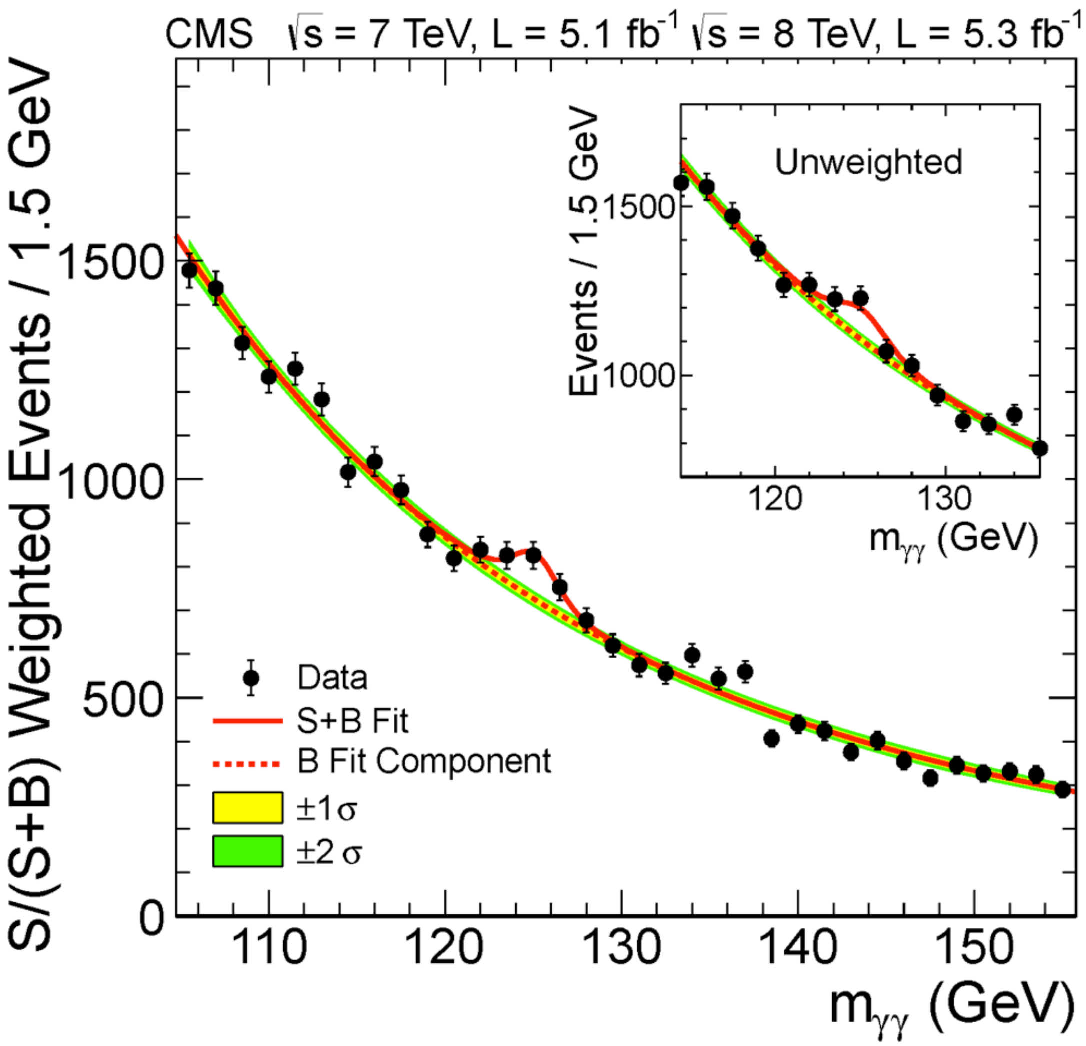
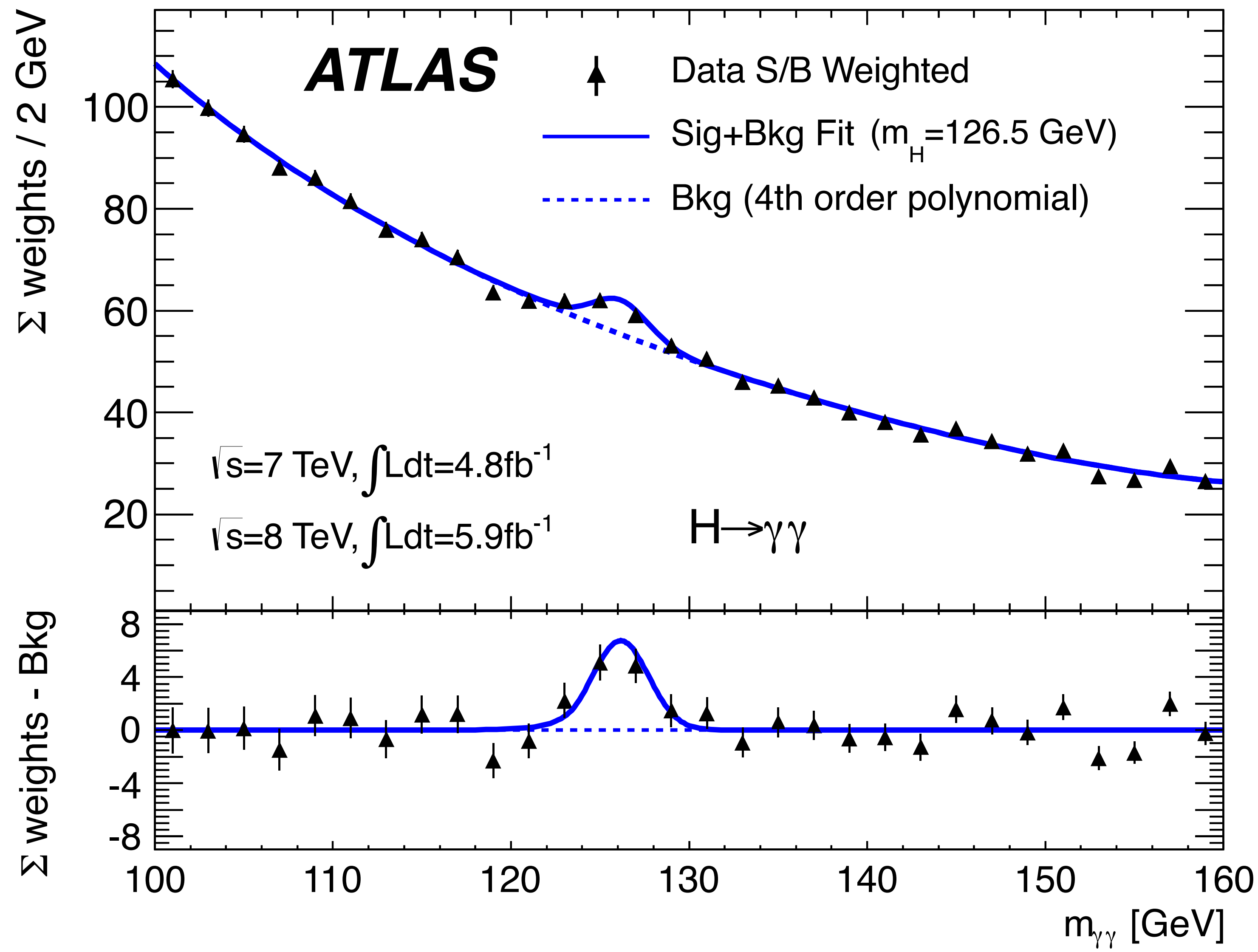
REVIEW OF MC'S : THE ACCURACY WAY

Fabio Maltoni
Centre for Cosmology,Particle Physics and Phenomenology (CP3)

Thursday 18 April 2013

INDEPENDENCE DAY 2012





Clear evidence for a new resonance!

Now reaching >10 σ

Grojean® (adapted)

REASONS FOR EXCITEMENT

Grojean® (adapted)

REASONS FOR EXCITEMENT

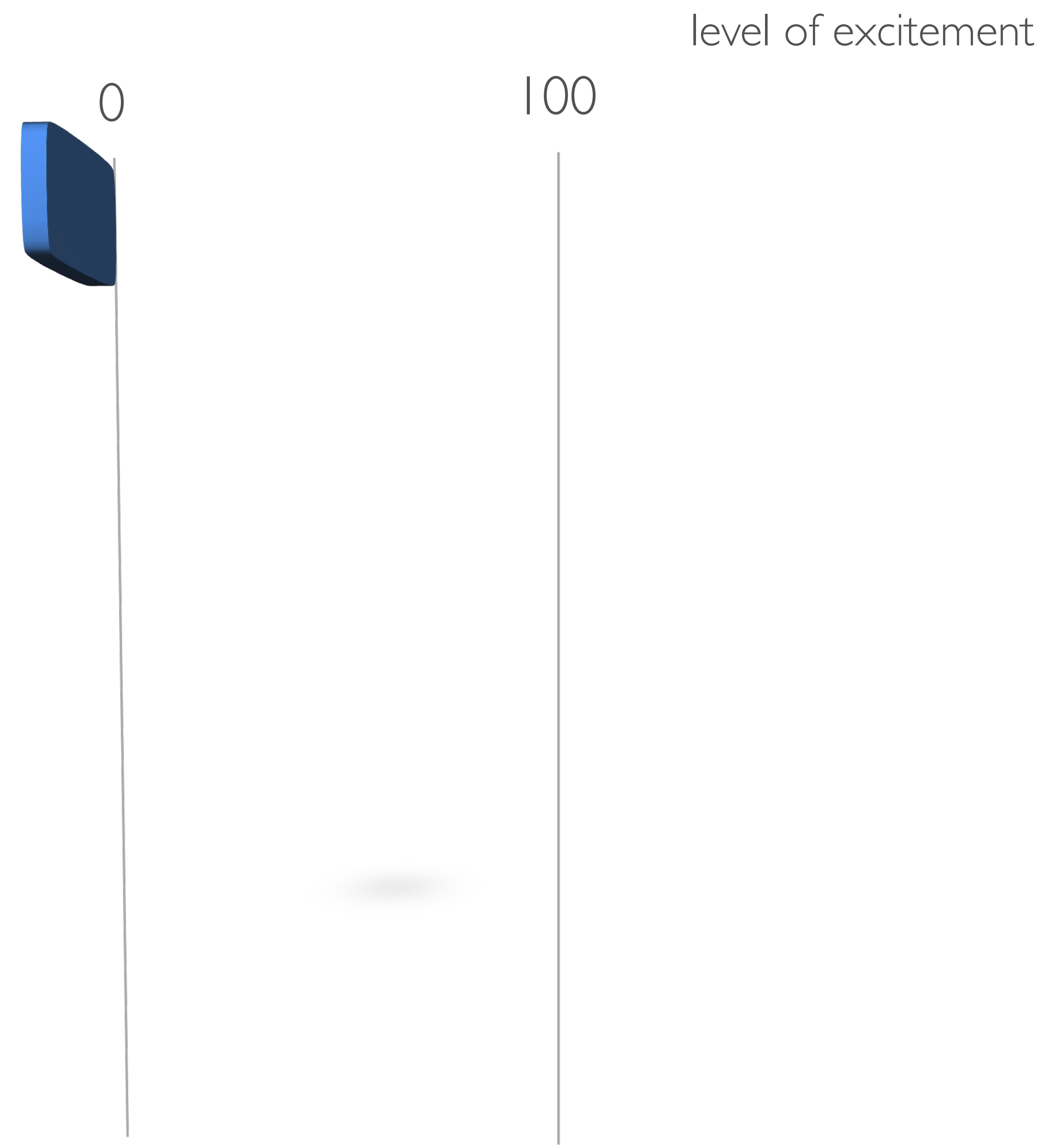
level of excitement

0 100

- The last missing piece of the SM

Grojean® (adapted)

REASONS FOR EXCITEMENT



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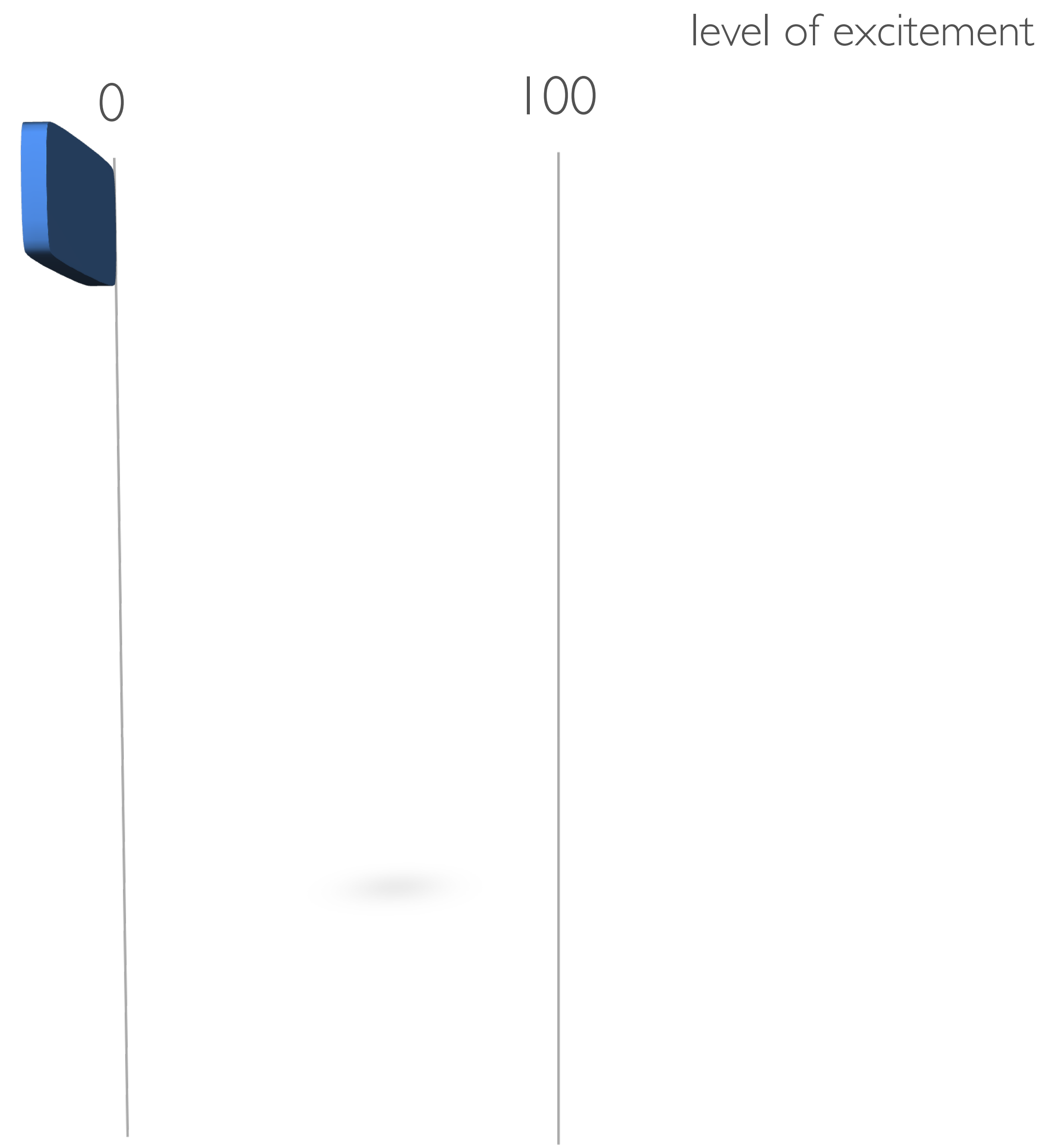

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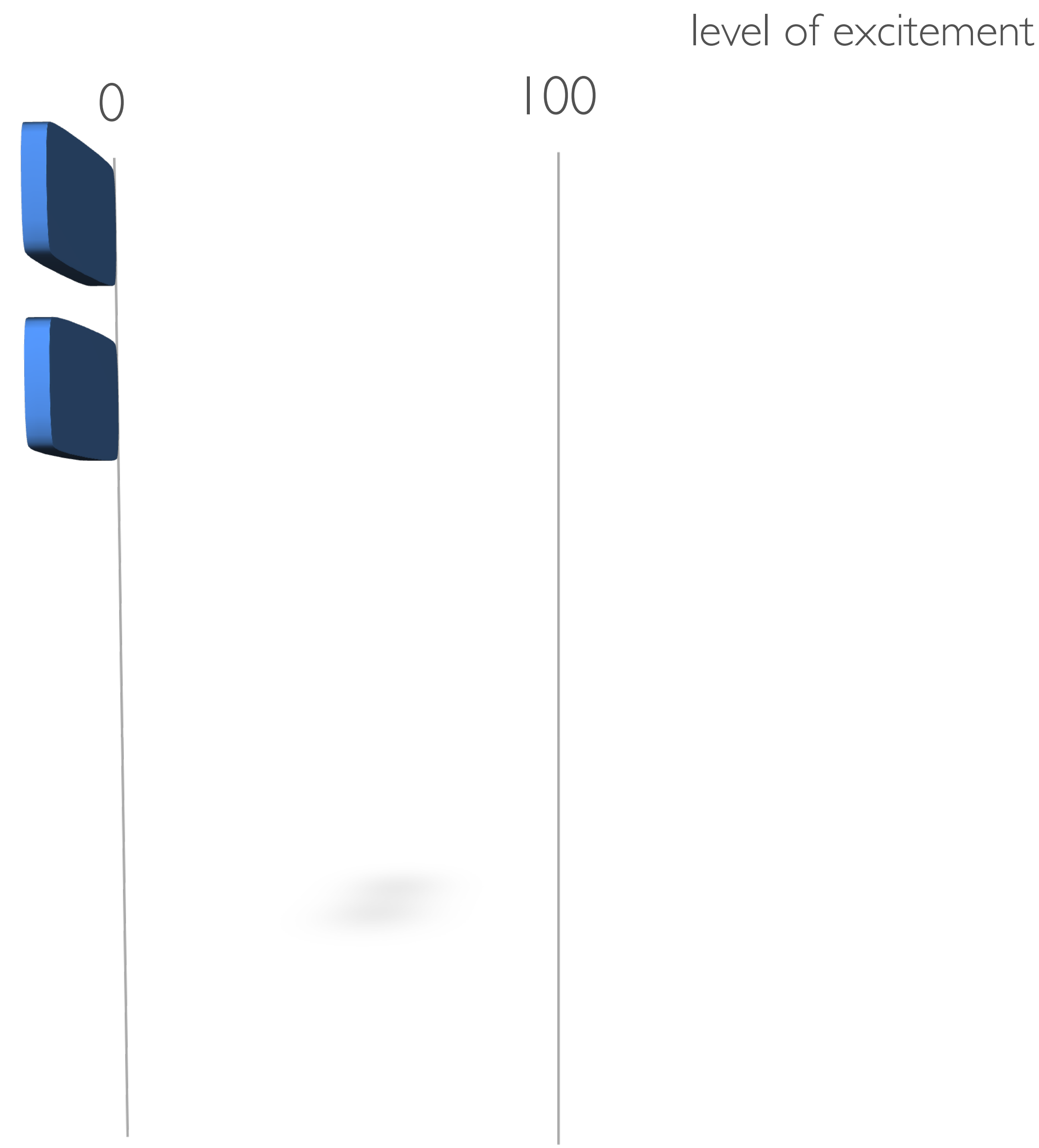

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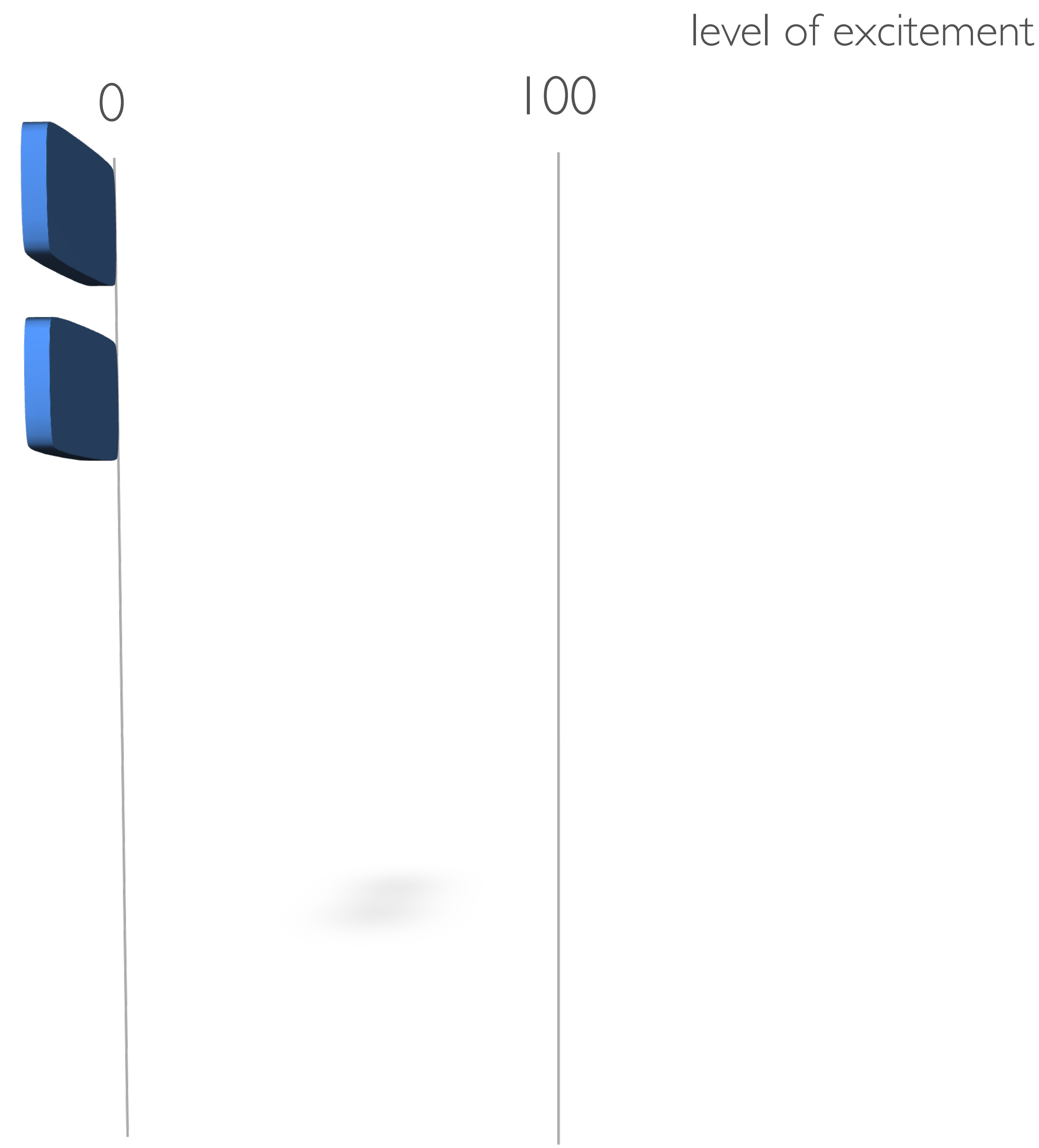

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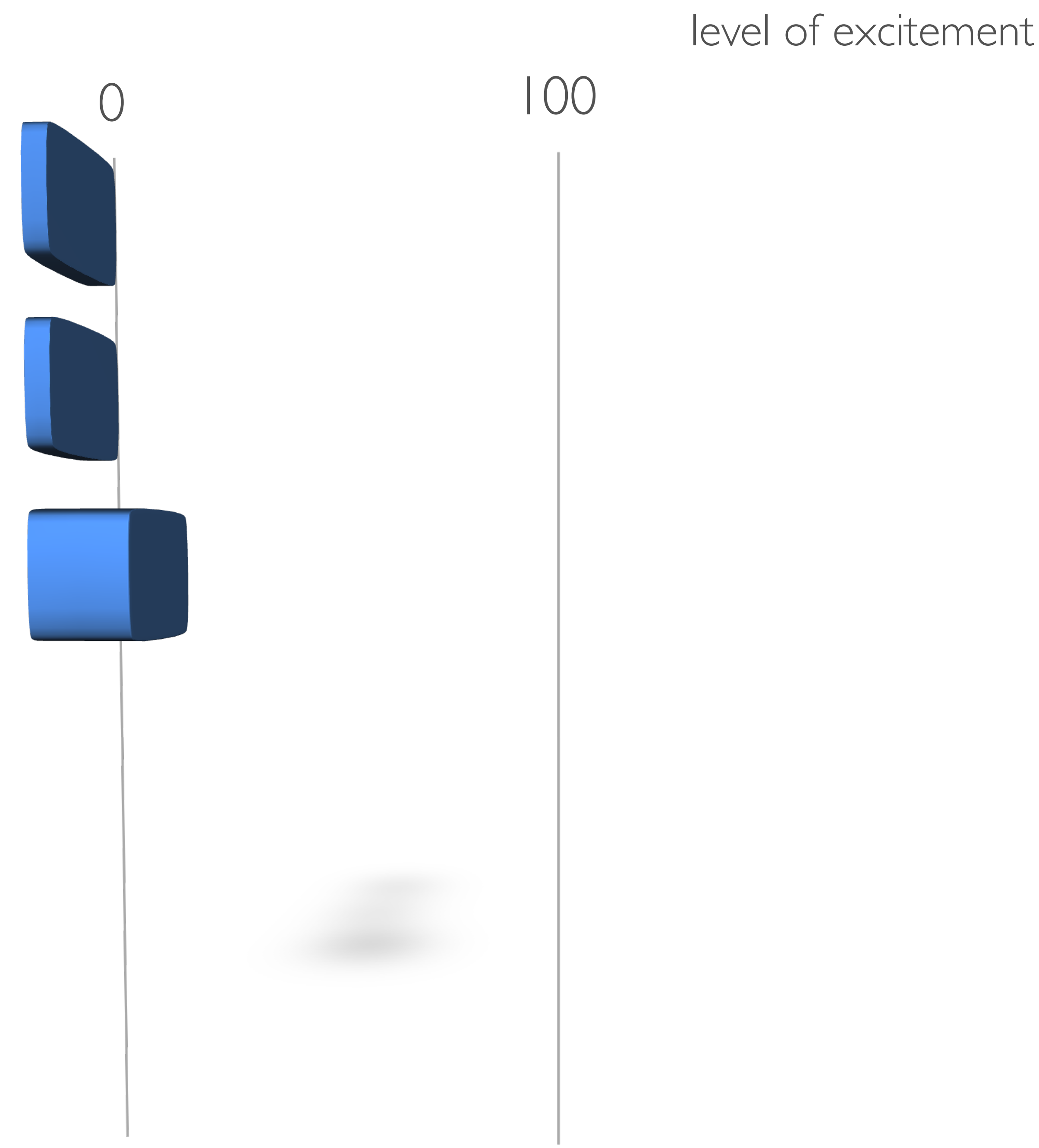

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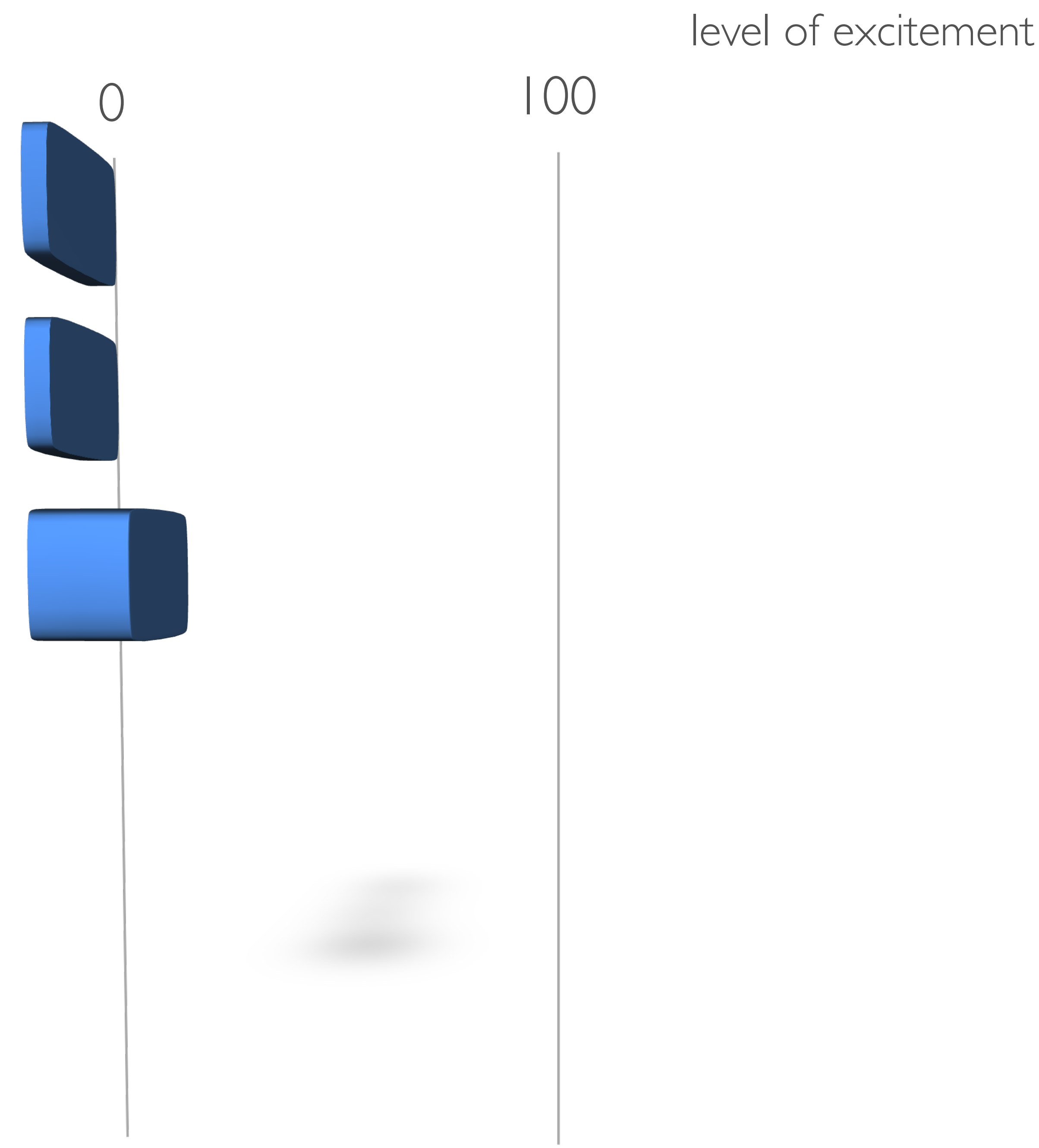

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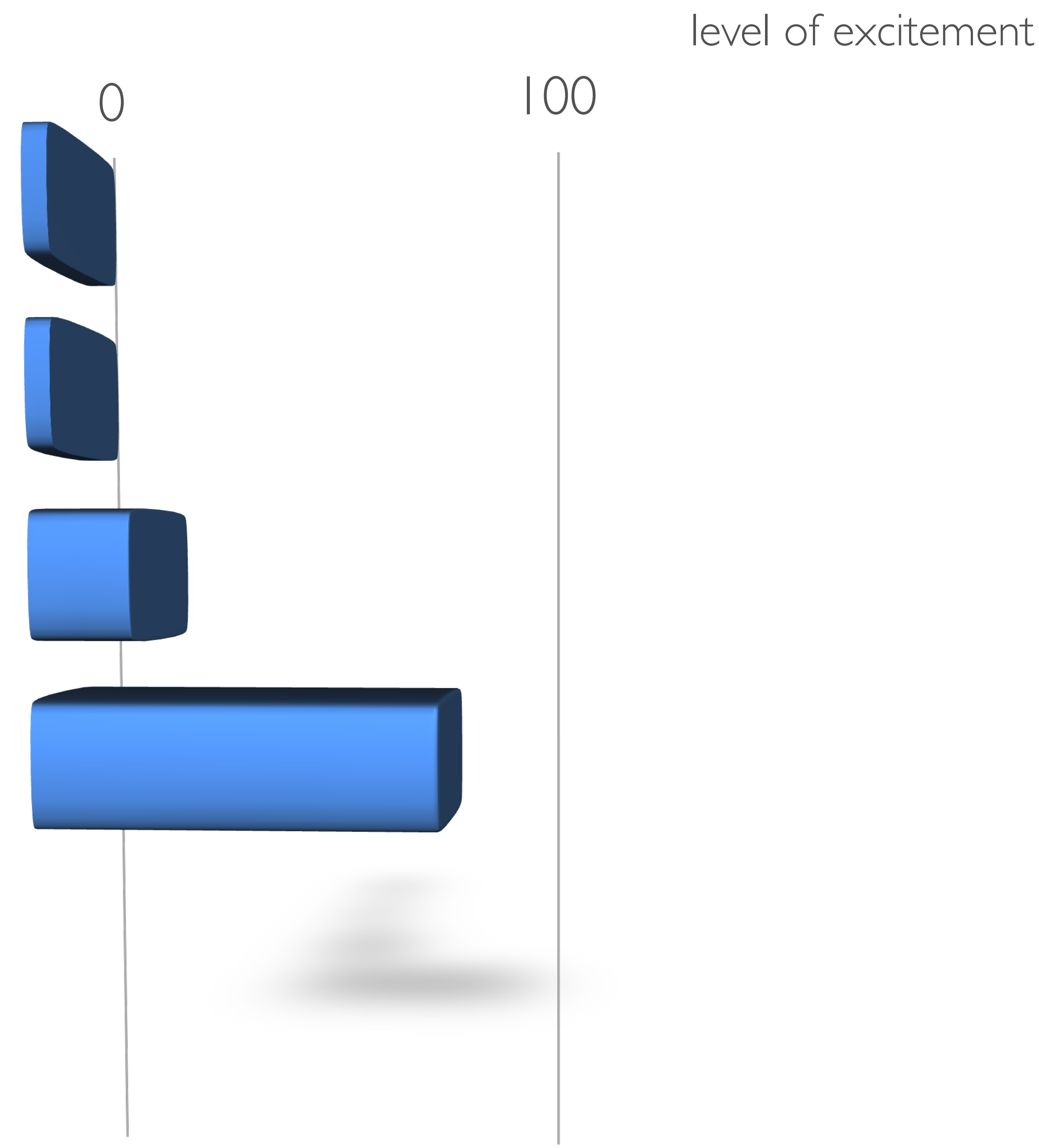

