ElectroWeak Corrections For LHC Physics

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Recontres de Physique des Particules 2020
30 January 2020

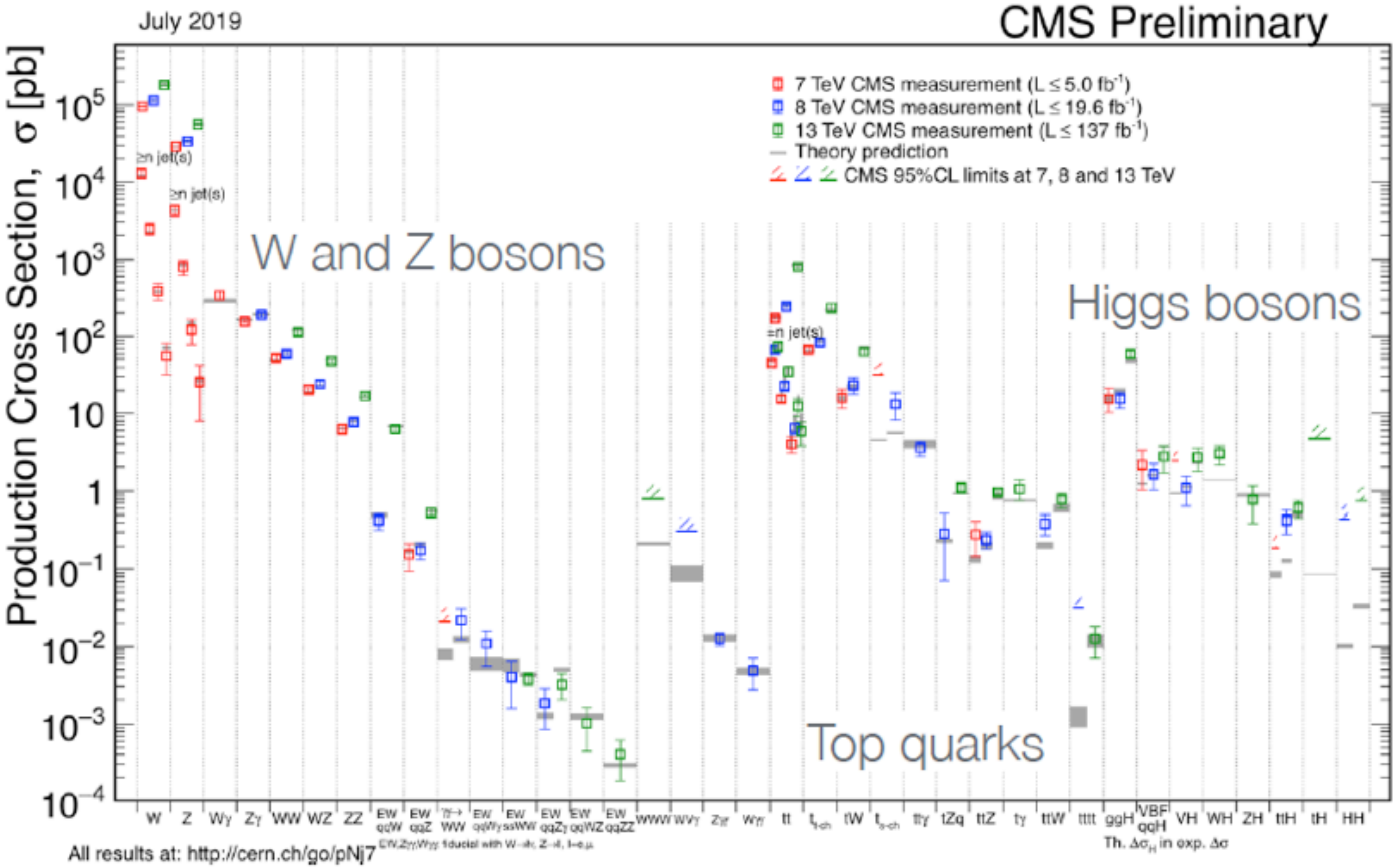
Plan

- Introduction (why bother ?)
- The current status
- The theoretical issues
- A few phenomenological implications

Introduction

PRECISION MEASUREMENTS AT THE LHC

- **A very impressive SM cross section measurements at the LHC**
  - **many processes are at percent even subpercent level**



In order to fully exploit these data, theoretical calculations are crucial to keep pace !

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  - energy reaches deeper into multi-TeV region & high integrated luminosity
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b.13	$pp \to W^+W^+jj$	$2.251 \pm 0.011 \cdot 10^{-1}$	$^{+10.5\%}_{-10.6\%}$	$^{+2.2\%}_{-1.6\%}$
b.14	$pp \to W^-W^-jj$	$1.003 \pm 0.003 \cdot 10^{-1}$	$^{+10.1\%}_{-10.4\%}$	$^{+2.5\%}_{-1.8\%}$
b.15	$pp \to W^+W^-jj$ (4f)	$1.396 \pm 0.005 \cdot 10^{1}$	$^{+5.0\%}_{-6.8\%}$	$^{+0.7\%}_{-0.6\%}$
b.16	$pp \to ZZjj$	$1.706 \pm 0.011 \cdot 10^{0}$	$^{+5.8\%}_{-7.2\%}$	$^{+0.8\%}_{-0.6\%}$
b.17	$pp \to ZW^\pm jj$	$9.139 \pm 0.031 \cdot 10^{0}$	$^{+3.1\%}_{-5.1\%}$	$^{+0.7\%}_{-0.5\%}$
b.18	$pp \to \gamma\gamma jj$	$7.501 \pm 0.032 \cdot 10^{0}$	$^{+8.8\%}_{-10.1\%}$	$^{+0.6\%}_{-1.0\%}$
b.19*	$pp \to \gamma Zjj$	$4.242 \pm 0.016 \cdot 10^{0}$	$^{+6.5\%}_{-7.3\%}$	$^{+0.6\%}_{-0.6\%}$
b.20*	$pp \to \gamma W^\pm jj$	$1.448 \pm 0.005 \cdot 10^{1}$	$^{+3.6\%}_{-5.4\%}$	$^{+0.6\%}_{-0.7\%}$

d.1	$pp \to jj$	$1.580 \pm 0.007 \cdot 10^{6}$	$^{+8.4\%}_{-9.0\%}$	$^{+0.7\%}_{-0.9\%}$
d.2	$pp \to jjj$	$7.791 \pm 0.037 \cdot 10^{4}$	$^{+2.1\%}_{-23.2\%}$	$^{+1.1\%}_{-1.3\%}$
d.7	$pp \to t\bar{t}$	$6.741 \pm 0.023 \cdot 10^{2}$	$^{+9.8\%}_{-10.9\%}$	$^{+1.8\%}_{-2.1\%}$
d.8	$pp \to t\bar{t}j$	$4.106 \pm 0.015 \cdot 10^{2}$	$^{+8.1\%}_{-12.2\%}$	$^{+2.1\%}_{-2.5\%}$
d.9	$pp \to t\bar{t}jj$	$1.795 \pm 0.006 \cdot 10^{2}$	$^{+9.3\%}_{-16.1\%}$	$^{+2.4\%}_{-2.9\%}$
d.10	$pp \to t\bar{t}t\bar{t}$	$9.201 \pm 0.028 \cdot 10^{-3}$	$^{+30.8\%}_{-25.6\%}$	$^{+5.5\%}_{-5.9\%}$
d.11	$pp \to t\bar{t}b\bar{b}$ (4f	$1.452 \pm 0.005 \cdot 10^{1}$	$^{+37.6\%}_{-27.5\%}$	$^{+2.9\%}_{-3.5\%}$

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro JHEP'14

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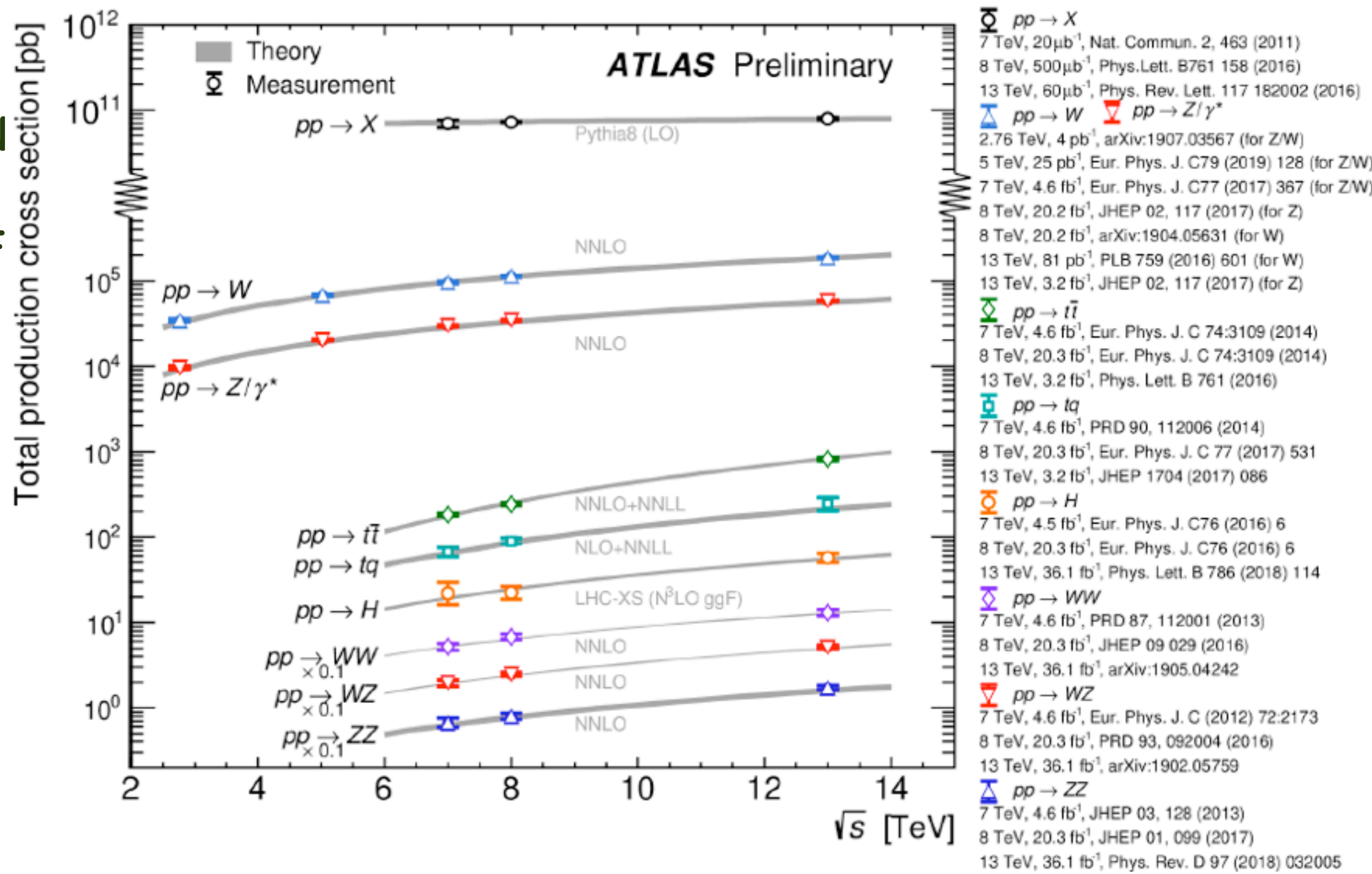

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  - High precision measurements are present or in planned
    - cross section ratios, e.g. different center-of-mass energy, different processes
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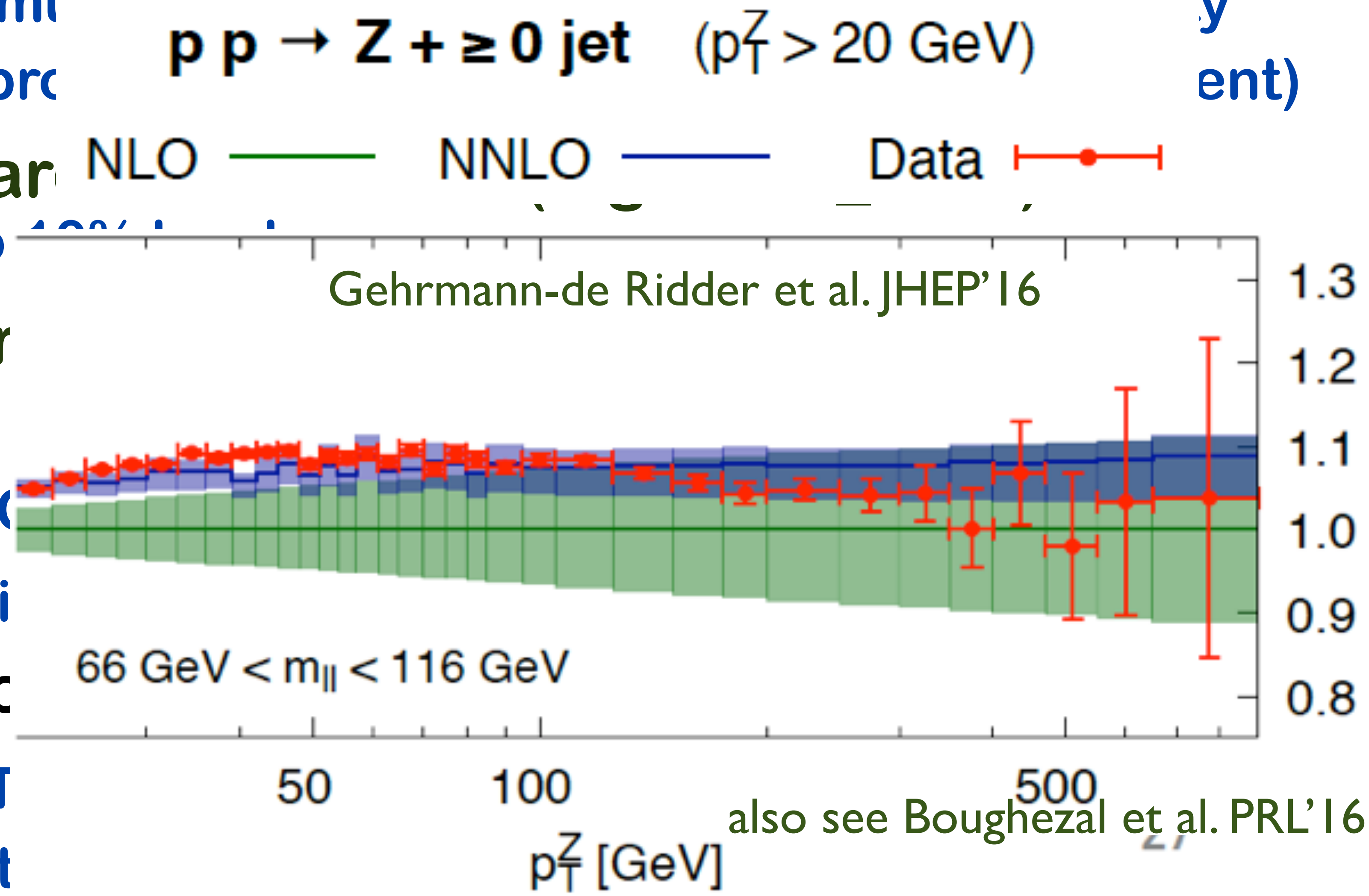

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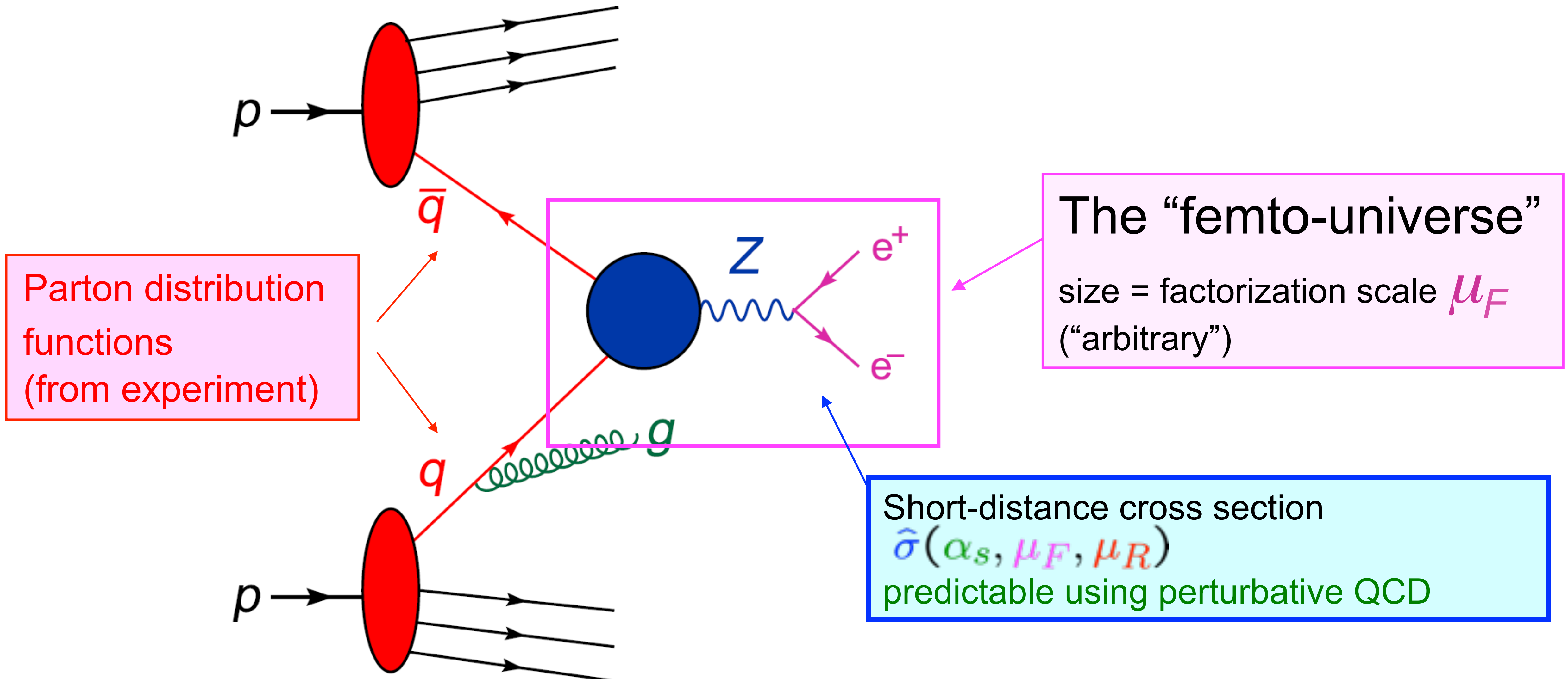

$$\sigma(pp \to Z + X) = \int dx_1 dx_2 f(x_1, \mu_F) f(x_2, \mu_F) \hat{\sigma}(\alpha_s, \mu_F, \mu_R)$$

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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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EW

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

$$+\sum_{i\geq 1}\sum_{j\geq 1}\left(\frac{\alpha_s}{2\pi}\right)^i\left(\frac{\alpha}{2\pi}\right)^j\hat{\sigma}^{(i,j)}(\mu_F,\mu_R)\Big]$$

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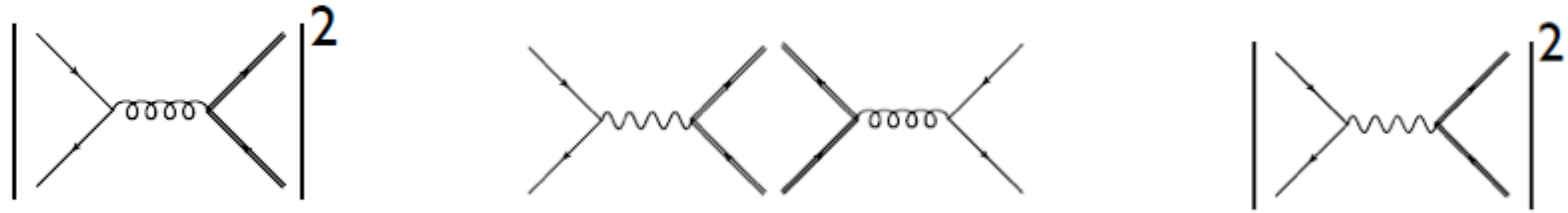

Wednesday, January 29, 20

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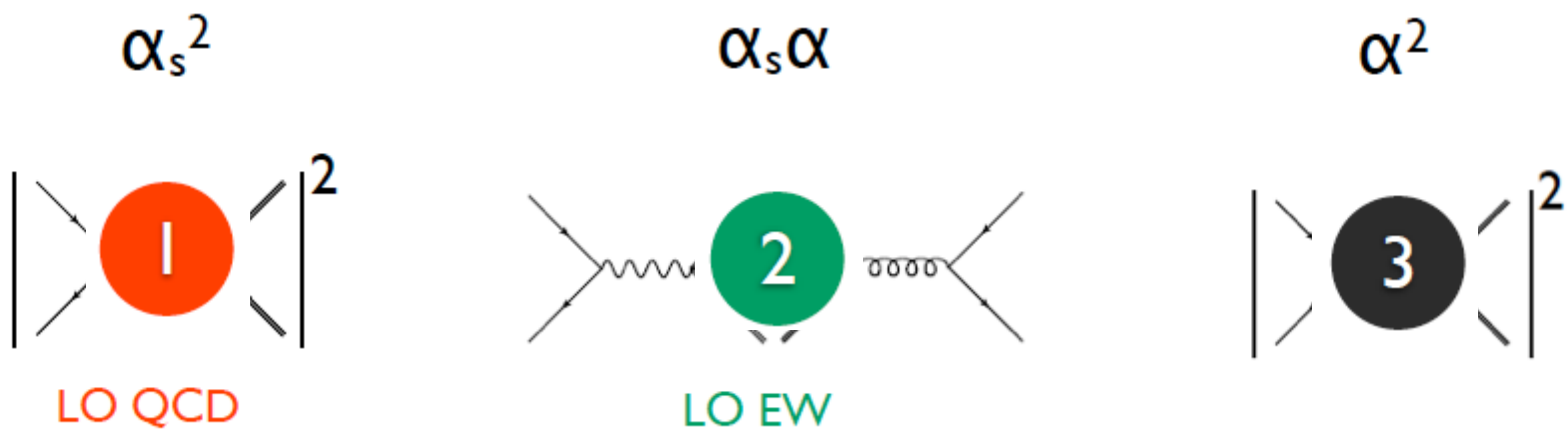

