MC'S AND TOOLS: THE ACCURACY WAY

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DISCOVERIES AT HADRON COLLIDERS

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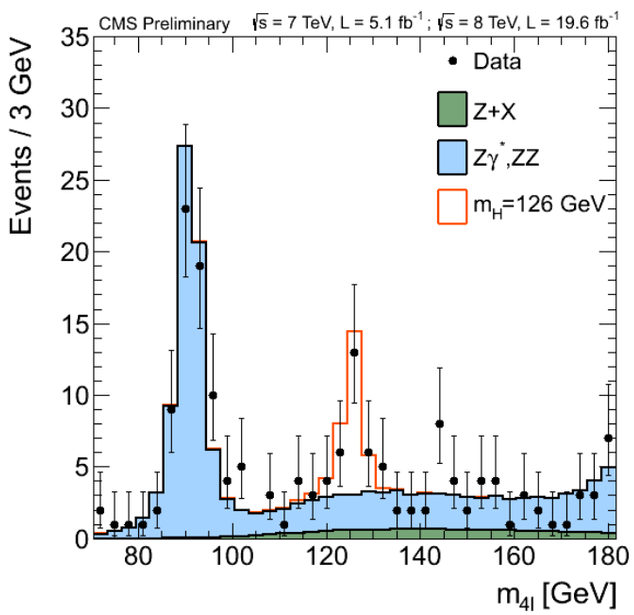
peak

pp→H→4l



"easy"

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

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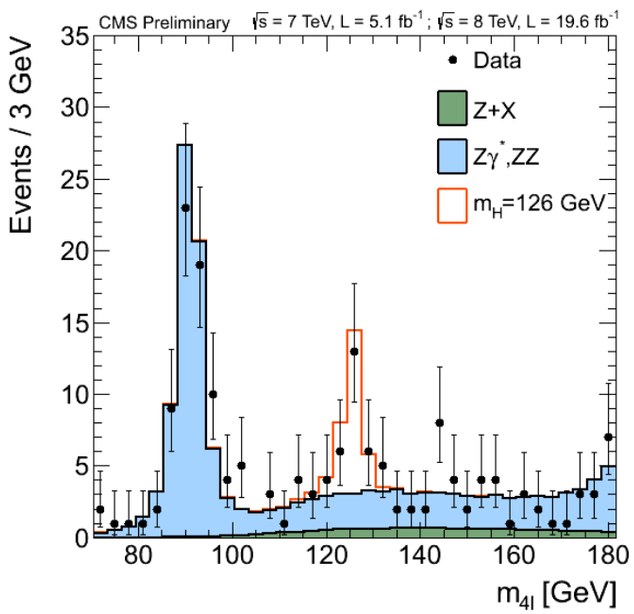

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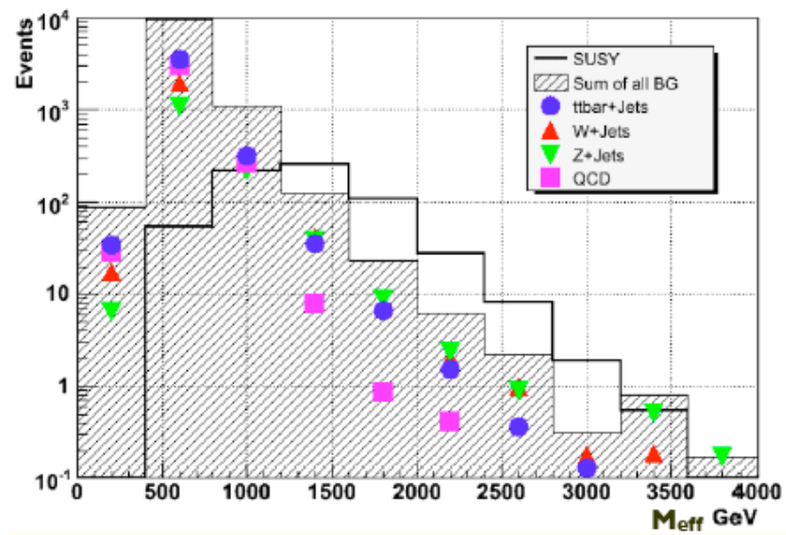
shape

$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + \not{E}_T$



hard

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

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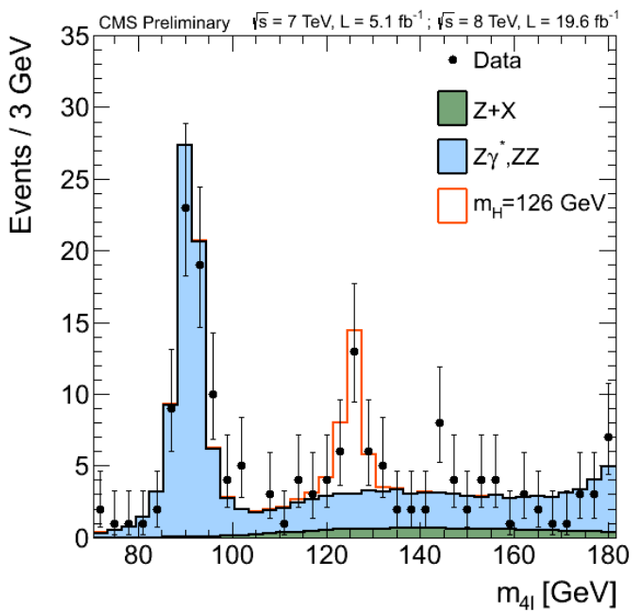

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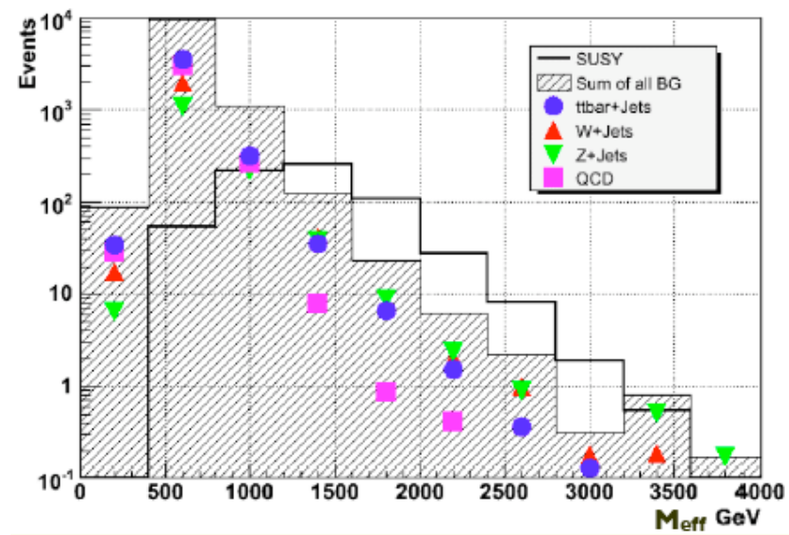

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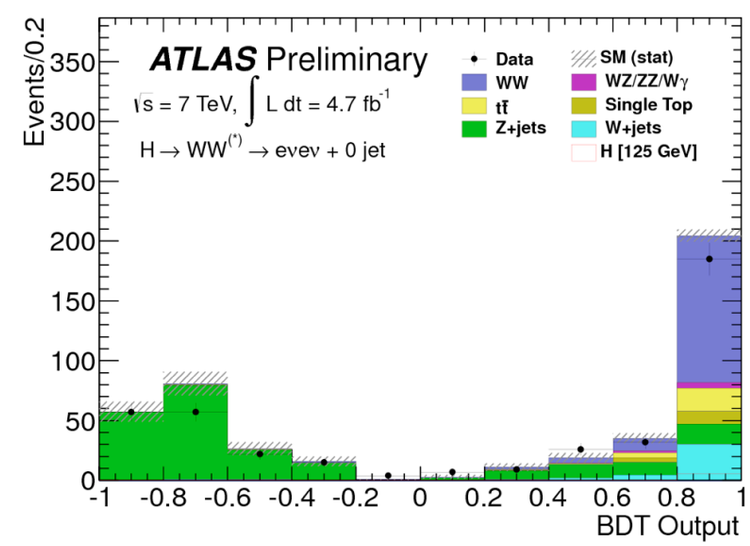
discriminant

$pp \to H \to W^+W^-$



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

WHY HAPPY?

- **Optimism**: New Physics could be hiding there already, just need to dig it out.
- **Democratization**: No evidence of most beaten BSM proposals, means more and more room for diversification. Possibility for small teams to make a big discovery.
- **Ingenuity/Creativity:** From new signatures to smart and new analysis techniques (MVA), and combination with non-collider searches (DM, Flavor...).
- **Massification** (the practice of making luxury products available to the mass market) : MC's in the hands of every th/exp might turn out to be the best overall strategy for discovering the Unexpected.
- **Flexibility**: We need MC that are able to predict the pheno of the Unexpected.
- **Accuracy:** accurate simulations for both SM and BSM are a must.

LHC MASTER FORMULA

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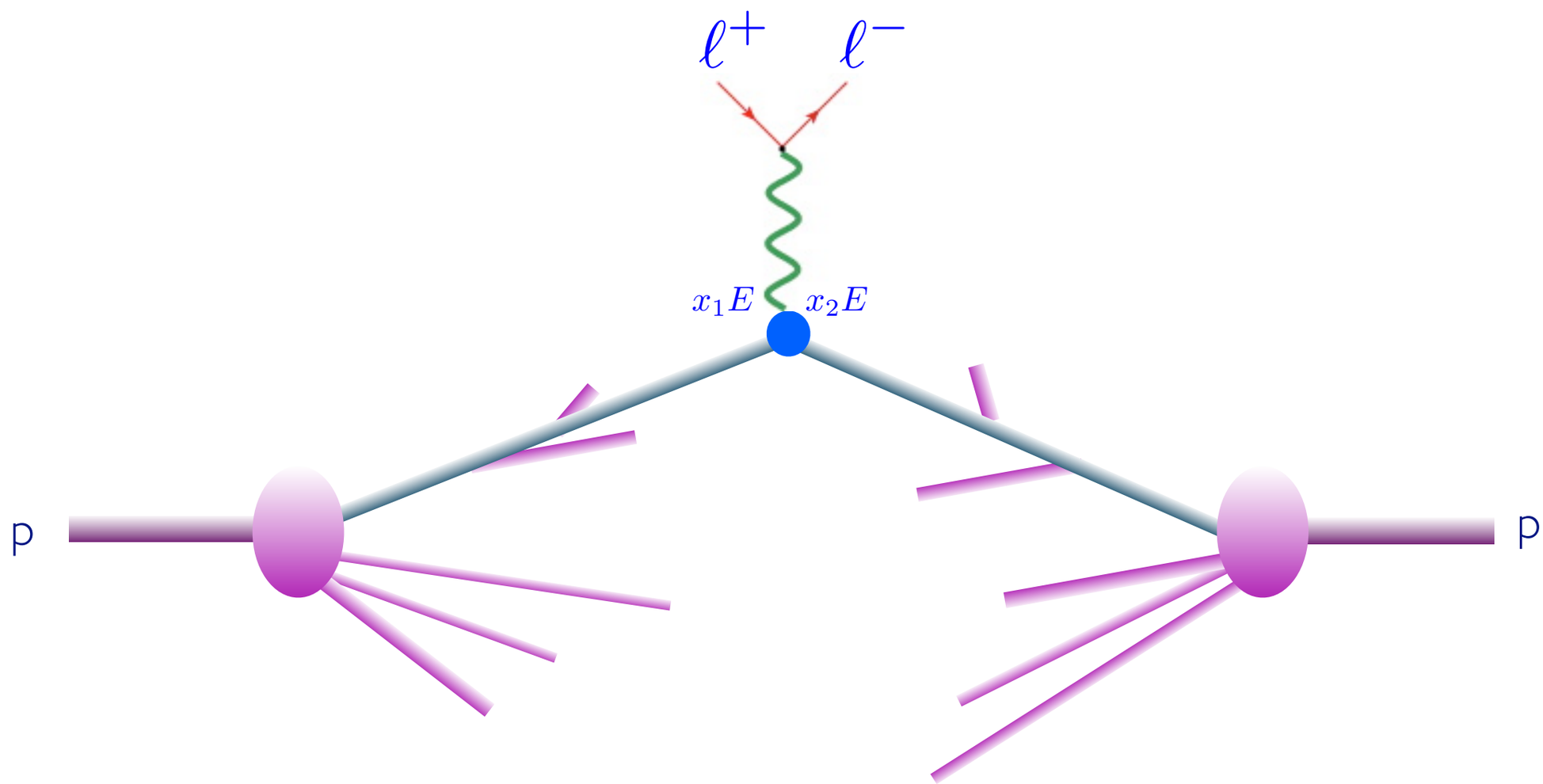

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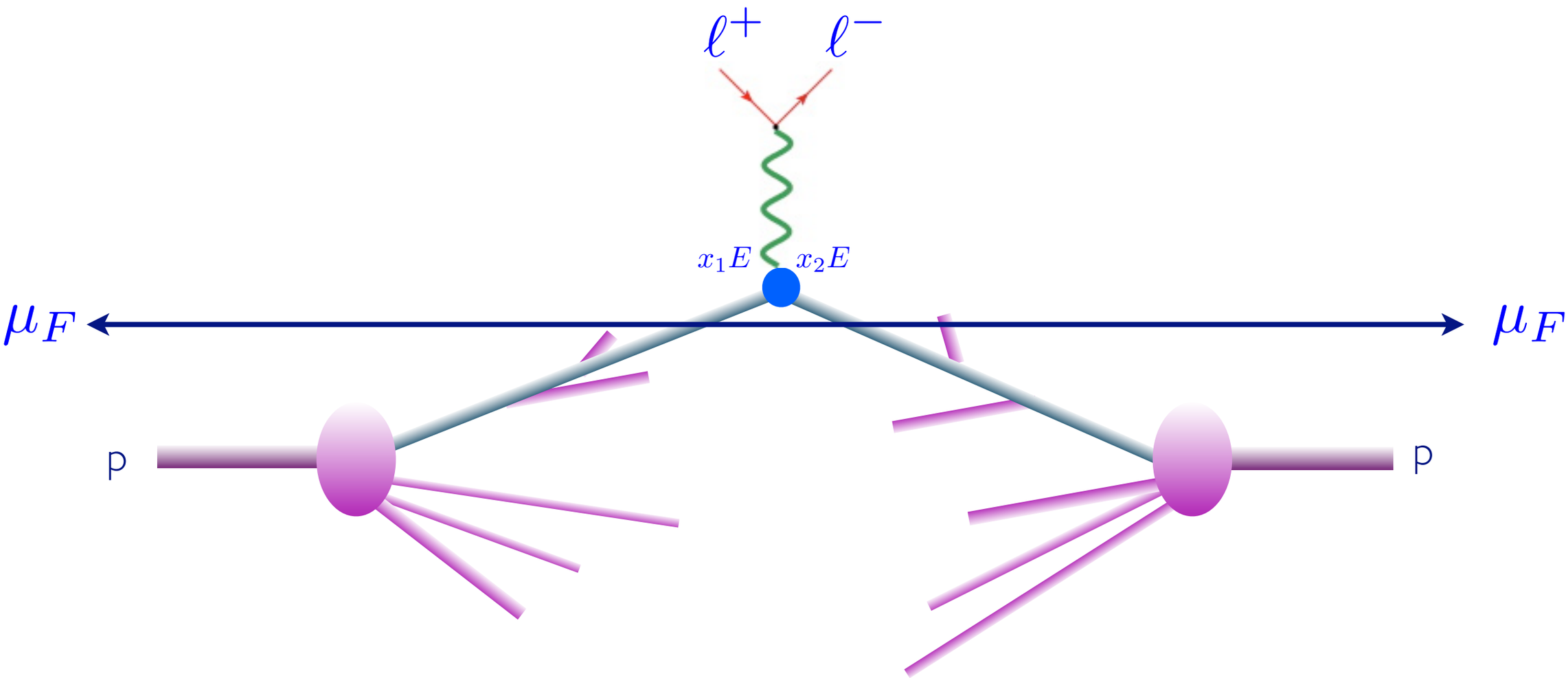

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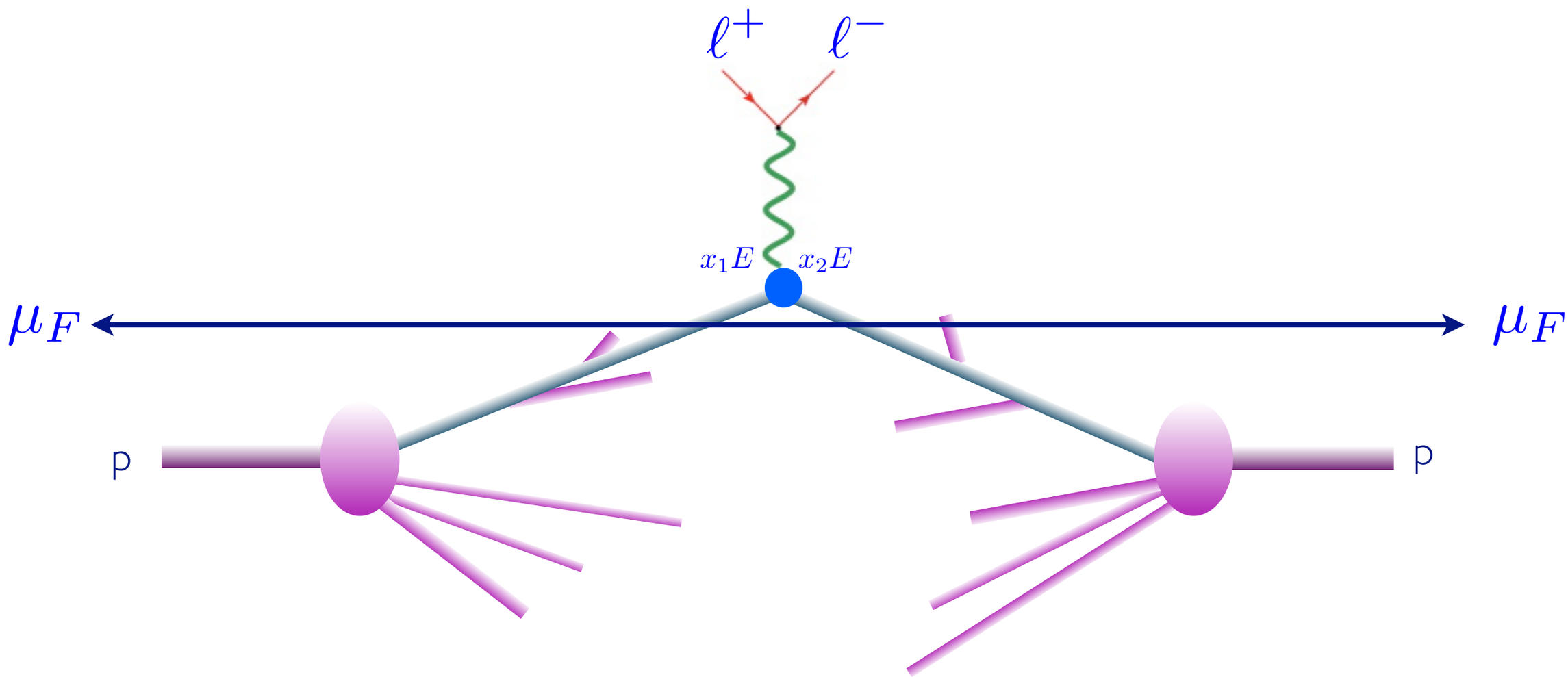

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

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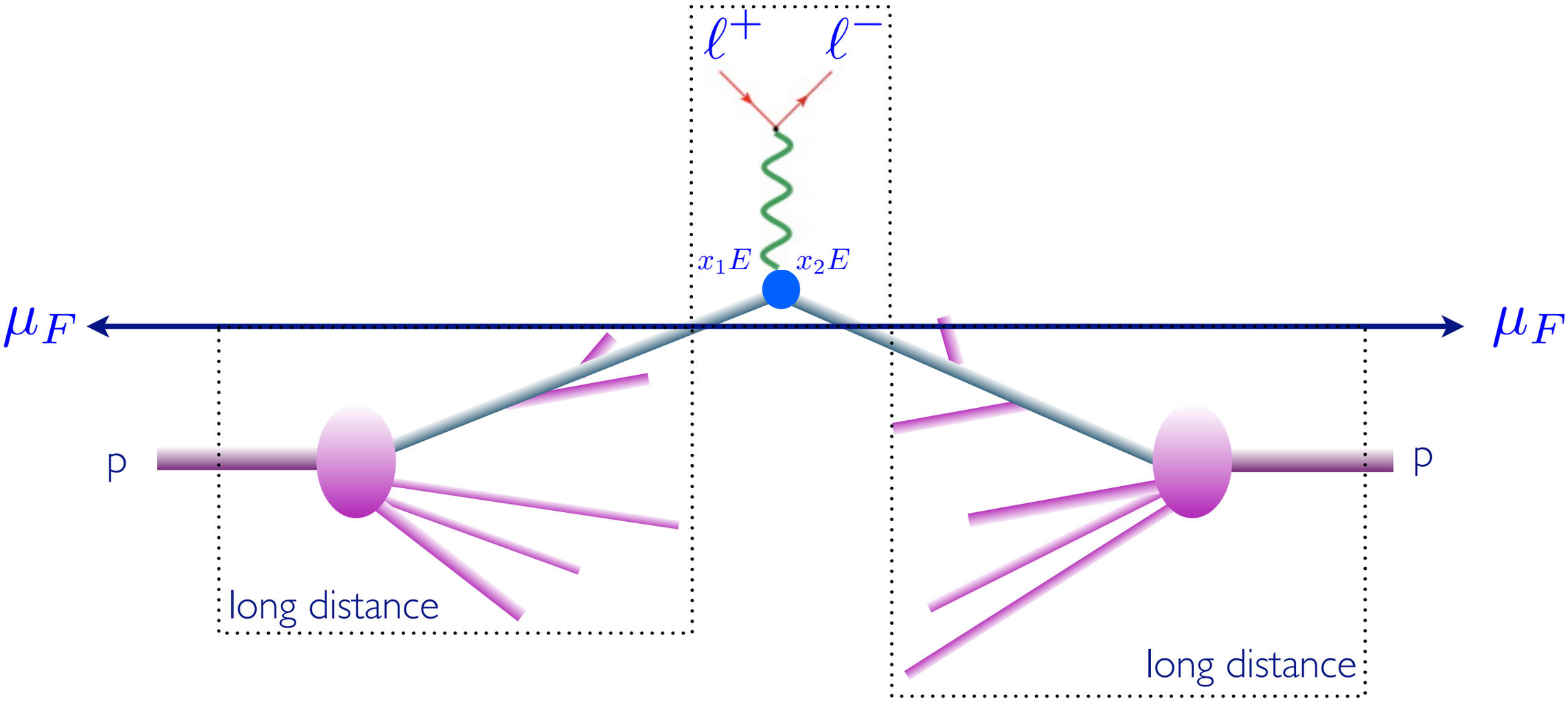

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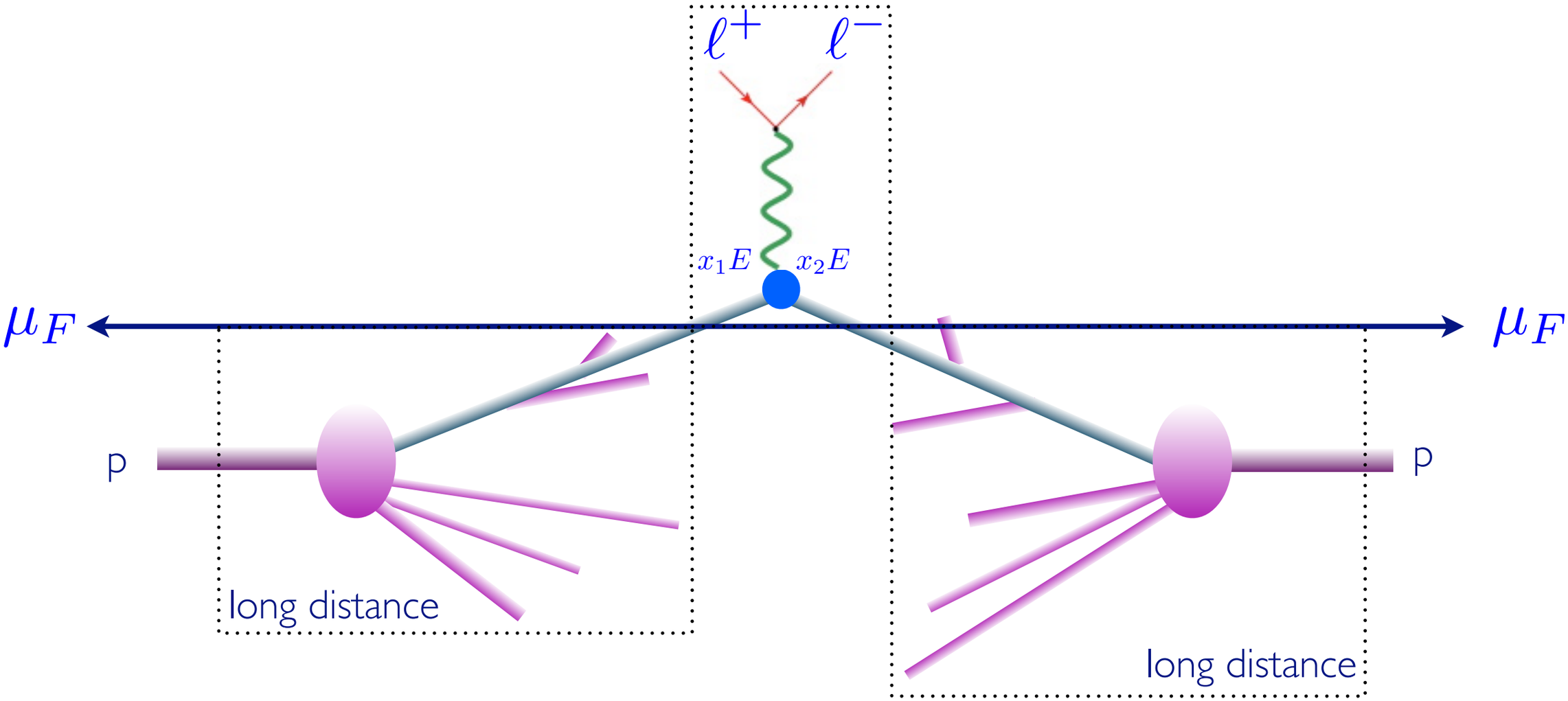

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Pheno/Th exploit this formula to provide accurate and flexible predictions from a given model (SM, MSSM,...)

