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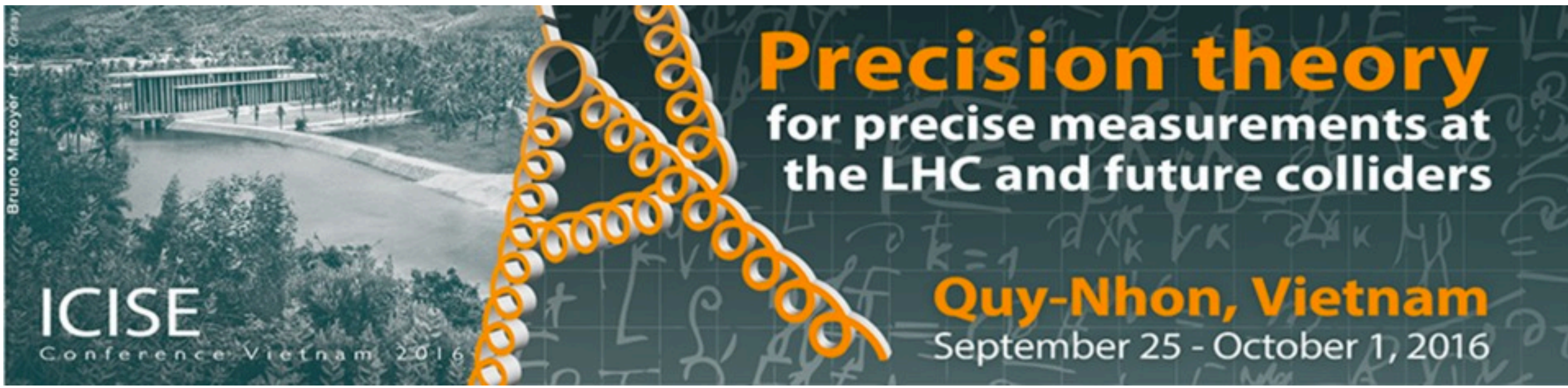
Automation of ElectroWeak Corrections



Hua-Sheng Shao

Theoretical Physics Department
CERN

28 September 2016

Tuesday, September 27, 16

FRONTIER OF PRECISION THEORY @ LHC

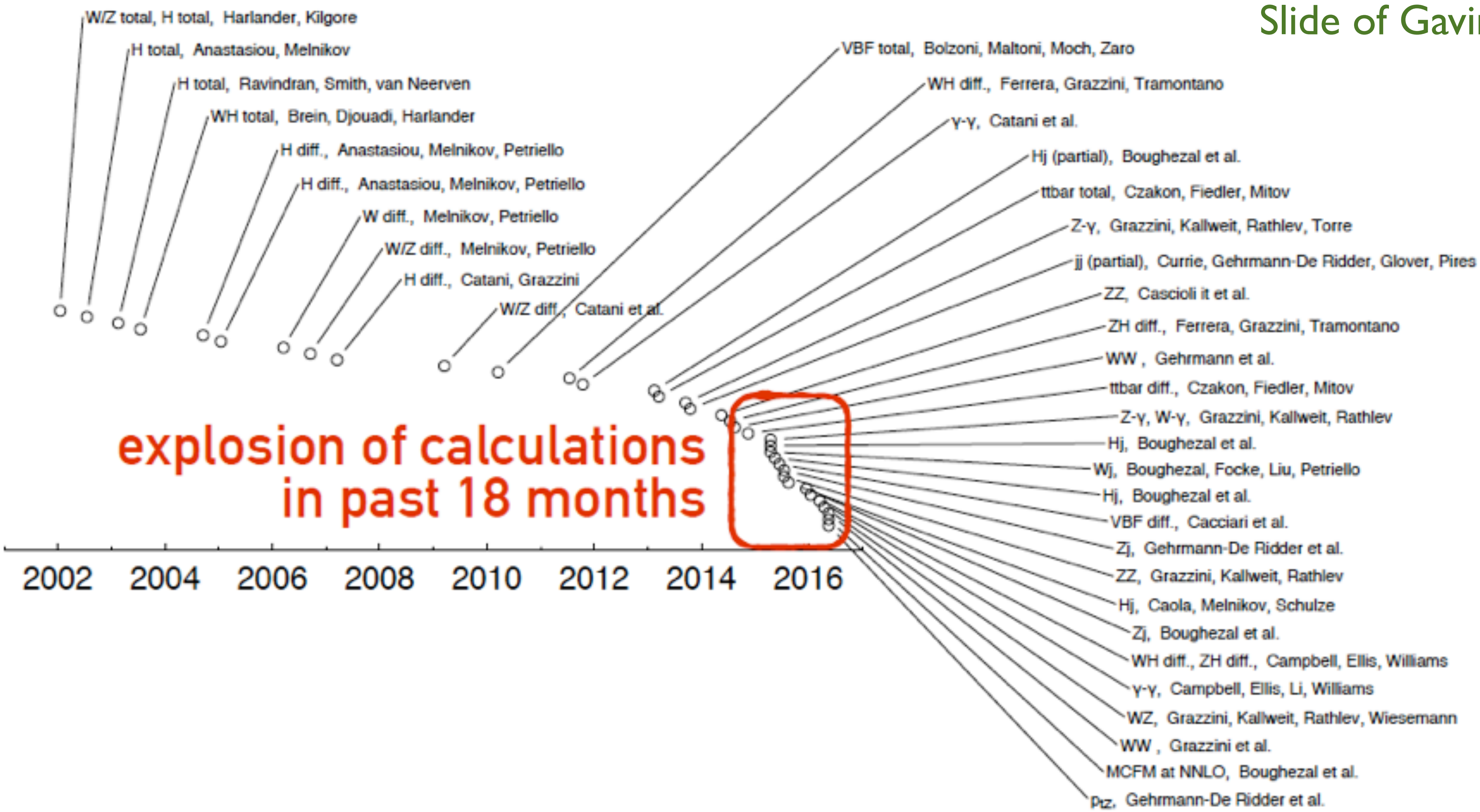
- LHC runs at 13 TeV and future colliders at 100 TeV
  - energy reaches deeper into multi-TeV region & high integrated luminosity
  - many processes (even rare processes before) reach precision era (precent)
- NLO QCD becomes standard: automation (e.g. MG5_aMC)
  - scale uncertainty reaches to 10% level
- 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: NNLO QCD (long way) and NLO EW (this talk)

FRONTIER OF PRECISION THEORY @ LHC

NNLO hadron-collider calculations v. time

as of mid June

Slide of Gavin Salam



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- Necessity of 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

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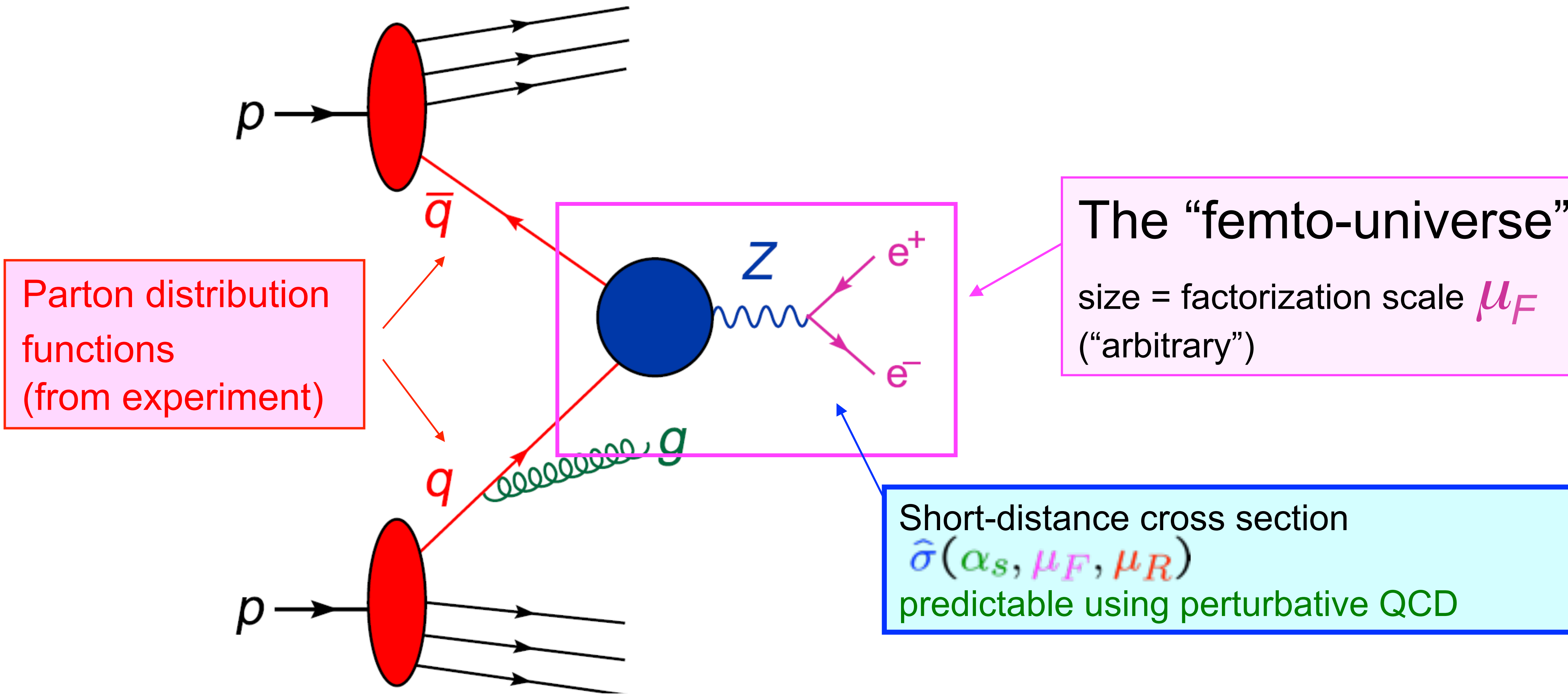

$$\sigma(pp \to Z + X) = \int dx_1 dx_2 f(x_1, \mu_F) f(x_2, \mu_F) \hat{\sigma}(\alpha_s, \mu_F, \mu_R)$$

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LO NLO NNLO

$$\hat{\sigma}(\alpha_s,\mu_F,\mu_R)=[\alpha_s(\mu_R)]^n\left[\hat{\sigma}^{(0)}+\frac{\alpha_s}{2\pi}\sigma^{(1)}(\mu_F,\mu_R)+\left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}^{(2)}(\mu_F,\mu_R)+\cdots\right]$$

QCD

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$$\hat{\sigma}(\alpha_s,\alpha,\mu_F,\mu_R)=[\alpha_s(\mu_R)]^n\alpha^m\Big[\hat{\sigma}^{(0,0)}+\frac{\alpha_s}{2\pi}\sigma^{(1,0)}(\mu_F,\mu_R)+\left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}^{(2,0)}(\mu_F,\mu_R)+\cdots$$

EW

$$+\frac{\alpha}{2\pi}\sigma^{(0,1)}(\mu_F,\mu_R)+\left(\frac{\alpha}{2\pi}\right)^2\hat{\sigma}^{(0,2)}(\mu_F,\mu_R)+\cdots$$

$$+\sum_{i\geq1}\sum_{j\geq1}\left(\frac{\alpha_s}{2\pi}\right)^i\left(\frac{\alpha}{2\pi}\right)^j\hat{\sigma}^{(i,j)}(\mu_F,\mu_R)\Big]$$

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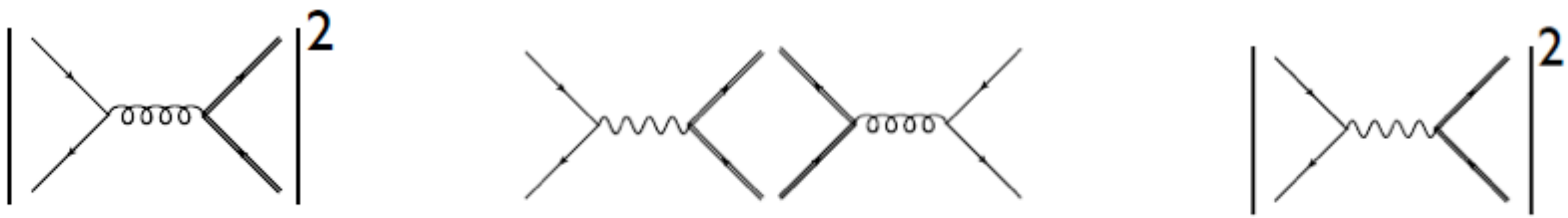

