THE 2018 INTERNATIONAL WORKSHOP ON HIGH ENERGY CIRCULAR ELECTRON POSITRON COLLIDER

QCD and EW corrections in light of precision measurements at CEPC-SppC

Hua-Sheng Shao

12 November 2018

INTRODUCTION

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

- **Energy frontier in lab:**
  - Direct and/or indirect to probe BSM and to improve our knowledge of SM
  - hadron-hadron colliders: LHC, SppC, FCC-hh
    - They are mainly QCD machines.
    - Require the good knowledge of PDF for hard probes.
    - The precision measurements are gained by large yields.
  - lepton-lepton colliders: CEPC, FCC-ee, ILC, CLIC
    - Importance of initial-state radiations and possible beamstrahlung.
    - Low background and large reconstruction efficiency.
  - lepton-hadron colliders: LHeC, FCC-eh, EIC
    - They are dedicated QCD machines.
    - Determine initial conditions for hadron-hadron colliders.

♦ Running

♦ In plan

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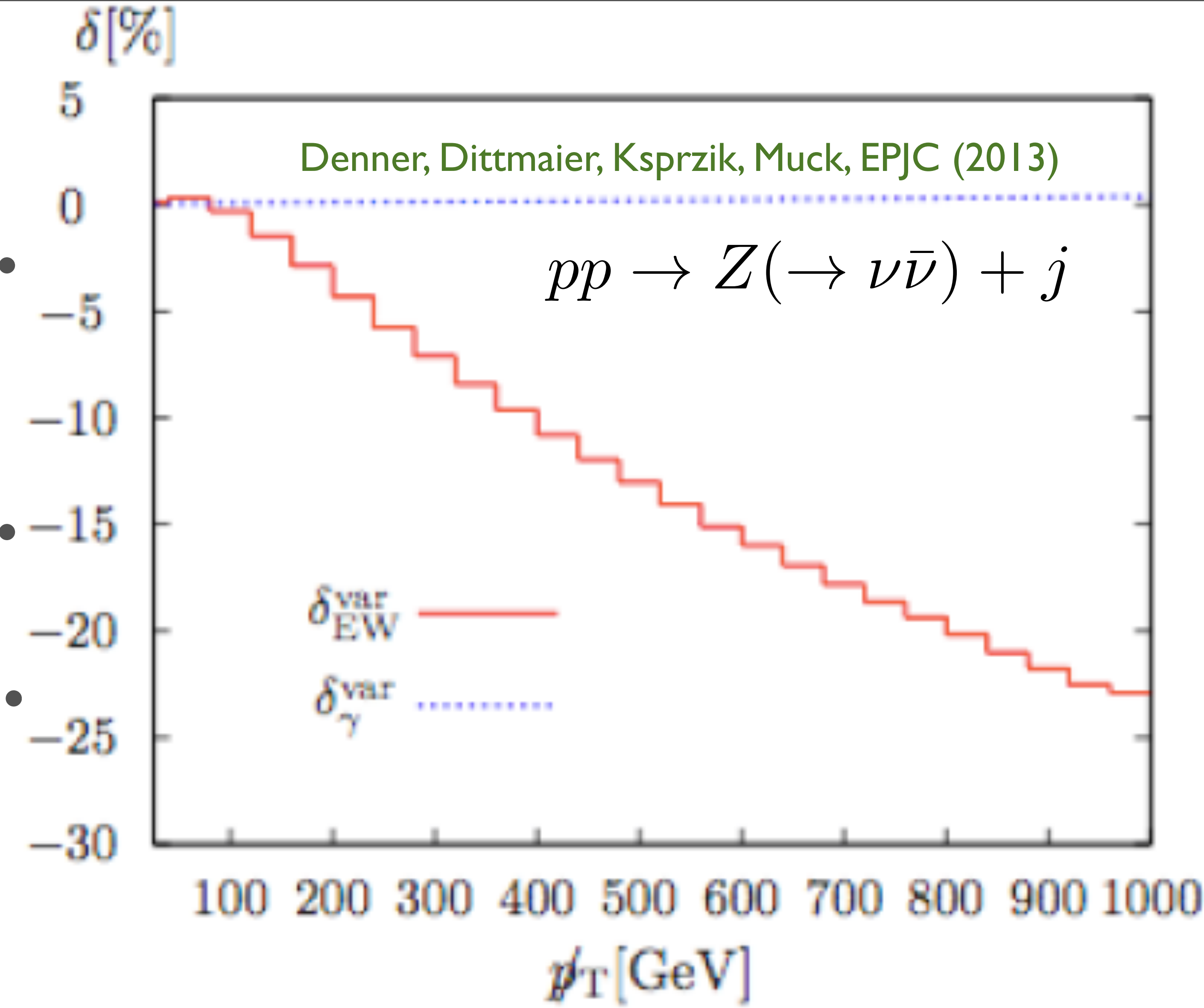
Precision Theory Meets Precision Measurements

FRONTIER OF PRECISION THEORY

- LHC runs at 13 TeV and future colliders at 100 TeV
  - energy reaches deeper into multi-TeV region & high integrated luminosity
  - many processes (even rare processes before) reach precision era (precent)
- NLO QCD becomes standard: automation (e.g. MG5_aMC)
  - scale uncertainty reaches to 10% level
- Frontier of precision theory for ElectroWeak scale observables
  - Goal: to achieve the precent level predictions
  - Request: NNLO QCD and NLO EW $\alpha_s^2 \simeq \alpha \simeq 1\%$
  - Automation: NLO EW (done at fixed order) and NNLO QCD (long way)
- Necessity of NLO EW corrections:
  - First opportunity to explore TeV scale kinematics, where EWC ~ 10%
  - High precision measurements are present or in planned
    - cross section ratios, e.g. different center-of-mass energy, different processes
    - fundamental parameters, e.g. W mass
    - (differential) cross sections for candle processes, e.g. top quark pair xs, Z pt

SION THEORY



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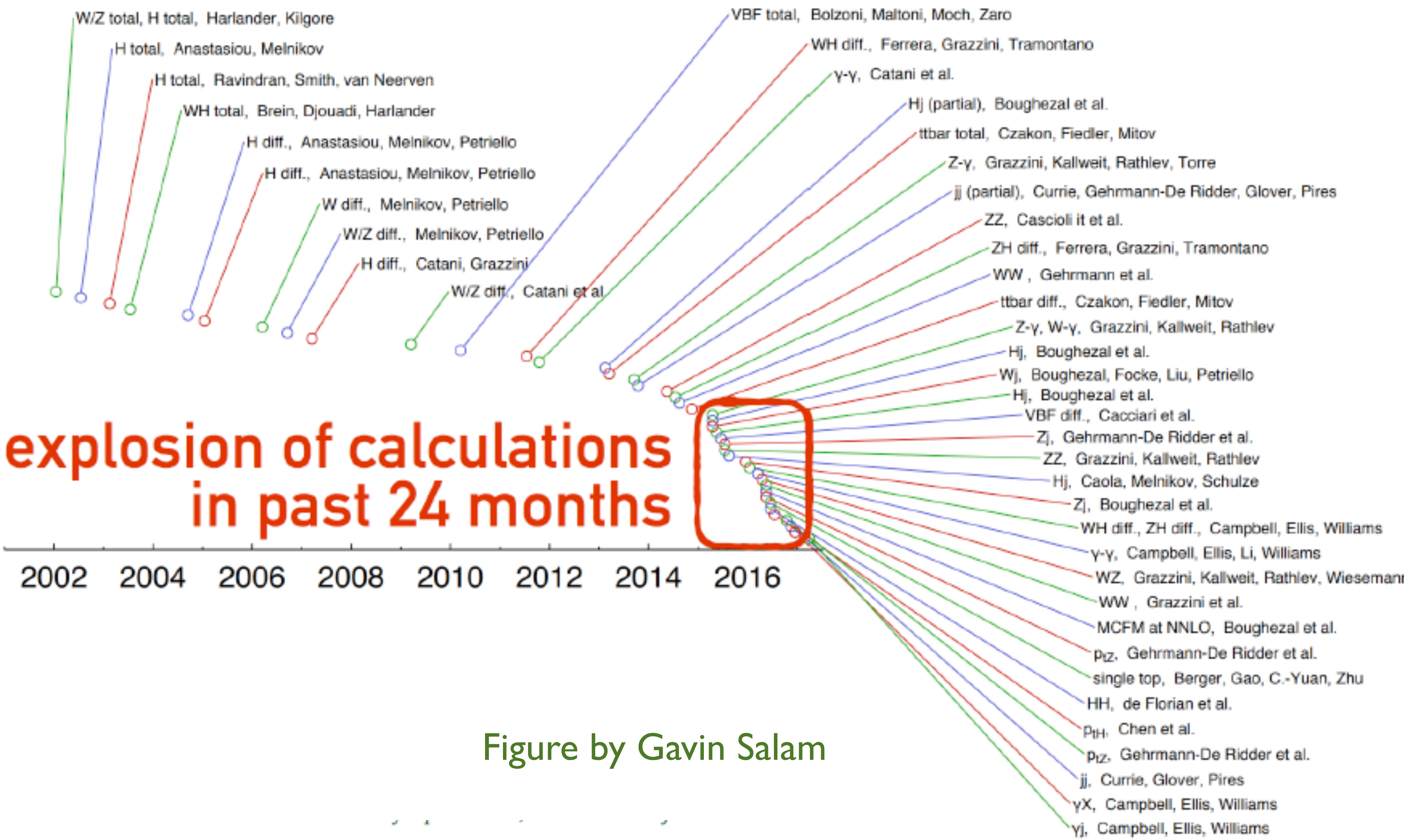


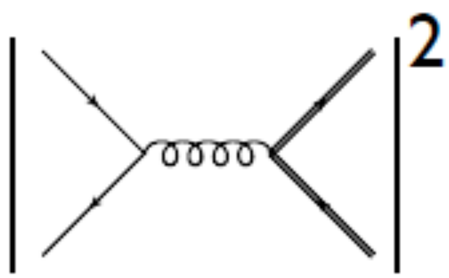
Figure by Gavin Salam

- **Explosion of NNLO QCD calculations**
  - **Necessary to reduce QCD scale uncertainty**

PERTURBATIVE CALCULATIONS

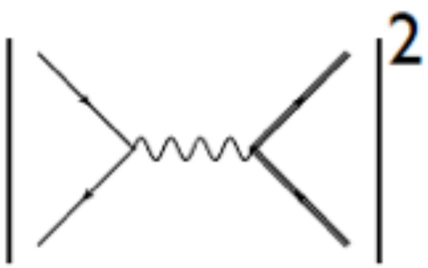
- **Perturbative expansion in the Standard Model**
  - Take dijet hadroproduction as an example Frederix, Frixione, Hirschi, Pagani, HSS, Zaro, JHEP (2017)