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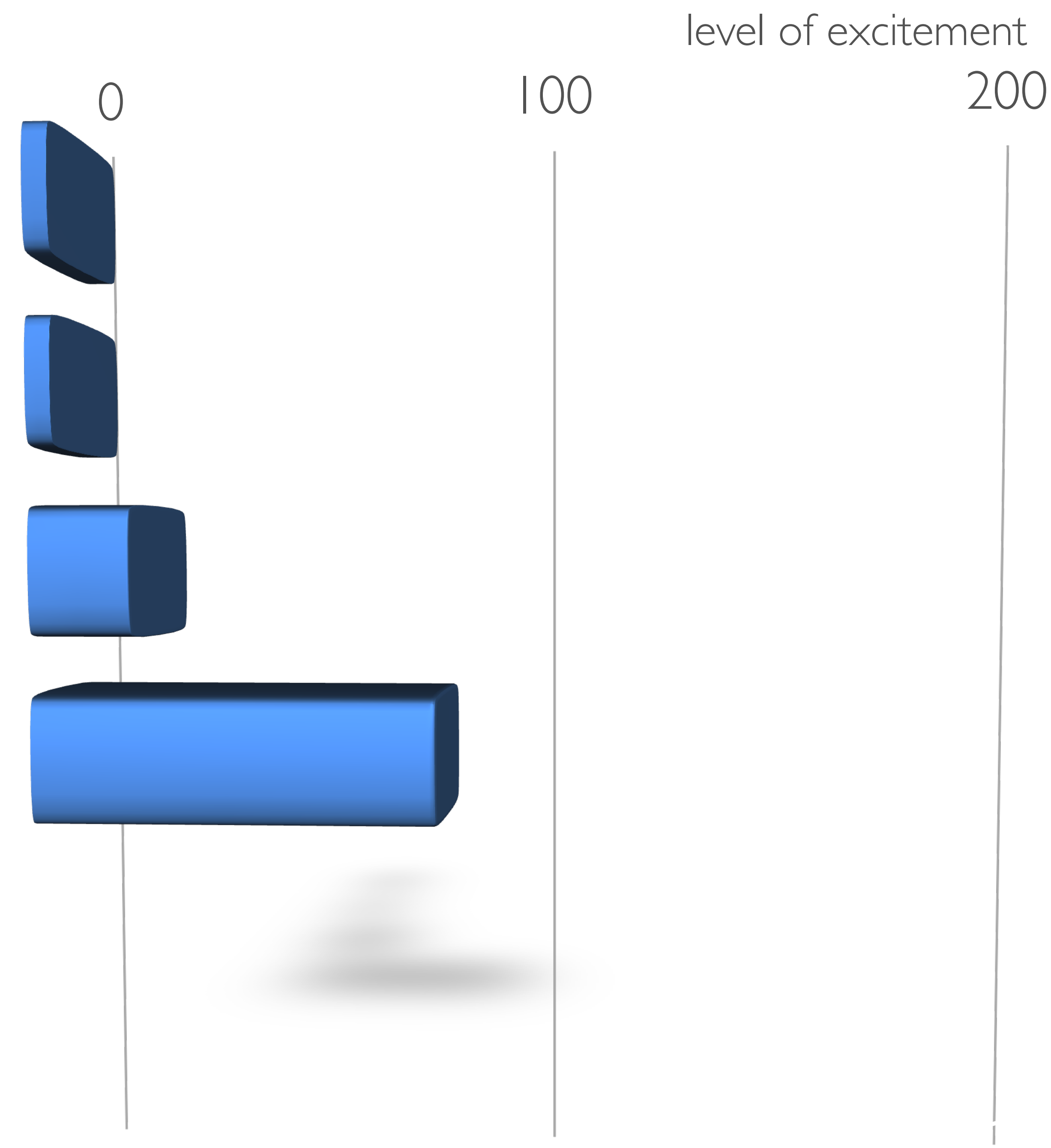

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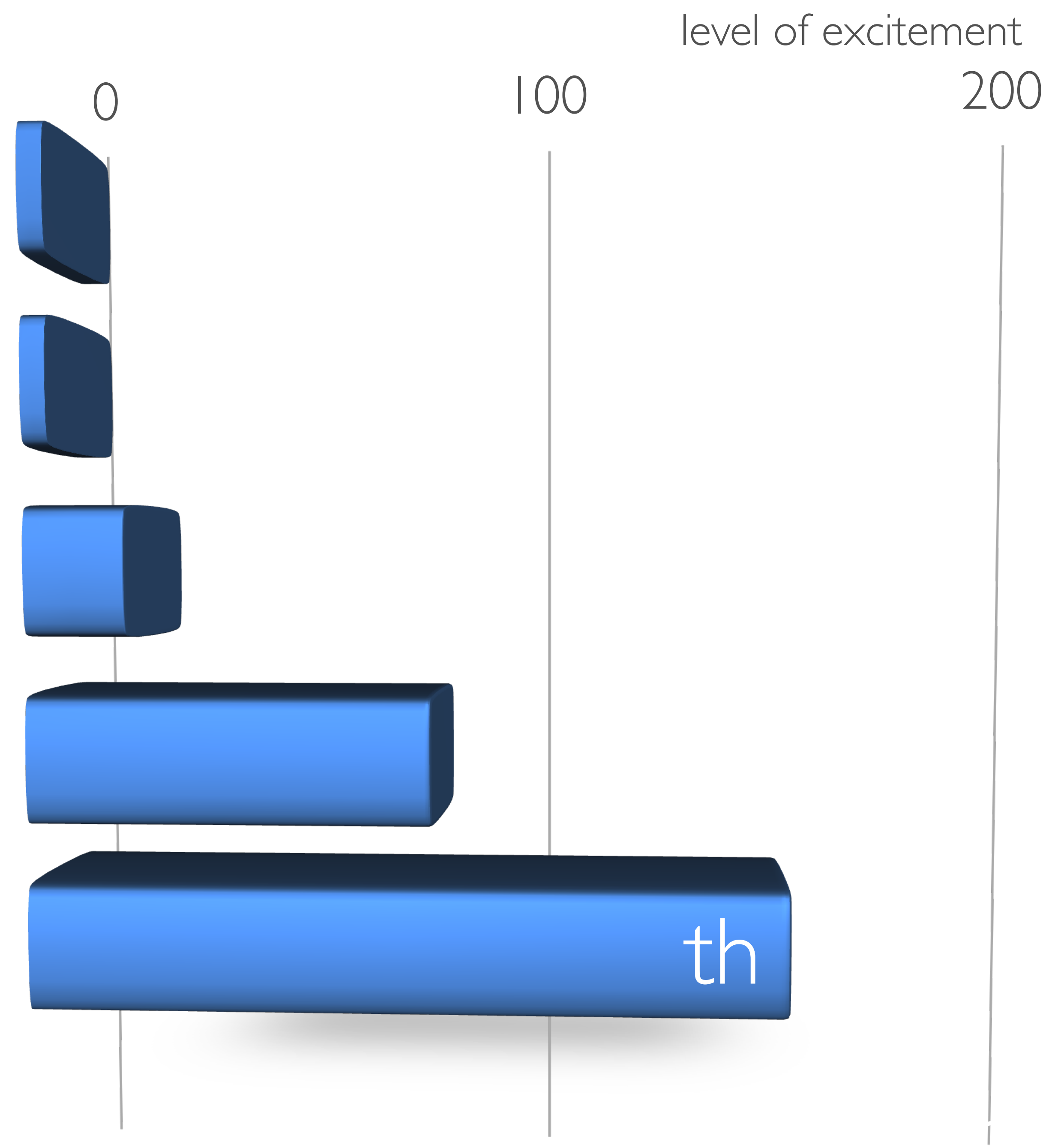

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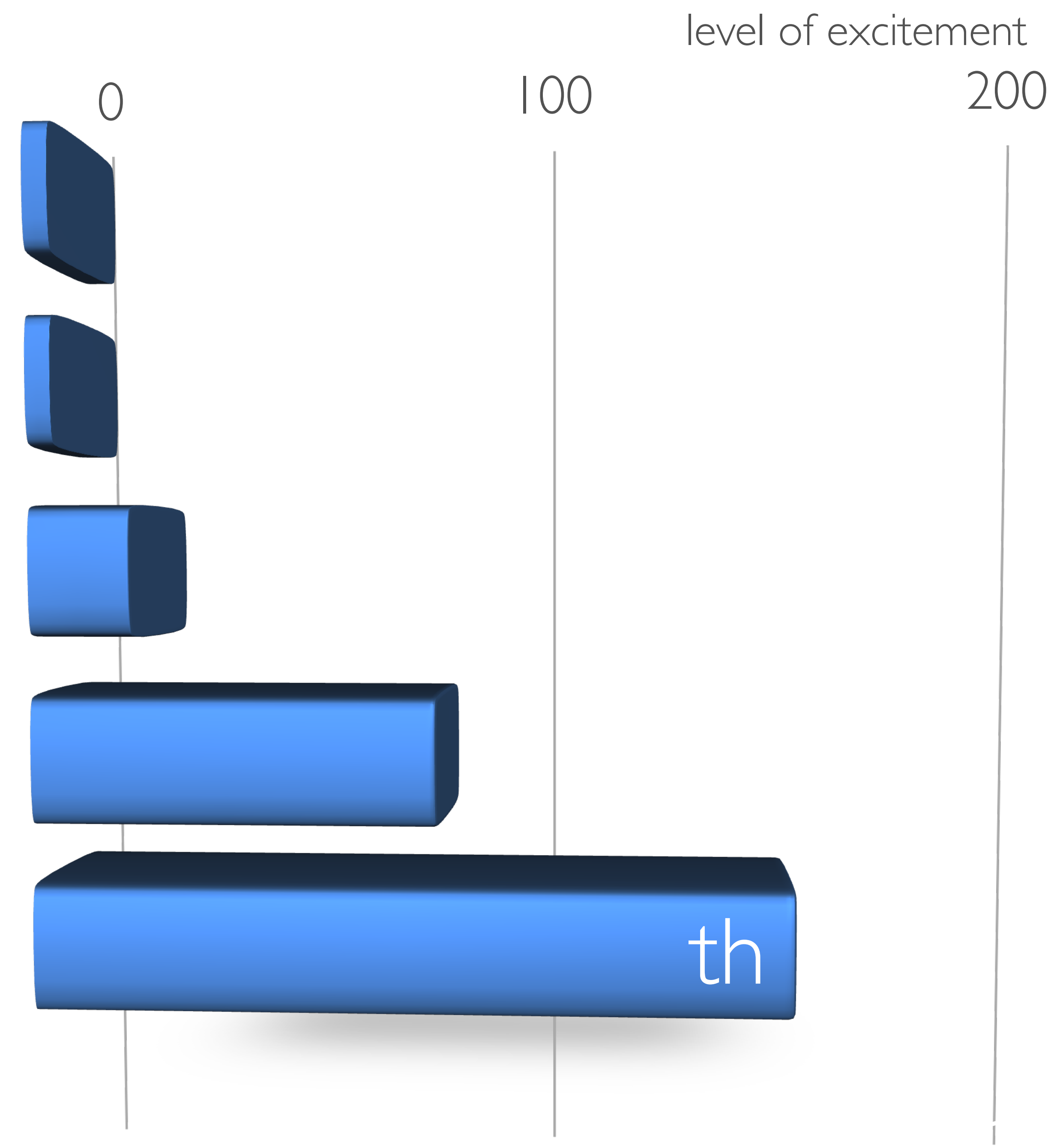

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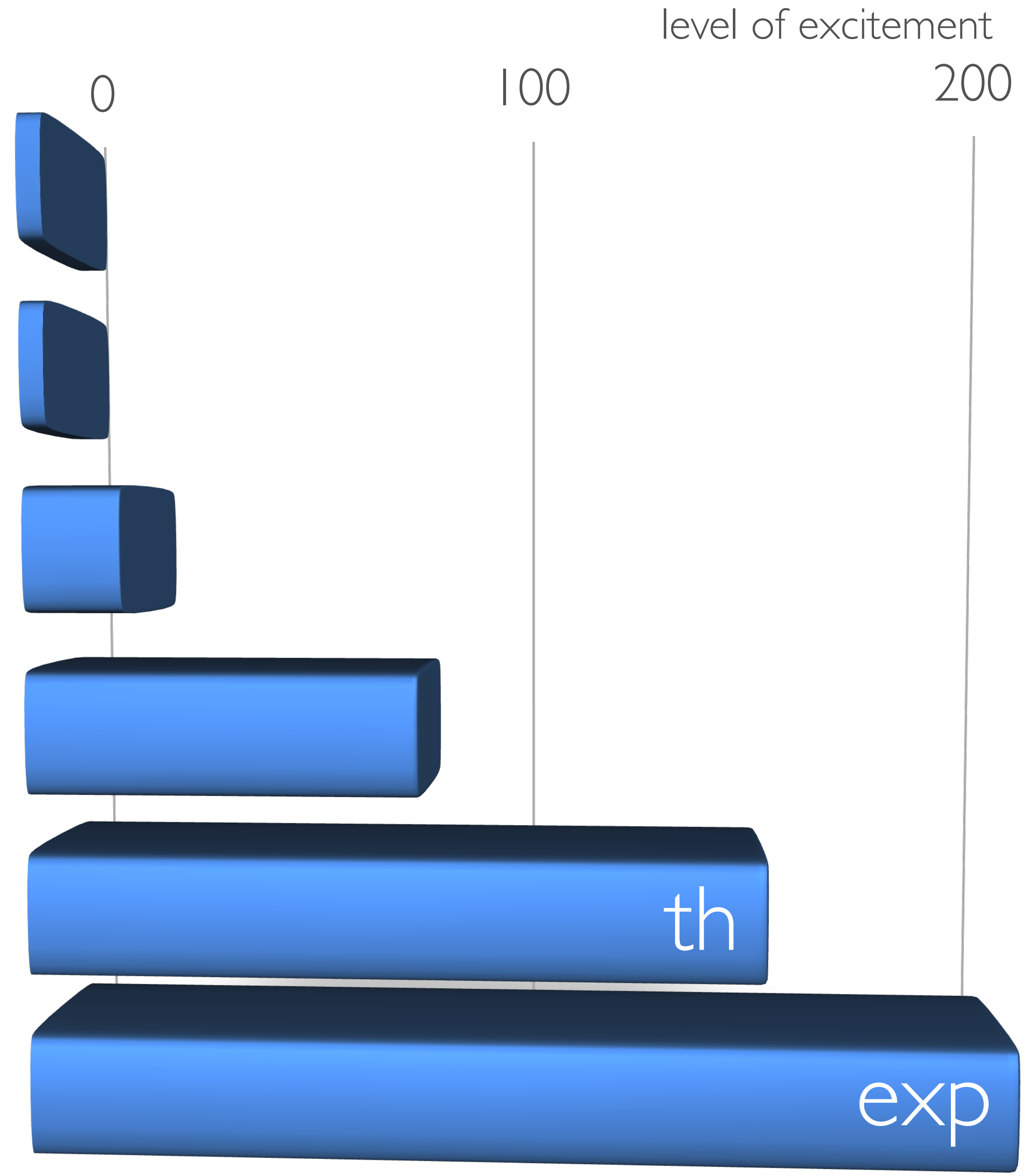

Mangano®

DISCOVERIES AT HADRON COLLIDERS

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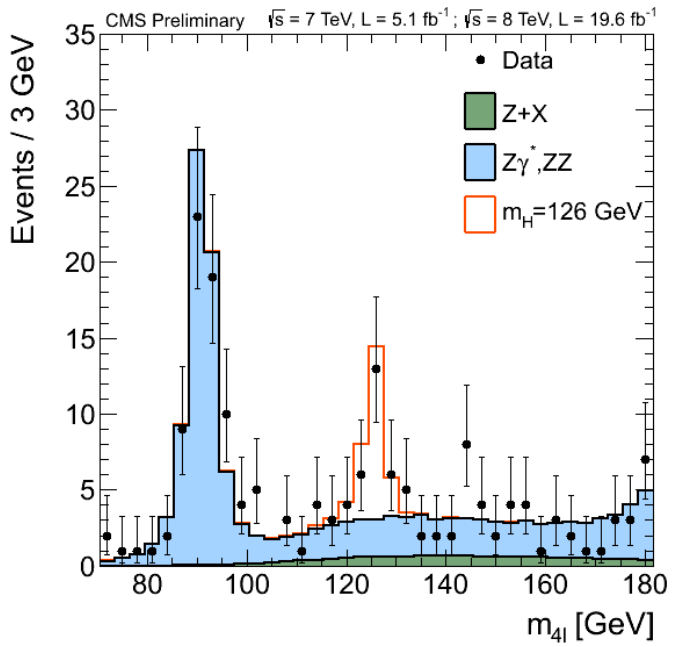
peak

pp→H→4l



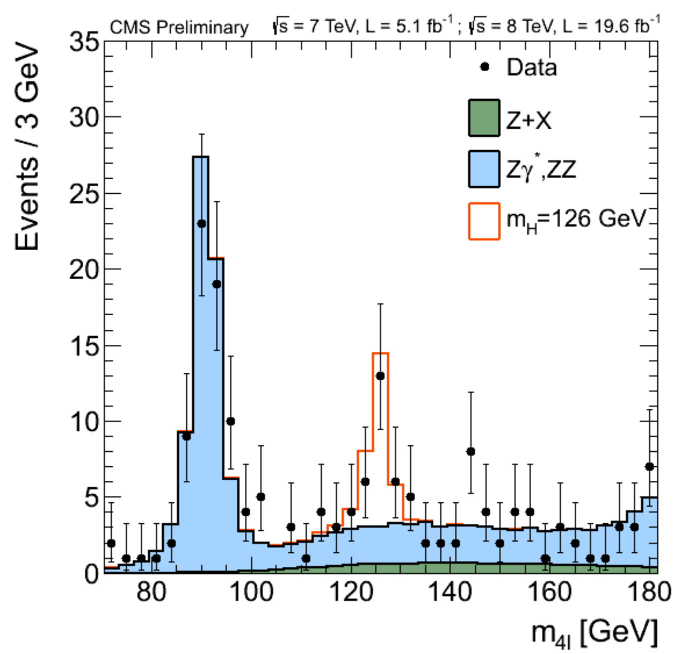
"easy"

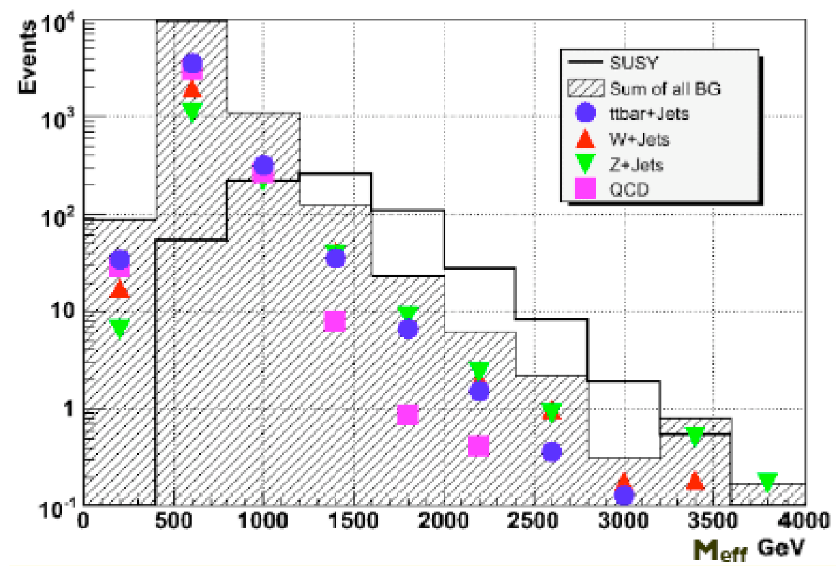
Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

Manganoâ

DISCOVERIES AT HADRON COLLIDERS

peak	shape
pp→H→4l	$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + \not{E}_T$





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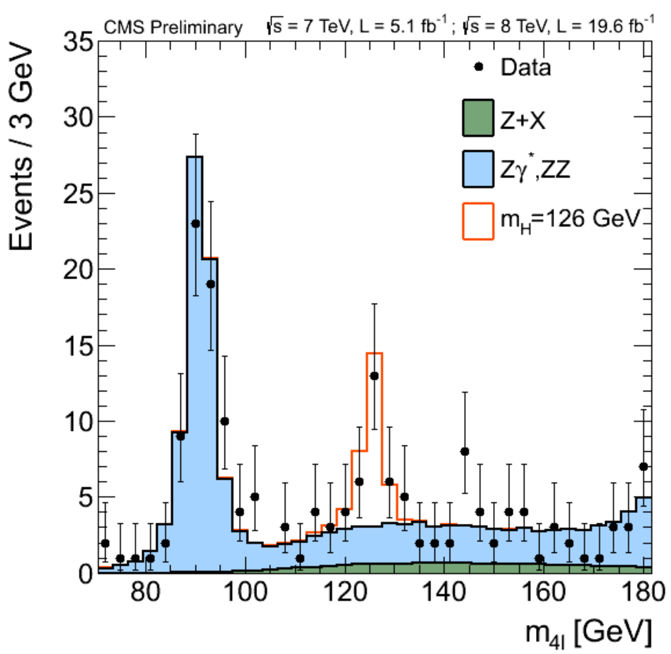
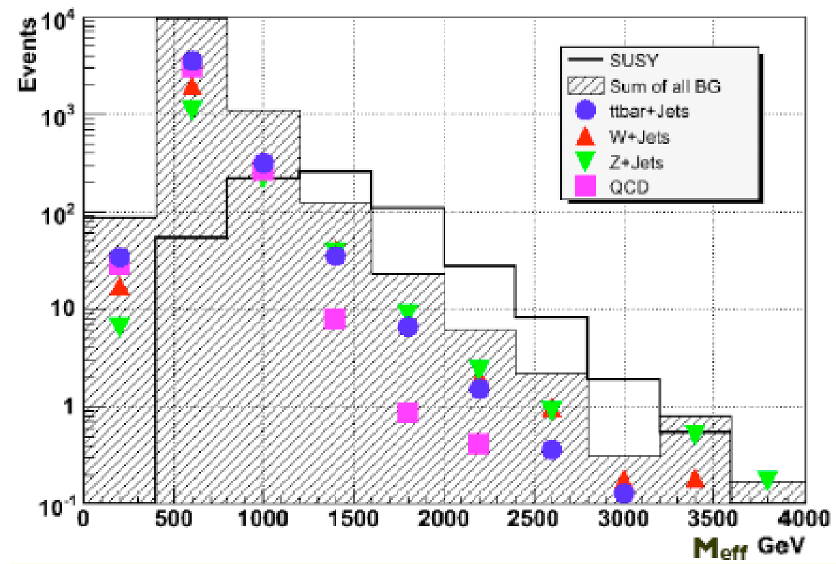
hard

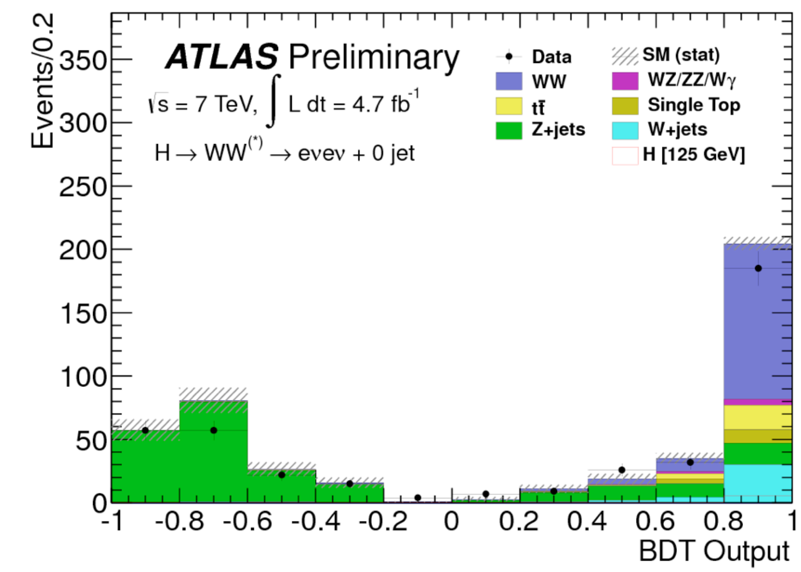
Background shapes needed. Flexible MC for both signal and background tuned and validated with data.

DISCOVERIES AT HADRON COLLIDERS

peak	shape	discriminant
pp→H→4l	pp→$\tilde{g}\tilde{g}$,$\tilde{g}\tilde{q}$,$\tilde{q}\tilde{q}$→jets+$\not{E}_T$	pp→H→W$^+$W$^-$







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very hard

Background normalization and shapes known very well. Interplay with the best theoretical predictions (via MC) and data.

No sign of new physics (so far)!


MC developer

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LHC MASTER FORMULA

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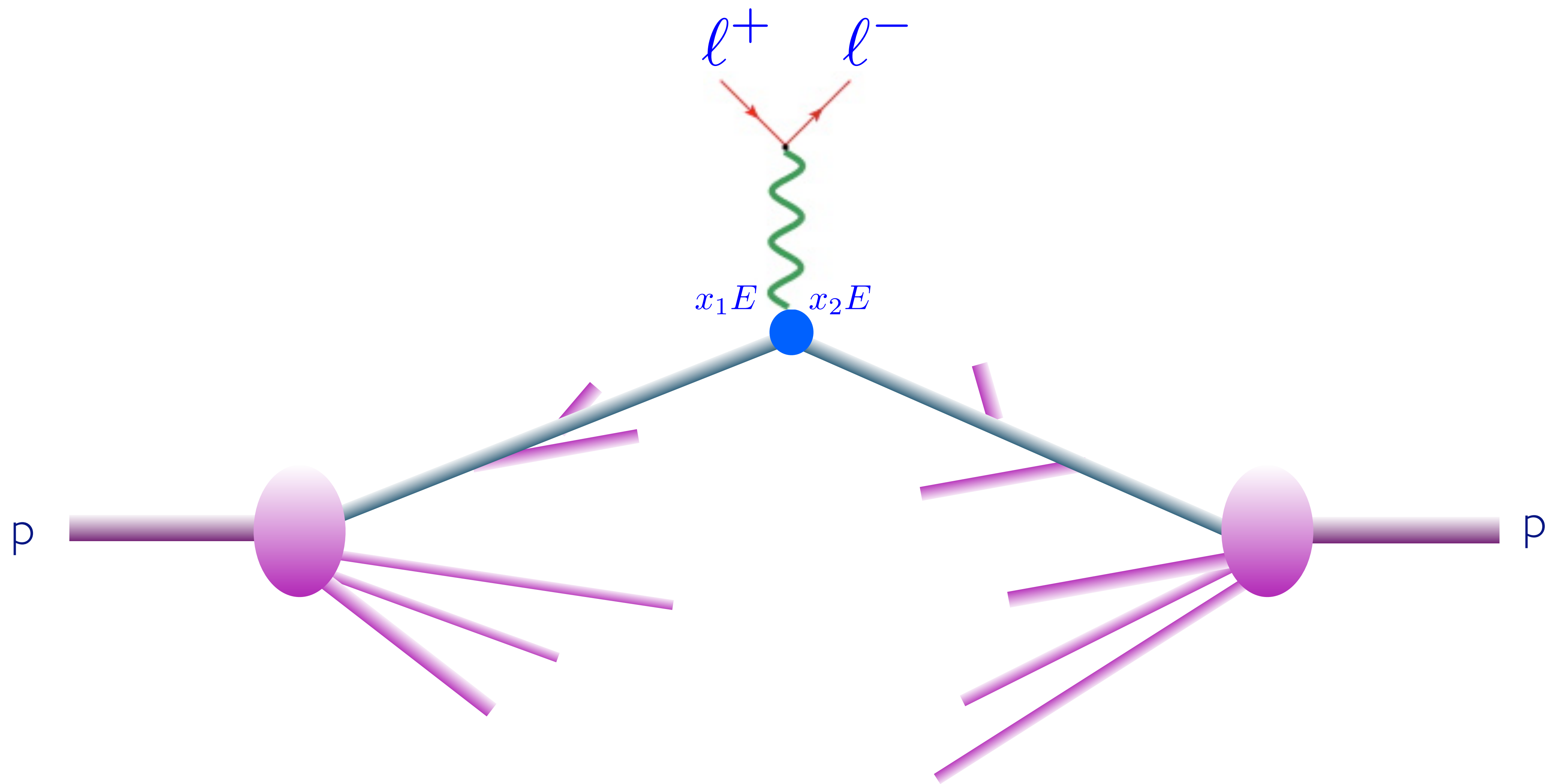

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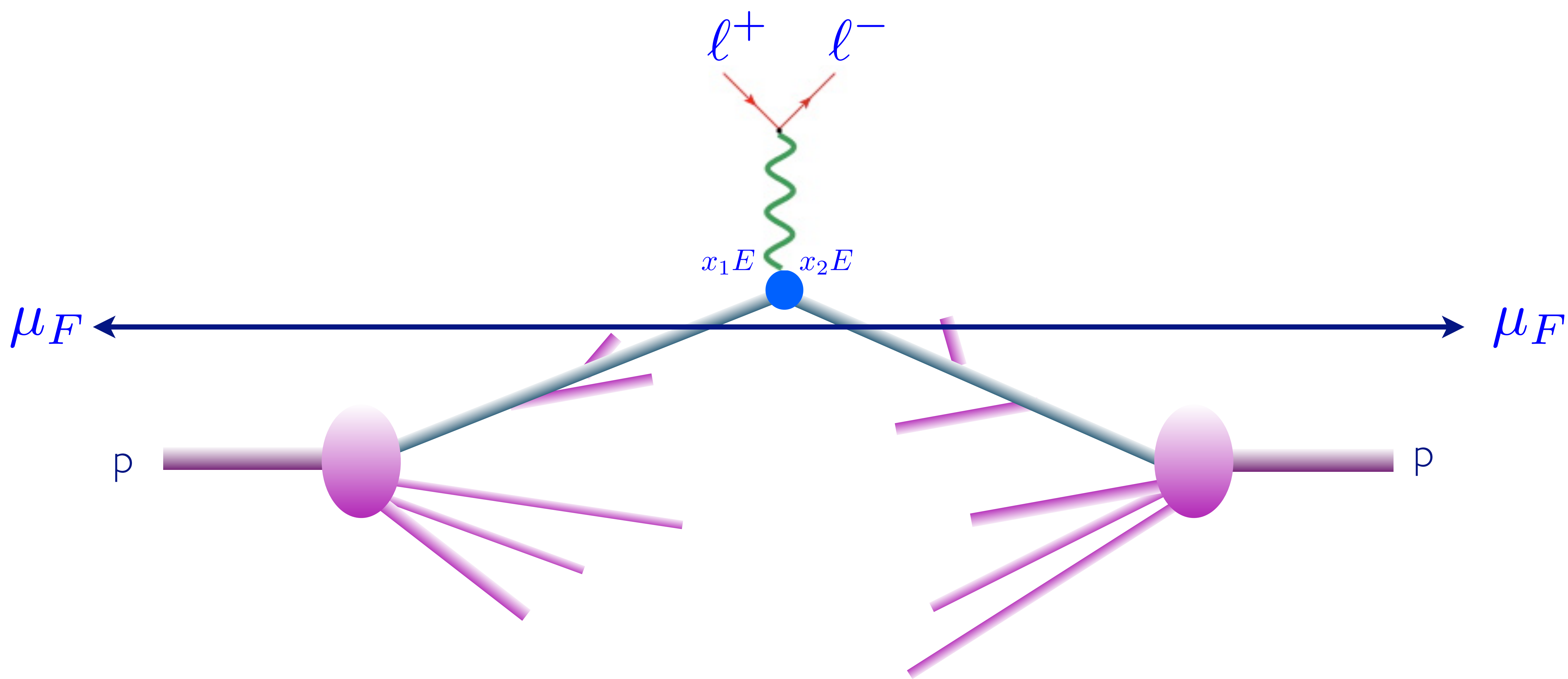

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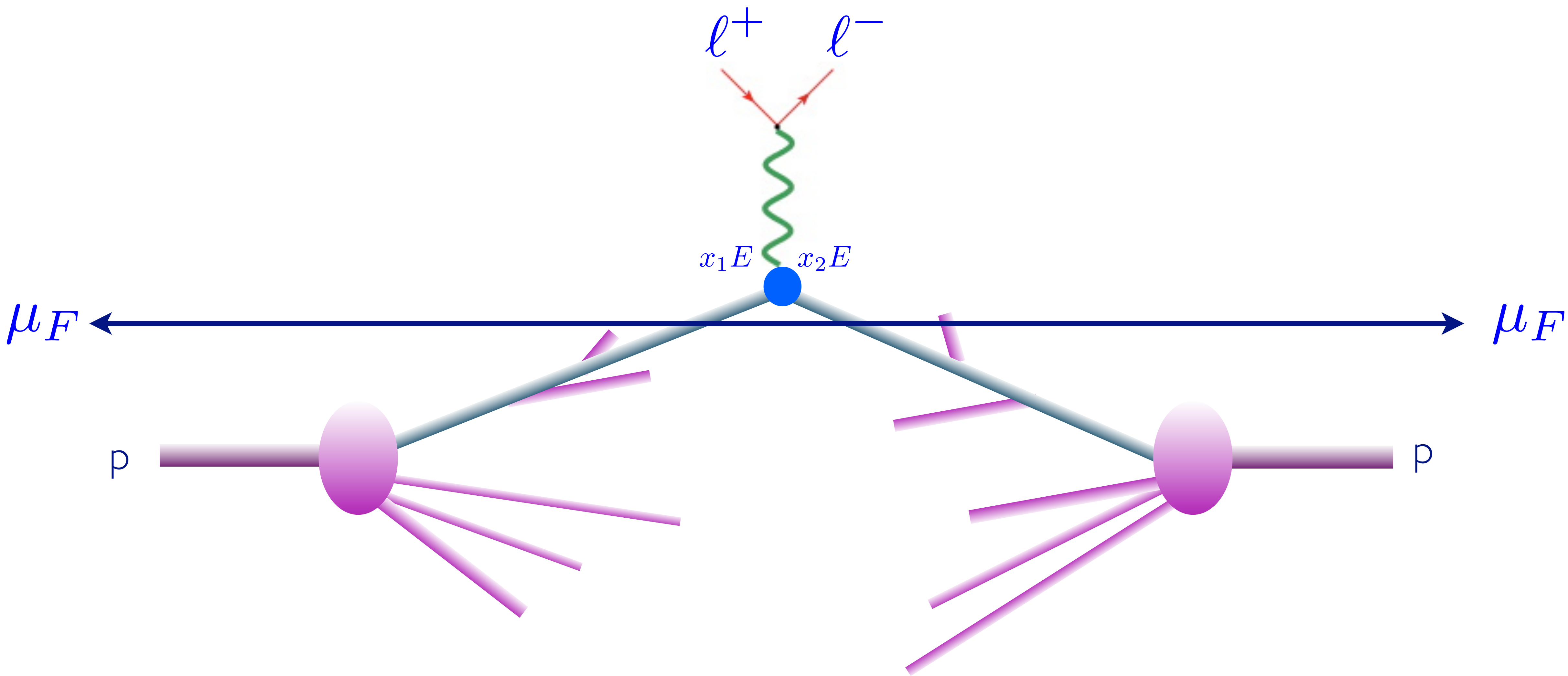

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

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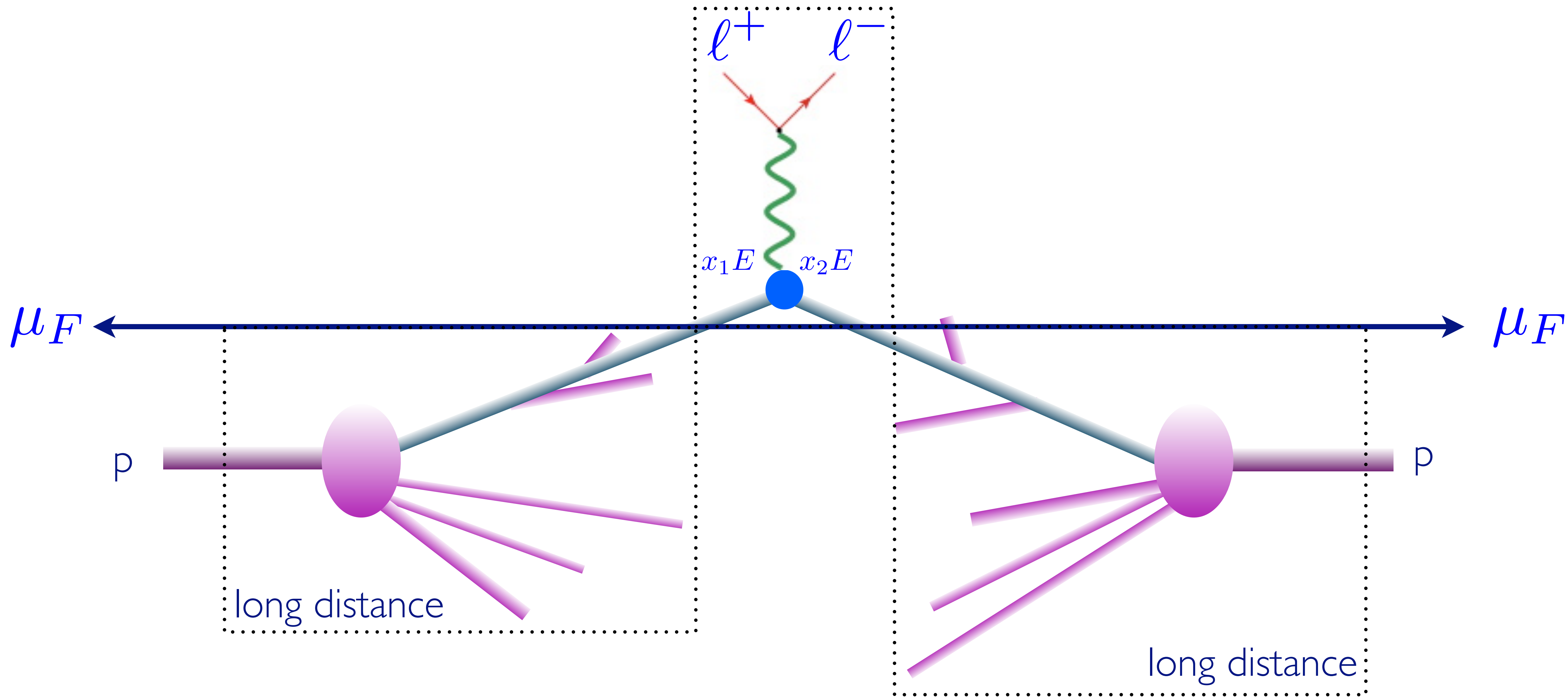

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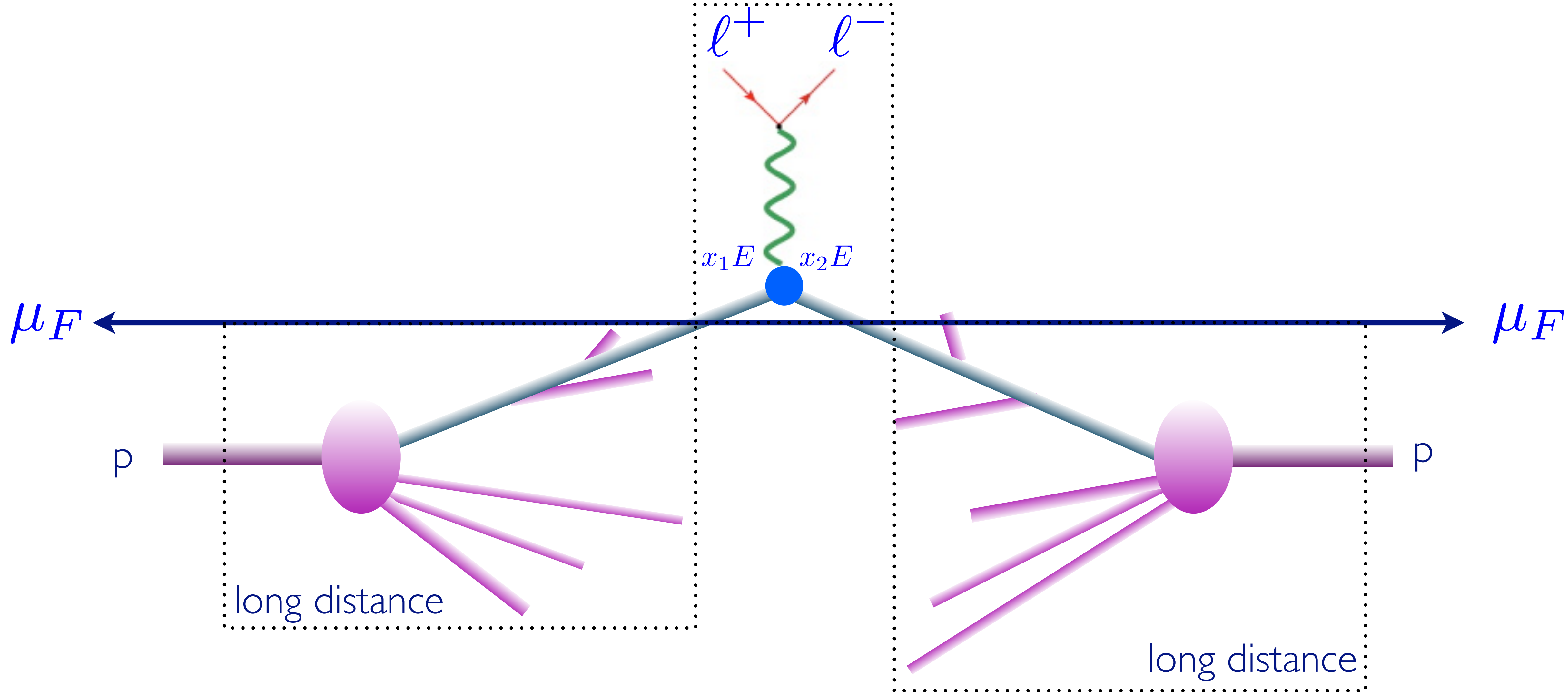

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Pheno/Th exploit this formula to provide accurate and flexible predictions from a given model (SM, MSSM,...)