HOW WE (USED TO) MAKE PREDICTIONS?

First way:

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

TH

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

SM STATUS BEFORE THE LHC

pp→ n particles

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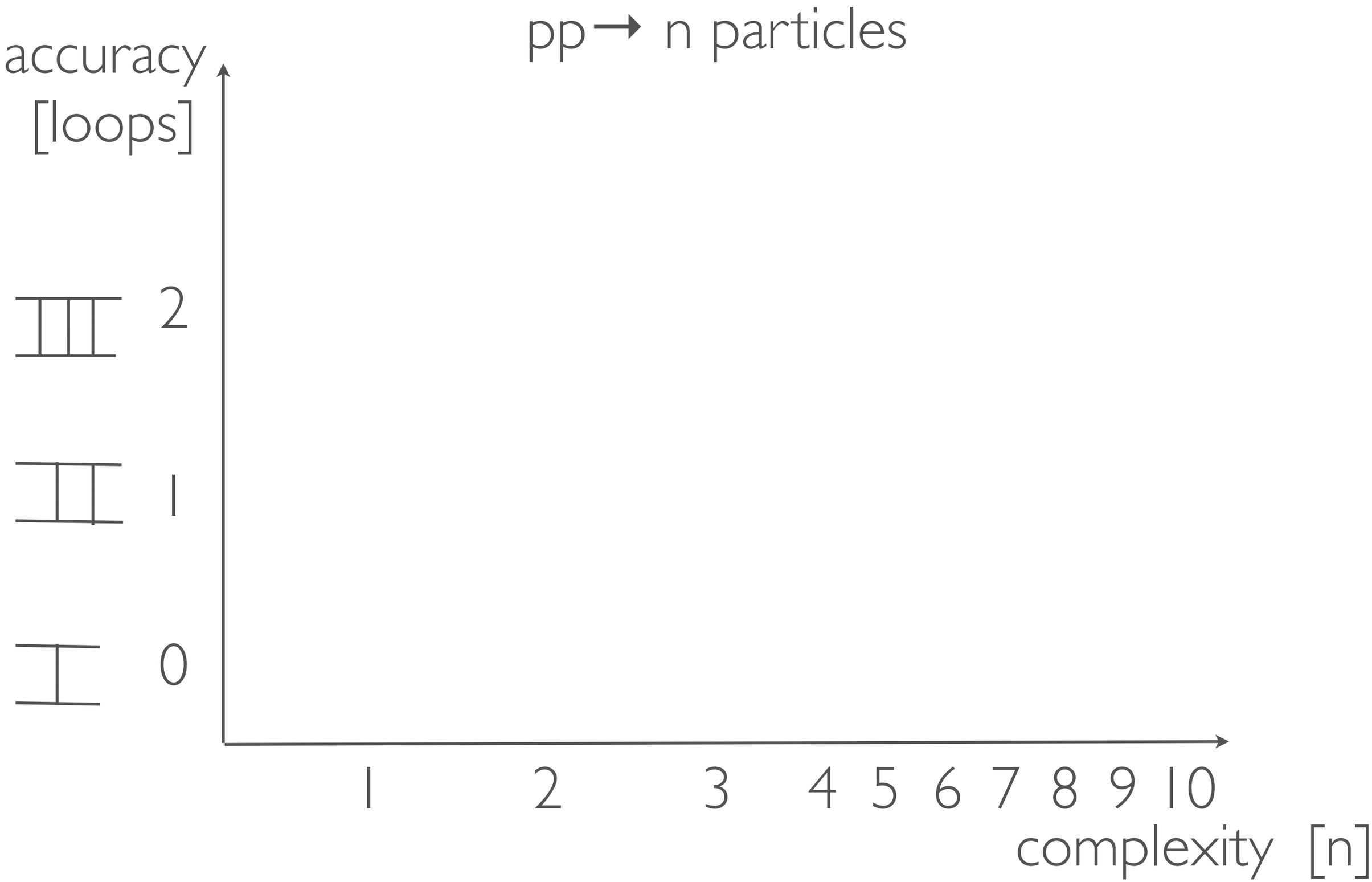

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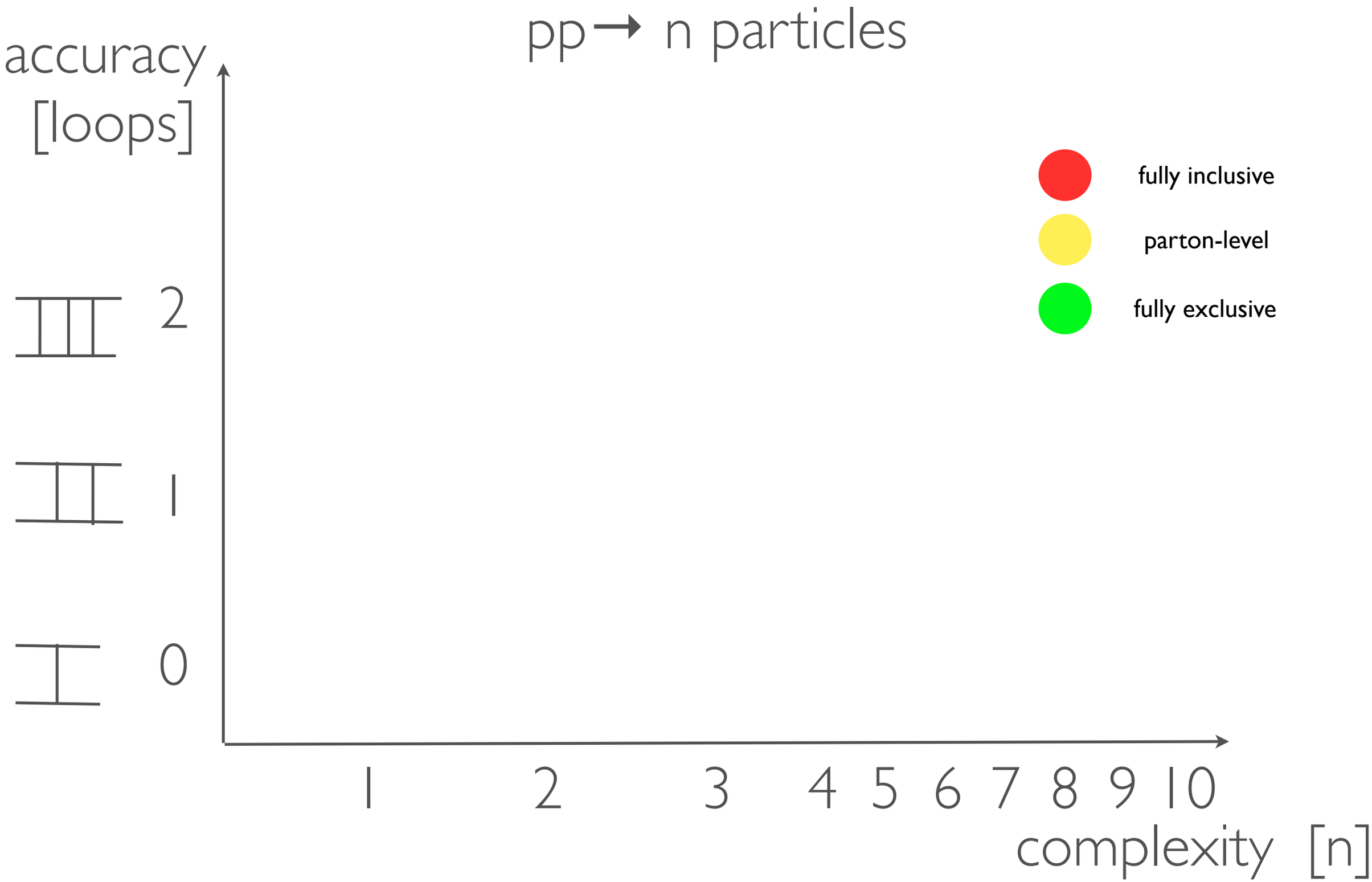

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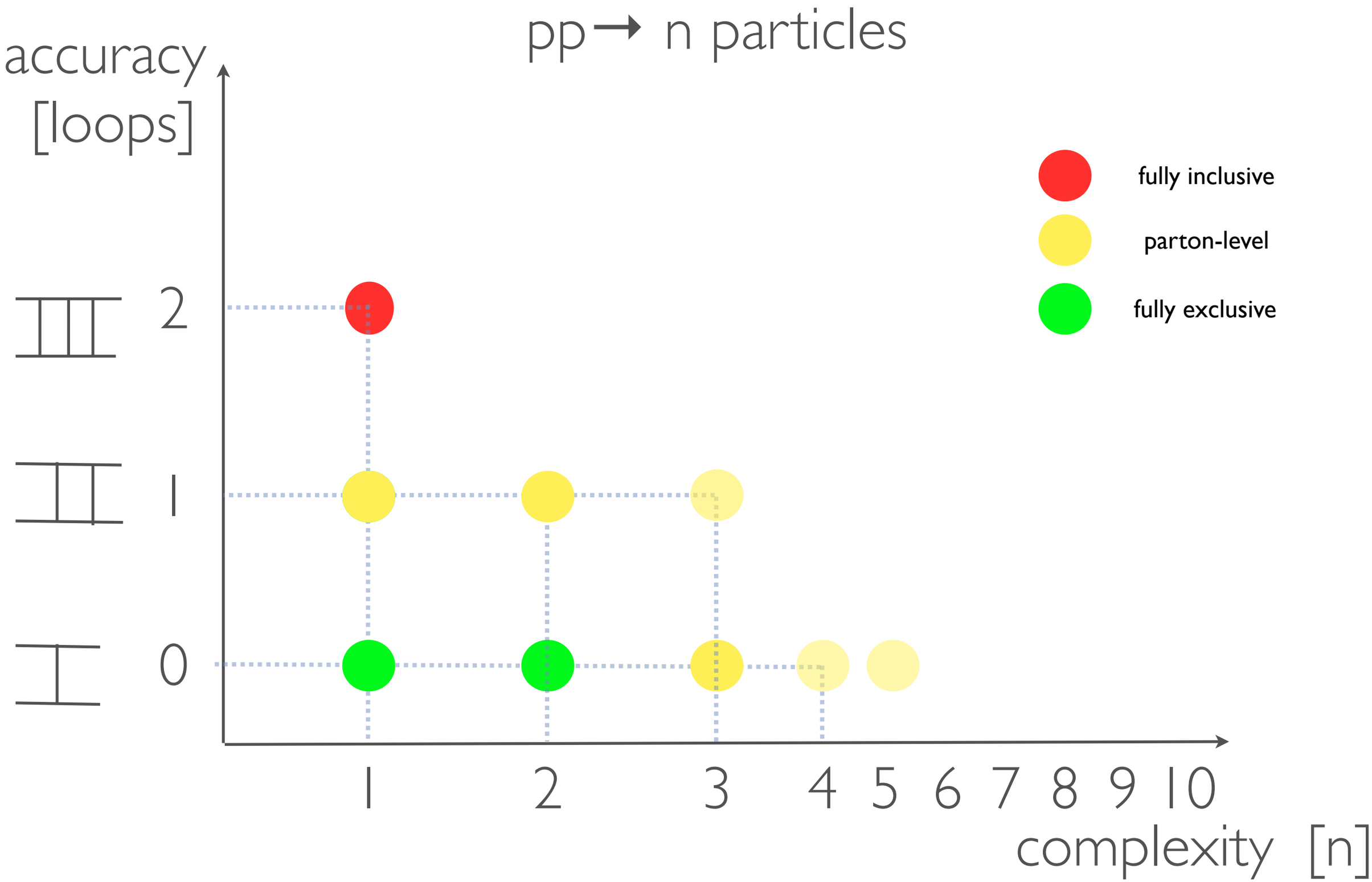
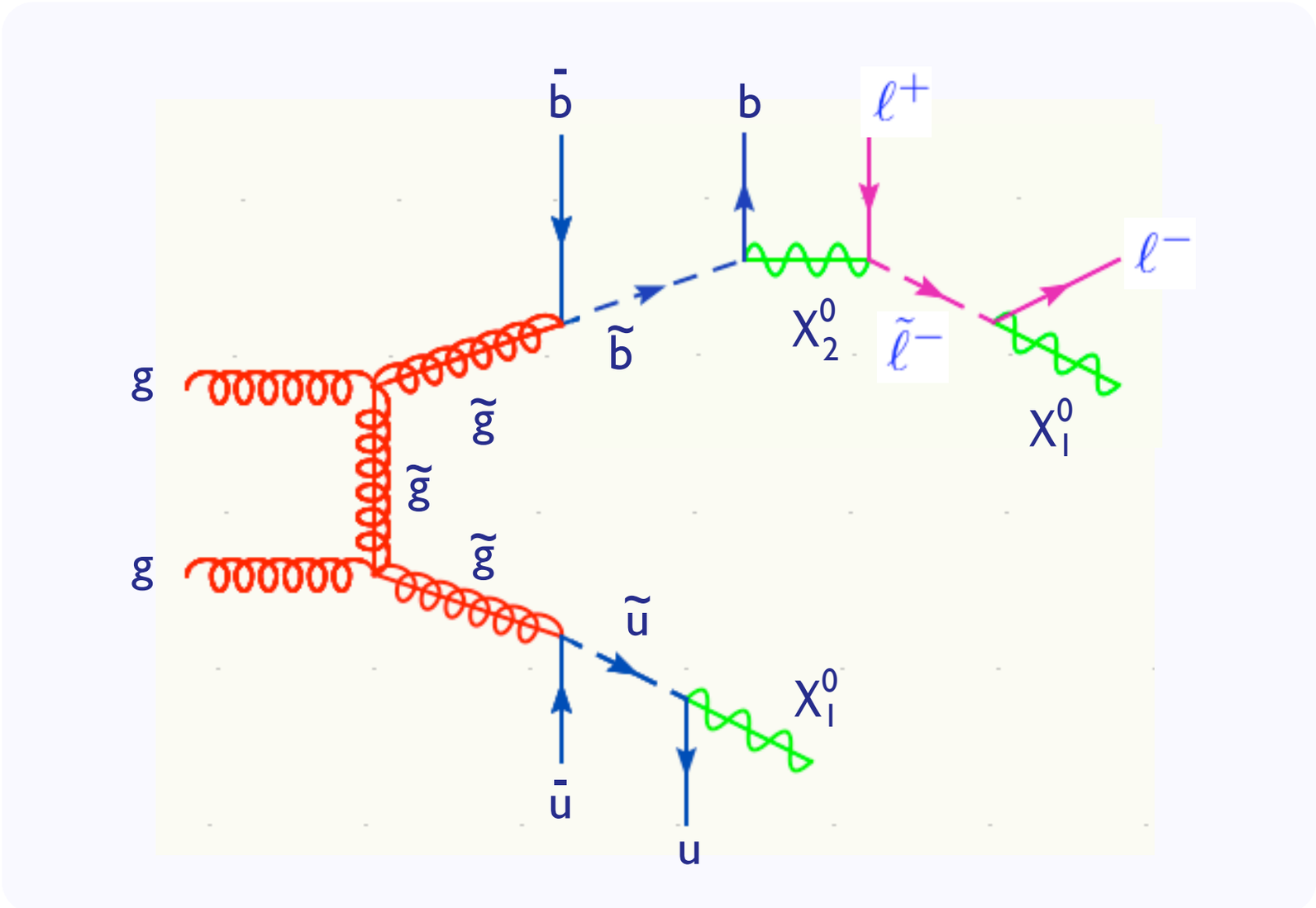
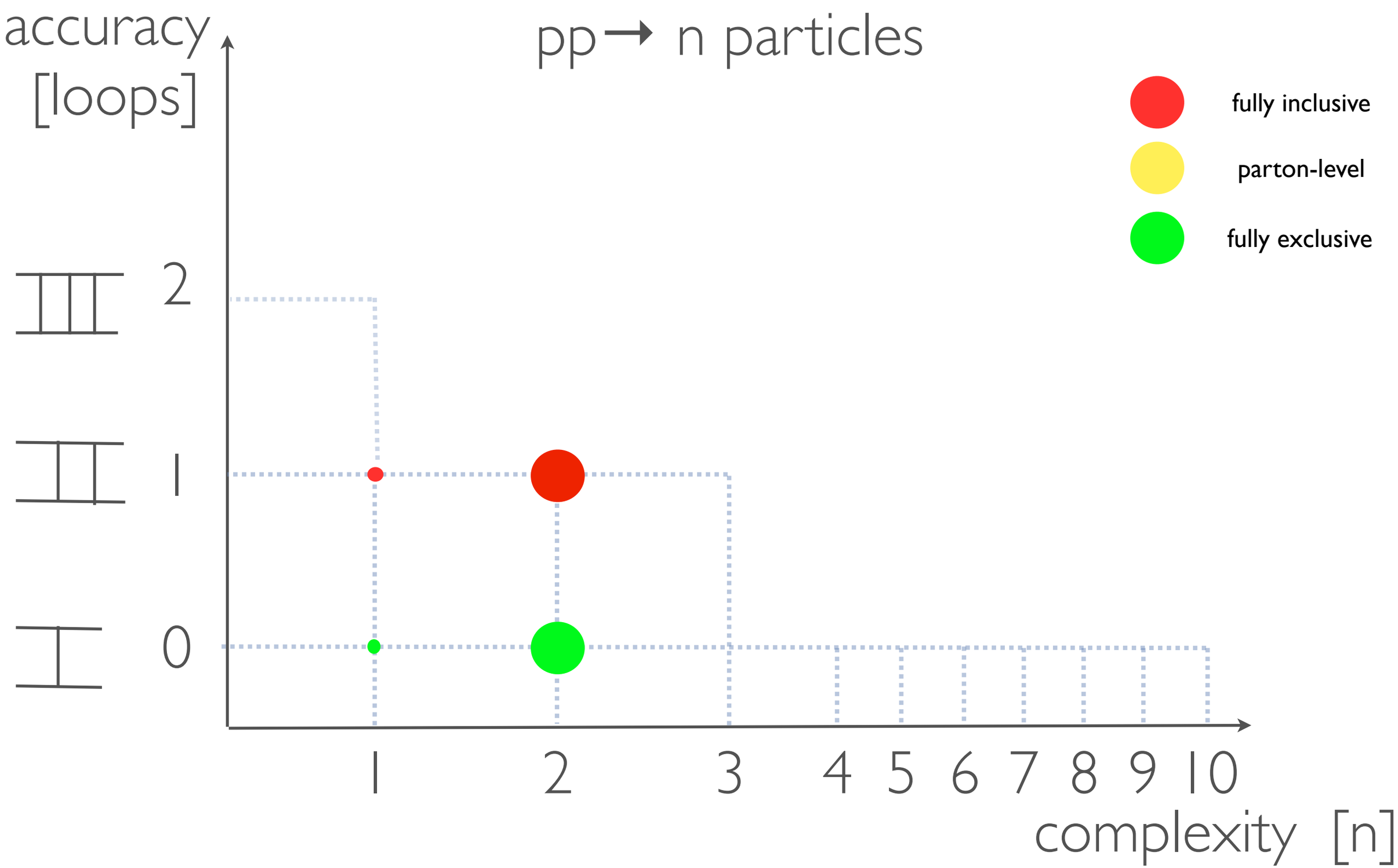


WHAT ABOUT NEW PHYSICS?



