AAA PHENOMENOLOGY AT THE LHC

Fabio Maltoni
CP3-UCLouvain

Durham, Annual Theory Meeting
16 Dec 2011

PHENOMENOLOGY

- AUTOMATIC
    - ACCURATE
        - AMAZING

new MC tools for hadron collider physics.

PLAN

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- What do we need from TH to make discoveries?

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- The first MC revolution

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- The first MC revolution
- The loop revolution

PLAN

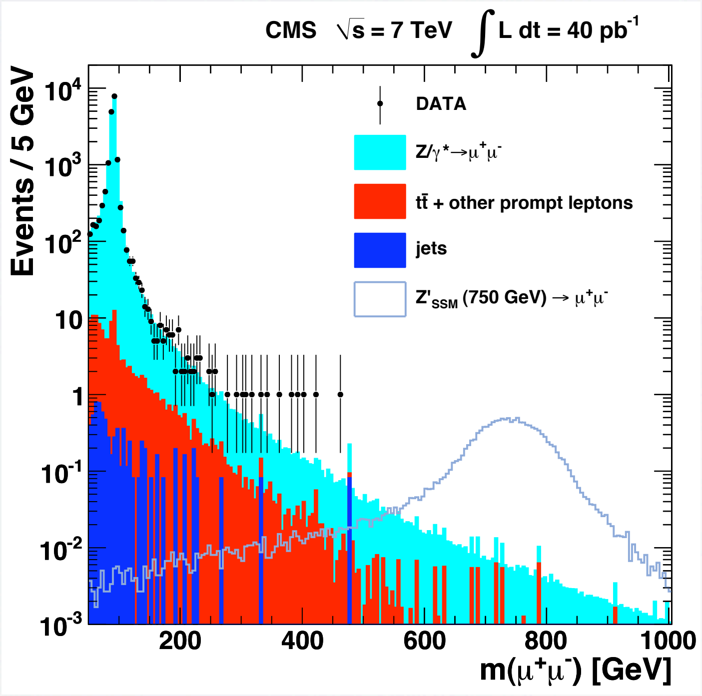
- What do we need from TH to make discoveries?
- The first MC revolution
- The loop revolution
- The dawn of the AAA era

MichalengeloMangano®

Discoveries at hadron colliders

Discoveries at hadron colliders

peak
pp→Z'→e+e-



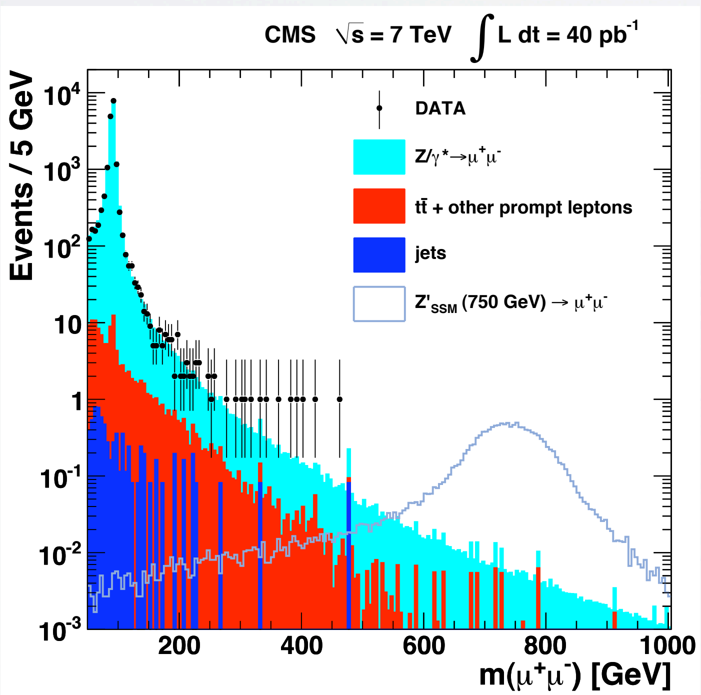
"easy"

Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

Discoveries at hadron colliders

peak

$pp \to Z' \to e^+e^-$



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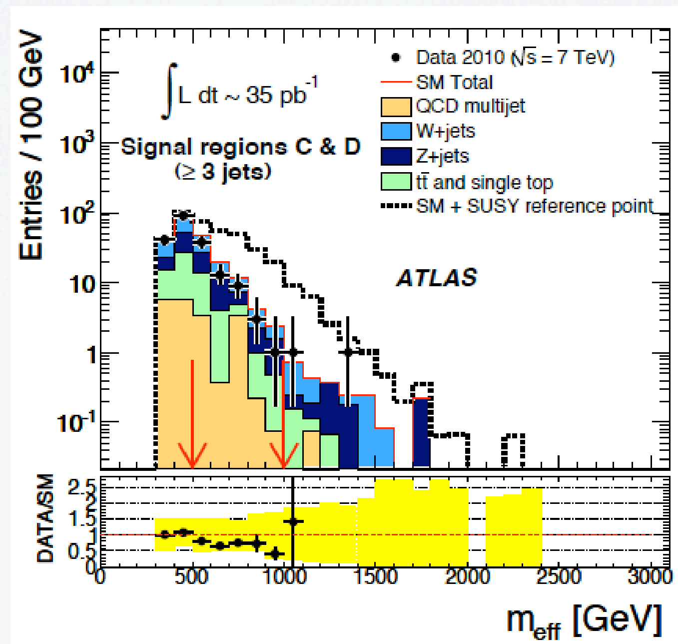
shape

$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + ET$



hard

Background shapes needed. Flexible MC for both signal and background tuned and validated with data.

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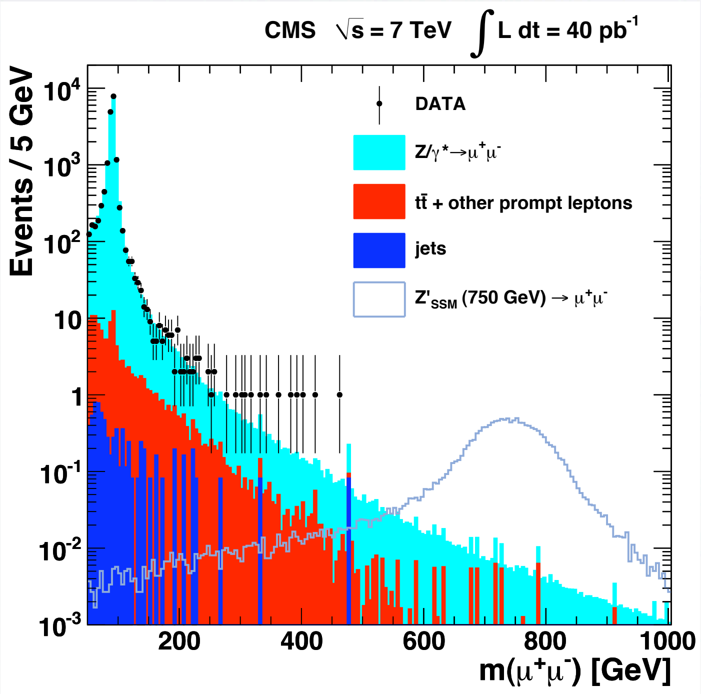
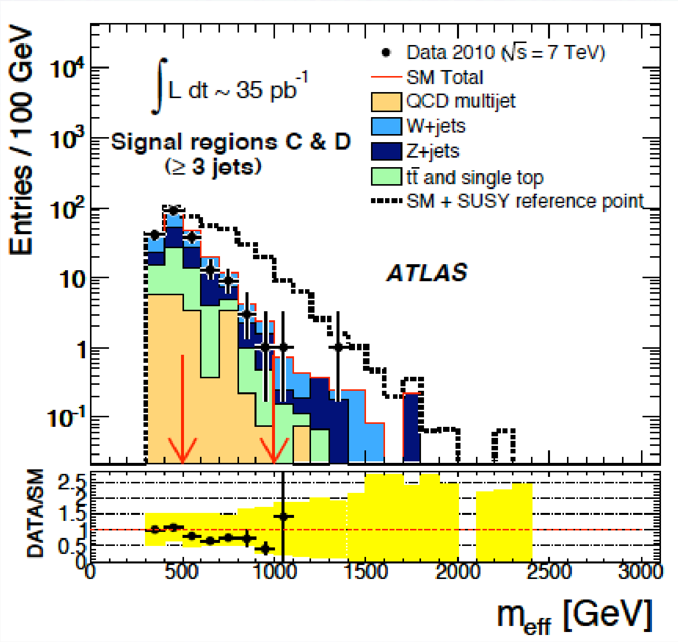
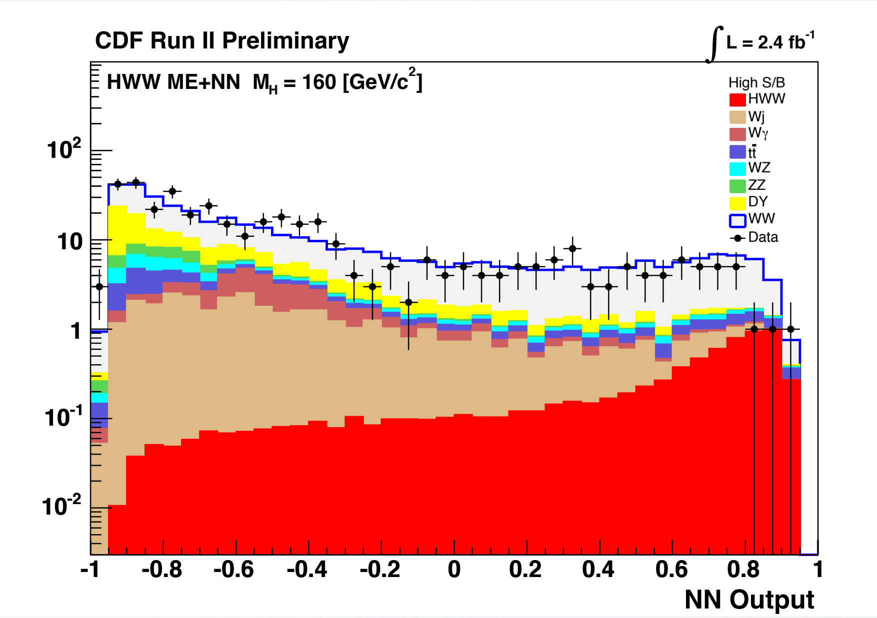
Discoveries at hadron colliders

peak	shape	rate
pp→Z'→e+e-	pp→g̃g̃,g̃q̃,q̃q̃→jets+ET	pp→H→W+W-



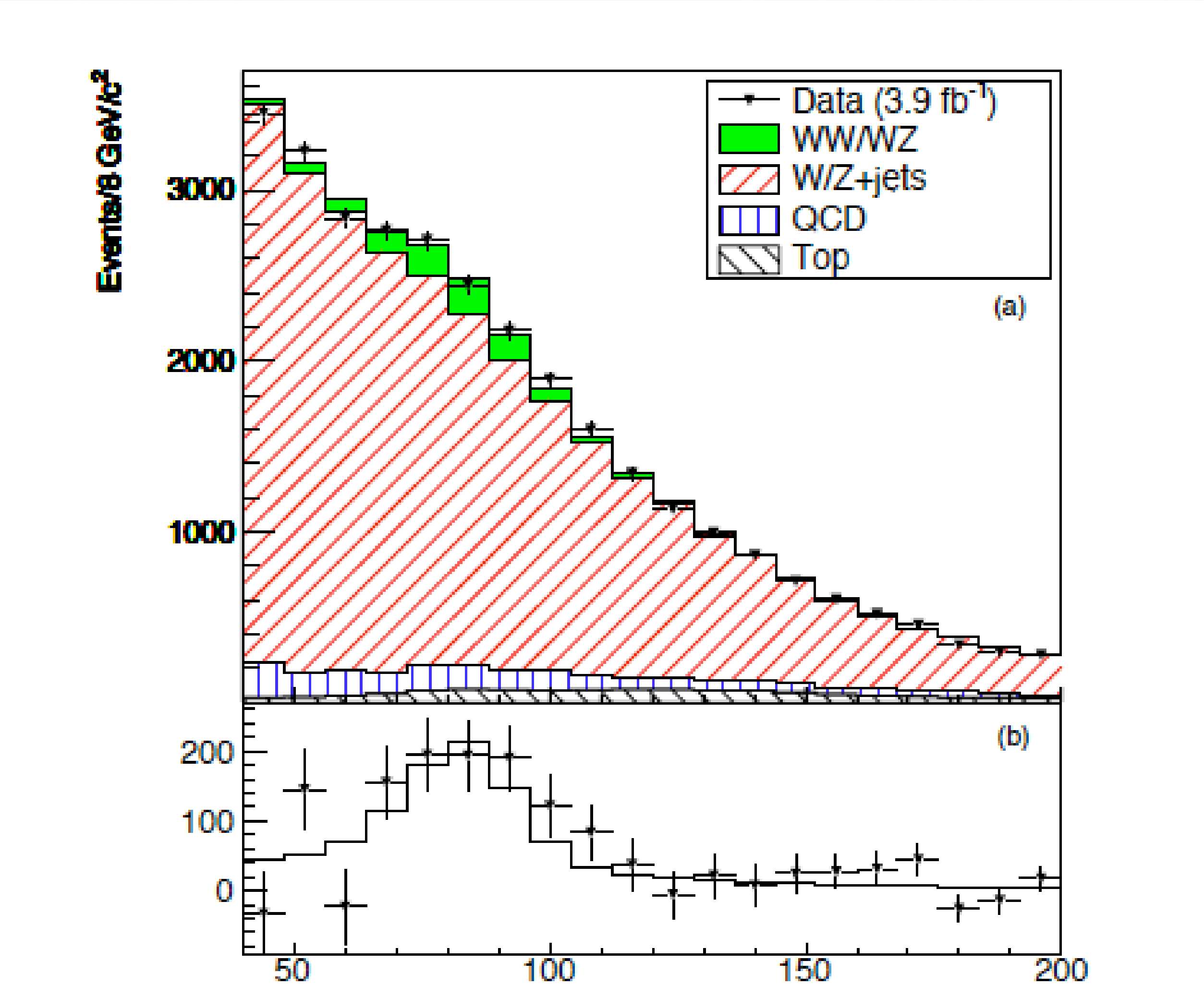




"easy"	hard	very hard
Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)	Background shapes needed. Flexible MC for both signal and background tuned and validated with data.	Background normalization and shapes known very well. Interplay with the best theoretical predictions (via MC) and data.

WJJ

CDF observes 3-σ deviation to the SM signal.

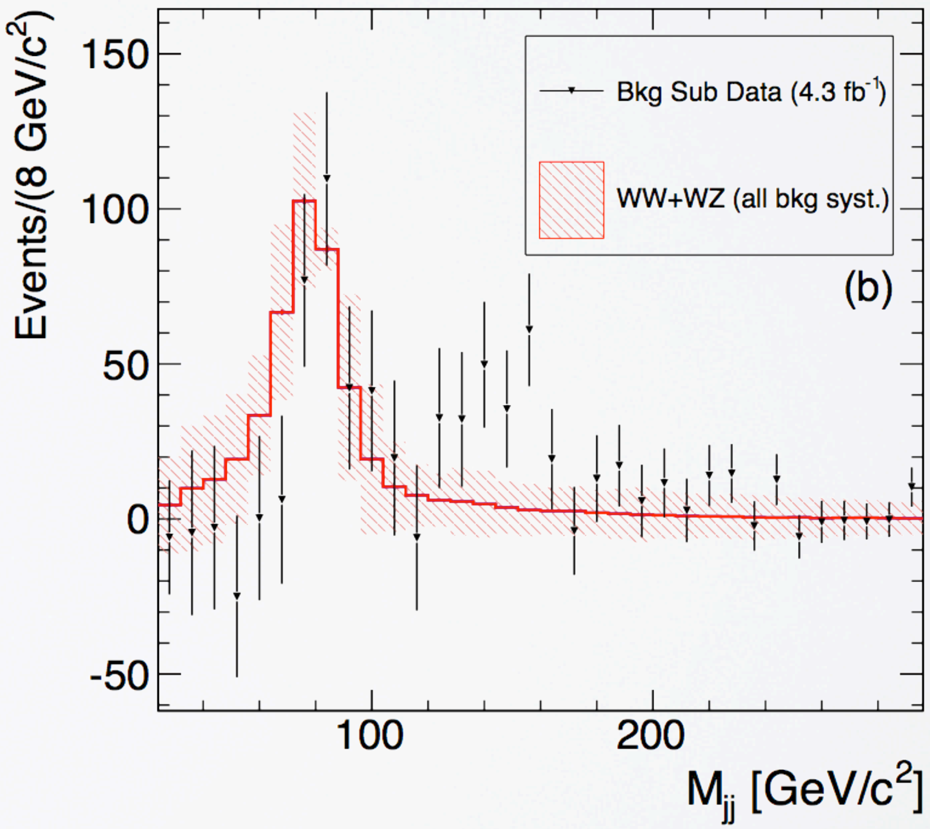


arXiv:1104.0699v1

- New Physics, stat. fluctuations?
- Unreliable prediction?

➡ W+jets treated at LO and distributions checked with MCFM!

➡ Top background from theory.



WJJ

~40 papers on BSM interpretations in the last weeks.

a handful of papers on SM backgrounds:
[Sullivan and Menon, 1104.3790]
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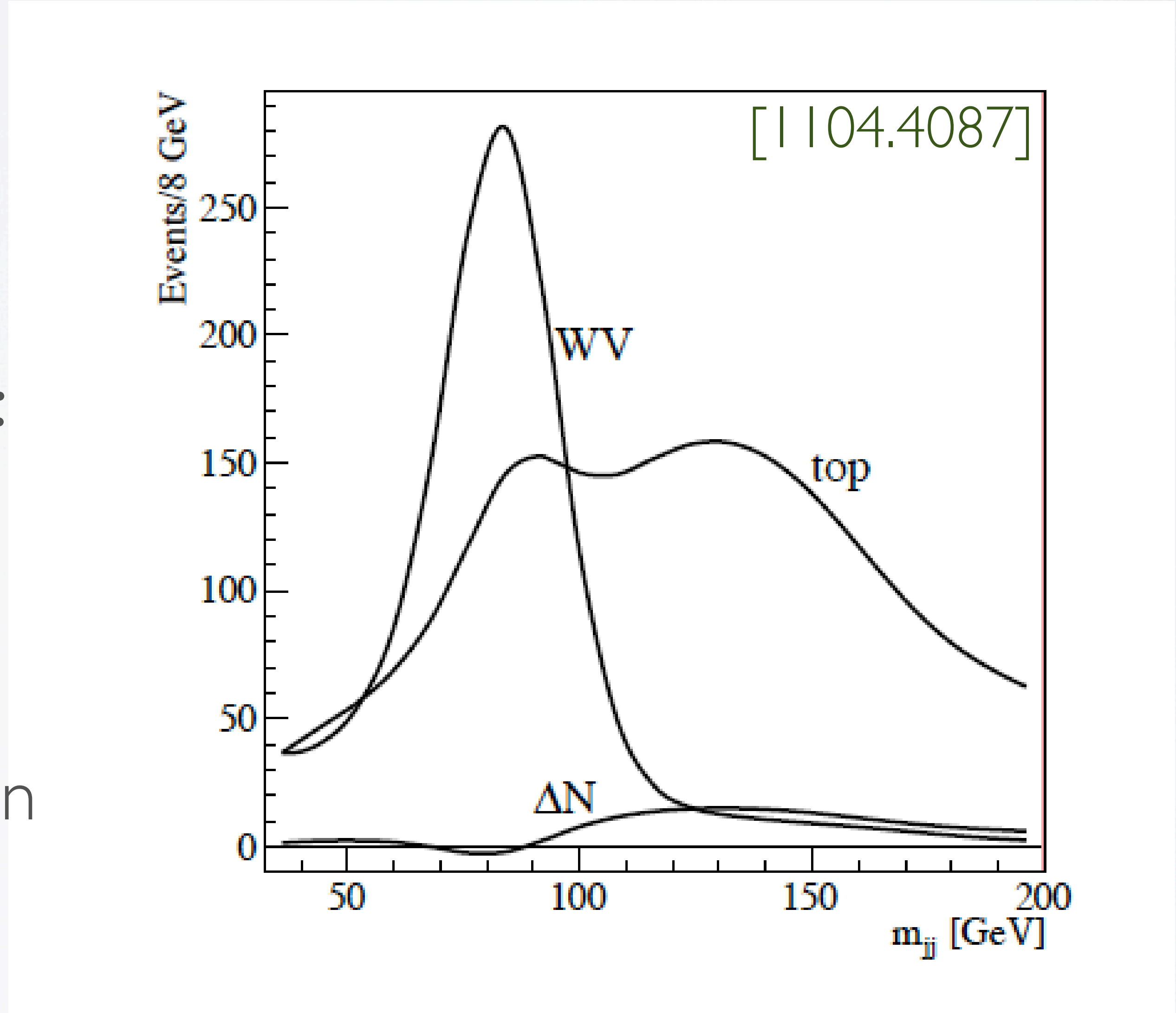
related to top production and in particular to single top.



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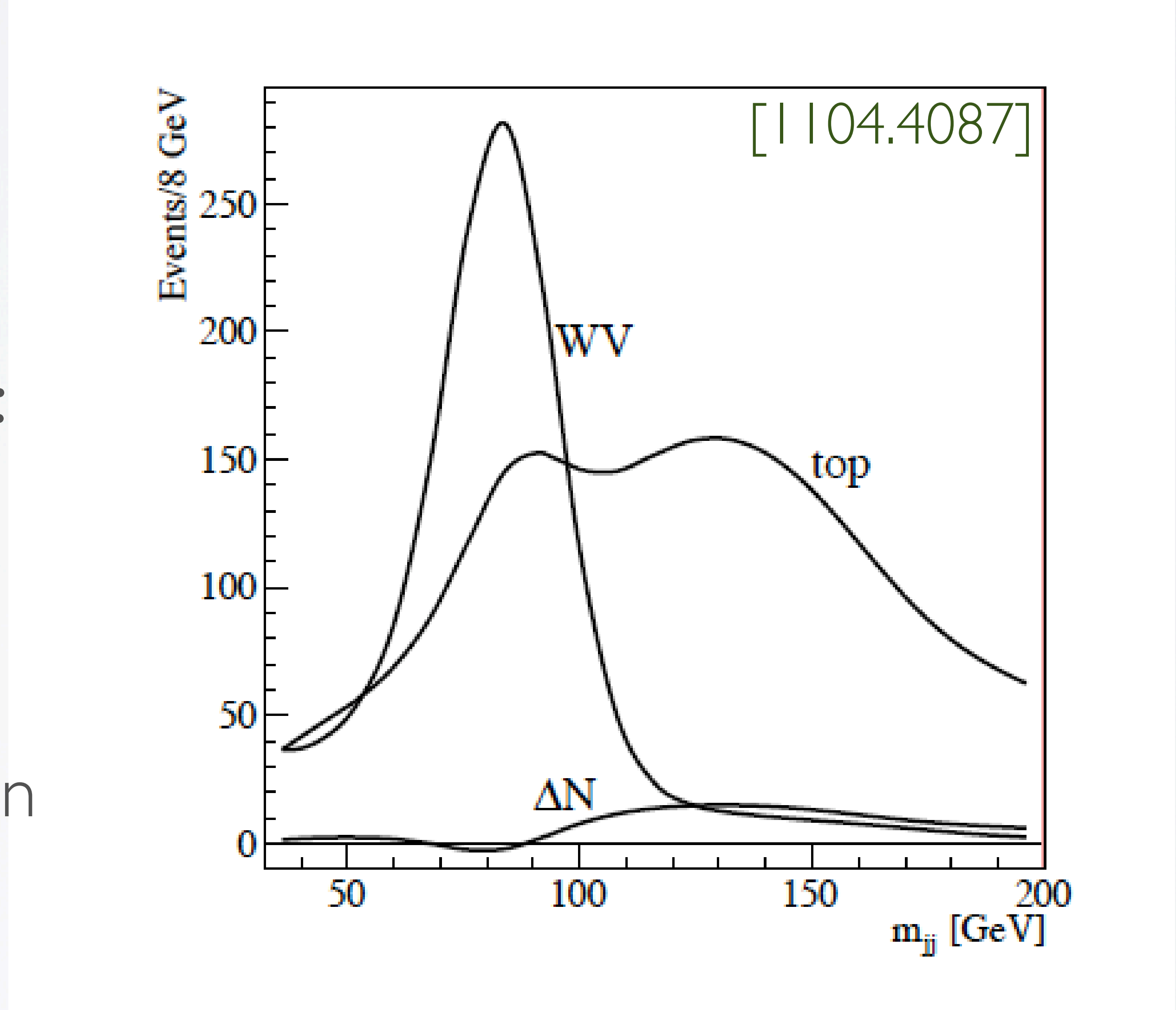

UPSHOT: Very challenging!
Best possible SM and ready-to-go BSM predictions necessary!

MOTIVATION : SUMMARY

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- Accurate and experimental friendly predictions for collider physics range from being very useful to strictly necessary.

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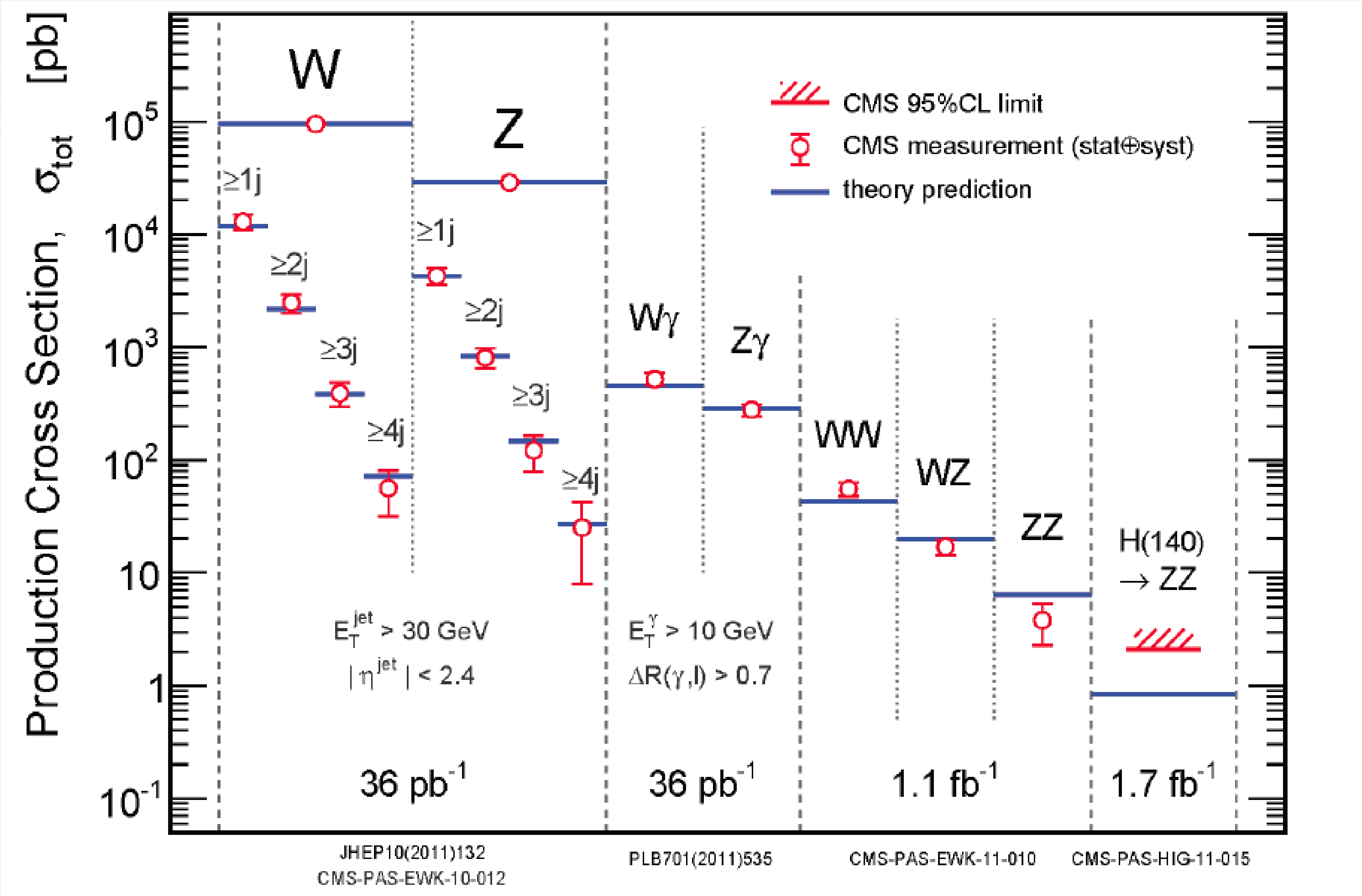

MOTIVATION : SUMMARY

Houston, thanks for your help
in the preliminaries...

... I can do it alone from now on....
no need of using Newton's law to walk ;-)

...I am much better off just
modeling the data...

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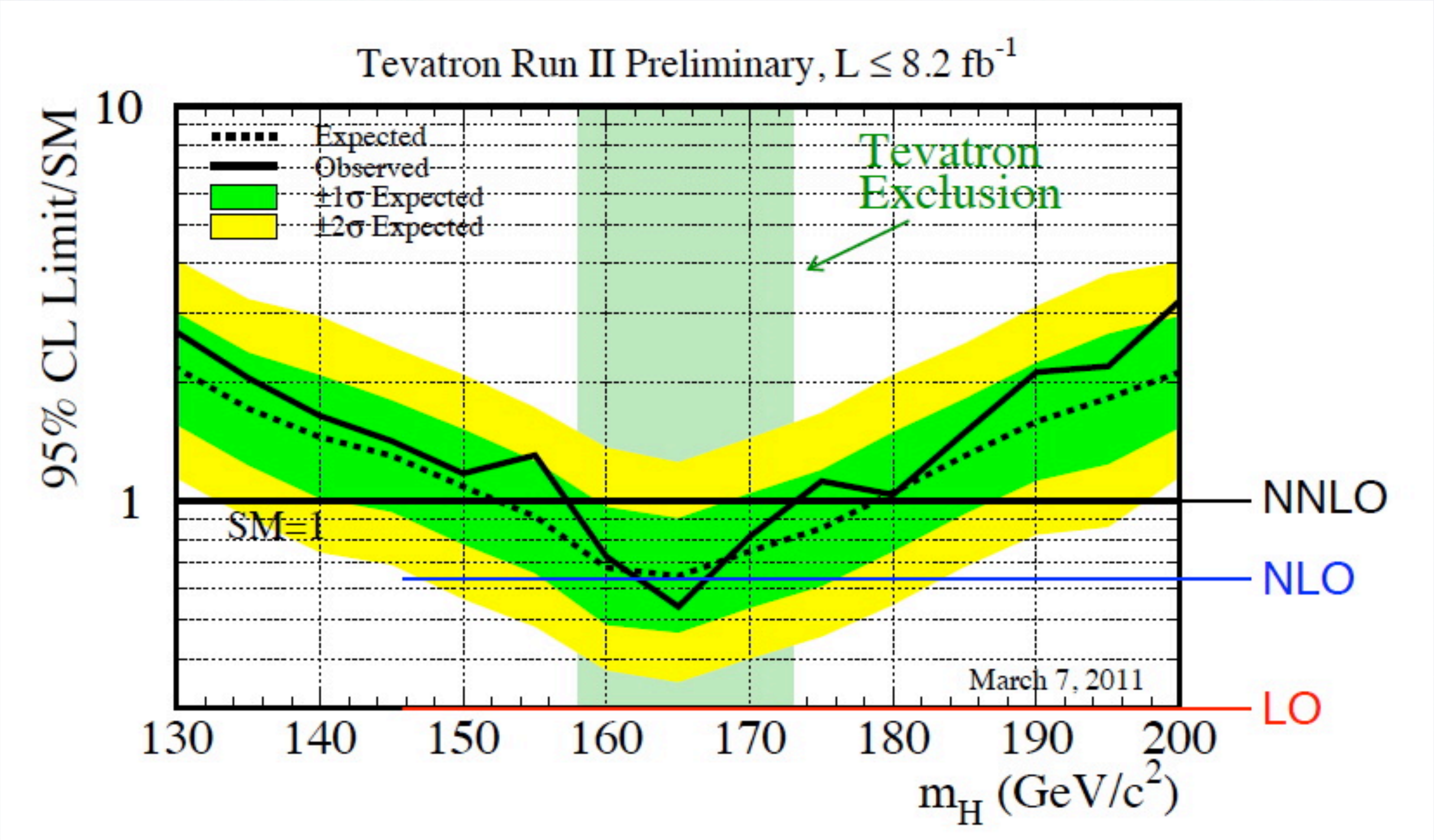

For illustration purposes only!

RobertHarlander®

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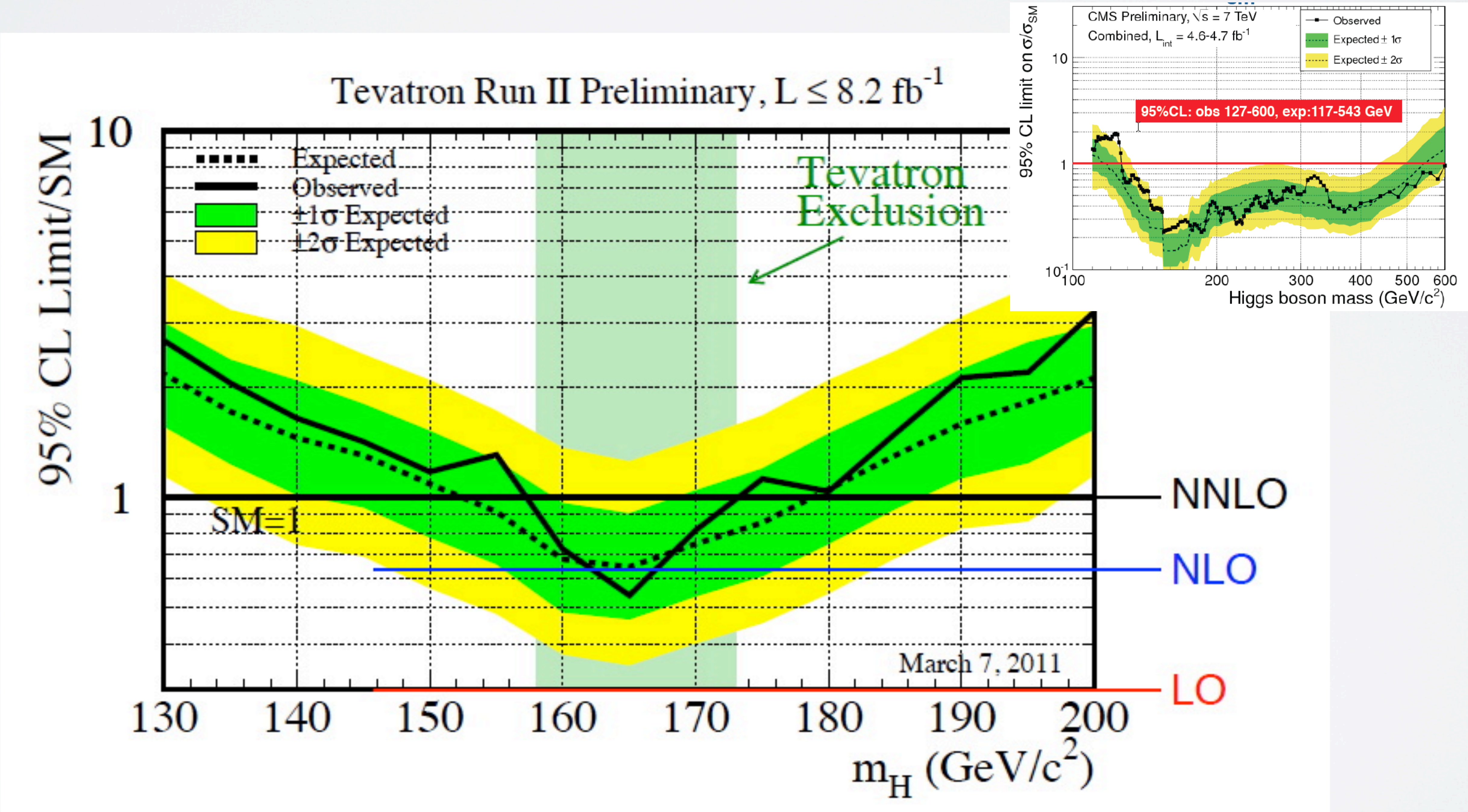

For illustration purposes only!

