HIGGS CHARACTERIZATION WITH aMC@NLO AND MADGRAPH5

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PREDICTIVE MC'S*

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MC ≡ a code that can generate (unweighted) events

PREDICTIVE MC'S*

- Accurate and experimental friendly predictions for collider physics range from being very useful to strictly necessary.
- Confidence on possible excesses, evidences and eventually discoveries builds upon an intense (and often non-linear) process of description/prediction of data via MC's.
- Both **measurements** and **exclusions** rely on accurate predictions.
- Predictions for both SM and BSM on the same ground.

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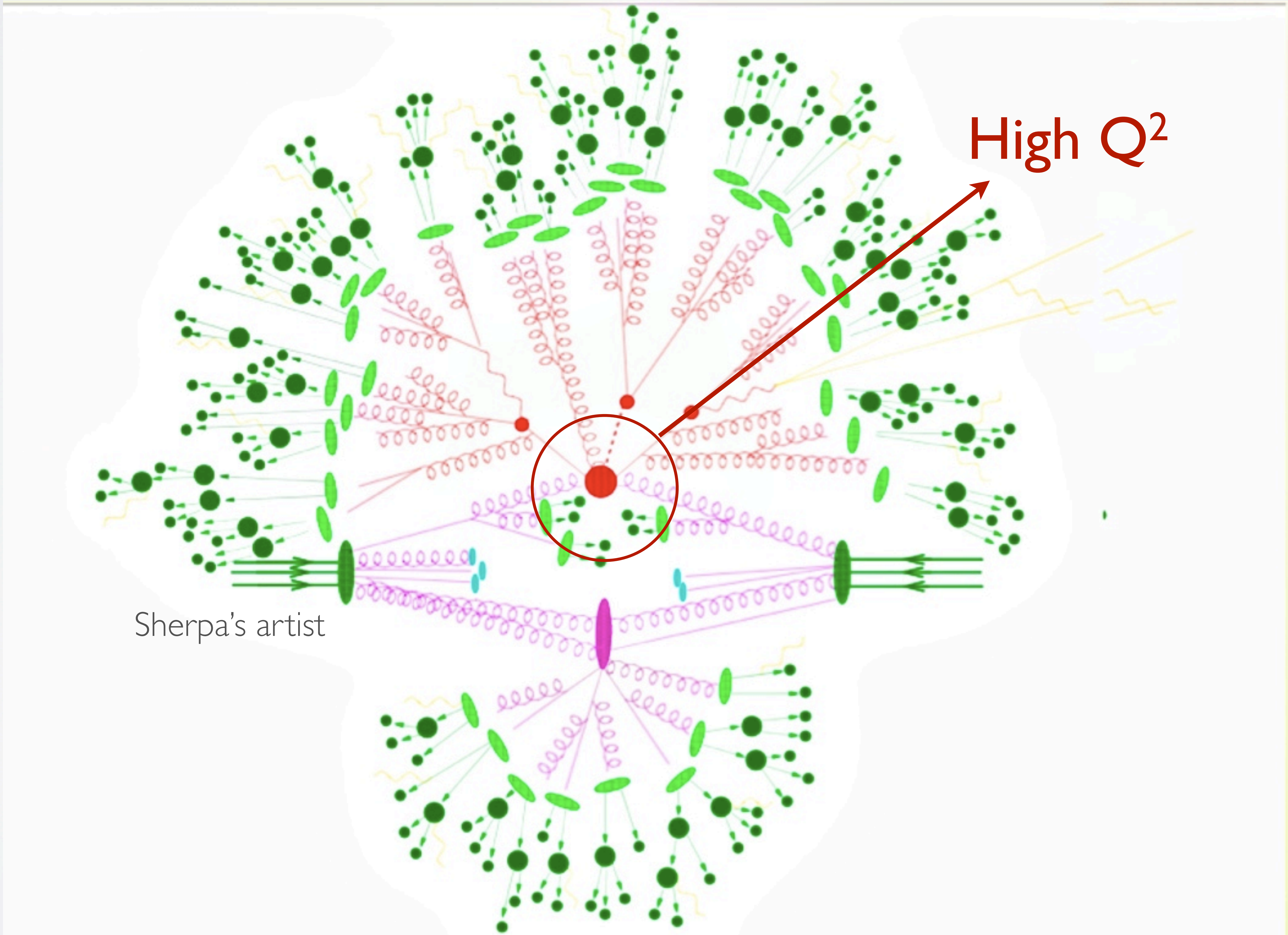
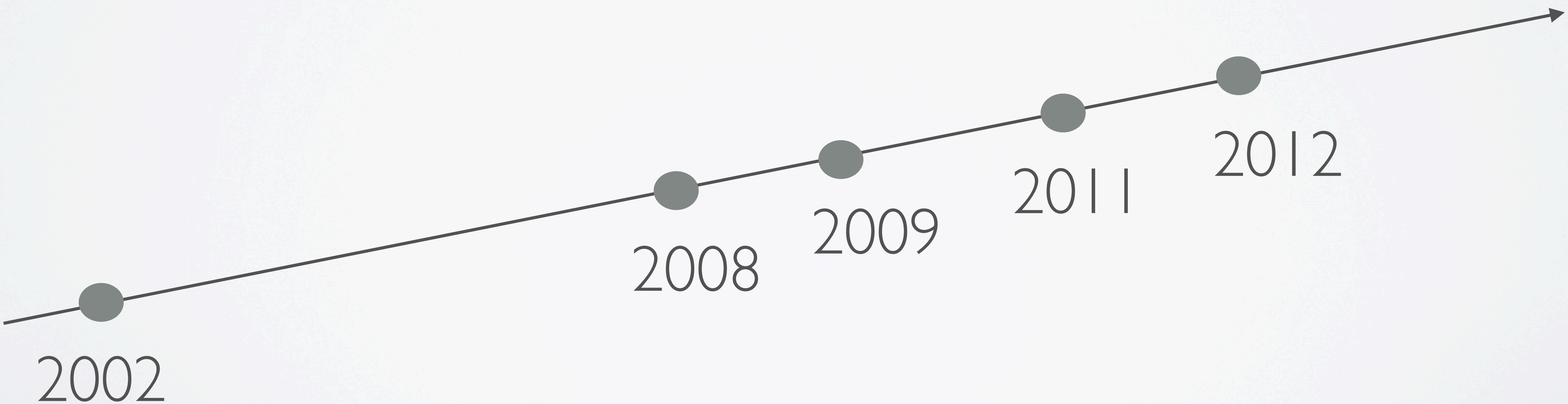
MC ≡ a code that can generate (unweighted) events


High Q^2
Sherpa's artist

MC (SIMPLIFIED) PROGRESS



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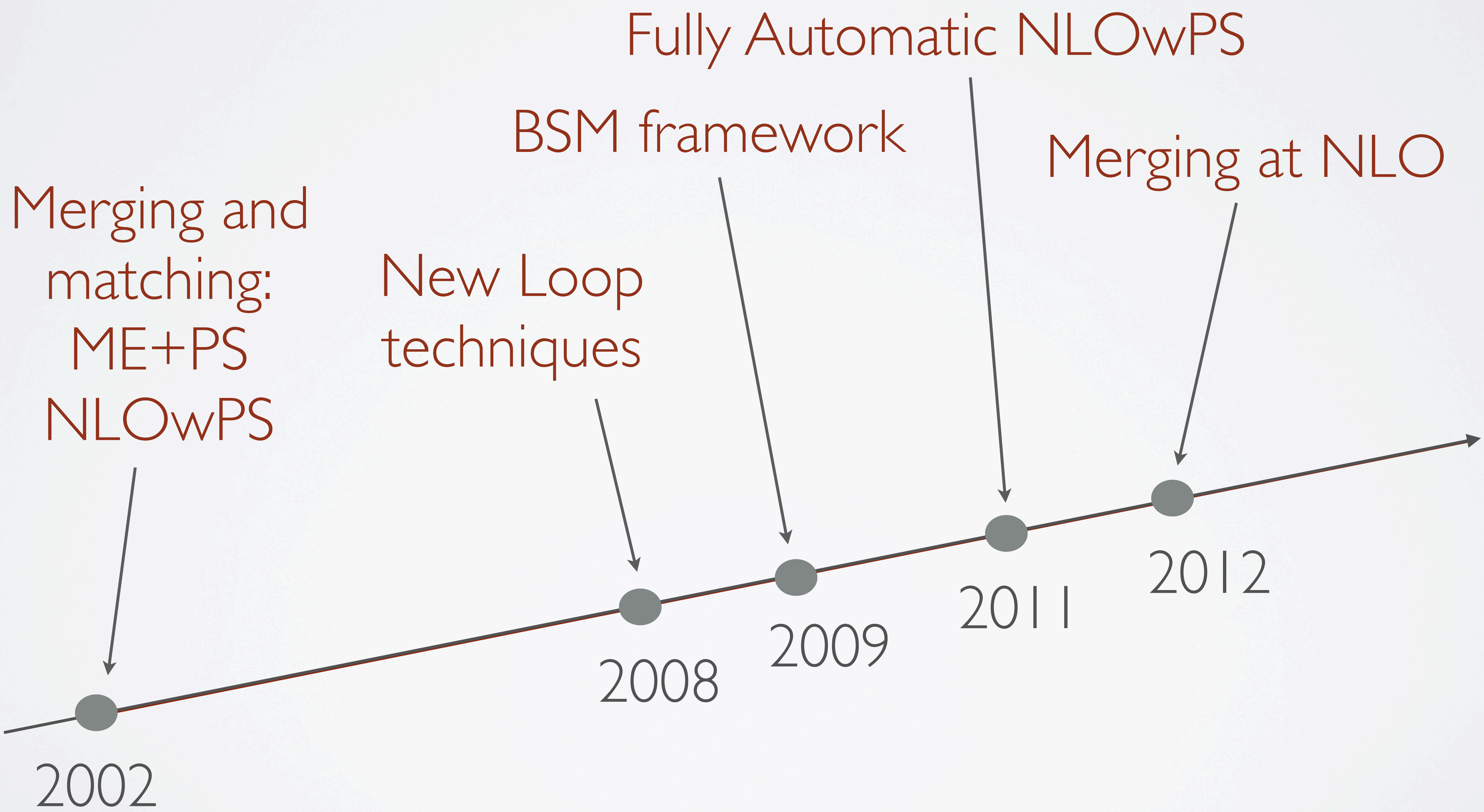
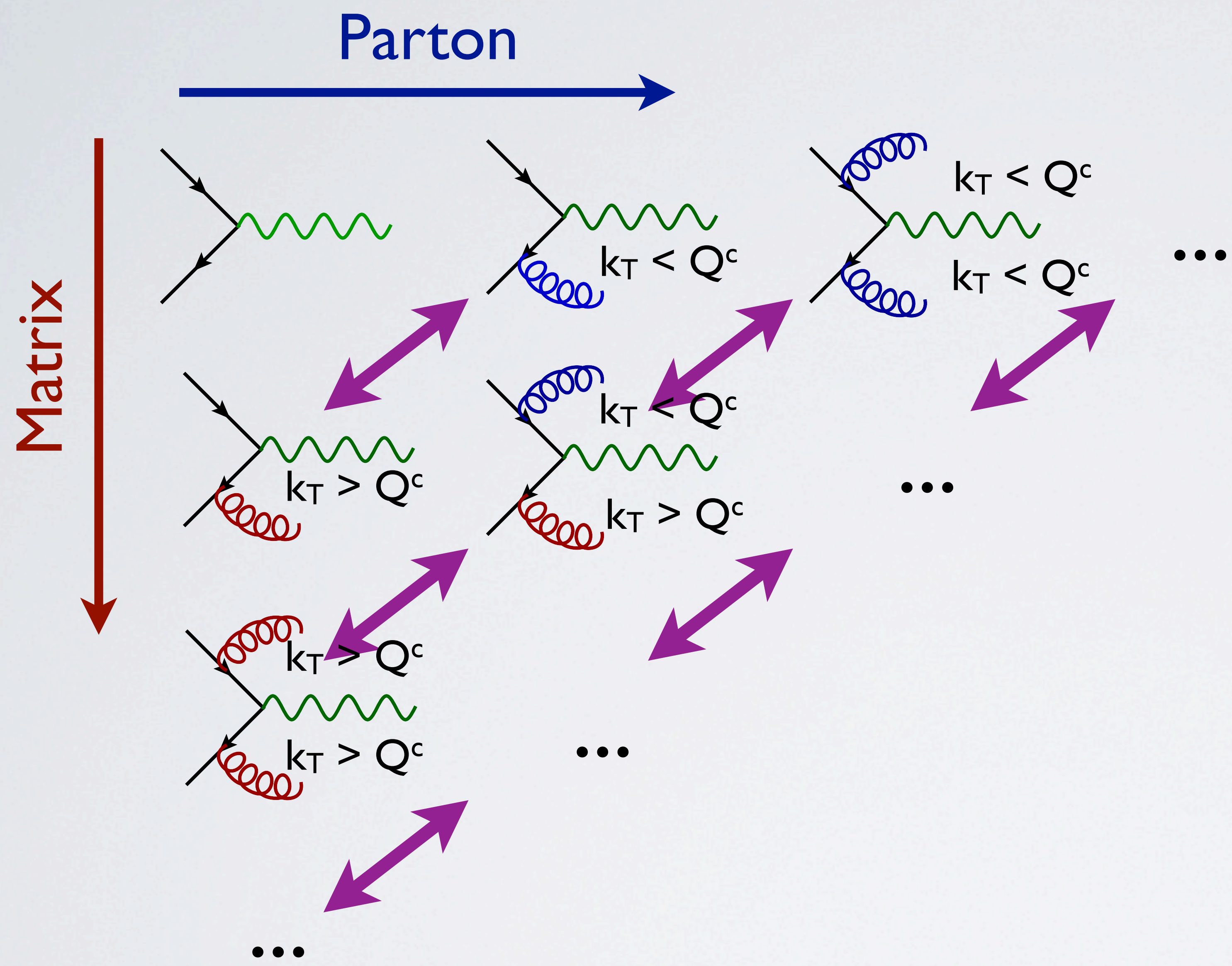


PREDICTIVE MC'S

- There are various ways to improve a Parton Shower Monte Carlo event generator with matrix elements:
  - ME+PS merging: Include matrix elements with more final state partons to describe hard, well-separated radiation better.

[Catani, Krauss, Kuhn, Webber, 2001]
[M.L. Mangano, 2002]

Merging fixed order with PS



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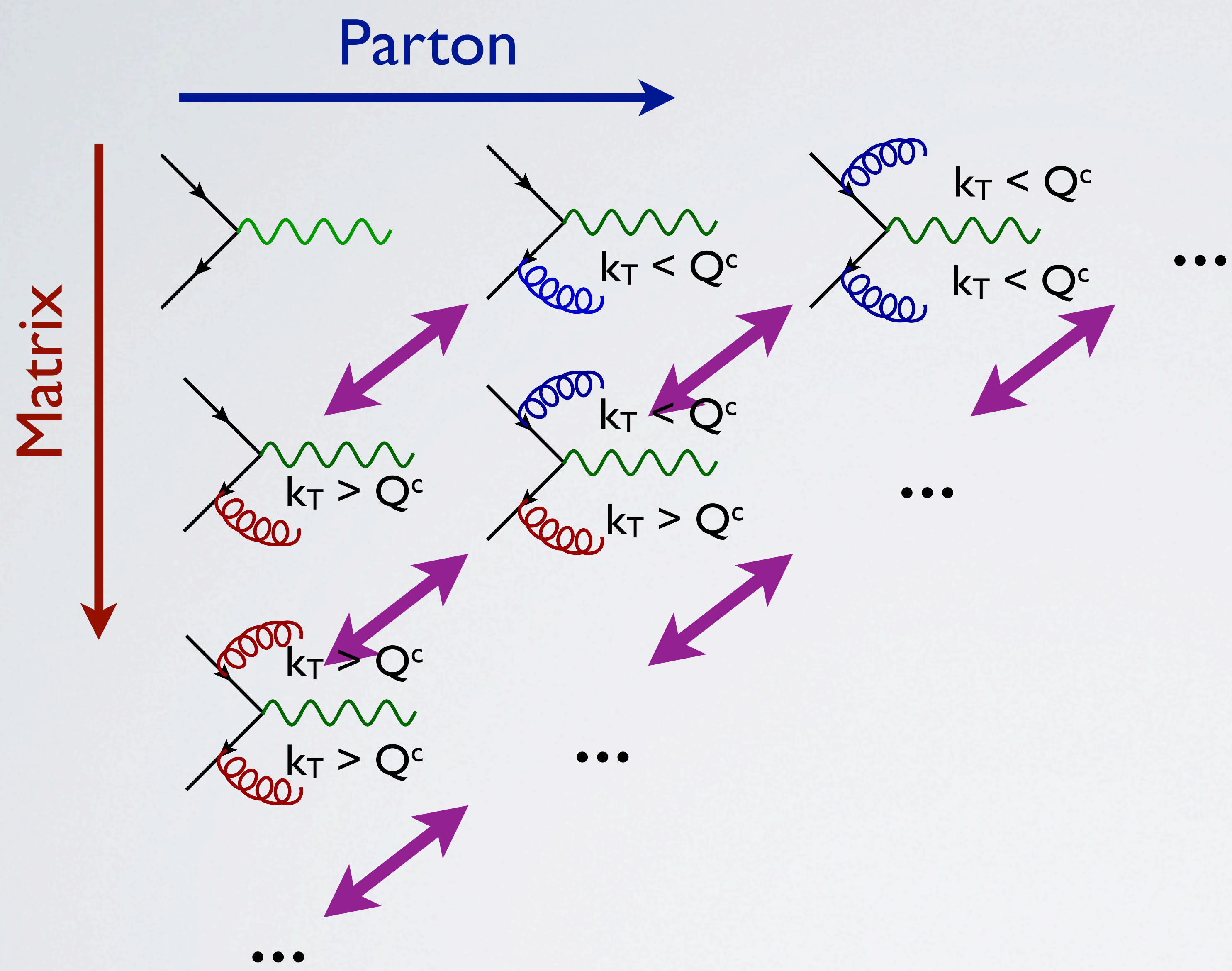

