UCL Université catholique de Louvain

MC tools and NLO Monte Carlos

Fabio Maltoni (CP3-Louvain)

ACCURATE MC'S: MOTIVATION

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- 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.

OUTLINE

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- Status and prospects for Higgs physics
- Discussion

Where do we come from?

Where are we going to?

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 CAN WE MAKE ACCURATE PREDICTIONS?

First way:

- For low multiplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)

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

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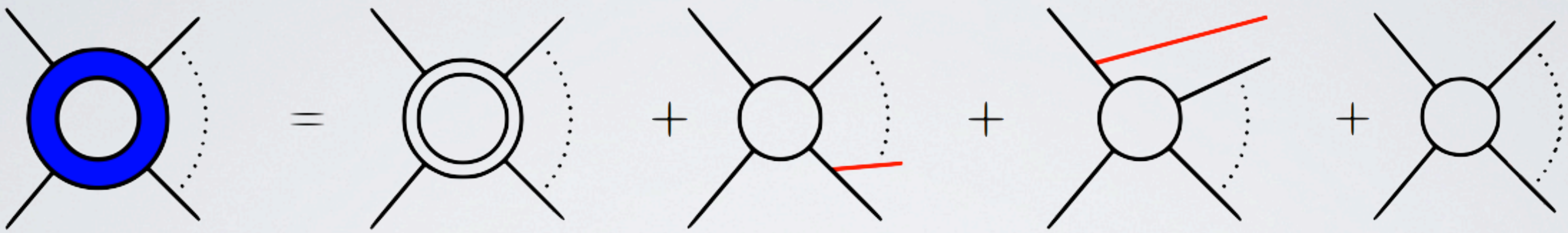
Comments:

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

INCREASING THE ACCURACY

NLO contributions have three parts:



Virtual part   Real emission part   Born

$$\int d\sigma^{(\mathrm{NLO})} O(\Phi) = \int d\Phi_B V(\Phi_B) O(\Phi_B) + \int d\Phi_R R(\Phi_R)\; O(\Phi_R) \int d\Phi_B B(\Phi_B) O(\Phi_B)$$

- Loops have been for long the bottleneck of NLO computations

LOOP TECHNIQUES

modified by the speaker

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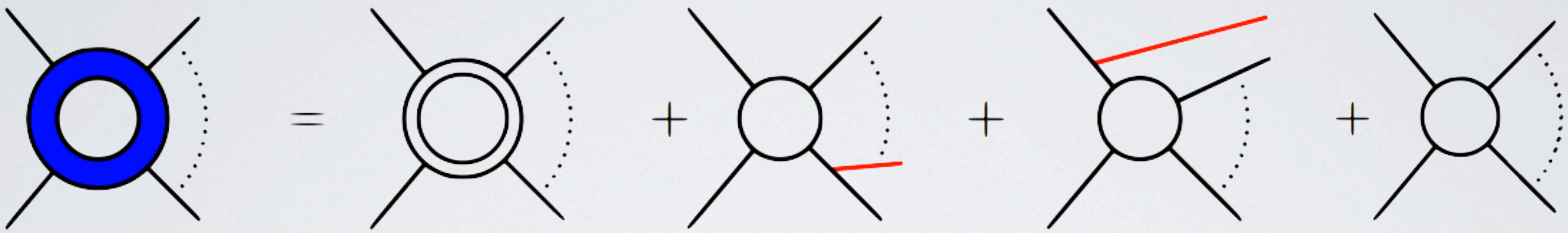

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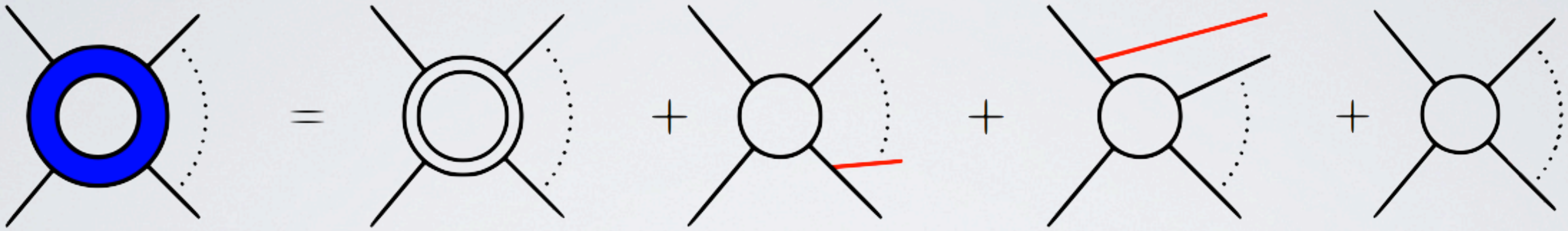

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$$= \int \mathrm{d}\Phi_B \left[B(\Phi_B) + V(\Phi_B) + \int \mathrm{d}\Phi_{R|B} S(\Phi_R) \right] O(\Phi_B)$$
$$+ \int \mathrm{d}\Phi_R \left[R(\Phi_R)\, O(\Phi_R) - S(\Phi_R) O(\Phi_B) \right]$$

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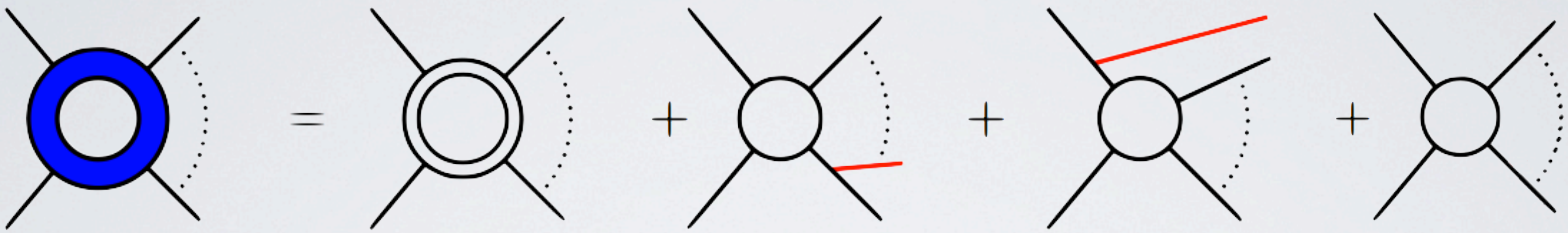

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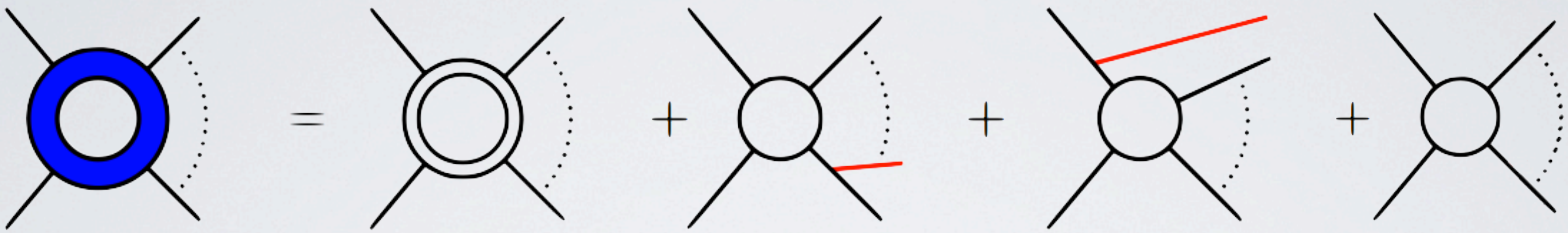

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The cost of a new prediction at NLO can easily exceed 100k$.

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

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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.

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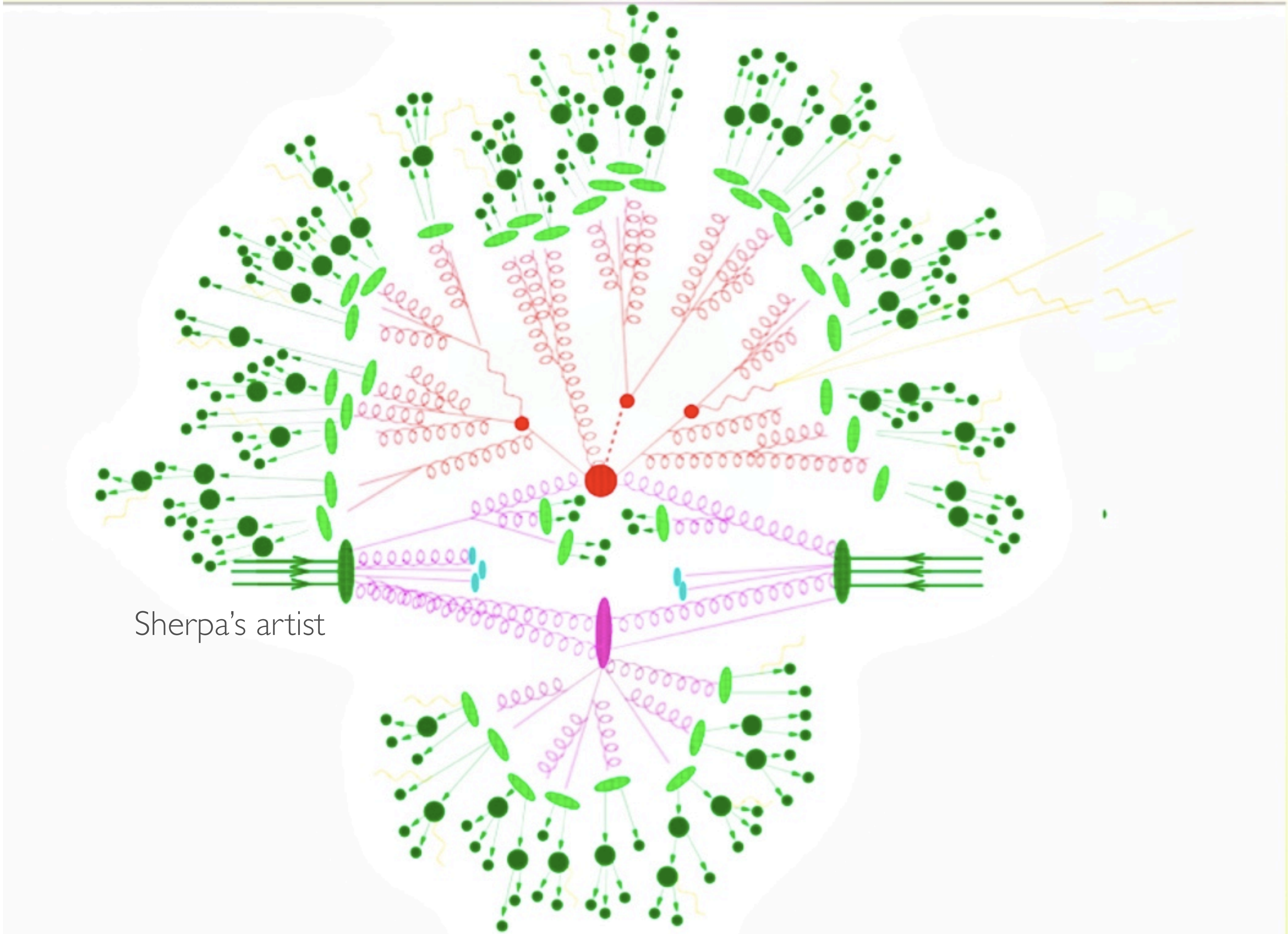
Events at hadron colliders



Sherpa's artist

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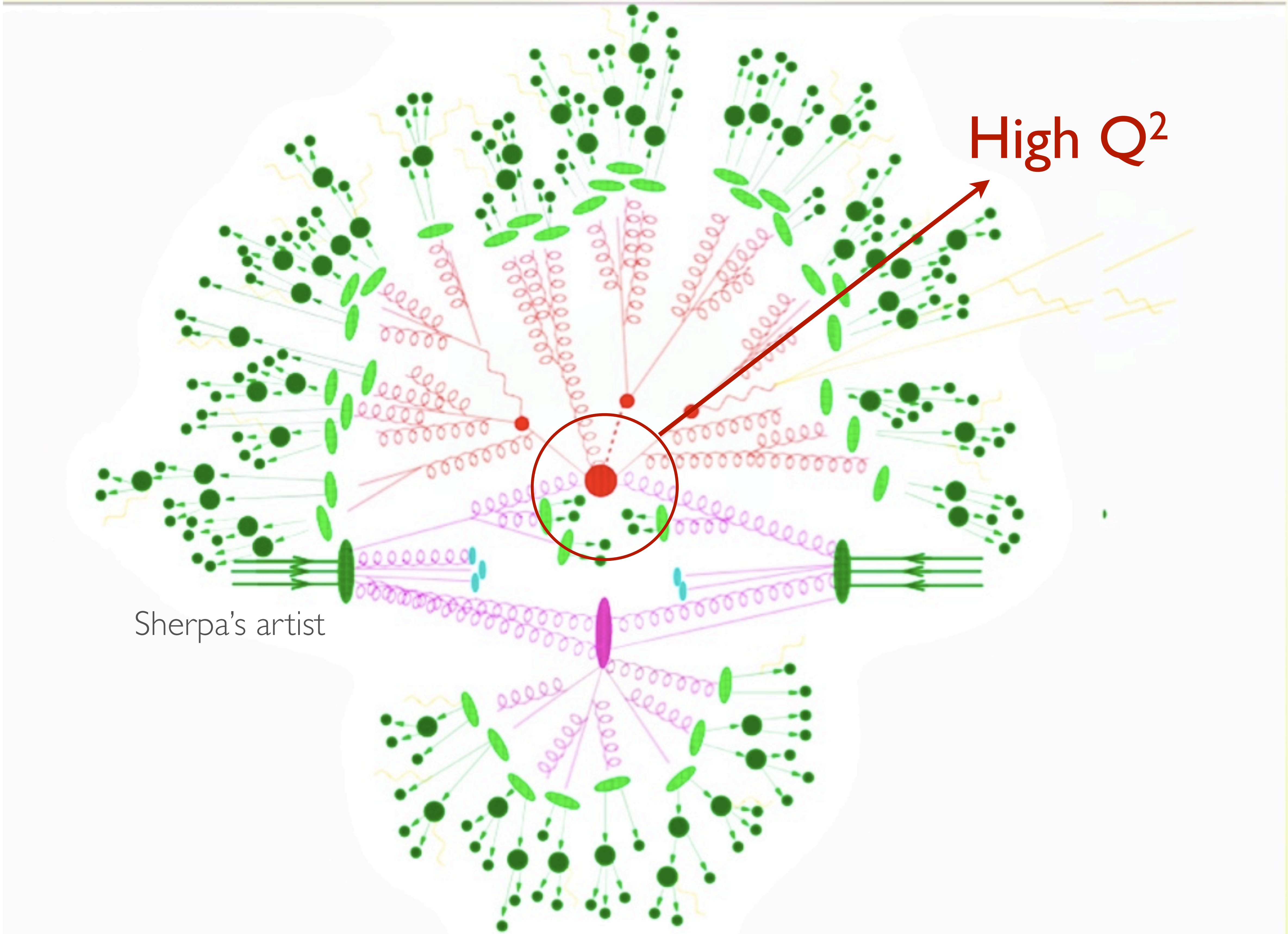

HOW CAN WE MAKE USEFUL PREDICTIONS?

Second way:

- Describe final states with high multiplicities starting from 2 →1 or 2 →2 procs, using parton showers,

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

$$\Delta(p_T) = \exp\left[-\int d\Phi_{R|B} \frac{R^{\rm PS}(\Phi_R)}{B(\Phi_B)} \Theta(p_T(\Phi_R) - p_T) \right] \quad \cdot \quad R^{\rm PS}(\Phi) = P(\Phi_{R|B})\, B(\Phi_B).$$

and then a hadronization model.

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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.

QCD AND MC (SIMPLIFIED) PROGRESS

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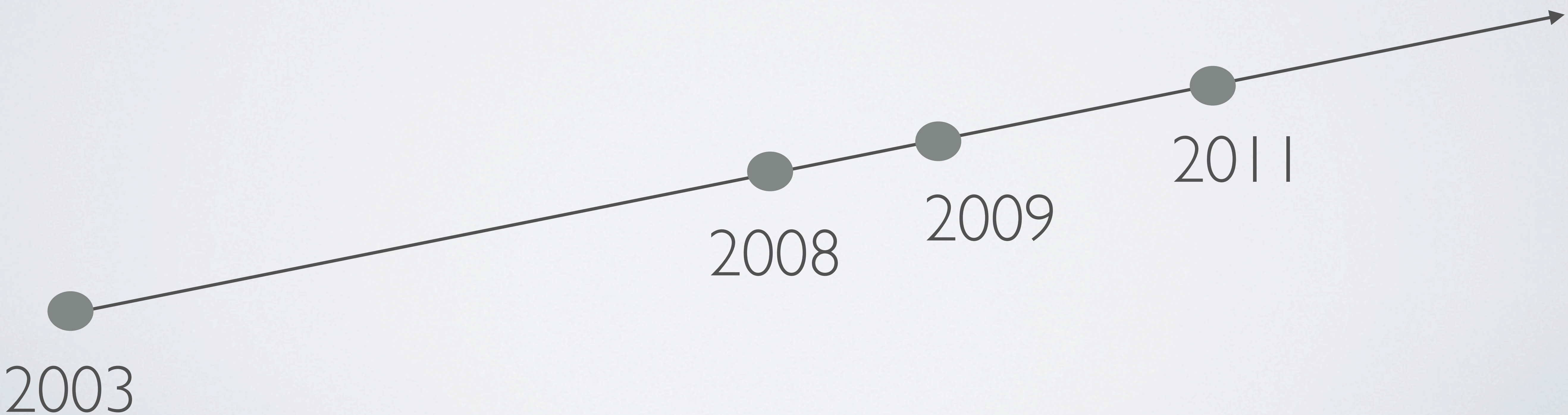

