MadGraph5_aMC@NLO

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(on behalf of the team)

LPTHE Paris/CNRS

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A QUICK INTRODUCTION

- A single framework to provide the following type of computations
  - **fLO**: fixed-order LO (= tree level or loop-induced)
  - **fNLO**: fixed-order NLO
  - **LO+PS**: hard LO events and parton shower (external PSMC)
  - **NLO+PS**: hard NLO events and parton shower (MC@NLO+external PSMC)
  - **LO merged**: merging of LO multijet samples (MLM/CKKW-L)
  - **NLO merged**: merging of NLO multijet samples (FxFx/UNLOPS)
- A fully automated chain from the (B)SM Lagrangian to events is:

LO FeynRules → MG5_aMC → PSMC

NLO FeynRules(+NLOCT) → MG5_aMC → PSMC

see C. Degrande's talk

- Colored particle production
  - Colored scalar pair production — Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)
  - Supersymmetric QCD — Degrande, Fuks, Hirschi, Proudom, HSS (PLB'16)
  - Vector-like quark pair production — Les Houches 2015 (1605.02684) ; Fuks, HSS (1610.04622)
  - MSSM — Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)
- BSM Higgs production
  - Higgs characterisation model — Artoisenet et al. (JHEP'13); Maltoni, Mawatari, Zaro (EPJC'14); Demartin, Maltoni, Mawatari, Page, Zaro (EPJC'14); Demartin, Maltoni, Mawatari, Zaro (EPJC'15)
  - Two-Higgs-Doublet Model — Degrande (CPC'15); Degrande, Ubiali, Wiesemann, Zaro (JHEP'15); Degrande, Frederix, Hirschi, Ubiali, Wiesemann, Zaro (1607.05291)
  - Georgi-Machacek model — Degrande, Hartling, Logan, Peterson, Zaro (PRD'16)
- Spin-2 particle production — Das, Degrande, Hirschi, Maltoni, HSS (1605.09359)
- Dark matter collider production
  - s-channel mediator
    - spin 0 or 1 mediator — Mattelaer Vryonidou (EPJC'15); Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen (EPJC'15); Neubert, Wang, Zhang (JHEP'16); Arina et al. (JHEP'16)
    - spin 2 mediator — Das, Degrande, Hirschi, Maltoni, Mawatari, HSS et al. (in preparation)
  - t-channel mediator — Fuks, Hirschi, Mattelaer et al. (in preparation)
- SM effective field theory
  - Top FCNC processes — Degrande, Maltoni, Wang, Zhang (PRD'15); Durieux, Maltoni, Zhang (PRD'15)
  - ttbarZ/gamma/Higgs production — Bylund, Maltoni, Tsinikos, Vryonidou, Zhang (JHEP'16); Maltoni, Vryonidou, Cen (JHEP'16)
  - Single-top production — Zhang (PRL'16)
  - Top pair production via chromomagnetic dipole momenta — Franzosi, Zhang (PRD'15)
  - Higgs production with dimension-6 operators — Degrande, Fuks, Mawatari, Mimasu, Sanz (1609.04833)
- Other colorless particle production
  - Heavy neutrino production — Degrande, Mattelaer, Ruiz, Tumer (PRD'16)

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BSM@NLO

before 2017

see C. Degrande's talk

A QUICK INTRODUCTION

- A framework with many useful tools for phenomenology studies
  - MadWidth: width and branching ratio computations
  - MadWeight: a phase-space generator for matrix-element method
  - MadSpin: spin-entangled decay
  - MadDM: dark-matter observable computations in (in)direct searches *see F. Ambrogi's talk*
  - Reweighting/Systematics/Bias
  - MadAnalysis5: event analysis and reinterpretation of collider searches
- A matrix-element provider
  - Both at tree-level and one-loop level
  - e.g. Pythia8 and MatchBox in Herwig7
  - Also your own format with the PLUGIN mode

A QUICK INTRODUCTION

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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In the following, I will focus on "new improvements" especially since last MC4BSM meeting

HIGHLIGHT OF RECENT ACTIVITIES

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- Extending the physics scope of the code

✓ covered
✗ uncovered

- ✓ NLO EW: **NLO EW corrections and complete-NLO calculations**
- ✓ Loop-induced@NLO: **towards NLO computations for loop-induced processes**
- ✓ MadOS: **resonance vs non-resonance**
- ✓ Madee: **simulation improvements for lepton-lepton colliders**
- ✓ MadDump: **a module for beam dump experiments for hidden particles**
- ✗ Heavy-ion/fixed-target: **rescaling one beam or heavy-ion PDF**
- ✗ MadDM v3.0: **improvements for dark-matter indirect searches** *see F. Ambrogi's talk*

- Improving the performance of the code

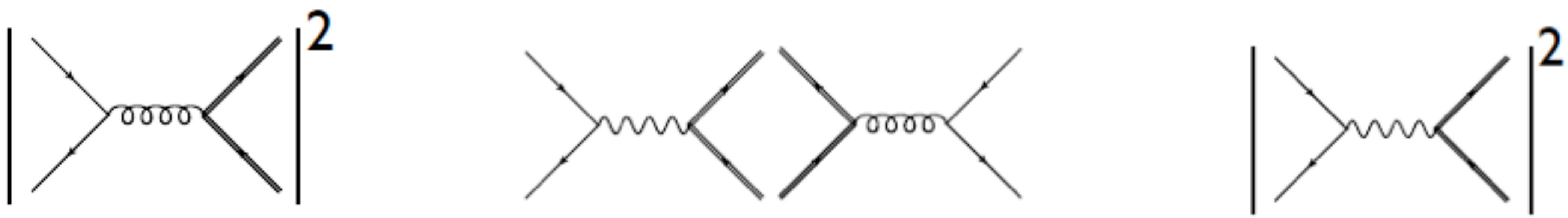
- ✓ A database of model: **make your model visible in MG5_aMC**
- ✓ BSM reweighting improvements: **mass scan**
- ✗ Many improvements in the plugin approach: **e.g. MPI implementation**

NLO EW

- Take dijet production at the LHC as an example

NLO EW

- Take dijet production at the LHC as an example

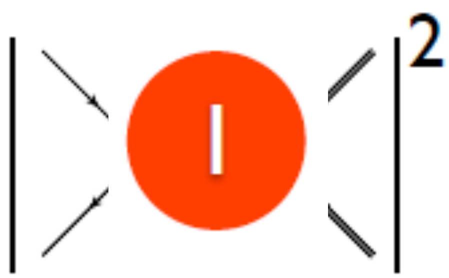


NLO EW

- Take dijet production at the LHC as an example

$$\Sigma_{jj}^{(\mathrm{LO})}(\alpha_S,\alpha) = \alpha_S^2\,\Sigma_{2,0} + \alpha_S\alpha\,\Sigma_{2,1} + \alpha^2\,\Sigma_{2,2}$$
$$\equiv \Sigma_{\mathrm{LO},1} + \Sigma_{\mathrm{LO},2} + \Sigma_{\mathrm{LO},3}$$