α_s^2



$\alpha_s\alpha$

α^2



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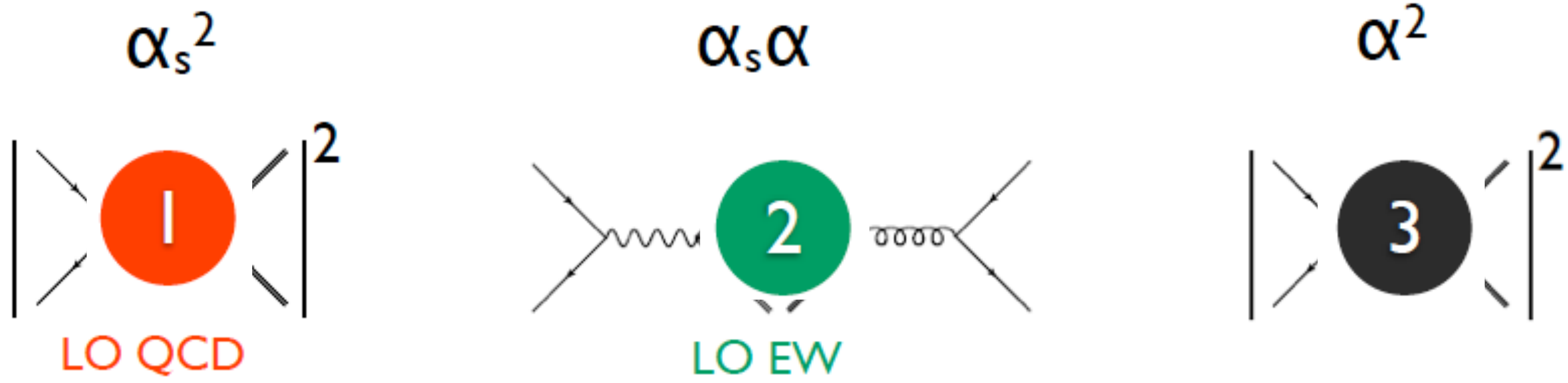

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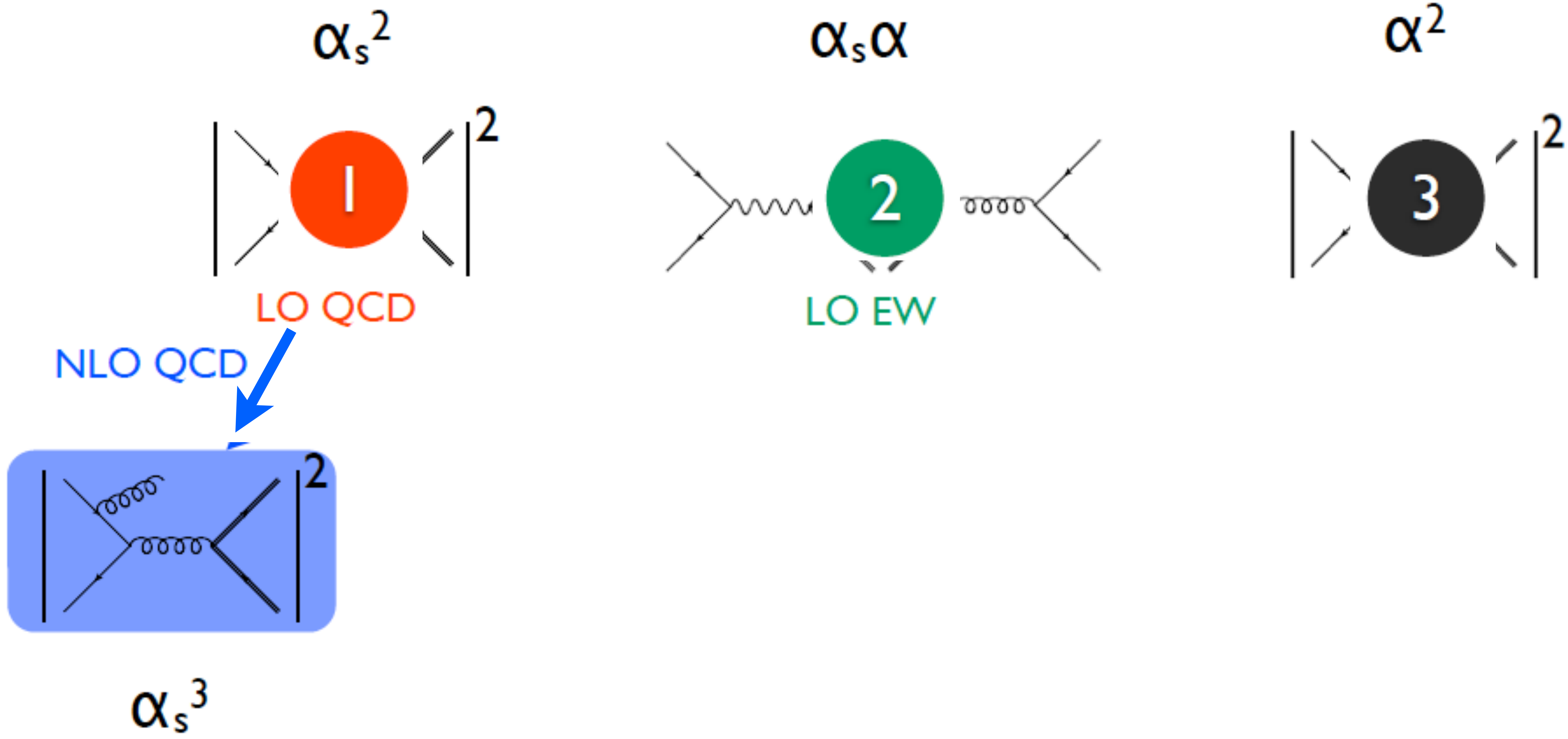

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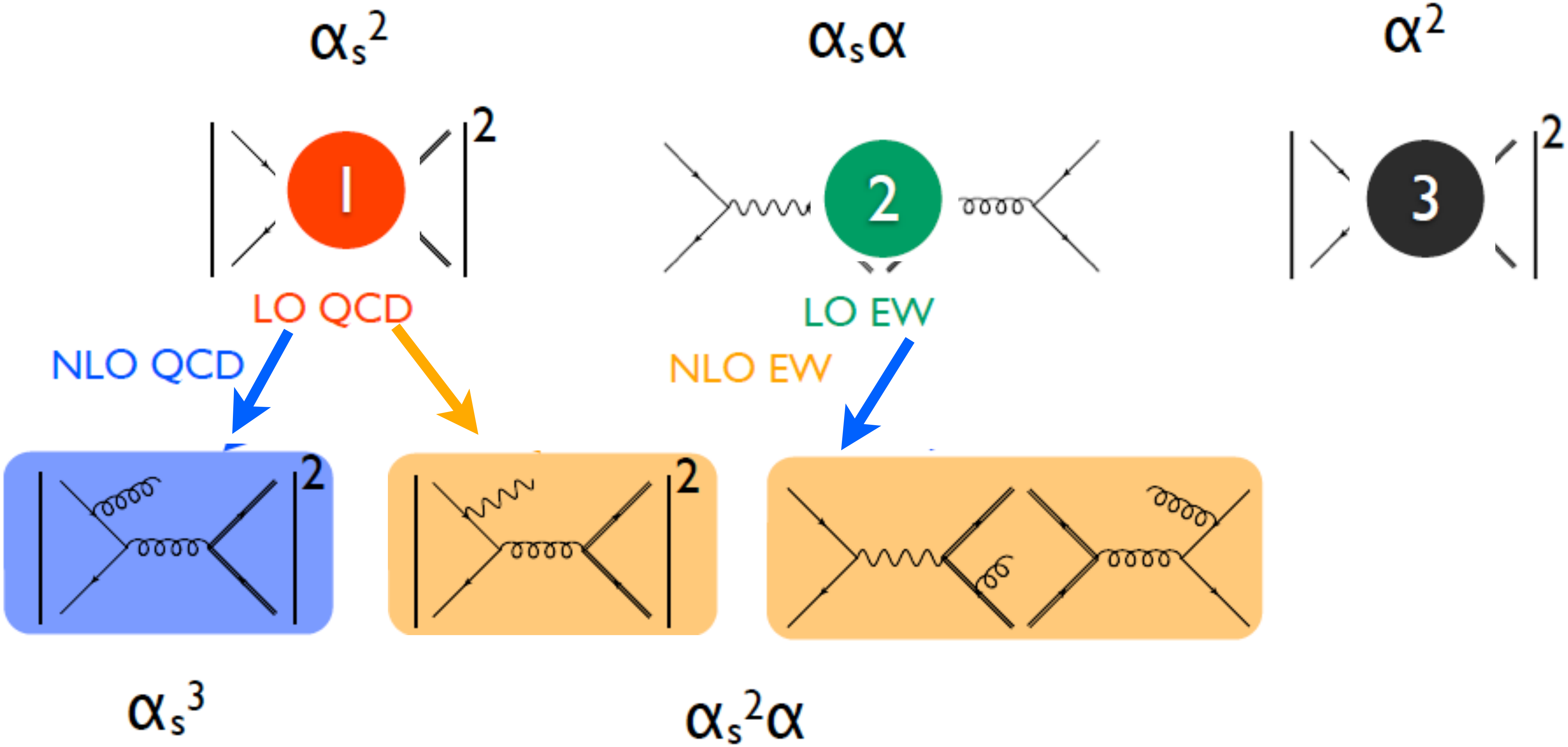

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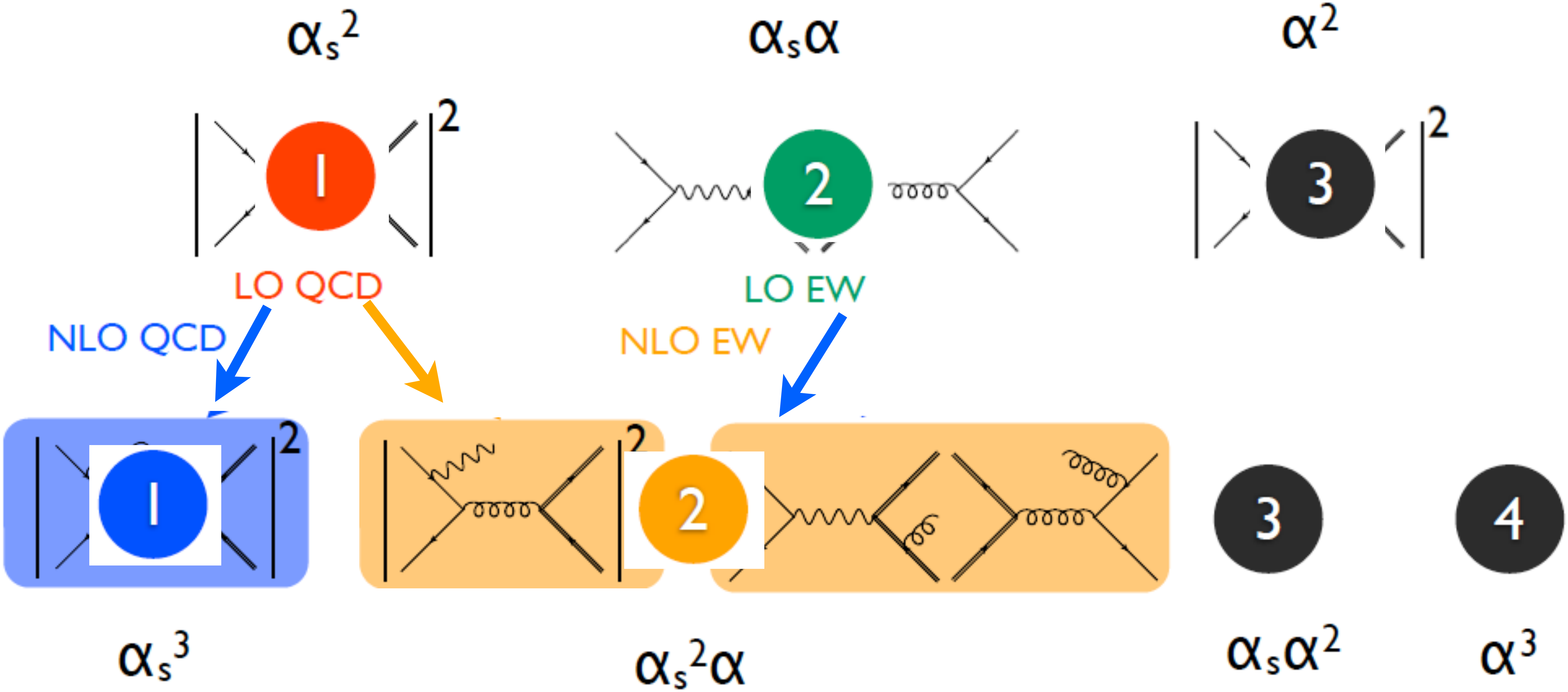