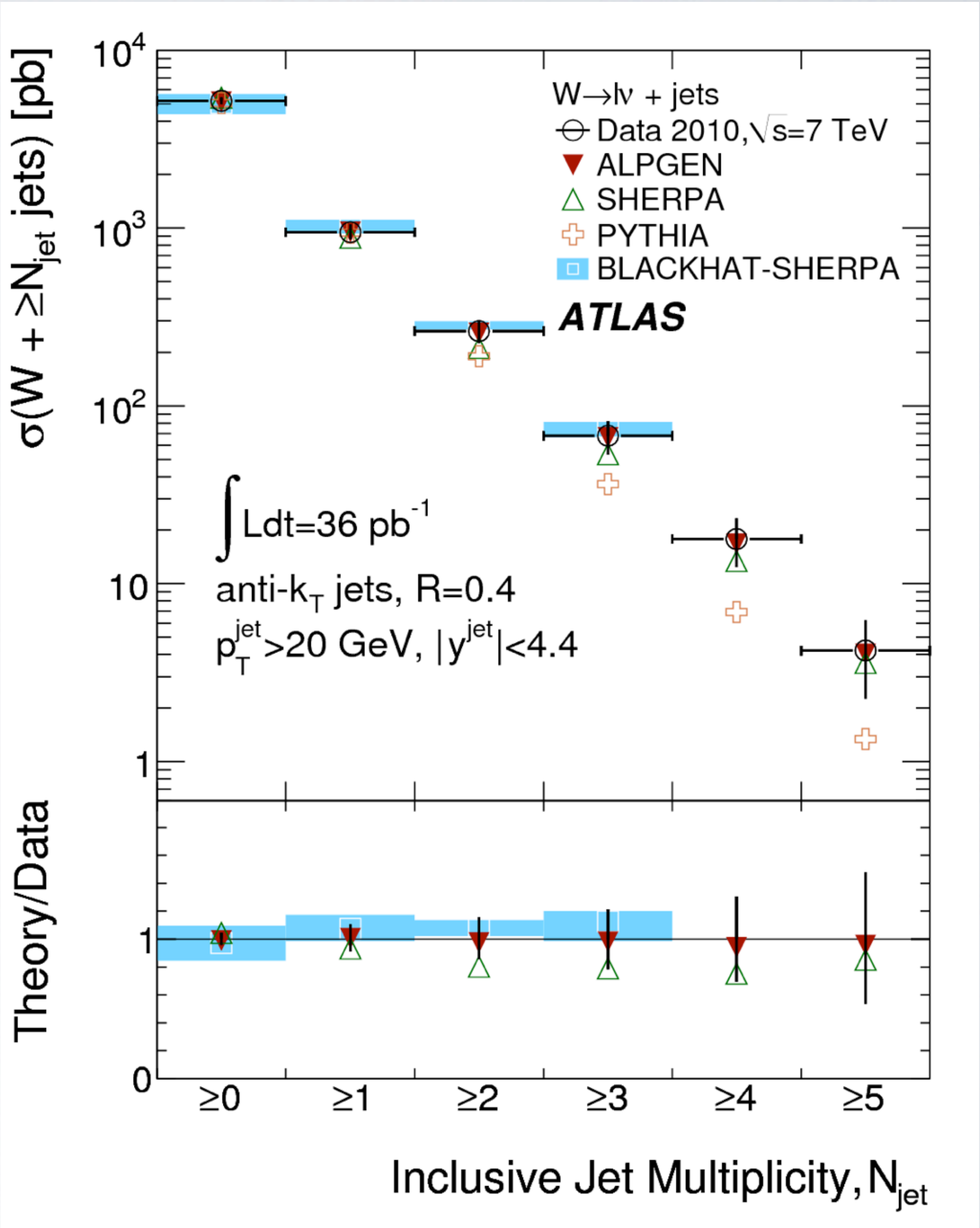

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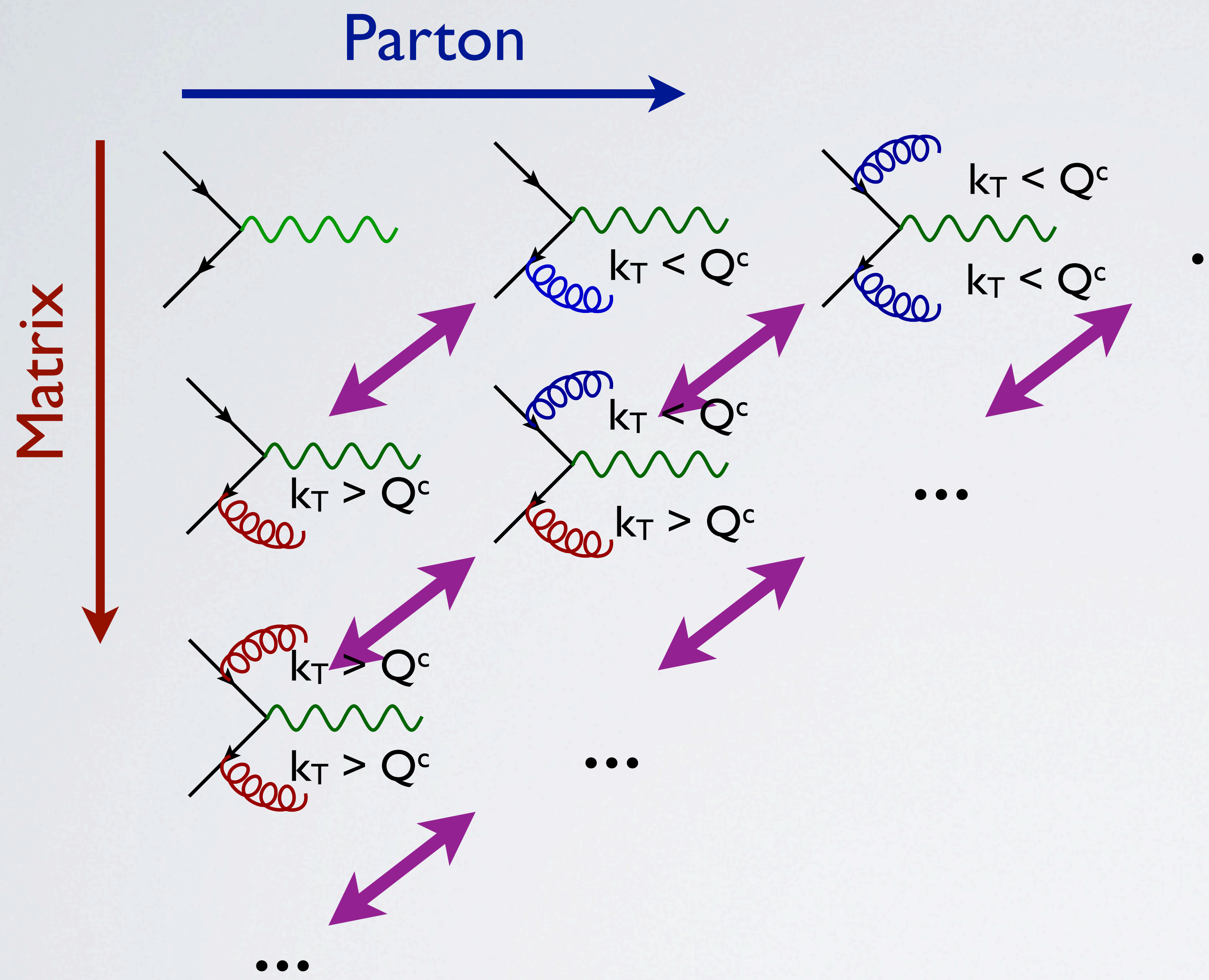

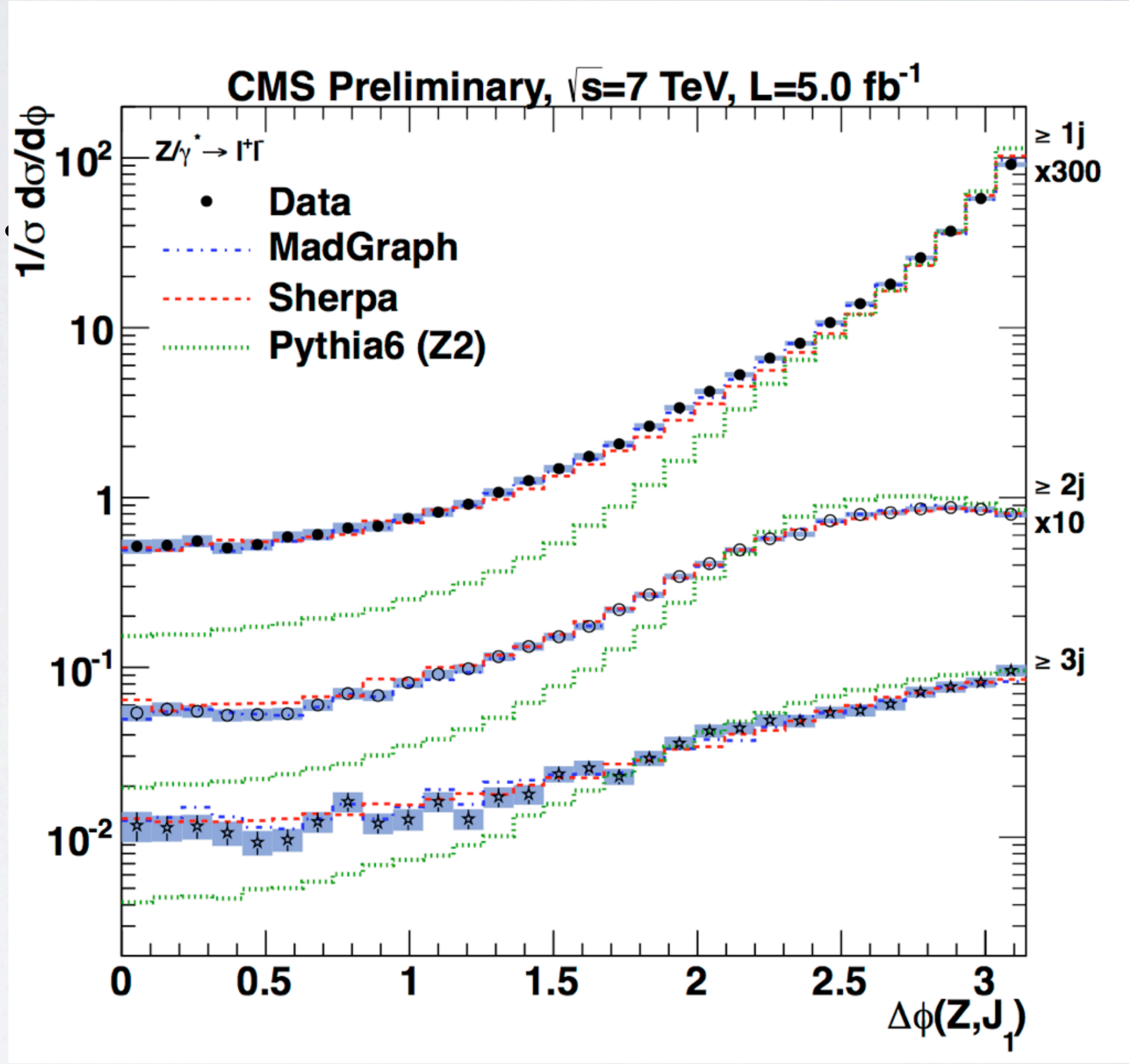

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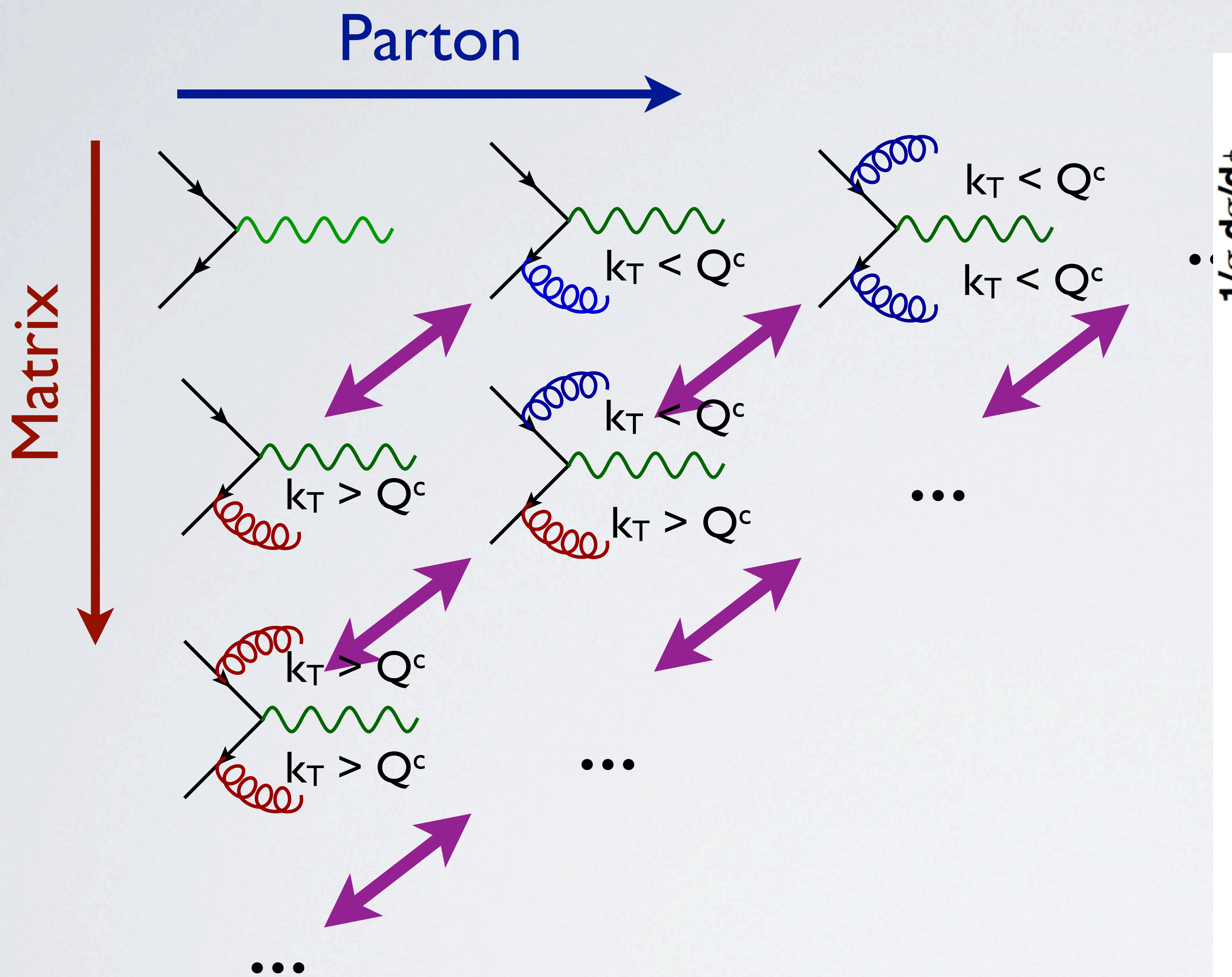

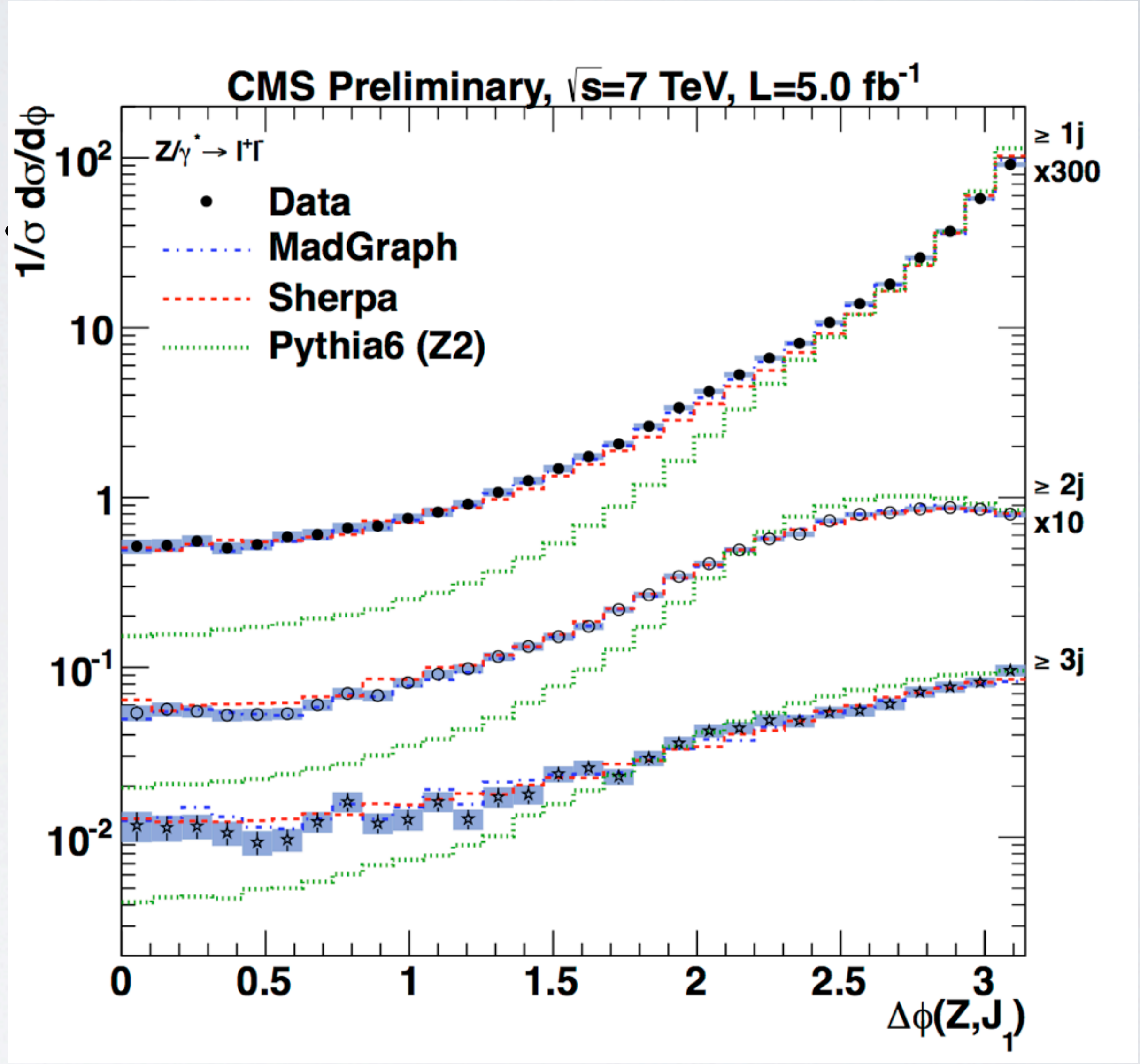

Works amazingly well...!!! Mature. Available in Alpgen, MadGraph and Sherpa.
Studies/Improvements/developments for procs with b quarks on going.

PREDICTIVE MC'S

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  - ME+PS merging: Include matrix elements with more final state partons to describe hard, well-separated radiation better.

    [Catani, Krauss, Kuhn, Webber, 2001]
    [M.L. Mangano, 2002]

  - NLO+PS matching: Include full NLO corrections to the matrix elements to reduce theoretical uncertainties in the matrix elements. The real-emission matrix elements will describe the hard radiation.

    [Frixione & Webber (2002)]
    [Nason (2004)]

NLOwPS IN A NUTSHELL

$$d\sigma^{\rm NLO+PS} = d\Phi_B \bar{B}^s(\Phi_B)\left[\Delta^s(p_\perp^{\rm min}) + d\Phi_{R|B}\frac{R^s(\Phi_R)}{B(\Phi_B)}\Delta^s(p_T(\Phi))\right] + d\Phi_R R^f(\Phi_R)$$

integrates to 1 (unitarity)

with

$$\bar{B}^s = B(\Phi_B) + \left[V(\Phi_B) + \int d\Phi_{R|B} R^s(\Phi_{R|B})\right]$$

Full cross section (if F=1) at fixed Born kinematics

$$R(\Phi_R) = R^s(\Phi_R) + R^f(\Phi_R)$$

This formula is valid both for both MC@NLO and POWHEG

MC@NLO: $R^s(\Phi) = P(\Phi_{R|B})\,B(\Phi_B)$

Needs exact mapping $(\Phi_B,\Phi_R) \to \Phi$

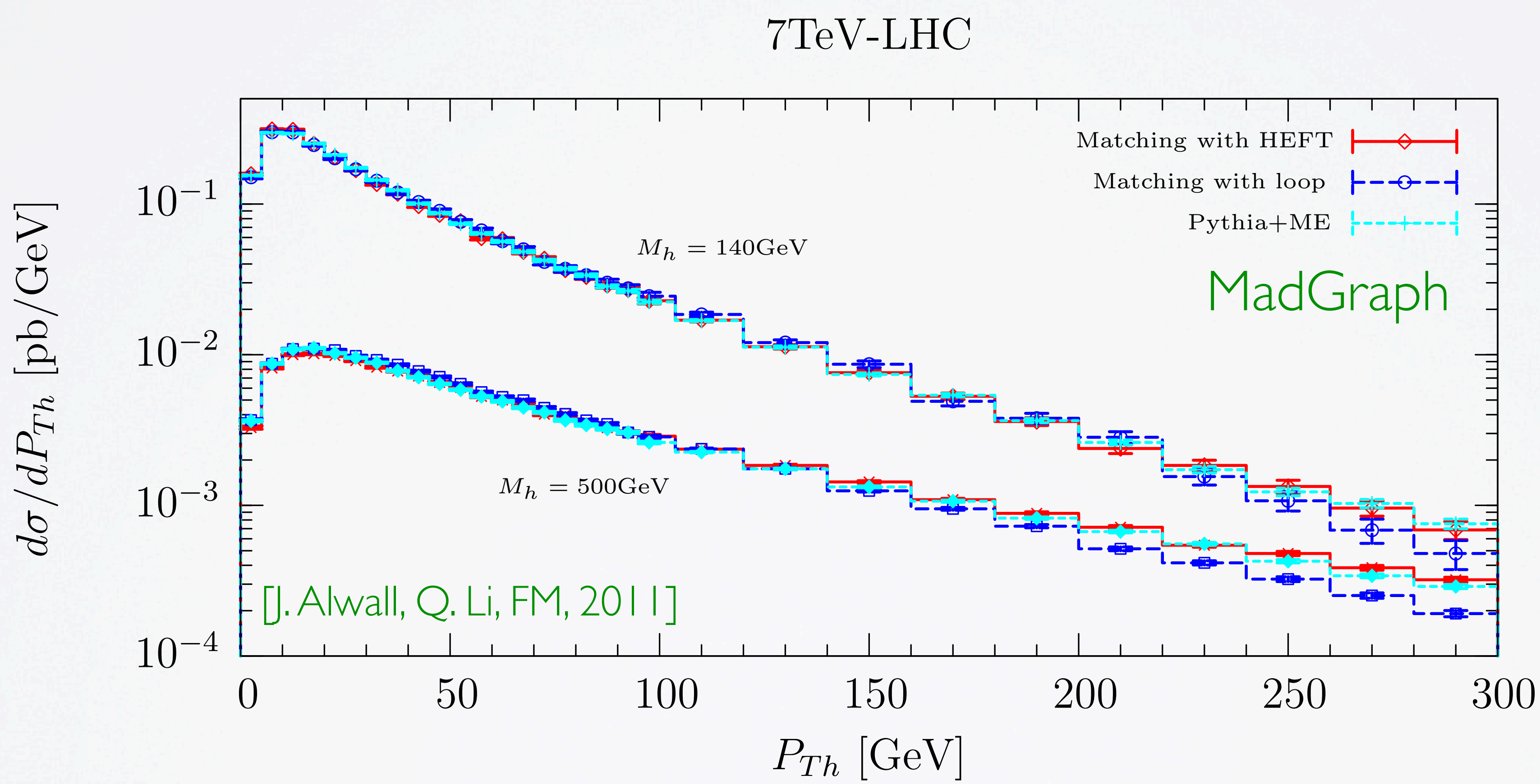
POWHEG: $R^s(\Phi) = F R(\Phi)\,, R^f(\Phi) = (1-F)R(\Phi)$

F=1 = Exponentiates the Real.
It can be damped by hand.

pp→H+Jets with finite mass corrections

H+jets MERGED in the HEFT available since a long time in Alpgen, Madgraph, Sherpa.