BSM (=SUSY)STATUS BEFORE THE LHC



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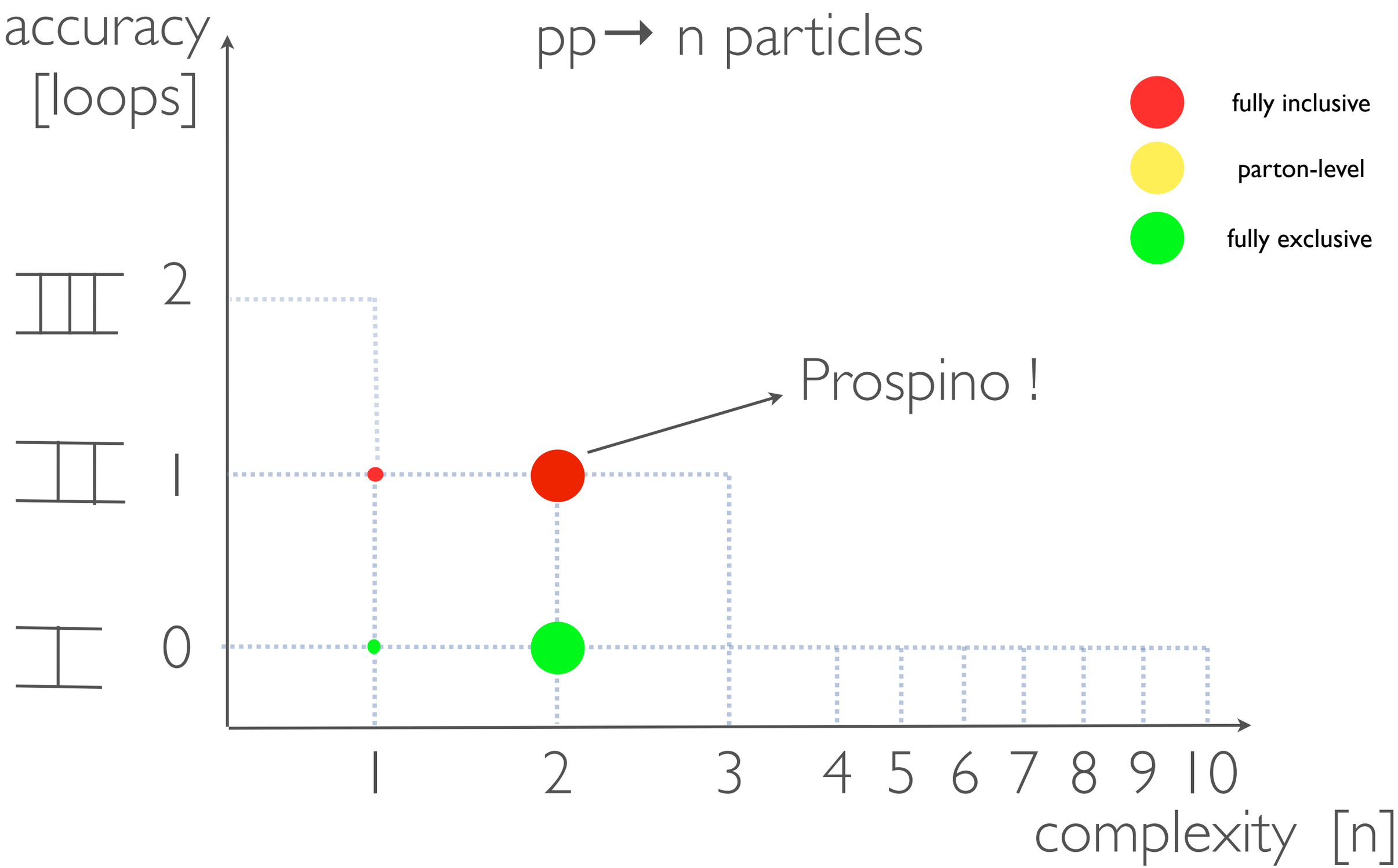
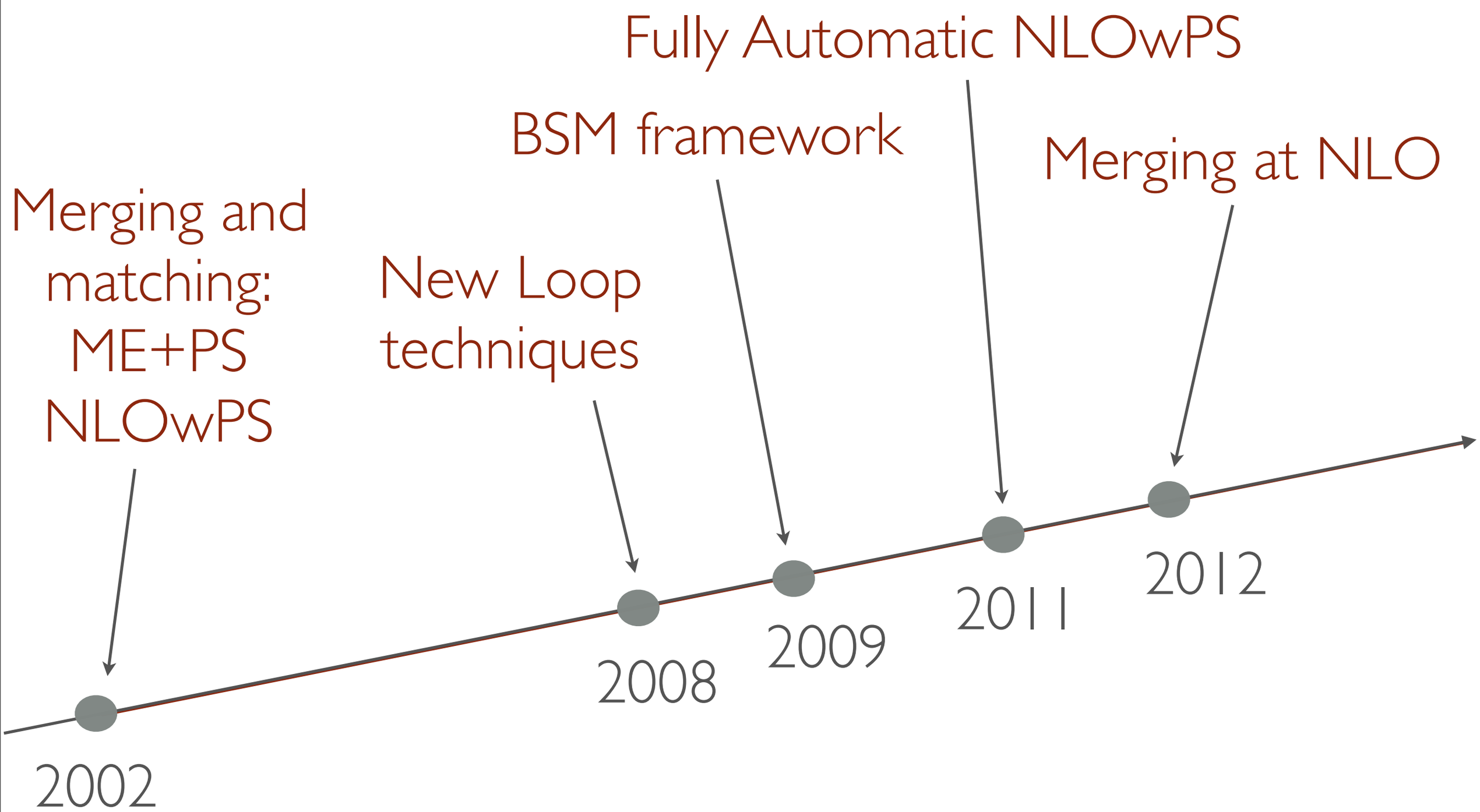


PREDICTIVE MC (SIMPLIFIED) PROGRESS



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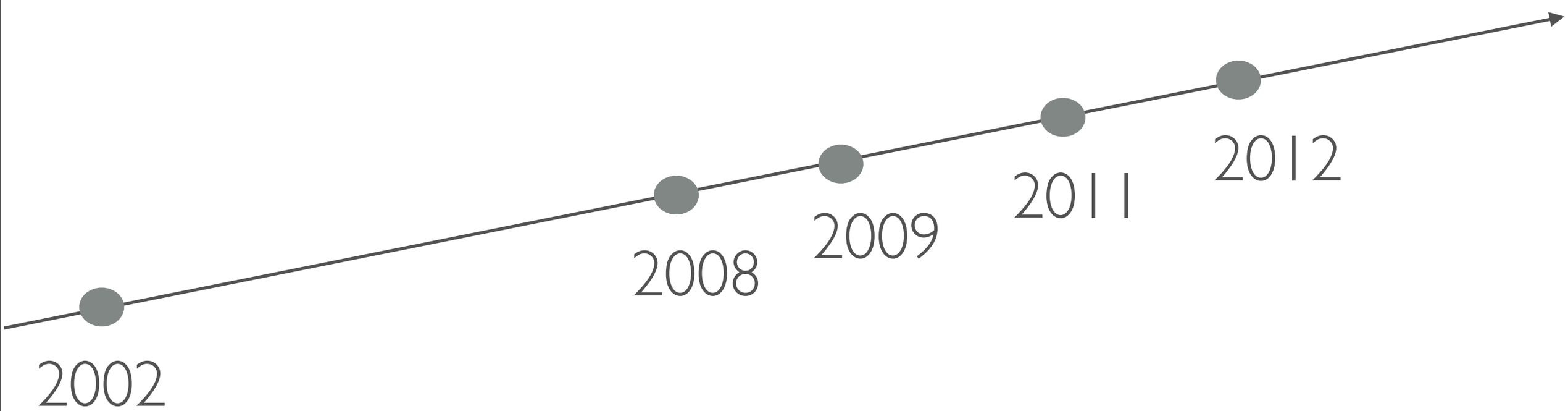

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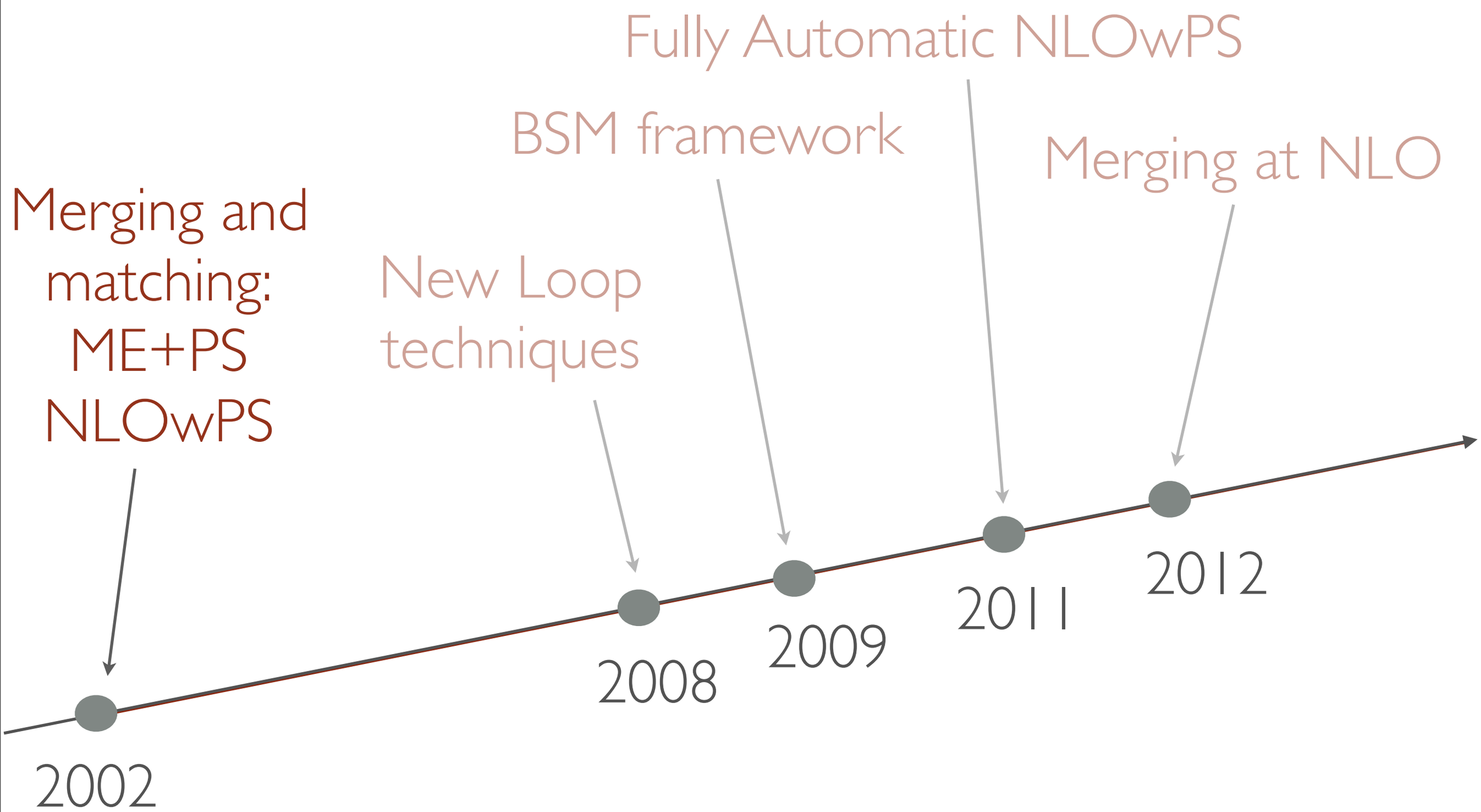
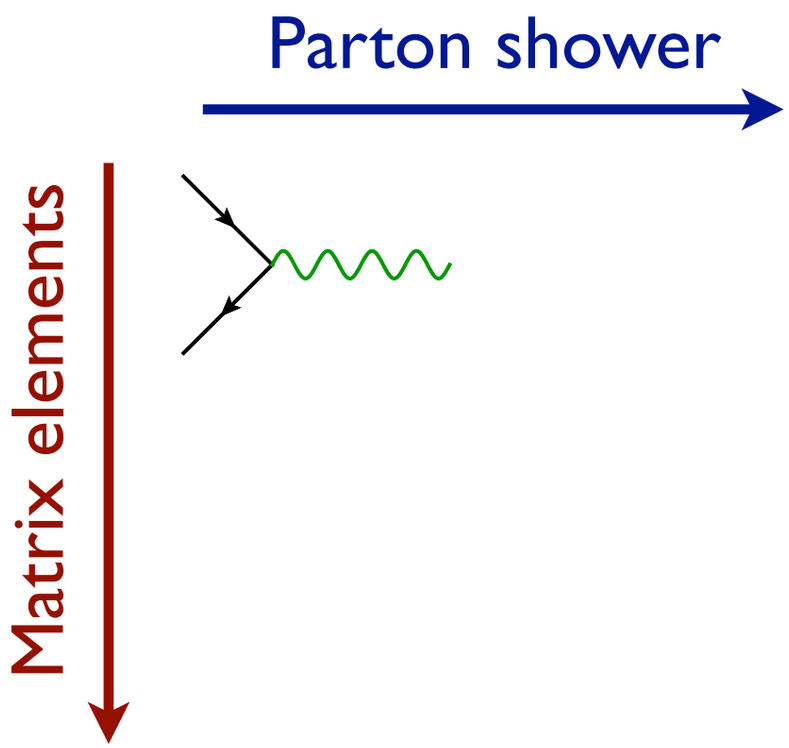


Merging fixed order with PS



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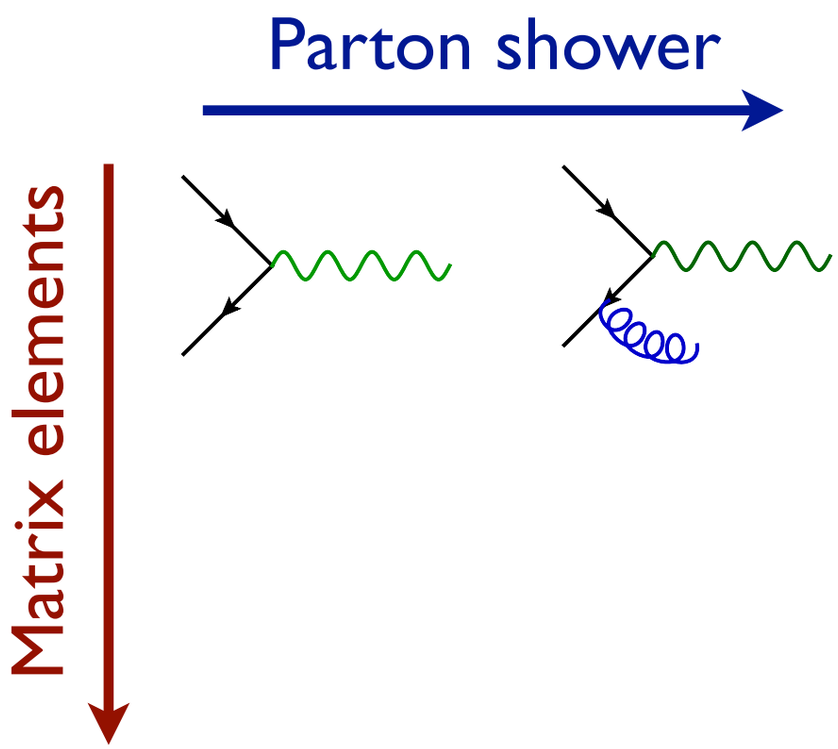

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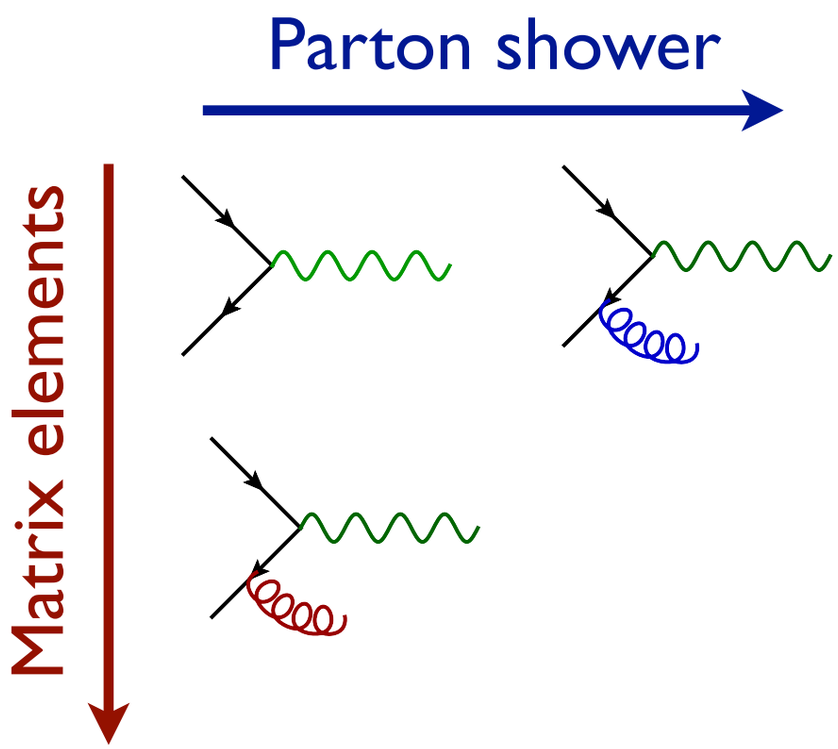

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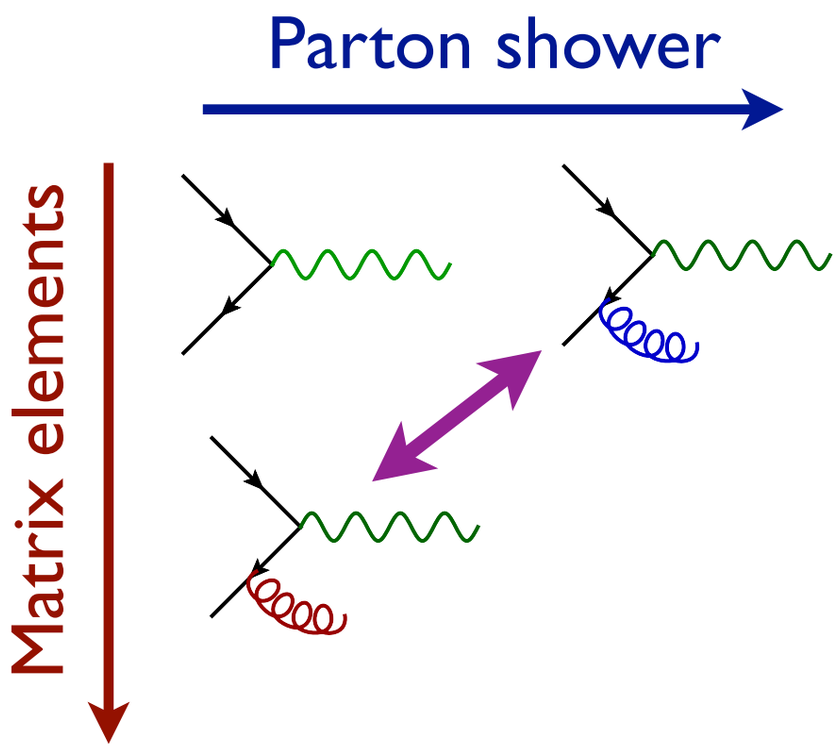

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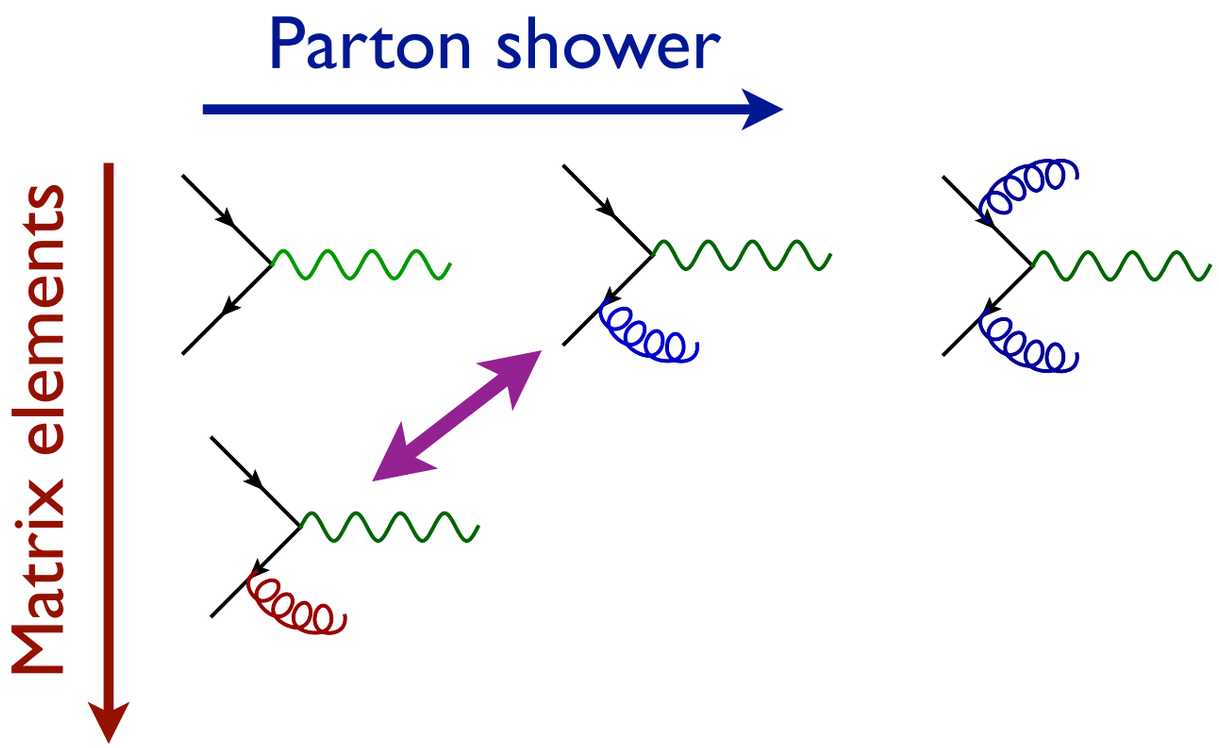

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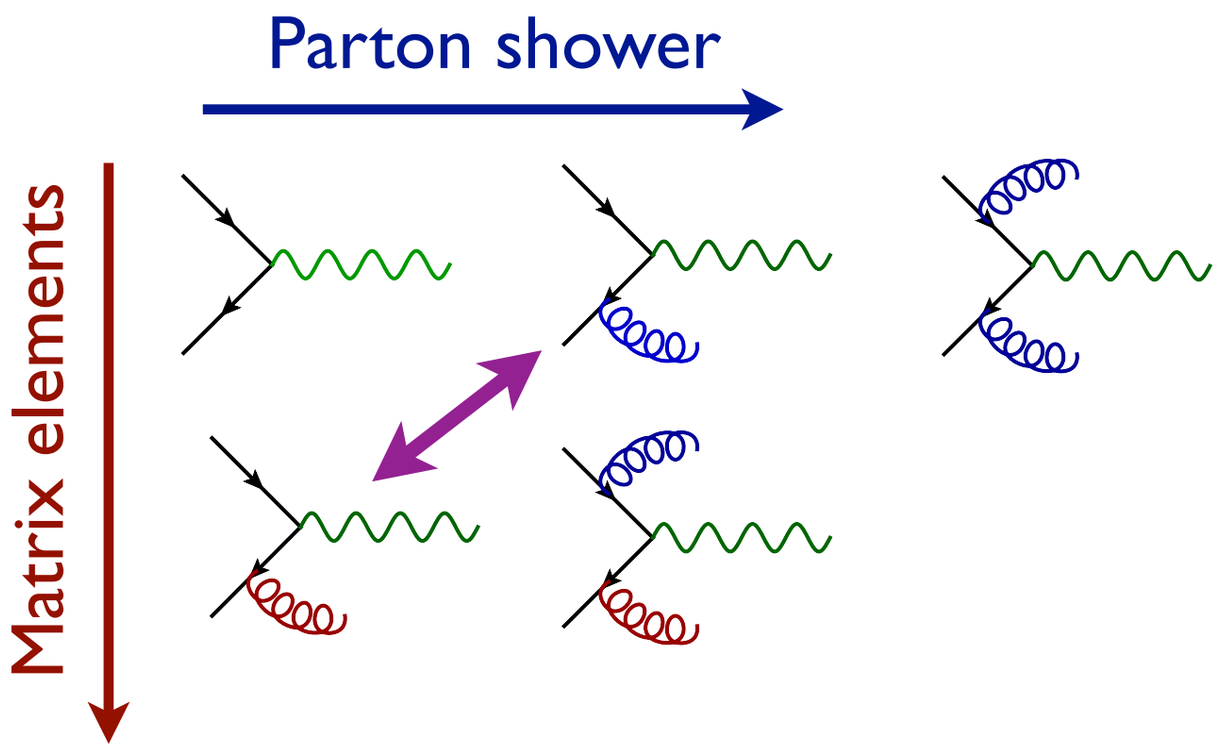

