012), IREGI HSS unpublished
  - Renormalization in $\alpha(M_Z)$ or G_μ scheme.
  - Well advanced validation for complex-mass scheme.
- IR subtraction and integ : MadFKS R. Frederix et al. (2011);J. Alwall et al. (2014)
  - QCD+EW splittings
  - Keep track of mixed order combinations
  - More tricks in NLO QCD are generalized to QCD+EW

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Work in progress:
matching to QCD+QED parton shower

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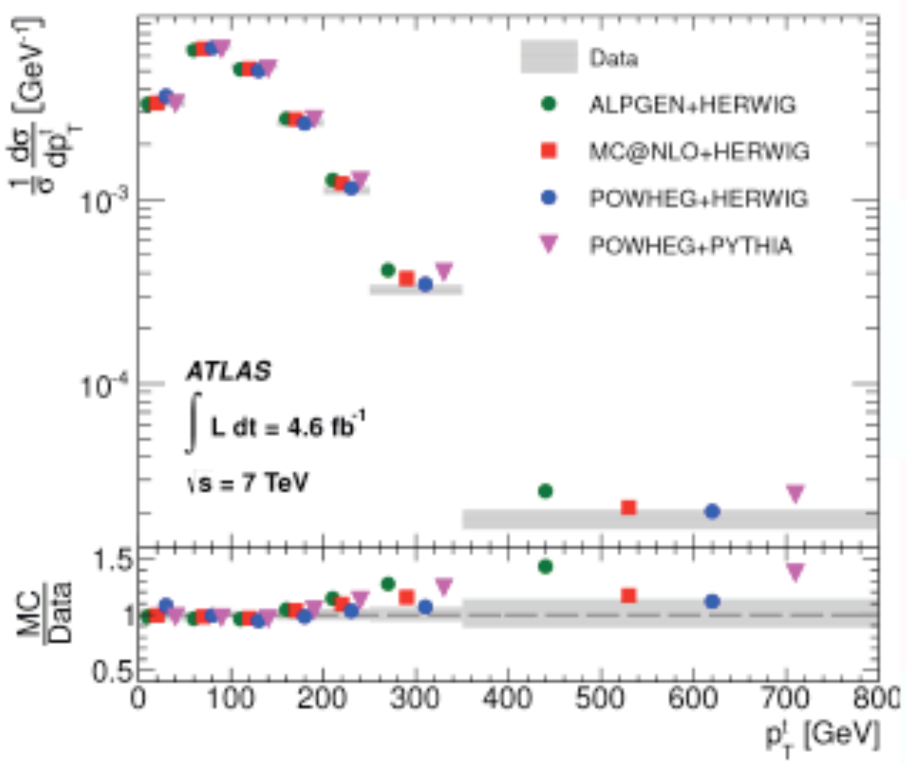
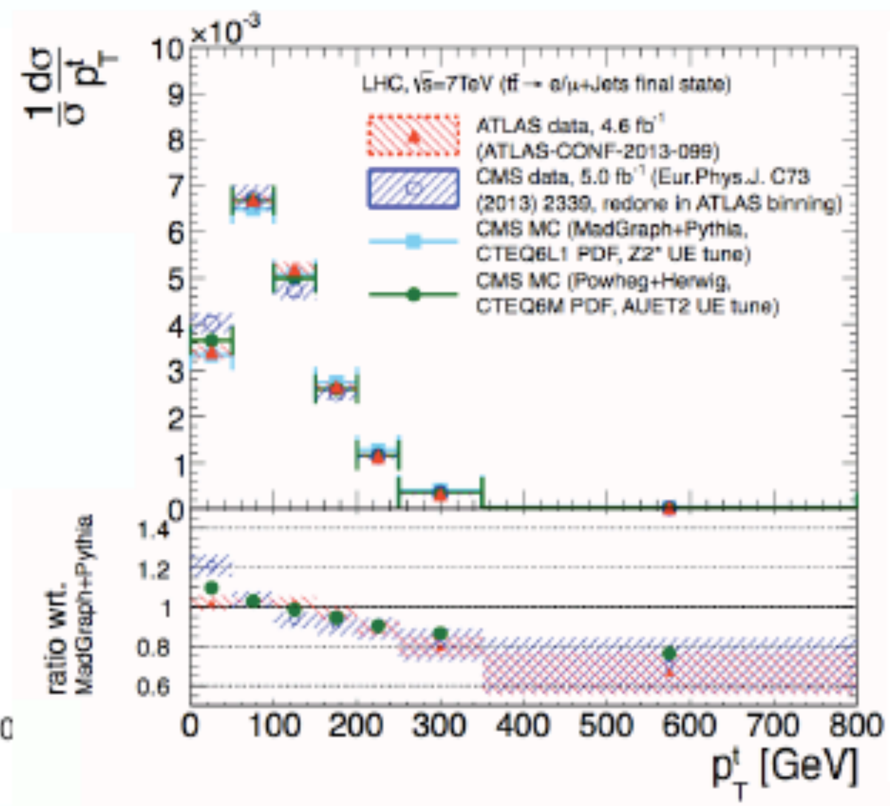
  - QCD+EW splittings
  - Keep track of mixed order combinations
  - More tricks in NLO QCD are generalized to QCD+EW