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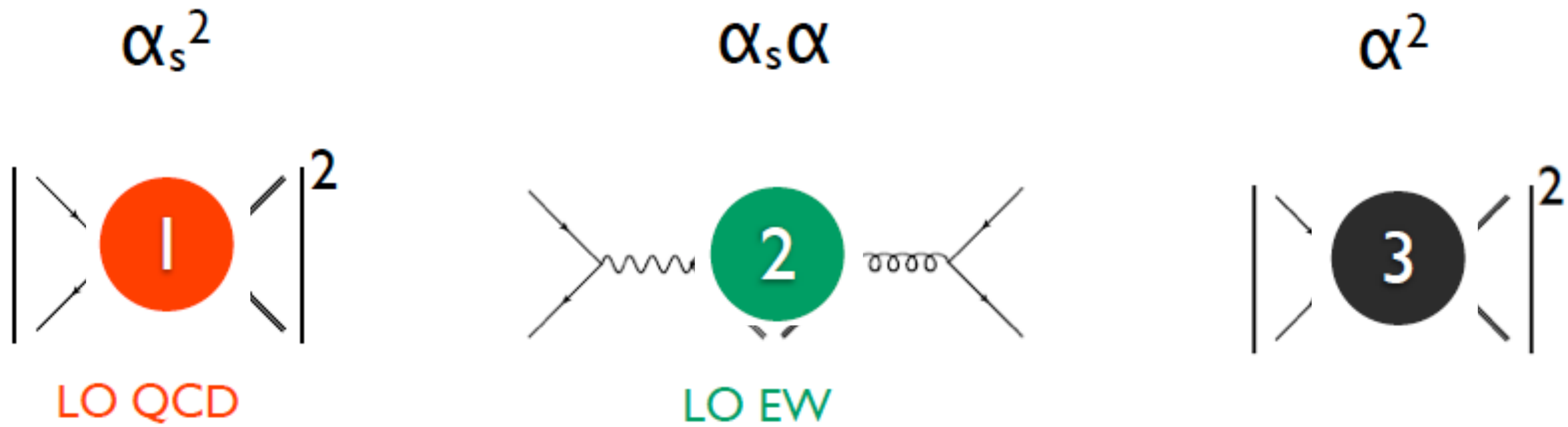

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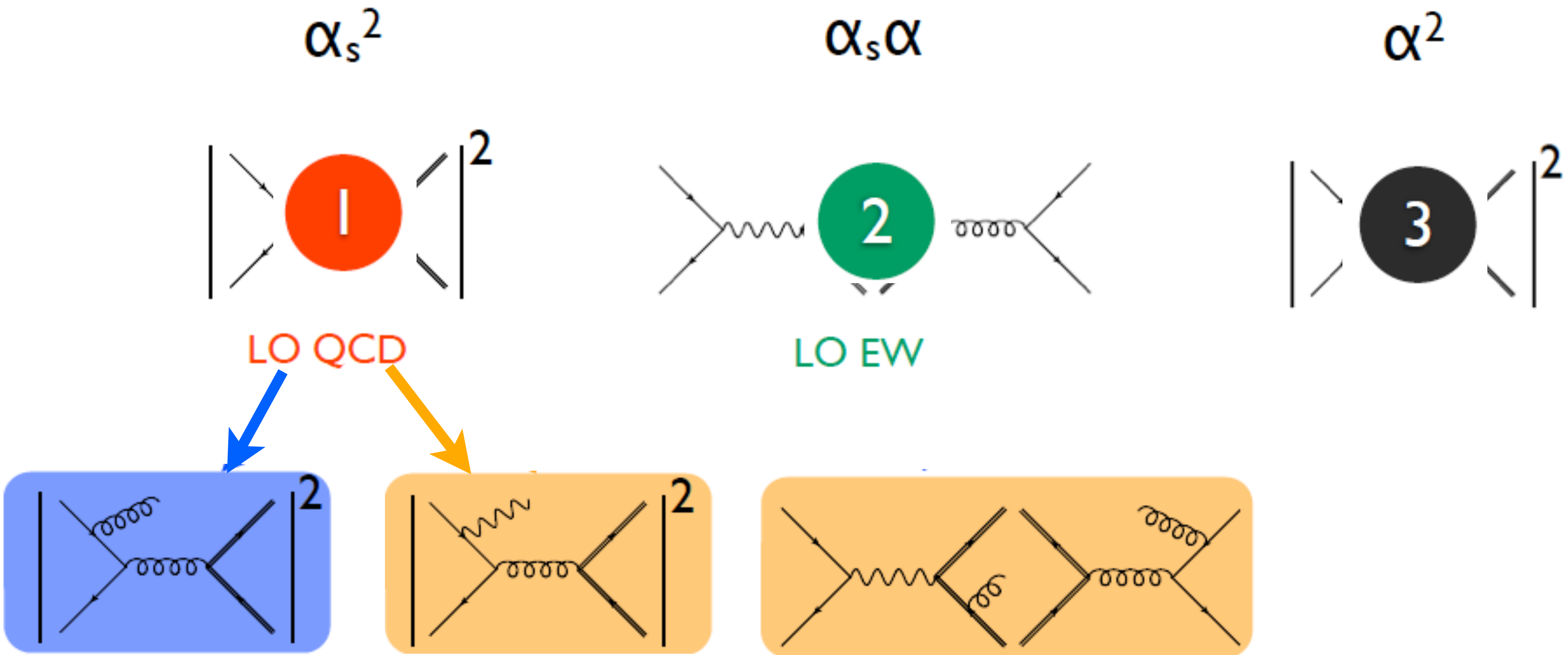

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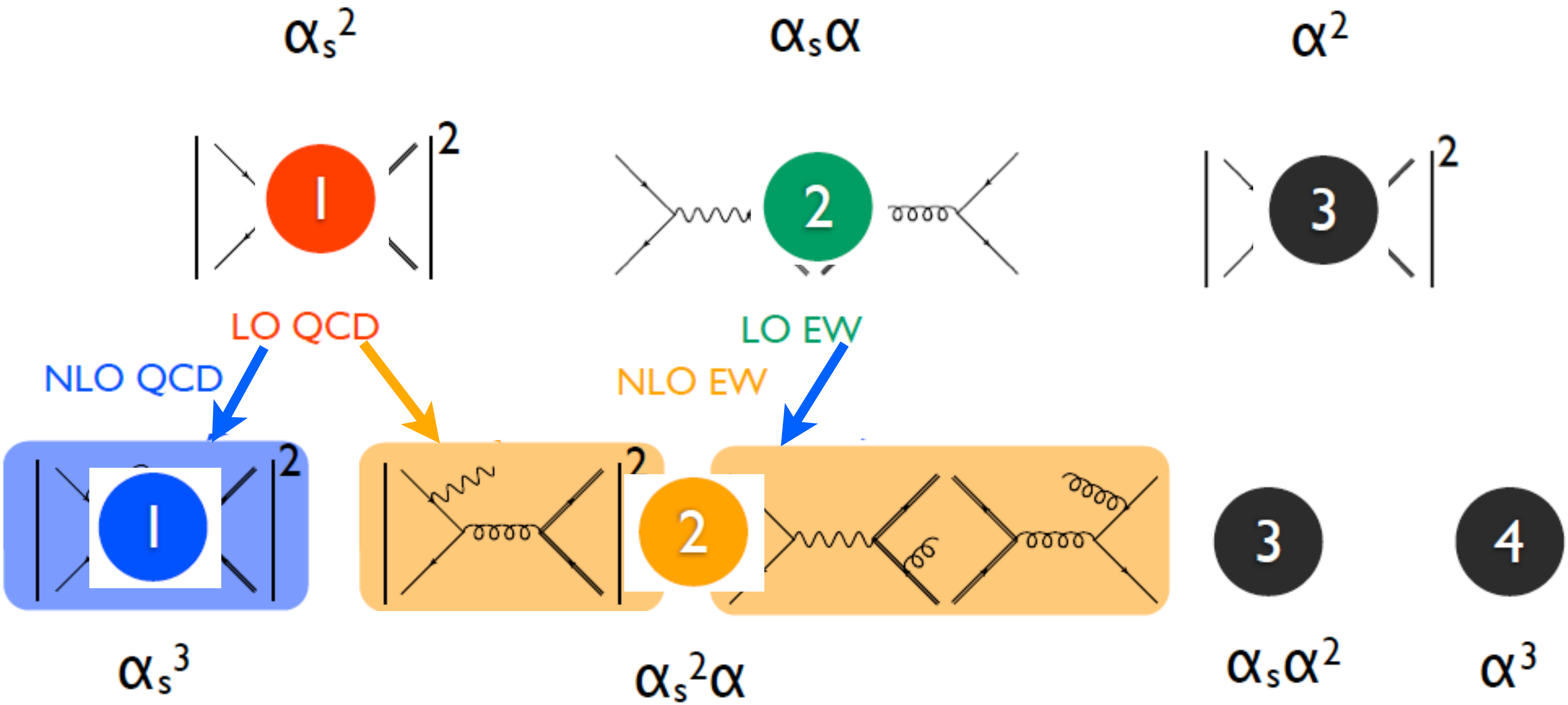

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- Use $K_{\rm NLO\ QCD} \times K_{\rm NLO\ EW}$ to capture the missing higher order ?

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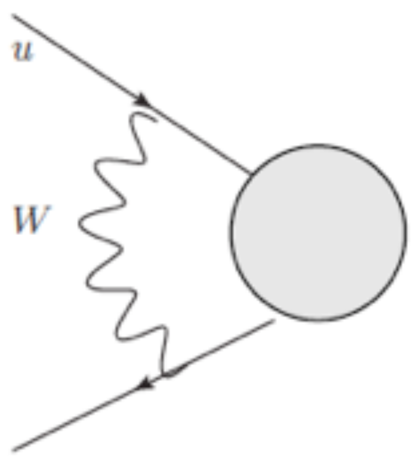

Leading Log *Next-to-Leading Log*

$$\sim -c_{\rm LL}\frac{\alpha}{\pi s_w^2}\log^2\frac{Q^2}{M_W^2} + c_{\rm NLL}\frac{3\alpha}{\pi s_w^2}\log\frac{Q^2}{M_W^2} + \cdots$$

soft **collinear**

e.g.

$$Q = 1\ \text{TeV} \qquad -c_{\rm LL}\times 26\% + c_{\rm NLL}\times 16\%$$

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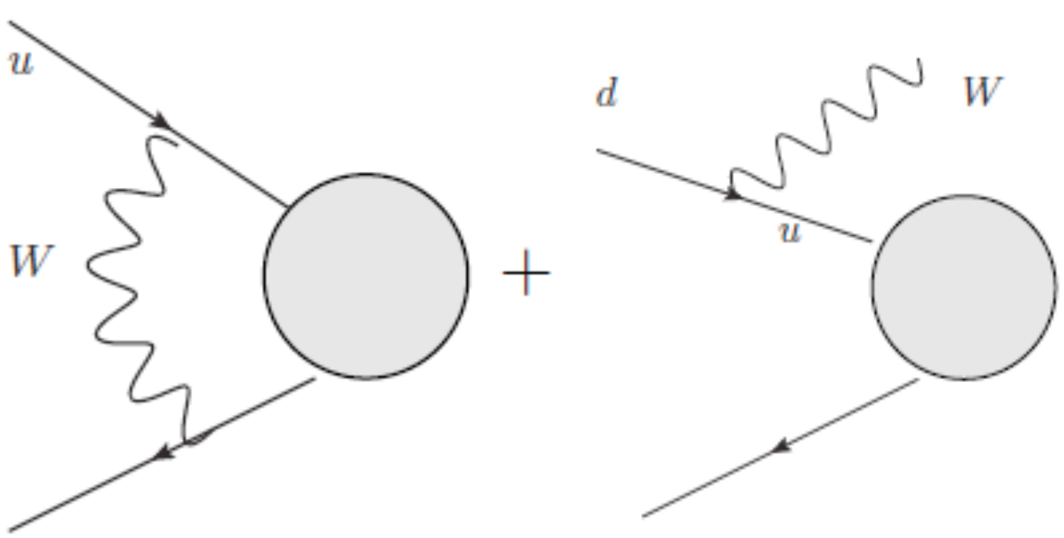

$$\sim (f_{u/p}-f_{d/p})\log\frac{Q^2}{M_W^2}$$

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  - Even treat W/Z as inclusive as gluon/photon: initial state is not SU(2) singlet
  - However, EW Sudakov logarithms is not always relevant in Sudakov regime
    - e.g. Drell-Yan at large invariant mass receives large contributions from small t Dittmaier et al.'10

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Apologize for not being able to mention many many important fundamental works as the basis of the above tools

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Processes	QCD	QED	QCD+QED
u u~ > u u~	28	36	64
g g > t t~	45	82	127
g g > t t~ h	164	533	697
a a > t t~ h	48	2102	2150
u u~ > w+ w- z	59	3111	3170
e+ e- > w+ w- e+ e-	-	27035	-
u u~ > w+ w- w+ w-	496	57879	58375