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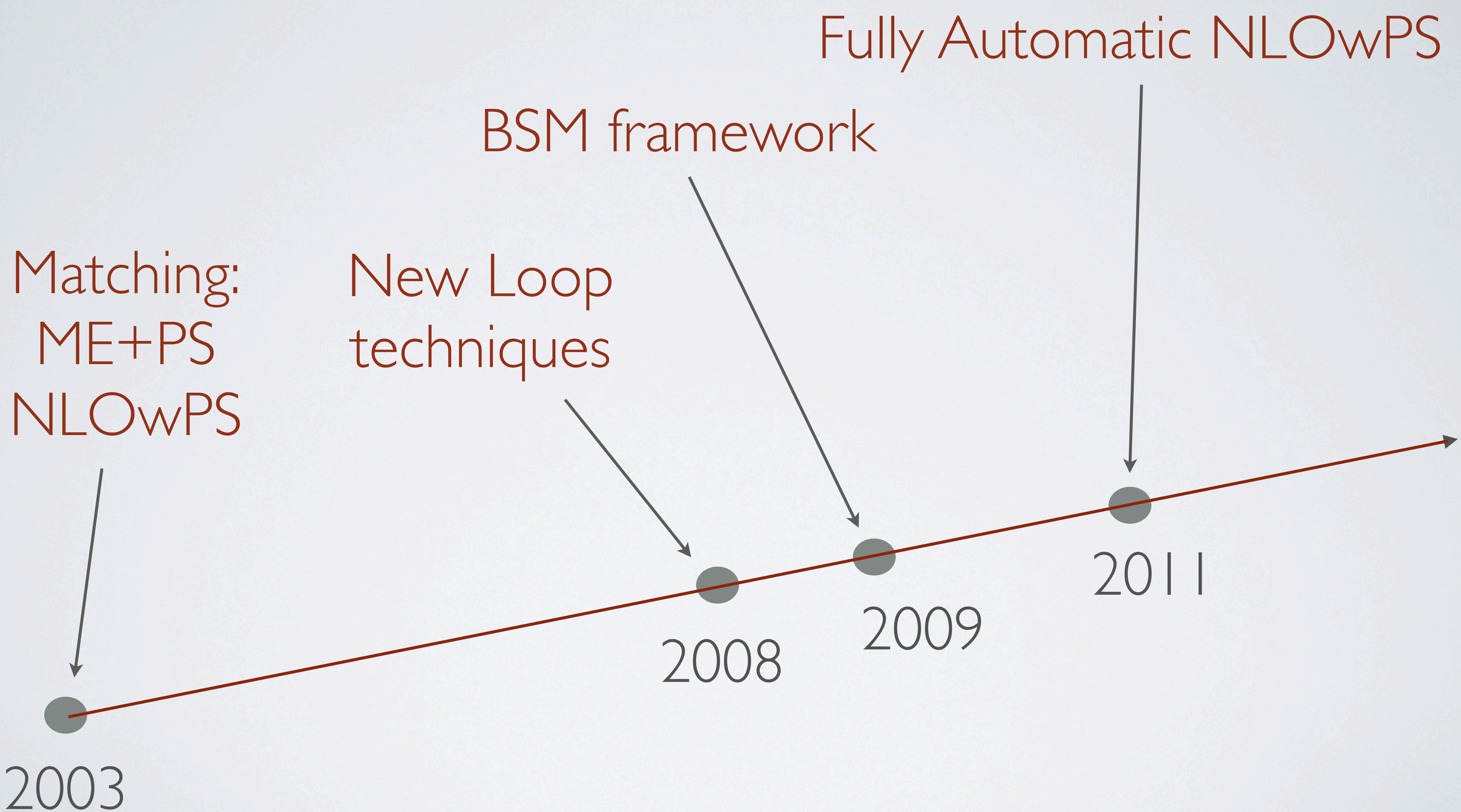

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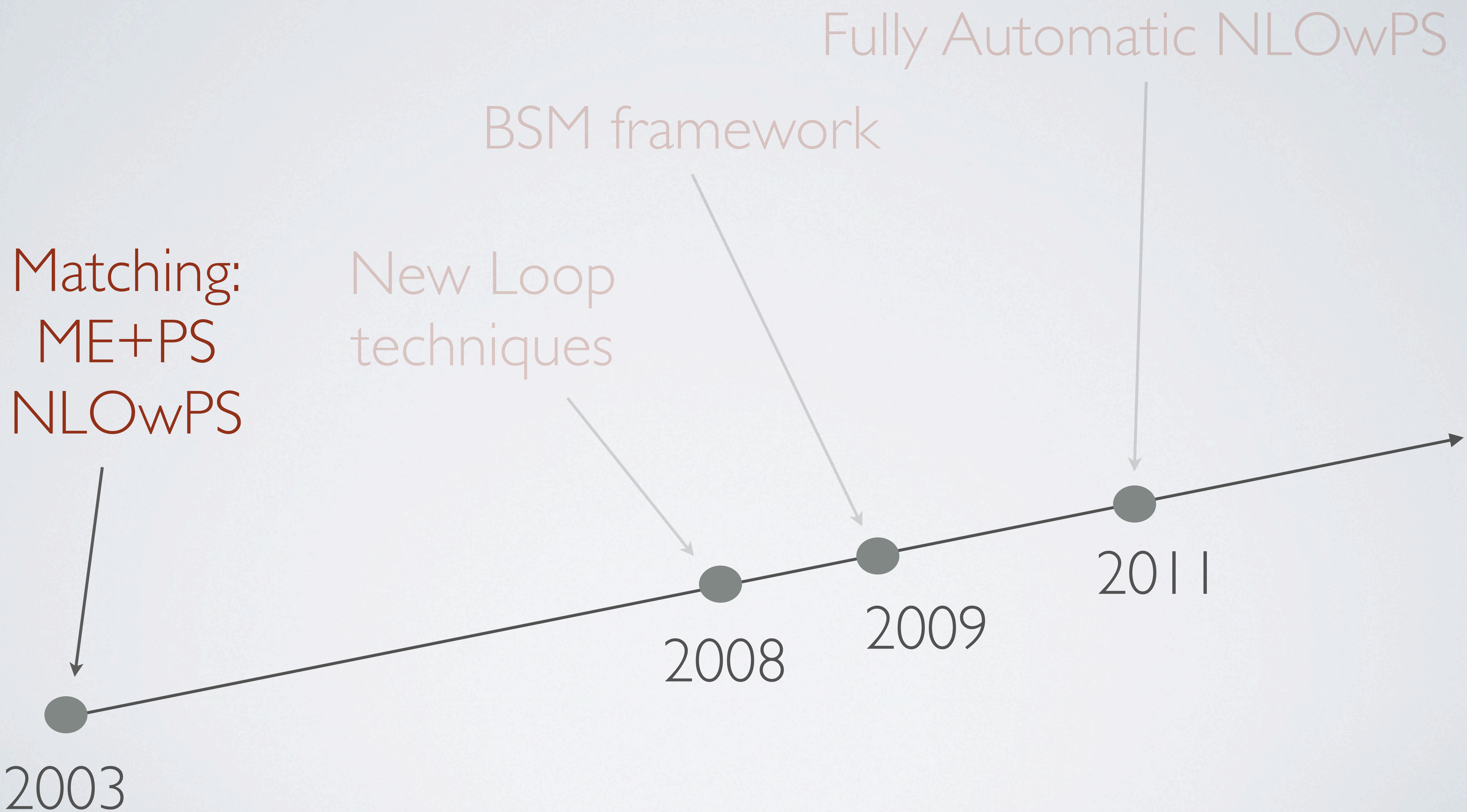

ME WITH PS

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

Matrix Element	Shower MC
1. parton-level description	1. hadron-level description
2. fixed order calculation	2. resums large logs
3. quantum interference exact	3. quantum interference through angular ordering
4. valid when partons are hard and well separated	4. valid when partons are collinear and/or soft
5. needed for multi-jet description	5. nedeed for realistic studies

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Difficulty: avoid double counting

Merging ME with PS

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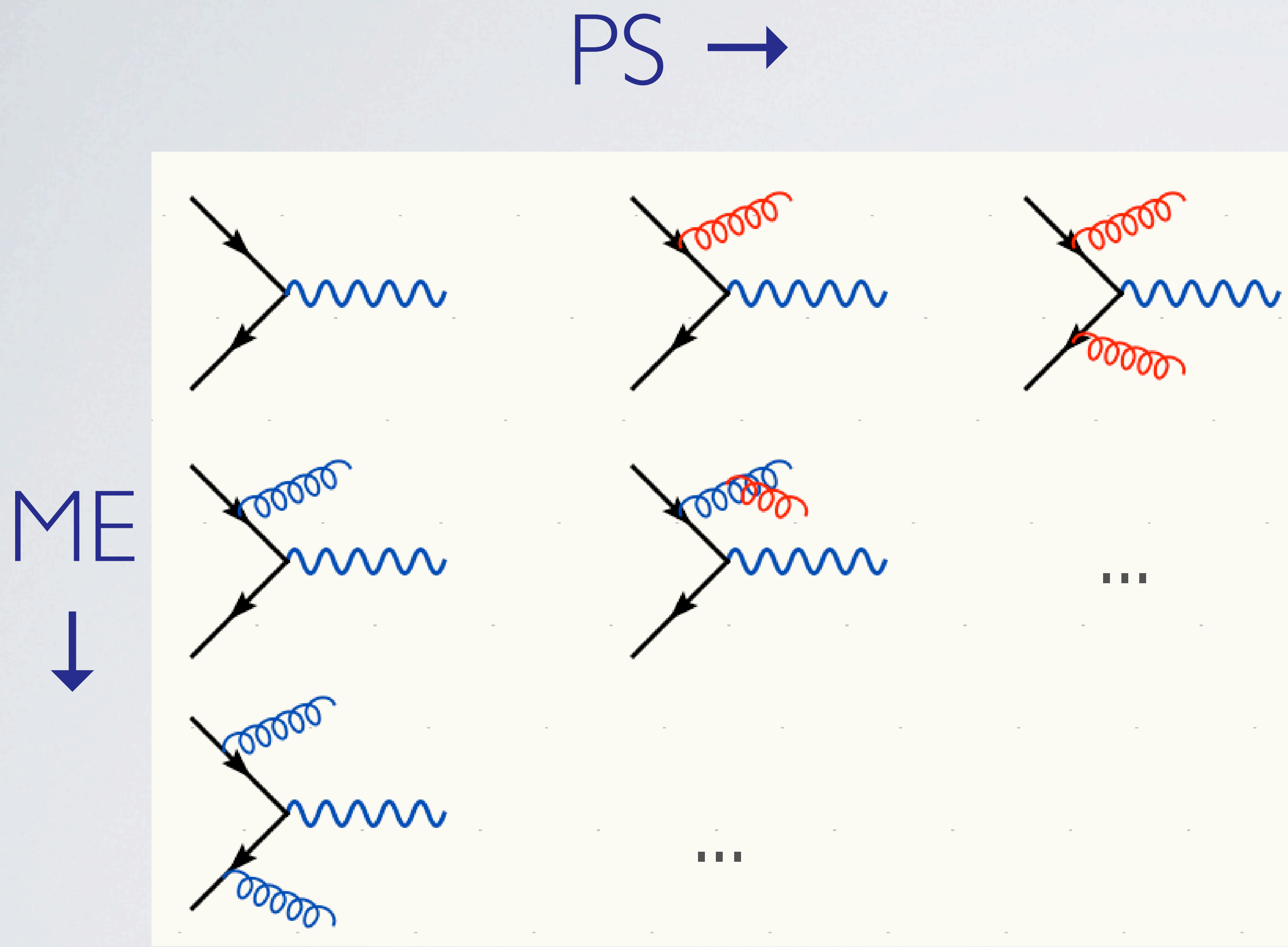
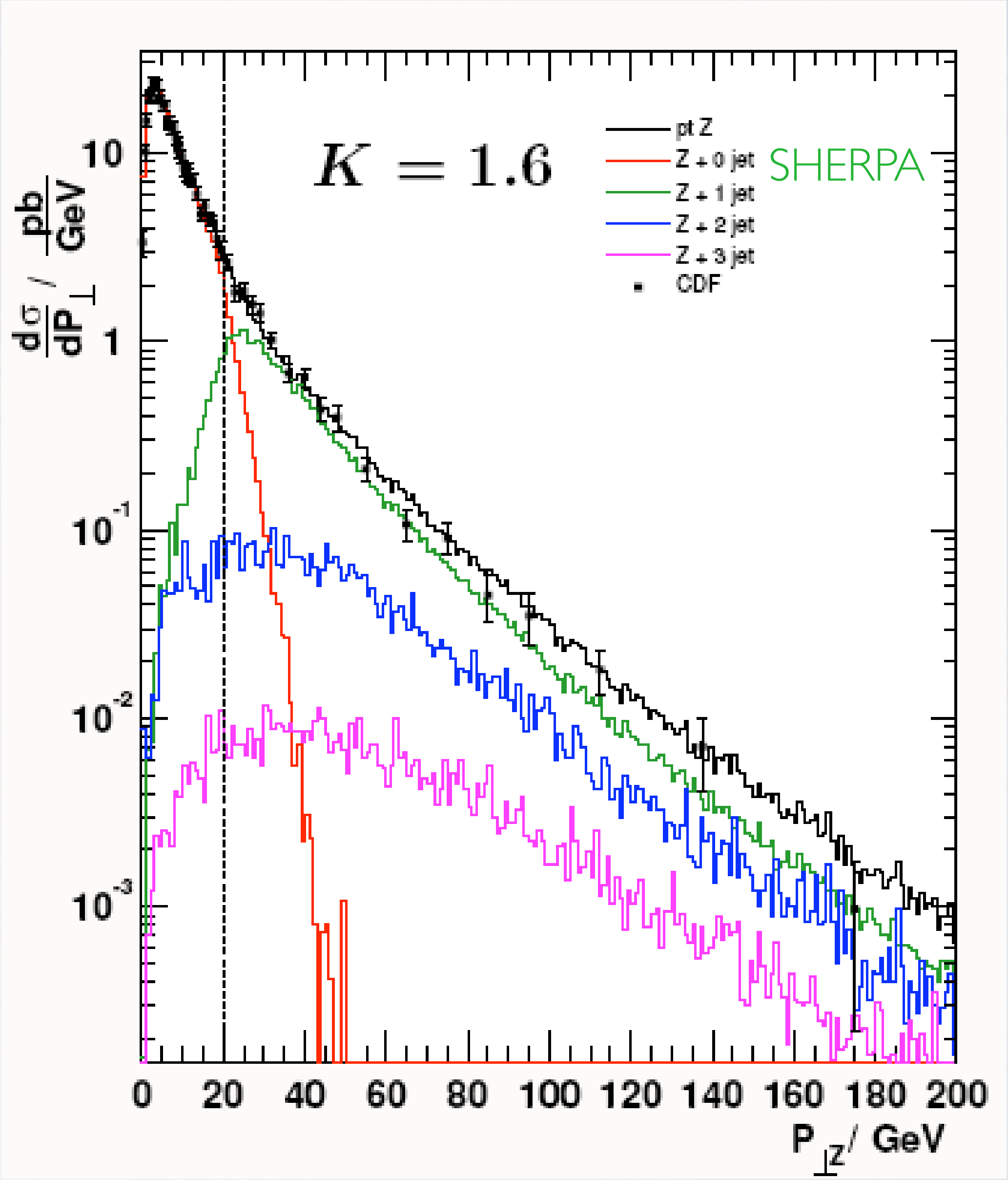
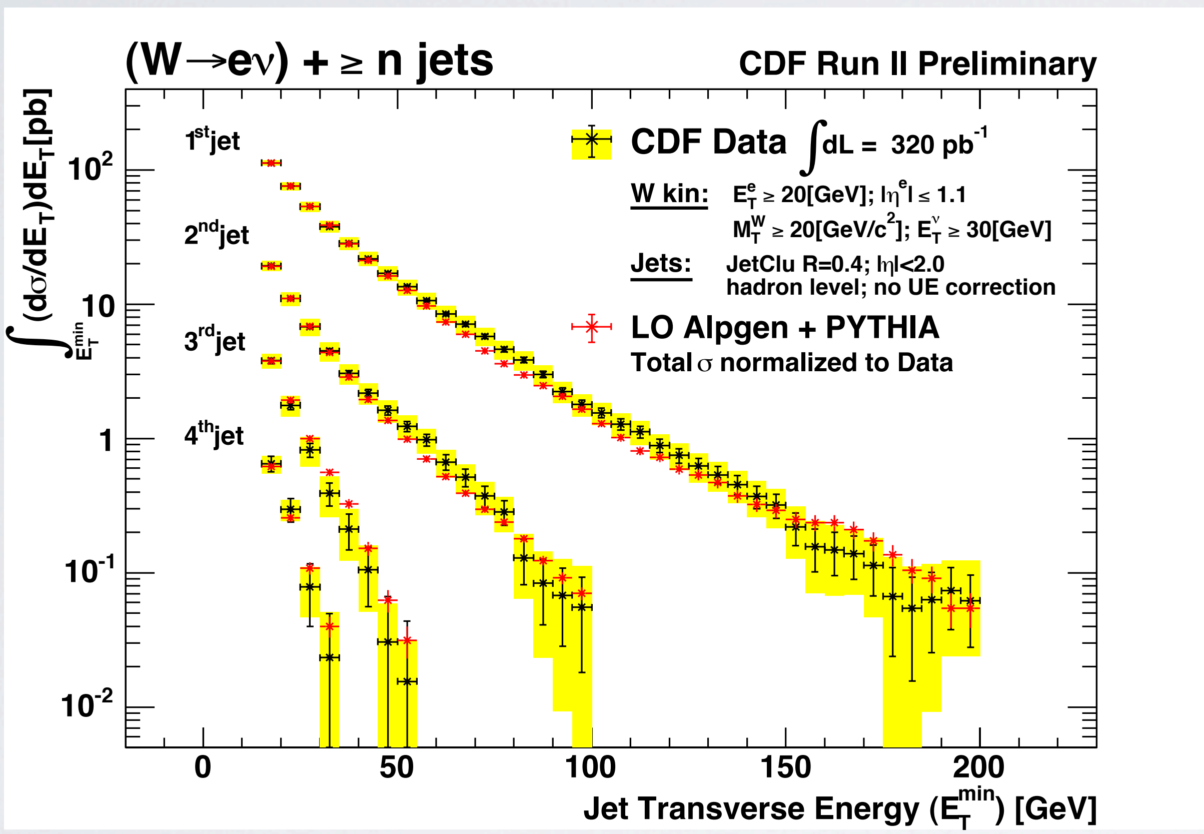
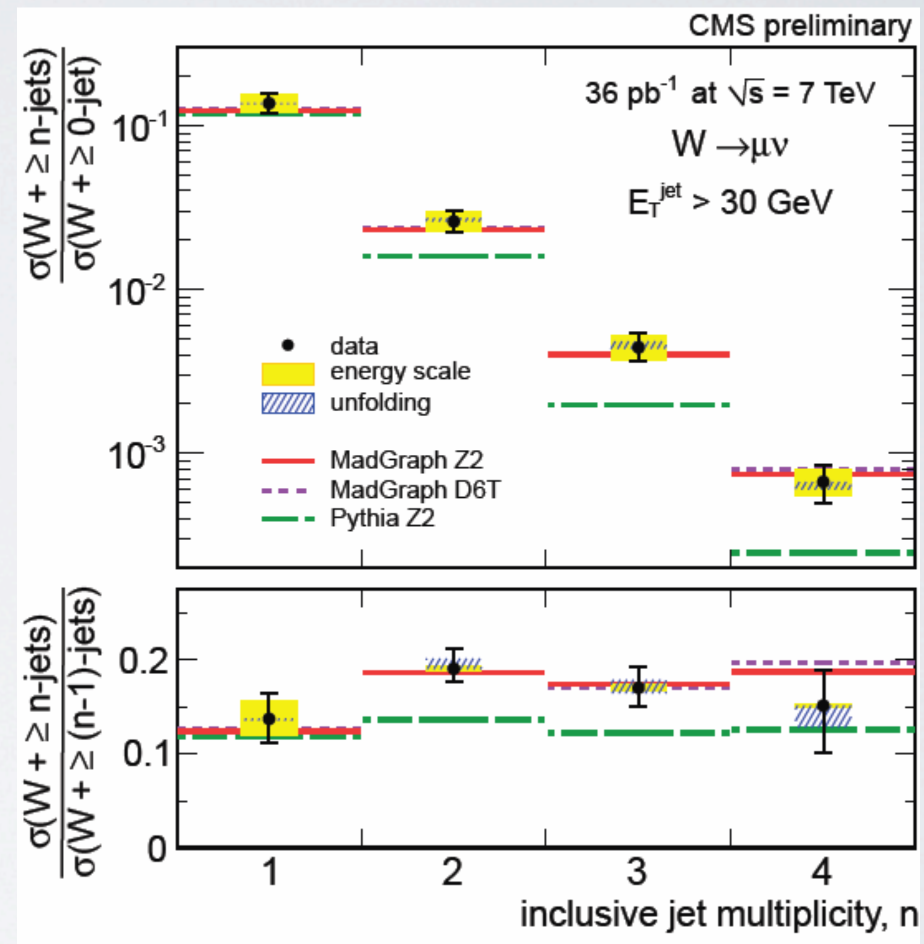




Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample.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

W+JETS FROM TEVATRON TO LHC





It works amazingly well!