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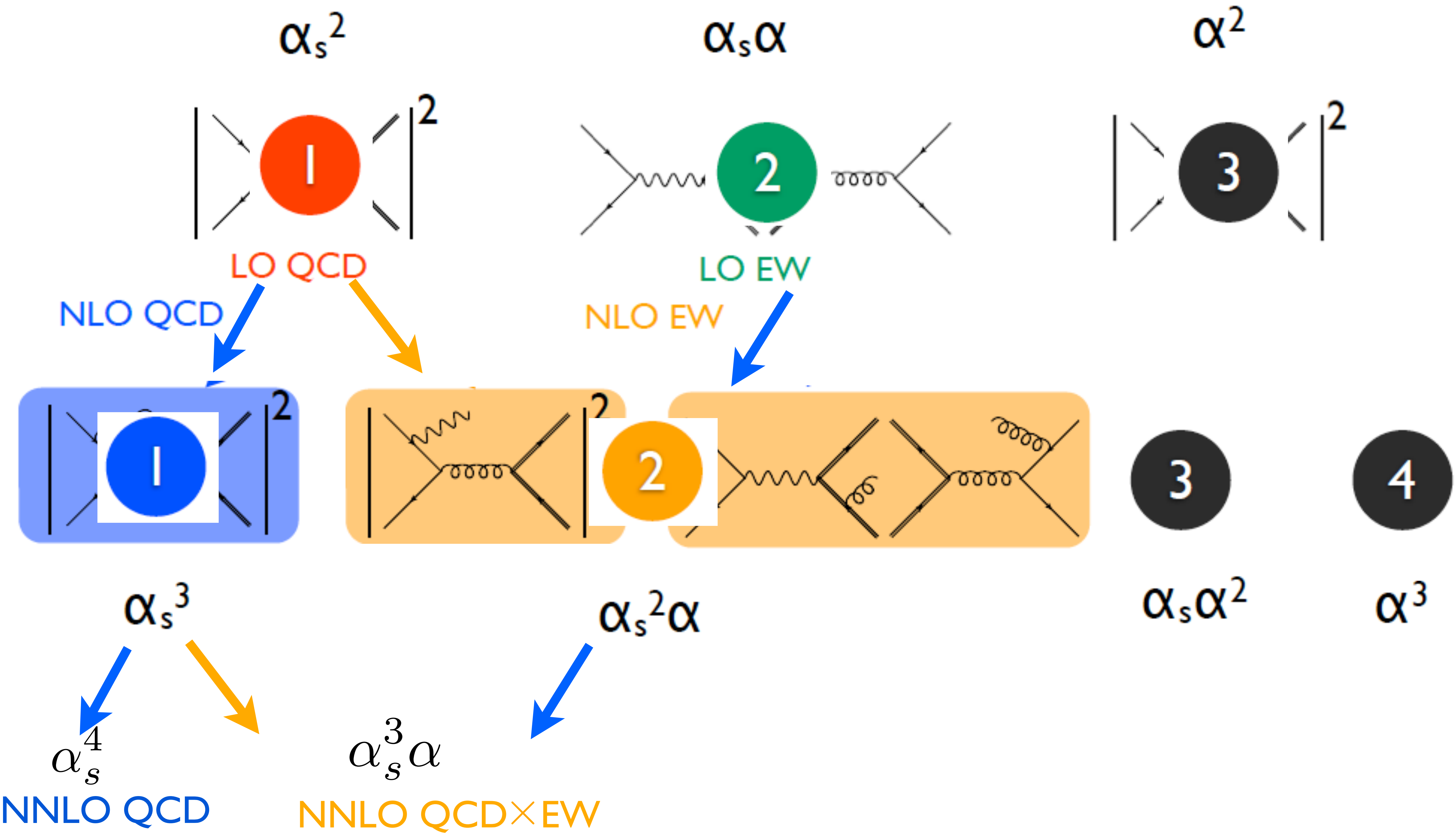
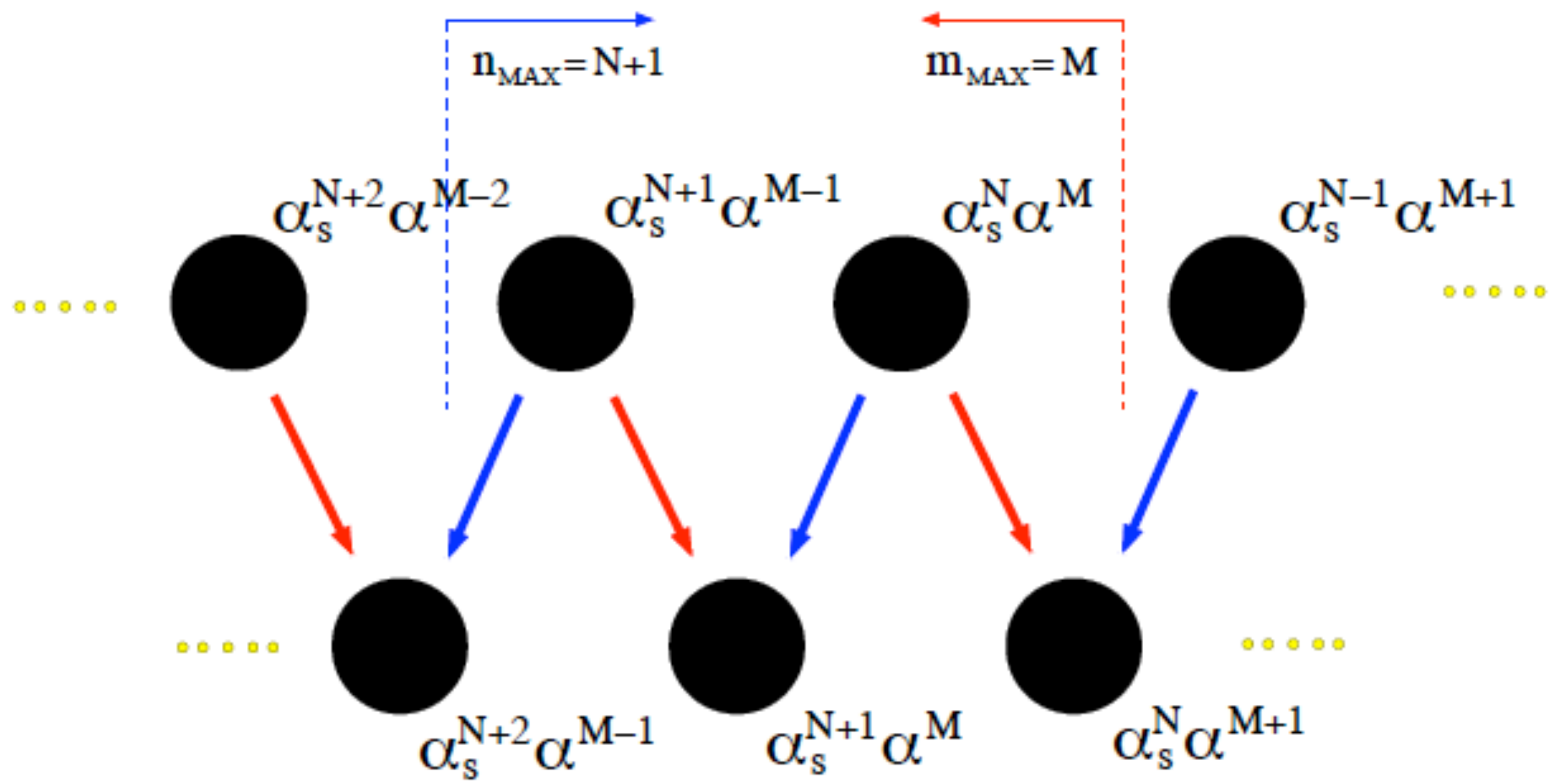


AUTOMATION OF COMPLETE NLO

- In MadGraph5_aMC@NLO v3.X Frederix, Frixione, Hirschi, Pagani, HSS, Zaro, JHEP (2018)

MG5_aMC> generate p_1 p_2 > p_3 p_4 p_5 p_6 QCD=n_{max} QED=m_{max} [QCD QED]



$$\text{LO}: \quad \alpha_s^n\alpha^m\,, \quad n \le \text{n}_{\text{max}}\,, \quad m \le \text{m}_{\text{max}}\,, \quad n+m=k_0\,,$$
$$\text{NLO}: \quad \alpha_s^n\alpha^m\,, \quad n \le \text{n}_{\text{max}}+1\,, \quad m \le \text{m}_{\text{max}}+1\,, \quad n+m=k_0+1$$