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```
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\
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                       },
                       texname = '\delta m_t')
```

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```
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(\
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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.*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**2*sw**2 - 24*MW**2*MZ\
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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*\
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W.value[0]},
```

AUTOMATION TOOLS FOR EW CORRECTIONS

- Automation tools for EWC so far (not as much as for QCD corr.)
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- Complications in EWC wrt QCD corrections (fixed order only)
  - More contributions like Feynman diagrams, off-shell currents
  - Usually involve many different mass scales (a problem of numerical stability)
  - More complicated CT vertices, e.g. top mass renormalization
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  - Need to deal with expansion into QCD and EW couplings
  - It is necessary to properly treat the photon

RECENT LHC PROCESSES WITH AUTOMATION TOOLS

tool	collaboration	process
MadGraph5_aMC@NLO	Frixione, Hirschi, Pagani, HSS, Zaro	$t\bar{t}+H/Z/W$
OpenLoops	Kallweit, Lindert, Poaaorini, Schonherr, Maierhofer	$W+\mathrm{n}-\mathrm{jets}, n=2,3$
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CERN

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MADGRAPH5_AMC@NLO IN A NUTSHELL

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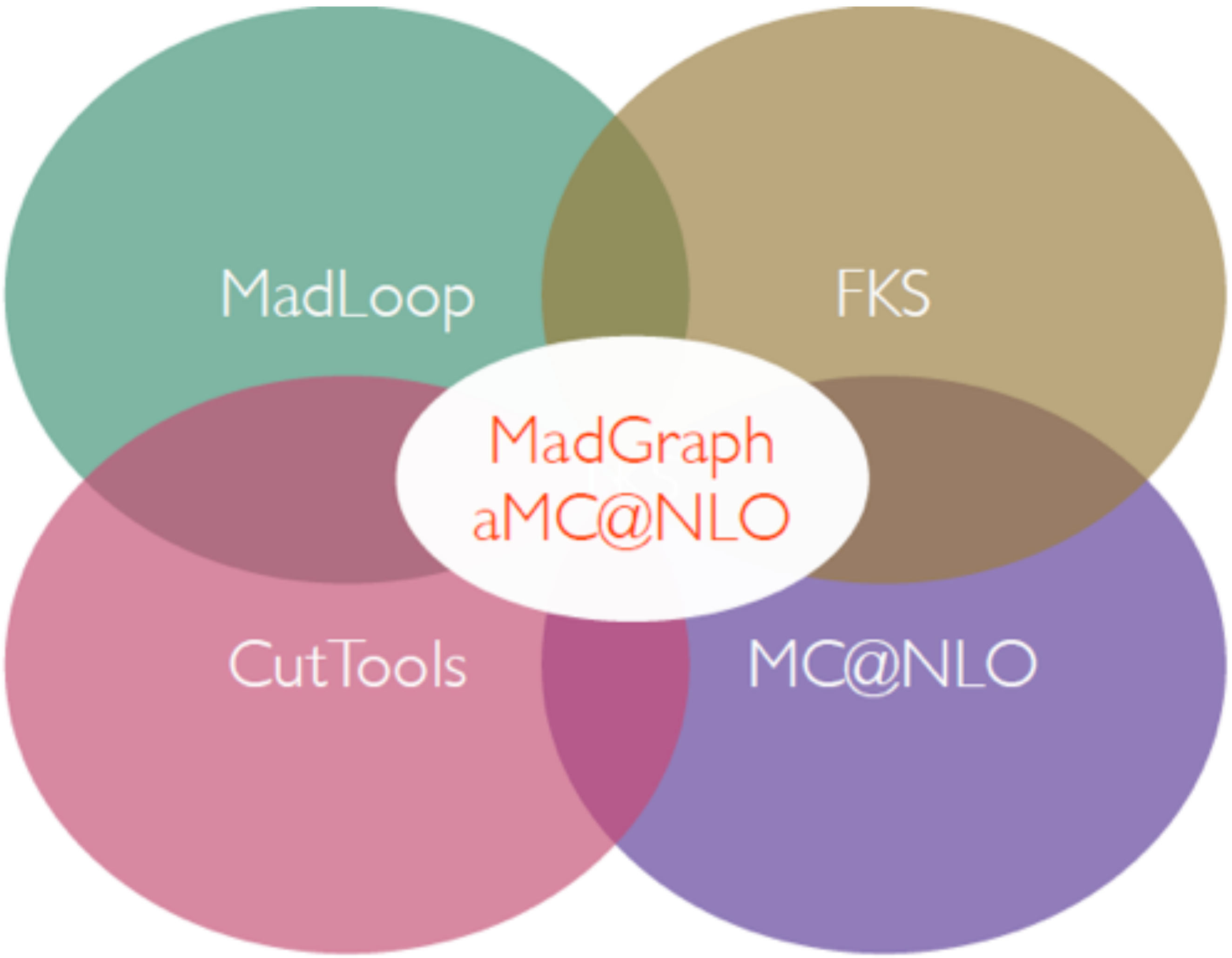

4 commands for a NLO calculation

```
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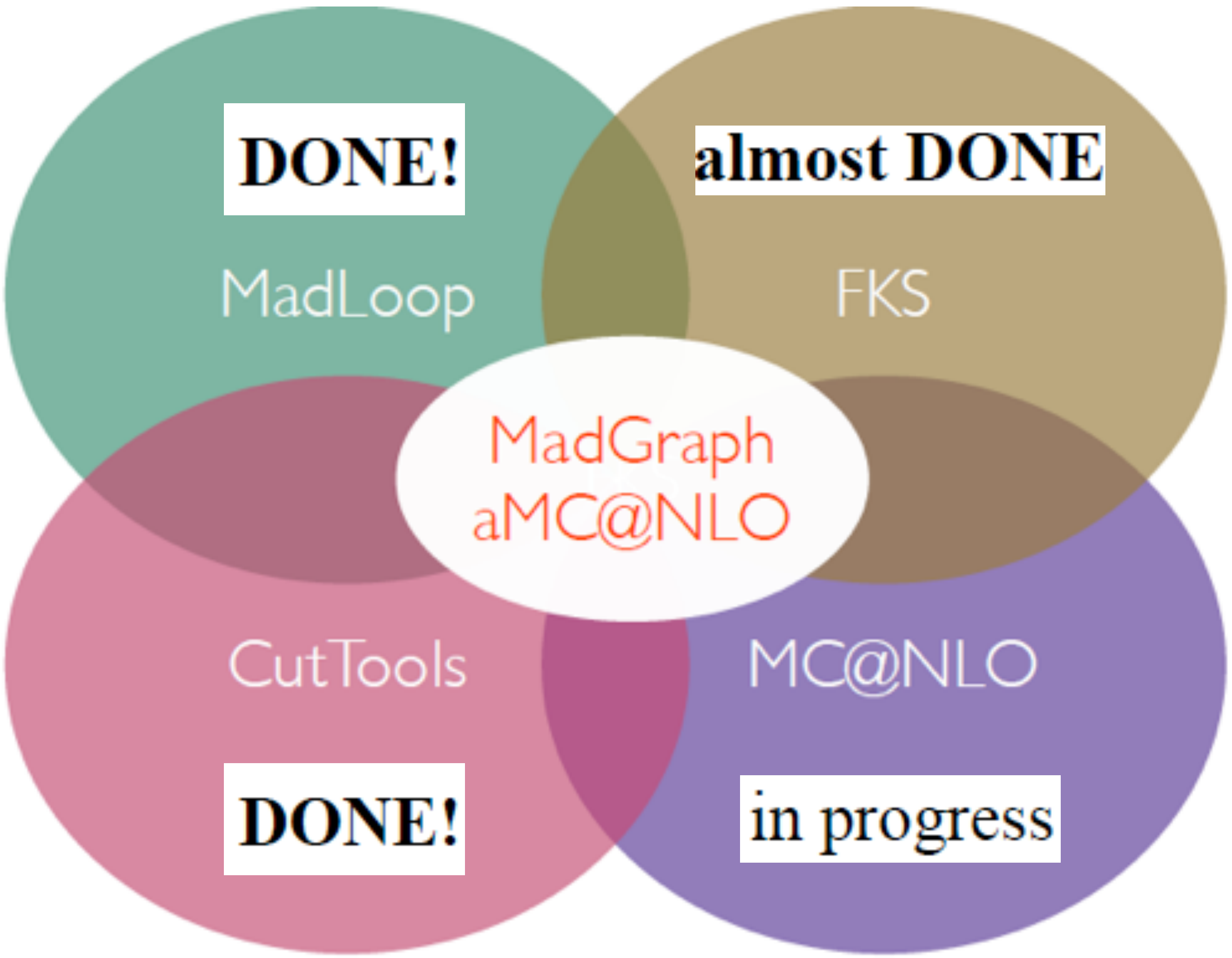

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complete automation for QCD+EW

```
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PHENOMENOLOGY STUDY: TTBAR

see D. Heymes's talk for NNLO QCD+NLO EW

- **Top quark pair**
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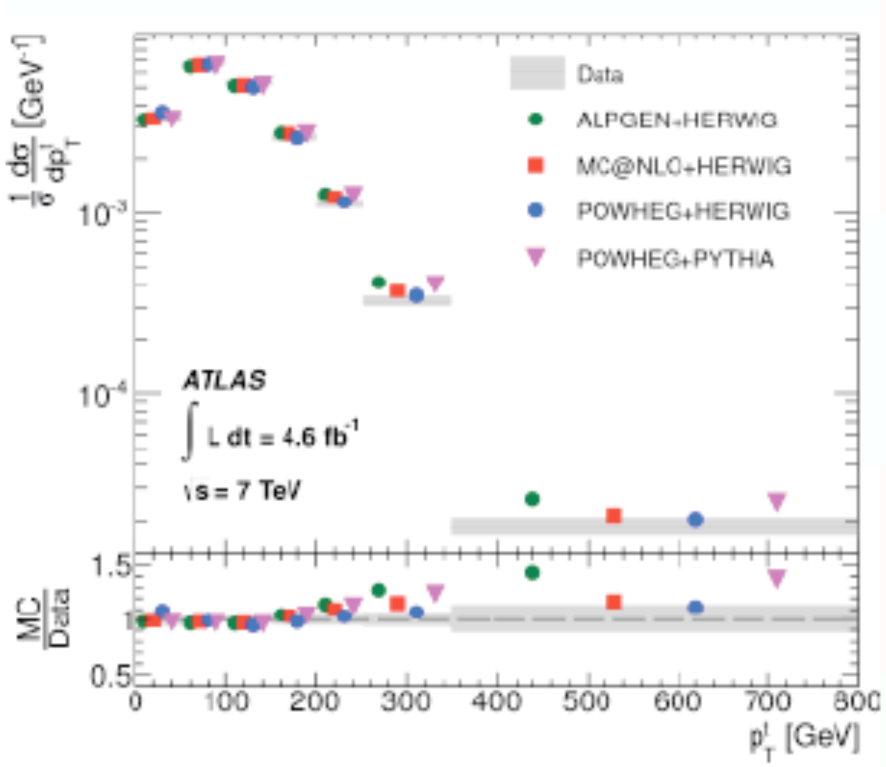

