AAA PHENOMENOLOGY

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Helmholtz Alliance, VTI Seminar
May, 23th

AAA PHENOMENOLOGY

- AUTOMATIC
    - ACCURATE
        - AMAZING

new MC tools for hadron collider physics.

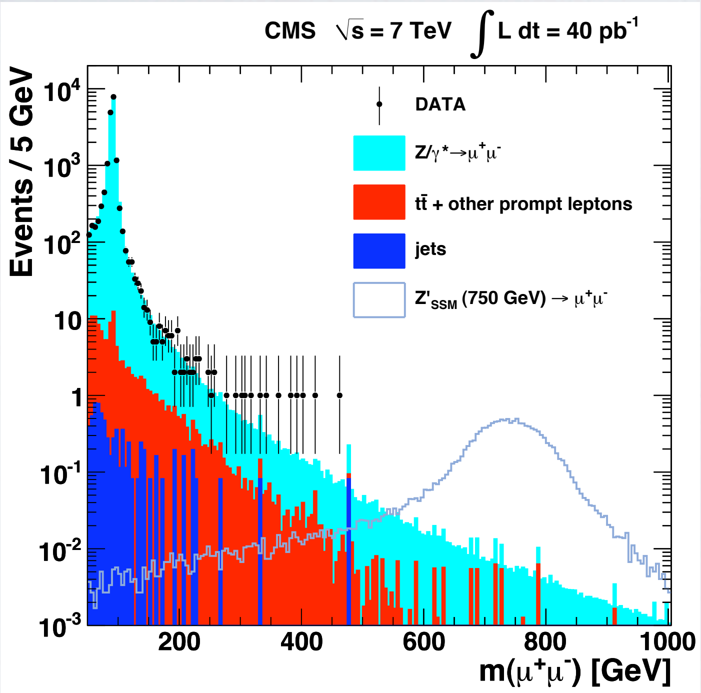
PLAN

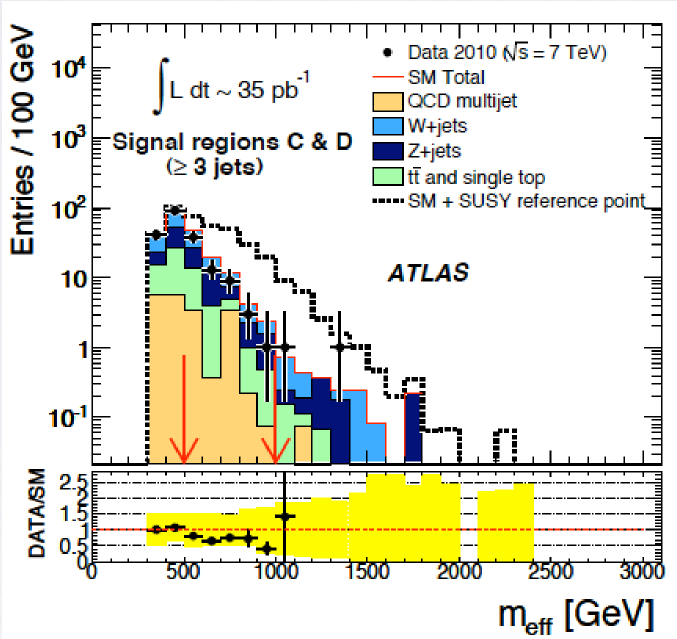
- What do we need from TH to make discoveries?
- The evolution of MC tools
- The dawn of the AAA era

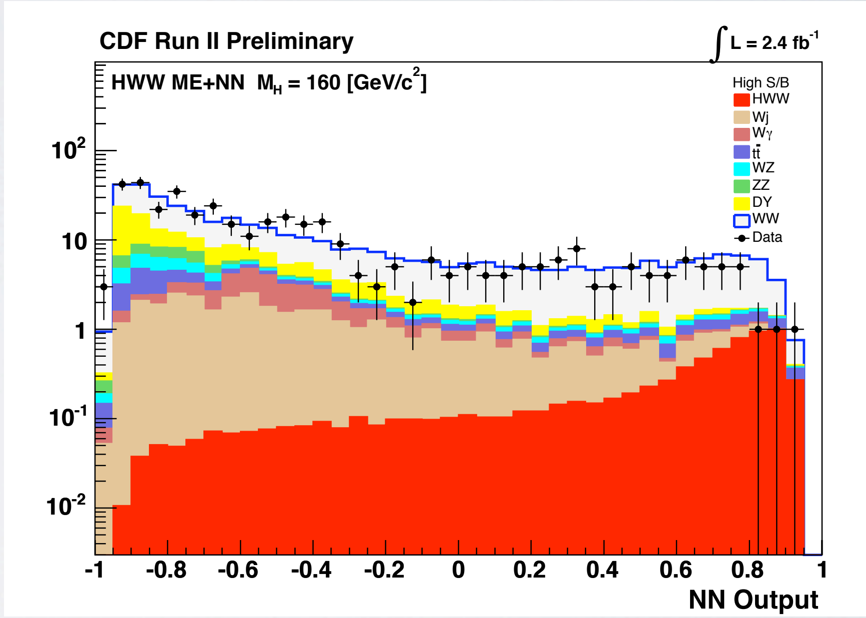
Discoveries at hadron colliders

[MLM, 2008]

peak	shape	rate
$pp \to Z' \to e+e-$	$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets+ET$	$pp \to H \to W+W-$



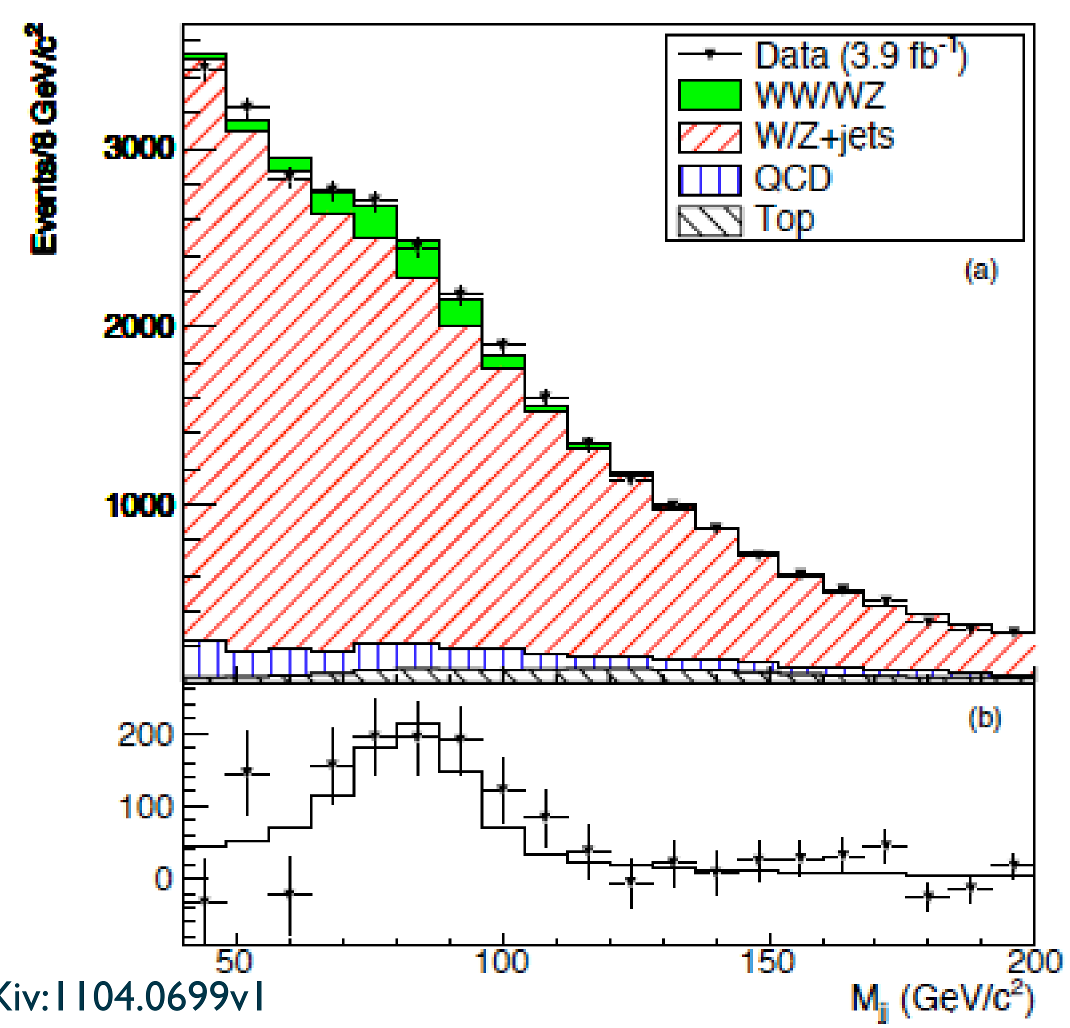




"easy"	hard	very hard
Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)	Background shapes needed. Flexible MC for both signal and background tuned and validated with data.	Background normalization and shapes known very well. Interplay with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

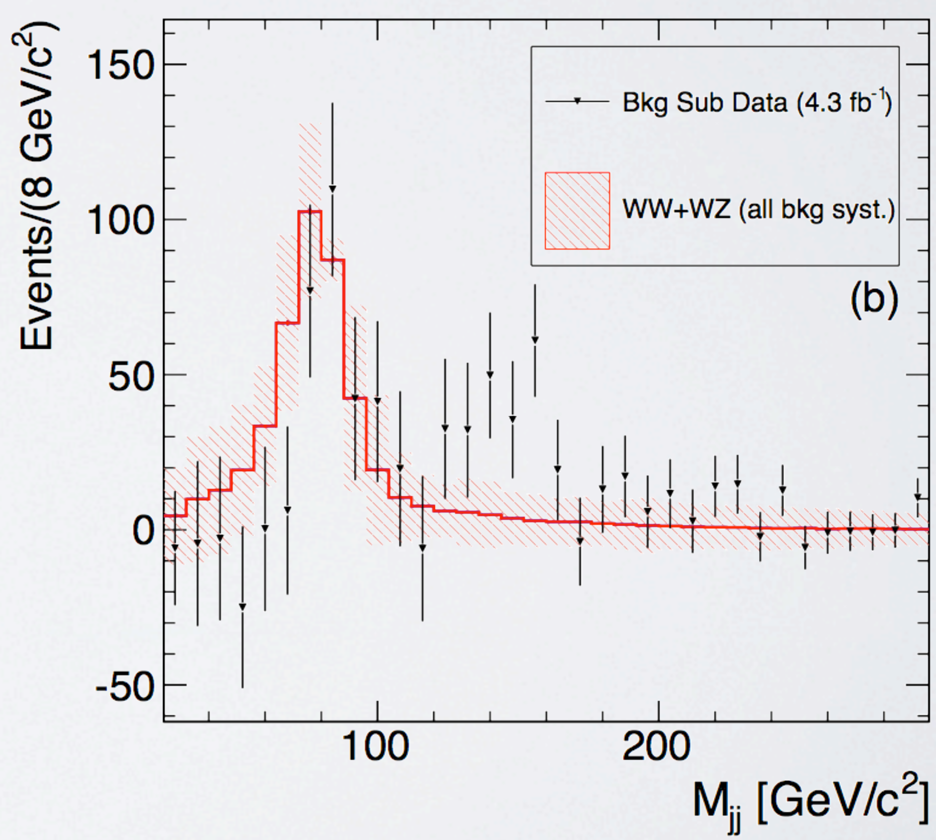
WJJ

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.

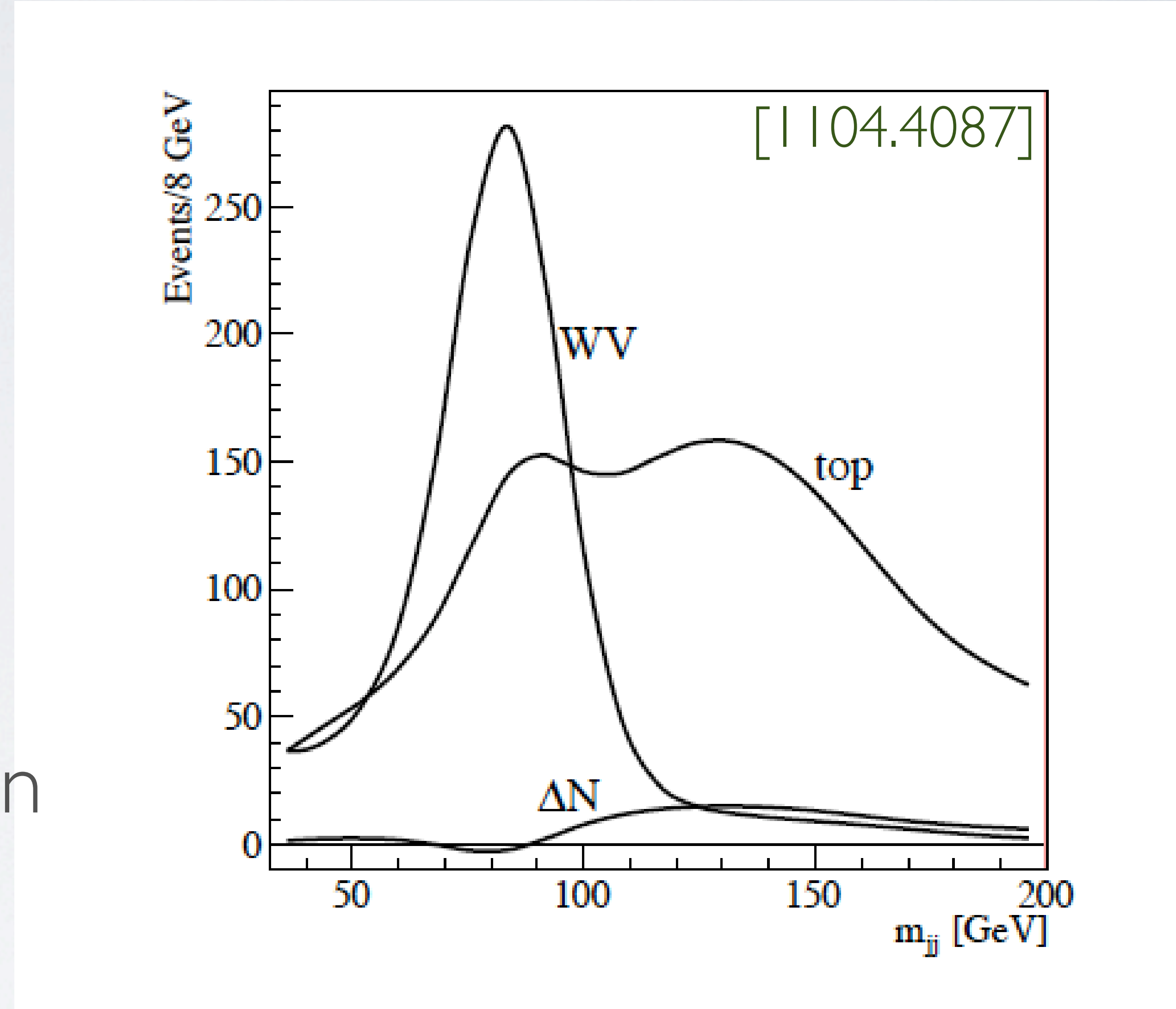


WJJ

~30 papers on BSM interpretations in the last weeks.

2 papers on SM backgrounds:
[Sullivan and Menon, 1104.3790]
[Plehn and Takeuchi, 1104.4087]

related to top production and in particular to single top.



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

MOTIVATION : SUMMARY

- 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.
- Measurements and exclusions always rely on accurate predictions.
- Predictions for both SM and BSM on the same ground.

...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).
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...)
  ⇒ $$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

TH

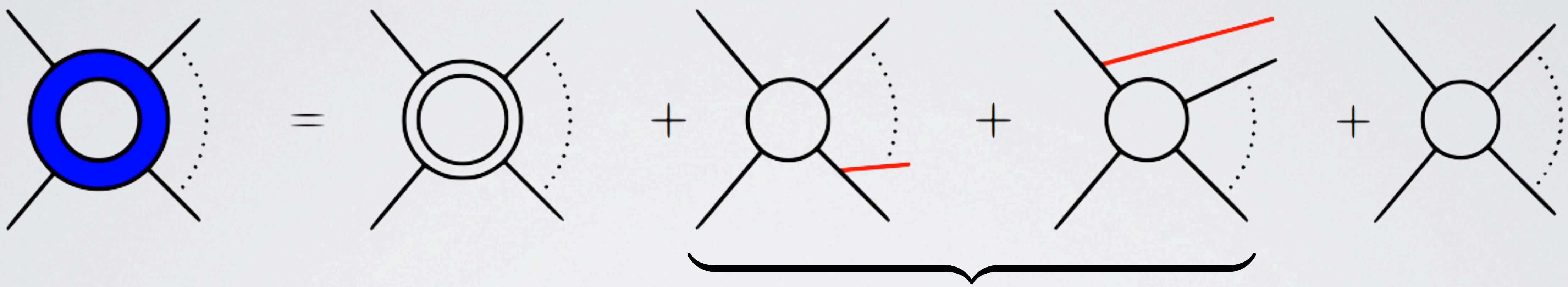
- For high multiplicity use the tree-level results

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



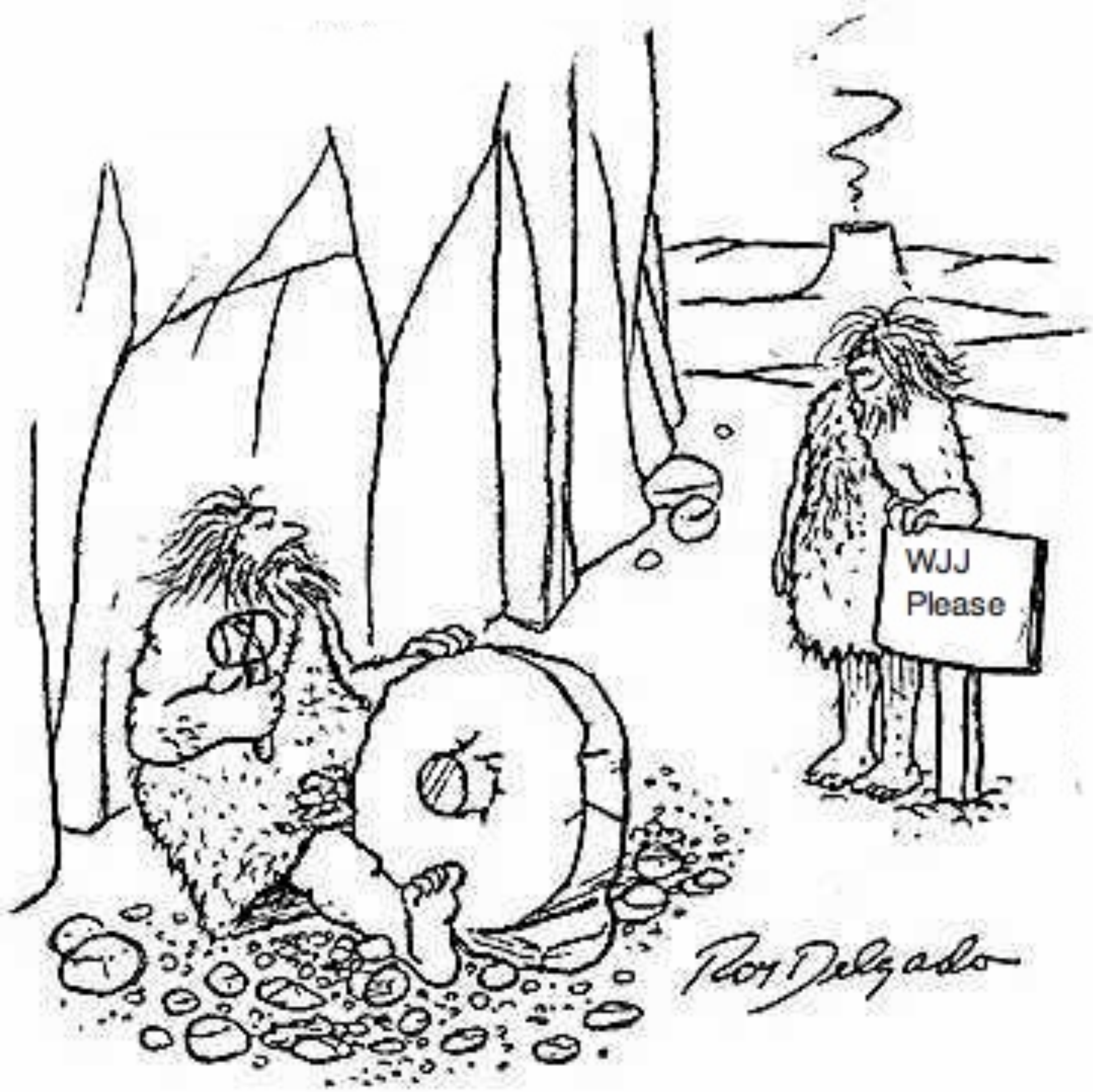
$$\sigma^{\rm NLO} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