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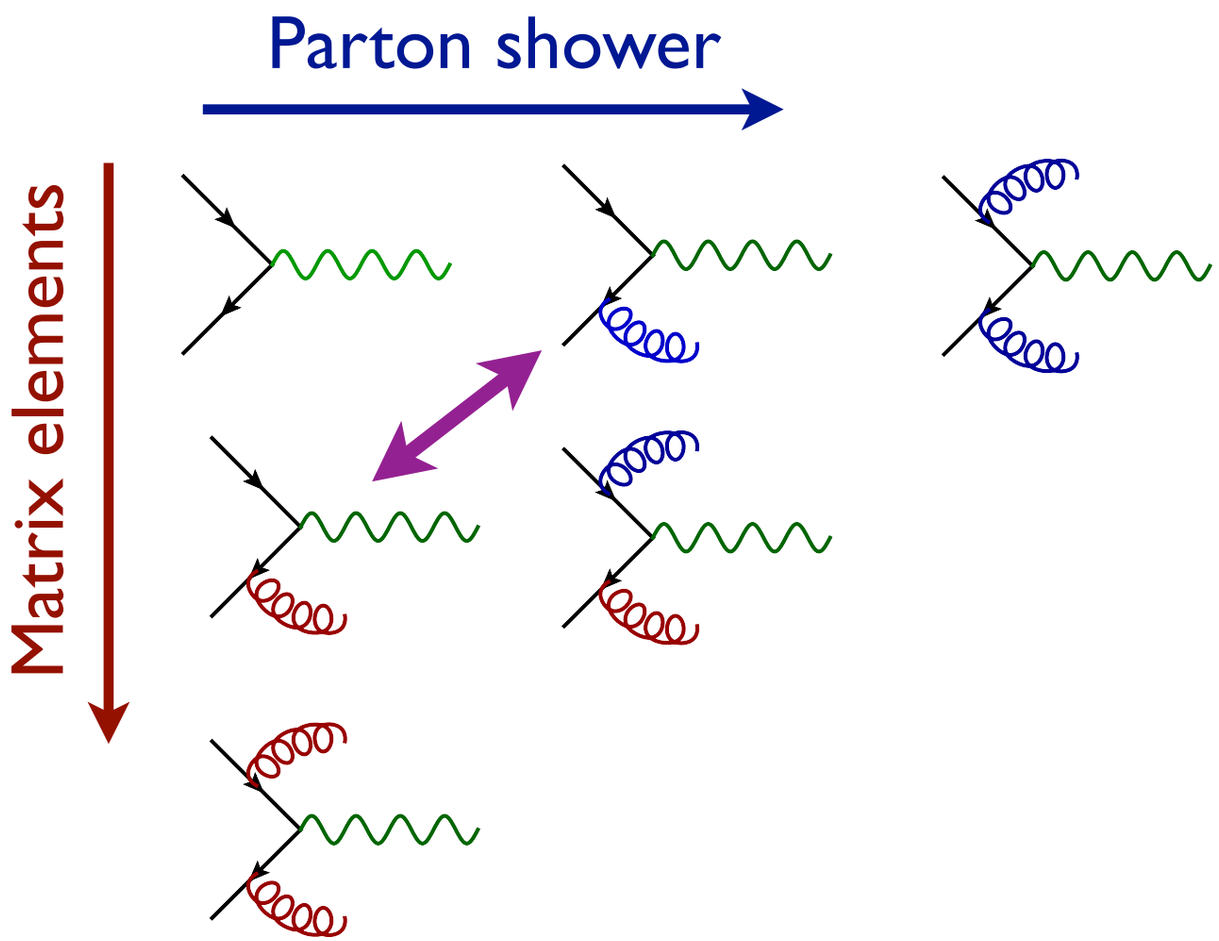

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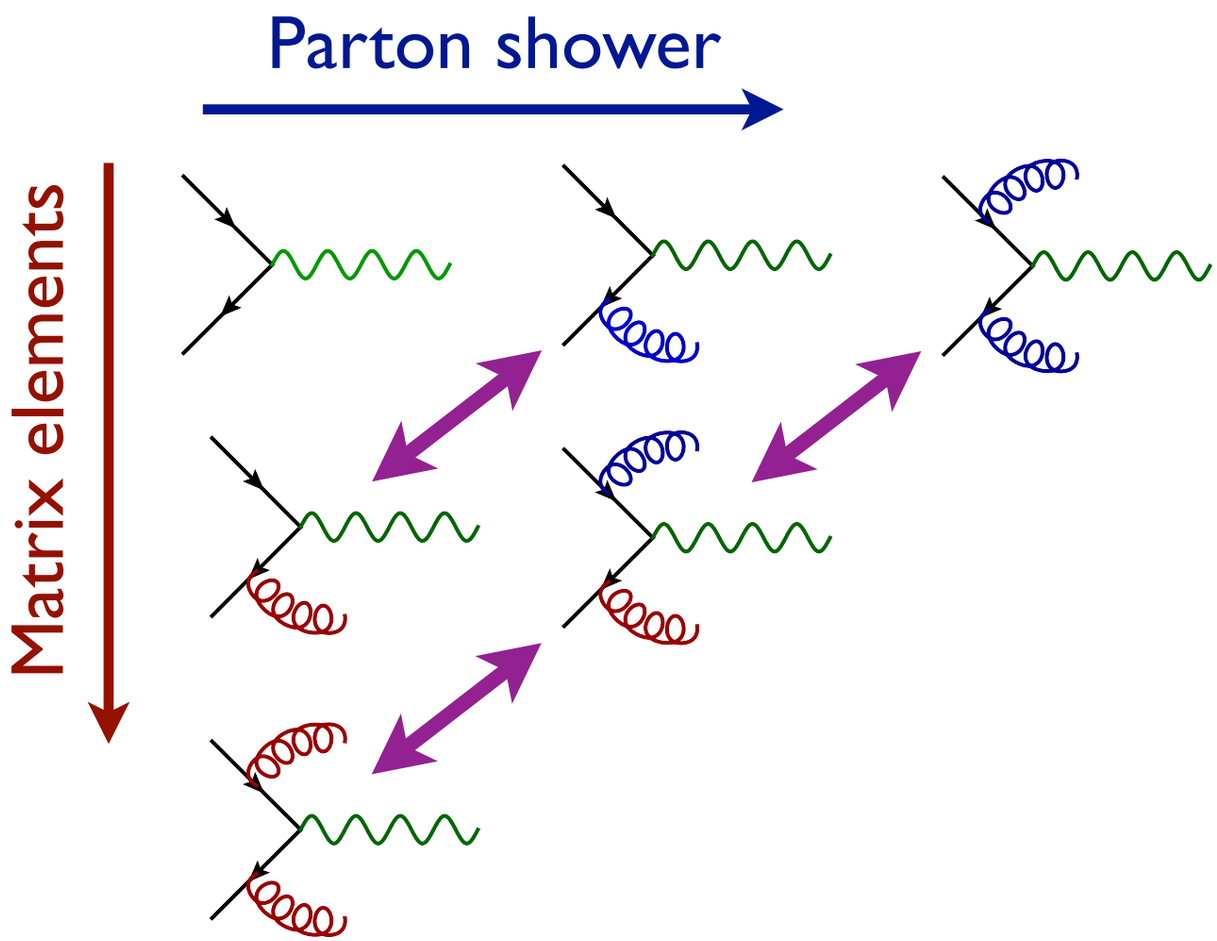

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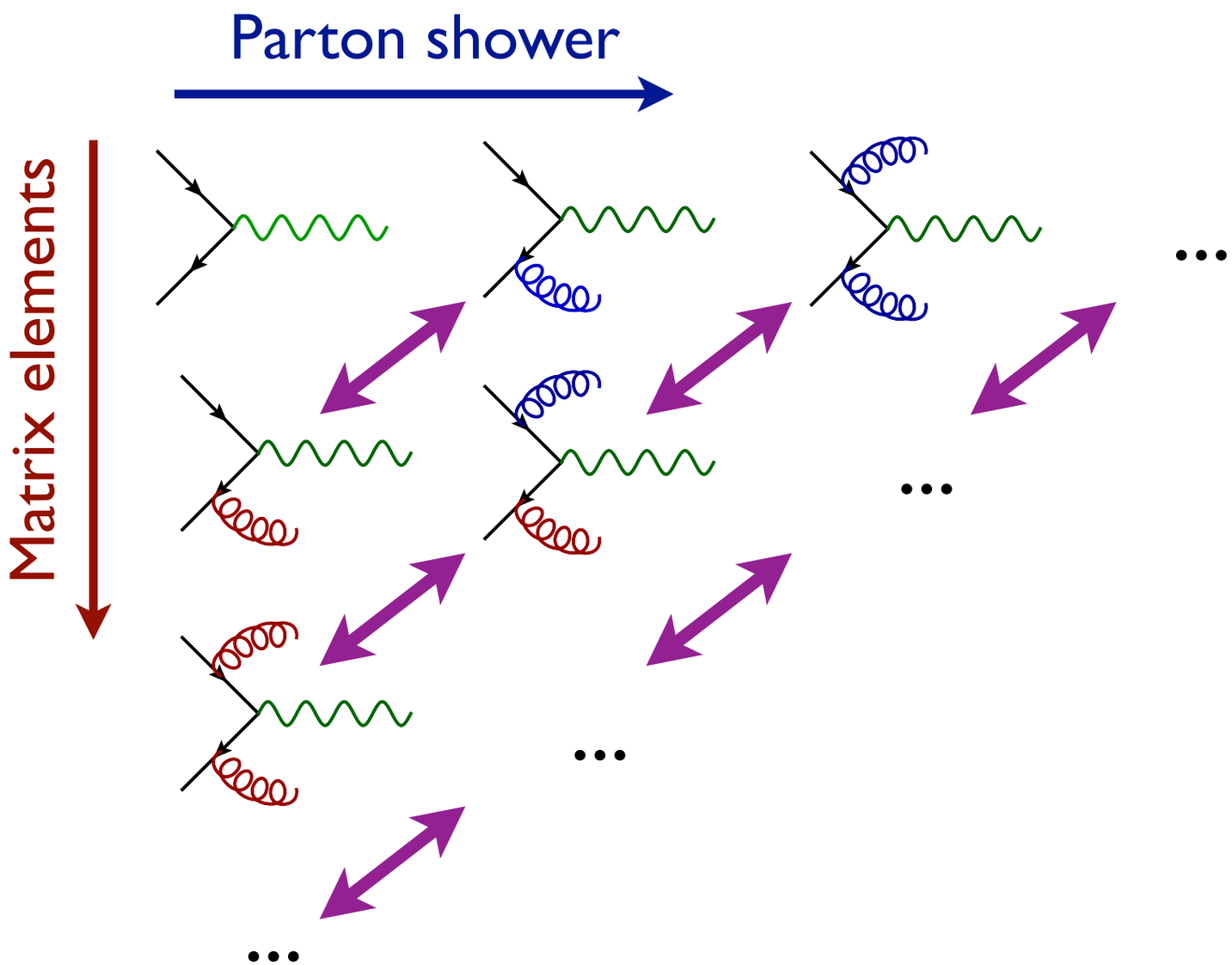

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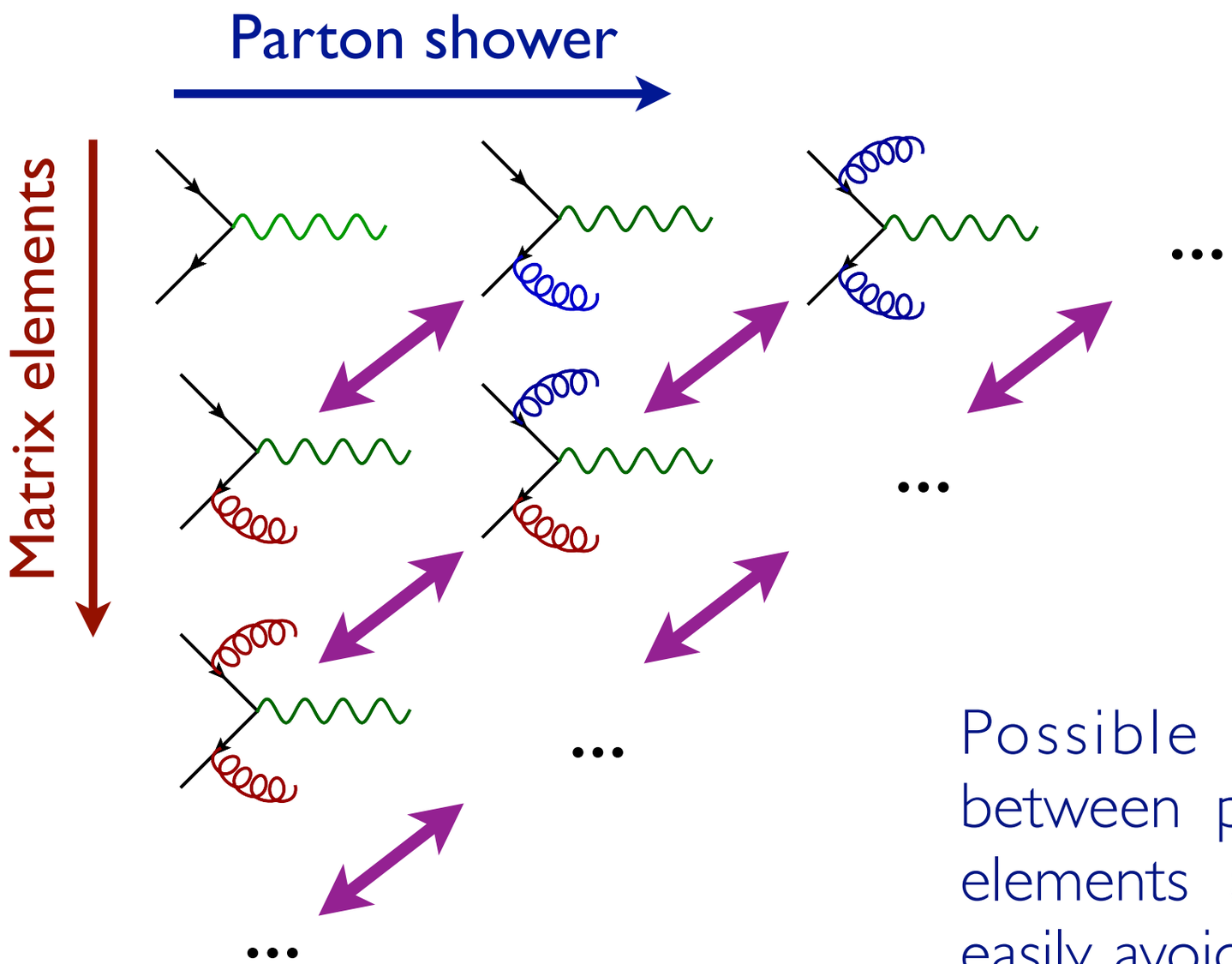

Possible double counting between partons from matrix elements and parton shower easily avoided by applying a cut in phase space

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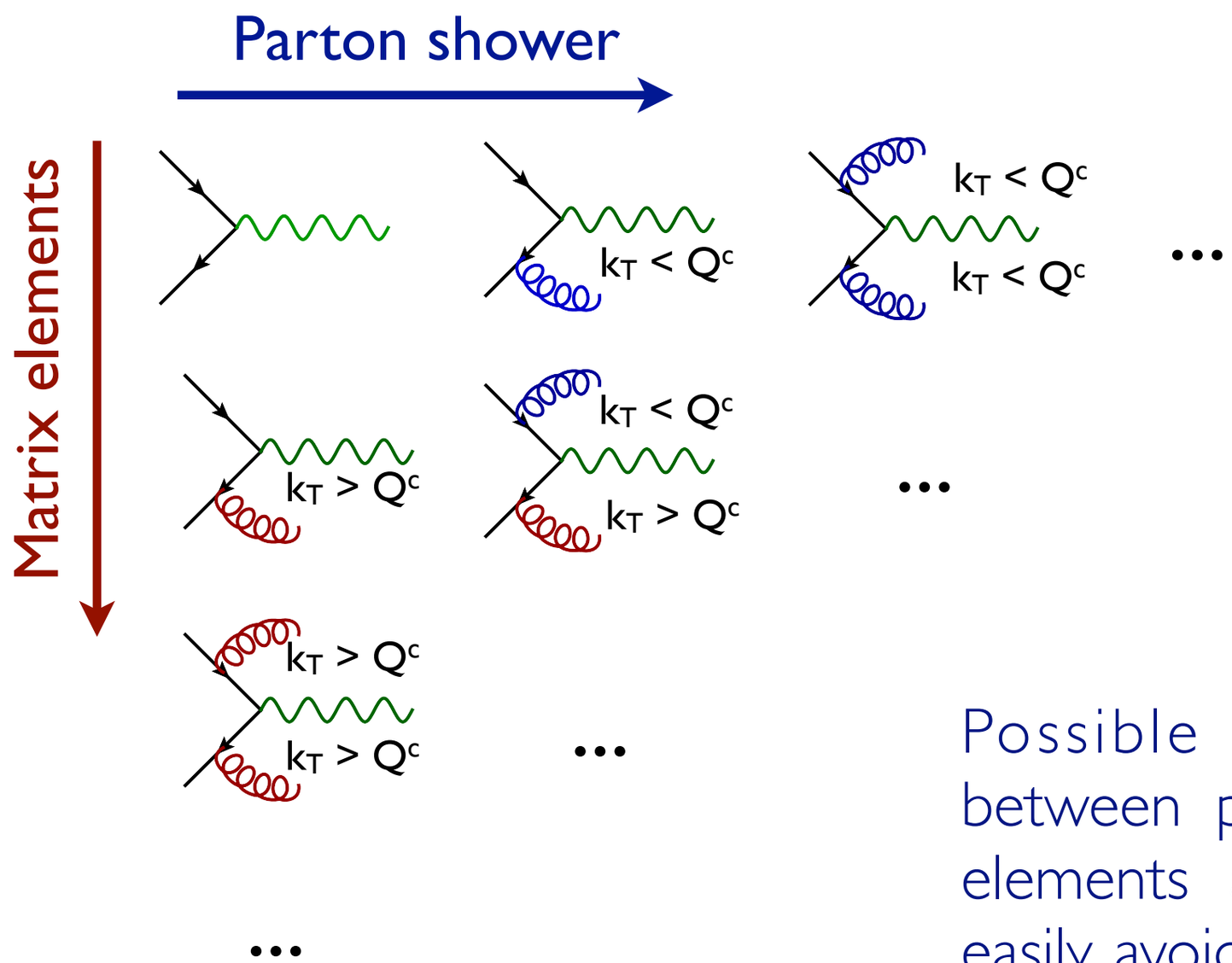

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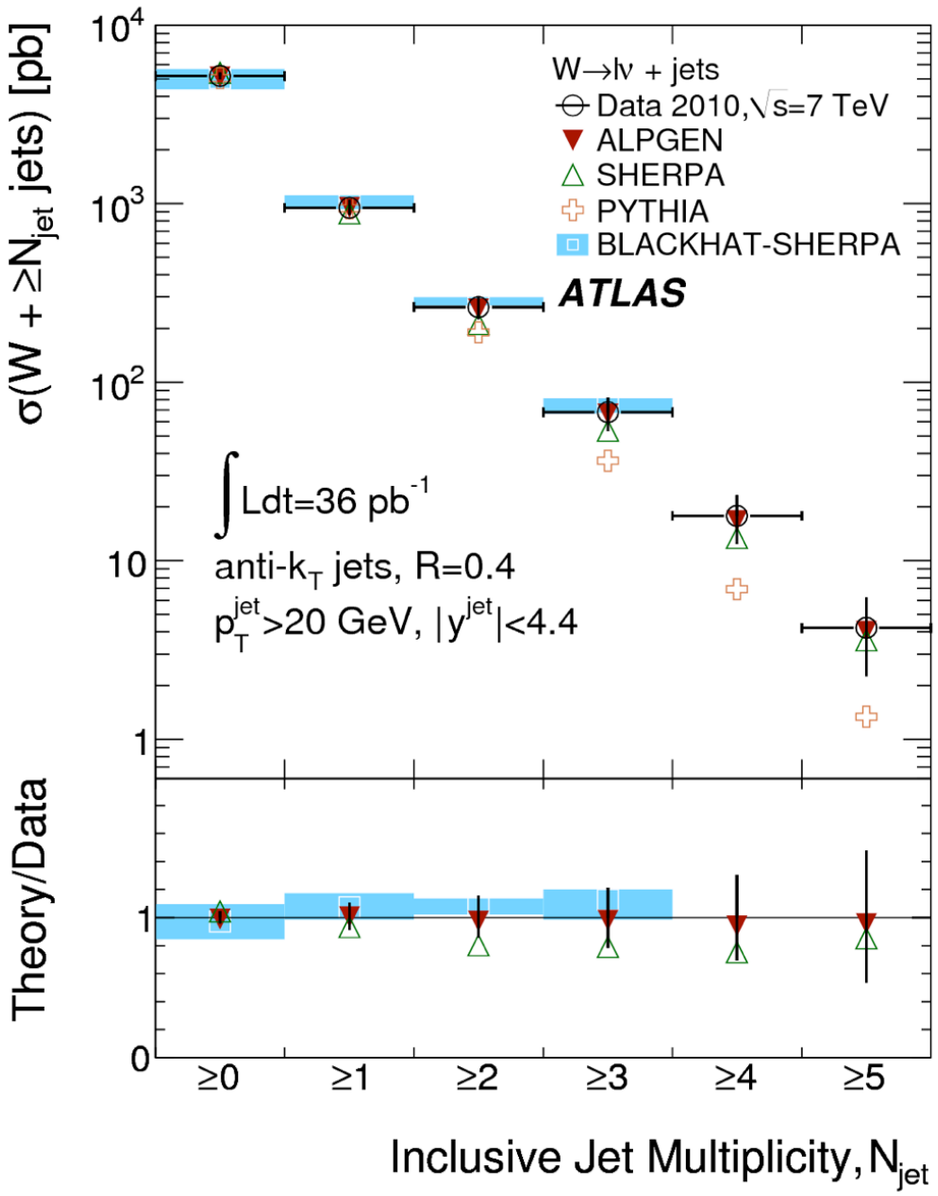
V+JETS AT THE LHC



Working amazingly well!