HOW WE (USED TO) MAKE PREDICTIONS?

First way:

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

TH

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

- 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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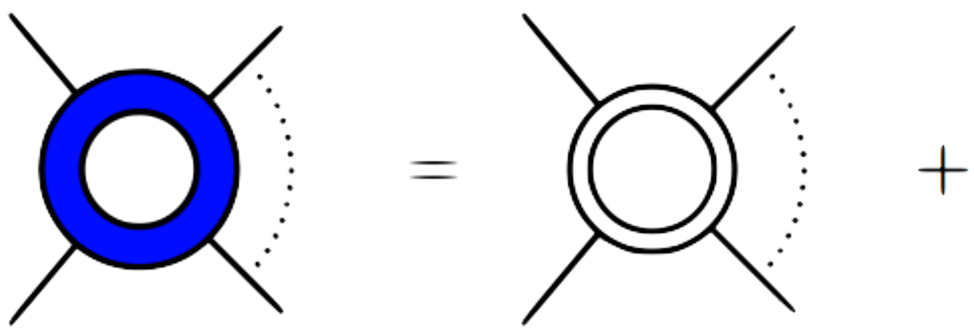
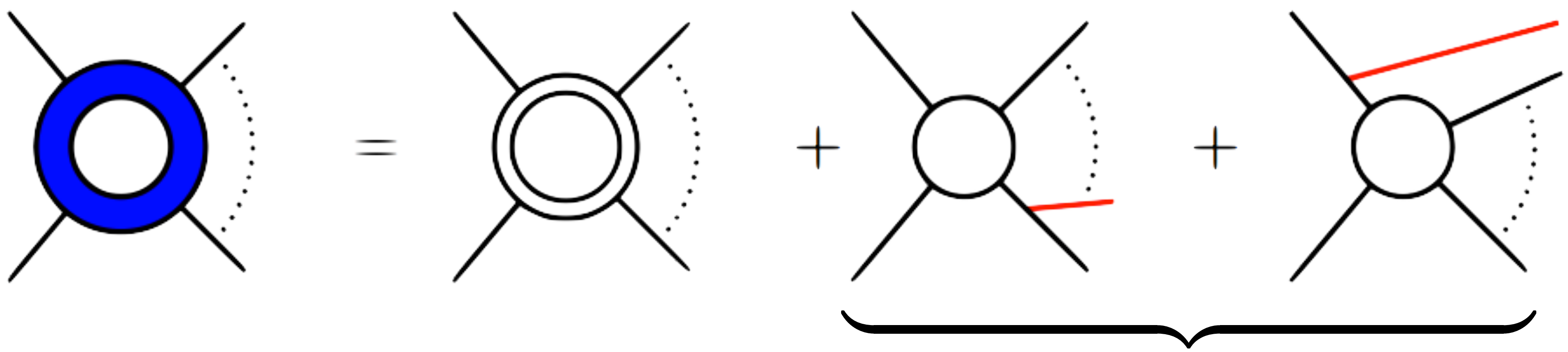


$$\sigma^{\rm NLO} = \int_m d^{(d)}\sigma^V +$$

Virtual part

NLO BASICS

NLO contributions have three parts



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

Virtual part

Real emission part

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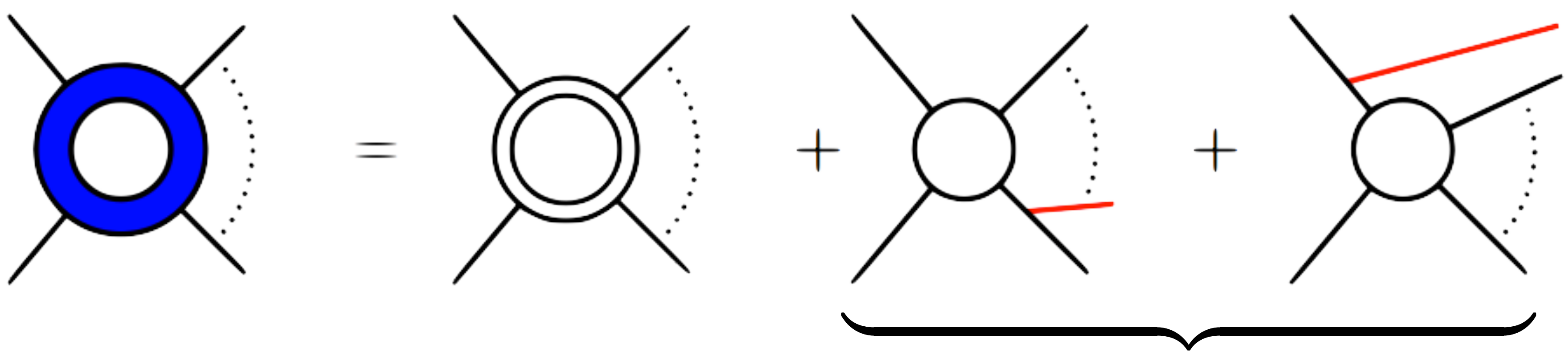

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Virtual part — Real emission part — Born

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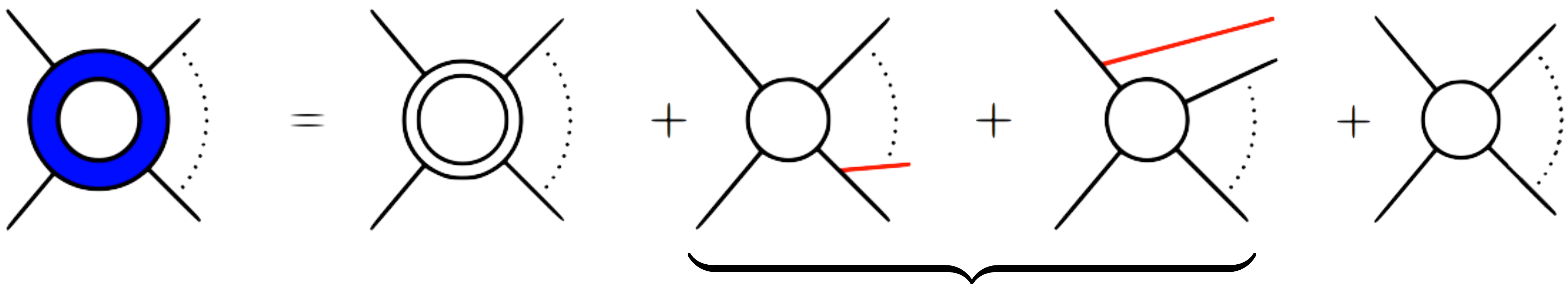

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- Loops have been for long the bottleneck of NLO computations (In fact they still are for BSM)
- Virtuals and Reals are each divergent and subtraction scheme need to be used (Dipoles, FKS, Antenna's)
- A lot of work is necessary for each computation

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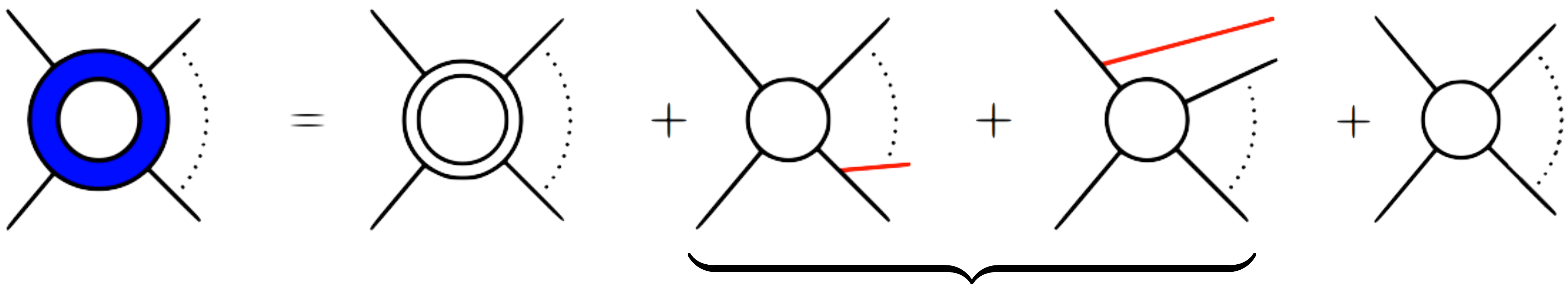

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The cost of a new prediction at NLO can easily exceed 100k€.

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	

- ~40 processes
- First results implemented in 1998 ...this is 13 years worth of work of several people (~5M $/€/CHF)
- Cross sections and parton-level distributions at NLO are provided
- One general framework. However, each process implemented by hand

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.

ON THE SHOULDERS OF THE GIANTS

HERWIG, PYTHIA and SHERPA intend to offer a convenient framework for LHC physics studies, but with slightly different emphasis:

PYTHIA (successor to JETSET, begun in 1978):
- originated in hadronization studies: the Lund string
- leading in development of multiple parton interactions
- pragmatic attitude to showers & matching
- the first multipurpose generator: machines & processes

HERWIG (successor to EARWIG, begun in 1984):
- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- large process library with spin correlations in decays

SHERPA (APACIC++/AMEGIC++, begun in 2000):
- own matrix-element calculator/generator
- extensive machinery for CKKW matching to showers
- PYTHIA-like MPI model + HERWIG-like hadronization mode

Sjostrand®

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Sakurai Prize

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SM STATUS A FEW YEARS AGO

pp→ 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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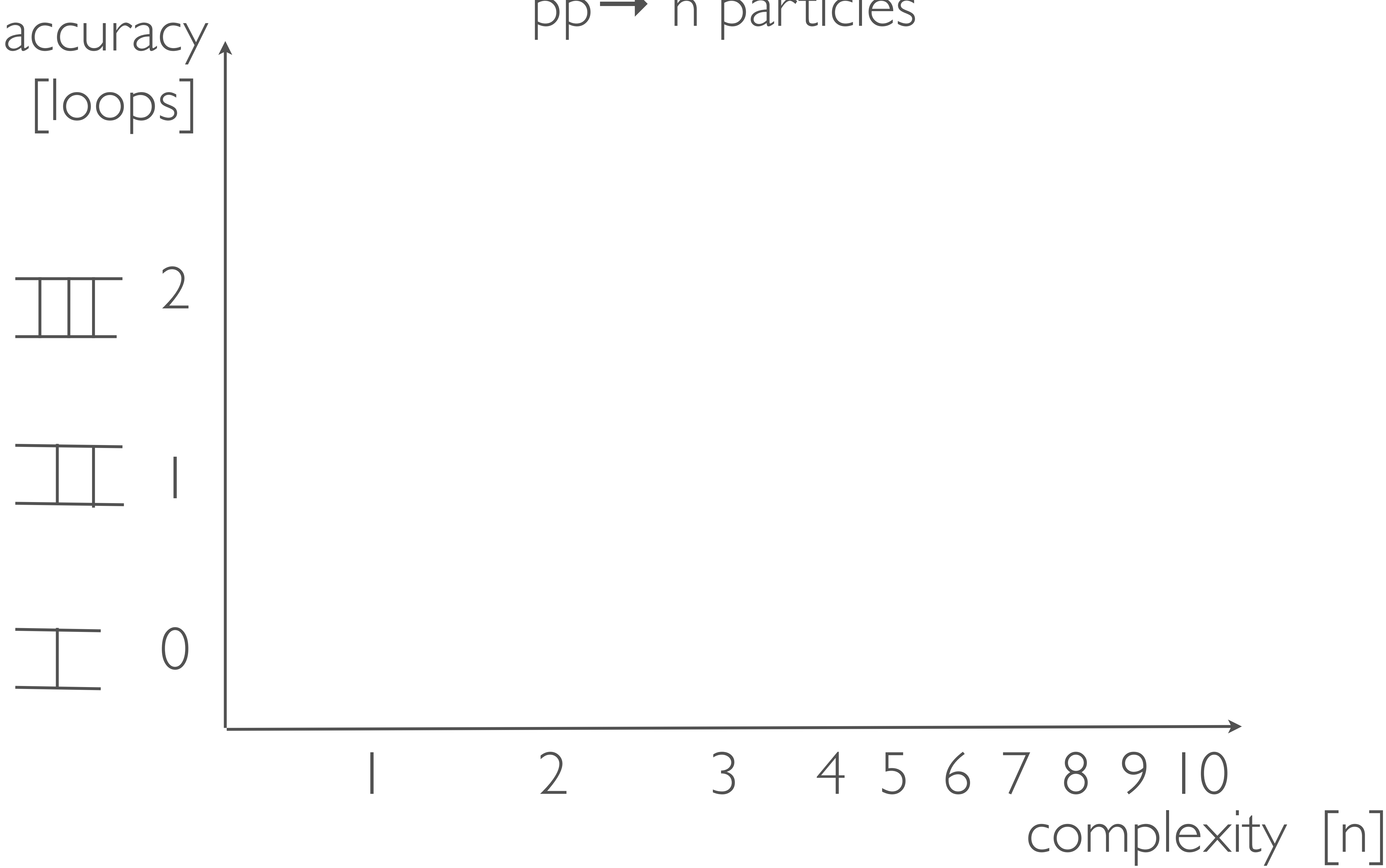
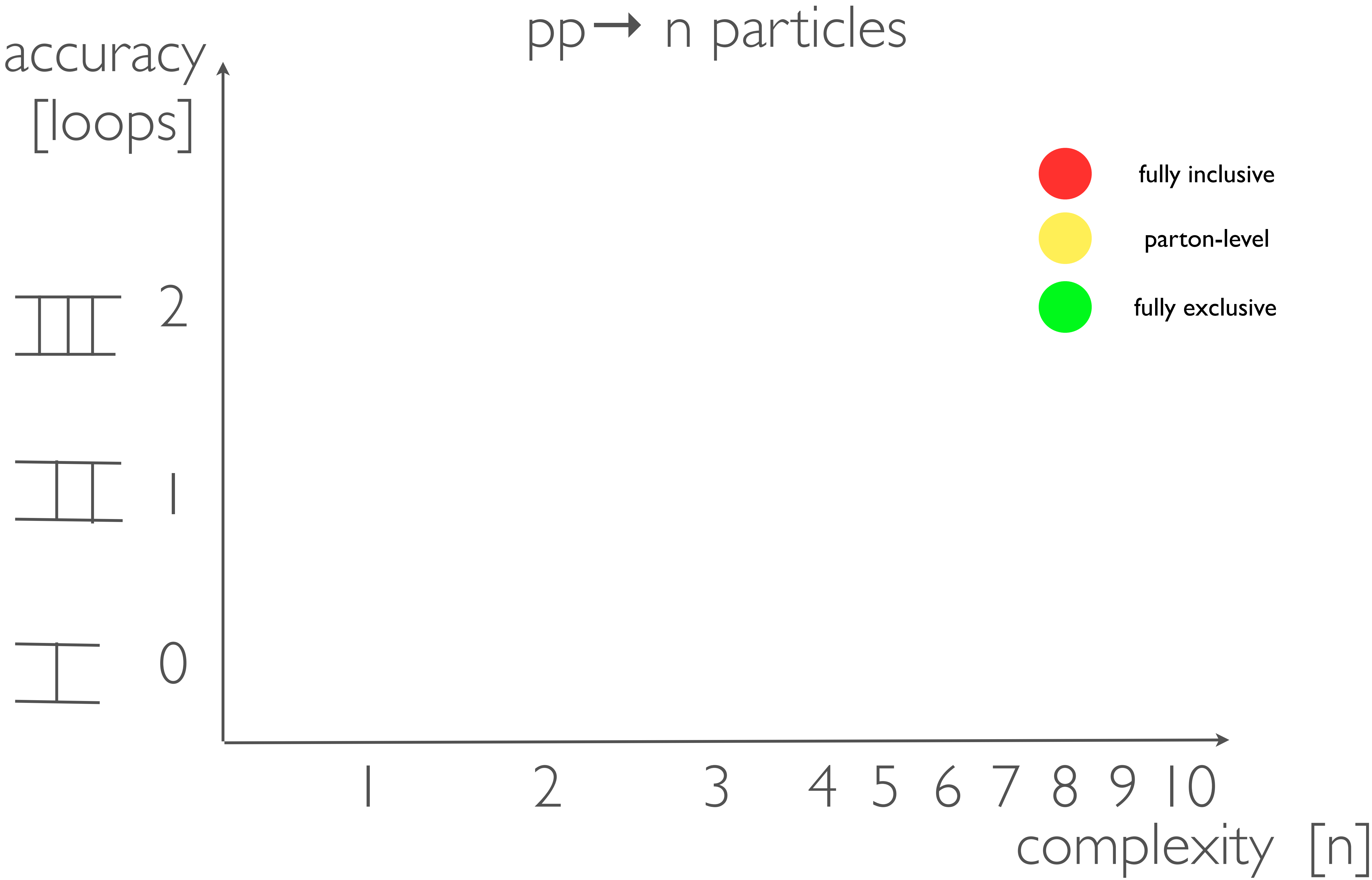


SM STATUS A FEW YEARS AGO



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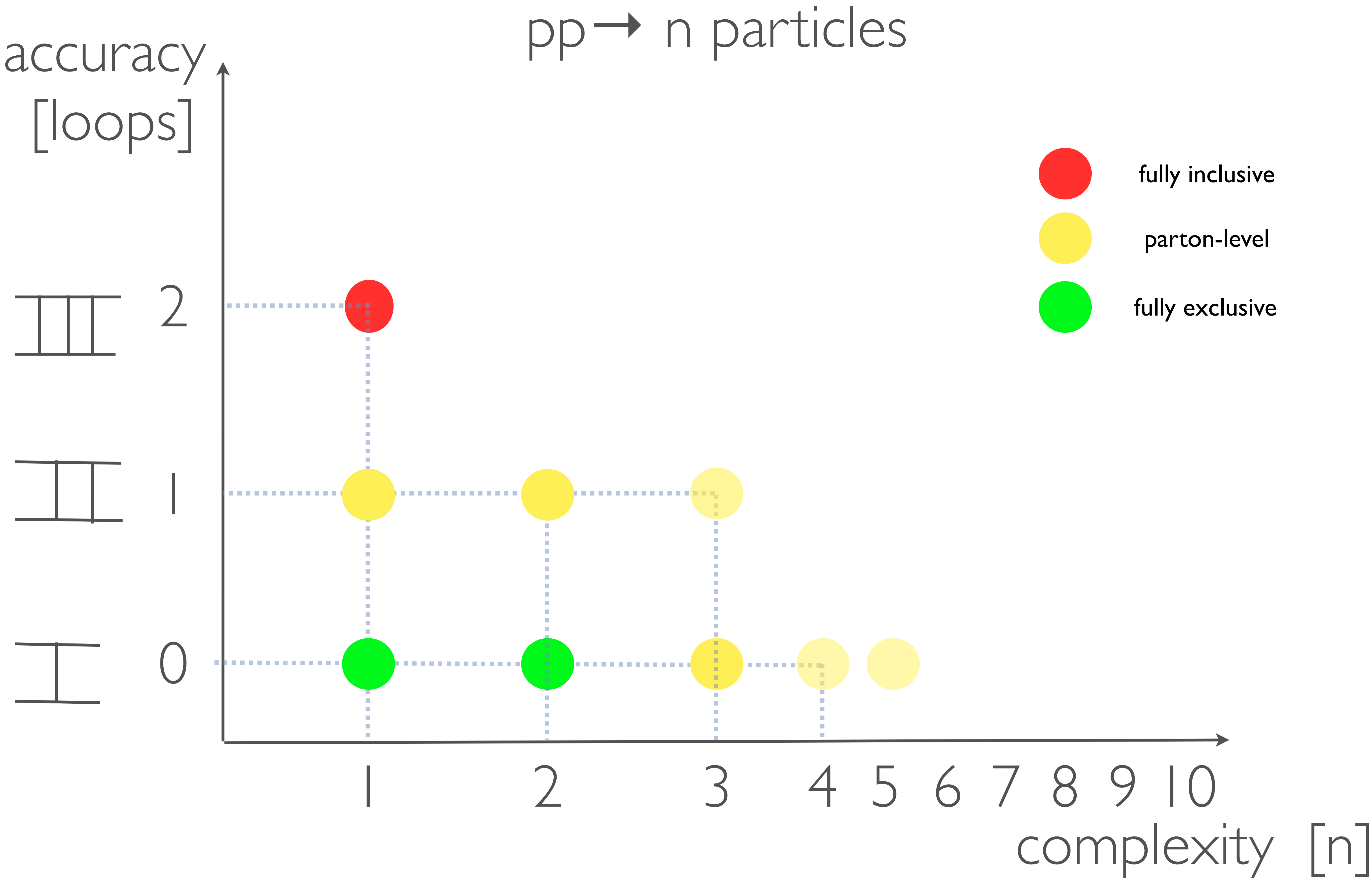
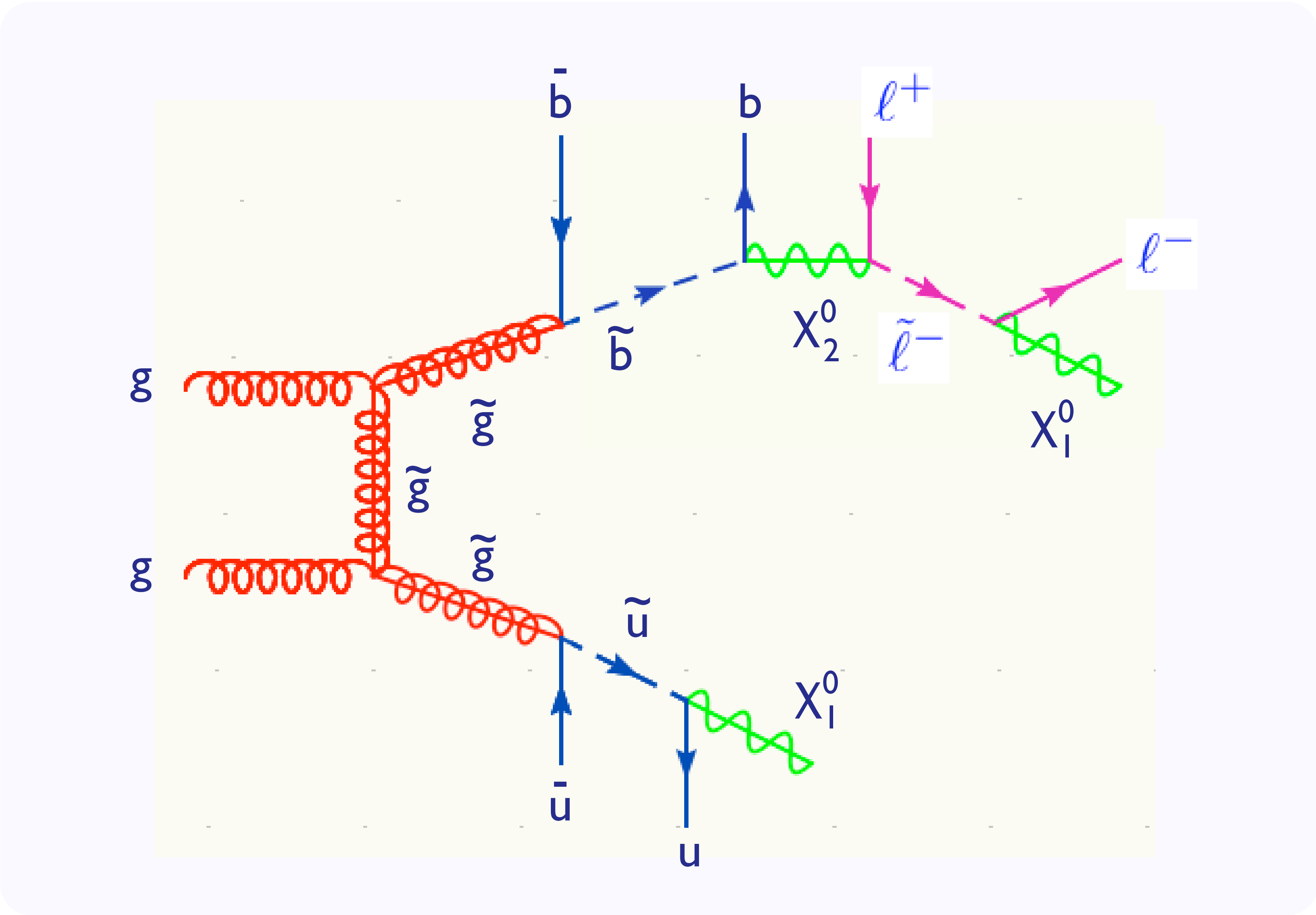
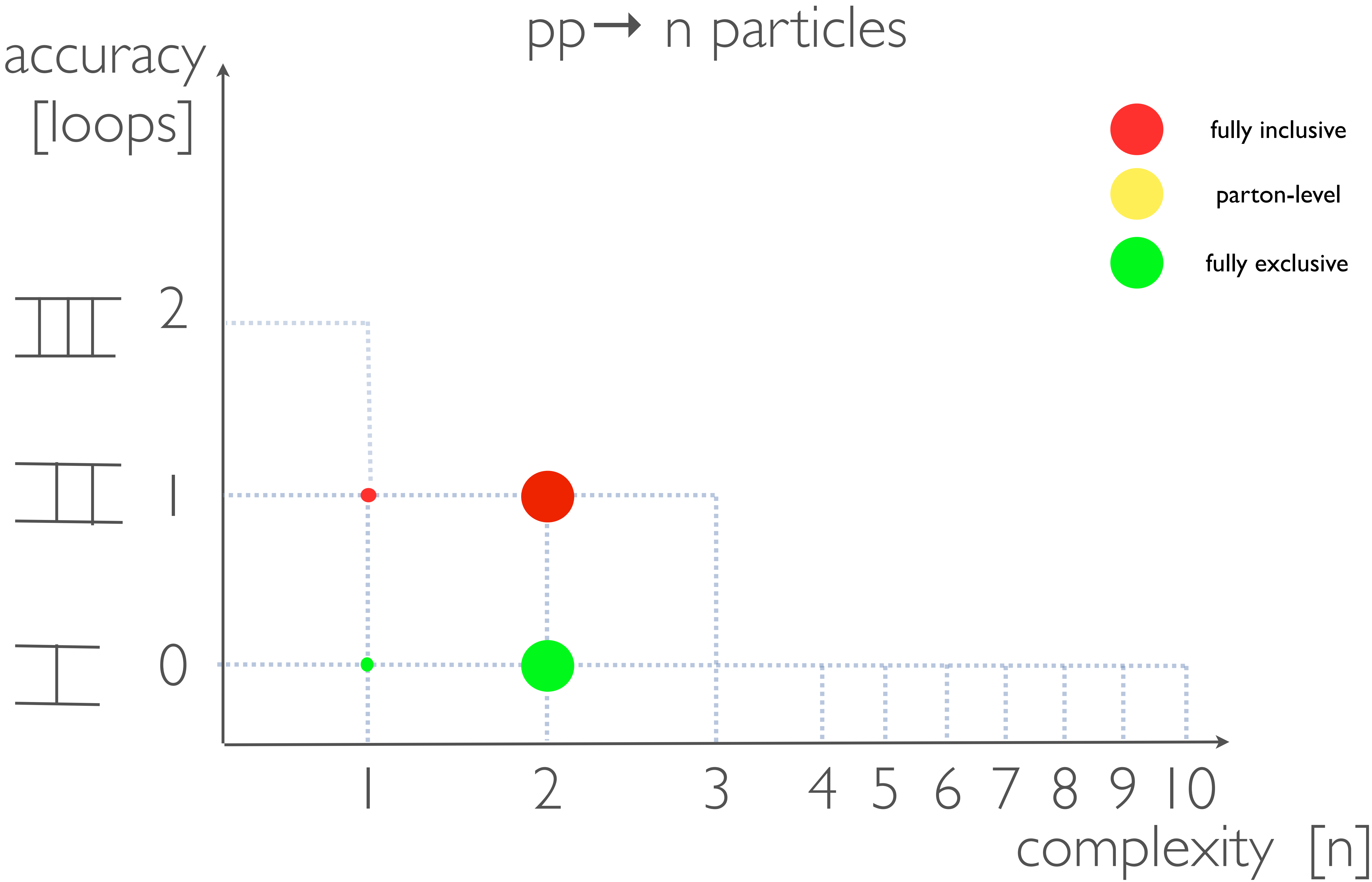


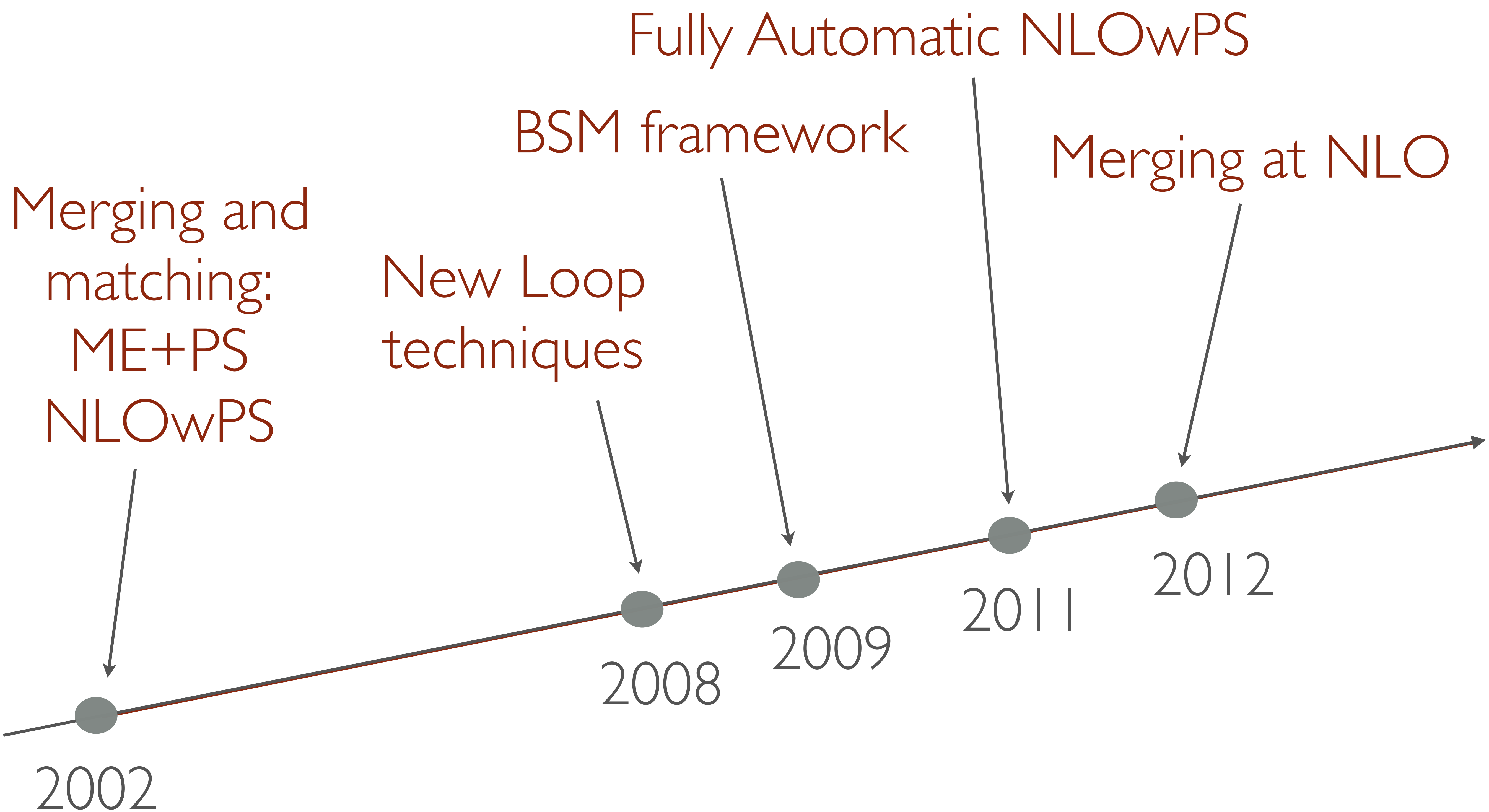
WHAT ABOUT NEW PHYSICS?