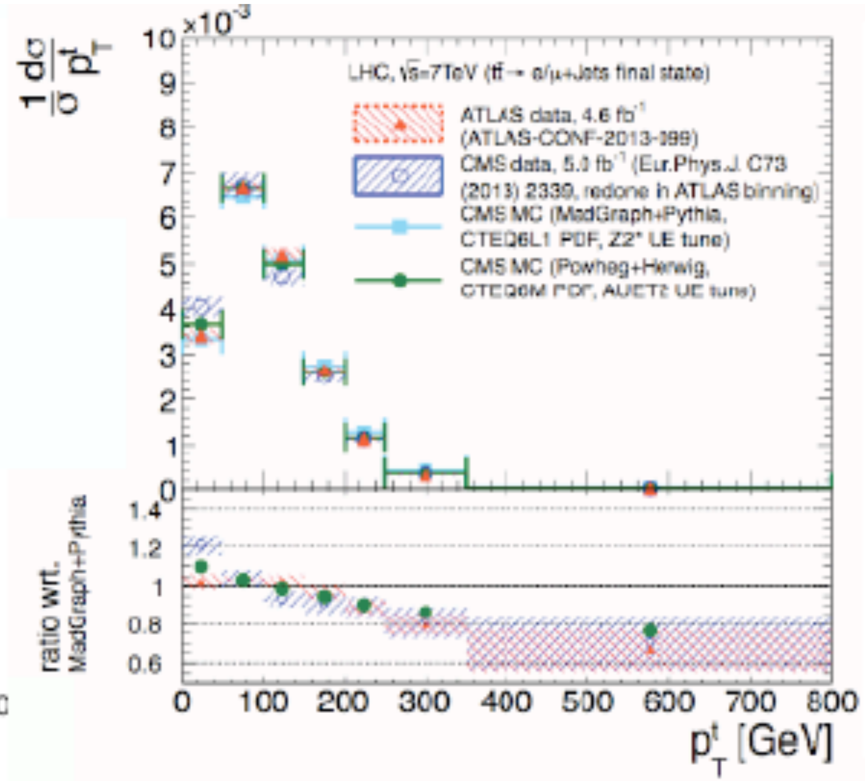

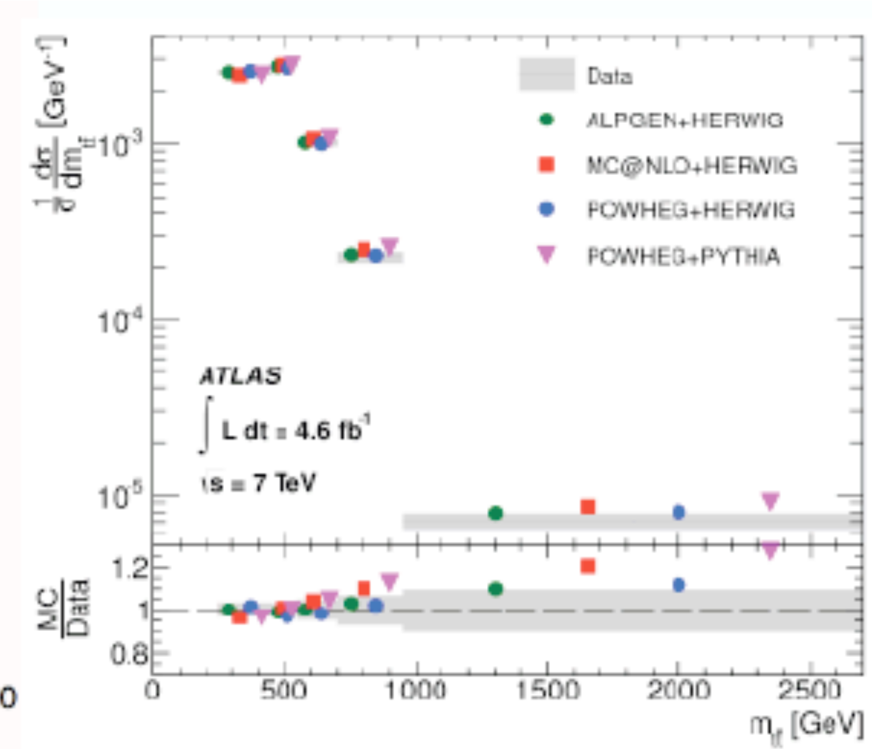

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NLO weak: Beenakker et al. '94; Kuhn, Scharf, Uwer '06,'13; Bernreuther, Fucker, Si '06
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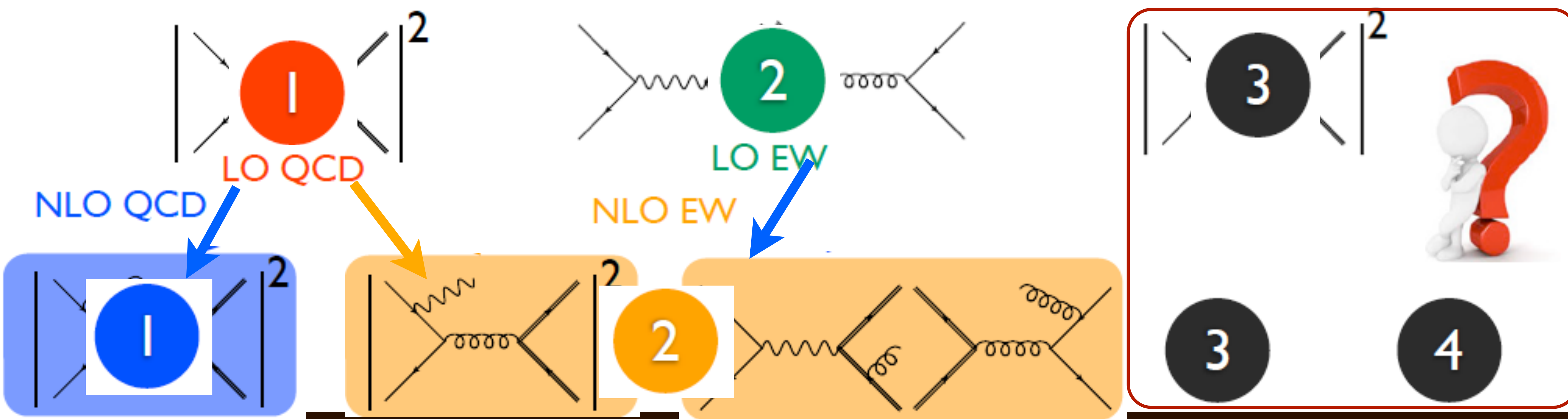

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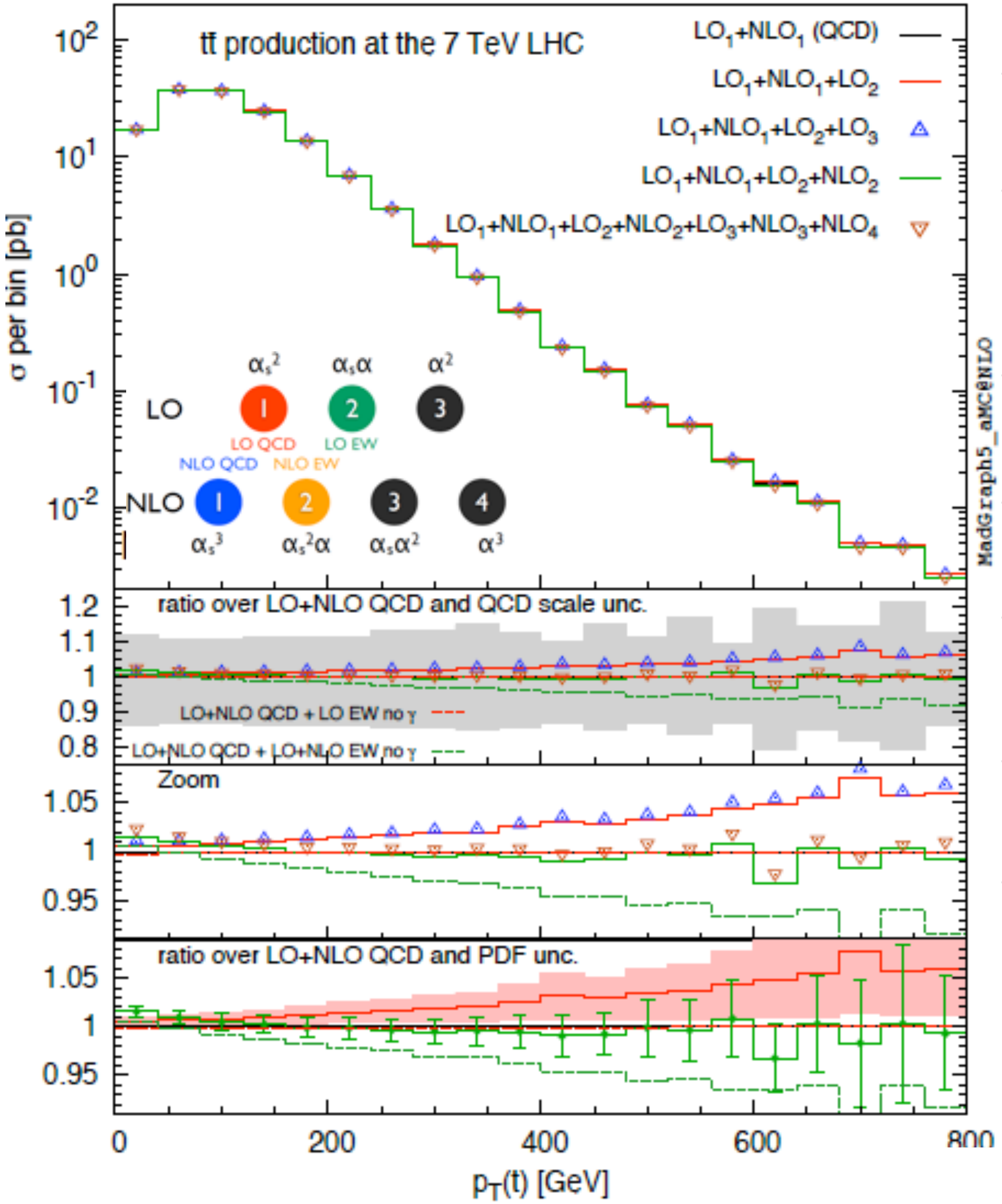

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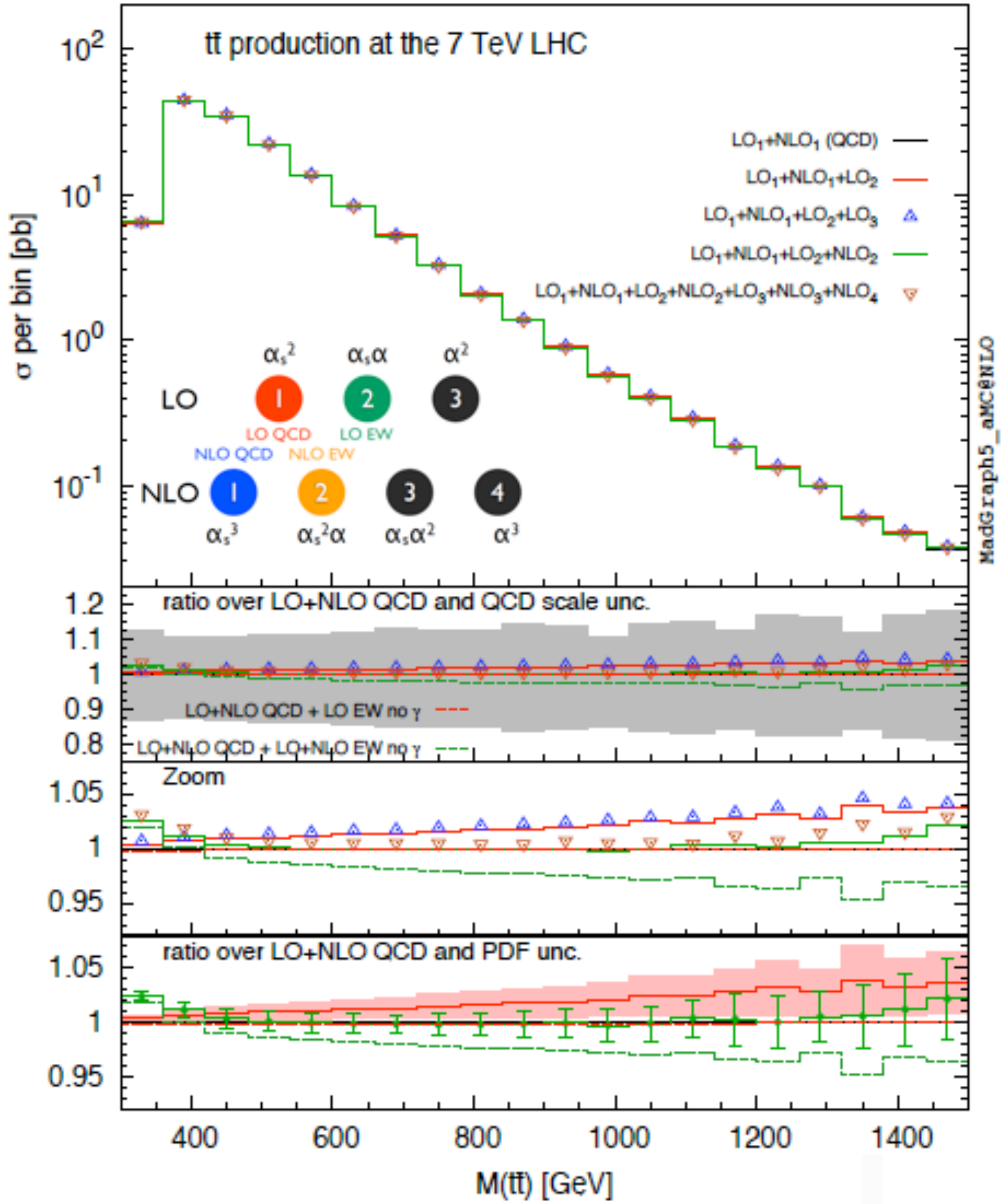

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Frixione, Hirschi, HSS, Pagani, Zaro '14,'15