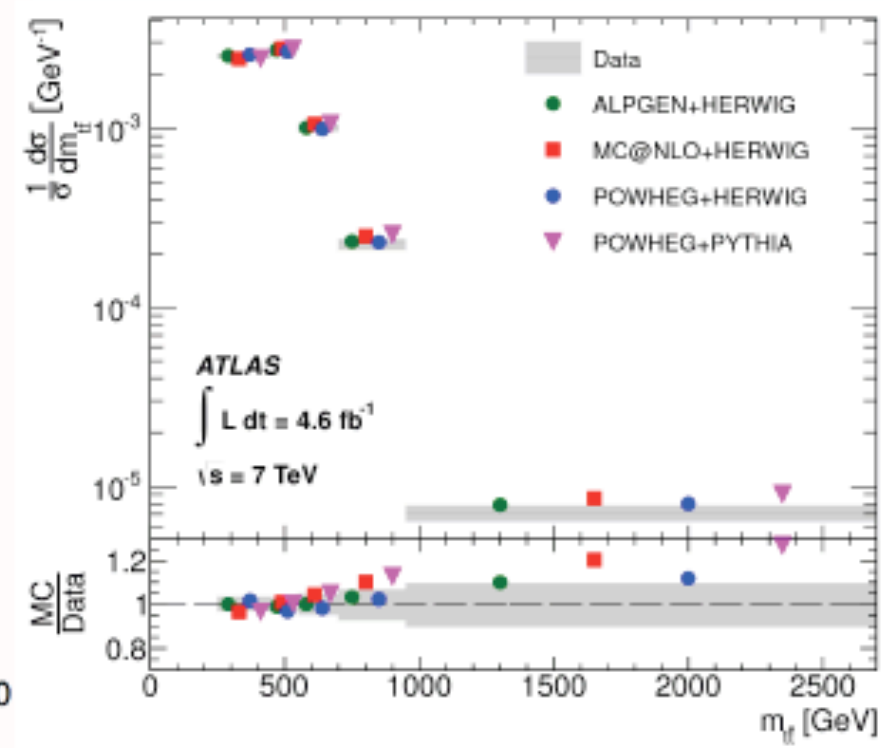
WARMUP: TOP QUARK PAIR

courtesy of M. Zaro

- ATLAS and CMS see some 'anomaly' on the top p_T distribution and $t\bar{t}$ invariant mass
- Data are softer than NLO QCD MonteCarlos (up to 30-40%)