BSM (=SUSY)STATUS A FEW YEARS AGO



PREDICTIVE MC (SIMPLIFIED) PROGRESS



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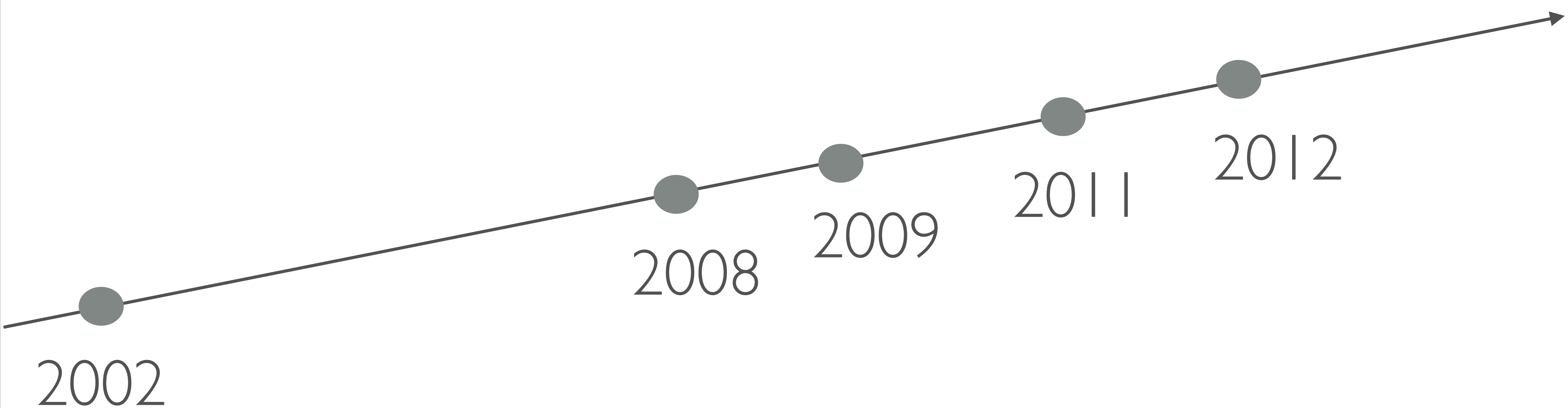

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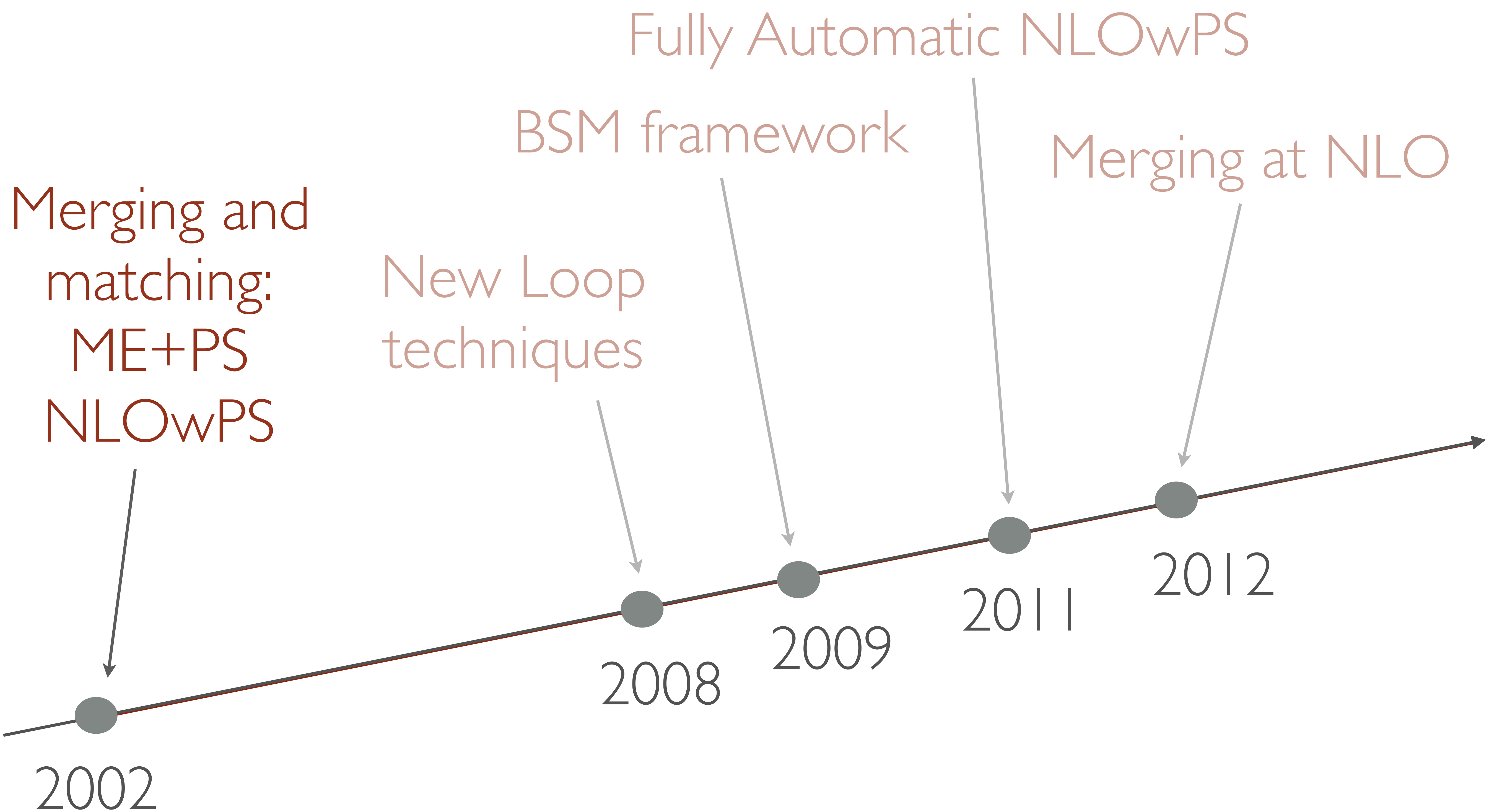

ME WITH PS

[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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Approaches are complementary: merge them!

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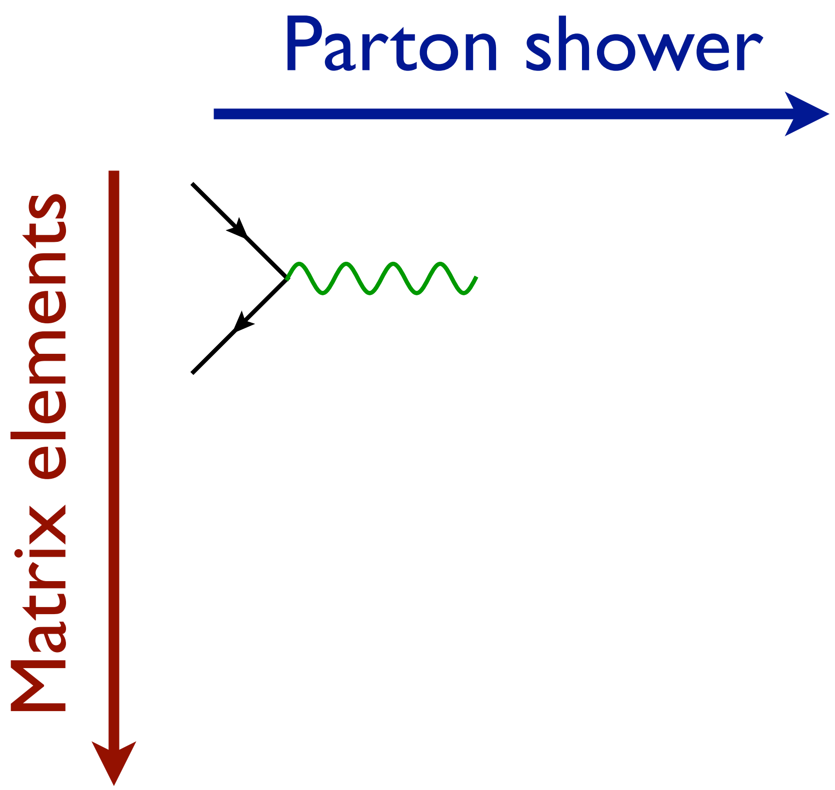
Approaches are complementary: merge them!

Difficulty: avoid double counting

Merging fixed order with PS



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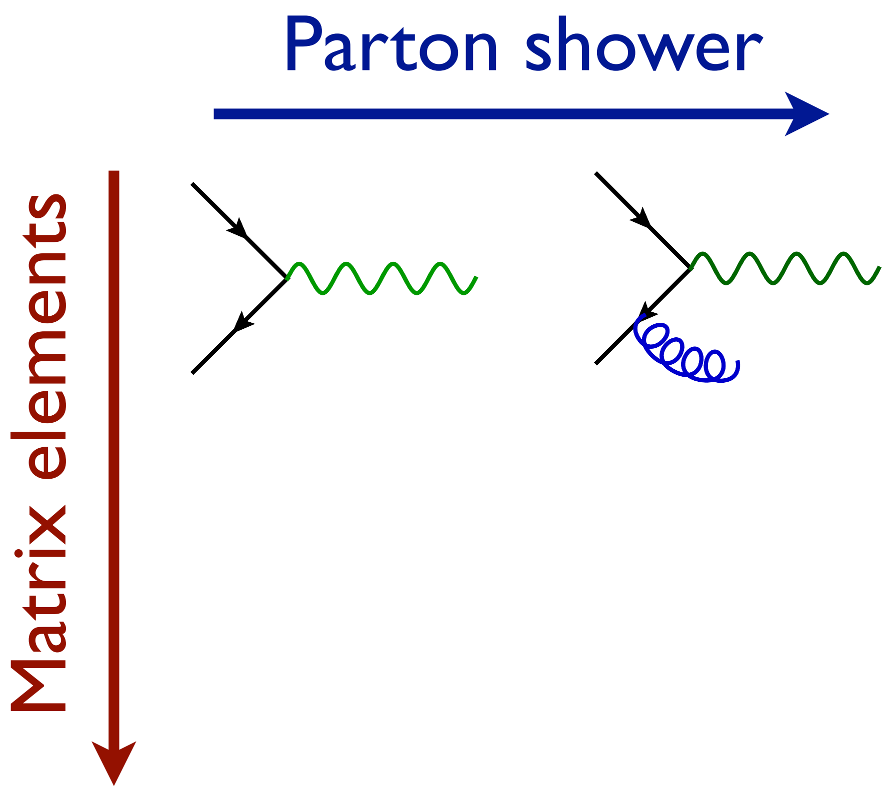

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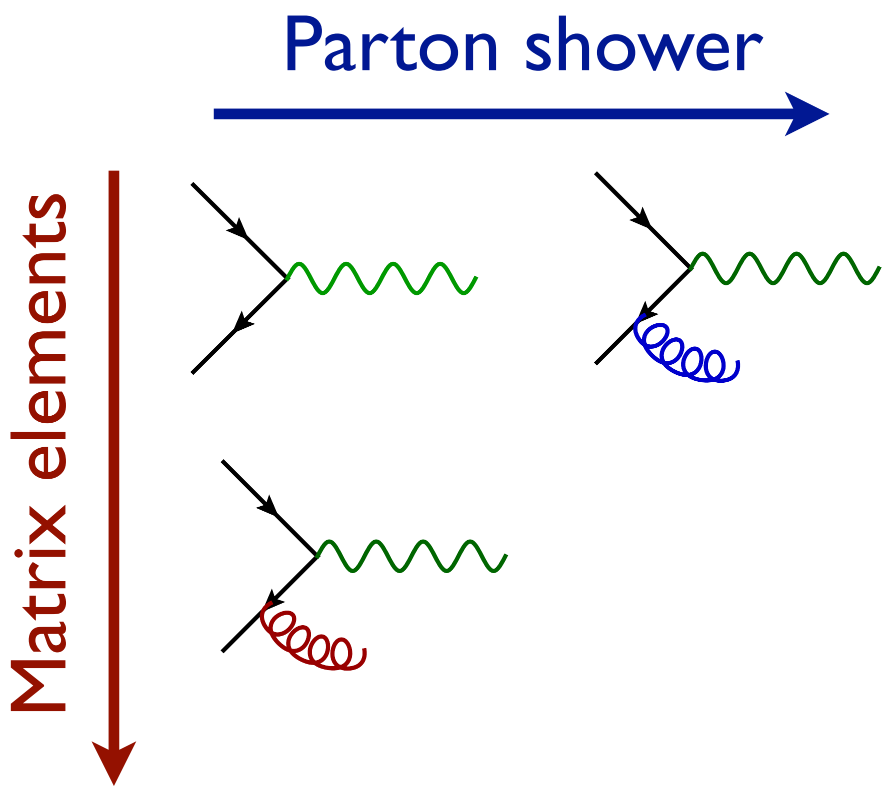
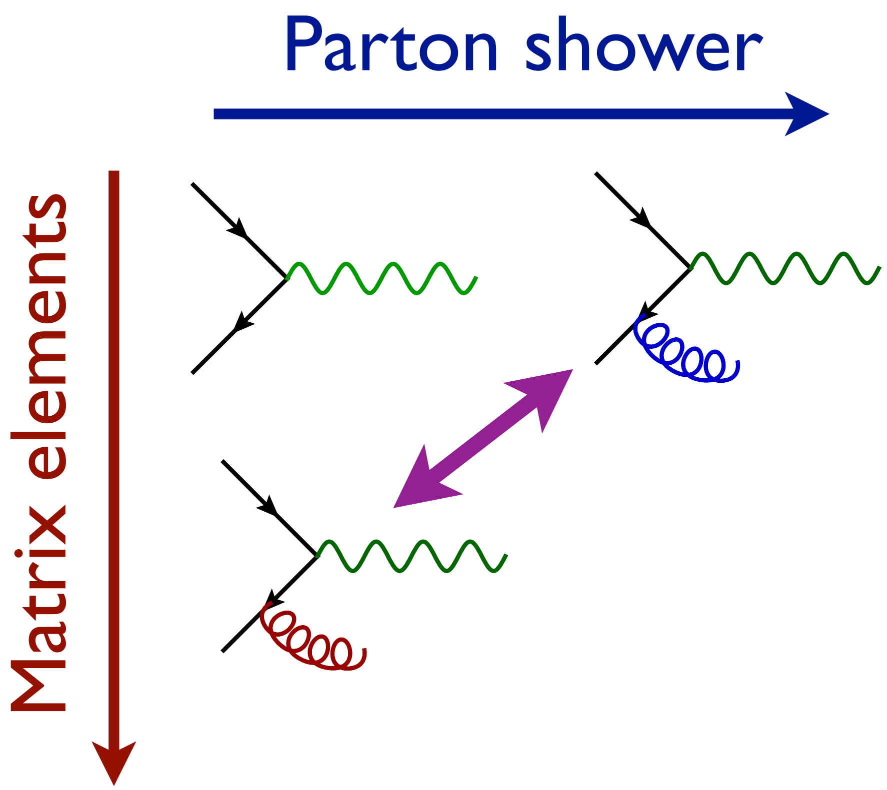
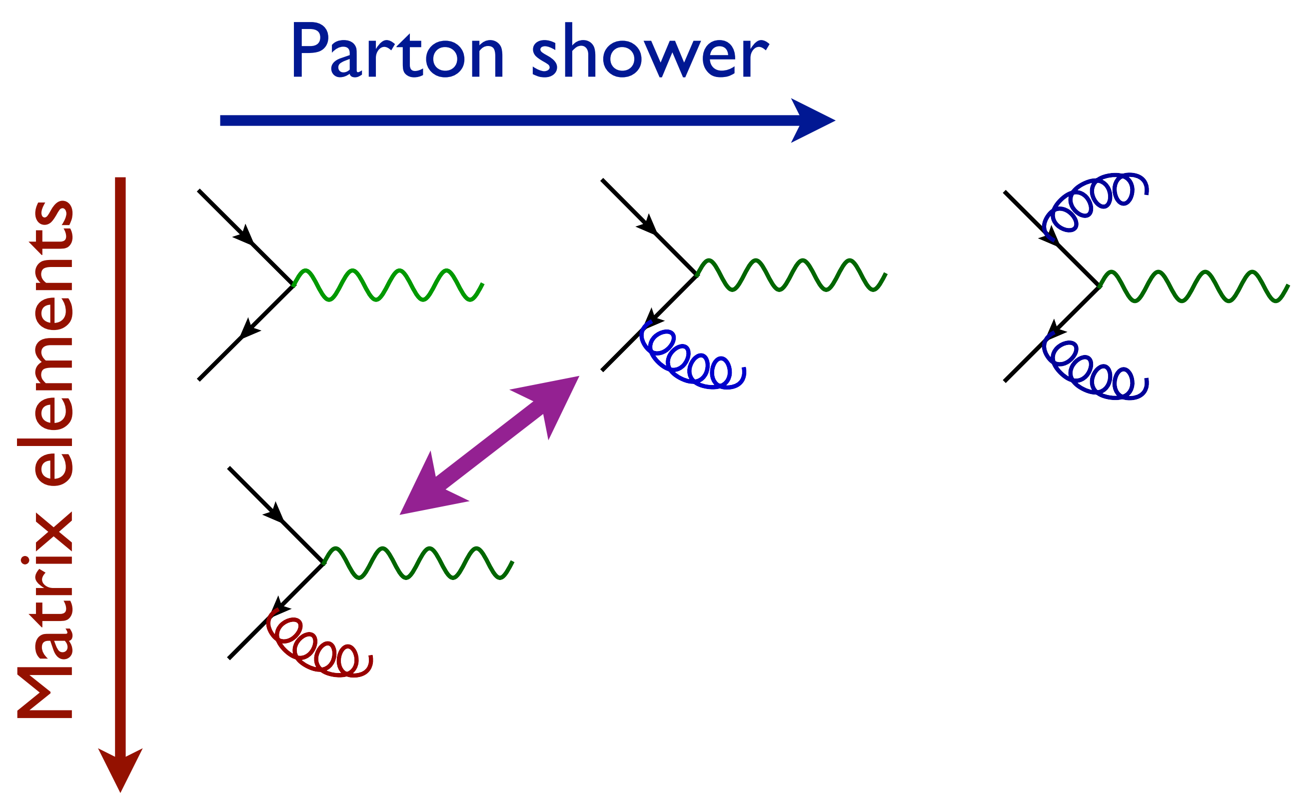



Parton shower
Matrix elements

Merging fixed order with PS



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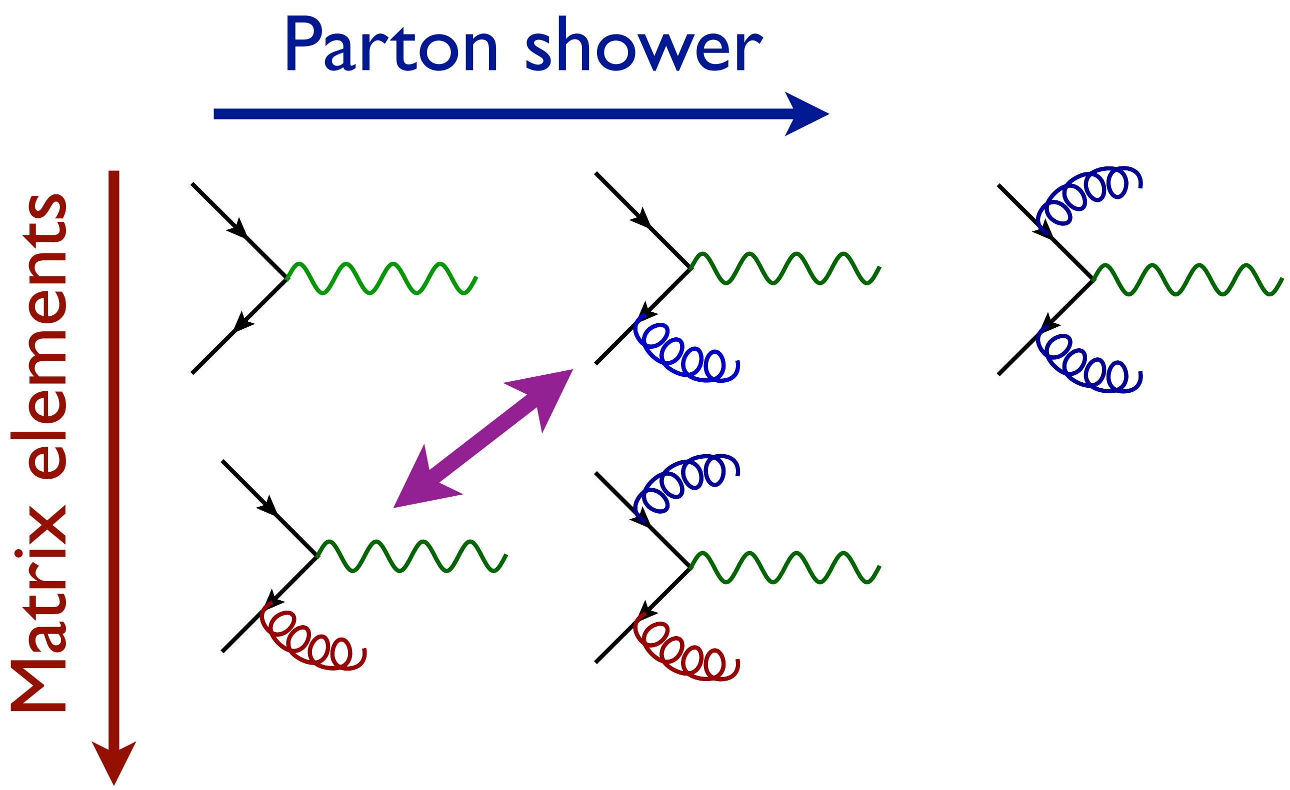

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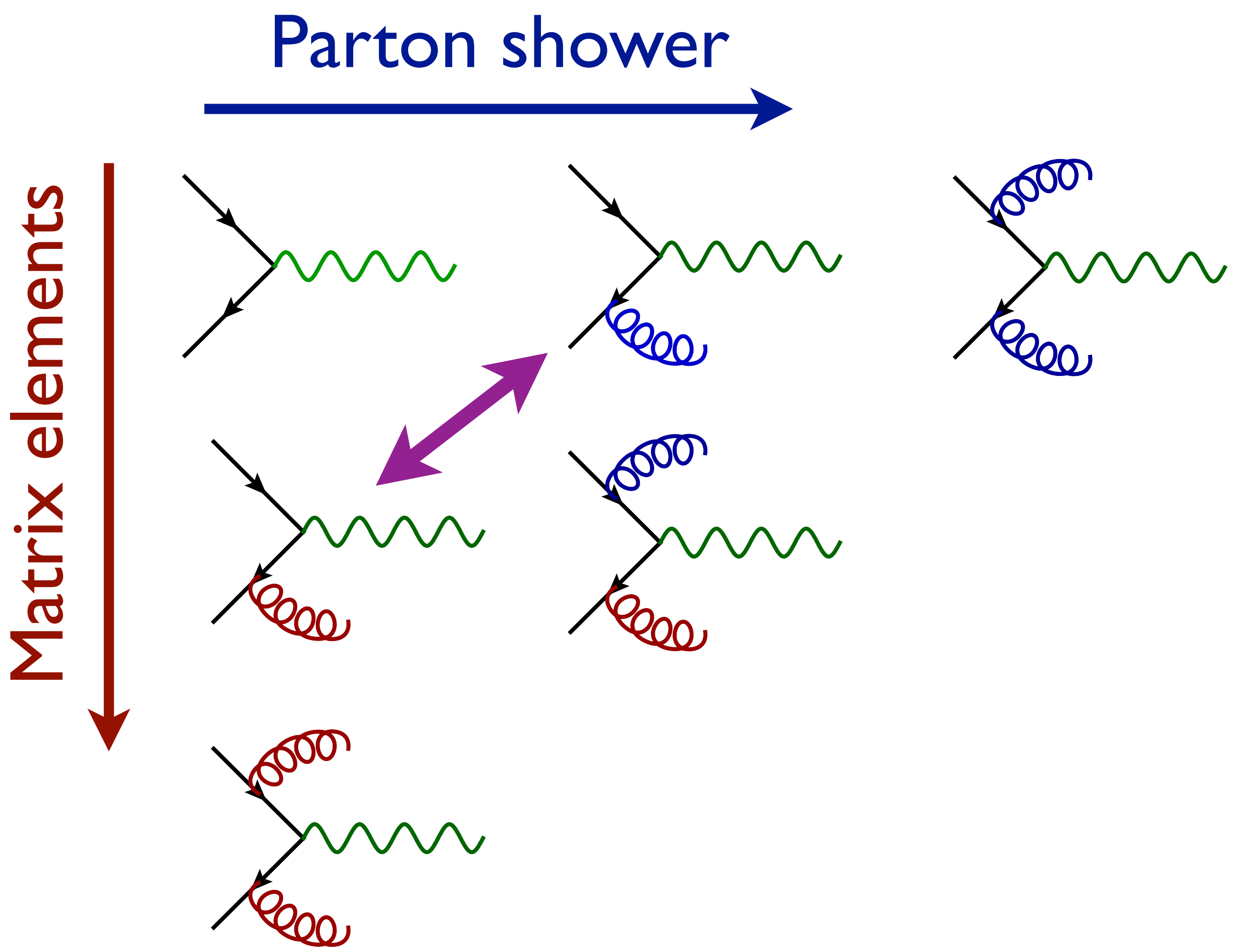
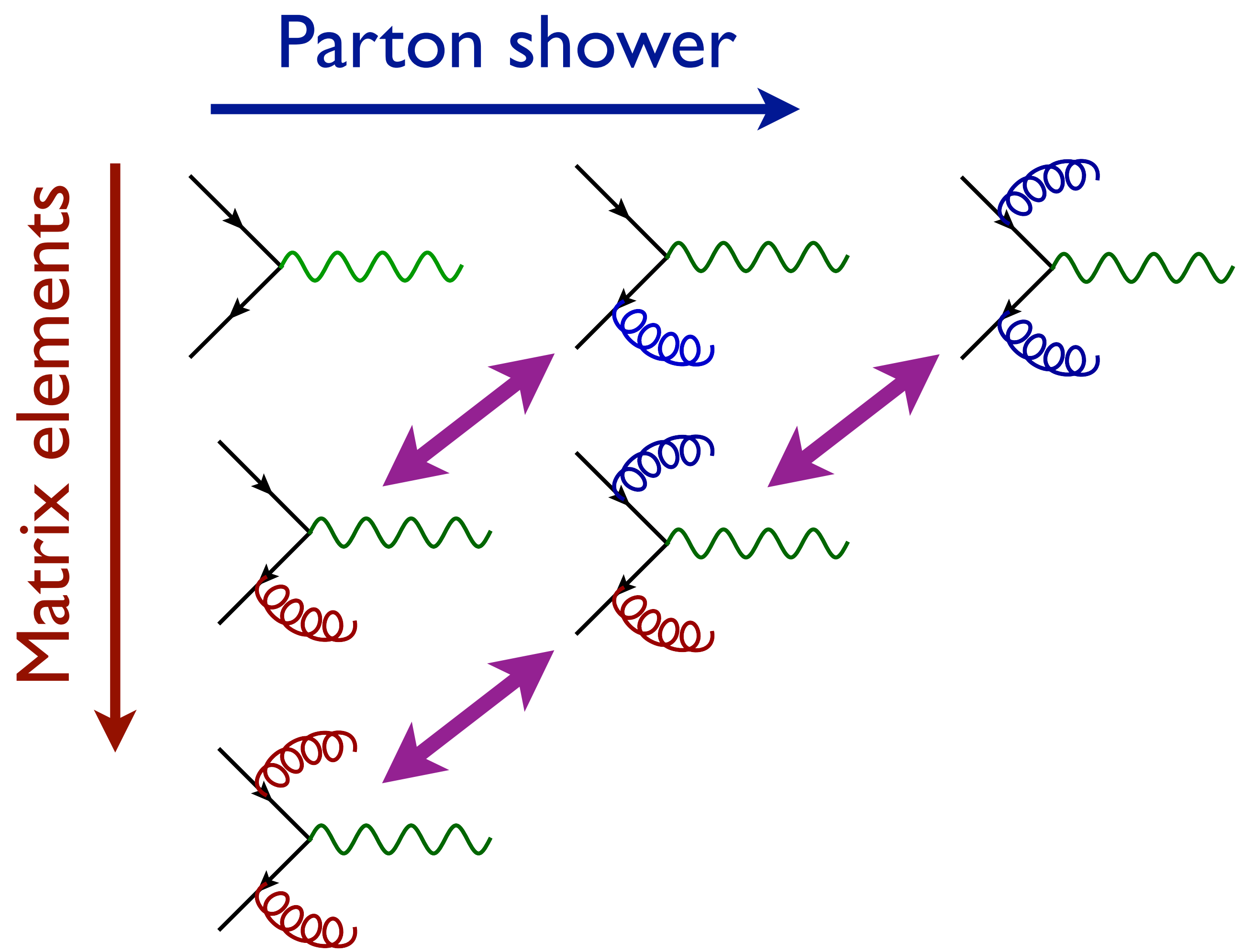


Thursday 18 April 2013

Merging fixed order with PS



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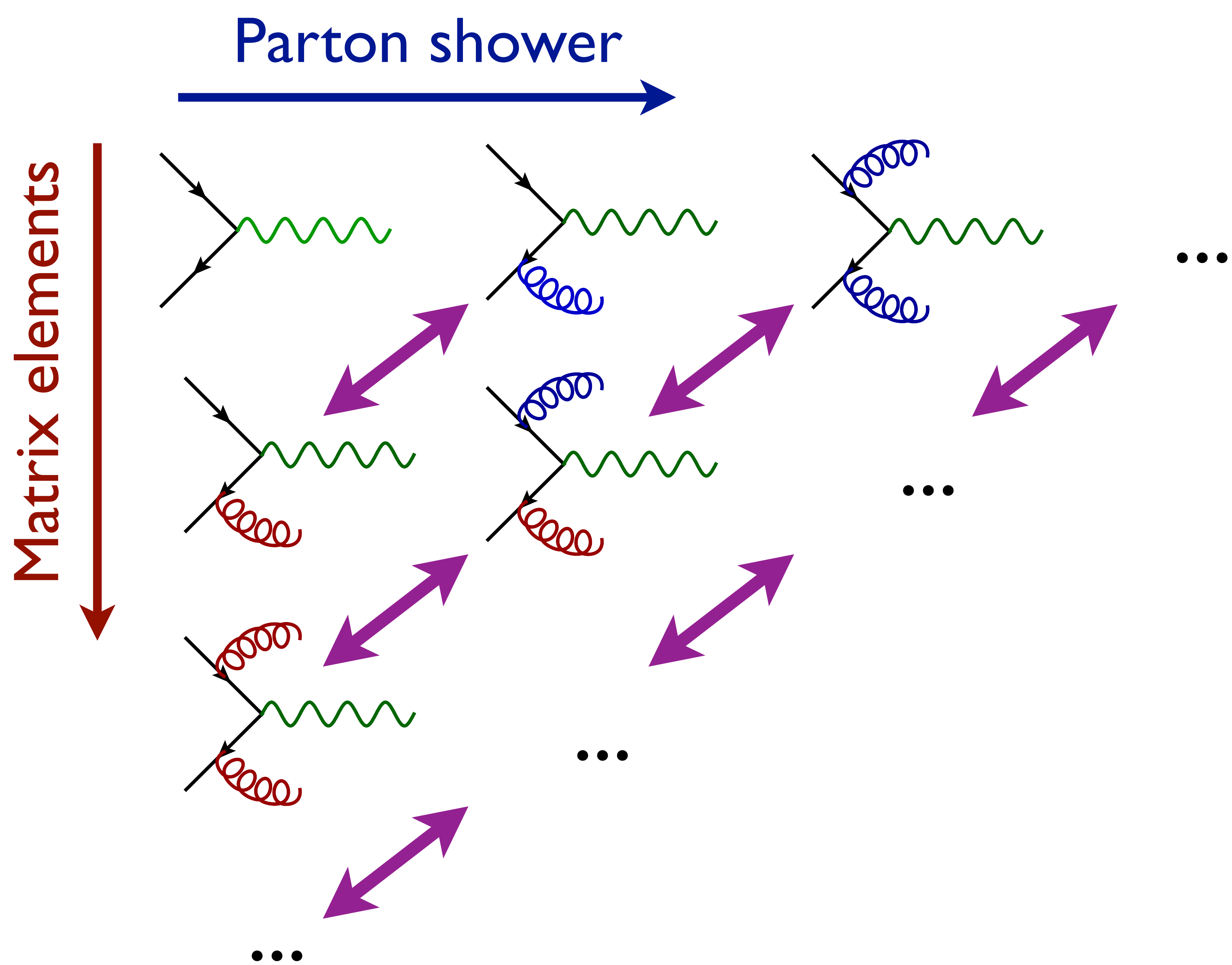