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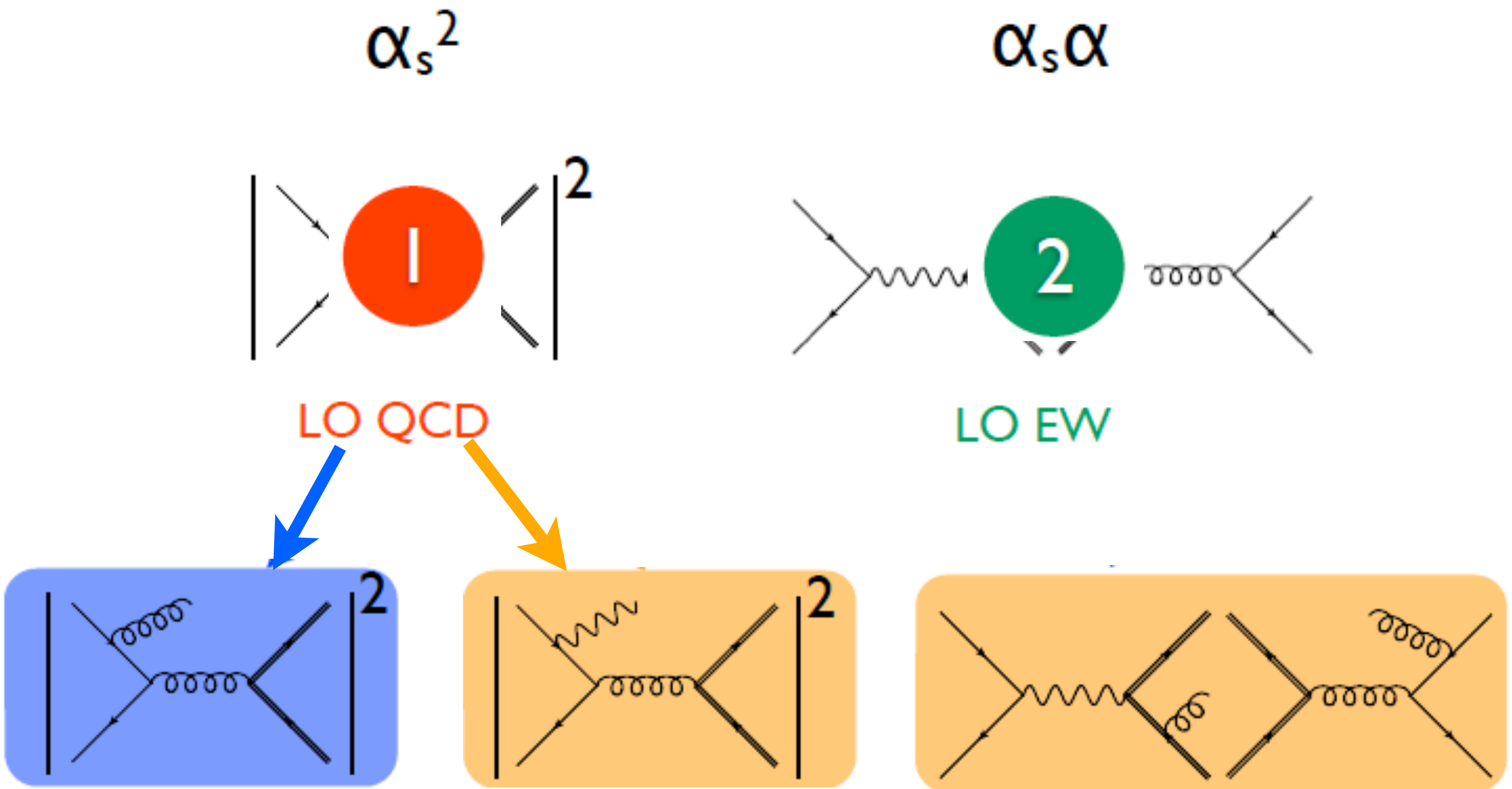

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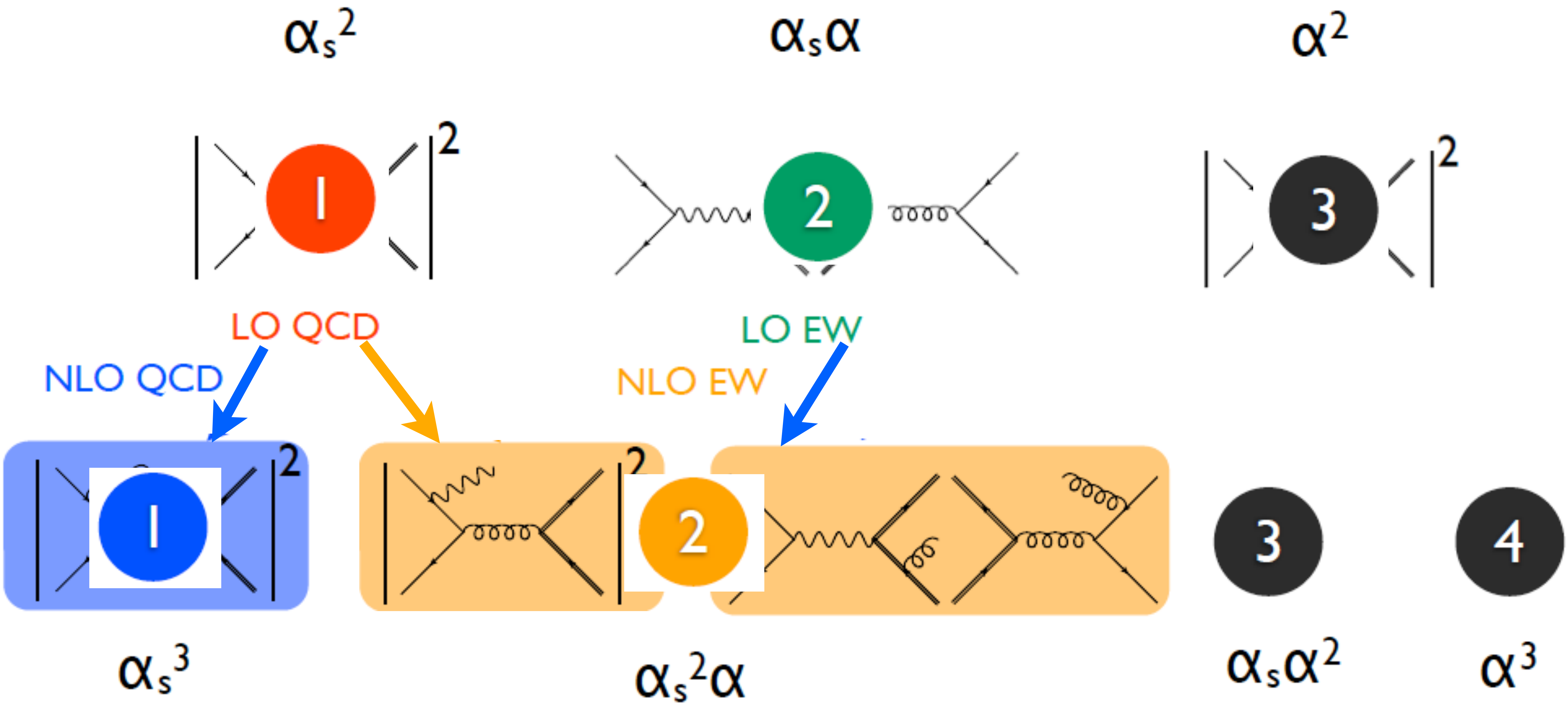

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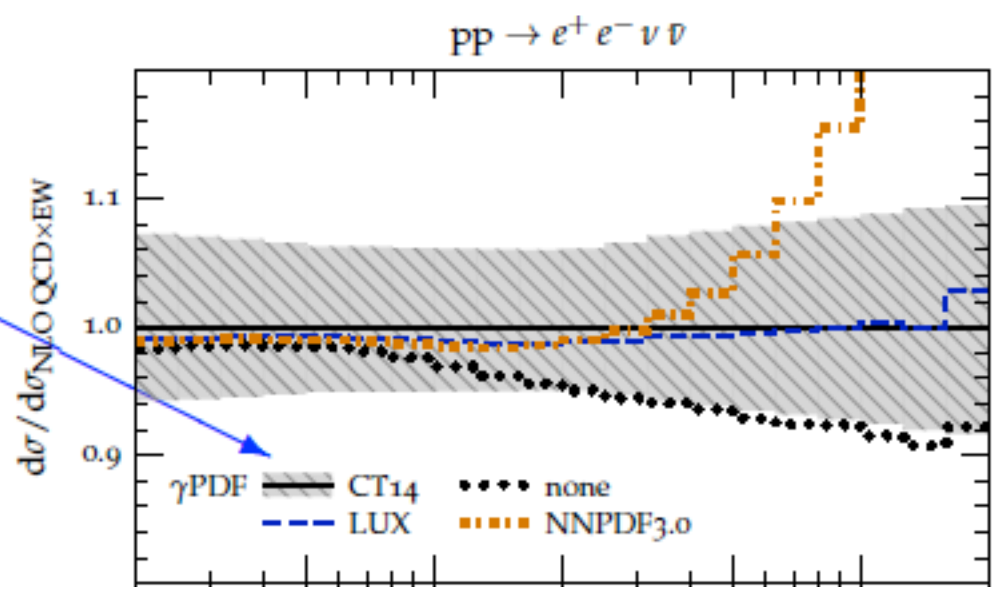
    - Photon PDF will be quite relevant, which is usually poorly determined (? LUXqed)
    - Photon and jet is not well separated (need fragmentation function or some approximations)
    - If phase space is enough, EW boson radiation will be quite often (do we need them ?)
    - The general matching between matrix element and parton shower will be difficult

relative importance of γ-induced channels wrt. NLO QCD×EW

CT14qed (baseline) no γPDF
LUXqed NNPDF3.0qed

Kallweit et al. JHEP'17



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

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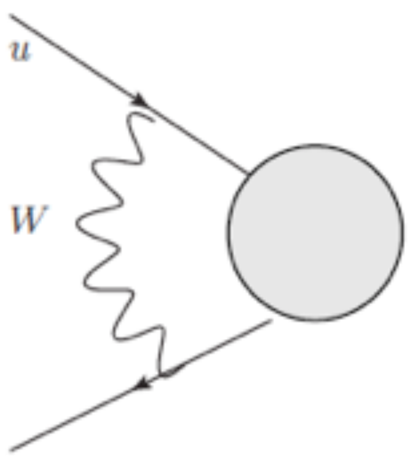

Leading Log — Next-to-Leading Log

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

soft — collinear

e.g.

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

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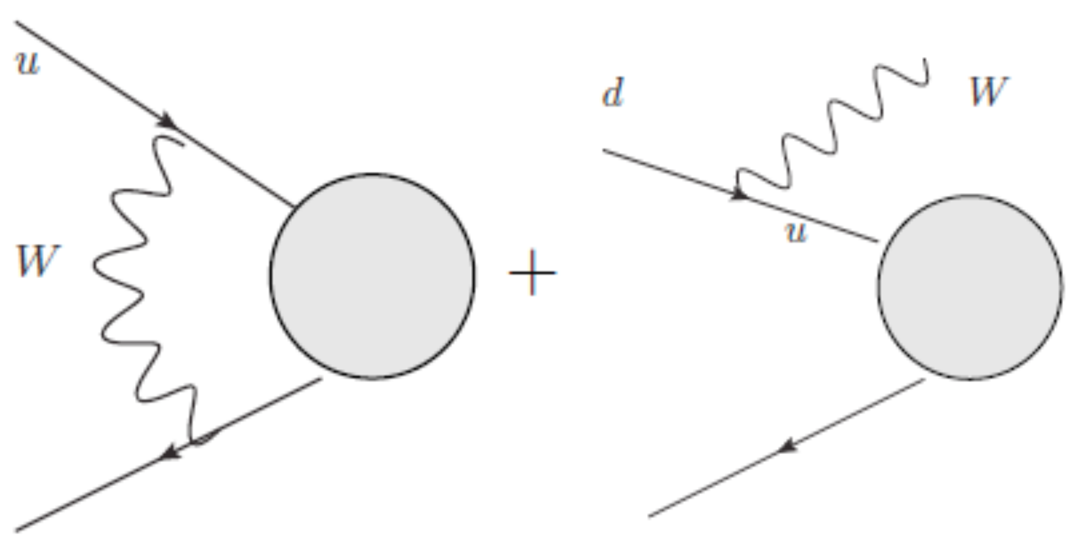

$$\sim (f_{u/p} - f_{d/p}) \log \frac{Q^2}{M_W^2}$$

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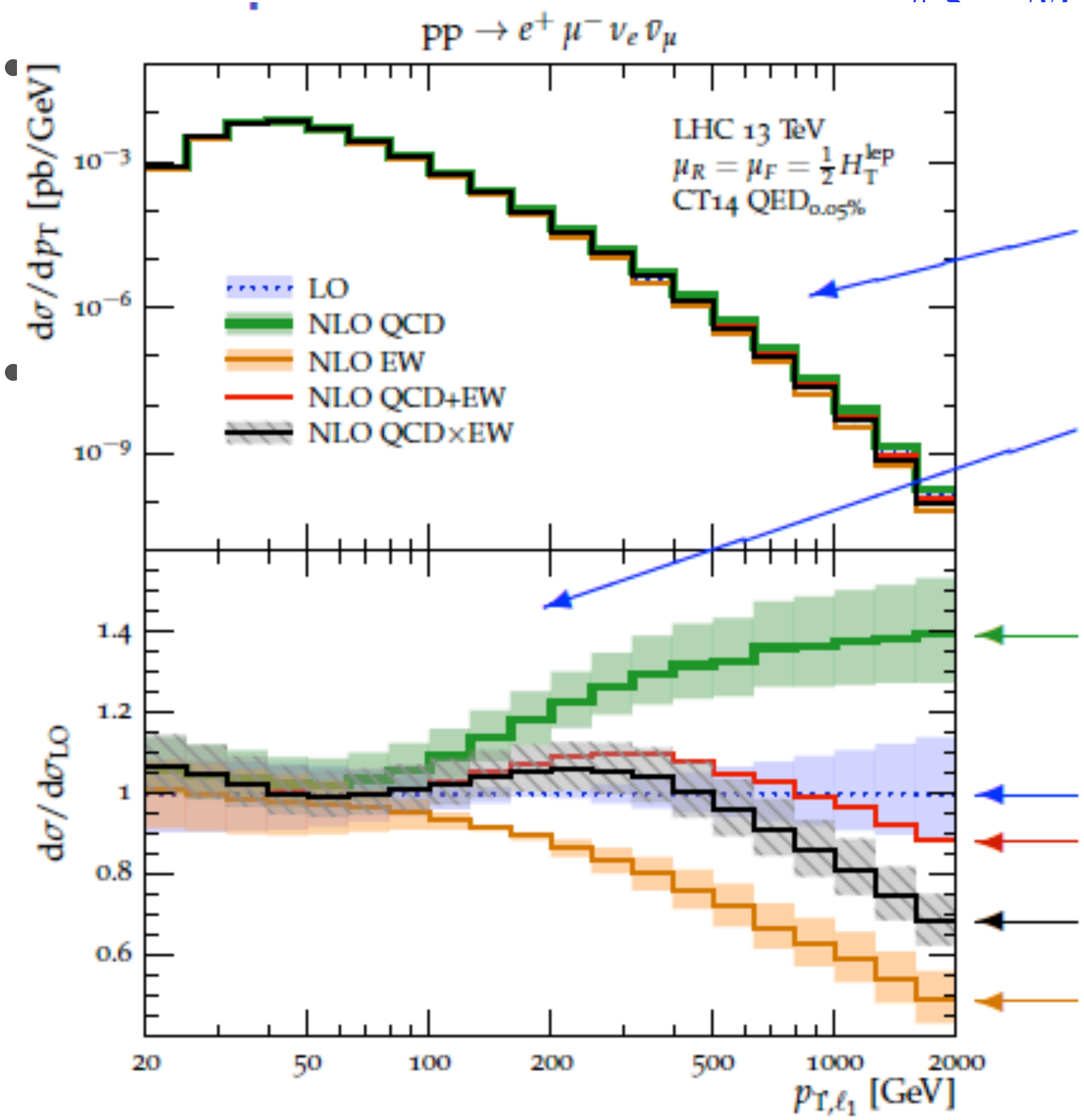
Kallweit et al. JHEP'17



absolute prediction

relative correction wrt. LO

NLO QCD

LO

NLO QCD+EW

NLO QCD×EW

NLO EW

Large +QCD corr. cancel with large -EW corr.

QCDxEW differs significantly wrt QCD+EW

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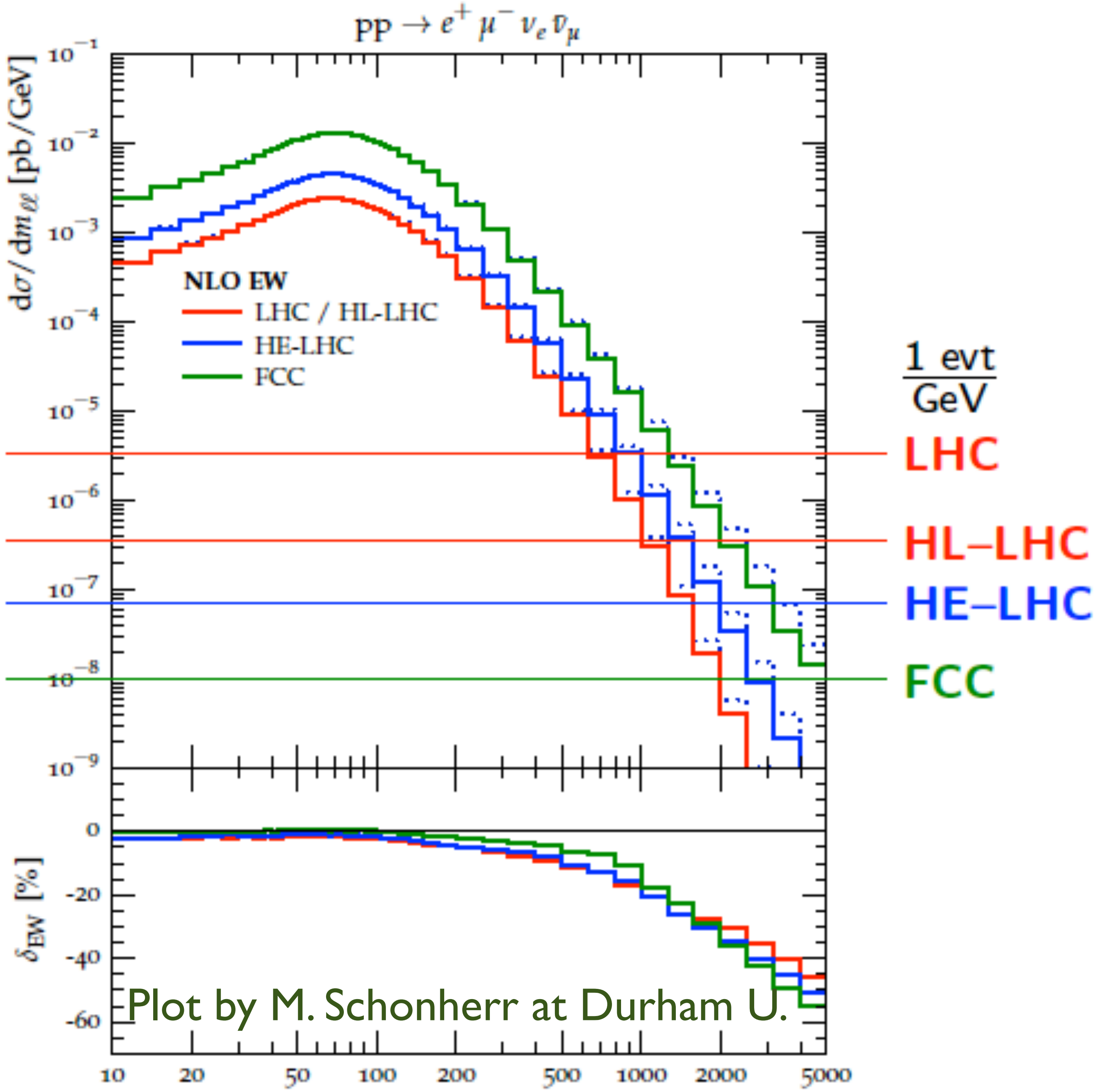
  - One does not treat W/Z inclusively as they can be (at least partially) reconst.
  - Even treat W/Z as inclusive as gluon/photon: initial state is not SU(2) singlet
  - However, EW Sudakov logarithms is not always relevant in Sudakov regime
    - e.g. Drell-Yan at large invariant mass receives large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

EW IN HIGH-ENERGY SCATTERINGS



- **BSM effects are expected to be enhanced in the high-energy scatterings**
- **-> motivated BSM search go to the tail**
- **EW corr. increase up to tens of percent due to EW Sudakov logs**
- **The EW log resummation is still not mandatory@ (HL-)LHC as**

$$\alpha L \ll 1$$

The Automation Era

AUTOMATION TOOLS FOR EW CORRECTIONS

- Automation tools for EWC so far (not as much as for QCD corr.)
  - MadGraph5_aMC@NLO Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18
  - Openloops+Sherpa Buccioni, Lang, Lindert, Maierhofer, Pozzorini, Zhang, Zoller (1907.13071)+ Schonherr EPJC'18
  - Recola+Sherpa Biedermann, Brauer, Denner, Pellen, Schumann, Thompson EPJC'17
  - GoSam+Sherpa Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano
- 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
  - Need to proper treat gamma5 issue for the chiral currents
  - Need to well implement complex mass scheme to treat unstable particles
  - Need to deal with expansion into QCD and EW couplings
  - It is necessary to properly treat the photon

VALIDATION: AN EXAMPLE

- **Extensive validation among various tools is extremely important**
  - **Better being correct and slow than being wrong and fast**

Les Houches SM report 2017 (1803.07977)

$pp \to e^+e^-\mu^+\mu^-$	σ^{LO} [fb]	σ^{NLO}_{EW} [fb]	$\Delta\sigma^{LO}$ [σ]	$\Delta\sigma^{LO}$ [‰]	$\Delta\sigma^{NLO}_{EW}$ [σ]	$\Delta\sigma^{NLO}_{EW}$ [‰]
average	11.49675[8]	10.88697[15]				
MCBB+RECOLA	11.49648[12]	10.88669[22]	−2.9	−0.02	−1.7	−0.03
MUNICH+OPENLOOPS	11.49702[11]	10.88720[25]	+3.2	+0.02	+1.2	+0.02
MOCANLO+RECOLA	11.49666[26]	10.88734[56]	−0.3	−0.01	+0.7	+0.03
SHERPA+GOSAM/OPENLOOPS/RECOLA	11.49670[34]	10.88737[77]	−0.1	−0.00	+0.5	+0.04
MADGRAPH5_AMC@NLO+MADLOOP	11.4956[22]	10.8860[63]	−0.5	−0.10	−0.1	−0.09