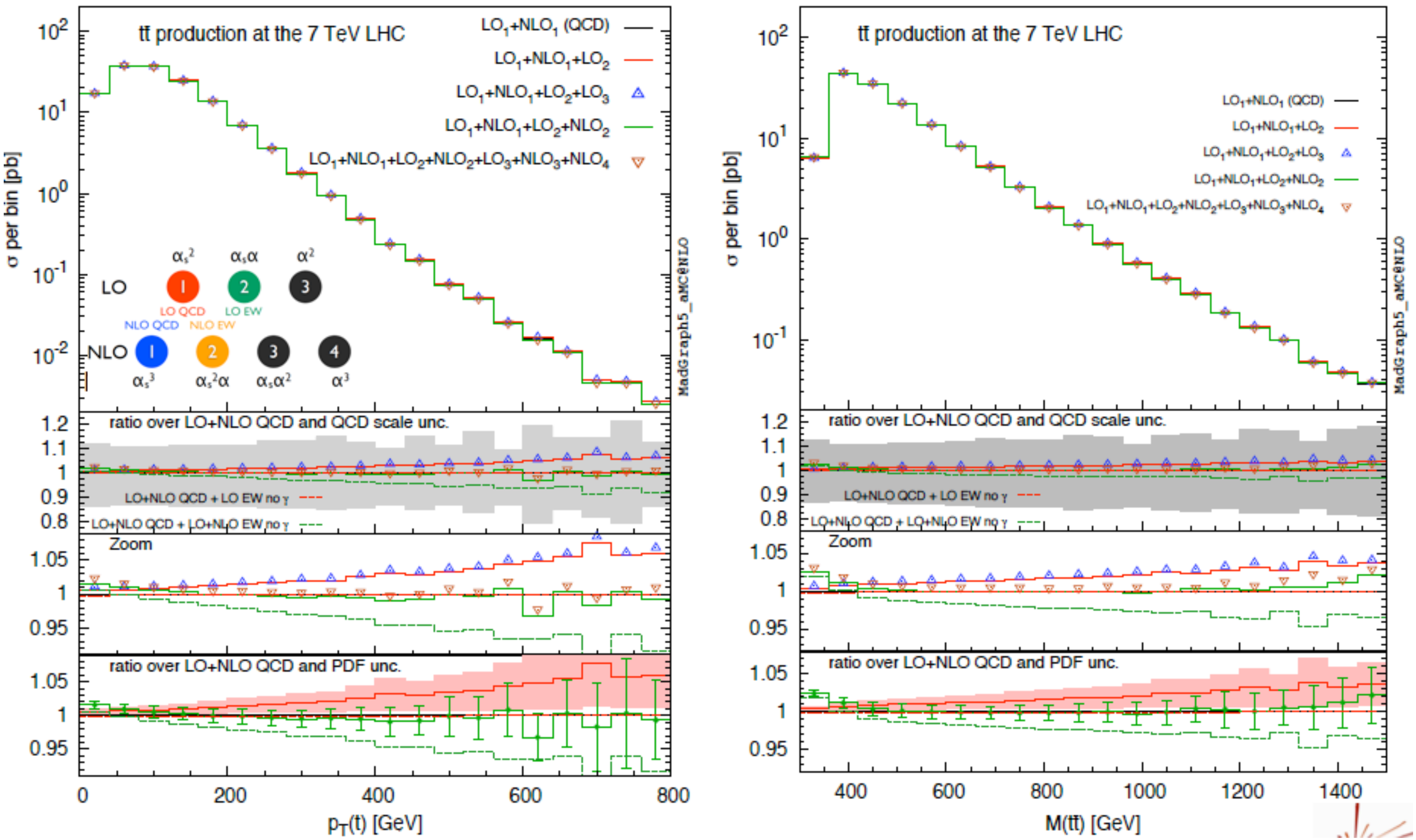






- Is it an EW effect?