...SO
HOW WE (USED TO) MAKE PREDICTIONS AT HADRON COLLIDERS?

Master QCD formula

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution functions (from exp, but evolution from th). (MSTW, CTEQ, NNPDF, ...)

2. Short distance coefficients as an expansion in α_S (from th).

HOW WE (USED TO) MAKE PREDICTIONS?

First way:

- For low multiplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)
  ⇒ $$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \ldots$$

TH

- For high multiplicity use the tree-level results

Comments:

1. The theoretical errors systematically decrease.
2. Pure theoretical point of view.
3. A lot of new techniques and universal algorithms have been developed.
4. Final description only in terms of partons and calculation of IR safe observables ⇒ not directly useful for simulations

NLO BASICS

NLO contributions have three parts

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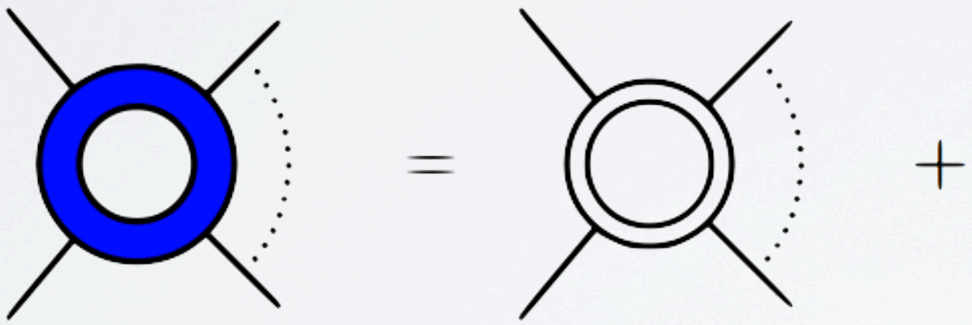
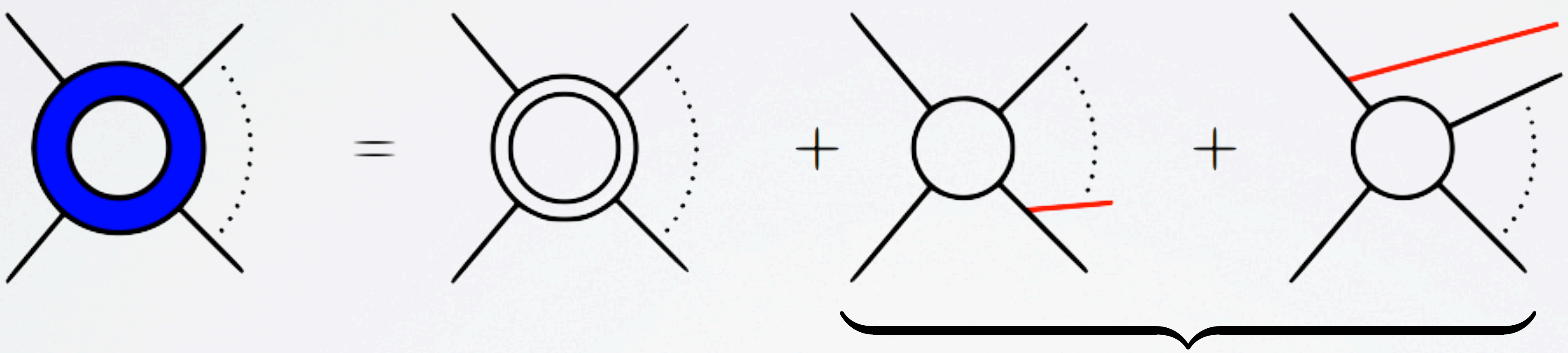


$$\sigma^{\rm NLO} = \int_m d^{(d)}\sigma^V +$$

Virtual part

NLO BASICS

NLO contributions have three parts



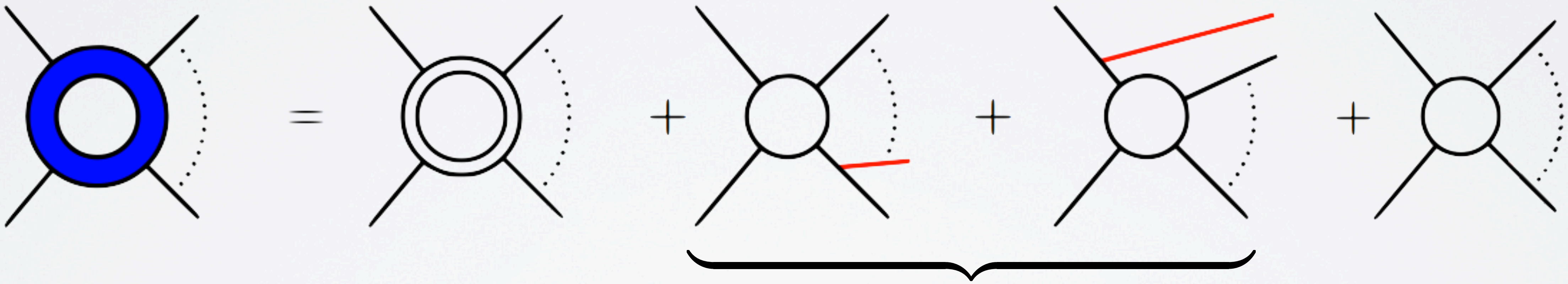
$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R +$$

Virtual part

Real emission part

NLO BASICS

NLO contributions have three parts



$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

Virtual part   Real emission part   Born

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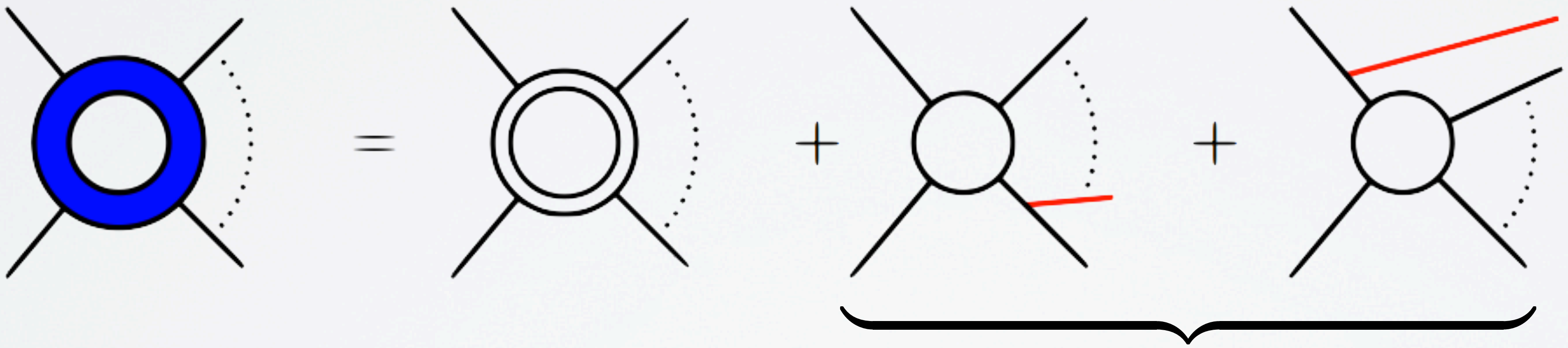

$$\sigma^{\rm NLO} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

Virtual part — Real emission part — Born

- Loops have been for long the bottleneck of NLO computations
- Virtuals and Reals are each divergent and subtraction scheme need to be used (Dipoles, FKS, Antenna's)
- A lot of work is necessary for each computation

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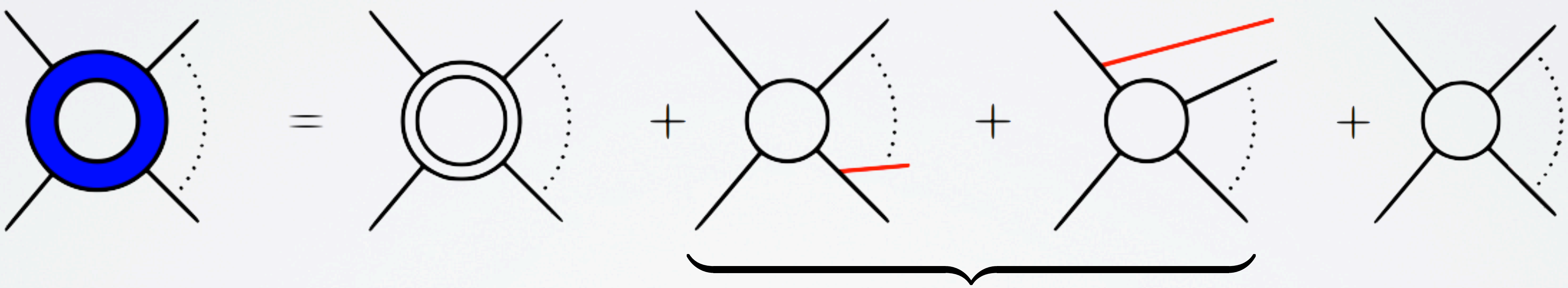

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The cost of a new prediction at NLO can easily exceed 100k$.

LOOP TECHNIQUES

modified by the speaker

BEST EXAMPLE: MCFM

Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]

Final state	Notes	Reference
W/Z		
diboson (W/Z/γ)	photon fragmentation, anomalous couplings	hep-ph/9905386, arXiv:1105.0020
Wbb	massless b-quark massive b quark	hep-ph/9810489 arXiv:1011.6647
Zbb	massless b-quark	hep-ph/0006304
W/Z+1 jet		
W/Z+2 jets		hep-ph/0202176, hep-ph/0308195
Wc	massive c-quark	hep-ph/0506289
Zb	5-flavour scheme	hep-ph/0312024
Zb+jet	5-flavour scheme	hep-ph/0510362

Final state	Notes	Reference
H (gluon fusion)		
H+1 jet (g.f.)	effective coupling	
H+2 jets (g.f.)	effective coupling	hep-ph/0608194, arXiv:1001.4495
WH/ZH		
H (WBF)		hep-ph/0403194
Hb	5-flavour scheme	hep-ph/0204093
t	s- and t-channel (5F), top decay included	hep-ph/0408158
t	t-channel (4F)	arXiv:0903.0005, arXiv:0907.3933
Wt	5-flavour scheme	hep-ph/0506289
top pairs	top decay included	

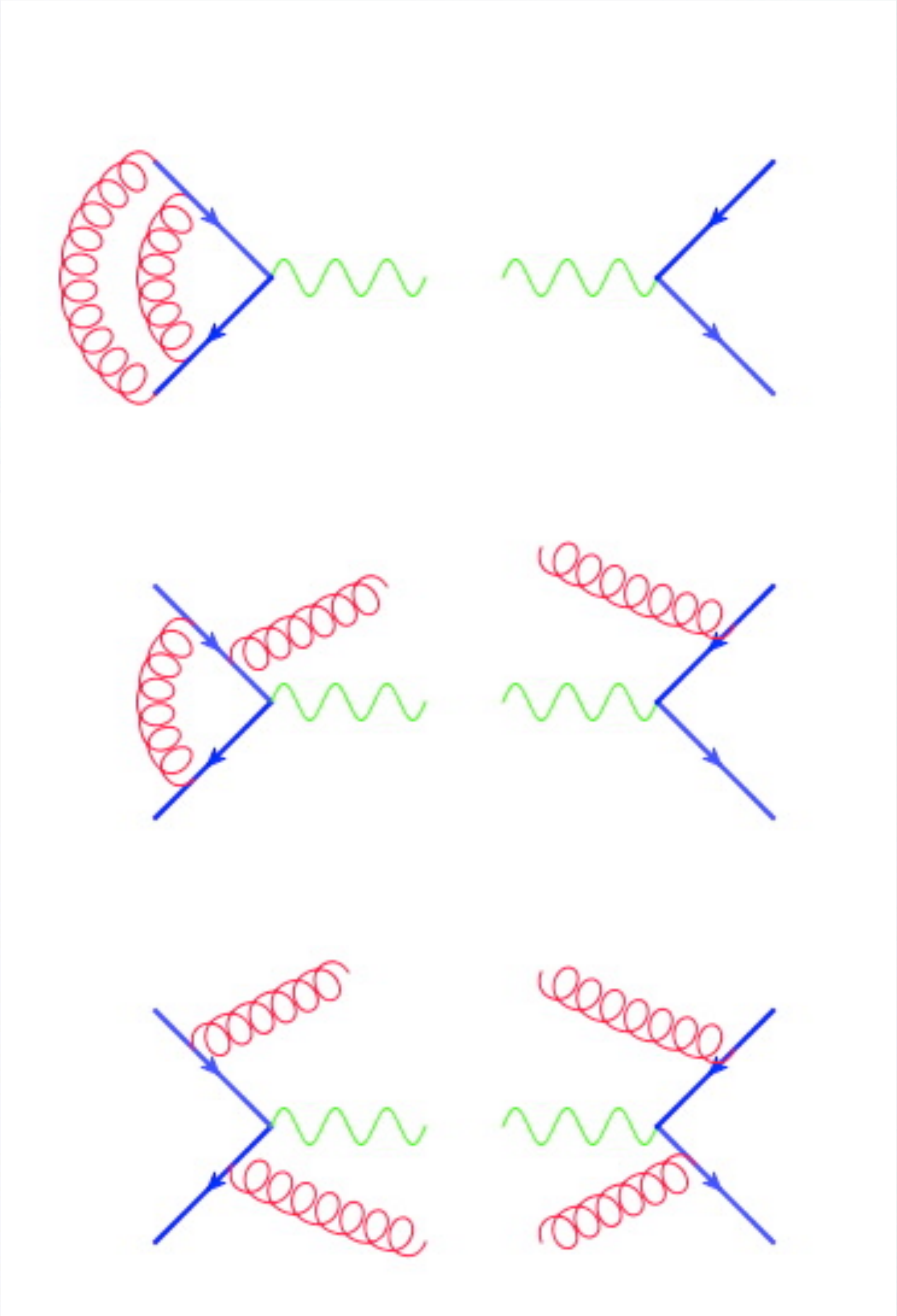
- ~30 processes
- First results implemented in 1998 ...this is 13 years worth of work of several people **(~4M$)**
- Cross sections and parton-level distributions at NLO are provided
- One general framework. However, each process implemented by hand.

What about NNLO?

- Virtual-Virtual : O(100) terms

- Real-Virtual : O(300) terms

- Real-Real : O(500) terms

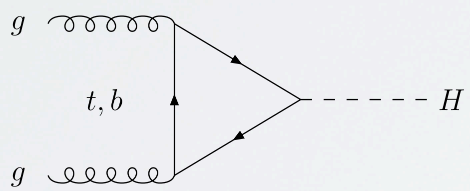


What about NNLO?

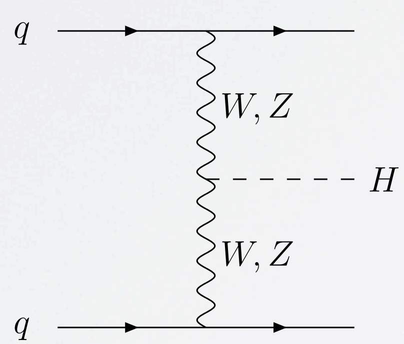
- Handful of parton-level results available mostly 2→1 at the Born level : Higgs, Drell-Yan, HV, VBF.
- Algorithms now available to deal any pp→color singlets at NNLO
- Bottleneck: numerical and local combination of all the various terms
- Several proposal based on CS, antenna's and FKS+sector decomposition.....

Apologies for absence of references here. Too hard to have all the efforts in one page.

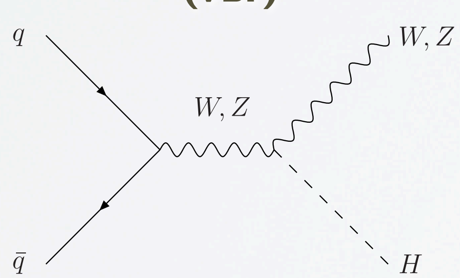
Higgs predictions at 7 TeV



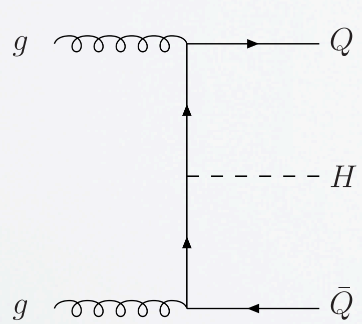
GluonFusion



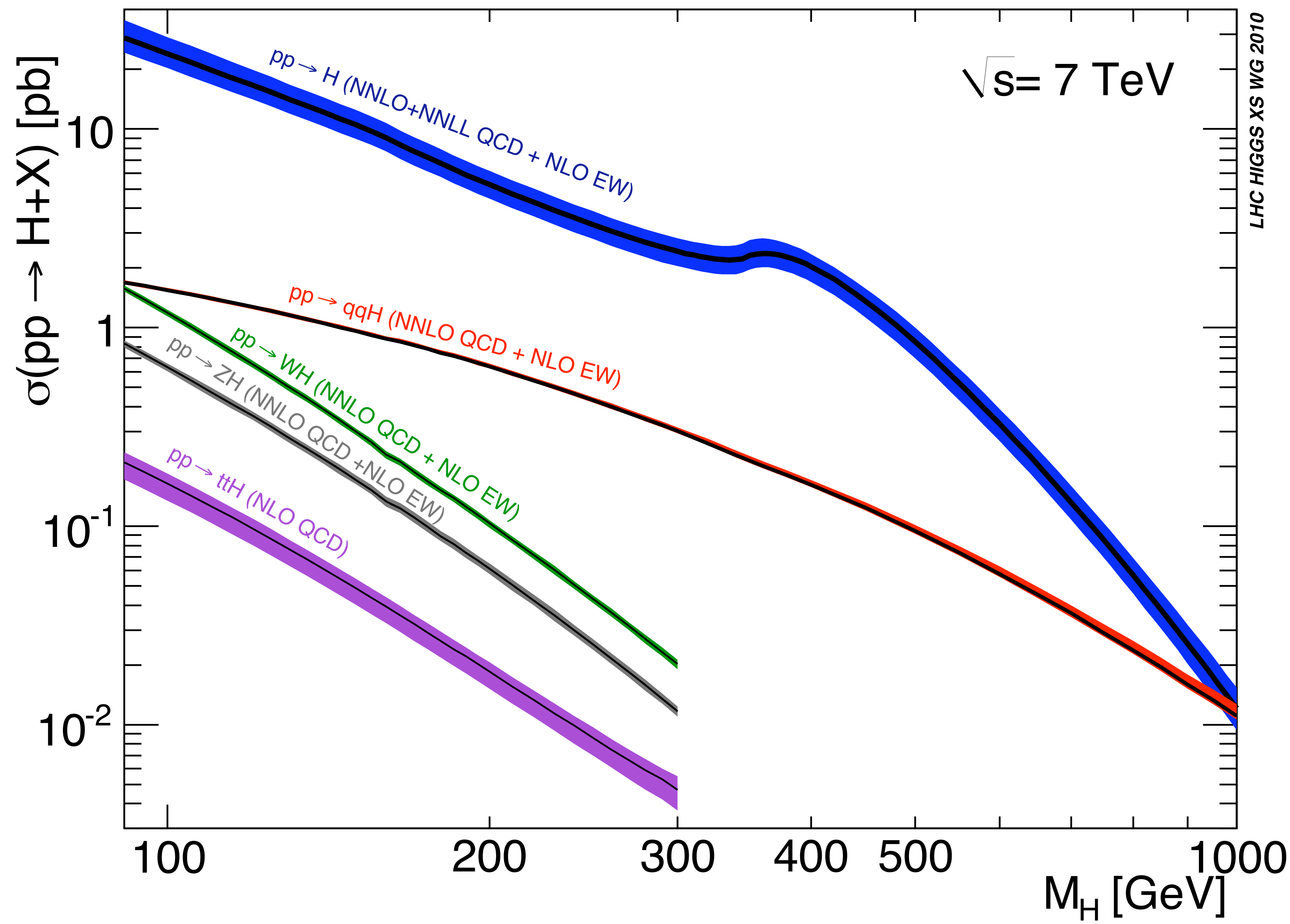
vector boson fusion (VBF)



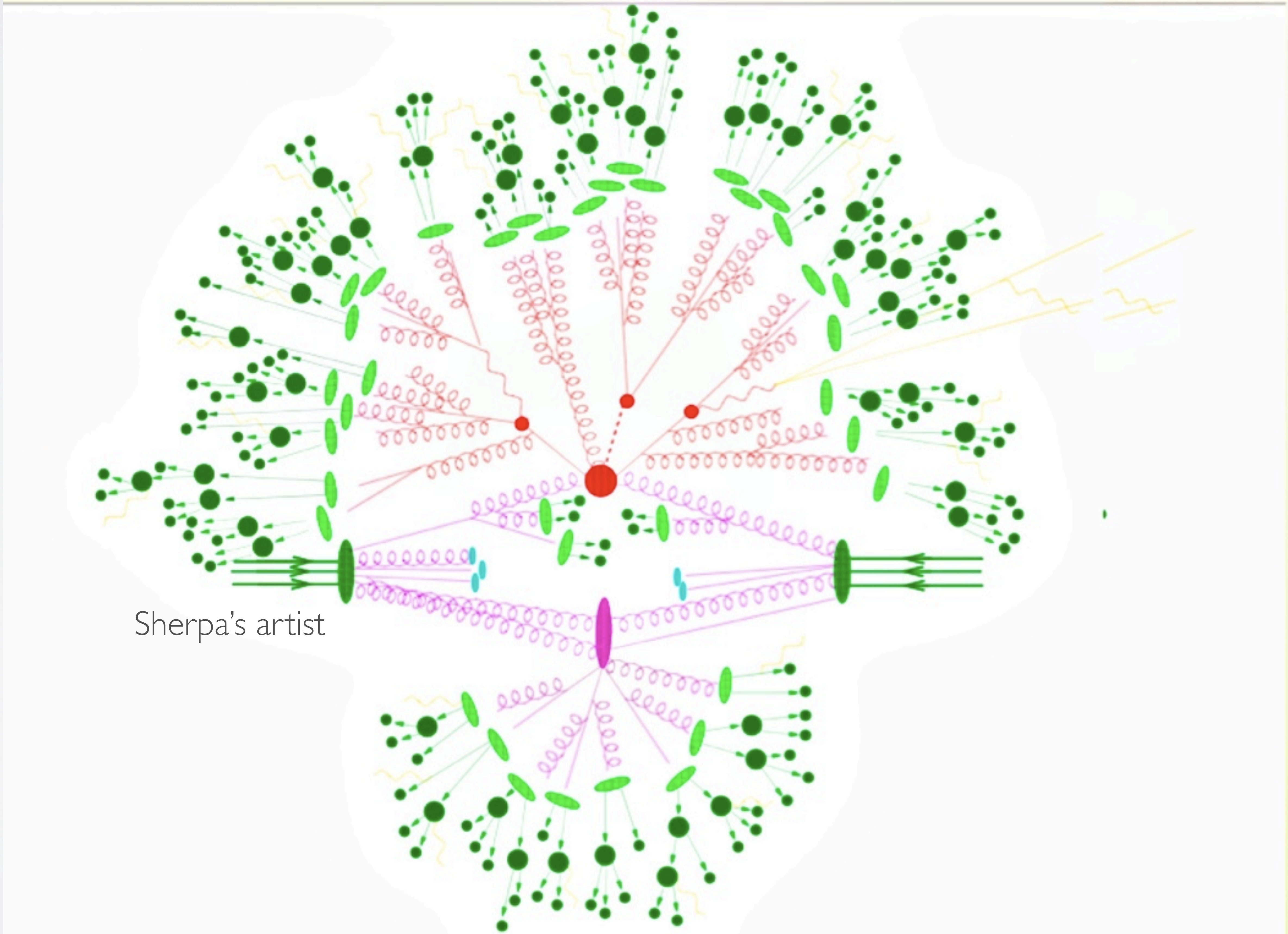
associated production with vector bosons



associated production with heavy quarks



Events at hadron colliders



Sherpa's artist

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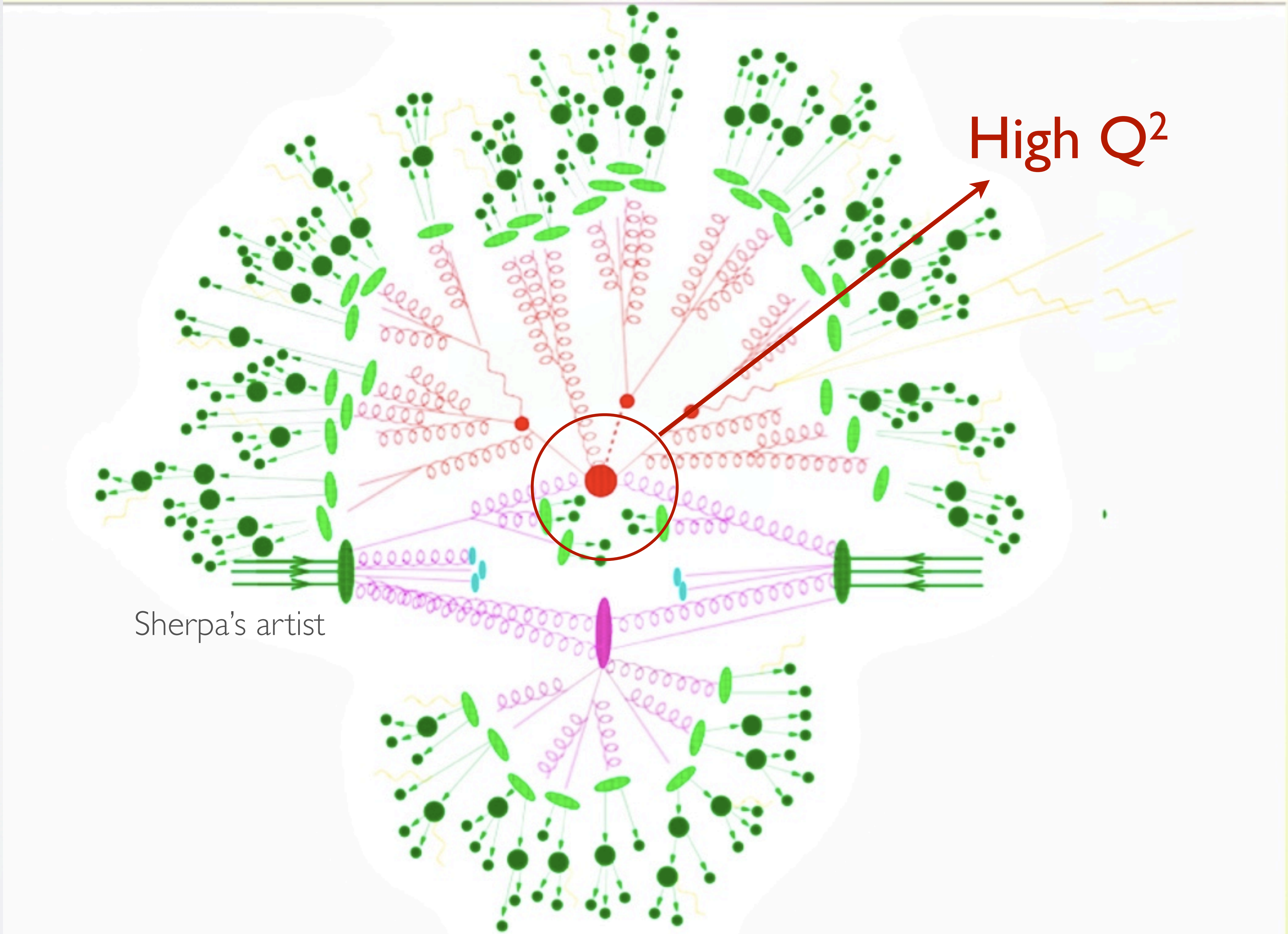

Sherpa's artist

HOW WE (USED TO) MAKE PREDICTIONS?

Second way:

- Describe final states with high multiplicities starting from $2 \to 1$ or $2 \to 2$ procs, using parton showers, and then an hadronization model.

EXP

Comments:

1. Fully exclusive final state description for detector simulations
2. Normalization is very uncertain
3. Very crude kinematic distributions for multi-parton final states
4. Improvements are only at the model level.

most known and used : PYTHIA, HERWIG, SHERPA

SM STATUS A FEW YEARS AGO

pp$\rightarrow$ n particles

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pp→ n particles

1 2 3 4 5 6 7 8 9 10

complexity [n]

SM STATUS A FEW YEARS AGO

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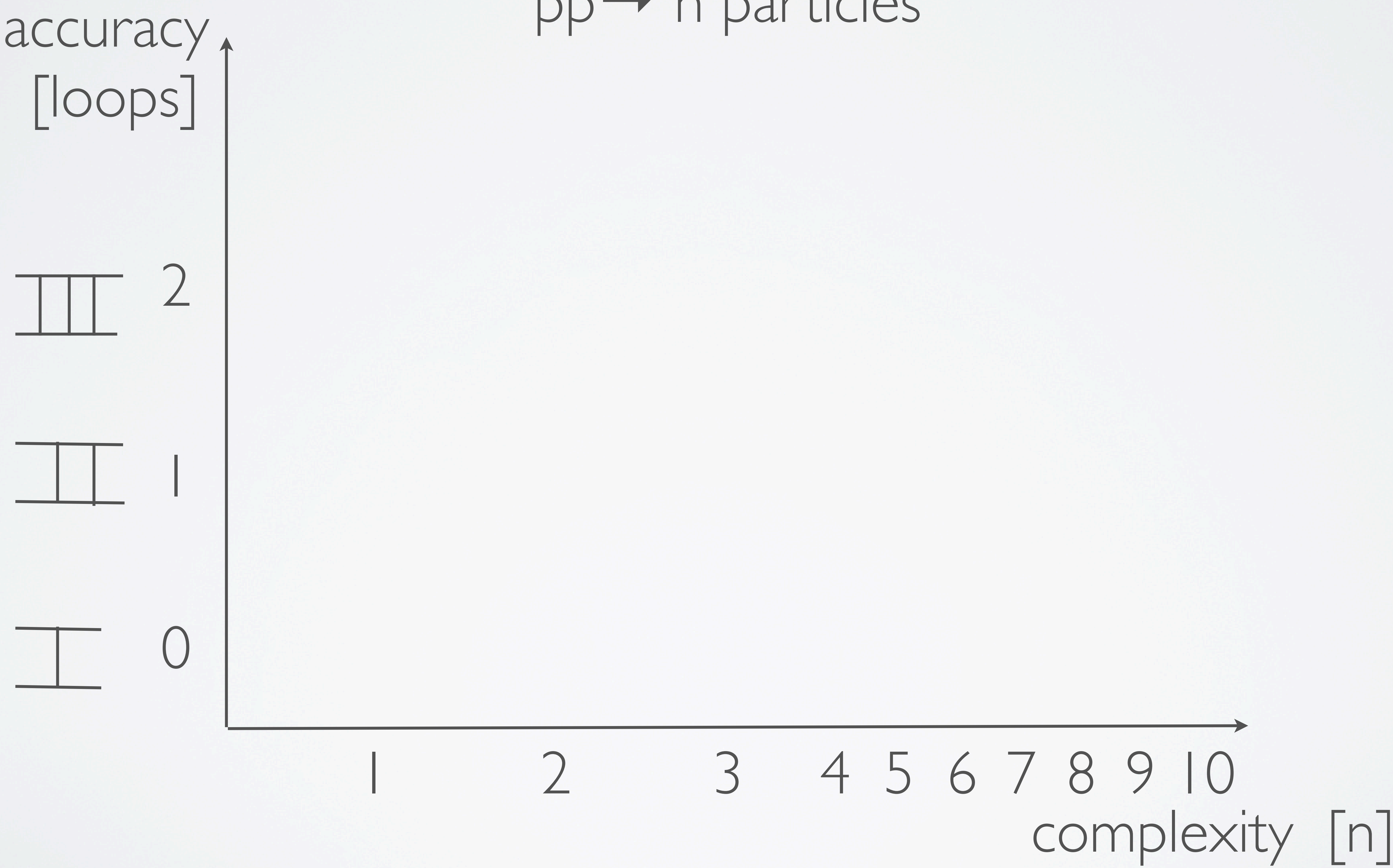