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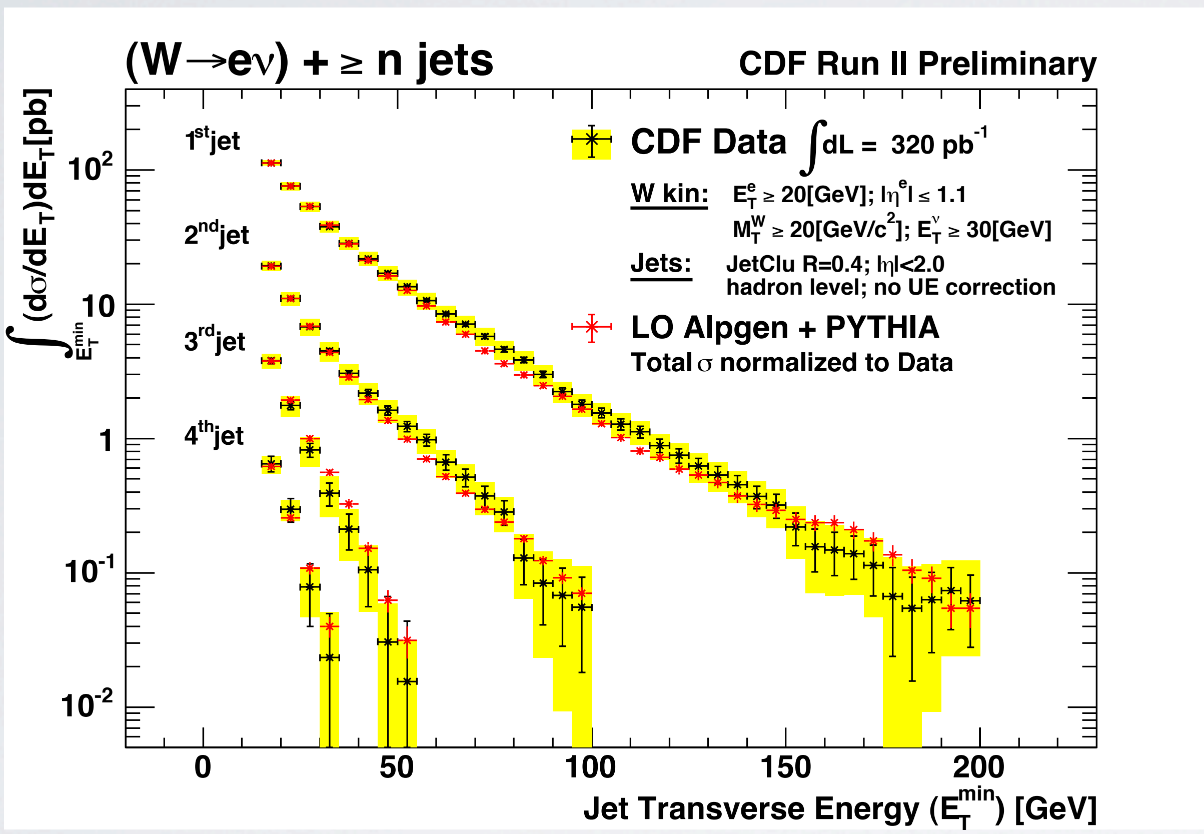

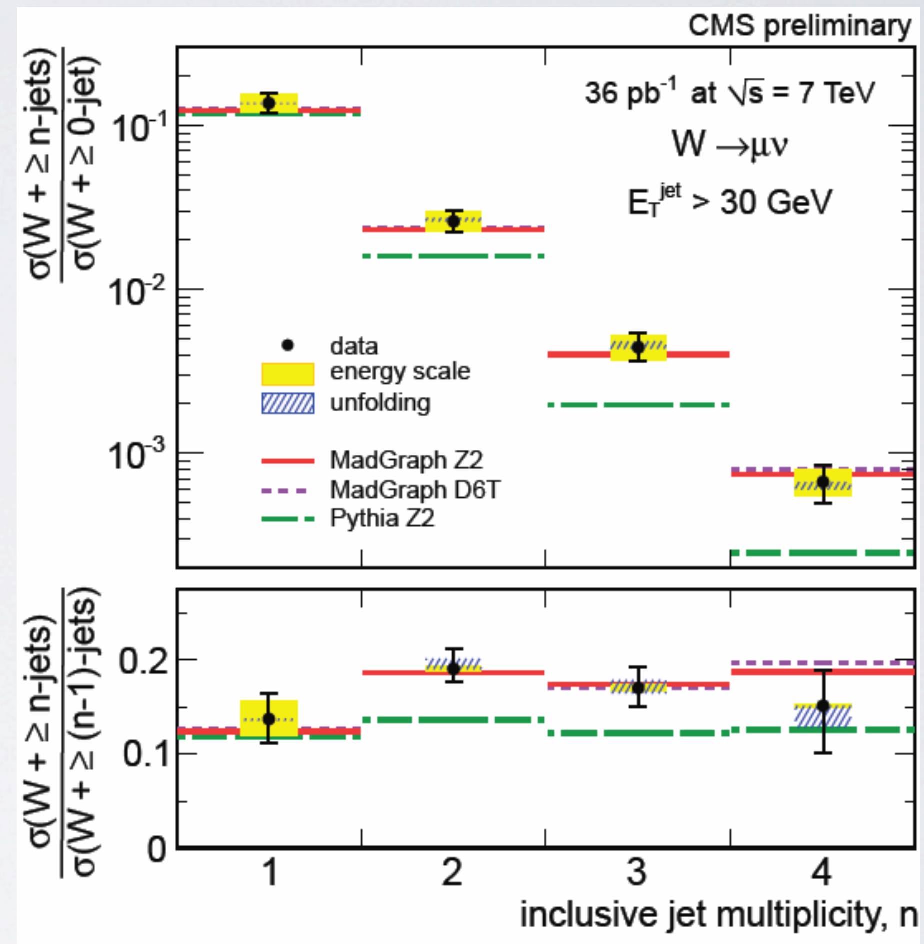

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Can we improve it further?

NLO with PS in a nutshell

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Full cross section at fixed Born kinematics

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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

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[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]

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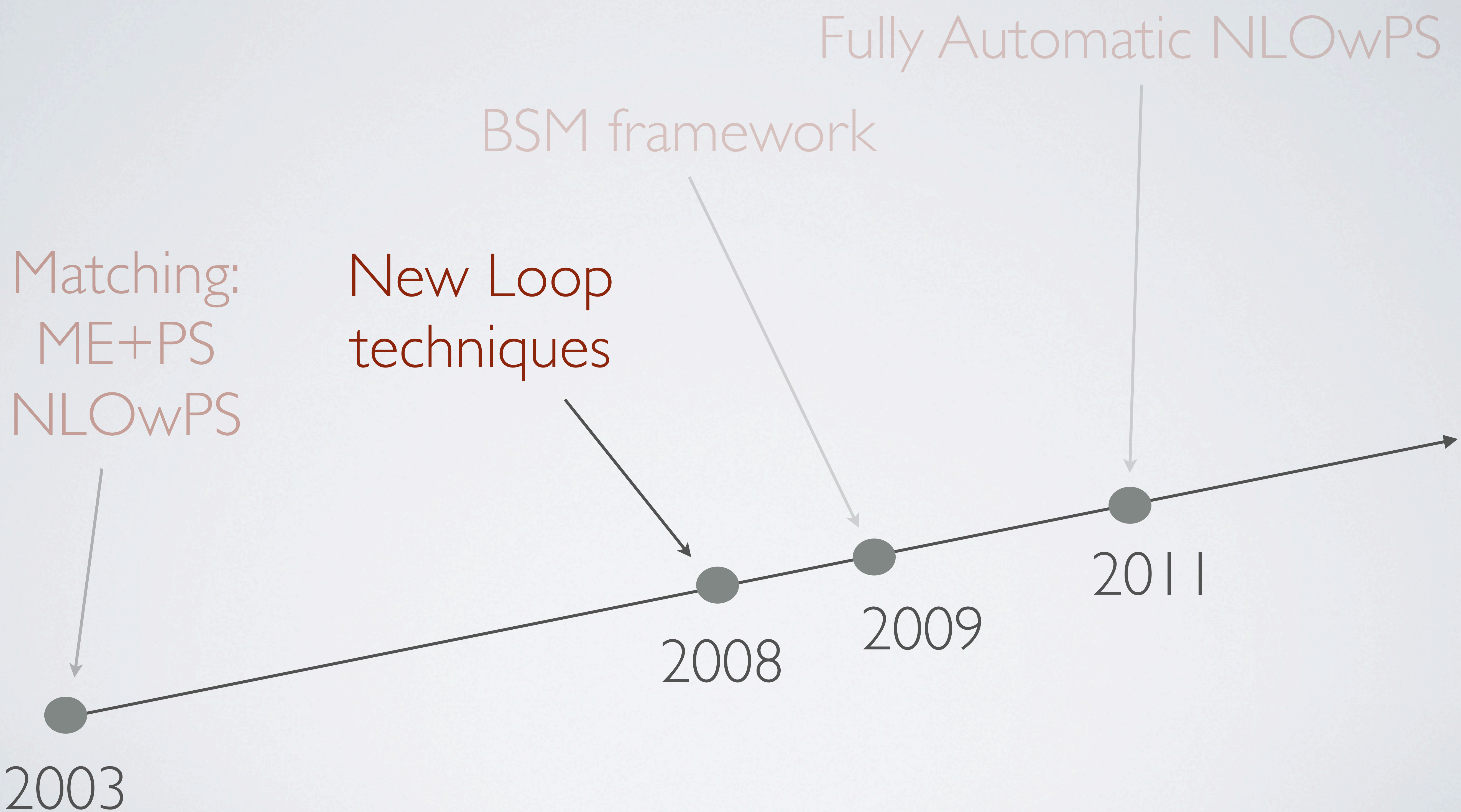
A thorough analysis of plus and cons in fact still to be done... see later.

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]

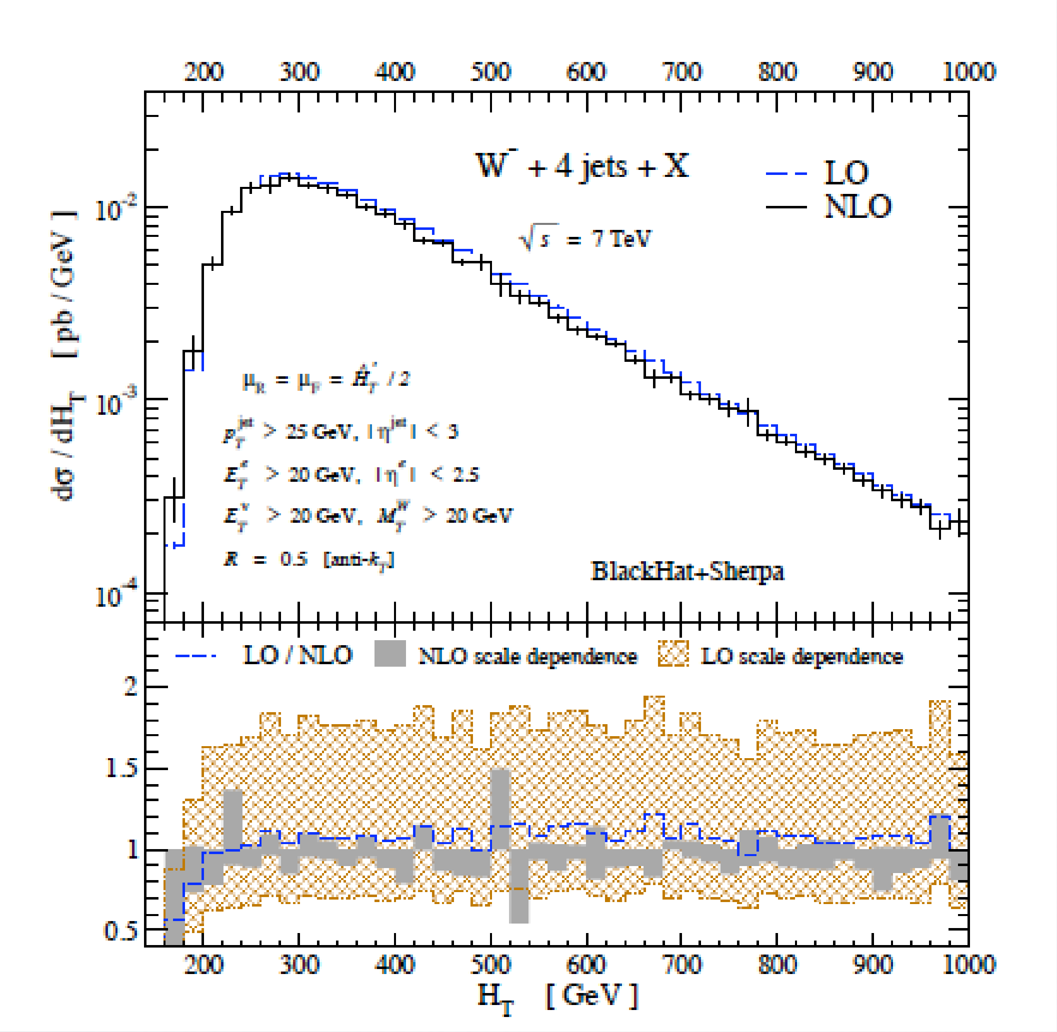
- Tensor Reduction (ex. Golem)

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

GUINNESS WR NLO CALCULATIONS

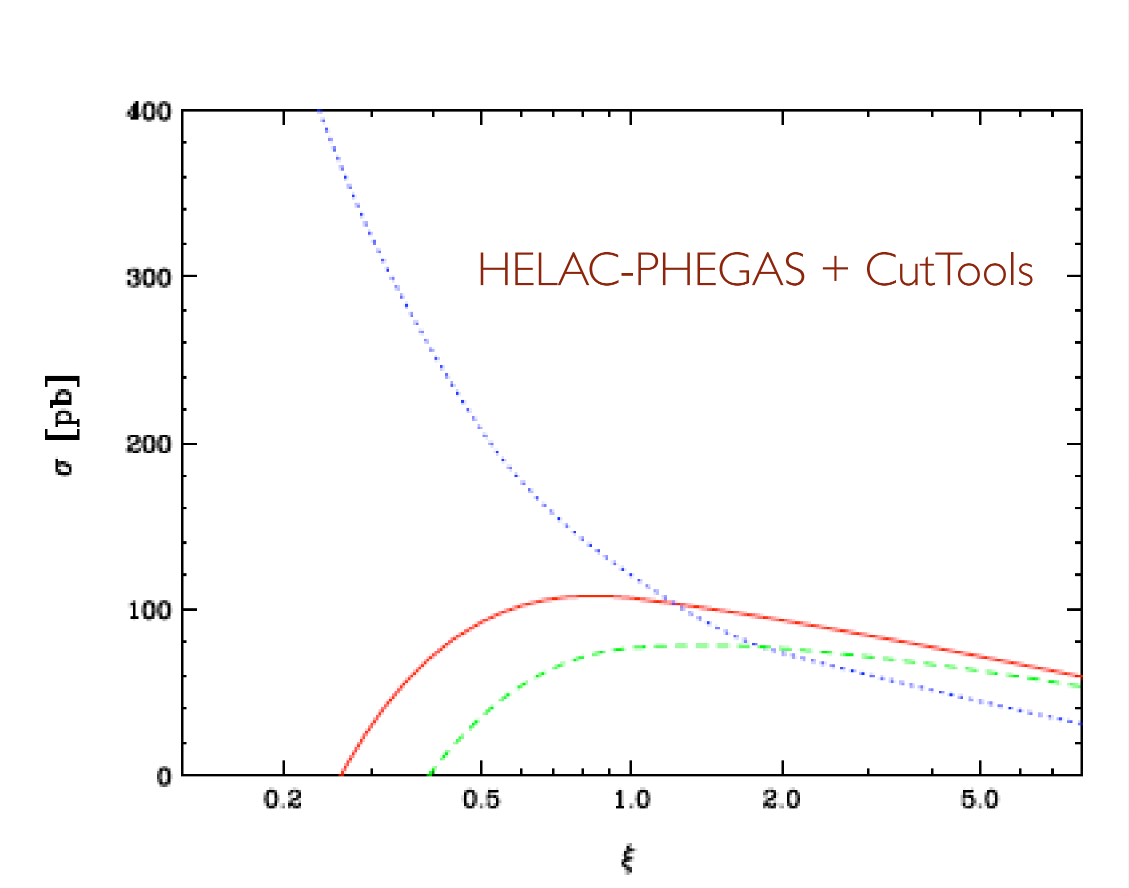
W+4 jets

[Berger et al., 1009.2338]



tt+2jets

[Bevilacqua et al., 1002.4009]



Both based on unitarity methods and recursive relations for trees.

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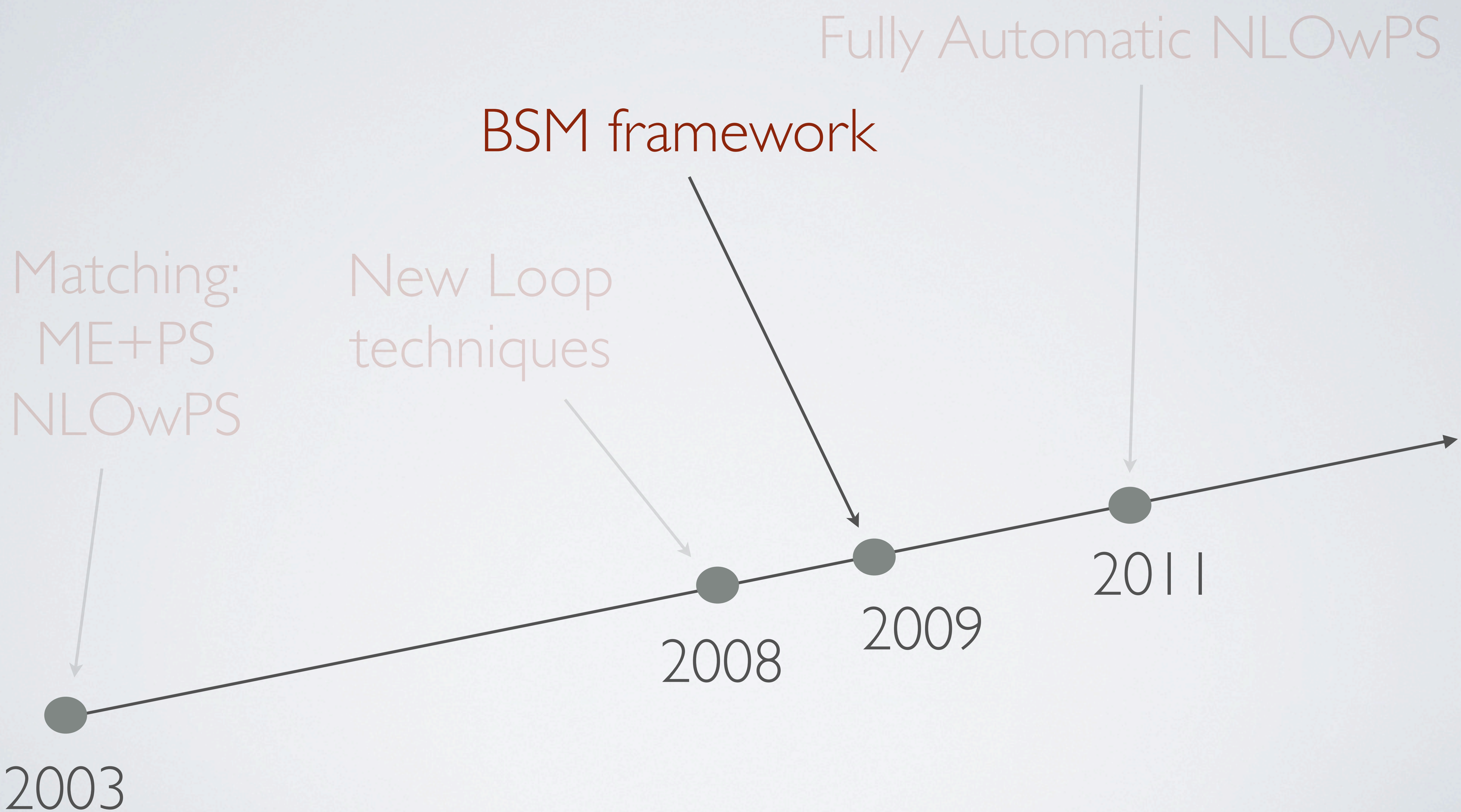