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$	σ^{LO} [fb]	σ^{NLO}_{EW} [fb]	$\Delta\sigma^{LO}$ [σ]	$\Delta\sigma^{LO}$ [‰]	$\Delta\sigma^{NLO}_{EW}$ [σ]	$\Delta\sigma^{NLO}_{EW}$ [‰]
average	448.5414[31]	438.1902[56]				
MUNICH+OPENLOOPS	448.5468[45]	438.1920[75]	+1.6	+0.01	+0.4	+0.00
MOCANLO+RECOLA	448.538[10]	438.193[13]	−0.4	−0.01	+0.2	+0.01
SHERPA+GOSAM/OPENLOOPS/RECOLA	448.5364[46]	438.186[11]	−1.4	−0.01	−0.4	−0.01
MADGRAPH5_AMC@NLO	448.541[40]	438.113[70]	−0.0	−0.00	−1.1	−0.18

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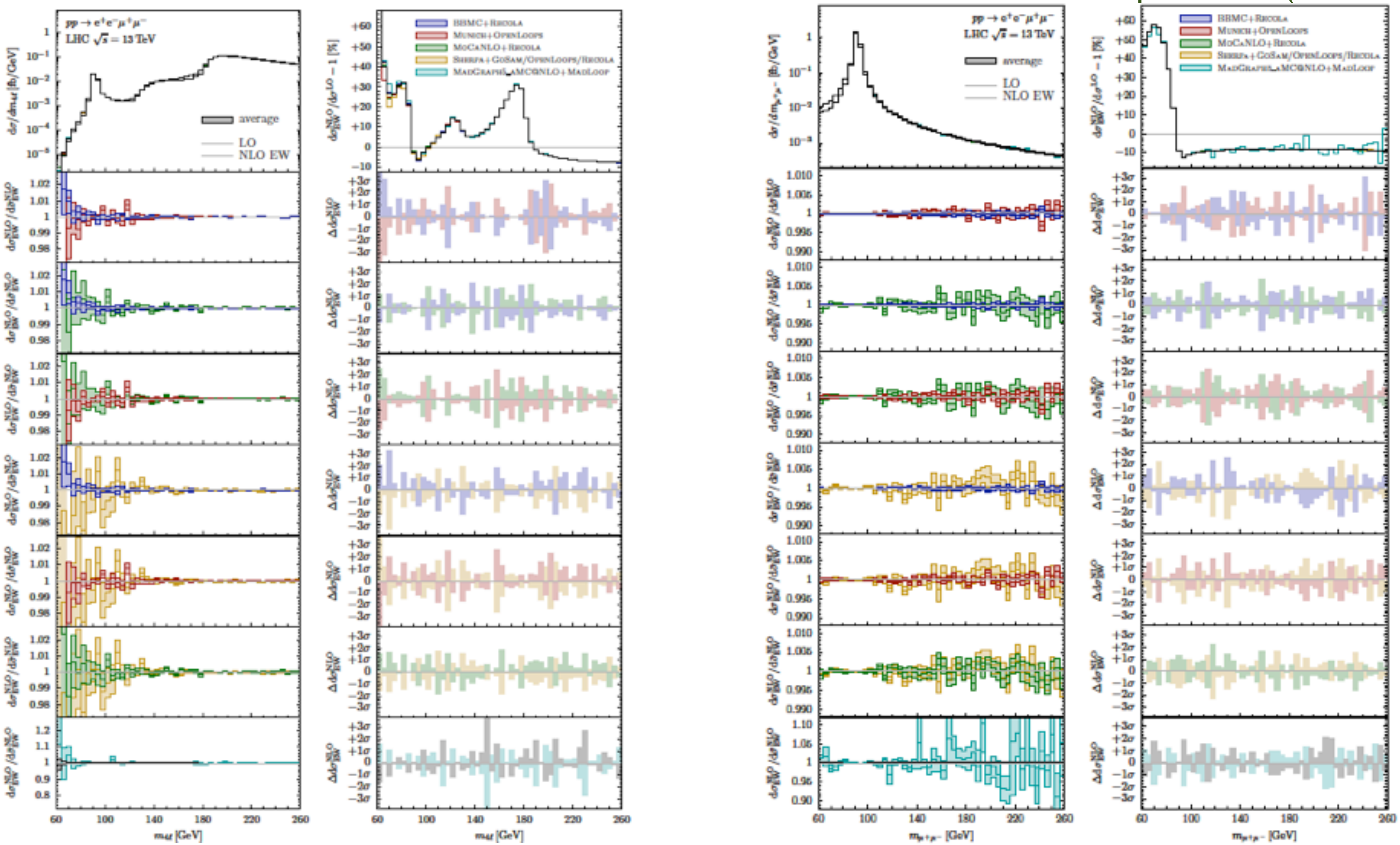
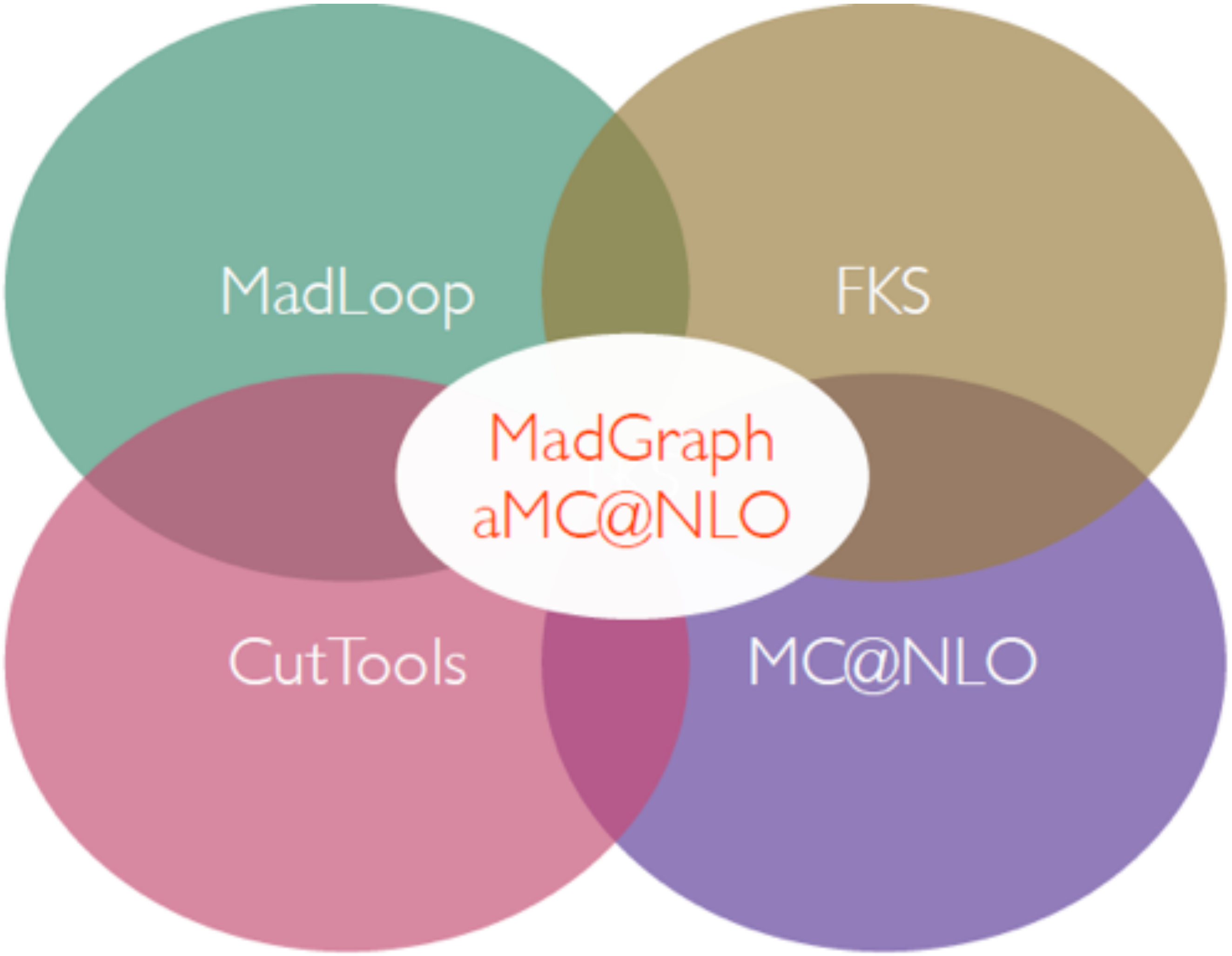


MADGRAPH5_AMC@NLO IN A NUTSHELL

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro JHEP'14



4 commands for a NLO calculation

```
> ./bin/mg5_aMC
> generate process [QCD]
> output
> launch
```

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Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro JHEP'14

complete automation for
QCD+EW

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Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

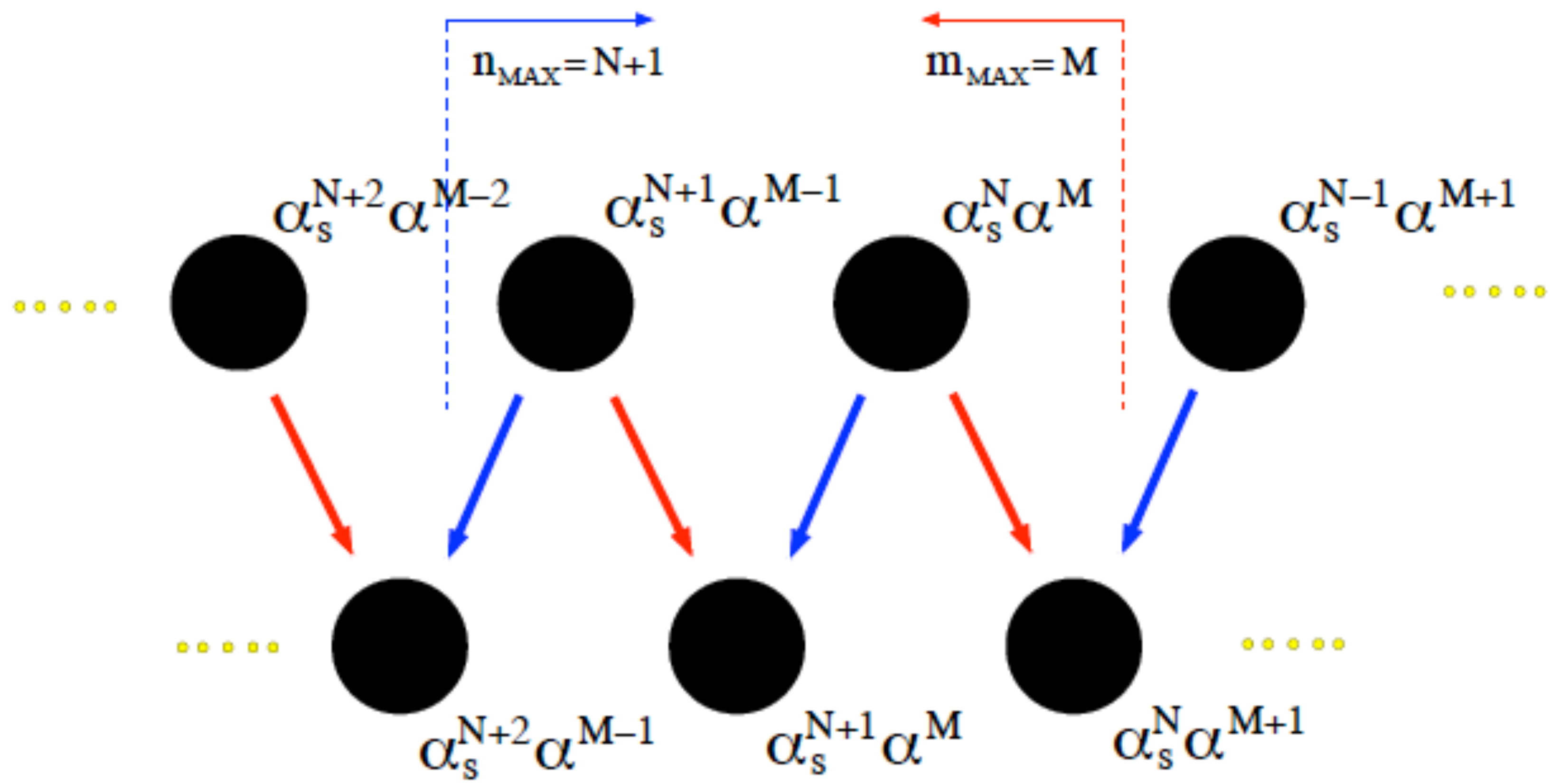
```
> ./bin/mg5_aMC
> generate process [QCD QED]
> output
> launch
```

MADGRAPH5_AMC@NLO: COMPLETE NLO

- Generation syntax for any LO and NLO (in v3.X):

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

```
MG5_aMC>  generate p1 p2 > p3 p4 p5 p6 QCD=n_max QED=m_max [QCD QED]
```

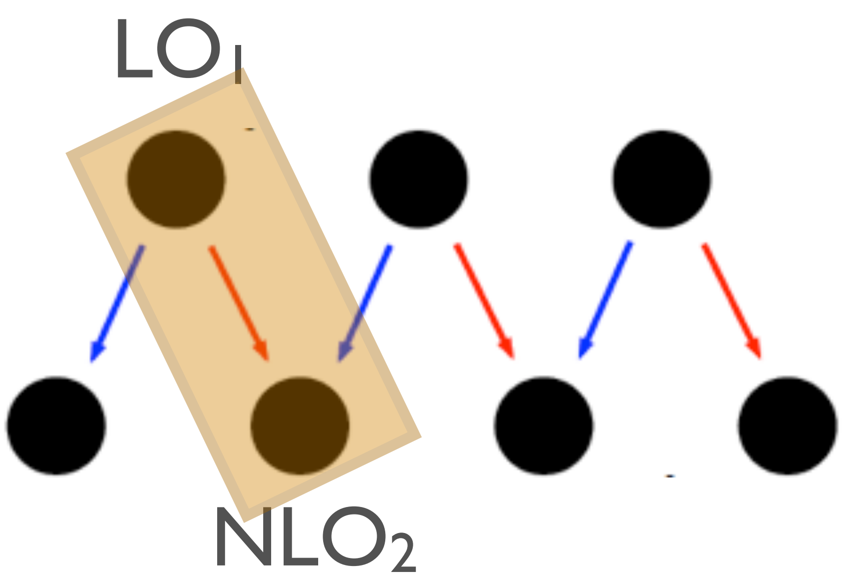


$$\text{LO}: \quad \alpha_s^n\alpha^m\,, \quad n \le \mathtt{n_{max}}\,, \quad m \le \mathtt{m_{max}}\,, \quad n+m=k_0\,,$$

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

MADGRAPH5_AMC@NLO: NLO EW

- Examples:



$$\delta_{\rm EW} = \frac{\rm NLO_2}{\rm LO_1}$$

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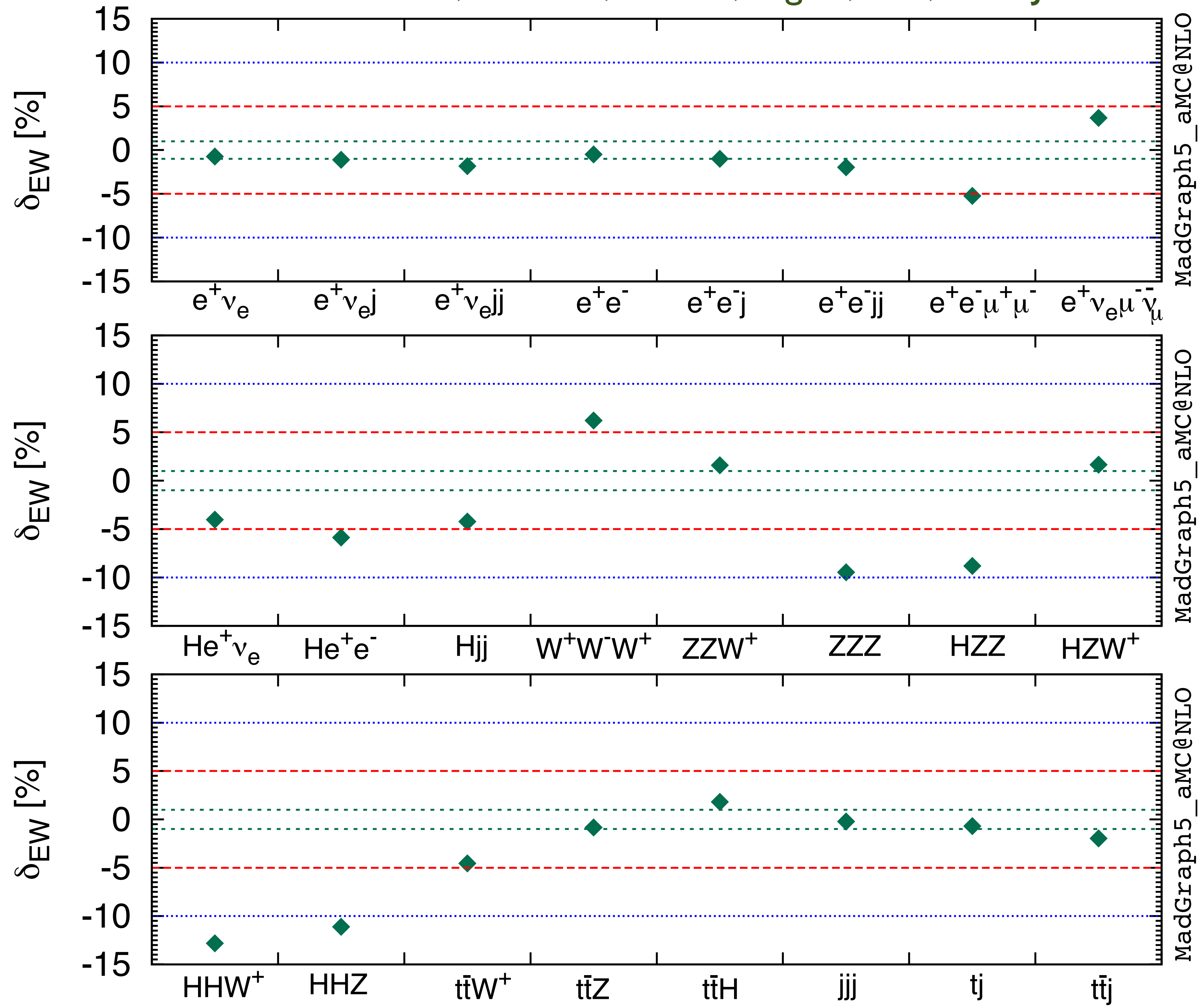

MADGRAPH5_AMC@NLO: NLO EW

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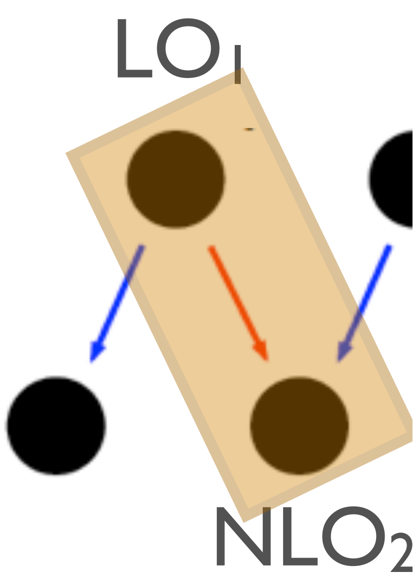