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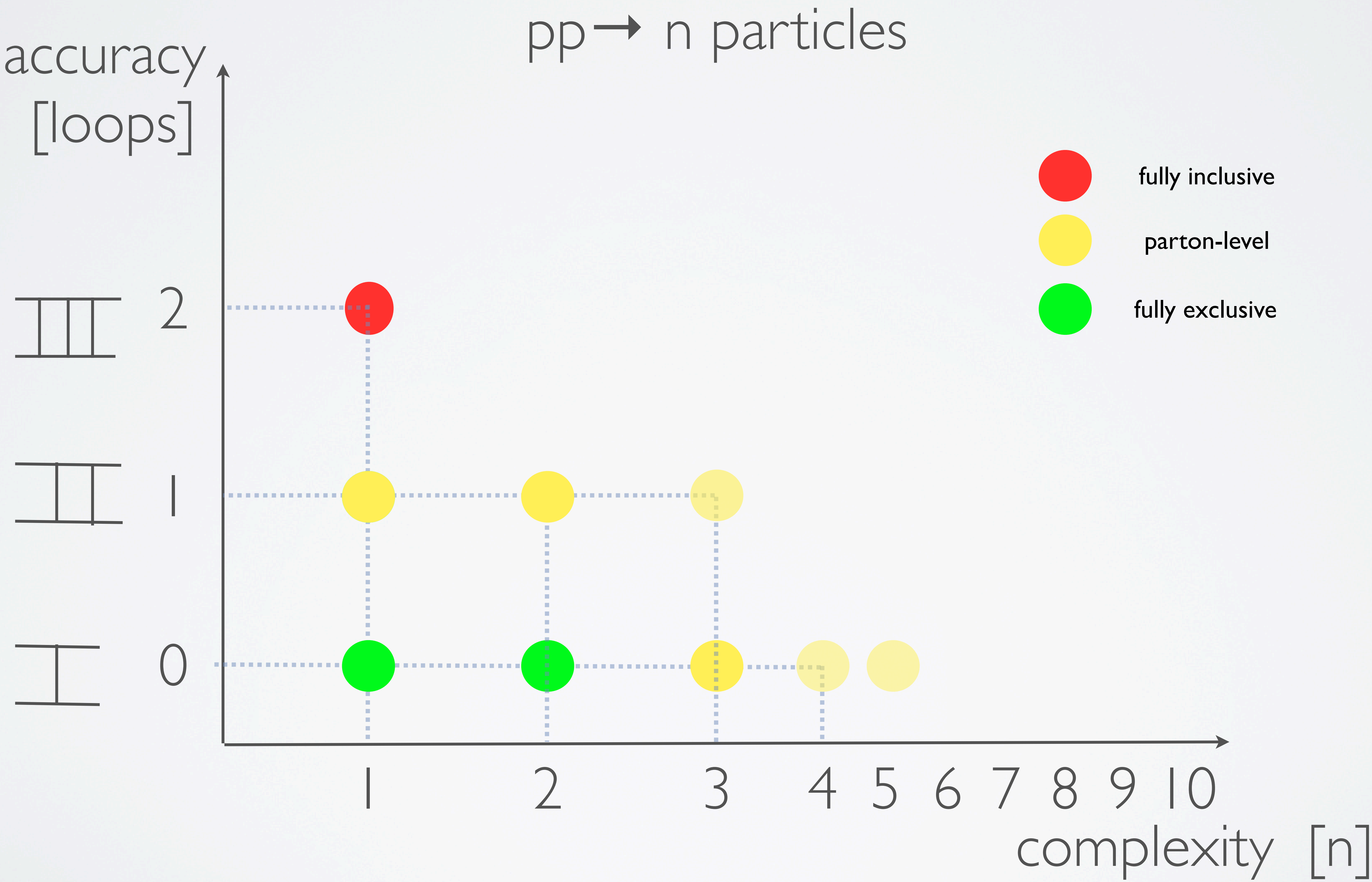
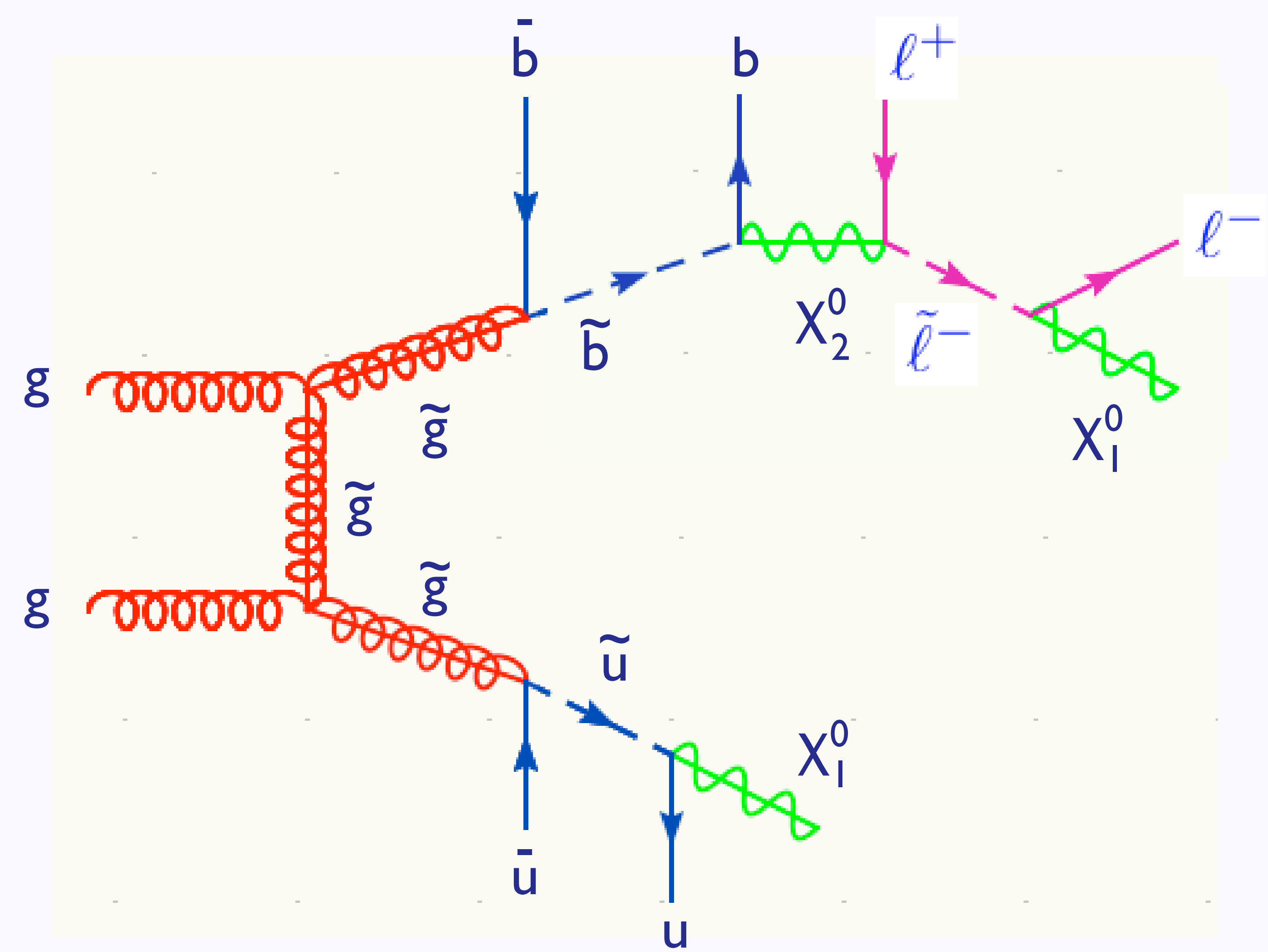
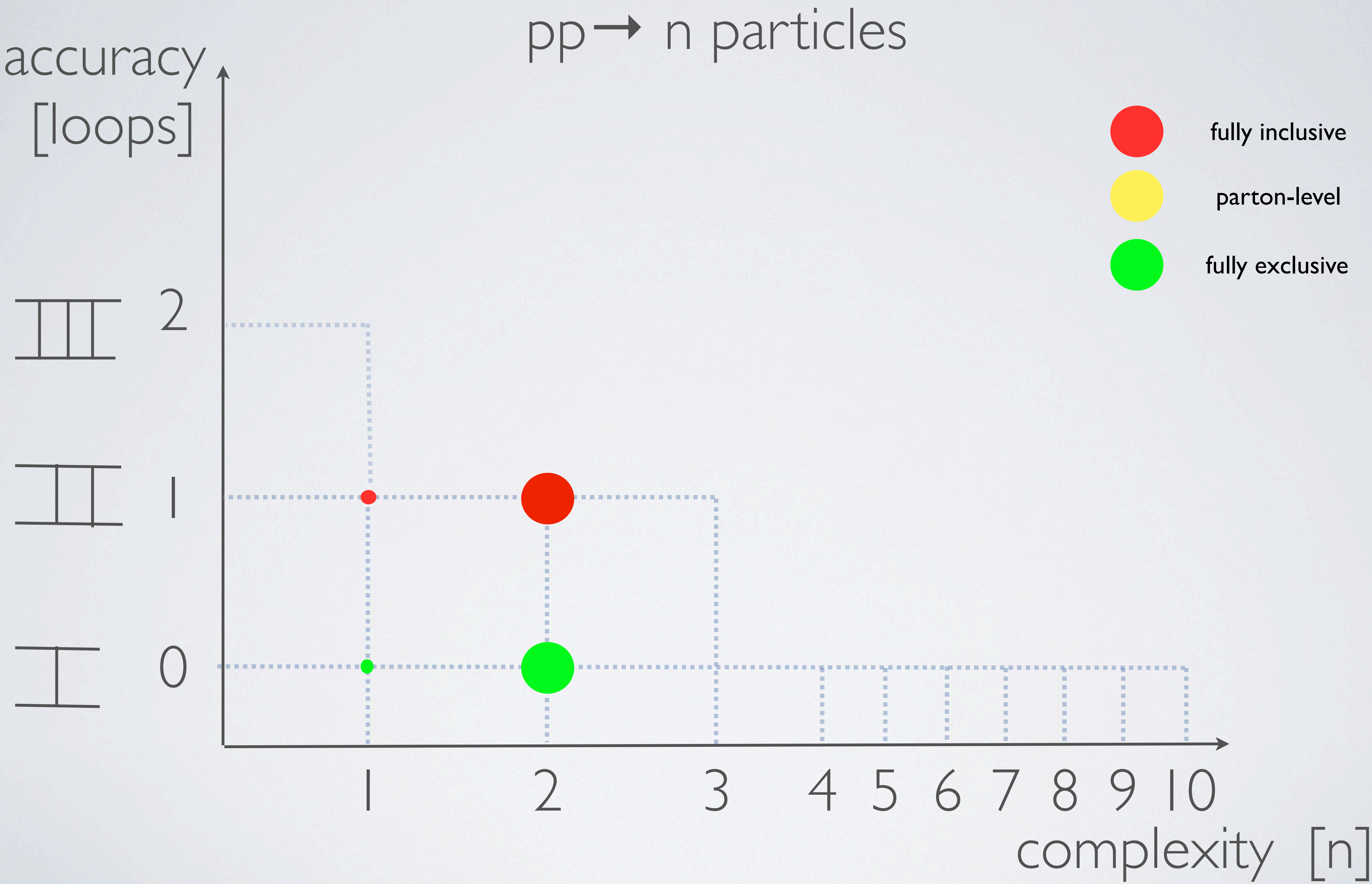


WHAT ABOUT NEW PHYSICS?



BSM (=SUSY)STATUS A FEW YEARS AGO



BSM TH/EXP INTERACTIONS : THE OLD WAY

TH

Idea

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Lagrangian

Feyn. Rules

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x secs

$\downarrow$

Paper

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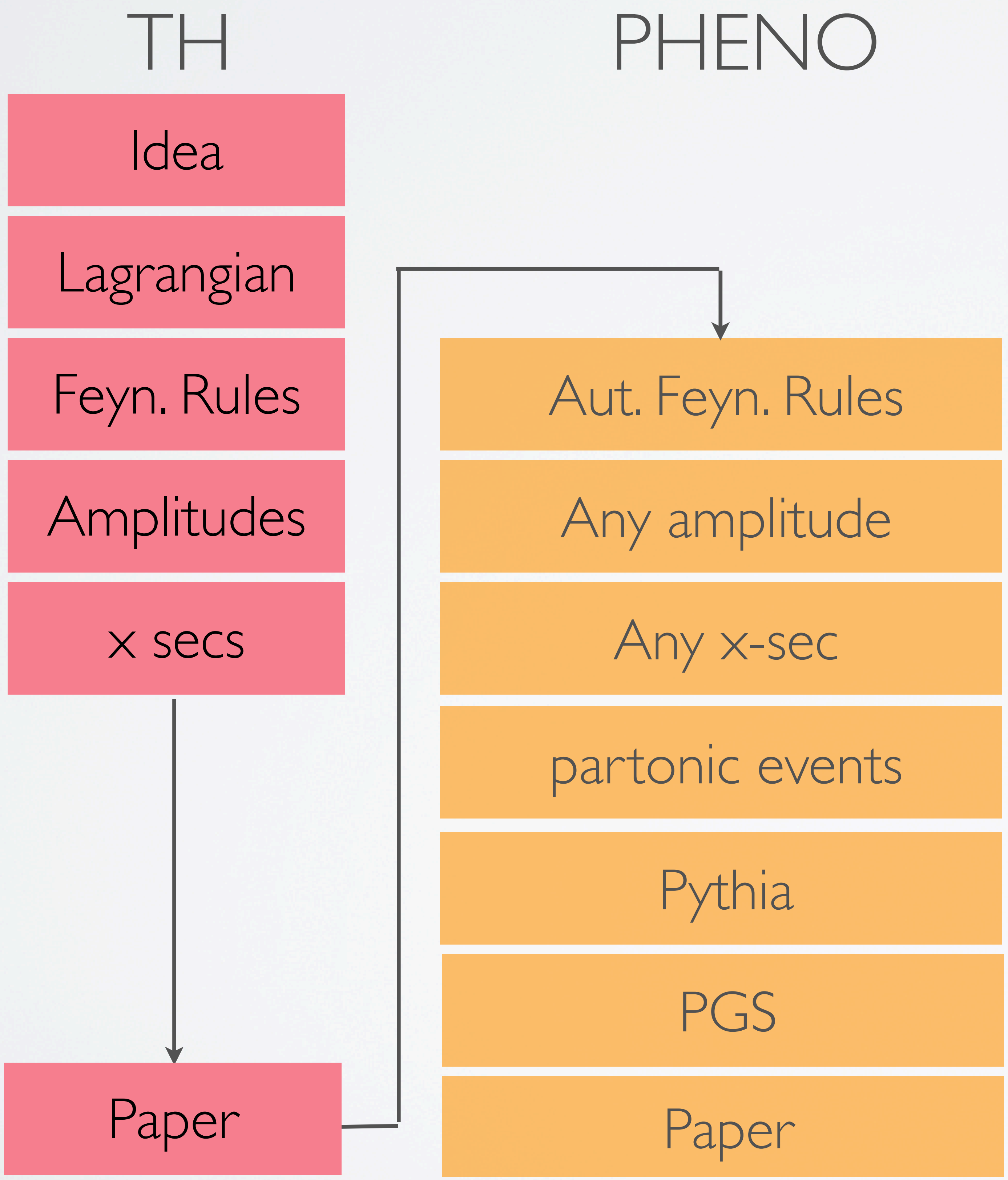

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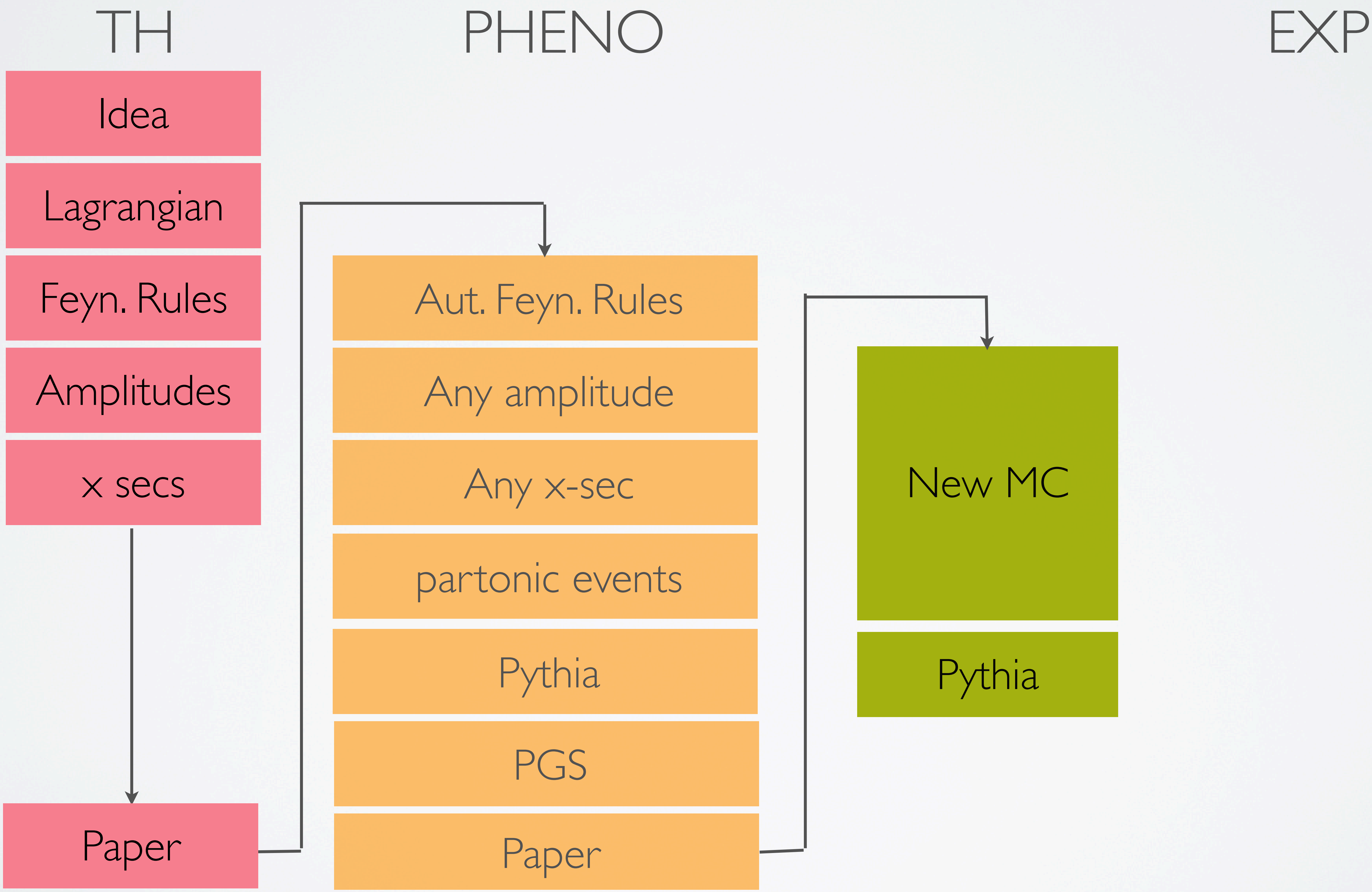

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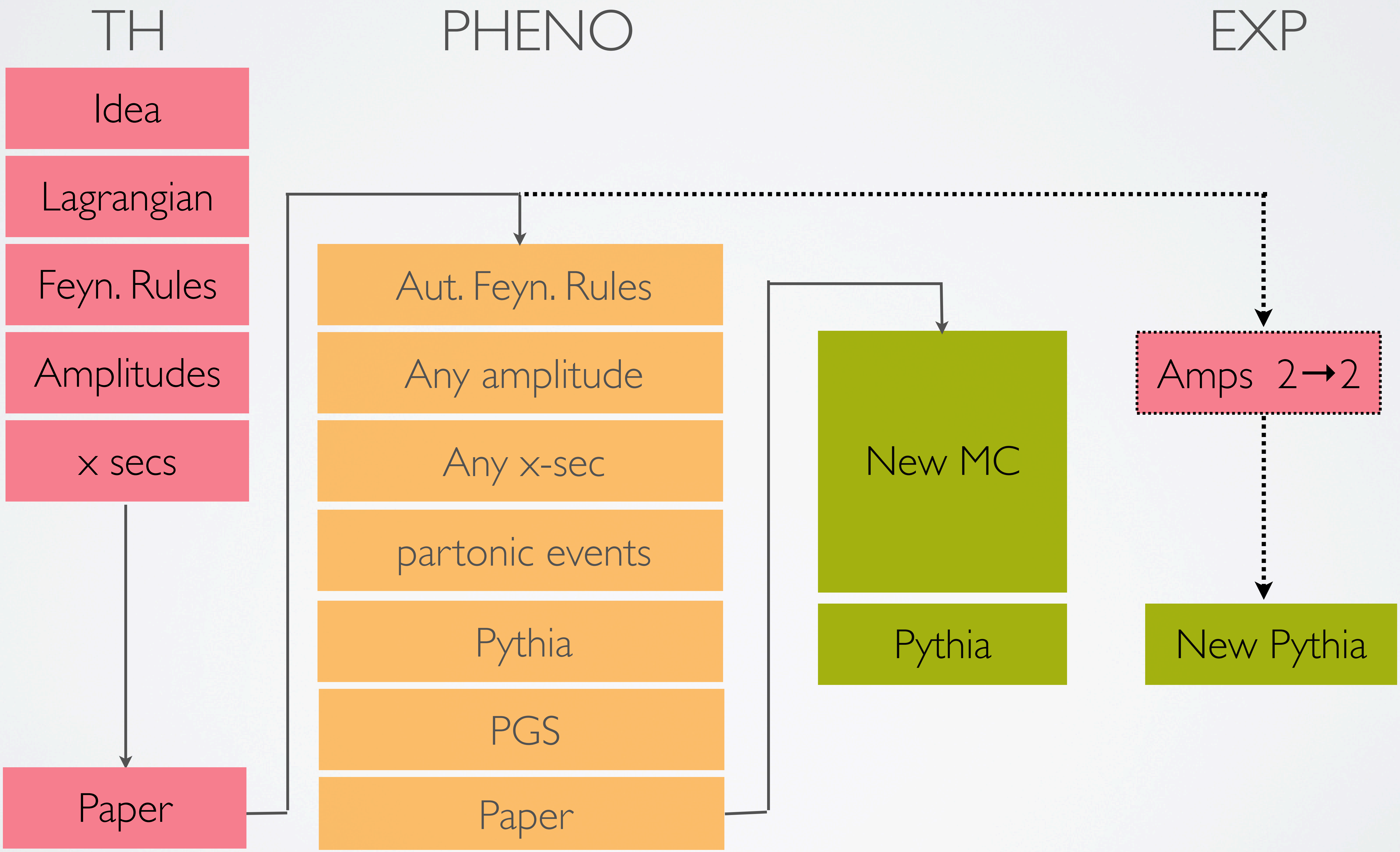

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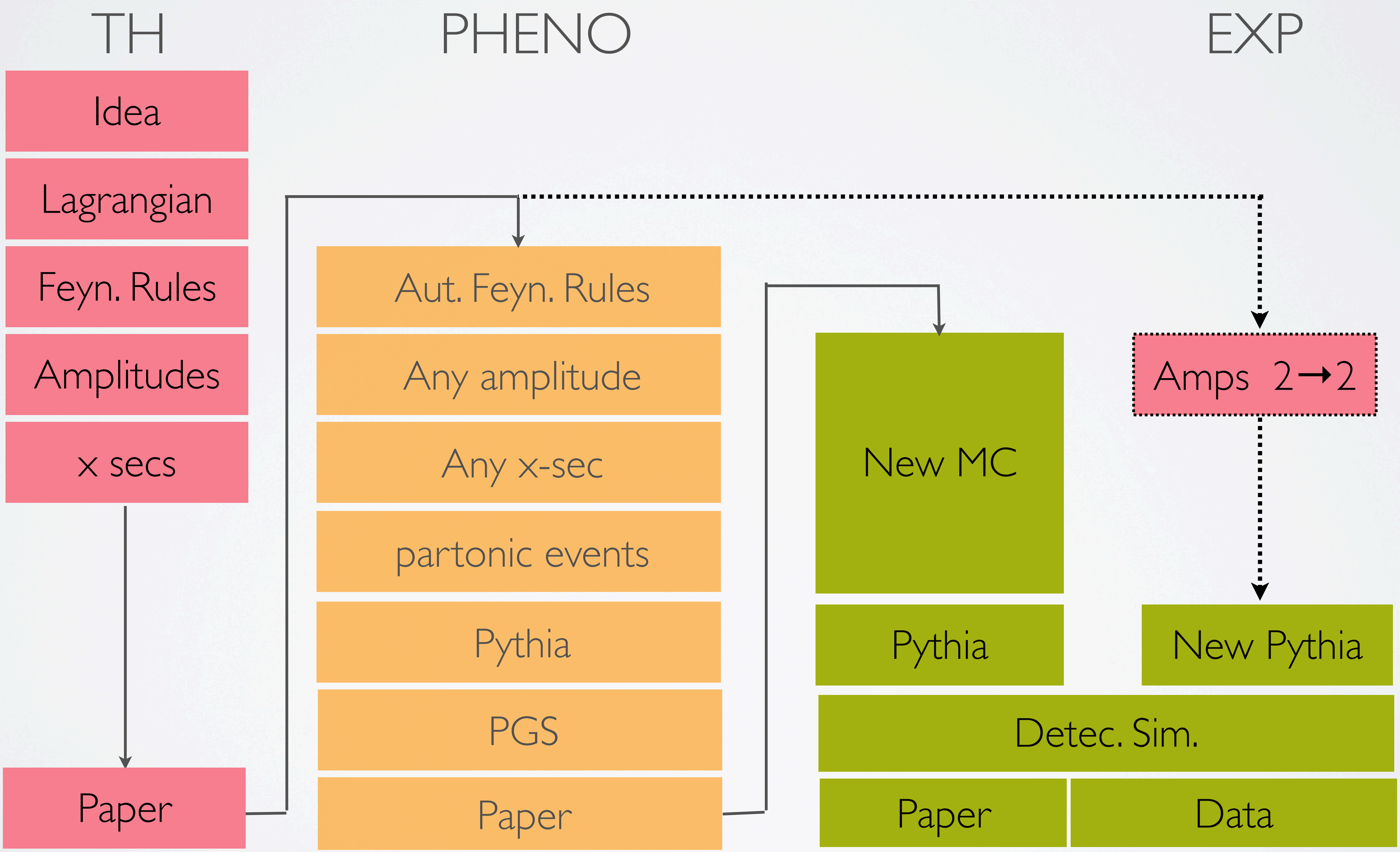

BSM TH/EXP INTERACTIONS : THE OLD WAY

- Workload is tripled!
- Long delays due to localized expertise and error prone. Painful validations are necessary at each step.
- It leads to a proliferation of private MC tools/sample productions impossible to maintain, document and reproduce on the mid- and long- term.
- Just publications is a very inefficient way of communicating between TH/PHENO/EXP.

“GAP ANALYSIS” (2003 CA)

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OK?

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We w

1. have ... theory by
   know
2. that ... colleagues.
3. have ... ty of parton
   show
4. have ... BSM signals.
5. have

QCD AND MC (SIMPLIFIED) PROGRESS

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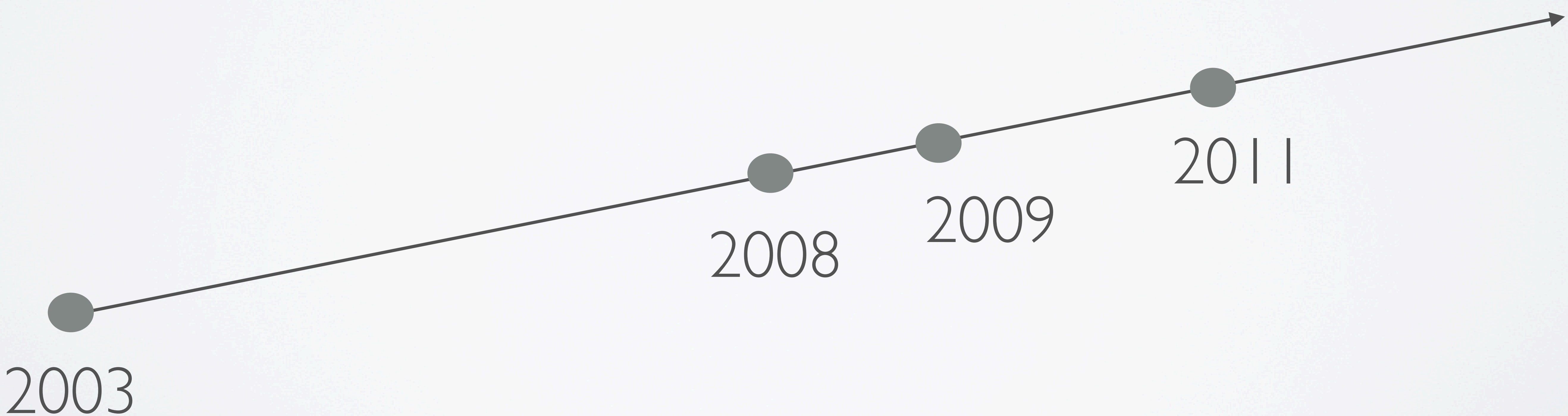

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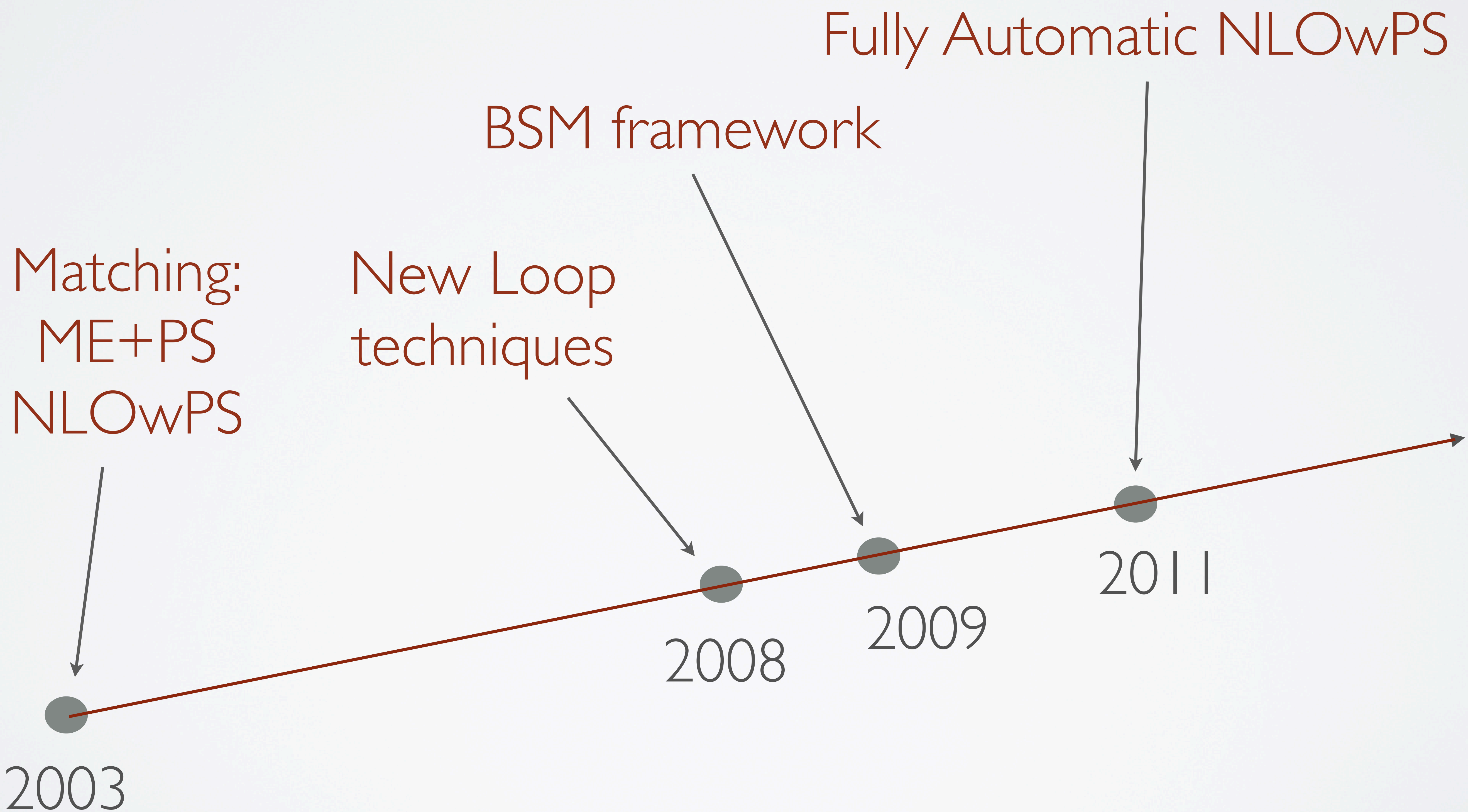
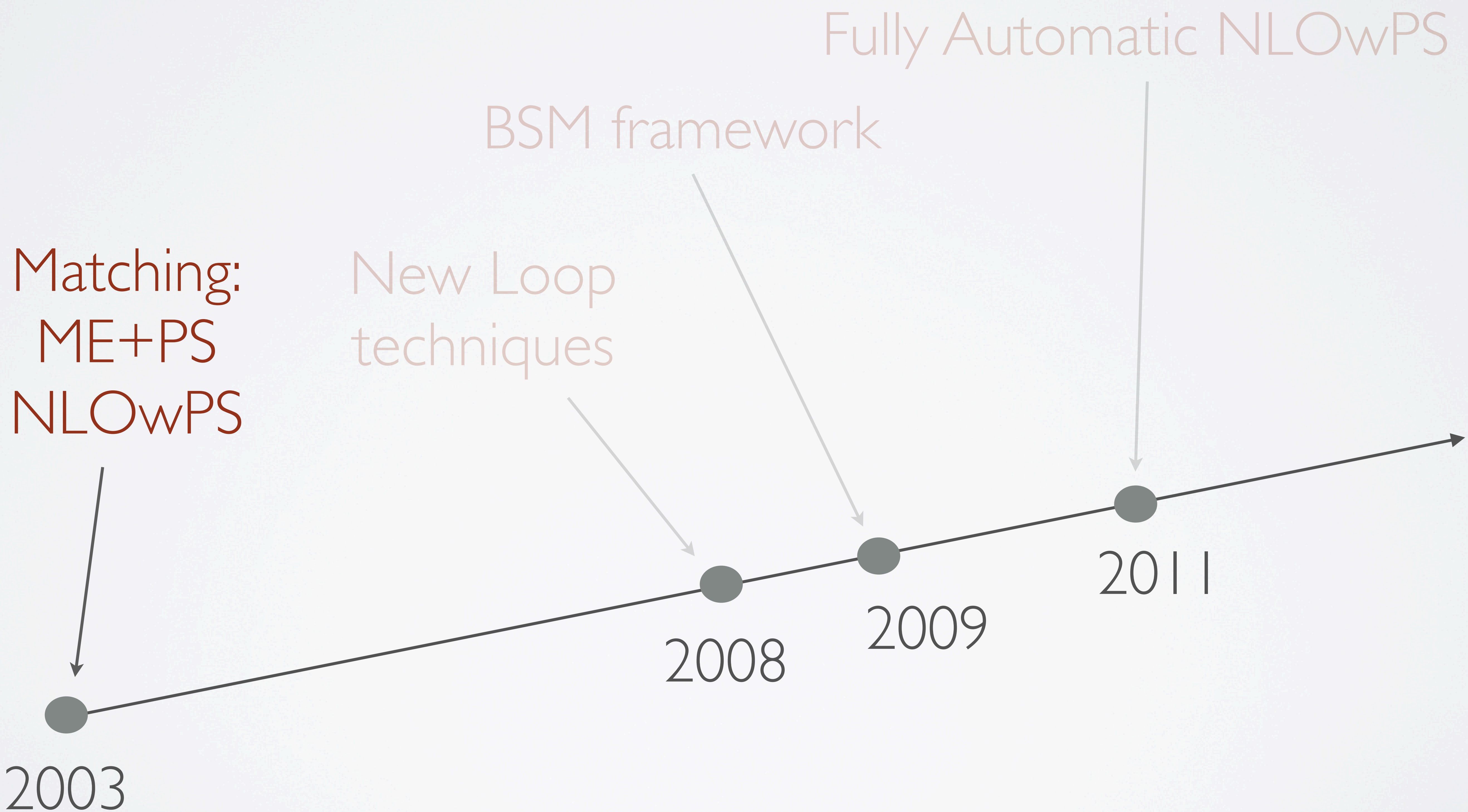


QCD AND MC (SIMPLIFIED) PROGRESS



ME WITH PS

[Mangano]
[Catani, Krauss, Kuhn, Webber]
[Frixione, Nason, Webber]

Matrix Element

1. parton-level description
2. fixed order calculation
3. quantum interference exact
4. valid when partons are hard and well separated
5. needed for multi-jet description

Shower MC

1. hadron-level description
2. resums large logs
3. quantum interference through angular ordering
4. valid when partons are collinear and/or soft
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Approaches are complementary: merge them!