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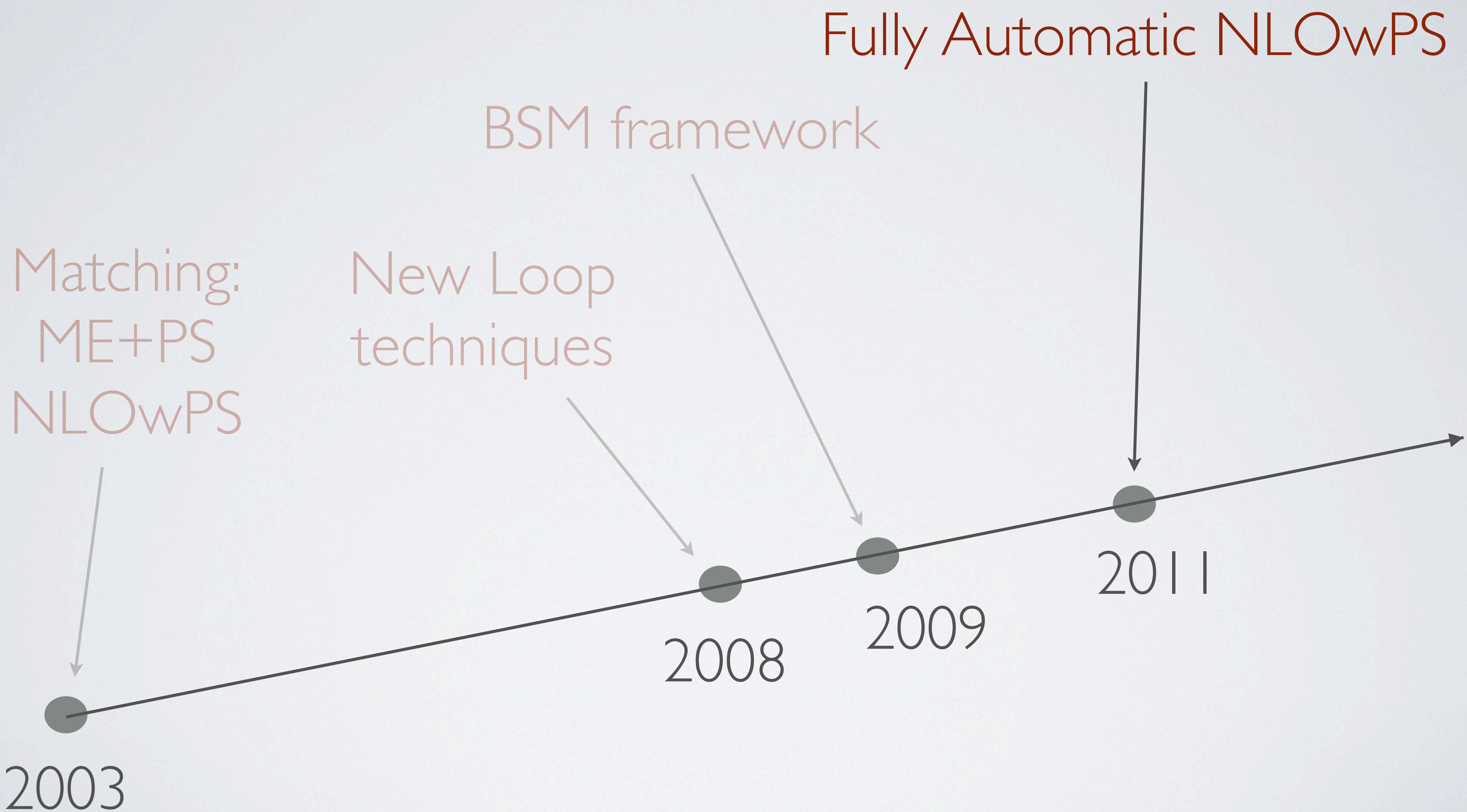

AUTOMATION

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- Cost saving

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

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- **Cost saving**

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- **Robustness**

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

- **Wide accessibility**

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

THE aMC@NLO JOINT VENTURE

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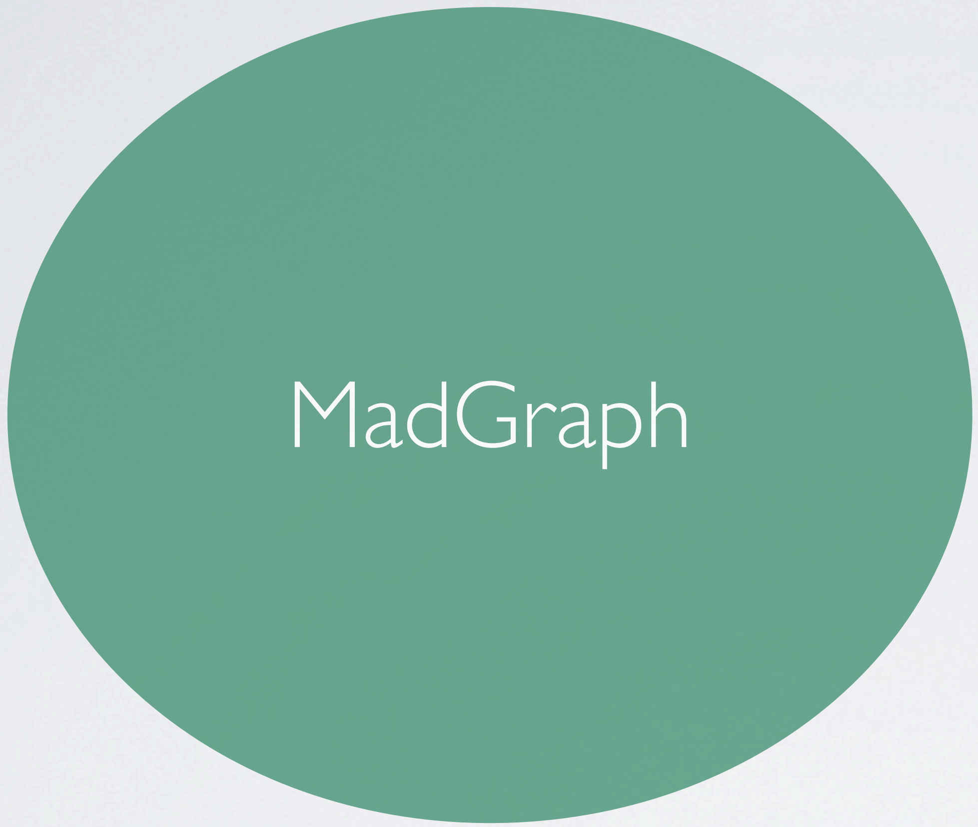

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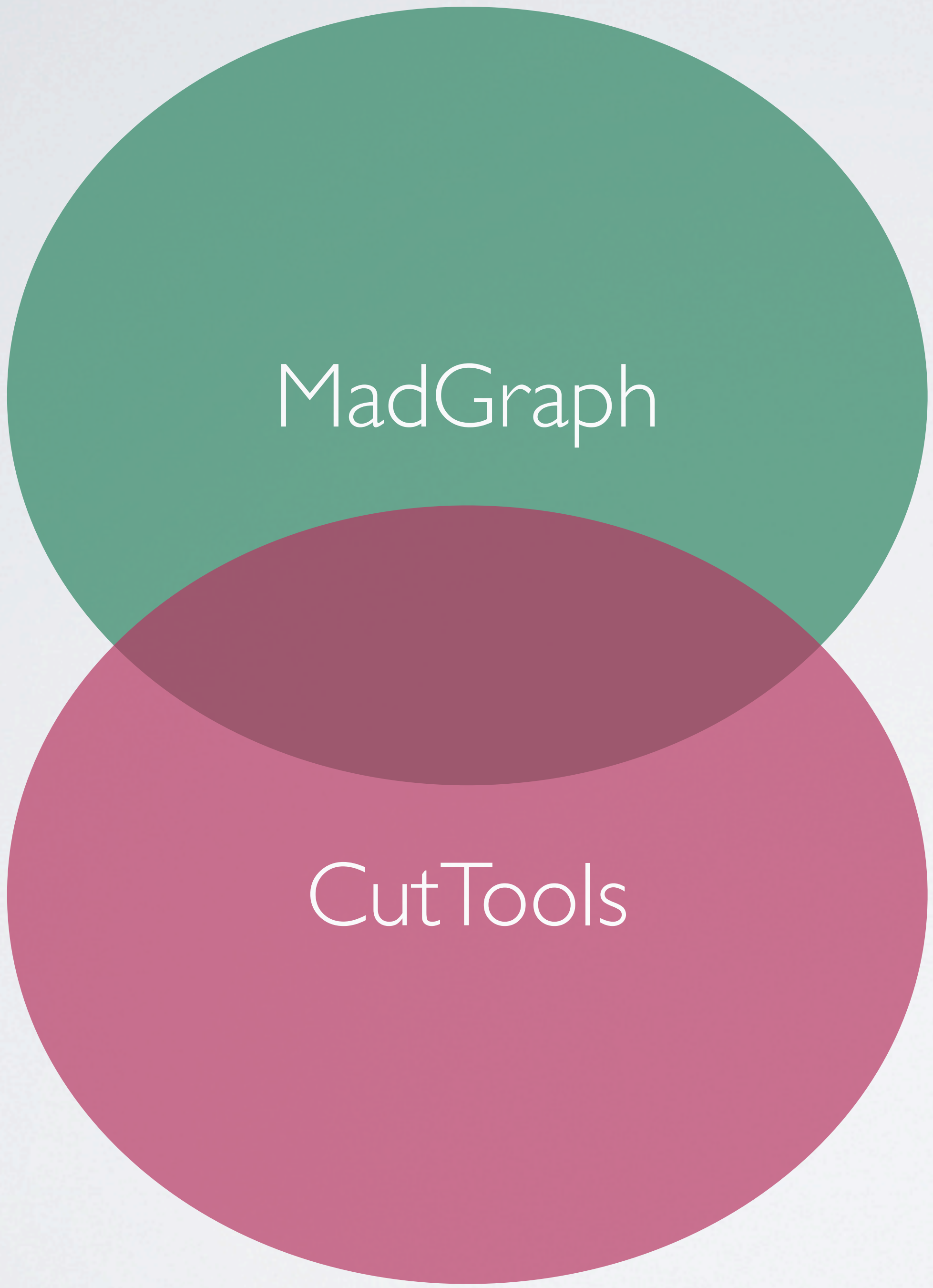

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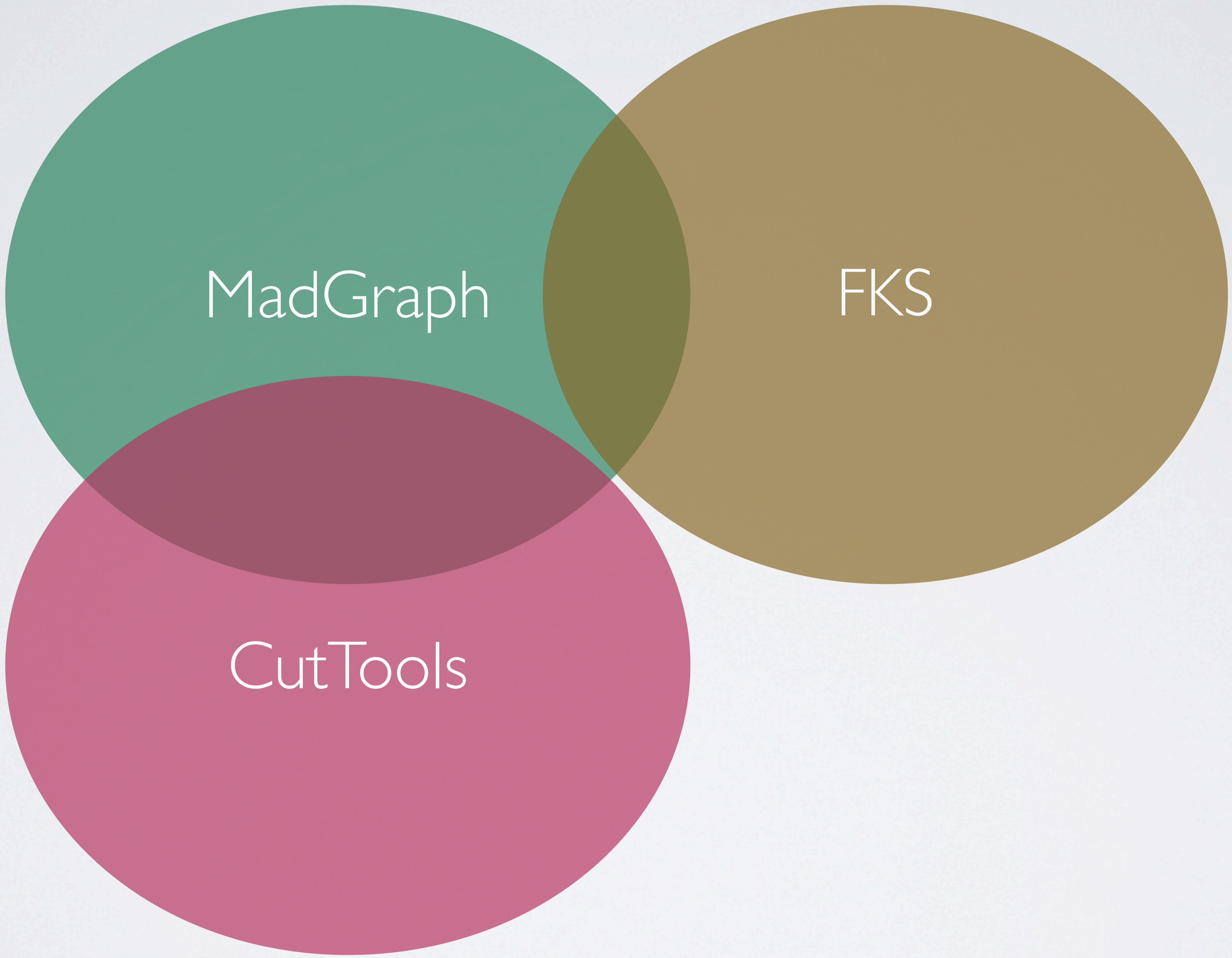

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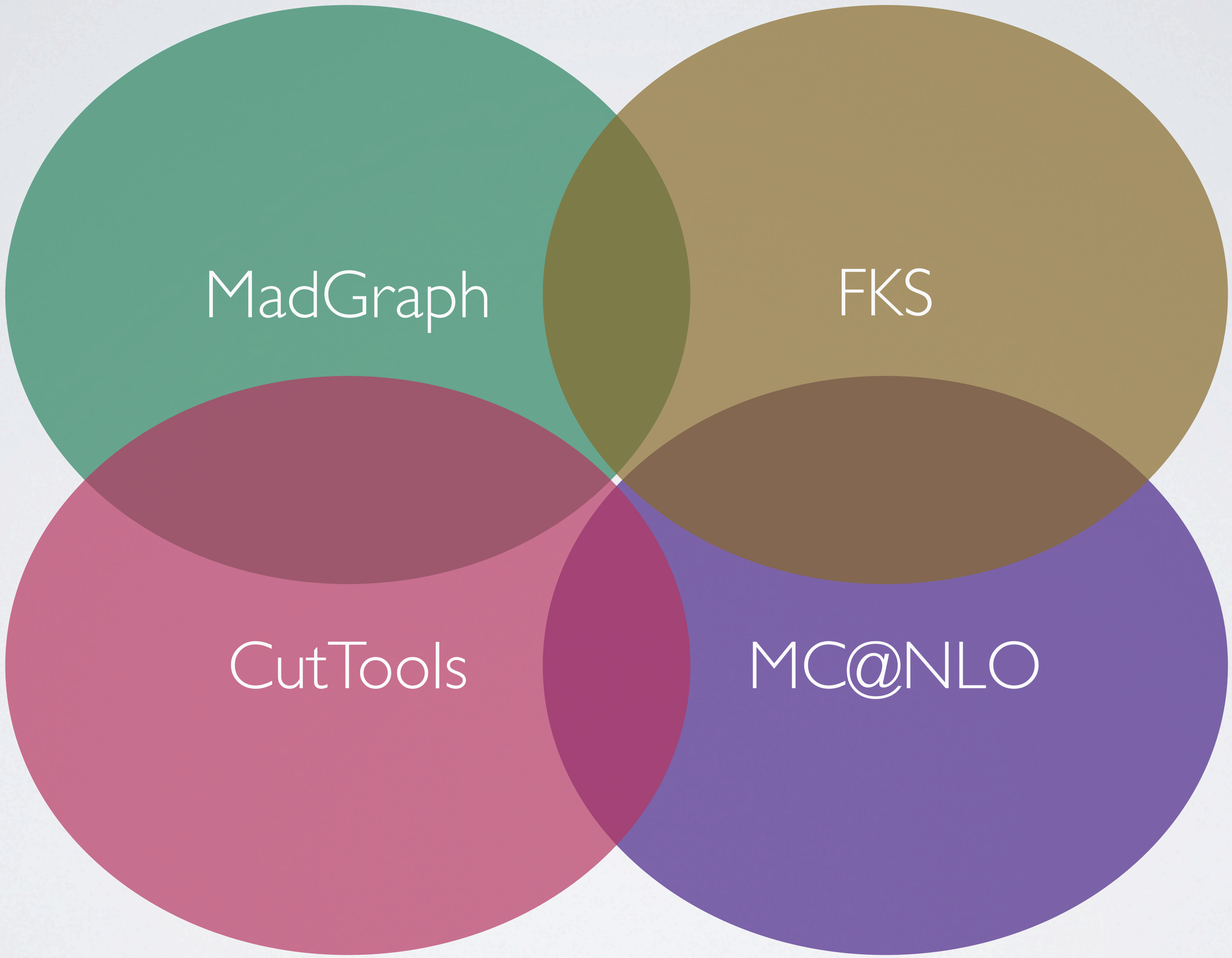