$\alpha_s{}^2$ | $\alpha_s\alpha$ | α^2

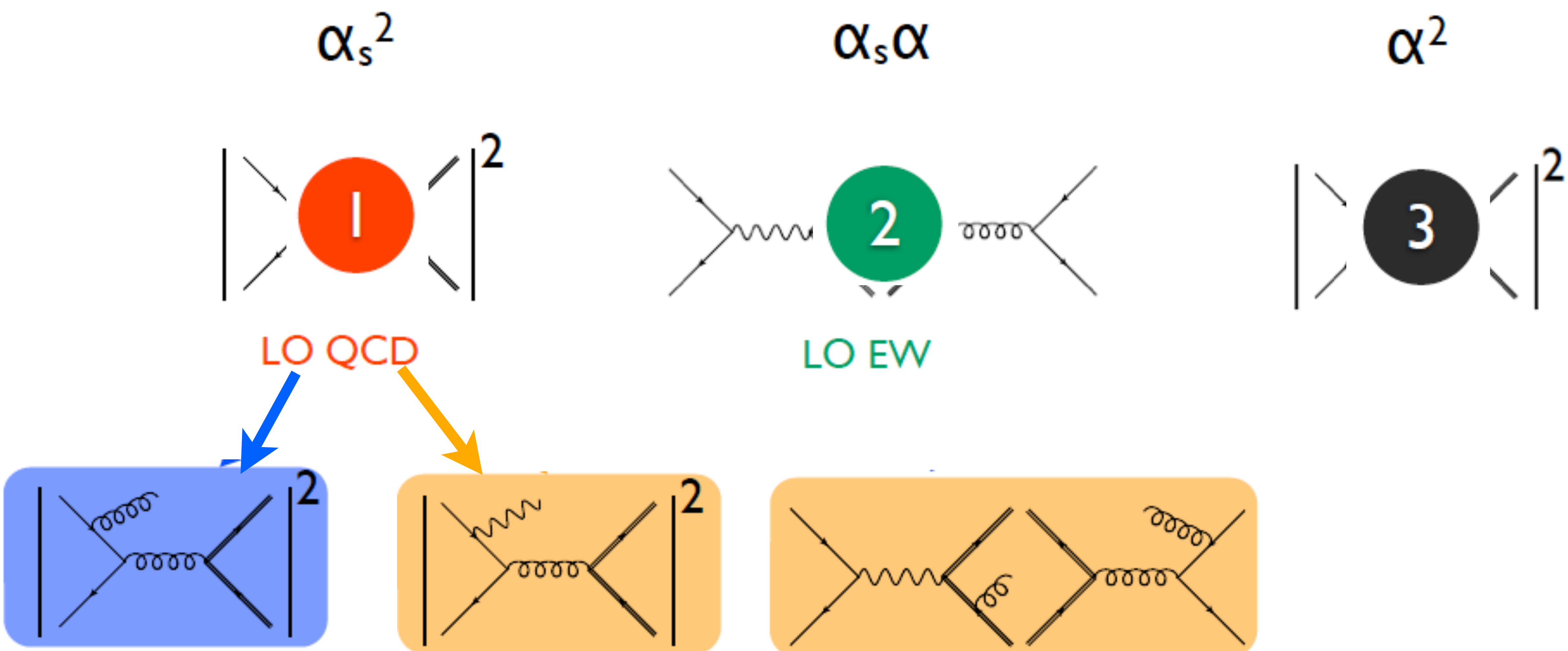


LO QCD

LO EW

NLO EW

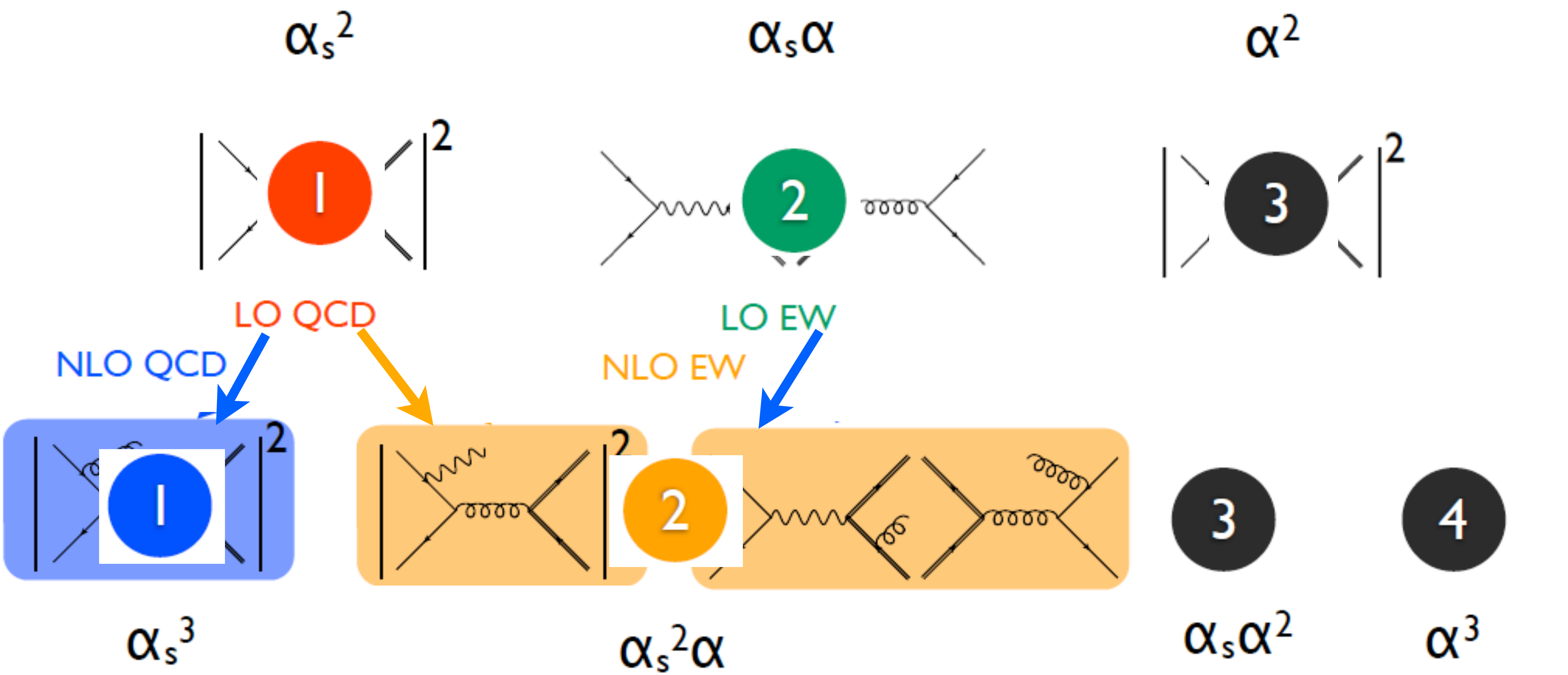
- Take dijet production at the LHC as an example



NLO EW

- Take dijet production at the LHC as an example

$$\Sigma_{jj}^{(\mathrm{NLO})}(\alpha_s,\alpha) = \alpha_s^3\,\Sigma_{3,0} + \alpha_s^2\alpha\,\Sigma_{3,1} + \alpha_s\alpha^2\,\Sigma_{3,2} + \alpha^3\,\Sigma_{3,3}$$
$$\equiv \Sigma_{\mathrm{NLO},1} + \Sigma_{\mathrm{NLO},2} + \Sigma_{\mathrm{NLO},3} + \Sigma_{\mathrm{NLO},4}$$

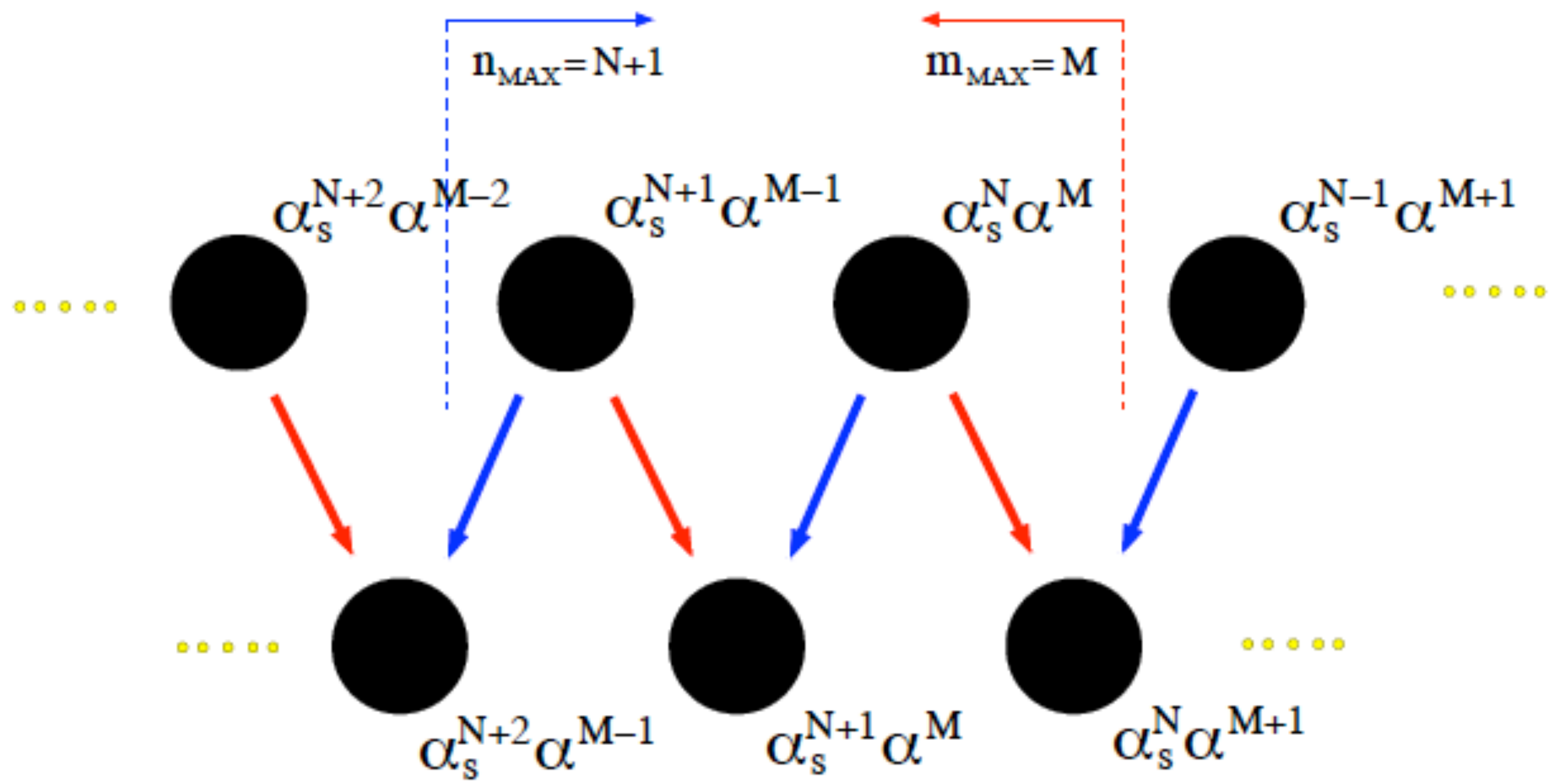


NLO EW

- New syntax:

Frederix, Frixione, Hirschi, Pagani, HSS, Zaro (appear soon)

```
MG5_aMC> generate p1 p2 > p3 p4 p5 p6 QCD=nmax QED=mmax [QCD QED]
```

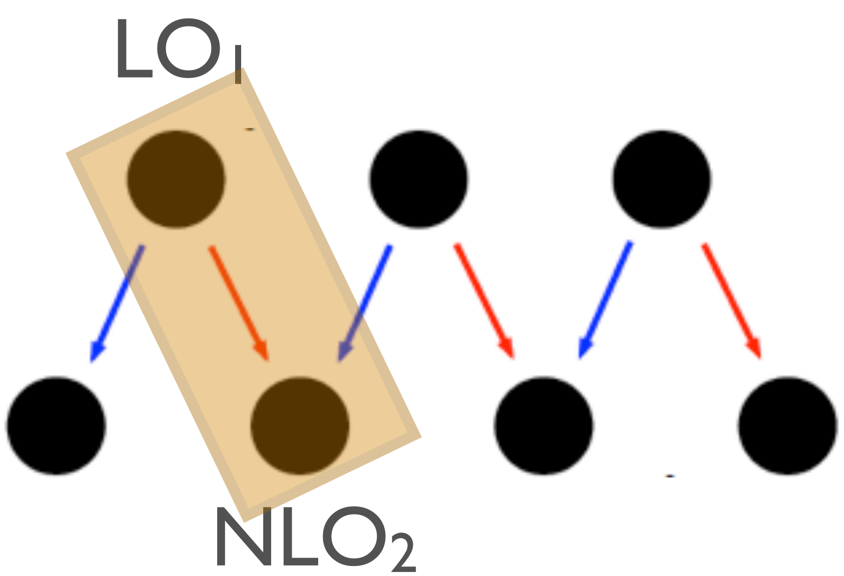


$$\text{LO}: \quad \alpha_s^n\alpha^m\,, \quad n \le \mathtt{n_{max}}\,, \quad m \le \mathtt{m_{max}}\,, \quad n+m=k_0\,,$$