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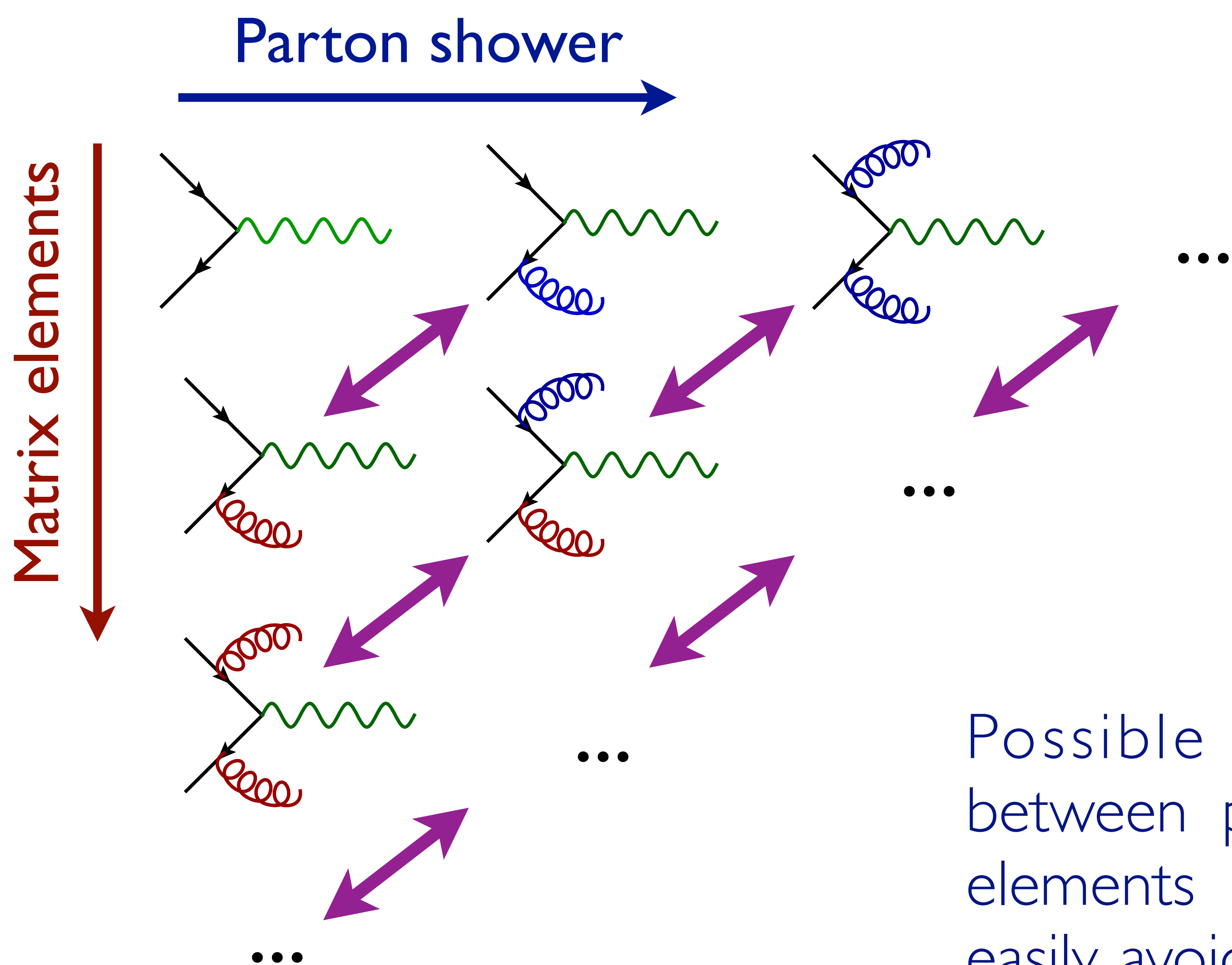

Possible double counting between partons from matrix elements and parton shower easily avoided by applying a cut in phase space

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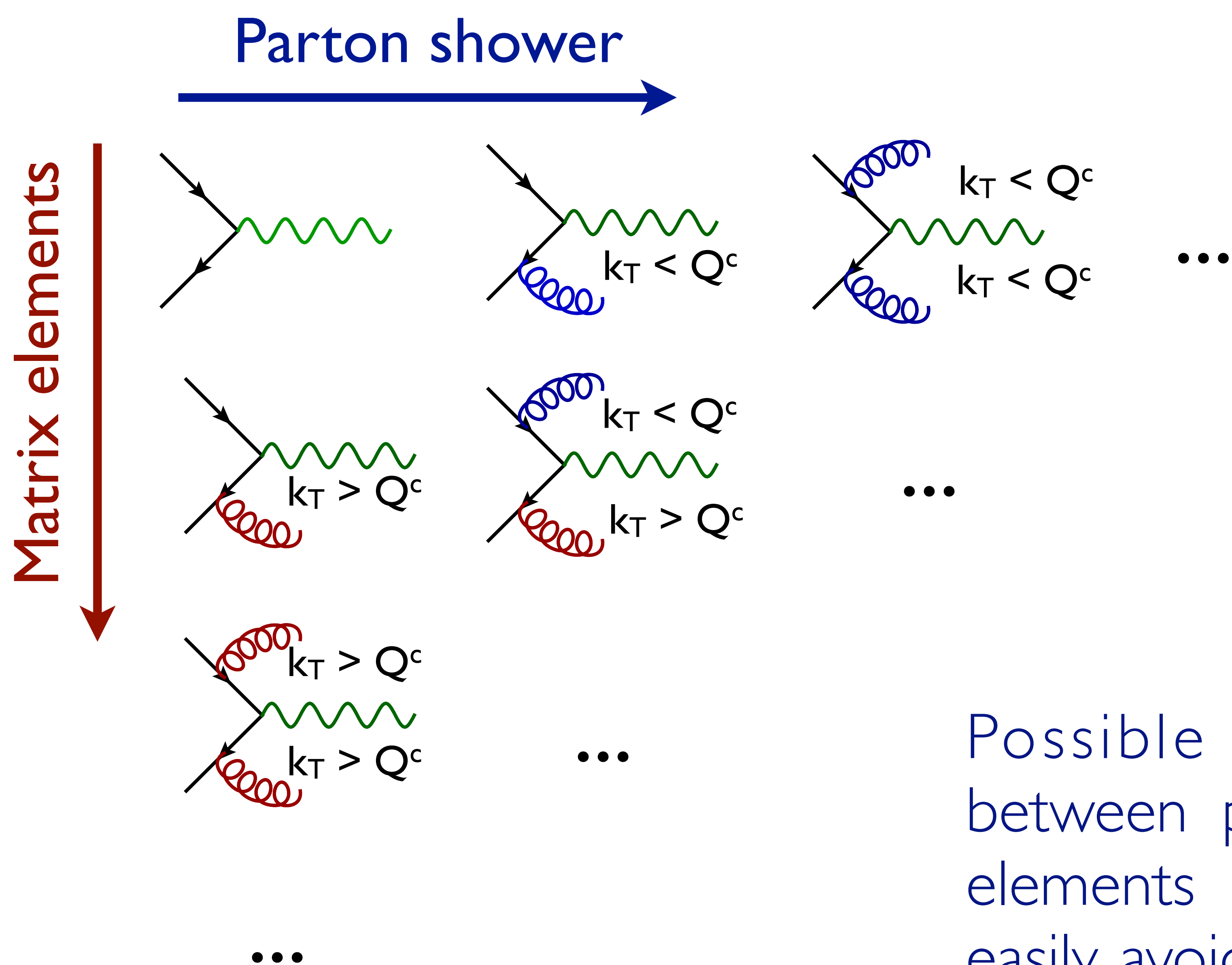

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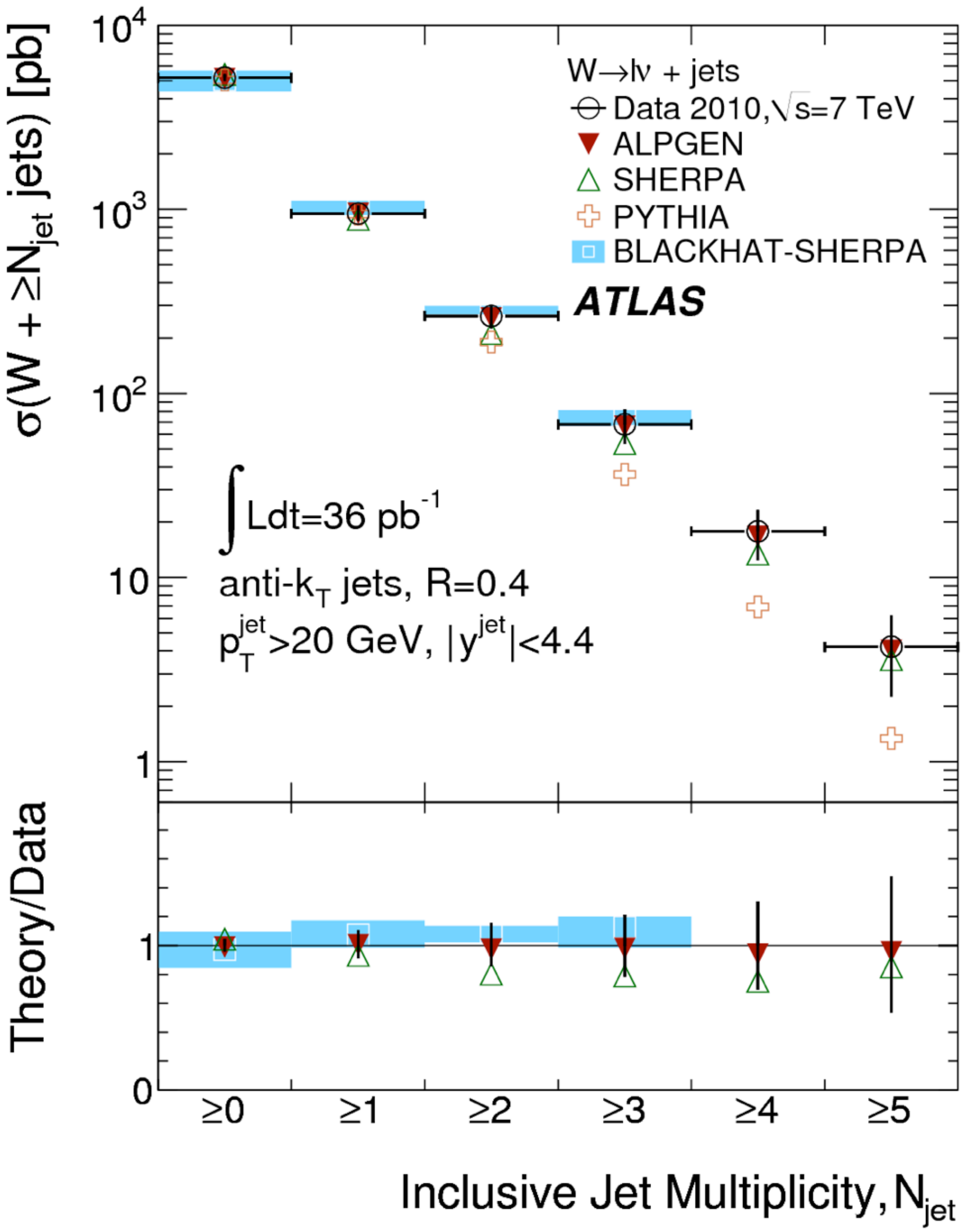
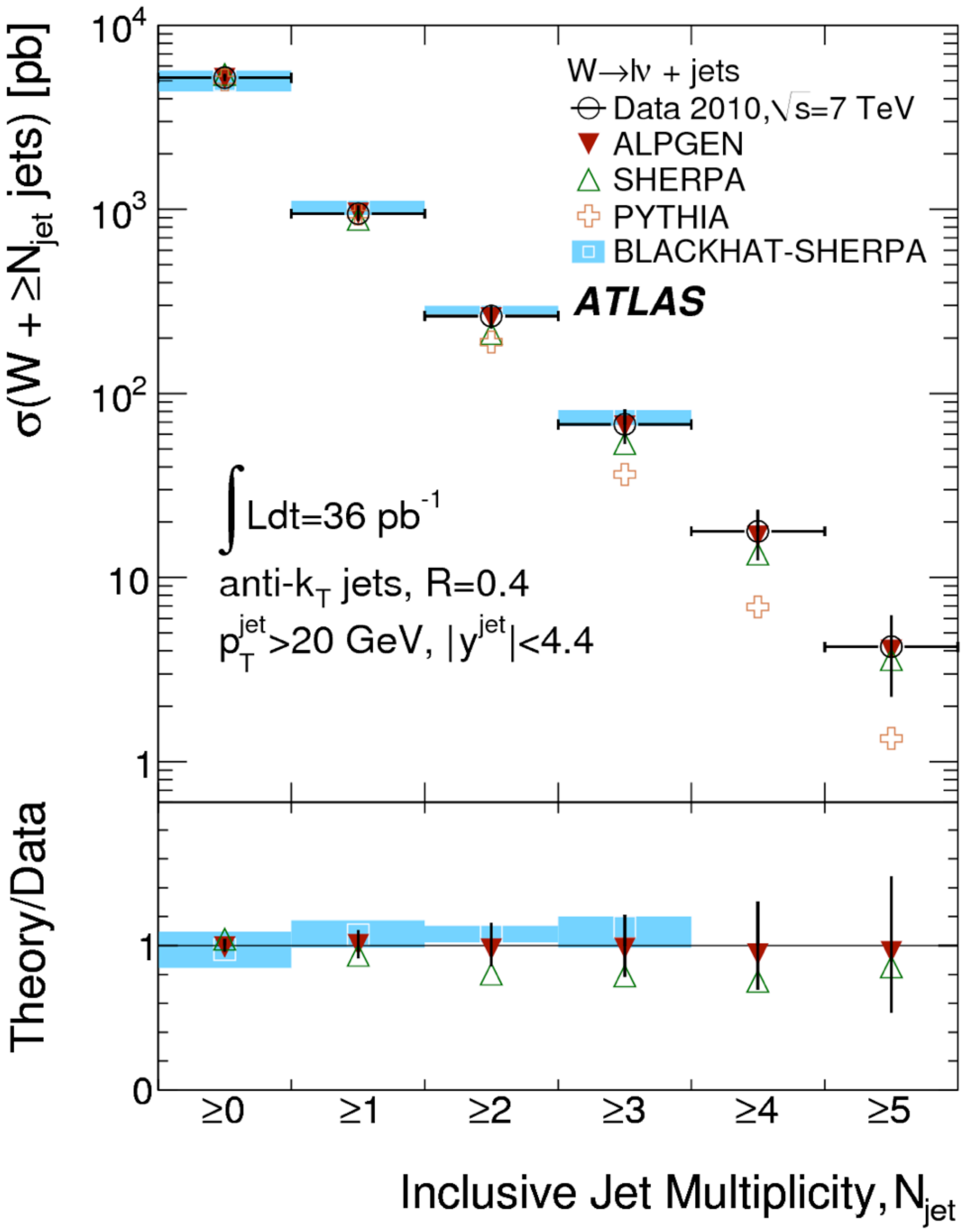
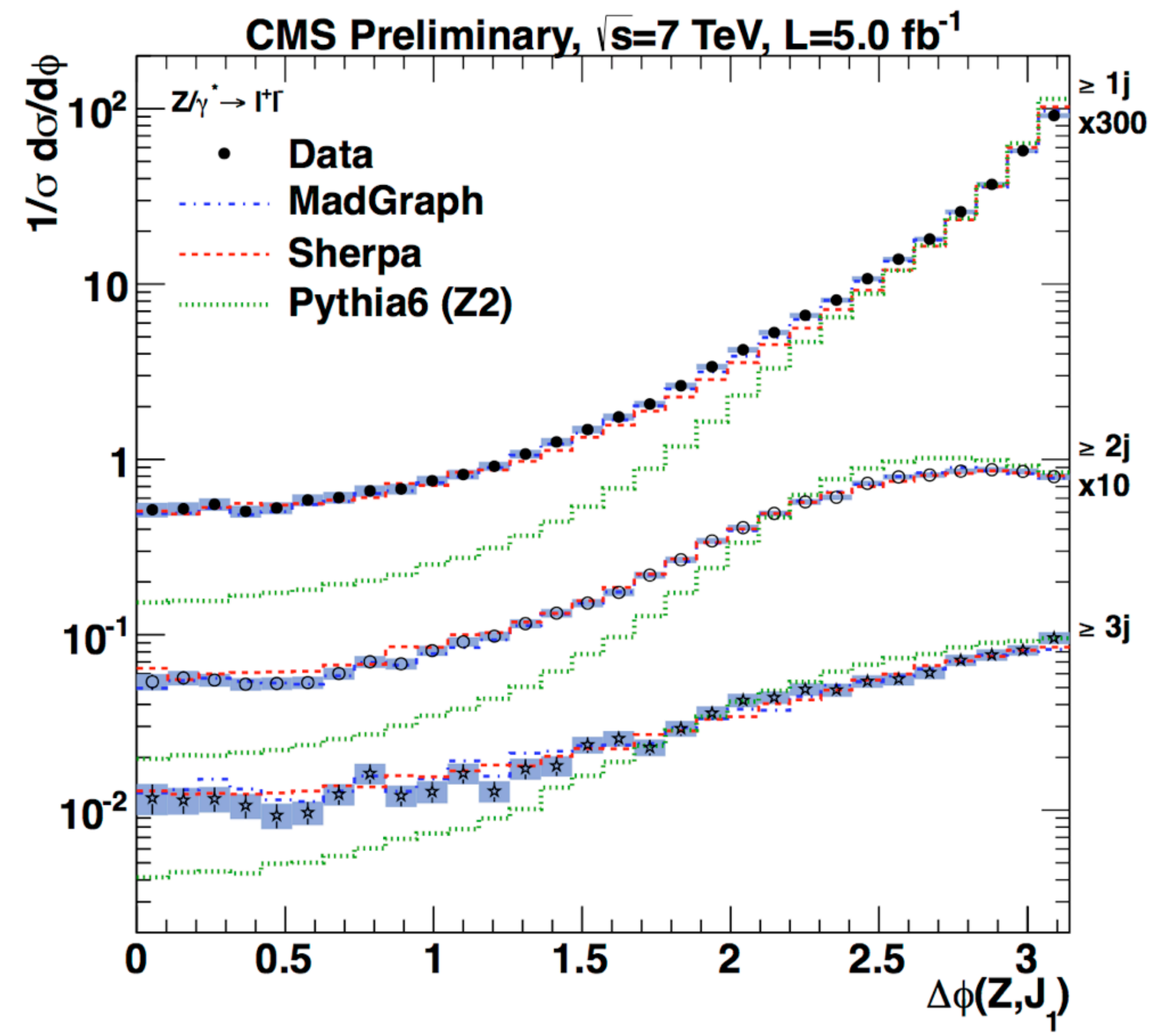
V+JETS AT THE LHC



Working amazingly well!

V+JETS AT THE LHC

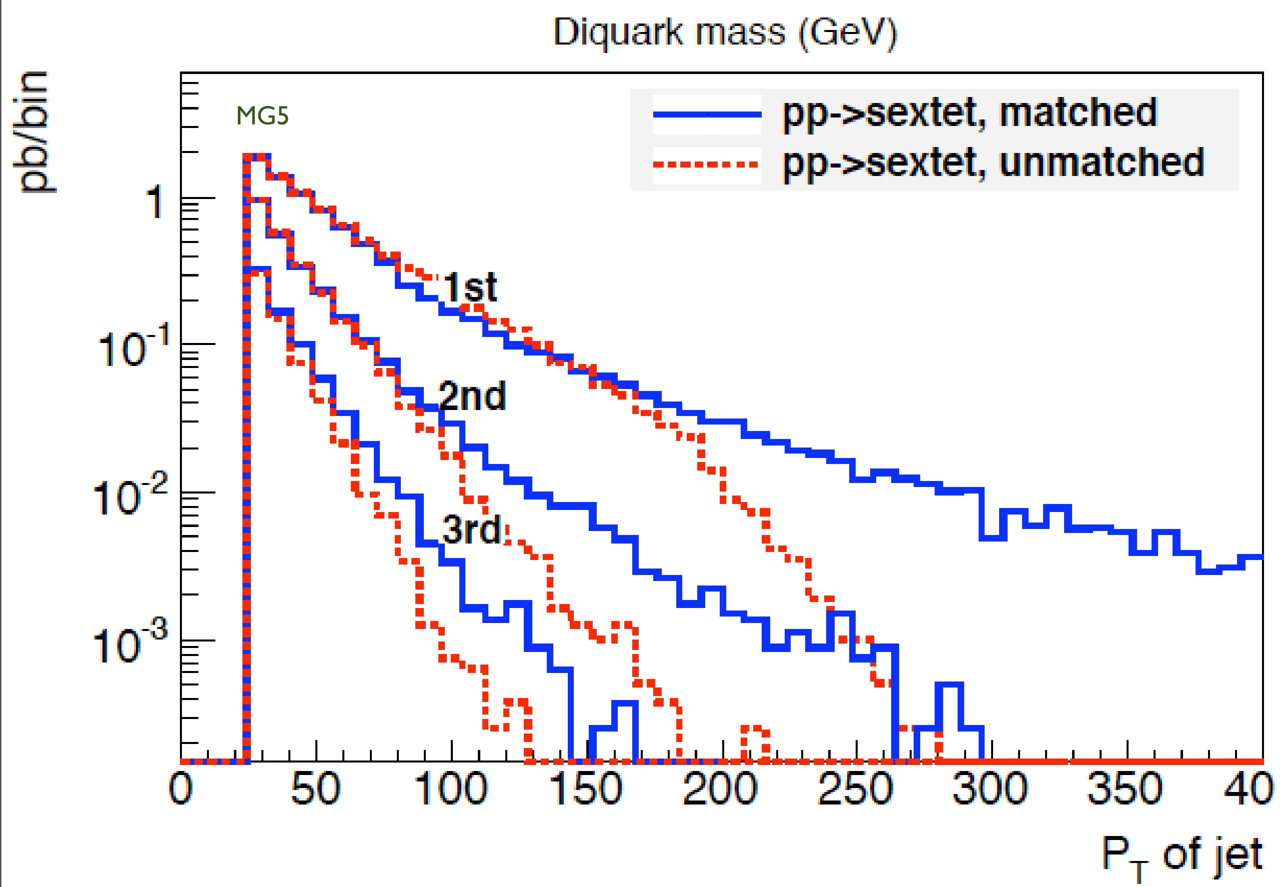




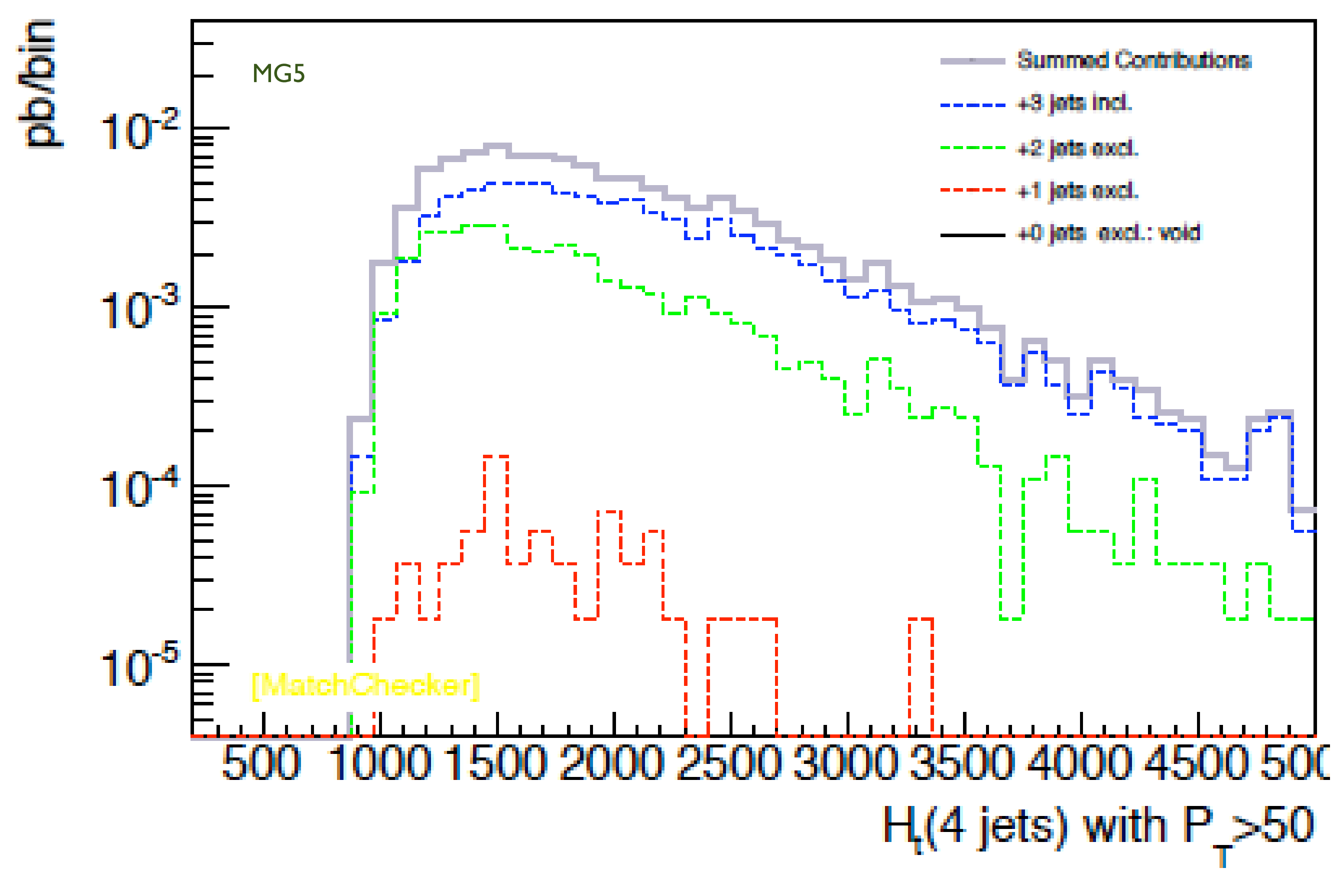
Working amazingly well!

EXAMPLE: BSM MULTIJET FINAL STATES

pp→X6 +jets

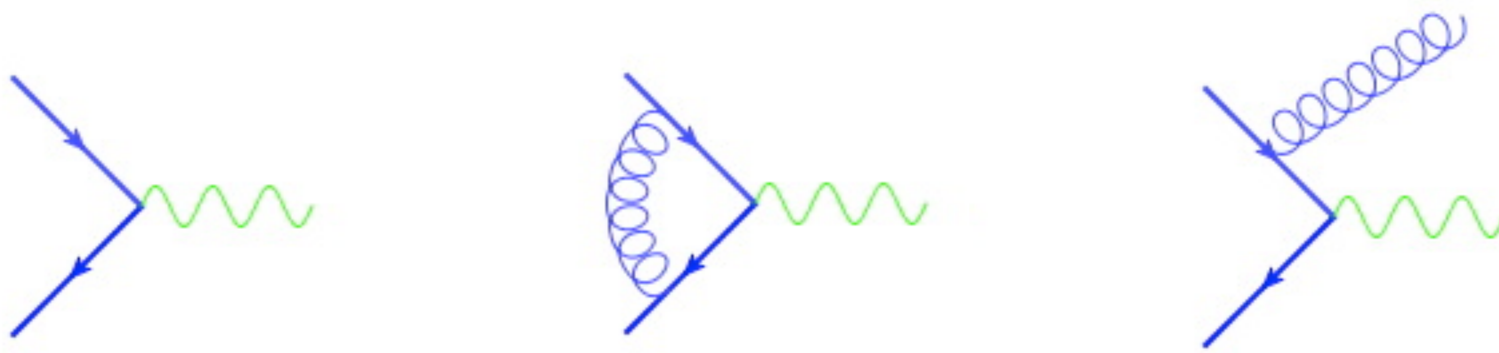


pp→Graviton (ADD&RS) +jets



New Physics models can be easily included in Matrix Element generators via FeynRules and results automatically for multi-jet inclusive final state obtained at the same level of accuracy that for the SM.

WHAT ABOUT NLO?



$$d\sigma^{\mathrm{NLOwPS}}_{\mathrm{NAIVE}} = \left[d\Phi_B(B(\Phi_B) + V + S^{\mathrm{int}}_{\mathrm{ct}})\right] I^n_{\mathrm{MC}} + \left[d\Phi_B d\Phi_{R|B}(R - S_{ct})\right] I^{n+1}_{\mathrm{MC}}$$

This simple approach does not work:

- Instability: weights associated to I^n_{MC} and I^{n+1}_{MC} are divergent pointwise (infinite weights).

- Double counting: $d\sigma^{naive}_{NLOwPS}$ expanded at NLO does not coincide with NLO rate. Some configurations are dealt with by both the NLO and the PSMC.

Currently, two solutions available

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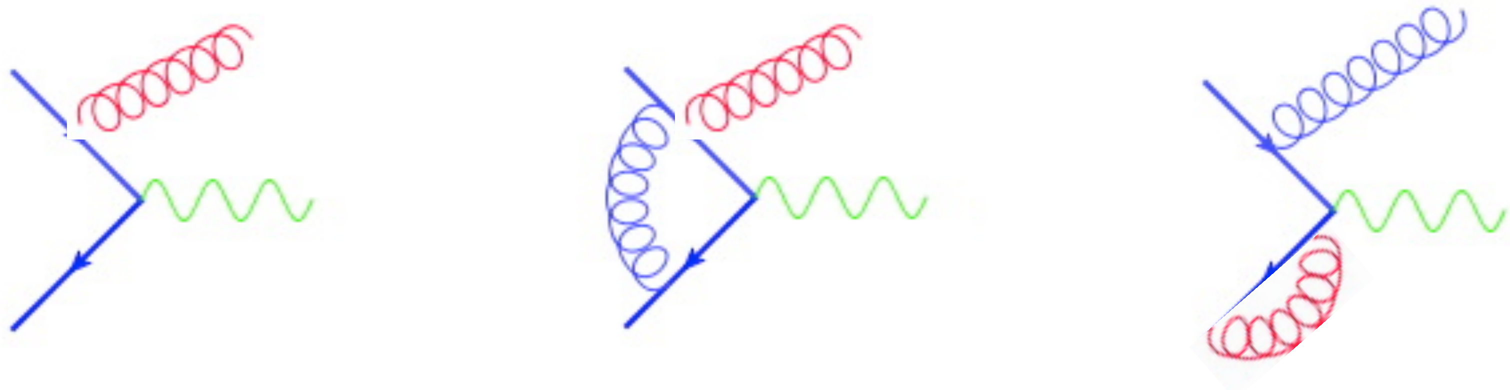

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Currently, two solutions available

NLOWPS IN A NUTSHELL

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

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)

MC@NLO AND POWHEG

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- Now available in aMC@NLO (see later)

POWHEG

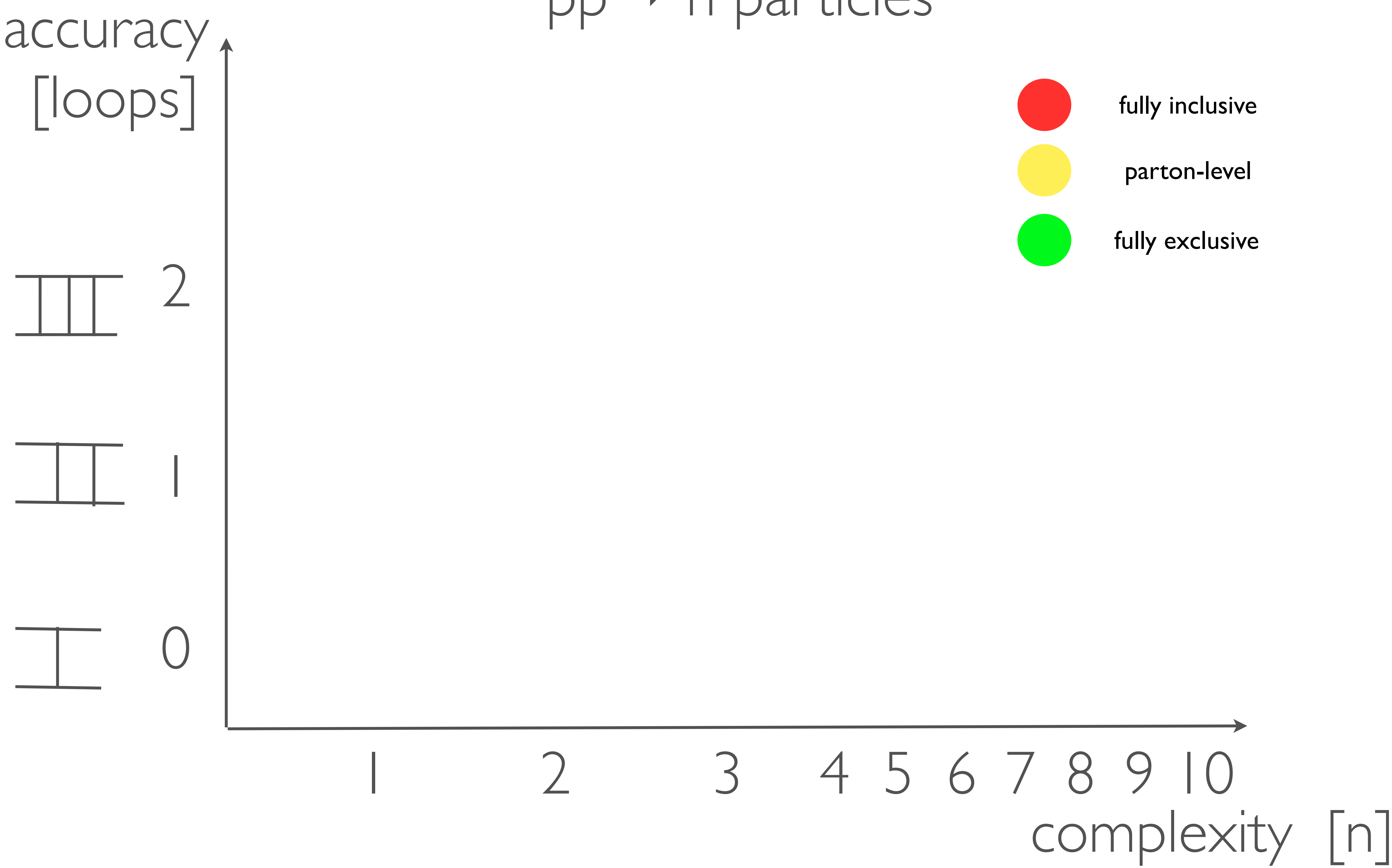
[Nason 2004;
Frixione, Nason, Oleari, 2007]

- 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]

SM STATUS : SINCE 2007

pp→ n particles



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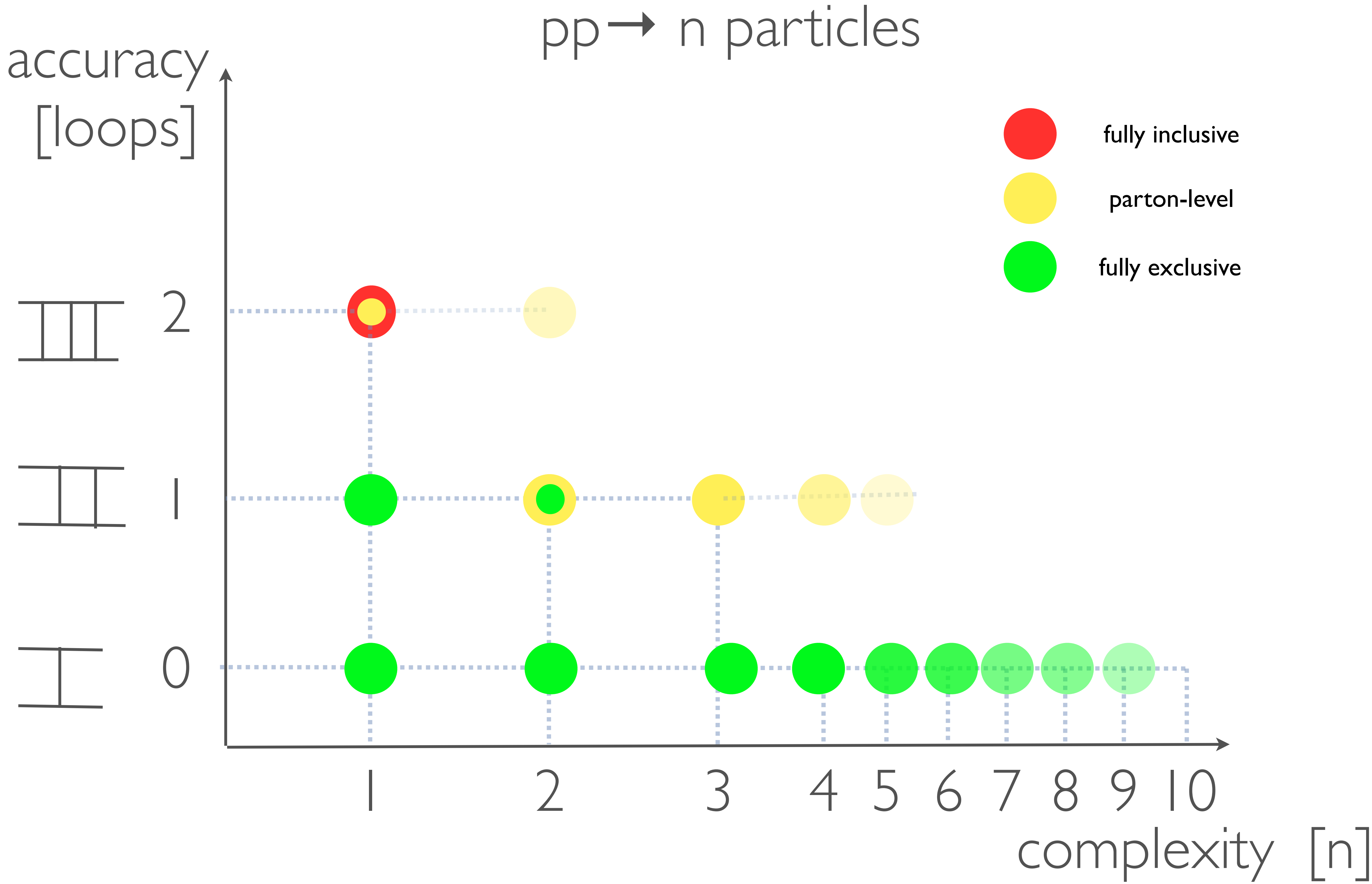


AUTOMATION

- **Cost saving**

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

- **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.