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ME WITH PS

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Approaches are complementary: merge them!

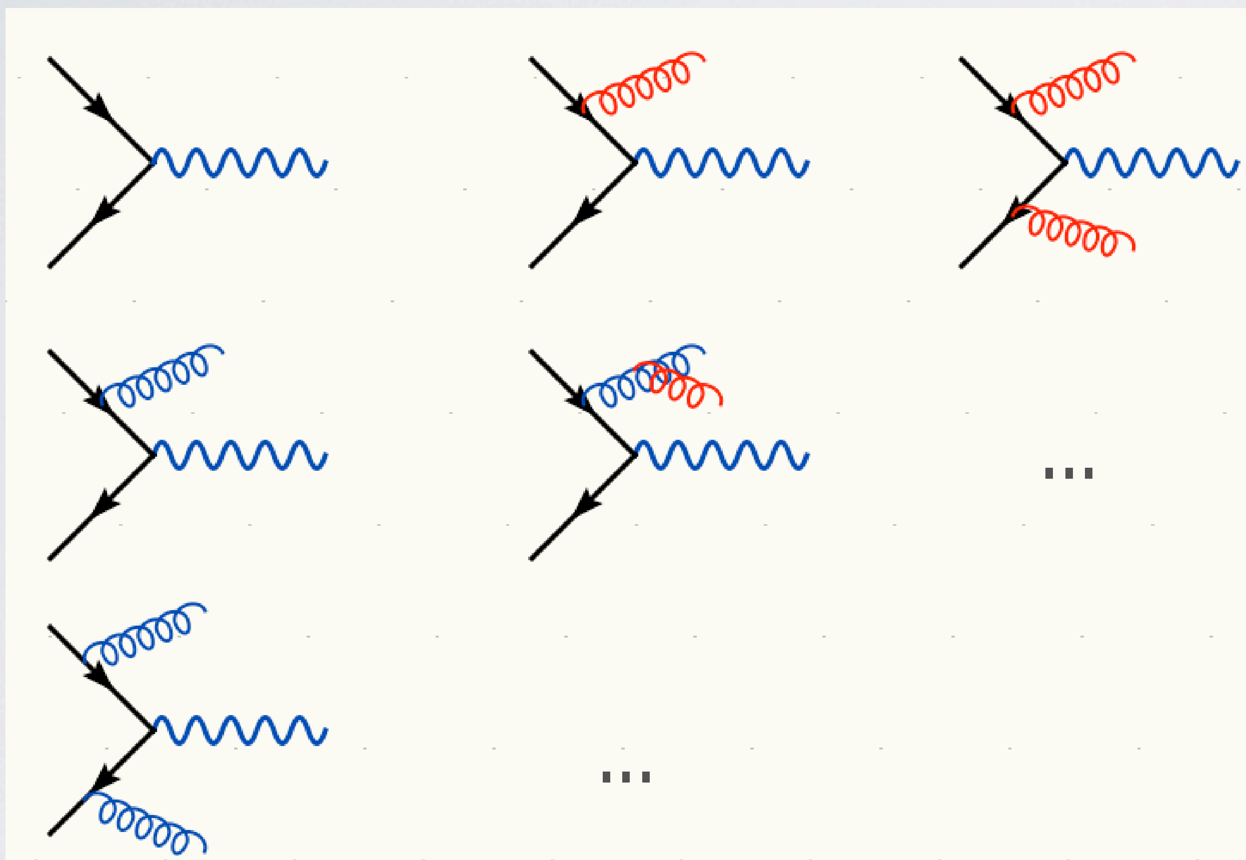
Difficulty: avoid double counting

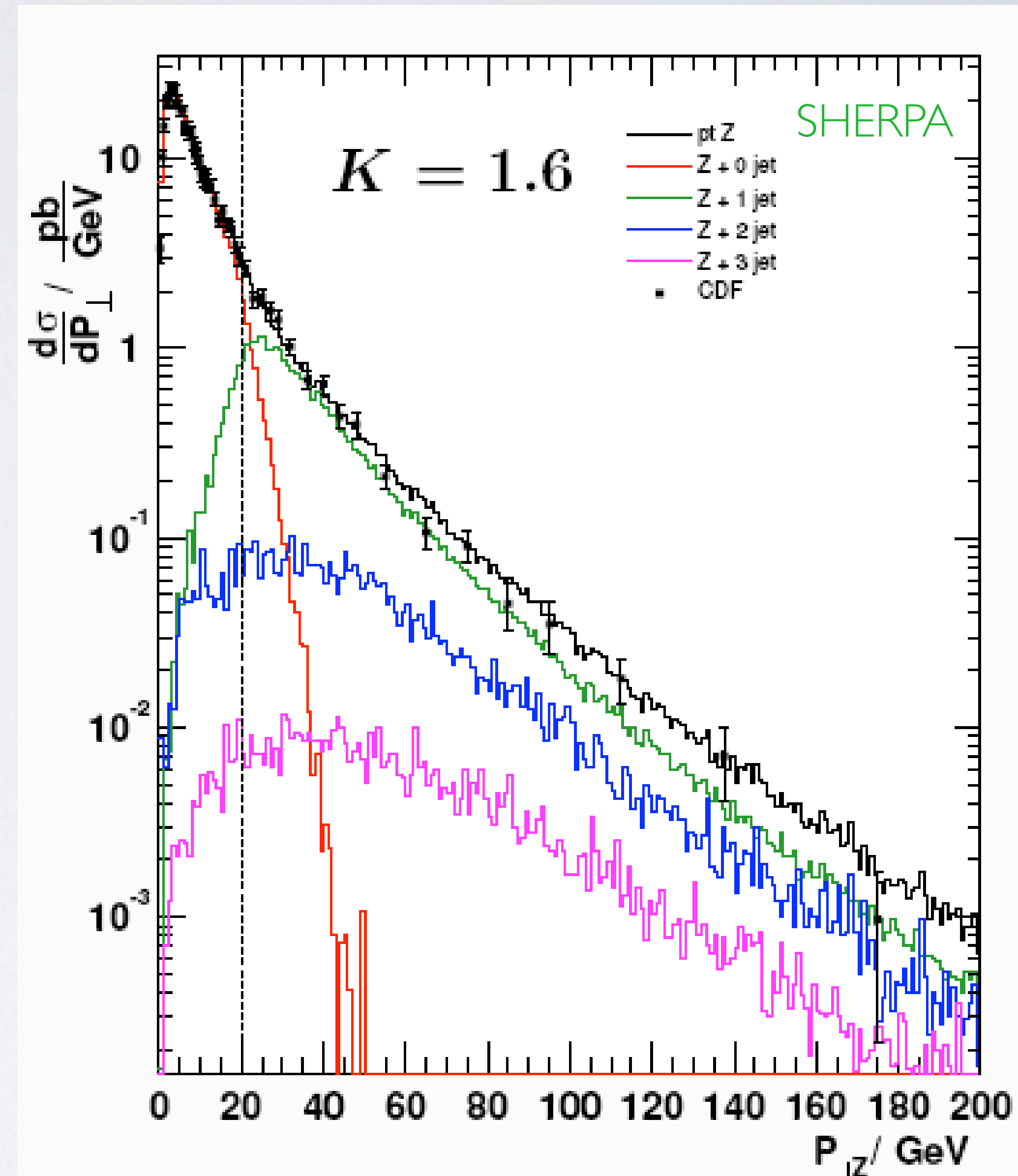
Merging fixed order with PS

[Mangano]
[Catani, Krauss, Kuhn, Webber]

PS →

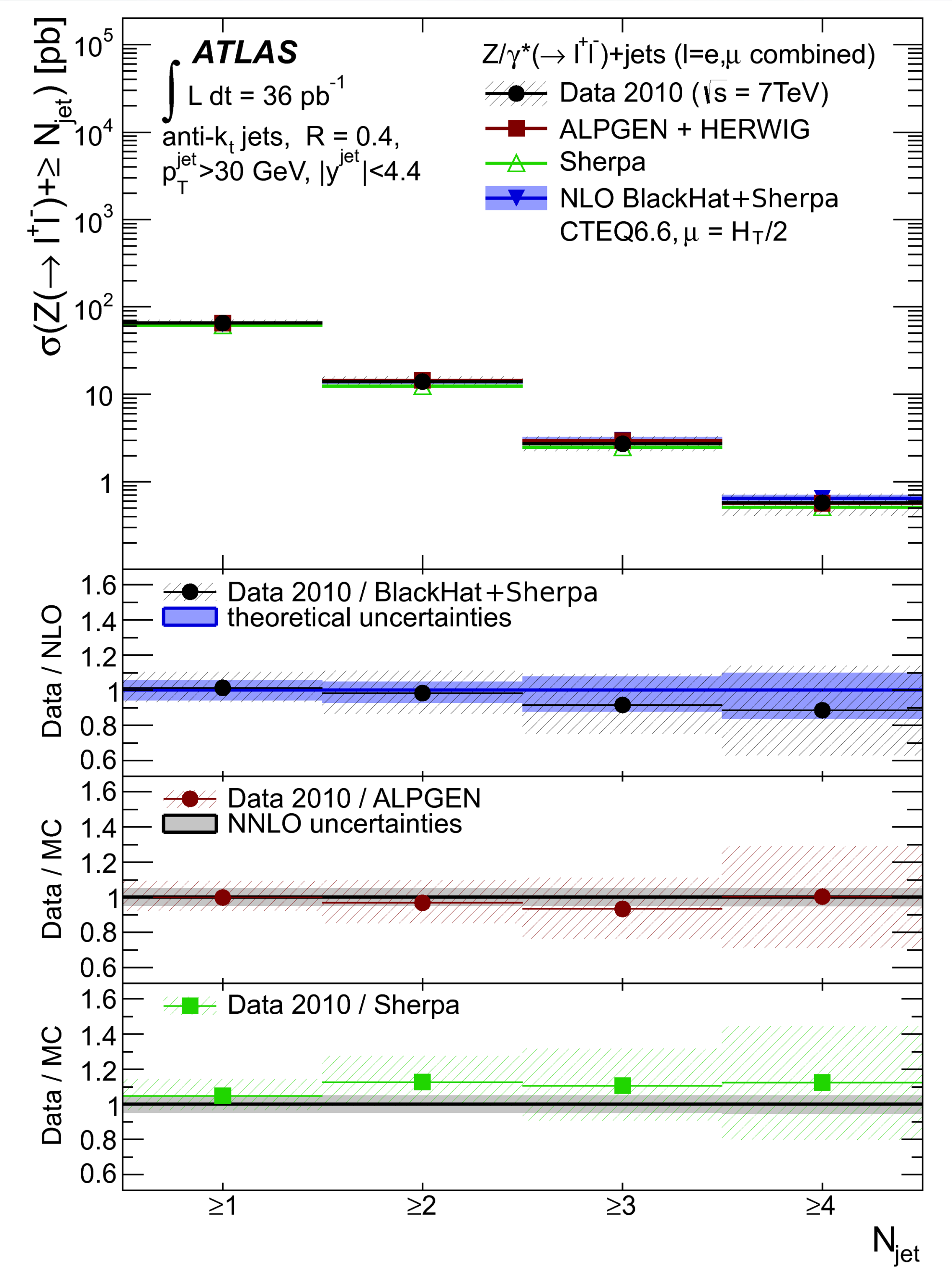
ME ↓

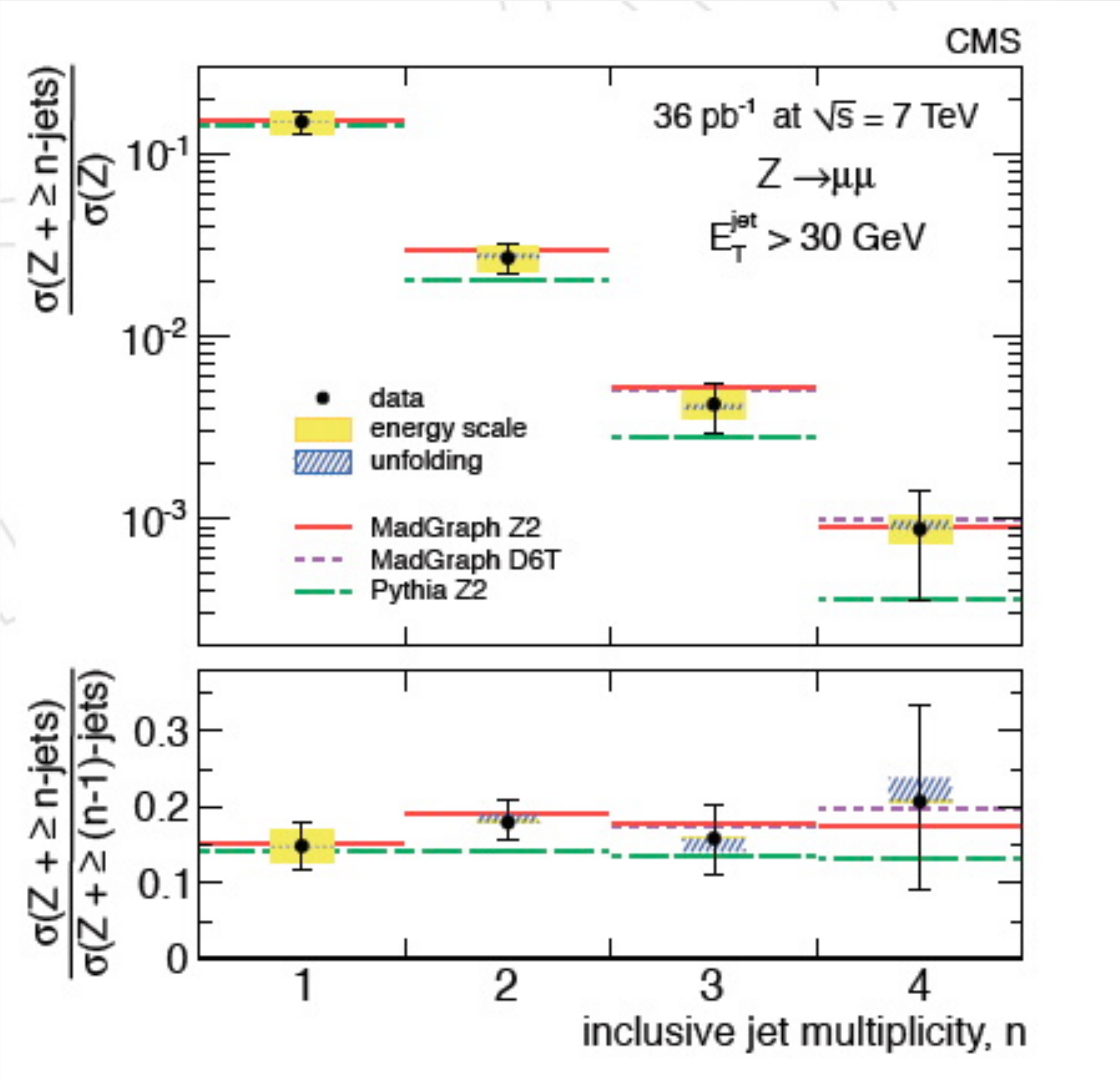




Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample. Distributions are accurate but overall normalization still "arbitrary".

V+JETS AT THE LHC





Working Amazingly well!

NLOwPS in a nutshell

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

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.

MC@NLO AND POWHEG

MC@NLO AND POWHEG

MC@NLO

[Frixione, Webber, 2003;
Frixione, Nason, Webber, 2003]

- Matches NLO to HERWIG and HERWIG++ angular-ordered PS.
- Some events have negative weights.
- Large and well tested library of processes.

- Now available also for Pythia (Q^2) [Torrielli, Frixione, 1002.4293]
- Now automatized [Frederix, Frixione, Torrielli]
- Now available in aMC@NLO (see later)

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POWHEG

[Nason 2004;
Frixione, Nason, Oleari, 2007]

- Is independent* of the PS. It can be interfaced to PYTHIA, HERWIG or SHERPA.
- Generates only* positive unit weights.

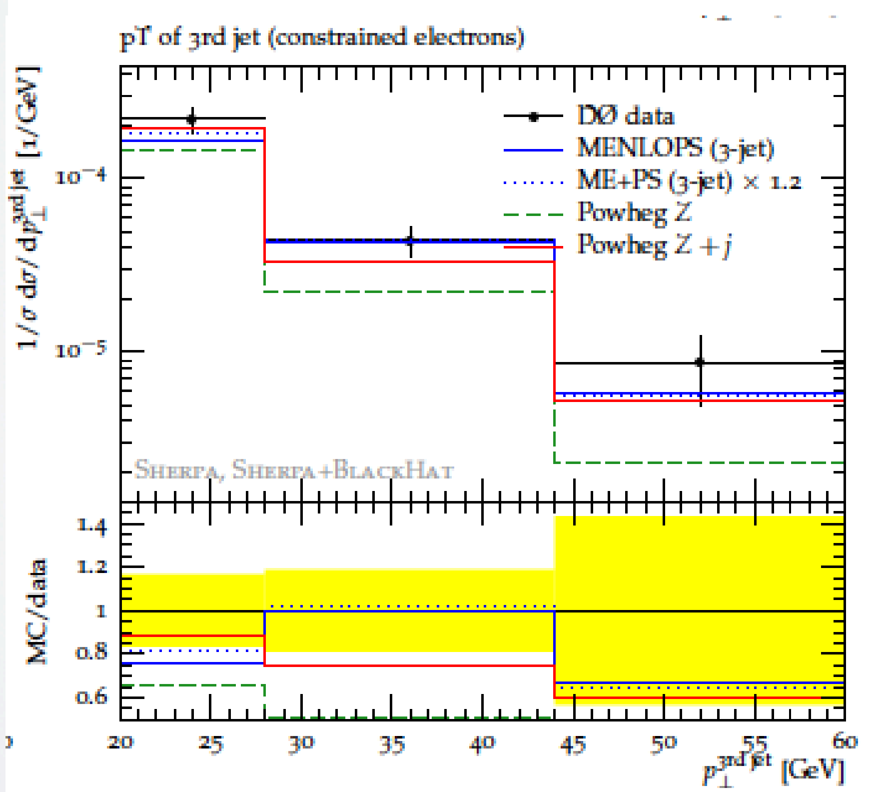
- Can use existing NLO results via the POWHEG-Box [Aioli, Nason, Oleari, Re et al. 2009]
- Method used by HELAC, HERWIG++ and SHERPA [Kardos, Papadopoulos, Trocsanyi 1101.2672], [Hoeche, Krauss, Schooenner, Siegert, 1008.5399]

GOING BEYOND: MENLOPS

[Hamilton, Nason,1004.1764]
[Hoeche et al , 1009.1127]
[Aioli, Hamilton Re, 1108.0909]

A fully consistent and working CKKW at NLO missing, one can still aim at having matched samples with a built in NLO normalization. This is the aim of the MENLOPS which is currently implemented in the POWHEG framework:

$$\langle O \rangle = \int d\Phi_B \, \bar{B}(\Phi_B) \Big[\Delta^{(\mathrm{ME})}(t_0)\, O(\Phi_B) + \overbrace{\int d\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\mathrm{ME})}(t)\, \Theta(Q_{\mathrm{cut}} - Q)\, O(\Phi_R)}^{\text{POWHEG domain}} + \underbrace{\int d\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\mathrm{PS})}(t)\, \Theta(Q - Q_{\mathrm{cut}})\, O(\Phi_R)}_{\text{ME domain}} \Big]$$

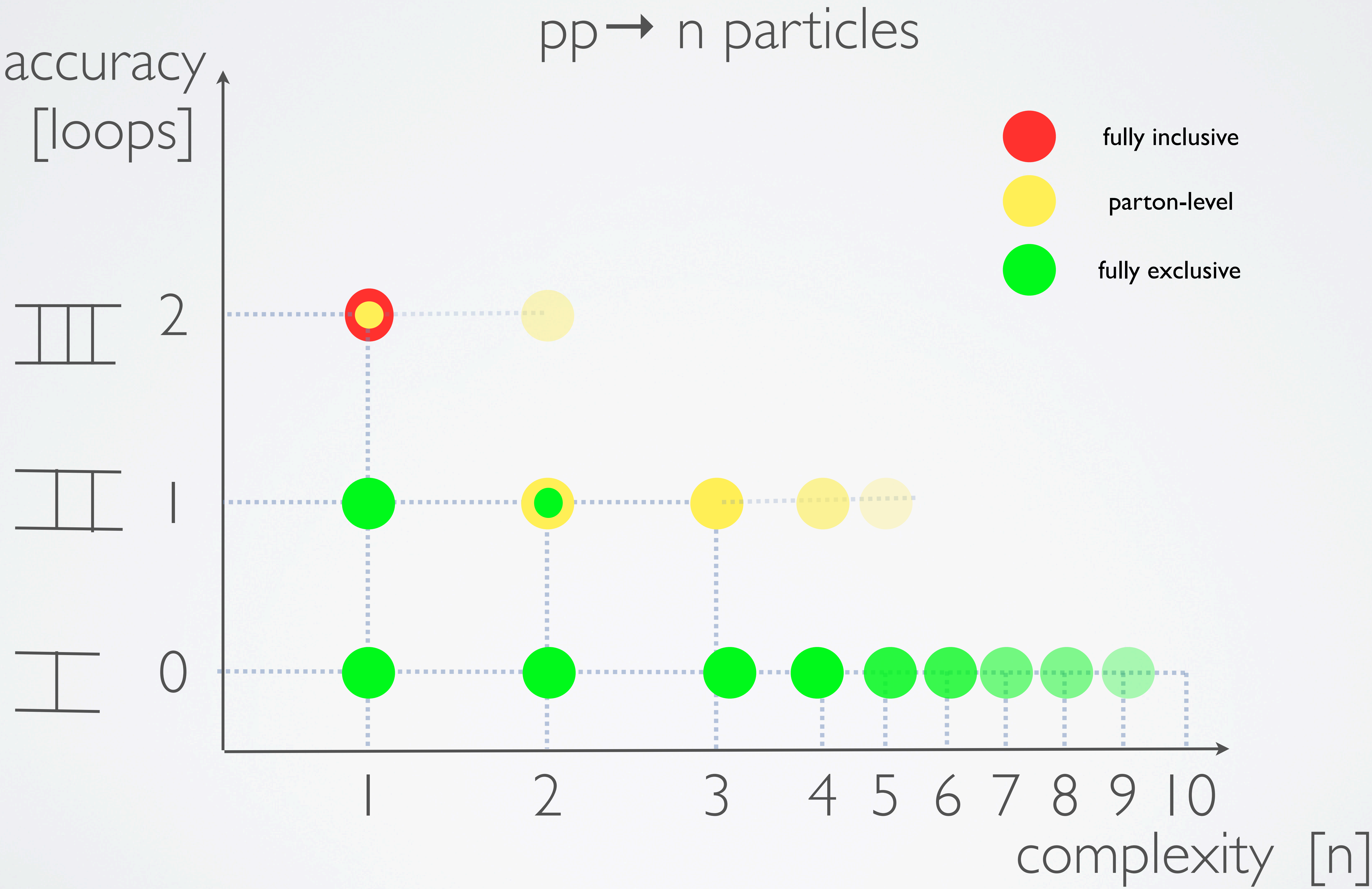


Still in exploration. Not many applications available so far, but promising.

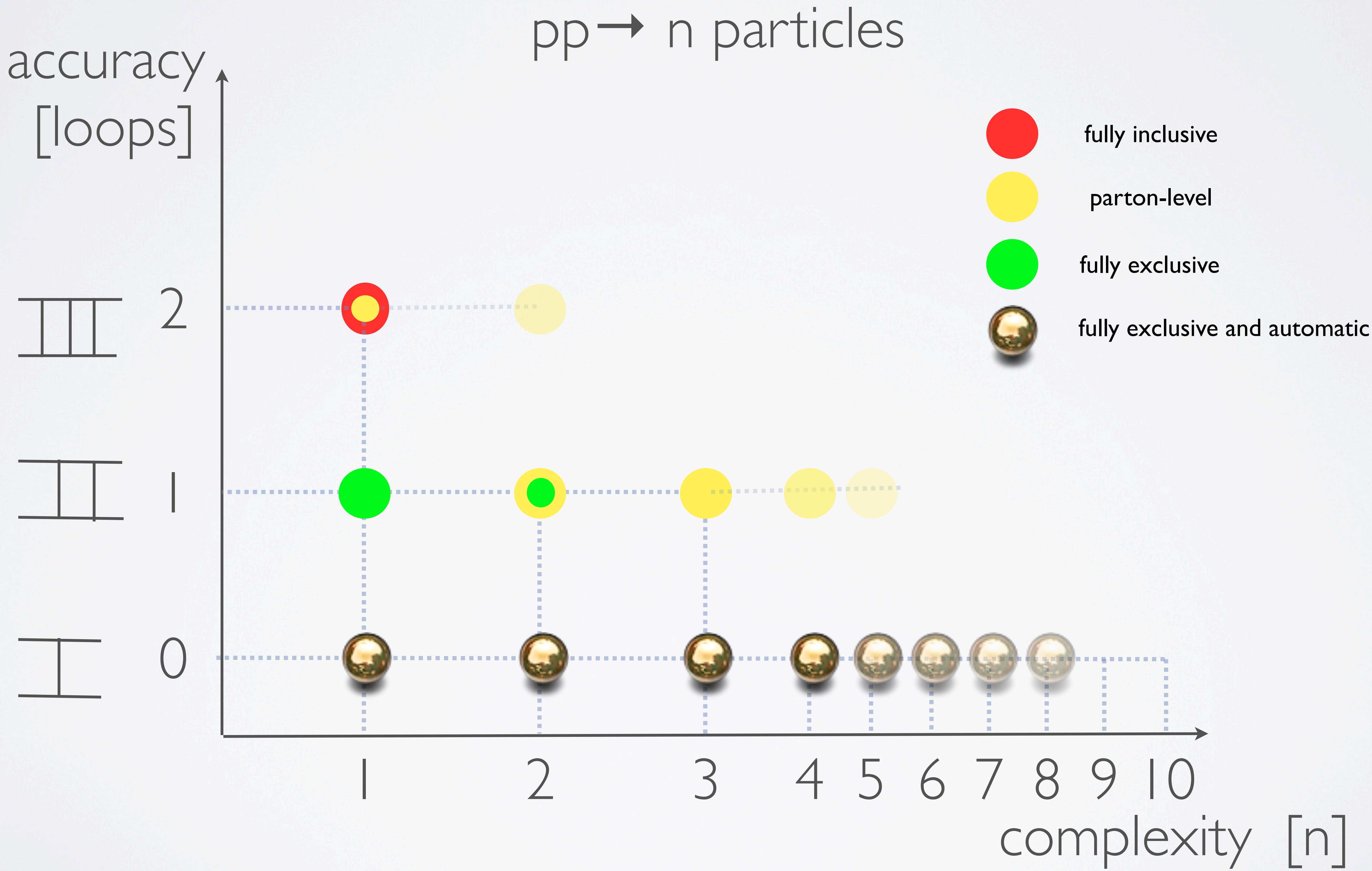
SM STATUS : SINCE 2007

pp→ n particles

SM STATUS : SINCE 2007



SM STATUS : SINCE 2007



AUTOMATION

- Cost saving

  Trade human time and expertise spent on computing one process at the time with time on physics and pheno.

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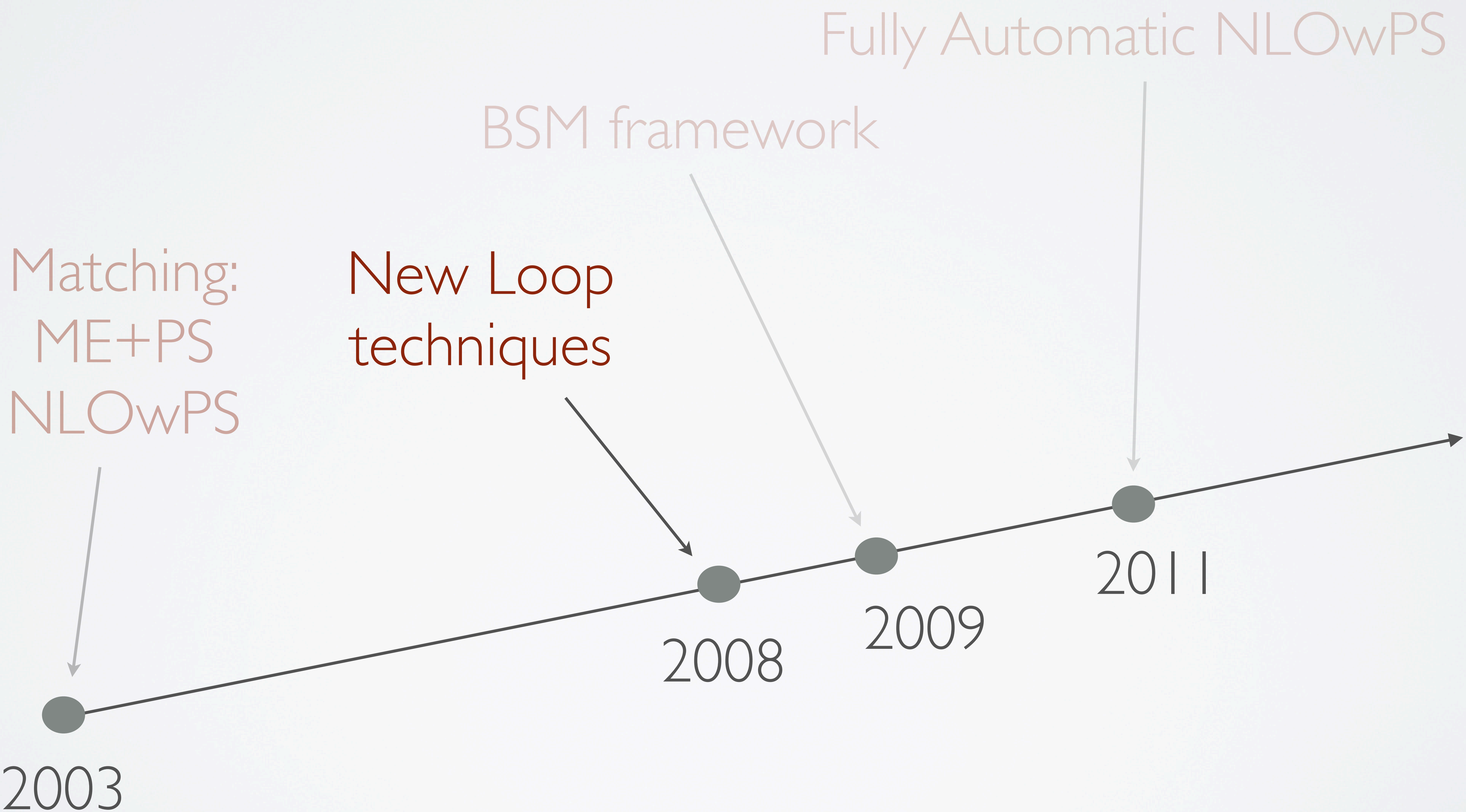
- Wide accessibility

  One framework for all. Available to everybody for an unlimited set of applications for all. Suitable to EXP collaboration.

QCD AND MC (SIMPLIFIED) PROGRESS



NEW LOOP TECHNIQUES

For the calculation of one-loop matrix elements, several methods are now established :

- Generalized Unitarity (ex. BlackHat, Rocket,...)

[Bern, Dixon, Dunbar, Kosower, hep-ph/9403226 + ...; Ellis, Giele, Kunszt 0708.2398, +Melnikov 0806.3467]

- Integrand Reduction (ex. CutTools, Samurai)

[Ossola, Papadopolulos, Pittau, hep-ph/0609007; del Aguila, Pittau, hep-ph/0404120; Mastrolia, Ossola, Reiter, Tramontano, 1006.0710]

- Tensor Reduction (ex. Golem)

[Passarino, Veltman, 1979; Denner, Dittmaier, hep-ph/0509141, Binoth, Guillet, Heinrivh, Pilon, Reiter 0810.0092]

SUBTRACTION TERMS

IR divergences are dealt with using subtraction terms

$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

$$\sigma^{\mathrm{NLO}} = \int_m \left[d^{(4)}\sigma^B + \int_l d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A \right] + \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A \right]$$

- Add local counterterms to make each of the two integrals separately finite.

ESTABLISHED SUB TECHNIQUES

For the calculation of one-loop matrix elements, several methods are now established :

- Dipoles (ex. MadDipoles, AutoDipole,)

[Catani, Seymour, hep-ph/9605323+..]

- Antenna (ex. Vincia...)