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

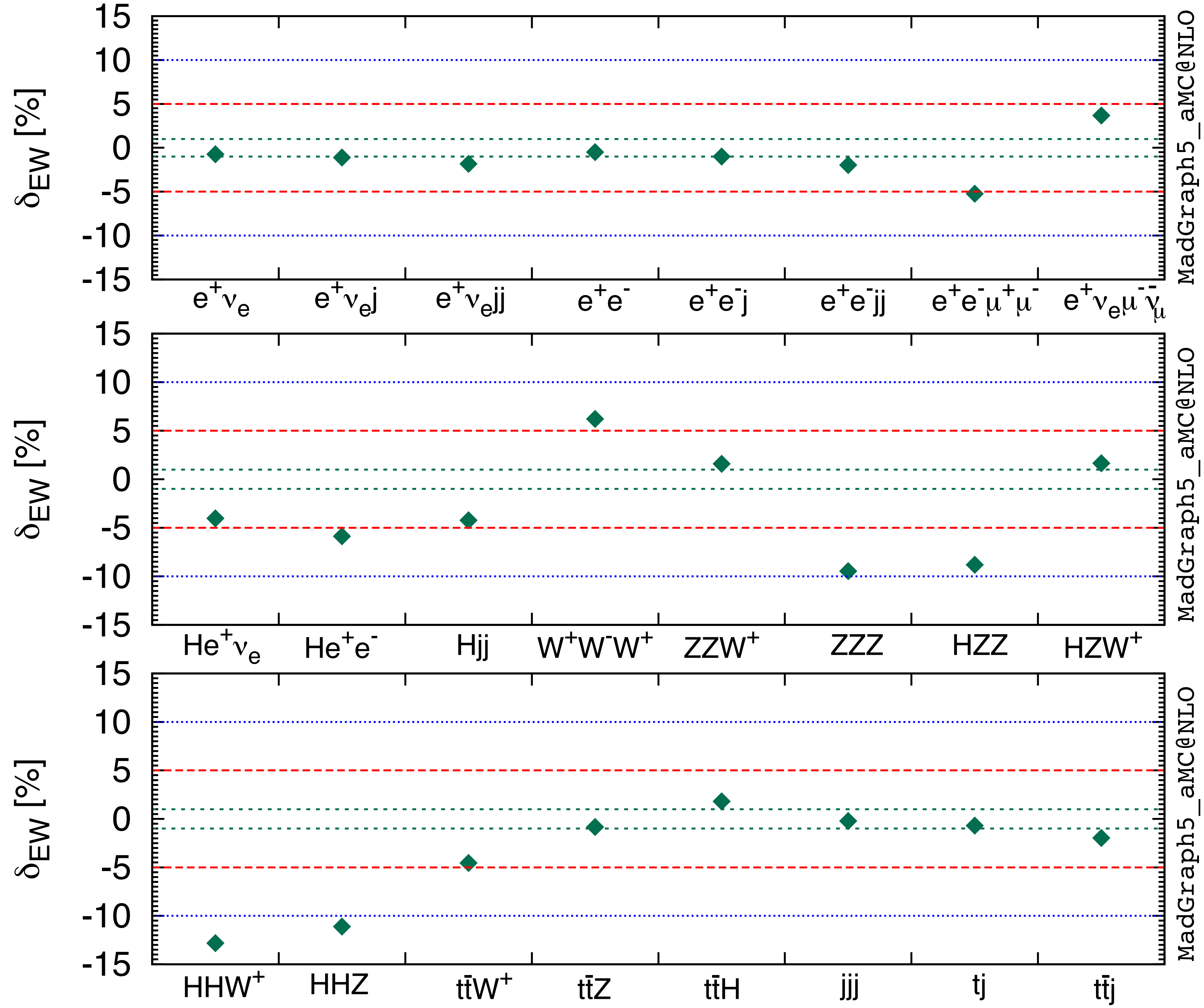
NLO EW

- Examples:



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

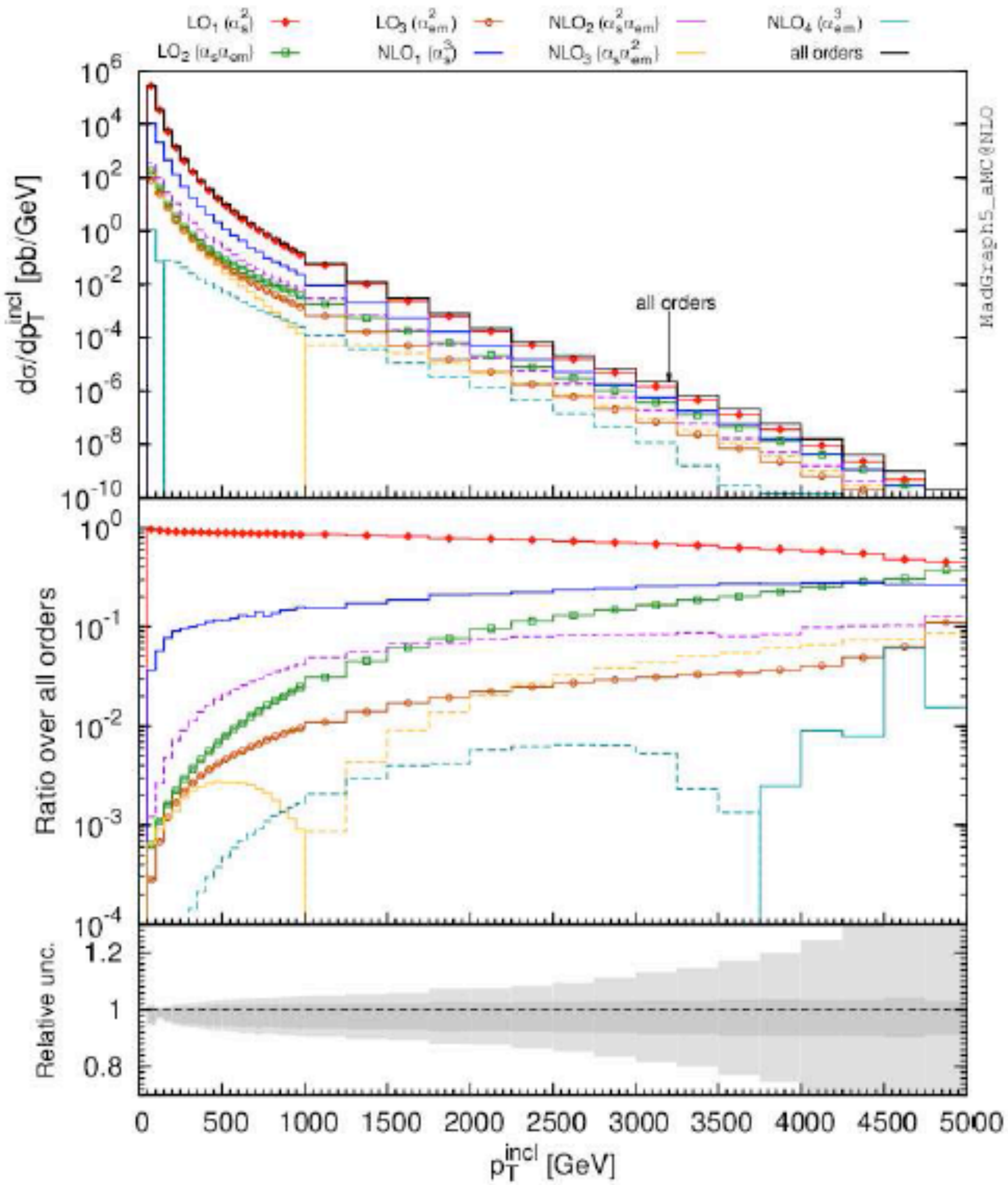
Frederix, Frixione, Hirschi, Pagani, HSS, Zaro (appear soon)



Thursday, April 19, 18

COMPLETE NLO

- single inclusive jet p_T:



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

- Owing to cancellations, both LO and NLO are necessary
- Non-QCD effects increase with p_T
- PDF uncertainty increases -- useful in constraining PDF
- Subleading NLO contributions can be larger than NLO EW in some cases (e.g. tW, tt, vector boson scatterings)

Frederix, Pagani, Zaro '17; Biedermann, Denner, Pellen '17

- First version of MG5_aMC for mixed-coupling cases (useful for BSM)

LOOP-INDUCED@NLO

- Loop-induced@LO works from v2.3.0 onwards   Hirschi, Mattelaer 15'
- First attempts to Loop-induced@NLO with MG5_aMC architectures
  Customised, not automated
- Both reweighting and direct phase space integration are possible, with pos and cons

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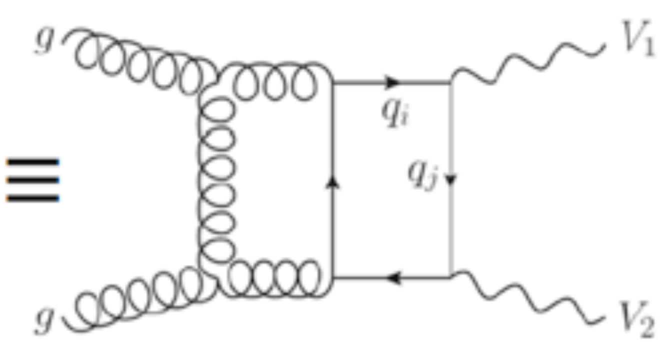
- Di virtual photon as a case study: Manteuffel, Tancredi 15'
  - 2-loop helicity amplitudes from VVamp in covariant form as a UFO vertex

$$
\begin{aligned}
S^{\mu\nu\rho\sigma}(p_1,p_2,p_3) &= a_1 g^{\mu\nu} g^{\rho\sigma} + a_2 g^{\mu\rho} g^{\nu\sigma} + a_3 g^{\mu\sigma} g^{\nu\rho} \\
&+ \sum_{j_1,j_2=1}^{3} \Big(b^{(1)}_{j_1j_2} g^{\mu\nu} p^{\rho}_{j_1} p^{\sigma}_{j_2} + b^{(2)}_{j_1j_2} g^{\mu\rho} p^{\nu}_{j_1} p^{\sigma}_{j_2} + b^{(3)}_{j_1j_2} g^{\mu\sigma} p^{\nu}_{j_1} p^{\rho}_{j_2} \\
&\quad + b^{(4)}_{j_1j_2} g^{\nu\rho} p^{\mu}_{j_1} p^{\sigma}_{j_2} + b^{(5)}_{j_1j_2} g^{\nu\sigma} p^{\mu}_{j_1} p^{\rho}_{j_2} + b^{(6)}_{j_1j_2} g^{\rho\sigma} p^{\mu}_{j_1} p^{\nu}_{j_2} \Big) \\
&+ \sum_{j_1,j_2,j_3,j_4=1}^{3} c_{j_1j_2j_3j_4} p^{\mu}_{j_1} p^{\nu}_{j_2} p^{\rho}_{j_3} p^{\sigma}_{j_4},
\end{aligned}
$$