AUTOMATION

AUTOMATION

GENIUS: 1% INSPIRATION AND 99% PERSPIRATION.

[Thomas Edison]

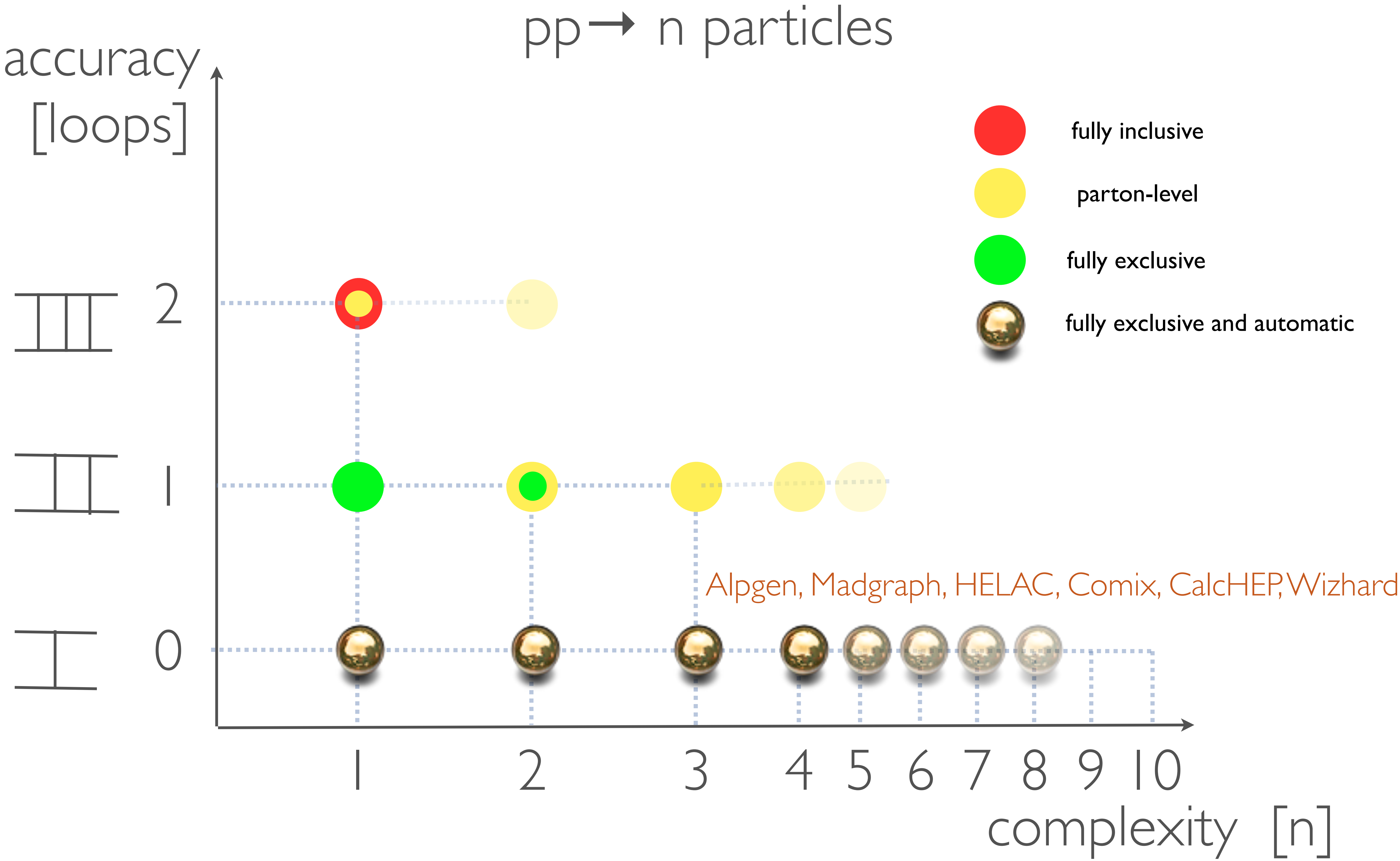
AUTOMATION

GENIUS: 1% INSPIRATION AND 99% PERSPIRATION.

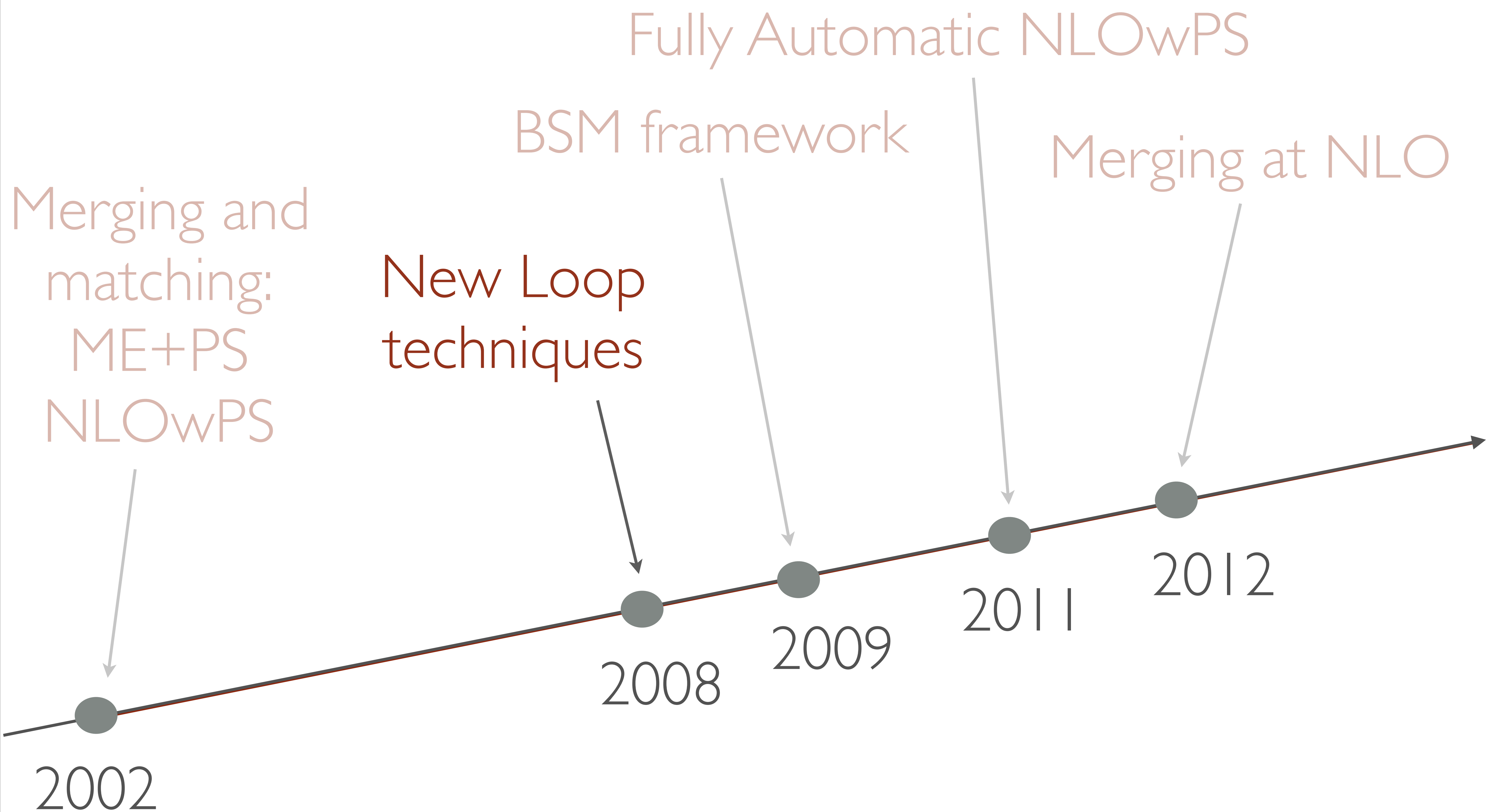
[Thomas Edison]

TRUE, BUT PERSPIRATION CAN BE AUTOMATED!

SM STATUS : SINCE 2007



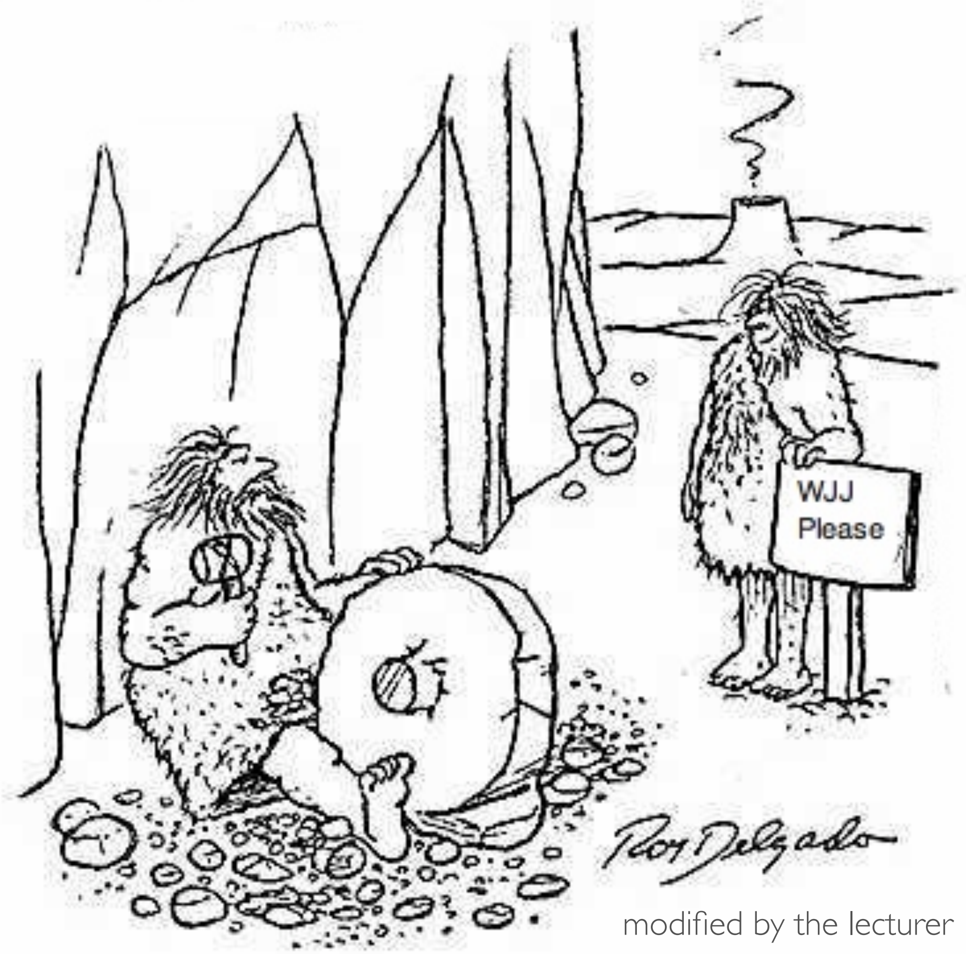
PREDICTIVE MC (SIMPLIFIED) PROGRESS



Predictions at NLO

modified by the lecturer

Predictions at NLO



modified by the lecturer

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

Integrand Reduction
(ex. CutTools, Samurai)

Tensor Reduction
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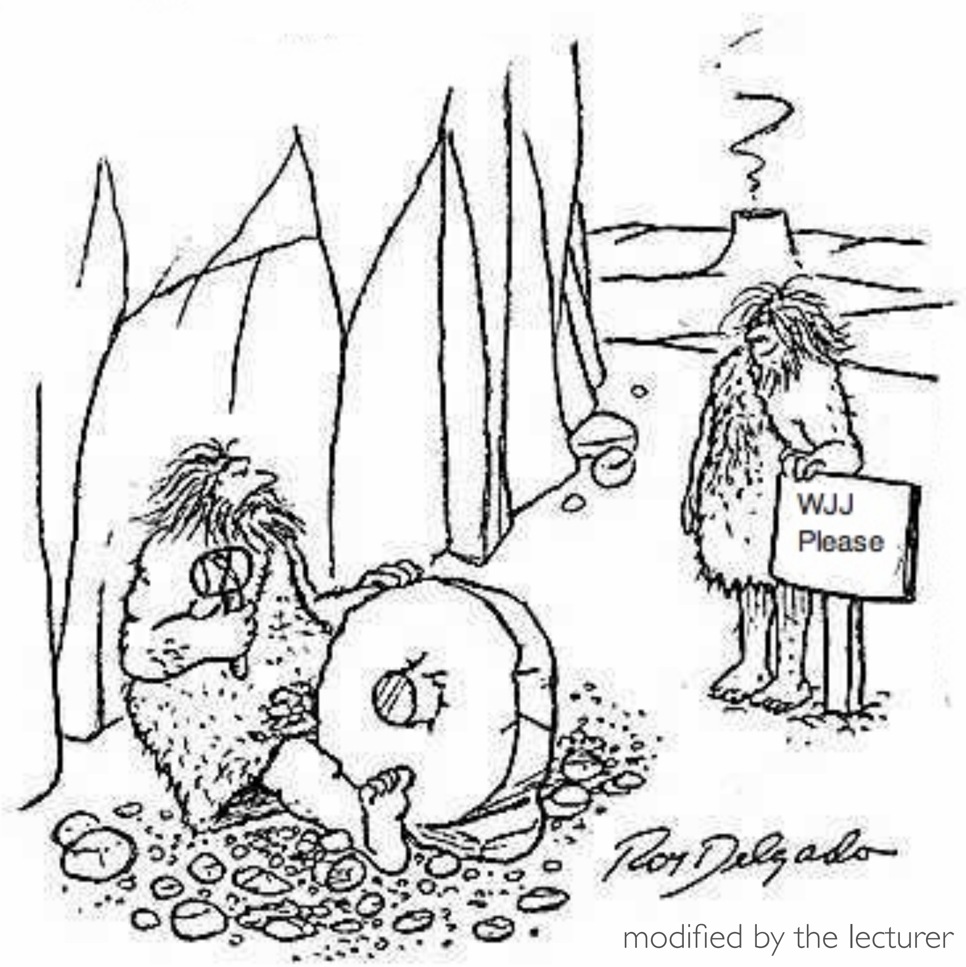
Predictions at NLO



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(ex. BlackHat, Rocket,...)

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(ex. CutTools, Samurai)

Tensor Reduction
(ex. Golem)

Thanks to new amazing results, some of them inspired by string theory developments, now the computation of loops has been extended to high-multiplicity processes or/and automated.

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

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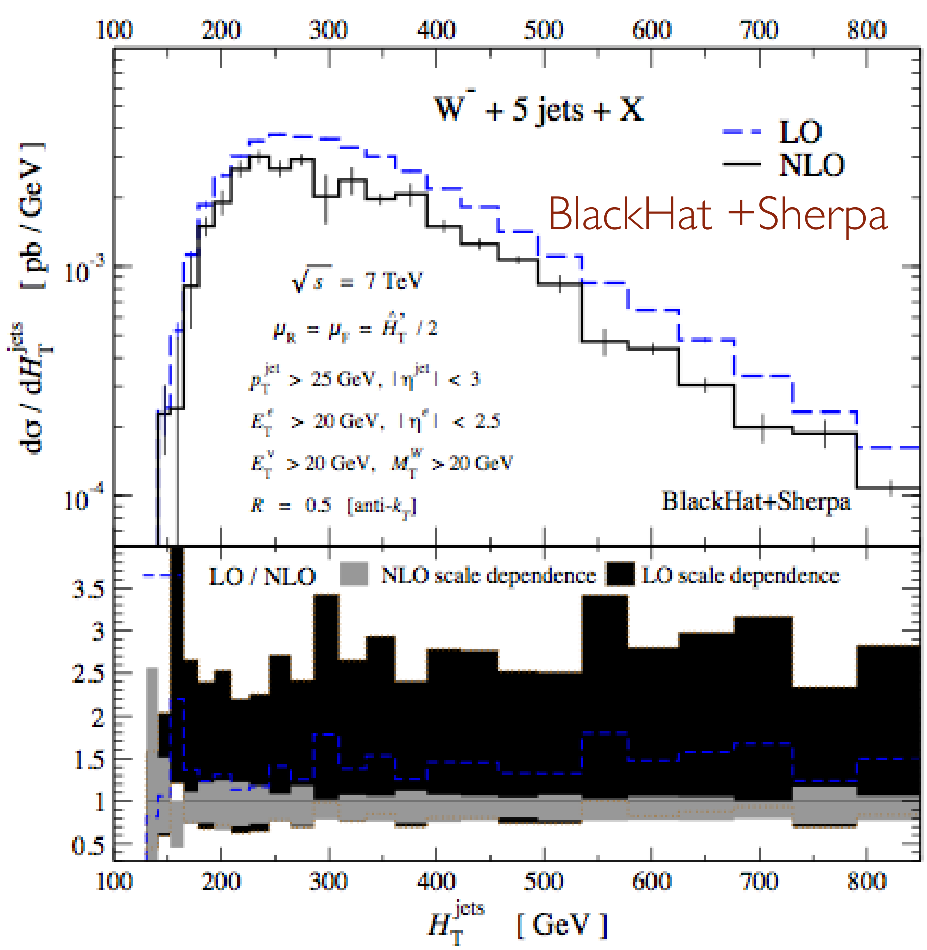
pp → W + 4 jets	2010	BH+Sherpa
pp → W + 5 jets	2013	BH+Sherpa

GUINNESS WR NLO CALCULATIONS

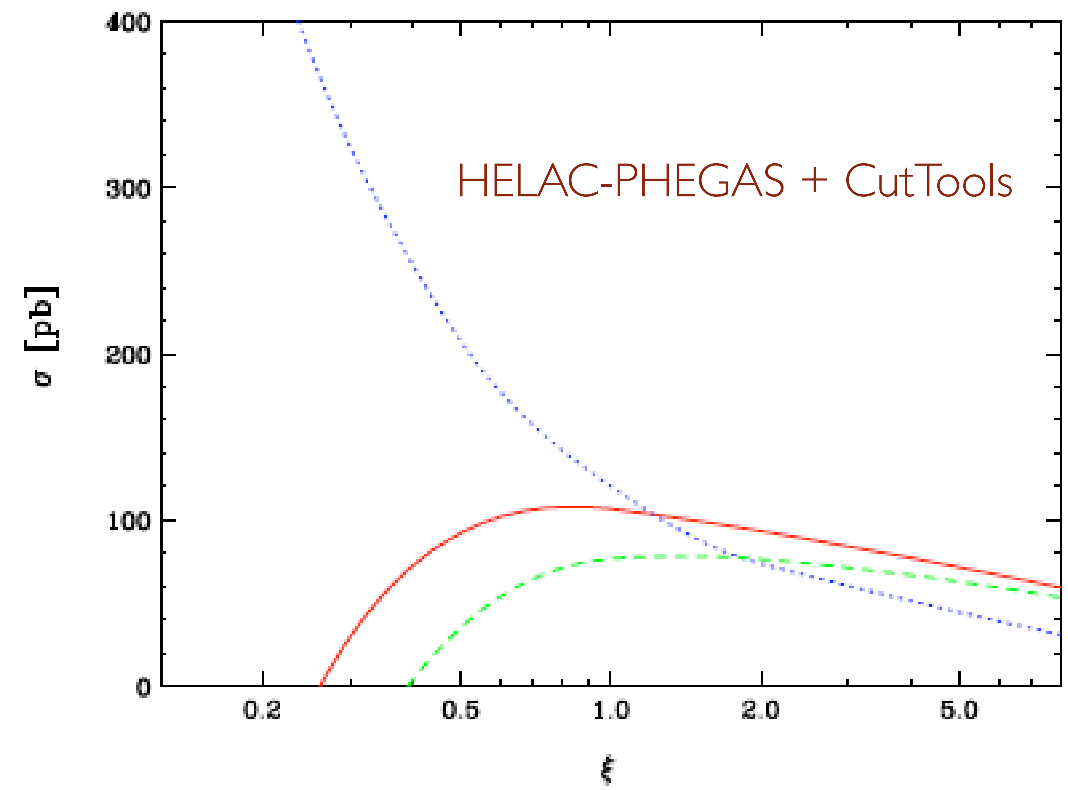
W+5 jets

[Bern et al., 1304.1253]



tt+2jets

[Bevilacqua et al., 1002.4009]



Both based on unitarity methods and recursive relations for trees.

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
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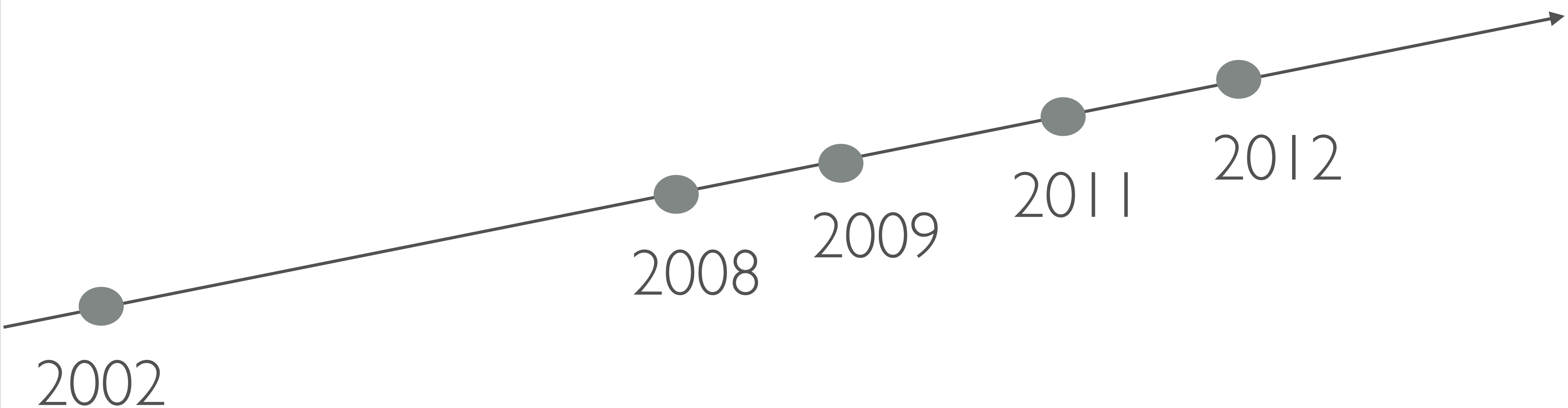
Limitations on applications (i.e. number of external partons or BSM) are systematically and quickly overcome:
"the wave function of the automatic loop effort has collapsed 2011"

PREDICTIVE MC (SIMPLIFIED) PROGRESS



Thursday 18 April 2013

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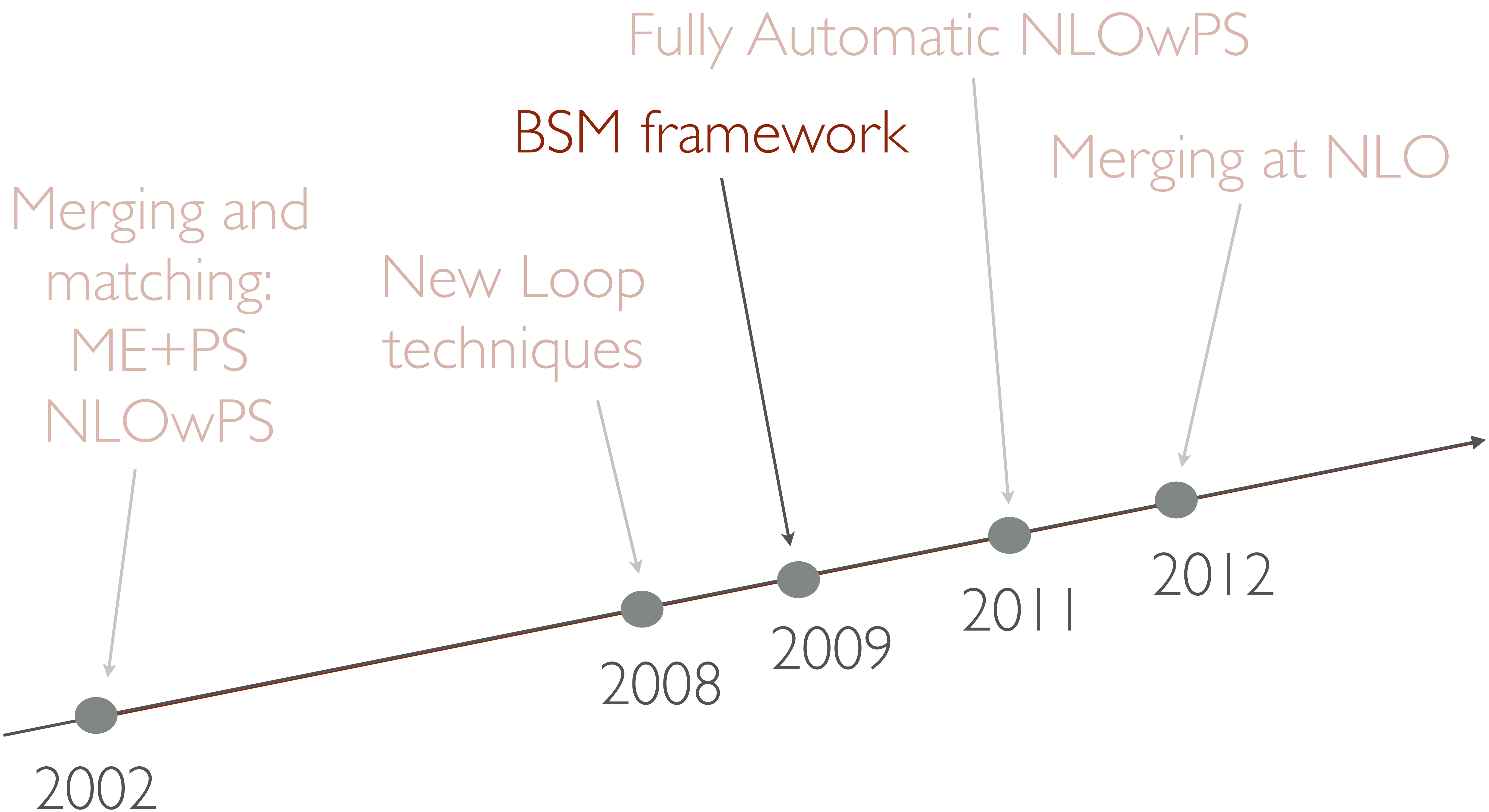
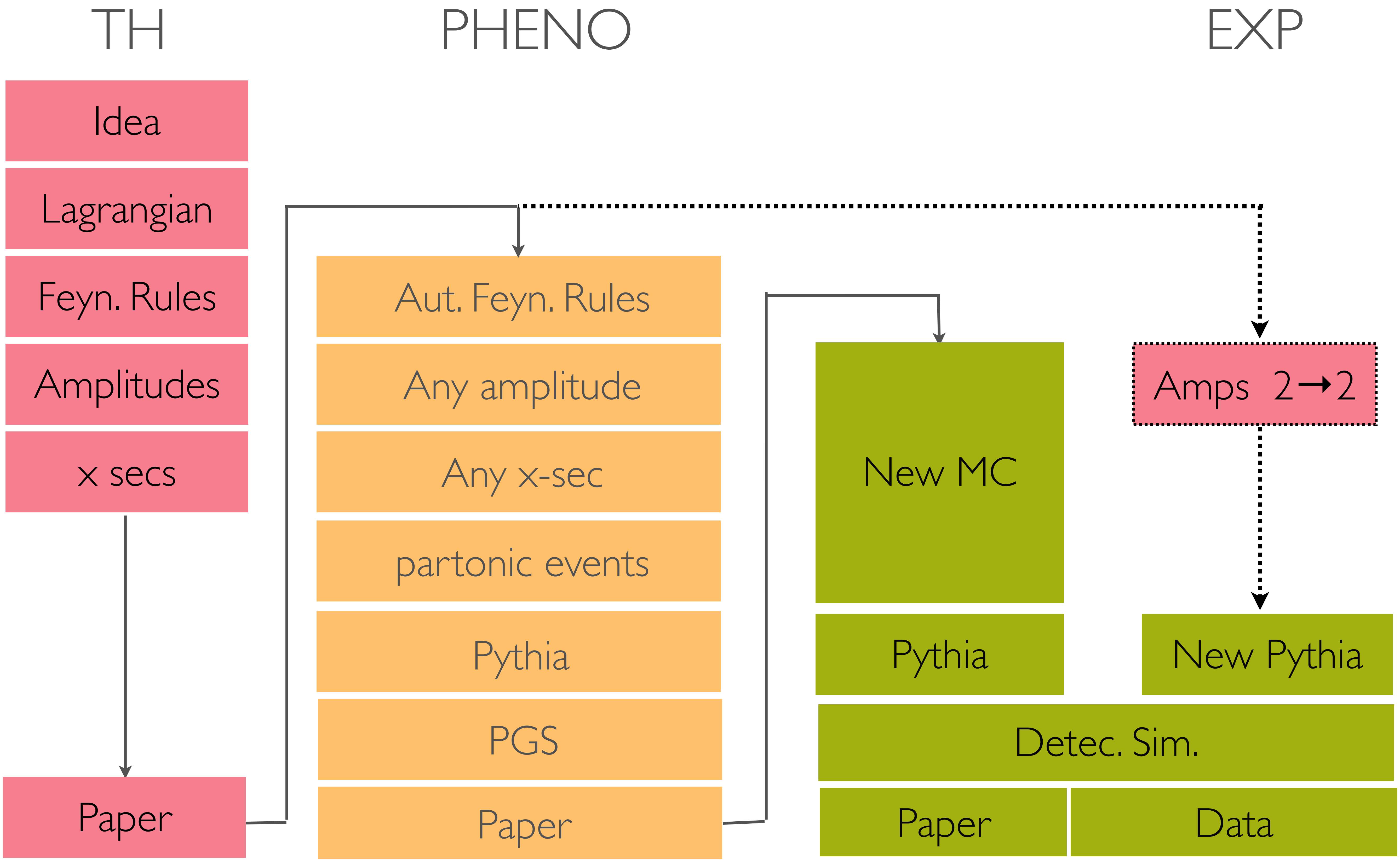


BSM TH/EXP INTERACTIONS : THE OLD WAY



BSM TH/EXP INTERACTIONS : THE OLD WAY

TH

PHENO

EXP

Idea

Lagrangian

Aut. Feyn. Rules

Any amplitude

Any x-sec

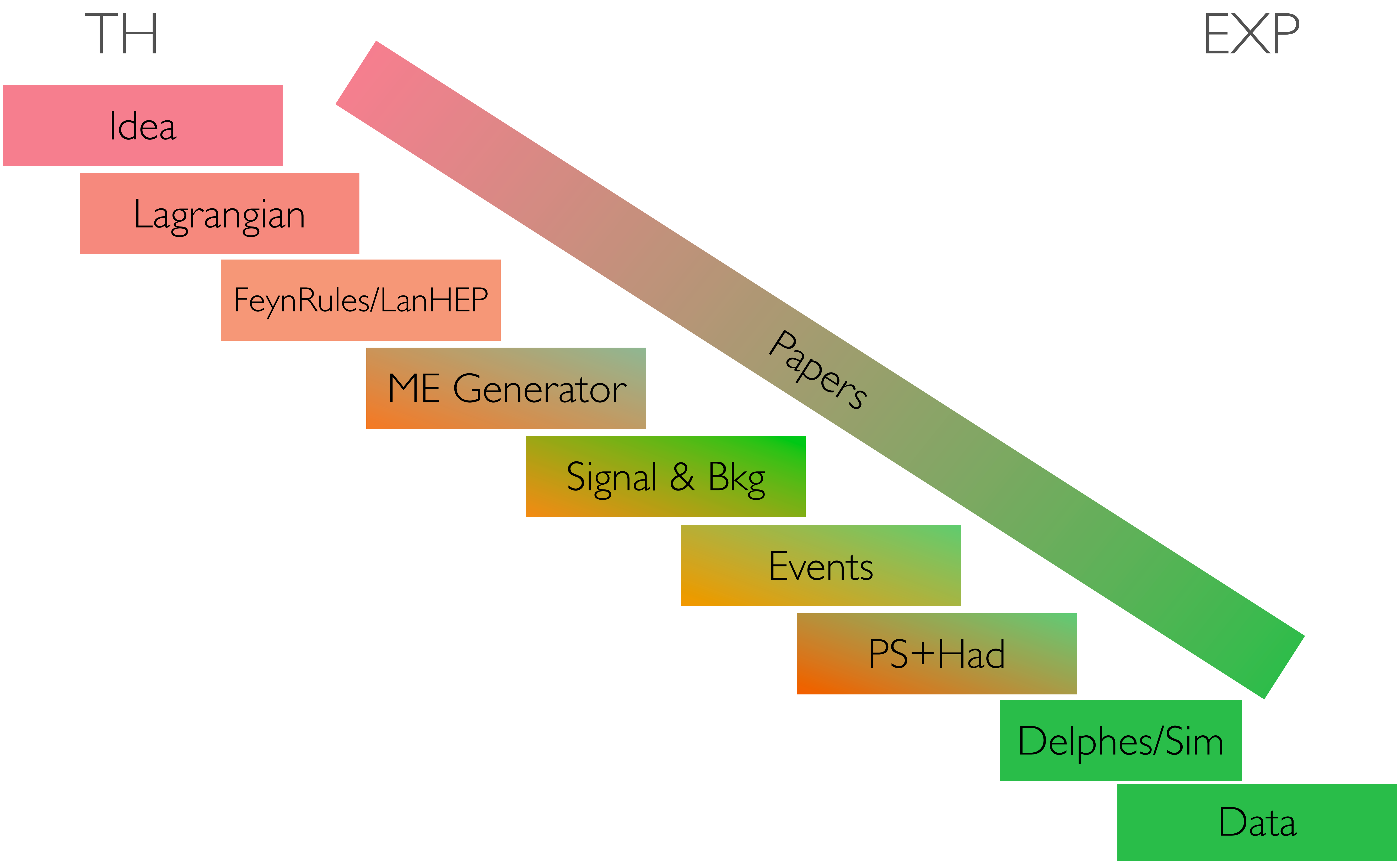
partonic events

Pythia

Detec. Sim.