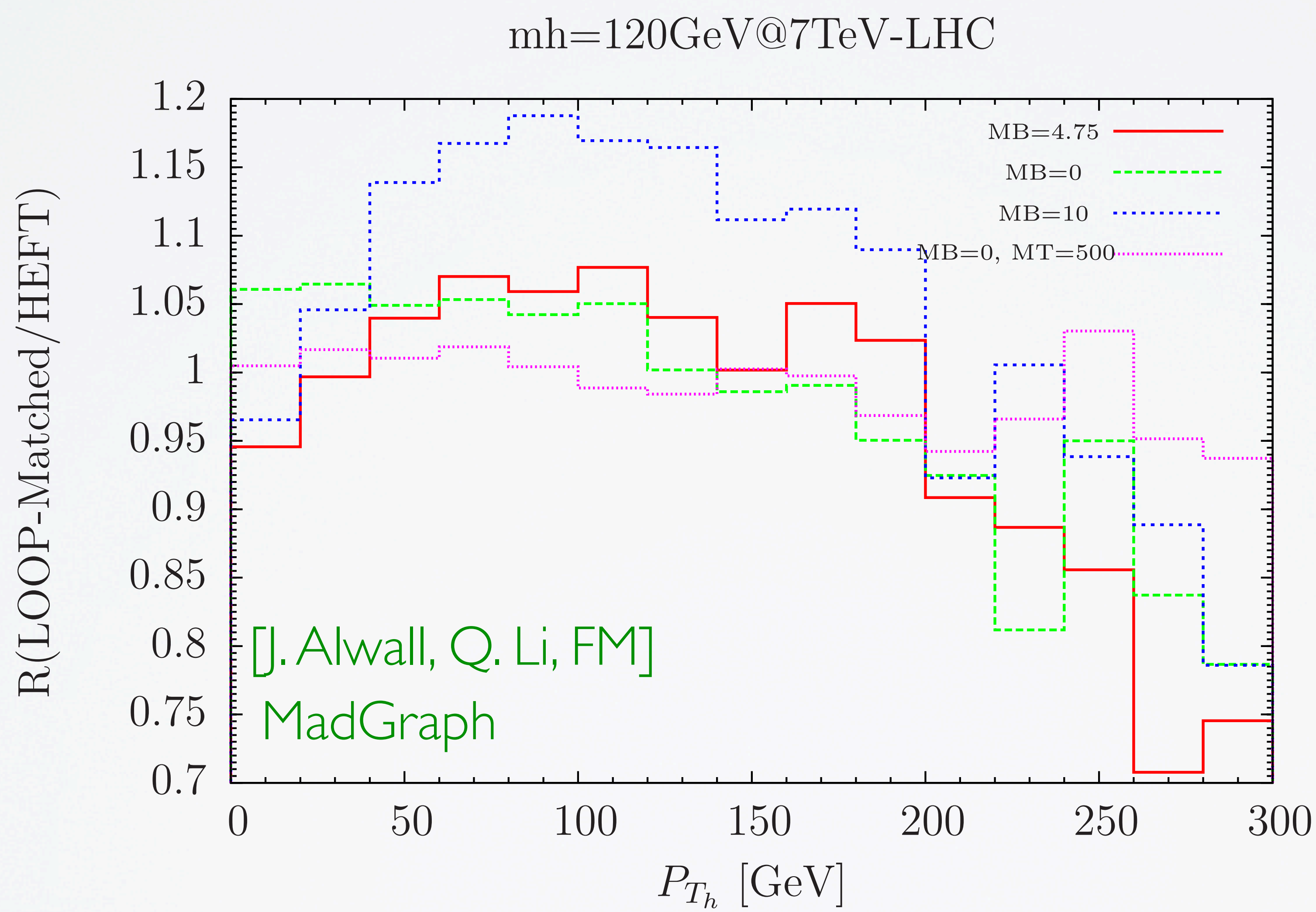
In total rates we know that large-m_{top} approximation works extremely well up (differences of the order of 0.5 % for mh<300 GeV !) [Harlander et al. (2009,2010), Steinhauser et al. (2009)]. In differential rates corrections show up only for very hard kinematics.



Illustrative example of **CONSISTENT** event-by-event reweighting: single events are generated in the HEFT, and then one by one reweigthed by $|M_{loop}|^2$ / $|M_{HEFT}|^2$. **(VERY DIFFERENT** from reweighting based on one distribution!!)

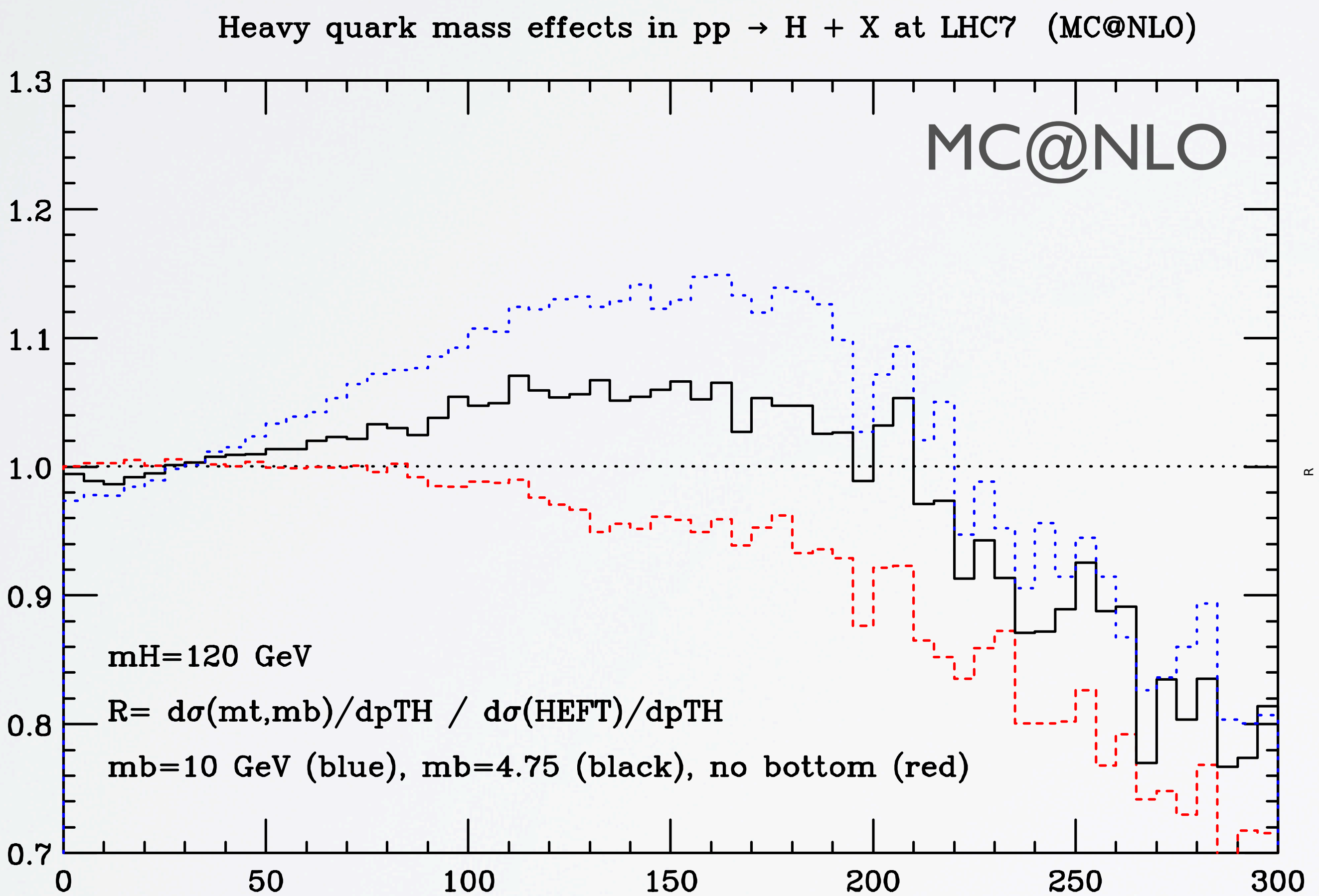
pp→H+Jets with finite mass corrections

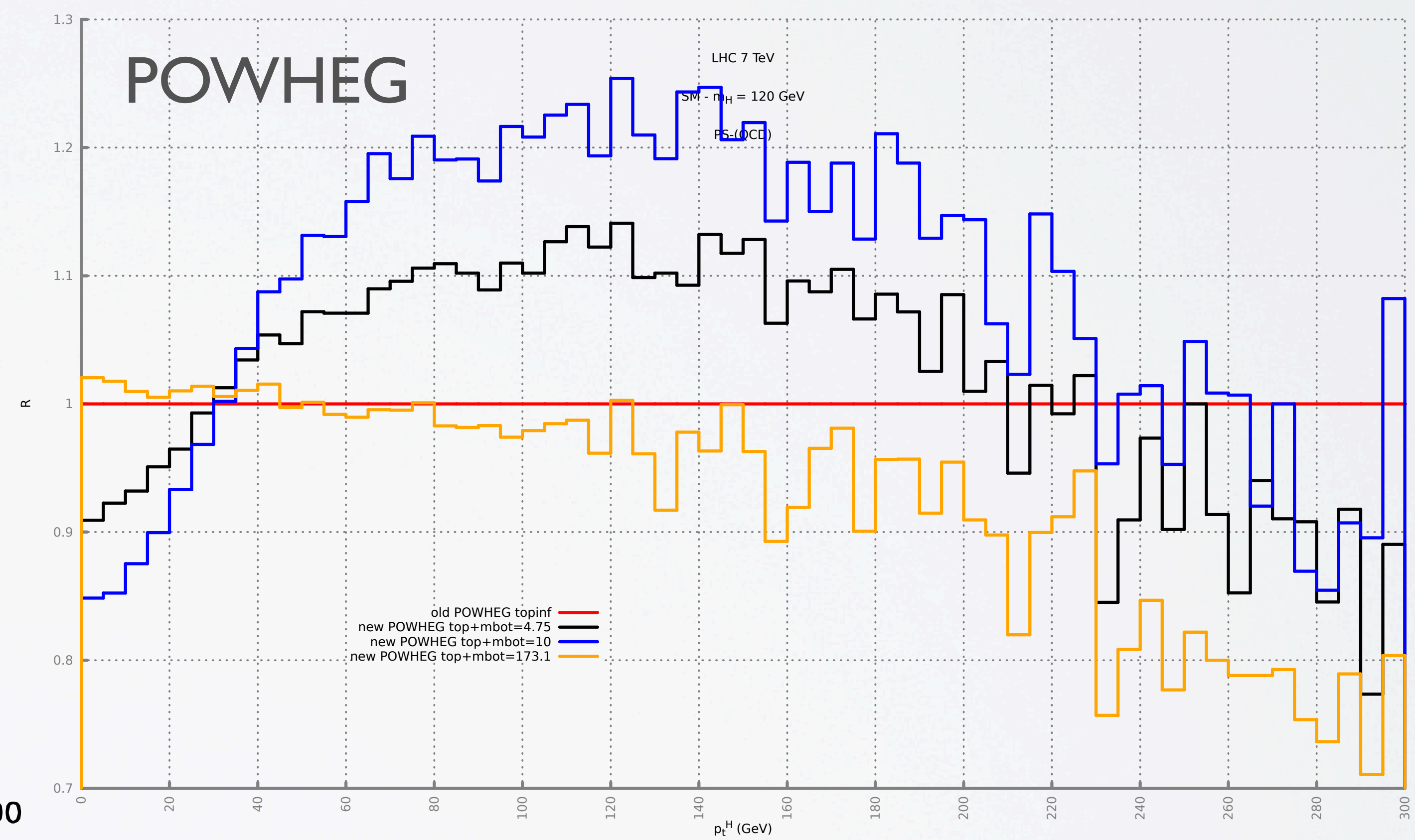
Application: Changes in the p_T spectrum of a mh=120 GeV with respect to the HEFT.



Possible to extend this study to a pseudo scalar.

Higgs pT : HEFT vs full theory





Beware : significant differences at small pT for the Higgs!

This is due to the different treatment of the probability of the first emission within the two methods. Note that POWHEG has been now tuned to HqT at high pT.

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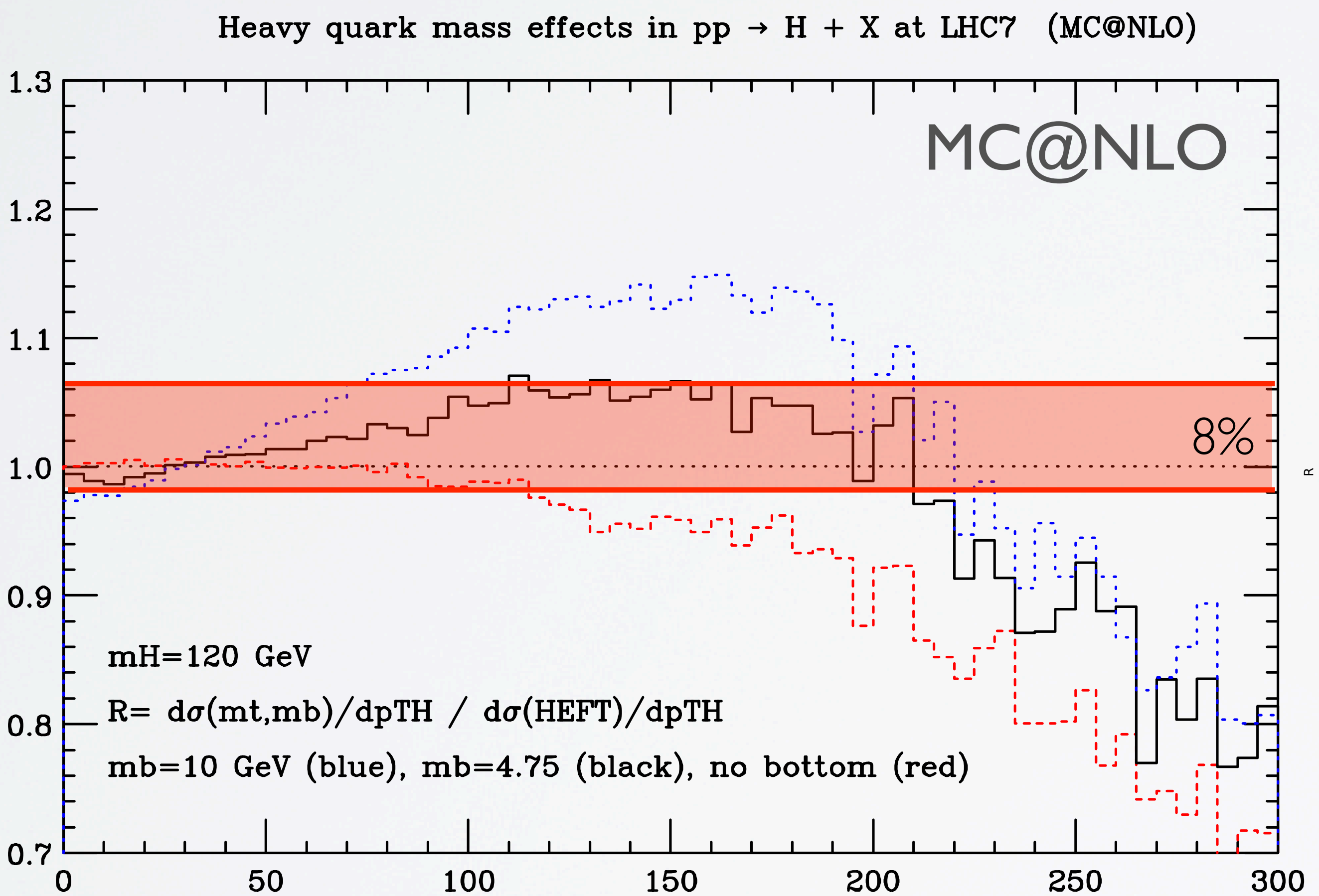