$\equiv$




```
GGAA = Vertex(name = 'GGAA',
              particles = [ P.G, P.G, P.A, P.A ],
              color = [ 'Identity(1,2)' ],
              lorentz = [ L.A, L.B, L.C, L.D, L.E,
                          L.F, L.G, L.H, L.I, L.J,
                          L.K, L.L, L.M, L.N, L.O,
                          L.P, L.Q, L.R, L.S, L.T
                        ],
               couplings = {(0,0):C.GGAA_C1, (0,1):C.GGAA_C2, (0,2):C.GGAA_C3, (0,3):C.GGAA_C4, (0,4):C.GGAA_C5,
                            (0,5):C.GGAA_C6, (0,6):C.GGAA_C7, (0,7):C.GGAA_C8, (0,8):C.GGAA_C9, (0,9):C.GGAA_C10,
                            (0,10):C.GGAA_C11, (0,11):C.GGAA_C12, (0,12):C.GGAA_C13, (0,13):C.GGAA_C14, (0,14):C.GGAA_C15,
                            (0,15):C.GGAA_C16, (0,16):C.GGAA_C17, (0,17):C.GGAA_C18, (0,18):C.GGAA_C19, (0,19):C.GGAA_C20
                          })
```

Slide from V. Hirschi

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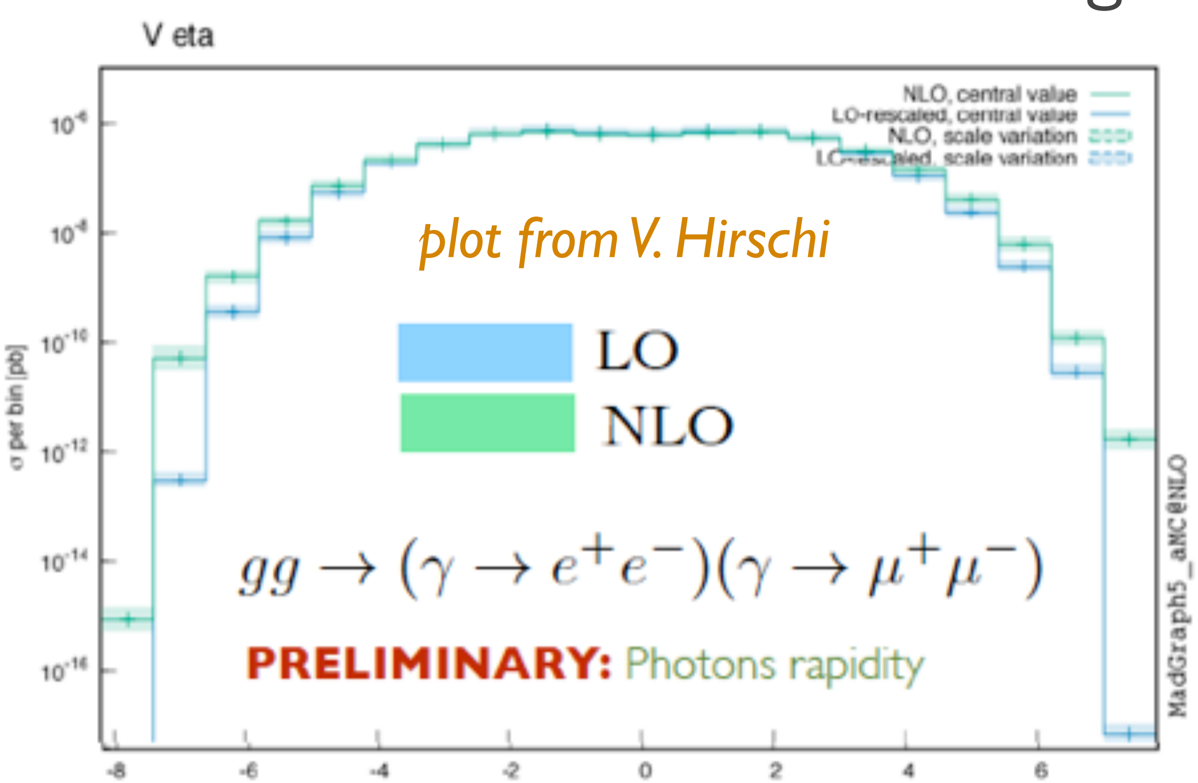
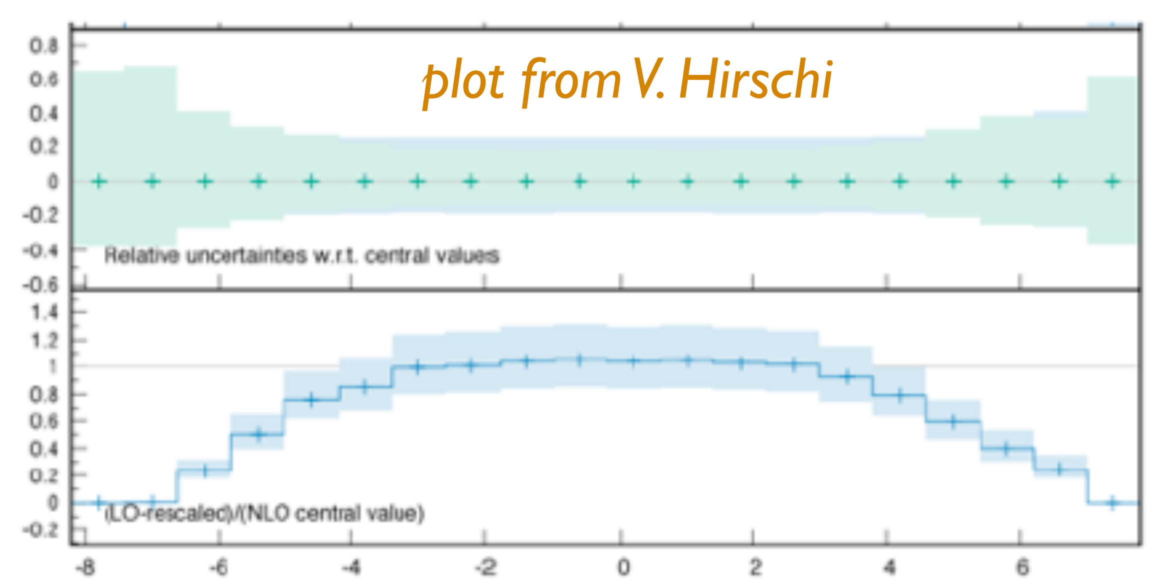
  Customised, not automated
- Both reweighting and direct phase space integration are possible, with pos and cons
- Di virtual photon as a case study: Manteuffel, Tancredi 15'
  - 2-loop helicity amplitudes from VVamp in covariant form as a UFO vertex
  - Needed ad-hoc parallelization and increased IR threshold of MadFKS
  - Performed with ad-hoc linking of 2-loop, Born (1-loop) and Real (1-loop) ME





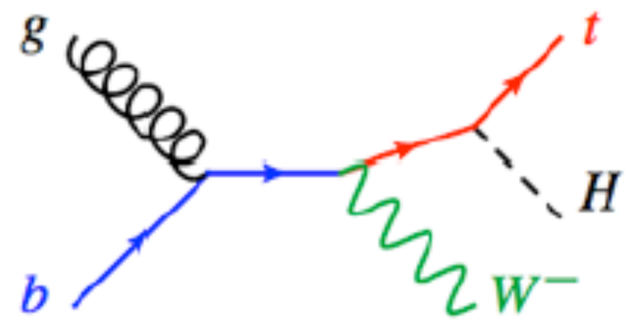
13 TeV. Rescaled curves. K-factor ~ 2

RESONANCE VS NON-RESONANCE

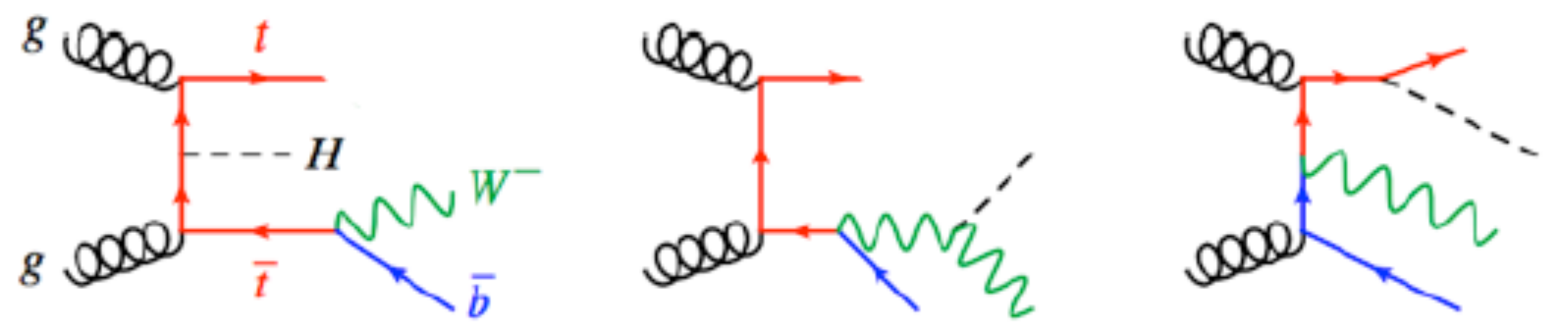
- The presence of intermediate resonance beyond LO will spoil the perturbative convergence
- The problem already exists in SM, e.g. (tW vs ttbar) or (tWH vs ttbarH)

e.g. Frixione, Laenen, Motylinski, Webber, White '08;
Demartin, Maier, Maltoni, Mawatari, Zaro '16