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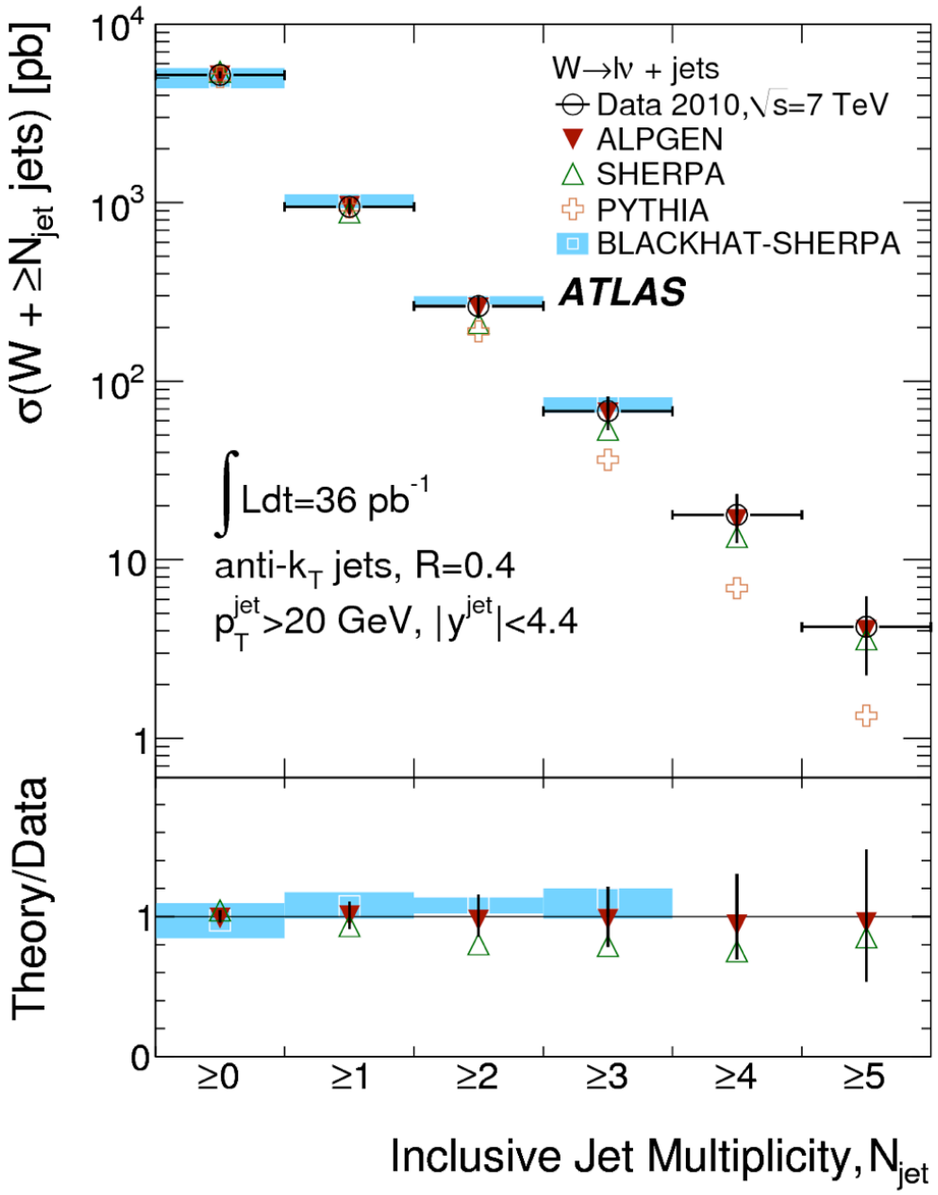

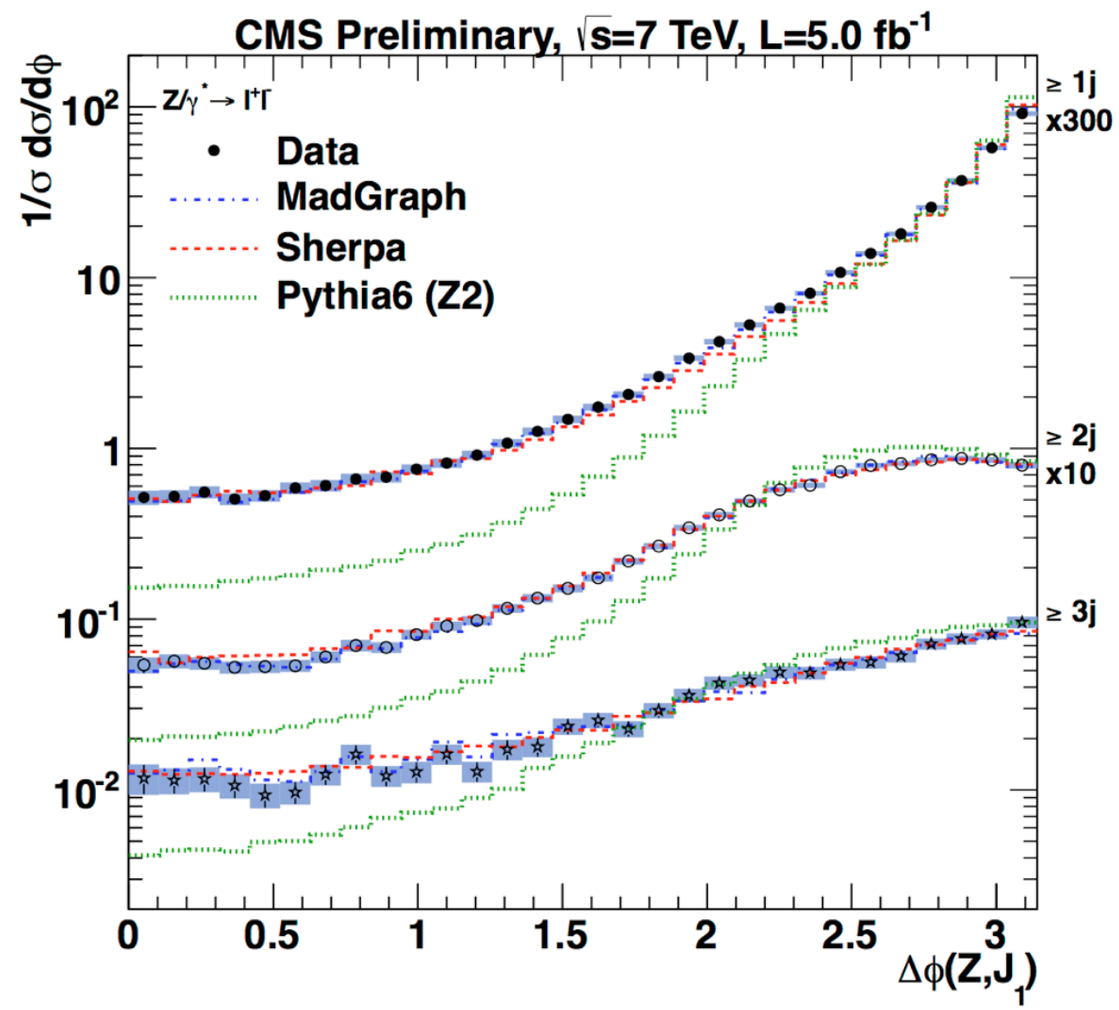

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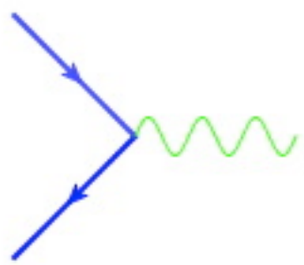
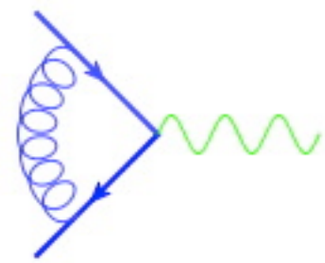
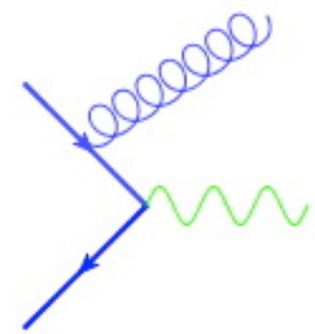
WHAT ABOUT NLO?

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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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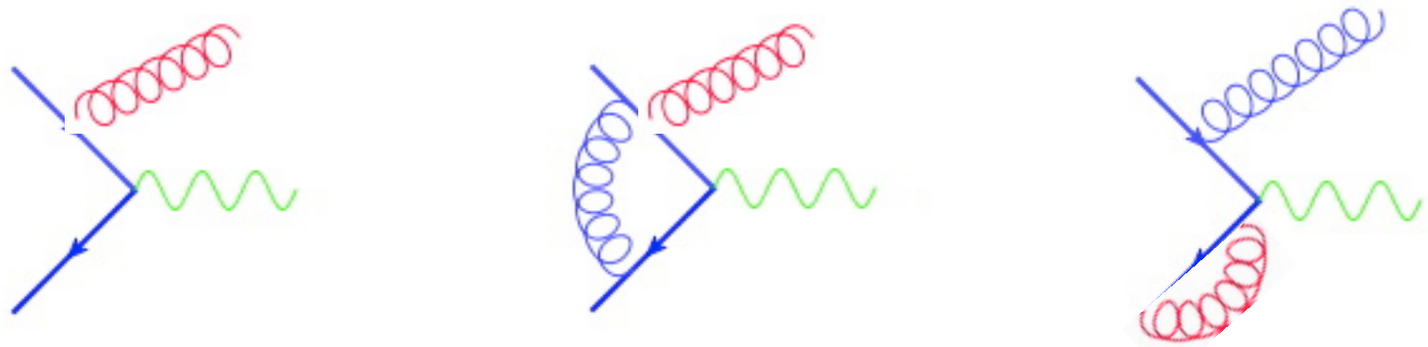

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MC@NLO AND POWHEG

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MC@NLO

[Frixione, Webber, 2002;
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 Pythia8, HW++
[Torrielli, Frixione, 1002.4293]
- Now automatized [Frederix, Frixione, Torrielli]
- Available in aMC@NLO (see later) and also in SHERPA

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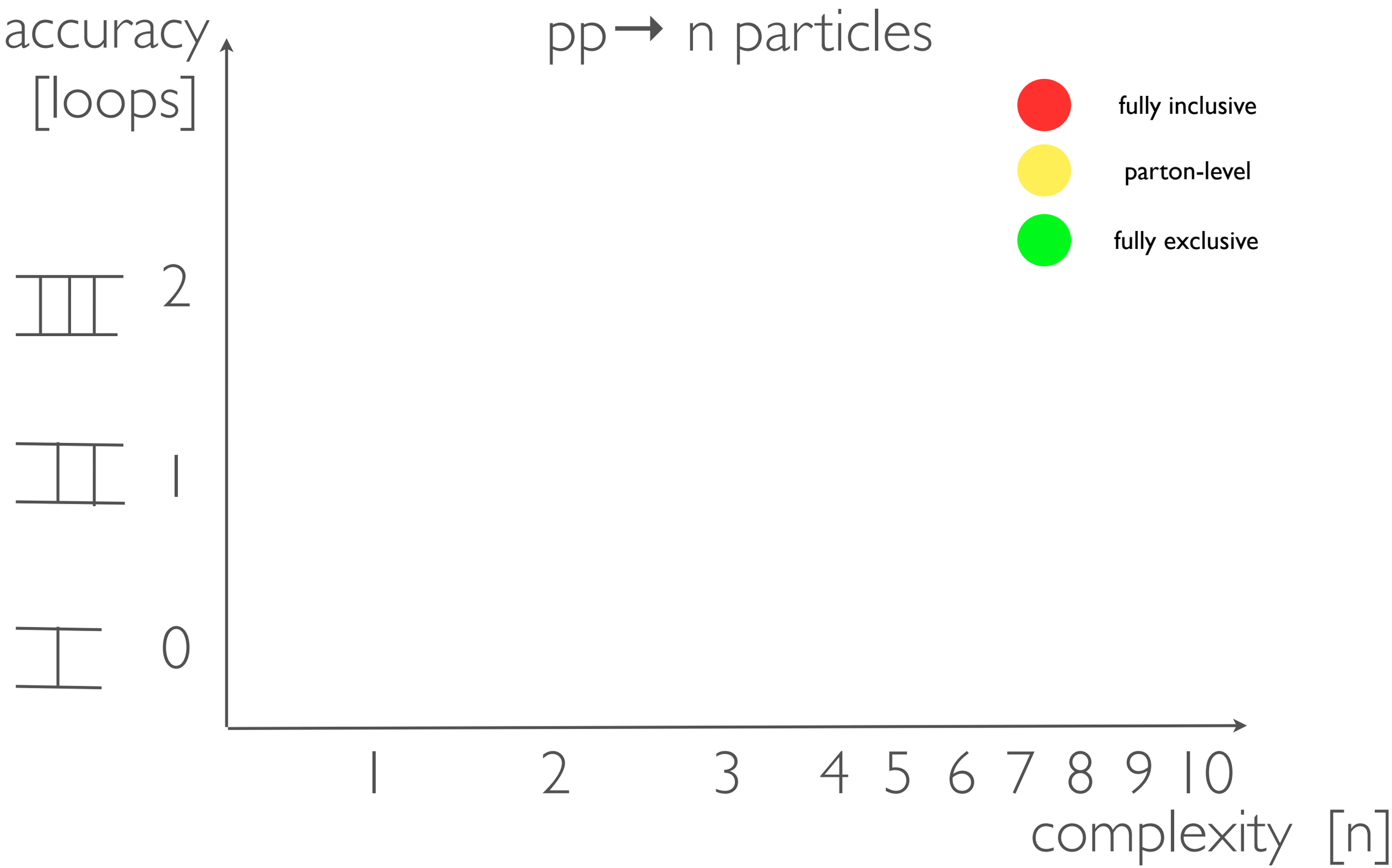
POWHEG

[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]

SM STATUS AT THE LHC START



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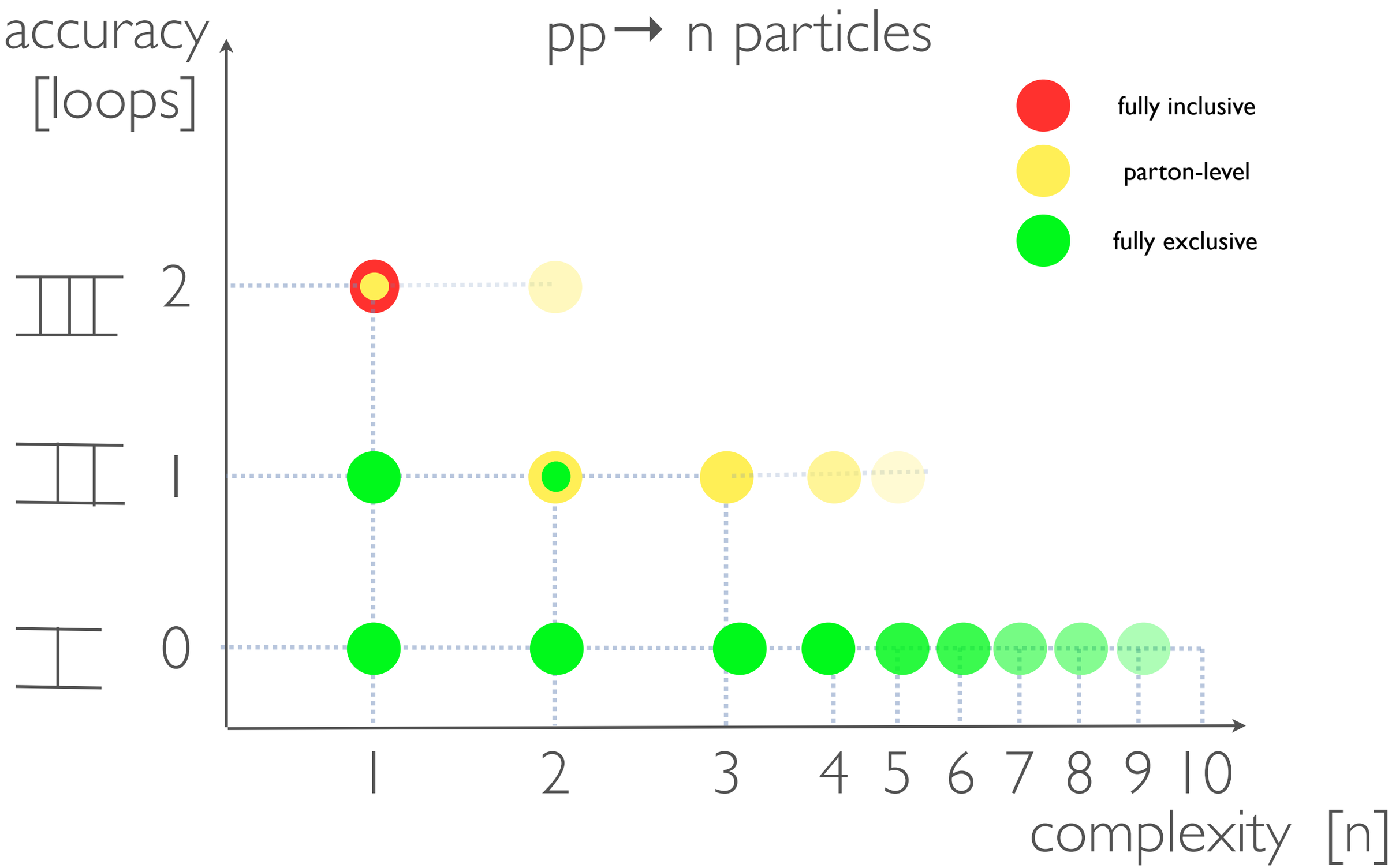

AUTOMATION

- **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

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Genius: 1% inspiration and 99% perspiration.

[Thomas Edison]

AUTOMATION

Genius: 1% inspiration and 99% perspiration.

[Thomas Edison]

True, but perspiration can be automated!

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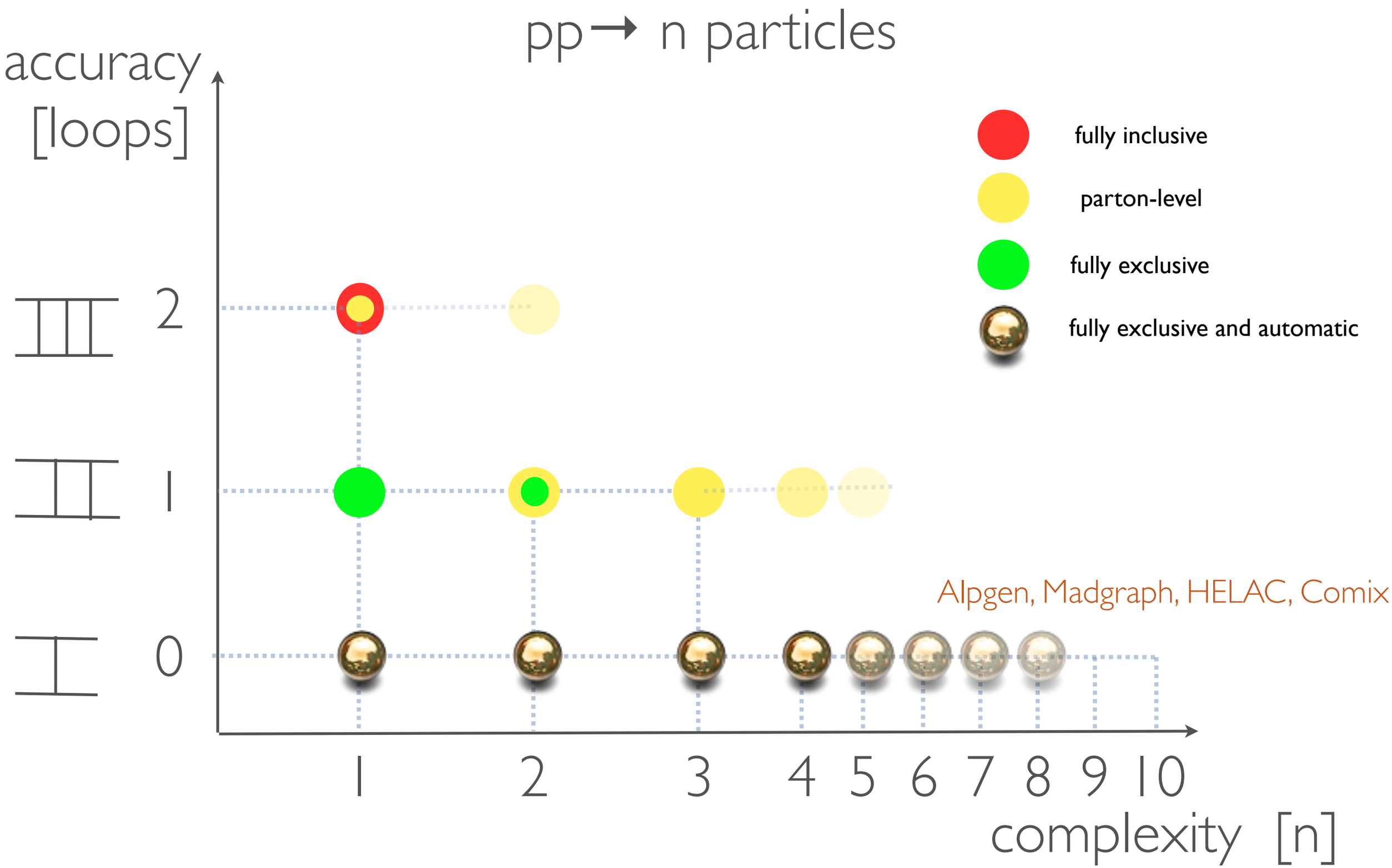

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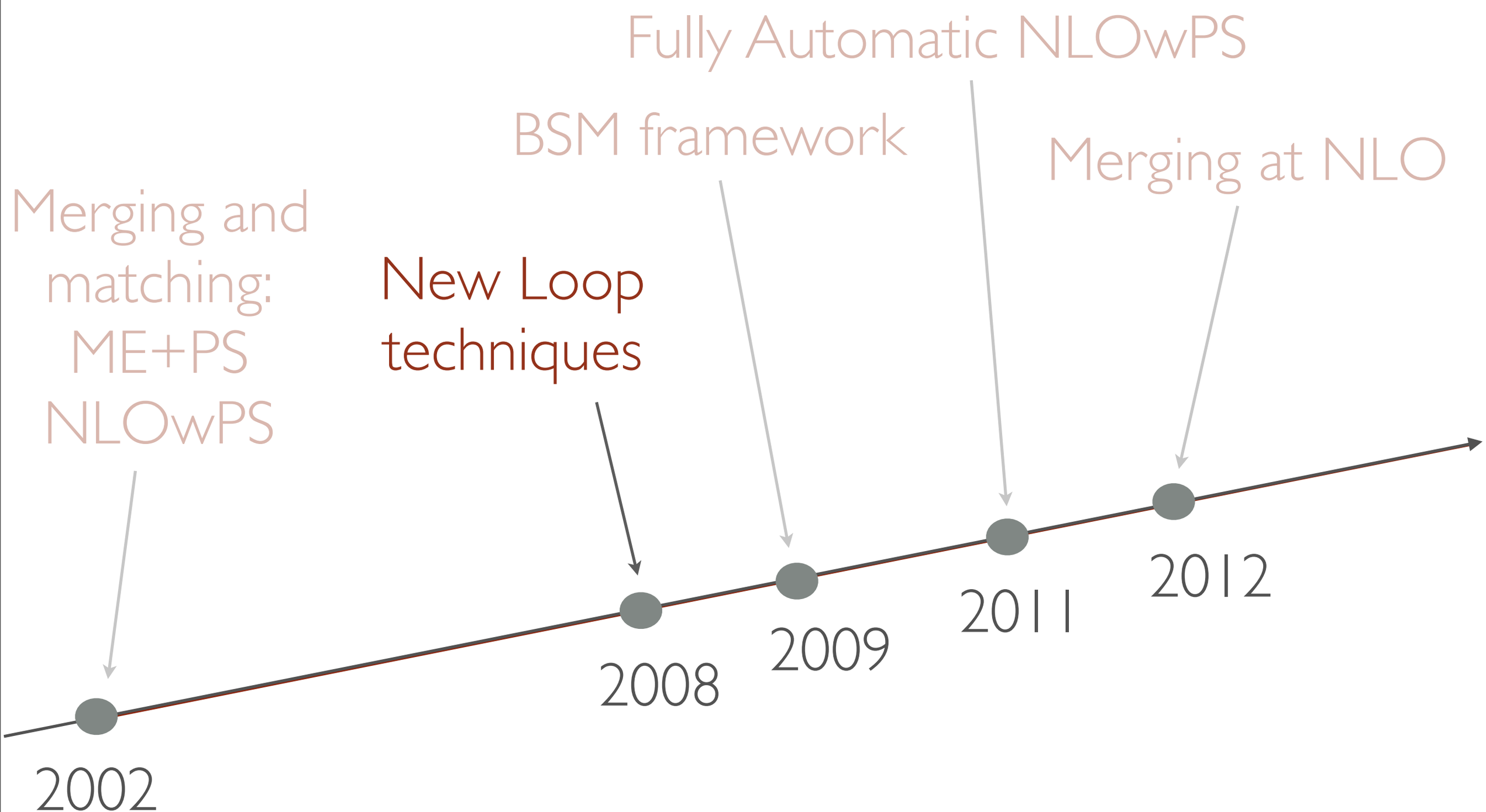


Predictions at NLO

modified by the speaker

Predictions at NLO

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

Integrand Reduction
(ex. CutTools, Samurai)

Tensor Reduction
(ex. Golem)

Predictions at NLO

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

Integrand Reduction
(ex. CutTools, Samurai)

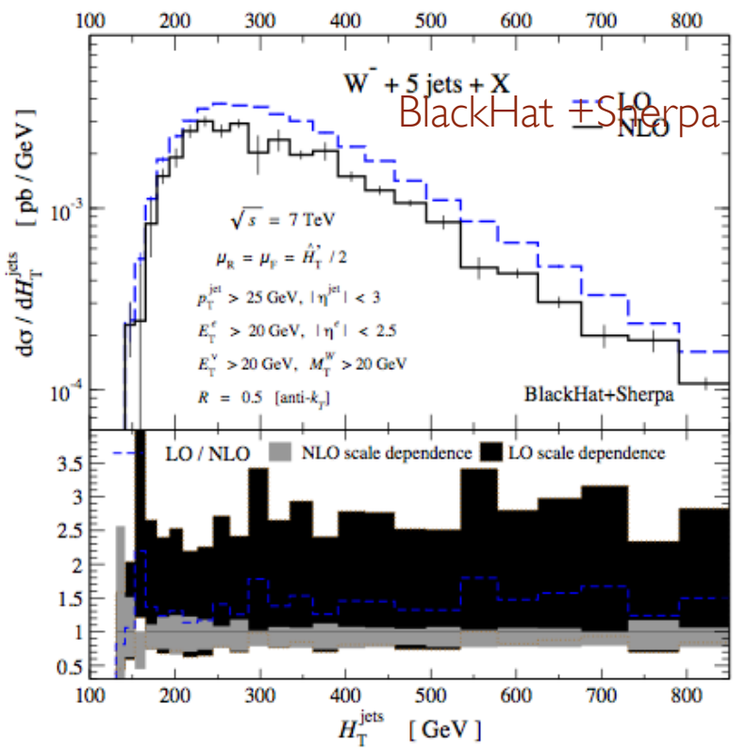
Tensor Reduction
(ex. Golem)

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.