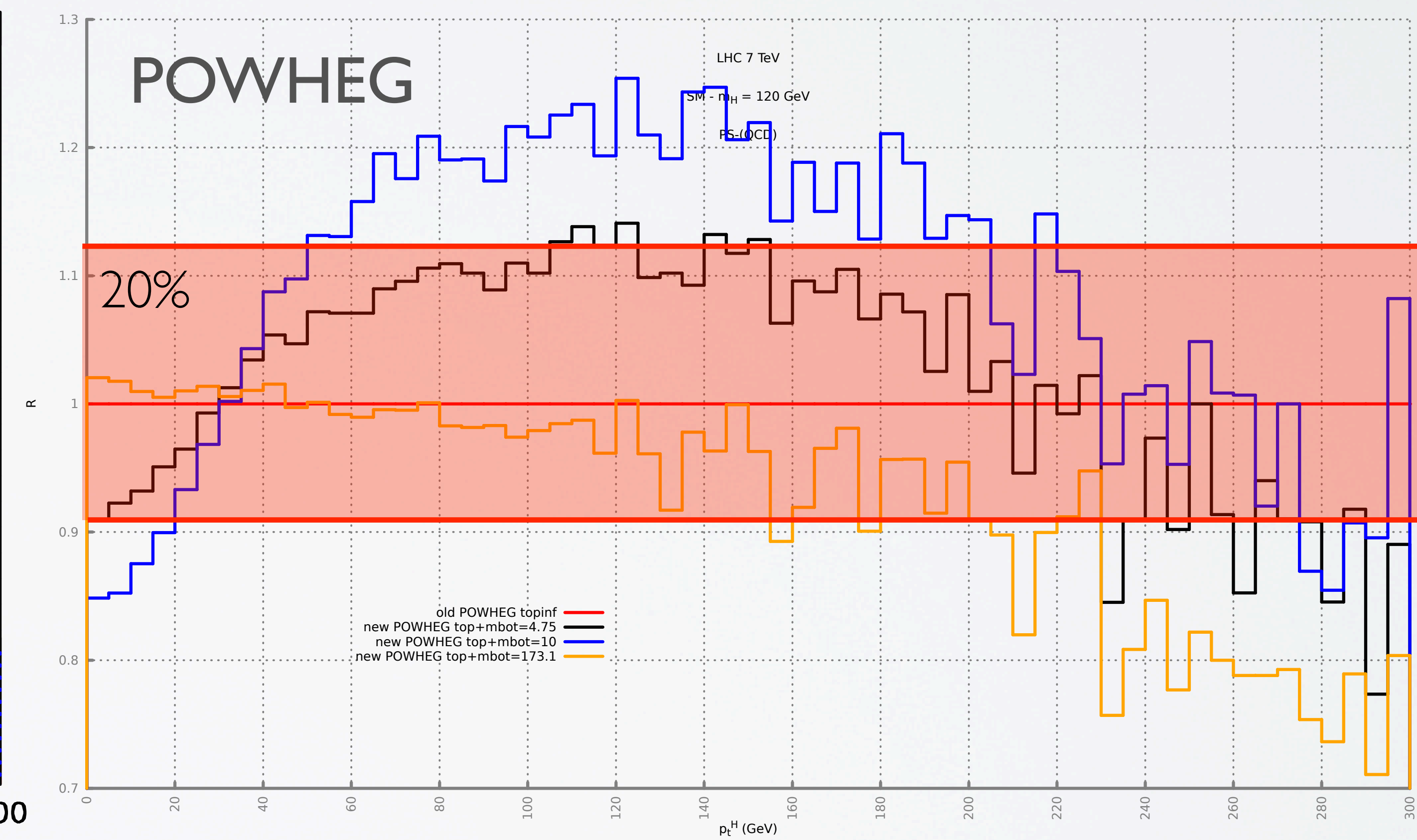

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X=J^P with MadGraph5

[De Aquino et al. for HC2012]

0+ $$\mathcal{L}_h = -\frac{1}{4} g_h G^a_{\mu\nu} G^{\mu\nu,a} \Phi$$

0- $$\mathcal{L}_A = \frac{1}{2} g_A G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \Phi_A$$

1-/+ $$\mathcal{L}_V = \bar{\psi}(a + b\gamma_5)\gamma^\mu \psi V^\mu + \mathrm{Int}(V_\mu, W^+_\nu, W^-_\rho) + \mathrm{Int}(V_\mu, Z_\nu, Z_\rho)$$

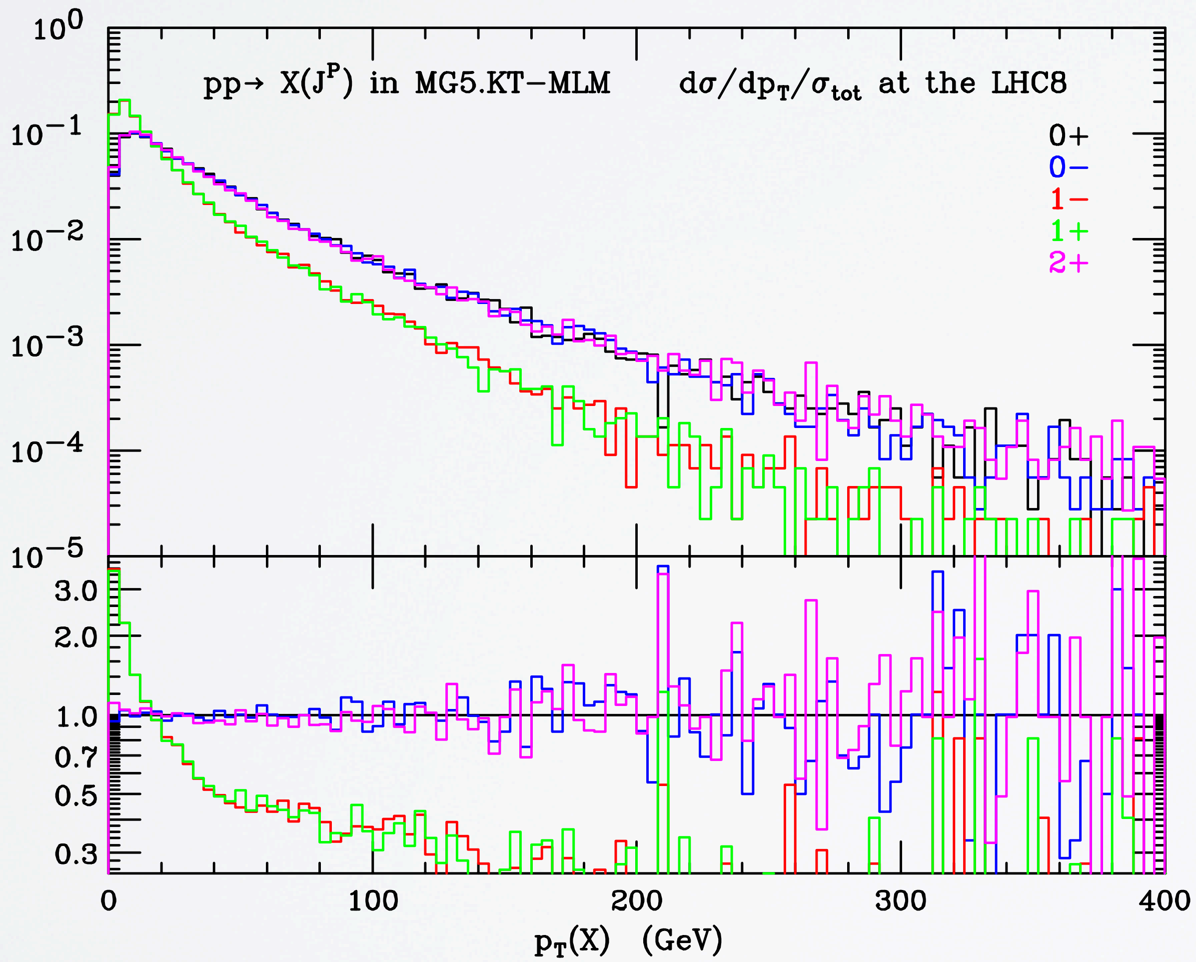
2+ $$\mathcal{L}_G = -\frac{1}{\Lambda} T_{\mu\nu} \mathcal{T}^{\mu\nu}$$

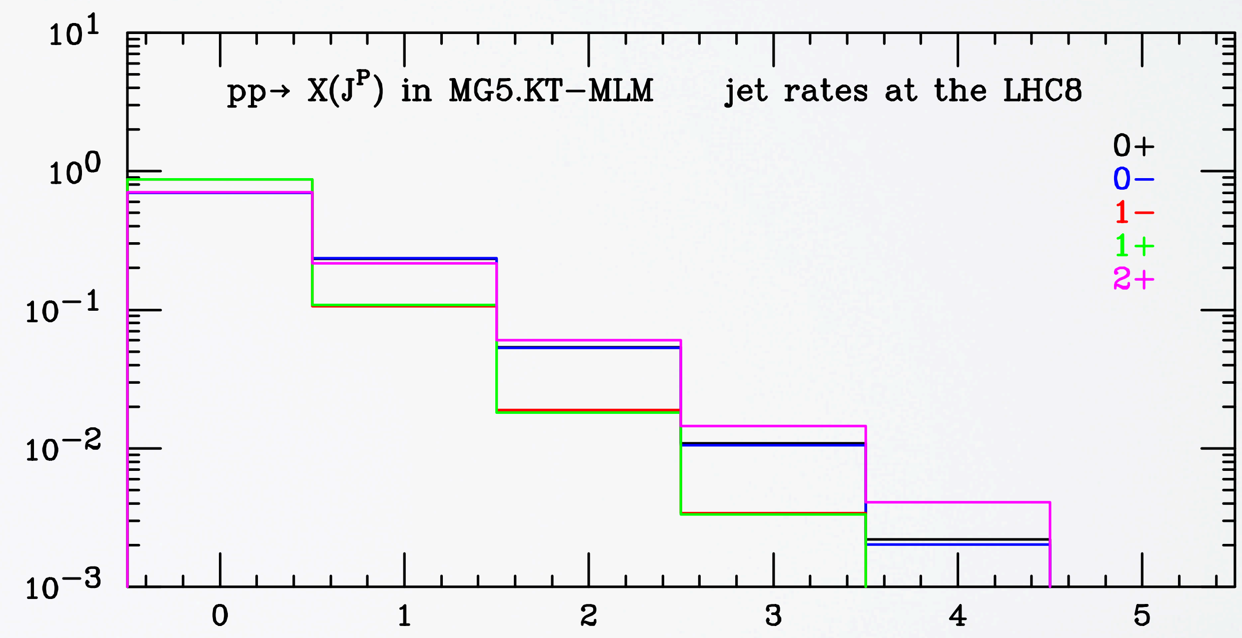
Any other state/interaction comes from higher-dimensional operators and it is therefore suppressed. For all the above interactions **production and decay,** (possibly including interference with SM processes), can be inherited by **FeynRules** and then simulated in **MadGraph5** as inclusive merged samples for any production channel (which works out of the box).

X=J^P with MadGraph5

[De Aquino et al. for HC2012]

You can now plot all you are interested in for production....

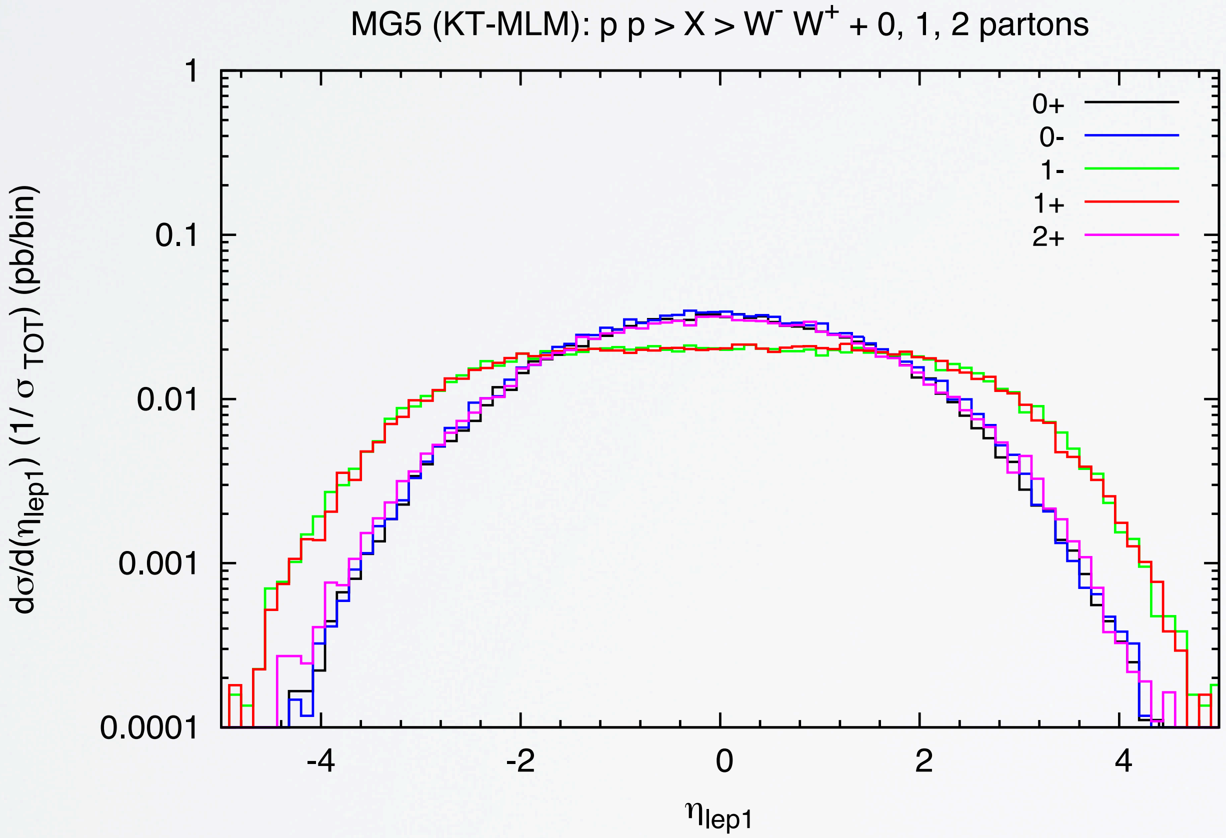


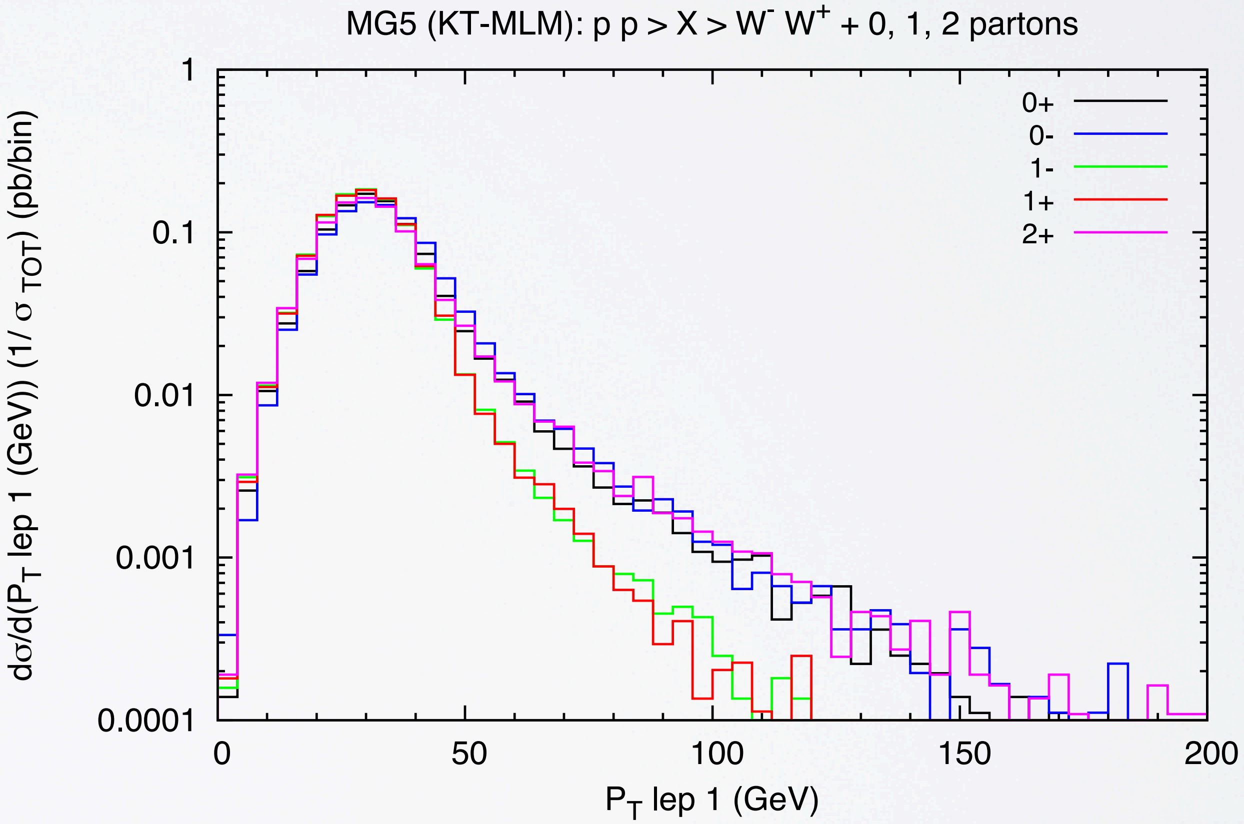


X=J^P with MadGraph5

[De Aquino et al. for HC2012]

and production with SPIN CORRELATED decays:





$X=J^P$ with MadGraph5 : MadWeight

[Artoisenet, De Aquino, FM, Mattelaer, in progress]

Since a few years, MadGraph has the possibility to test hypotheses using an automatized implementation of the Matrix Element Method using **MadWeight** [Artoisenet, Lemaitre, FM, Mattelaer, 1007.3300]

$$P(\boldsymbol{x}_i, \alpha) = \frac{1}{\sigma^{obs}} \frac{1}{N} \sum_{\text{jet perm.}} \int d\phi_{\boldsymbol{y}} |M|^2(\boldsymbol{y}) W(\boldsymbol{x}_i, \boldsymbol{y}) Acc(x)$$

MG5 automatic integration on the parton-level phase-space (non trivial!)

MG5 tree-level matrix element

transfer function extracted from MC simulation

This can be applied to ANY process in the SM and BSM, including the effects of ISR.

Easy to apply the method to the spin and parity of pp→ X →VV + jets production.

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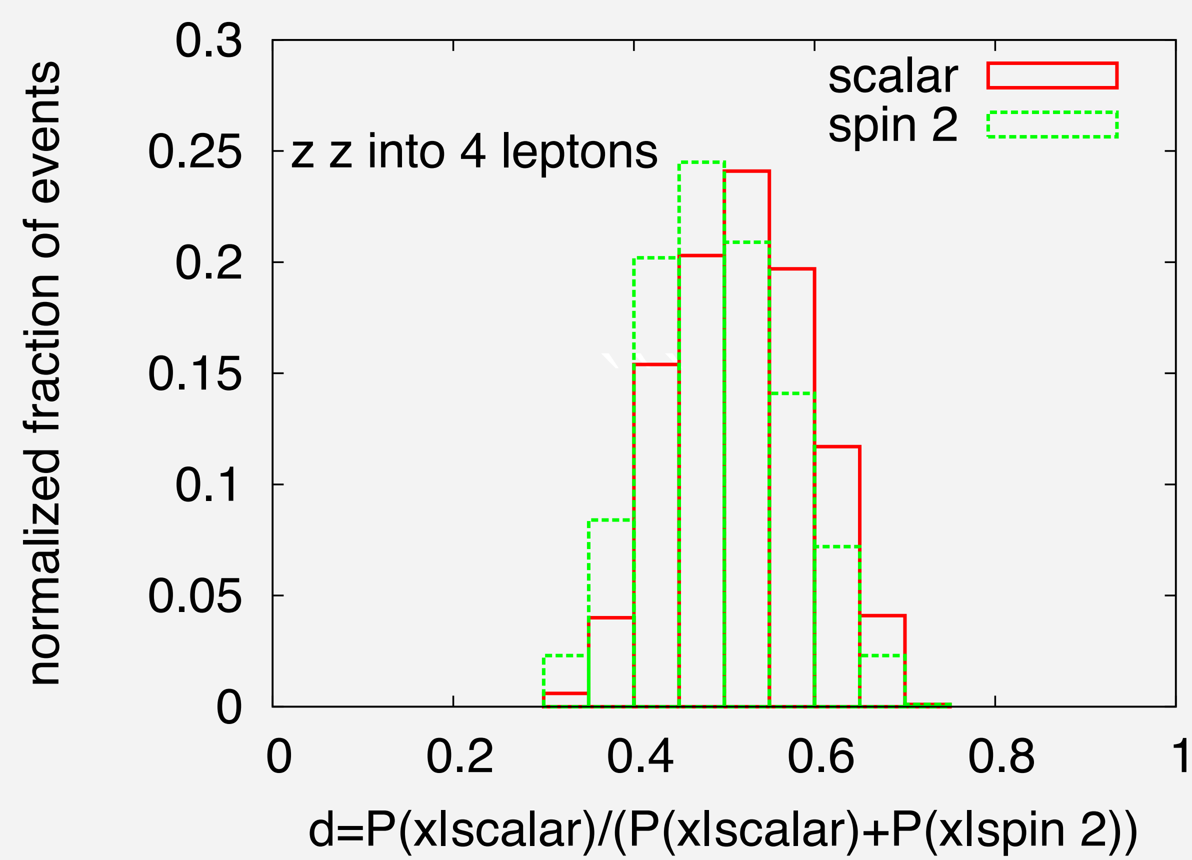