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

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

LOOP TECHNIQUES



modified by the speaker

BEST EXAMPLE: MCFM

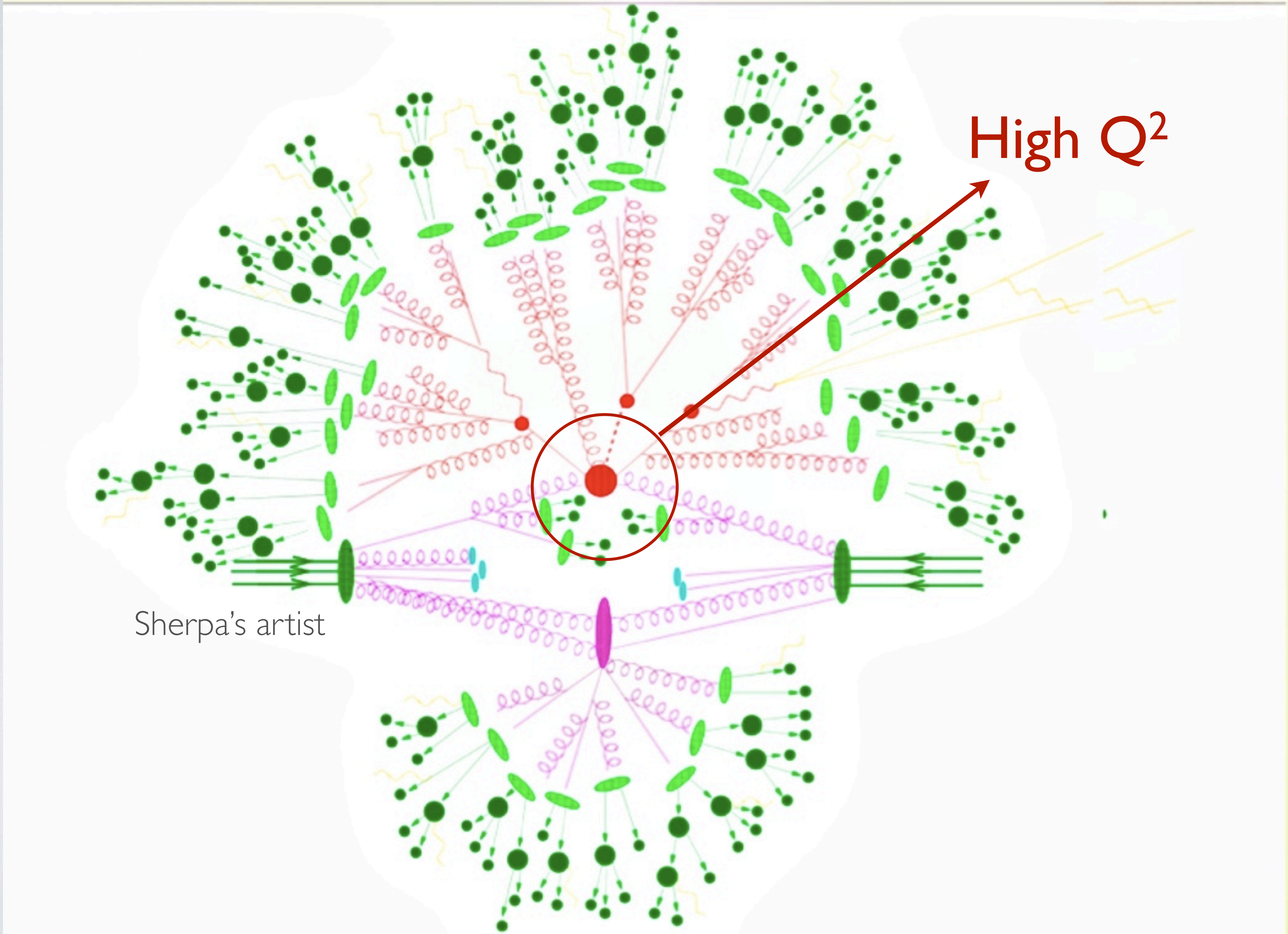
Downloadable general purpose NLO code [Campbell & Ellis+ collaborators]

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.

Events at hadron colliders



HOW WE (USED TO) MAKE PREDICTIONS?

Second way:

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

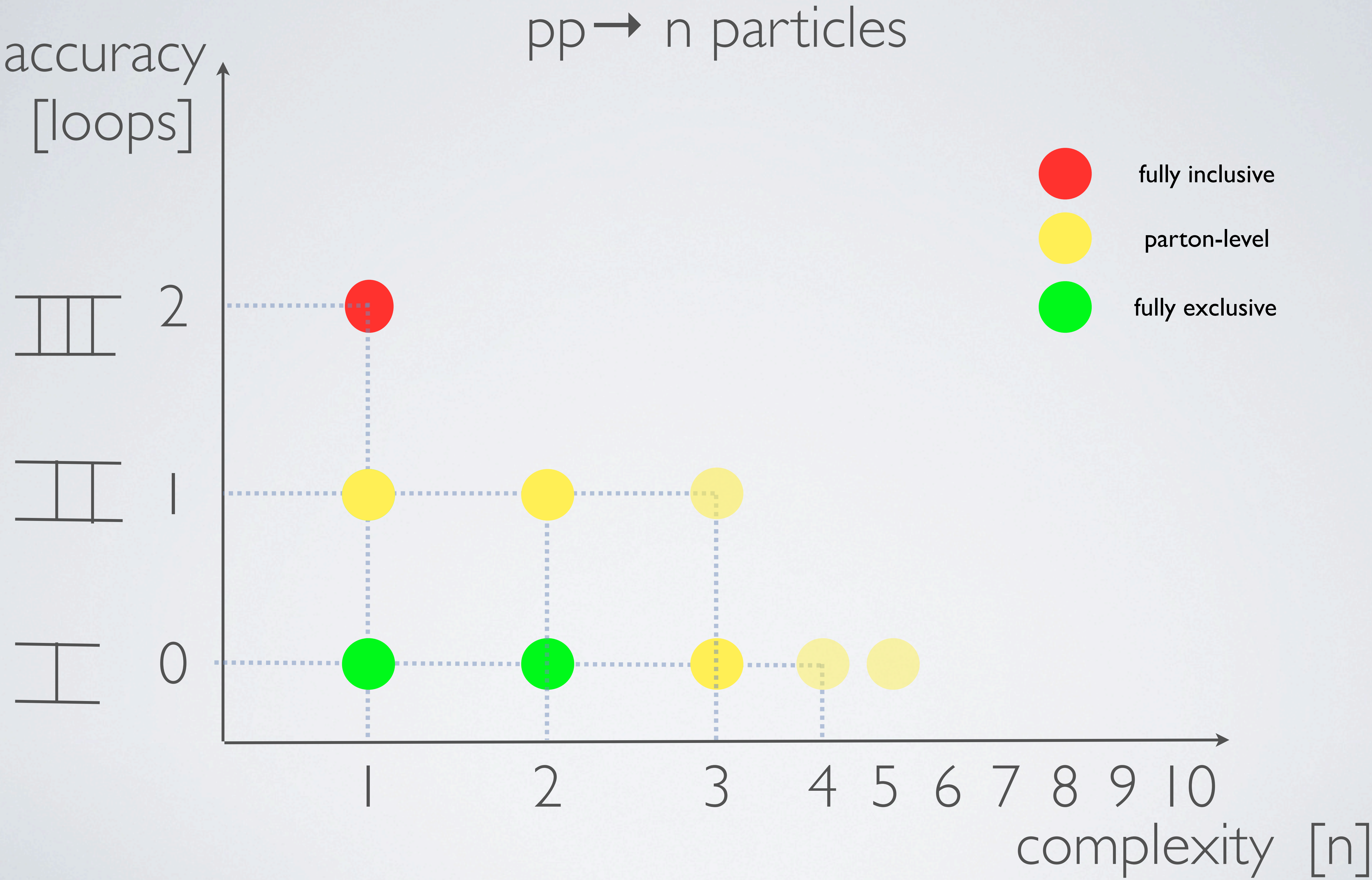
EXP

Comments:

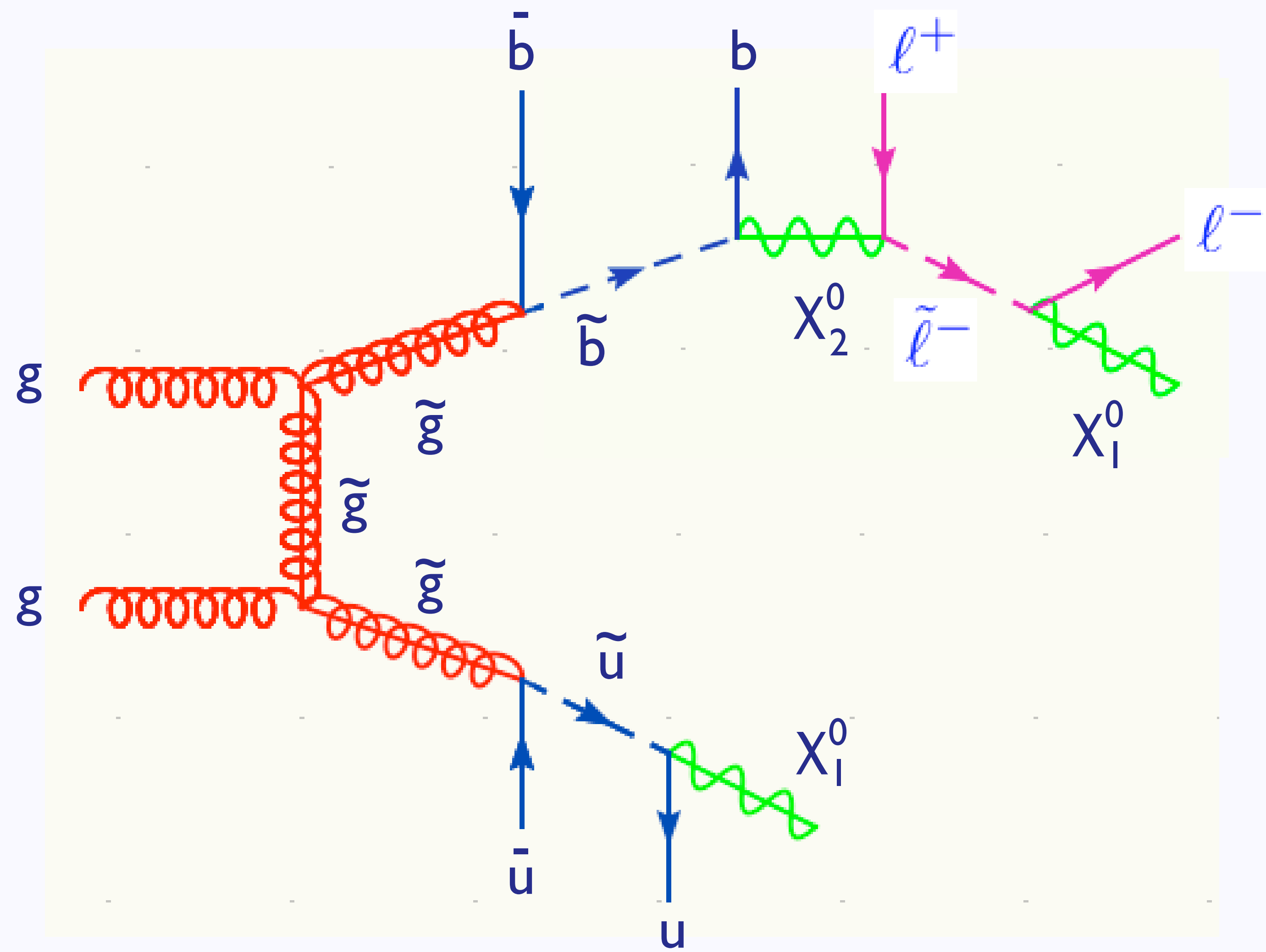
1. Fully exclusive final state description for detector simulations
2. Normalization is very uncertain
3. Very crude kinematic distributions for multi-parton final states
4. Improvements are only at the model level.

most known and used : PYTHIA, HERWIG

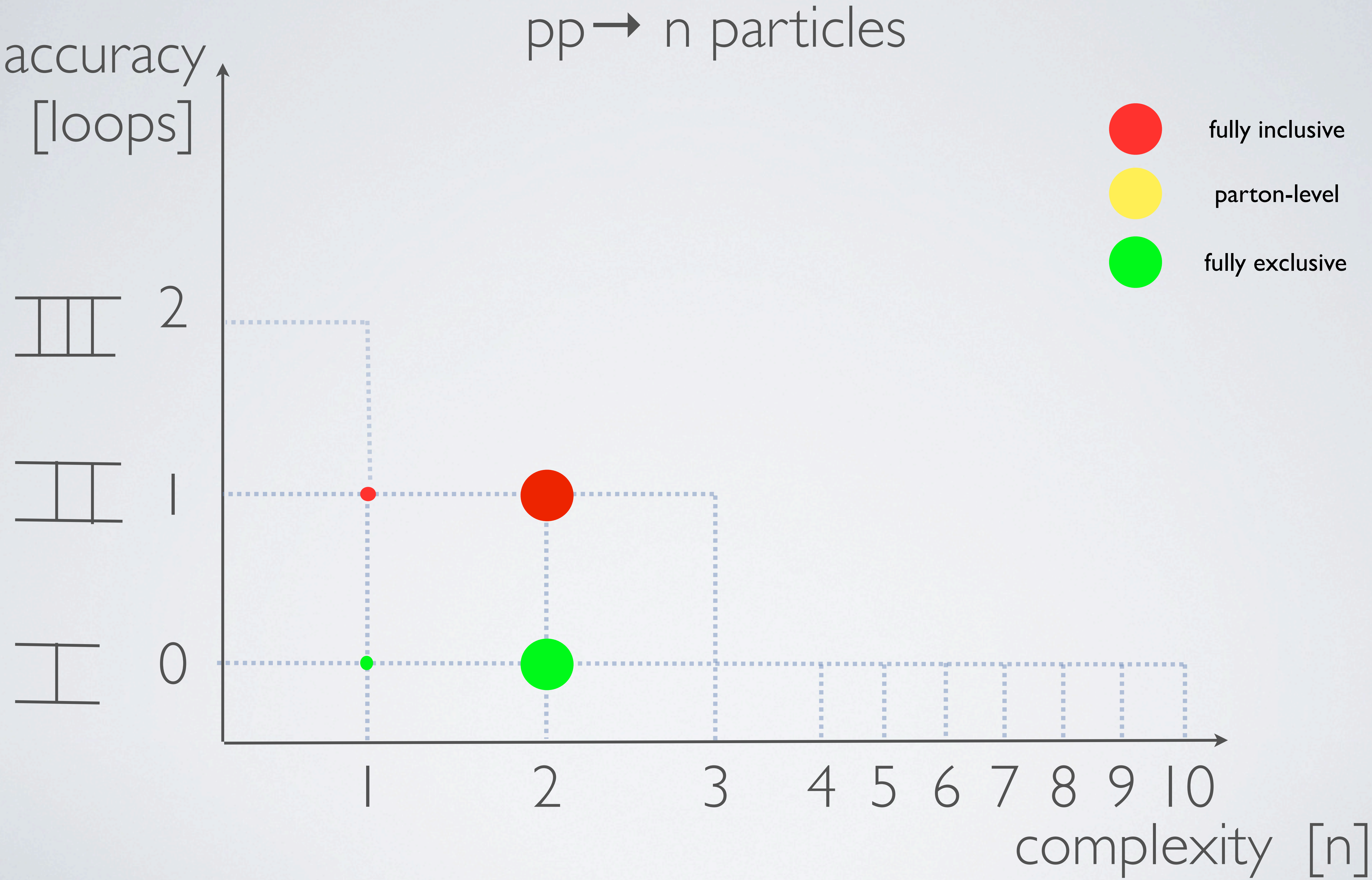
SM STATUS A FEW YEARS AGO



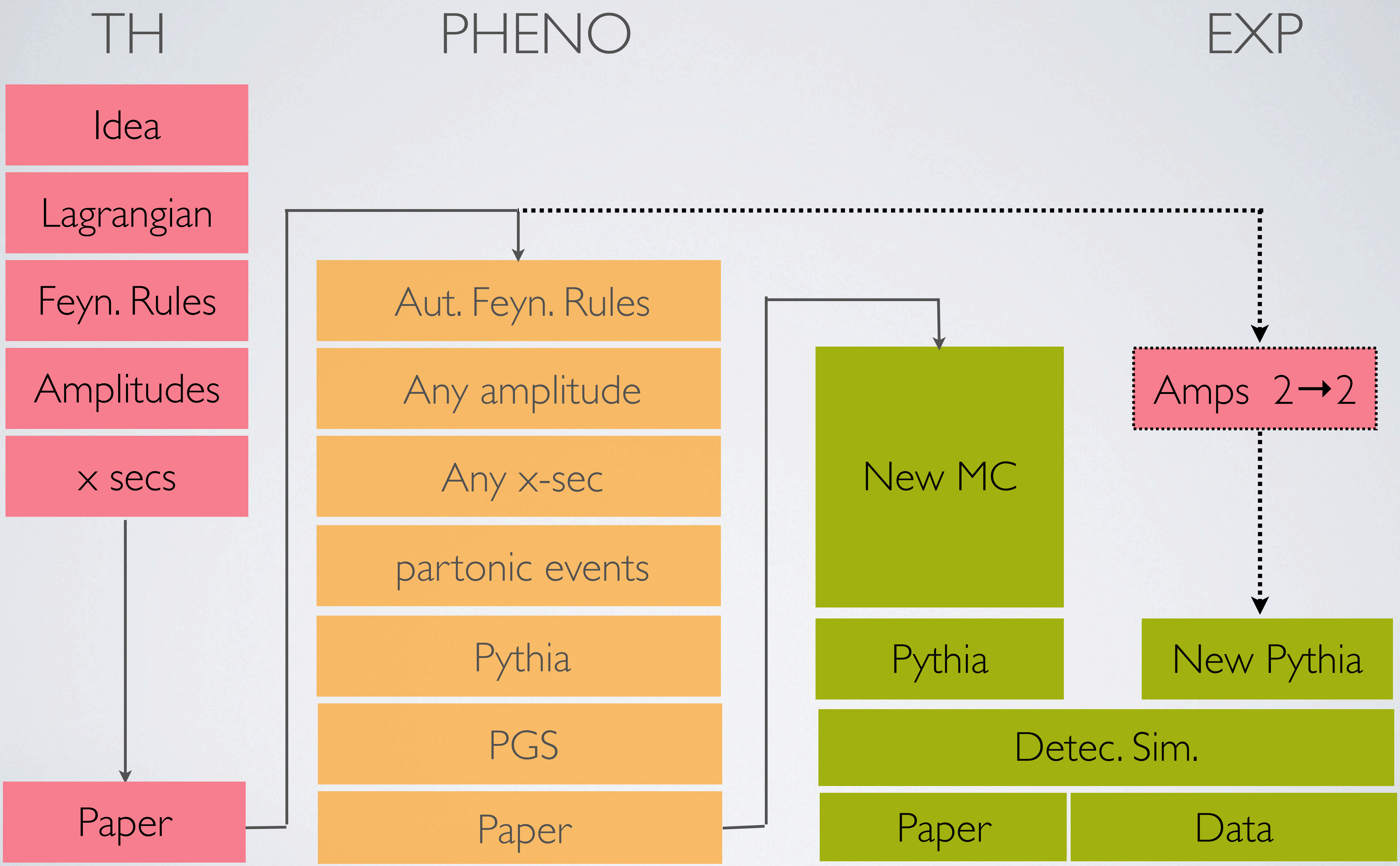
WHAT ABOUT NEW PHYSICS?