Data

BSM TH/EXP INTERACTIONS : THE NEW PATH



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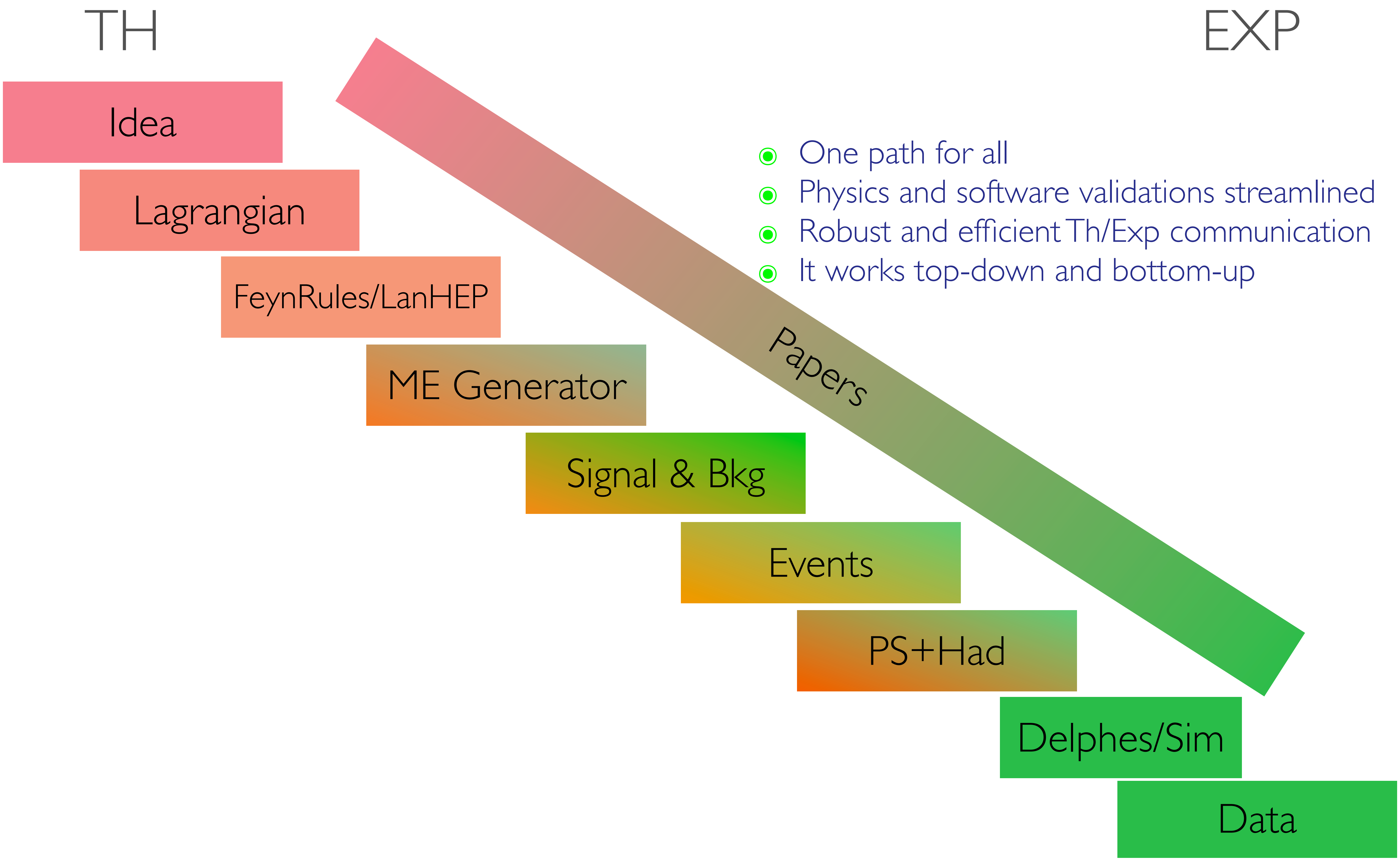


- One path for all
- Physics and software validations streamlined
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

BSM TH/EXP INTERACTIONS : THE NEW PATH

TH

EXP

Idea

Lagrangian

FeynRules/LanHEP

ME Generator

Signal & Bkg

Events

PS+Had

Delphes/Sim

Data

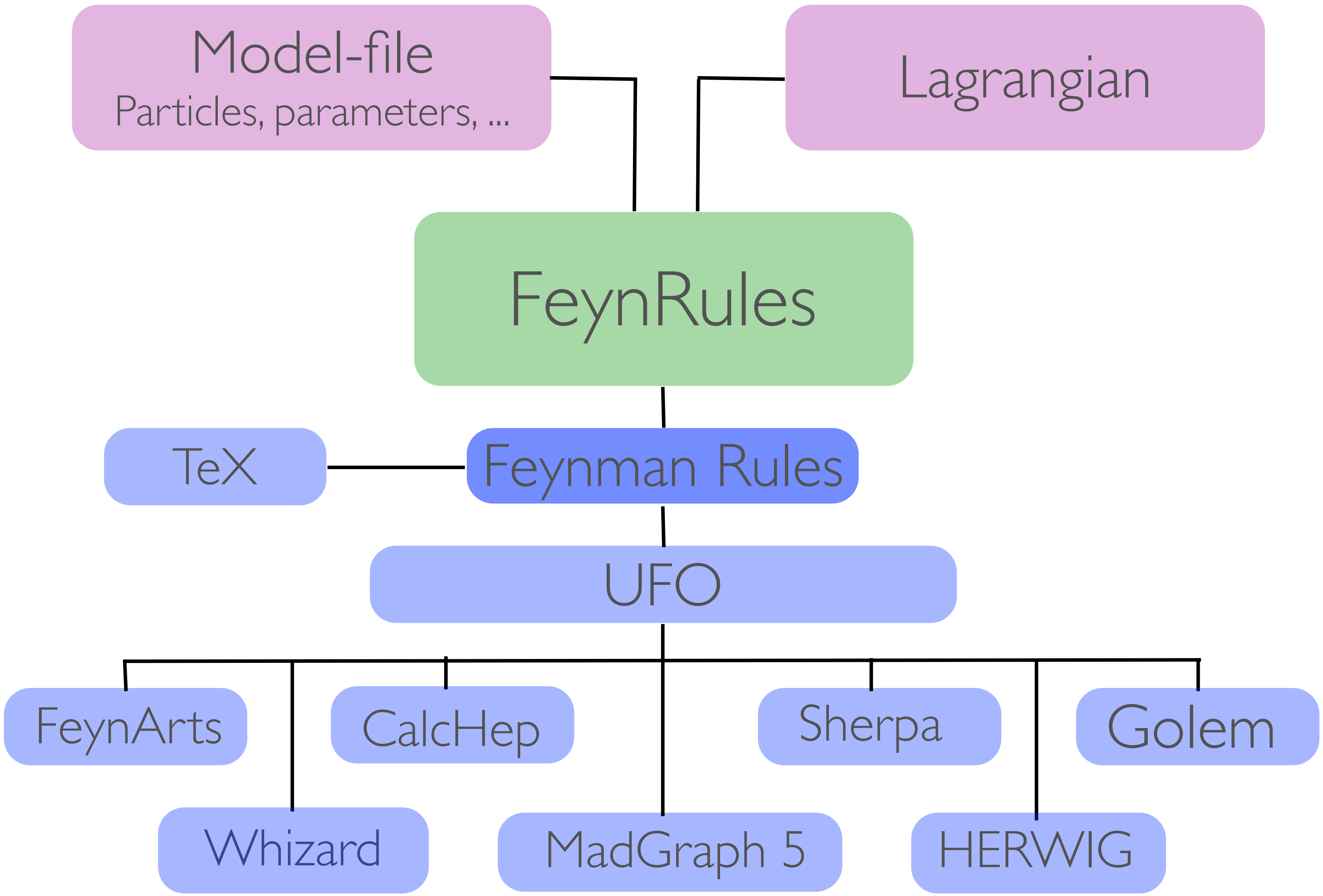
Papers

- 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...

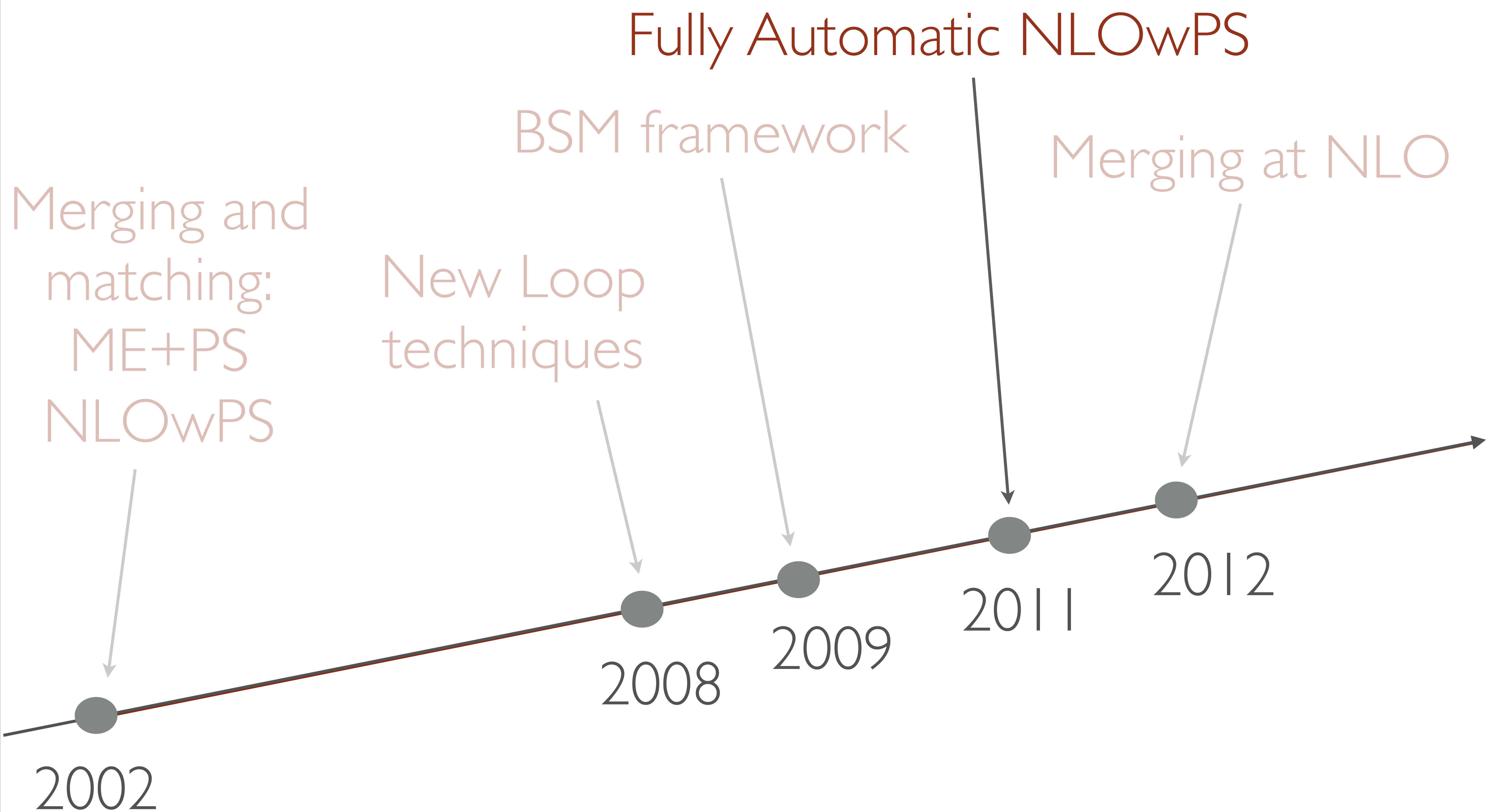
THE FEYNRULES PROJECT

[Christensen, Degrande, Duhr, Fuks]



Now quickly moving to NLO....

PREDICTIVE MC (SIMPLIFIED) PROGRESS



FROM SEMI TO FULLY AUTOMATIC MC'S AT NLO

Processes involving tops can be simulated at the NLO+PS level, via:

- POWHEG-Box (public) library : many SM procs
- POWHEL (not public) : a few procs involving top
- Sherpa + external loop codes (to be public): many procs
- aMC@NLO(public): process directly generated by the user

AUTOMATIC MC'S AT NLO

Suppose now you are interested in studying Higgs production in association with t tbar :

```
./bin/mg5
> generate p p > t t~ h [QCD]
> output tth
> launch
```

or with single top (both t and t~):

```
./bin/mg5
> define tx = t t~
> generate p p > tx h j[QCD]
> output thj
> launch
```

AUTOMATIC MC'S AT NLO

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

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BSM) is only limited by computing power. It basically
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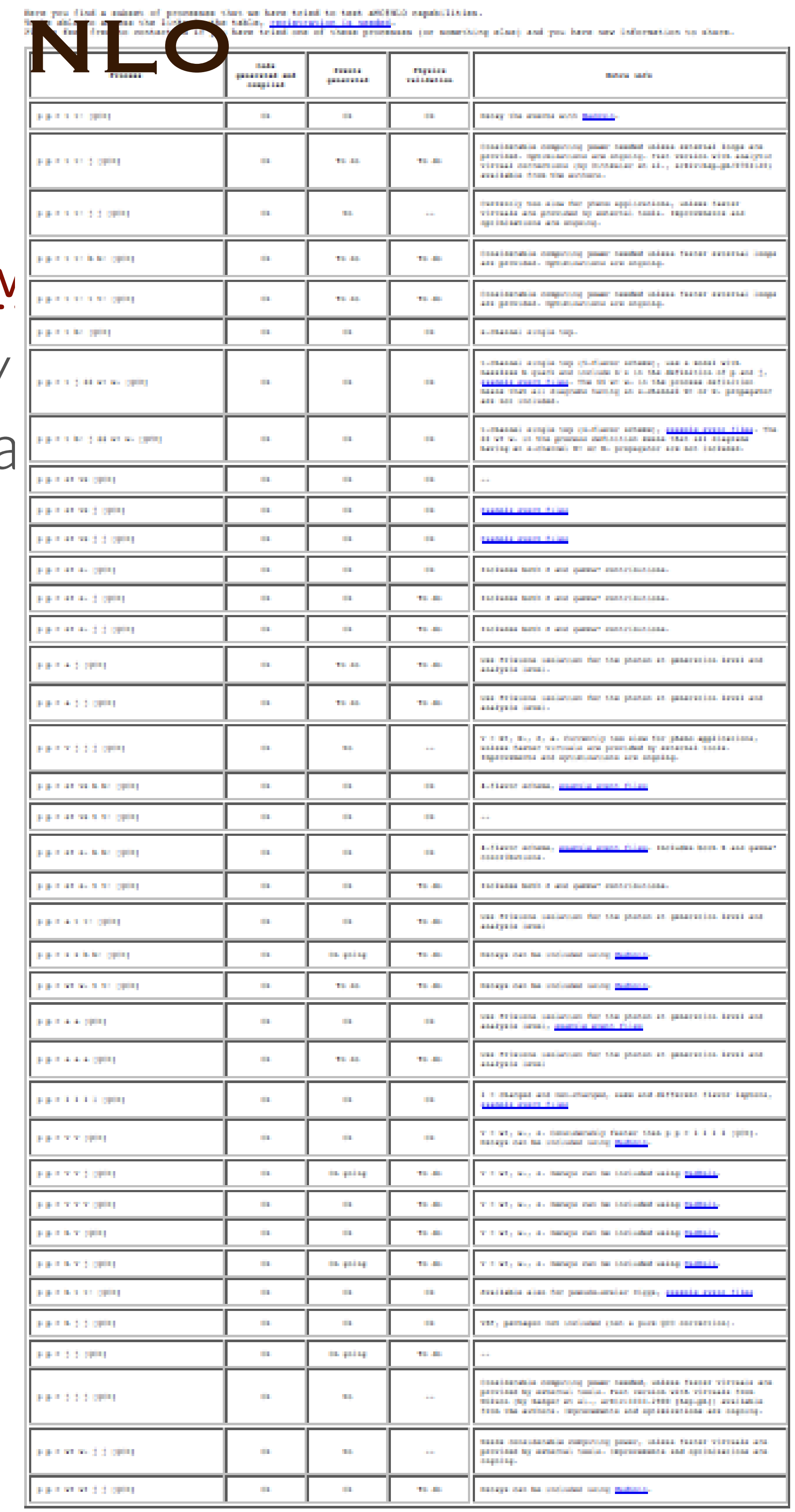

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The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power. It basically encompasses (and goes beyond) the current MCFM and POWHEG-Box libraries.

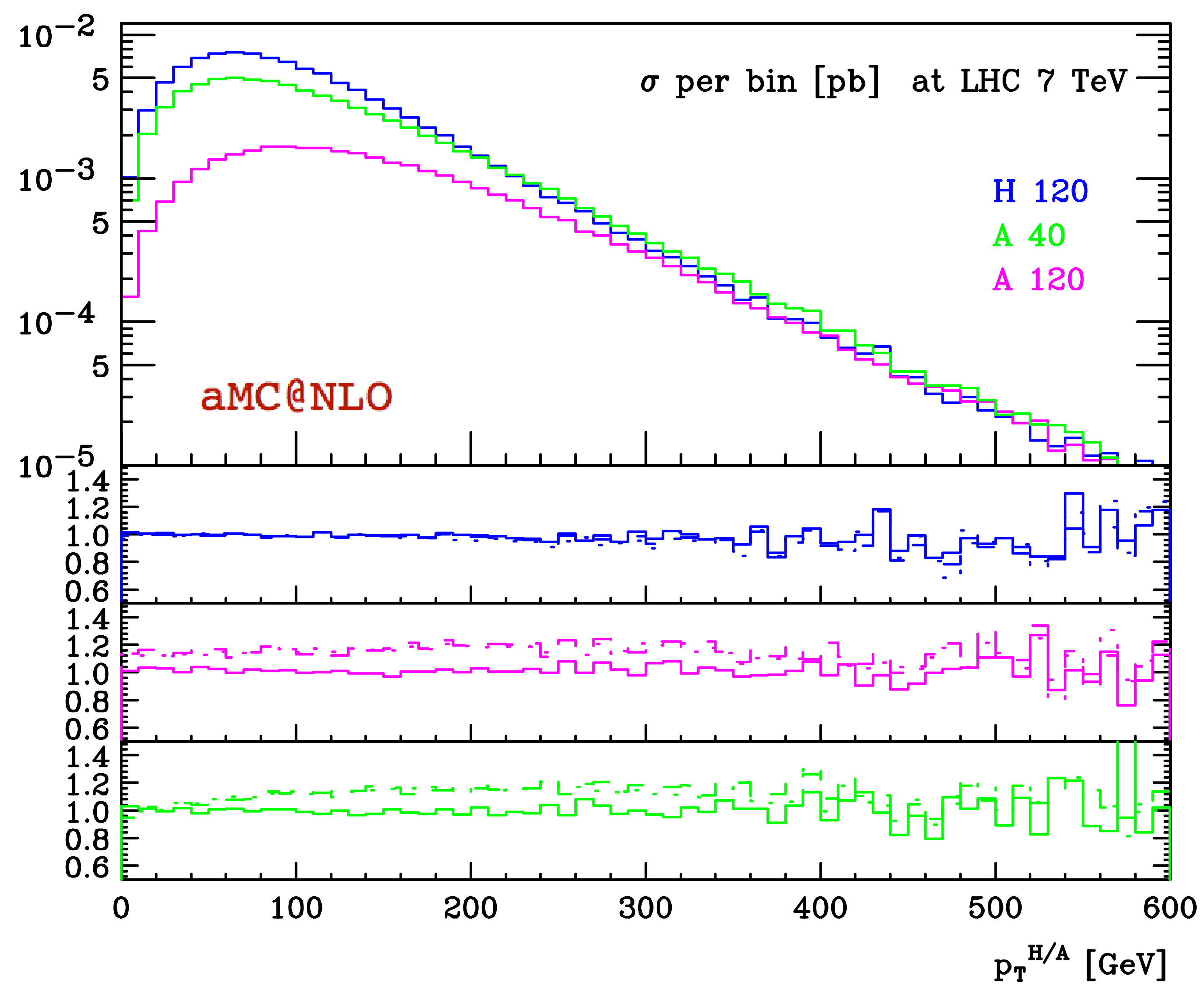
- **Signal simulation in the SM:**
  - Automatic : e.g., pp→VBF, WH(+j),ZH(+j),ttH,...
  - Available : pp→H +0,1,2 extra jets + FxFx (NLO) merging.
- **Bkg simulation:**
  - Automatic : e.g., pp→tt, tj, V V, V V V,Vbb, V, Vj, Vjj, ttV,....
  - Available: QCD rich final states.
- **Higgs characterization**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

AUTOMATIC MC'S AT NLO

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

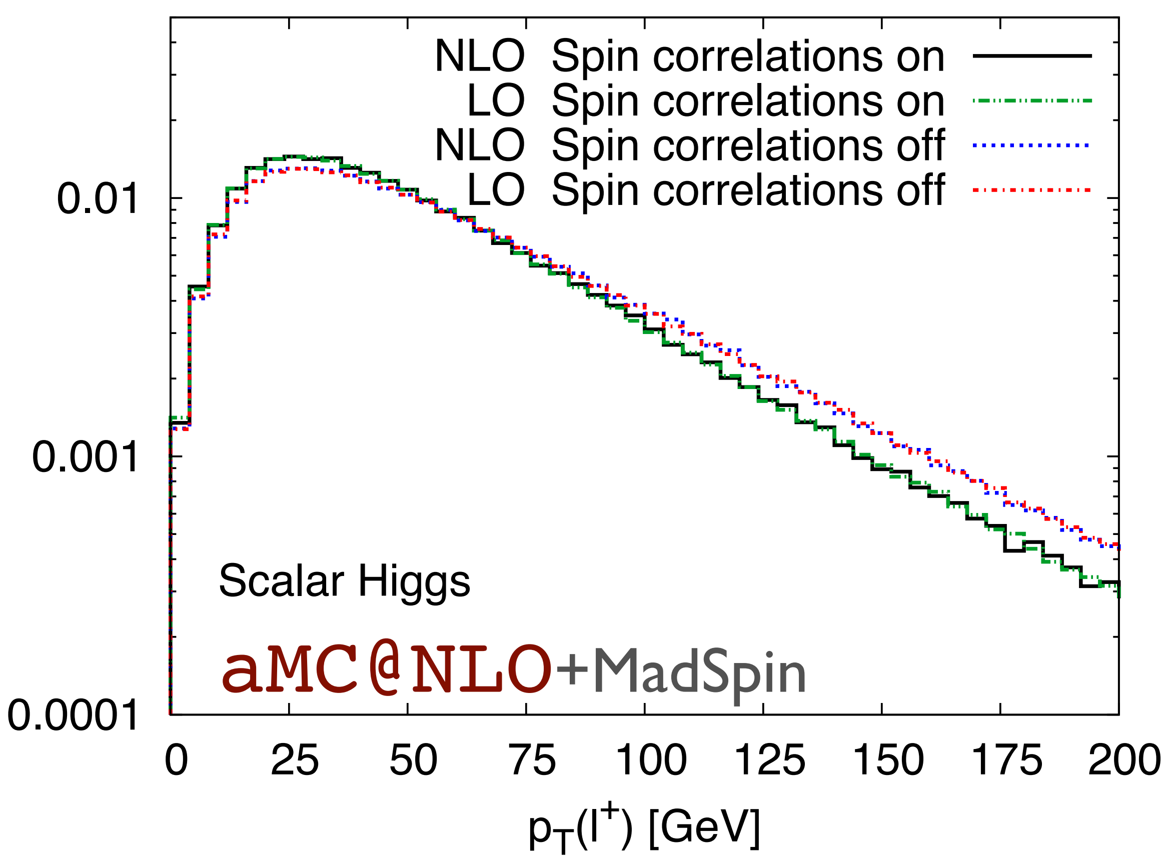
First fully automatic results for both H and A *[aMC@NLO:1104.5613]*.

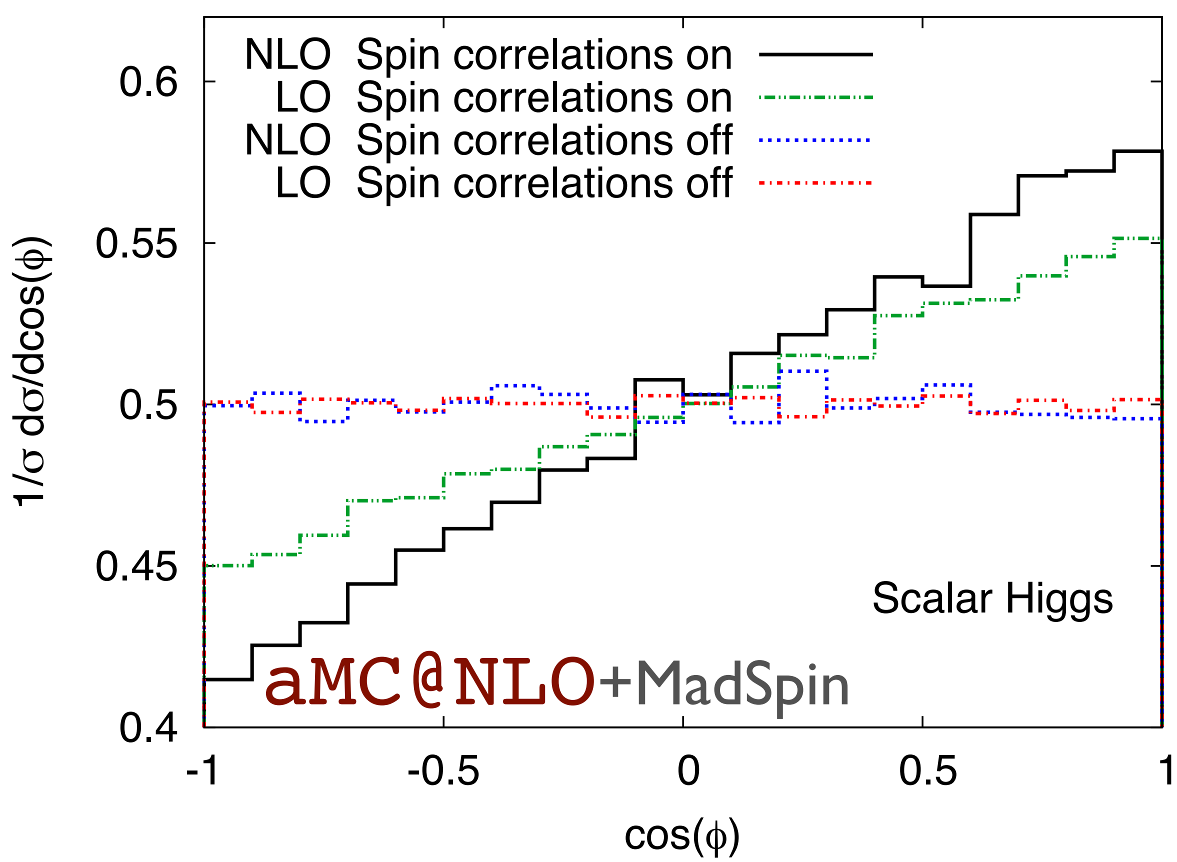
Mild corrections to the shapes for m_h=120 GeV. p_T pseudoscalar is harder. At high p_T (boosted Higgs) the three curves are equal in shape and normalization.



AUTOMATIC MC'S AT NLO

Inclusion of spin correlations in top decays, can now be done via post-processing of NLO event samples out in the Les Houches format with top on shell.





For example, in tth, the effects of the spin correlations on the pt shape of the charged lepton is more important than that of NLO QCD corrections!

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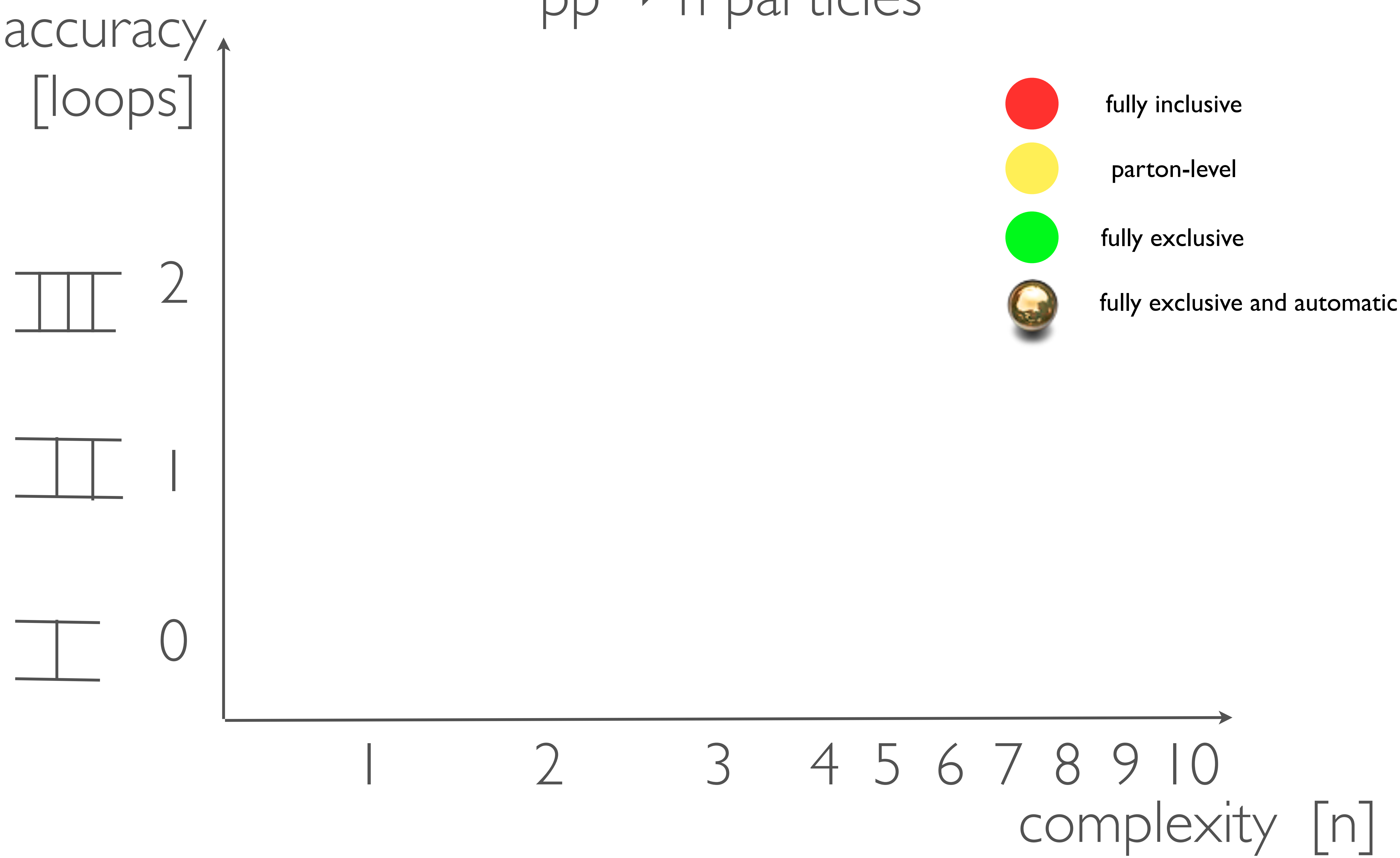
SM STATUS : YEAR 2013

pp→ n particles



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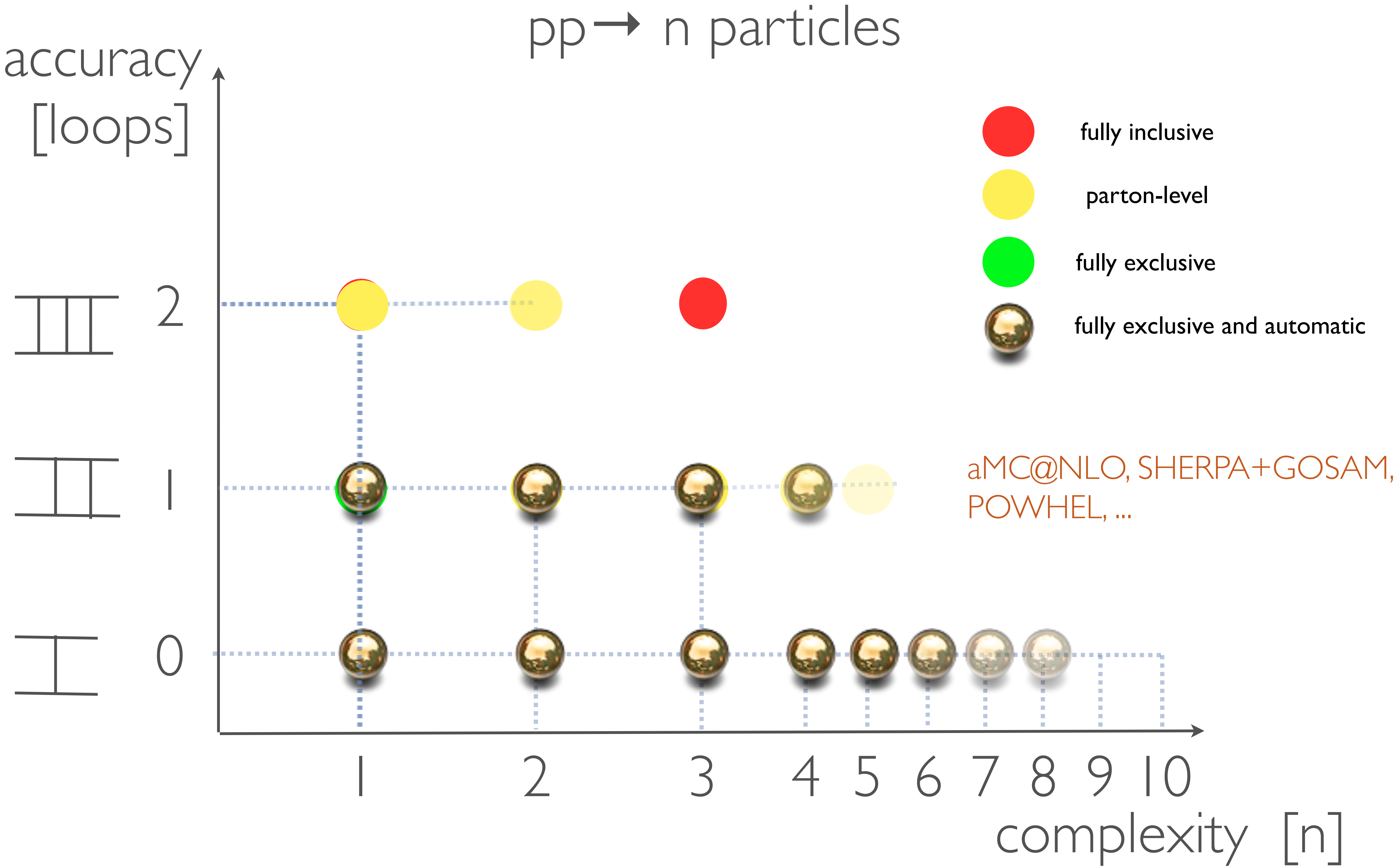

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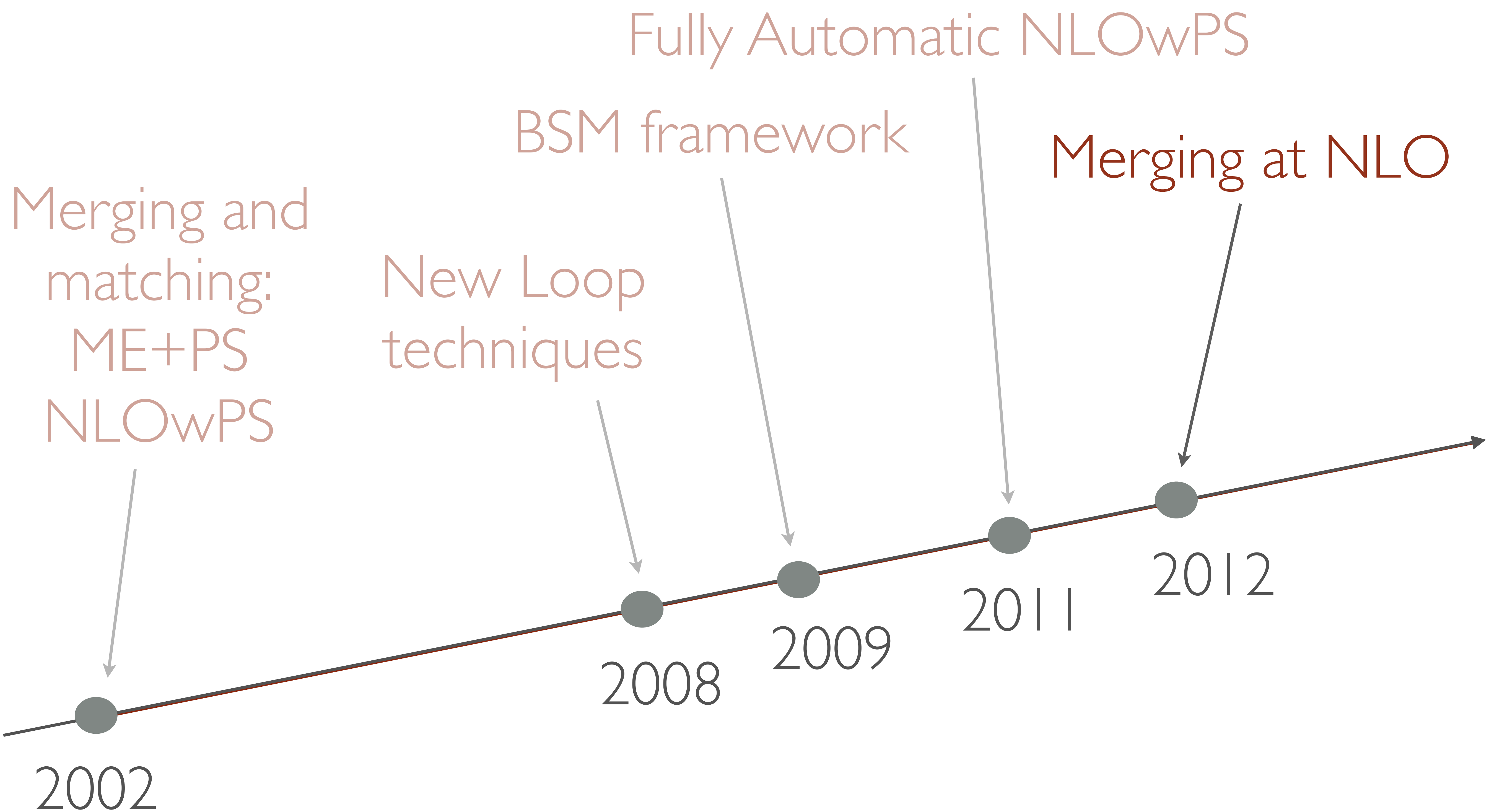
PREDICTIVE MC (SIMPLIFIED) PROGRESS



MULTI-JET MERGING @ NLO

The problem consists in merging samples for S+0j, S+1j, S+2j, S+...j computed at NLO consistently without double counting (where S can be a Higgs, a ttbar pair, a W-boson, etc.)