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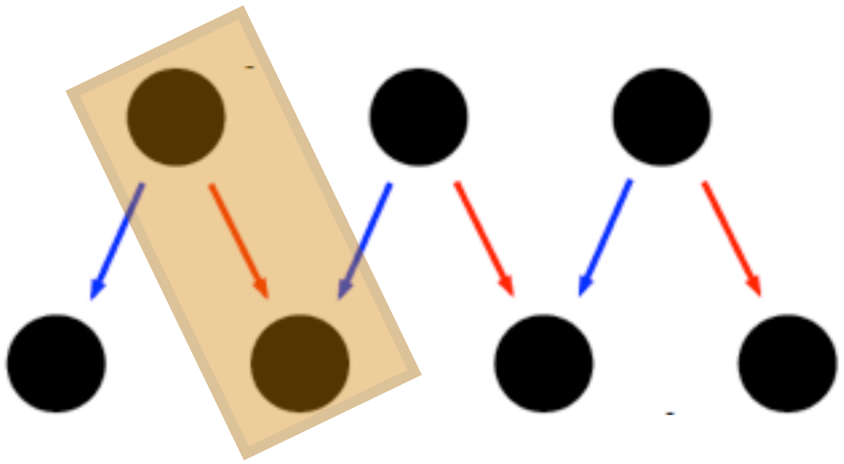
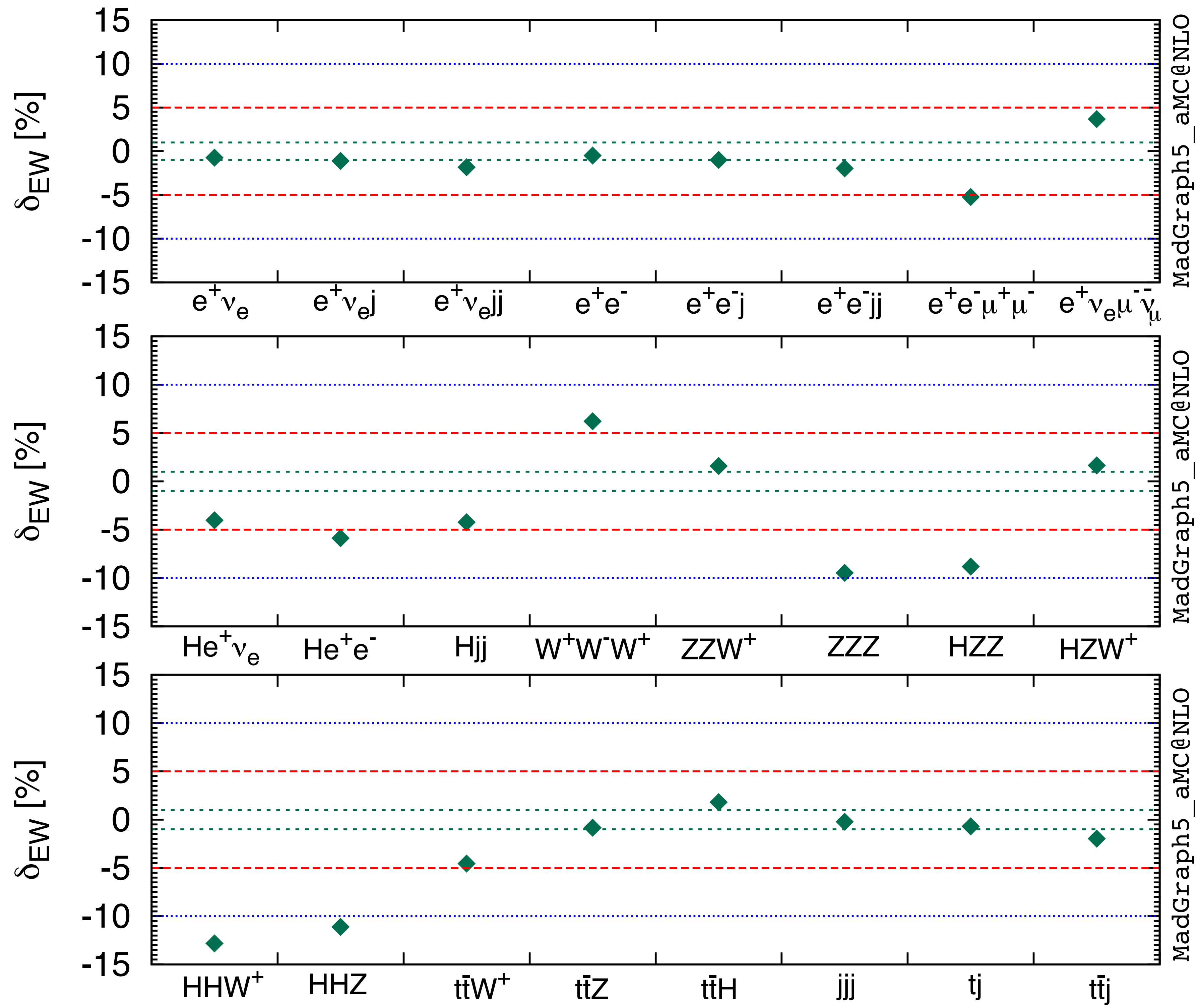
NLO EW @ LHC

- Inclusive cross sections

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro, JHEP (2018)



$$\delta_{\mathrm{EW}} = \frac{\mathrm{NLO}_2}{\mathrm{LO}_1}$$



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Future Electron-Positron Colliders

GENERATOR ISSUES FOR LEPTON COLLIDER

- Processes at e^+e^- without beam issues is an easier case of those at pp

MG5_aMC paper, JHEP (2014)

Process	Heavy quarks and jets	Cross section (pb) LO 1 TeV		NLO 1 TeV		$\delta_{QCD} = NLO_1/LO_1$
i.1	$e^+e^- \to jj$	$6.223 \pm 0.005 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$6.389 \pm 0.013 \cdot 10^{-1}$	$^{+0.2\%}_{-0.2\%}$	+2.7%
i.2	$e^+e^- \to jjj$	$3.401 \pm 0.002 \cdot 10^{-1}$	$^{+9.6\%}_{-8.0\%}$	$3.166 \pm 0.019 \cdot 10^{-1}$	$^{+0.2\%}_{-2.1\%}$	-6.9%
i.3	$e^+e^- \to jjjj$	$1.047 \pm 0.001 \cdot 10^{-1}$	$^{+20.0\%}_{-15.3\%}$	$1.090 \pm 0.006 \cdot 10^{-1}$	$^{+0.0\%}_{-2.8\%}$	+4.1%
i.4	$e^+e^- \to jjjjj$	$2.211 \pm 0.006 \cdot 10^{-2}$	$^{+31.4\%}_{-22.0\%}$	$2.771 \pm 0.021 \cdot 10^{-2}$	$^{+4.4\%}_{-8.6\%}$	+25%
i.5	$e^+e^- \to t\bar{t}$	$1.662 \pm 0.002 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$1.745 \pm 0.006 \cdot 10^{-1}$	$^{+0.4\%}_{-0.4\%}$	+5.0%
i.6	$e^+e^- \to t\bar{t}j$	$4.813 \pm 0.005 \cdot 10^{-2}$	$^{+9.3\%}_{-7.8\%}$	$5.276 \pm 0.022 \cdot 10^{-2}$	$^{+1.3\%}_{-2.1\%}$	+9.6%
i.7*	$e^+e^- \to t\bar{t}jj$	$8.614 \pm 0.009 \cdot 10^{-3}$	$^{+19.4\%}_{-15.0\%}$	$1.094 \pm 0.005 \cdot 10^{-2}$	$^{+5.0\%}_{-6.3\%}$	+27%
i.8*	$e^+e^- \to t\bar{t}jjj$	$1.044 \pm 0.002 \cdot 10^{-3}$	$^{+30.5\%}_{-21.6\%}$	$1.546 \pm 0.010 \cdot 10^{-3}$	$^{+10.6\%}_{-11.6\%}$	+48%
i.9*	$e^+e^- \to t\bar{t}t\bar{t}$	$6.456 \pm 0.016 \cdot 10^{-7}$	$^{+19.1\%}_{-14.8\%}$	$1.221 \pm 0.005 \cdot 10^{-6}$	$^{+13.2\%}_{-11.2\%}$	+89%
i.10*	$e^+e^- \to t\bar{t}t\bar{t}j$	$2.719 \pm 0.005 \cdot 10^{-8}$	$^{+29.9\%}_{-21.3\%}$	$5.338 \pm 0.027 \cdot 10^{-8}$	$^{+18.3\%}_{-15.4\%}$	+96%
i.11	$e^+e^- \to b\bar{b}$ (4f)	$9.198 \pm 0.004 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$	$9.282 \pm 0.031 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$	+0.9%
i.12	$e^+e^- \to b\bar{b}j$ (4f)	$5.029 \pm 0.003 \cdot 10^{-2}$	$^{+9.5\%}_{-8.0\%}$	$4.826 \pm 0.026 \cdot 10^{-2}$	$^{+0.5\%}_{-2.5\%}$	-4.0%
i.13*	$e^+e^- \to b\bar{b}jj$ (4f)	$1.621 \pm 0.001 \cdot 10^{-2}$	$^{+20.0\%}_{-15.3\%}$	$1.817 \pm 0.009 \cdot 10^{-2}$	$^{+0.0\%}_{-3.1\%}$	+12%
i.14*	$e^+e^- \to b\bar{b}jjj$ (4f)	$3.641 \pm 0.009 \cdot 10^{-3}$	$^{+31.4\%}_{-22.1\%}$	$4.936 \pm 0.038 \cdot 10^{-3}$	$^{+4.8\%}_{-8.9\%}$	+36%
i.15*	$e^+e^- \to b\bar{b}b\bar{b}$ (4f)	$1.644 \pm 0.003 \cdot 10^{-4}$	$^{+19.9\%}_{-15.3\%}$	$3.601 \pm 0.017 \cdot 10^{-4}$	$^{+15.2\%}_{-12.5\%}$	+119%
i.16*	$e^+e^- \to b\bar{b}b\bar{b}j$ (4f)	$7.660 \pm 0.022 \cdot 10^{-5}$	$^{+31.3\%}_{-22.0\%}$	$1.537 \pm 0.011 \cdot 10^{-4}$	$^{+17.9\%}_{-15.3\%}$	+101%
i.17*	$e^+e^- \to t\bar{t}b\bar{b}$ (4f)	$1.819 \pm 0.003 \cdot 10^{-4}$	$^{+19.5\%}_{-15.0\%}$	$2.923 \pm 0.011 \cdot 10^{-4}$	$^{+9.2\%}_{-8.9\%}$	+61%
i.18*	$e^+e^- \to t\bar{t}b\bar{b}j$ (4f)	$4.045 \pm 0.011 \cdot 10^{-5}$	$^{+30.5\%}_{-21.6\%}$	$7.049 \pm 0.052 \cdot 10^{-5}$	$^{+13.7\%}_{-13.1\%}$	+74%

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MG5_aMC paper, JHEP (2014)

- The following aspects to be improved in order to have realistic simulations at lepton-lepton colliders
  - Beam polarization
  - Photon initial state: **improved Weizsaecker-Williams formula (elastic)**
  - Initial-state radiation
  - Beamstrahlung **technical-related feature, important at ILC**

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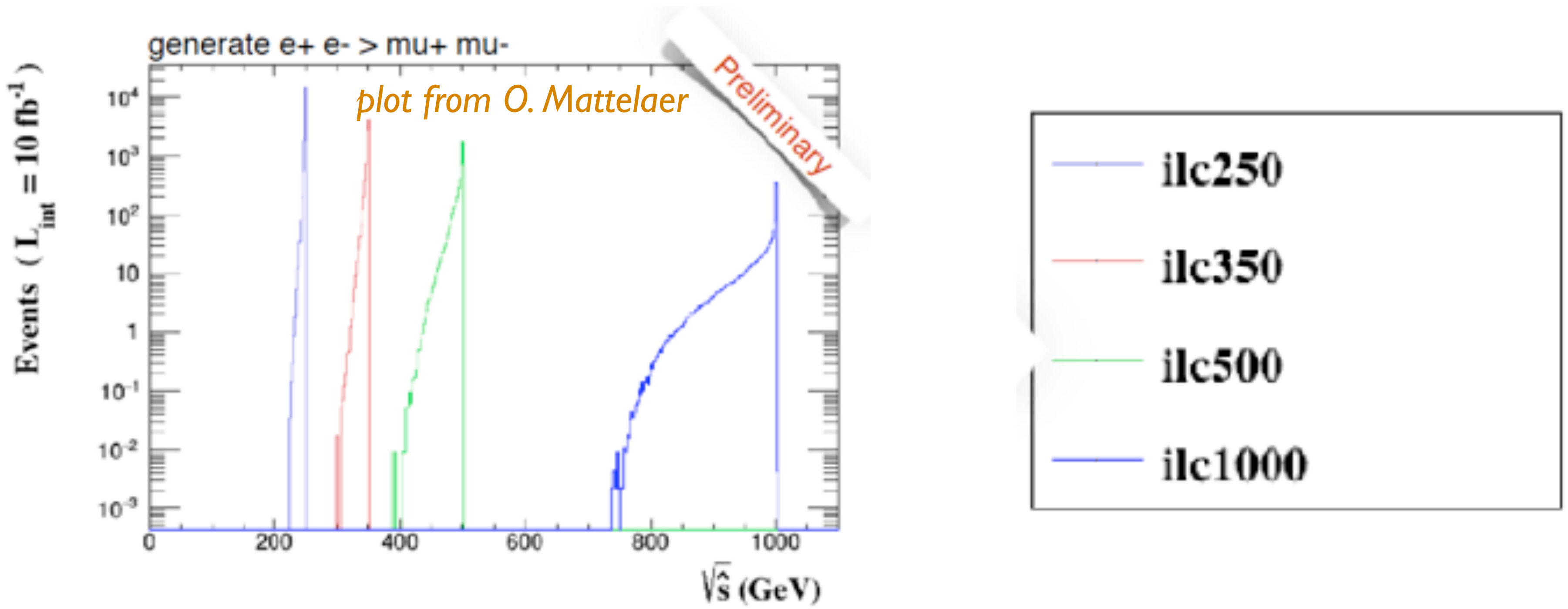

A FEW PROCESSES AT CEPC

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- A (developing and not public) MG5_aMC branch is under construction to solve all the mentioned beam issues at lepton-lepton colliders. Frixione, Zaro, Zhao, ...
- I take the branch with rush runs at CEPC (240 GeV) WITH initial-state radiation (beamstrahlung is expected to be small within CEPC configuration).