WARMUP: TOP QUARK PAIR



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WARMUP: TOP QUARK PAIR

- EW corrections account at most -10% at large p_T, -5% at large mass
- LO_2 has only $g\gamma$ and $b\bar{b}$ initial states; dominant γ-initiated contribution, need for PDFs with photons
- Photon effect as large as EW corrections, but almost 100% uncertain
- NLO_2 formally also includes heavy boson radiation (HBR). HBR not included for $t\bar{t}$
- Subleading corrections (LO_3, $NLO_{3,4}$) very small

A FIRST APPLICATION: TOP QUARK PAIR+H/Z/W

S. Frixione, V. Hirschi, D. Pagani, HSS, M. Zaro (2014,2015)

- Setup:
  - Masses $m_t = 173.3\ \text{GeV}\,, \quad m_H = 125\ \text{GeV}\,,$
    $m_W = 80.385\ \text{GeV}\,, \quad m_Z = 91.188\ \text{GeV}\,.$
  - Coupling:

$$\frac{1}{\alpha(m_Z)} = 128.93\,. \quad \longrightarrow \quad \alpha(m_Z)\ \text{scheme}$$

$$G_\mu = 1.16639 \cdot 10^{-5} \longrightarrow \frac{1}{\alpha} = 132.23\,. \quad \longrightarrow \quad G_\mu\ \text{scheme}$$

  - Scales:

$$\mu = \frac{H_T}{2} \equiv \frac{1}{2}\sum_i \sqrt{m_i^2 + p_T^2(i)}\,,$$

LO+NLO QCD scale uncertainties in the range

$$\frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu\,,$$

  - PDF: NNPDF2.3QED $\alpha_S(m_Z) = 0.118\,.$
- Boosted regime: $p_T(t) \geq 200\ \text{GeV}\,, \quad p_T(\bar{t}) \geq 200\ \text{GeV}\,, \quad p_T(V) \geq 200\ \text{GeV}\,.$

A FIRST APPLICATION: TOP QUARK PAIR+H/Z/W

S. Frixione, V. Hirschi, D. Pagani, HSS, M. Zaro (2014,2015)

$t\bar{t}H$: σ(pb)	13 TeV
LO QCD	$3.617 \cdot 10^{-1}$ $(1.338 \cdot 10^{-2})$
NLO QCD	$1.073 \cdot 10^{-1}$ $(3.230 \cdot 10^{-3})$
LO EW	$4.437 \cdot 10^{-3}$ $(3.758 \cdot 10^{-4})$
LO EW no γ	$-1.390 \cdot 10^{-3}$ $(-2.452 \cdot 10^{-5})$
NLO EW	$-4.408 \cdot 10^{-3}$ $(-1.097 \cdot 10^{-3})$
NLO EW no γ	$-4.919 \cdot 10^{-3}$ $(-1.131 \cdot 10^{-3})$
HBR	$3.216 \cdot 10^{-3}$ $(2.496 \cdot 10^{-4})$

$$\sigma_{\rm HBR}(t\bar{t}H) = \sigma(t\bar{t}HH) + \sigma(t\bar{t}HZ) + \sigma(t\bar{t}HW^+) + \sigma(t\bar{t}HW^-),$$

$t\bar{t}H$: $\delta(\%)$	13 TeV
NLO QCD	$29.7^{+6.8}_{-11.1} \pm 2.8$ $(24.2^{+4.8}_{-10.6} \pm 4.5)$
LO EW	1.2 ± 0.9 (2.8 ± 2.0)
LO EW no γ	-0.4 ± 0.0 (-0.2 ± 0.0)
NLO EW	-1.2 ± 0.1 (-8.2 ± 0.3)
NLO EW no γ	-1.4 ± 0.0 (-8.5 ± 0.2)
HBR	0.89 (1.87)

- EW correction is moderate in inclusive cross sections.
- It can be important in the boosted regime (values in parentheses)
- Photon-induced contribution is important, especially in boosted regime.
- HBR contribution is small. It is only partly cancel NLO EW.