- Why top quark pair+(H,Z,W) ?
  - These processes are very important at the LHC
    - ttbar+Higgs: the last missing of 4 main Higgs production channel (progress this year)
    - ttbar+Z/W: the background of ttbar+Higgs and important to study anomalous couplings
  - Missing of EWC for these processes in the literature
  - No conceptual problem in principle
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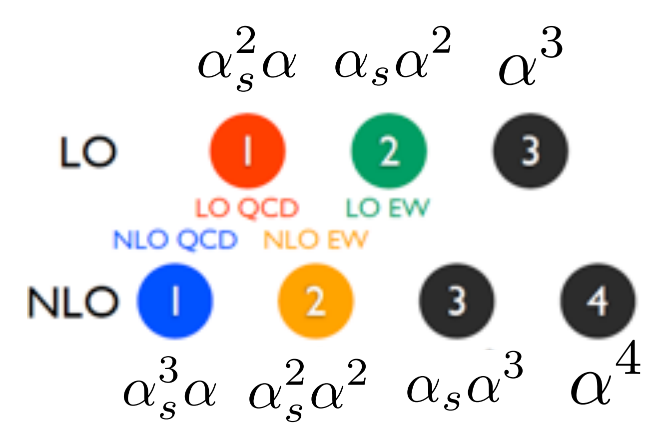
  - First public EWC results with MadGraph5_aMC@NLO
- **EWC on the inclusive total cross sections**
  - EWC is moderate (% level)
  - Increase with center-of-mass energy in general (not a real surprise)
  - LO_2 and NLO_2 accidentally cancel at 13 TeV
  - HBR only partly cancels NLO EW
  - EWC is enhanced by boosted final states $p_T(t) \geq 200$ GeV, $p_T(\bar{t}) \geq 200$ GeV, $p_T(V) \geq 200$ GeV

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

$t\bar{t}H$: $\delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$25.9^{+5.4}_{-11.1} \pm 3.5$	$29.7^{+6.8}_{-11.1} \pm 2.8$ $(24.2^{+4.8}_{-10.6} \pm 4.5)$	$40.8^{+9.3}_{-9.1} \pm 1.0$
LO EW	1.8 ± 1.3	1.2 ± 0.9 (2.8 ± 2.0)	0.0 ± 0.2
LO EW no γ	-0.3 ± 0.0	-0.4 ± 0.0 (-0.2 ± 0.0)	-0.6 ± 0.0
NLO EW	-0.6 ± 0.1	-1.2 ± 0.1 (-8.2 ± 0.3)	-2.7 ± 0.0
NLO EW no γ	-0.7 ± 0.0	-1.4 ± 0.0 (-8.5 ± 0.2)	-2.7 ± 0.0
HBR	0.88	0.89 (1.87)	0.91



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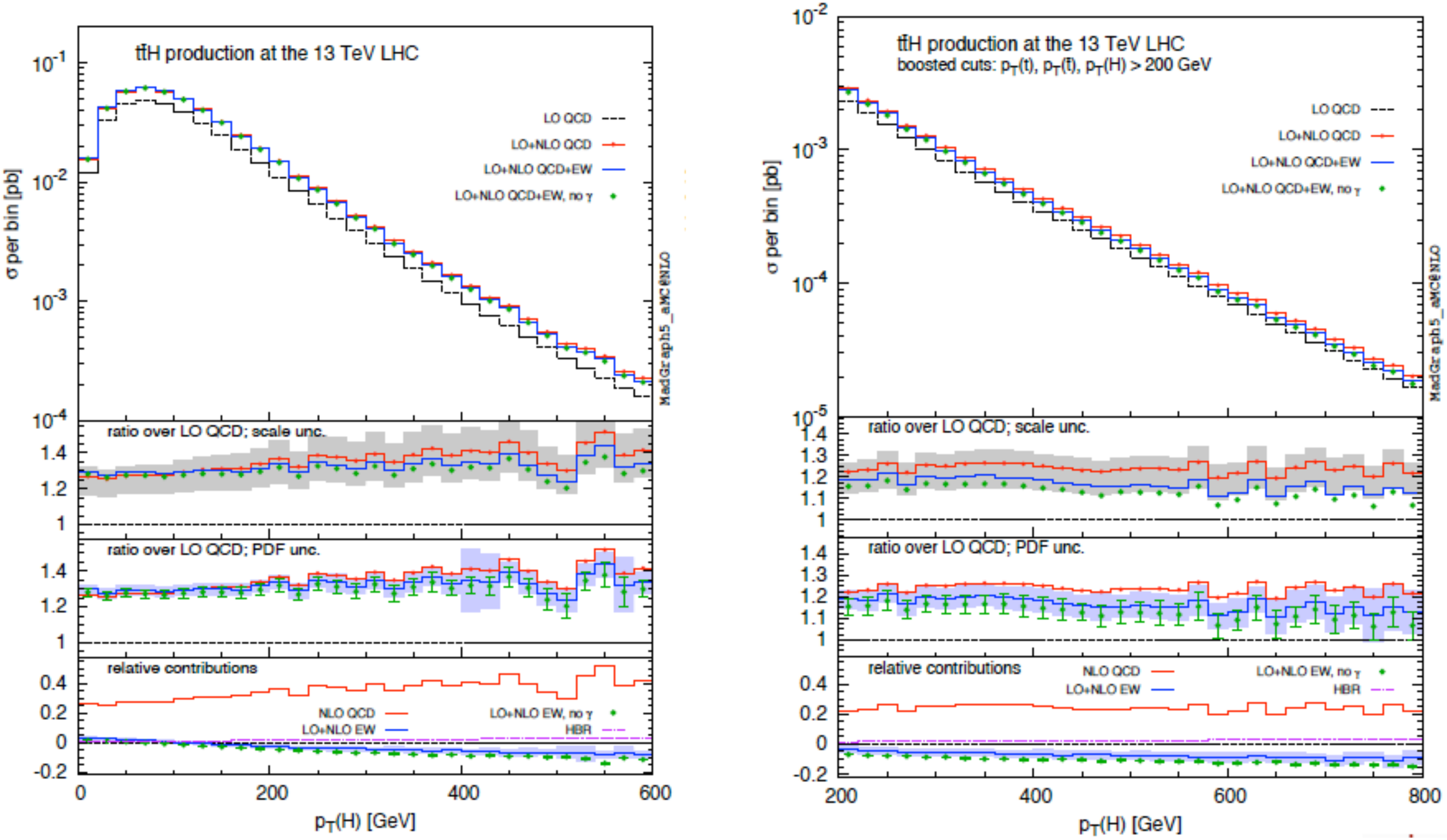
  - **Both NLO EW and photon PDF become important when boost final states**

NNPDF2.3QED here



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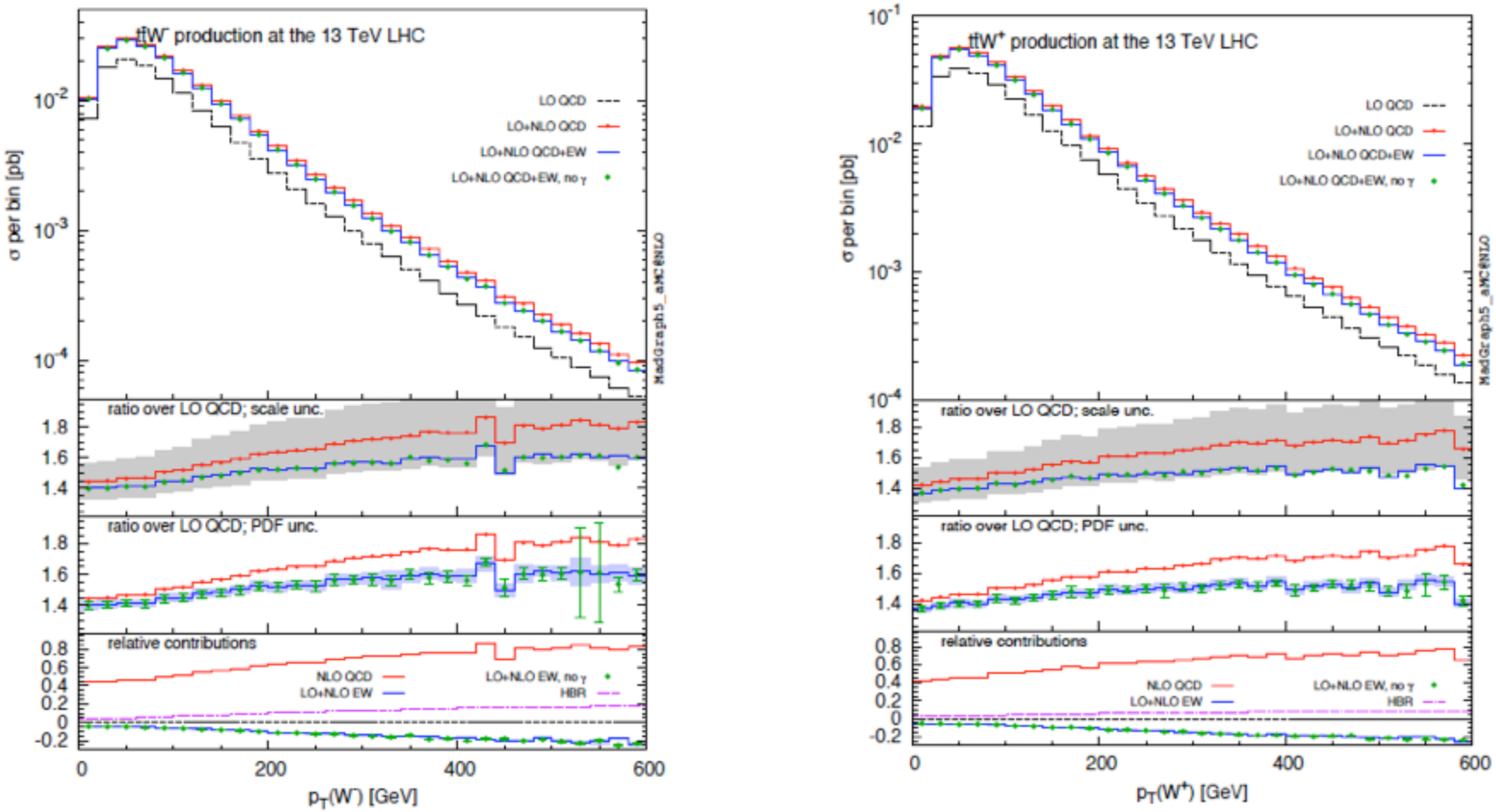

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    - No LO EW to cancel NLO EW (color flow) and HBR opens gg initial states
- Is EWC for ttbarH (or ttbarV) relevant ? YES
  - Current scale uncertainty in NLO QCD is 10%
  - Will be improved by the theory community with NNLO QCD corrections
  - Even at the moment, EWC will be relevant, especially at Sudakov region
  - EWC is also quite important for the cross section ratios, e.g. ttbarH/ttbarZ

Mangano, Plehn, Reimitz, Schell, HSS '15

		$\alpha(m_Z)$ 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

PHENOMENOLOGY STUDY: TTBAR+H/V

CERN

Frixione, Hirschi, HSS, Pagani, Zaro '14,'15

- EWC on differential distributions (and for fiducial xs)
  - Both NLO EW and photon PDF become important when boost final states
    NNPDF2.3QED here
  - EWC for ttW is more significant (~-8% at 13 TeV) than ttH and ttZ
    - No LO EW to cancel NLO EW (color flow) and HBR opens gg initial states
- Is EWC for ttbarH (or ttbarV) relevant ? YES
  - Current scale uncertainty in NLO QCD is 10%
  - Will be improved by the theory community with NNLO QCD corrections
  - Even at the moment, EWC will be relevant, especially at Sudakov region
  - EWC is also quite important for the cross section ratios, e.g. ttbarH/ttbarZ
  - The results are in the LHCHXSWG recommendation in YR4