$\delta_{\mathrm{EW}} =$

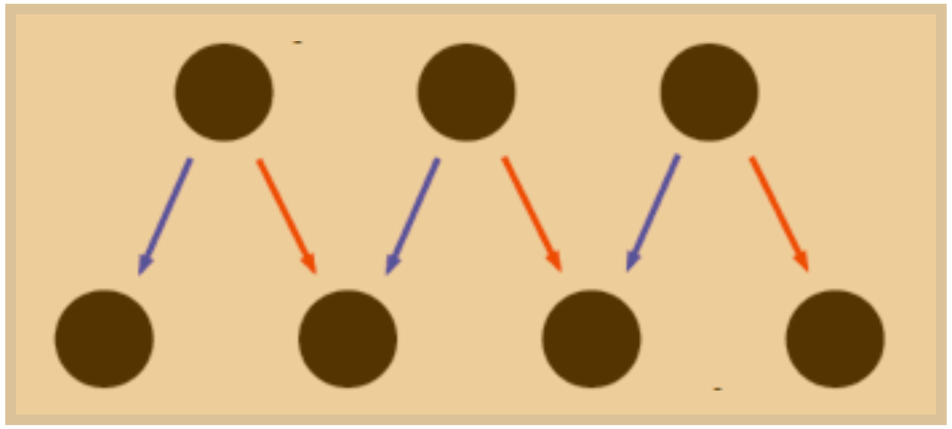
Process	Syntax	Cross section (in pb) LO	Cross section (in pb) NLO	Correction (in %)
$pp \to e^+\nu_e$	p p > e+ ve QCD=0 QED=2 [QED]	$5.2498 \pm 0.0005 \cdot 10^3$	$5.2113 \pm 0.0006 \cdot 10^3$	-0.73 ± 0.01
$pp \to e^+\nu_e j$	p p > e+ ve j QCD=1 QED=2 [QED]	$9.1468 \pm 0.0012 \cdot 10^2$	$9.0449 \pm 0.0014 \cdot 10^2$	-1.11 ± 0.02
$pp \to e^+\nu_e jj$	p p > e+ ve j j QCD=2 QED=2 [QED]	$3.1562 \pm 0.0003 \cdot 10^2$	$3.0985 \pm 0.0005 \cdot 10^2$	-1.83 ± 0.02
$pp \to e^+e^-$	p p > e+ e- QCD=0 QED=2 [QED]	$7.5367 \pm 0.0008 \cdot 10^2$	$7.4997 \pm 0.0010 \cdot 10^2$	-0.49 ± 0.02
$pp \to e^+e^-j$	p p > e+ e- j QCD=1 QED=2 [QED]	$1.5059 \pm 0.0001 \cdot 10^2$	$1.4909 \pm 0.0002 \cdot 10^2$	-1.00 ± 0.02
$pp \to e^+e^-jj$	p p > e+ e- j j QCD=2 QED=2 [QED]	$5.1424 \pm 0.0004 \cdot 10^1$	$5.0410 \pm 0.0007 \cdot 10^1$	-1.97 ± 0.02
$pp \to e^+e^-\mu^+\mu^-$	p p > e+ e- mu+ mu- QCD=0 QED=4 [QED]	$1.2750 \pm 0.0000 \cdot 10^{-2}$	$1.2083 \pm 0.0001 \cdot 10^{-2}$	-5.23 ± 0.01
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$	p p > e+ ve mu- vm~ QCD=0 QED=4 [QED]	$5.1144 \pm 0.0007 \cdot 10^{-1}$	$5.3019 \pm 0.0009 \cdot 10^{-1}$	$+3.67 \pm 0.02$
$pp \to He^+\nu_e$	p p > h e+ ve QCD=0 QED=3 [QED]	$6.7643 \pm 0.0001 \cdot 10^{-2}$	$6.4914 \pm 0.0012 \cdot 10^{-2}$	-4.03 ± 0.02
$pp \to He^+e^-$	p p > h e+ e- QCD=0 QED=3 [QED]	$1.4554 \pm 0.0001 \cdot 10^{-2}$	$1.3700 \pm 0.0002 \cdot 10^{-2}$	-5.87 ± 0.02
$pp \to Hjj$	p p > h j j QCD=0 QED=3 [QED]	$2.8268 \pm 0.0002 \cdot 10^0$	$2.7075 \pm 0.0003 \cdot 10^0$	-4.22 ± 0.01
$pp \to W^+W^-W^+$	p p > w+ w- w+ QCD=0 QED=3 [QED]	$8.2874 \pm 0.0004 \cdot 10^{-2}$	$8.8017 \pm 0.0012 \cdot 10^{-2}$	$+6.21 \pm 0.02$
$pp \to ZZW^+$	p p > z z w+ QCD=0 QED=3 [QED]	$1.9874 \pm 0.0001 \cdot 10^{-2}$	$2.0189 \pm 0.0003 \cdot 10^{-2}$	$+1.58 \pm 0.02$
$pp \to ZZZ$	p p > z z z QCD=0 QED=3 [QED]	$1.0761 \pm 0.0001 \cdot 10^{-2}$	$0.9741 \pm 0.0001 \cdot 10^{-2}$	-9.47 ± 0.02
$pp \to HZZ$	p p > h z z QCD=0 QED=3 [QED]	$2.1005 \pm 0.0003 \cdot 10^{-3}$	$1.9155 \pm 0.0003 \cdot 10^{-3}$	-8.81 ± 0.02
$pp \to HZW^+$	p p > h z w+ QCD=0 QED=3 [QED]	$2.4408 \pm 0.0000 \cdot 10^{-3}$	$2.4809 \pm 0.0005 \cdot 10^{-3}$	$+1.64 \pm 0.02$
$pp \to HHW^+$	p p > h h w+ QCD=0 QED=3 [QED]	$2.7827 \pm 0.0001 \cdot 10^{-4}$	$2.4259 \pm 0.0027 \cdot 10^{-4}$	-12.82 ± 0.10
$pp \to HHZ$	p p > h h z QCD=0 QED=3 [QED]	$2.6914 \pm 0.0003 \cdot 10^{-4}$	$2.3926 \pm 0.0003 \cdot 10^{-4}$	-11.10 ± 0.02
$pp \to t\bar{t}W^+$	p p > t t~ w+ QCD=2 QED=1 [QED]	$2.4119 \pm 0.0003 \cdot 10^{-1}$	$2.3025 \pm 0.0003 \cdot 10^{-1}$	-4.54 ± 0.02
$pp \to t\bar{t}Z$	p p > t t~ z QCD=2 QED=1 [QED]	$5.0456 \pm 0.0006 \cdot 10^{-1}$	$5.0033 \pm 0.0007 \cdot 10^{-1}$	-0.84 ± 0.02
$pp \to t\bar{t}H$	p p > t t~ h QCD=2 QED=1 [QED]	$3.4480 \pm 0.0004 \cdot 10^{-1}$	$3.5102 \pm 0.0005 \cdot 10^{-1}$	$+1.81 \pm 0.02$
$pp \to t\bar{t}j$	p p > t t j QCD=3 QED=0 [QED]	$3.0277 \pm 0.0003 \cdot 10^2$	$2.9683 \pm 0.0004 \cdot 10^2$	-1.96 ± 0.02
$pp \to jjj$	p p > j j j QCD=3 QED=0 [QED]	$7.9639 \pm 0.0010 \cdot 10^6$	$7.9472 \pm 0.0011 \cdot 10^6$	-0.21 ± 0.02
$pp \to tj$	p p > t j QCD=0 QED=2 [QED]	$1.0613 \pm 0.0001 \cdot 10^2$	$1.0539 \pm 0.0001 \cdot 10^2$	-0.70 ± 0.02

MADGRAPH5_AMC@NLO: COMPLETE NLO

- Examples:

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

	$pp \to t\bar{t}$	$pp \to t\bar{t}Z$	$pp \to t\bar{t}W^+$	$pp \to t\bar{t}H$	$pp \to t\bar{t}j$
LO_1	$4.3803 \pm 0.0005 \cdot 10^2$ pb	$5.0463 \pm 0.0003 \cdot 10^{-1}$ pb	$2.4116 \pm 0.0001 \cdot 10^{-1}$ pb	$3.4483 \pm 0.0003 \cdot 10^{-1}$ pb	$3.0278 \pm 0.0003 \cdot 10^2$ pb
LO_2	$+0.405 \pm 0.001$ %	-0.691 ± 0.001 %	$+0.000 \pm 0.000$ %	$+0.406 \pm 0.001$ %	$+0.525 \pm 0.001$ %
LO_3	$+0.630 \pm 0.001$ %	$+2.259 \pm 0.001$ %	$+0.962 \pm 0.000$ %	$+0.702 \pm 0.001$ %	$+1.208 \pm 0.001$ %
LO_4					$+0.006 \pm 0.000$ %
NLO_1	$+46.164 \pm 0.022$ %	$+44.809 \pm 0.028$ %	$+49.504 \pm 0.015$ %	$+28.847 \pm 0.020$ %	$+26.571 \pm 0.063$ %
NLO_2	-1.075 ± 0.003 %	-0.846 ± 0.004 %	-4.541 ± 0.003 %	$+1.794 \pm 0.005$ %	-1.971 ± 0.022 %
NLO_3	$+0.552 \pm 0.002$ %	$+0.845 \pm 0.003$ %	$+12.242 \pm 0.014$ %	$+0.483 \pm 0.008$ %	$+0.292 \pm 0.007$ %
NLO_4	$+0.005 \pm 0.000$ %	-0.082 ± 0.000 %	$+0.017 \pm 0.003$ %	$+0.044 \pm 0.000$ %	$+0.009 \pm 0.000$ %
NLO_5					$+0.005 \pm 0.000$ %



Theoretical Issues

AN OVERVIEW OF SUBTLETIES

solved

open

- How bright of the proton (the initial photon) ?

AN OVERVIEW OF SUBTLETIES

✓ solved
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✓ **How bright of the proton (the initial photon) ?**

- **Both elastic and inelastic sources of photons**
- **Photon PDF was acknowledged to be solved by using the LUXqed approach**

Manohar, Nason, Salam, Zanderighi PRL'16, JHEP'17

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- Photons and massless leptons must be part of a jet (IR safety)
- But to what extent ? Democratic (simplest but a big disadvantage) ?
- Better: tagging photons and leptons and/or anti-tagging jets via FFs

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'16; Frixione (1909.03886)

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- However, there are subtleties in the complex-mass scheme
  Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

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    Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18
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Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

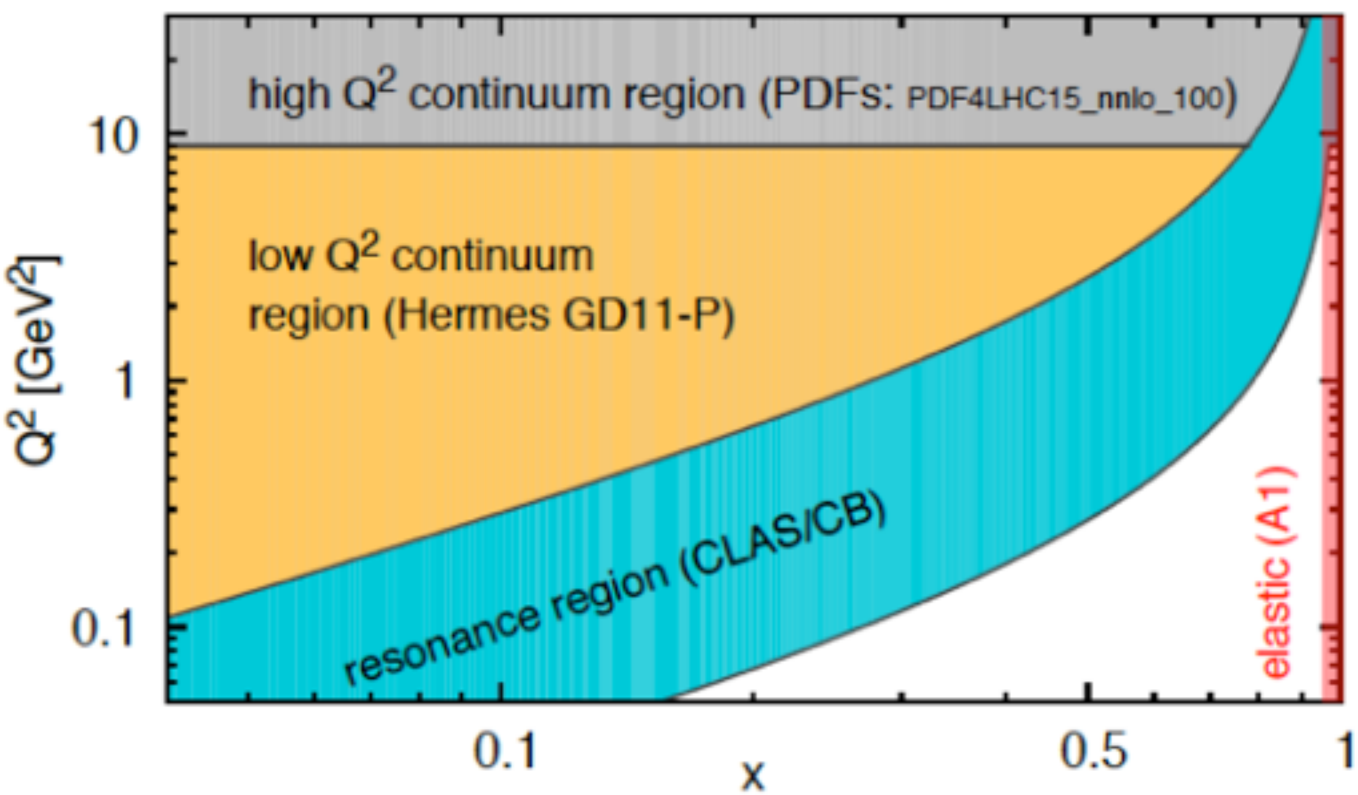
✘ How to match parton showers (PS) ?

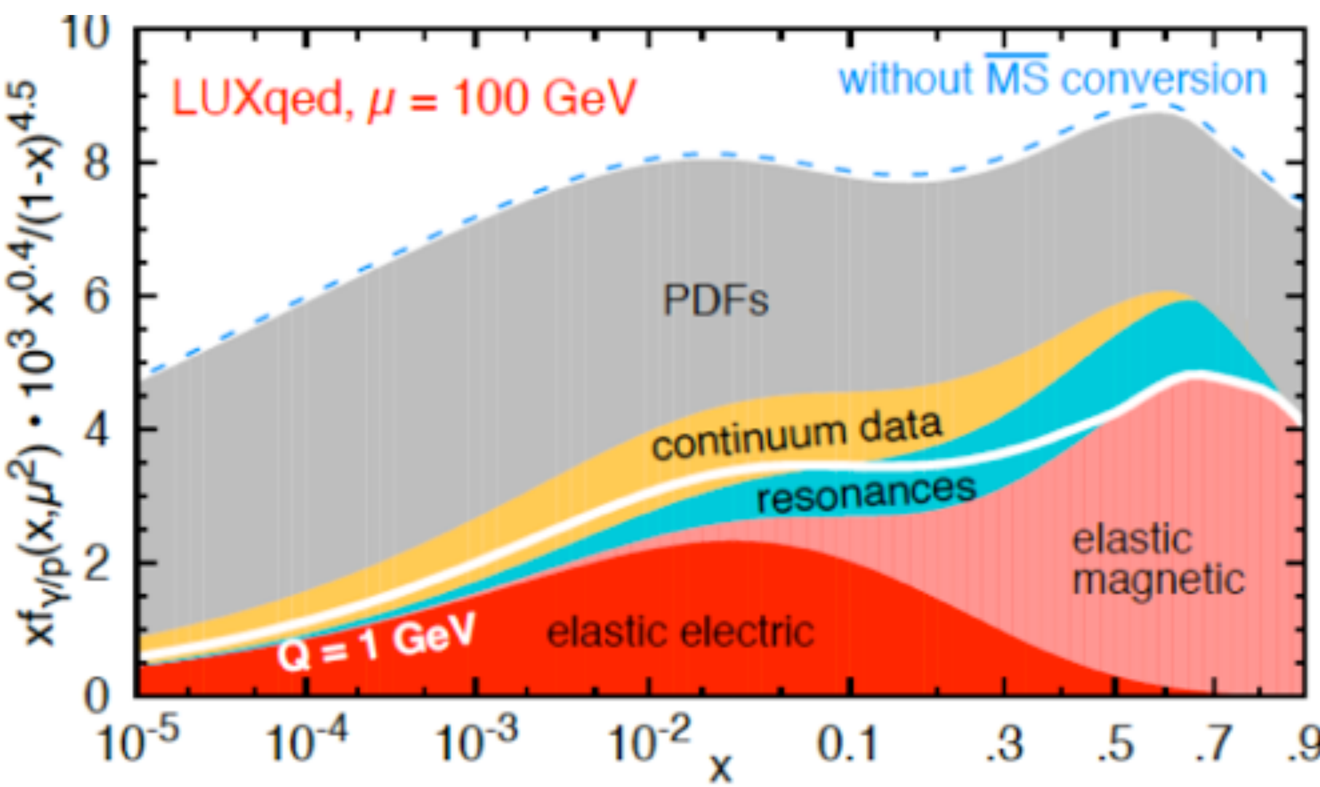
- In the simultaneous presence of QCD and EW corrections:
- no general solution because PS is classic (as opposed to quantum)
- some dedicated approximated solutions exist for a few case studies

PHOTON PDF: THE LUXQED APPROACH

Manohar, Nason, Salam, Zanderighi PRL'16, JHEP'17

- How bright of the proton (the initial photon) ?
- Photon PDF written in terms of inclusive DIS structure functions
  - elastic component given by magnetic/electric form factors from A1 + dipole
  - inelastic source:
    - resonance region : $(m_p + m_\pi)^2 < W^2 < 3.5\ \mathrm{GeV}^2$
    - low-Q^2 continuous region : $W^2 > 3.5\ \mathrm{GeV}^2$ and $Q^2 < 9\ \mathrm{GeV}^2$
    - high-Q^2 continuous region : $W^2 > 3.5\ \mathrm{GeV}^2$ and $Q^2 > 9\ \mathrm{GeV}^2$





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  - elastic compo[...]s from A1 + dipole
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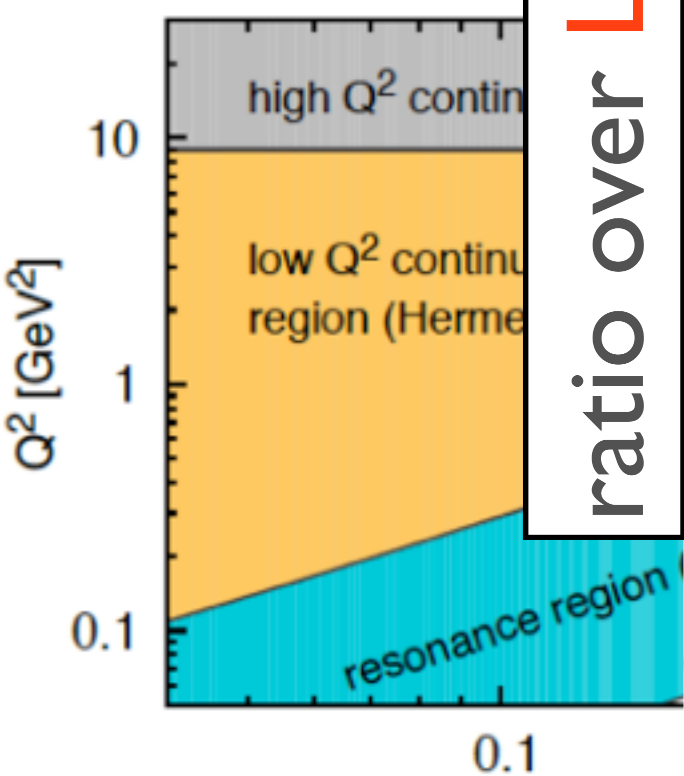
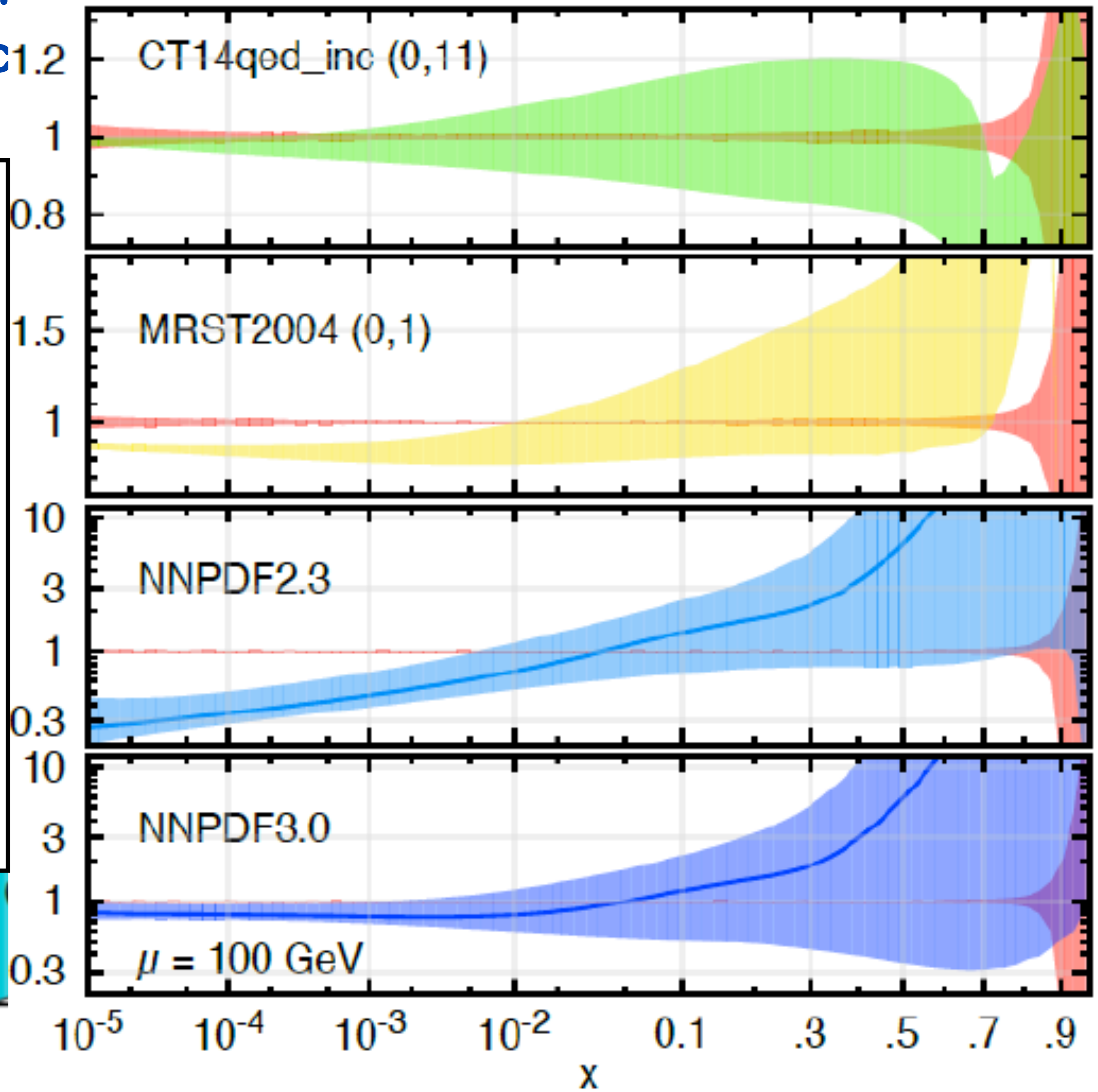
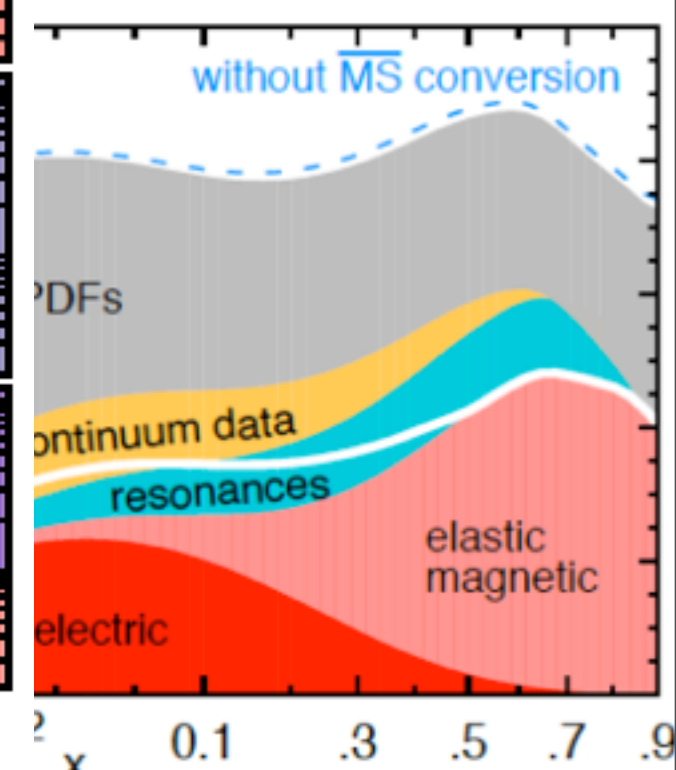
    - resonance V^2
    - low-Q² $< 9\ \mathrm{GeV}^2$
    - high-Q $> 9\ \mathrm{GeV}^2$