LO $\supset$



NLO (reals) $\supset$

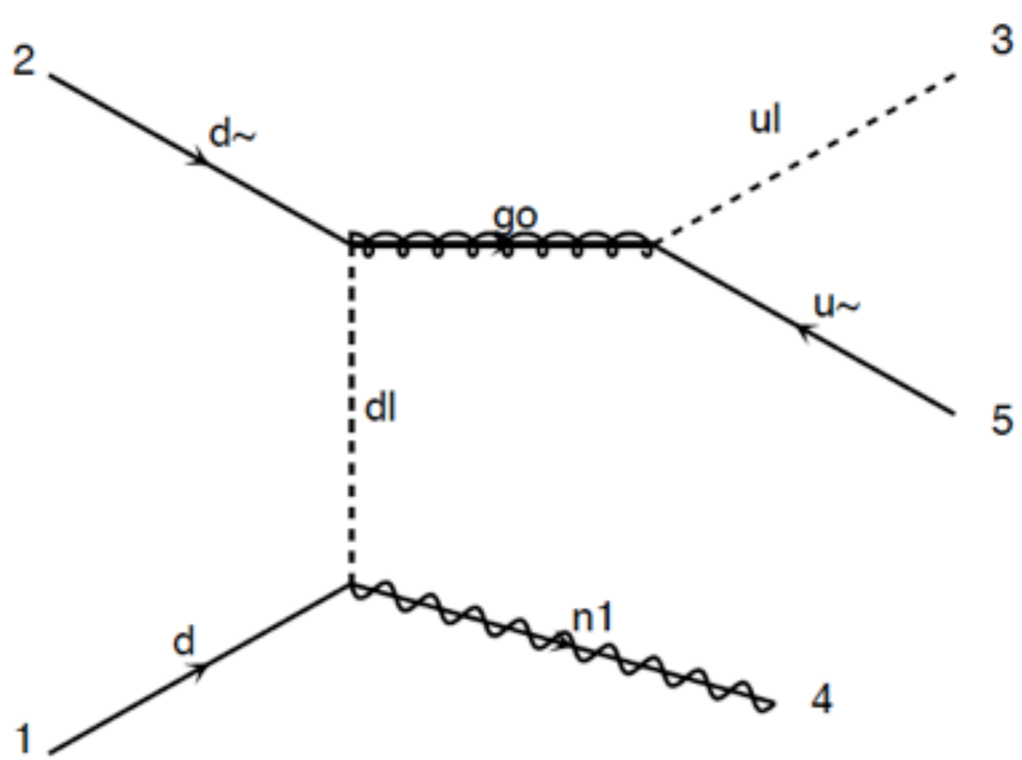


$(\mathcal{A}_{2t})$ X | $(\mathcal{A}_{1t})$ ✓ | $(\mathcal{A}_{1t})$ ✓

RESONANCE VS NON-RESONANCE

- The presence of intermediate resonance beyond LO will spoil the perturbative convergence
- The problem already exists in SM, e.g. (tW vs ttbar) or (tWH vs ttbarH)
- The problem appears more often for BSM with rich particle spectrum

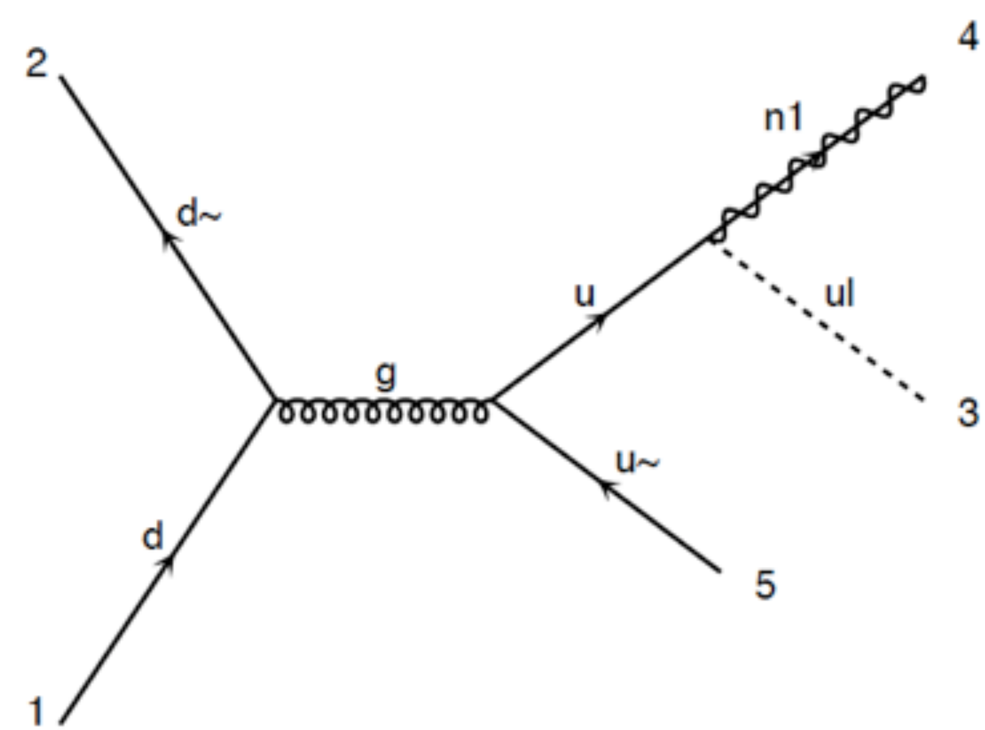
e.g. squark-neutralino in SUSY



Resonance diagram

Bad integration with MadFKS based on Born !!!

VS



Non-Resonance diagram

ON-SHELL SUBTRACTION

- The formulation of the problem is: MadOS: Frixione, Mawatari, Zaro ...

LO: $a + b \longrightarrow \delta + X$

NLO(Real): $a + b \longrightarrow \delta + \gamma + X$ with/without $\beta \longrightarrow \delta + \gamma$

$$\mathcal{A}_{ab\to\delta\gamma X} = \underline{\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}} + \underline{\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}}$$

non-resonance
resonance

$$\left|\mathcal{A}_{ab\to\delta\gamma X}\right|^2 = \left|\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\right|^2 + 2\Re\left(\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\mathcal{A}^{(\beta)\dagger}_{ab\to\delta\gamma X}\right) + \left|\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}\right|^2$$

- No fully satisfactory solutions but a few proposals:

Diagram Removal

- DR: **remove the resonance diagrams/amplitude**
- DRI: **remove the resonance amplitude squared**

Diagram Subtraction

$$d\sigma^{(\mathrm{DS})}_{ab\to\delta\gamma X} \propto \left\{\left|\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\right|^2 + 2\Re\left(\mathcal{A}^{(\not\beta)}_{ab\to\delta\gamma X}\mathcal{A}^{(\beta)\dagger}_{ab\to\delta\gamma X}\right) + \left|\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}\right|^2\right\} d\phi$$
$$- f(m^2_{\delta\gamma})\,\mathbb{P}\left(\left|\mathcal{A}^{(\beta)}_{ab\to\delta\gamma X}\right|^2 d\phi\right), \quad (18)$$

DS subtraction term

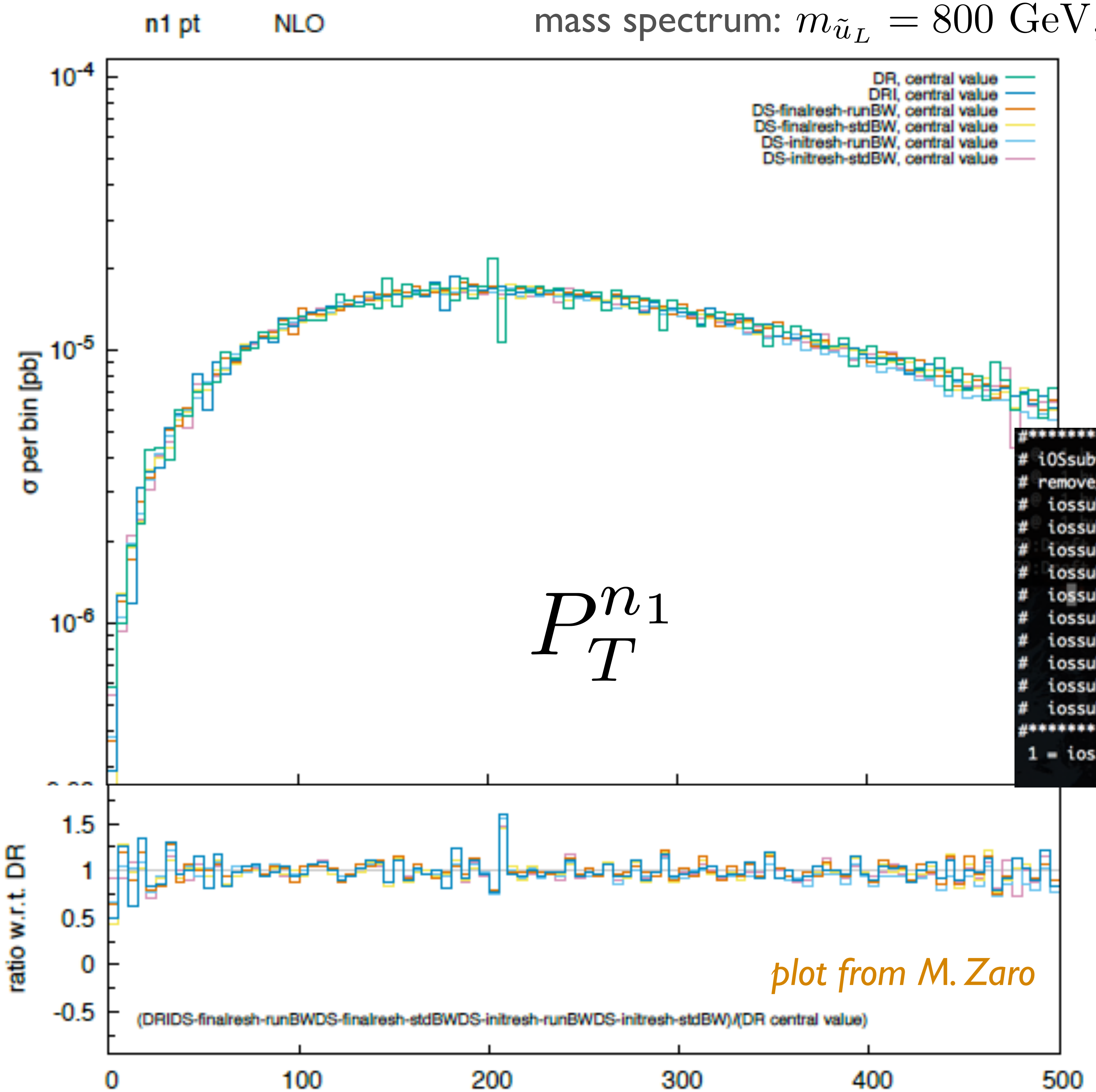
- DS-finalresh-runBW: **P (FS momenta reshuffling), f (ratio of two BWs with running width**
- DS-initresh-runBW: **P (IS momenta reshuffling), f (ratio of two BWs with running width)**
- DS-finalresh-stdBW: **P (FS momenta reshuffling), f (ratio of two standard BWs)**
- DS-initresh-stdBW: **P (IS momenta reshuffling), f (ratio of two standard BWs)**