PHENOMENOLOGY STUDY: HW

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

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

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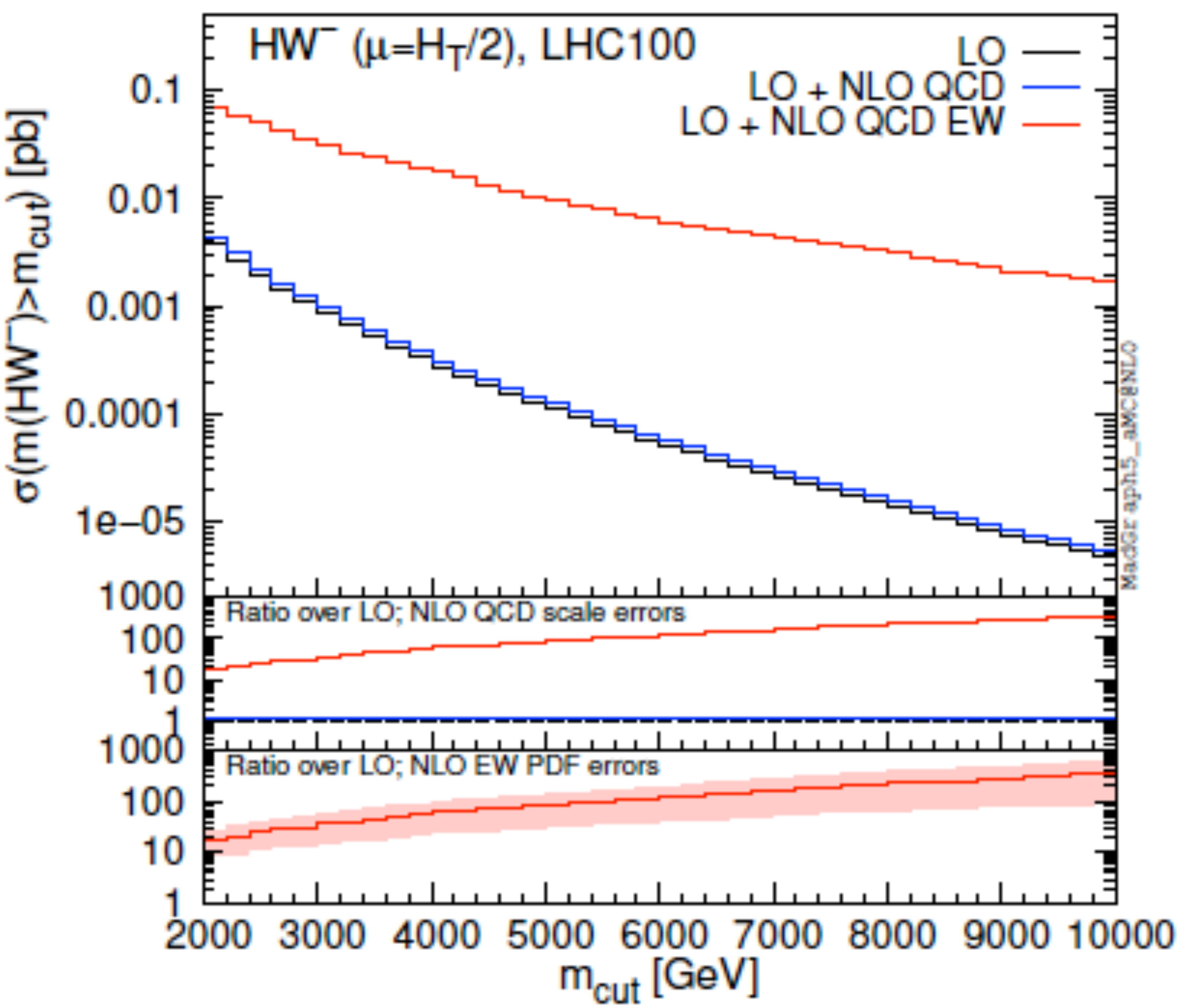

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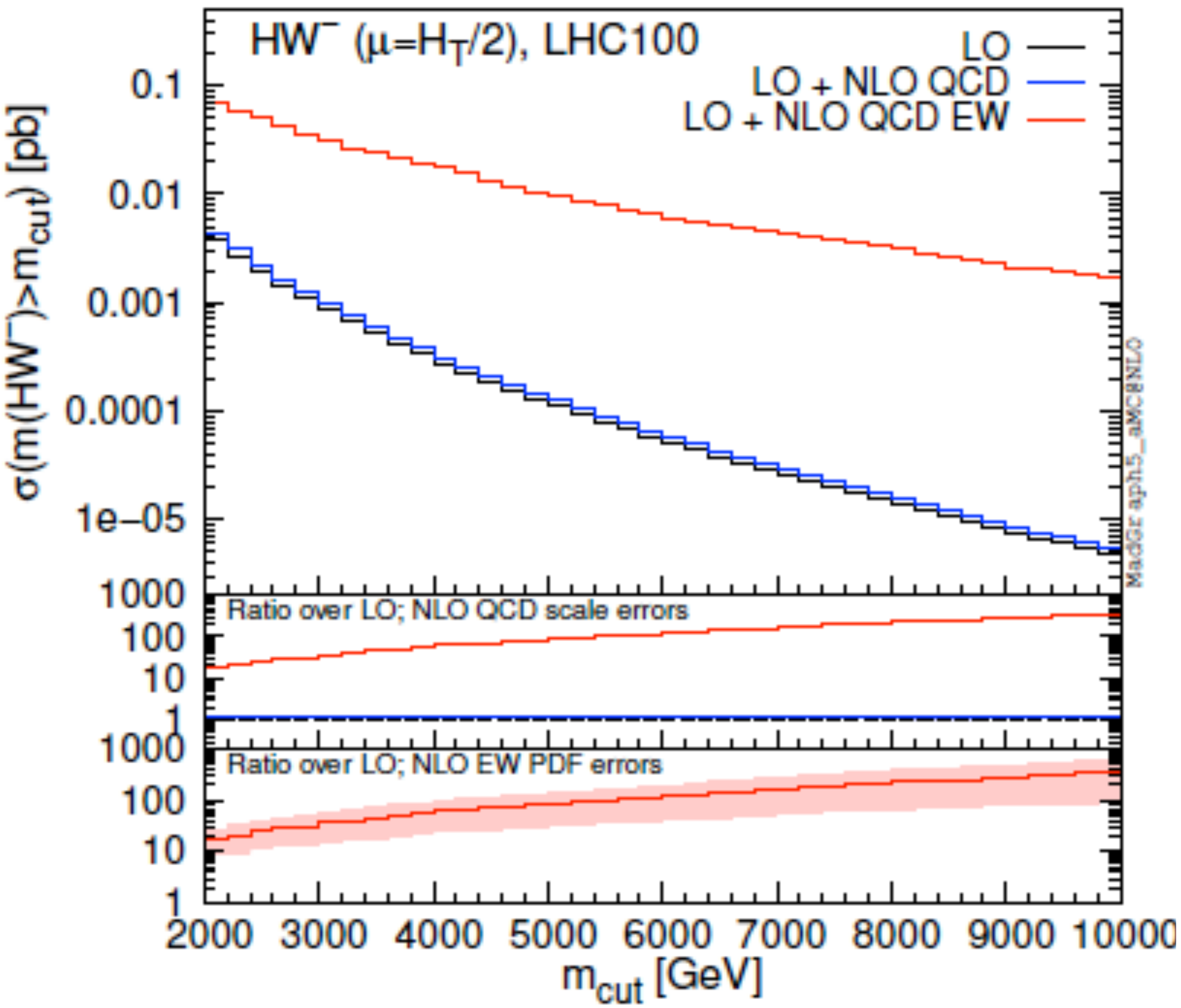

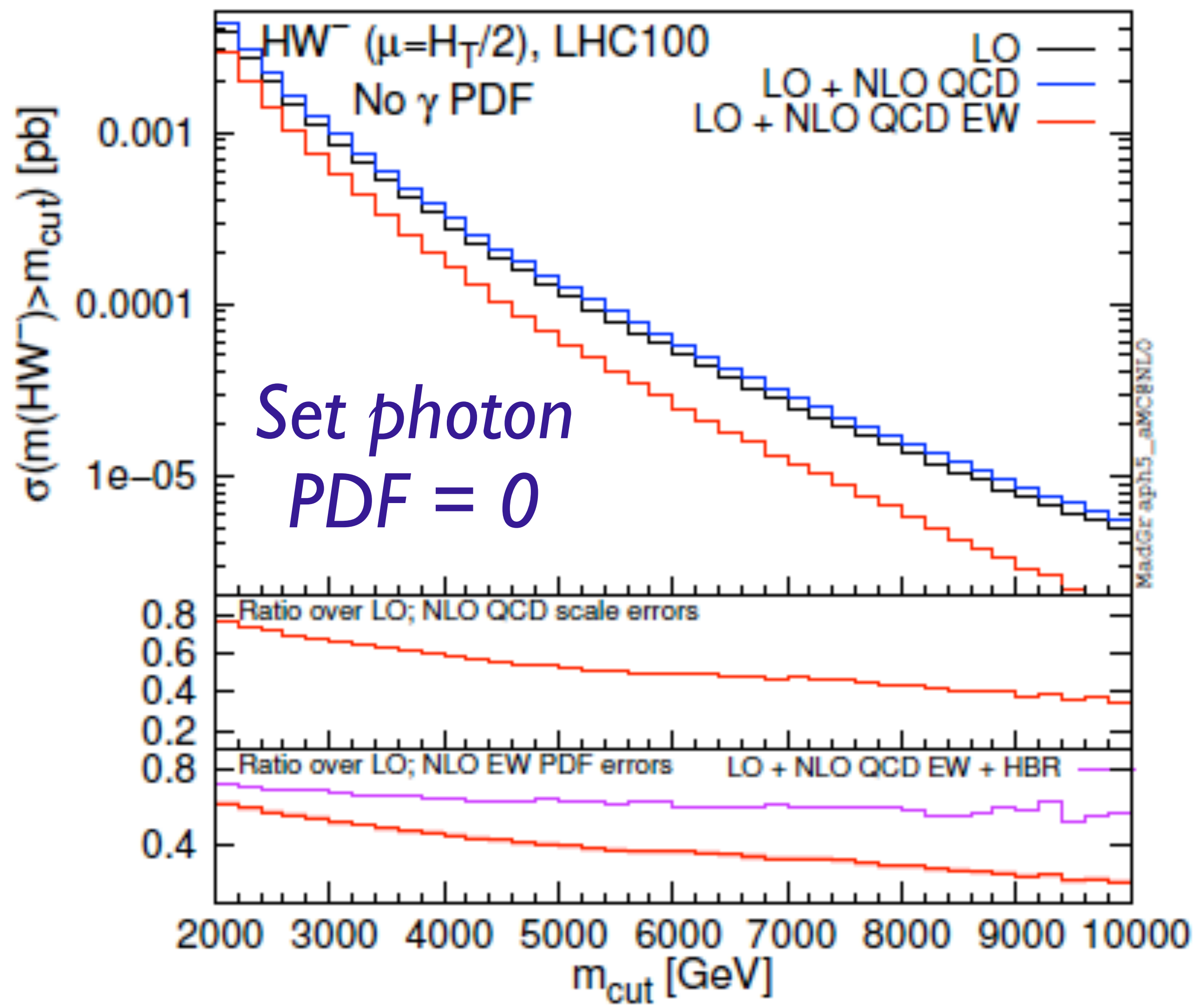

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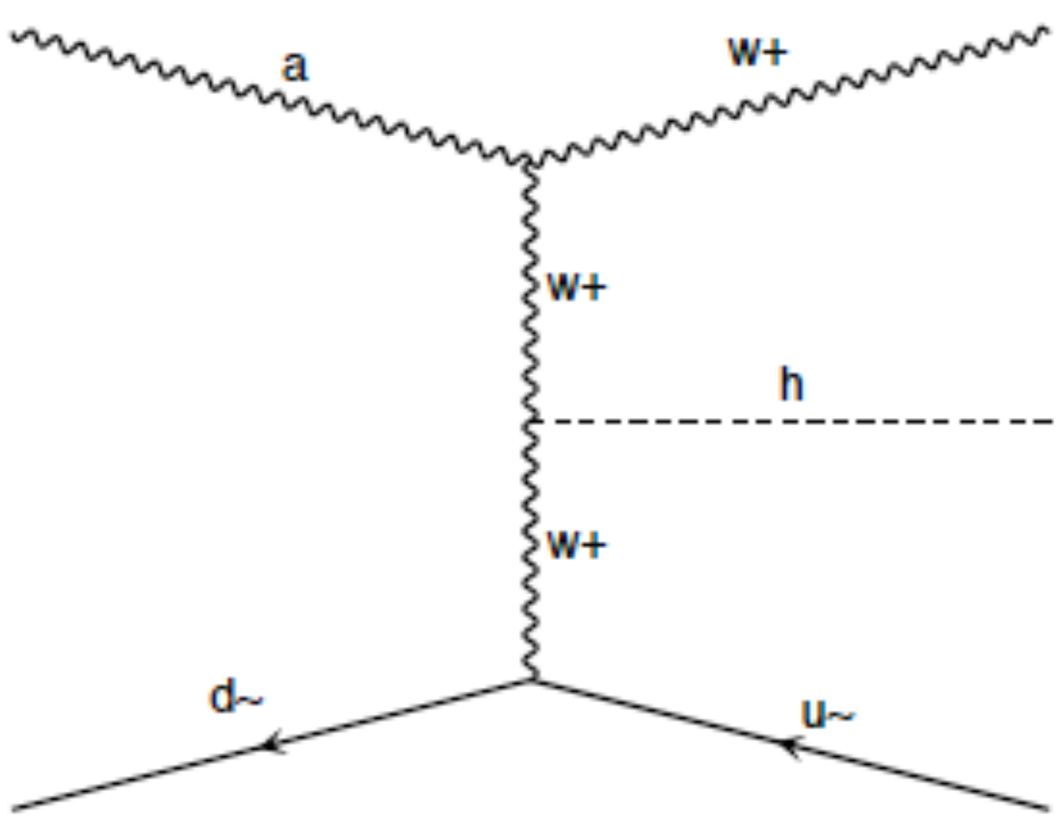
  - At Born, HW is produced via s-channel only, while NLO introduces t-channel
  - At large inv. mass, t-channel is dominant