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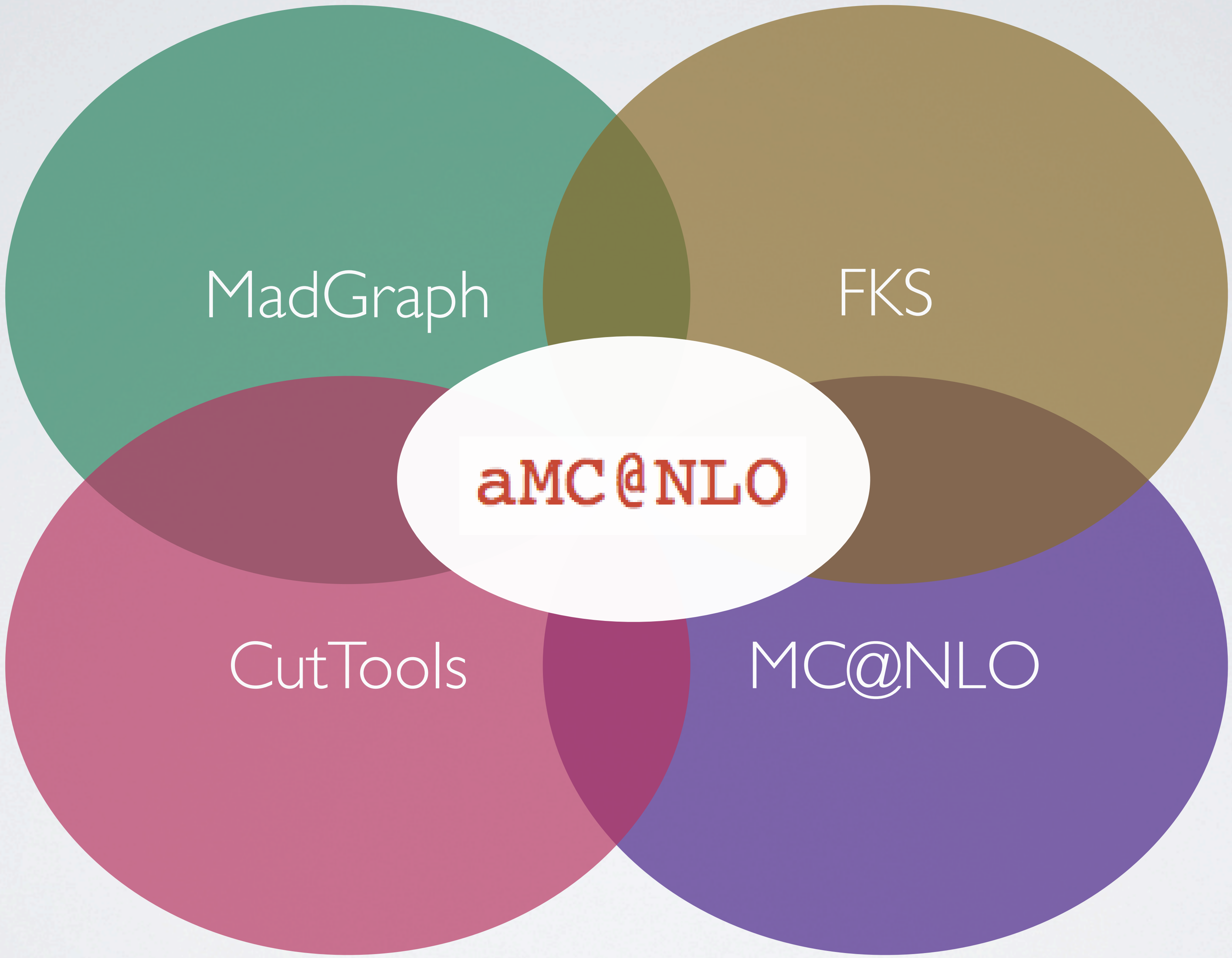

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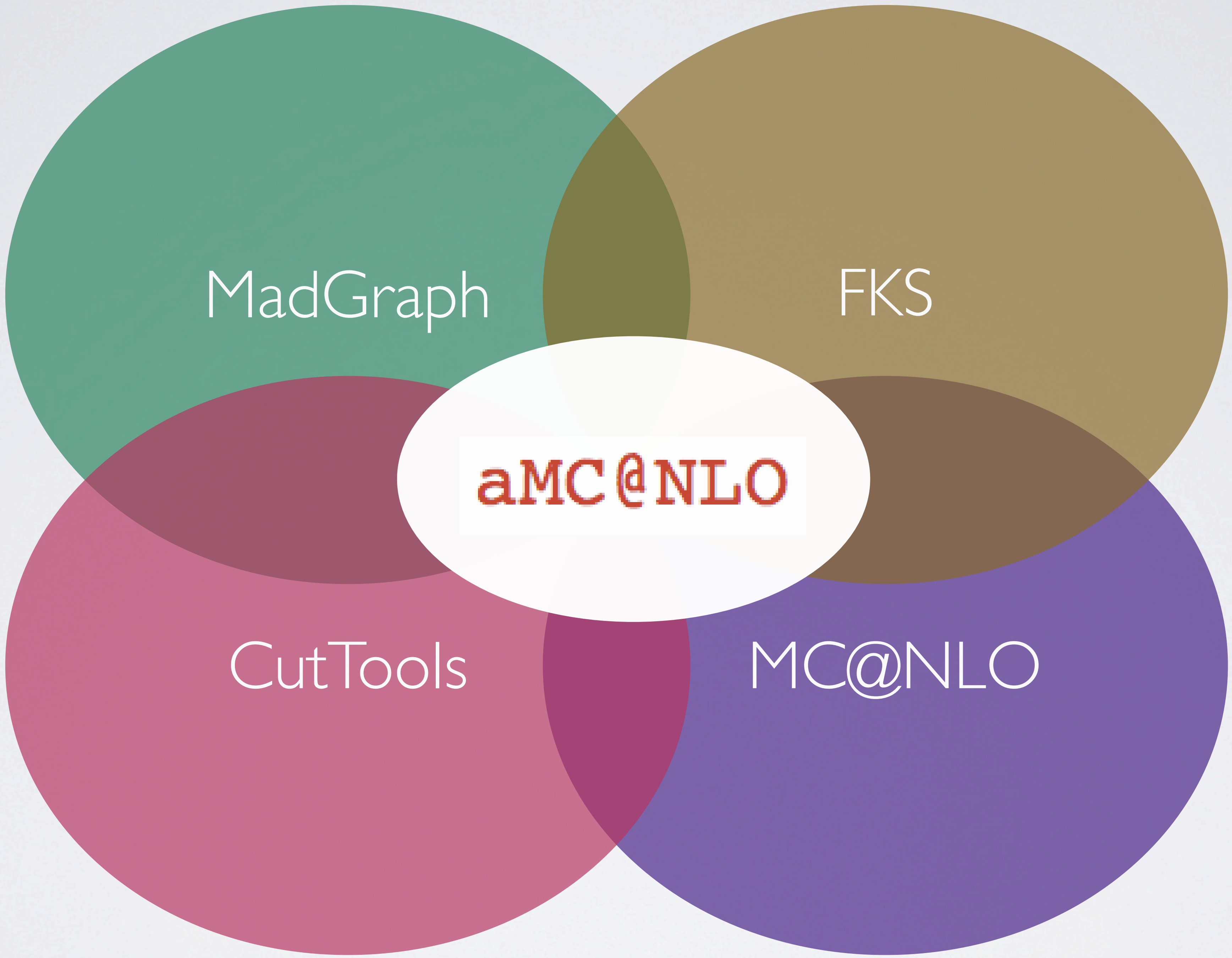


http://amcatnlo.cern.ch

AUTOMATIC NLO IN SM
MADFKS+MADLOOP+AMC@NLO

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

- Total sample 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)
- All processes can be in aMC@NLO...

	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 Prospects

- “99%” of the elements needed to calculate QCD corrections for SM processes are present. The missing bits are being 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. Codes for processes will follow and then meta code public in MadGraph 5.

APPLICATIONS TO HIGGS PHYSICS

1. GLUON-GLUON FUSION: PP→H+X
2. VBF : PP→HJJ
3. VH : PP→HZ/HW
4. TTH : PP→HTT

Based on:
NLO MC, by M. Felcini, F. Maltoni, P. Nason, J. Yu
Report of the LHC Higgs Cross Section Working Group, Arxiv:1101.0593
+UPDATES

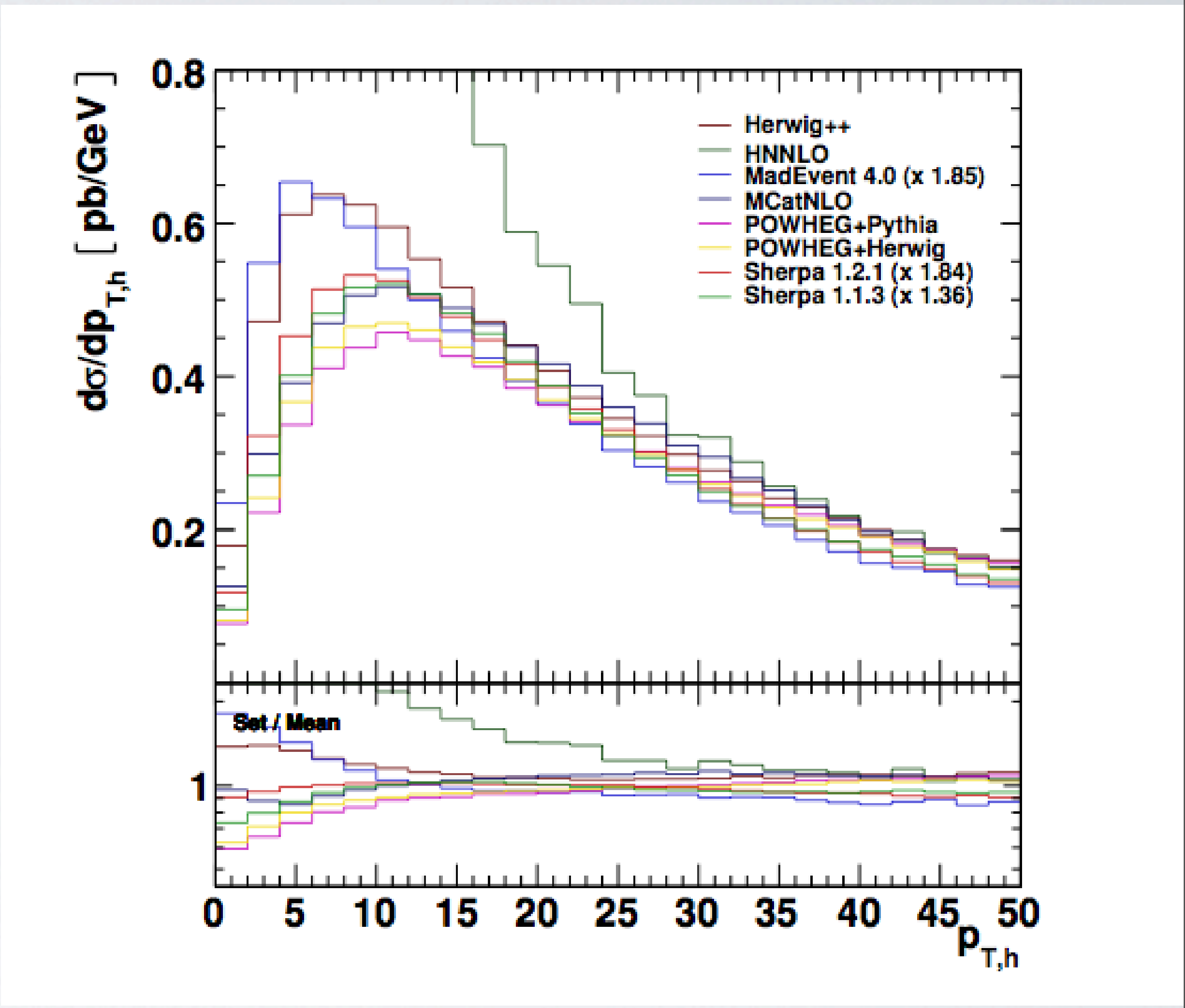
PP→H+X

SIGNAL:

Available in NLOwPS implementations in the EFT:

- (a)MC@NLO [Frixione et al. 0805.4802]
- POWHEG Box [Aioli et al, 0805.4802]
- HERWIG++ (POWHEG)[Hamilton et al. 0903.4345]
- SHERPA (POWHEG)[Hoeche et al, 1008.5399]

Available also in the EFT MEwPS [MadGraph, SHERPA]

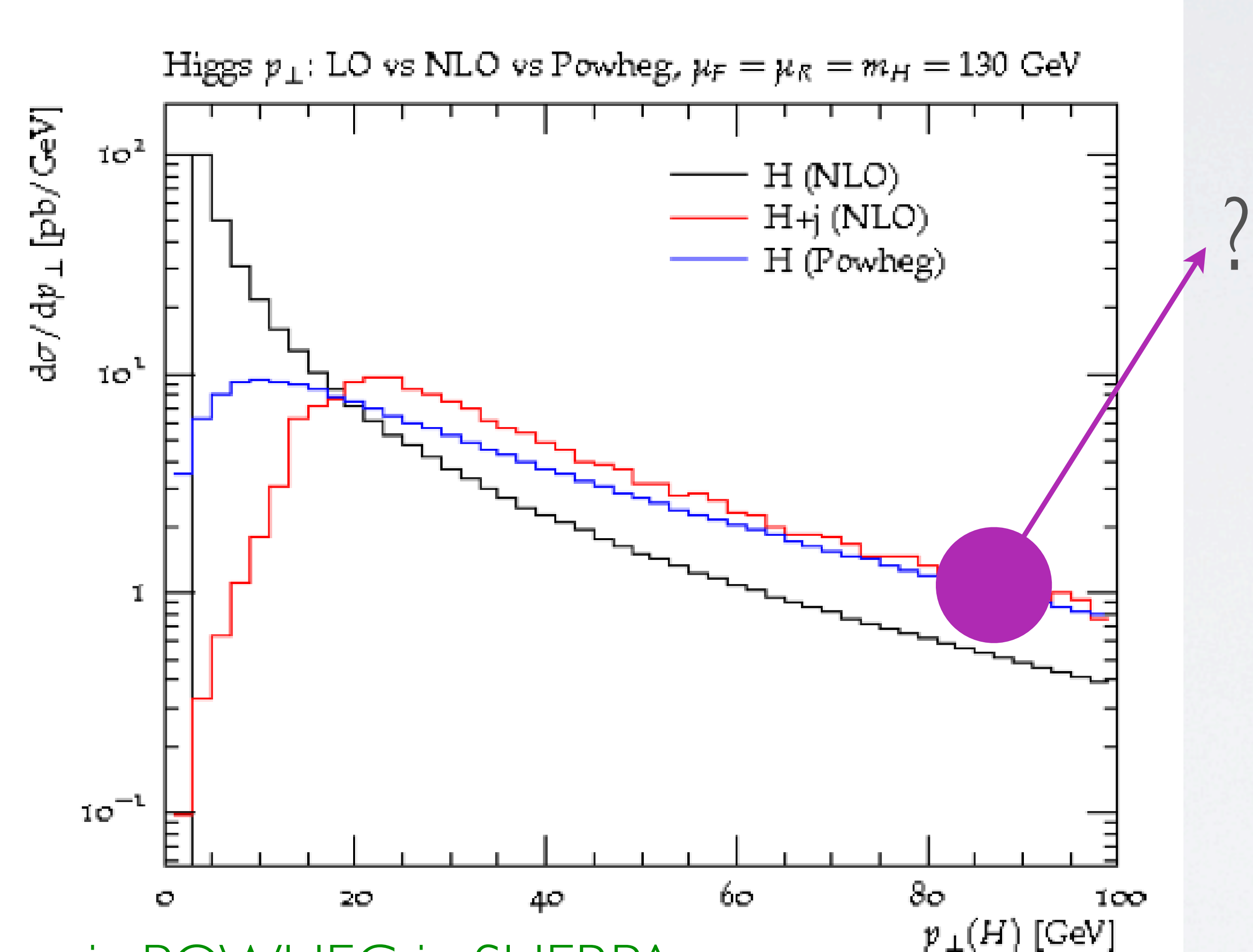


[Butterworth, Les Houches 2009]

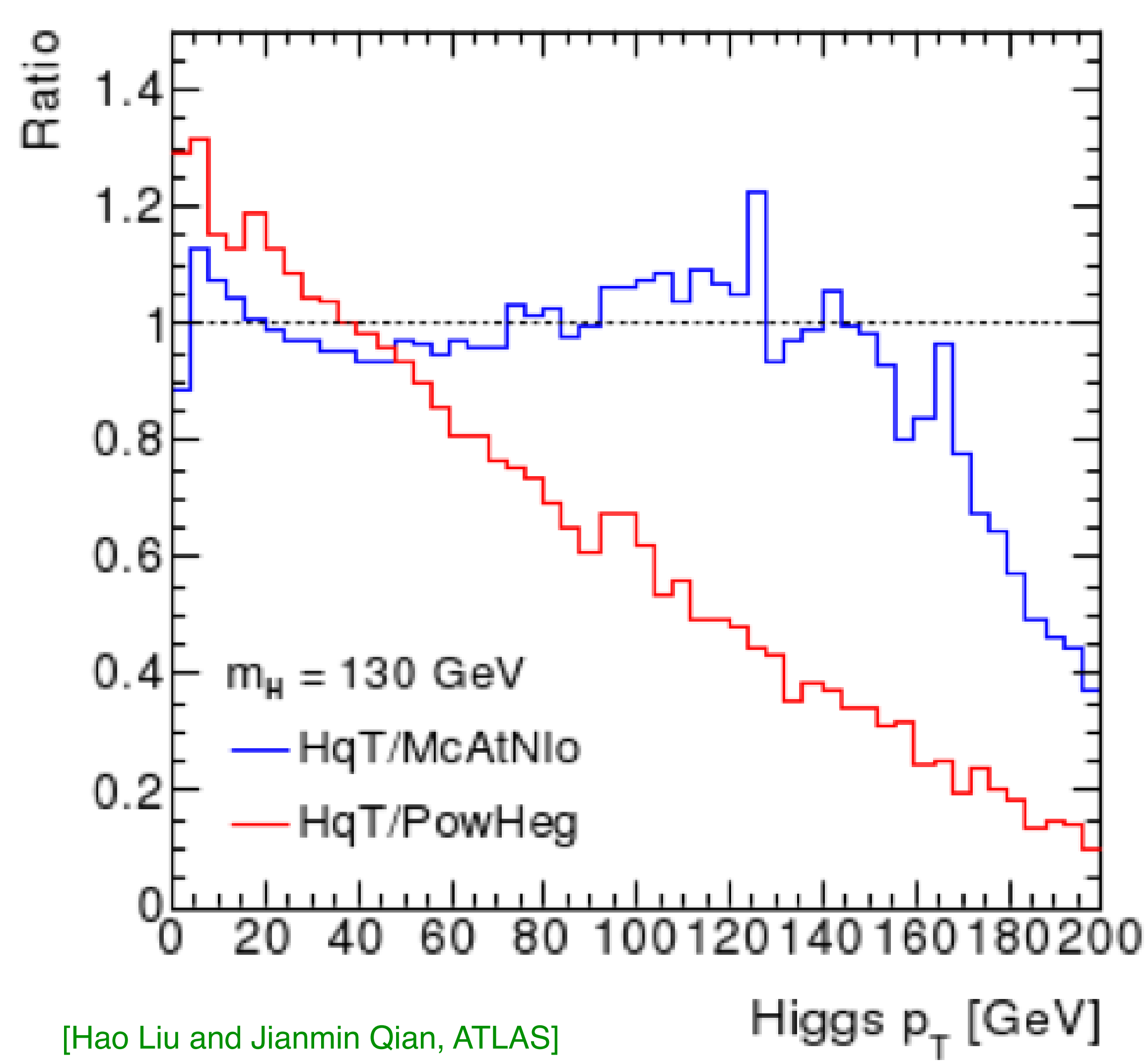
COMMENTS ON THE SIGNAL:

-pp → H + 1,2 jets not available jet in NLOwPS!!!
-Heavy-quark loop effects
-BSM production not available yet.
-Missing: interference between signal and backgrounds in MC's.

pp→H+X : DISCUSSION



via POWHEG in SHERPA



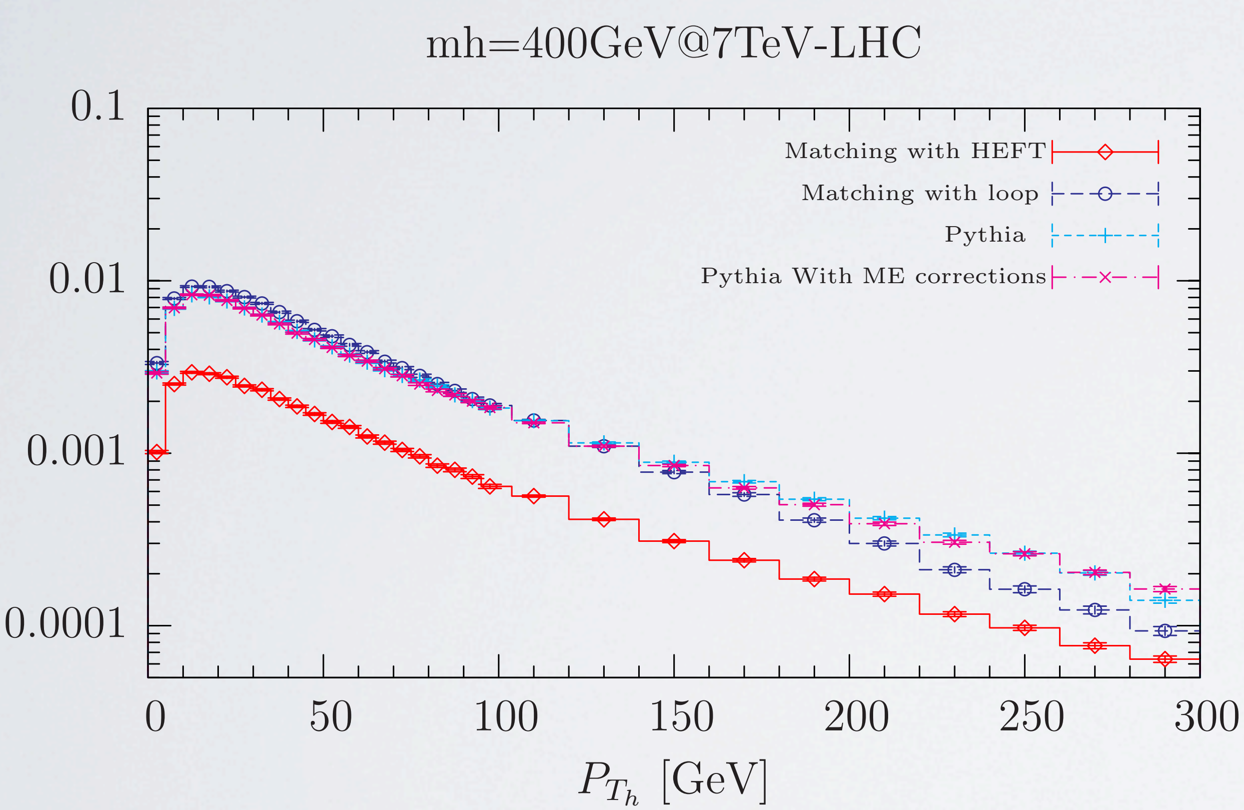
"Artificial" enhancement at large pt :
By chance on the NLO result for this observable.