BSM (=SUSY)STATUS A FEW YEARS AGO



BSM TH/EXP INTERACTIONS : THE OLD WAY



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)

We would like to:

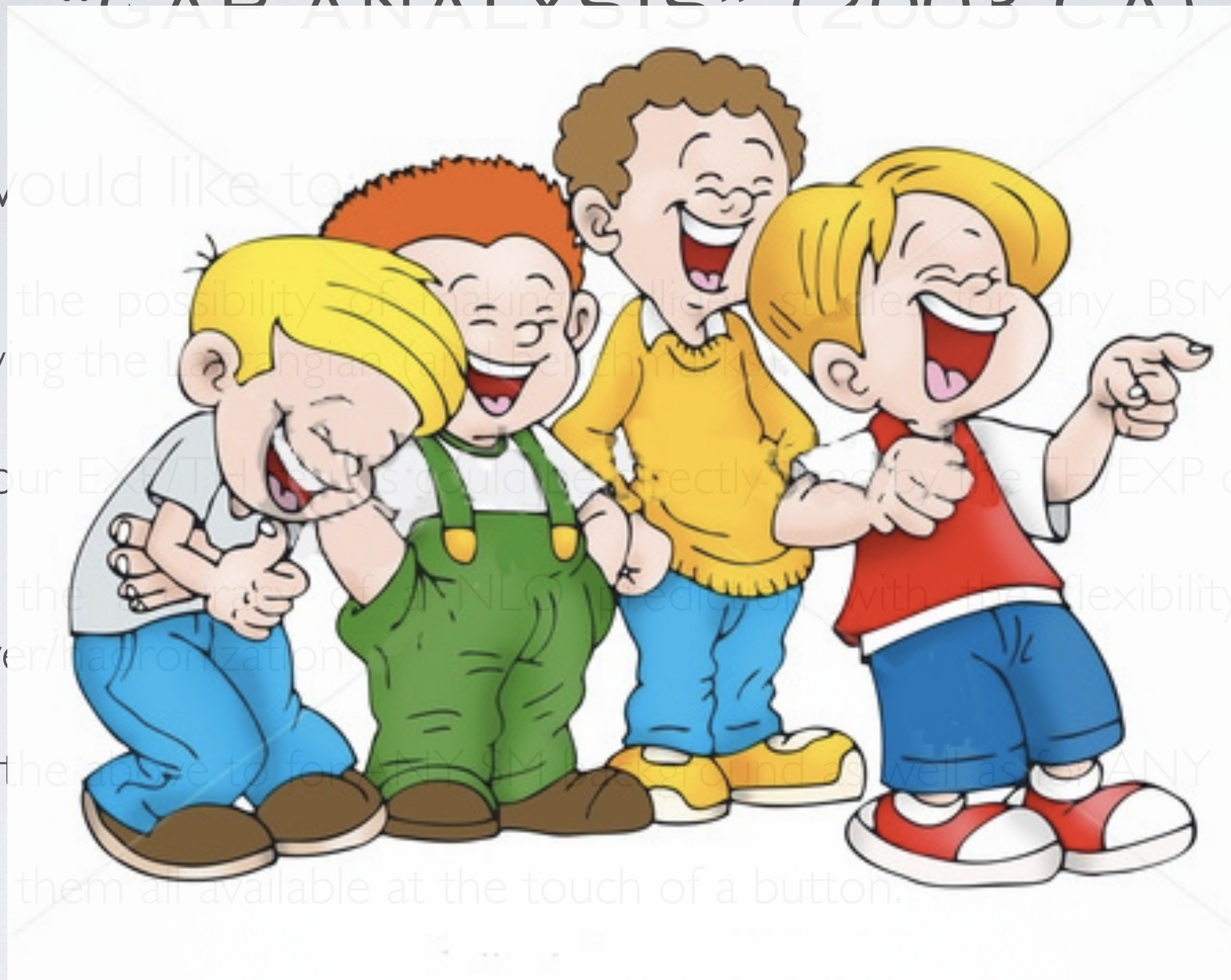
1. have the possibility of making collider studies for any BSM theory by knowing the Lagrangian (and benchmarks).

2. that our EXP/TH results could be directly used by the TH/EXP colleagues.

3. have the accuracy of NLO predictions with the flexibility of parton shower/hadronization.

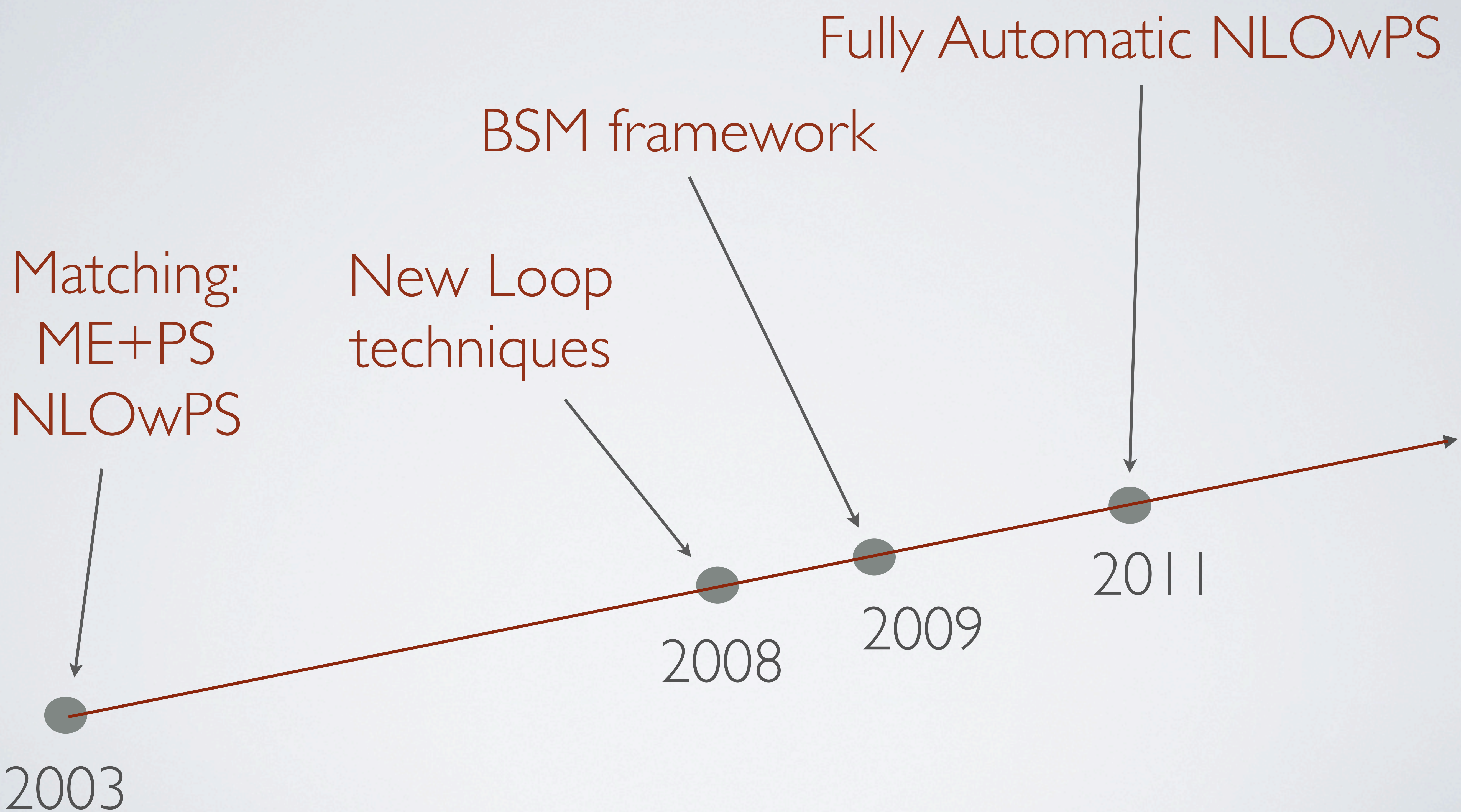
4. have the ability to form ANY SM background as well as ANY BSM signals.

5. have them all available at the touch of a button.



OK? REACTIONS?

QCD AND MC (SIMPLIFIED) PROGRESS



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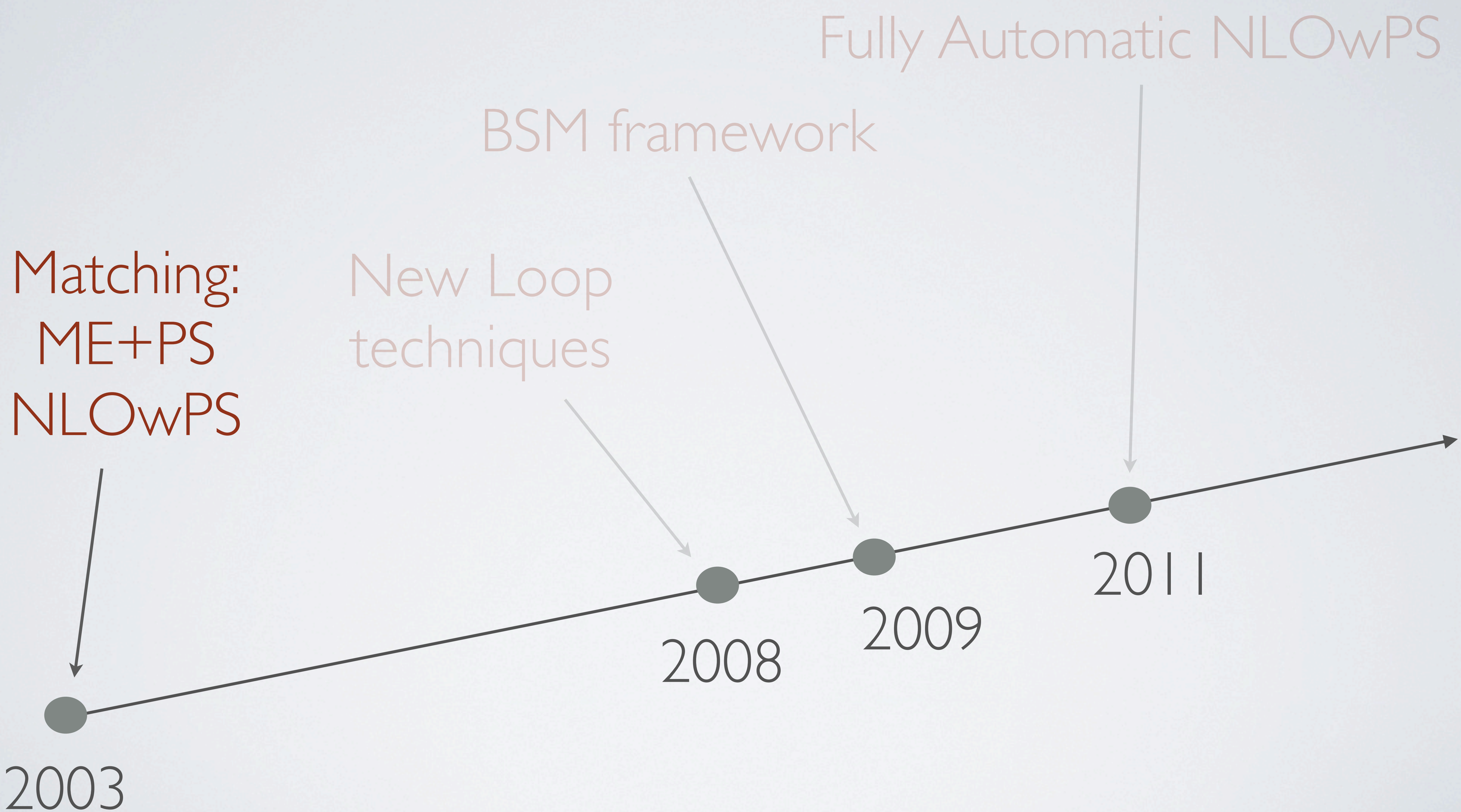


ME WITH PS

[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
5. nedeed for realistic studies

Approaches are complementary: merge them!