Wednesday, January 29, 20

JET DEFINITIONS

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'16

- **Jet in QCD**
  - a cluster of hadronic objects
  - At parton level, cluster all massless quarks and gluons
  - Unambiguous and well defined up to all orders in perturbative QCD
- **Jet with both strong and electromagnetic radiations**
  - democratic jet: a cluster of hadronic and electromagnetic objects
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  - How to define leptons and photons in terms of jets ?
- **QCD parton-photon recombination in jet processes**

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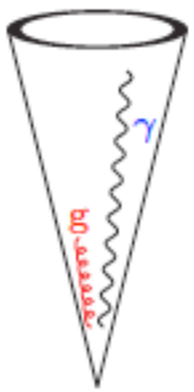

Wednesday, January 29, 20

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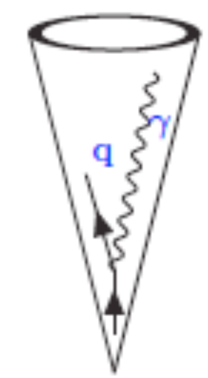

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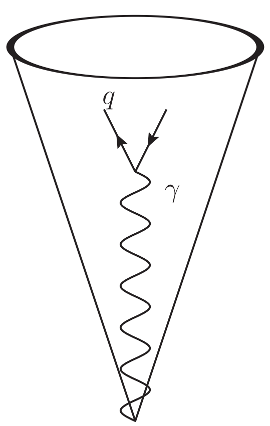
  - Unambiguous and well defined up to all orders in perturbative QCD
- Jet with both strong and electromagnetic radiations
  - democratic jet: a cluster of hadronic and electromagnetic objects
  - At parton level, cluster all massless quarks/leptons and gluons/photons
  - How to define leptons and photons in terms of jets ?
- QCD parton-photon recombination in jet processes
  - Hard photon containing gluon is not QCD IR safe
  - hard photon containing quark is not QED IR safe
  - 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



JET DEFINITIONS

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'16

- **Jet in QCD**
  - a cluster of hadronic objects
  - At parton level, cluster all massless quarks and gluons
  - Unambiguous and well defined up to all orders in perturbative QCD
- **Jet with both strong and electromagnetic radiations**
  - democratic jet: a cluster of hadronic and electromagnetic objects
  - At parton level, cluster all massless quarks/leptons and gluons/photons
  - How to define leptons and photons in terms of jets ?
- **QCD parton-photon recombination in jet processes**
  - Hard phot
  - hard phot
  - Two curre ... rk-photon = quark

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

t, Maierhofer, Pozzorini, Schonherr,'14

  - For the first issue: they both use a cut on the energy fraction of photon
  - Cut o ... antitag n-jets ... democratic n-jets ... n-jets with k photon jets
- **Photon jet**
  - A tagged photon with the FFs (not well determined bar quark-to-photon)

PHOTON & LEPTON DEFINITIONS

- What is a photon ?
  - There are two types of "photon":
    - short-distance photon same as QCD parton
    - long-distance photon (tagged or observed)
  - A tagged photon must be defined through FFs (like any other hadrons)

$$D_{\gamma}^{\gamma}(z,\mu) = \frac{\alpha(0)}{\alpha_{sd}}\delta(1-z) + \mathcal{O}(\alpha^2)$$

→ tagged photon is using $\alpha(0)$ scheme

- What is a lepton ?
  - bare lepton: keep lepton massive
  - dressed lepton: massless lepton and dressed with other massless objects

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

	Processes without jets		Processes with jets		Physical objects
	PDF(qg)	PDF($qg\gamma$)	PDF(qg)	PDF($qg\gamma$)	
$i=1$	p = q g	p = q g a	p = q g j = q g	p = q g a j = q g	$j(qg)$, γ, l, ν, massive particles
$i=2$	inconsistent	p = q g a	inconsistent	p = q g a j = q g a	$j(qg\gamma)$, l, ν, massive particles
$i\geq 3$	inconsistent	p = q g a	inconsistent	p = q g a l j = q g a l	$j(qg\gamma l)$, ν, massive particles

be careful with infrared safety

$$\Sigma_{\mathrm{NLO}_{i-k}} + \ldots + \Sigma_{\mathrm{NLO}_i}$$

for any k such that $1 \leq i-k \leq i$

COMPLEX-MASS SCHEME

- How to deal with resonances ?
  - A widely used approach is the complex-mass scheme Denner et al. NPB'99, NPB'05

$$i\frac{\not{p}+\bar{M}}{p^2-\bar{M}^2+i\bar{\Gamma}\bar{M}} \xrightarrow{m_{cms}\equiv\sqrt{\bar{M}^2-i\bar{\Gamma}\bar{M}}} i\frac{\not{p}+m_{cms}}{p^2-m_{cms}^2}$$

  - Renormalisation:

OS scheme

$$\Sigma_{\mathrm{R}}(p^2) = \Sigma_{\mathrm{U}}(p^2) - \delta M^2 + (p^2 - M^2)\delta Z$$

$$\Re\left[\Sigma_{\mathrm{R}}(p^2)\right]\big|_{p^2=M^2} = 0\,,$$

$$\lim_{p^2\to M^2}\frac{1}{p^2-M^2}\Re\left[\Sigma_{\mathrm{R}}(p^2)\right] = 1\,,$$

$$\Re\left[\Sigma_{\mathrm{R}}(p^2=M^2)\right]=0 \quad\Longrightarrow\quad \delta M^2=\Re\left[\Sigma_{\mathrm{U}}(p^2=M^2)\right]$$

$$\Re\left[\Sigma'_{\mathrm{R}}(p^2=M^2)\right]=0 \quad\Longrightarrow\quad \delta Z=-\Re\left[\Sigma'_{\mathrm{U}}(p^2=M^2)\right]$$

vs

CM scheme

$$\bar{M}^2 - i\bar{\Gamma}\bar{M} \equiv m^2 = M_0^2 - \delta m^2\,.$$

$$\Sigma_{\mathrm{R}}(p^2) = \Sigma_{\mathrm{U}}(p^2) - \delta m^2 + (p^2 - m^2)\delta z$$

$$\Sigma_{\mathrm{R}}(p^2=\bar{M}^2-i\bar{\Gamma}\bar{M})=0 \quad\Longrightarrow\quad \delta m^2=\Sigma_{\mathrm{U}}(p^2=\bar{M}^2-i\bar{\Gamma}\bar{M})$$

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$$\Im[m^2] = -\bar{\Gamma}\bar{M} = -\Im[\delta m^2] = -\Im[\Sigma_{\mathrm{U}}(p^2=\bar{M}^2-i\bar{\Gamma}\bar{M})]$$

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The CM scheme reorganises the perturbative expansion

$$(m^2+\delta m^2)-(M^2+\delta M^2) \stackrel{\rm NLO}{=} \mathcal{O}(\alpha^2)$$

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The CM scheme reorganises the perturbative expansion

$$(m^2+\delta m^2)-(M^2+\delta M^2)$$

$$\stackrel{\text{NLO}}{=}\ \mathcal{O}(\alpha^2)$$

Analytic continuation !

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COMPLEX-MASS SCHEME: ANALYTIC CONTINUATION

- For example:

$$\Sigma^{\gamma W}_{\mathrm{U},T}(\bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W) \supset B_0\left(p^2, 0, \bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W\right)\Big|_{p^2 \to \bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W}$$

- Exact expression:

$$\frac{1}{i\pi^2} B_0\left(p^2, 0, \bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W\right)\Big|_{p^2 \to \bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W}$$
$$= \frac{1}{\epsilon} + 2 + \log \frac{\mu^2}{\bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W}$$

- The Taylor expansion:

$$B_0\left(p^2, 0, \bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W\right) = B_0\left(\bar{M}_W^2, 0, \bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W\right)$$
$$+ \left(\frac{p^2 - \bar{M}_W^2}{\bar{M}_W^2}\right) B_0'\left(\bar{M}_W^2, 0, \bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W\right) + \mathcal{O}\left(\left(\frac{p^2 - \bar{M}_W^2}{\bar{M}_W^2}\right)^2\right)$$

- Taylor missing:

$$\Sigma^{\gamma W}_{\mathrm{U},T}(\bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W) - \Sigma^{\gamma W,(1)}_{\mathrm{U},T}(\bar{M}_W^2 - i\bar{\Gamma}_W \bar{M}_W) = \frac{\pi^2 \bar{\Gamma}_W}{\bar{M}_W} + \mathcal{O}\left(\left(\frac{\bar{\Gamma}_W}{\bar{M}_W}\right)^2\right)$$

COMPLEX-MASS SCHEME: ANALYTIC CONTINUATION

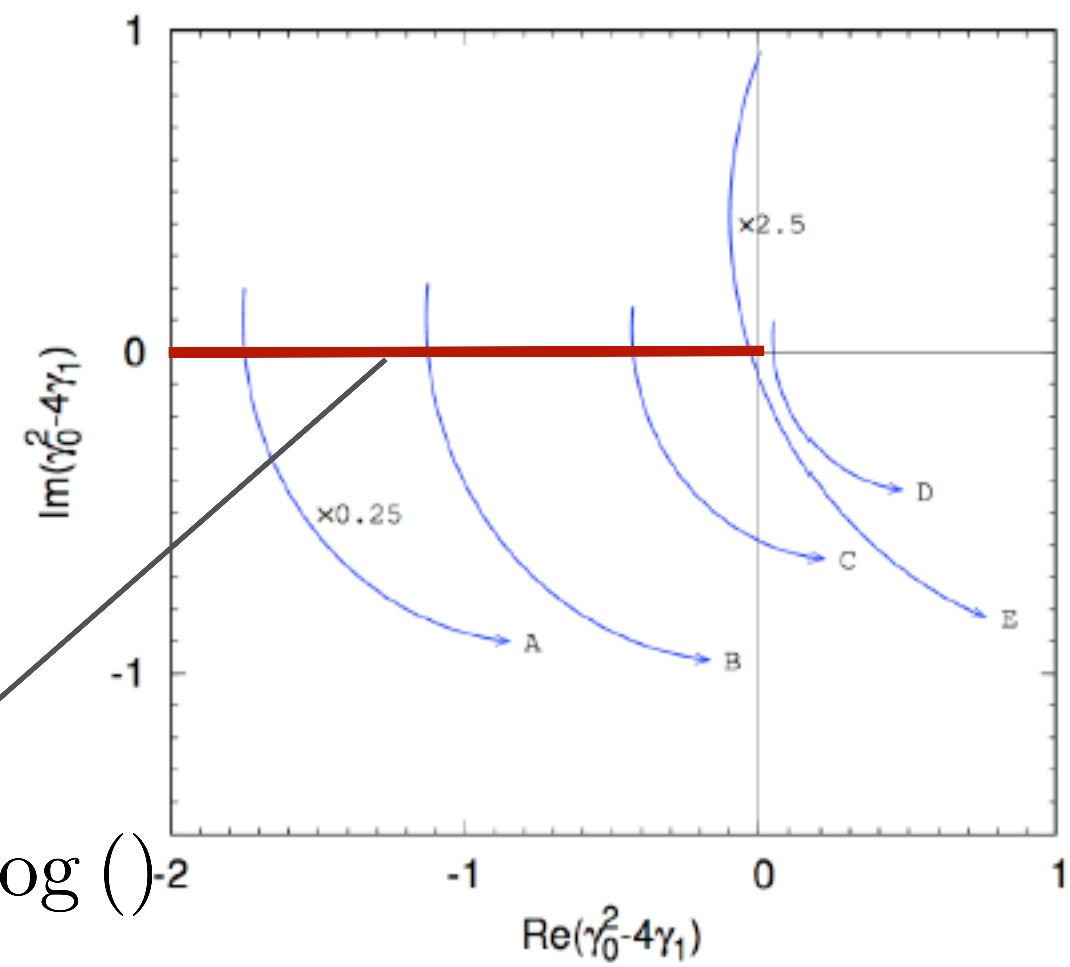
- **In general:**

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

$$\frac{1}{i\pi^2}B_0(p^2,\mu_1^2,\mu_2^2)=\frac{1}{\epsilon}+2-\log\frac{p^2-i0}{\mu^2}+\sum_{i=\pm}\left[\gamma_i\log\frac{\gamma_i-1}{\gamma_i}-\log\left(\gamma_i-1\right)\right]$$

$$\gamma_\pm=\frac{1}{2}\left(\gamma_0\pm\boxed{\sqrt{\gamma_0^2-4\gamma_1}}\right),\quad \gamma_0=1+\frac{\mu_1^2}{p^2}-\frac{\mu_2^2}{p^2},\quad \gamma_1=\frac{\mu_1^2}{p^2}-\frac{i0}{p^2}$$

	$\bar{M}^2/\bar{M}_1^2$	$\bar{M}_2^2/\bar{M}_1^2$	$\bar{\Gamma}_1/\bar{M}_1$	$\bar{\Gamma}_2/\bar{M}_2$
A	0.5	1	0.1	0.1
B	1.88	1	0.1	0.1
C	2.8	1	0.1	0.1
D	4.2	1	0.1	0.1
E	5.9	2	0.8	0.1

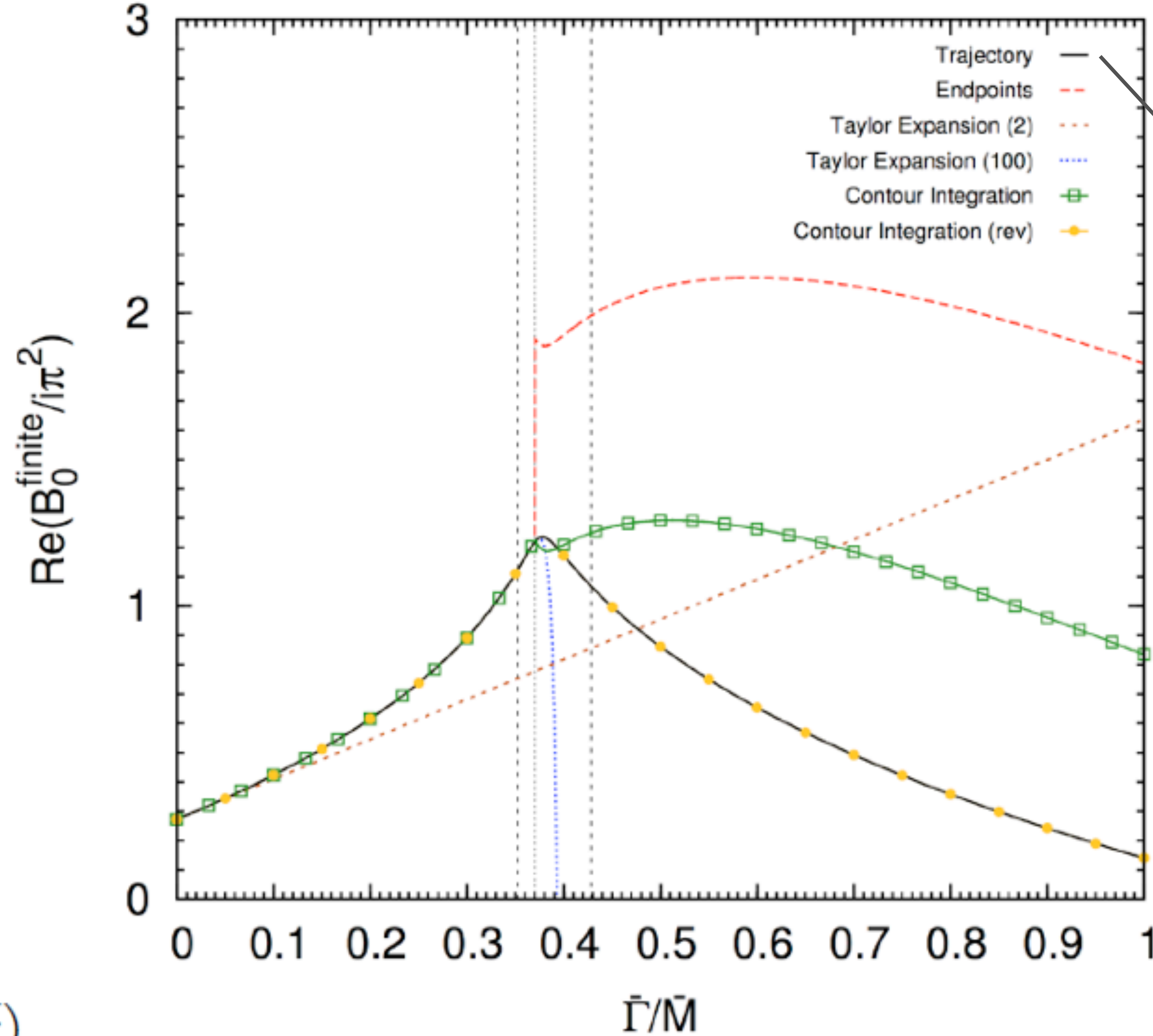


branching cuts of $\sqrt{()}$ *and* $\log()$

COMPLEX-MASS SCHEME: ANALYTIC CONTINUATION

- **The general solution (regardless of mass/width spectrum):**

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18



A first general solution

Config. E)

Wednesday, January 29, 20

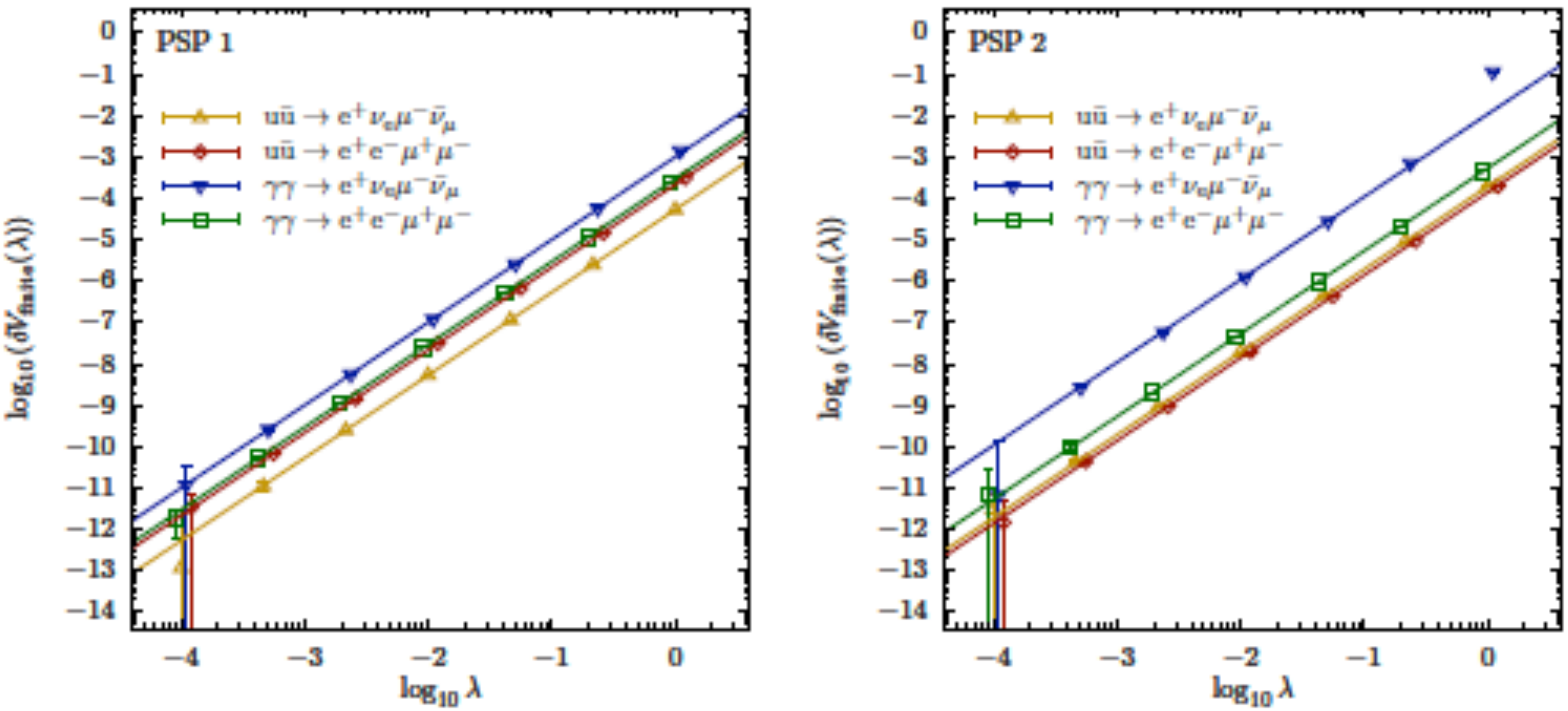
COMPLEX-MASS SCHEME: ANALYTIC CONTINUATION

- **Exact analytic continuation (MG5_aMC) vs Taylor exp. (others)**

Les Houches SM report 2017 (1803.07977)

$$G_\mu \to \lambda G_\mu\,, \quad \alpha \to \lambda\alpha\,, \quad \Gamma_Z \to \lambda\Gamma_Z\,, \quad \Gamma_W \to \lambda\Gamma_W$$

$$\delta V_{\rm finite}(\lambda) = 2\left|\frac{V^{\rm MadLoop}_{\rm finite}(\lambda) - V^{\rm Recola/OpenLoops}_{\rm finite}(\lambda)}{V^{\rm MadLoop}_{\rm finite}(\lambda) + V^{\rm Recola/OpenLoops}_{\rm finite}(\lambda)}\right|$$