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aMC@NLO

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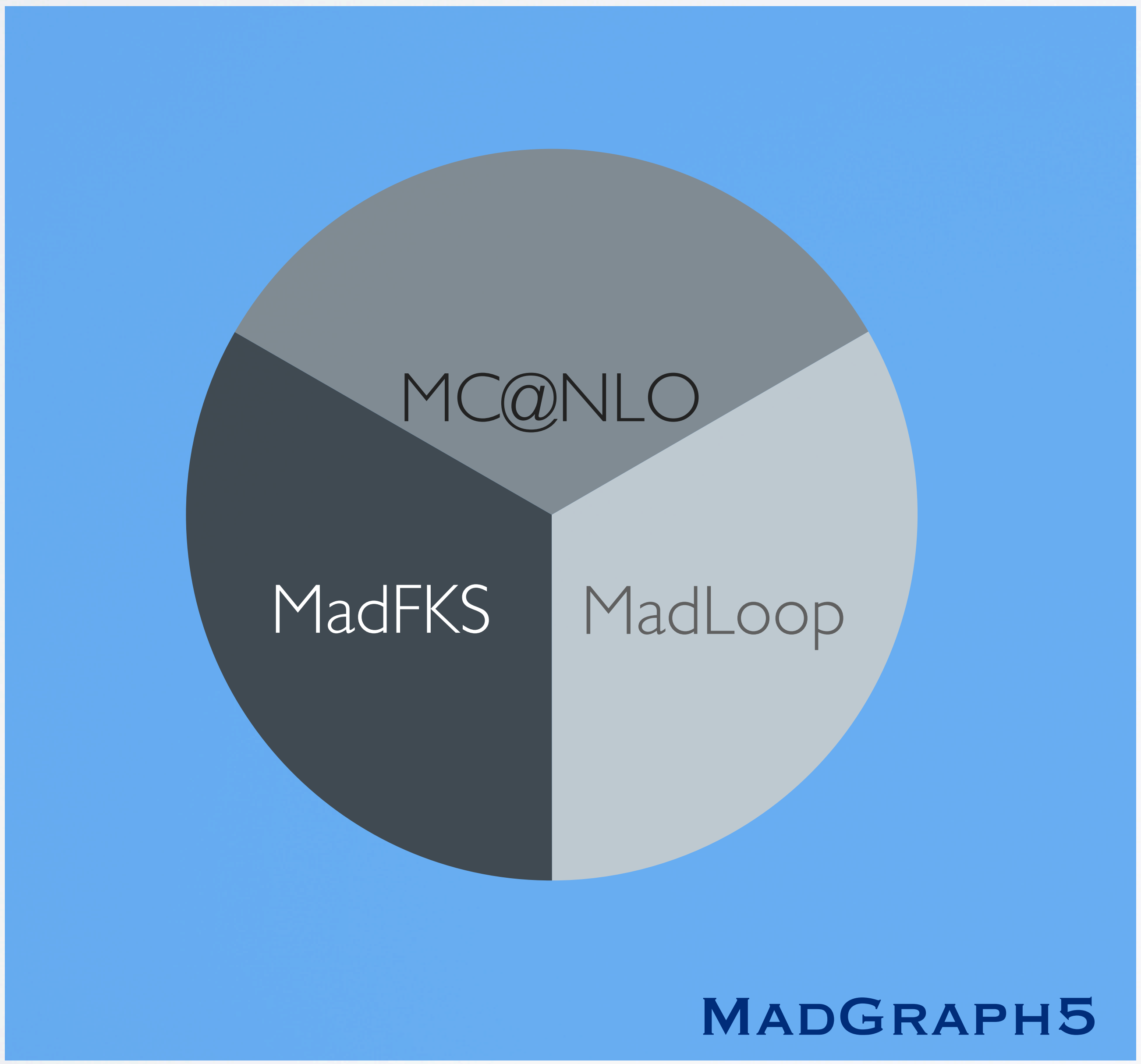
Modular structure in the **MadGraph5** framework:

aMC@NLO

[Alwall, Hirschi, Frederix, Frixione, FM, Mattelaer, Pittau, Torrielli, Zaro]



Modular structure in the MadGraph5 framework:

- MadLoop (w/ Cuttools)
- MadFKS for subtractions
- MC@NLO counterterms for Pythia6Q^2, Herwig, HW++. (Pythia8 validation on-going).

aMC@NLO

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aMC@NLO possibilities

The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power. It basically encompasses (and goes beyond) the current MCFM and POWHEG-Box libraries.

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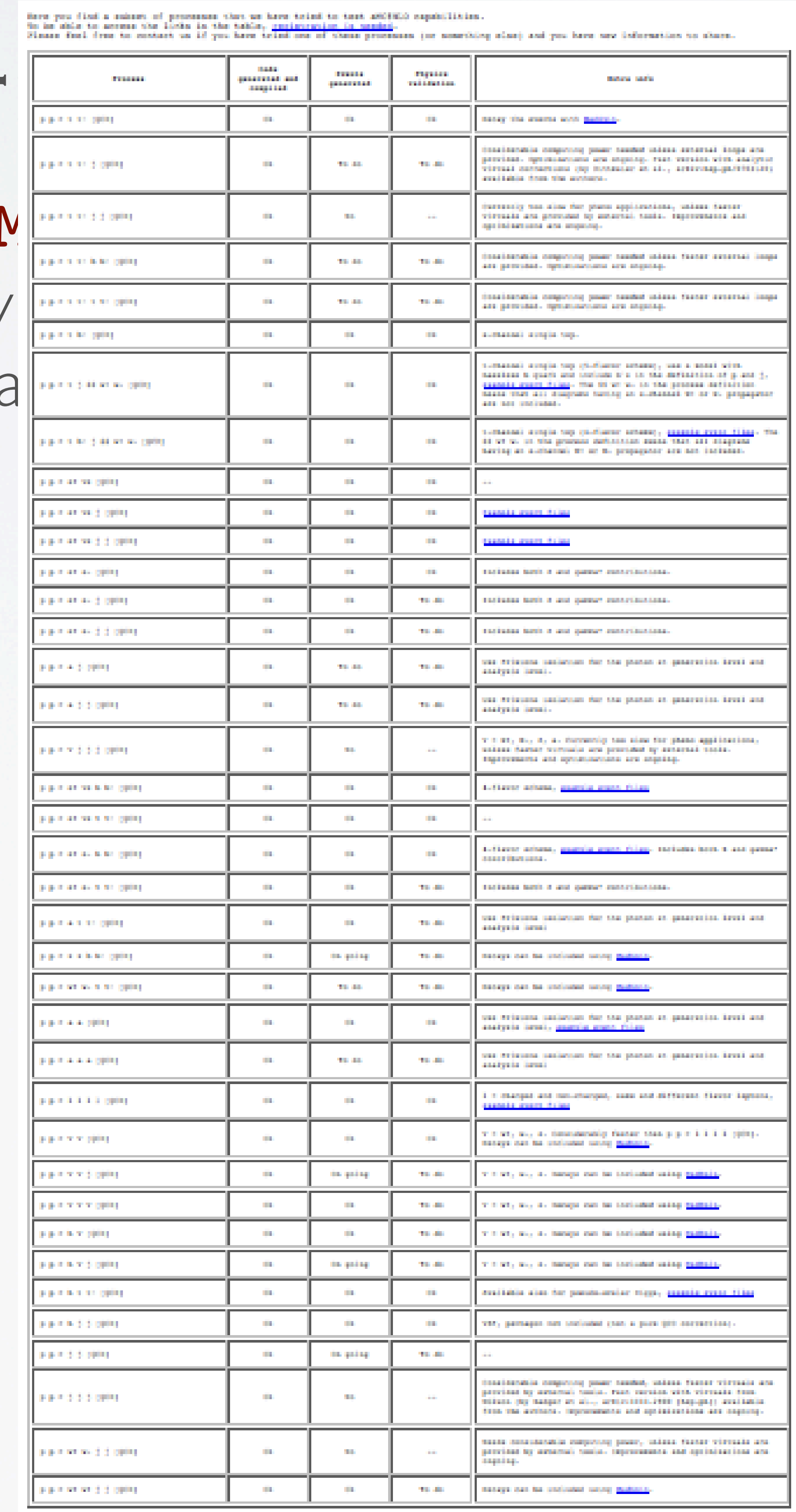

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- Signal simulation in the SM:
  - Automatic : e.g., pp→VBF, WH(+j),ZH(+j),ttH,...
  - Available : pp→H +0,1,2 extra jets + FxFx (NLO) merging.
- Bkg simulation:
  - Automatic : e.g., pp→tt, tj, V V, V V V, Vbb, V, Vj, Vjj, ttV,....
  - Available: QCD rich final states.
- Spin correlated decays can be obtained after event generation via MadSpin.
- Higgs characterization pp→X(J^P)+jets: codes publicly available.
- Extended Higgs sectors straightforward (in progress).

THE a OF aMC@NLO

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Suppose now you are interested in studying HH production in VBF:

```
./bin/mg5
> generate p p > H H j j [QCD]
> output HHvbf
> launch
```

or in studying spin-2 production in association with a vector boson:

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> import model RS_NLO
> generate p p > Gr Z, Gr > b b~ [QCD]
> output vbf_gr
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The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power so it improves with time. It already encompasses and goes beyond the currently public tools based on libraries (MCFM, POWHEG-BOX,..)

aMC@NLO applications to Higgs physics

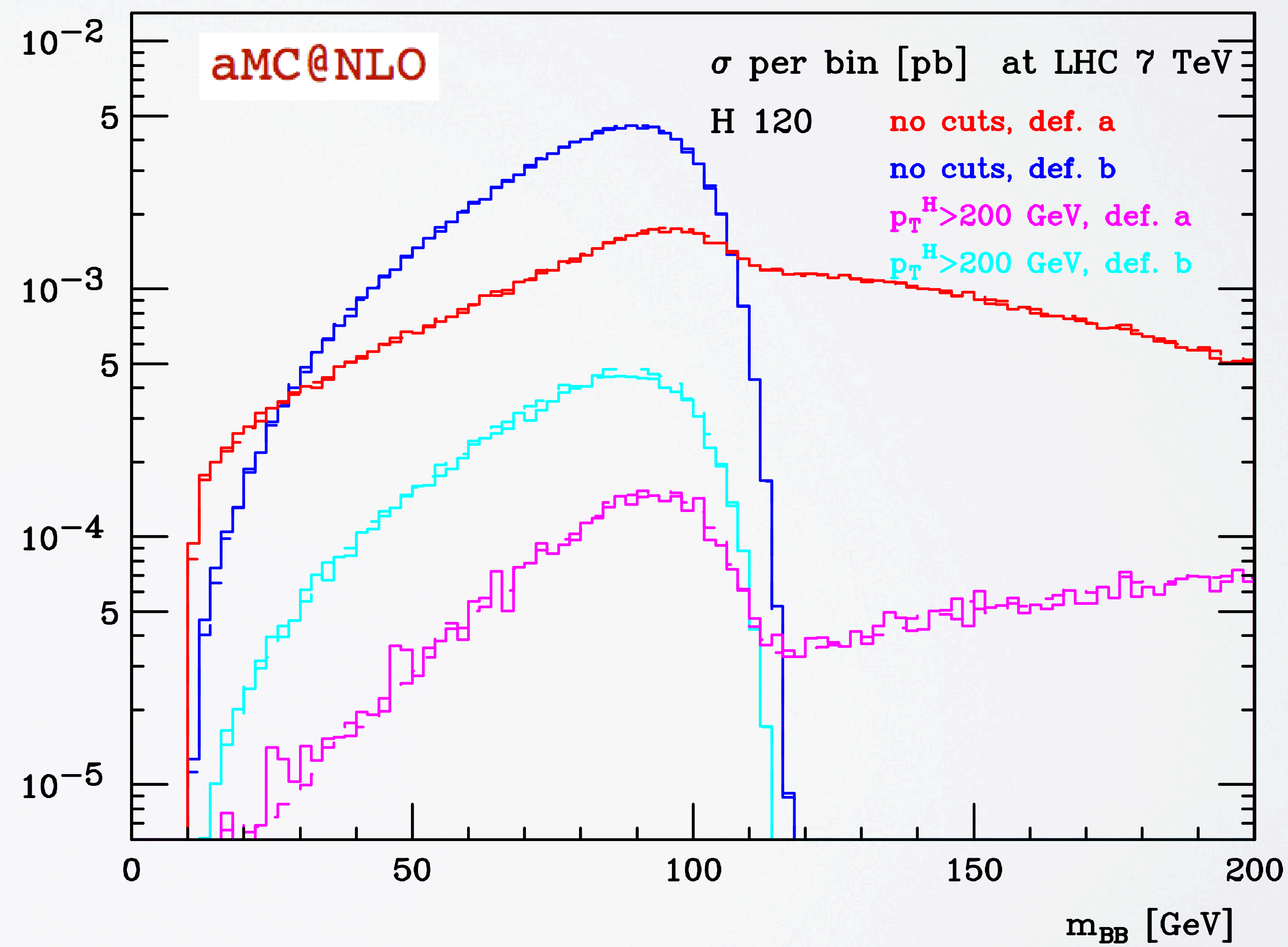
ttH/ttA (Z/W→ll/lν)bb VV→4l

[aMC@NLO:1104.5613]

For H, NLO results known (but no public code available) for scalar Higgs since some time. No results for pseudoscalar A were known.

First fully automatic results for both H and A.

Experimental grade distributions for decaying tops and Higgs can be plotted.
Spin correlated decays included via MadSpin.
Combinatorics very hard to manage, is improved in the boosted case.



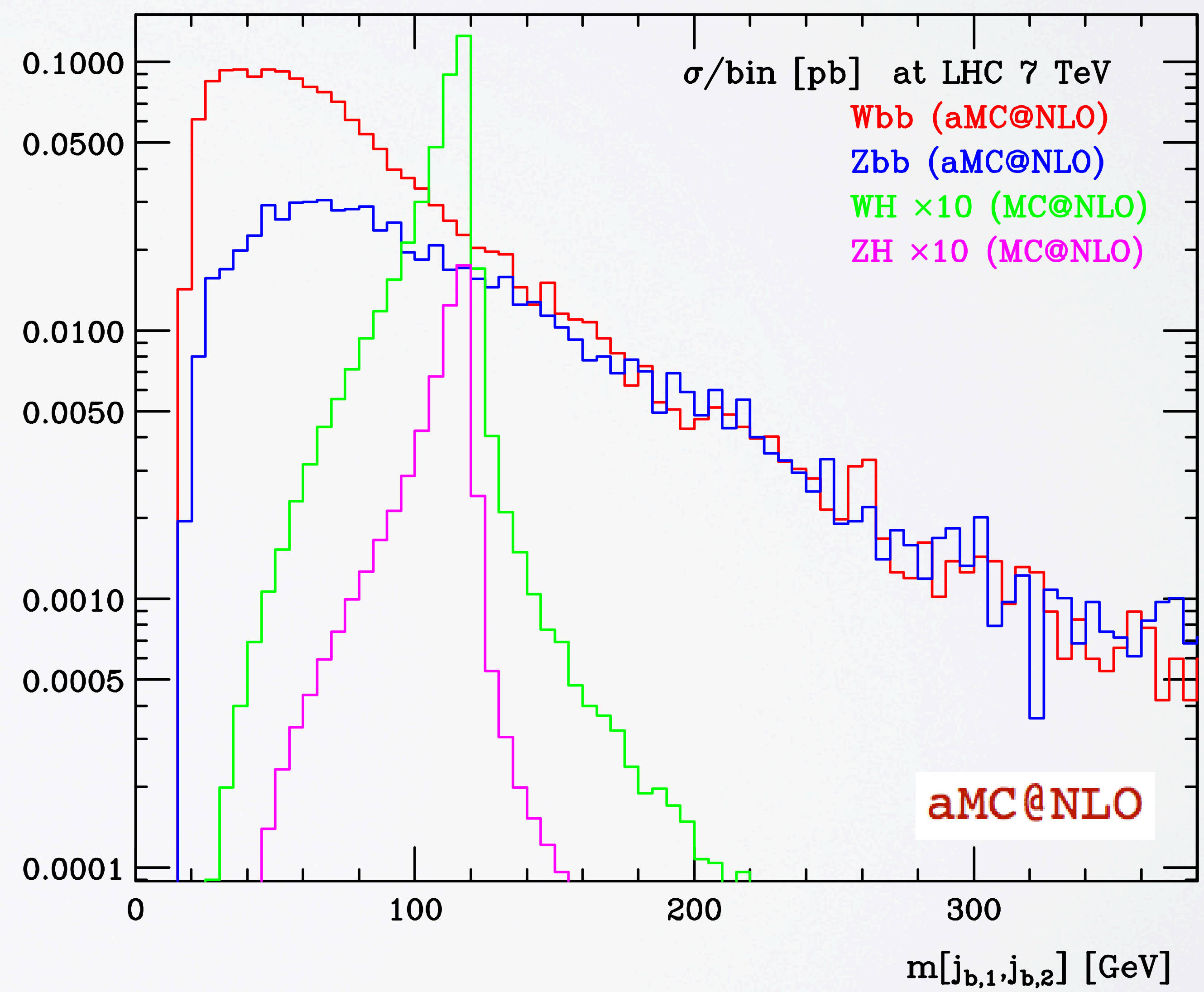
aMC@NLO applications to Higgs physics

ttH/ttA (Z/W→ll/lν)bb VV→4l

Extremely interesting QCD laboratory and background to the Higgs searches. Historically source of TH/EXP discrepancies at Tevatron and now at the LHC. Topological difference between Z and W.

Very different m_{bb} distributions. Full simulation for signal and background at NLOwPS!!

[aMC@NLO: 1106.6019]



aMC@NLO applications to Higgs physics

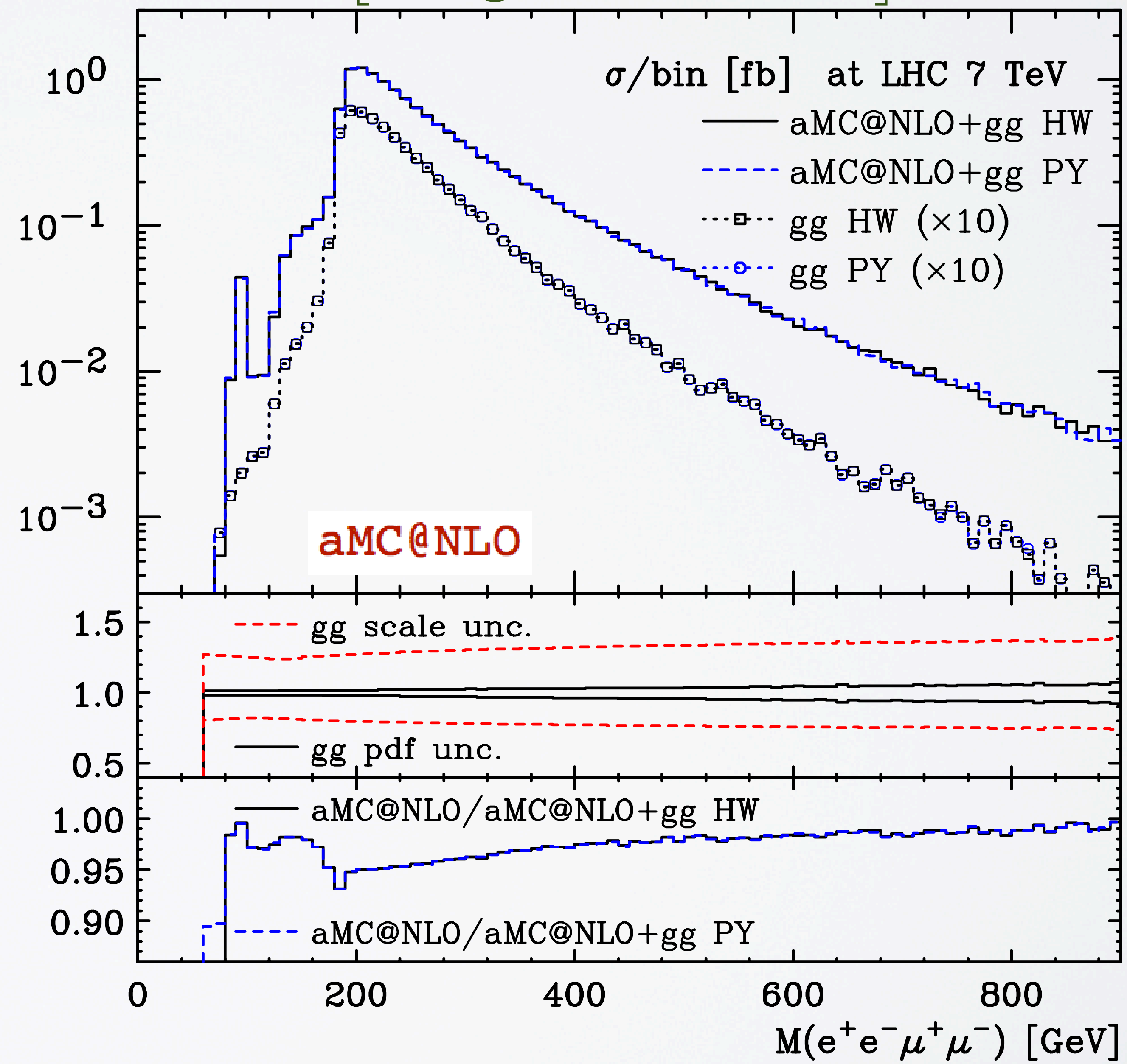
ttH/ttA (Z/W→ll/lν)bb **VV→4l**

[aMC@NLO: 1110.4738].