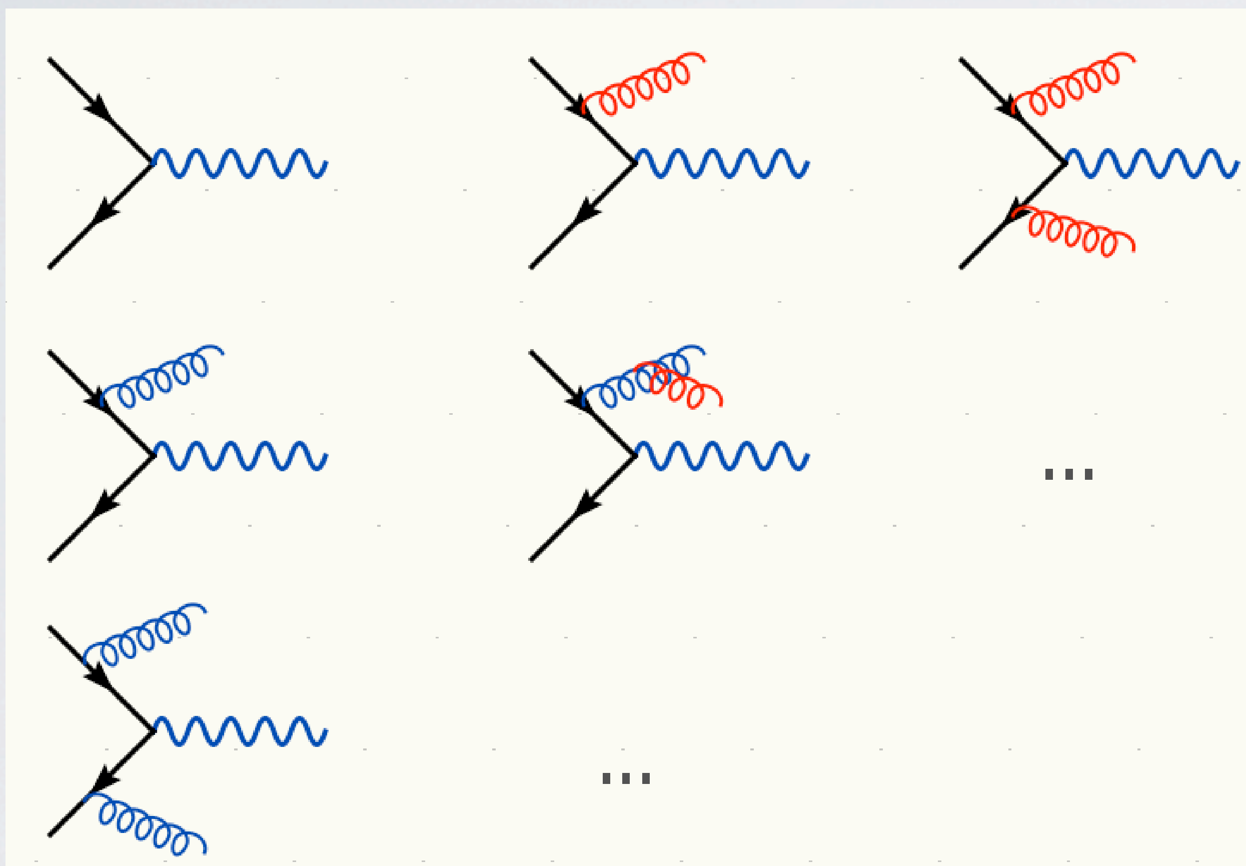
Difficulty: avoid double counting

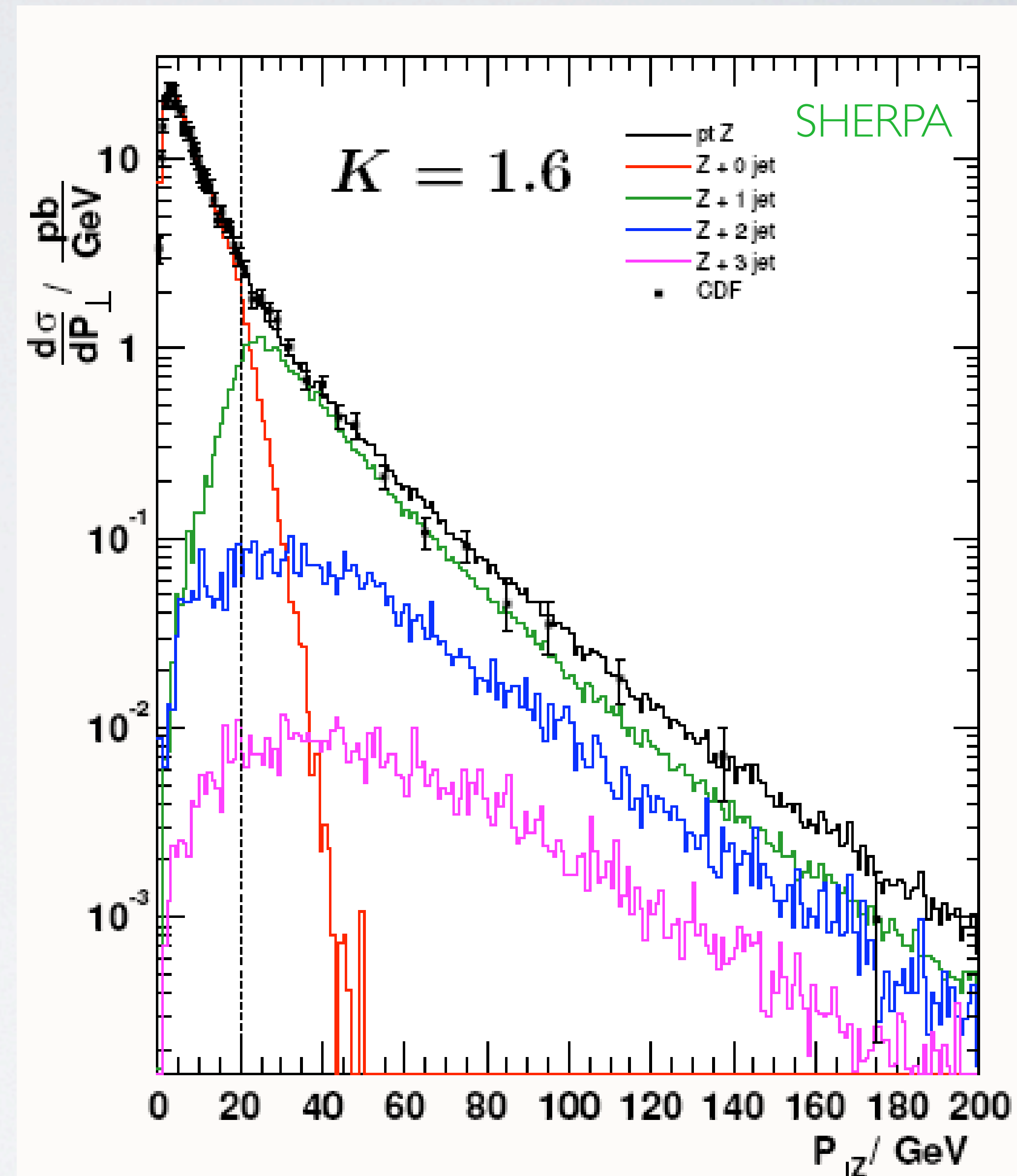
Merging fixed order with PS

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

PS →

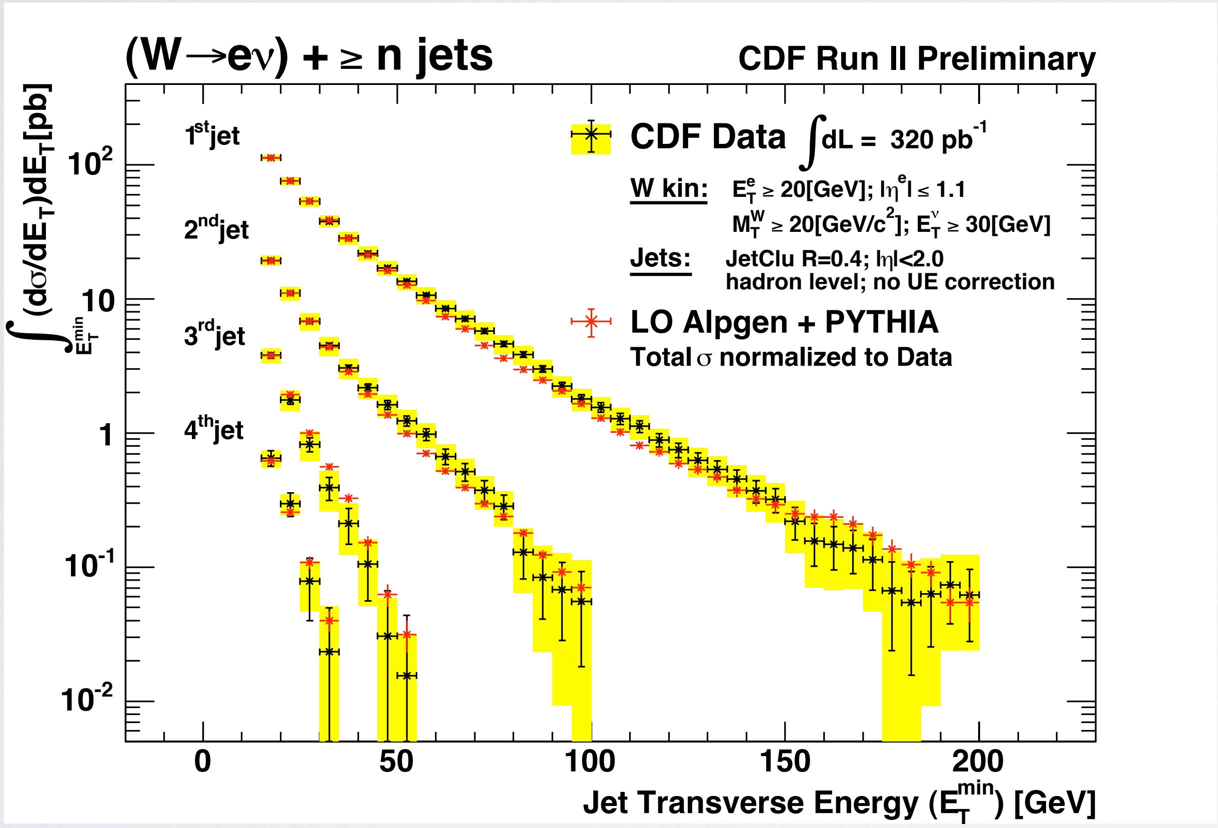
ME ↓

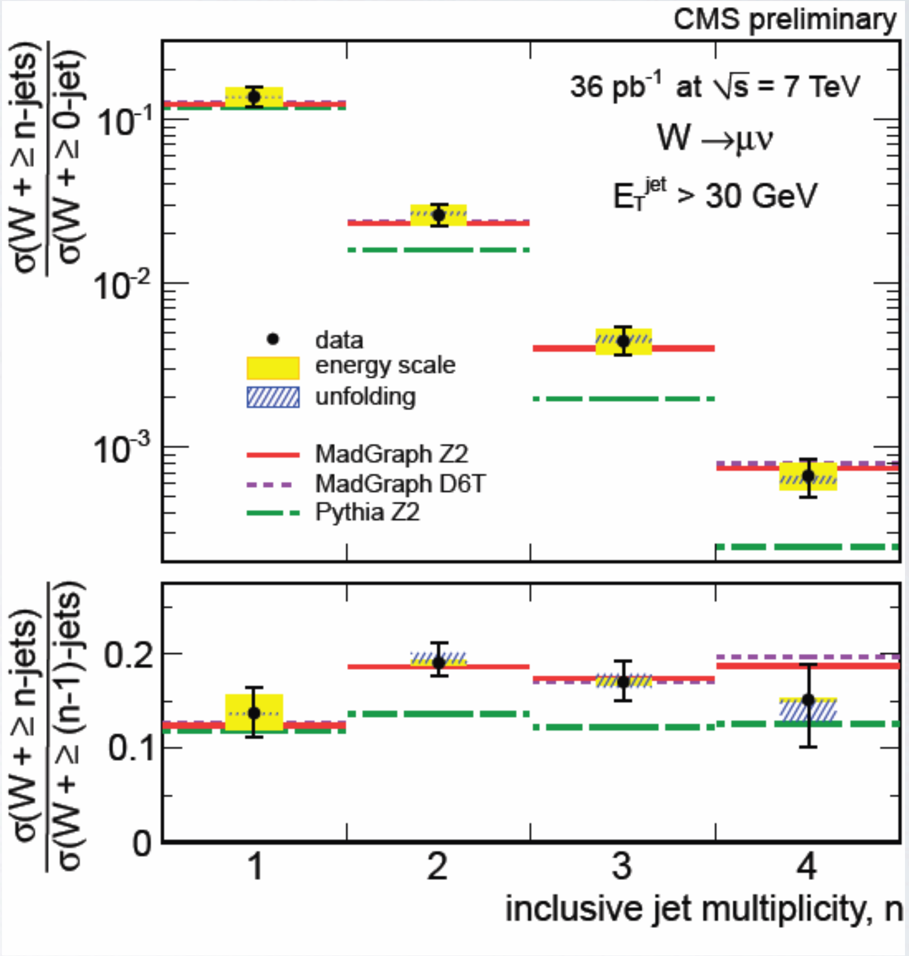




Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample.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

W+JETS FROM TEVATRON TO LHC





Working **A**mazingly well!

NLOwPS

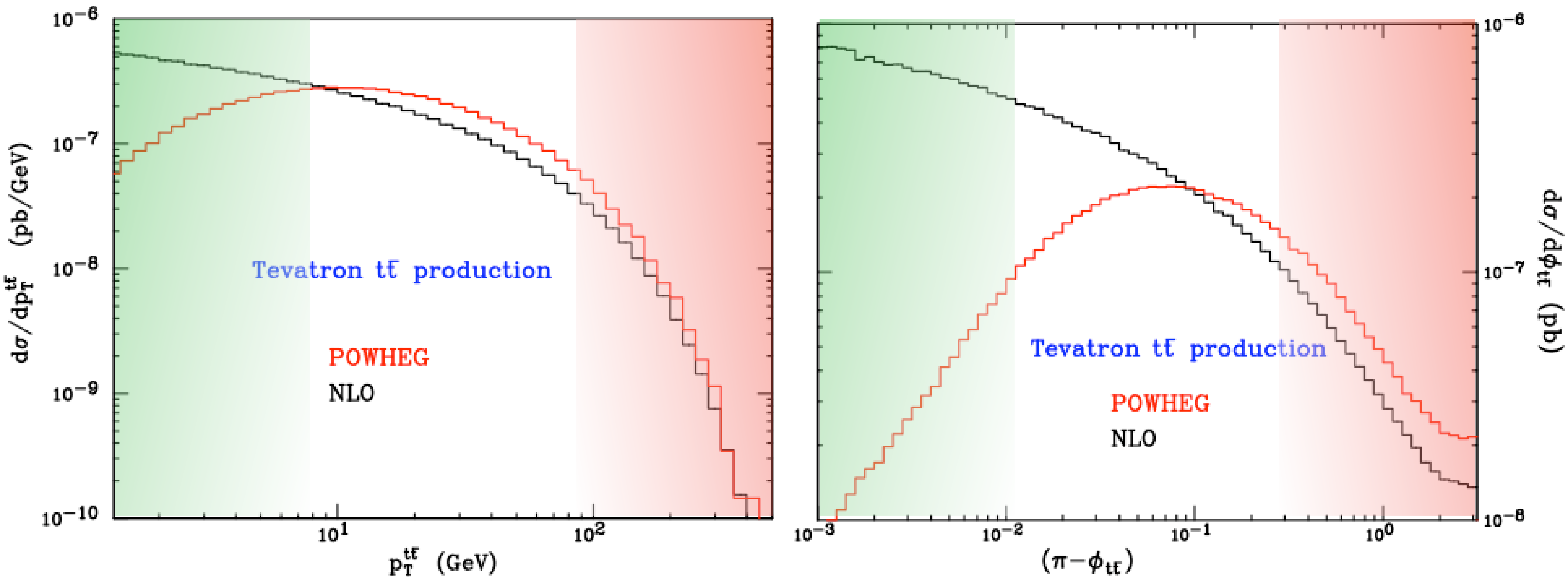
Problem of double counting becomes even more severe at NLO
* Real emission from NLO and PS has to be counted once
* Virtual contributions in the NLO and Sudakov should not overlap

Current available (and working) solutions:

MC@NLO [Frixione, Webber, 2003; Frixione, Nason, Webber, 2003]
- Matches NLO to HERWIG angular-ordered PS.
- Some events have negative weights.
- Available also for Pythia now.
- Automation [Frederix, Frixione, Torrielli]

POWHEG [Nason 2004; Frixione, Nason, Oleari, 2007]
- Is independent from the PS. It can be interfaced to PYTHIA or HERWIG.
- Generates only positive unit weights.
- Can use existing NLO results via the POWHEG-Box [Aioli, Nason, Oleari, Re et al. 2009]
- Used by HELAC [Kardos, Papadopoulos, Trocsanyi 1101.2672] and SHERPA [Hoeche,Krauss, Schooenner, Siegert, 1008.5399]

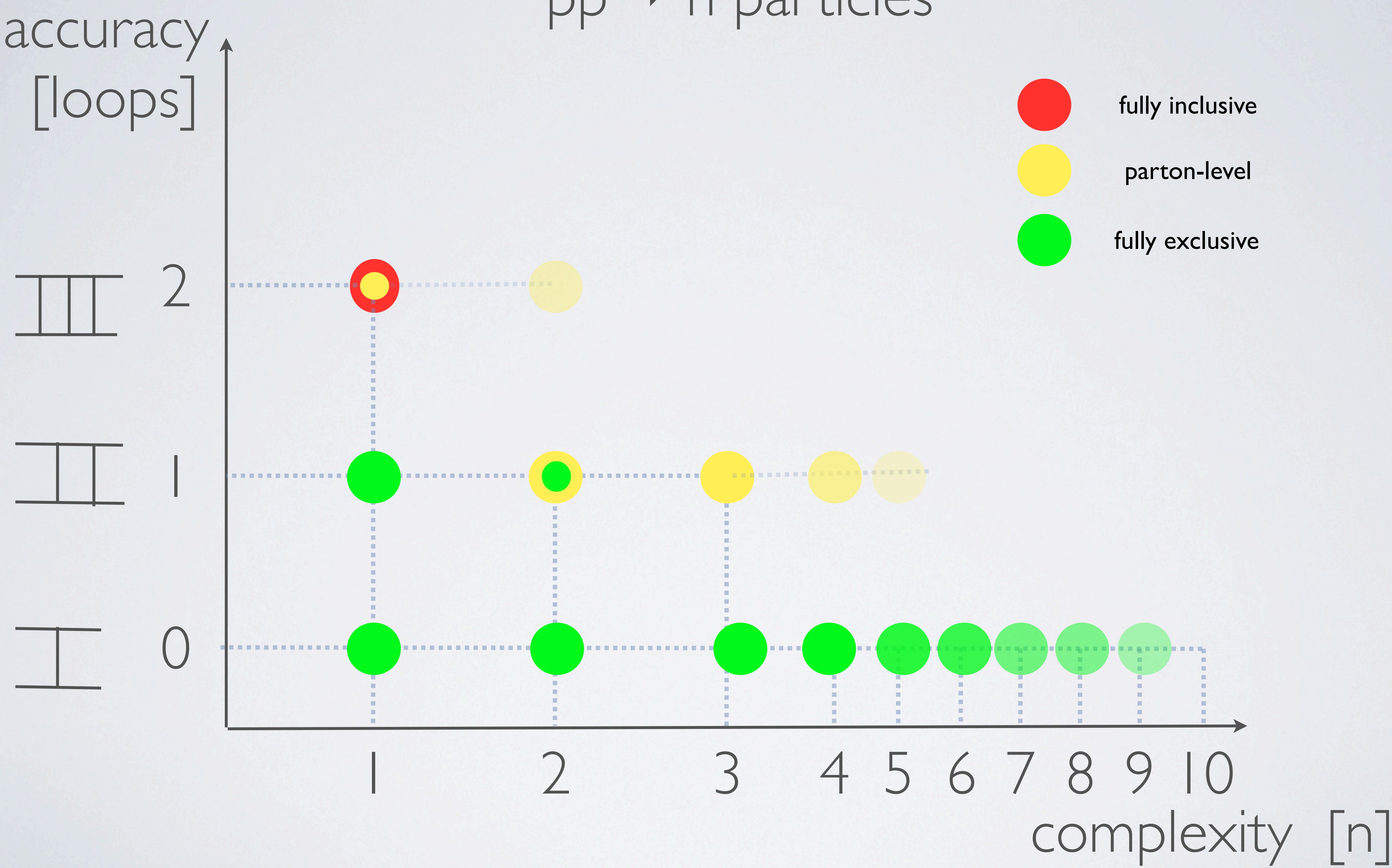
TTBAR : NLOWPS VS NLO



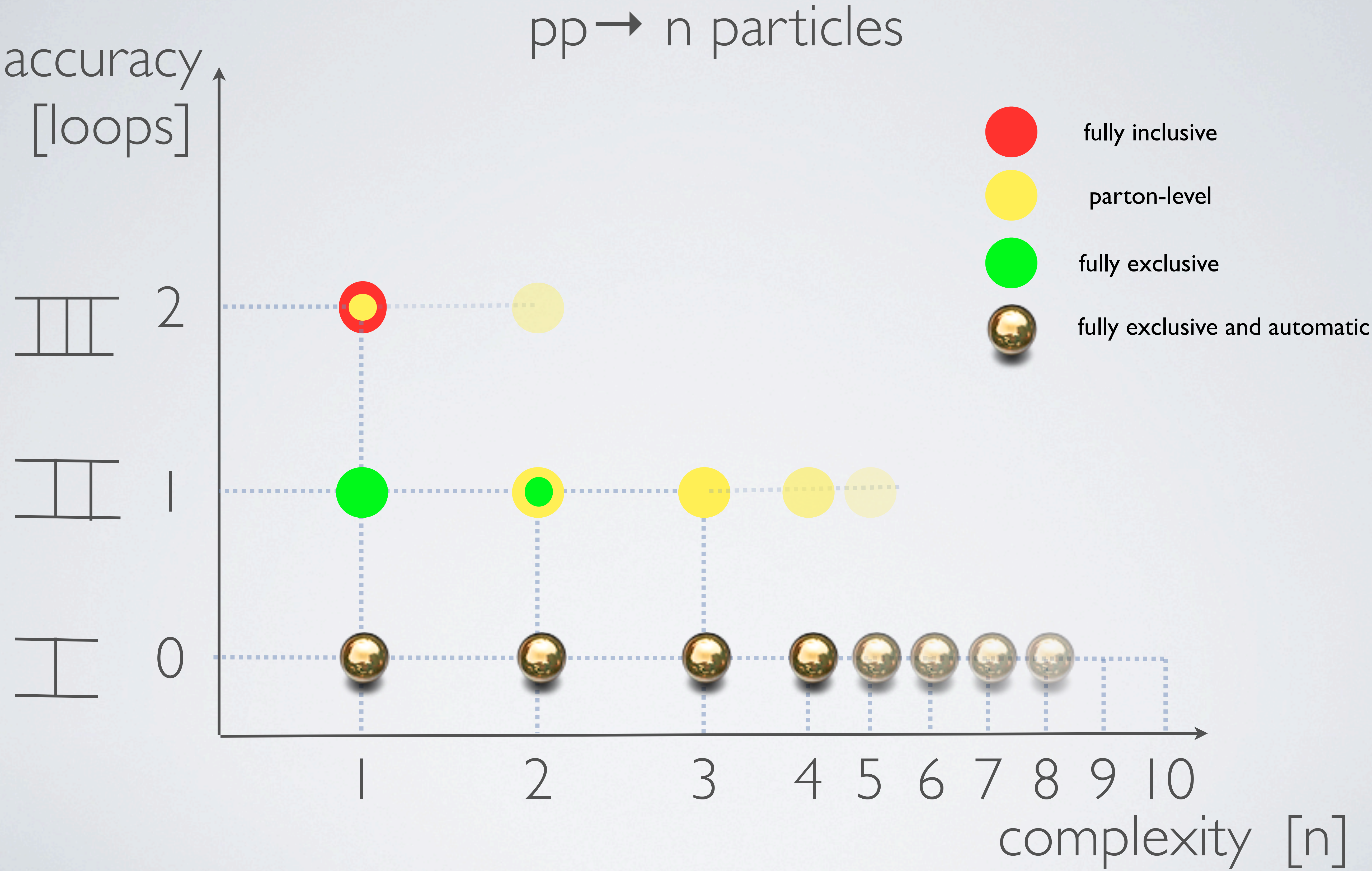
* Soft/Collinear resummation of the p_T(tt) →0 region.
* At high p_T(tt) it approaches the tt+parton (tree-level) result.
* When Φ(tt)→0 (Φ(tt)→ π) the emitted radiation is hard (soft).
* Normalization is FIXED and non trivial!!

SM STATUS : SINCE 2007

pp→ n particles



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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  Programs are modular and computations based on elements that can be systematically and extensively checked. Trust can be easily built.