ON-SHELL SUBTRACTION

- Let us take *squark-neutralino* as an example:

MadOS: Frixione, Mawatari, Zaro ...

mass spectrum: $m_{\tilde{u}_L} = 800$ GeV, $m_{n_1} = 300$ GeV, $m_{\tilde{g}} = 1500$ GeV



> set remove_os True
> generate p p > ul n1 [QCD]
> add process p p > ul~ n1 [QCD]

```
#*****************************************************************
# iOSsubtr parameter: used if the process is generated with     *
# remove_os = True                                              *
#  iossubtr = 1 -> DR without interference                      *
#  iossubtr = 2 -> DR with interferece                          *
#  iossubtr = 3 -> DS with reshuffling on initial state, standard BW *
#  iossubtr = 4 -> DS with reshuffling on initial state, running BW  *
#  iossubtr = 5 -> DS with reshuffling on all FS particles, standard BW*
#  iossubtr = 6 -> DS with reshuffling on all FS particles, running BW *
#  iossubtr = 7 -> DS with option C, standard BW                *
#  iossubtr = 8 -> DS with option C, running BW                 *
#  iossubtr = 9 -> DS with reshuffling on spectator, standard BW *
#  iossubtr = 10-> DS with reshuffling on spectator, running BW  *
#*****************************************************************
 1 = iossubtr ! strategy to be used to remove resonances
              ! appearing in real emissions
```

Important to check the systematic dependences !

BEAM FOR LEPTON COLLIDER

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- Processes at e^+e^- without beam issues is an easier case of those at pp
- Improve MG5_aMC for e^+e^- physics in the following aspects:
  - ♦ Beam polarization
  - ♦ Photon initial state: **improved Weizsaecker-Williams formula (elastic)**
  - ♦ Beamstrahlung
  - ♦ Initial-state radiation

♦ Done

♦ To be done

INITIAL STATE RADIATION

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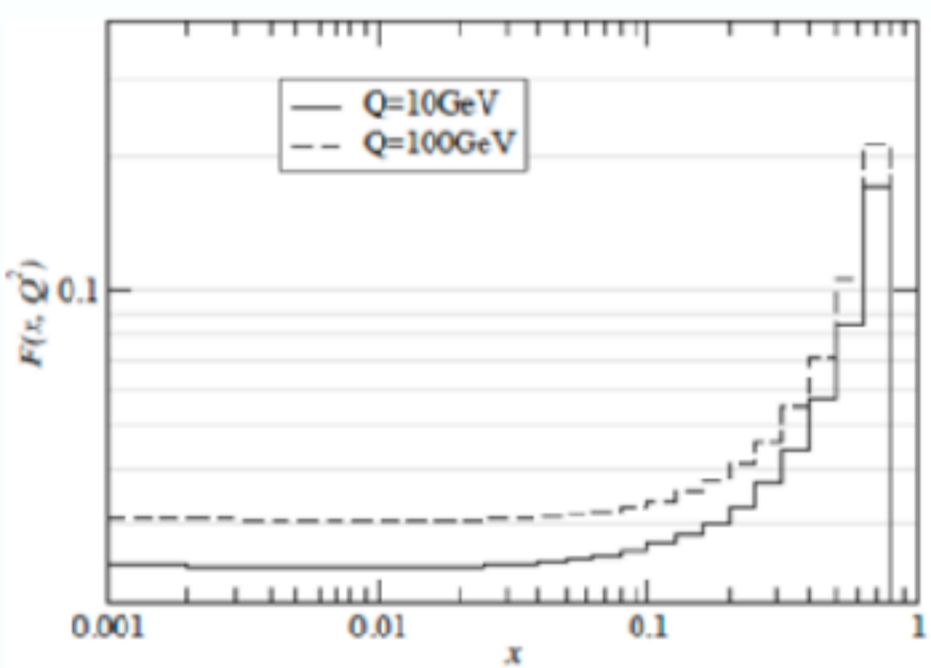
Madee starting by: Mawatari, Maltoni, Ge, Hagiwara, Mattelaer etc

- define e- beam = e- a e+
- define e+ beam = e+ a e-
- replace the proton PDFs by the electron PDFs



$$\beta = \frac{\alpha}{\pi}(L-1), \quad \eta = \frac{\alpha}{\pi}L, \quad L = \ln\frac{Q^2}{m_e^2} \qquad (1)$$

$$P_{e^-/e^-}(x,Q^2) = \frac{e^{(-\gamma_E+\frac{3}{4})\beta}}{\Gamma(1+\beta)}\beta(1-x)^{\beta-1} - \frac{1}{2}\beta(1+x) - \frac{1}{8}\beta^2\left[\frac{1+3x^2}{1-x}\ln(x) + 4(1+x)\ln(1-x) + 5 + x\right] \qquad (2)$$

$$P_{\gamma/e^-}(x,Q^2) = \frac{1}{2}\eta\frac{1+(1-x)^2}{x} \qquad (3)$$

$$P_{e^+/e^-}(x,Q^2) = \frac{1}{8x}\beta^2\left[\frac{4}{3} + x - x^2 - \frac{4}{3}x^3 + 2x(1+x)\ln(x)\right] \qquad (4)$$

```
#*********************************************************************
# Collider type and energy                                          *
# lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton,     *
#                                    3=e-/a/e+ from electron        *
#*********************************************************************
   3     = lpp1 ! beam 1 type
  -3     = lpp2 ! beam 2 type
  250.0 = ebeam1 ! beam 1 total energy in GeV
  250.0 = ebeam2 ! beam 2 total energy in GeV
```

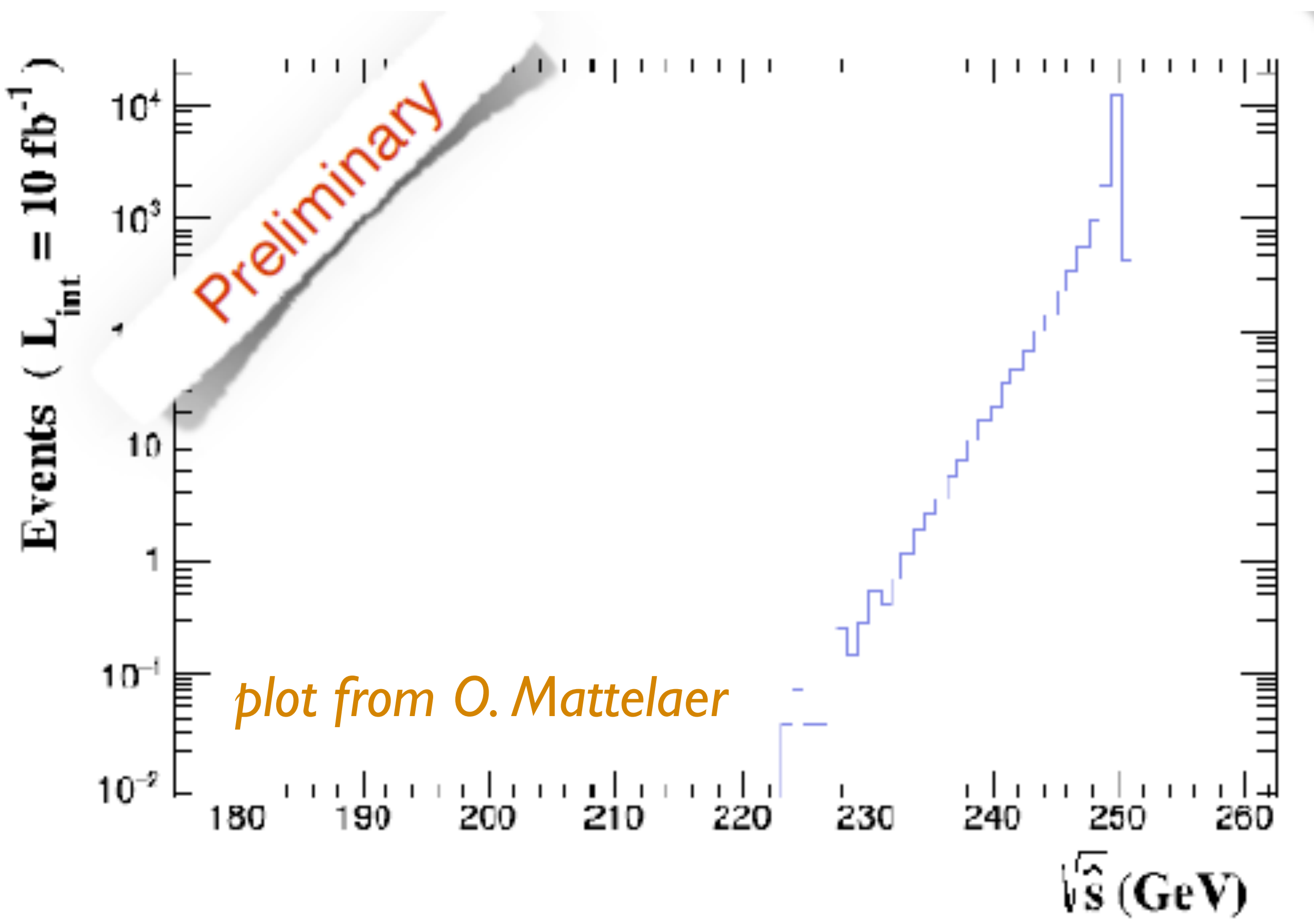
Slide from O. Mattelaer

BEAMSTRAHLUNG

- Beamstrahlung is included via beam profile file generated by guina-pig

MG5_aMC syntax:

```
generate e+ e- > mu+ mu-
output
launch
set lep 250
set beamstrahlung_file ./ilc250.dat
set nevents 500000
```