[Kosower hep-ph/9720213]

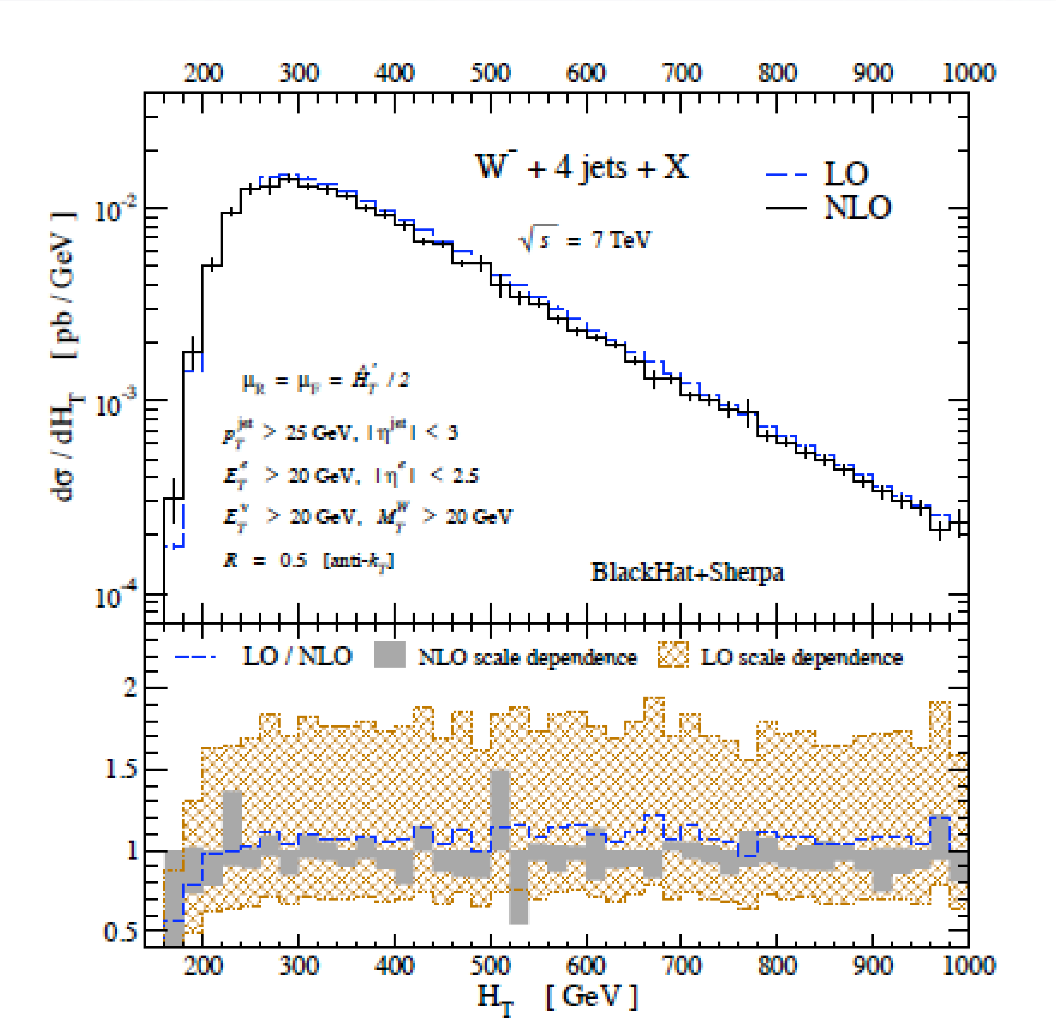
- Residue (ex. MadFKS)

[Frixione, Kunszt, Signer, hep-ph/9512328]

GUINNESS WR NLO CALCULATIONS

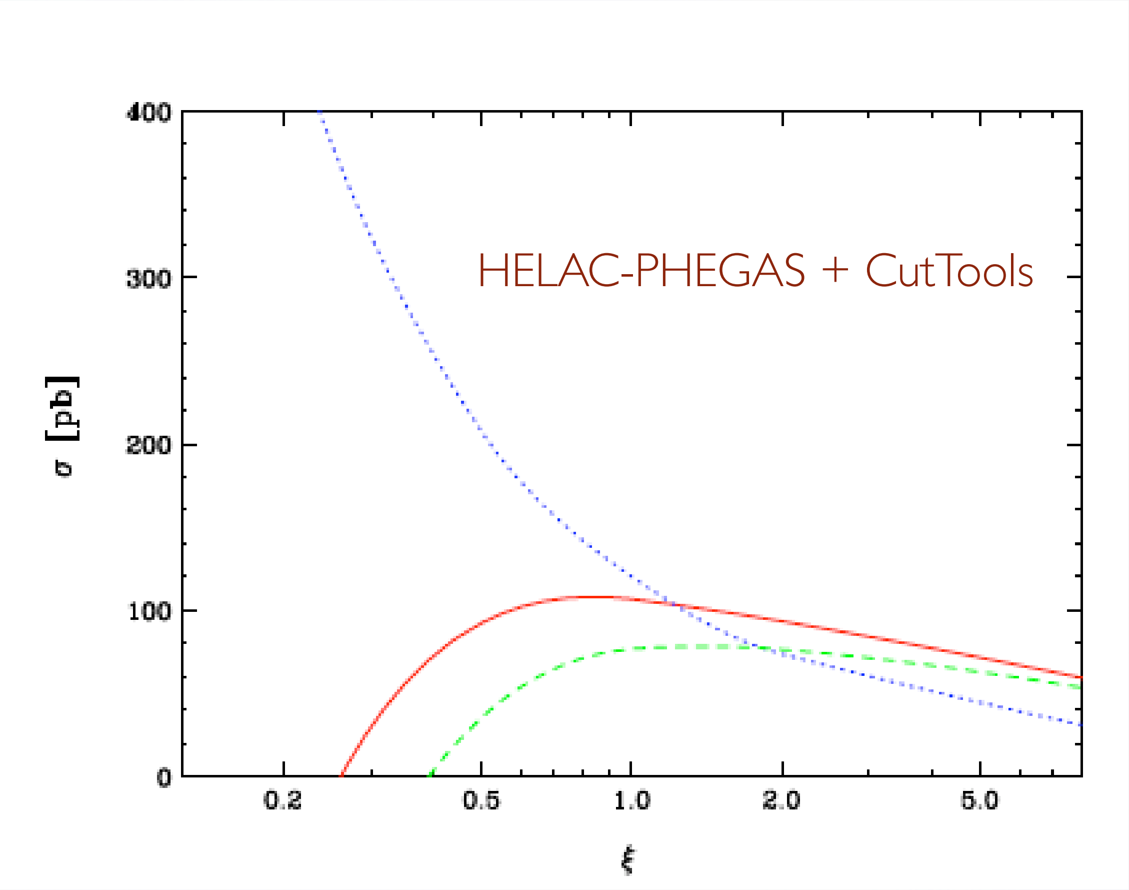
W+4 jets

[Berger et al., 1009.2338]



tt+2jets

[Bevilacqua et al., 1002.4009]



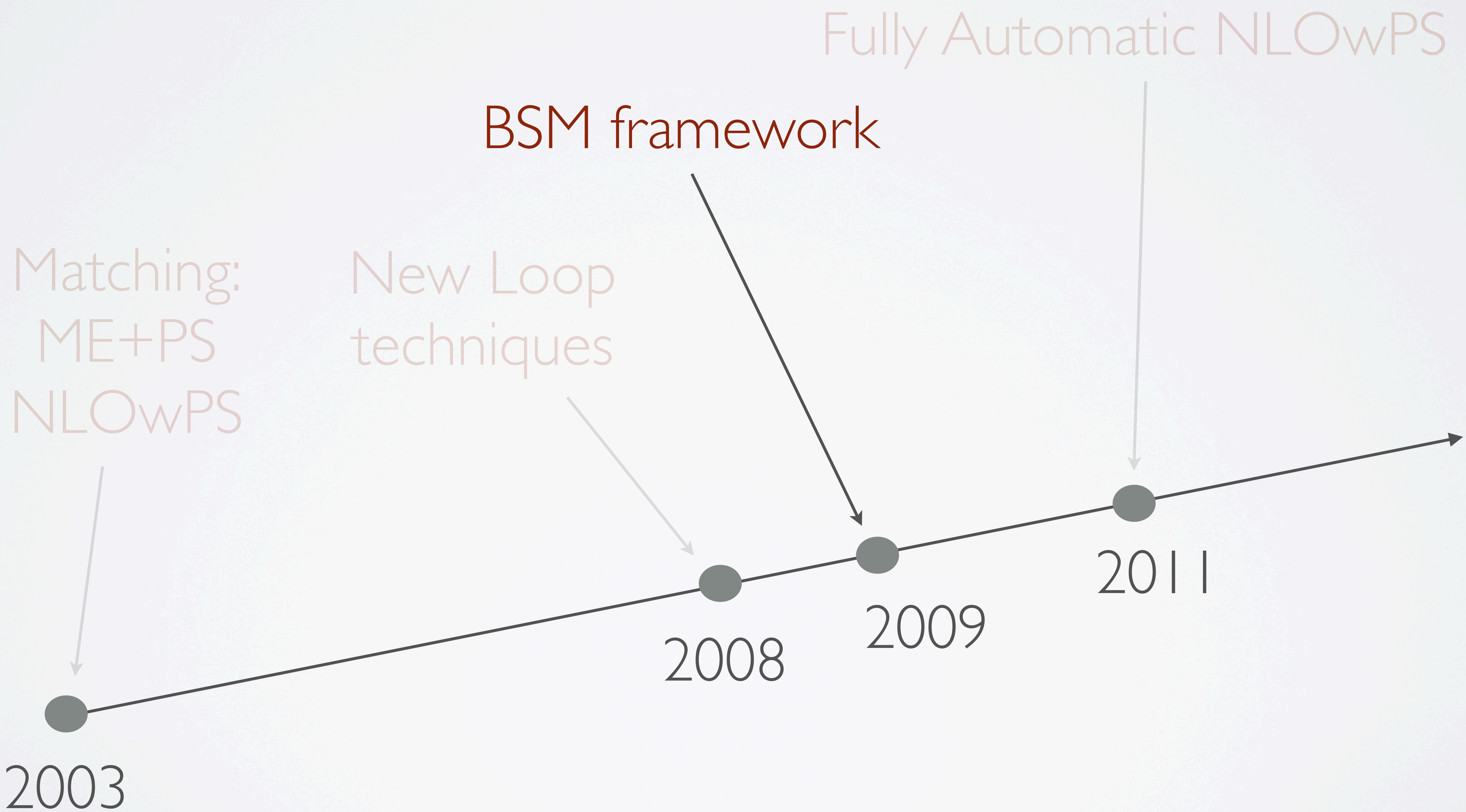
Both based on unitarity methods and recursive relations for trees.

One indicator of NLO progress

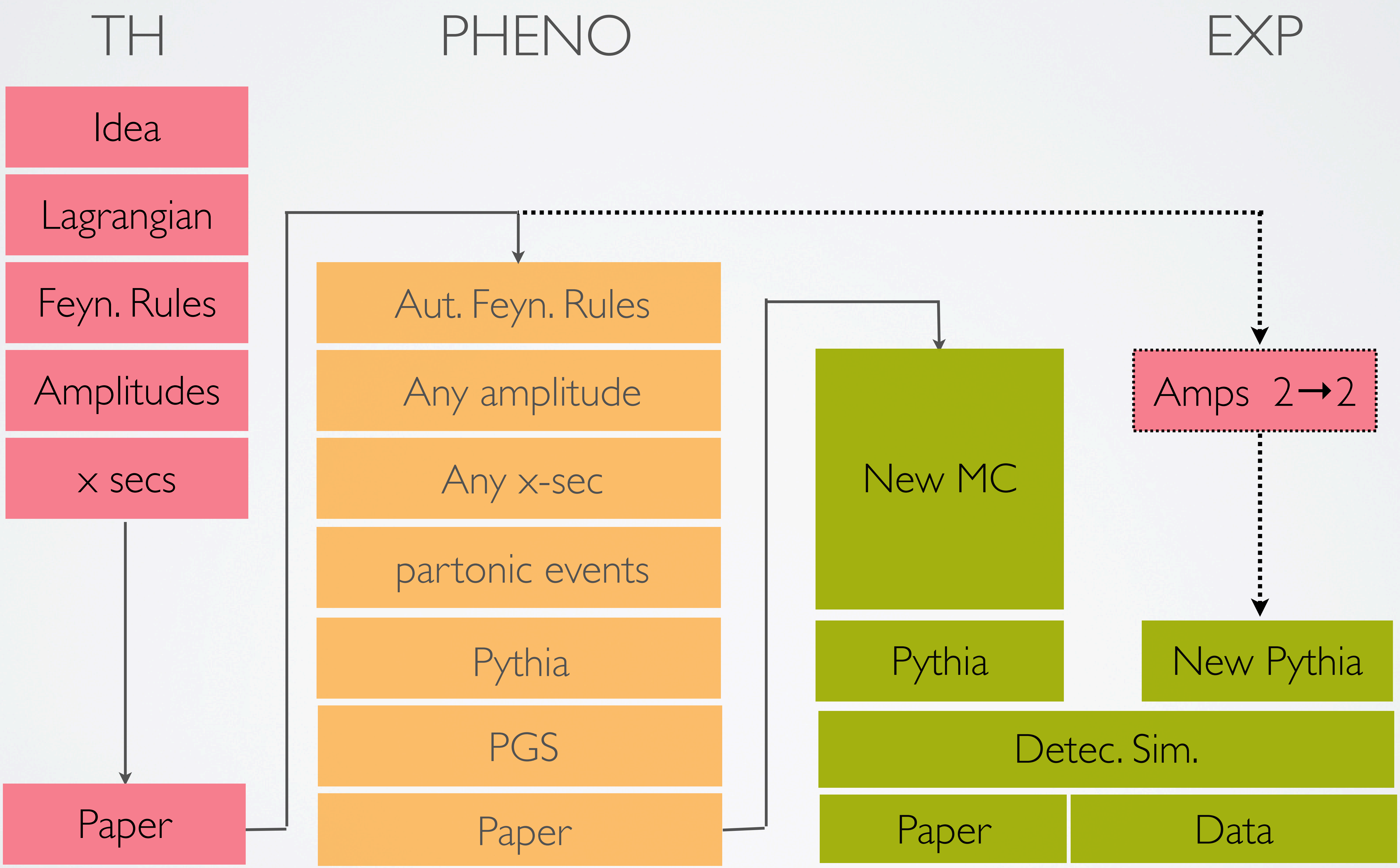
pp → W + 0 jet	1978	Altarelli, Ellis, Martinelli
pp → W + 1 jet	1989	Arnold, Ellis, Reno
pp → W + 2 jets	2002	Campbell, Ellis
pp → W + 3 jets	2009	BH+Sherpa Ellis, Melnikov, Zanderighi
pp → W + 4 jets	2010	BH+Sherpa

Slide from L. Dixon

QCD AND MC (SIMPLIFIED) PROGRESS



BSM TH/EXP INTERACTIONS : THE OLD WAY



BSM TH/EXP INTERACTIONS : THE OLD WAY

TH	PHENO	EXP
Idea		
Lagrangian		
	Aut. Feyn. Rules	
	Any amplitude	
	Any x-sec	
	partonic events	
		Pythia
		Detec. Sim.
		Data

BSM TH/EXP INTERACTIONS : THE NEW PATH

TH

EXP

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

Events

PS+Had

PGS

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- One path for all
- Physics and software validations streamlined
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

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- One path for all
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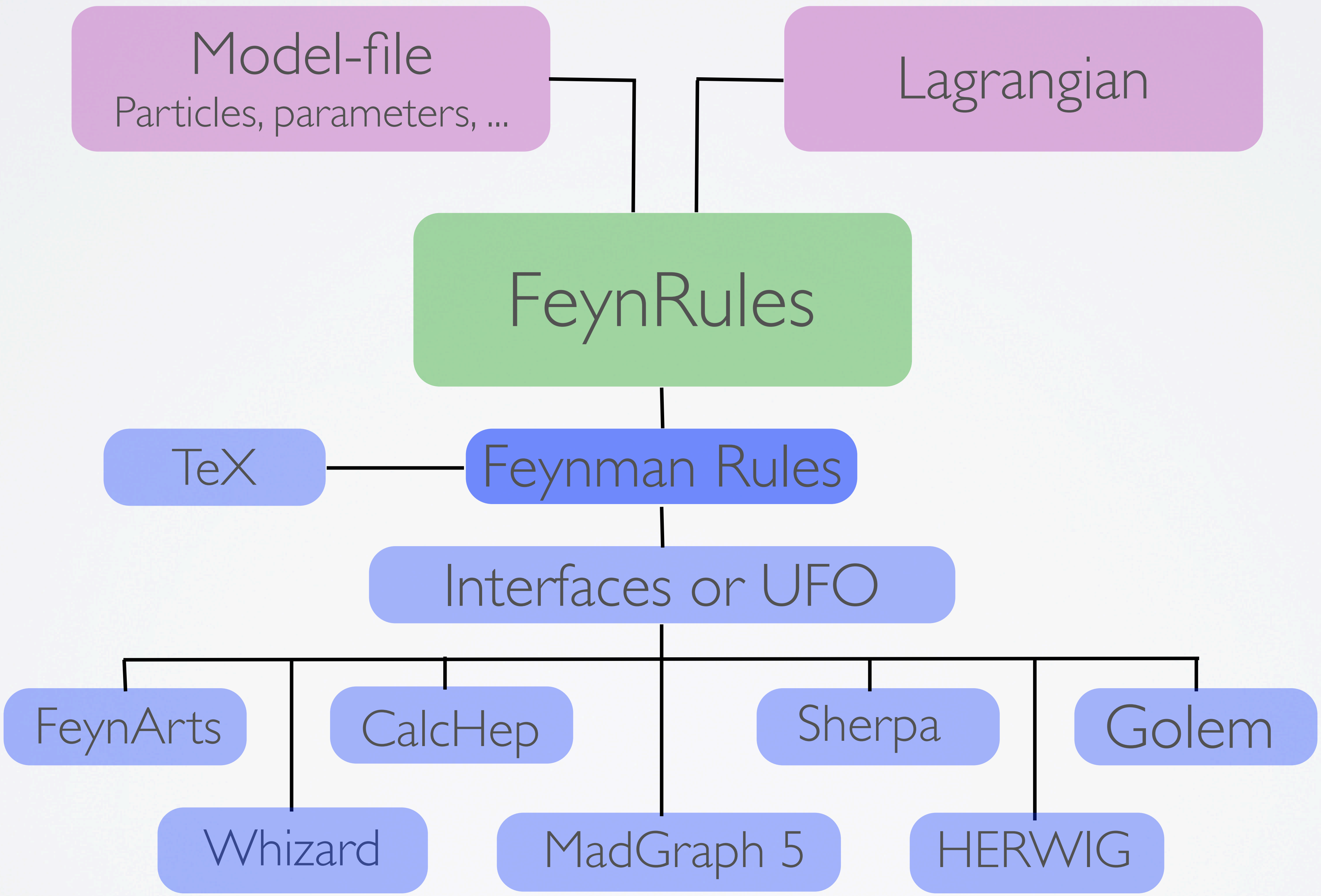
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

Complete automatization LO (and now NLO) calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics. Automatization of NLO is very promising now...

THE FEYNRULES PROJECT

[Christensen, Duhr, Fuks+ many collaborators]



THE FEYNRULES PROJECT

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (9)	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models (4)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories (4)	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators.
Miscellaneous (0)	

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Extra-din	
Strongly theories	
Miscellan	

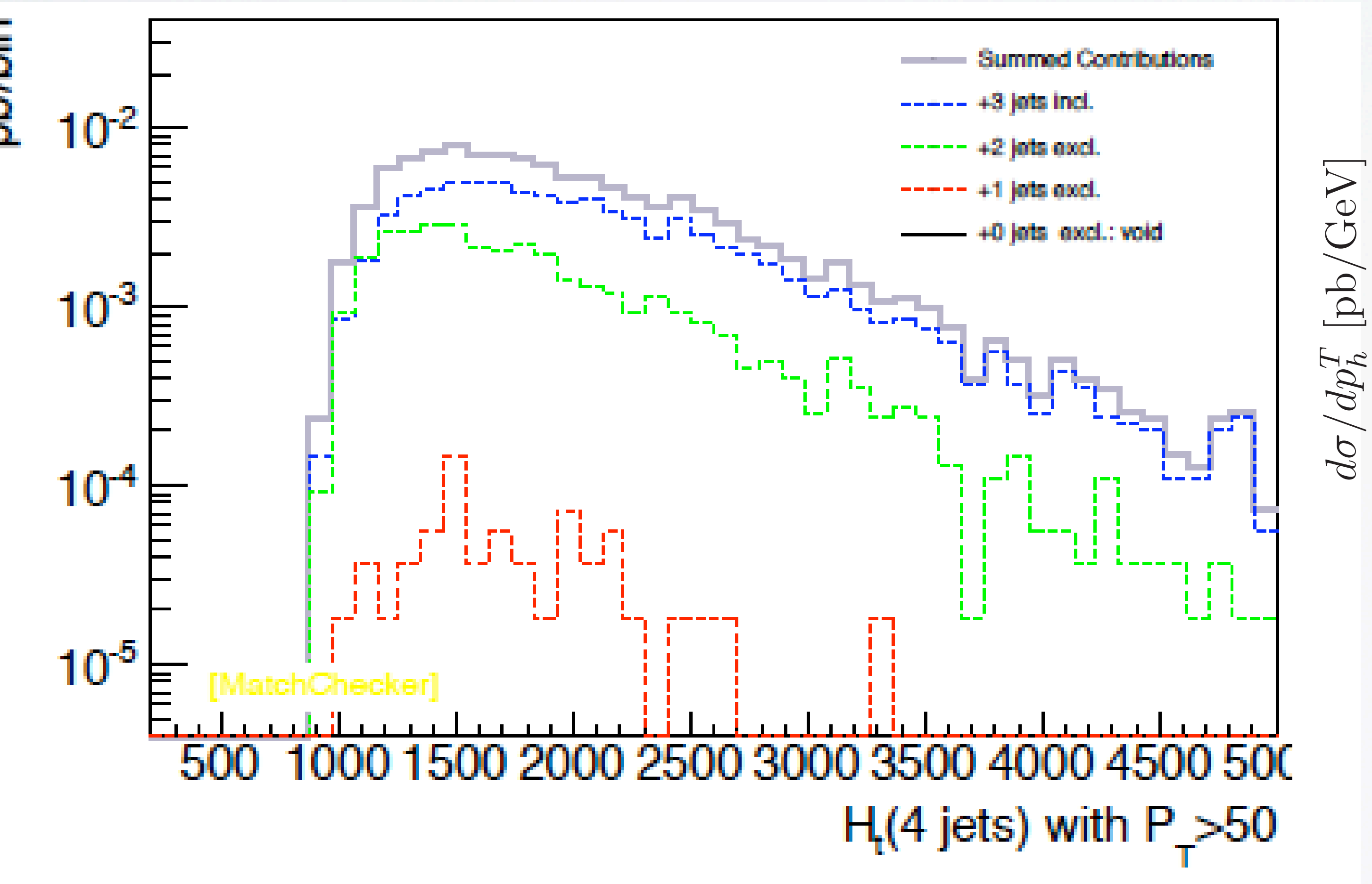
Model	Short Description	Contact	Status
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	**Available**
4th generation model	A fourth generation model including a t' and a b'	C. Duhr	**Available**
Standard model + Scalars	The SM, together with a set of singlet scalar particles coupling only to the SM Higgs, and allowing it to decay invisibly into this new scalar sector.	C. Duhr	**Available**
Hidden Abelian Higgs Model	A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings.	C. Duhr	**Available**
Hill Model	A model with an unusual extension of the SM Higgs sector.	P. de Aquino, C. Duhr	**Available**
The general 2HDM	The most general 2HDM, including all flavor violation and mixing terms.	C. Duhr, M. Herquet	**Available**
Triplet diquarks	The SM plus triplet diquark scalars.	J. Alwall, C. Duhr	**Available**
Sextet diquarks	The SM plus sextet diquark scalars.	J. Alwall, C. Duhr	**Available**

THE FEYNRULES PROJECT

- Public database, user driven, easy legacy
- All automatic ME generators supported
- Unprecedented validation and robustness
- It can be systematically improved/extended
- Superfield notation, higher spin-particles, more...
- User driven easy new functionalities (eg, NLO)

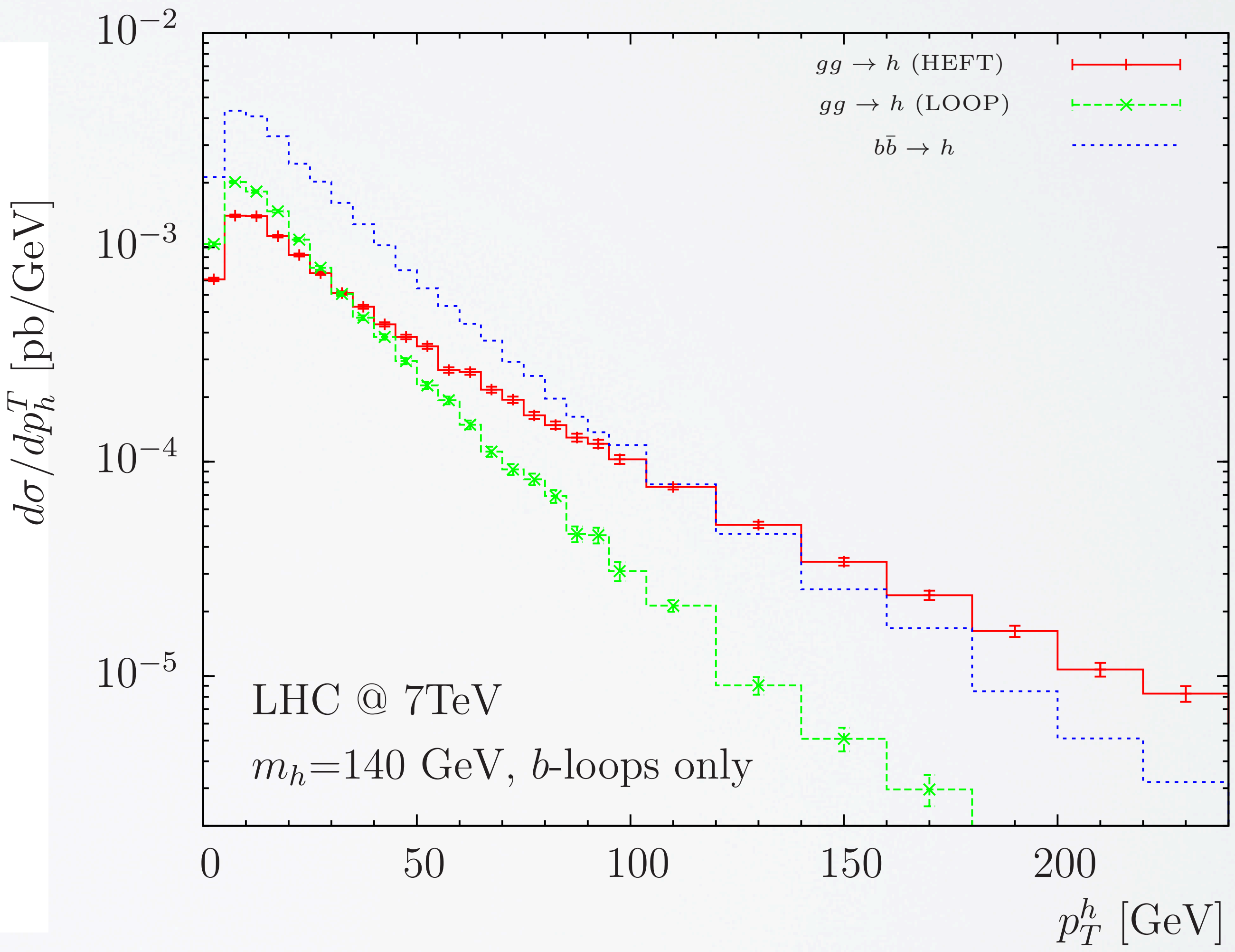
State of the art: BSM multijet final states

pp→Graviton (ADD&RS) +jets



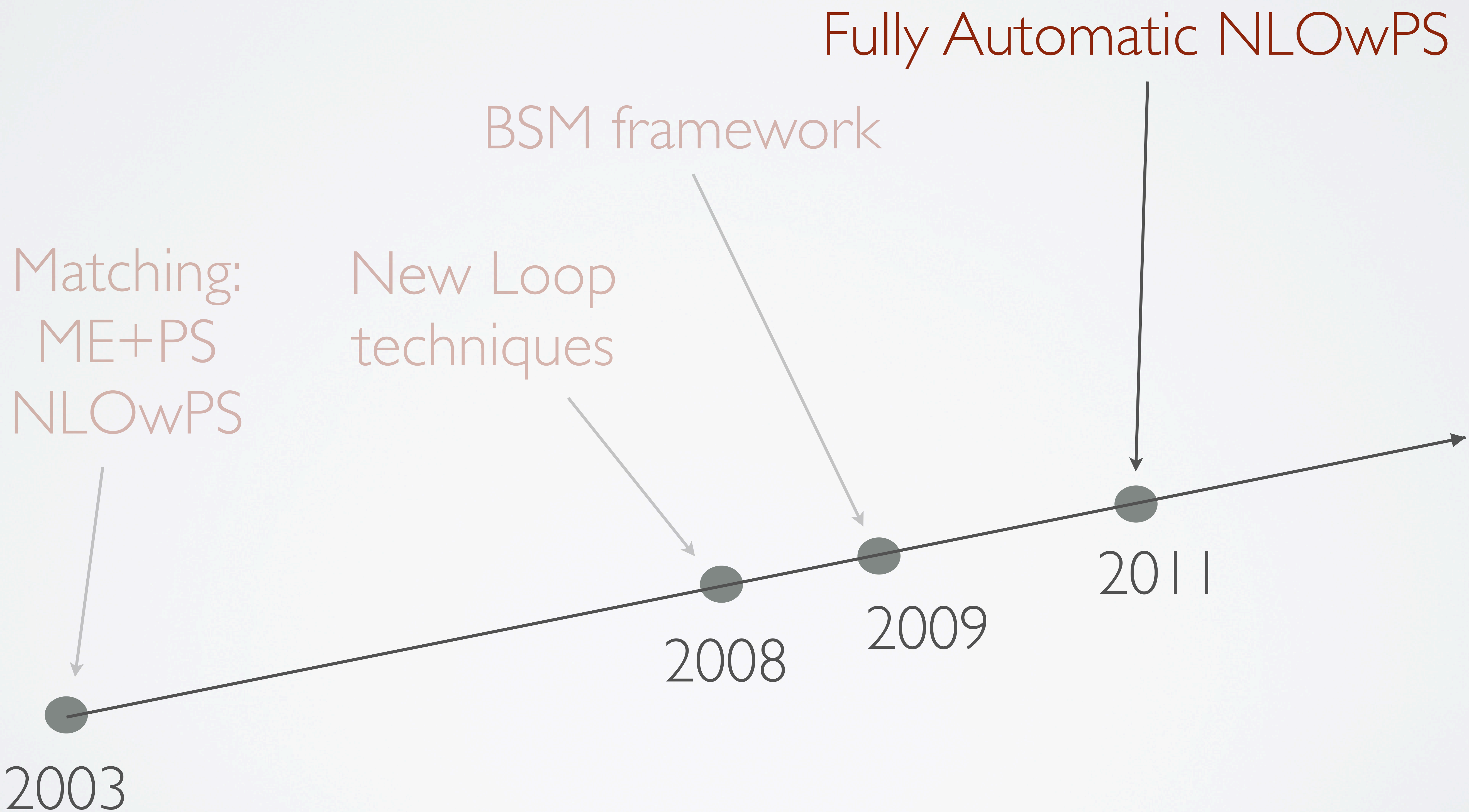
[de Aquino et al., 1108.2041]

pp→SUSY Higgs +jets



[Alwall et al. 1110.1728]

QCD AND MC (SIMPLIFIED) PROGRESS



NEW CODES FOR AUTOMATIC LOOP AMPLITUDES

- MadLoop : **Hirschi et al., 1103.0621,** based on MadGraph + CutTools
- HELAC-NLO : **Bevilacqua et al. , 1110.1499**, based on HELAC + CutTools
- GoSam : **Cullen et al. , 1111.6534** , based on QGRAF+SAMURAI+Golem
- Open Loops : **Cascioli et al., 1111.5206**, based on the combination of several approaches

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Limitations on applications (i.e. number of external partons or BSM) are systematically and quickly overcome: "the wave function of the automatic loop effort has collapsed!"

NEW NLO+PS FRAMEWORKS

- **POWHEG-BOX** and applications: Alioli et al, 1002.2581, 1009.2450, 1009.5594, 1012.3380, 1102.4846, 1105.4488, 1107.5051, 1108.0909:

  Framework which allows to promote a standard NLO calculation into a MC at NLO generator. Very popular choice. More than ~20 processes implemented in the last two years.

- **NEW SHERPA** Hoeche et al, 1008.5399, 1009.1127, 1111.1220 :

  Flexible framework having both MC@NLO and POWHEG methods based on CS dipoles, needs virtuals.

- **HERWIG++** D'Errico et Richardson 1106.2983,1106.3939, Hamilton et al. 0806.0290, 0903.4345, 1004.1764, 1009.5391:

  POWHEG method, several processes implemented. Need the NLO elements.