AUTOMATION

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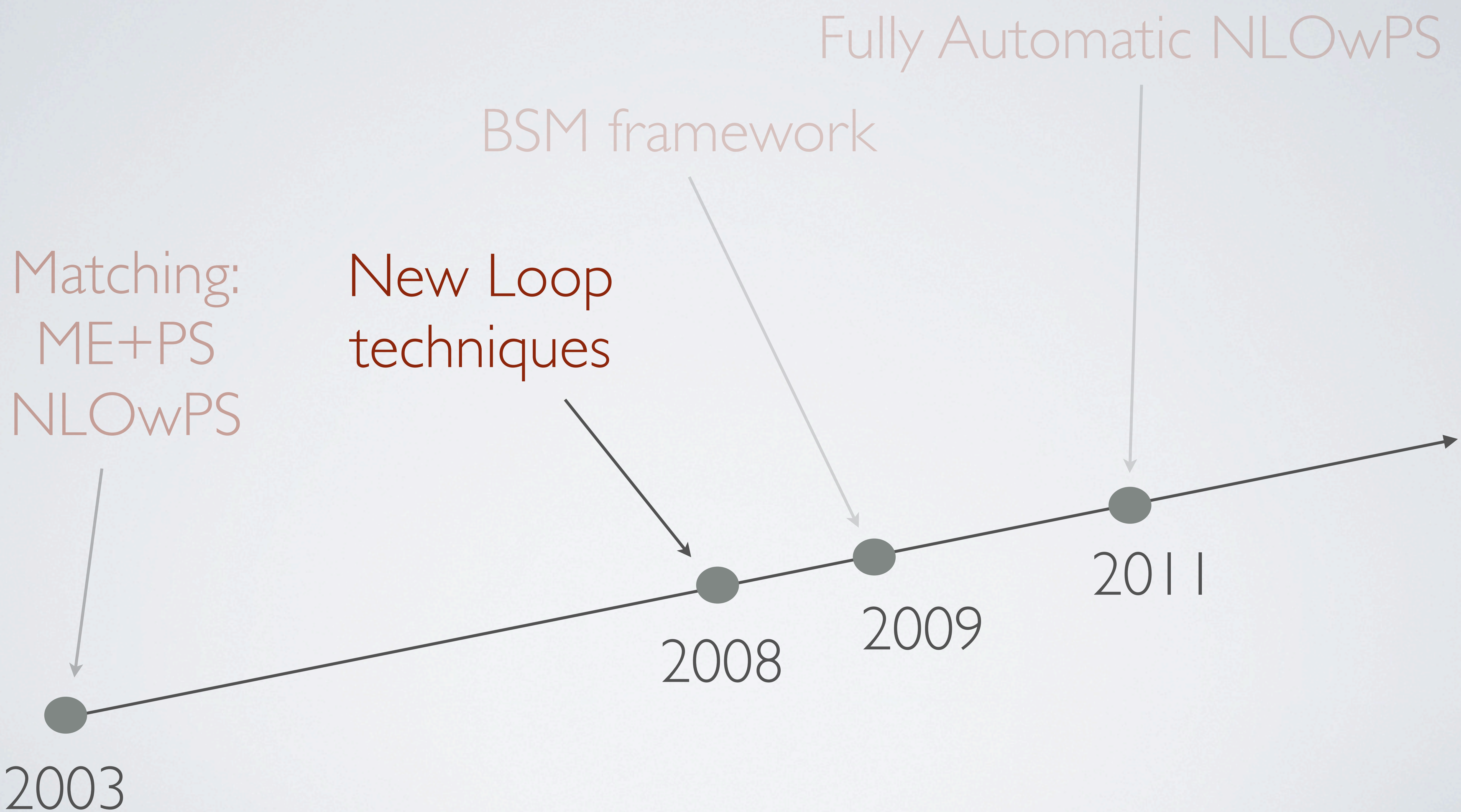
- Wide accessibility

  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

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

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

- 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]

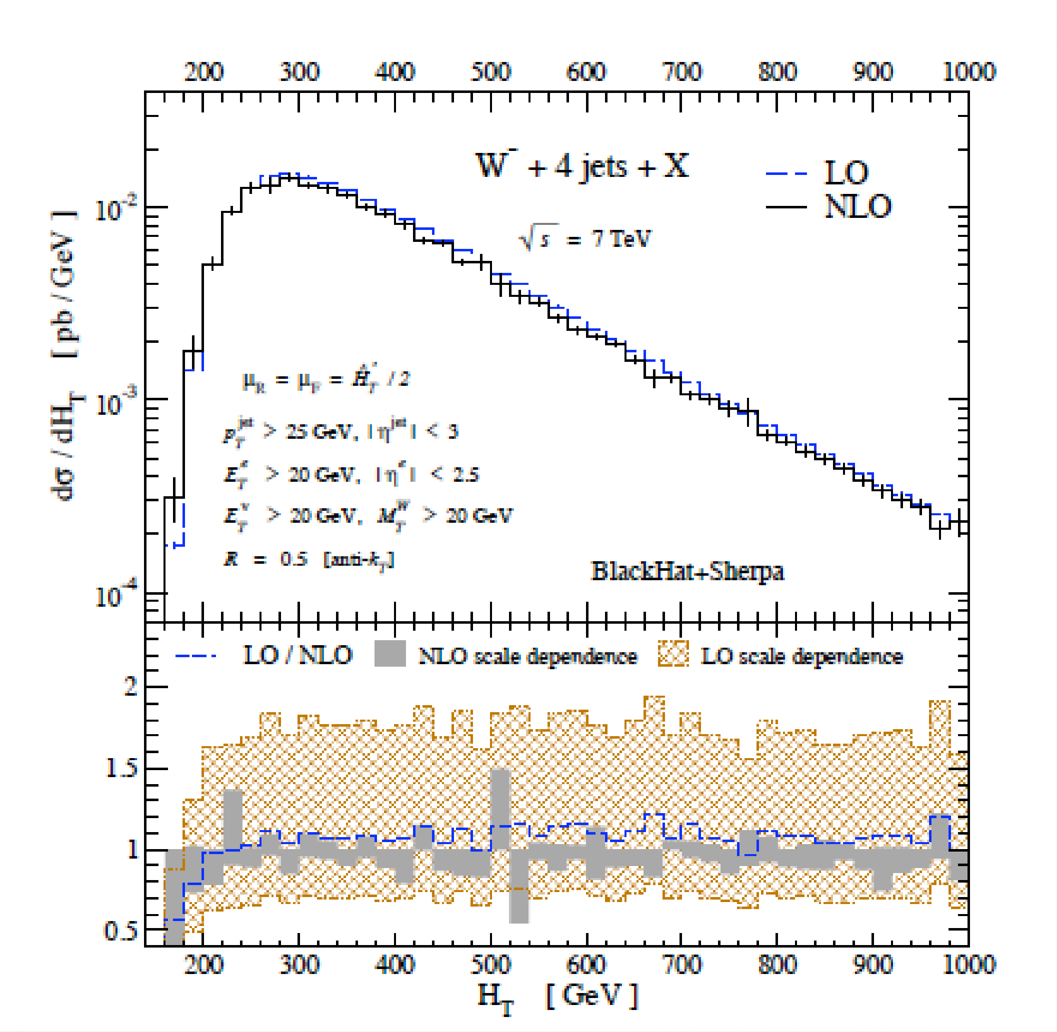
- Residue (ex. MadFKS)

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

GUINNESS WR NLO CALCULATIONS

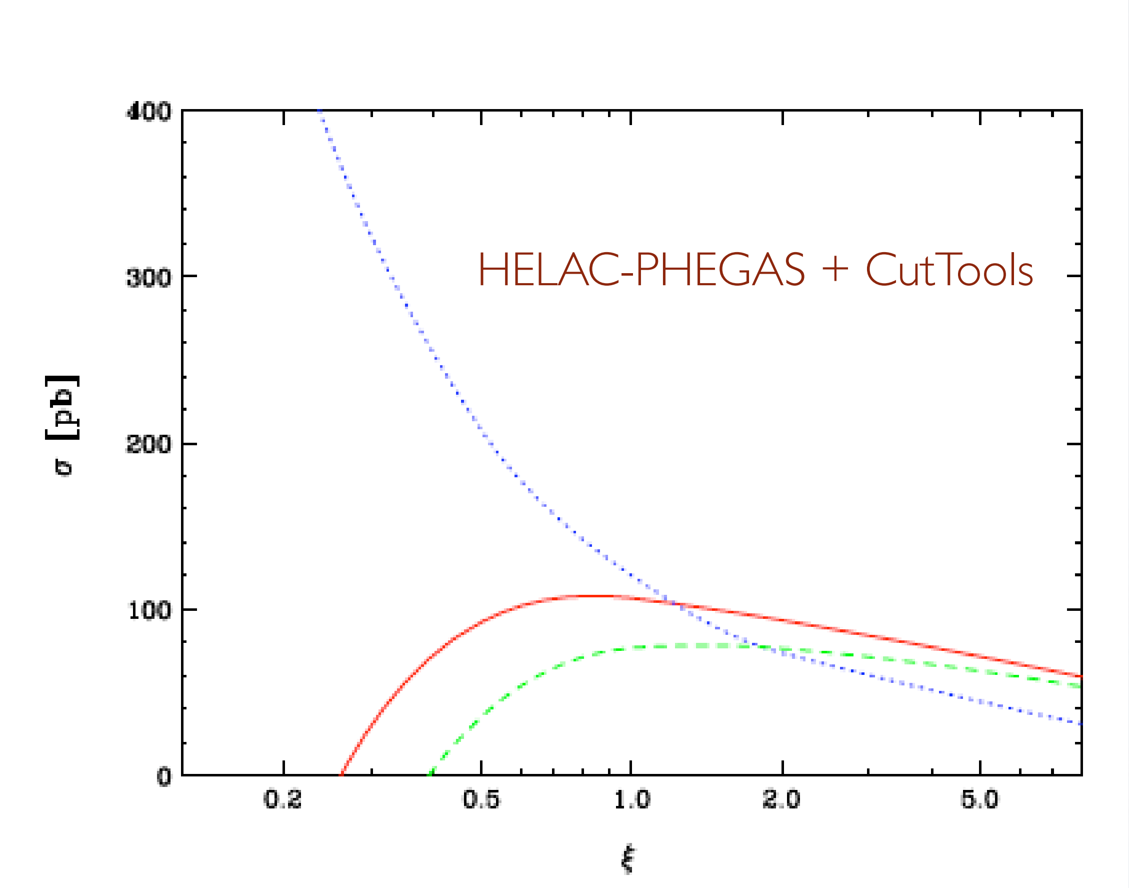
W+4 jets

[Berger et al., 1009.2338]



tt+2jets

[Bevilacqua et al., 1002.4009]



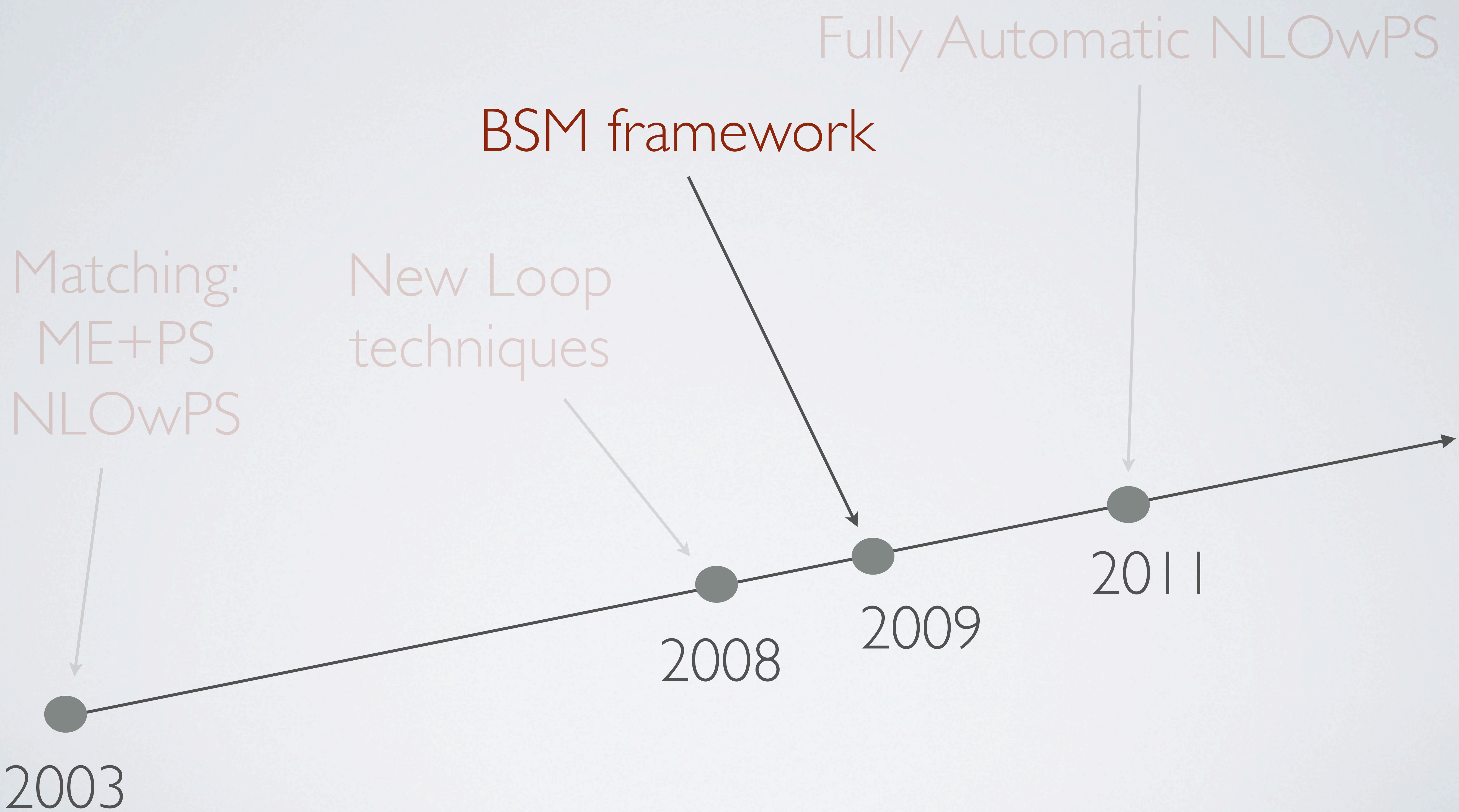
Both based on unitarity methods and recursive relations for trees.

One indicator of NLO progress

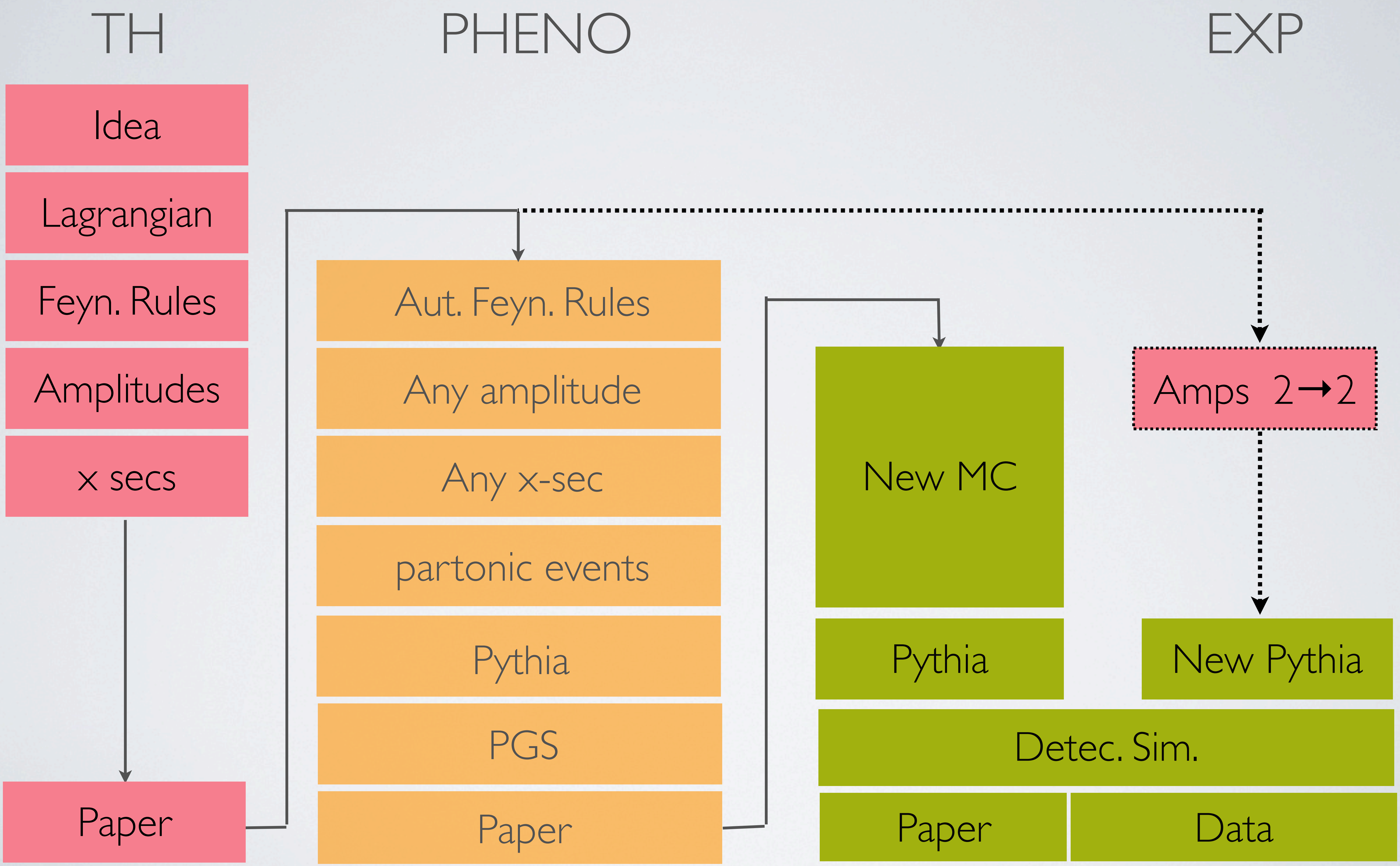
pp → W + 0 jet	1978	Altarelli, Ellis, Martinelli
pp → W + 1 jet	1989	Arnold, Ellis, Reno
pp → W + 2 jets	2002	Campbell, Ellis
pp → W + 3 jets	2009	BH+Sherpa Ellis, Melnikov, Zanderighi
pp → W + 4 jets	2010	BH+Sherpa

Slide from L. Dixon

QCD AND MC (SIMPLIFIED) PROGRESS



BSM TH/EXP INTERACTIONS : THE OLD WAY



BSM TH/EXP INTERACTIONS : THE NEW PATH

TH

EXP

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

Events

PS+Had

PGS | Detect. Sim.