GUINNESS WR NLO CALCULATIONS

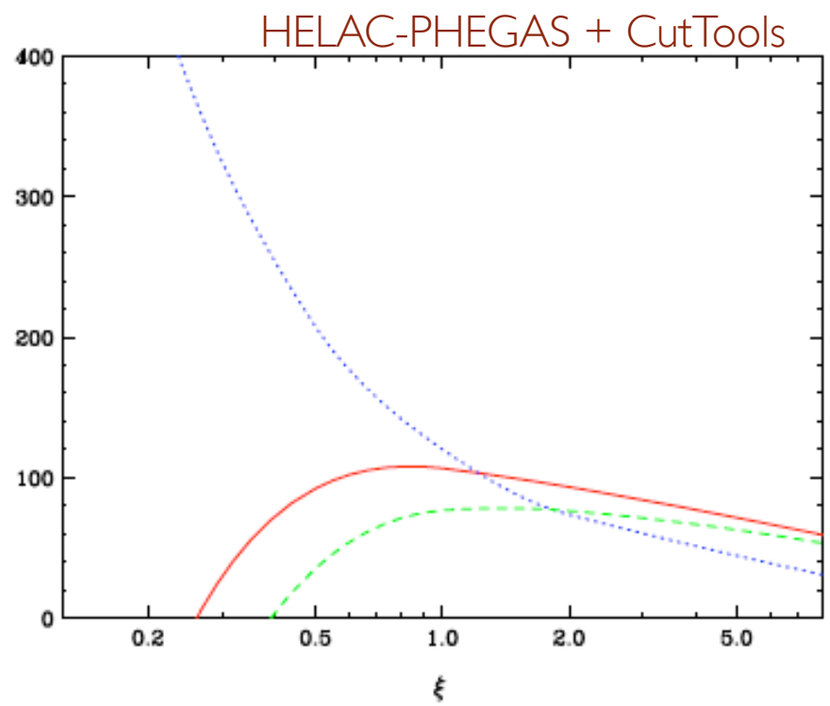
W+5 jets

[Bern et al., 1304.1253]



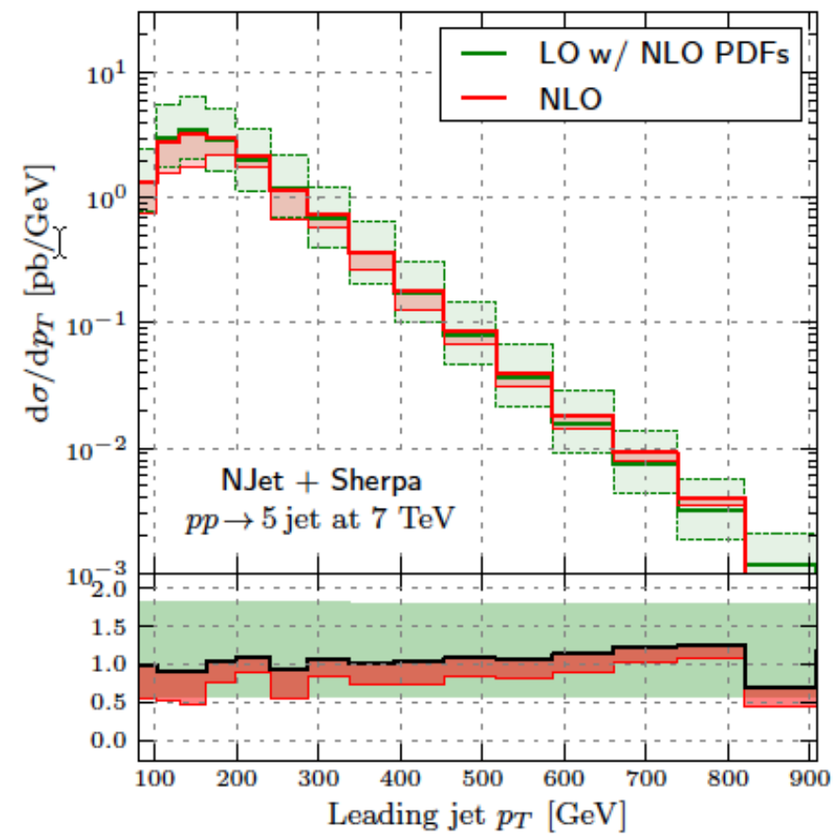
tt+2jets

[Bevilacqua et al., 1002.4009]



5 jets

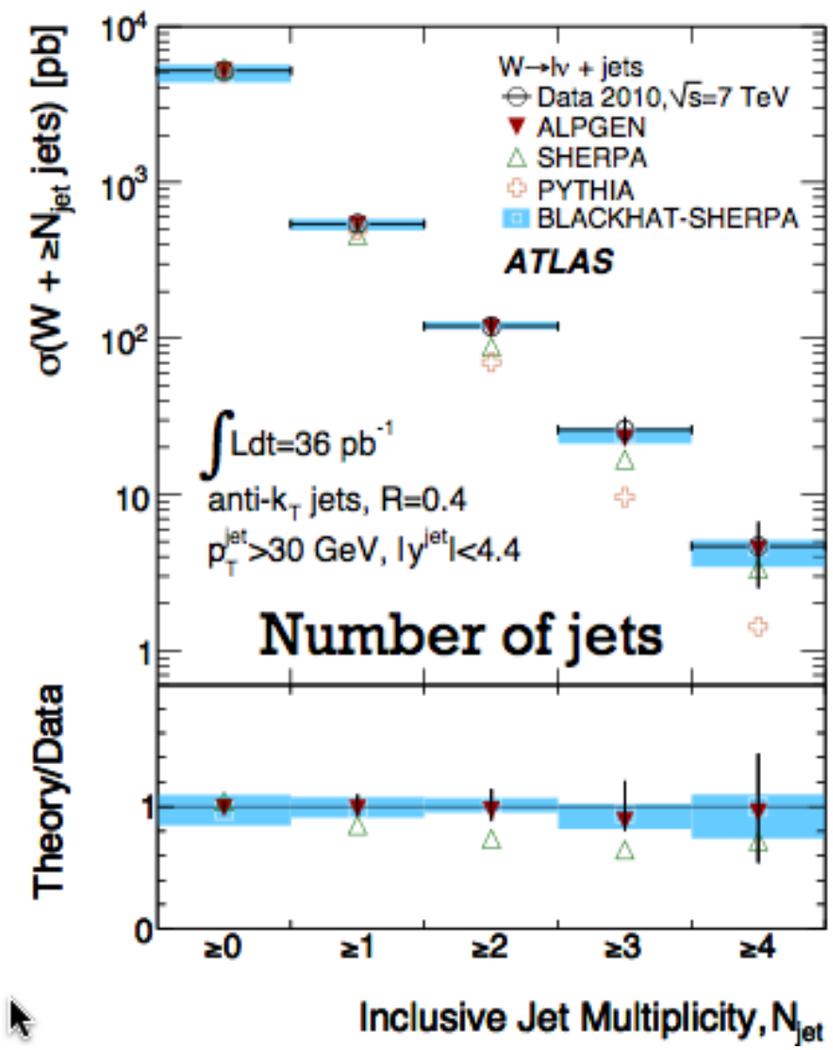
[Badger et al. 1309.6585]



Both based on unitarity methods and recursive relations for trees.

COMPARISON WITH DATA

W+5 jets



[Bern et al., 1304.1253]

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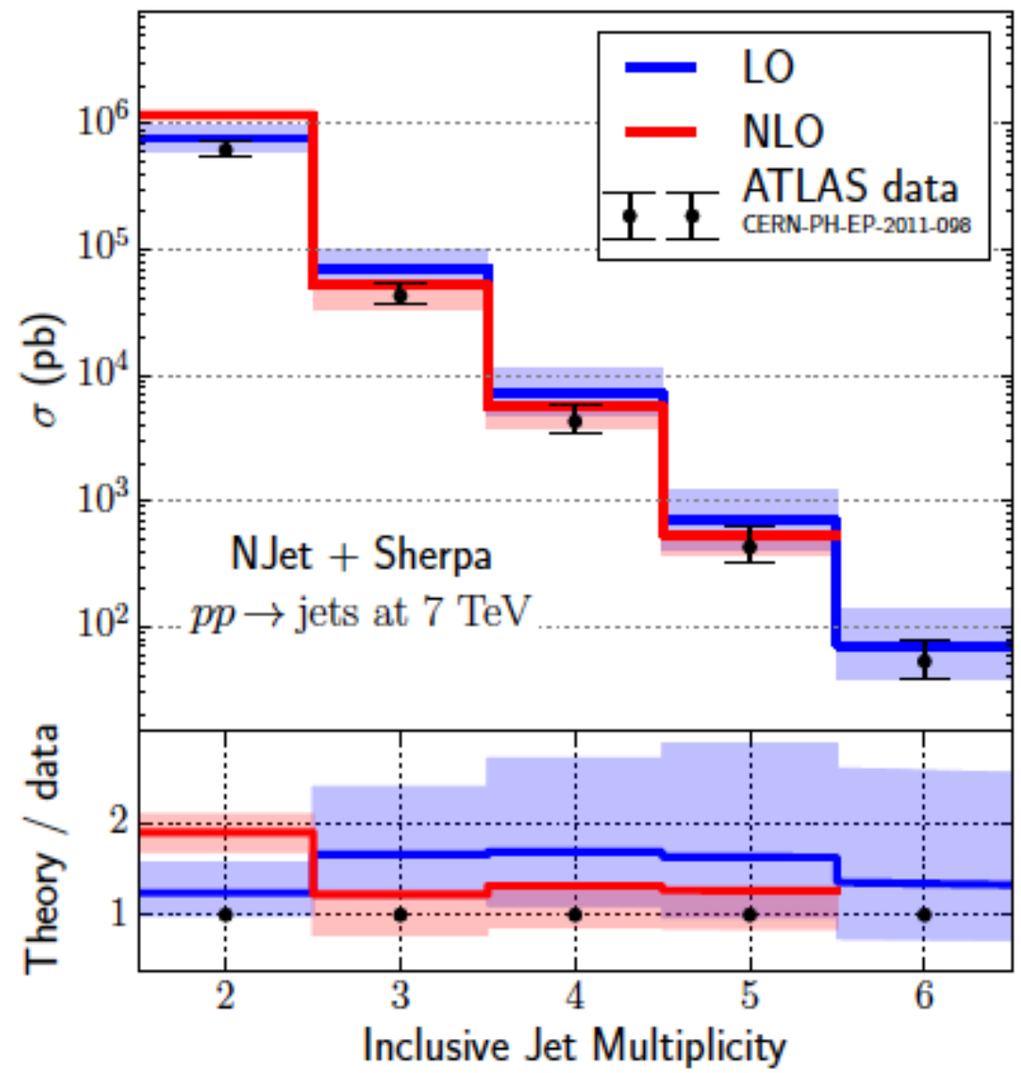

[Badger et al. 1309.6585]

NEW CODES FOR AUTOMATIC LOOPS

- 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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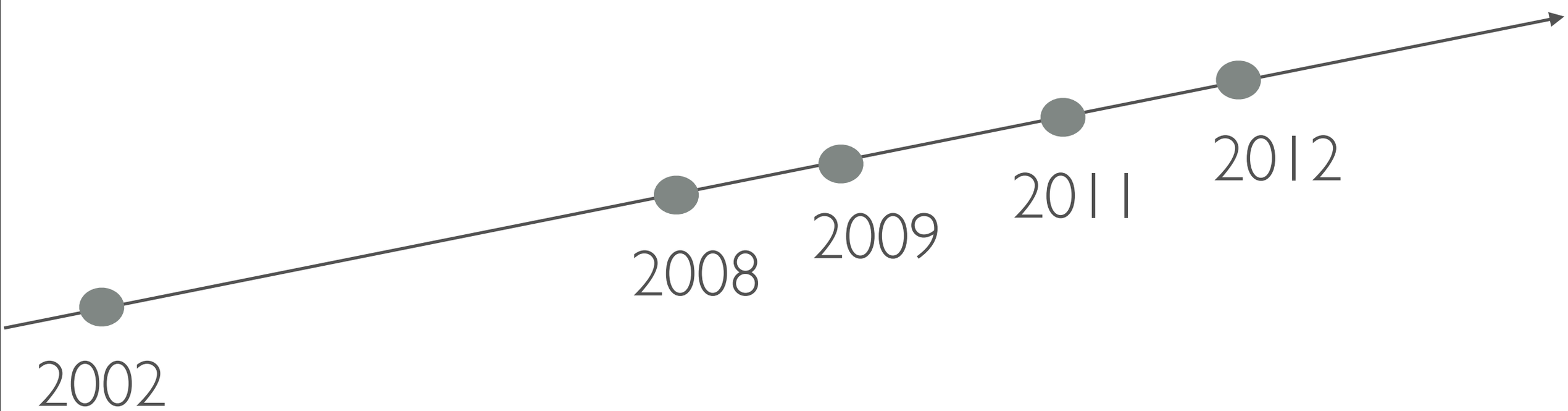
Limitations on applications (i.e. number of external partons or BSM) are systematically and quickly overcome:

"the wave function of the automatic loop effort has collapsed 2011"

PREDICTIVE MC (SIMPLIFIED) PROGRESS



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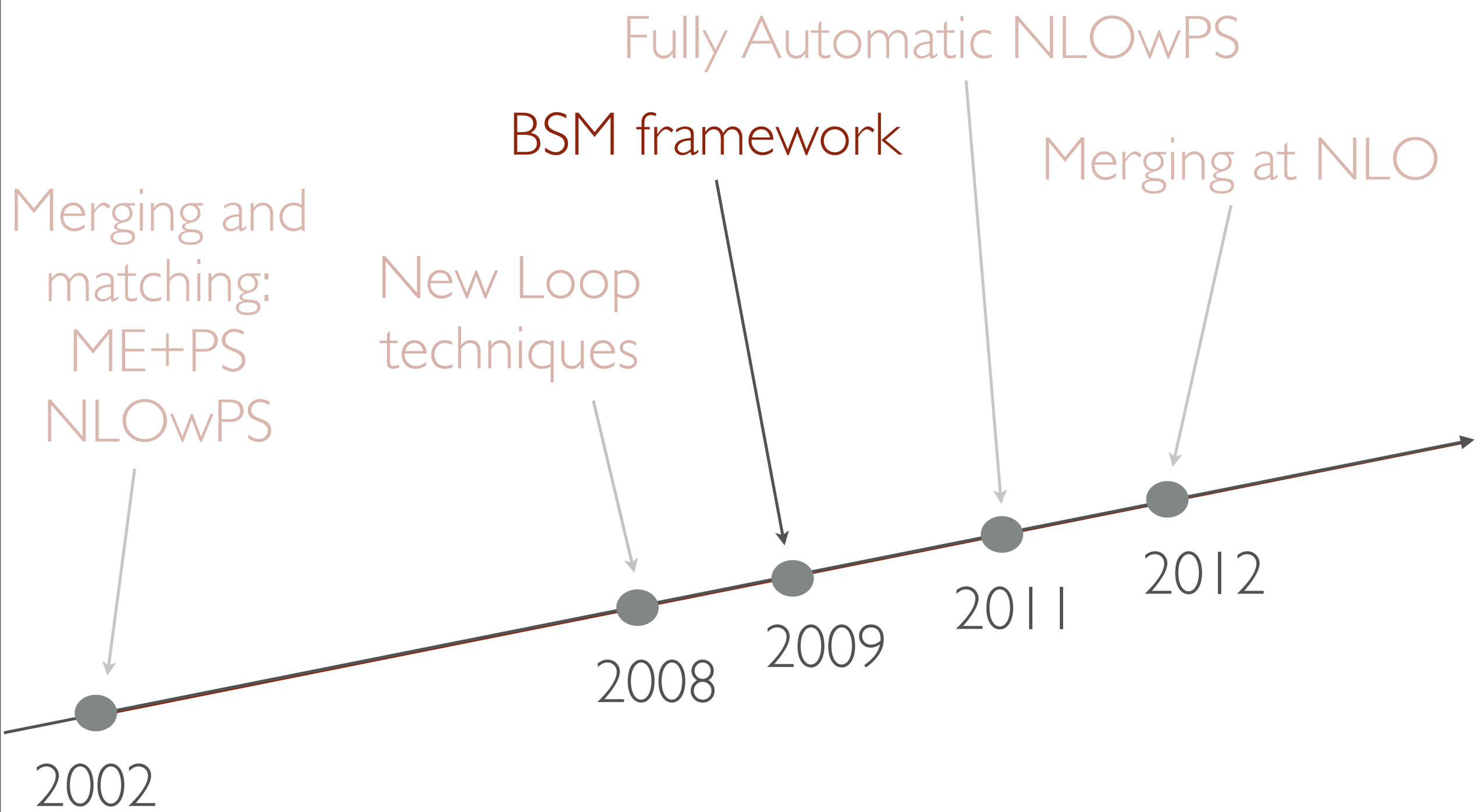
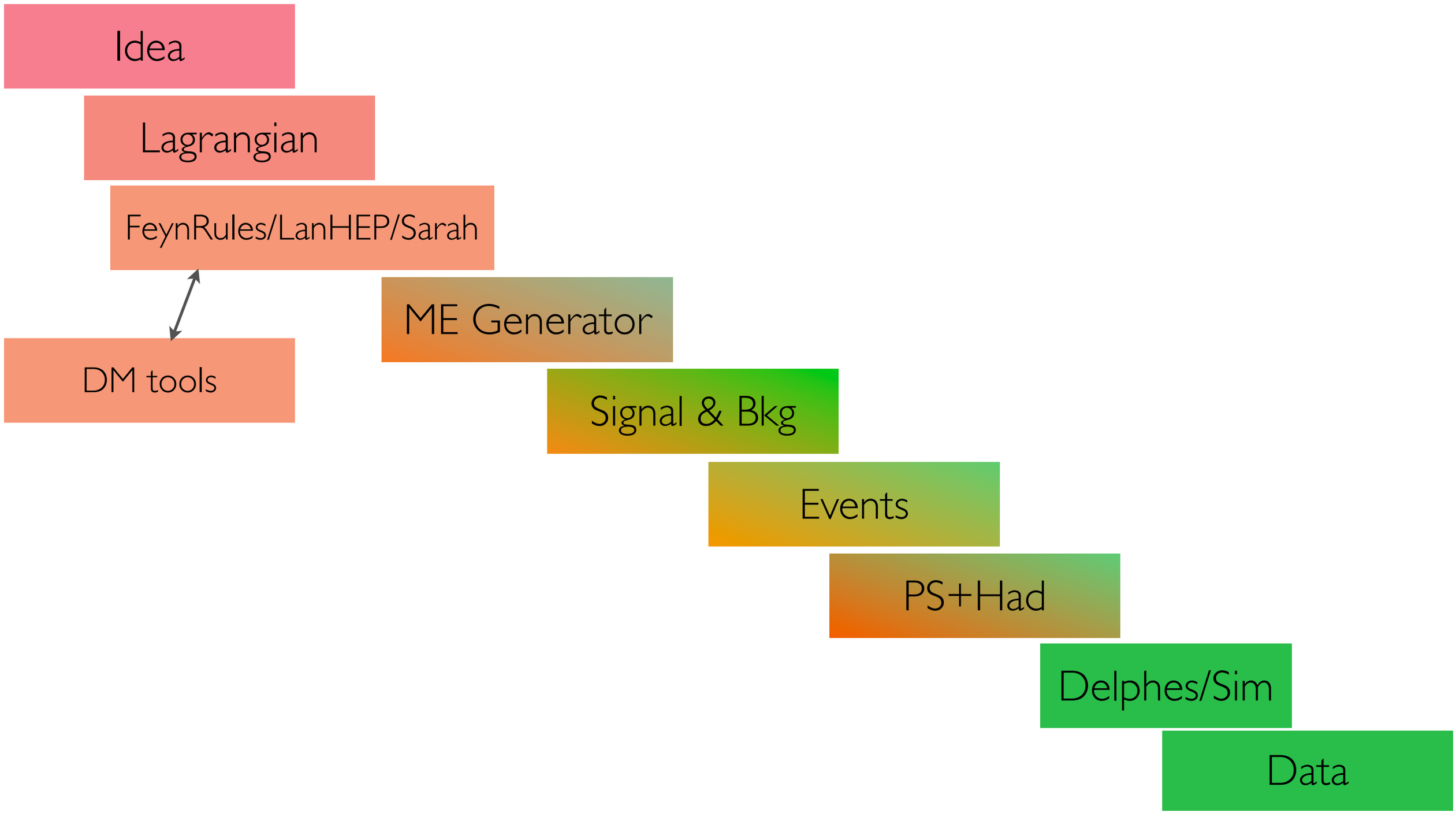


BSM TH/EXP INTERACTIONS : THE NEW PATH

TH EXP



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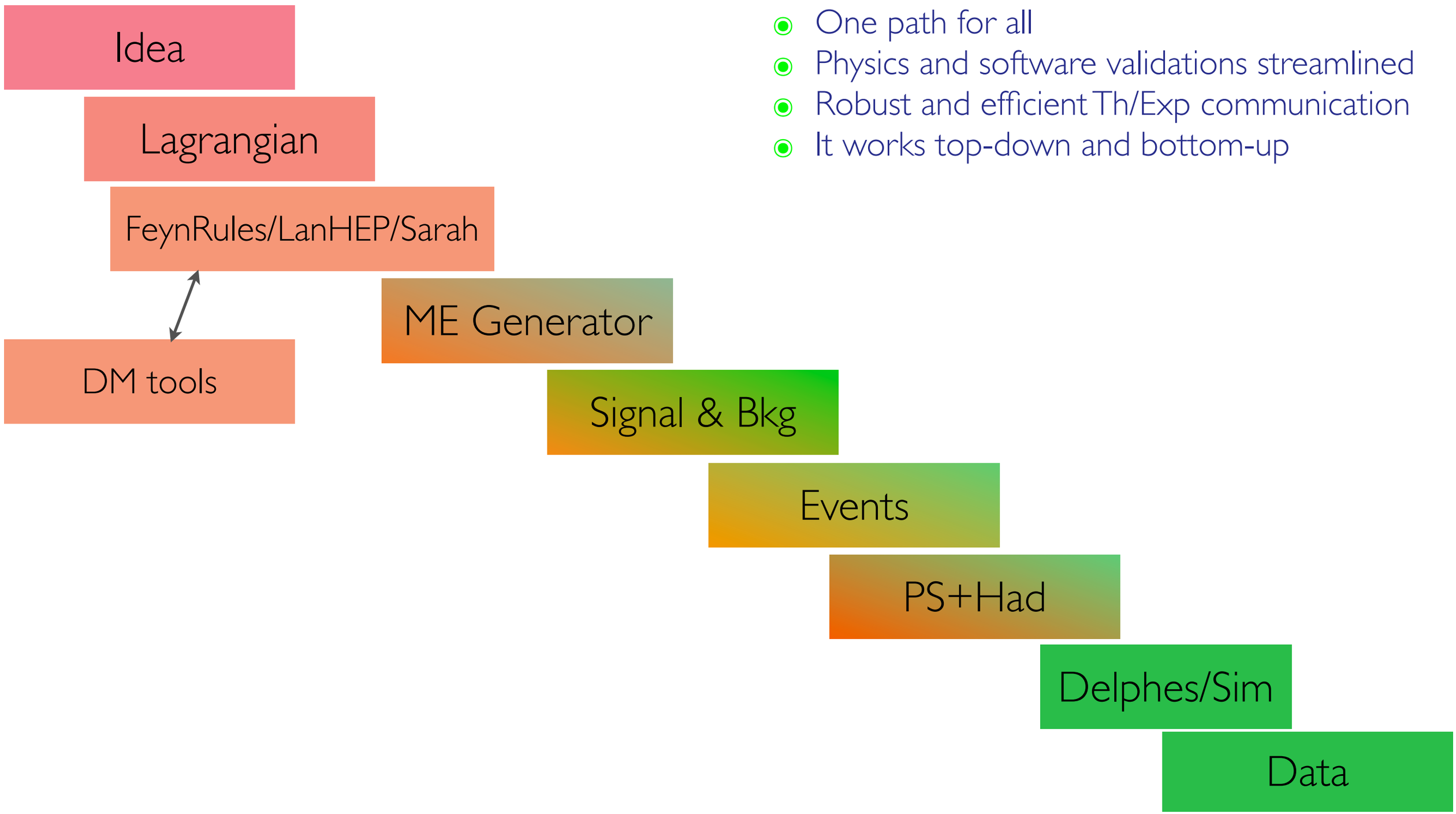