Well known agreement between MC@NLO +HERWIG and the resummed result. Not quite for POWHEG.

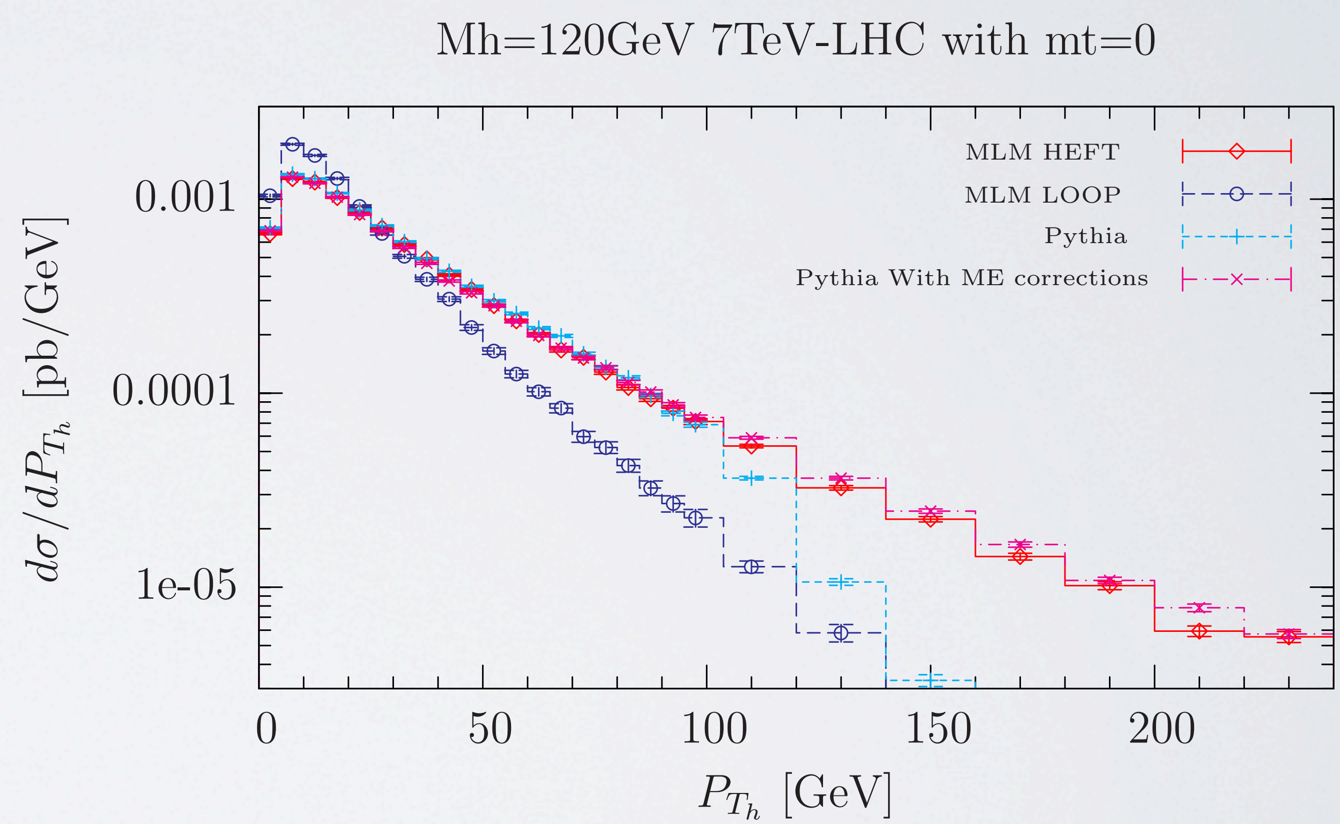
pp→H+jets via MEwPS with heavy-quark loop effects

[Alwall, Li, FM, to appear]

Events are generated in the EFT and reweighted by the analytic (but slow) loop matrix elements.
Very efficient event generation achieved.



SM, m_H=400 GeV



SUSY (~large tan(beta)) m_H=120 GeV

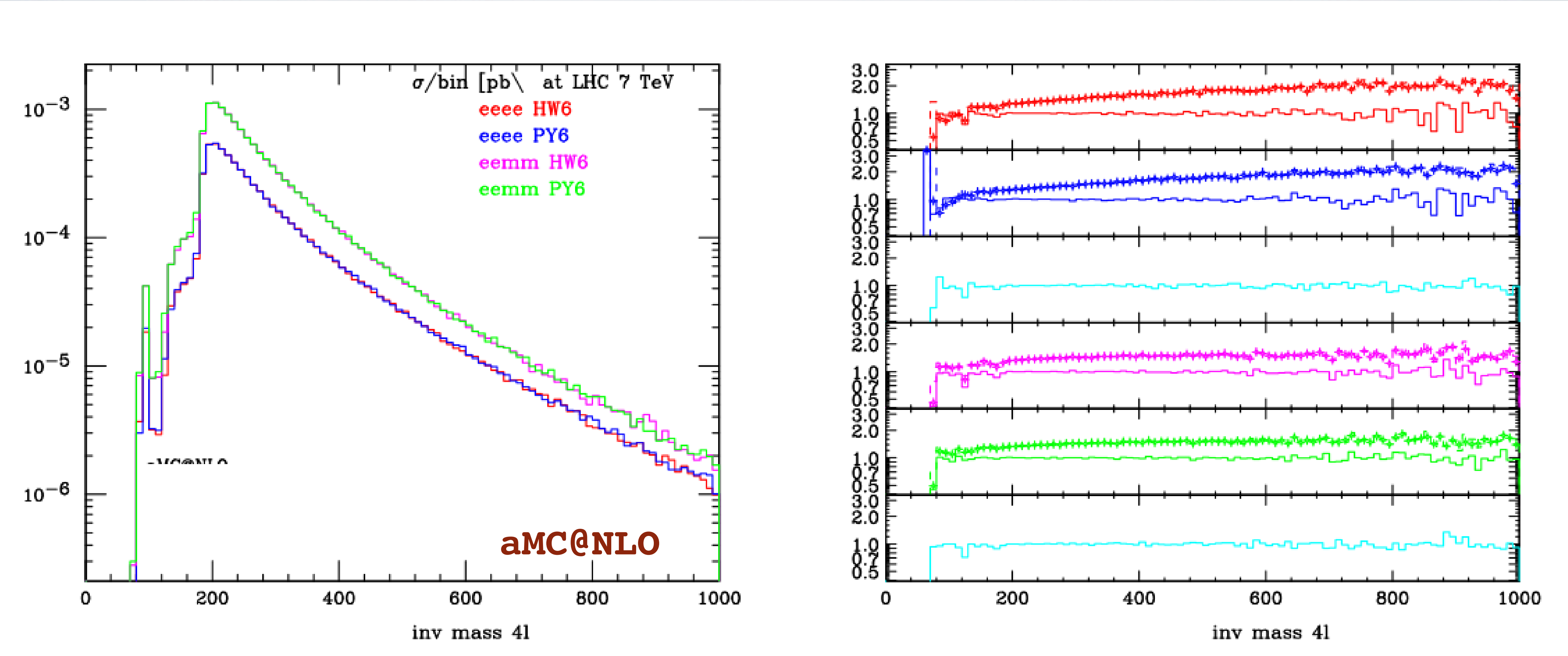
pp→H+X : Backgrounds

Almost everything is a background to Higgs in gluon-gluon fusion, depending of course on the decay channels. Let me consider the basics and the most obvious ones.

- H→ γγ : Available in HERWIG++ via POWHEG [D'Errico et al., 1106.3939] . gg at NLO channel not available. Soon possible the comparison with [Catani et al., 11xx.xxxx].
- H→WW, ZZ : WW,ZZ,WZ in MC@NLO since long time. WW,ZZ also available in HERWIG++. Now in the POWHEG-Box [Melia et al., 1107.5051]. Ready in aMC@NLO. Gluon channels from gg2WW and gg2ZZ [Kauer et al., 0807.0024,hep/ph/0611170]
- WW+1jet, ZZ+1jet and tt+1jet possible but not available yet.

PP→ZZ→4L

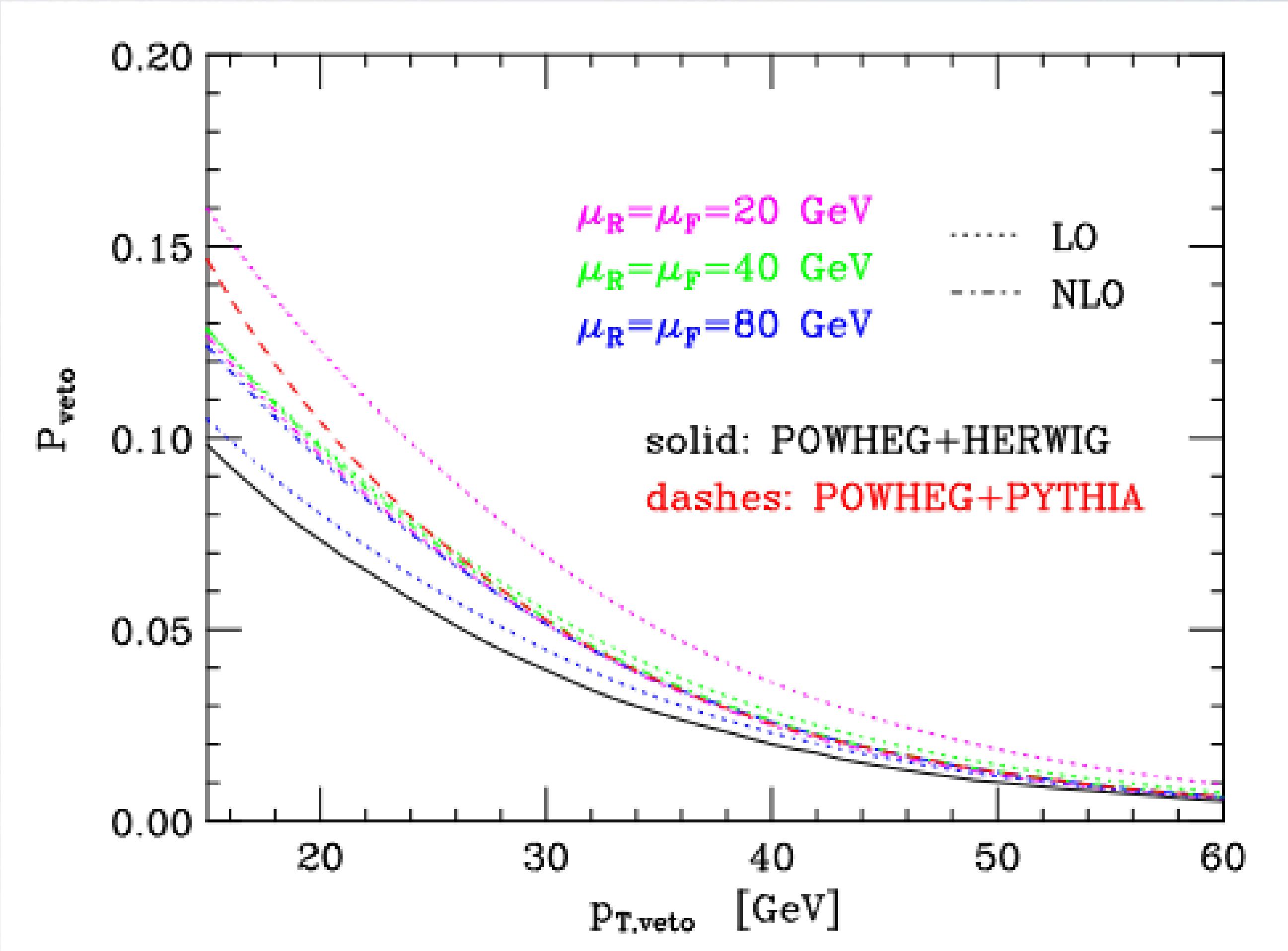
NLO calculation includes γ^*/Z interference, full spin correlations and interferences and single resonant diagrams. Interfaced to Pythia and HERWIG. Extremely stable predictions.



(Also available in POWHEG-box now together with ZW, WW. No gg channel.) [Melia et al, 1107.5051]

PP→HJJ (VBF)

SIGNAL:
Available in the POWHEG-BOX
[Nason, Oleari, 0911.5299]

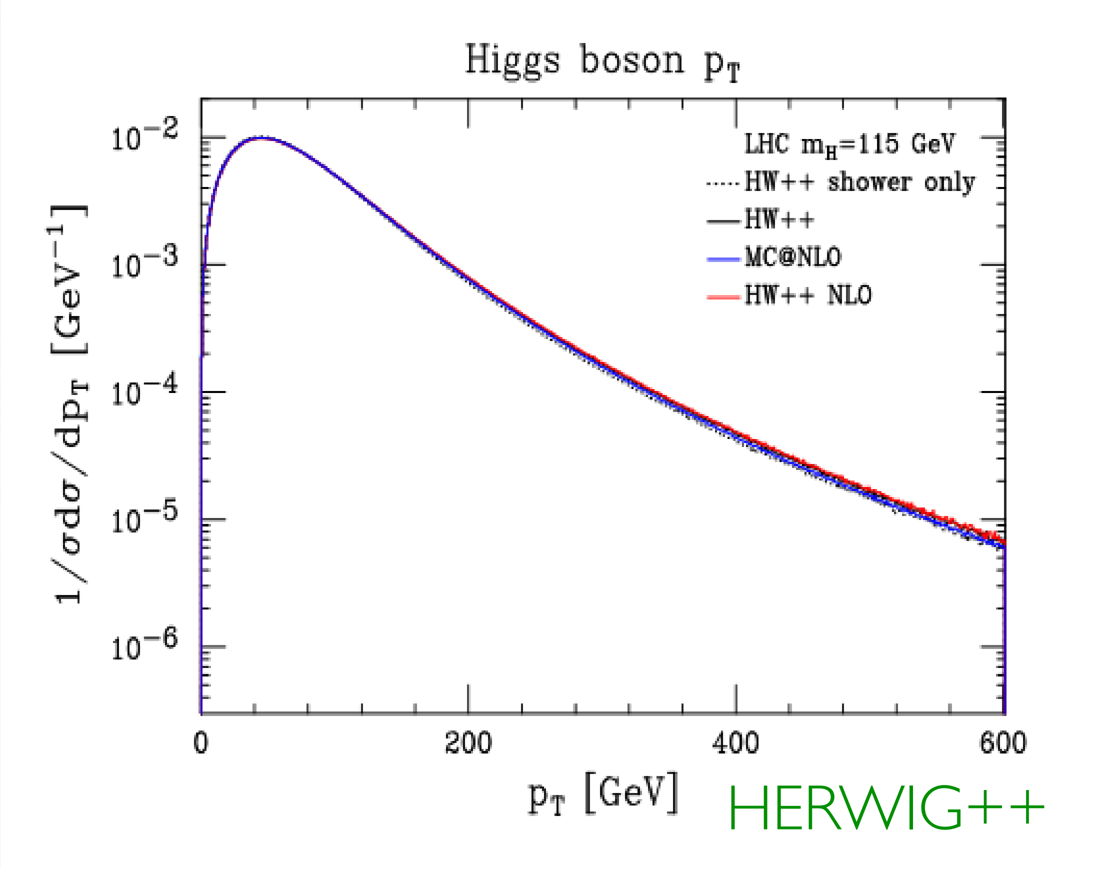


BACKGROUNDS:
NONE available at NLOwPS yet.