A FIRST APPLICATION: TOP QUARK PAIR+H/Z/W

S. Frixione, V. Hirschi, D. Pagani, HSS, M. Zaro (2014,2015)

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$t\bar{t}Z$: σ(pb)	13 TeV
LO QCD	$5.282 \cdot 10^{-1}$ $(1.955 \cdot 10^{-2})$
NLO QCD	$2.426 \cdot 10^{-1}$ $(7.856 \cdot 10^{-3})$
LO EW	$-2.172 \cdot 10^{-4}$ $(4.039 \cdot 10^{-4})$
LO EW no γ	$-5.771 \cdot 10^{-3}$ $(-6.179 \cdot 10^{-5})$
NLO EW	$-2.017 \cdot 10^{-2}$ $(-2.172 \cdot 10^{-3})$
NLO EW no γ	$-2.158 \cdot 10^{-2}$ $(-2.252 \cdot 10^{-3})$
HBR	$5.056 \cdot 10^{-3}$ $(4.162 \cdot 10^{-4})$

$t\bar{t}Z$: δ(%)	13 TeV
NLO QCD	$45.9^{+13.2}_{-15.5} \pm 2.9$ $(40.2^{+11.1}_{-15.0} \pm 4.7)$
LO EW	0.0 ± 0.7 (2.1 ± 1.6)
LO EW no γ	-1.1 ± 0.0 (-0.3 ± 0.0)
NLO EW	-3.8 ± 0.2 (-11.1 ± 0.5)
NLO EW no γ	-4.1 ± 0.1 (-11.5 ± 0.3)
HBR	0.96 (2.13)

- EW correction is moderate in inclusive cross sections.
- It can be important in the boosted regime (values in parentheses)
- Photon-induced contribution is important, especially in boosted regime.
- HBR contribution is small. It is only partly cancel NLO EW.
  - ttZ is similar to ttH.

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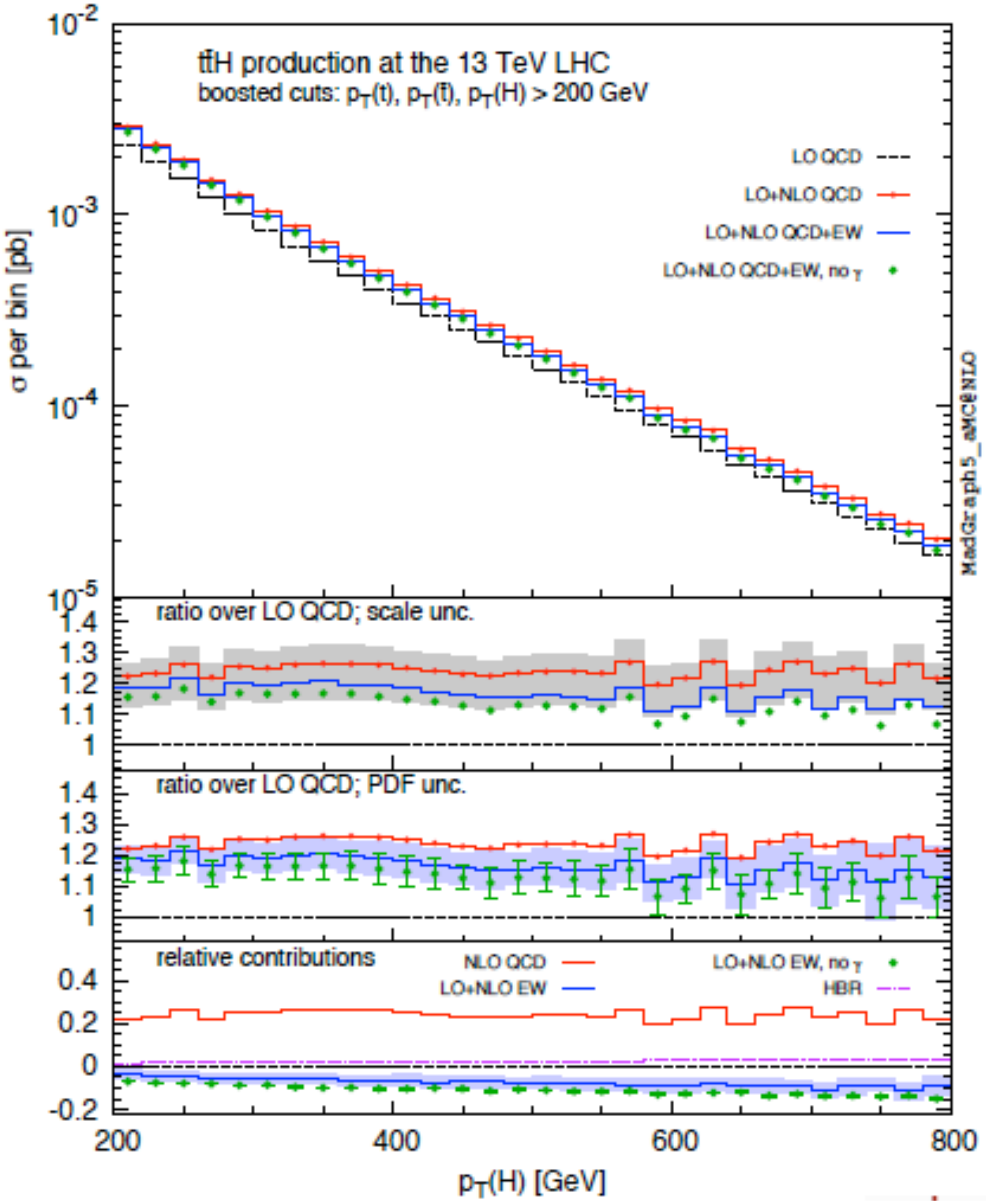