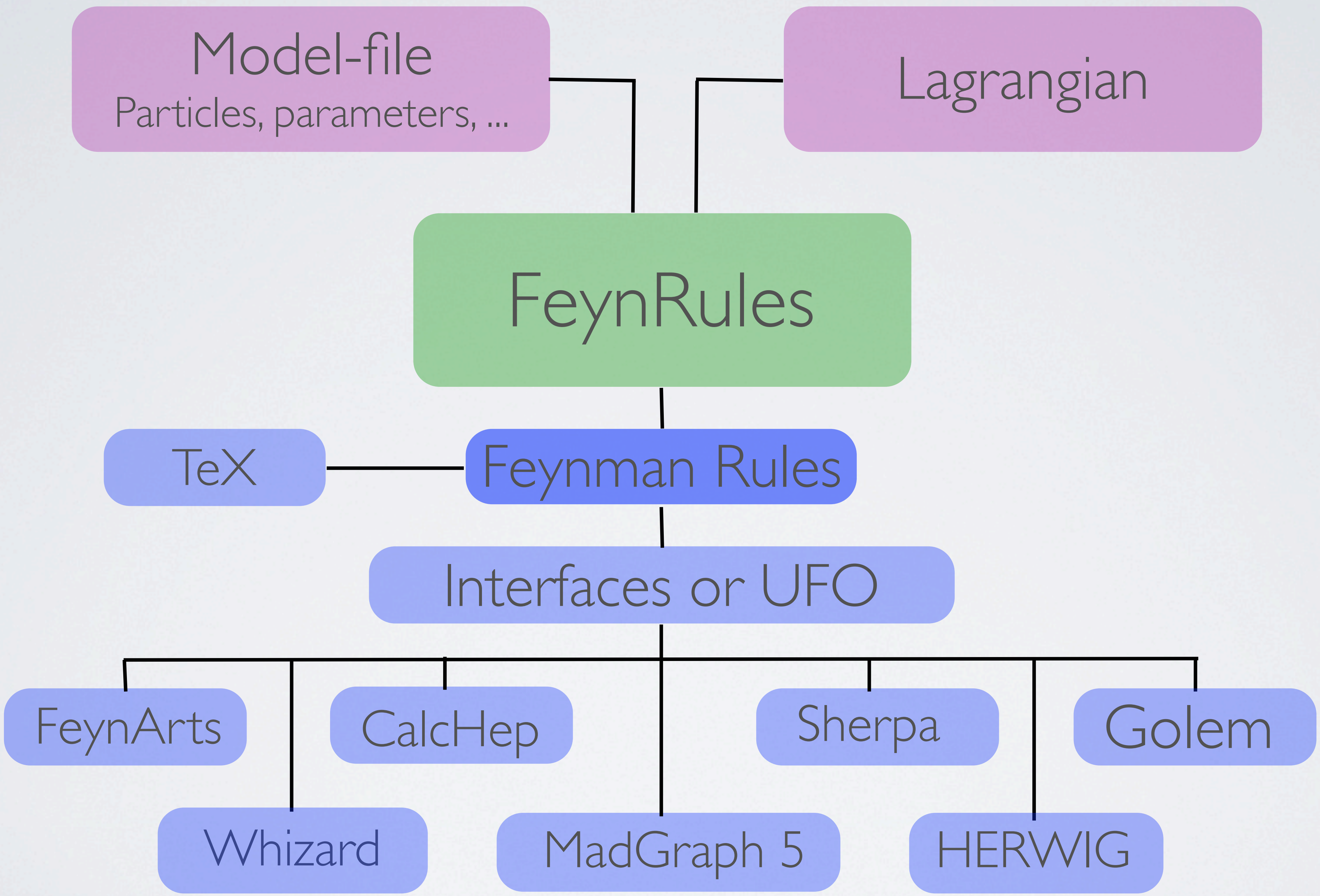
Papers | Data

- One path for all
- Physics and software validations streamlined
- 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-din	
Strongly theories	
Miscellan	

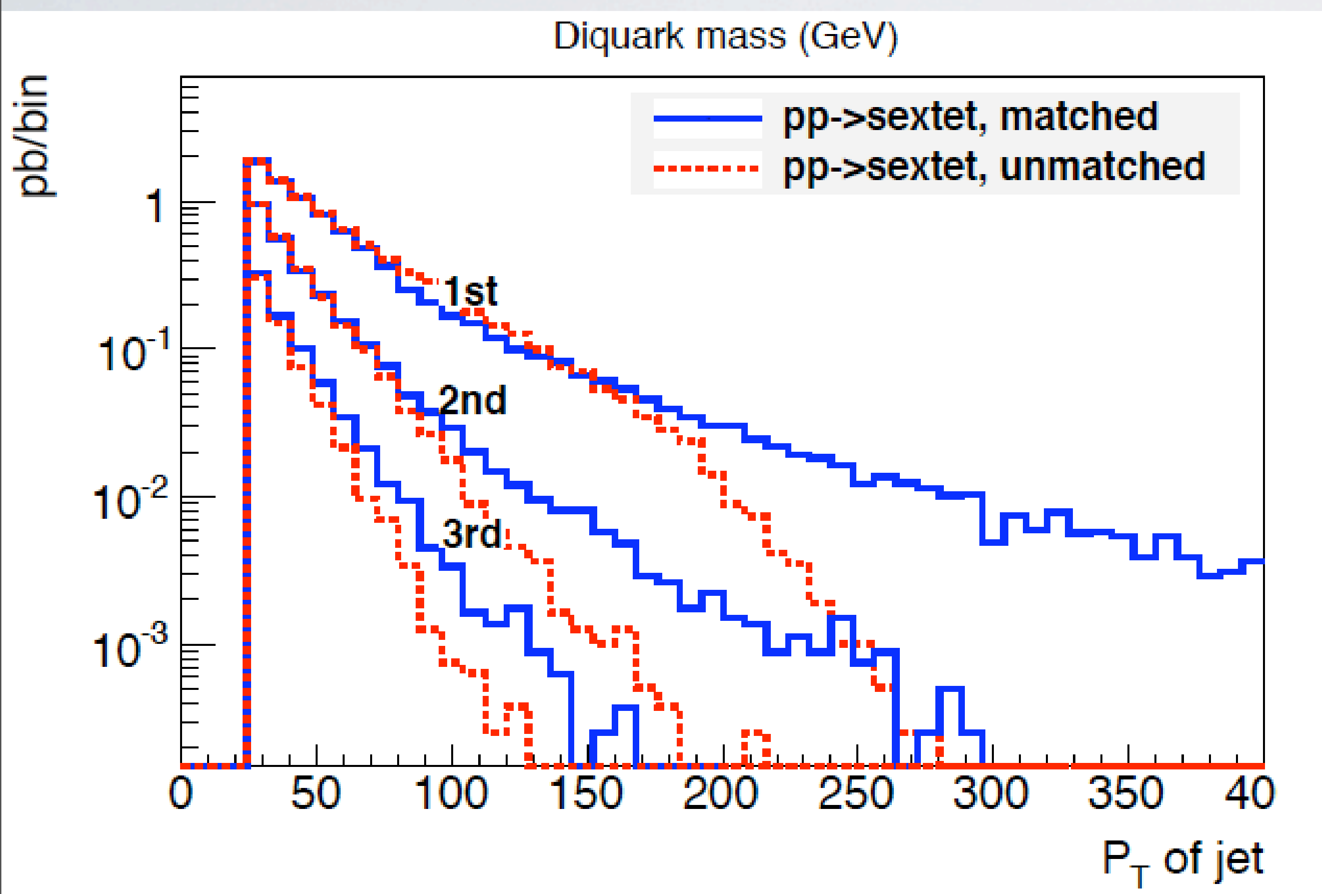
Model	Short Description	Contact	Status
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	**Available**
4th generation model	A fourth generation model including a t' and a b'	C. Duhr	**Available**
Standard model + Scalars	The SM, together 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)

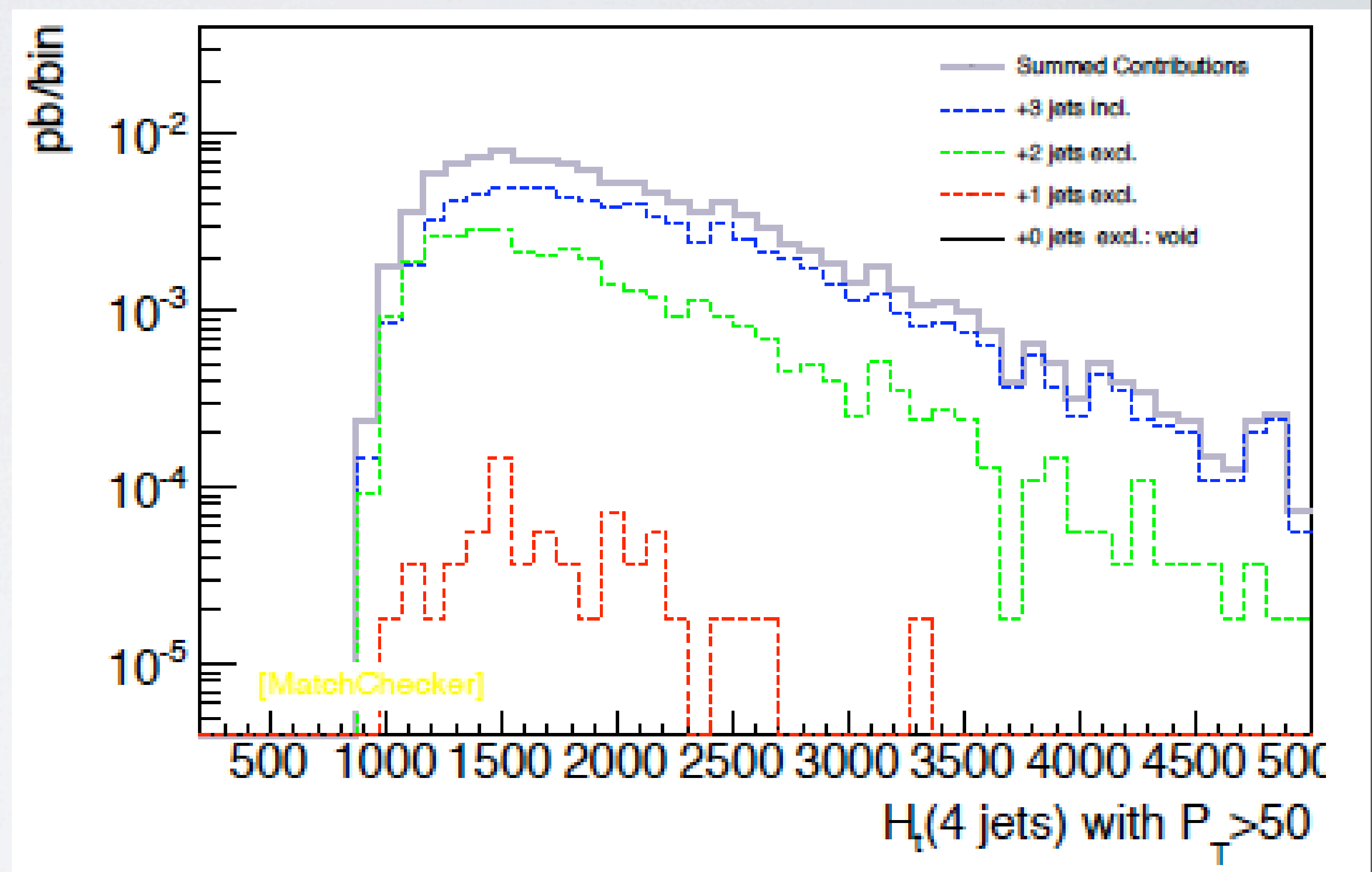
Example: BSM multijet final states

pp→X6 +jets



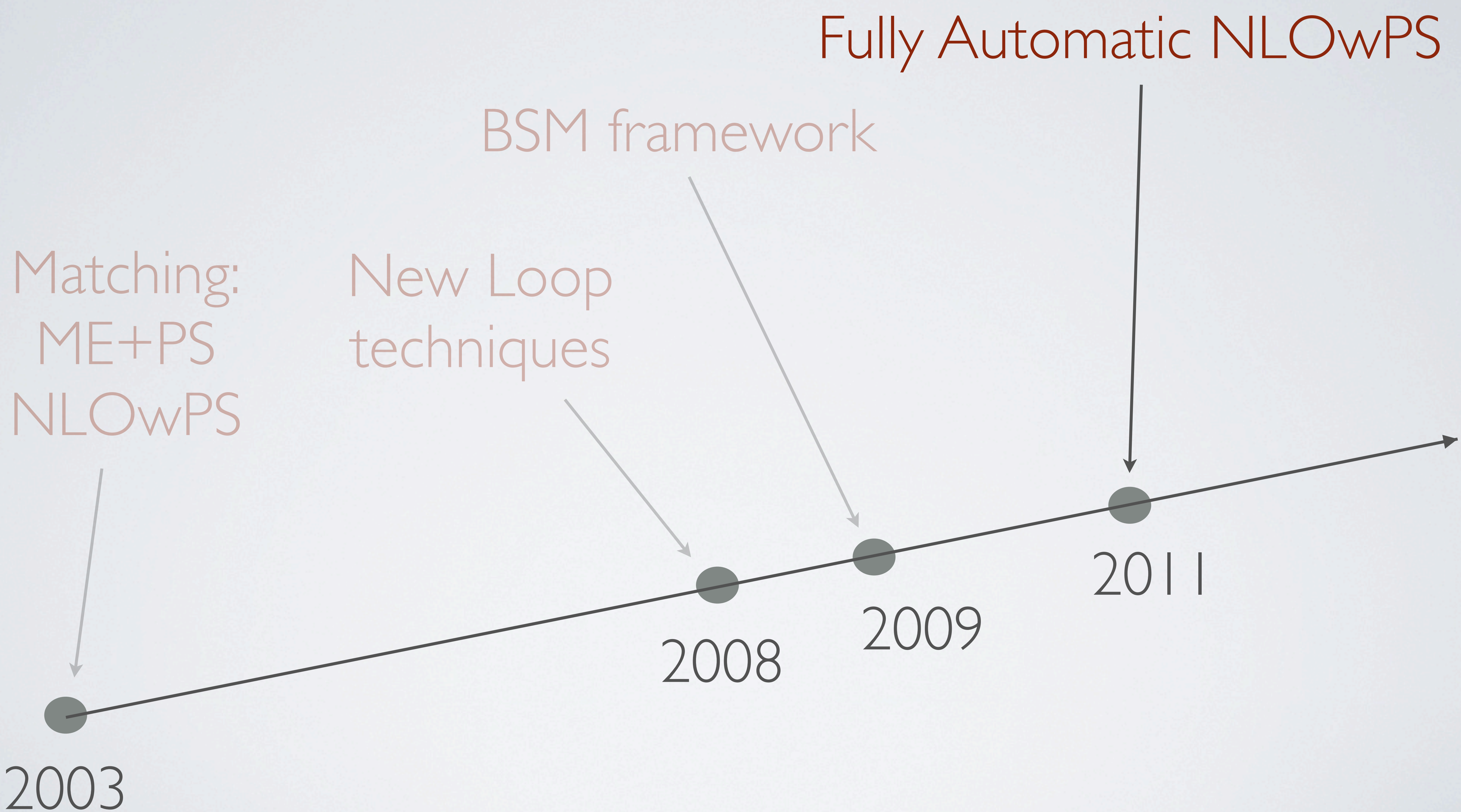
[Alwall 2011]

pp→Graviton (ADD&RS) +jets

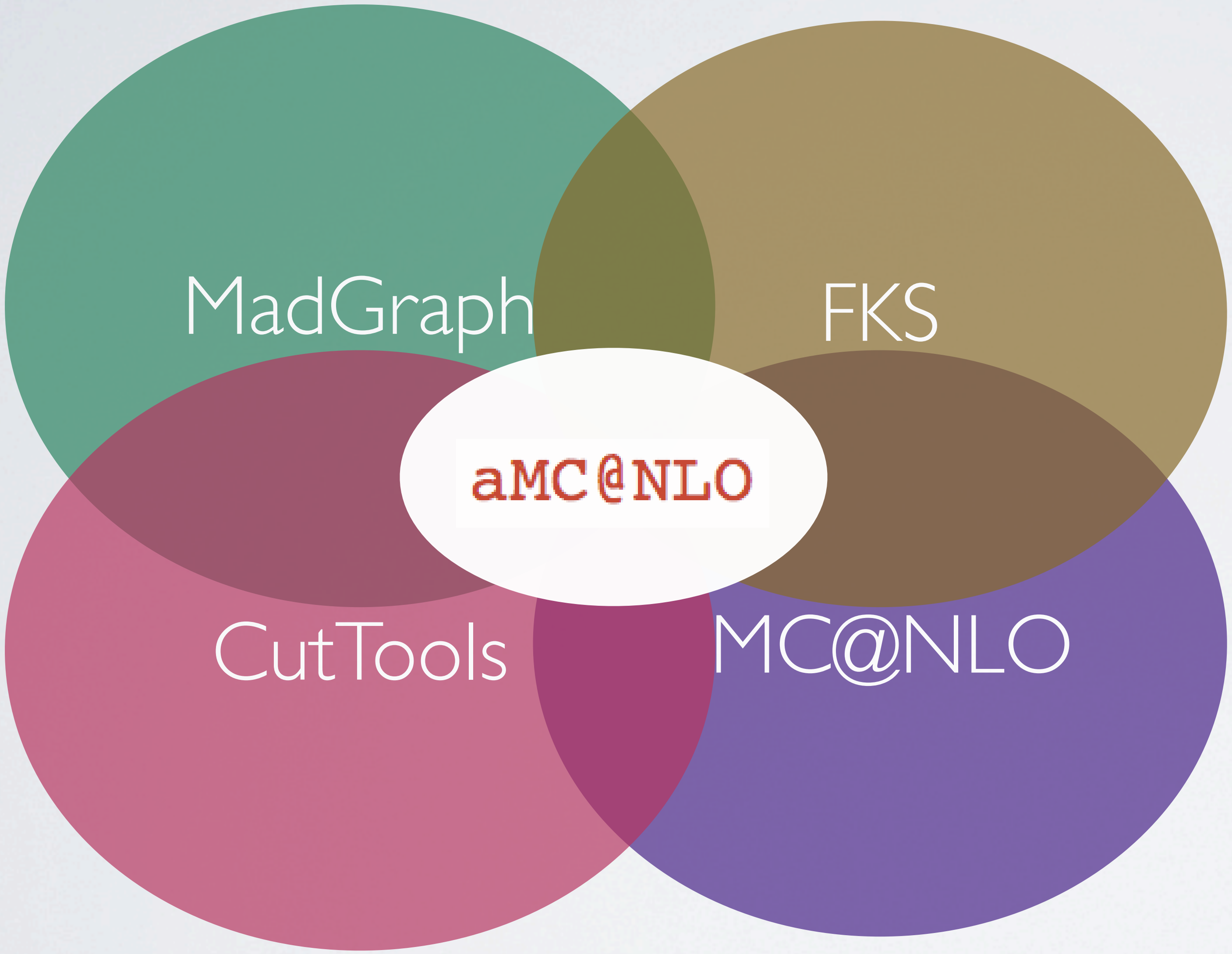


[de Aquino, Hagiwara, Qiang Li, FM, 2011]

QCD AND MC PROGRESS



THE aMC@NLO JOINT VENTURE



Modular structure:

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

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 with ttZ.
- Successful cross-check against known results (and bugs found in other NLO codes Zjj, W+W+jj)