Several NLO and NLO+PS results available (Herwig++ and POWHEG-BOX).

NLO calculation includes γ*/Z interference, full spin correlations and single resonant diagrams **+ one-loop gg channel.**

First fully automatic NLO+PS results **including automatic theoretical uncertainty band**



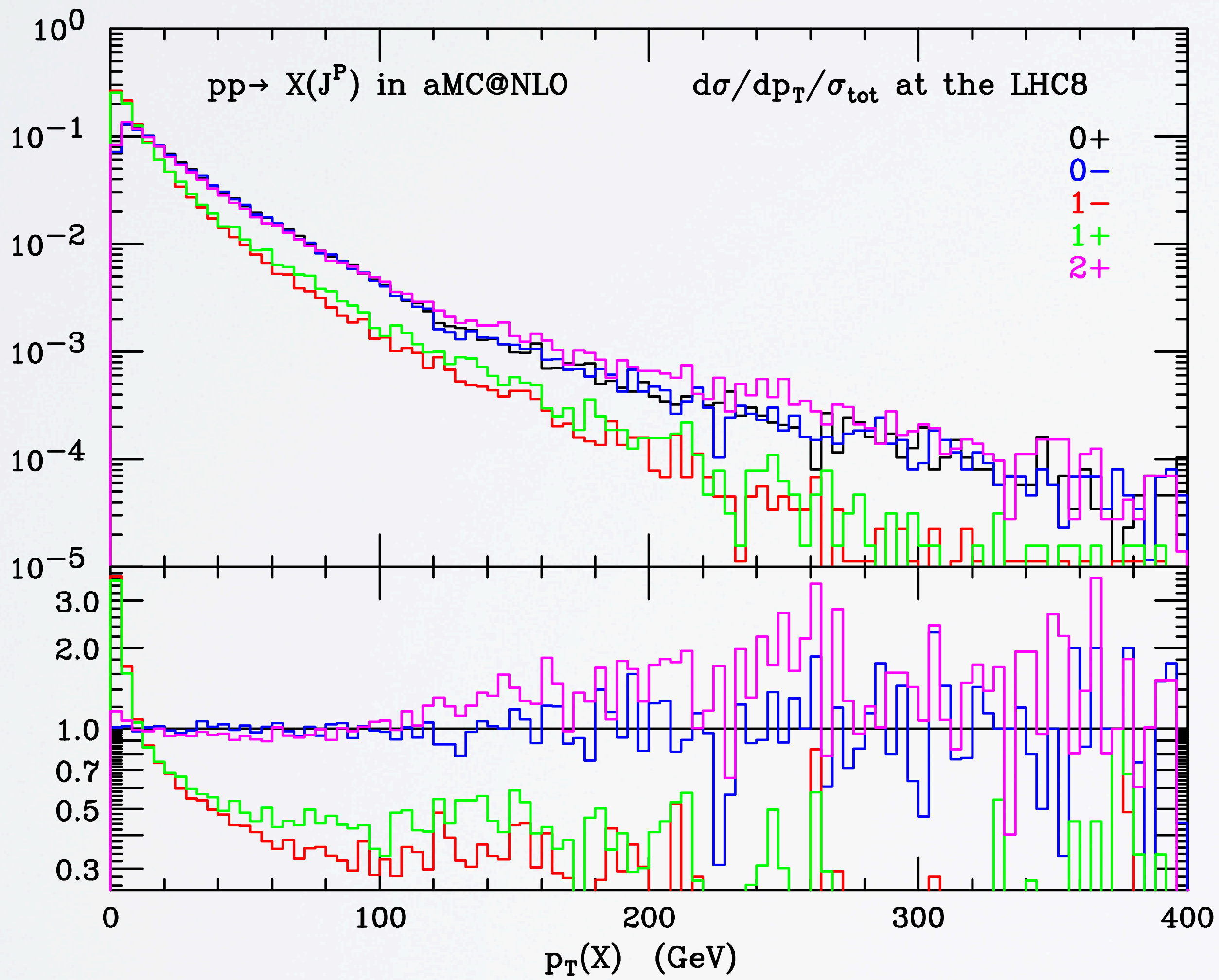
aMC@NLO applications to X(J^P) physics

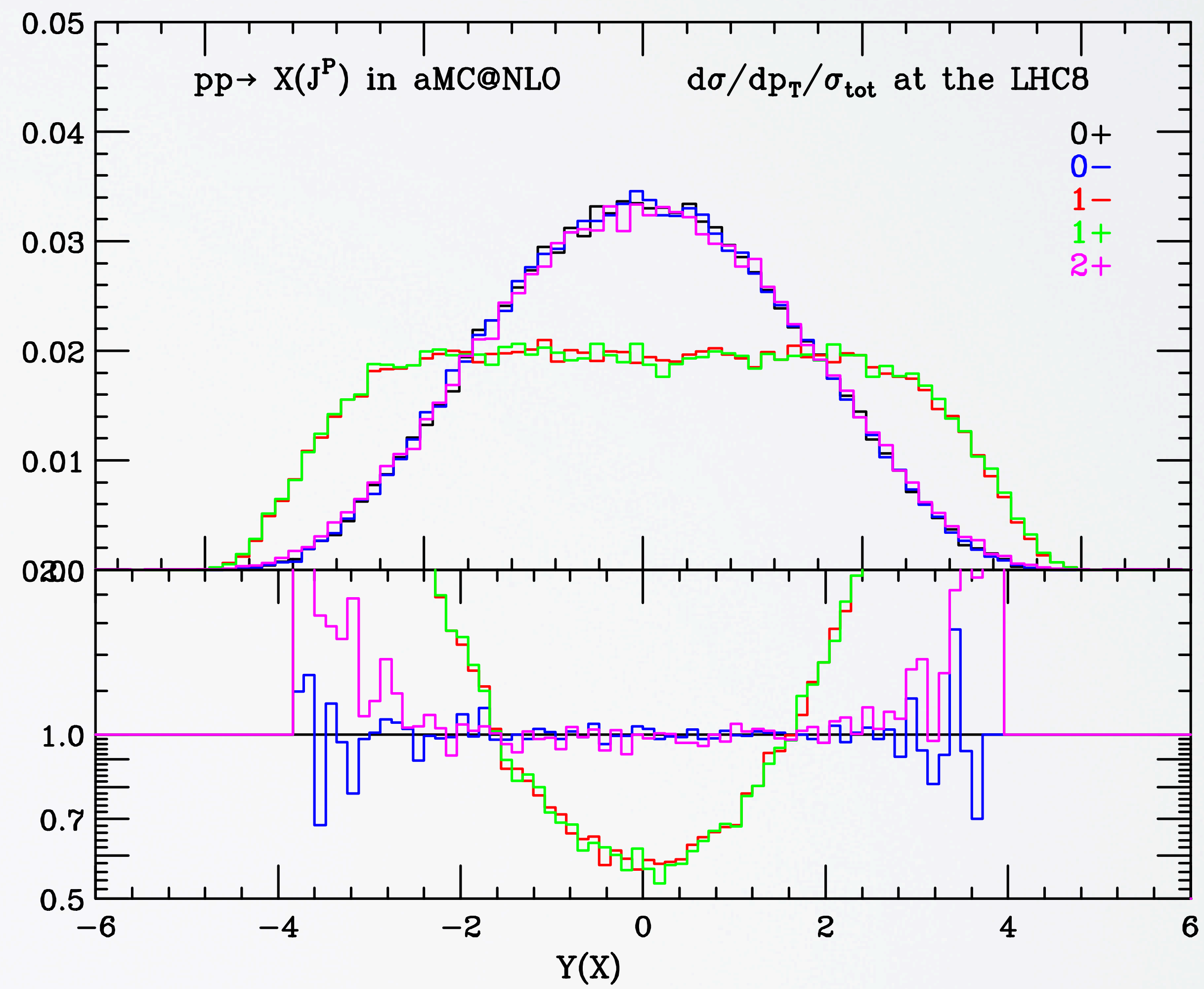
[P. Artoisenet, P. de Aquino, R. Frederix, F. Maltoni, M.~K. Mandal, P. Mathews, V. Ravindran, S. Seth, P. Torrielli, M. Zaro, for HC2012]

Process	Codes	Plots	Extra info
Higgs characterization. **Comparison plots:** pt of the "Higgs" rapidity of the "Higgs" jet rates			
$pp \to 0^+ + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. Scalar resonance. Process generated in the HEFT model
$pp \to 0^- + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. Pseudo scalar resonance. Process generated in the HEFT model
$pp \to 1^- + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Fully automatic in aMC@NLO. Vector resonance (Obtained from the Z using only vector coupling to quarks).
$pp \to 1^+ + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Fully automatic in aMC@NLO. Pseudo vector resonance (Obtained from the Z using only axial coupling to quarks).
$pp \to (2^+ \to \gamma\gamma) + X$	Code	aMC@NLO+Pythia aMC@NLO+Herwig	Virtuals Provided by Frederix et al. arXiv:1209.6527 Code generated using the RS model. Spin 2 (graviton like)
More to come soon...			

http://amcatnlo.cern.ch

aMC@NLO APPLICATIONS TO X(J^P) PHYSICS

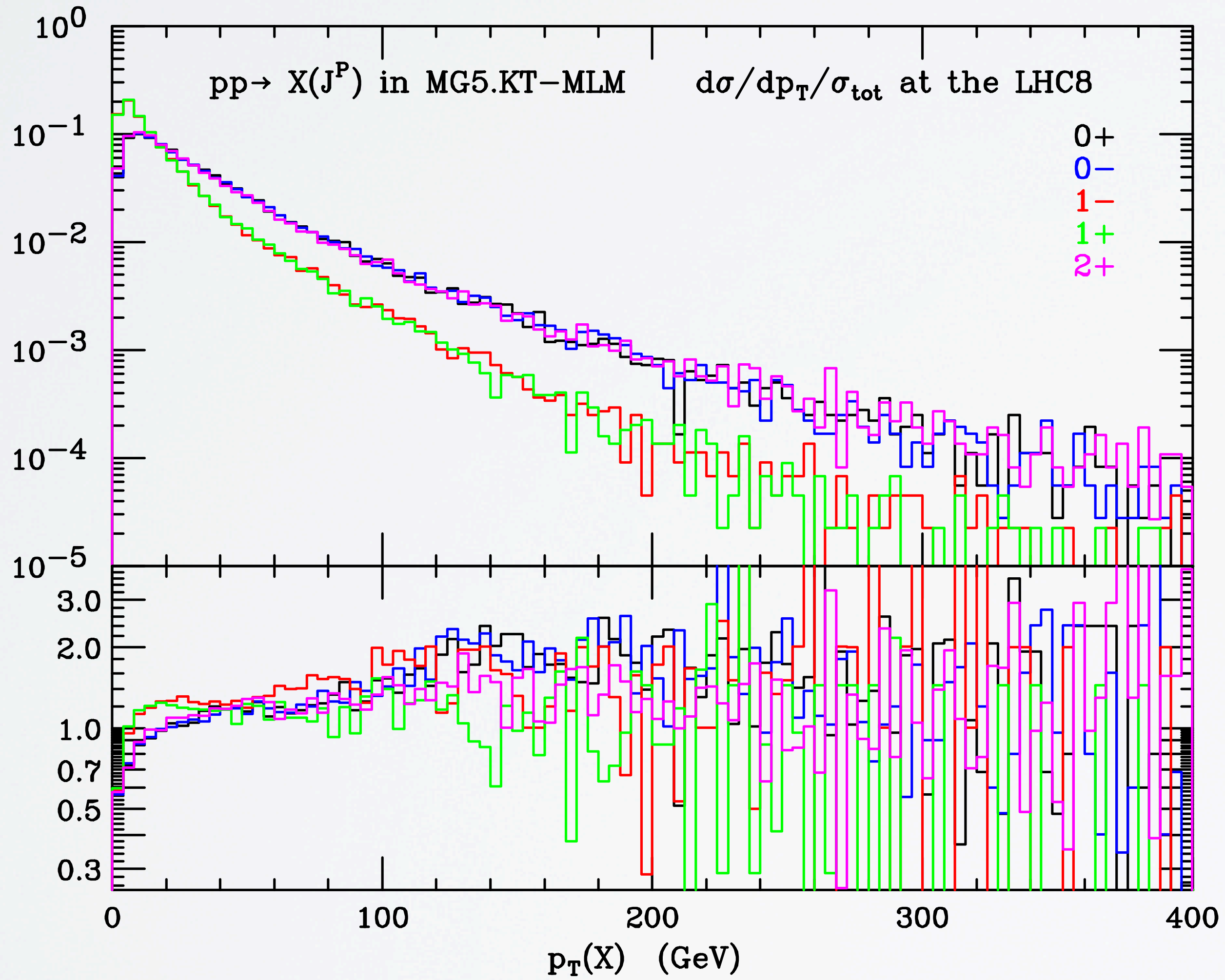


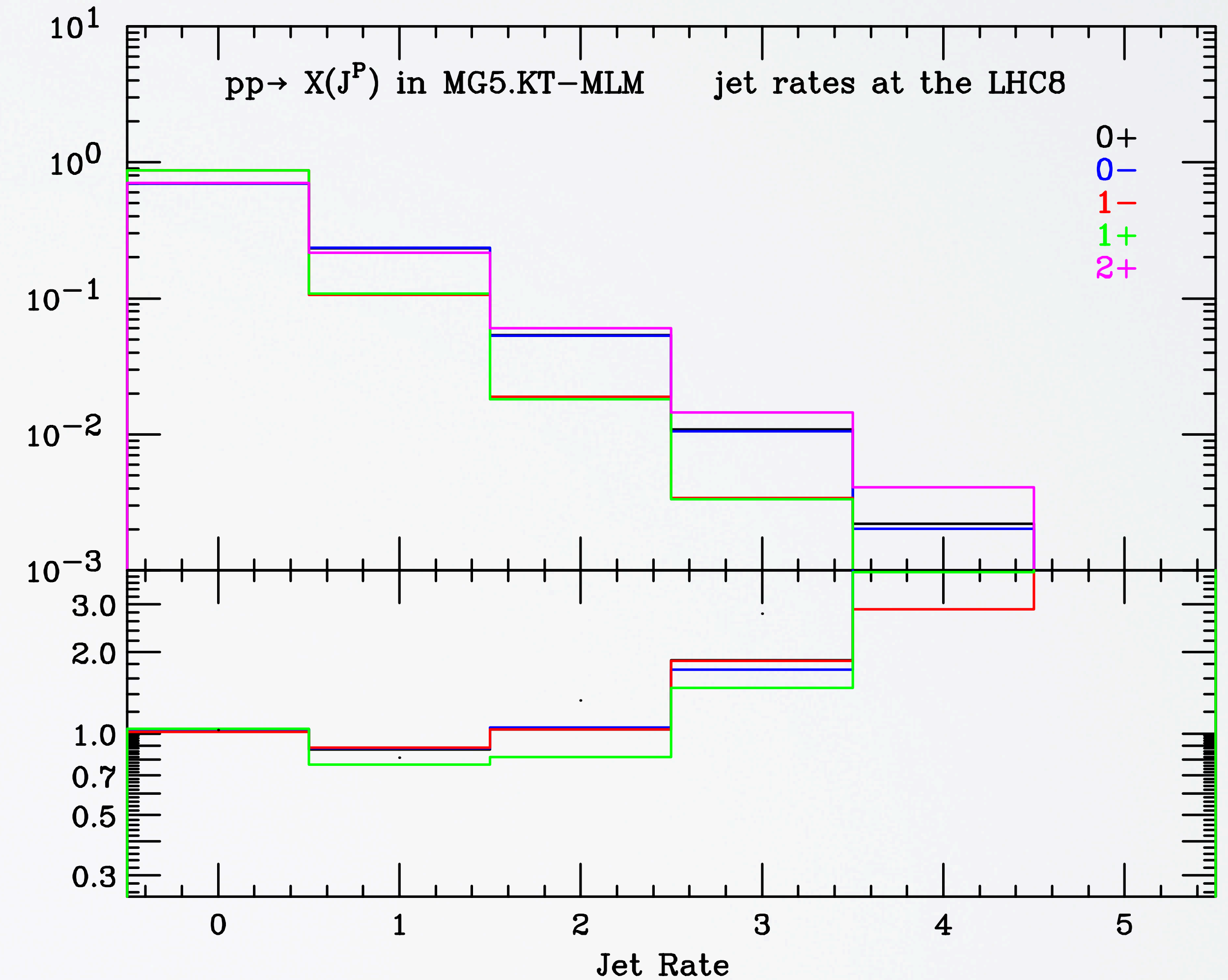


Shapes for 0 and 2 very similar and different from 1.