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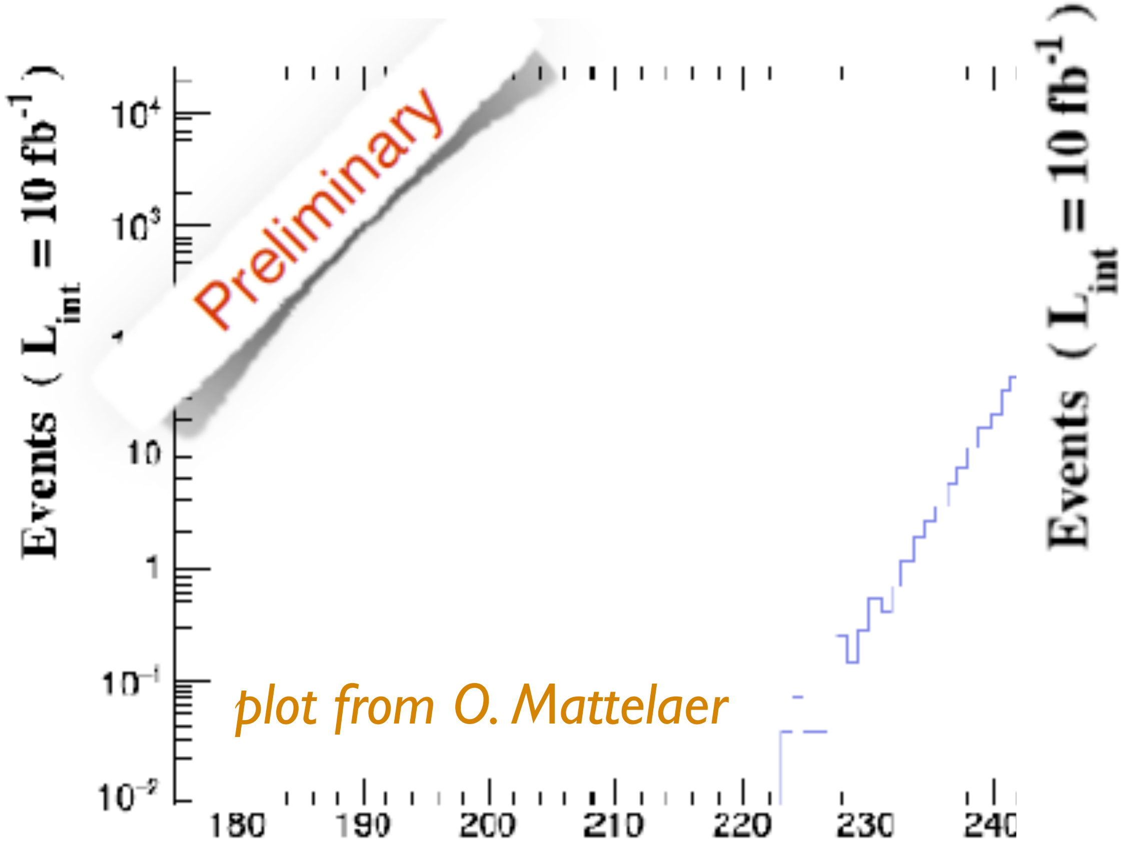
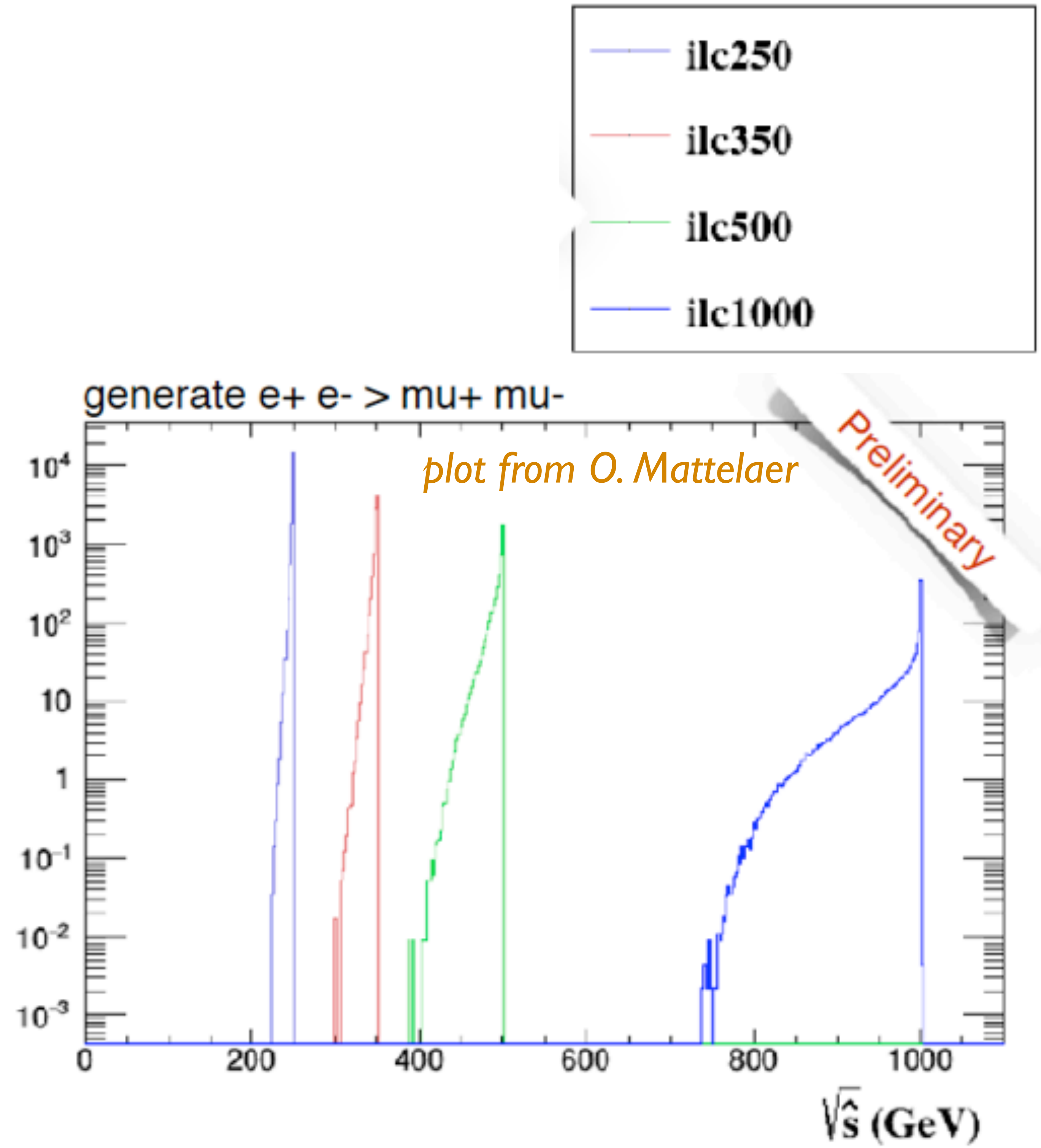
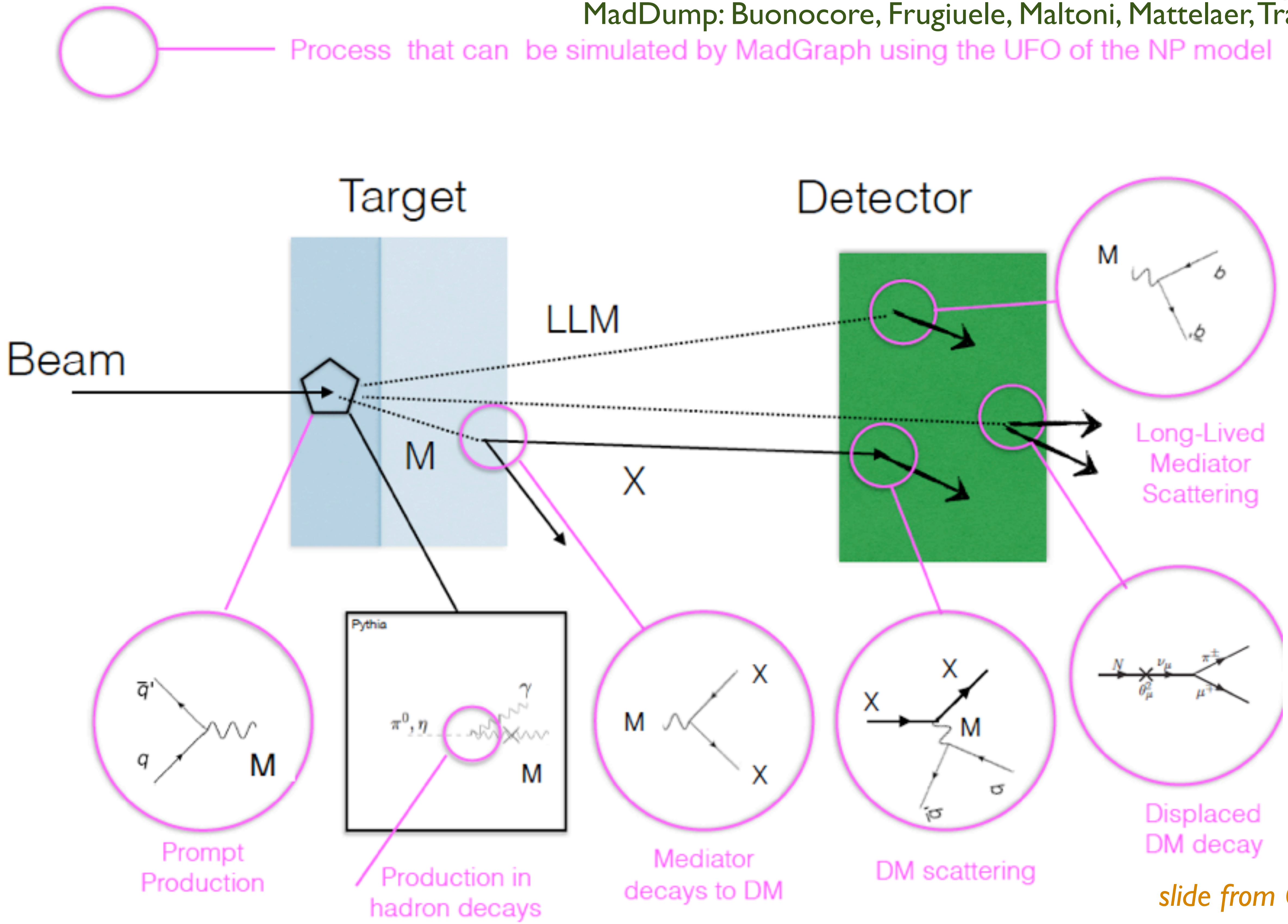