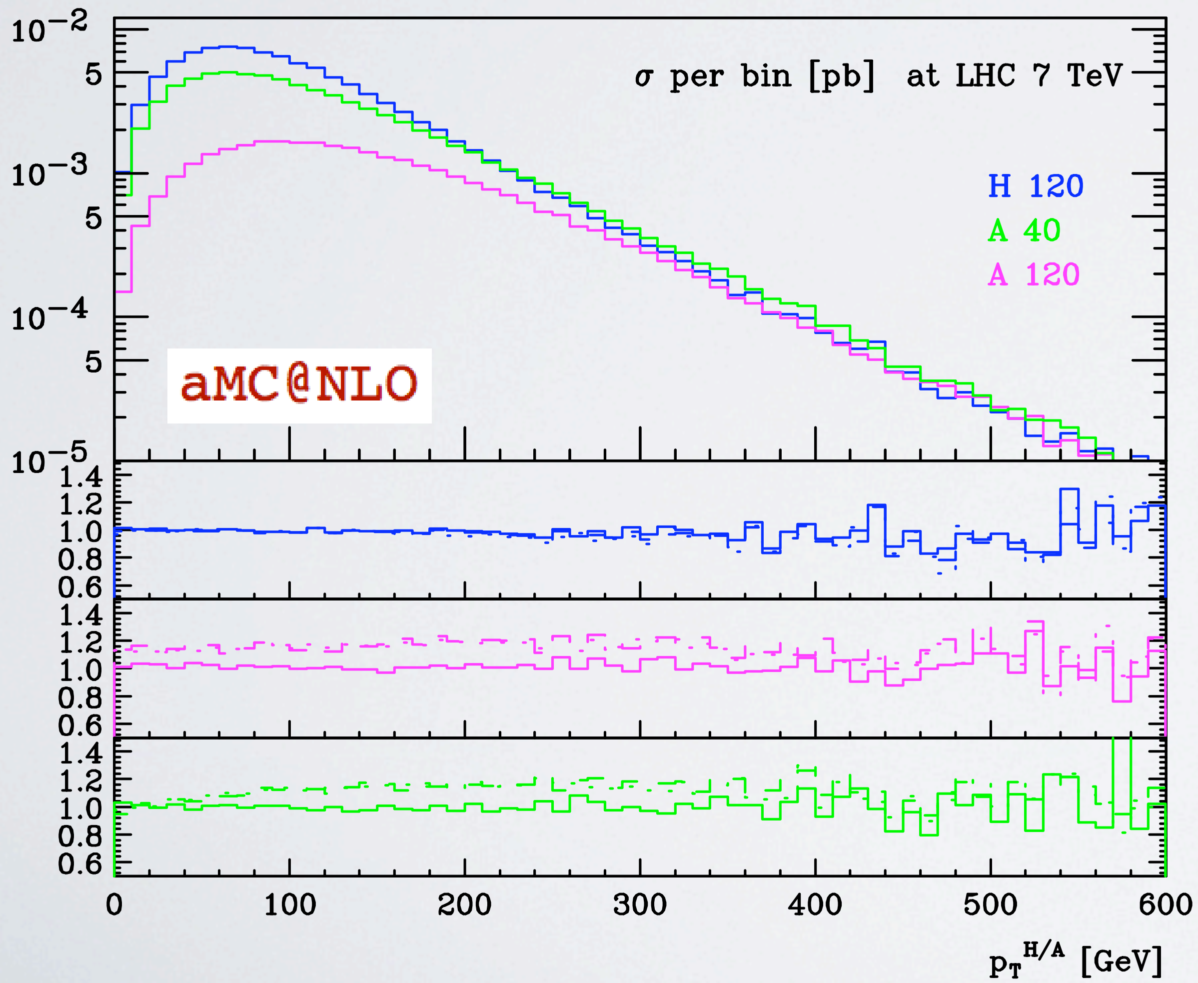
	Process	μ	n_{lf}	Cross section (pb) LO	NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	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

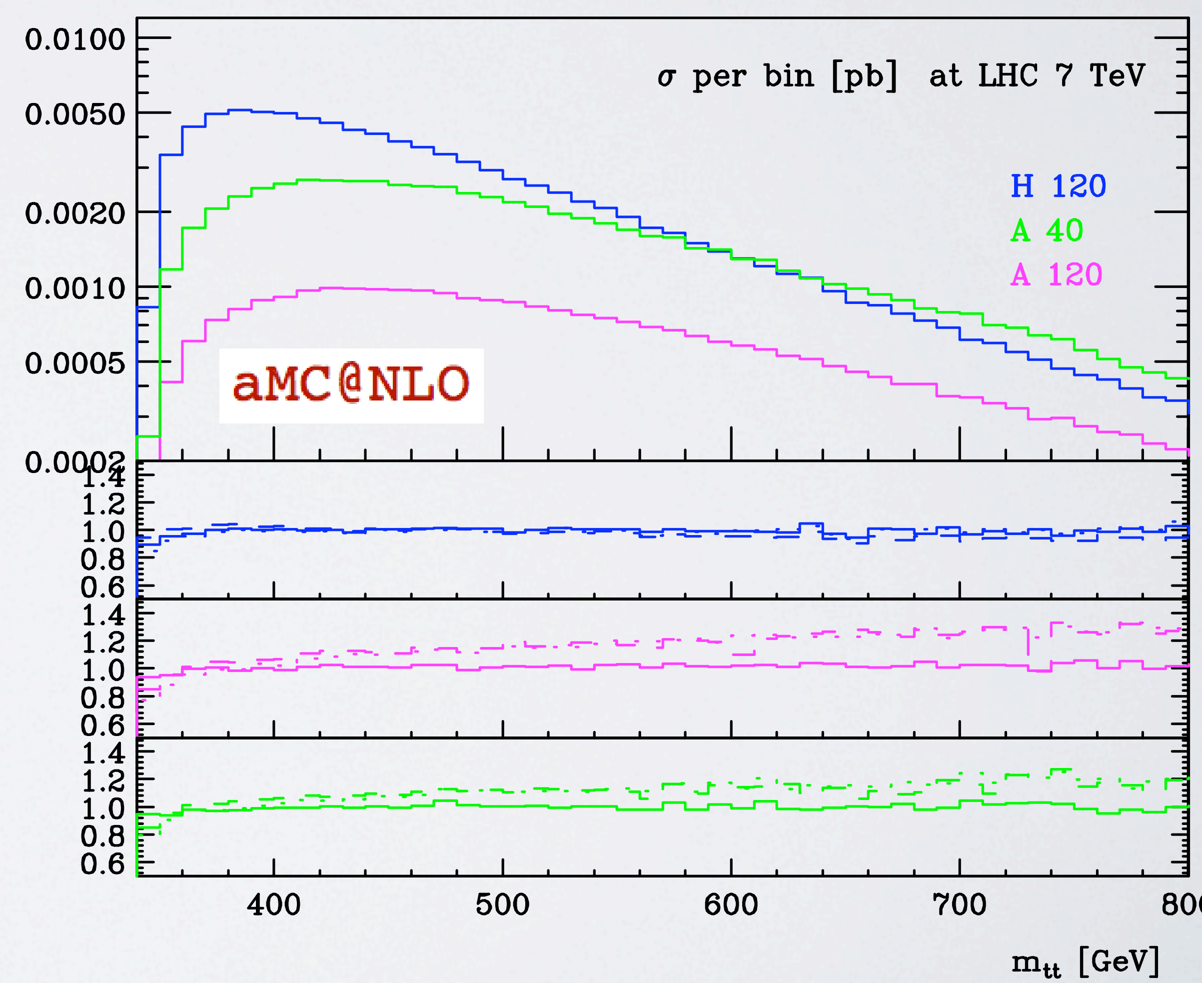
FIRST aMC@NLO APPLICATIONS

ttH/ttA ZZ→4l (W→eν)bb

NLO results known (but no public code) for scalar Higgs since some time.
No results for pseudoscalar known.
First fully automatic results for both H and A [Frederix, Frixione, Hirschi, FM, Pittau, Torrielli, 1104.5613].

MadLoop (CutTools)+MadFKS+MC@NLO+Herwig6





FIRST aMC@NLO APPLICATIONS

ttH/ttA ZZ→4l (W→eν)bb

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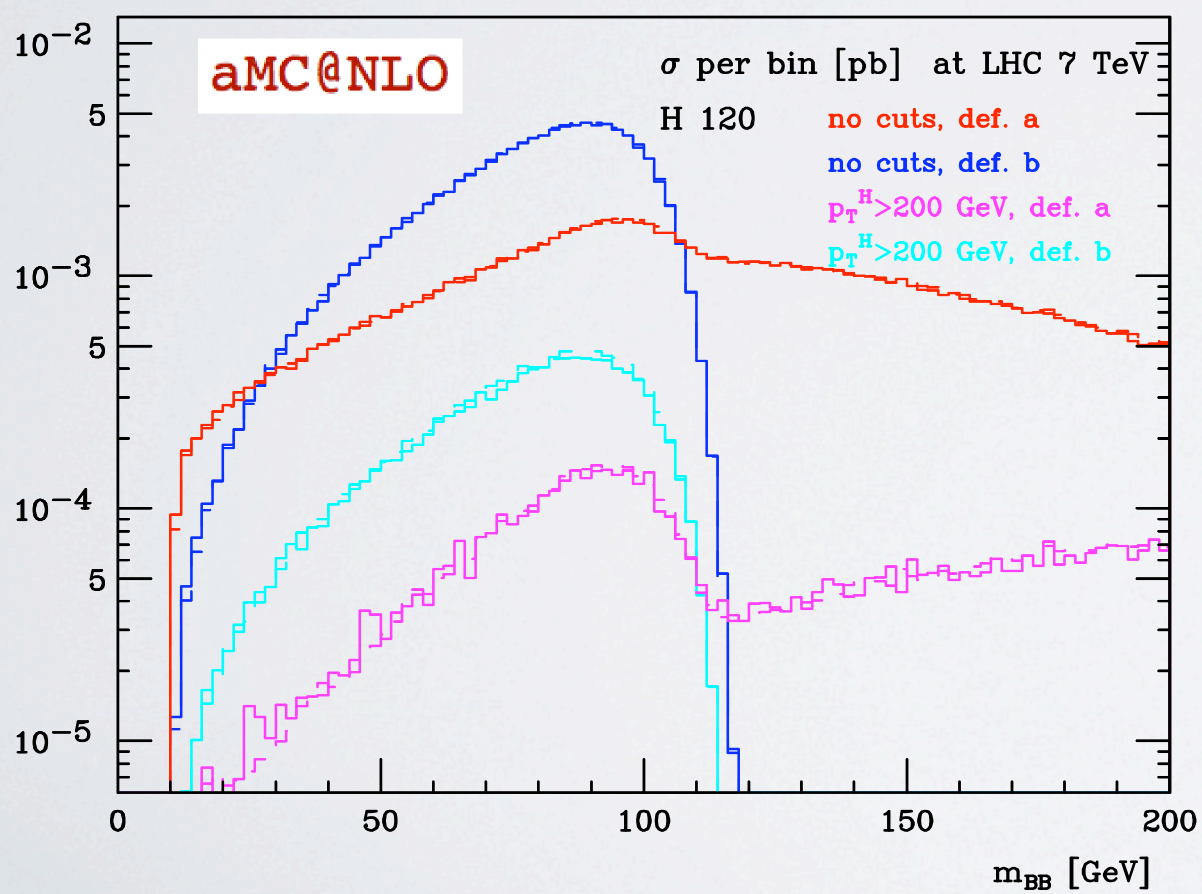
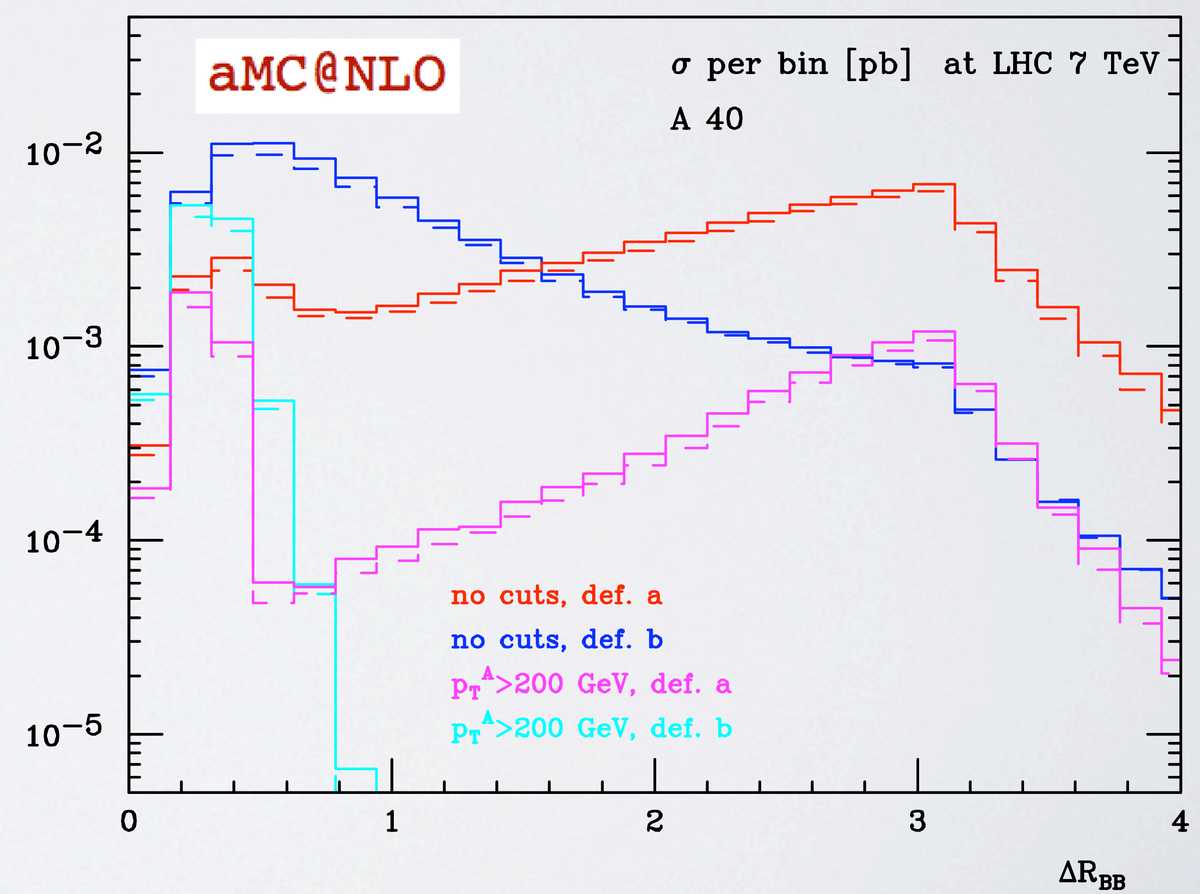


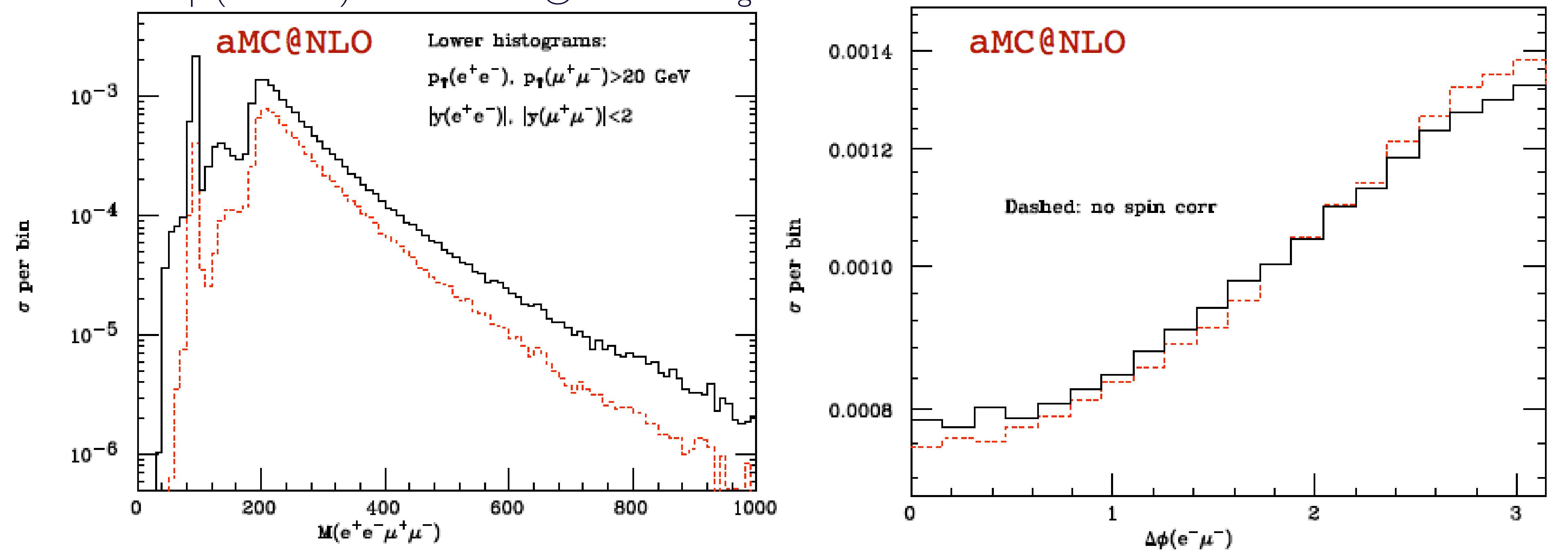


FIRST aMC@NLO APPLICATIONS

ttH/ttA | ZZ→4l | (W→eν)bb

NLO calculation includes γ^*/Z interference, full spin correlations and single resonant diagrams.
Equivalent at pure NLO to MCFM.

MadLoop (CutTools)+MadFKS+MC@NLO+Herwig6

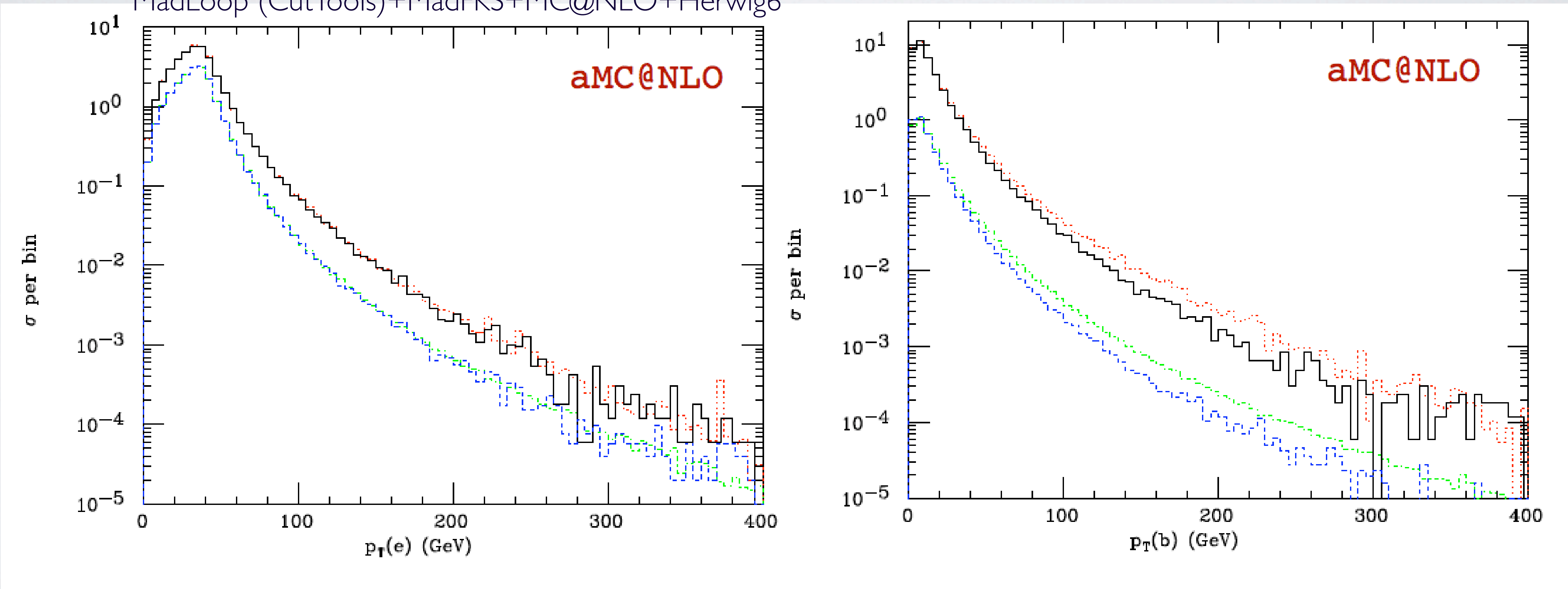


FIRST aMC@NLO APPLICATIONS

ttH/ttA   ZZ→4l   (W→eν)bb

Several NLO results available since some time but all with approximations (ie, m_b=0 or no spin correlations). No approximations here and NLO equivalent to recent [Badger, Campbell, Ellis, 1011.6647].