- **POWHEL** Papadopoulous, Garzelli, Kardos Trocsanyi, 1108.0387,1111.1444:

  HELAC-NLO (fully automatic) + POWHEG-Box

THE aMC@NLO JOINT VENTURE

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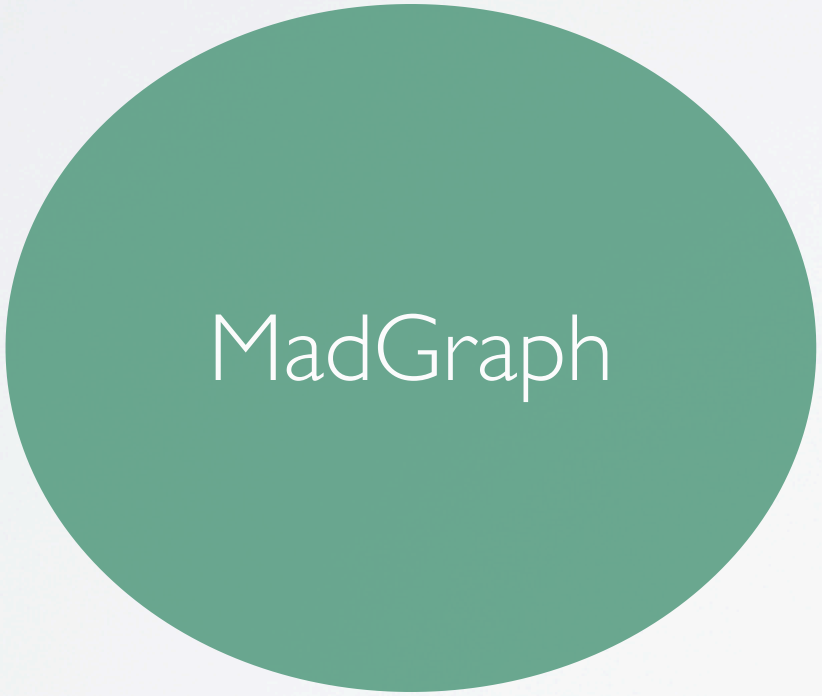
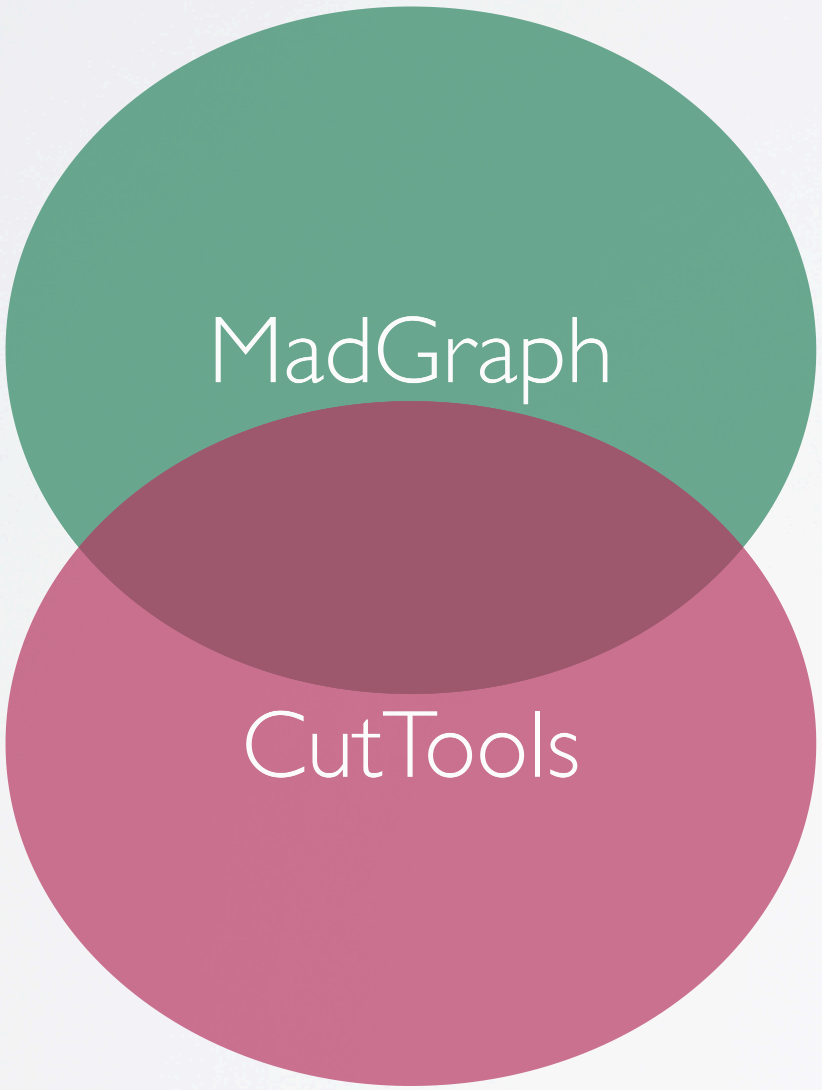


THE aMC@NLO JOINT VENTURE



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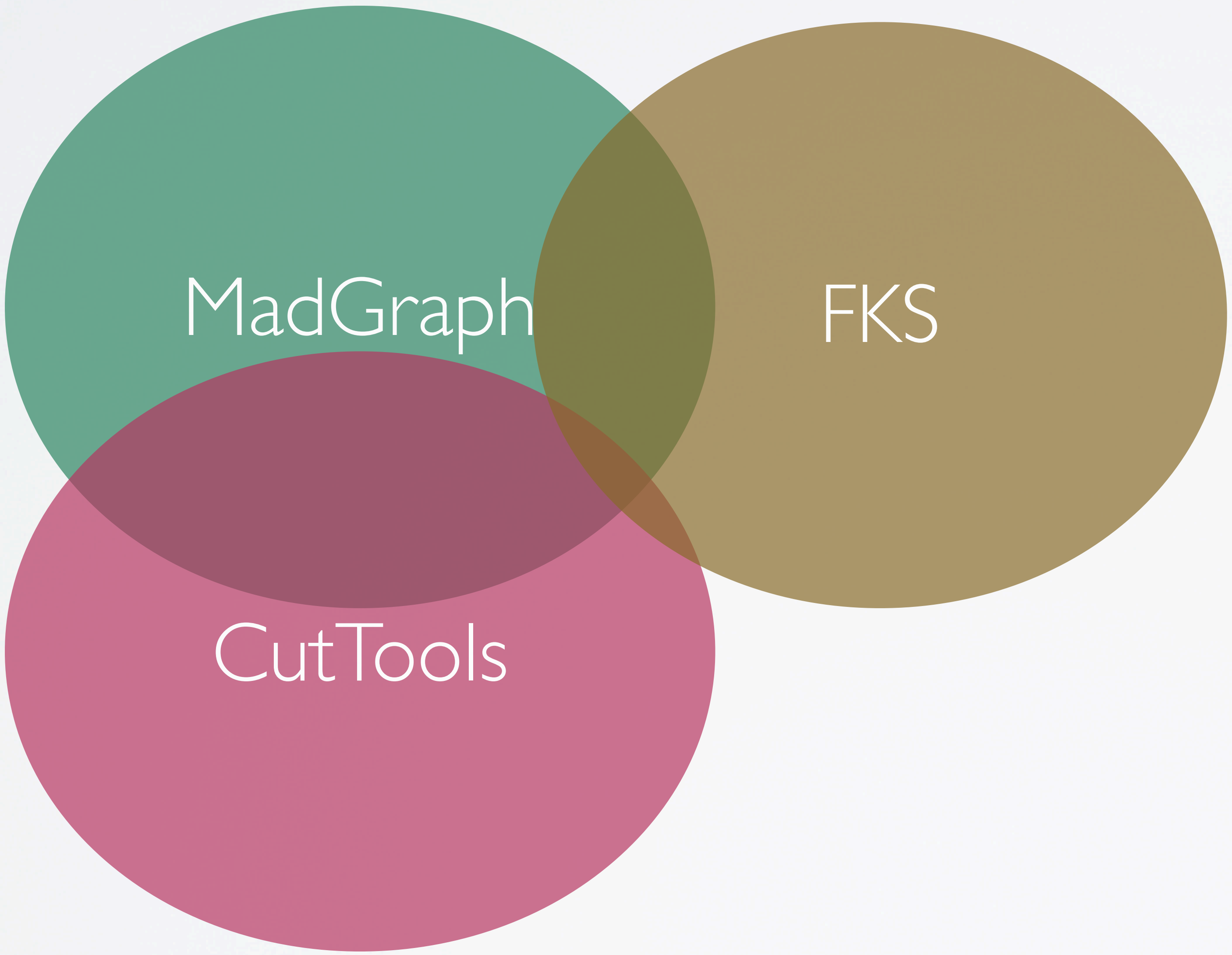

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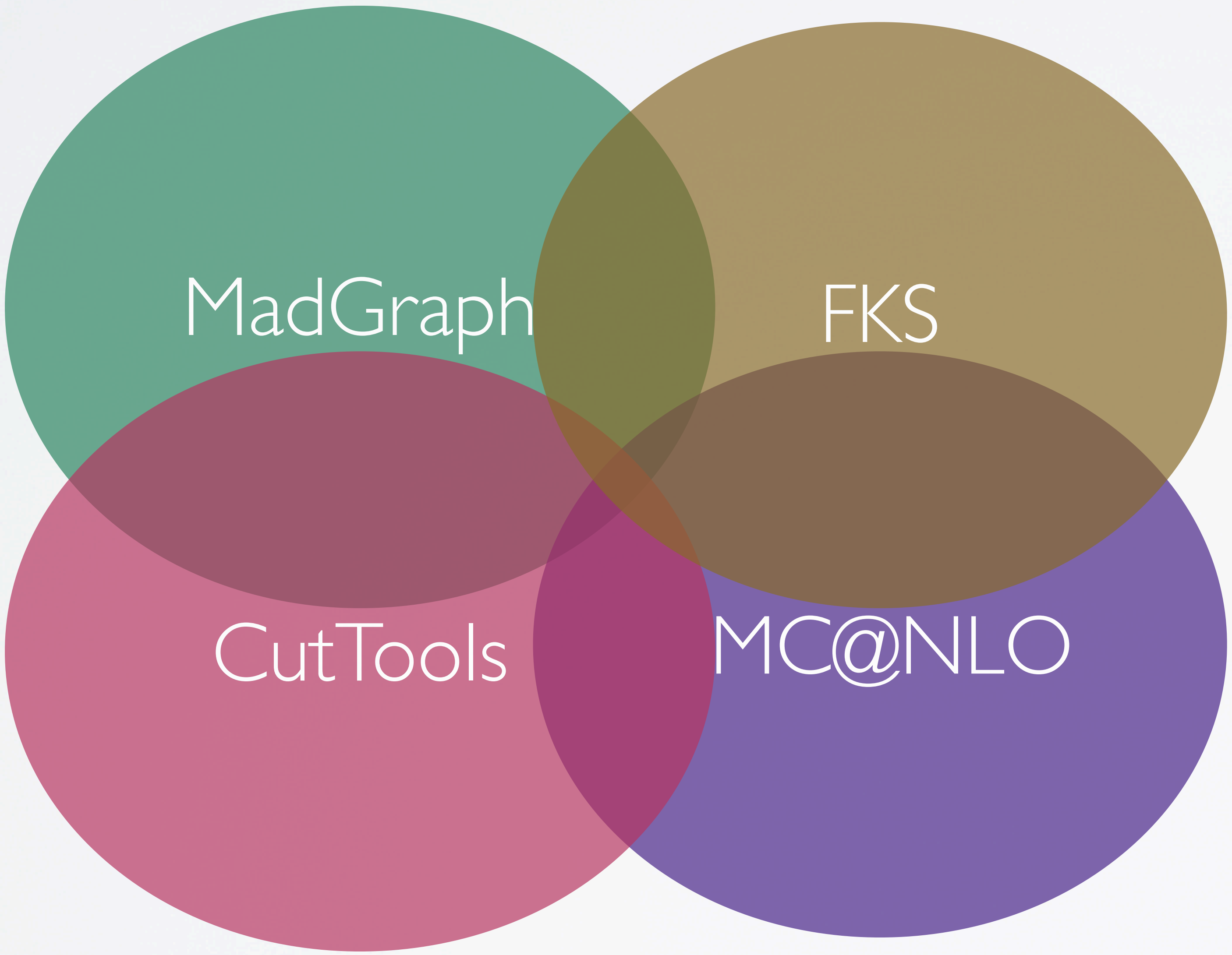

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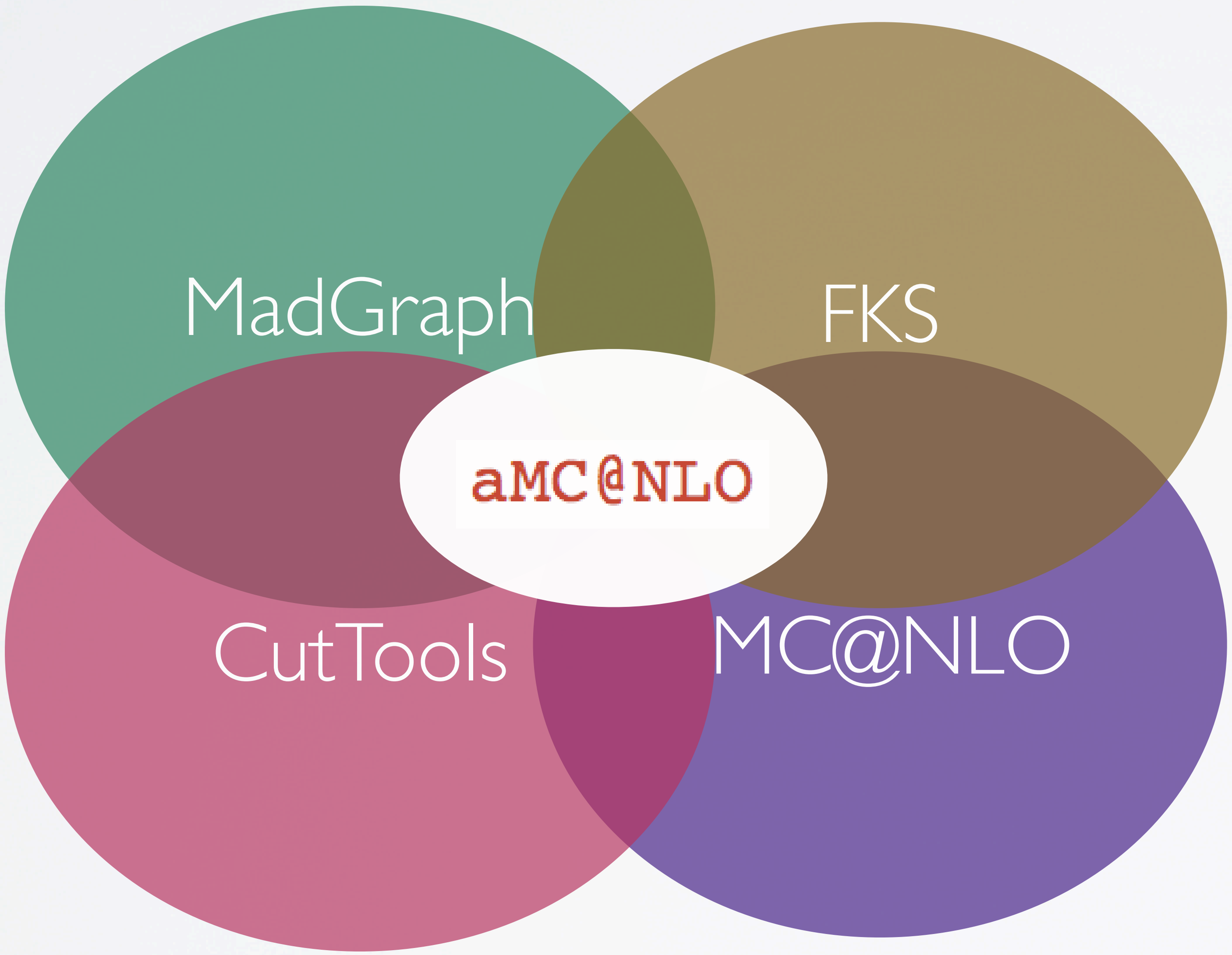

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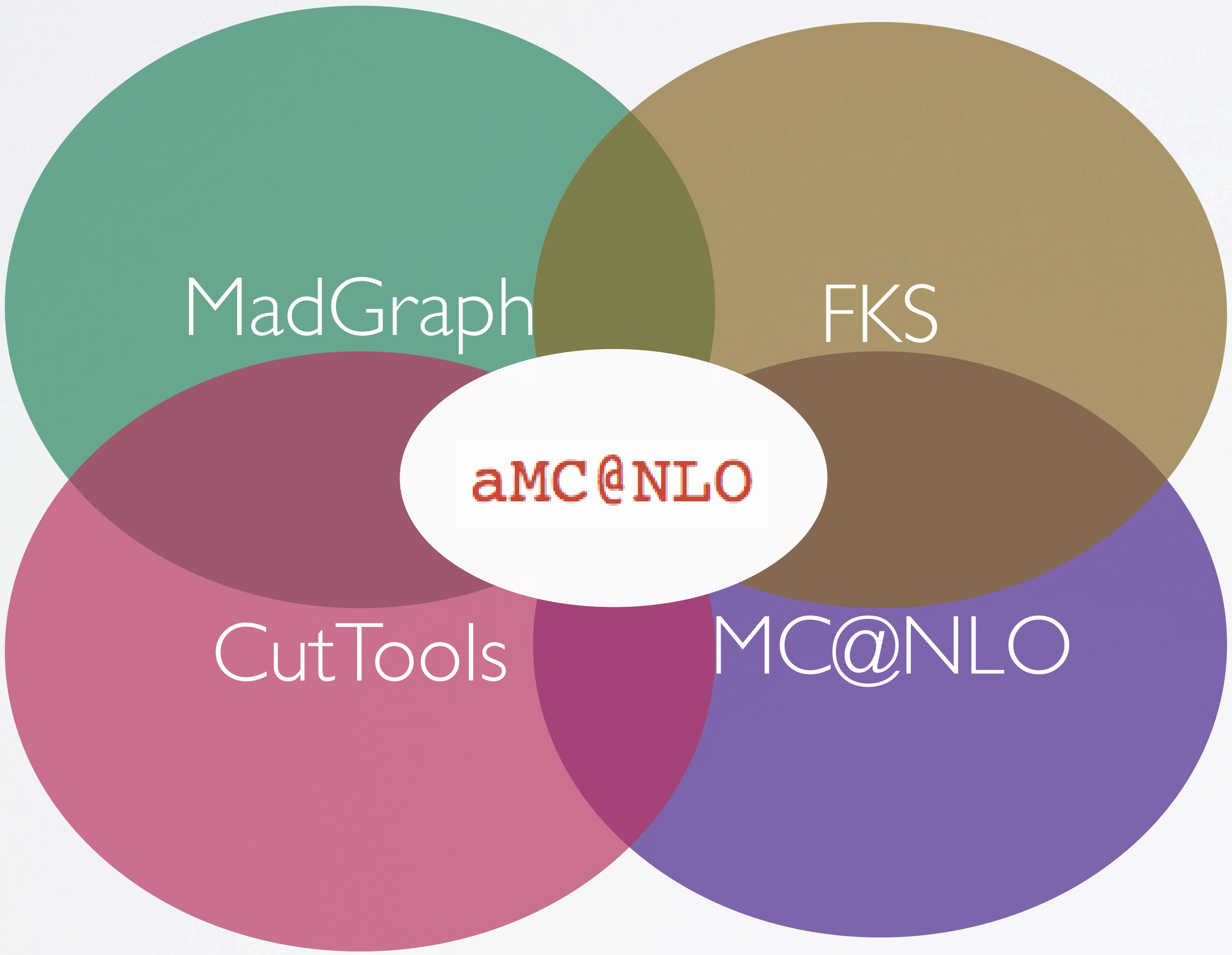
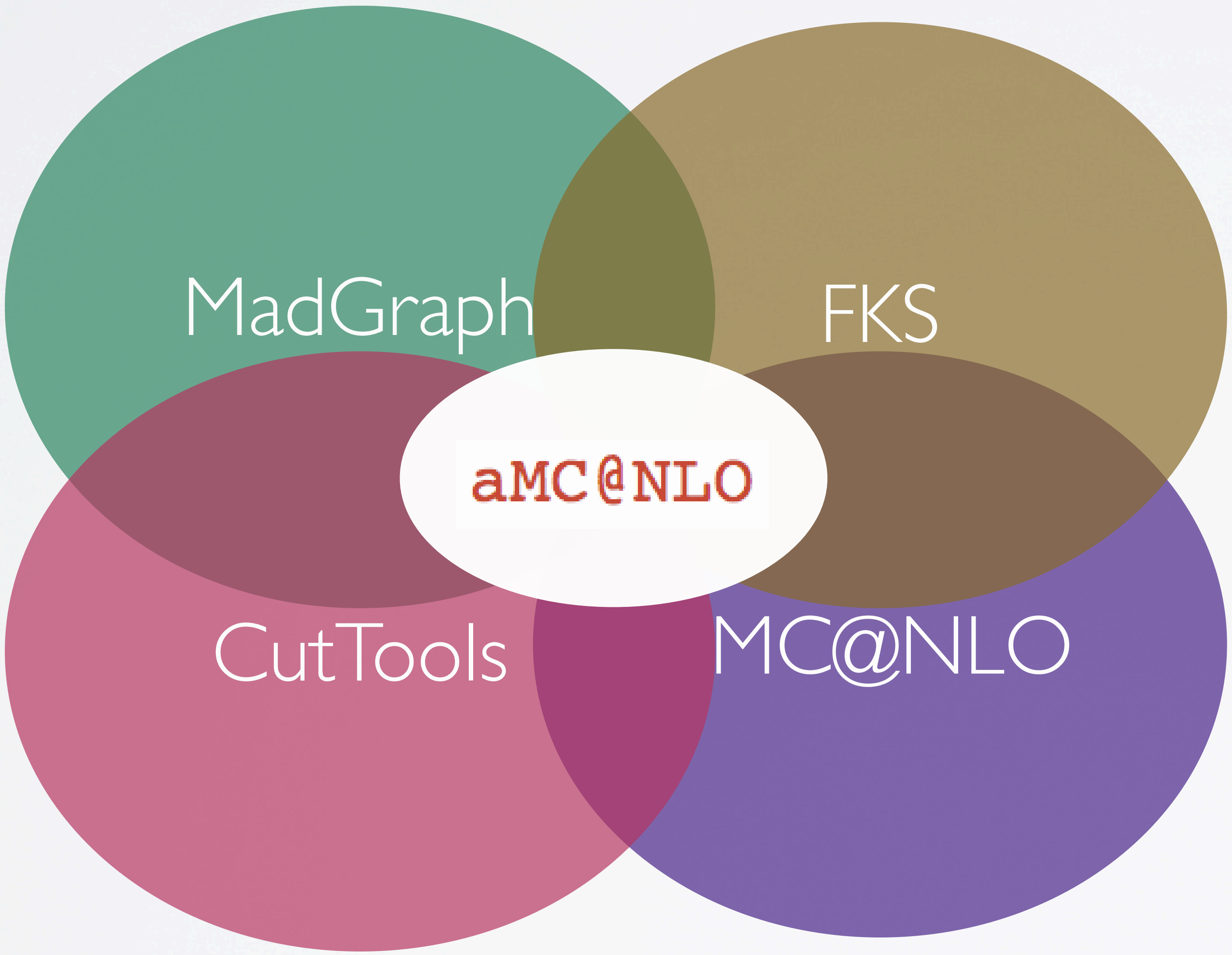


Modular structure:

- MadLoop or External Tool (via Binoth LH accord)
- MadFKS
- MC@NLO counterterms
- Interfaced to Herwig and Pythia

THE aMC@NLO JOINT VENTURE



Modular structure:

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http://amcatnlo.cern.ch

AUTOMATIC NLO IN SM
MADFKS+MADLOOP

[Hirshi, Frederix, Frixione, FM, Garzelli, Pittau, Torrielli, 1103.0621].

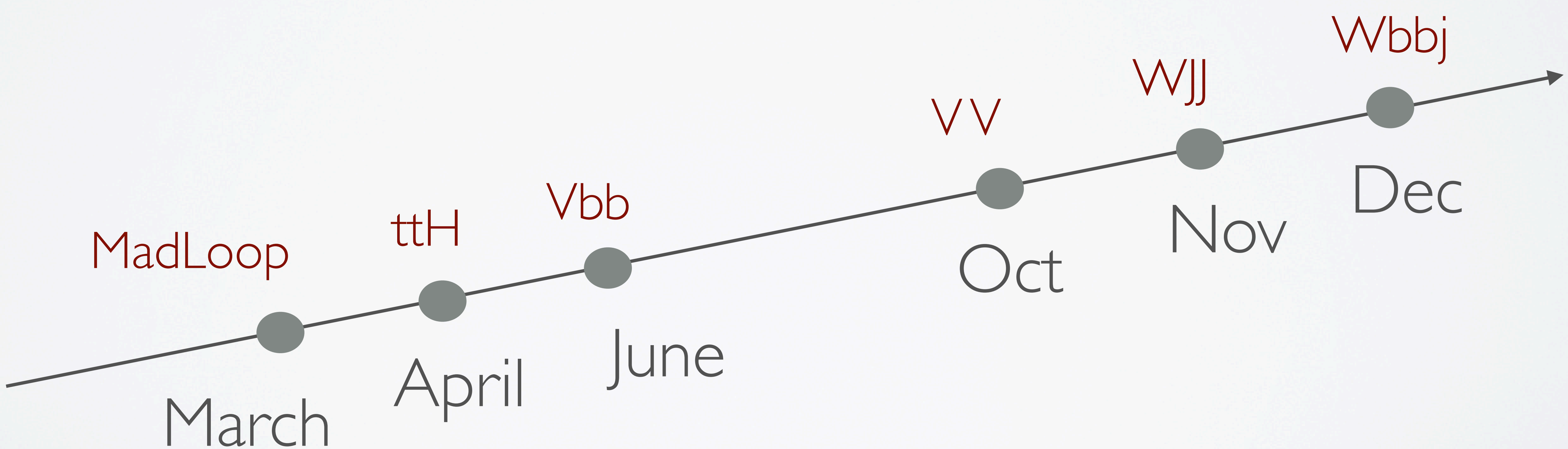
- Total cross sections at the LHC for 26 sample procs
- Very loose cuts just when needed
- Running time: Two weeks on a 150+ node cluster
- Proof of efficient EPS handling.
- Successful cross-check against known results (and small bugs found in other NLO codes Zjj, W^+W^+jj)

	Process	μ	n_{lf}	Cross section (pb) LO	Cross section (pb) NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+\, j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ\, j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

aMC@NLO YEAR 2011

aMC@NLO project : Frederix, Frixione, Hirschi, FM, Pittau, Torrielli

aMC@NLO YEAR 2011



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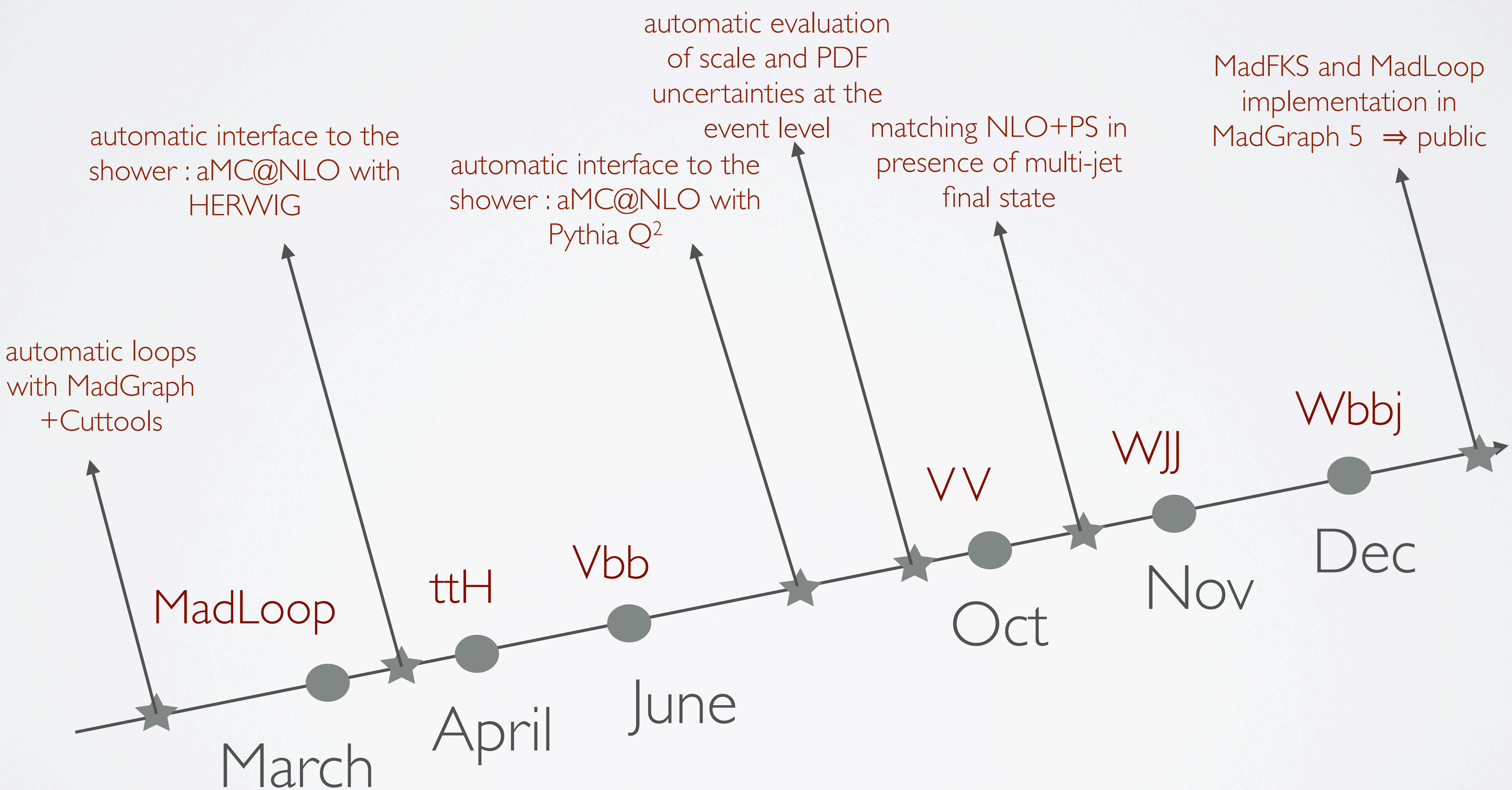
aMC@NLO YEAR 2011



aMC@NLO project : Frederix, Frixione, Hirschi, FM, Pittau, Torrielli

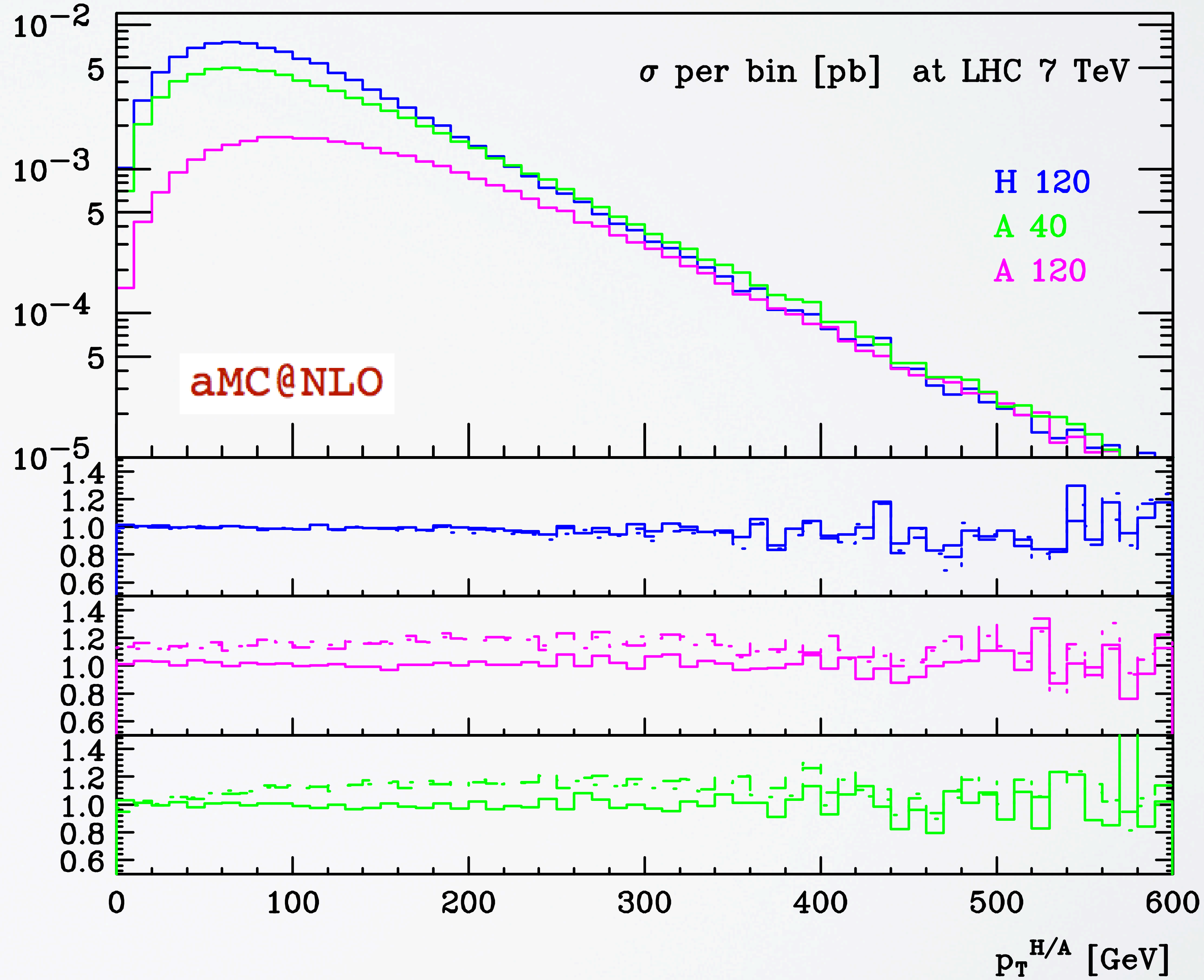
FIRST aMC@NLO APPLICATIONS

ttH/ttA (Z/W→ll/lv)bb(+j) ZZ→4l Wjj

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

First fully automatic results for both H and A [aMC@NLO:1104.5613].

Mild corrections to the shapes for m_h=120 GeV. p_T pseudoscalar is harder. At high p_T (boosted Higgs) the three curves are equal in shape and normalization.



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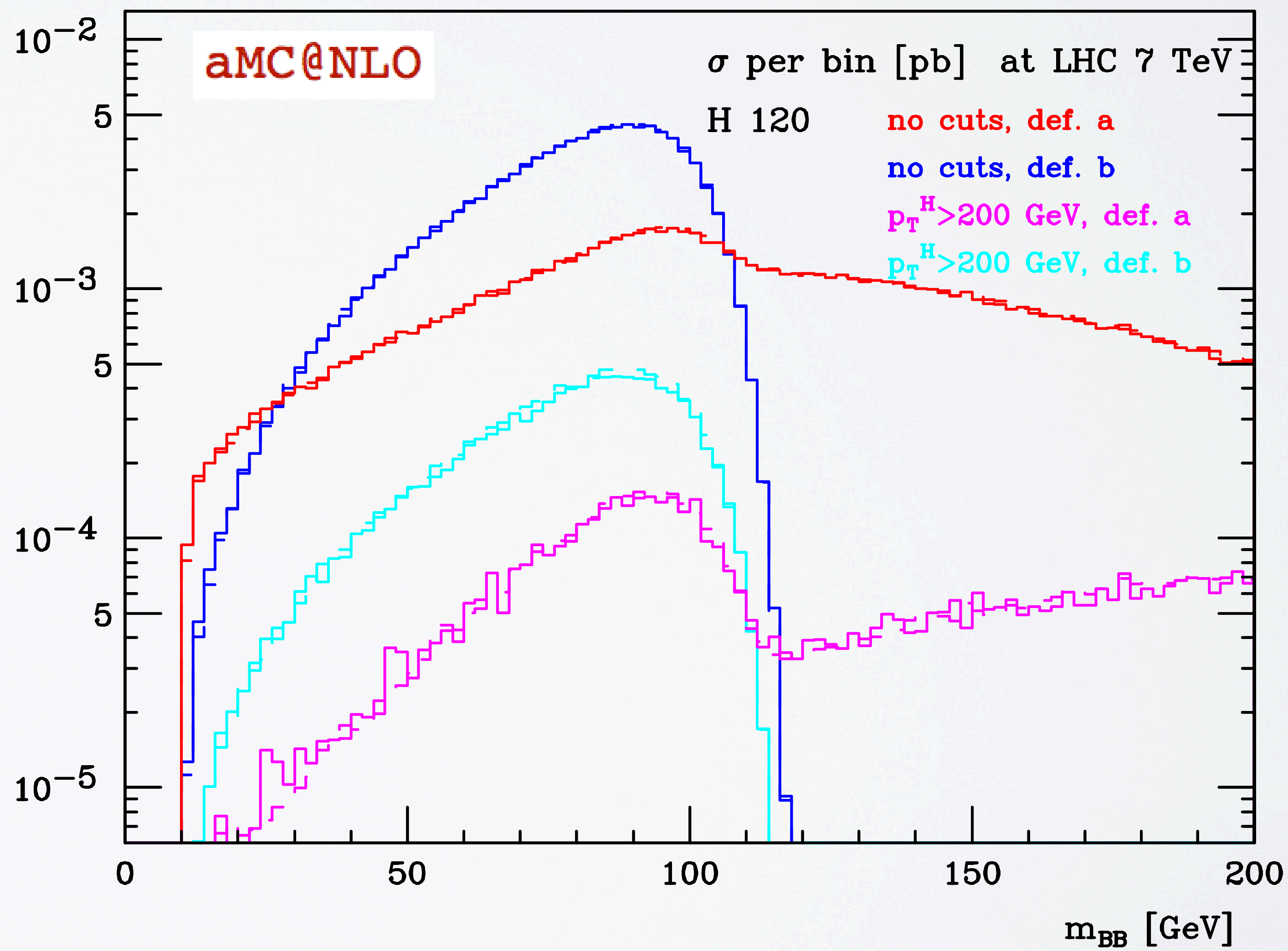
Experimental grade distributions for decaying tops and Higgs can be plotted. Combinatorics very hard to manage, is improved in the boosted case.