- One path for all
- Physics and software validations streamlined
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

BSM TH/EXP INTERACTIONS : THE NEW PATH

TH

Idea

Lagrangian

FeynRules/LanHEP/Sarah

DM tools

ME Generator

Signal & Bkg

Events

PS+Had

Delphes/Sim

Data

EXP

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

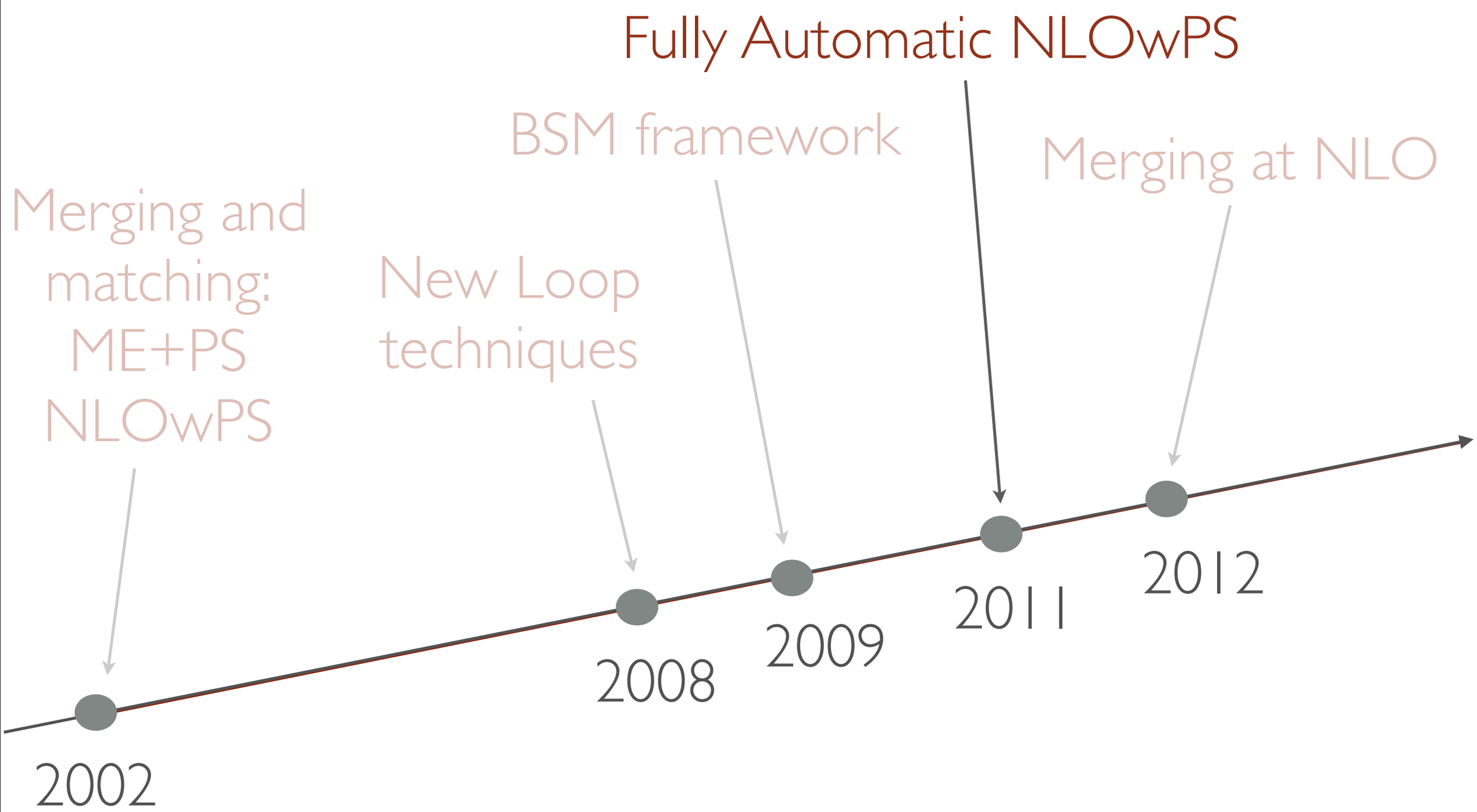
Complete automatization LO (and now NLO) calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics.

BSM FRAMEWORKS : THE NEW PATH

- **FeynRules :** Mathematica Package, Library of models, Spectrum generator and 1-loop RGE's, general UFO interface to ME's.
- **Sarah :** Mathematic Package, mainly for SUSY, two-loop RGE's, interfaces to several other tools.
- **LanHep :** Lagrangians for CalcHEP and microOmega.

For DM constraints can be obtained from
MicroOmega, DarkSUSY and recently, MadDM

PREDICTIVE MC (SIMPLIFIED) PROGRESS



FROM SEMI TO FULLY AUTOMATIC MC'S AT NLO

Processes for backgrounds 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 (pre-release version): many procs
- `aMC@NLO` (public in beta): process directly generated by the user

AUTOMATIC MC'S AT NLO

Suppose now you are interested in multi-lepton backgrounds to SUSY. You might want to check:

```
./bin/mg5
> generate p p > t t~ W+ W- [QCD]
> output ttww
> launch
```

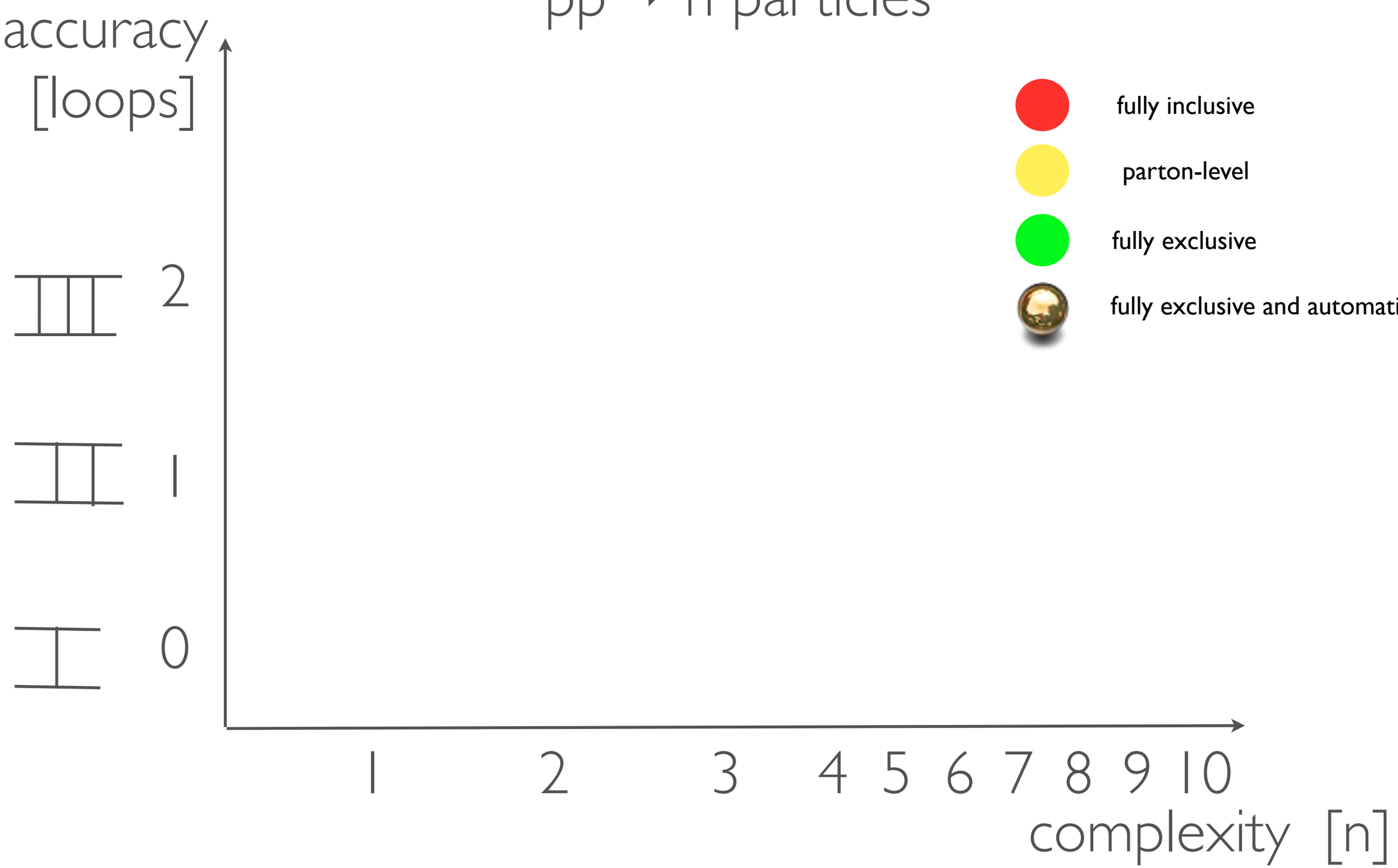
or

```
./bin/mg5
> define V = W+ W- Z
> generate p p > V V V[QCD]
> output VVV
> launch
```

where heavy states can also be decayed keeping spin correlations.

SM STATUS : YEAR 2013

pp→ n particles



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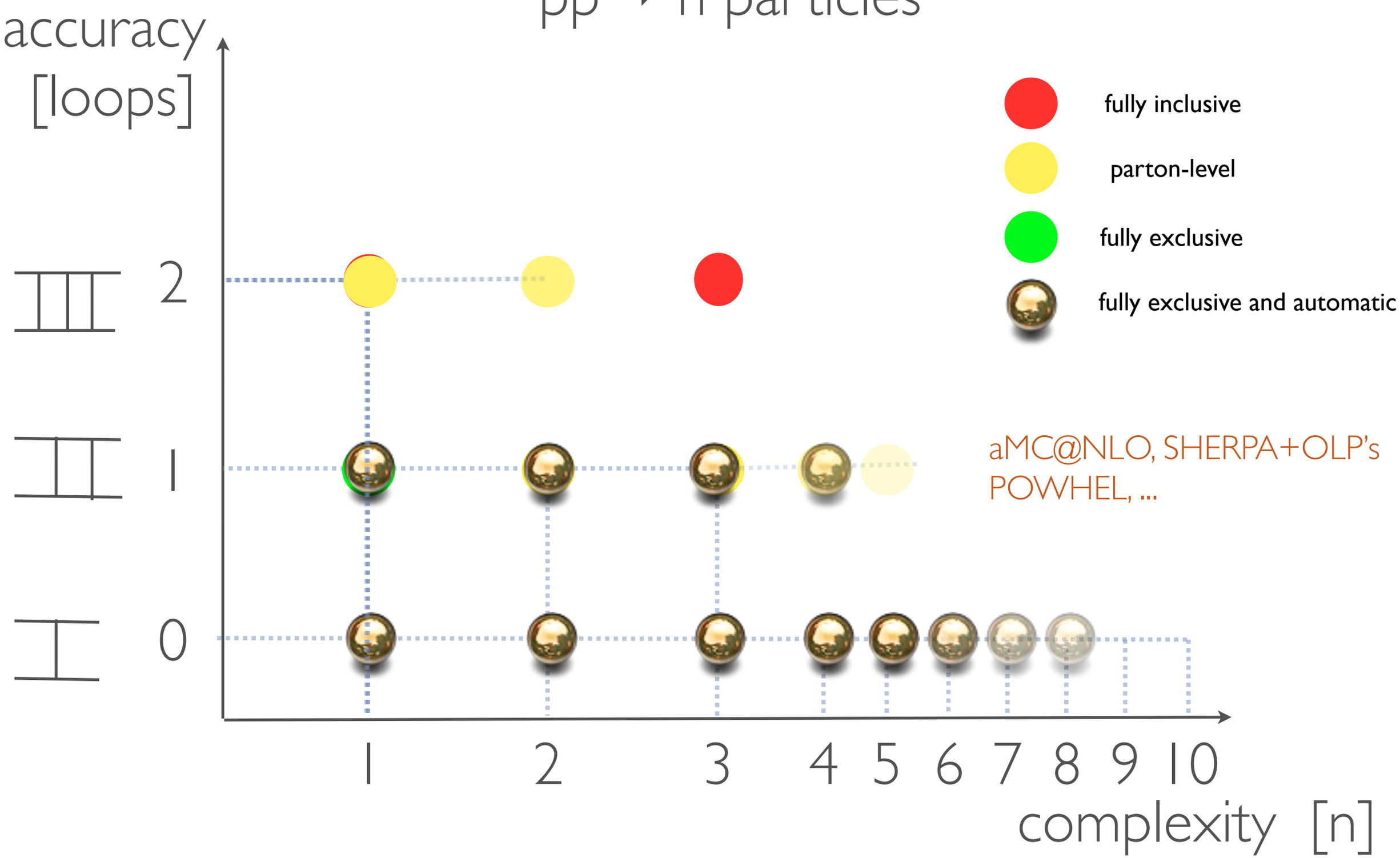

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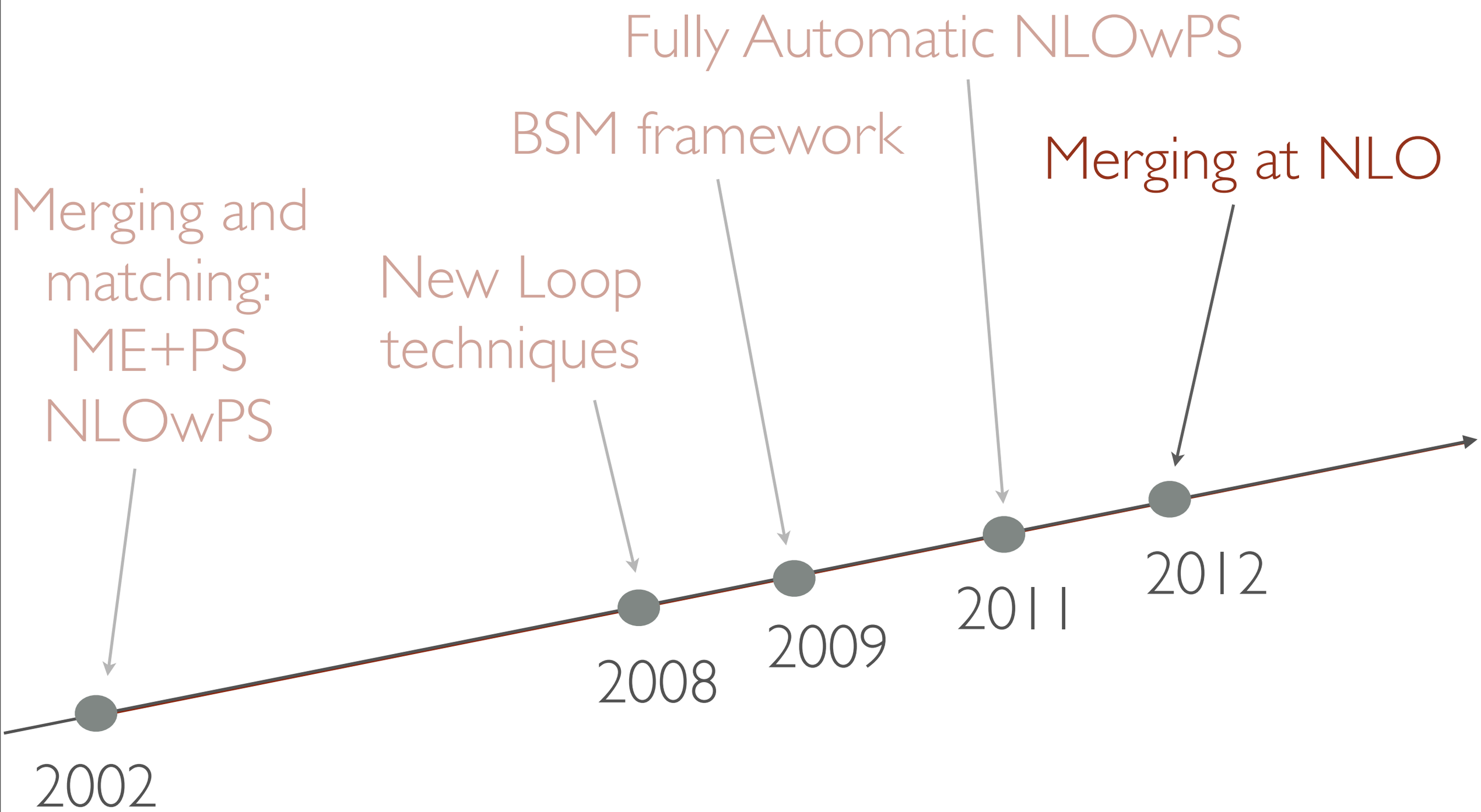

MULTI-JET MERGING @ NLO

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

Geneva approach : Alioli et al. 1212.4504 and see also 1311.0286 (with NNLO proposal)

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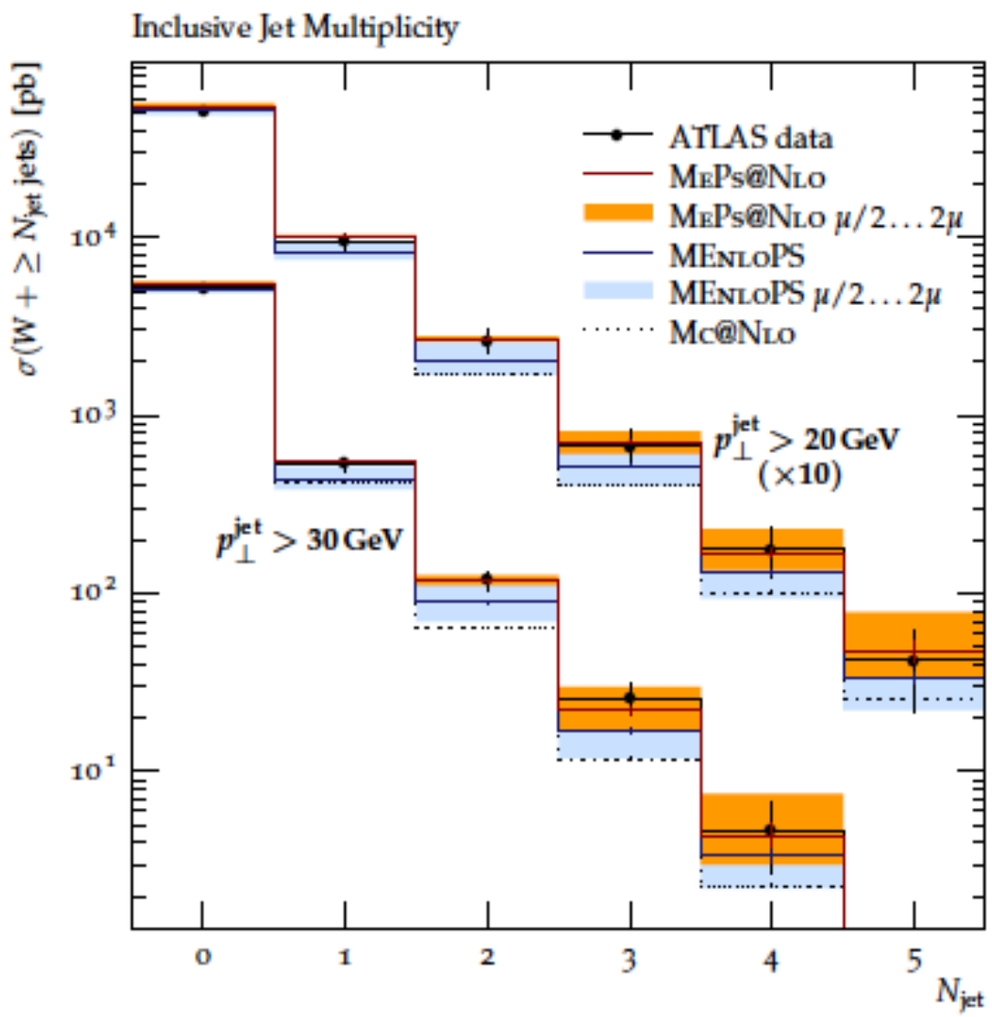
The wave function of the merging at NLO effort has collapsed in 2012

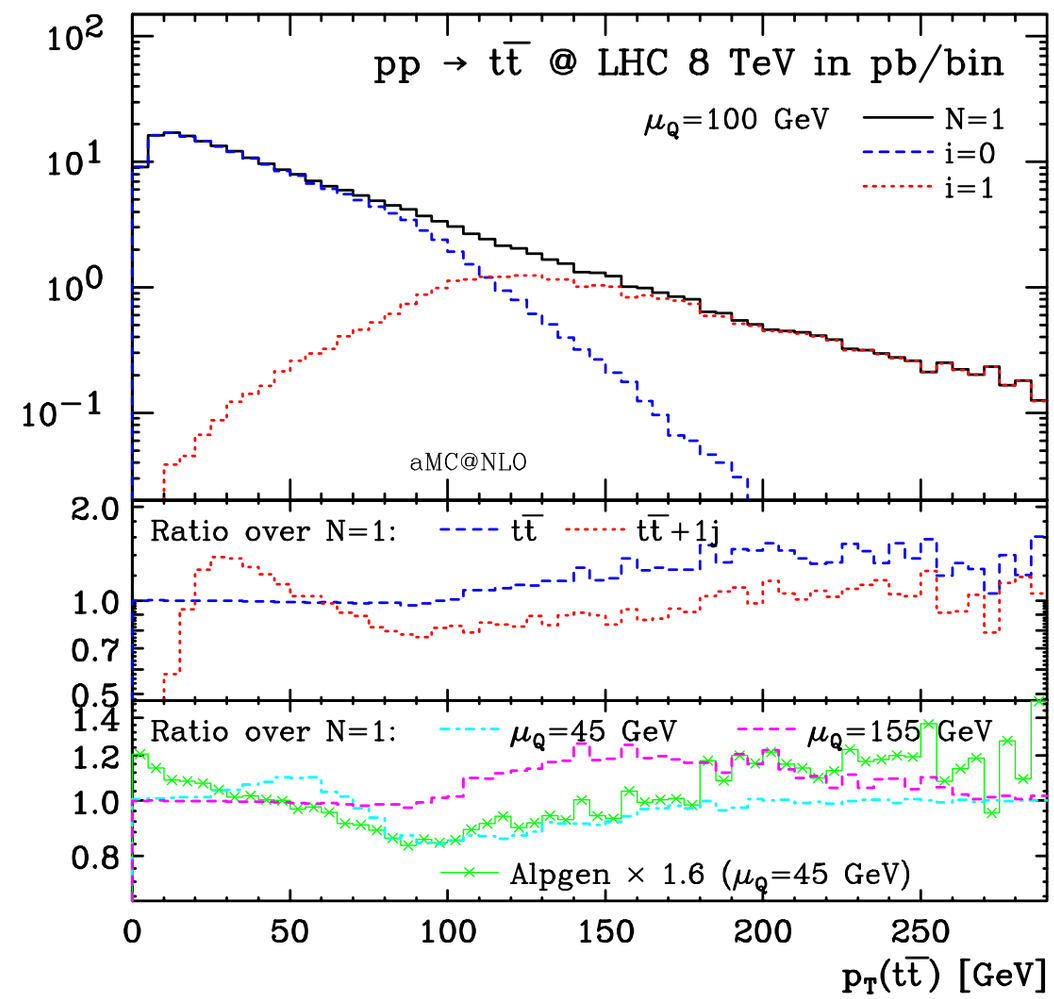
MULTI-JET MERGING @ NLO

[Hoeche et al., 1207.5030]



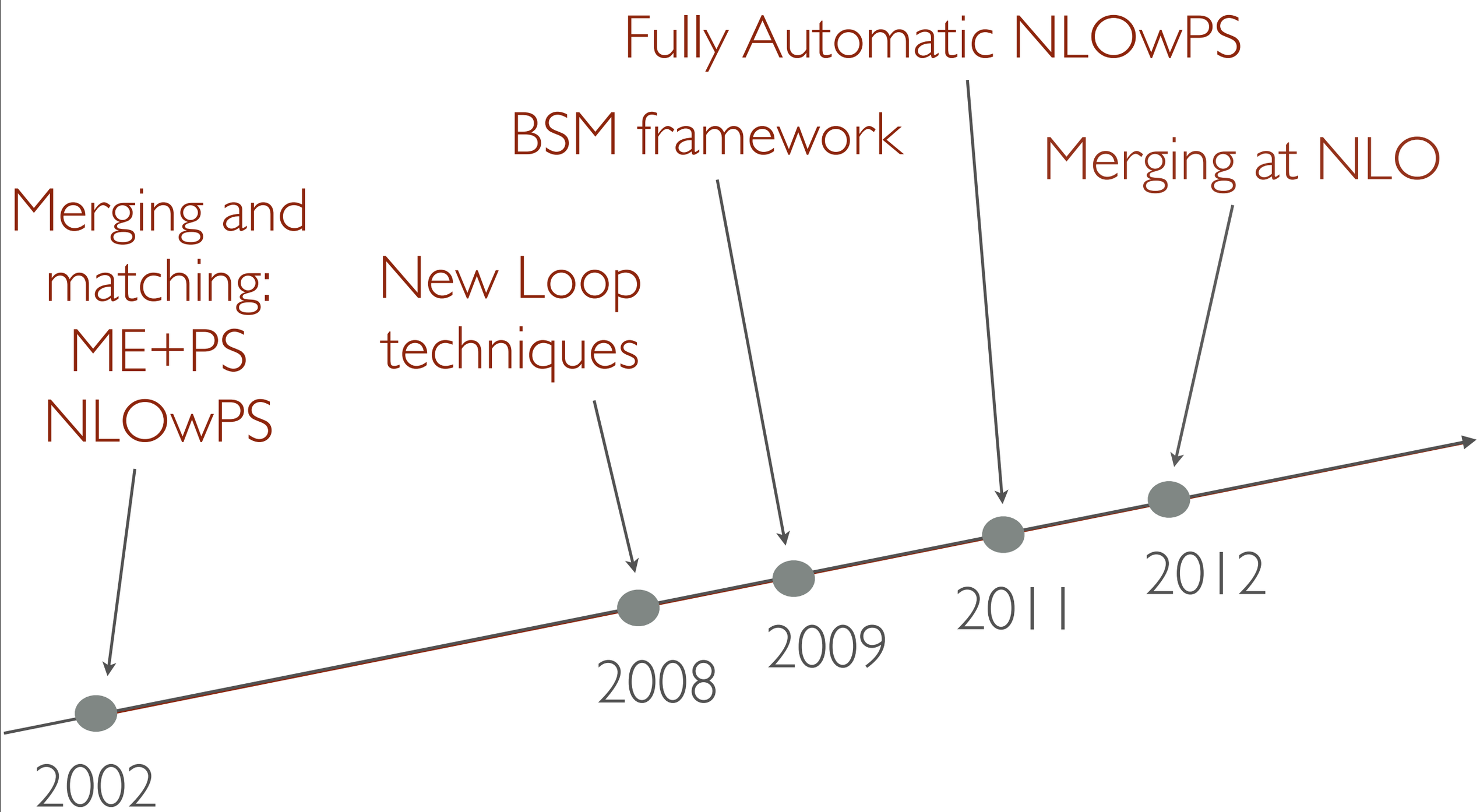
- Jet rates
- Up to 3 extra jets at NLO
- Various approaches give consistent results

[Frederix, Frixione, 1209.6215]



- Differential jet rates
- Matching up to 1 extra jet at NLO
- Method works for H+jets and W+jets equally well.