COMMENTS:
NLO for several "VBF" background processes known (see for instance VBF@NLO [Zeppenfeld et al.]) but not yet at NLOwPS. QCD backgrounds not available either. pp→Hjjj might be important. NLO EW corrections are known and could be included. For measurements also pp→Hjj via gluon-fusion might be relevant.

pp→ZH/WH

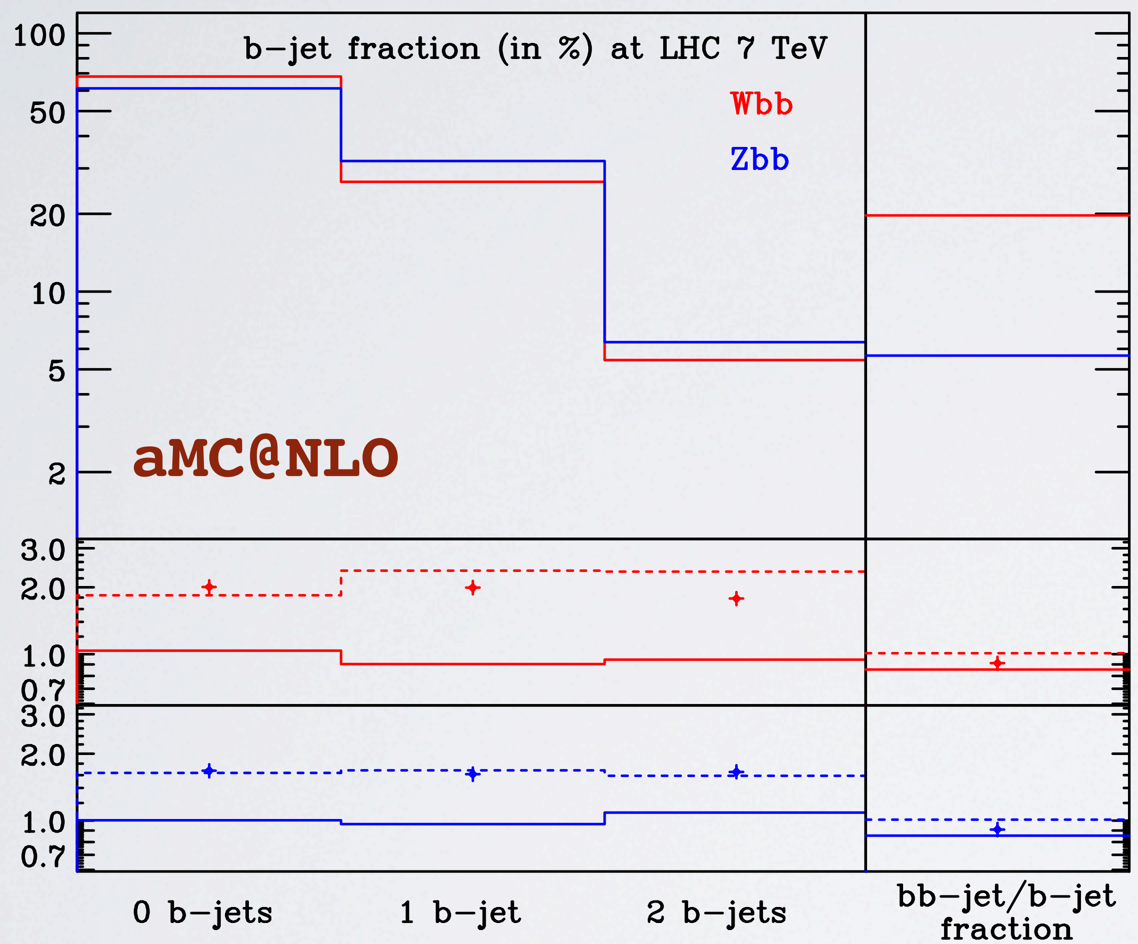
SIGNAL:
Available in
HERWIG++ (POWHEG),
POWHEG-BOX,
MC@NLO (and aMC@NLO).

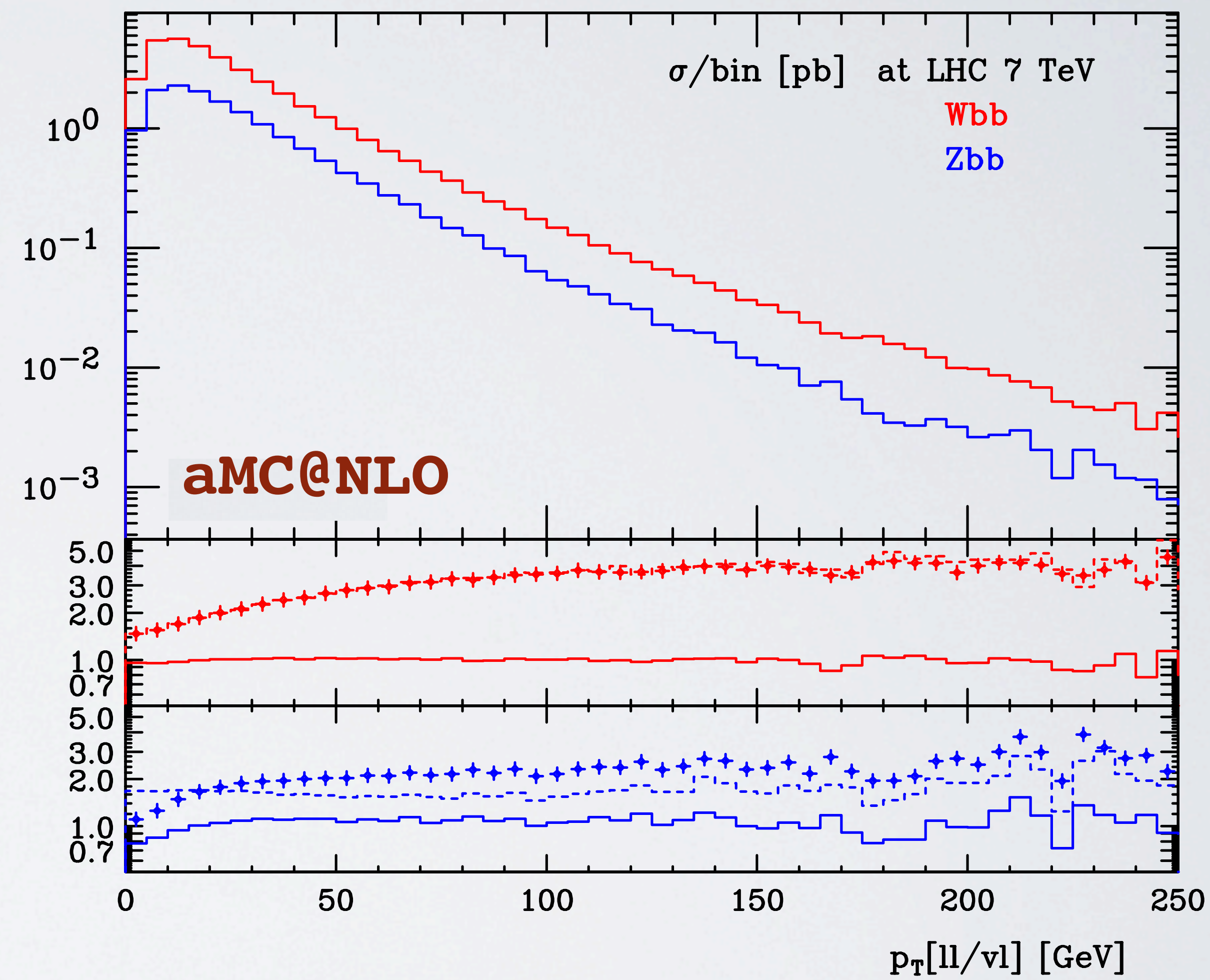


BACKGROUNDS:
pp→Wbb
available in POWHEG [Oleari, Reina, 1105.4488]
and aMC@NLO [Frederix et al, 1106.6019]
pp→Zbb available in aMC@NLO
[Frederix et al. 1106.6019]
pp→Wjj done in aMC@NLO, soon to be available
pp→Zjj not yet available.

COMMENTS:
Now available at NNLO [Ferrera, Grazzini, Tramontano, 1107.1164]: it would be interesting to make comparisons. Inclusion of EW corrections? This process seems in pretty good shape.

pp→Zbb/Wbb via aMC@NLO



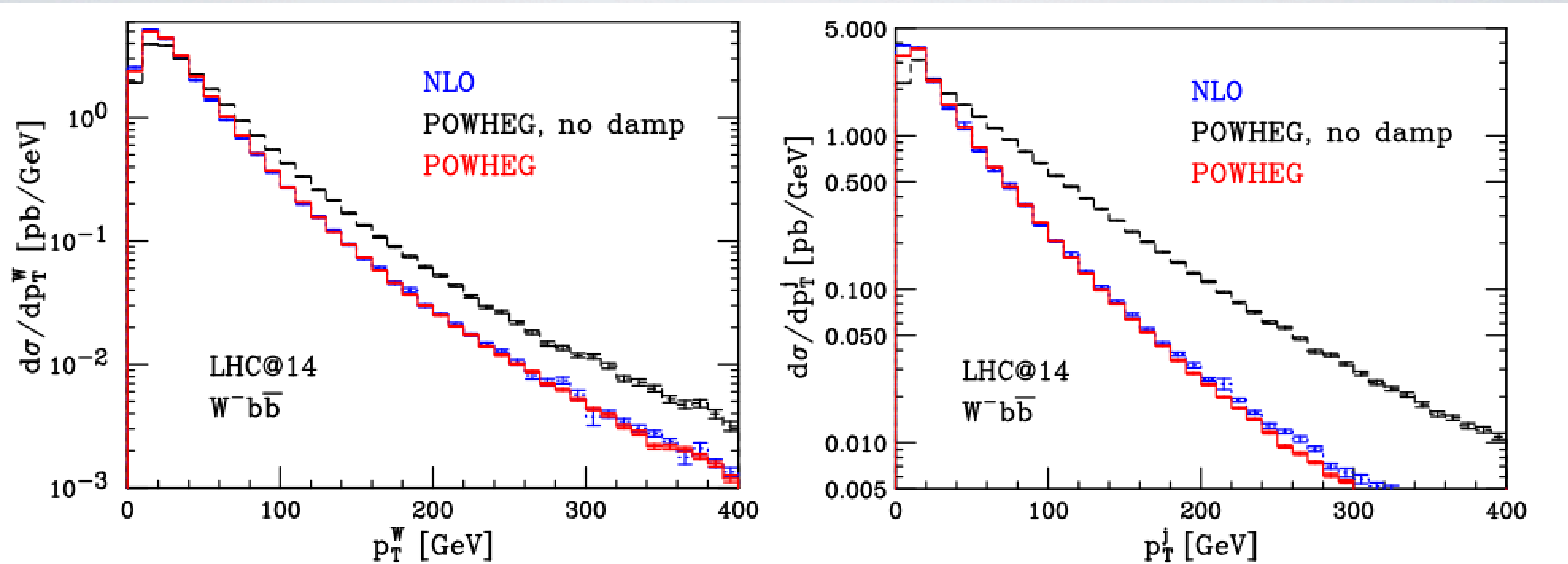


b-jet and bb-jet rates in the 4F scheme

NLO and NLOwPS very similar and consistent.

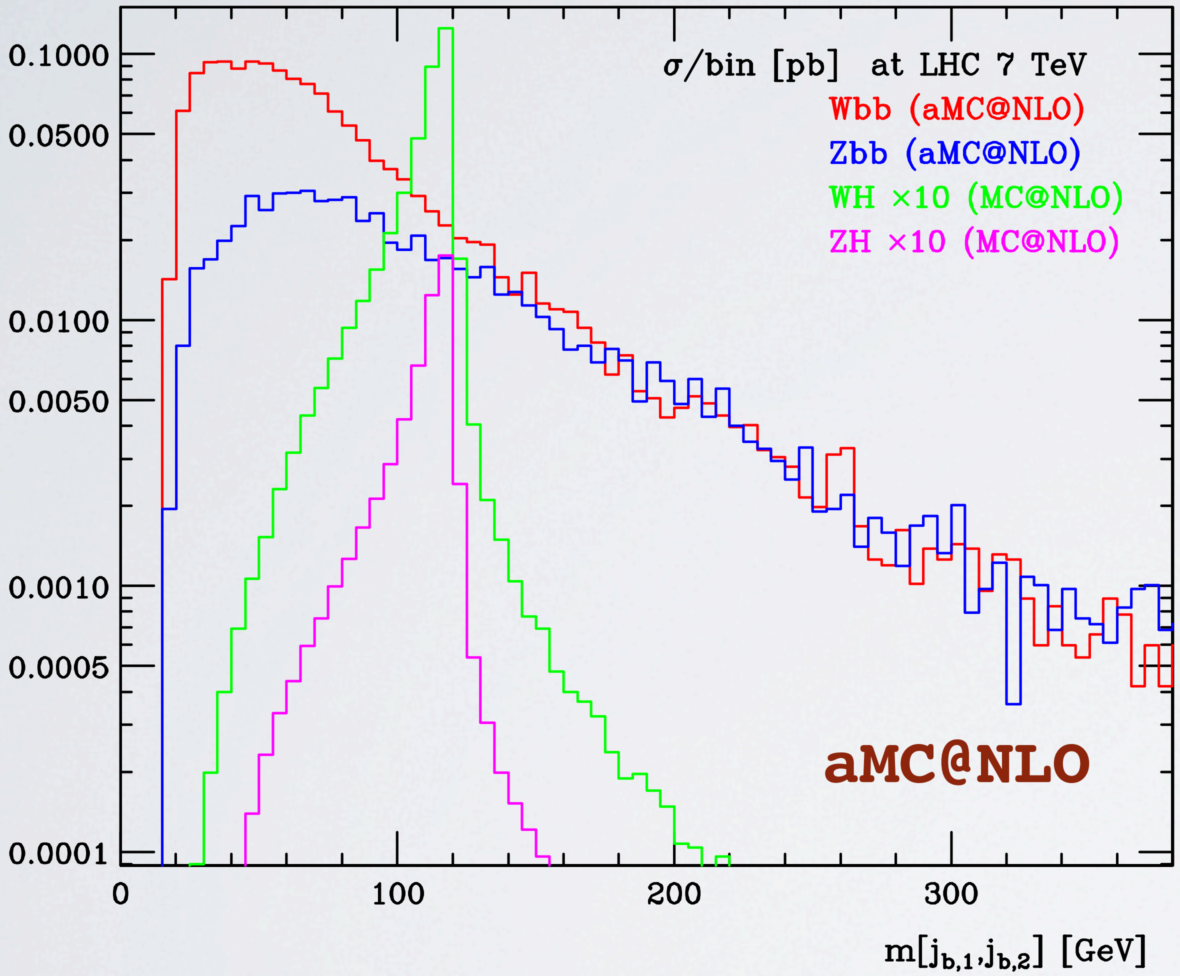
pp→Wbb via POWHEG

[Oleari, Reina, 1105.4488]



Perturbative tuning necessary in this case. Similar effect in the pt of H production, but more serious as ptW is a NLO observable in Wbb

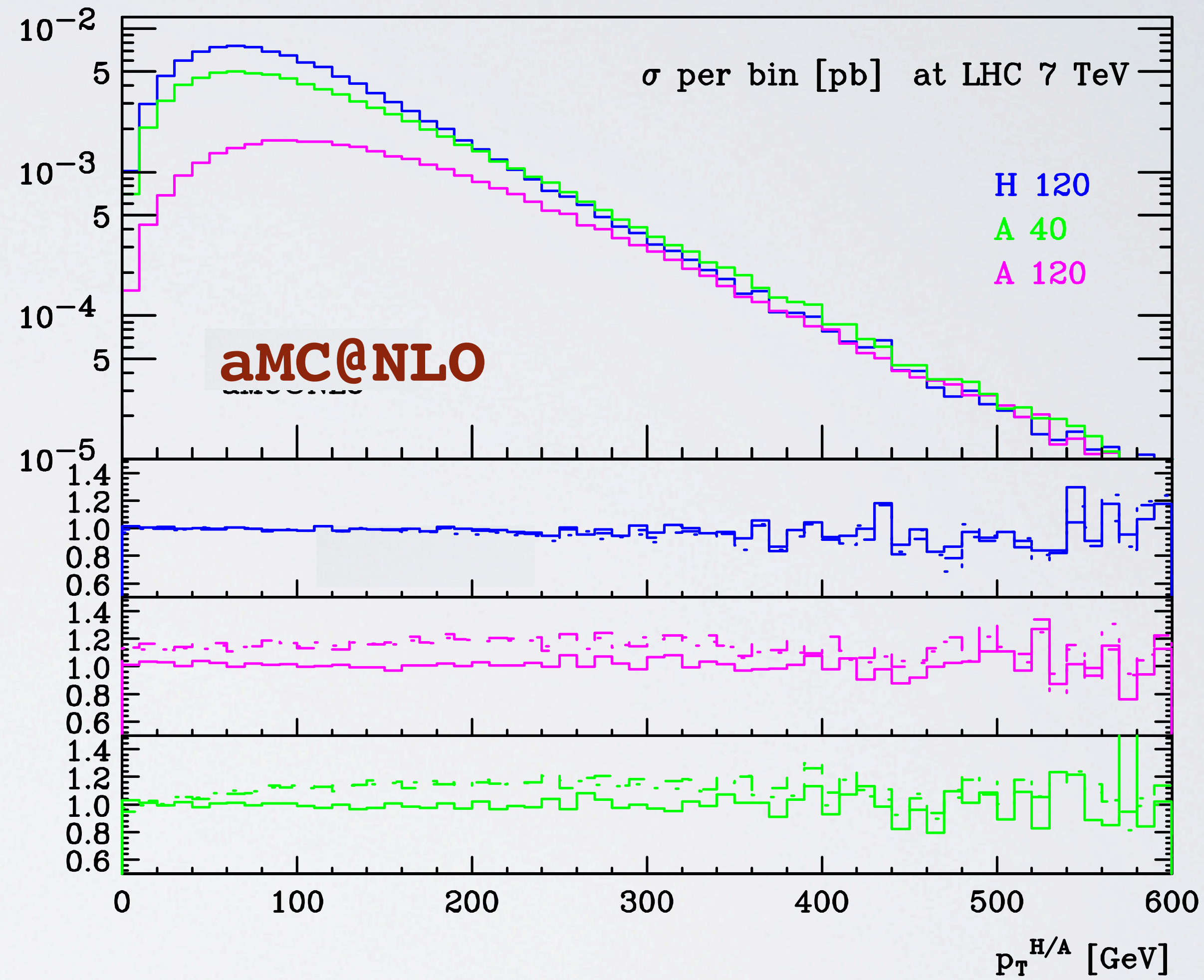
pp→Zbb/Wbb via aMC@NLO



Signal and irreducible background now known at the same level of accuracy!

PP→TTH/TTA

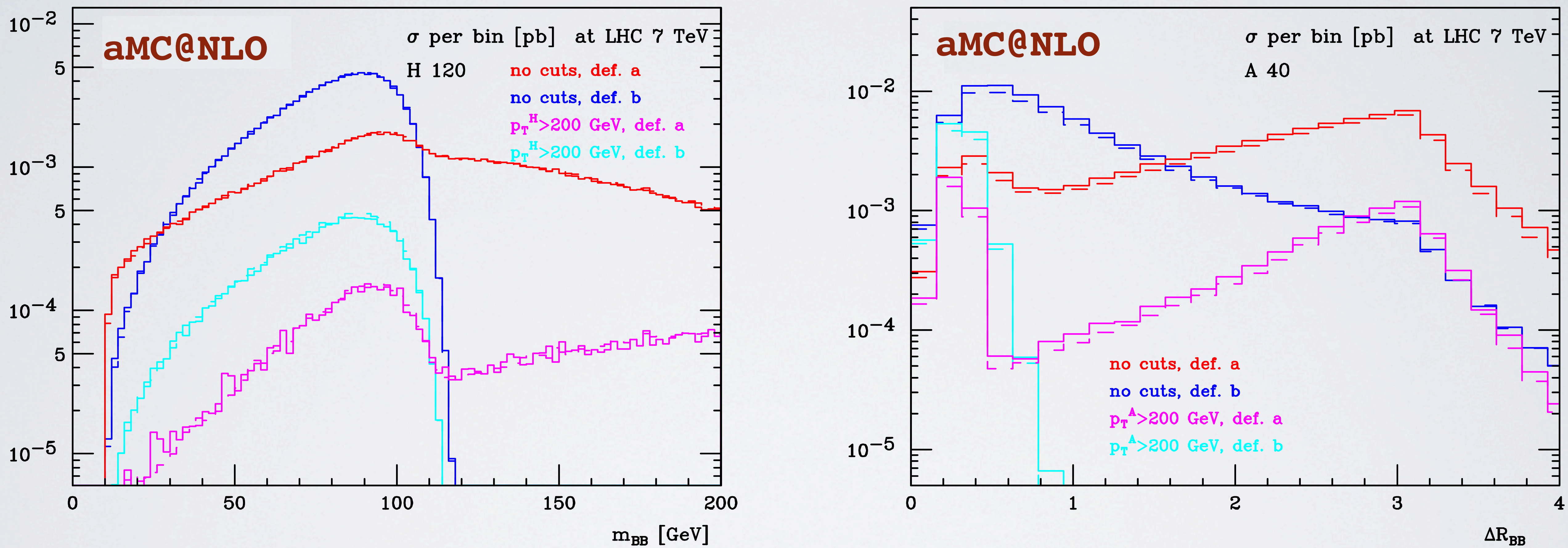
SIGNAL:
Available now in aMC@NLO
for both Scalar and Pseudoscalar
[Frederix, et al. 104.5613].