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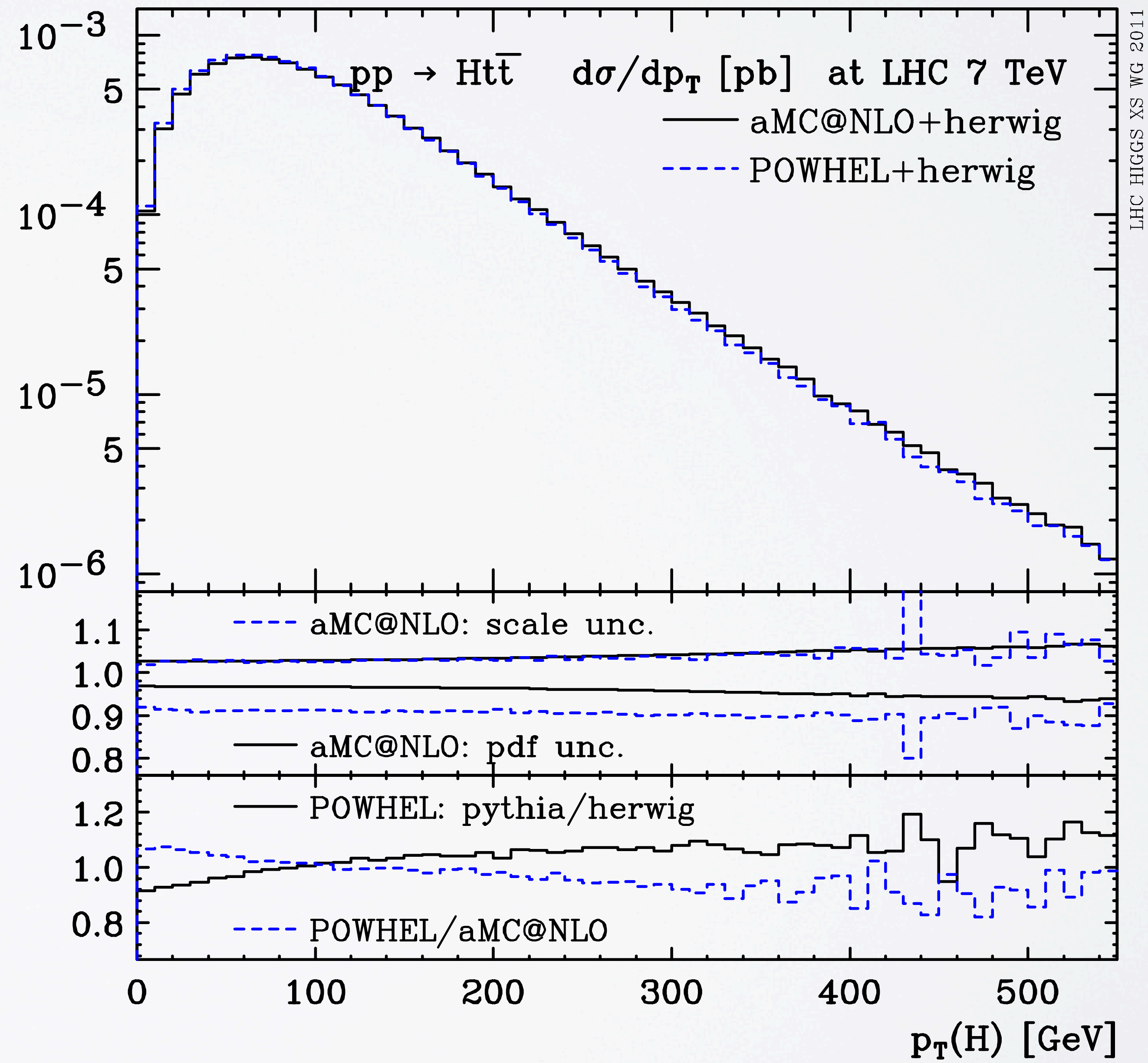
Comparison in the LHC Higgs XS WG with the recent implementation in POWHEL. Differences of the order 10%/15%, between MC@NLO/POWHEL and Pythia/Herwig.



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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.

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First fully automatic NLO+PS results for Vbb [aMC@NLO: 1106.6019].

Wbb

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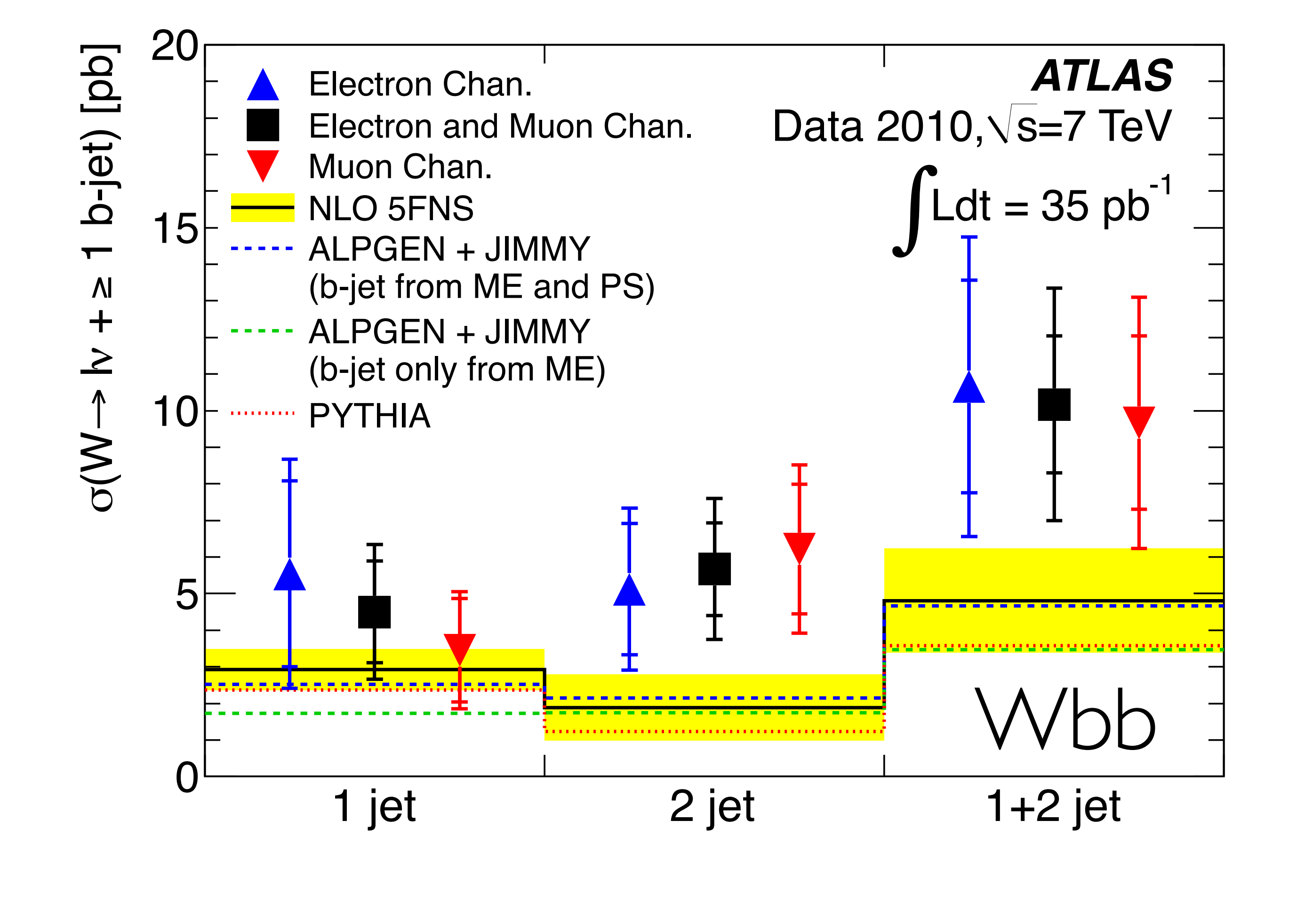

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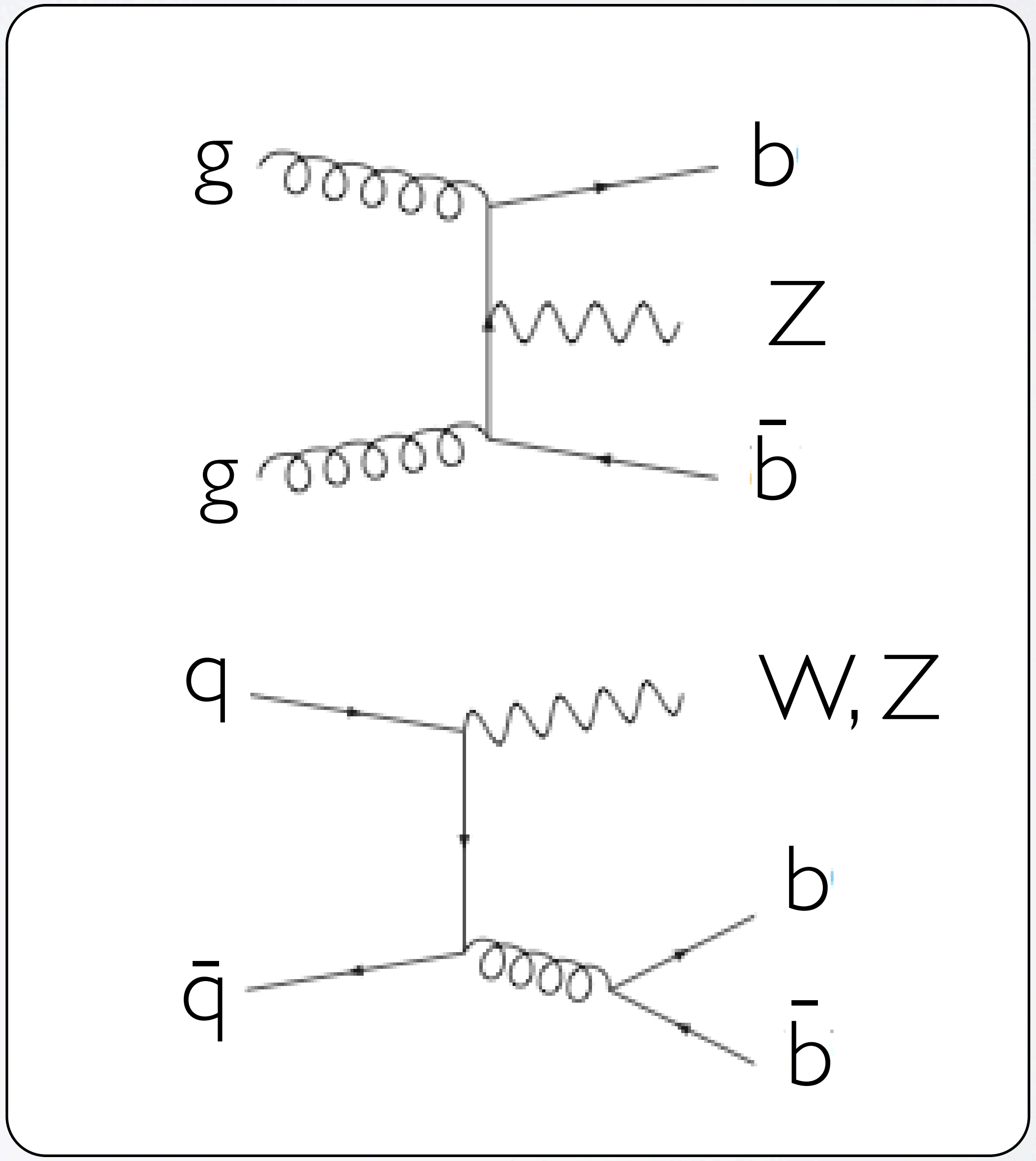

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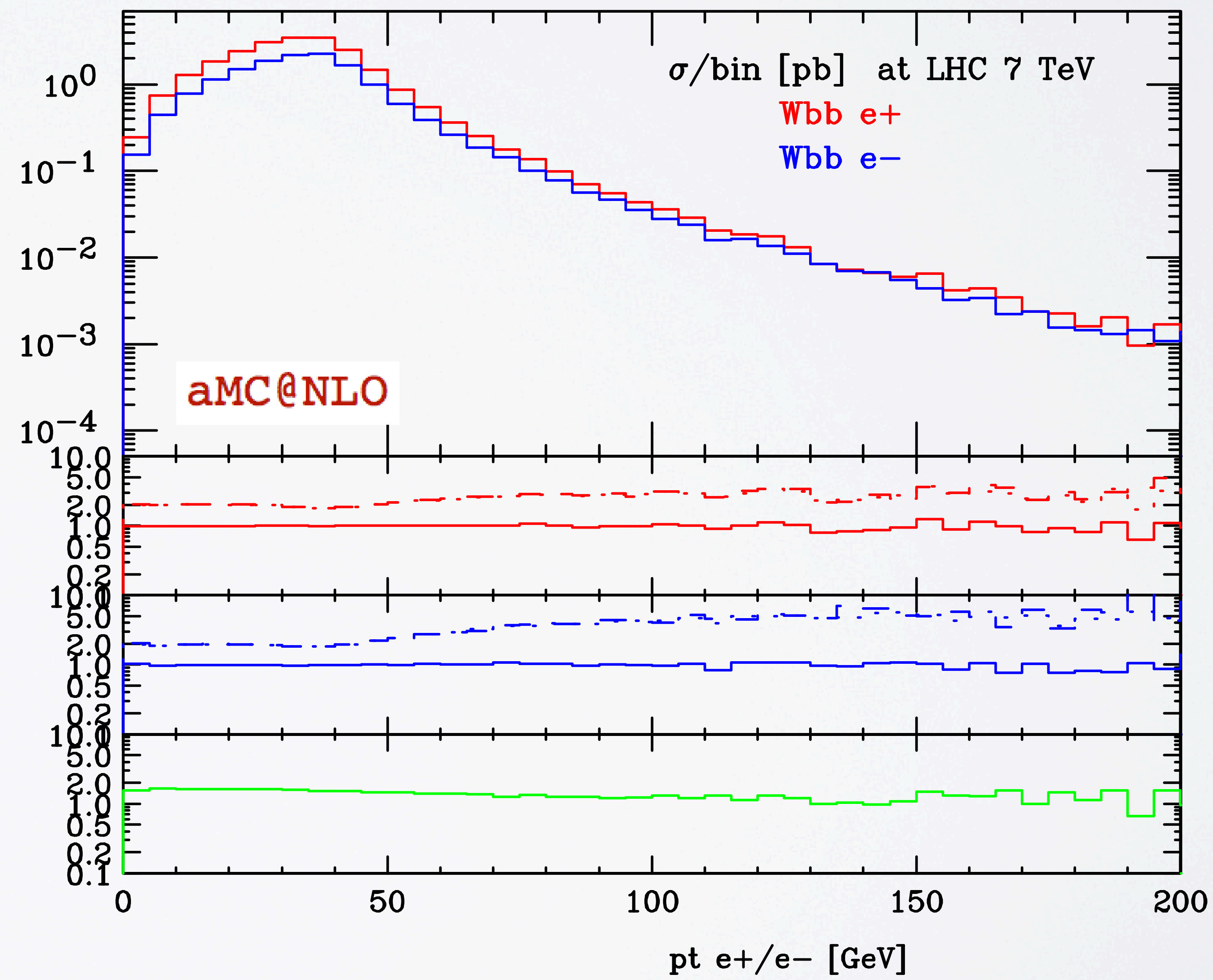

W+ W- asymmetry. K-factors of order two in the tails. No difference between NLO and MC@NLO for this observable.

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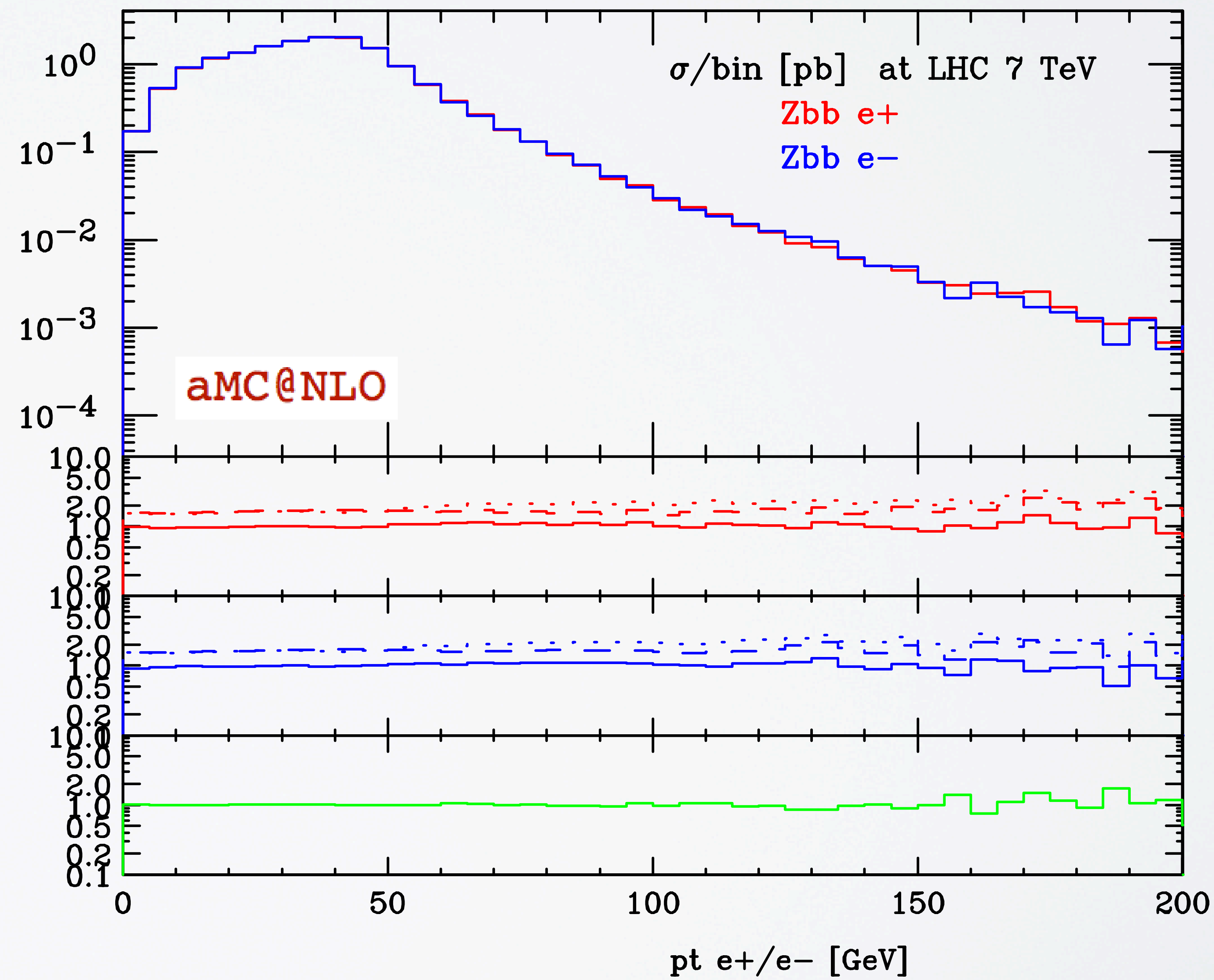

Similar pattern for Zbb. No difference between NLO and MC@NLO for this observable.

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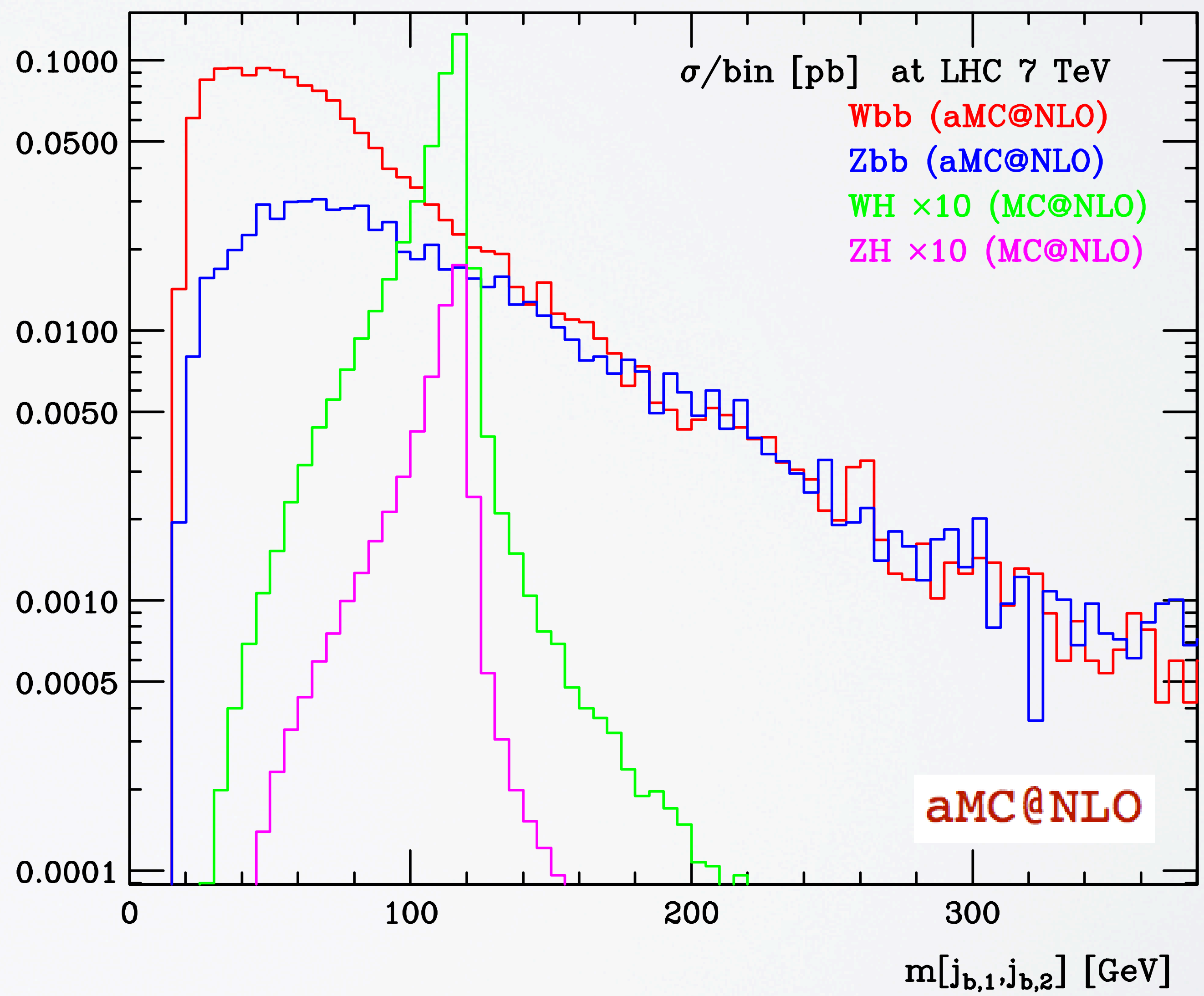
Very different m_{bb} distributions. Full simulation for signal and background at NLOwPS!!



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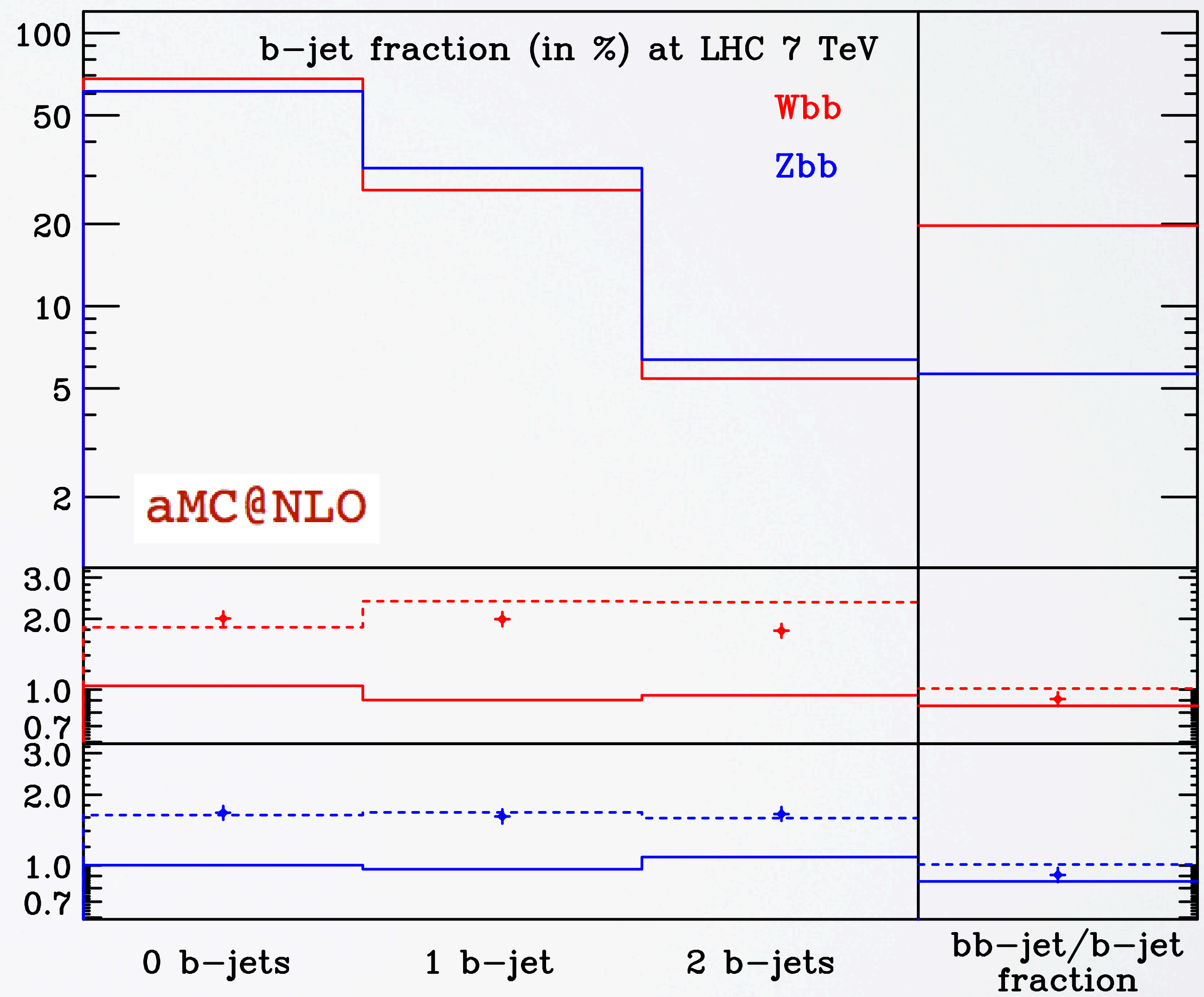
b-jet rates are NLO observables and can be determined exactly as EXP's do.



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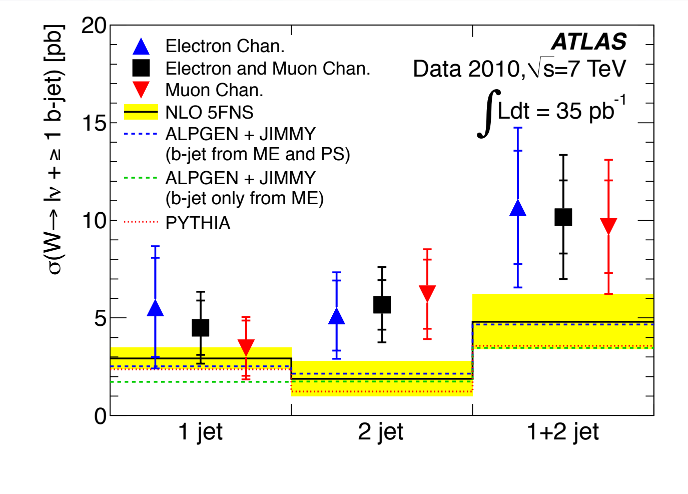

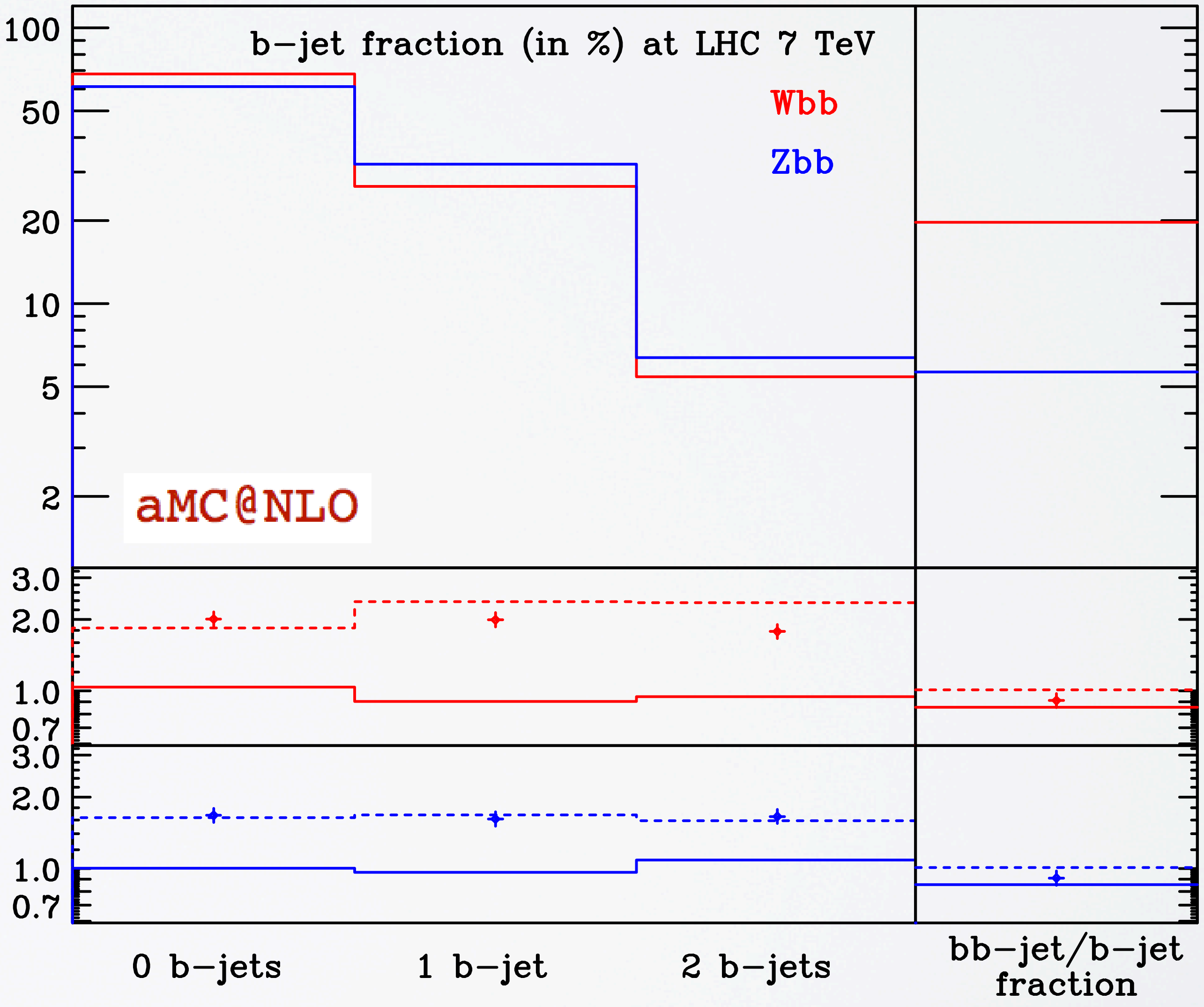

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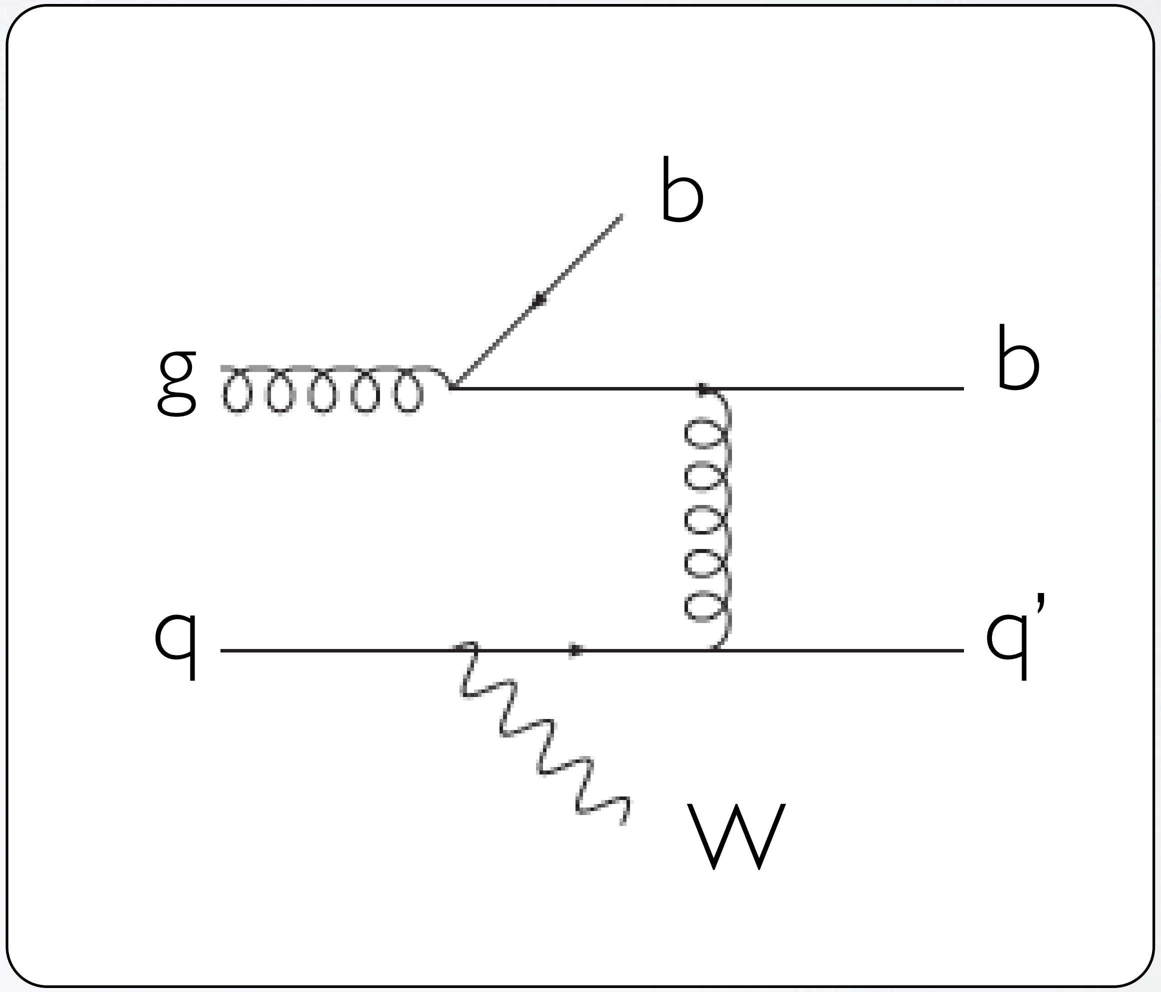
Is this enough? Not Really! Very large contributions from new channels at NLO to the 1bjet+1jet bin.



Solution: Calculate Wbbj at NLO with $m_b>0$!!