Democratic jet (include gluon, light quark, photon, light charged lepton)

$\text{anti}-k_T, R=1.0, p_T(j)>10\text{ GeV}, |\eta(j)|<4.5$

PRELIMINARY

$\sqrt{S}=240$ GeV	$\sigma(e^+e^-\to jj)$ [pb]	$\sigma(e^+e^-\to jjj)$ [pb]	$\sigma(e^+e^-\to jjjj)$ [pb]
LO_1	Blocked	Blocked	Blocked
LO_2		Blocked	Blocked
LO_3			Blocked
NLO_1	Blocked	Blocked	Blocked
NLO_2	Blocked	Blocked	Blocked
NLO_3		Blocked	Blocked
NLO_4			Blocked
Sum	Blocked	Blocked	Blocked

* Gmu scheme and same parameter setup as done in Frederix, Frixione, Hirschi, Pagani, HSS, Zaro, JHEP (2018)

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$\text{anti}-k_T, R = 1.0, p_T(j) > 10 \text{ GeV}, |\eta(j)| < 4.5$

PRELIMINARY

$\sqrt{S} = 240$ GeV	$\sigma(e^+e^- \to jj)$ [pb]	$\sigma(e^+e^- \to jjj)$ [pb]	$\sigma(e^+e^- \to jjjj)$ [pb]
LO_1	$2.78 \cdot 10^3$	Running	Blocked
LO_2		Running	Blocked
LO_3			Blocked
NLO_1	$1.44 \cdot 10^0$	Running	Blocked
NLO_2	$6.76 \cdot 10^1$	Running	Blocked
NLO_3		Running	Blocked
NLO_4			Blocked
Sum	$2.85 \cdot 10^3 \pm 0.03\%_{\text{scale}}$	Running	Blocked

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PRELIMINARY

$\sqrt{S} = 240$ GeV	$\sigma(e^+e^- \to ZH)$ [pb]	$\sigma(e^+e^- \to ZZ)$ [pb]	$\sigma(e^+e^- \to W^+W^-)$ [pb]
LO_1	$2.05 \cdot 10^{-1}$	$1.11 \cdot 10^{0}$	$1.67 \cdot 10^{1}$
LO_2			
LO_3			
NLO_1			
NLO_2	$-4.1 \cdot 10^{-3}$	$-5.0 \cdot 10^{-2}$	$-4.0 \cdot 10^{-2}$
NLO_3			
NLO_4			
Sum	$2.01 \cdot 10^{-1} \pm 0.1\%_{\rm scale}$	$1.06 \cdot 10^{0} \pm 0.05\%_{\rm scale}$	$1.67 \cdot 10^{1} \pm 0.03\%_{\rm scale}$

* Gmu scheme and same parameter setup as done in Frederix, Frixione, Hirschi, Pagani, HSS, Zaro, JHEP (2018)

BEYOND NLO EXAMPLE: ZH

Gong, Li, Xu, Yang, Zhang, PRD (2017);
Sun, Feng, Jia, Sang, PRD (2017)

$\sqrt{s}$	schemes	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)
240	$\alpha(0)$	223.14 ± 0.47	229.78 ± 0.77	$232.21^{+0.75+0.10}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.03 ± 0.60	$228.36^{+0.82}_{-0.81}$	$231.28^{+0.80+0.12}_{-0.79-0.25}$
	G_μ	239.64 ± 0.06	$232.46^{+0.07}_{-0.07}$	$233.29^{+0.07+0.03}_{-0.06-0.07}$
250	$\alpha(0)$	223.12 ± 0.47	229.20 ± 0.77	$231.63^{+0.75+0.12}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.01 ± 0.60	$227.67^{+0.82}_{-0.81}$	$230.58^{+0.80+0.14}_{-0.79-0.25}$
	G_μ	239.62 ± 0.06	231.82 ± 0.07	$232.65^{+0.07+0.04}_{-0.07-0.07}$

- Fixed order without initial state radiations (and beamstrahlung).
- The inclusion of NLO EW corrections significantly reduce the EW scheme dependence.
- NNLO QCD$\times$ EW increases the cross section around 1-3 fb.
- The remaining dominant uncertainty is from the EW scheme dependence, which is expected to be reduced only when one includes NNLO EW (pure EW) corrections.

LOOP-INDUCED NLO EXAMPLE: H+PHOTON

Sang, Chen, Feng, Jia, Sun, PLB (2017)

$\sqrt{s}$(GeV)	150	200	220	240	250	270	290	310	330	340
$\sigma^{\rm LO}$ (10^{-2} fb)	1.054	6.214	7.339	7.758	7.764	7.479	6.909	6.134	5.151	4.522
$\tilde{T}_{\gamma,5}$(10^{-2}GeV^{-1})	-0.793	-0.378	-0.112	0.251	0.485	1.12	2.11	3.90	8.16	14.26
$\sigma^{\rm NLO}/\sigma^{\rm LO}$	0.56%	0.30%	0.09%	-0.21%	-0.41%	-0.96%	-1.86%	-3.45%	-6.85%	-10.59%

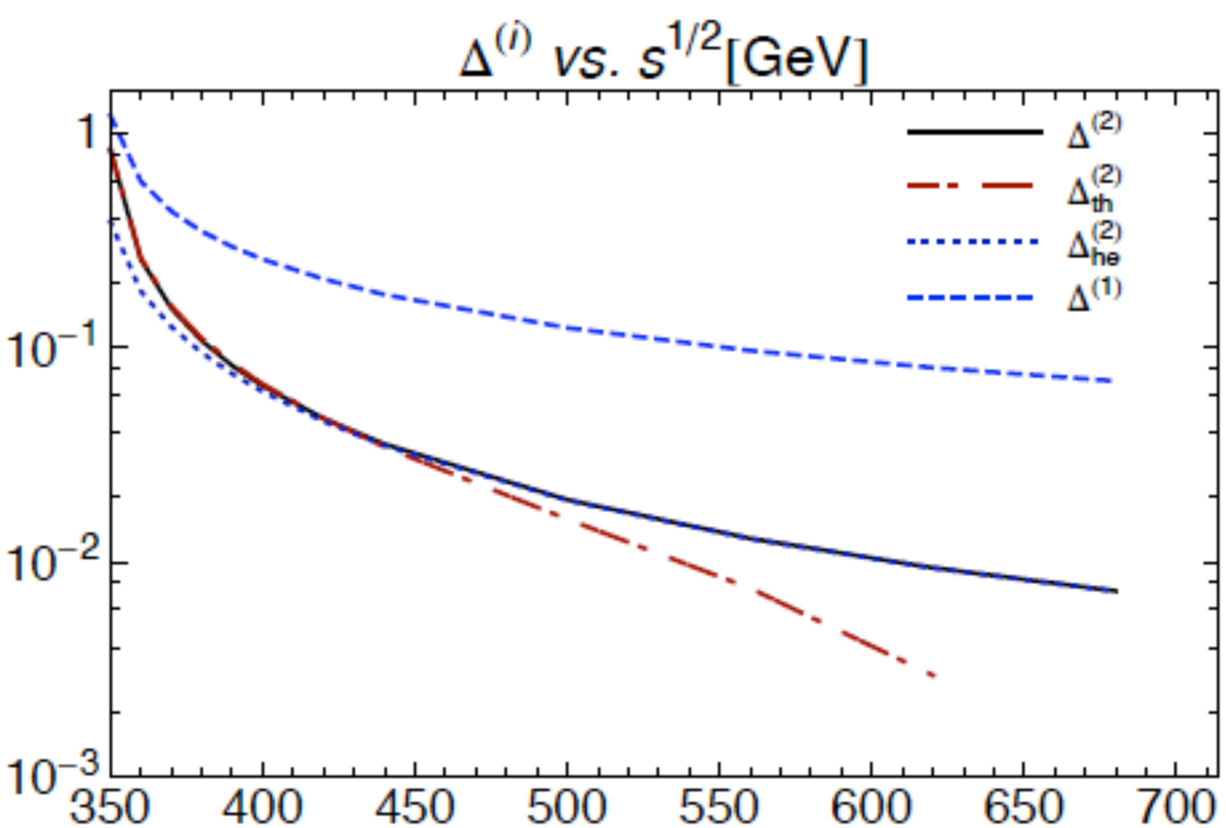
$\sqrt{s}$(GeV)	360	380	400	420	500	600	700	800	900	1000
$\sigma^{\rm LO}$ (10^{-2} fb)	2.570	2.977	3.433	3.763	4.079	3.604	3.018	2.518	2.118	1.801
$\tilde{T}_{\gamma,5}$ (10^{-2}GeV^{-1})	$-2.26 +28.2\,i$	$-11.6 +16.6\,i$	$-13.4 +9.81\,i$	$-13.24 +5.76\,i$	$-9.65 -1.29\,i$	$-6.31 -3.21\,i$	$-4.45 -3.48\,i$	$-3.35 -3.38\,i$	$-2.63 -3.19\,$i	$-2.13 -3.00\,i$
$\sigma^{\rm NLO}/\sigma^{\rm LO}$	-4.99%	16.81%	19.87%	19.24%	13.67%	9.60%	7.37%	5.98%	5.02%	4.31%

- Fixed order without initial state radiations (and beamstrahlung).
- NLO QCD correction is quite small (-0.21%) at 240 GeV but increases quickly to ~20% when top-quark pair threshold is opened.

BEYOND NLO EXAMPLE: TOP PAIR

Gao, Zhu, PRL (2014); Chen, Dekkers, Heisler, Bernreuther, Si , JHEP (2016)

$$\sigma_{NNLO} = \sigma_{LO}\left(1+\Delta^{(1)}+\Delta^{(2)}\right)$$



- NNLO QCD corrections (fixed order without ISR)
- The large QCD correction is from the threshold region, in which there are higher order corrections known.

  Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser, PRL (2015); Beneke, Maier, Rauh, Ruiz-Femenia , JHEP (2018)
- The NNLO QCD correction decreases when energy increases. It is around percent level > 400 GeV.

Future 100 TeV hadron Colliders

CURRENT THEORETICAL PRECISION

Theoretical uncertainty on production rates (FCC-hh physics report arXiv:1606.09408)

100 TeV	cross section [pb]	pert. error	param. error
$gg \to H$	802	6-7%	4-5%
WH	15.710	0.1%	0.2%
ZH	11.178	0.5%	0.2%
VBF H	69.0	1%	2%
ttH	32.1	8%	2%

EXAMPLE: TTH VS TTZ

LPTHE
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- Theoretical calculations of ttH and ttZ are known at complete NLO level

Frederix, Hirschi, Pagani, HSS, Zaro, JHEP (2015,2018)

- NLO EW contributes -3% (ttH) and -5% (ttZ) for inclusive cross sections.

$t\bar{t}H\ :\ \delta(\%)$	100 TeV
NLO QCD	$40.8^{+9.3}_{-9.1} \pm 1.0$
LO EW	0.0 ± 0.2
LO EW no γ	-0.6 ± 0.0
NLO EW	-2.7 ± 0.0
NLO EW no γ	-2.7 ± 0.0
HBR	0.91

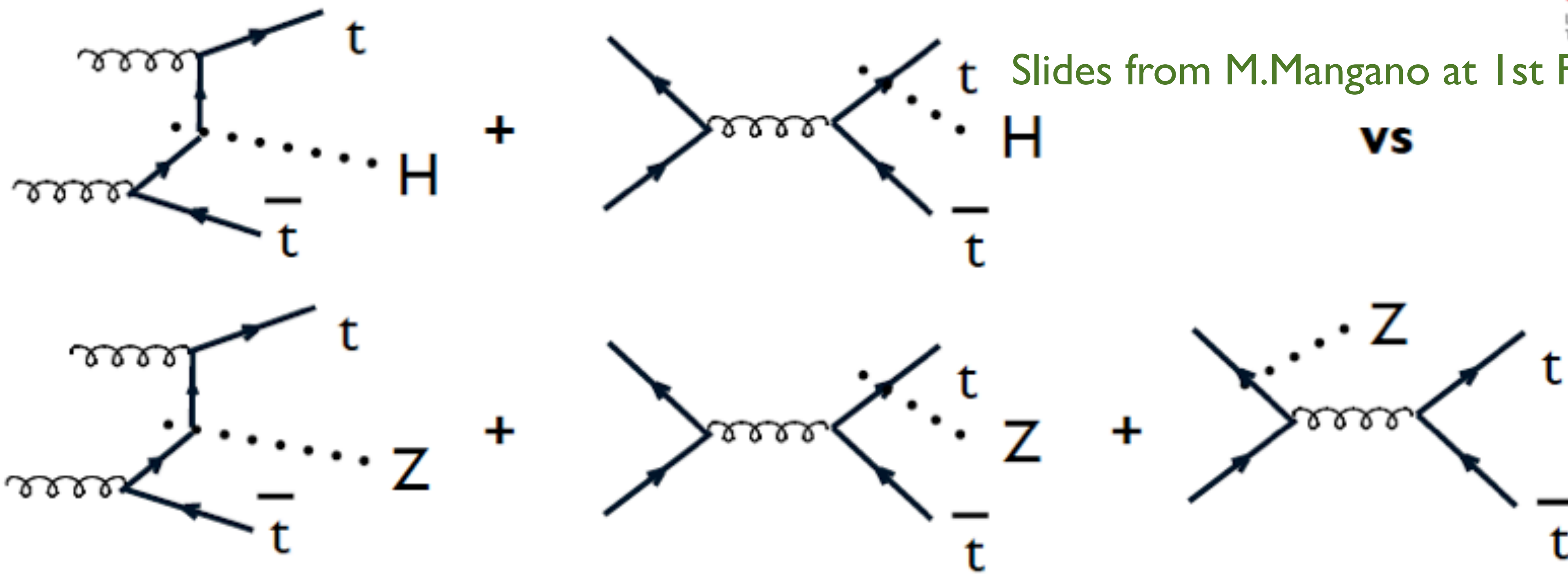
$t\bar{t}Z\ :\ \delta(\%)$	100 TeV
NLO QCD	$50.4^{+11.4}_{-10.9} \pm 1.1$
LO EW	-1.1 ± 0.2
LO EW no γ	-1.6 ± 0.0
NLO EW	-5.2 ± 0.1
NLO EW no γ	-5.4 ± 0.0
HBR	0.85

- Subleading NLO terms are <1% for inclusive cross sections (at 13 TeV).
- QCD scale uncertainty does not capture these EW corrections
- How to measure percent-level Higgs Yukawa coupling ?
  - NNLO QCD corrections
  - Measure and calculate ttH/ttZ

Mangano, Plehn, Reimitz, Pagani, Schell, HSS, JPG (2015)

$pp \to tt\ H$ vs $pp \to tt\ Z$

Slides from M.Mangano at 1st FCC-hh Workshop



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**
  - **o correlated QCD corrections, correlated scale dependence**
  - **o correlated α_S systematics**
- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**
  - **o correlated PDF systematics**
  - **o correlated m_{top} systematics**

For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

MSTW2008NLO, $\mu_0 = H_T/2$, NLO QCD

Mangano, Plehn, Reimitz, Schell, HSS, JPG (2015)

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

- Scale uncertainty reduces to 2% for the ratio.
- PDF+as uncertainty reduces to < 1% level

$\mu_0 = H_T/2$, NLO QCD

		$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	MSTW2008	$0.475^{+5.79\%+2.02\%}_{-9.04\%-2.50\%}$	$0.785^{+9.81\%+1.93\%}_{-11.2\%-2.39\%}$	$0.606^{+2.45\%+0.216\%}_{-3.66\%-0.249\%}$
	CT10	$0.450^{+5.70\%+6.00\%}_{-8.80\%-5.34\%}$	$0.741^{+9.50\%+5.91\%}_{-10.9\%-5.29\%}$	$0.607^{+2.34\%+0.672\%}_{-3.47\%-0.675\%}$
	NNPDF2.3	$0.470^{+5.26\%+2.22\%}_{-8.58\%-2.2[illegible]\%}$	$0.771^{+8.97\%+2.16\%}_{-10.6\%-2.16\%}$	$0.609^{+2.23\%+0.205\%}_{-3.[illegible]\%-0.205\%}$
100 TeV	MSTW2008	$33.9^{+7.06\%+0.9[illegible]\%}_{-8.29\%-1.26\%}$	$57.9^{+8.93\%+0.90\%}_{-9.46\%-1.20\%}$	$0.585^{+1.2[illegible]\%+[illegible]0.0526\%}_{-2.02\%-0.0758\%}$
	CT10	$32.4^{+6.87\%+2.29\%}_{-8.11\%-2.95\%}$	$55.5^{+8.73\%+2.16\%}_{-9.27\%-2.78\%}$	$0.584^{+1.27\%+0.189\%}_{-1.99\%-0.260\%}$
	NNPDF2.3	$33.2^{+6.62\%+0.78\%}_{-6.47\%-0.78\%}$	$56.9^{+7.62\%+0.75\%}_{-7.29\%-0.75\%}$	$0.584^{+1.29\%+0.0493\%}_{-2.01\%-0.0493\%}$

5-6%

0.5%

EXAMPLE: TTH VS TTZ

Mangano, Plehn, Reimitz, Schell, HSS, JPG (2015)

Parameter	value	Parameter	value
G_μ	$1.1987498350461625 \cdot 10^{-5}$	n_{lf}	5
m_t	173.3	y_t	173.3
m_W	80.419	m_Z	91.188
m_H	125.0	α^{-1}	128.930

		$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	default	$0.475^{+5.79\%}_{-9.04\%}$	$0.785^{+9.81\%}_{-11.2\%}$	$0.606^{+2.45\%}_{-3.66\%}$
	$\mu_0 = m_t + m_{H,Z}/2$	$0.529^{+5.96\%}_{-9.42\%}$	$0.885^{+9.93\%}_{-11.6\%}$	$0.597^{+2.45\%}_{-3.61\%}$
	$m_t = y_t v = 174.1$ GeV	$0.474^{+5.74\%}_{-9.01\%}$	$0.773^{+9.76\%}_{-11.2\%}$	$0.614^{+2.45\%}_{-3.66\%}$
	$m_t = y_t v = 172.5$ GeV	$0.475^{+5.81\%}_{-9.05\%}$	$0.795^{+9.82\%}_{-11.2\%}$	$0.597^{+2.45\%}_{-3.65\%}$
	$m_H = 126.0$ GeV	$0.464^{+5.80\%}_{-9.04\%}$	$0.785^{+9.81\%}_{-11.2\%}$	$0.593^{+2.42\%}_{-3.62\%}$
100 TeV	default	$33.9^{+7.06\%}_{-8.29\%}$	$57.9^{+8.93\%}_{-9.46\%}$	$0.585^{+1.29\%}_{-2.02\%}$
	$\mu_0 = m_t + m_{H,Z}/2$	$39.0^{+9.76\%}_{-9.57\%}$	$67.2^{+10.9\%}_{-10.6\%}$	$0.580^{+1.16\%}_{-1.80\%}$
	$m_t = y_t v = 174.1$ GeV	$33.9^{+7.01\%}_{-8.27\%}$	$57.2^{+8.90\%}_{-9.42\%}$	$0.592^{+1.27\%}_{-2.00\%}$
	$m_t = y_t v = 172.5$ GeV	$33.7^{+6.99\%}_{-8.31\%}$	$58.6^{+8.93\%}_{-9.46\%}$	$0.576^{+1.27\%}_{-1.99\%}$
	$m_H = 126.0$ GeV	$33.2^{+7.04\%}_{-8.28\%}$	$57.9^{+8.93\%}_{-9.46\%}$	$0.575^{+1.25\%}_{-1.95\%}$

- Scale choice from dynamical scale to fixed scale, the results are well embed in scale uncertainty

- Mass dependences are similar at percent level for the ratio.

EXAMPLE: TTH VS TTZ

Mangano, Plehn, Reimitz, Schell, HSS, JPG (2015)

		$\alpha(m_Z)$ scheme			G_μ scheme		
		$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	NLO QCD	0.475	0.785	0.606	0.462	0.763	0.606
	$\mathcal{O}(\alpha_S^2\alpha^2)$ Weak	−0.006773	−0.02516		0.004587	−0.007904	
	$\mathcal{O}(\alpha_S^2\alpha^2)$ EW	−0.0045	−0.022		0.0071	−0.0033	
	NLO QCD+Weak	0.468	0.760	0.617	0.467	0.755	0.619
	NLO QCD+EW	0.471	0.763	0.617	0.469	0.760	0.618
100 TeV	NLO QCD	33.9	57.9	0.585	32.9	56.3	0.585
	$\mathcal{O}(\alpha_S^2\alpha^2)$ Weak	−0.7295	−2.146		0.0269	−0.8973	
	$\mathcal{O}(\alpha_S^2\alpha^2)$ EW	−0.65	−2.0		0.14	−0.77	
	NLO QCD+Weak	33.1	55.8	0.594	32.9	55.4	0.594
	NLO QCD+EW	33.2	55.9	0.594	33.1	55.6	0.595

- (E)WK can be negative. Its impact is also at 2% level.