BEAM DUMP EXPERIMENTS

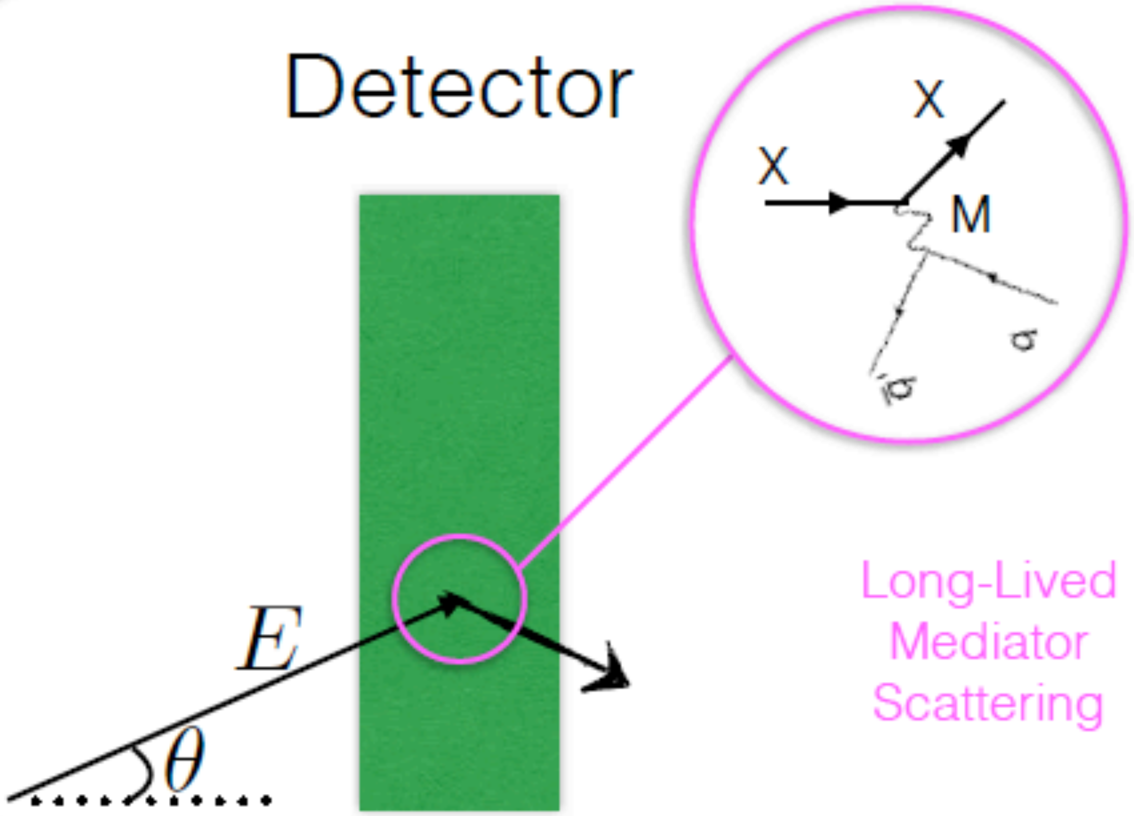
MadDump: Buonocore, Frugiuele, Maltoni, Mattelaer, Tramontano



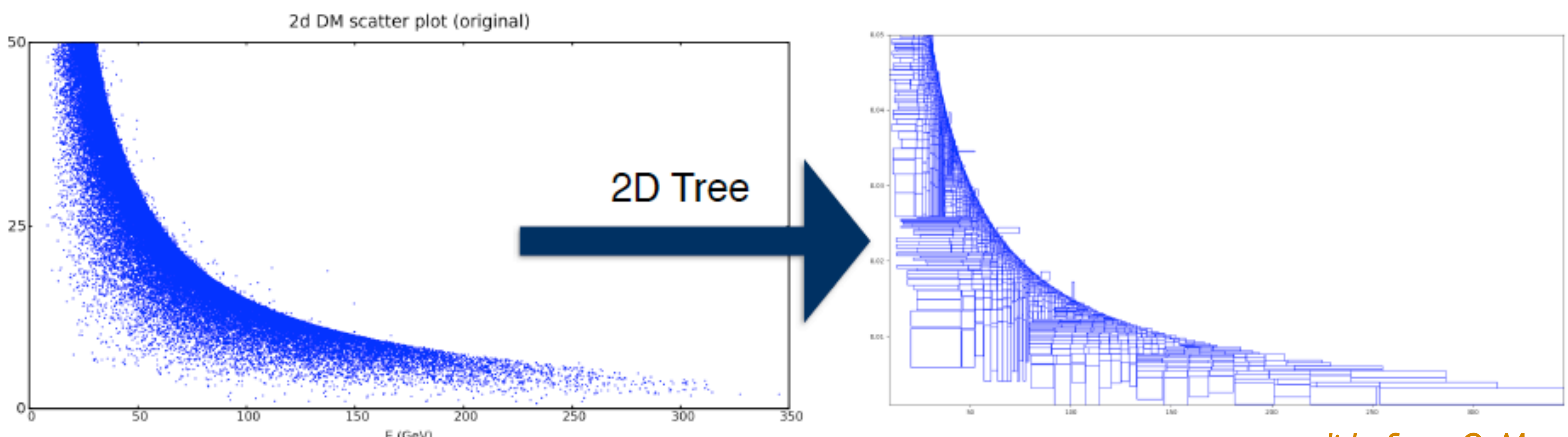
slide from O. Mattelaer

BEAM DUMP EXPERIMENTS

MadDump: Buonocore, Frugiuele, Maltoni, Mattelaer, Tramontano



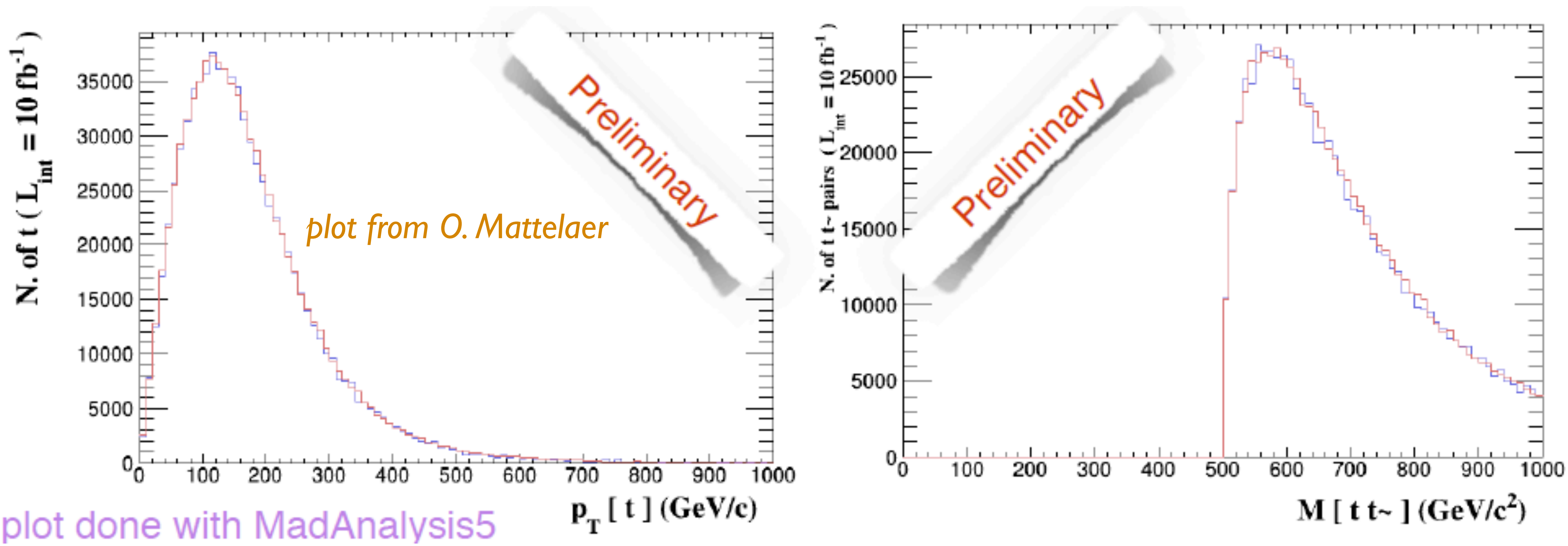
- Need “special” PDF for the incoming beam (in Energy/ angle)
- Using a 2D Tree



slide from O. Mattelaer

OTHERS

- Make your model visible in MG5_aMC database (v2.6.1 onwards)
  - Contact Olivier Mattelaer <olivier.mattelaer@uclouvain.be> with http link to your UFO model
  - Add __arXiv__ in the __init__ file to get the credit
  - Everyone uses MG5_aMC will access your model via “display modellist”
- BSM reweighting supports mass scan
  - Example: change the top mass in a tt~ sample to 250 GeV without regenerating sample



SUMMARY

- MadGraph5_aMC@NLO is a framework to support both SM and BSM physics.
- Several progress have been achieved since last MC4BSM meeting.
- The code is too big for a single person to know it all.
- Users are encouraged to submit questions/requests through Launchpad.

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Thank you for your attention !