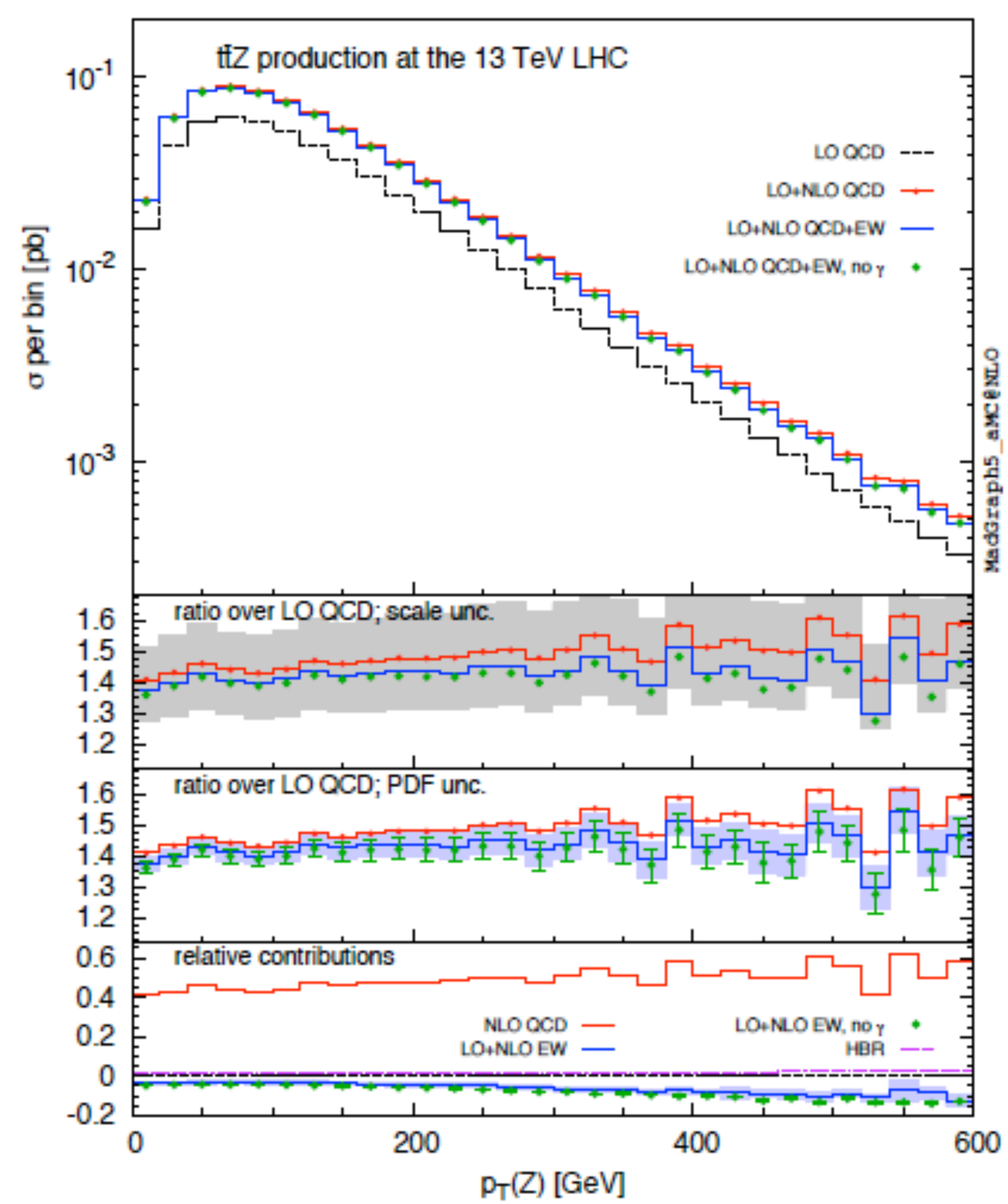

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$t\bar{t}W^+$: σ(pb)	13 TeV
LO QCD	$2.496 \cdot 10^{-1}$ $(7.749 \cdot 10^{-3})$
NLO QCD	$1.250 \cdot 10^{-1}$ $(4.624 \cdot 10^{-3})$
LO EW	0
LO EW no γ	0
NLO EW	$-1.931 \cdot 10^{-2}$ $(-1.490 \cdot 10^{-3})$
NLO EW no γ	$-1.988 \cdot 10^{-2}$ $(-1.546 \cdot 10^{-3})$
HBR	$9.677 \cdot 10^{-3}$ $(5.743 \cdot 10^{-4})$

$t\bar{t}W^+$: δ(%)	13 TeV
NLO QCD	$50.1^{+14.2}_{-13.5} \pm 2.4$ $(59.7^{+18.9}_{-17.7} \pm 3.1)$
LO EW	0
LO EW no γ	0
NLO EW	-7.7 ± 0.2 (-19.2 ± 0.7)
NLO EW no γ	-8.0 ± 0.2 (-20.0 ± 0.5)
HBR	3.88 (7.41)

- EW correction is bigger in ttW.
- HBR is enhanced by initial parton luminosity: e.g. ttWW has gluon-gluon initial states.
- No LO EW because of color flow.