aMC@NLO applications to X(J^P) physics

Comparison between MLM-KT merged and aMC@NLO

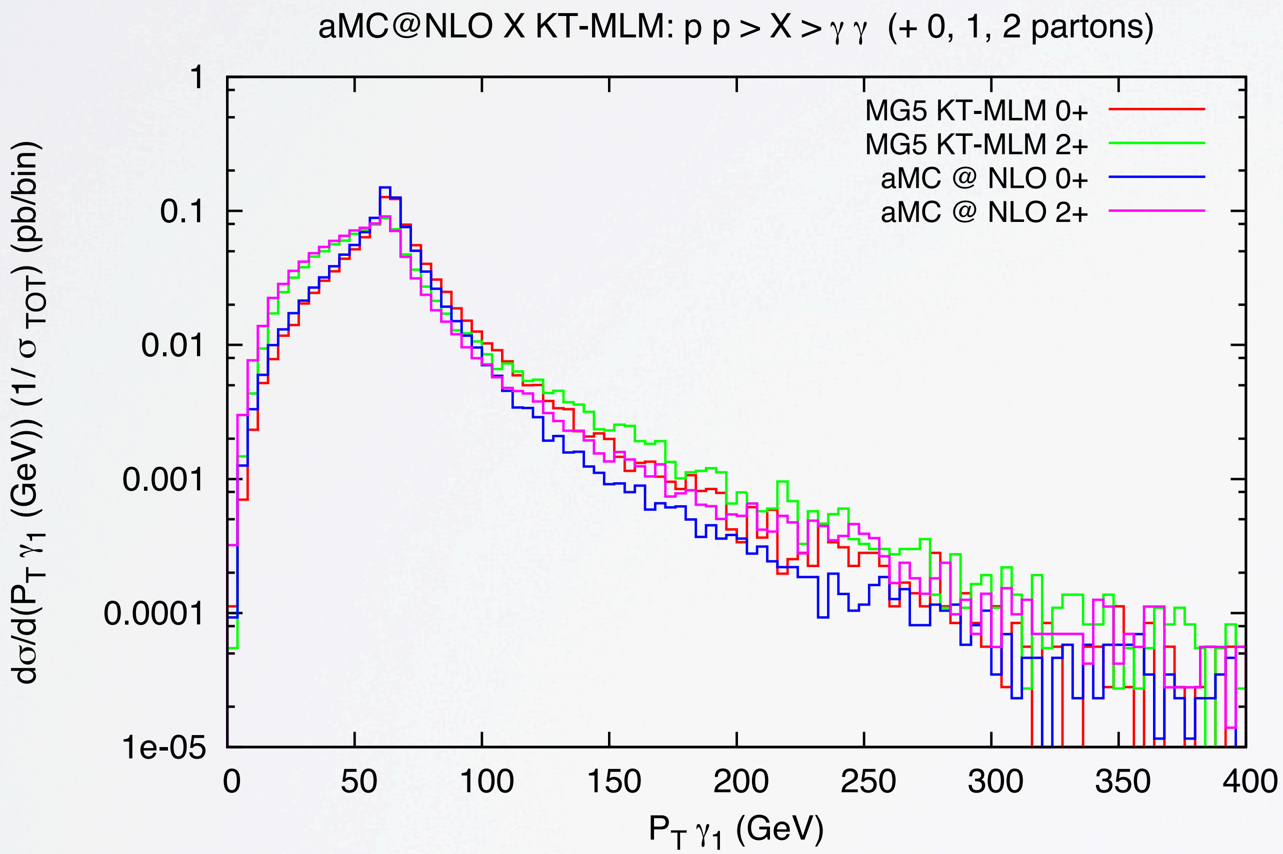


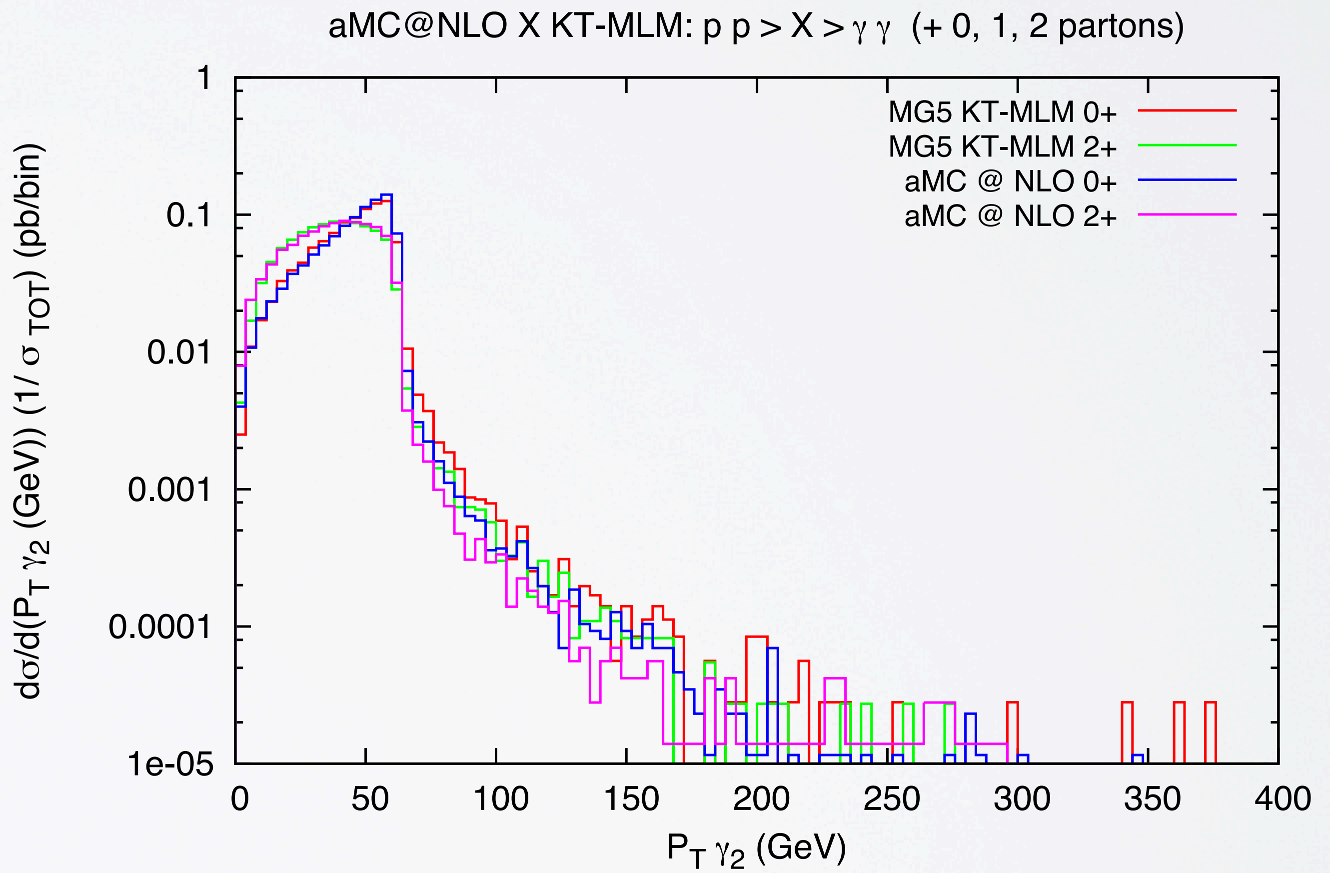


The p_T shapes and jet rates are harder in the merged samples.

aMC@NLO applications to X(J^P) physics

Comparison between MLM-KT merged and aMC@NLO





Quite different spectra between spin 0 and spin 2 hypothesis.
Very consistent p_T shapes between k_T-MLM and aMC@NLO.

CONCLUSIONS

- The **MadGraph5** framework offers a flexible platform for LO and NLO automatic simulations in the SM and BSM.
- **aMC@NLO** is now public (8 Nov 2012).
- Many applications to Higgs physics available:
  - At LO, any production channel for $X(J^P)$ is possible, including multi-jet merging.
  - Signal simulation **aMC@NLO:**
    - All SM procs:
      - pp→H +jets including b,t mass effects (at two loops) in MC@NLOv4.09 .
      - pp→H +jets with FxFx (NLO) merging available.
      - pp→VBF,VH,ttH,...
    - Higgs characterization pp→$X(J^P)$+jets: codes publicly available.
  - Bkg simulation **aMC@NLO:** pp→VV,Vbb,Vjj, ...

MERGING AT NLO

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- There are various ways to improve a Parton Shower Monte Carlo event generator with matrix elements:

  - ME+PS merging: Include matrix elements with more final state partons to describe hard, well-separated radiation better.

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  - NLO+PS matching: Include full NLO corrections to the matrix elements to reduce theoretical uncertainties in the matrix elements. The real-emission matrix elements will describe the hard radiation.

    [Frixione & Webber (2002)]
    [Nason (2004)]

  - NLO+PS matching+merging: Include full NLO for each jet multiplicity and merge the various multiplicities

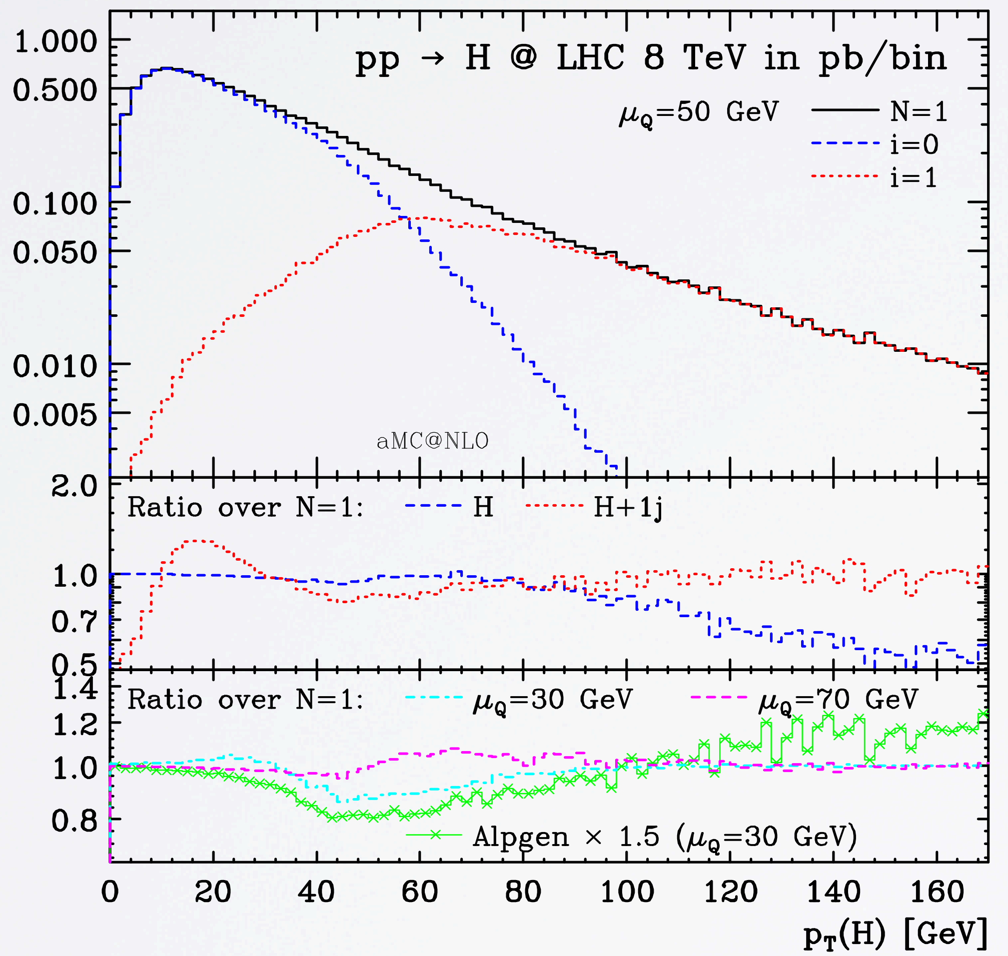
    [Hoche, Krauss, Schonherr, Sieger (2012)]
    [Frixione, Frederix (2012)]

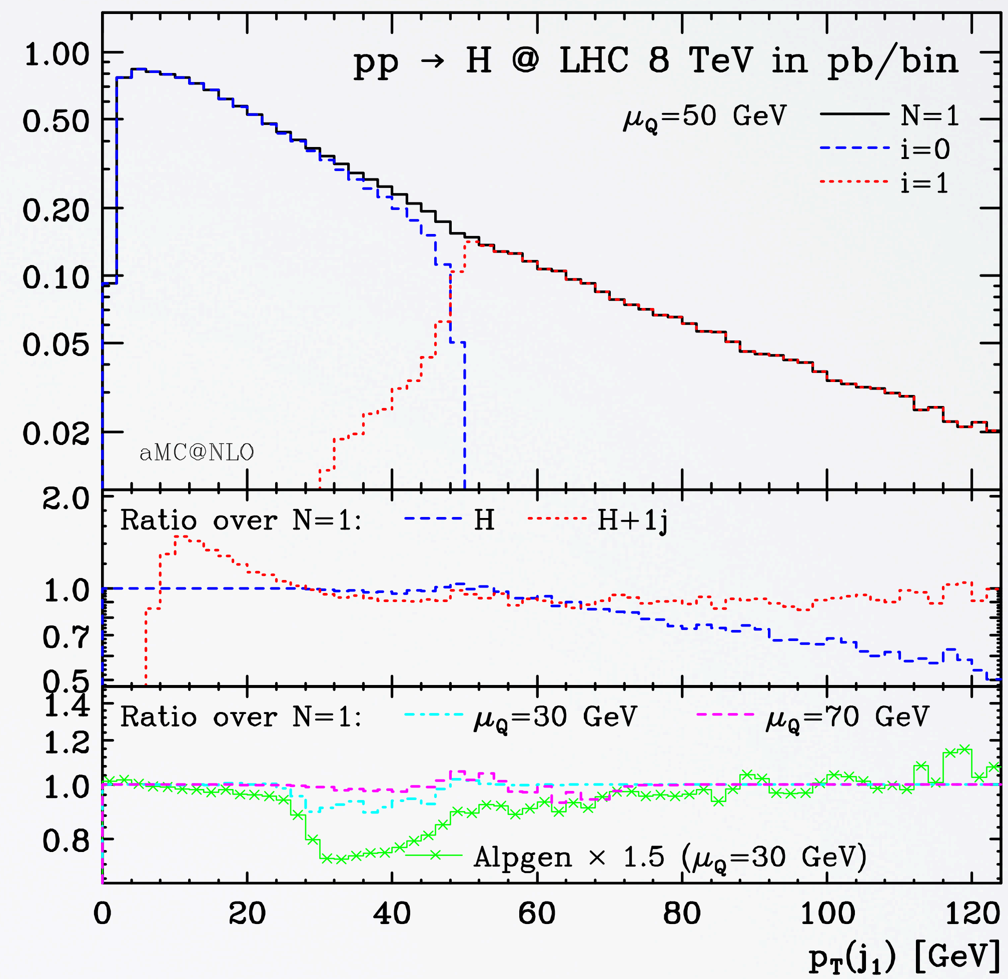
FxFx Multi-jet merging in aMC@NLO

[Frederix, Frixione, 1209.6215]

- aMC@NLO samples for S+0j, S+1j, S+2j, S+...j consistently without double counting (where S can be a Higgs, a ttbar pair, a W-boson, etc.)
- Use techniques from CKKW/MLM and multi-scale improved fixed order NLO or "MINLO" (Hamilton, Nason & Zanderighi, 2012) to define **exclusive event samples** for S+0j, S+1j, etc.
  - In such a way that the exclusive samples can simply be combined to one big event sample
- Special care needed for the highest multiplicity sample

FxFx Multi-jet merging in aMC@NLO





- Transverse momentum of the Higgs and of the 1st jet.
- Agreement with H+0j at MC@NLO and H+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale

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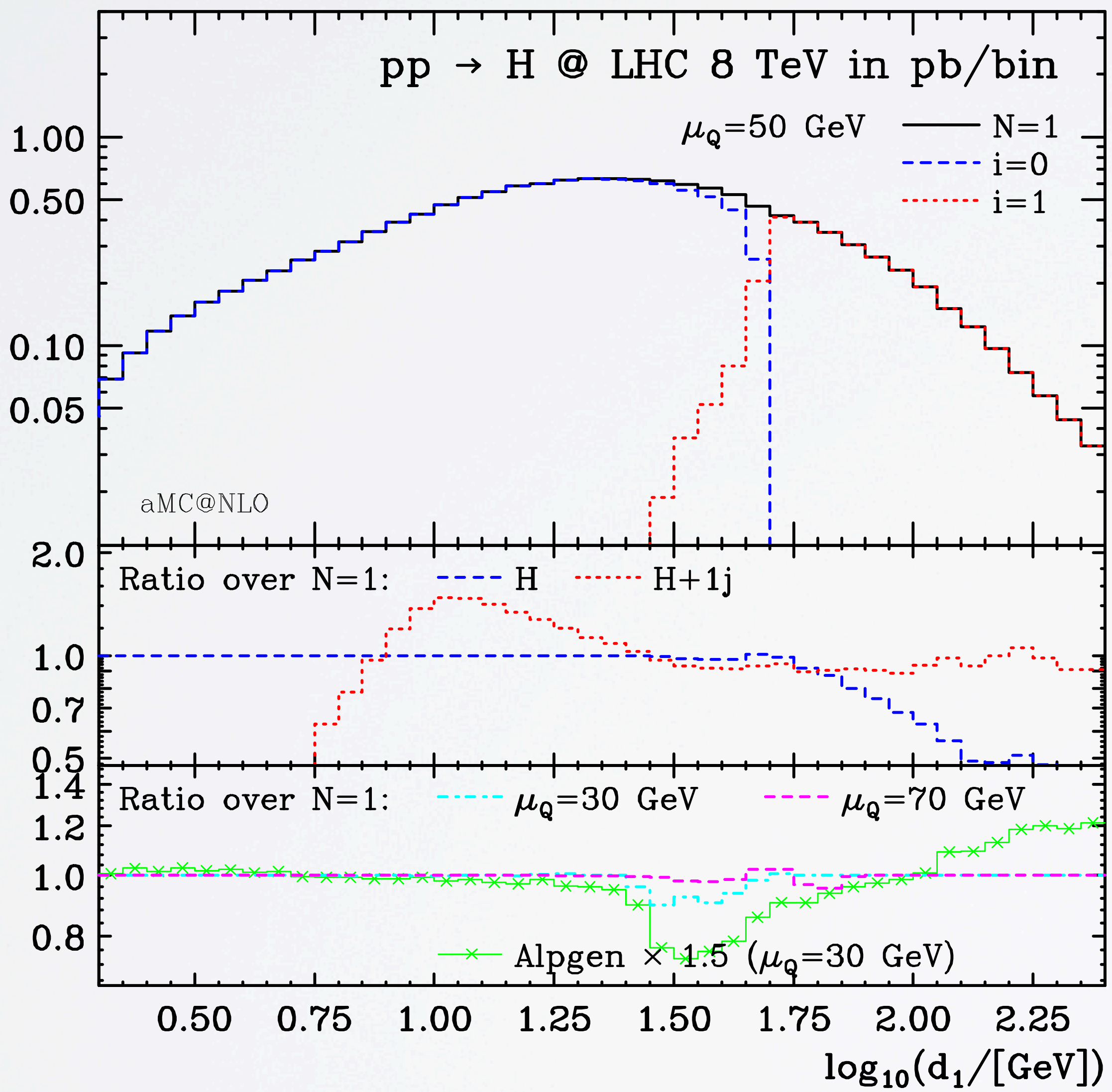