PREDICTIVE MC (SIMPLIFIED) PROGRESS



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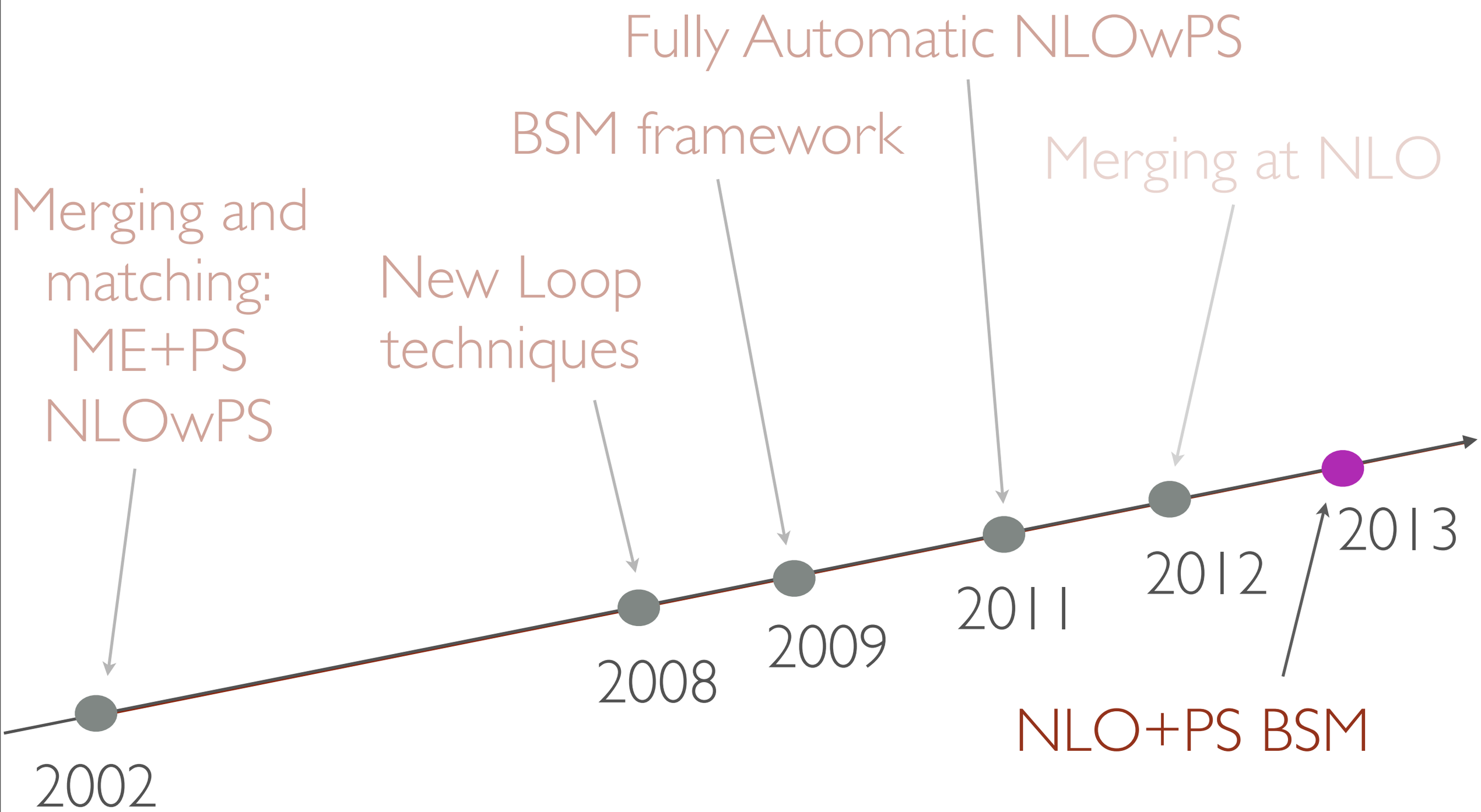

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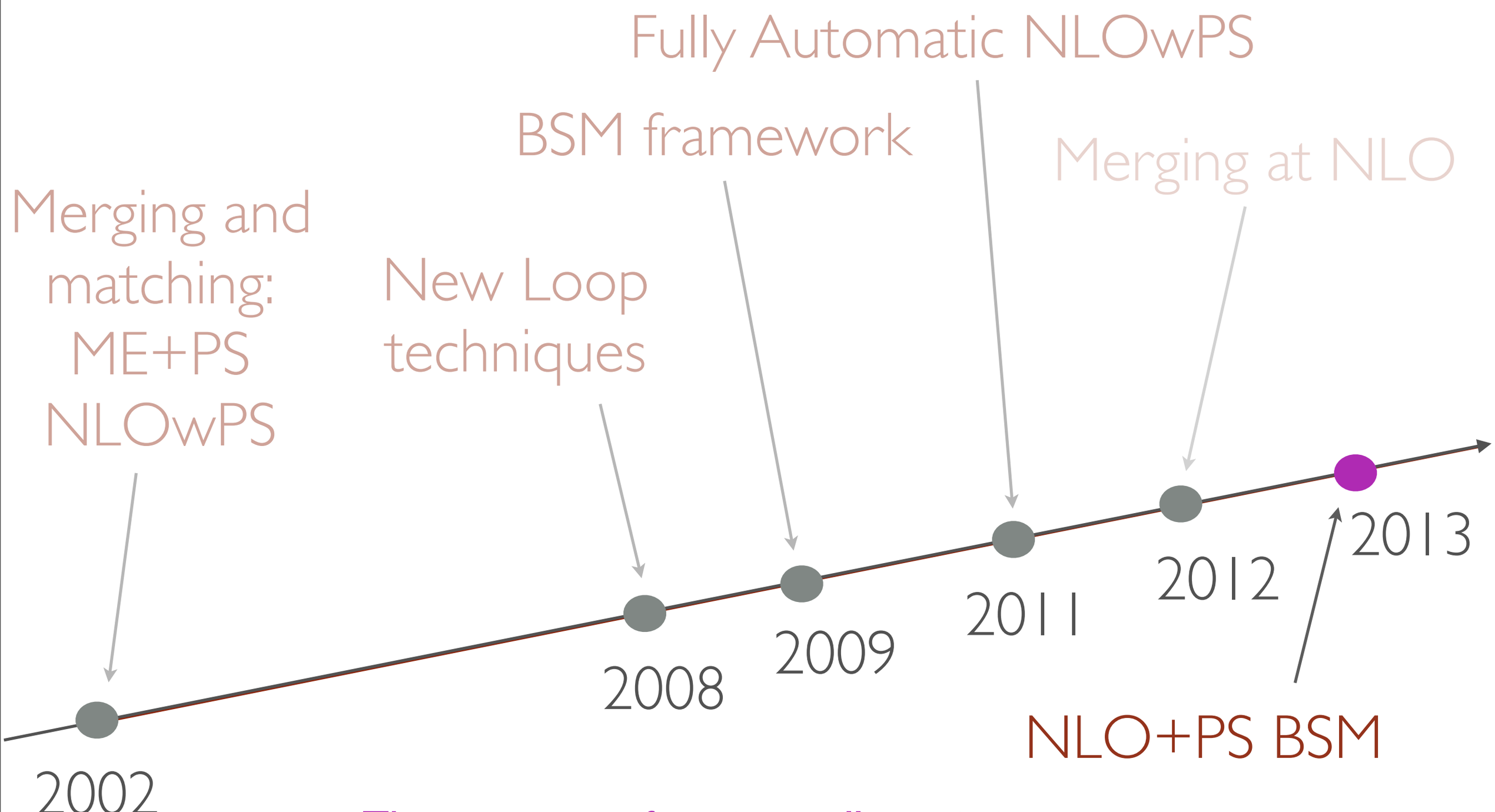
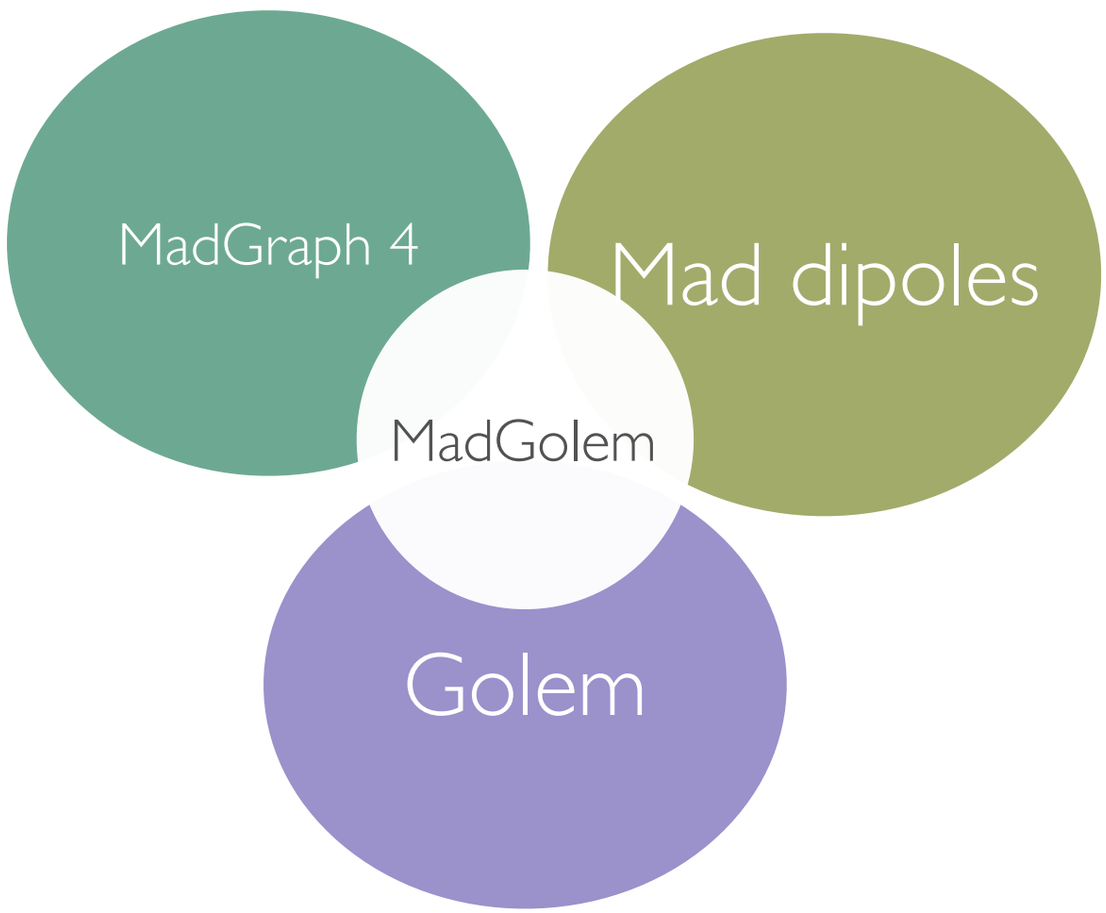
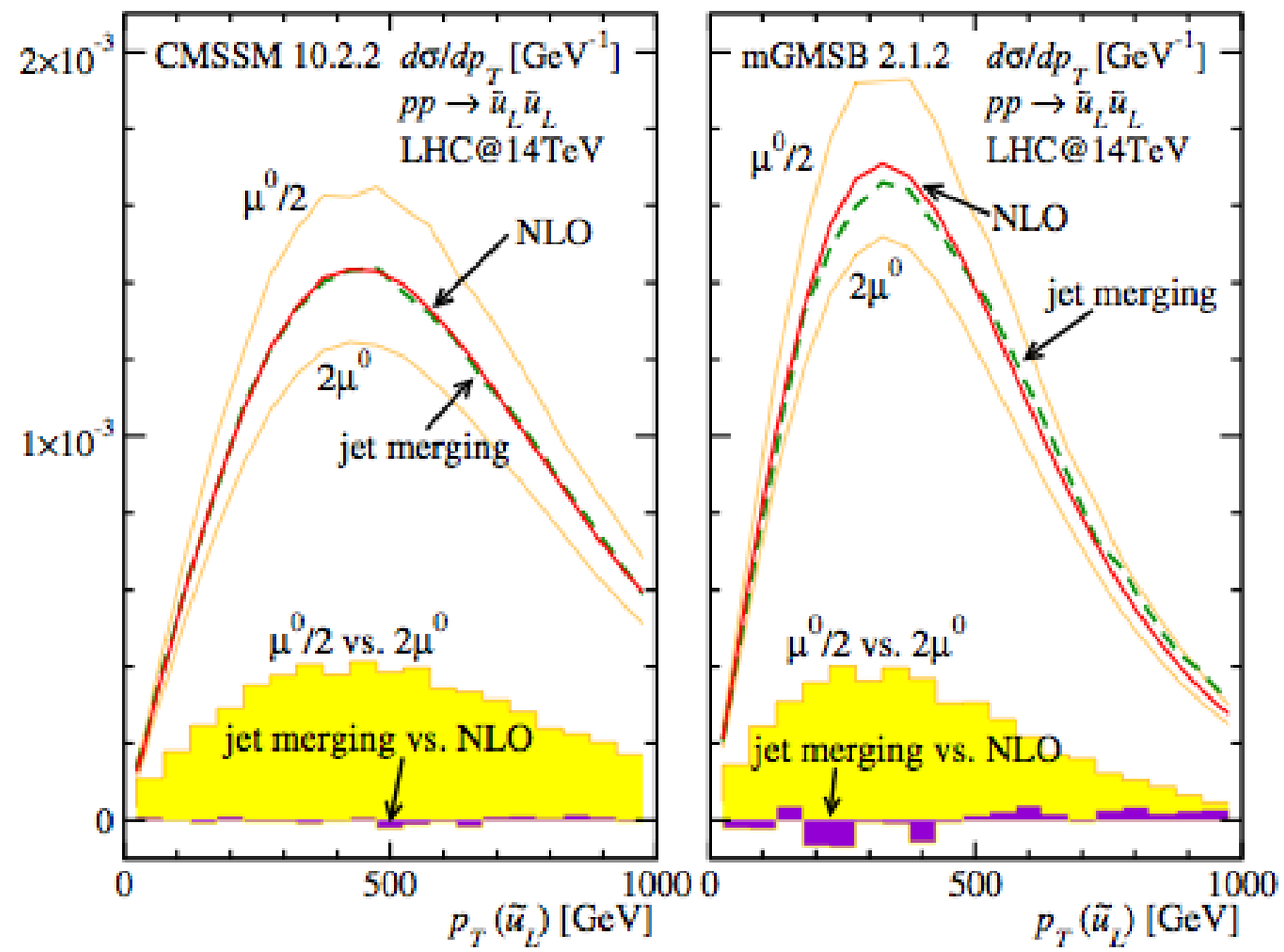


The next wave-function collapse is in progress....

AUTOMATIC SUSY AT NLO WITH MADGOLEM



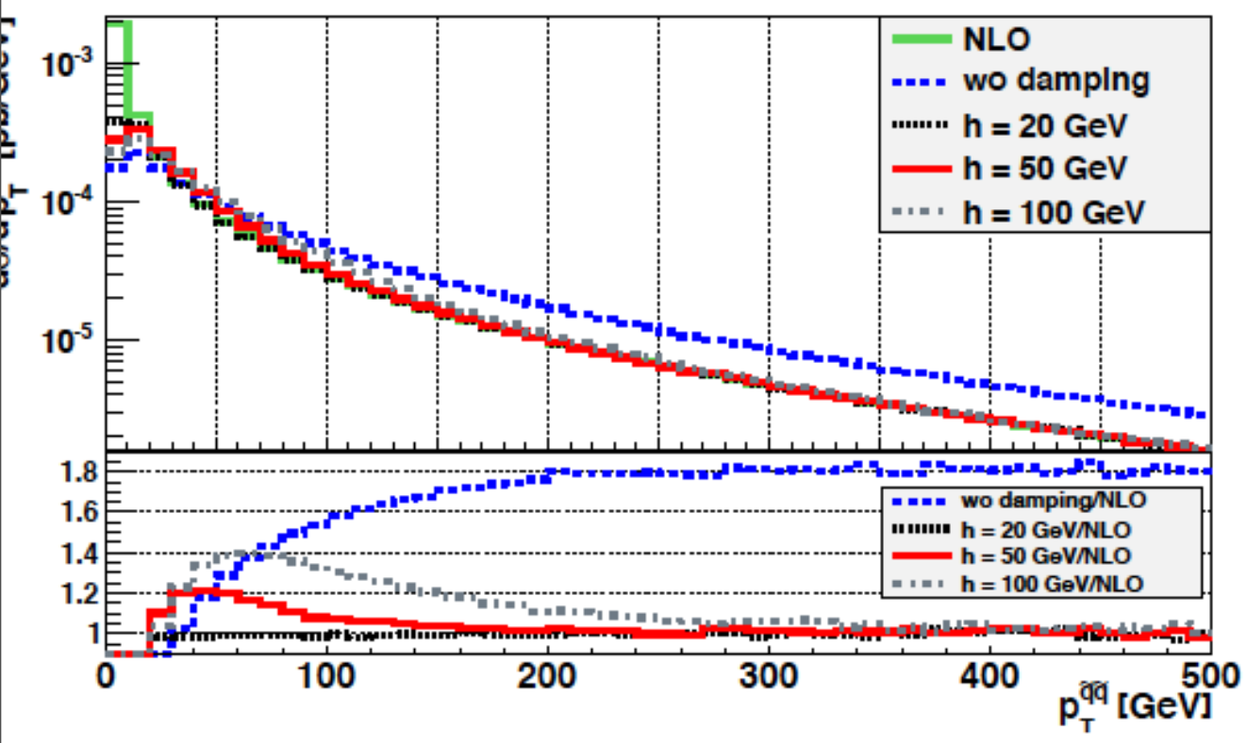
[Goncalves-Netto et al., 1108.1250, 1203.6358, 1211.0286]

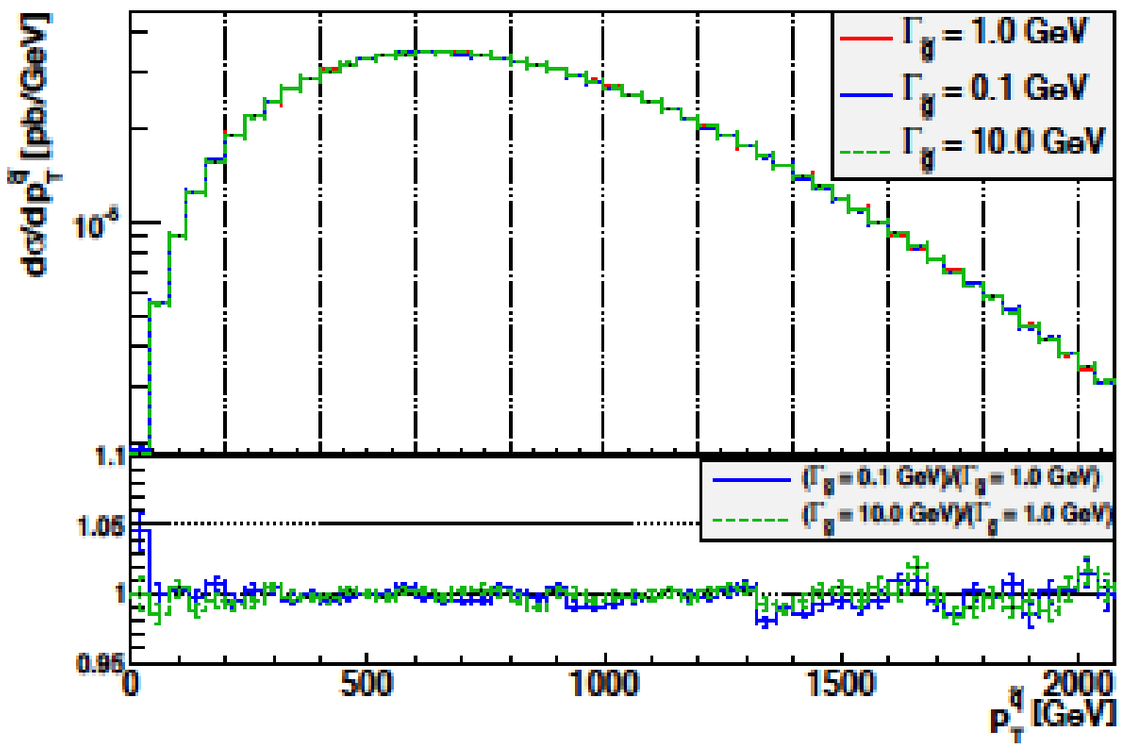


- All pp to sparticle-sparticle channels available
- No events, but completely differential in partonic observables.
- Shapes very similar to those obtained with ME+PS merging at LO.

SQUARK-SQUARK PRODUCTION IN POWHEG

[Gavin et al. 1305.4061]





- First implementation of a SUSY process into NLO+PS MC.
- Commonly found tuning needed to reproduce NLO.
- Efficient and MC friendly solution of the "resonant" double-counting problem.

WHAT'S NEXT IN ACCURATE MC'S FOR BSM

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

SUMMARY


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

SUMMARY

- MC and tool development are in their golden era.

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

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