EXAMPLE: HW

Mangano, Zanderighi et al., FCC-hh Physics report: SM processes '16

- **A funny example is HW production**
  - **NLO EW:** Ciccolini, Dittmaier, Kramer '03
  - **NLO EW with W decay:** Denner, Dittmaier, Kallweit, Much '12

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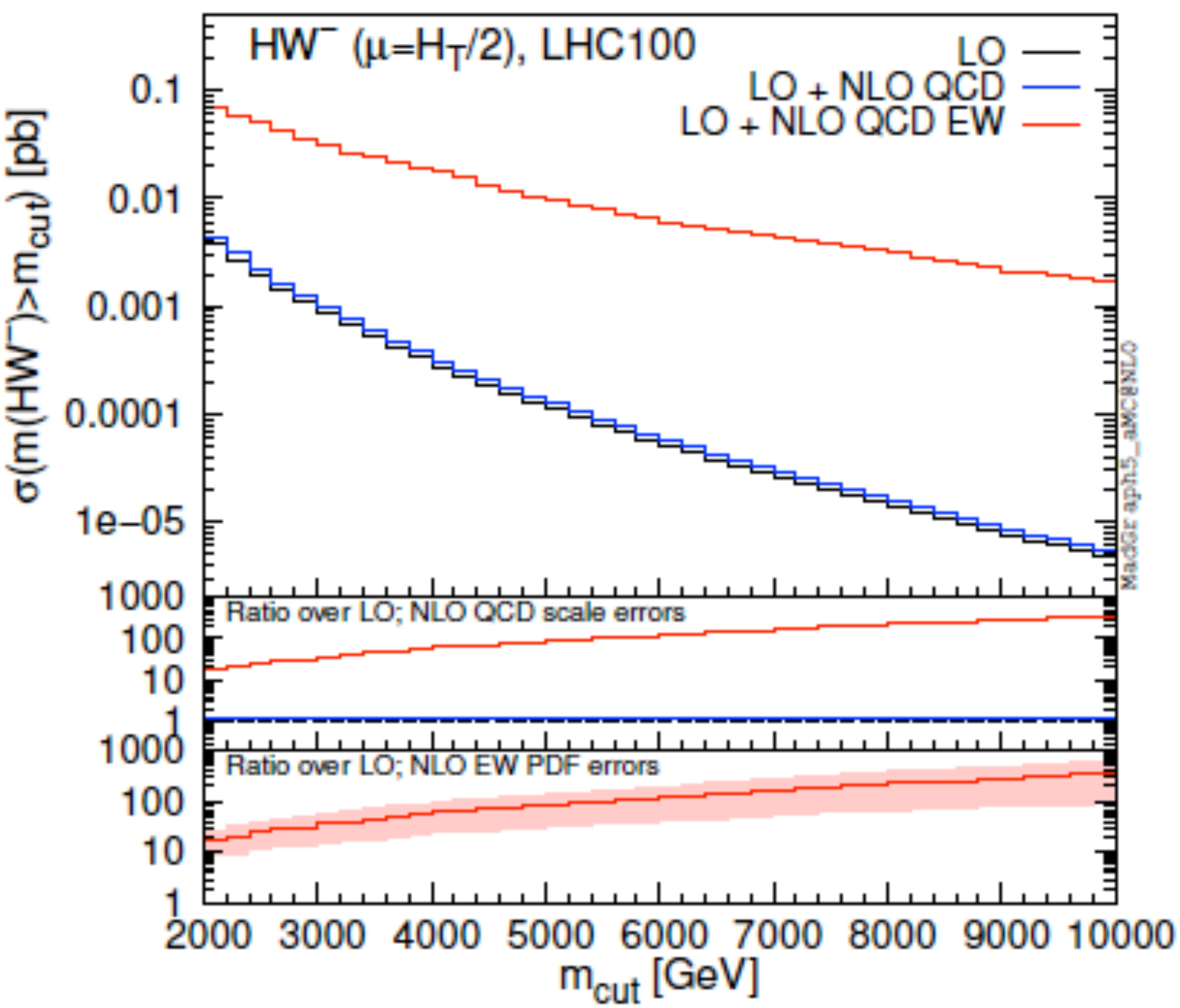

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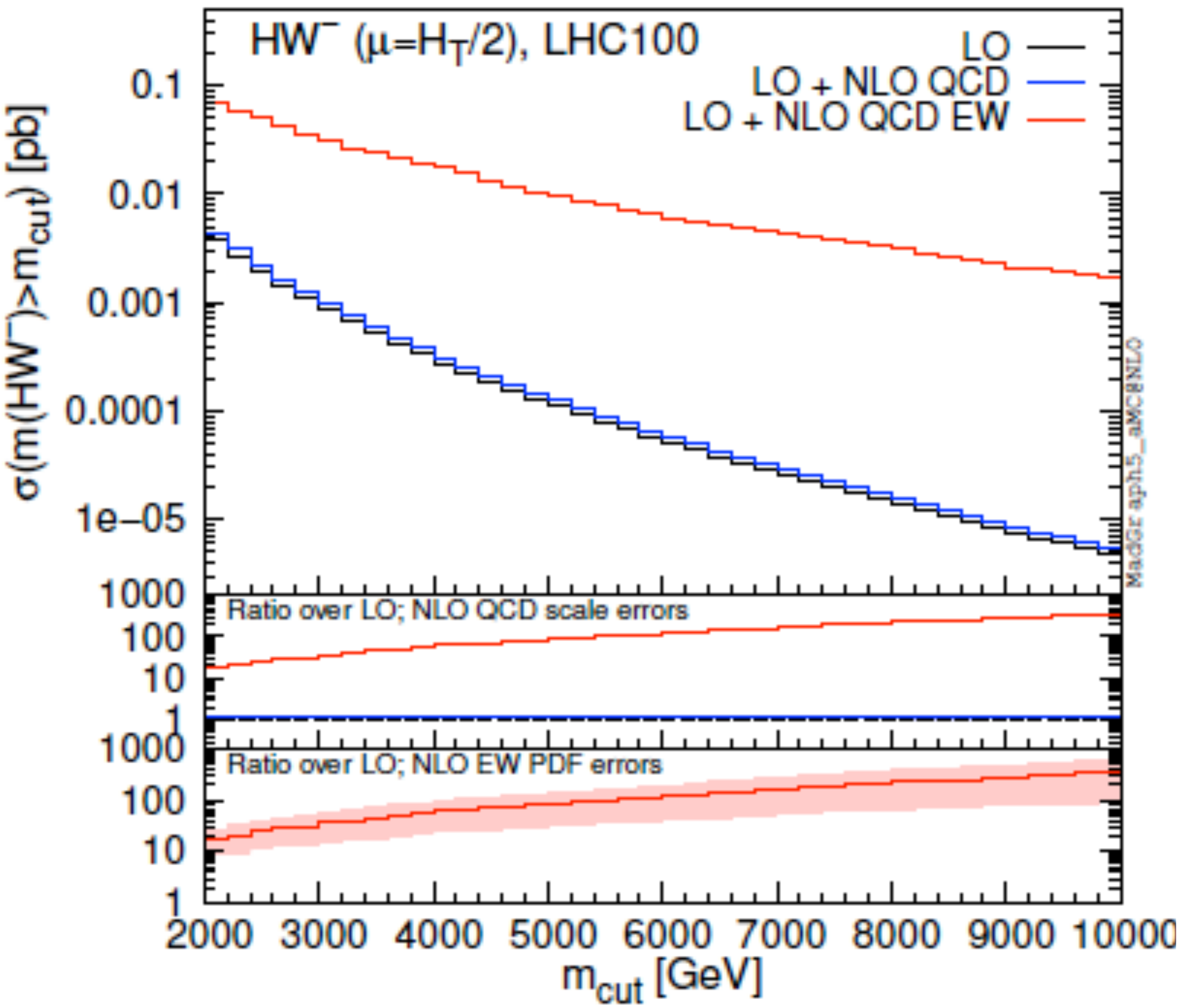