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MATCHING TO PARTON SHOWERS

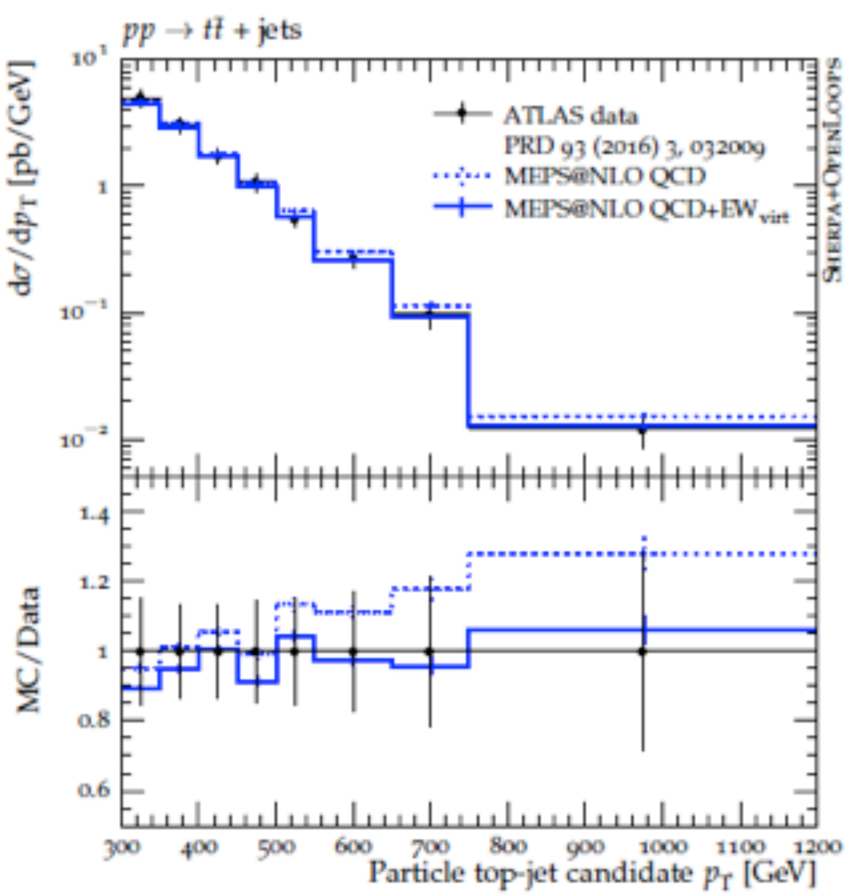
- How to match parton showers (PS) ?
  - no general solution !
  - some dedicated approximations !
  - For example, modify MC@NLO $\overline{B}$ function

optionally include subleading Born

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

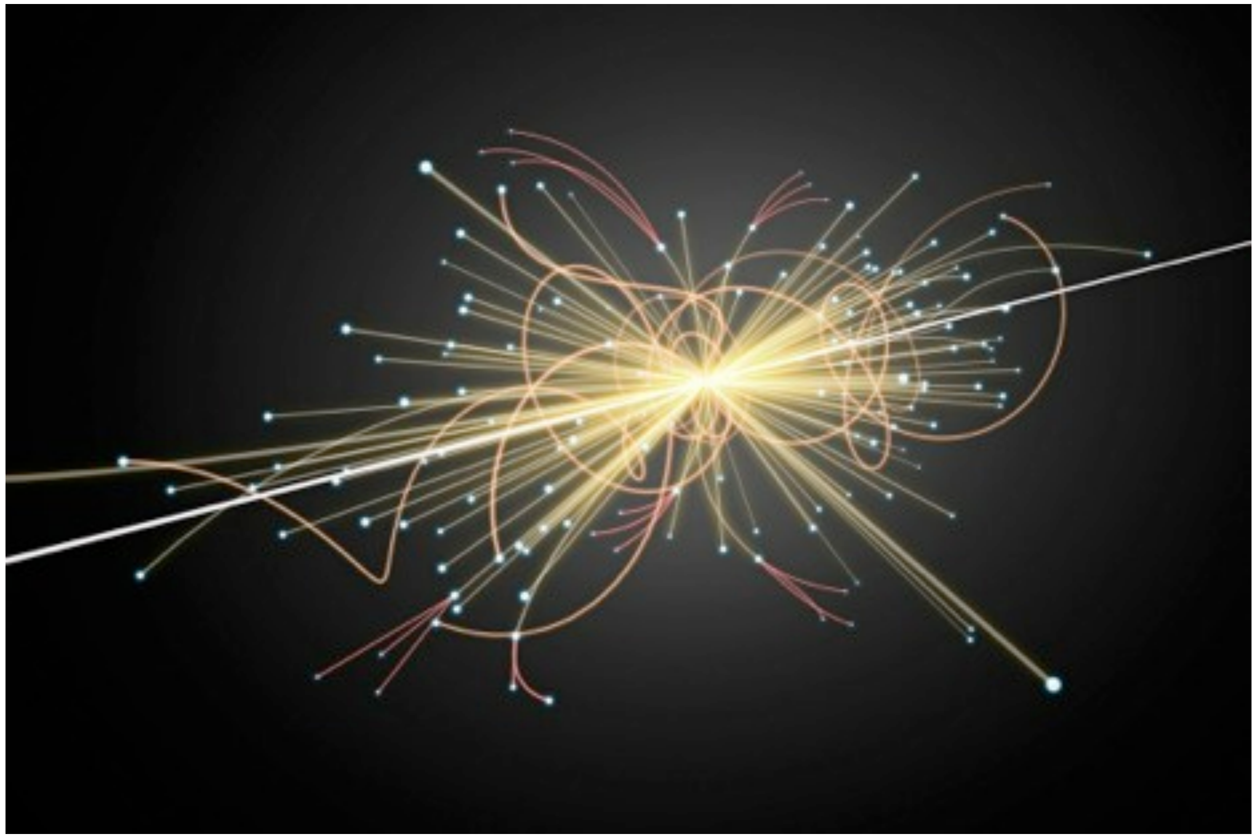
exact virtual contribution

approximate integrated real contribution



Gutschow, Lindert, Schonherr EPJC'18

Phenomenology @ LHC



Phenomenology @ LHC:

when NLO EW matters precision

Wednesday, January 29, 20

PHENOMENOLOGY STUDY: TTBAR+H/V

Frixione, Hirschi, Pagani, HSS, 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
  - First public EWC results with MadGraph5_aMC@NLO

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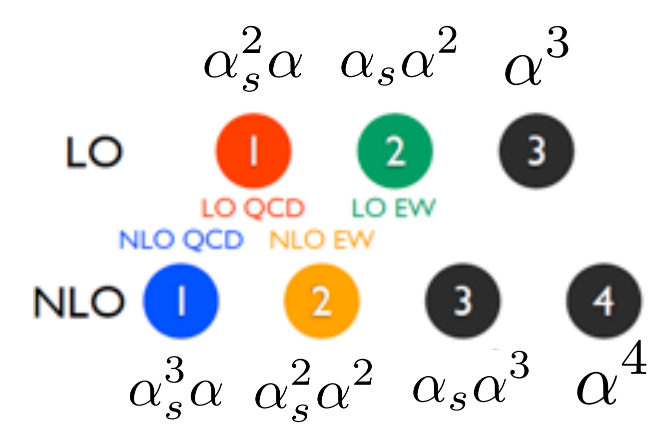
  - Missing of EWC for these processes in the literature
  - No conceptual problem in principle
  - First public EWC results with MadGraph5_aMC@NLO
- EWC on the inclusive total cross sections
  - EWC is moderate (% level)
  - Increase with center-of-mass energy in general (not a real surprise)
  - LO_2 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

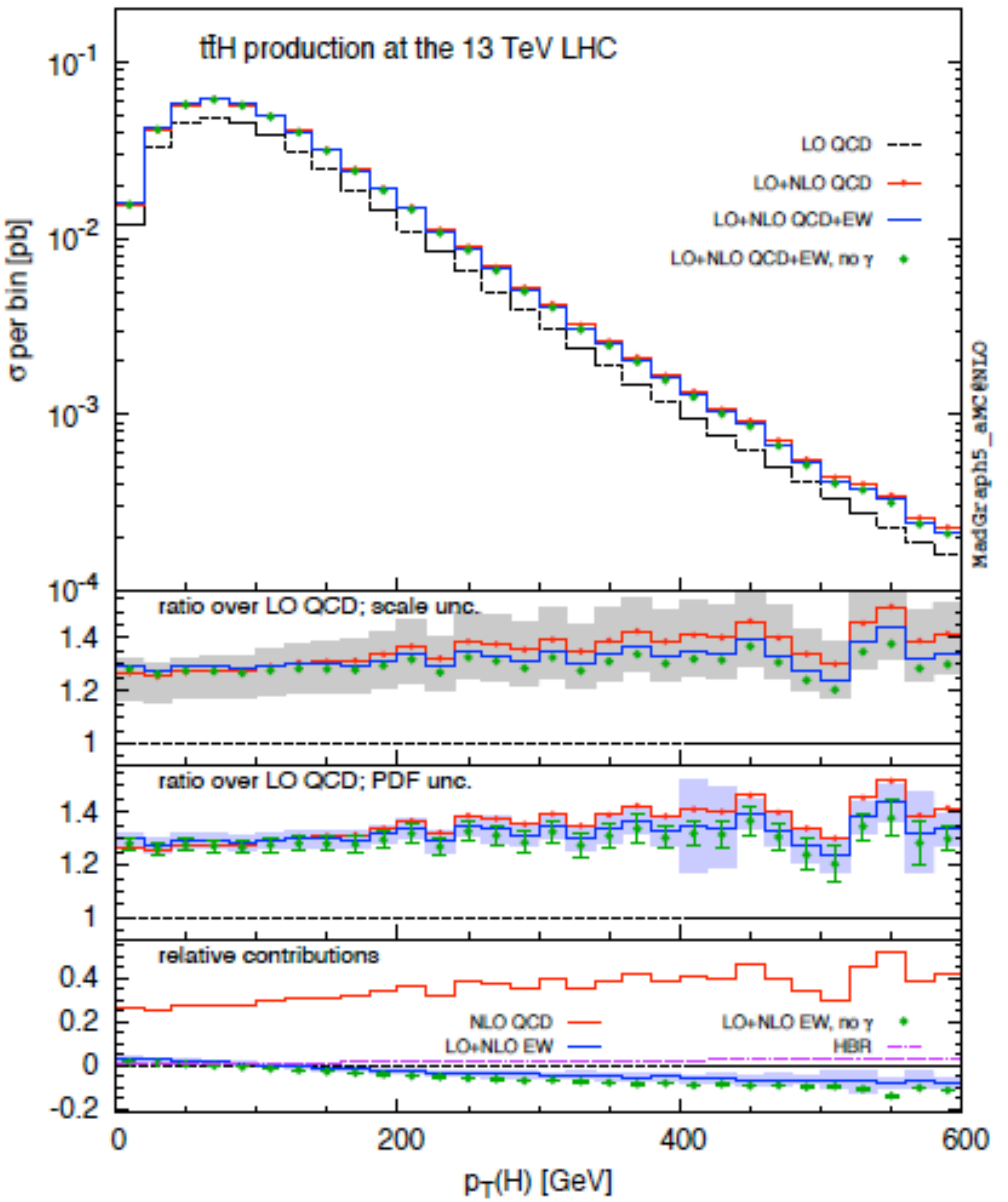


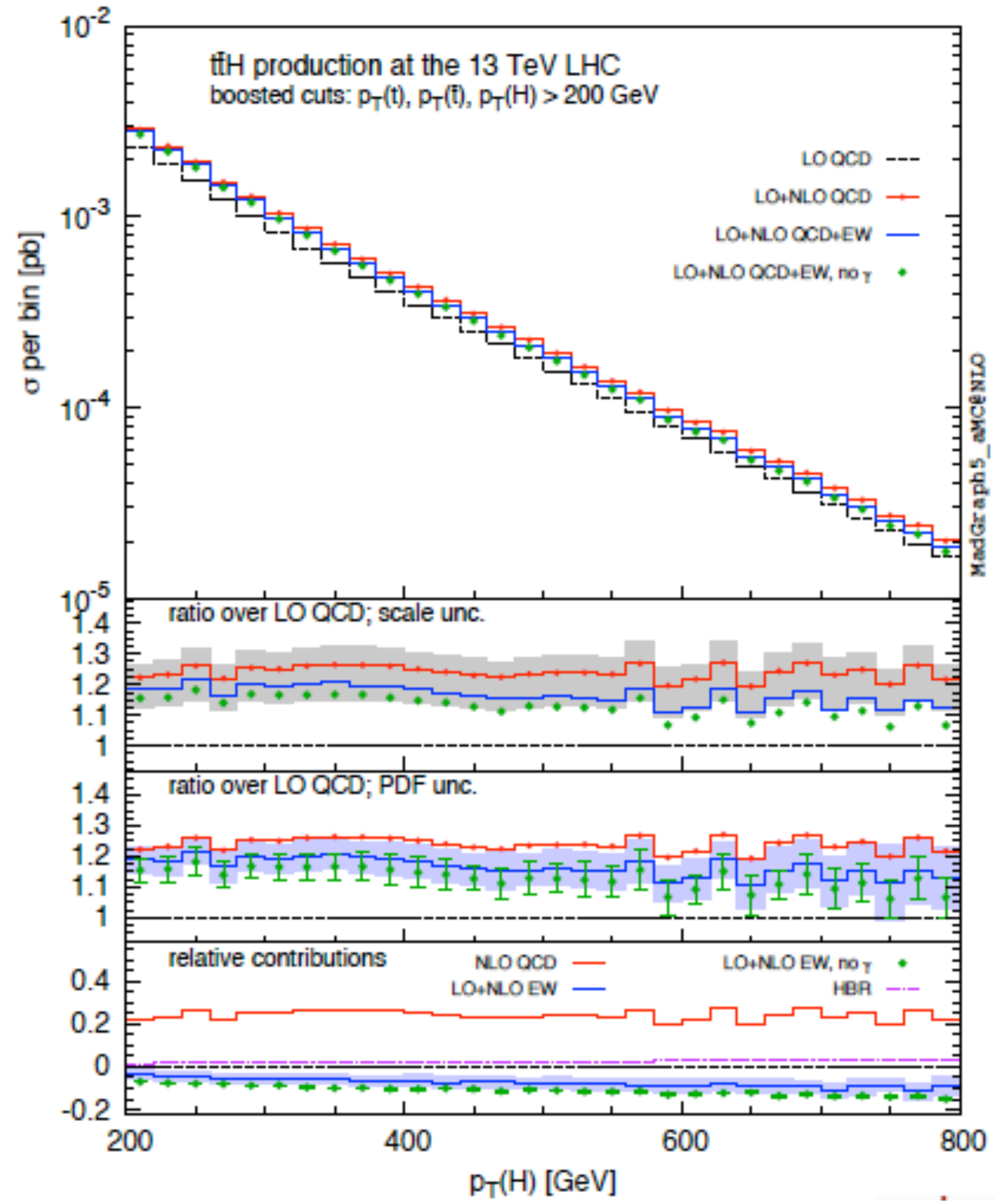
PHENOMENOLOGY STUDY: TTBAR+H/V

Frixione, Hirschi, Pagani, HSS, 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





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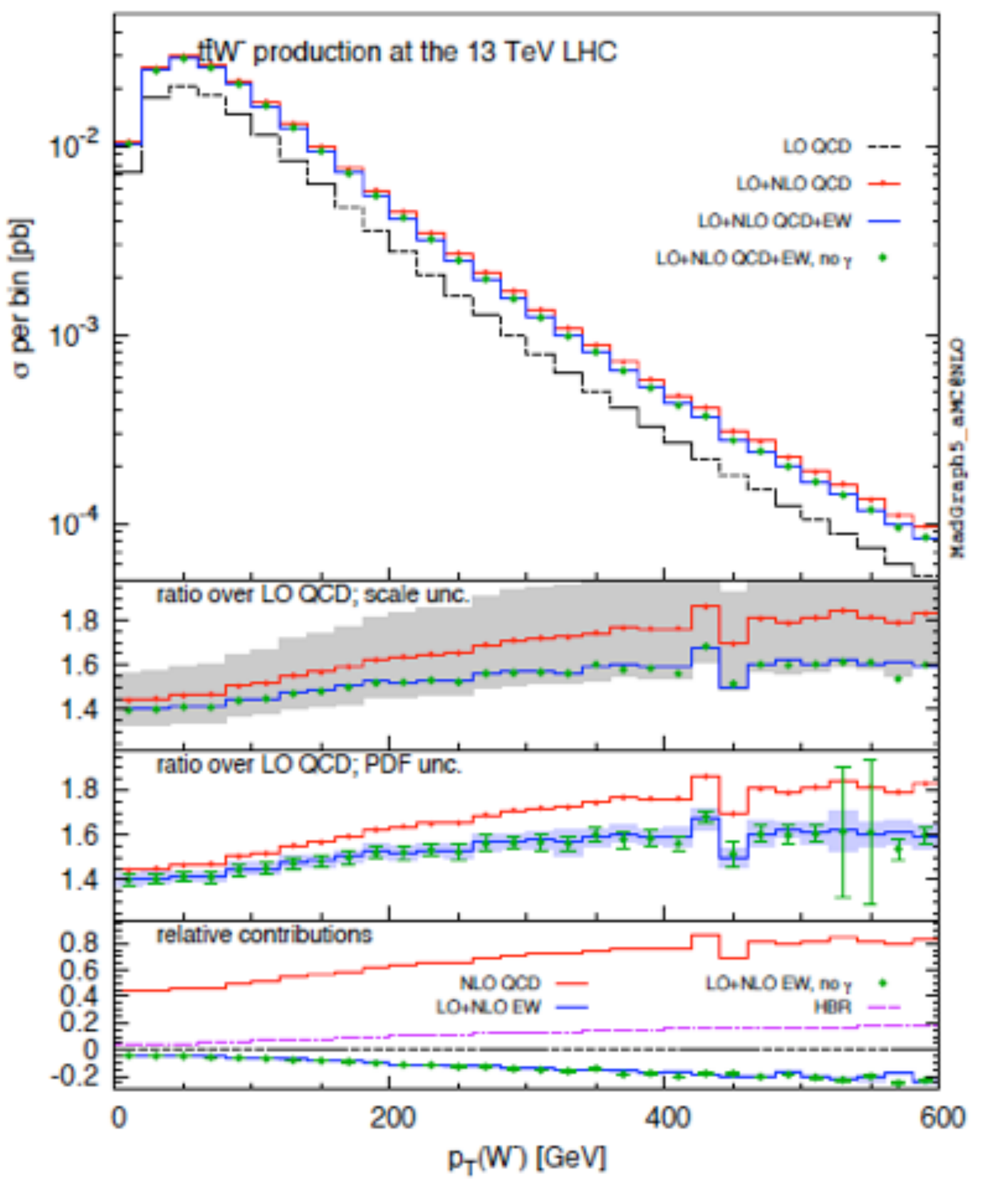
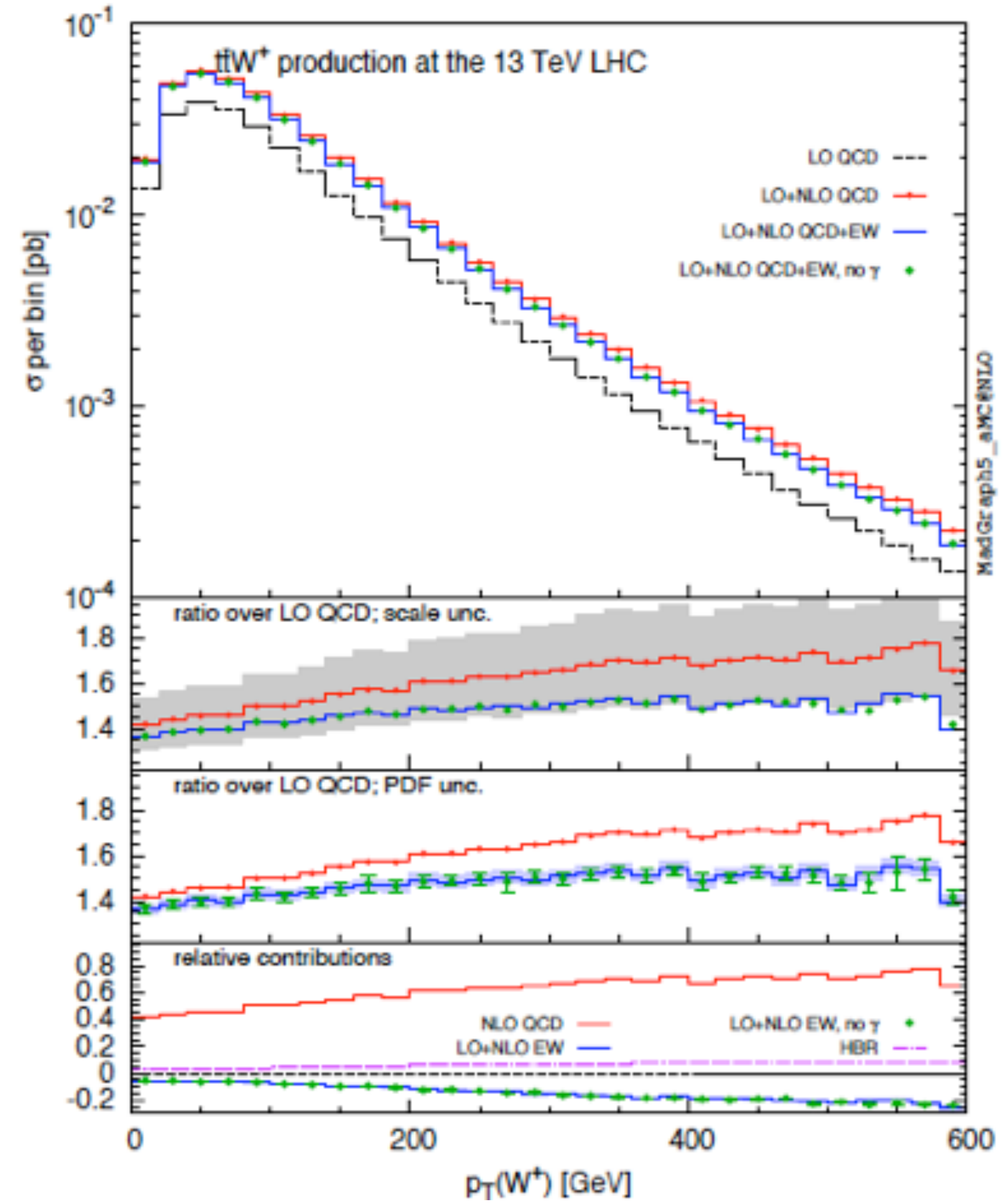
    - **No LO EW to cancel NLO EW (color flow) and HBR opens gg initial states**





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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

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  - EWC is also quite important for the cross section ratios, e.g. ttbarH/ttbarZ
  - The results are in the LHCHXSWG recommendation in YR4