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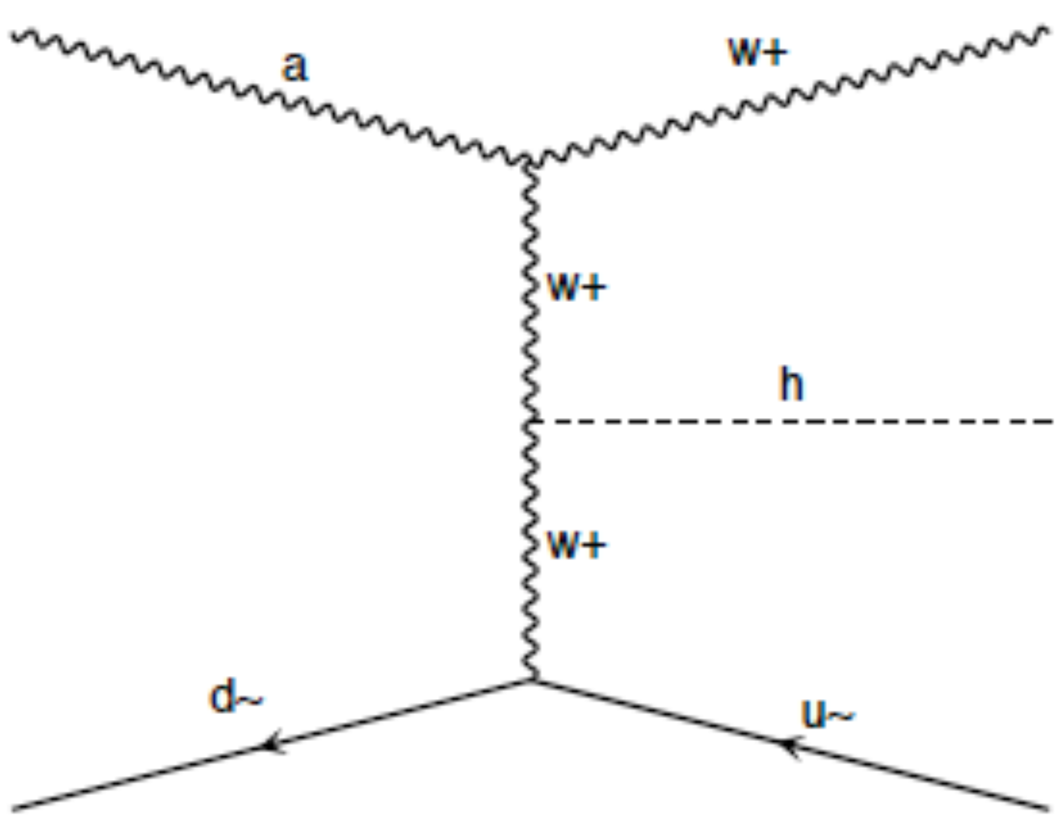

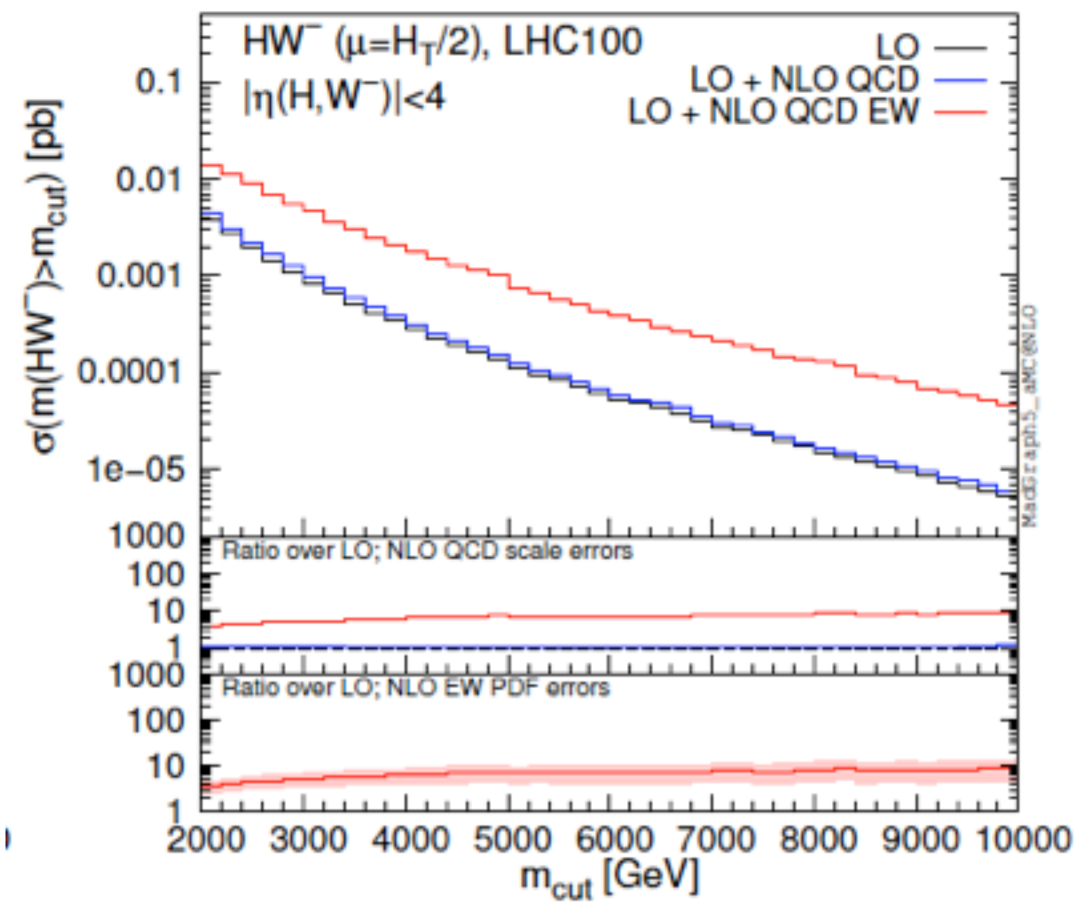

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  - At large inv. mass, t-channel is dominant
  - Such a contribution can be suppressed by cut e.g. on pseudorapidity
- Message: do not simply overlook EWC even you are not a precision guy

PHENOMENOLOGY STUDY: DIJET

- **A nontrivial (but important) process lacking EWC (surprising ?)**

PHENOMENOLOGY STUDY: DIJET

- A nontrivial (but important) process lacking EWC (surprising ?)
  - In the Les Houches wishlist 2013

Process	known	desired	details
$t\bar{t}$	σ_{tot} @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	with top decays
$t\bar{t}+j$	$d\sigma$(NWA top decays) @ NLO QCD		
single-top			
dijet	$d\sigma(gg)$ @ NNLO QCD $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	
$\gamma+j$			$\gamma+b$ for bottom PDF

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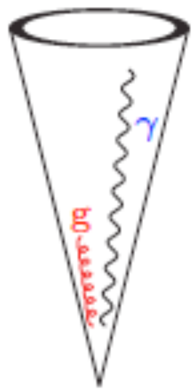

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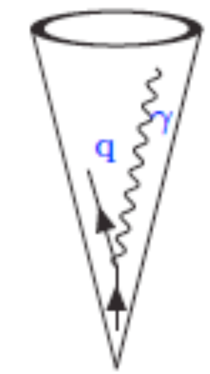

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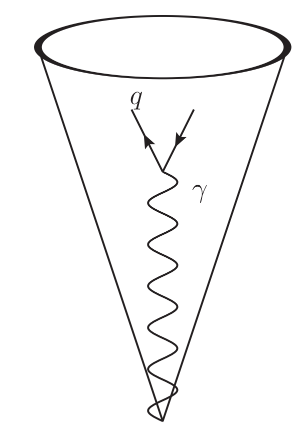
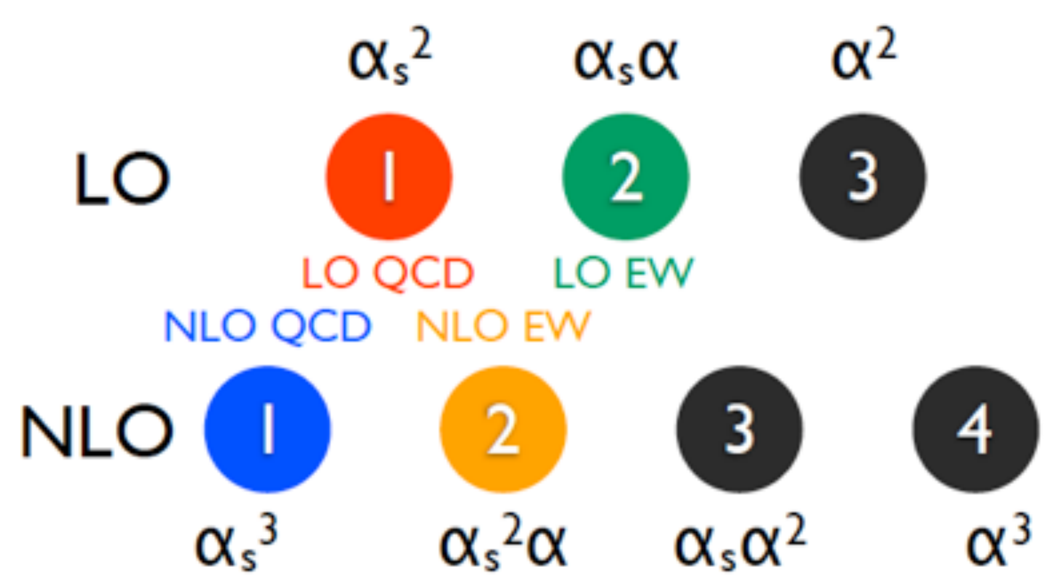
    - Two current methods for second issue: FF and close quark-photon = quark

Denner, Hofer, Scharf, Uccirati'14 Kallweit, Lindert, Maierhofer, Pozzorini, Schonherr,'14

    - For the first issue: they both use a cut on the energy fraction of photon
    - cut on the energy fraction of photon is not always working
    - Very often in subleading contr., sometimes also in leading EWC





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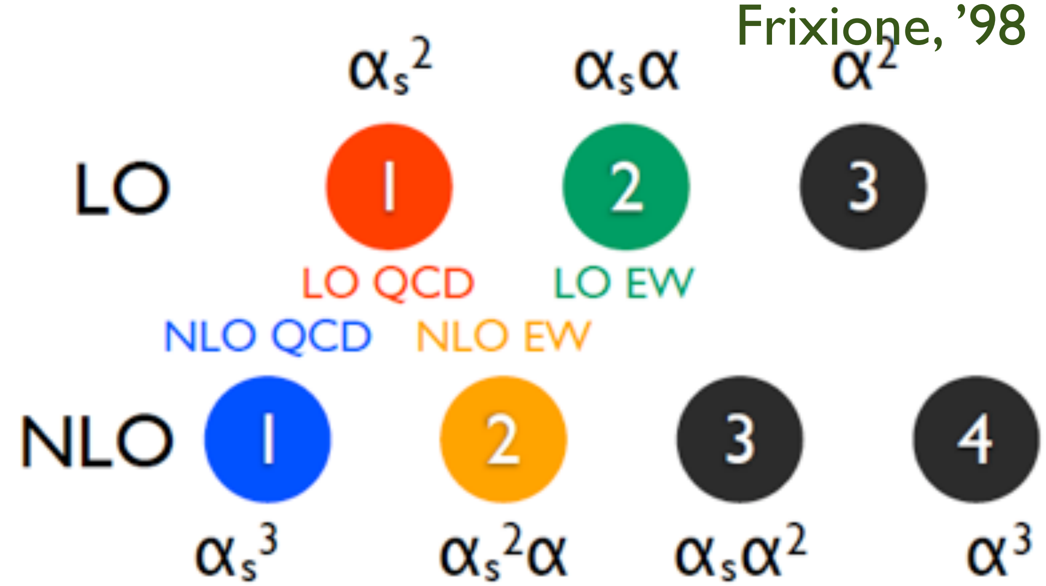
  - We try to include all blobs for dijet production
  - Democrate jet clustering and Frixione-type criterion for "photon jet"