- **Sherpa approach:** Hoeche et al., **1207.5031**
- **CKKW-L approach:** Lavesson, Lonnblad, **0811.2912**, Lonnblad, Prestel, **1211.4827-7278**
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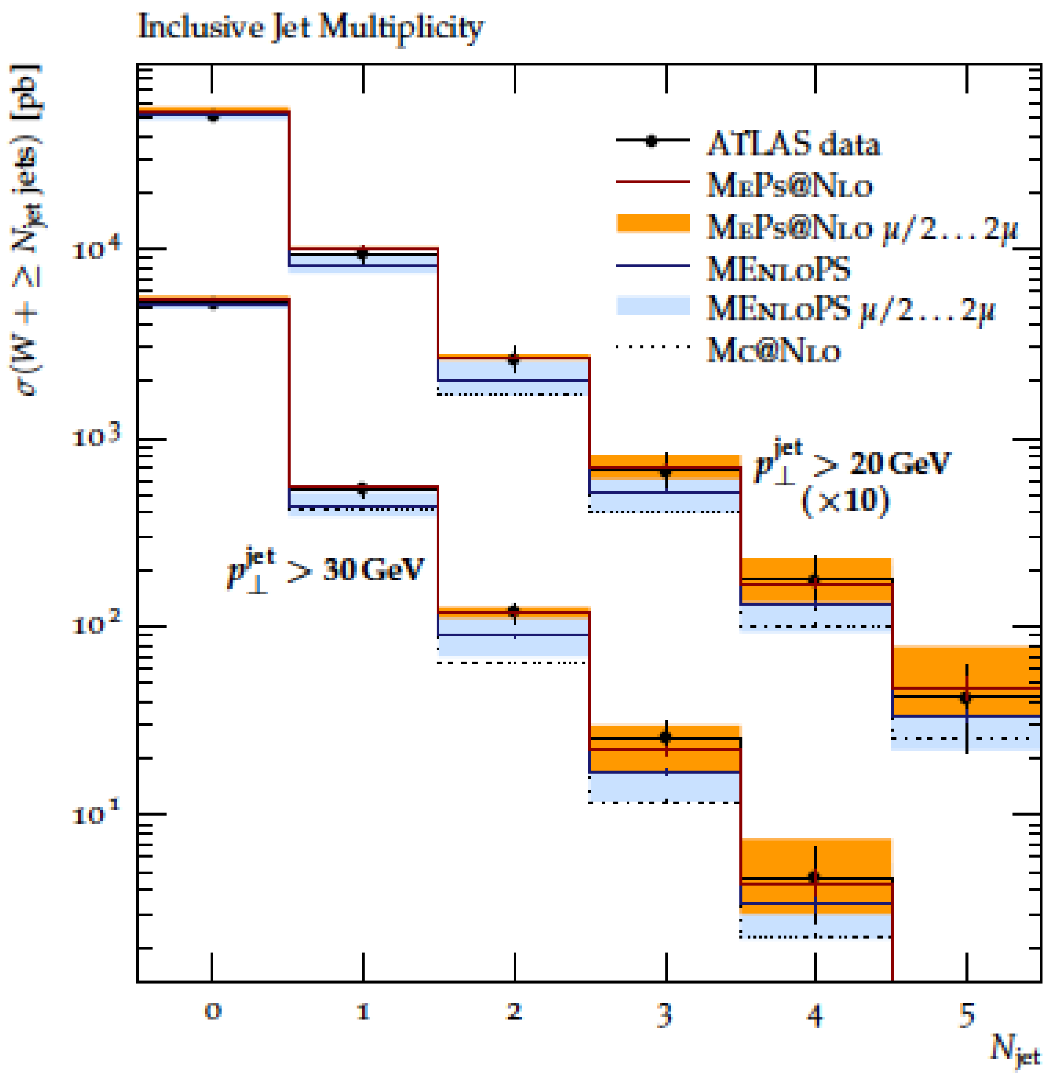
The wave function of the merging at NLO effort has collapsed in 2012

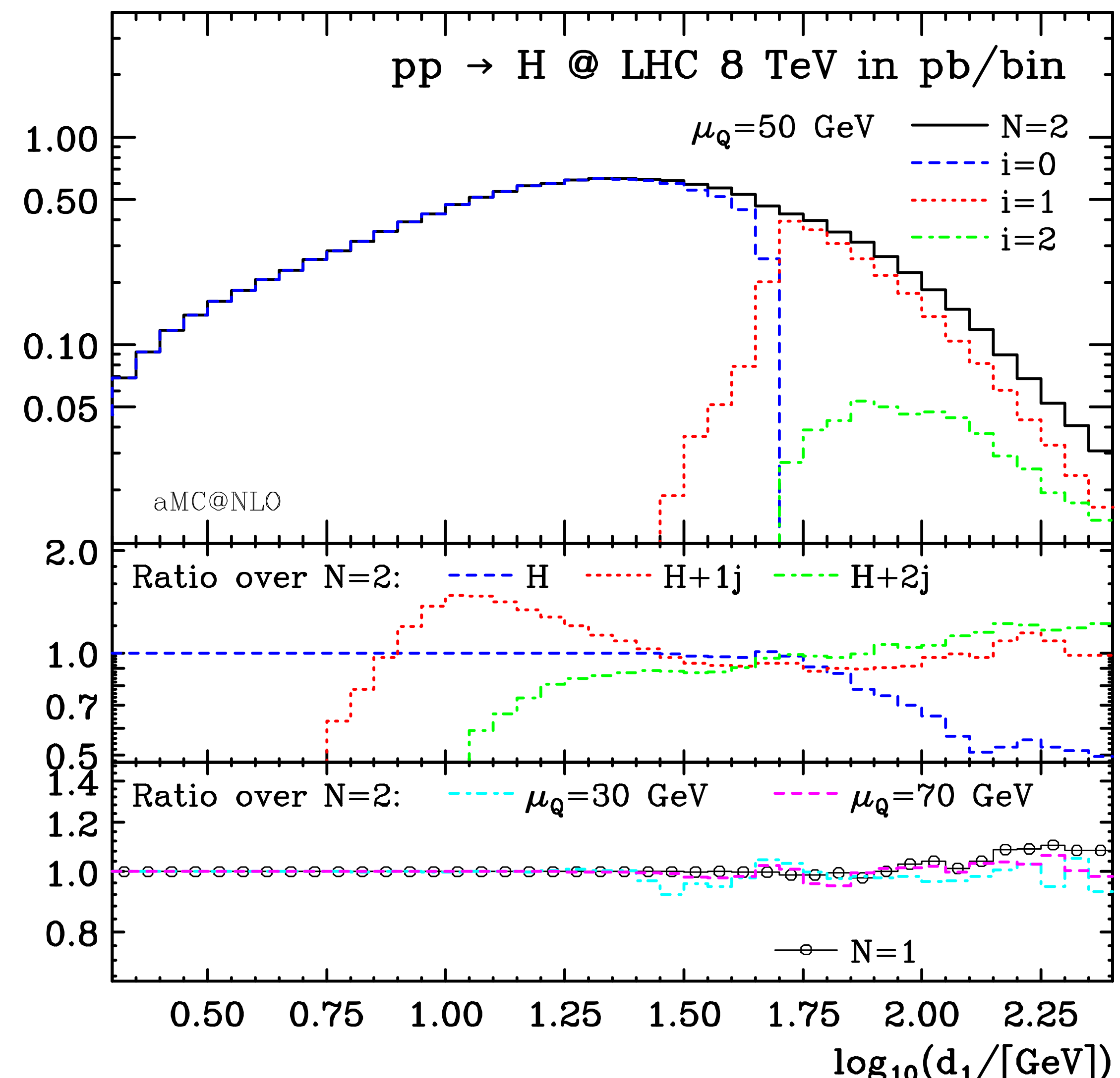
MULTI-JET MERGING @ NLO

[Hoeche et al. , 1207.5030]



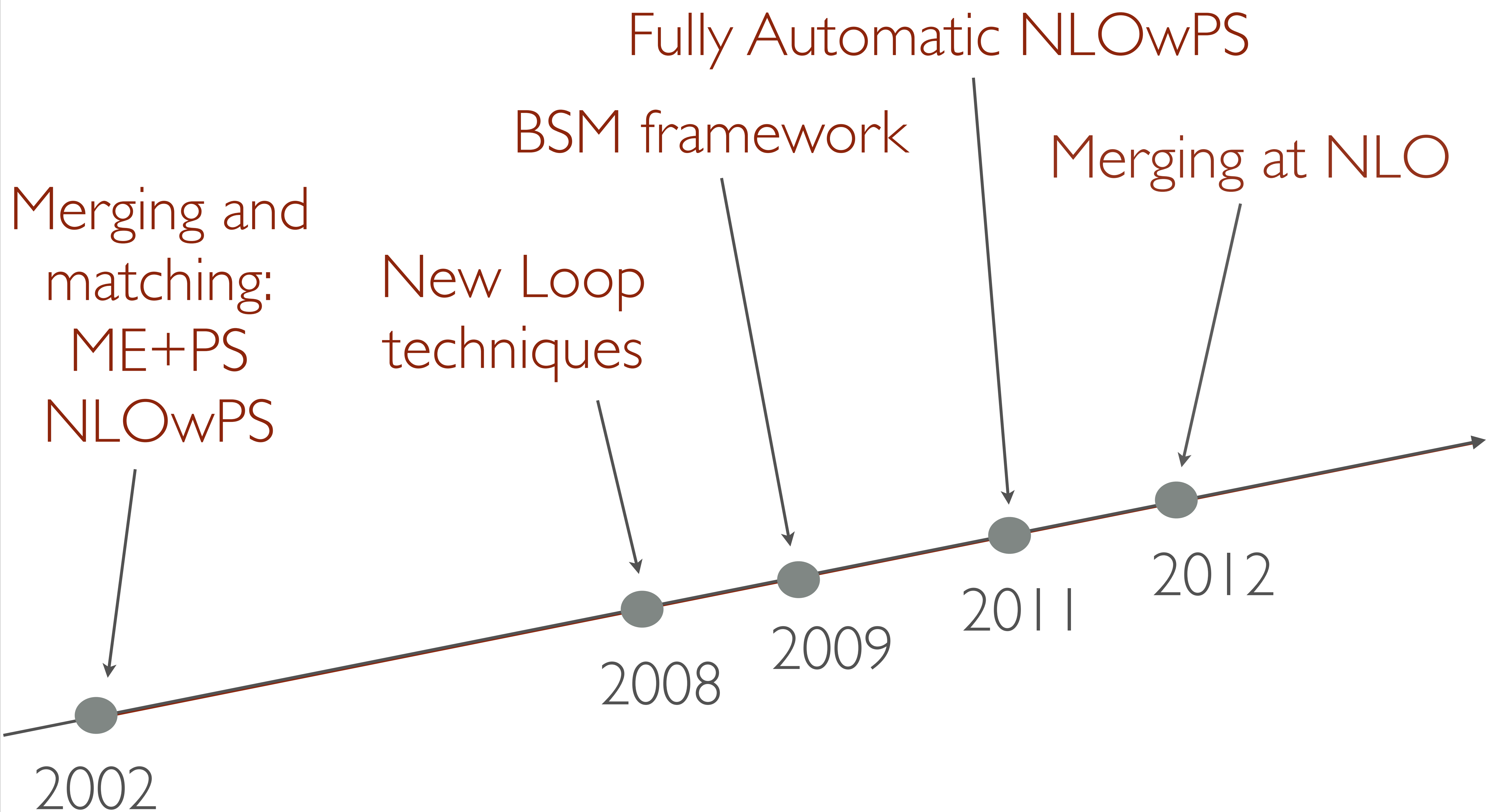
- Jet rates
- Up to 3 extra jets at NLO
- Various approaches give consistent results

[Frederix, Frixione, 1209.6215]



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

PREDICTIVE MC (SIMPLIFIED) PROGRESS



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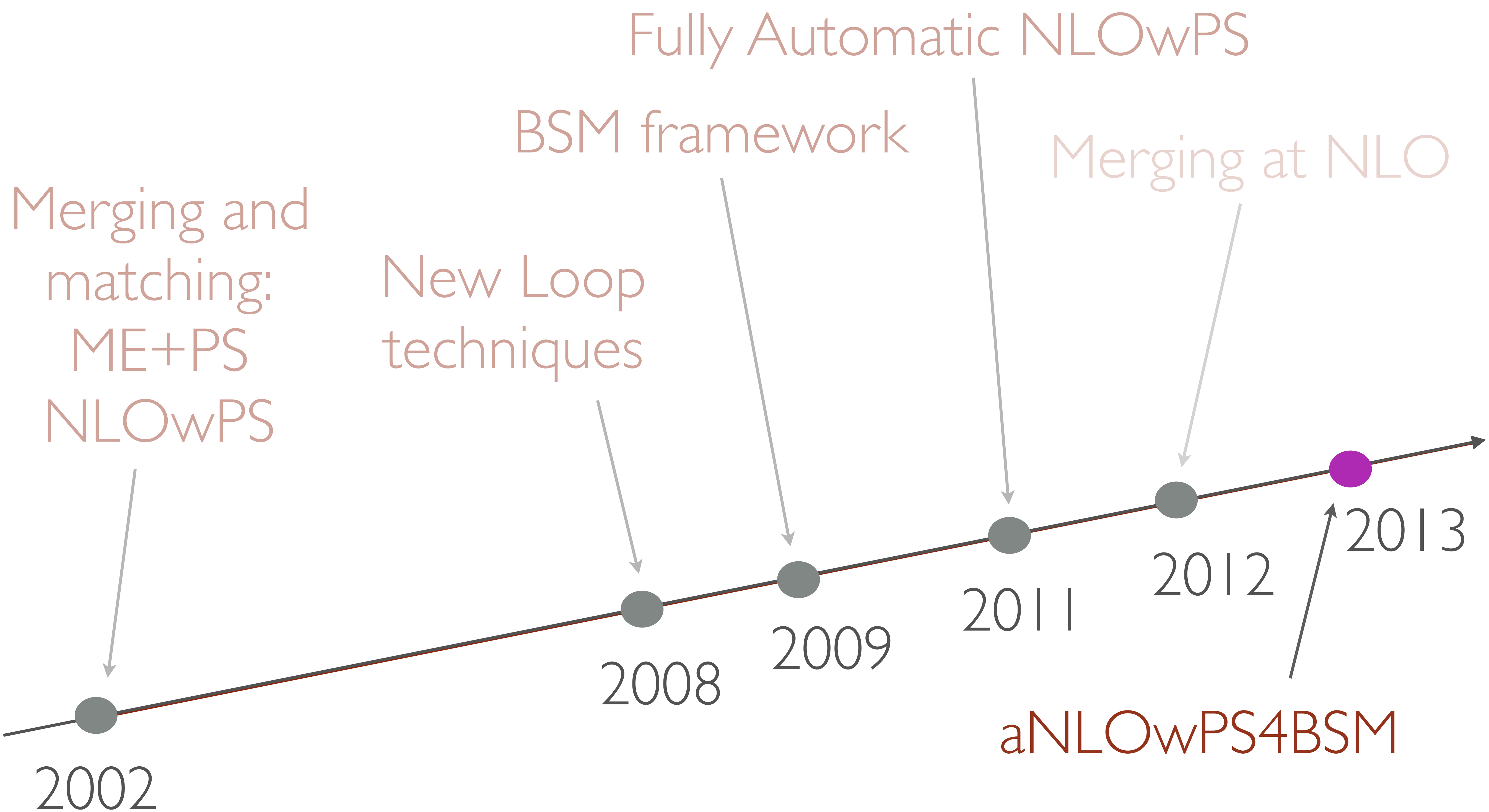

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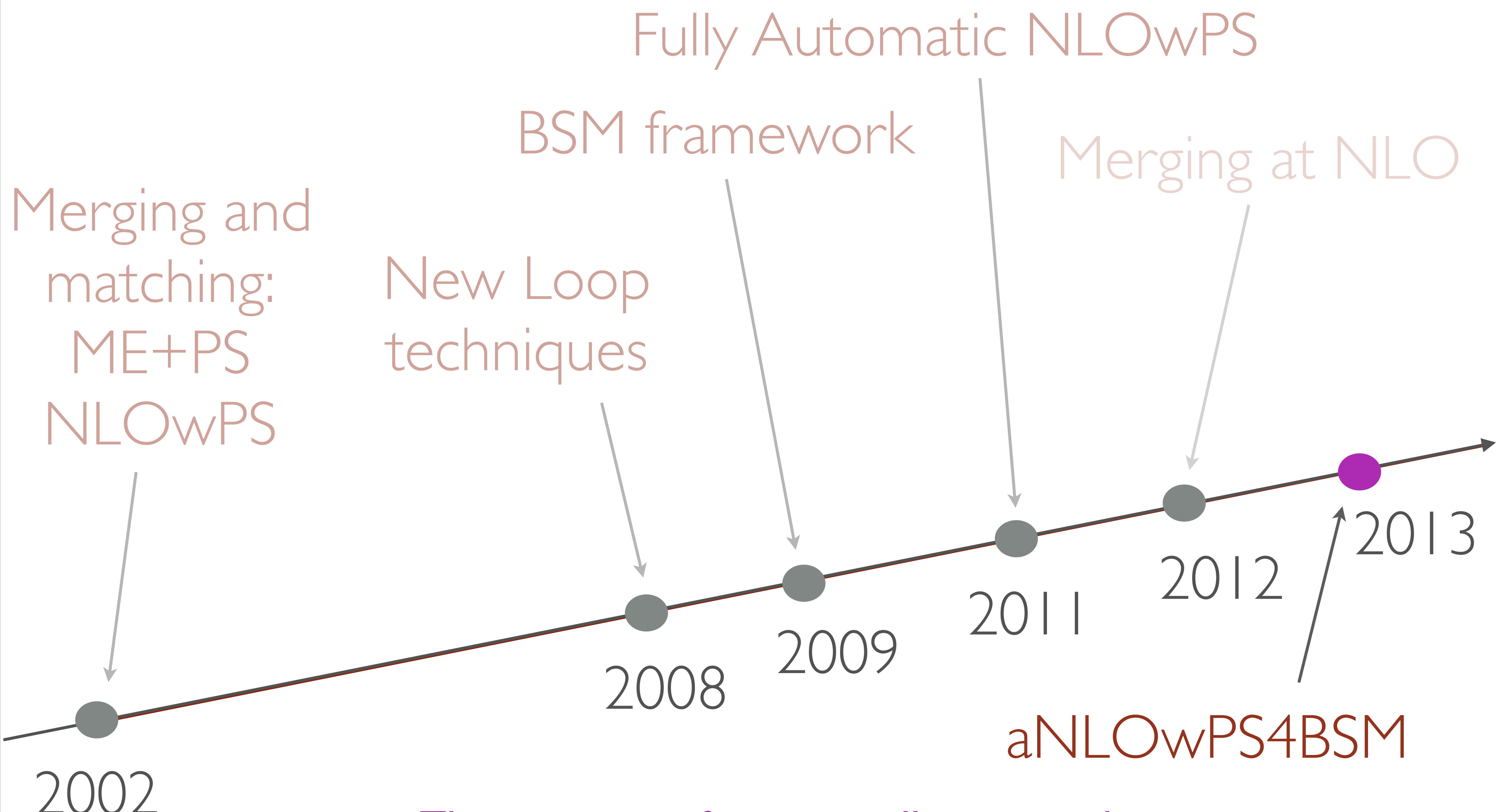
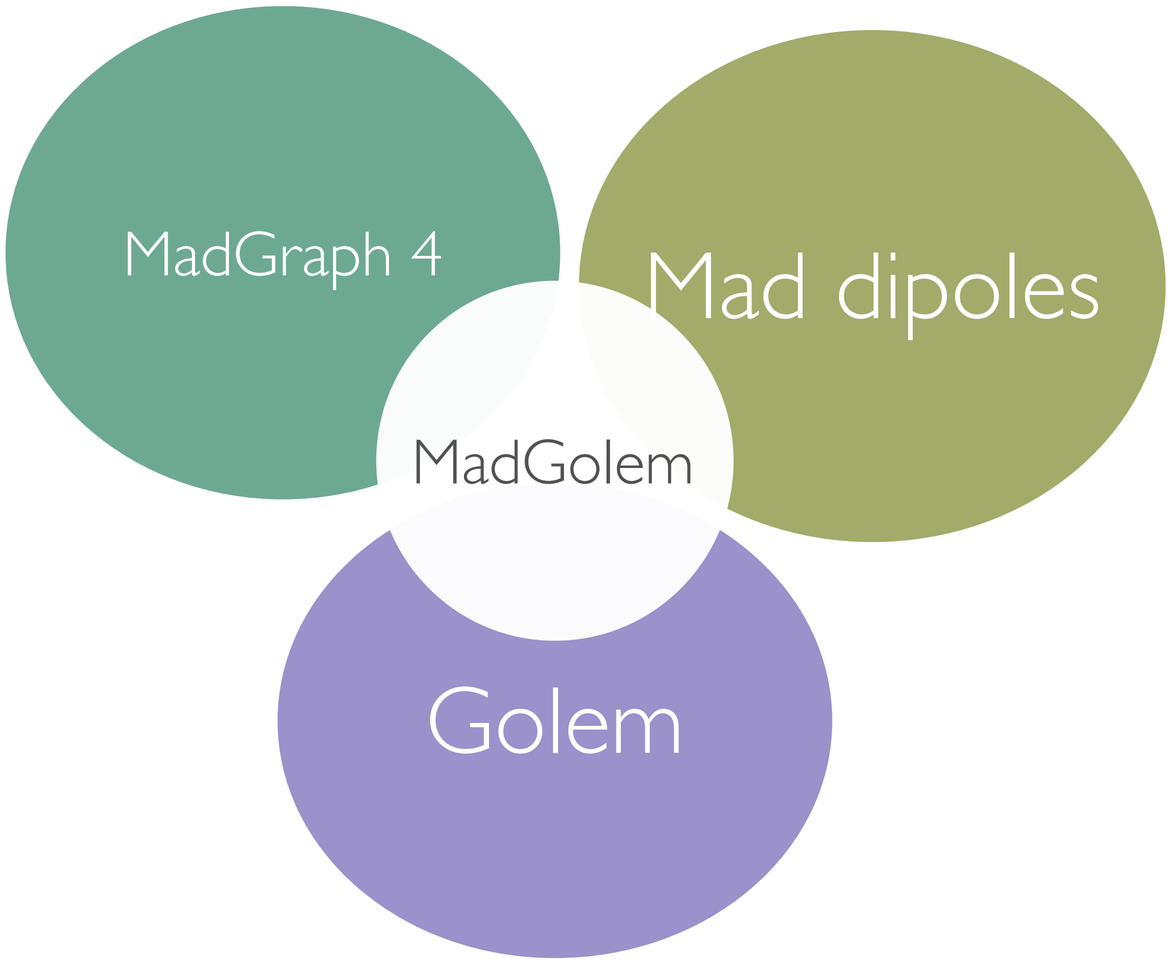
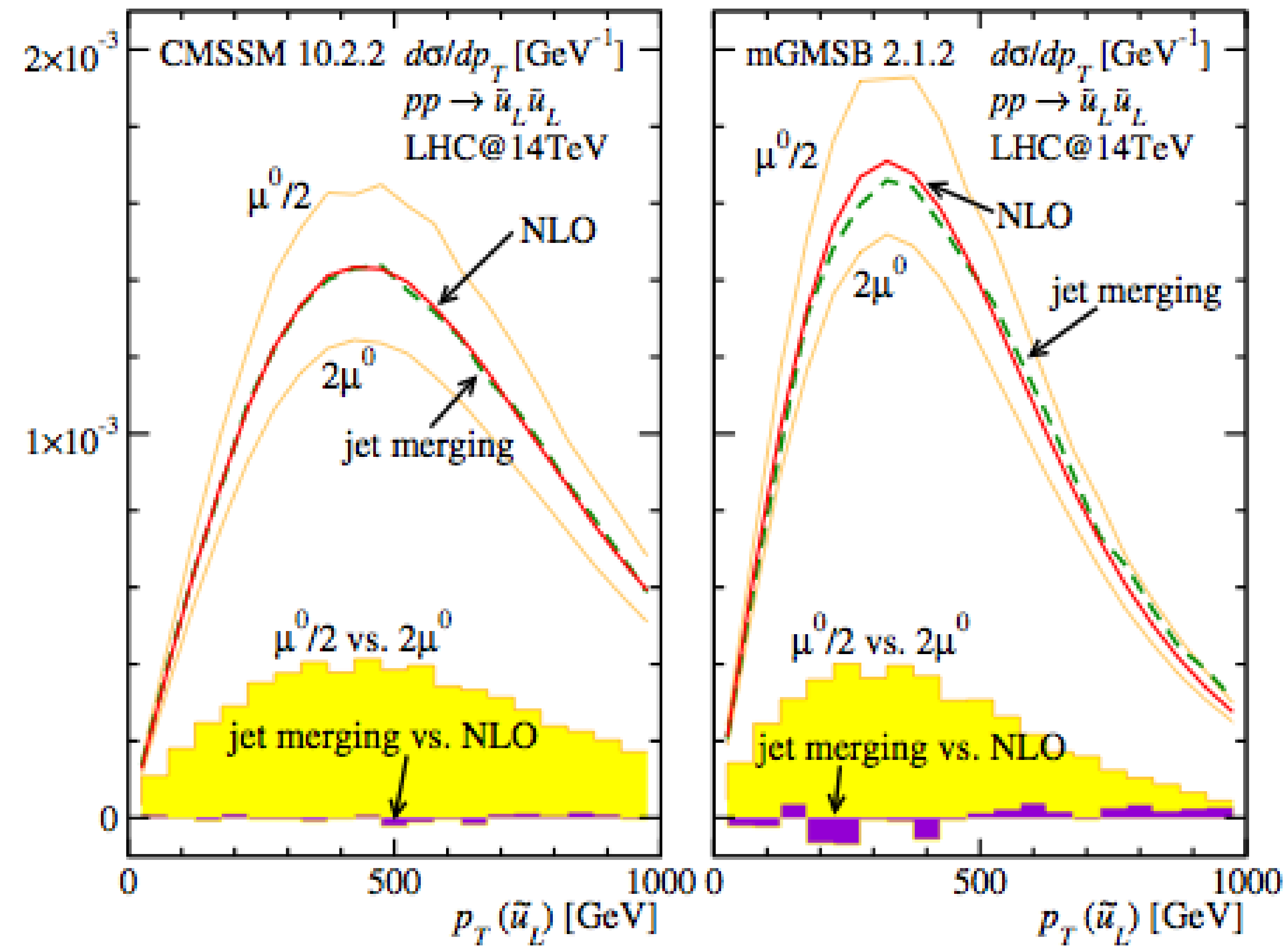


The next wave function collapse in sight....

AUTOMATIC SUSY AT NLO WITH MADGOLEM



[Goncalves-Netto et al., 1108.1250, 1203. 6358, 1211.0286]



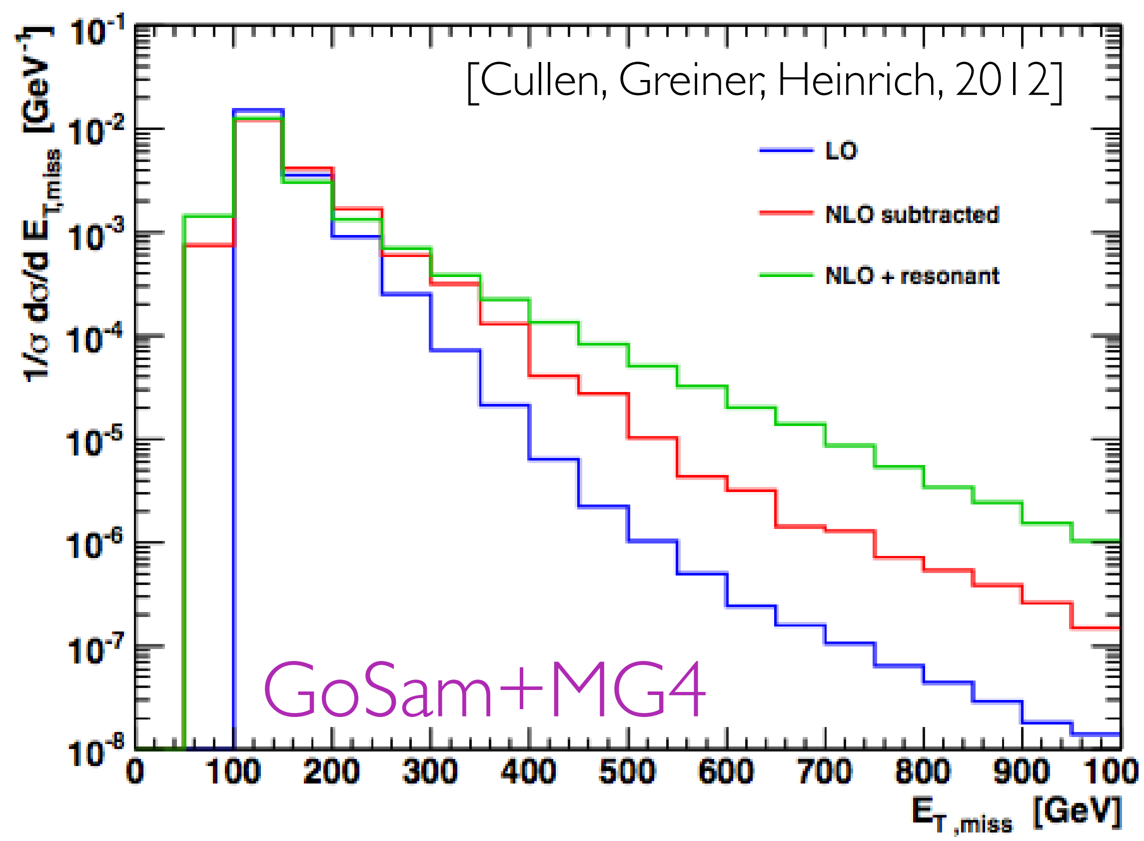
- All pp to sparticle-sparticle channels available
- No events, but completely differential in partonic observables.
- Shapes very similar to those obtained with ME+PS merging at LO.

AUTOMATIC BSM AT NLO WITH GOSAM

GoSam is ready to provide BSM loop amplitudes

- Model inheritance from FeynRules and LANHEP
- Fully automated (apart from renormalization beyond QCD)
- NO NEED for additional Feynman rules for rational part.
- Support for effective vertices, spin-two particles
- Interface (via BLHA) to any Monte Carlo program which can provide the NLO real radiation (or events)

$pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + \text{jet}$



More to come:

$pp \to (G \to \gamma\gamma) + 1$ jet

[Greiner et al. to appear]

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NEXT IN ACCURATE MC'S 4 BSM

- Promote the available automatic NLO BSM to MC's and make them available to the exp community.
- Extend capabilities to cover effective field theories.
- Improve/Extend the BLHA interface → LH 2013
- Include automatic evaluation of uncertainties via reweighting → LH 2013
- Feeding down improvements in advanced analyses techniques (MVA, MEM, Boosted objects)
- ....

SUMMARY

NP
EXP
Merging at NLO
BSM at NLO
CalcHEP Whizard
MG5 aMC@NLO
GoSam Cuttools
POWHEG-BOX
FR/LanHEP
Pythia8
HERWIG ++
Sherpa

SUMMARY

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  - **Flexibility:** simulation of any new physics, resonant or not, pairing with DM and Flavor constraints.
  - **Accuracy:** Automatic NLO, NLO event generators, merging at NLO for BSM.

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  - **Accuracy:** Automatic NLO, NLO event generators, merging at NLO for BSM.

  - **Modularity/Automation:** quickly capitalize on technical/ conceptual breakthroughs at the community level.

http://www.montecarlonet.org/Goettingen2013