BACKGROUNDS:
NONE available at NLOwPS yet.

COMMENTS:
For the signal bbH/bbA under study in the aMC@NLO framework. For the NLO backgrounds ttjj and ttbb are known. ttZ possible straightforward in the aMC@NLO framework.

PP→TTH/TTA VIA AMC@NLO



MC gives the possibility to study fully exlusive (and/or hadronic) kind of variables for this process for the first time at the NLO.

SUMMARY

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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.

SM STATUS CIRCA 2002

pp→ n particles

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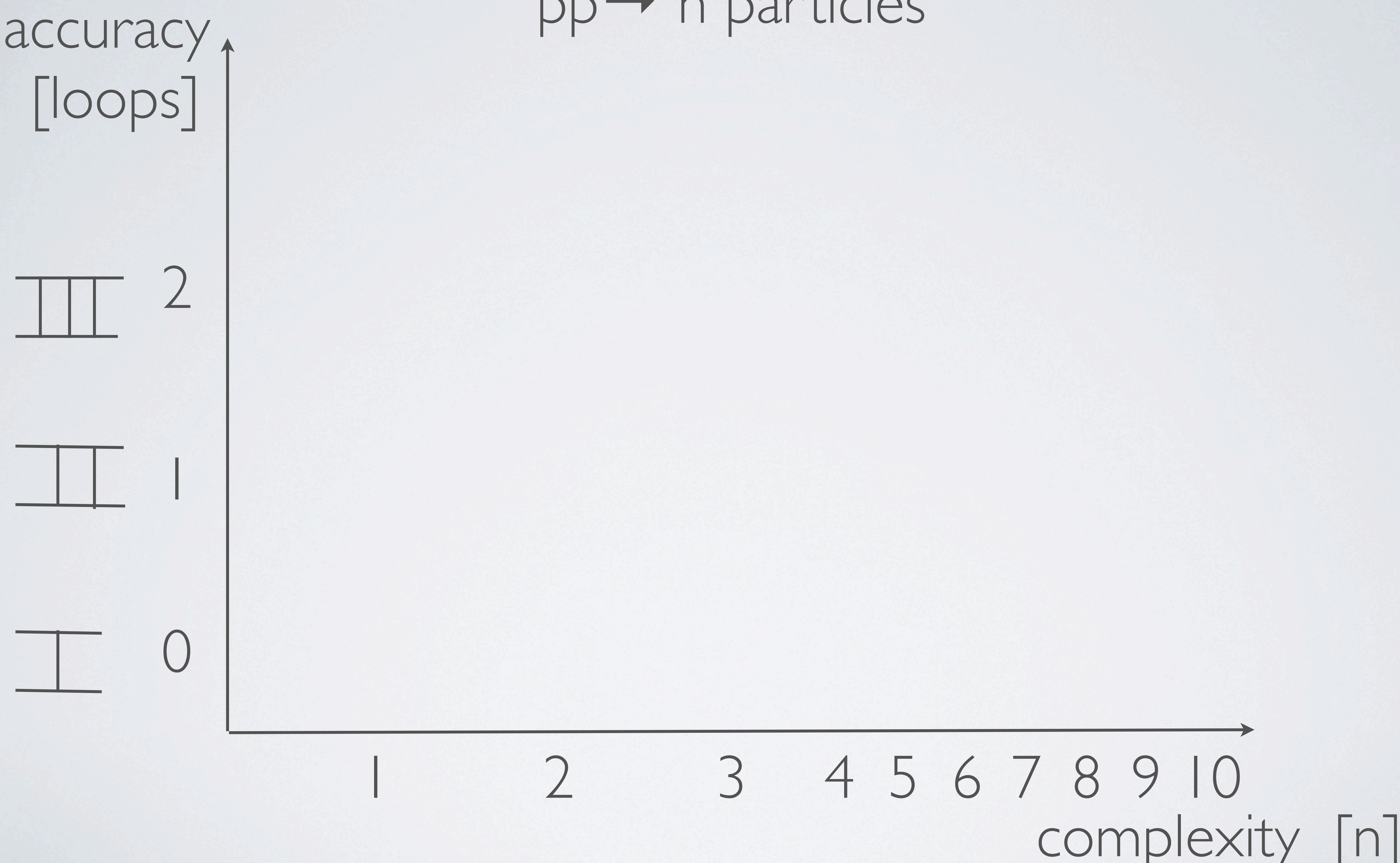
pp→ n particles

1 2 3 4 5 6 7 8 9 10

complexity [n]

SM STATUS CIRCA 2002

pp$\to$ n particles



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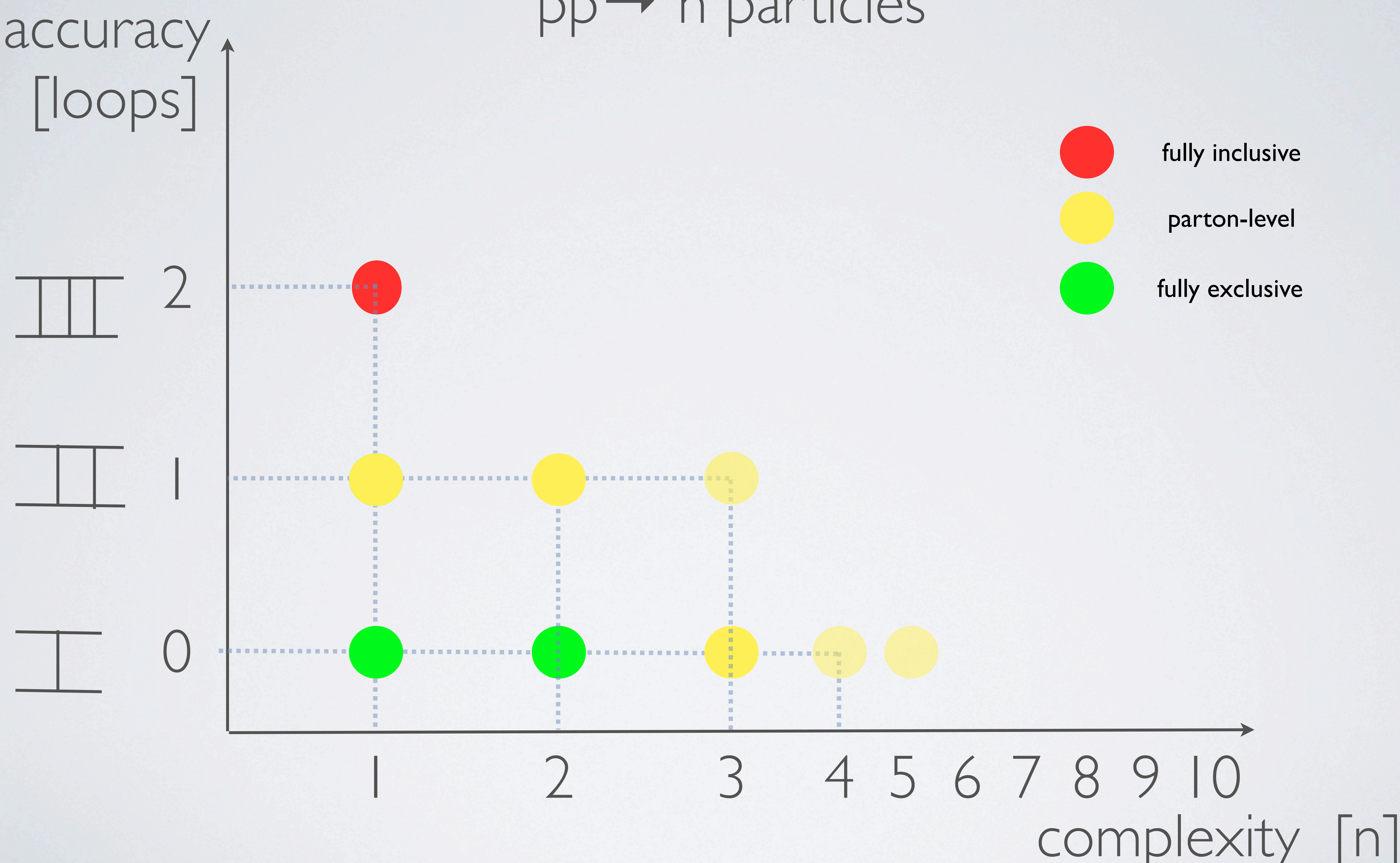

SM STATUS : SINCE 2007

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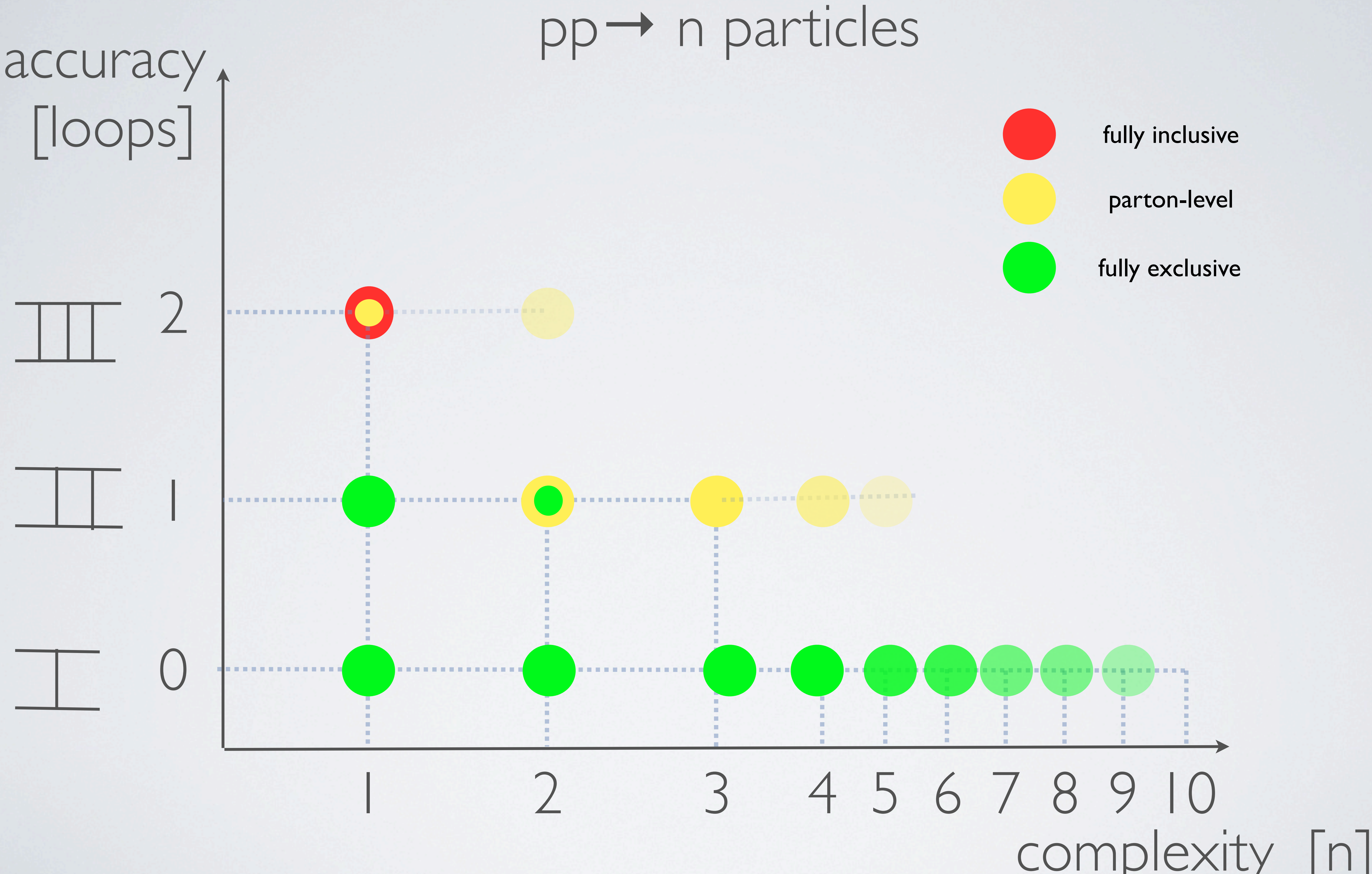

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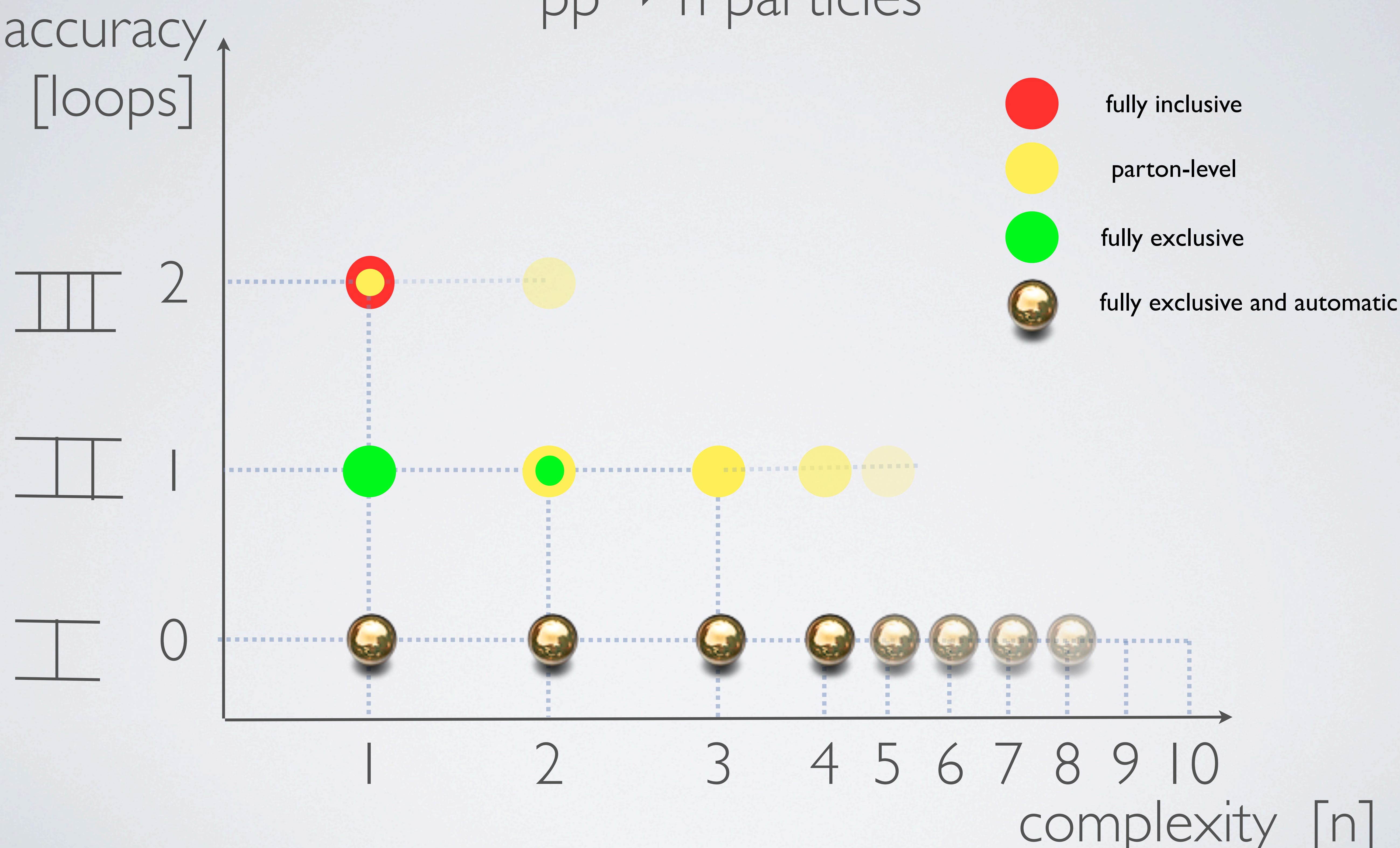

SM STATUS: NOW

pp → n particles

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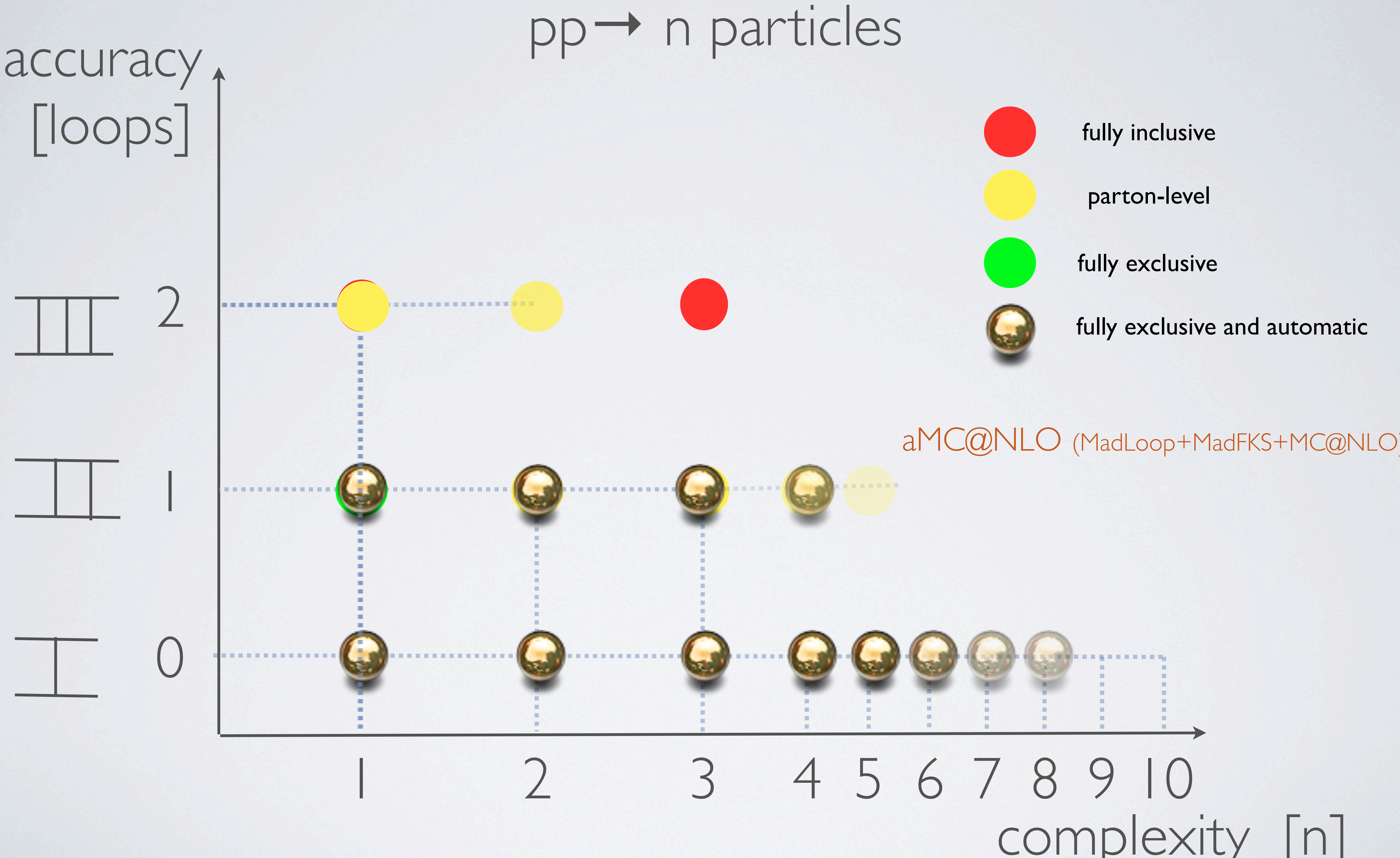

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- Higgs backgrounds quickly approaching the NLOwPS level.