Phenomenology @ LHC:

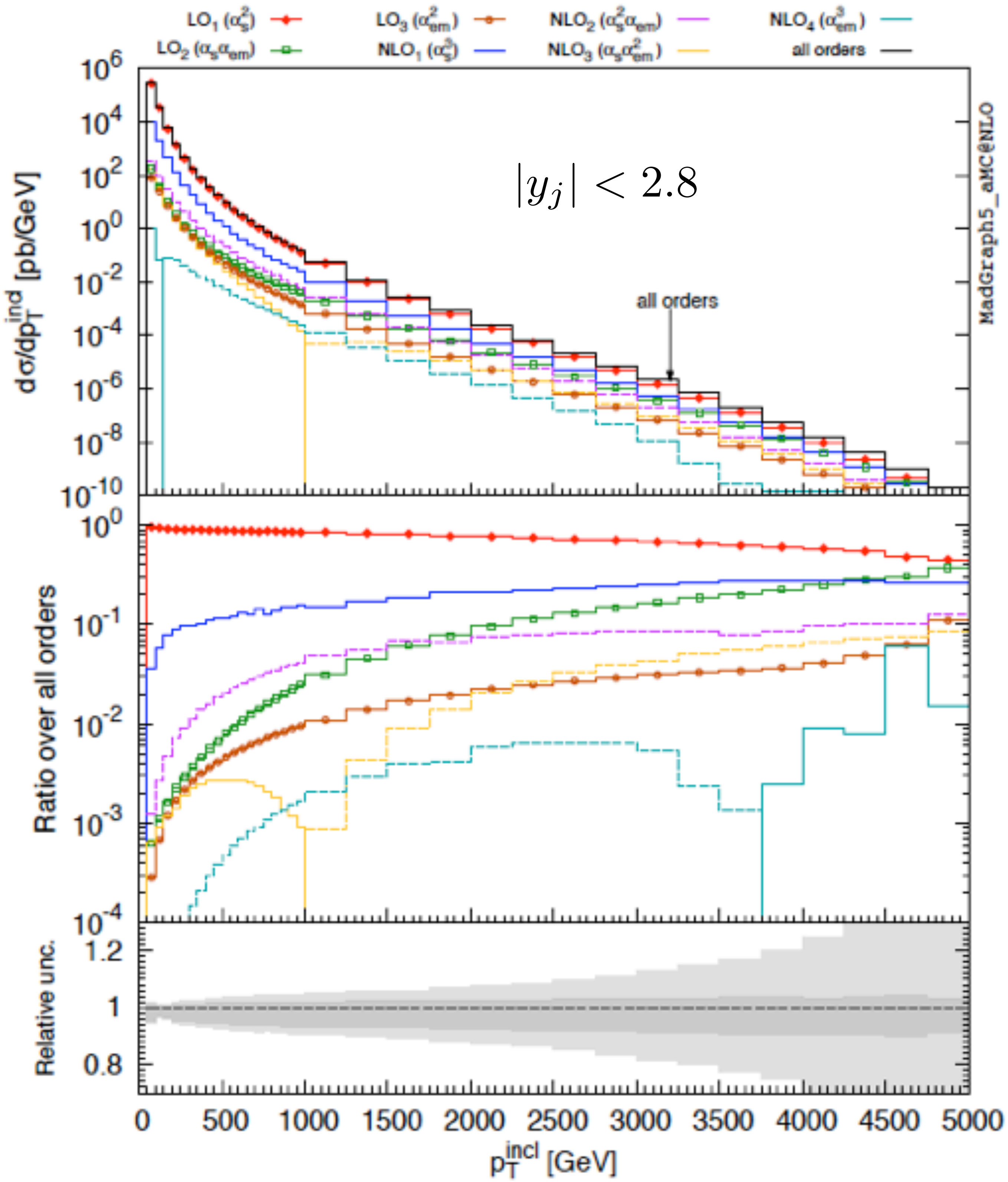
when complete NLO are necessary

TWO JETS

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'16

jets: k_T with D=0.7

$p_T^{(j)} \geq 60$ GeV $\quad |y| < 2.8$



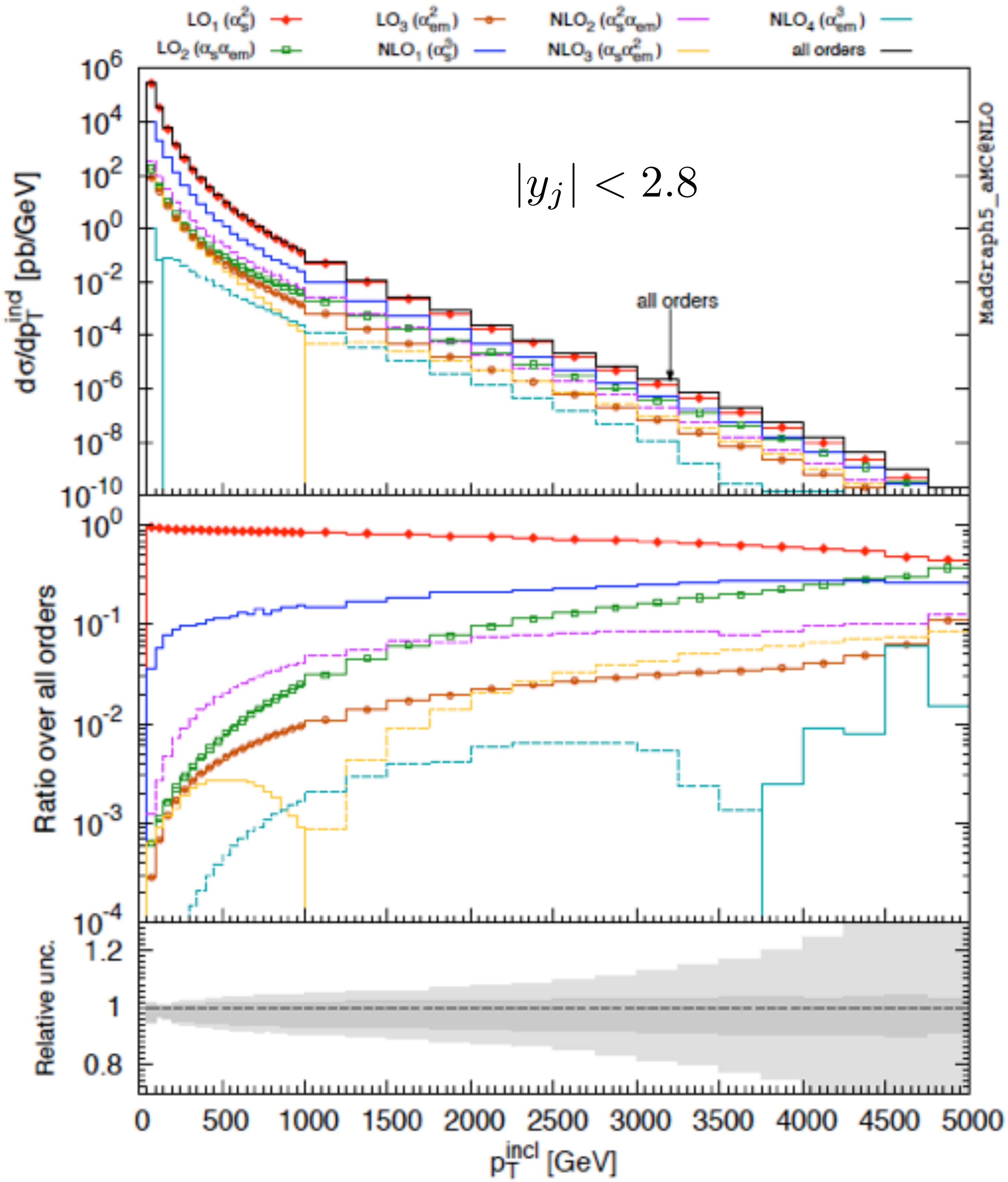
- p_T inclusive is crucial for PDF fit
- Breakdown of different contributions
- QCD correction is dominant in NLO
- EWC (LO_2) is important in the tail
- Hierarchy between different orders
- Subleading is indeed subleading

TWO JETS

jets: k_T with D=0.7

$p_T^{(j)} \geq 60$ GeV $\quad |y| < 2.8$

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'16



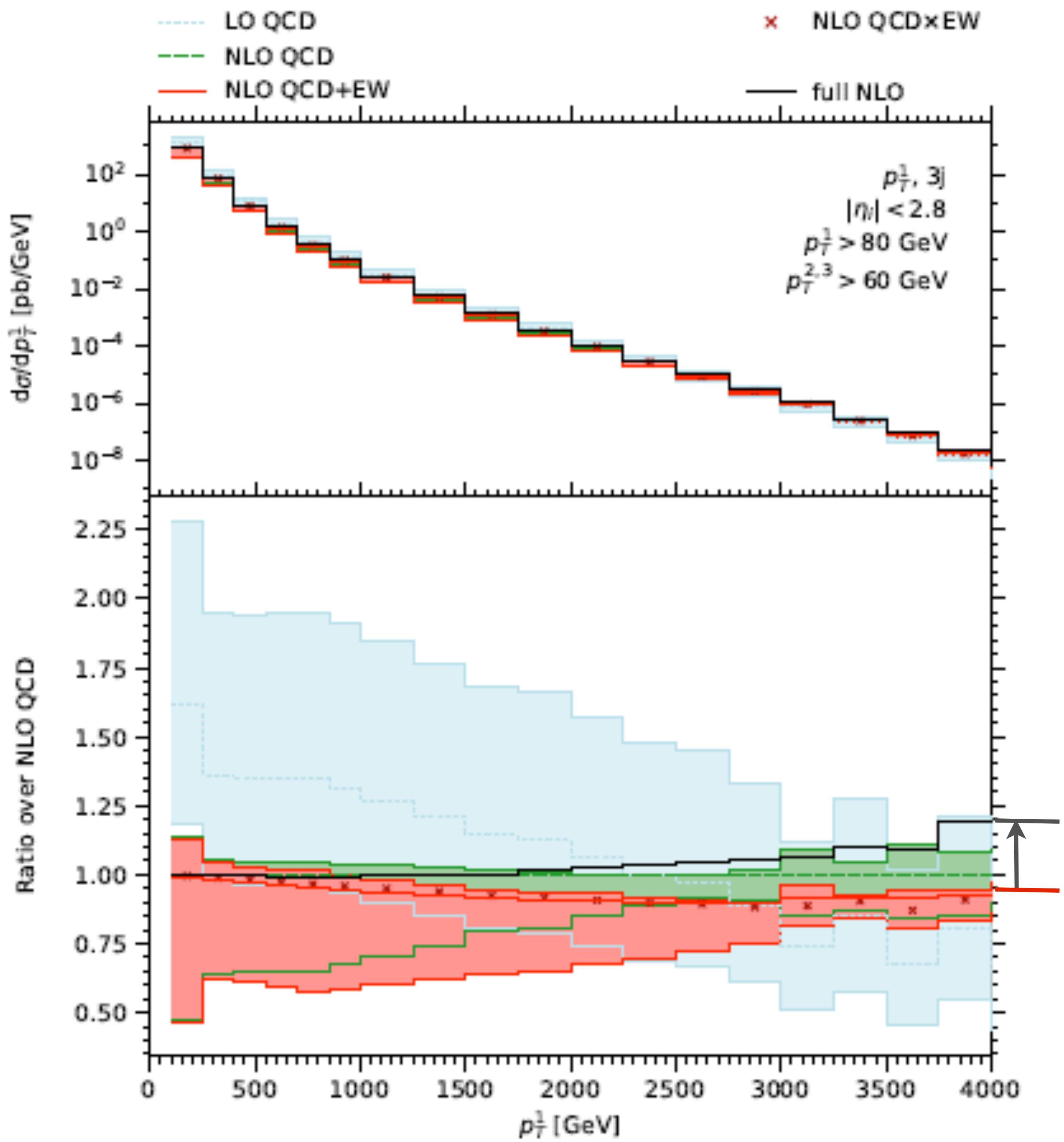
- p_T inclusive is crucial for PDF fit
- Breakdown of different contributions
- QCD correction is dominant in NLO
- EWC (LO_2) is important in the tail
- Hierarchy between different orders
- Subleading is indeed subleading

subleading is small

THREE JETS

- **however ...**

Reyer, Schonherr, Schumann EPJC'19



subleading contribution

still do not understand why however

Wednesday, January 29, 20

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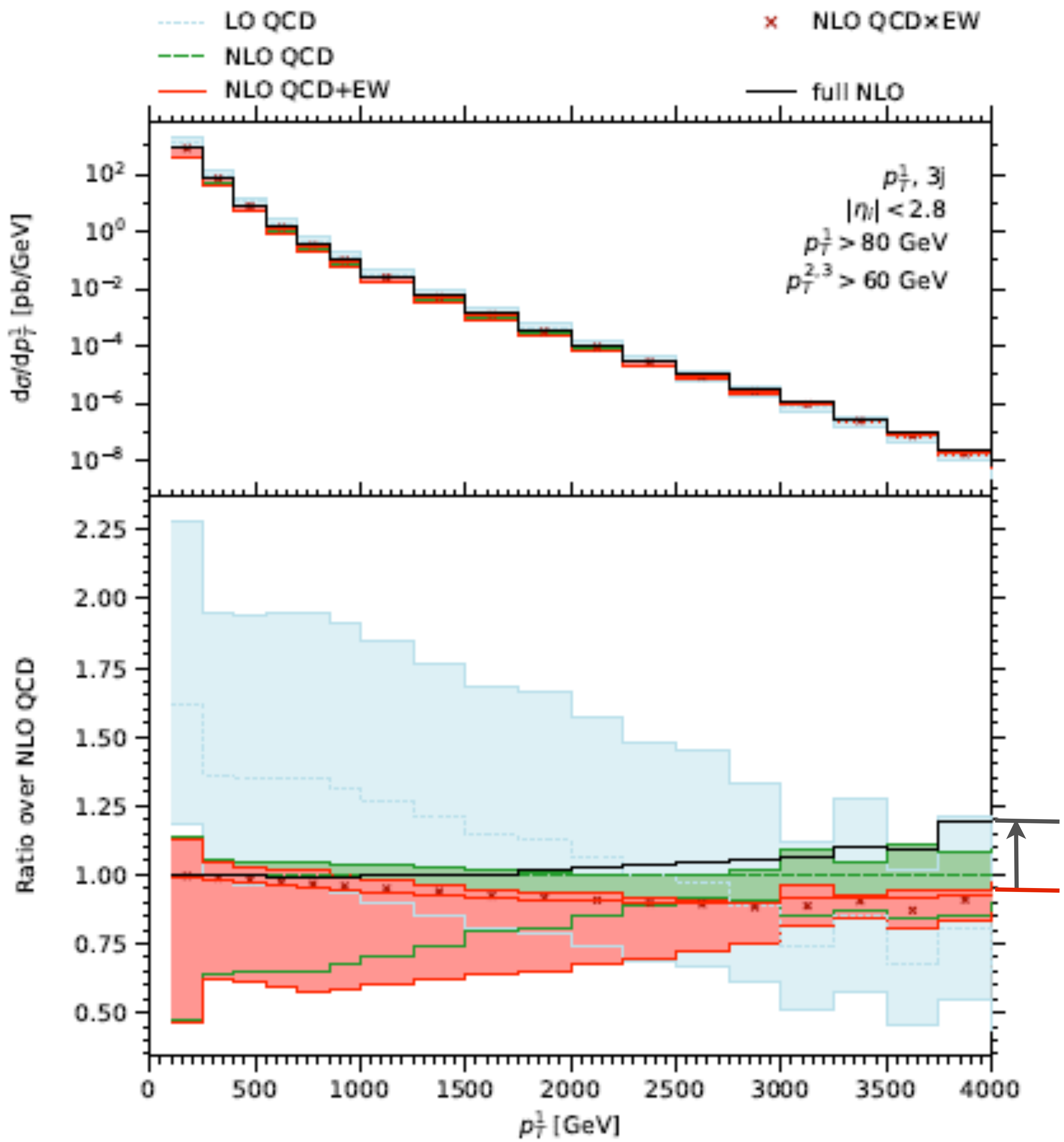

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subleading starts to be relevant

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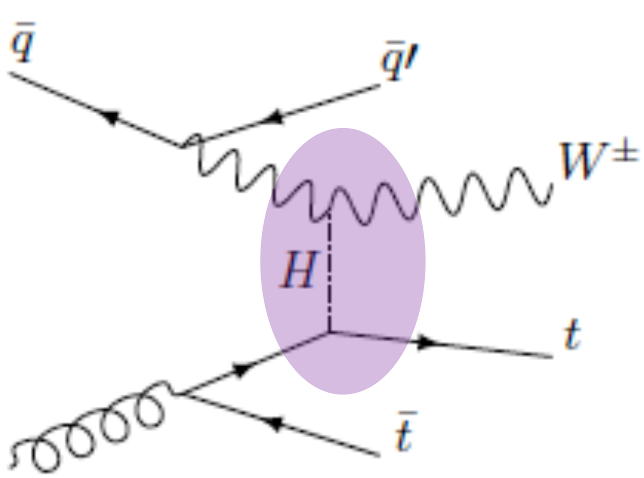
TOP PAIR + W

Frederix, Pagani, Zaro JHEP'18
Frederix, Frixione, Hirschi, Pagani, HSS, Zaro JHEP'18

$t\bar{t}W^{\pm}$ production at 13 TeV

$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO_2	-	-	-
LO_3	0.8	0.9	1.1
NLO_1	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)
NLO_2	−4.4 (−4.8)	−4.2 (−4.6)	−4.0 (−4.4)
NLO_3	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)
NLO_4	0.02 (−0.02)	0.04 (−0.02)	0.05 (−0.01)

$NLO_3 > NLO_2$ (NLO EW)



$tW \to tW$ scattering

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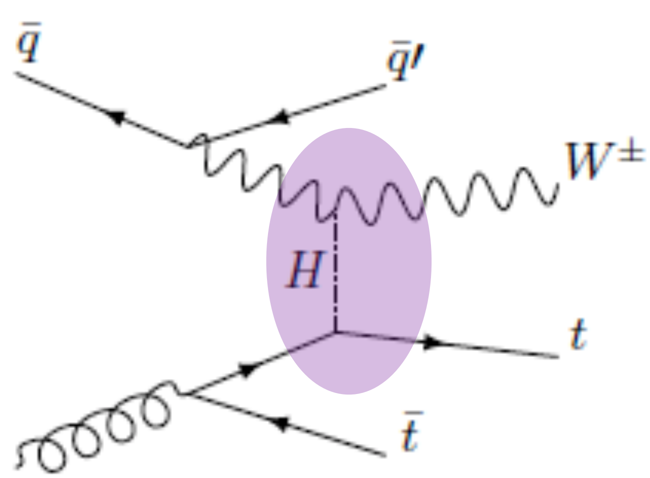

$tW \to tW$ scattering

subleading is larger than NLO EW

VBS OF SAME-SIGN WW

Biedermann, Denner, Pellen JHEP'17

$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1
	NLO_4	NLO_3	NLO_2	NLO_1	

$$\mathrm{NLO}_4 > \mathrm{NLO}_3 > \mathrm{NLO}_{1,2}$$

VBS cuts determines the pattern !