FIRST aMC@NLO APPLICATIONS

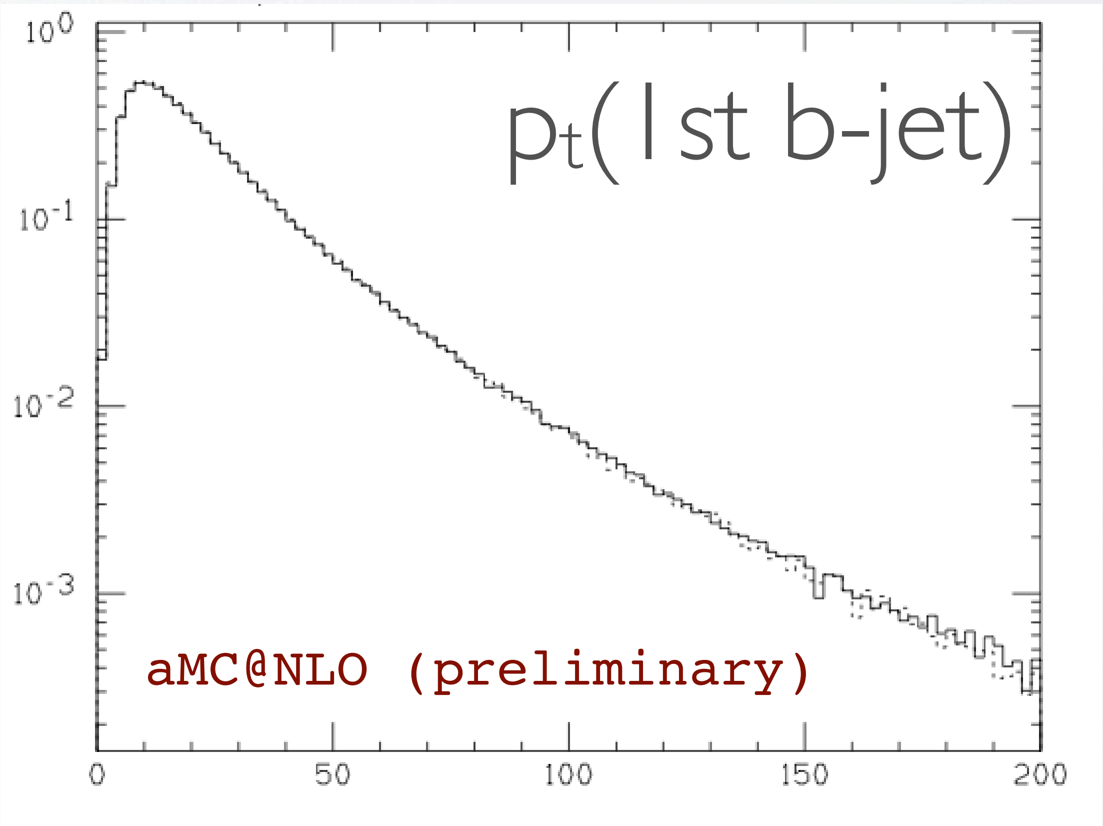
ttH/ttA (Z/W→ll/lν)bb(+j) ZZ→4l Wjj

Wbbj

NLO not known so far. **First NLO computation** (m_b>0) and fully automatic NLO +PS results [aMC@NLO: 1201.XXXX].

Sample depends on generation cut on the p_T(jet) >5,10 GeV. However, at analysis level p_T(jet)>20 GeV, no dependence is left. Necessary sanity check.

Observables at NLO :
3 jets with 2 b-tags
2 jets with 1 b-tag
2 jets with 1 bb-tag



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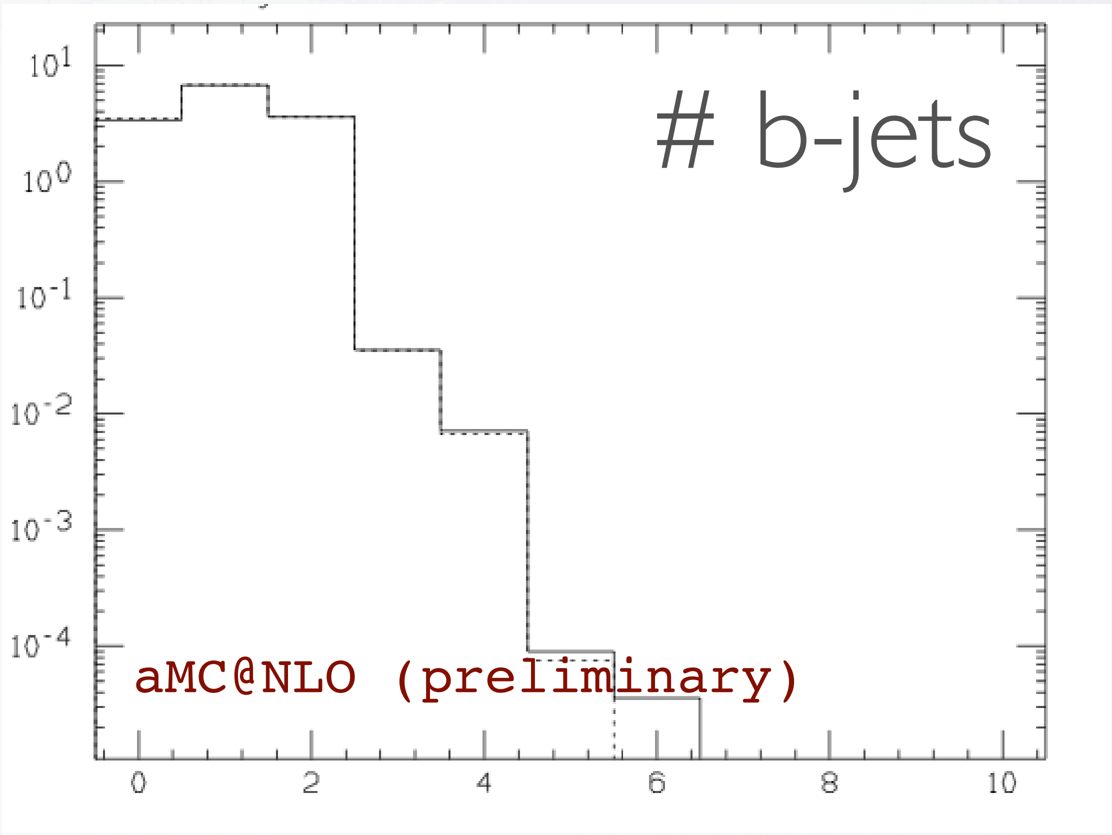


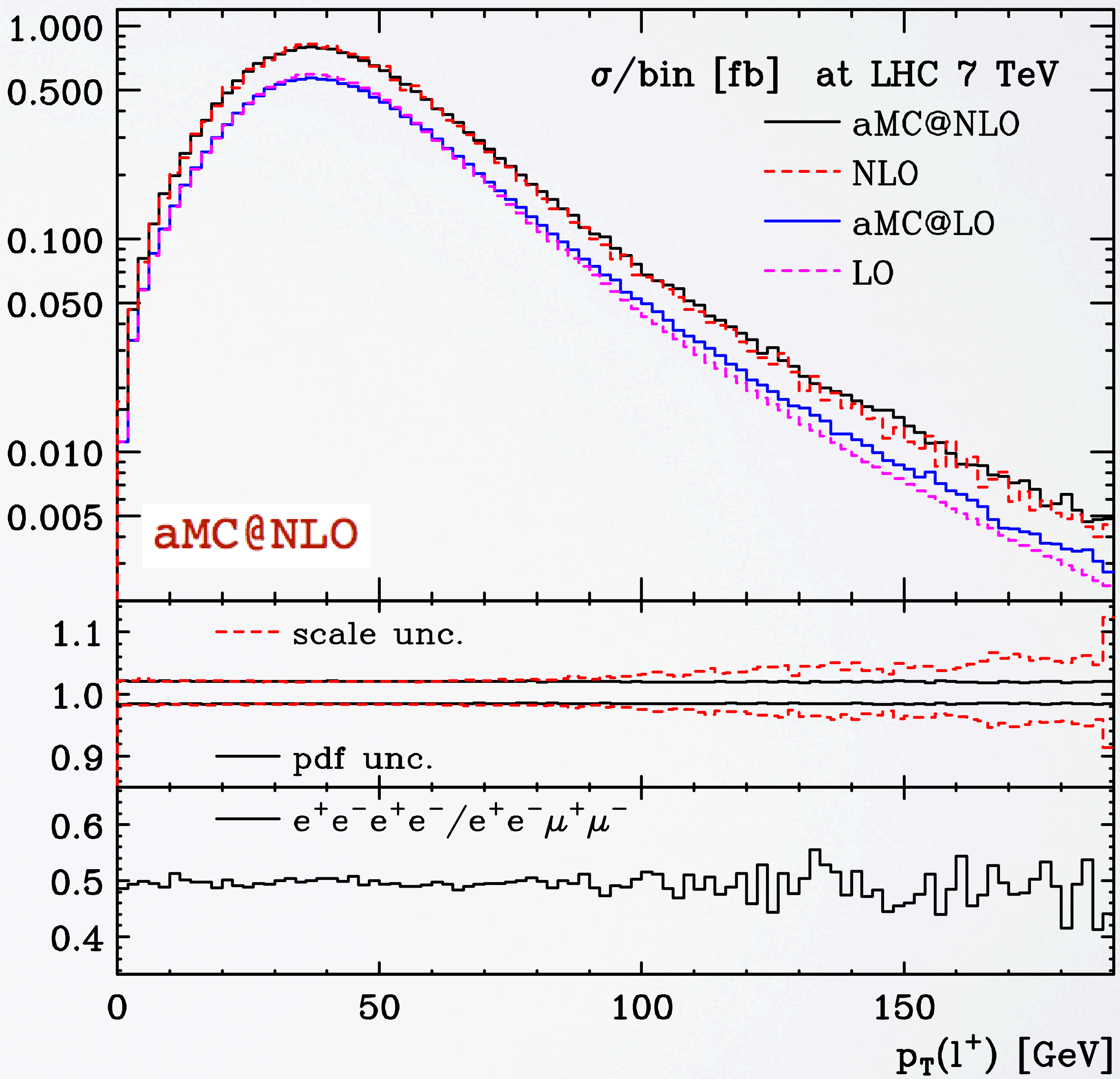
FIRST aMC@NLO APPLICATIONS

ttH/ttA (Z/W→ll/lν)bb(+j) ZZ→4l Wjj

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: 1110.4738].



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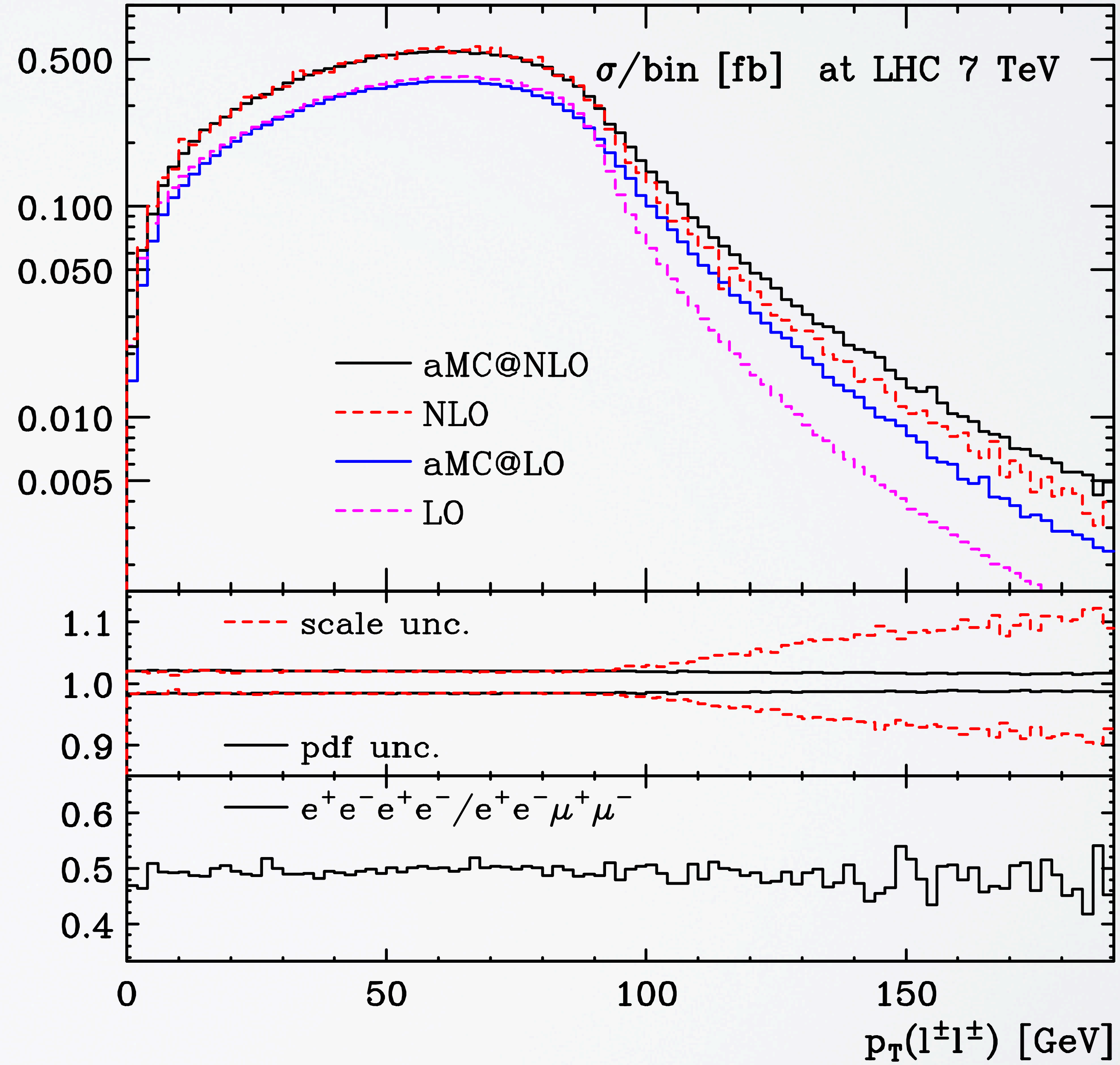
Perturbative expansion is well-behaved.



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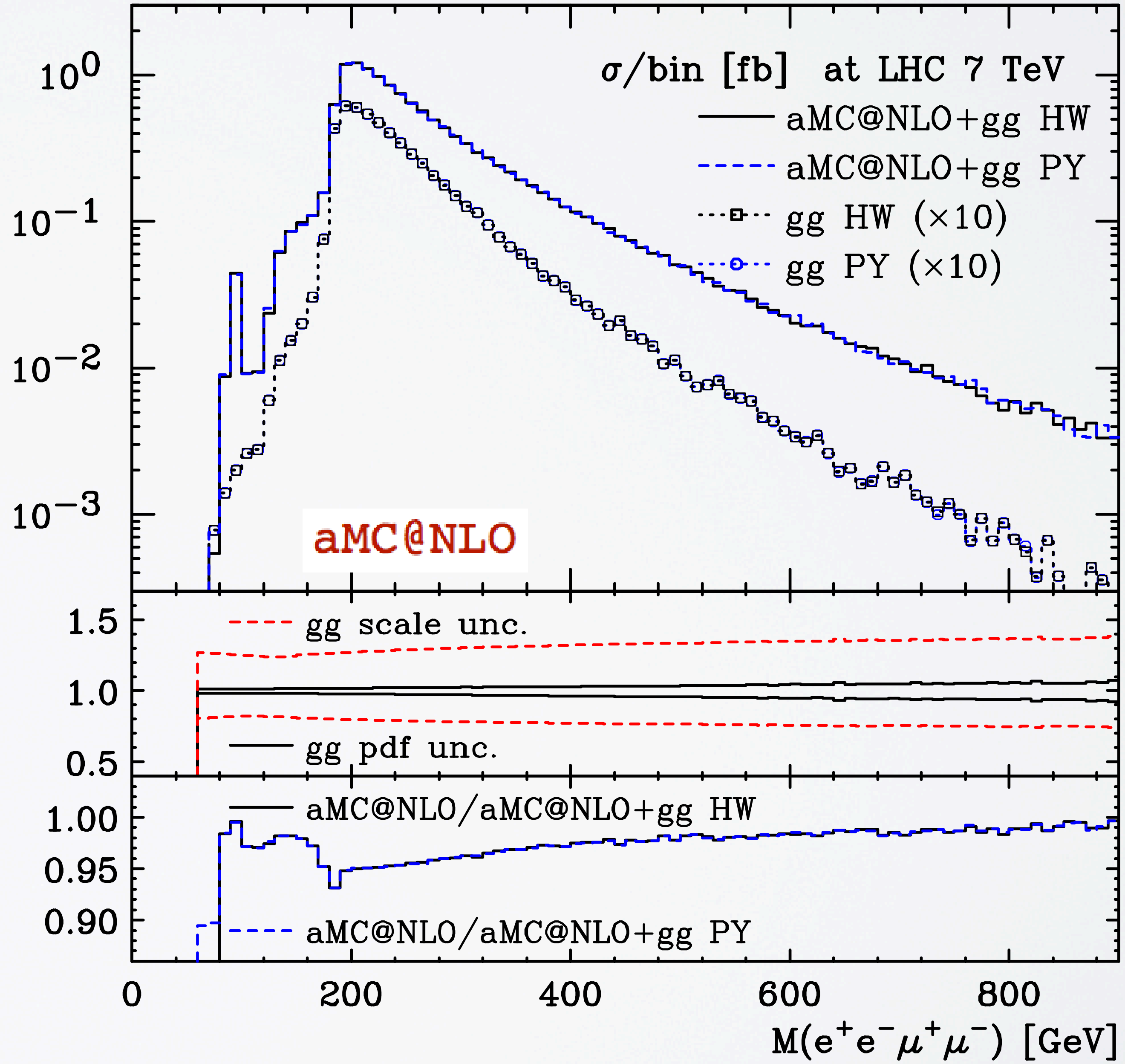
Interface to HERWIG and PYTHIA.



FIRST aMC@NLO APPLICATIONS

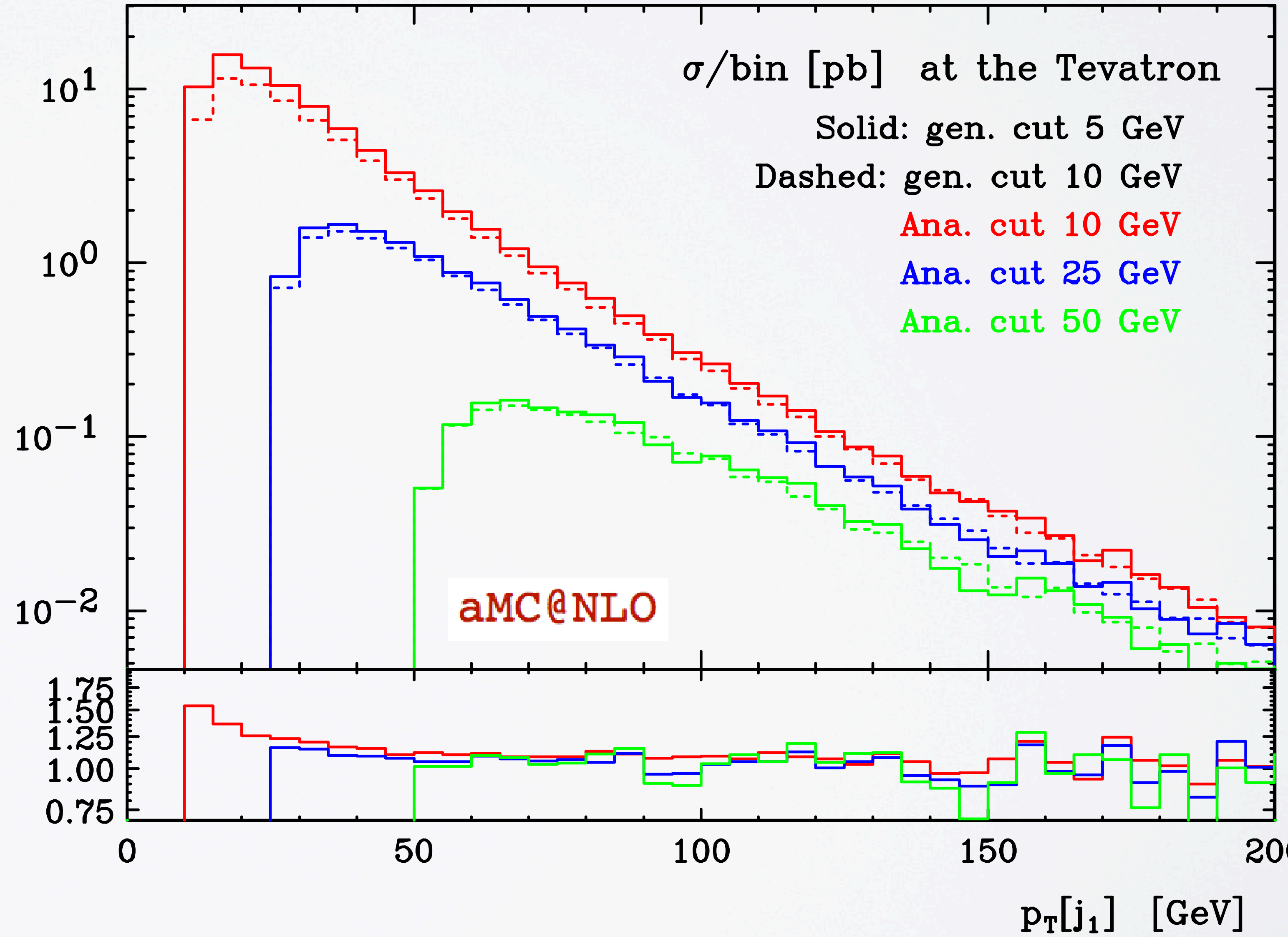
ttH/ttA (Z/W→ll/lν)bb(+j) ZZ→4l $\boxed{\text{Wjj}}$

NLO known and available in MCFM since a long time.

First fully automatic NLO+PS results for a non-trivial multi-jet final state including uncertainties.

[aMC@NLO: 1110.5502].

Check of generation cut independence. NLOwPS for this process "proves" feasibility for any jet multiplicity and opens the way to CKKW@NLO studies.



FIRST aMC@NLO APPLICATIONS

ttH/ttA (Z/W→ll/lν)bb(+j) ZZ→4l **Wjj**

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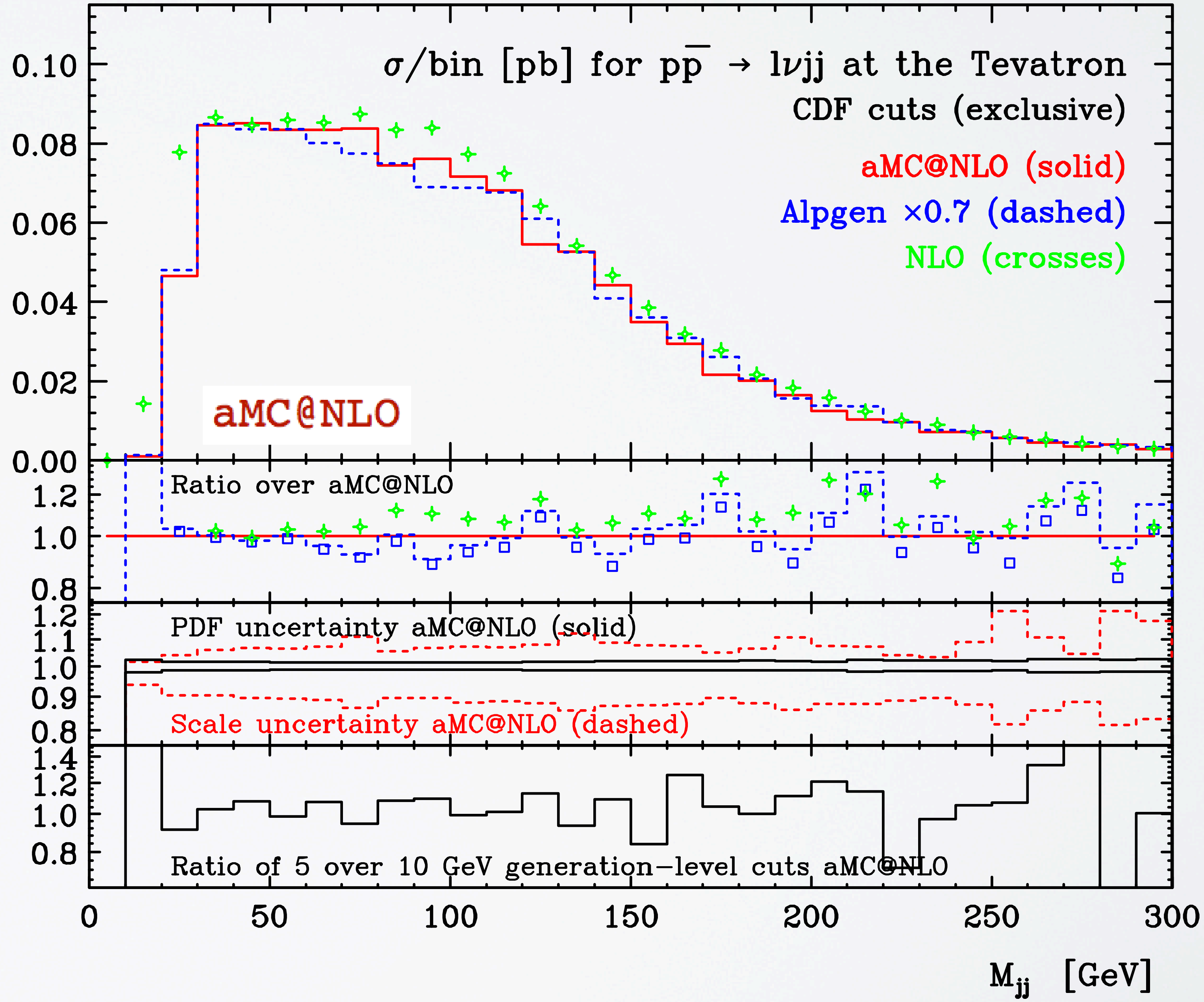
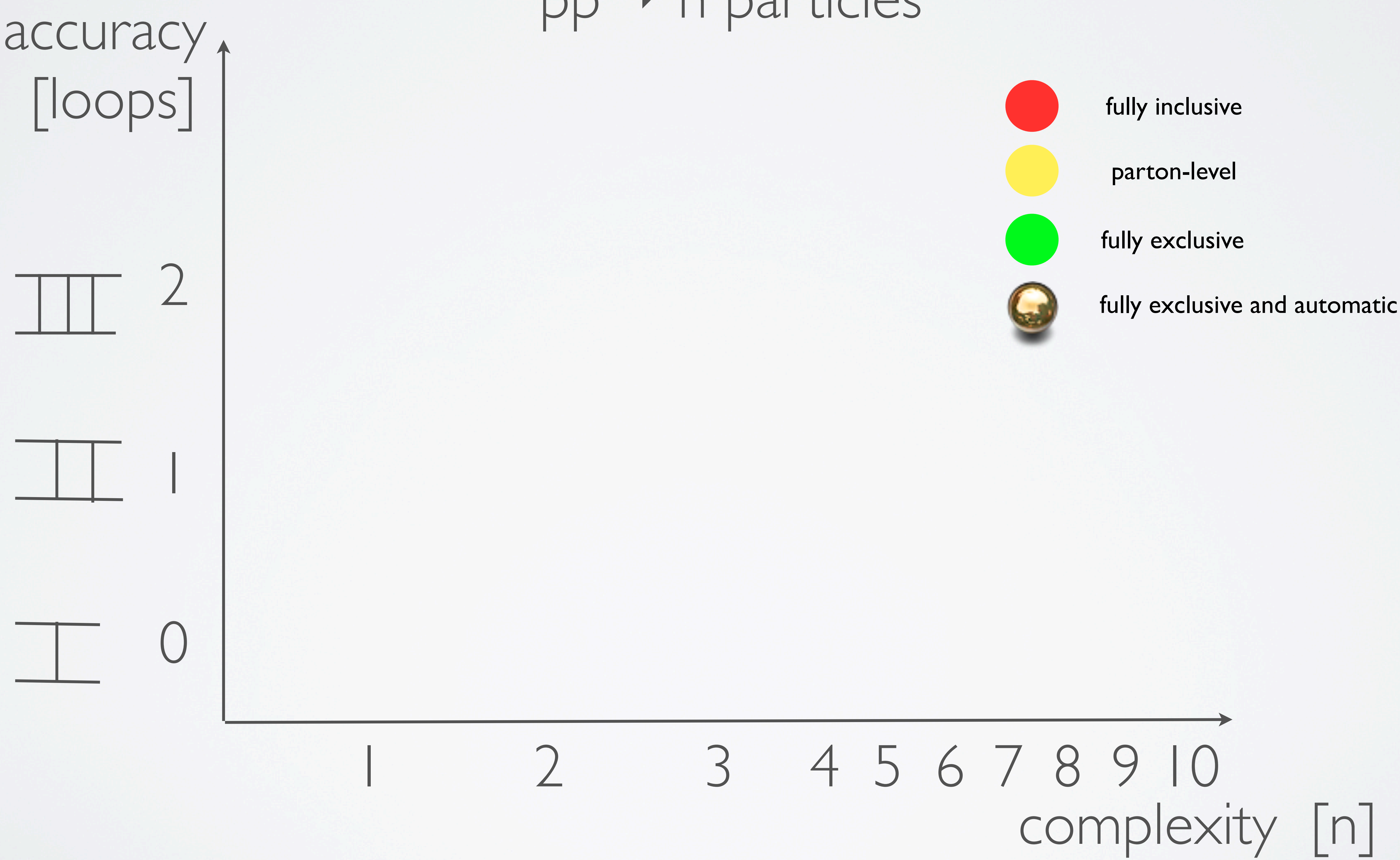
[aMC@NLO: 1110.5502].

aMC@NLO prediction sits between NLO and merged Alpgen sample. Results are automatically given with an uncertainty band that includes scale and PDF errors.



SM STATUS : YEAR 2011

pp→ n particles



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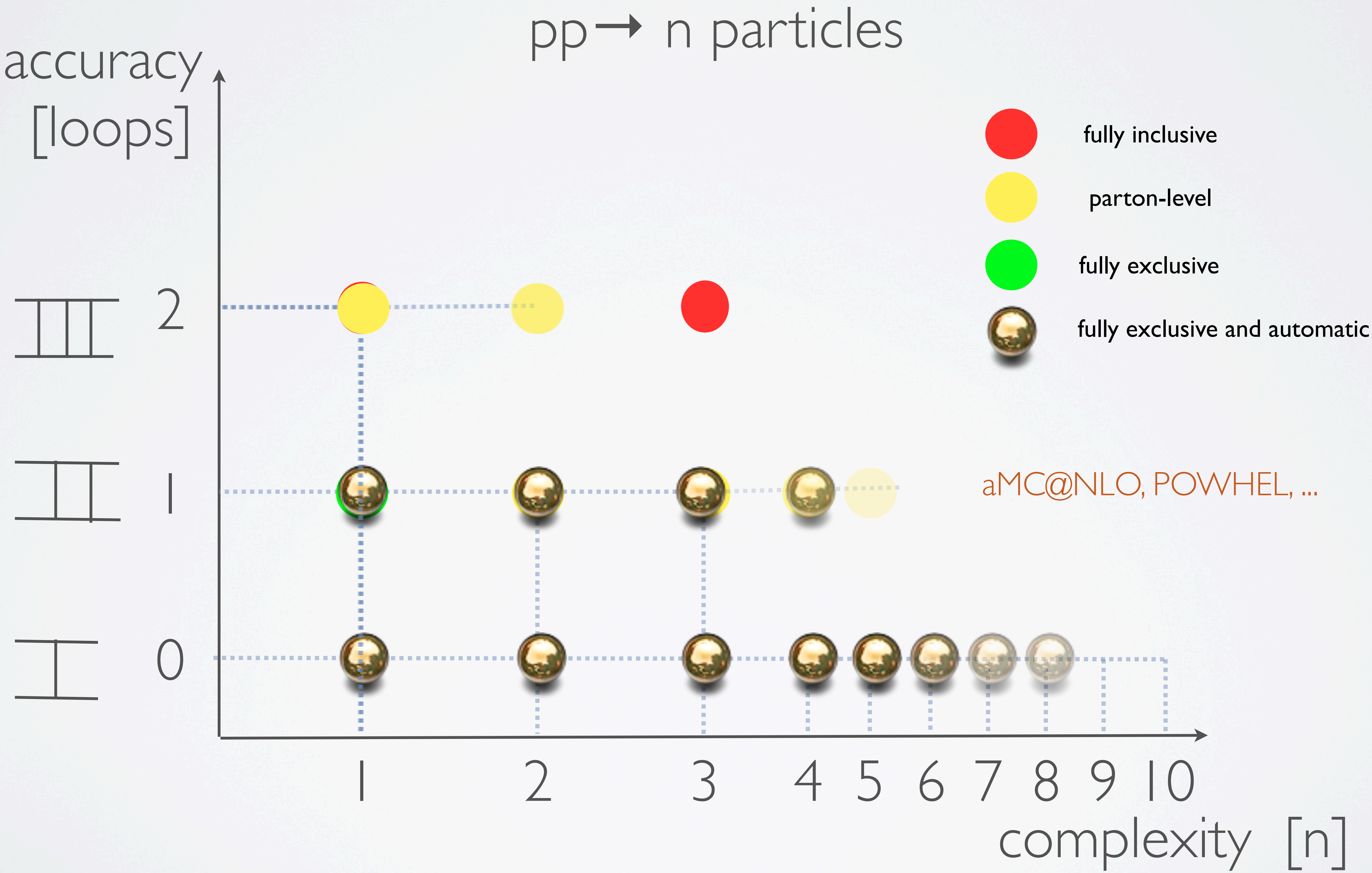

BOTTOM LINE

NNLO and NLO+PS stay to the LHC era

as

NLO and LO+PS stayed to the Tevatron era

WHAT NOW?

- Precision physics and comparison with the data at a new level directly accessible to LHC experimentalists as well as phenomenologists.
- Questions at a different level can be now be posed:
  - Is there any systematic behaviour at NLO for what concerns scale dependence? What about the best choices?
  - Are virtual contributions really important (cfr ME+PS merging)?
  - Are there systematic ways to approximate exact NLO results? What about NNLO? Can we automate NNLO computations?
  - Can we exploit our NLO+PS knowledge for designing better multivariate analyses?
  - ....

CONCLUSIONS

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- The need for better description and more reliable predictions for SM processes for the LHC has motivated a significant increase of theoretical and phenomenological activity in the last years, leading to several important achievements.

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- EXP/TH interactions enhanced by a new framework and not limited anymore by the burden of heavy/long and inefficient calculations...

Automation

Accurate

Amazing

AAA

Automation

Accurate

Amazing

AAA PHENOMENOLOGY MOTTO

Free to Pheno

aMC@NLO PROSPECTS

- "99%" of the elements needed to calculate QCD corrections for SM processes are present. The missing bits will be included in MadGraph 5.
- QCD+EW corrections possible but need more work on MadLoop.
- Automatic loop computations in BSM need new elements. Work is in progress to automate them.
- Analytic/numeric loop amplitudes from other codes can be easily interfaced via the Binoth Les Houches Accord, SM or BSM.
- Use of the code will be made public via the web asap. Codes for processes will follow and then meta code public in MadGraph 5.