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$t\bar{t}W^-$: σ(pb)	13 TeV
LO QCD	$1.265 \cdot 10^{-1}$ $(3.186 \cdot 10^{-3})$
NLO QCD	$6.515 \cdot 10^{-2}$ $(2.111 \cdot 10^{-3})$
LO EW	0
LO EW no γ	0
NLO EW	$-8.502 \cdot 10^{-3}$ $(-5.838 \cdot 10^{-4})$
NLO EW no γ	$-8.912 \cdot 10^{-3}$ $(-6.094 \cdot 10^{-4})$
HBR	$8.219 \cdot 10^{-3}$ $(4.781 \cdot 10^{-4})$

$t\bar{t}W^-$: $\delta(\%)$	13 TeV
NLO QCD	$51.5^{+14.8}_{-13.8} \pm 2.8$ $(66.3^{+21.7}_{-19.6} \pm 3.9)$
LO EW	0
LO EW no γ	0
NLO EW	-6.7 ± 0.2 (-18.3 ± 0.8)
NLO EW no γ	-7.0 ± 0.2 (-19.1 ± 0.6)
HBR	6.50 (15.01)

- EW correction is bigger in ttW.
- HBR is enhanced by initial parton luminosity: e.g. ttWW has gluon-gluon initial states.
- No LO EW because of color flow.