MadLoop (CutTools)+MadFKS+MC@NLO+Herwig6

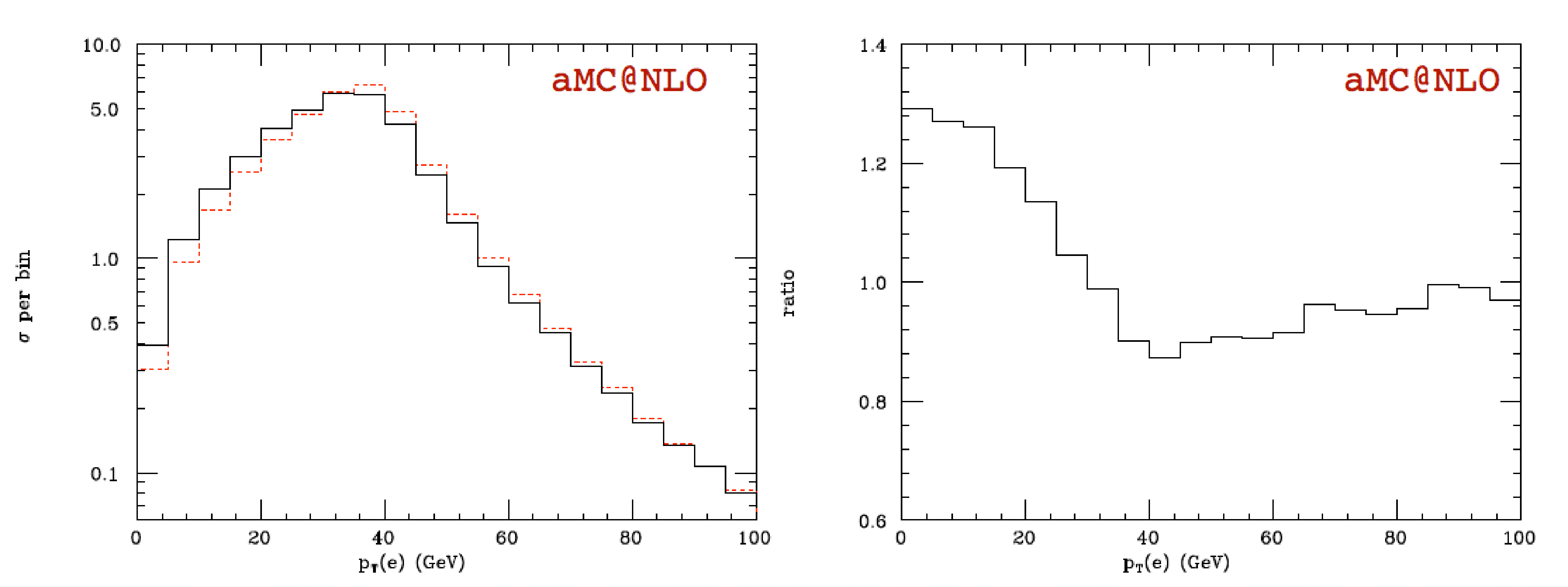


Solid: aMC@NLO   Dashed: aMC@LO   Dotted: NLO   Dotdashed: LO

FIRST aMC@NLO APPLICATIONS

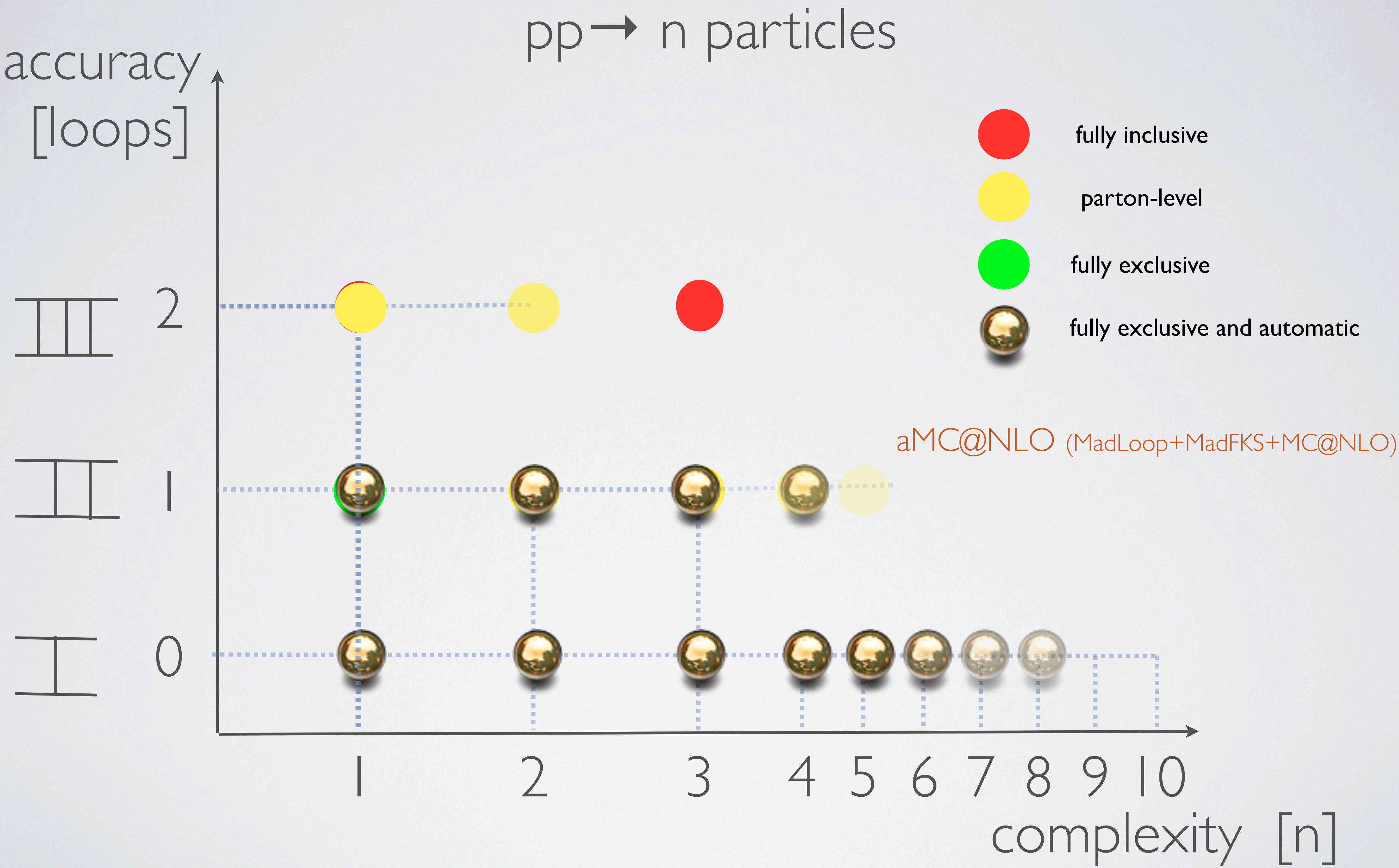
ttH/ttA   ZZ→4l   (W→eν)bb

Several NLO results available since some time but all with approximations (ie, m_b=0 or no spin correlations). No approximation here and NLO equivalent to recent [Badger, Campbell, Ellis, 1011.6647].

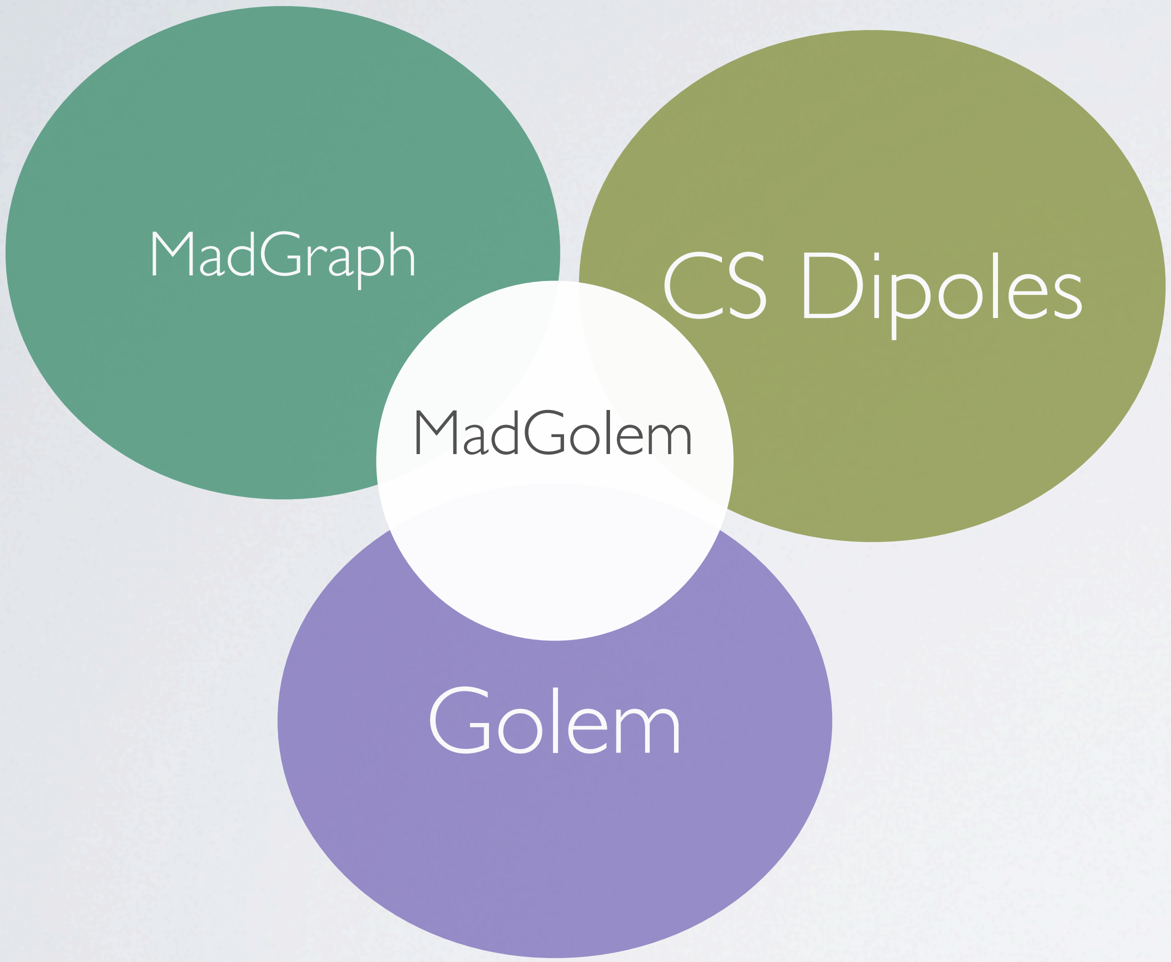


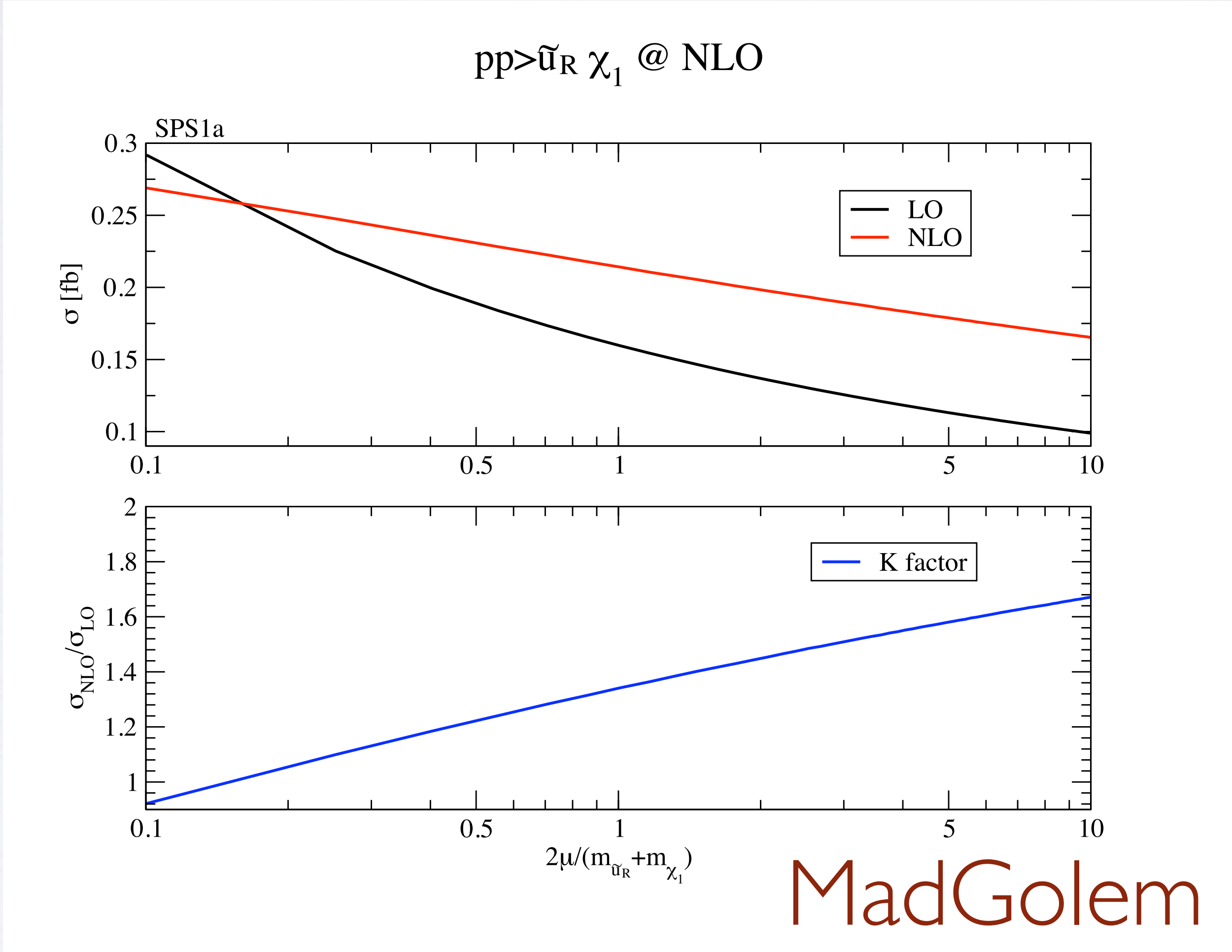
Solid: w/ spin correlations   Dashed: w/o spin correlations

SM STATUS : SINCE LAST WEEK



FIRST STEPS TOWARDS AUTOMATIC SUSY AT NLO





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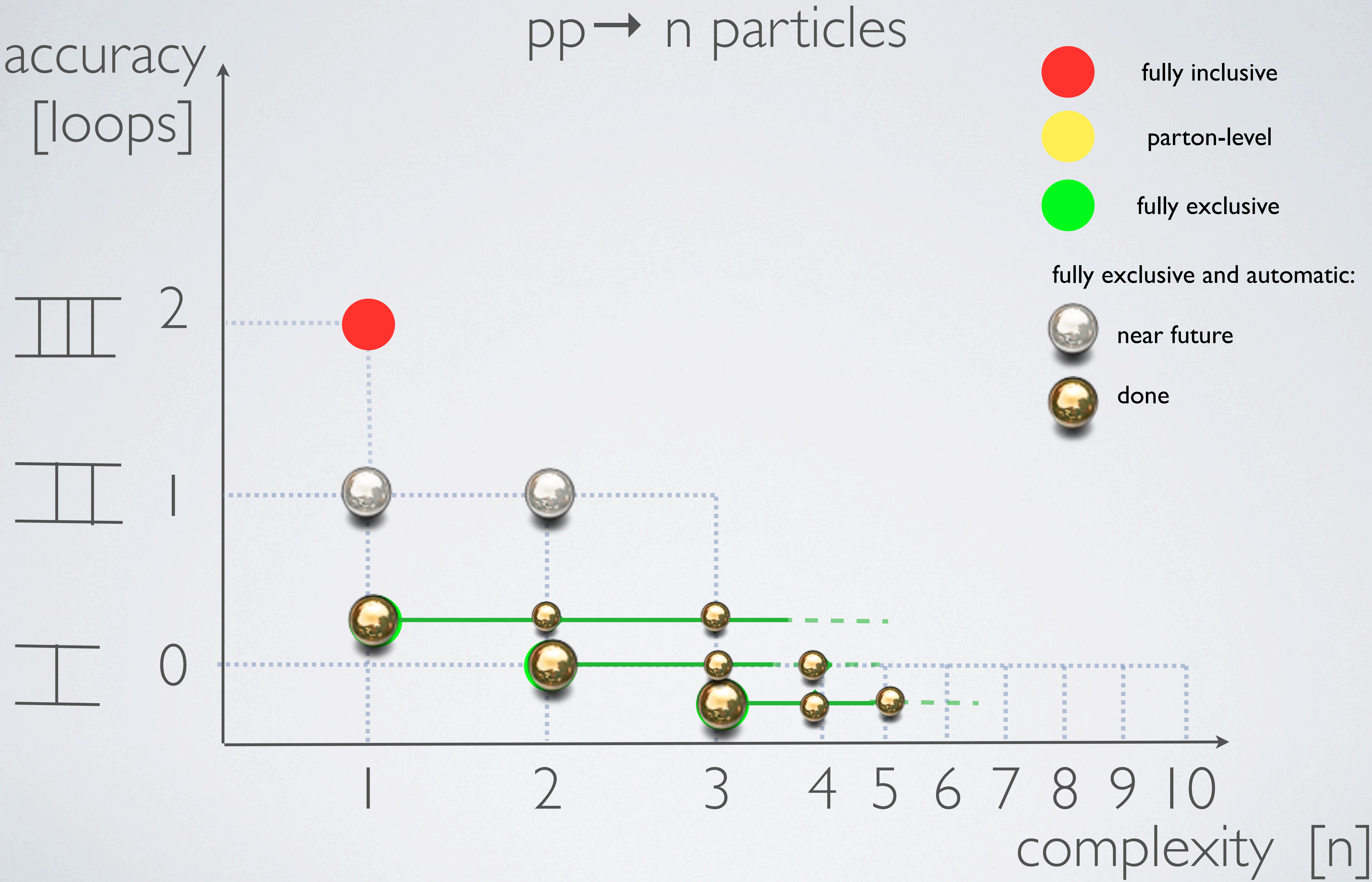
BSM STATUS AND OUTLOOK



CONCLUSIONS

- 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.

- A new generation of tools and techniques is now available. Full **A**utomation of **A**ccurate (NLO) computations at fixed order as well as their the matching to parton-shower has been proven for the SM.

- **A**mazingly efficient, flexible and robust BSM simulation chain available and being continuously improved. Same level of sophistication as SM processes can be attained. Both top-down and bottom-up approaches included.

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

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.

CREDITS

- Thanks to all the MadGraph team/collaborators/friends for continuous and exciting collaborations
- Thanks to the MC community for always fruitful collaborations.
- The material (and very often the presentation itself) shown in this talk is the work of many people, including Claude Duhr, Stefano Frixione, Valentin Hirshi, Rikkert Frederix, Johan Alwall,...