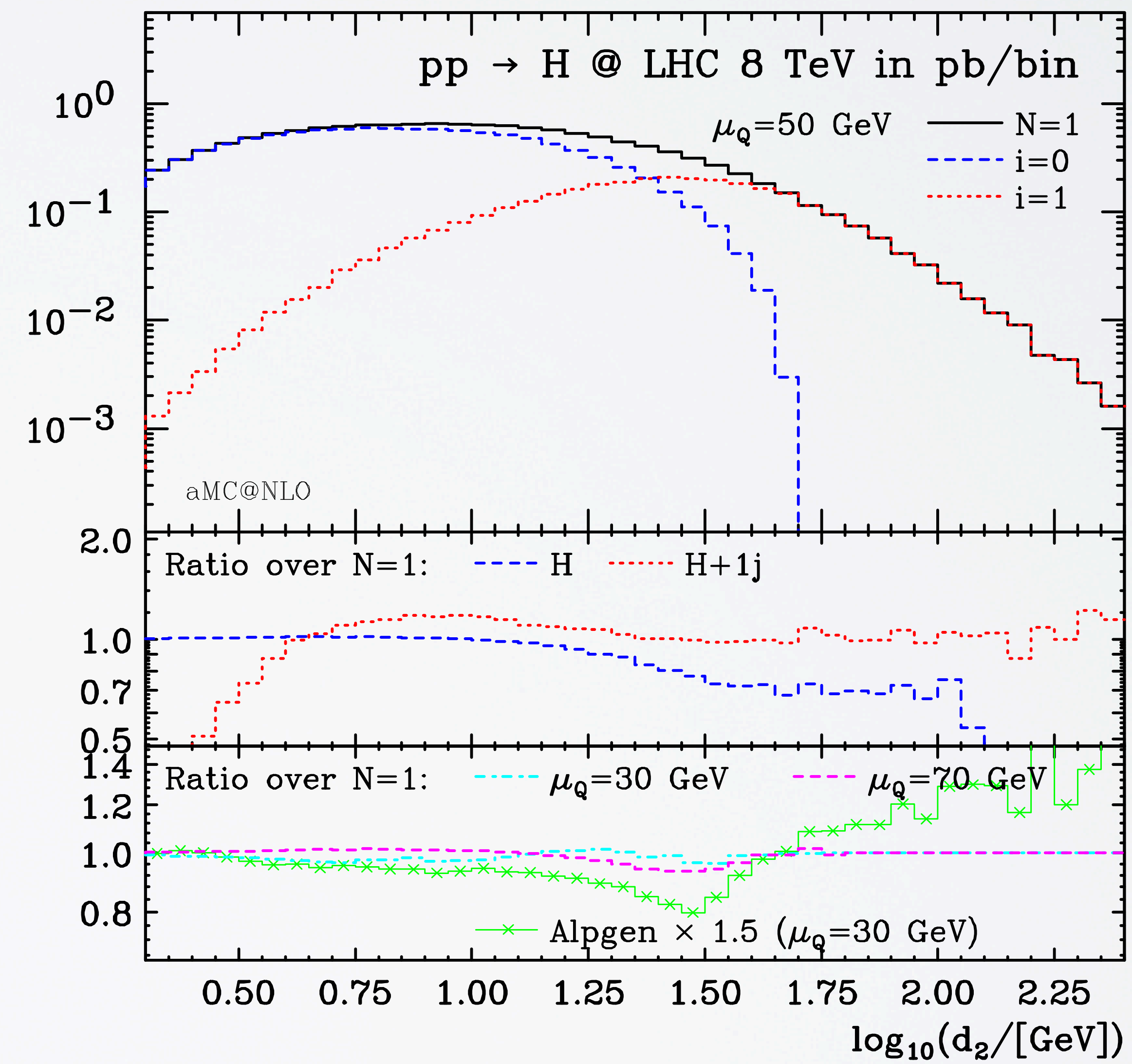

- Differential jet rates for 1→0 and 2→1

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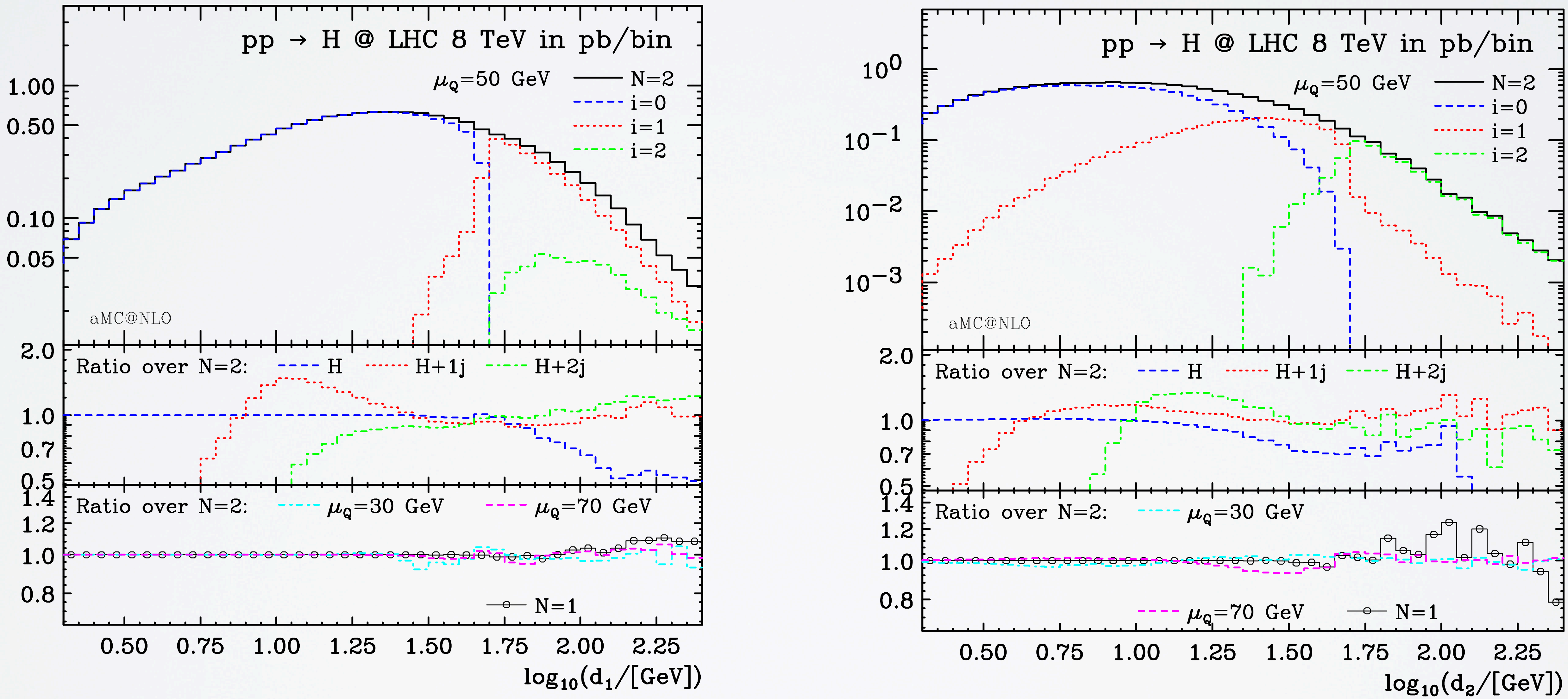


- Differential jet rates
- Matching up to 2 jets at NLO : consistent with up to 1 more jet.
- Method works for ttbar+jets and W+jets equally well.

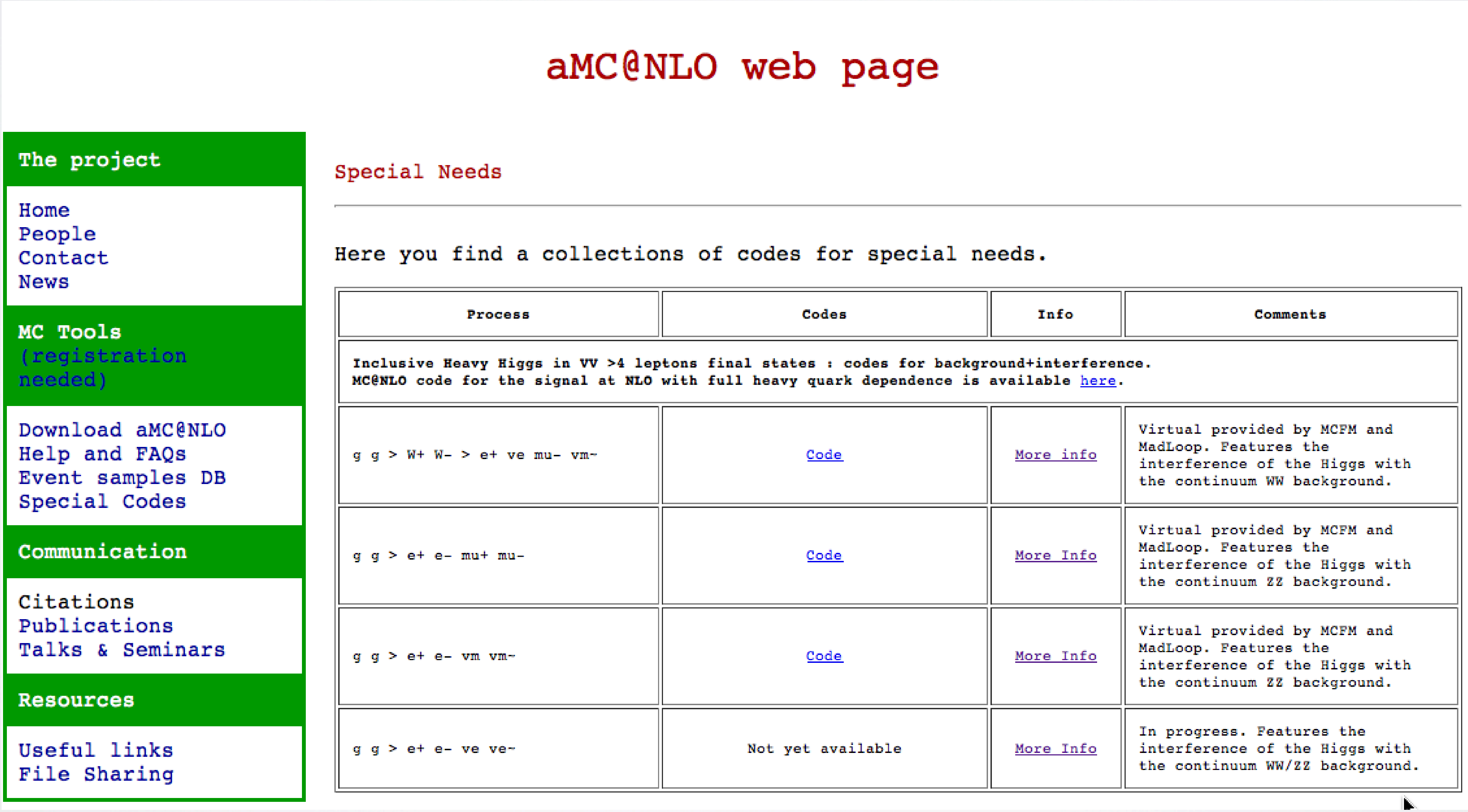
aMC@NLO LIMITATIONS AND PLANS (STATUS)

NOW	FUTURE (status)
• QCD corrections only	➡ NLO EW (development)
• SM processes (+ weak BSM) only	➡ SUSY (on-going)
• Pythia6Q^2, Herwig,HW++	➡ Pythia8 (validation)
• Rather simple final state with up to 1 or max 2 extra jets	➡ Multiparton optimizations (development)
• Loop induced procs not automatic yet	➡ Automation (on-going)
• FxFx merging not automatic yet	➡ Automation (to do)

HEAVY HIGGS

(a)MC@NLO APPLICATIONS TO HIGGS PHYSICS

[Hirschi, Frixione, Laureys, Maltoni]



Process	Codes	Info	Comments
Inclusive Heavy Higgs in VV >4 leptons final states : codes for background+interference. MC@NLO code for the signal at NLO with full heavy quark dependence is available here.			
g g > W+ W- > e+ ve mu- vm~	Code	More info	Virtual provided by MCFM and MadLoop. Features the interference of the Higgs with the continuum WW background.
g g > e+ e- mu+ mu-	Code	More Info	Virtual provided by MCFM and MadLoop. Features the interference of the Higgs with the continuum ZZ background.
g g > e+ e- vm vm~	Code	More Info	Virtual provided by MCFM and MadLoop. Features the interference of the Higgs with the continuum ZZ background.
g g > e+ e- ve ve~	Not yet available	More Info	In progress. Features the interference of the Higgs with the continuum WW/ZZ background.

(a)MC@NLO APPLICATIONS TO HIGGS PHYSICS

[Hirschi, Frixione, Laureys, Maltoni]

A MadLoop based code generates:

$$\sigma^{\mathrm{LO}}_{\mathrm{S+i+B}} = |\mathcal{M}_{\mathrm{S}}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{\mathrm{S}}\mathcal{M}^*_{\mathrm{B}}) + |\mathcal{M}_{\mathrm{B}}|^2$$

Events for the signal at NLO accuracy can be generated via the latest MC@NLOv4.09 i.e. with the FULL TOP AND BOTTOM MASS DEPENDENCE UP TO TWO LOOPS (in the virtuals) and ONE LOOP in the real contributions.

One can combine Signal and Interference+Background ADDITIVELY, schematically:

$$\sigma^{\mathrm{NLO}}_{\mathrm{S}} + \sigma^{\mathrm{LO}}_{\mathrm{i+B}} = \sigma^{\mathrm{NLO}}_{\mathrm{S}} + 2\,\mathrm{Re}(\mathcal{M}_{\mathrm{S}}\mathcal{M}^*_{\mathrm{B}}) + |\mathcal{M}_{\mathrm{B}}|^2$$

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[Hirschi, Frixione, Laureys, Maltoni]

Available :

gg (→H)→ ZZ → 4 ℓ

gg (→H)→ ZZ → $\ell\,\ell\,\nu\,\nu$

gg (→H)→ WW → $\ell\,\ell\,\nu\,\nu$

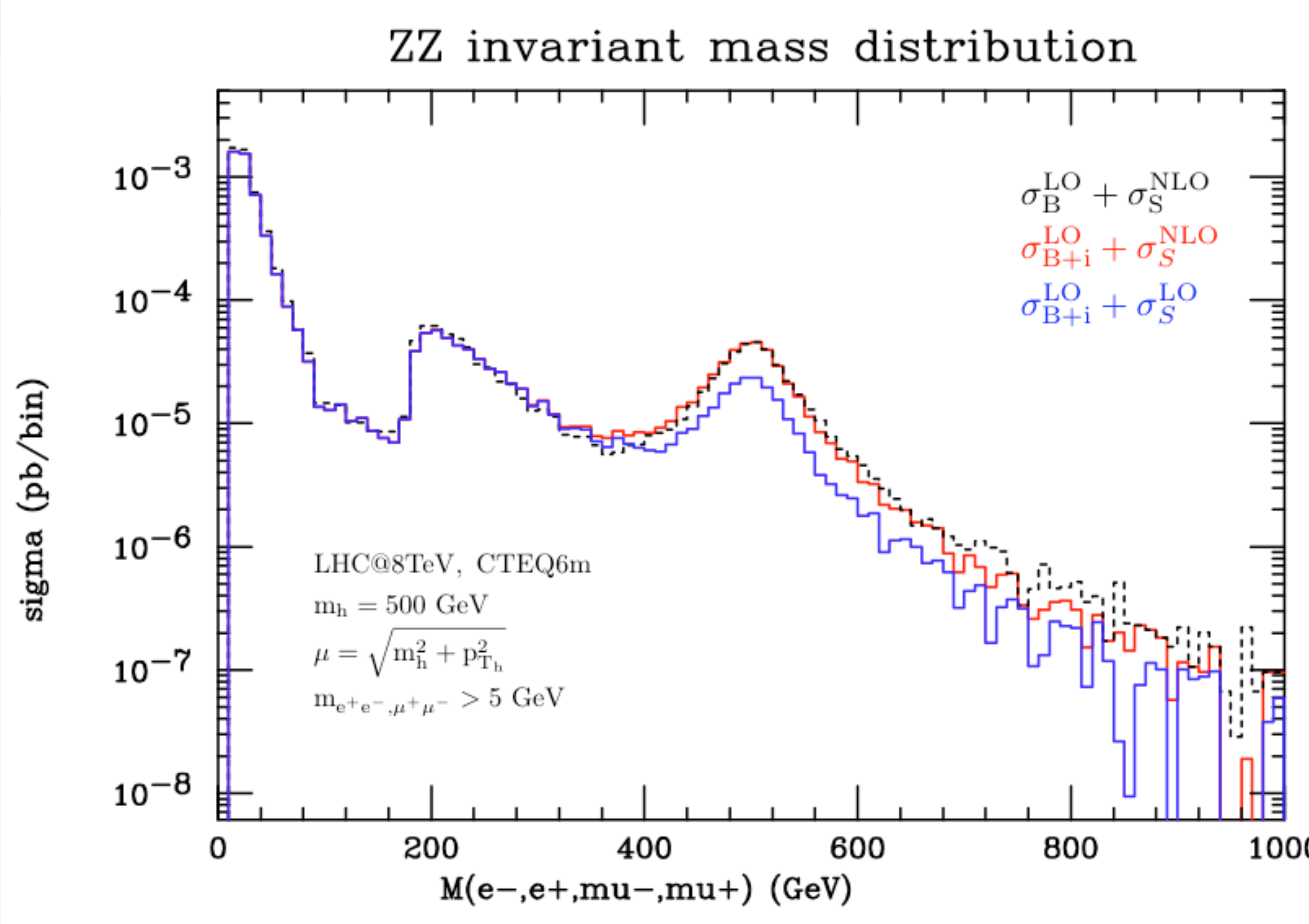
gg →H H (SM)

On going :

gg (→H)→ WW/ZZ → $\ell\,\ell\,\nu\,\nu$

gg →H H' (BSM)

any loop induced proc in SM and BSM



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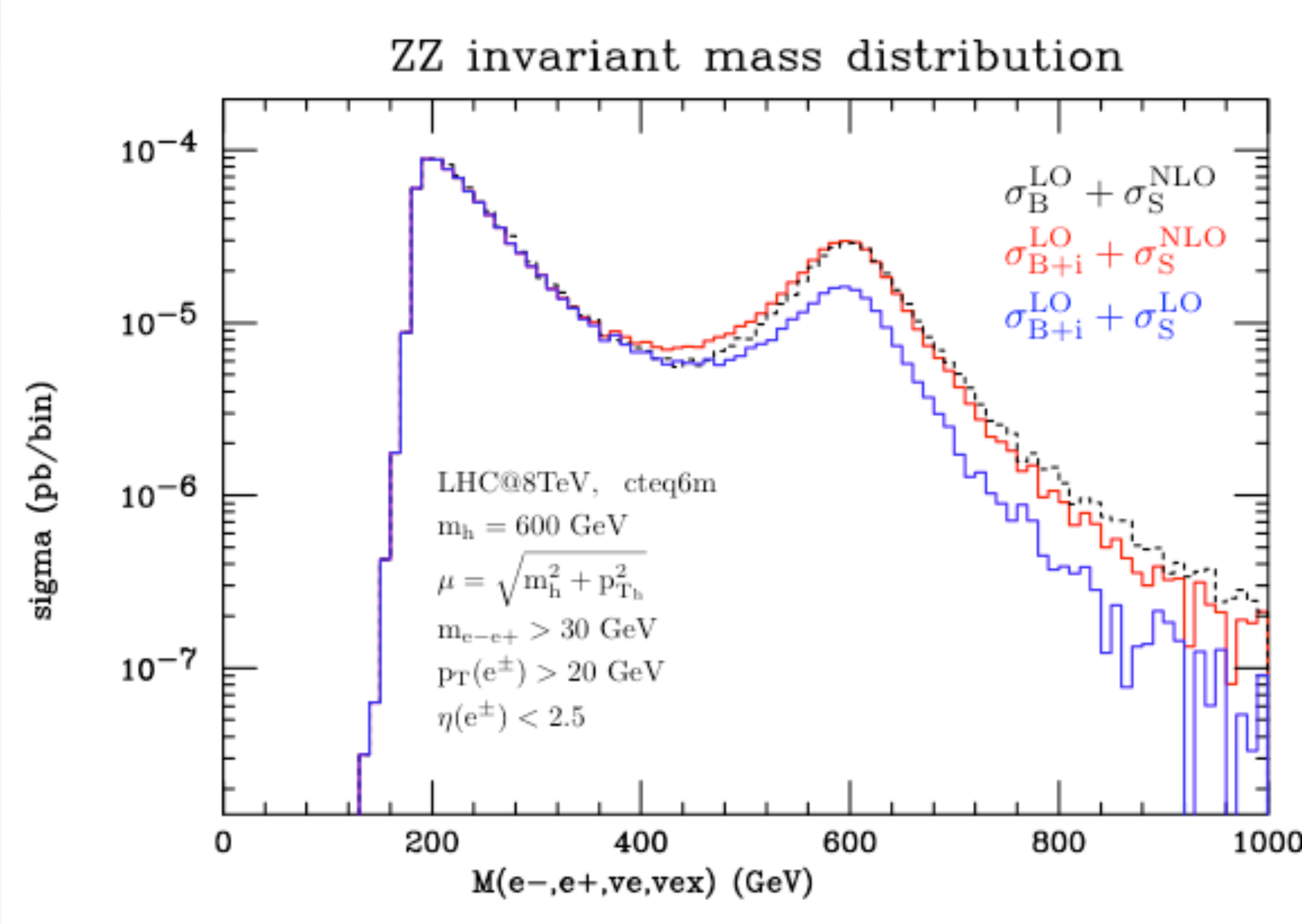

MADSPIN

THE MADSPIN DECAY PACKAGE

[Artoisenet, Frederix, Mattelaer, Rietkerk. ready to go, to appear]

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Anything in between?

THE MADSPIN DECAY PACKAGE

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$$|M_{P+D}|^2 / |M_P|^2 > \mathrm{Rand}() \ \max\left(|\mathrm{M_{P+D}}|^2 / |\mathrm{M_P}|^2\right)$$

- Validated with for t t~ and singletop

THE MADSPIN DECAY PACKAGE

Frixione, Laenen, Motylinski & Webber, hep-ph/0702198

aMC@NLO+DecayPackage