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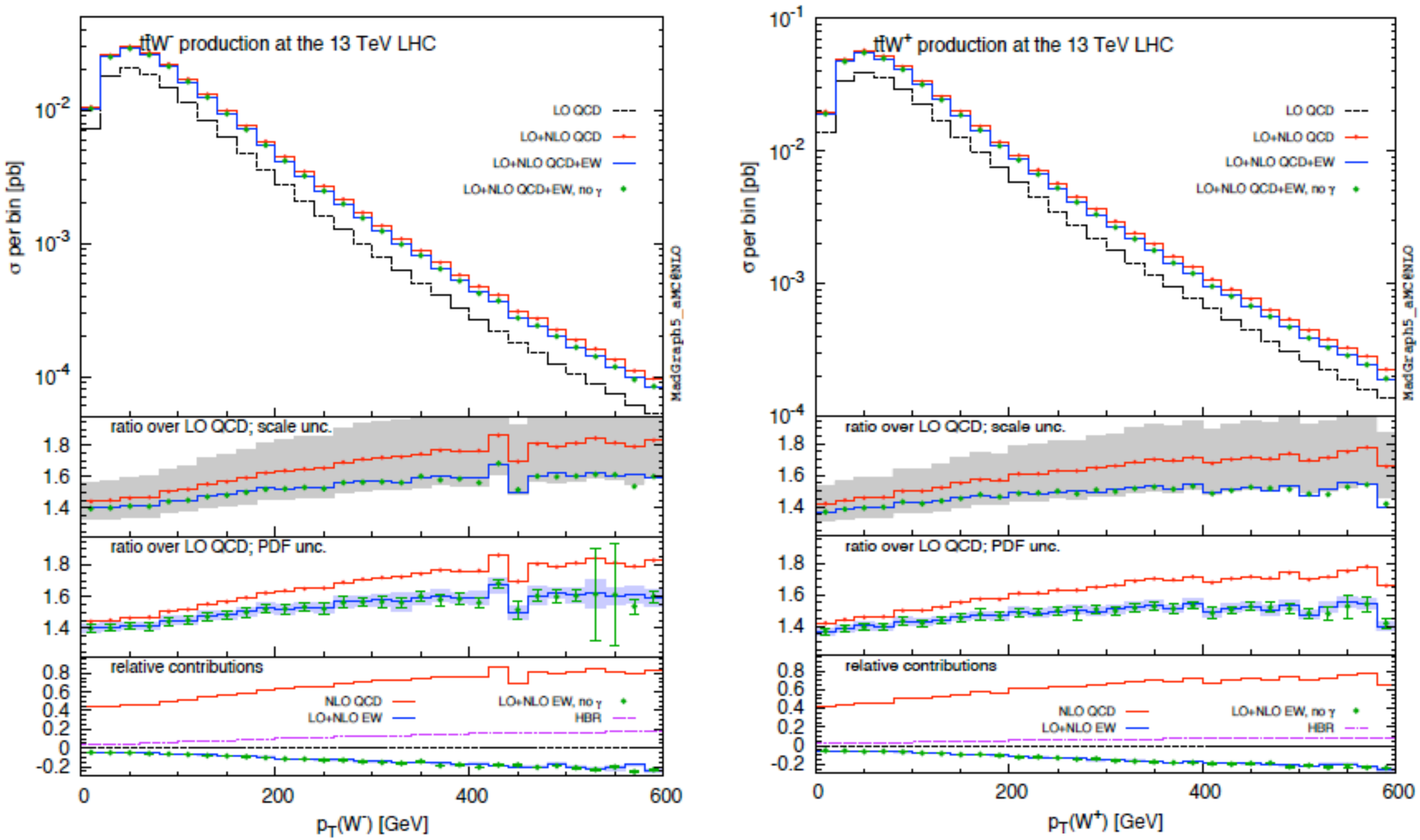

Saturday, January 23, 16

SUMMARY & OUTLOOK

- NLO EW predictions are well motivated and they become important at LHC Run II and future colliders.

- Much progress in automation of EW corrections has been achieved in MadGraph5_aMC@NLO. A first phenomenology application was out.

- Comparisons with other tools are ongoing, which were established in Les Houches Monte-Carlo workshop 2015. It will also be used in LHCHXSWG YR4 and FCC-hh physics report.

- The code will be public in the near future.

Thank you for your attention !