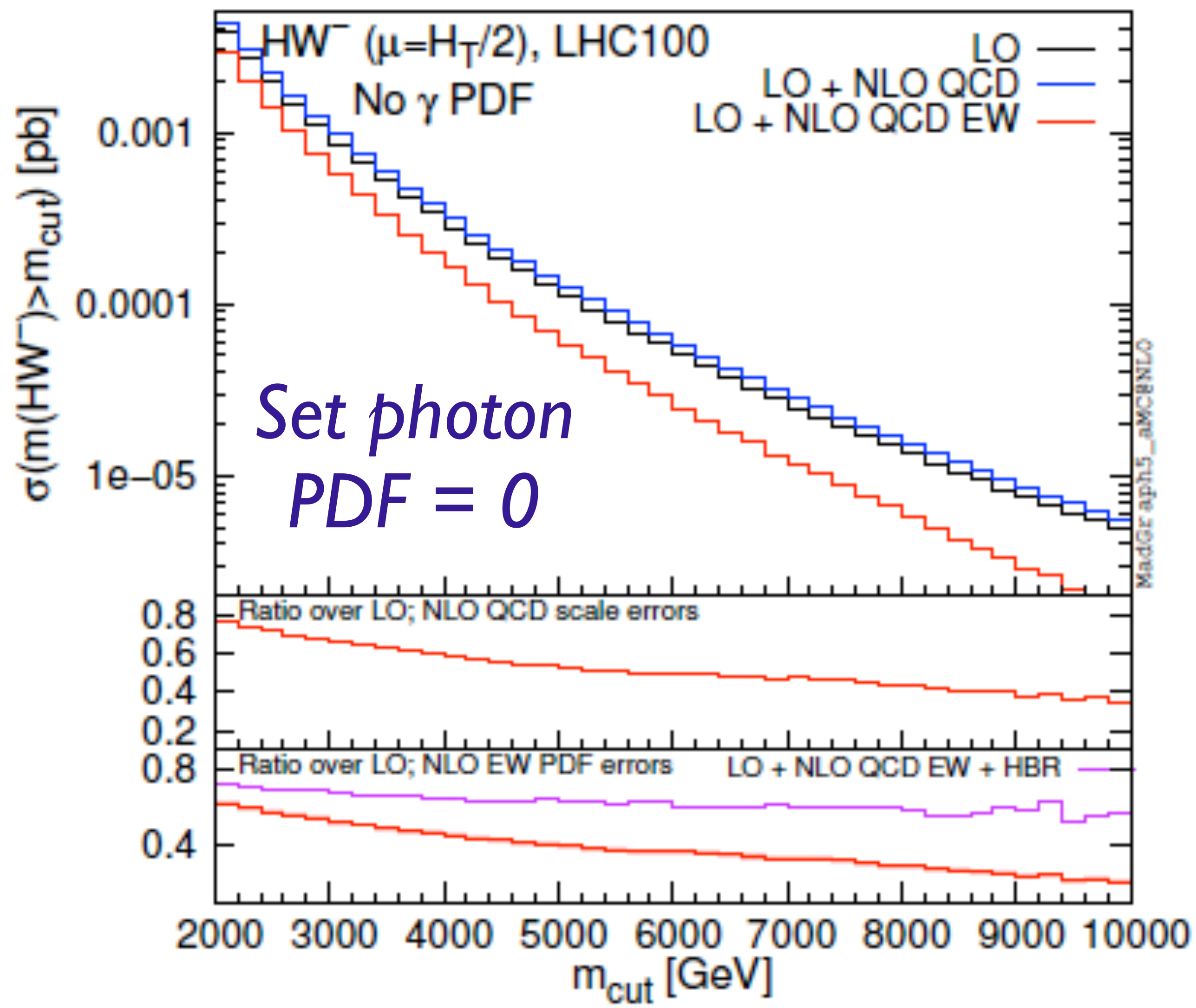

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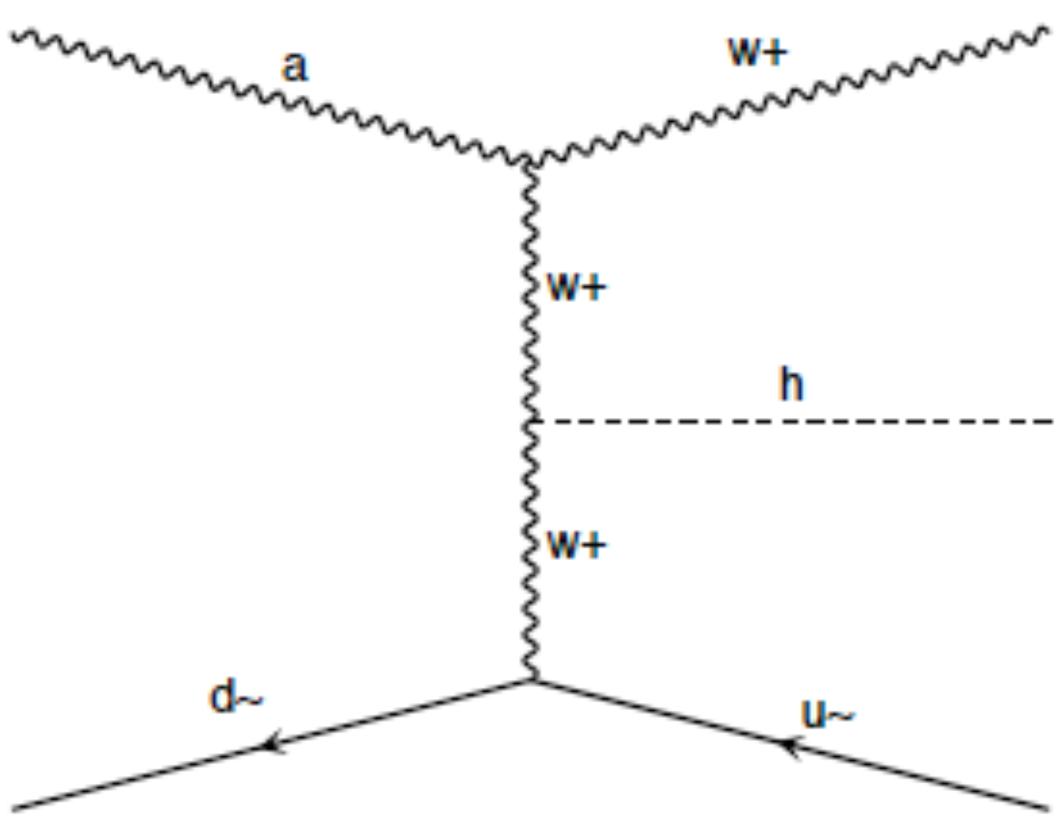
  - There is no photon-quark or gluon-quark for H+jet at Born, when W soft/coll.
  - At Born, HW is produced via s-channel only, while NLO introduces t-channel
  - At large inv. mass, t-channel is dominant



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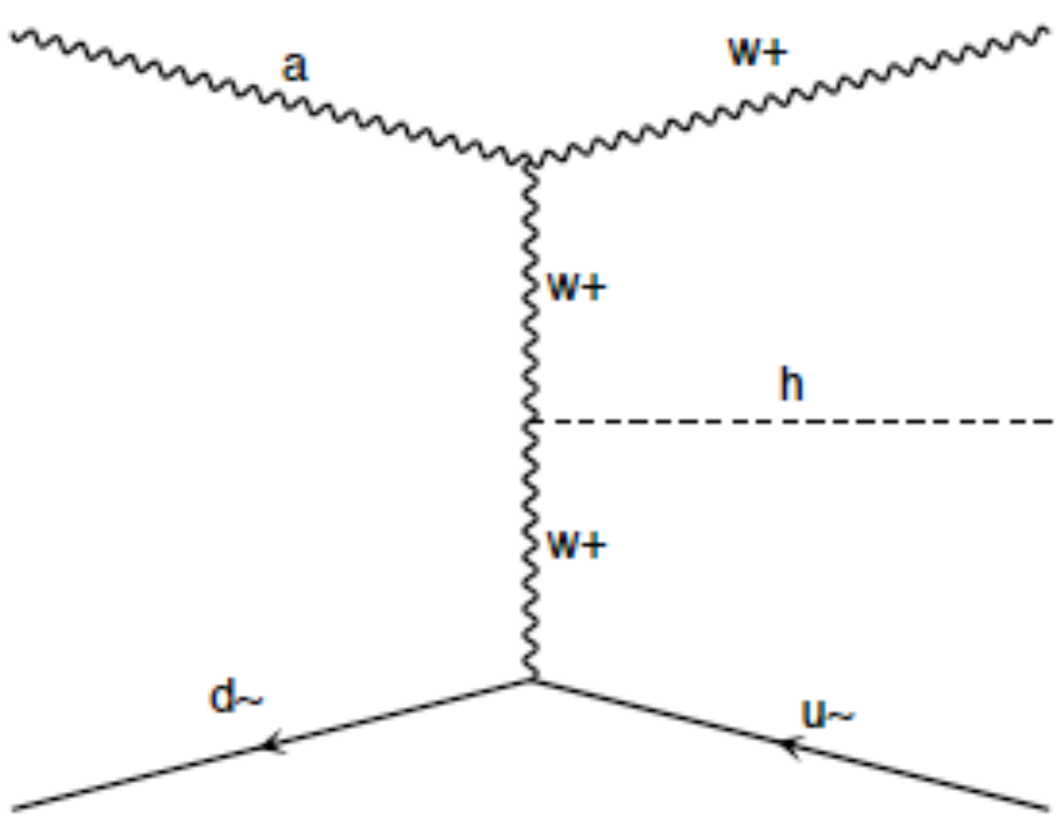
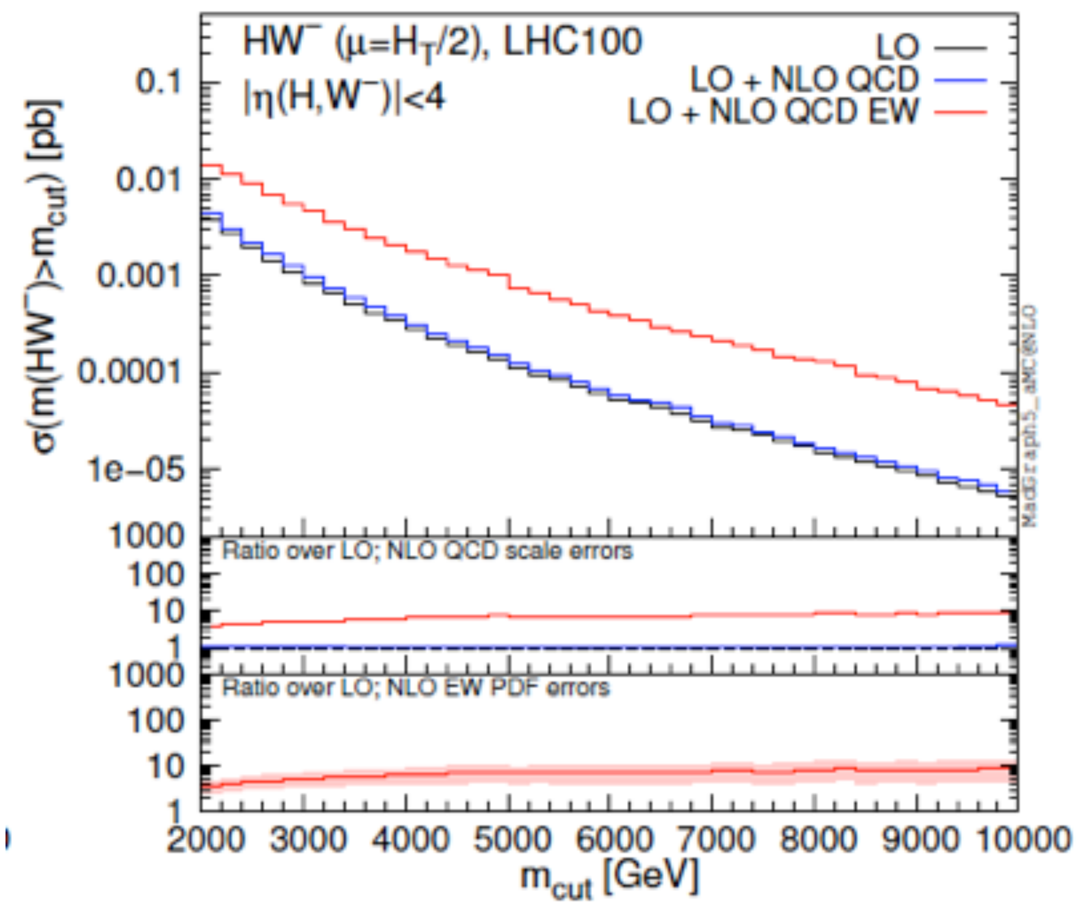
  - Such a contribution can be suppressed by cut e.g. on pseudorapidity





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EXAMPLE: 4-TOP AND TTW

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- Large subleading NLO corrections were found in 4-top and ttbarW due to tt and tW scattering appears.

Frederix, Pagani, Zaro, JHEP (2018)

$\sqrt{S} = 100$ TeV $\quad pp \to t t \bar{t} \bar{t}$ $\quad pp \to t\bar{t}W^{\pm}$

NLO QCD
NLO EW

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-18.7	-20.7	-22.8
LO_3	26.3	31.8	37.8
LO_4	0.05	0.07	0.09
LO_5	0.03	0.05	0.08
NLO_1	33.9	68.2	98.0
NLO_2	-0.3	-5.7	-11.6
NLO_3	-3.9	1.7	8.9
NLO_4	0.7	0.9	1.2
NLO_5	0.12	0.14	0.16
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-4.2	-4.0	2.7

$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO_2	-	-	-
LO_3	0.9	1.1	1.3
NLO_1	159.5 (69.8)	149.5 (71.1)	142.7 (73.4)
NLO_2	-5.8 (-6.4)	-5.6 (-6.2)	-5.4 (-6.1)
NLO_3	67.5 (55.6)	68.8 (56.6)	70.0 (57.6)
NLO_4	0.2 (0.1)	0.2 (0.2)	0.3 (0.2)

SUMMARY

- CEPC-SppC will provide many invaluable studies on particle physics, which requires the theoretical predictions at least at the same precision level.
- The proposal will trigger new theoretical discussions and new theoretical calculations in the new collider enviroment, where the main studies are still LHC oriented.
- Complete NLO (QCD and EW) calculations were automated in the proton proton collision case and will be automated soon in the electron-positron collision case.

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Stay tuned and thanks for listening !