VBS cuts $m_{\mathrm{jj}} > 500\,\mathrm{GeV}, \qquad |\Delta y_{\mathrm{jj}}| > 2.5$

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subleading is the dominant correction

Phenomenology @ LHC:

NLO EW can be much larger than LO

PHENOMENOLOGY STUDY: HW

Mangano et al., FCC-hh Physics report: SM processes (1607.01831)

- **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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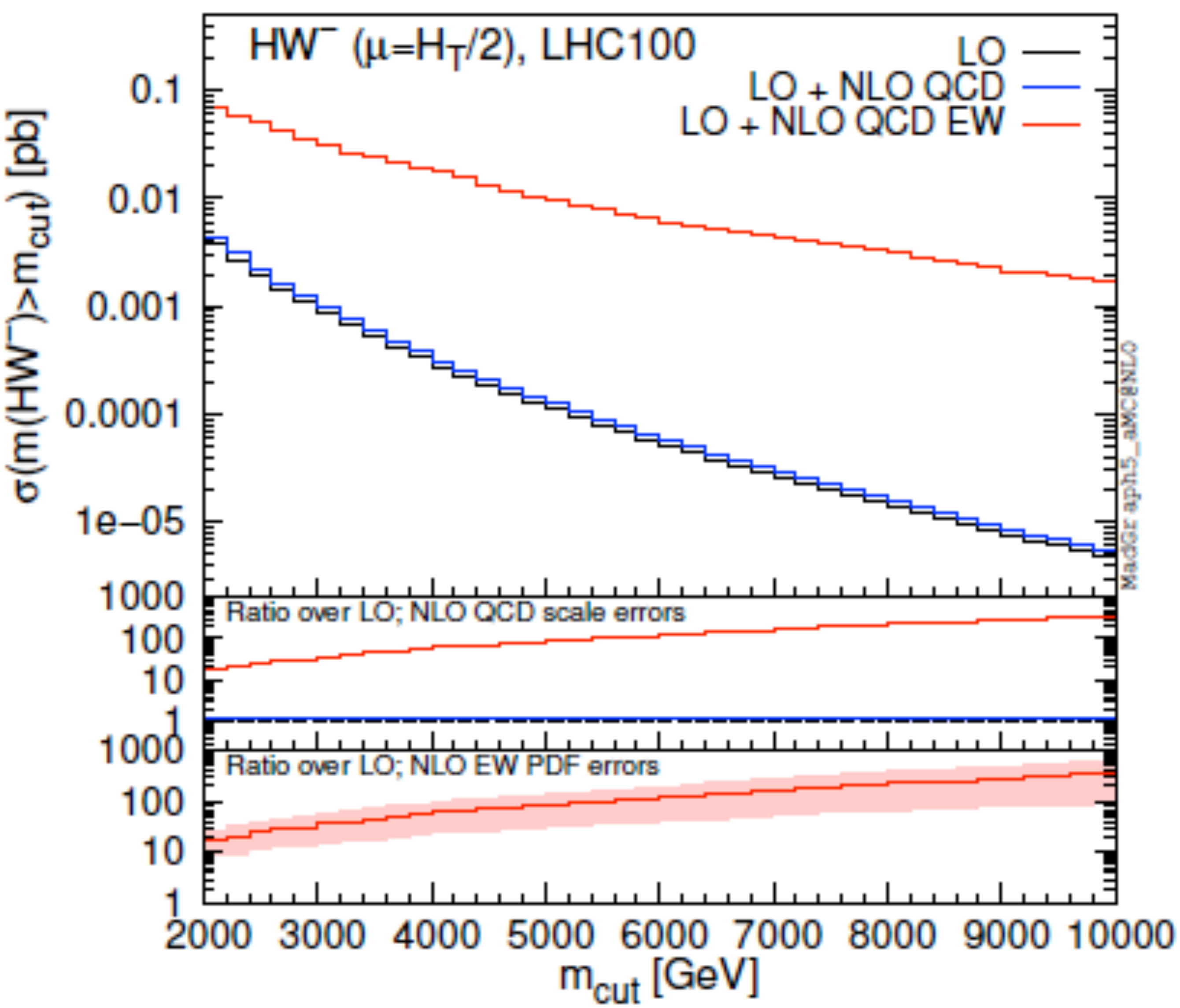

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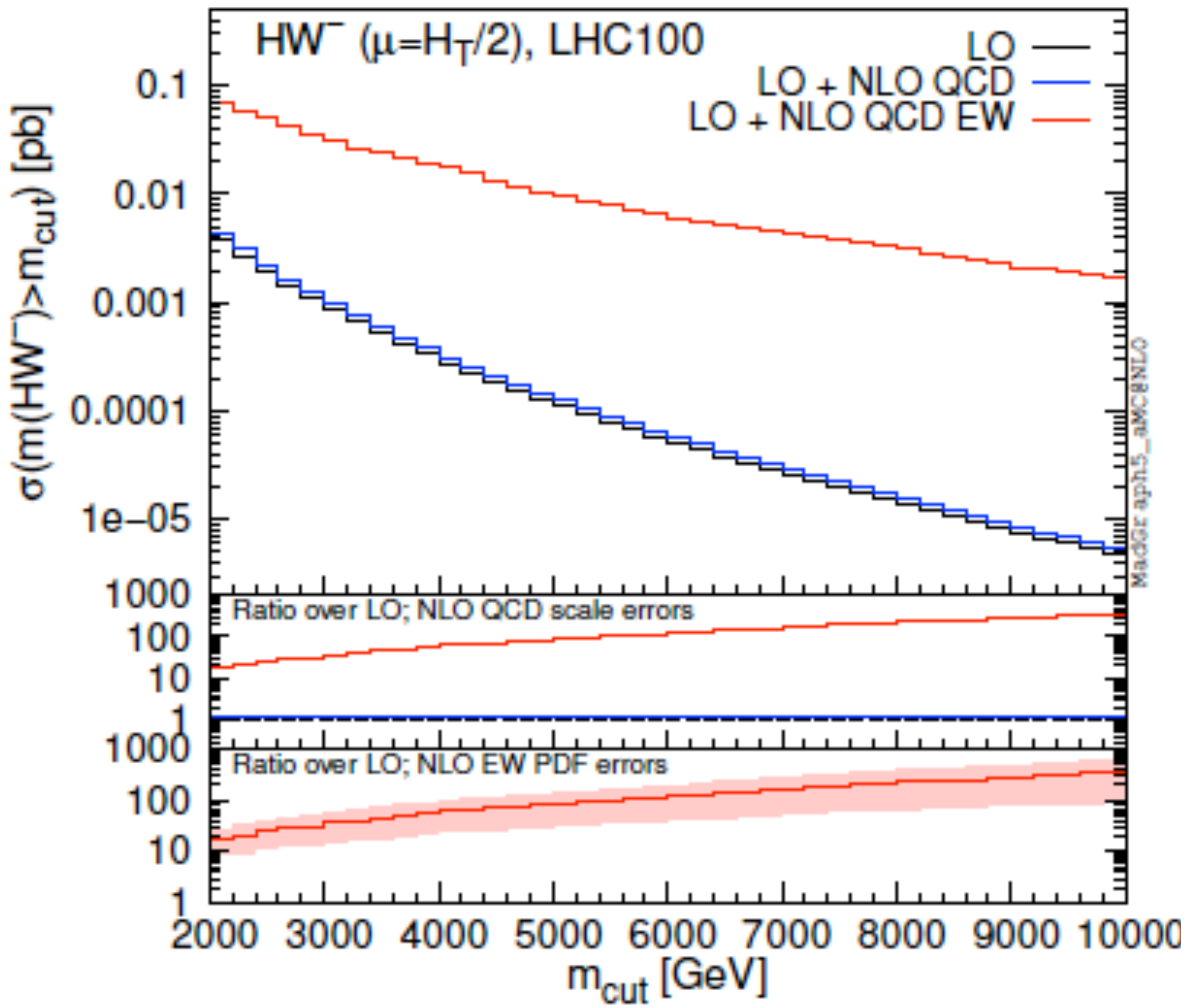

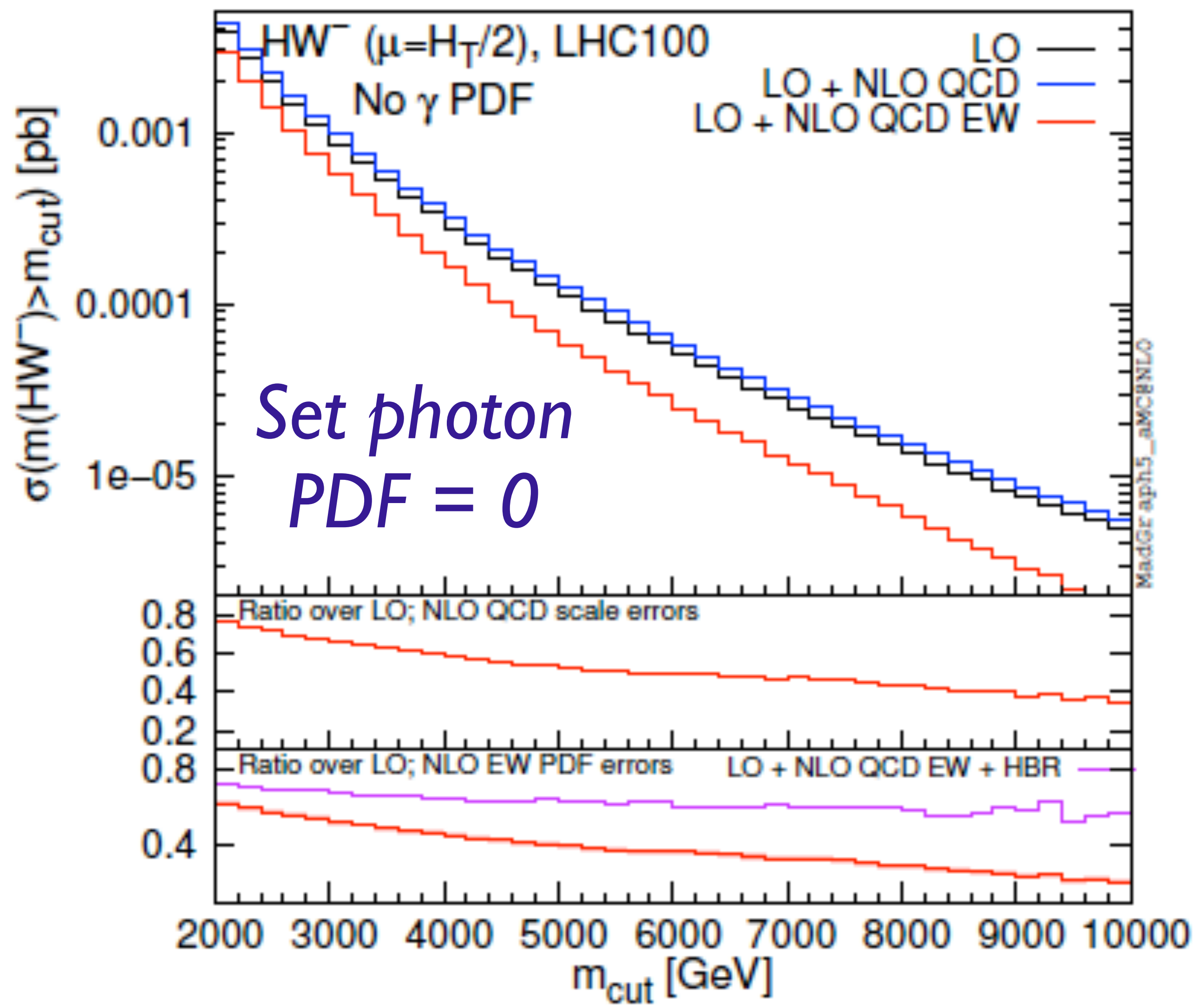

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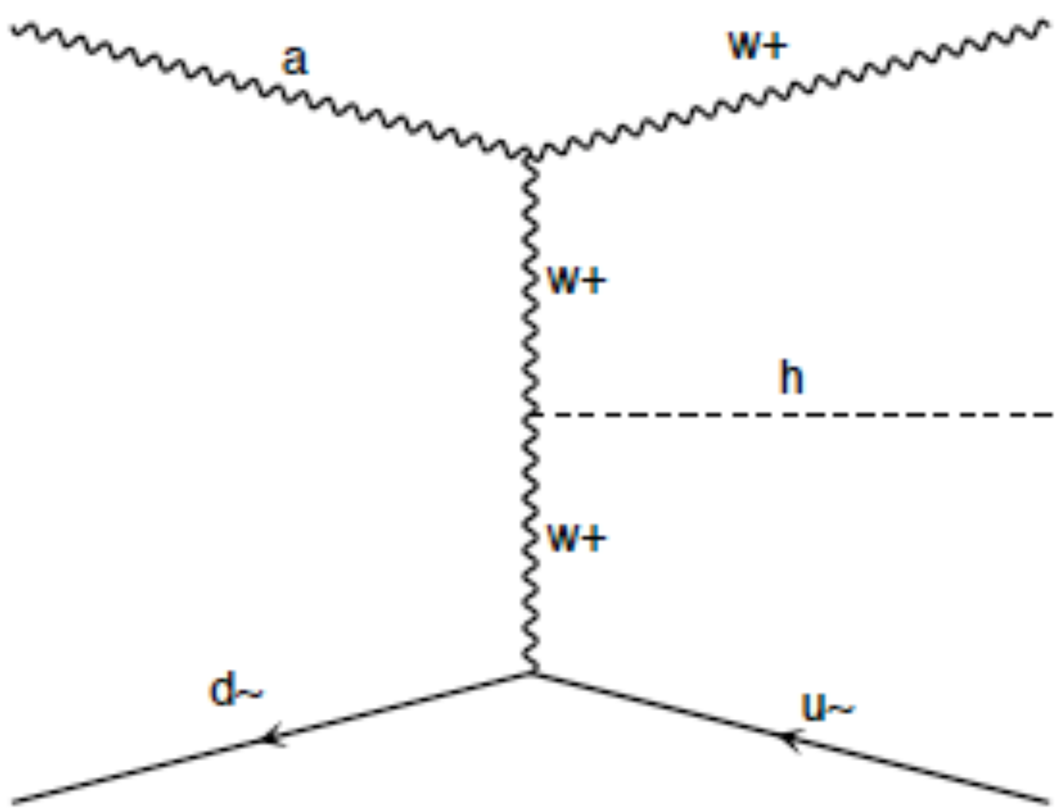
  - At large inv. mass, t-channel is dominant



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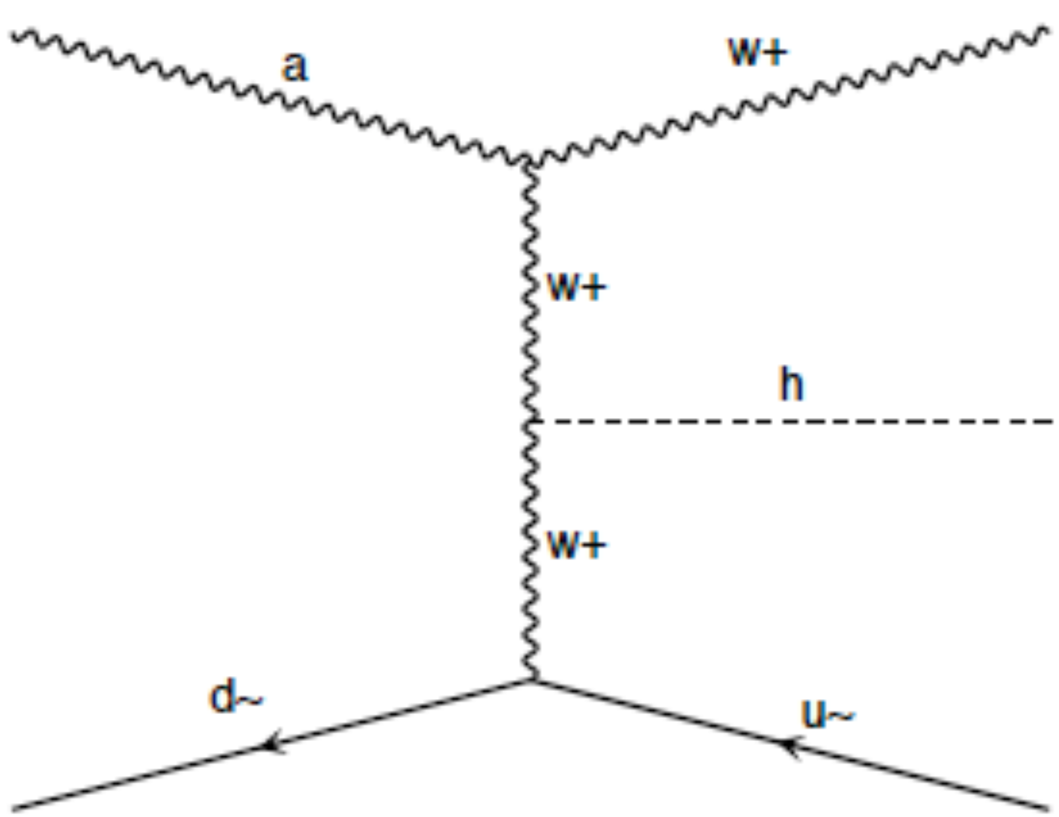

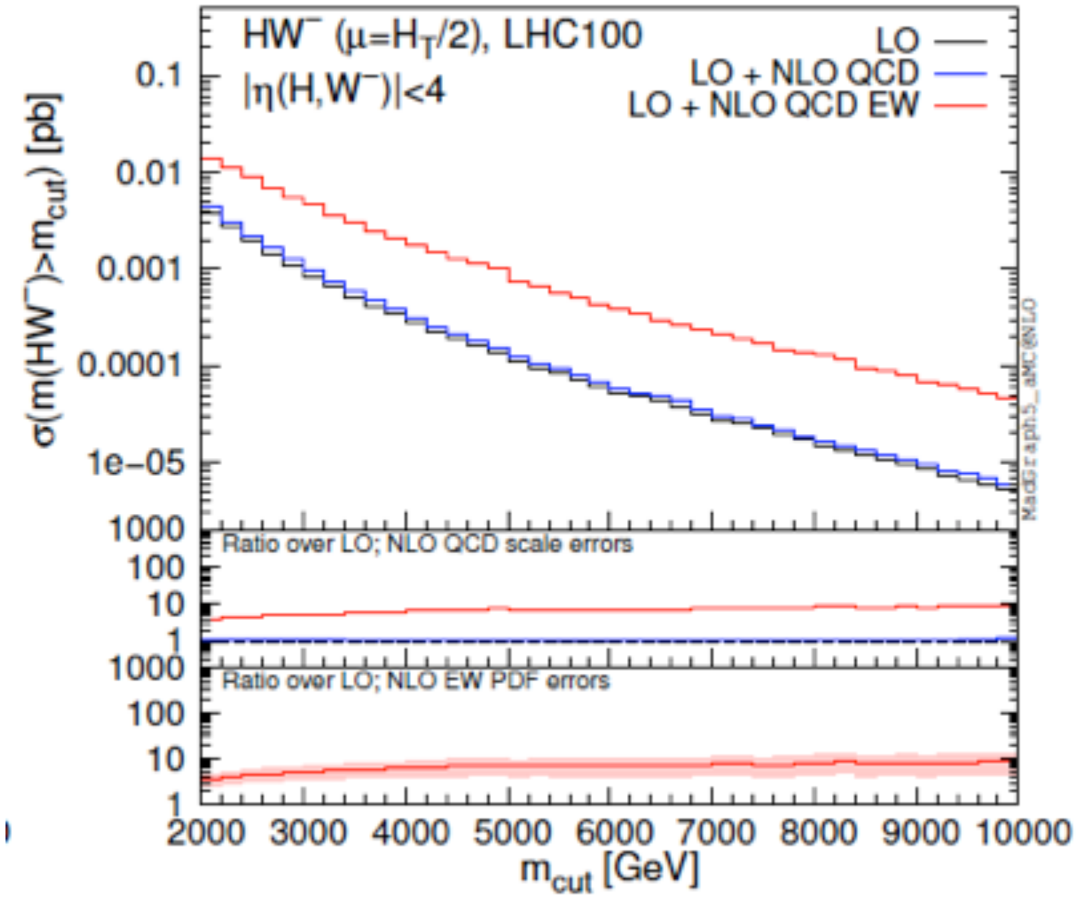

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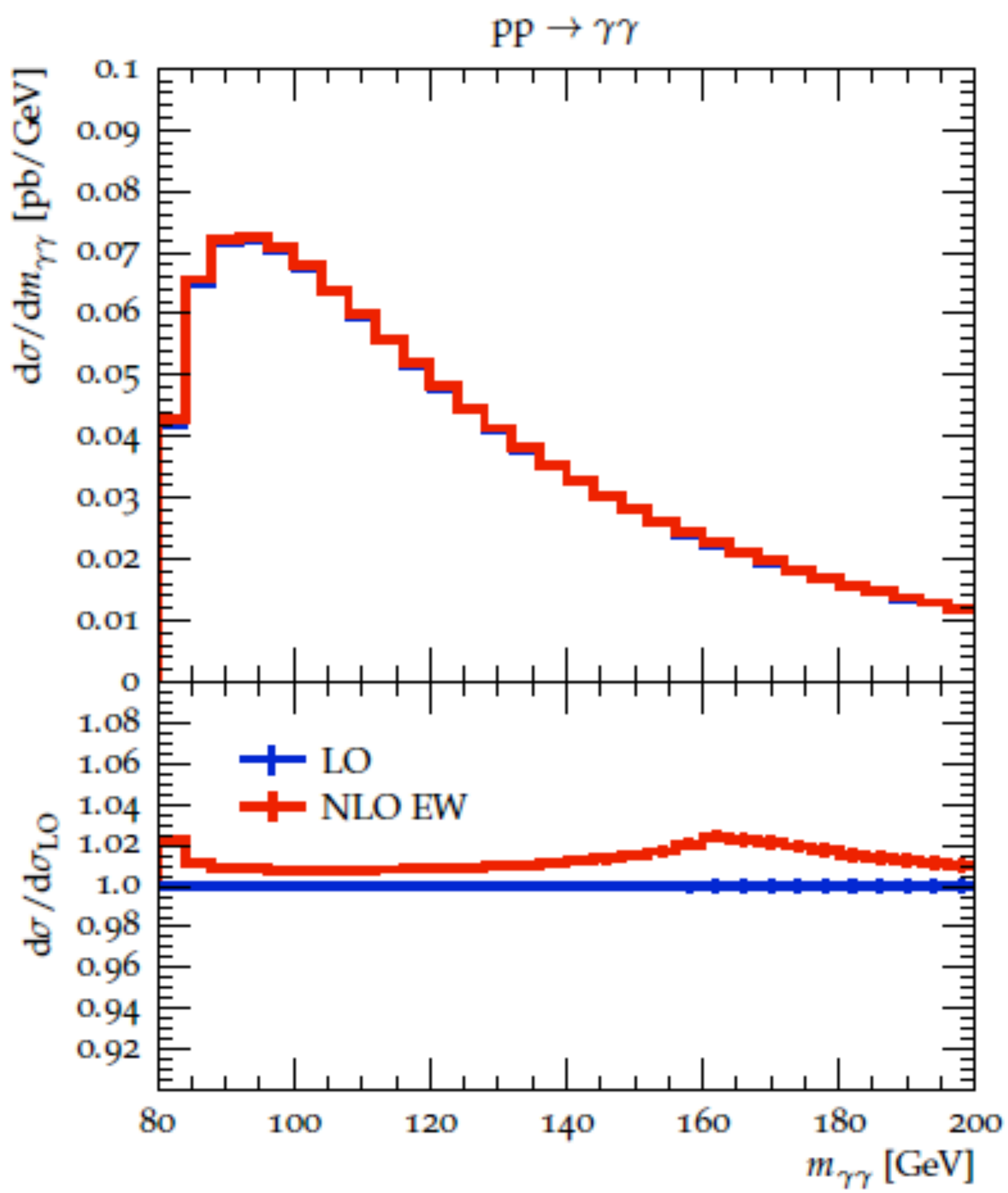
  - Such a contribution can be suppressed by cut e.g. on pseudorapidity
- Message: do not simply overlook EWC even you are not a precision guy

Phenomenology @ LHC:

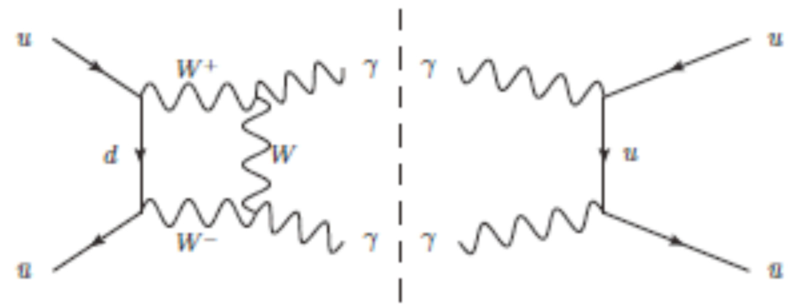
A caveat in data-driven BK estimate

Talk by M. Schonherr at Durham '19



NLO EW corrections to diphoton production

- peak-like enhancement around $m_{\gamma\gamma} = 2\, m_W$
- induced by W-box creating pseudo-resonant structures



- should be accounted for in data-driven background fits in diphoton resonance searches

Conclusion

CONCLUSION

- 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
- Automation of complete NLO at fixed order is there !
- MadGraph5_aMC@NLO v3.X has been released (EWC & complete NLO)

https://launchpad.net/mg5amcnlo

A recent nice review: Denner & Dittmaier (1912.06823)

Thank you for your attention !