Frixione, '98



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PHENOMENOLOGY STUDY: DIJET

CERN

jets: k_T with R=0.7

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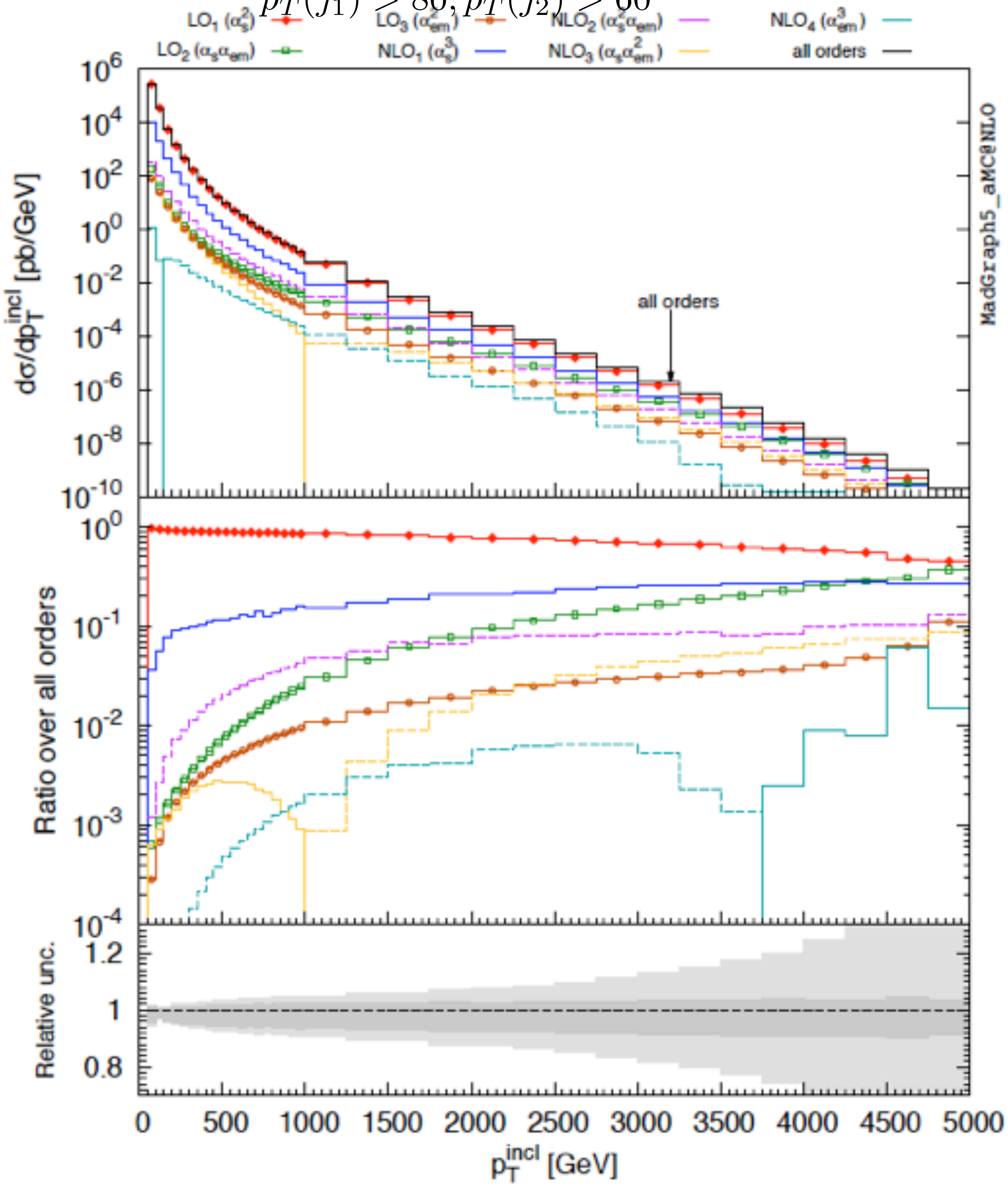
$p_T(j_1) > 80, p_T(j_2) > 60$



- p_T inclusive is crucial for PDF fit
- Breakdown of different contributions
- QCD correction is small in this obser.
- EWC (LO_2) is important in the tail
- Hierarchy between different orders

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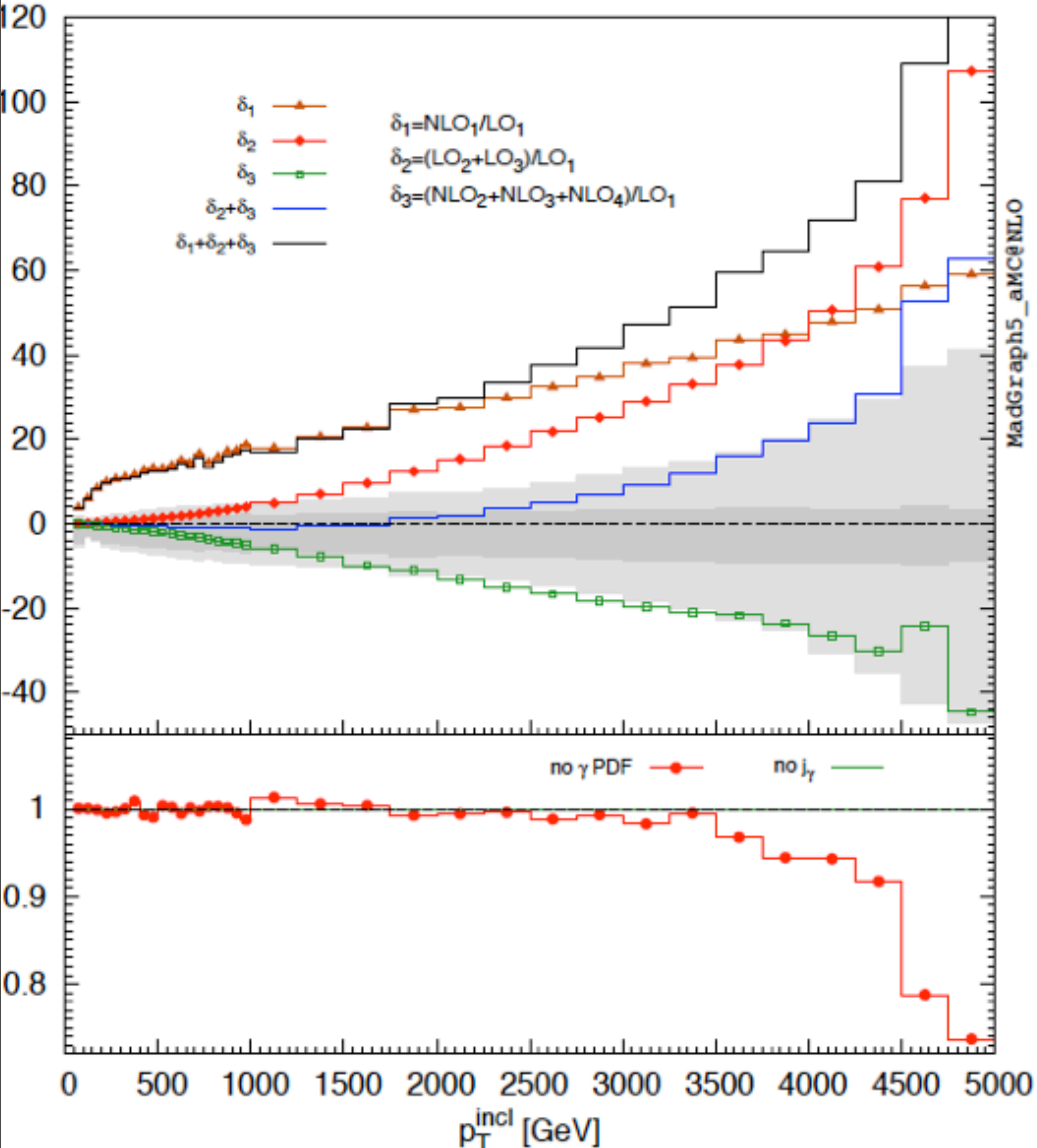

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- **We use NNPDF2.3QED (max photon)**
- **Photon jet is very rare in general**

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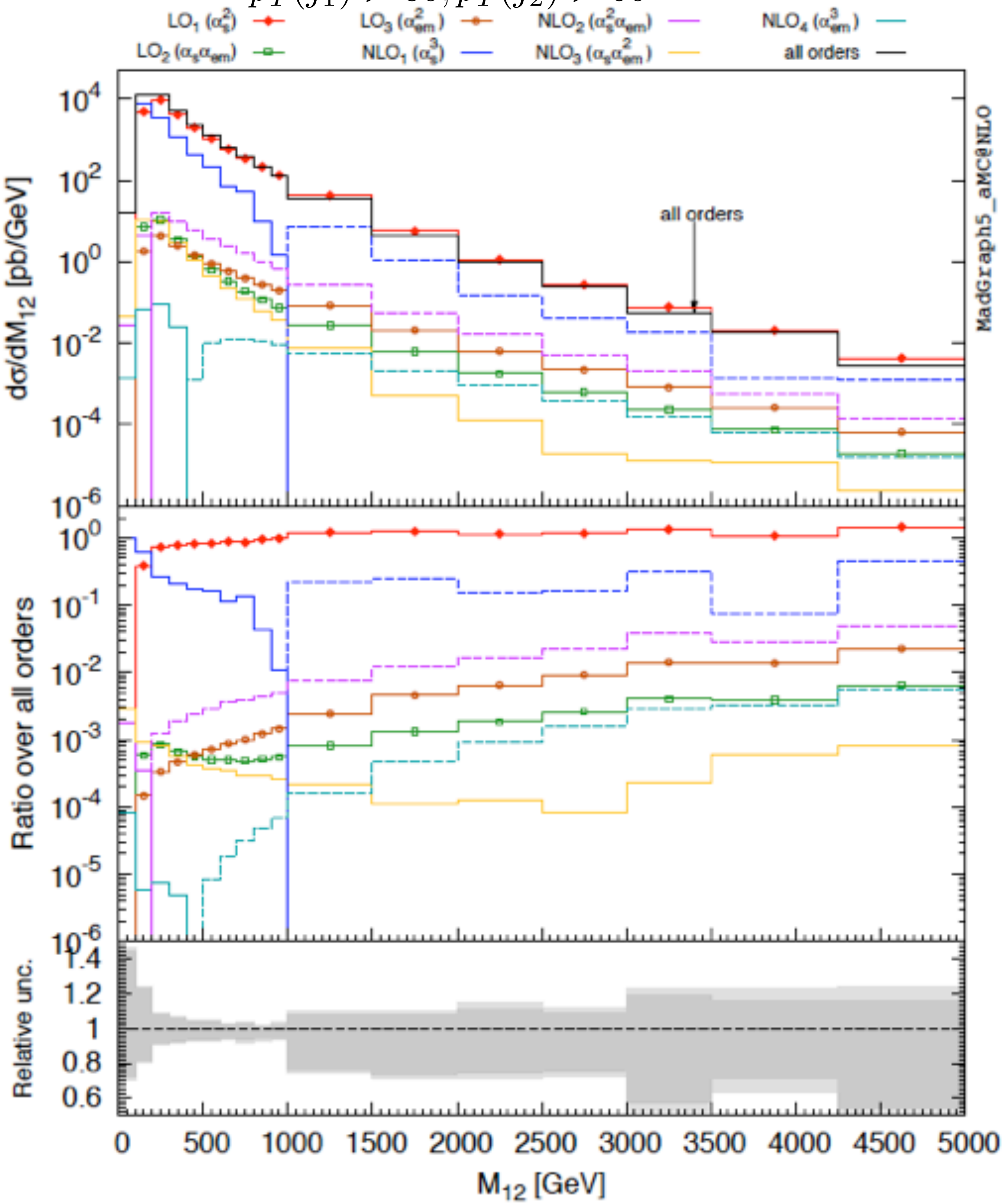

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- We use NNPDF2.3QED (max photon)
- Photon jet is very rare in general
- inv. mass is crucial in BSM search
- inv. mass is insensitive to photon PDF

SUMMARY

- **Precision theory requires the good knowledge of EW corrections**
- **EW corrections can also be enhanced in some (not rare) cases**
- **It also requires more study on the new ingredients: e.g. PDF and FF**
- **Many challenges are still present with both QCD and EWC, e.g. to PS**
- **Great progress in automation has been seen in the recent years**
- **MadGraph5_aMC@NLO will be released with EWC soon (hopefully:-)**

Cho tôi biết !

Thank you for your attention !