AAA PHENOMENOLOGY AT THE LHC

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PRISMA - Mainz University
20 Nov 2013

PHENOMENOLOGY

- AUTOMATIC
- ACCURATE
- AUGMENTED

new MC tools for hadron collider physics.

MichelangeloMangano®

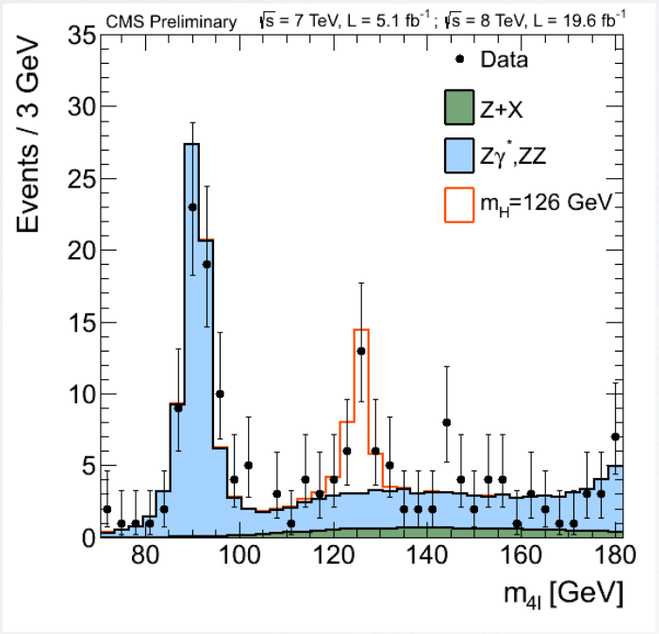
Discoveries at hadron colliders

Wednesday 20 November 2013

Discoveries at hadron colliders

peak

pp→H→4l



"easy"

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

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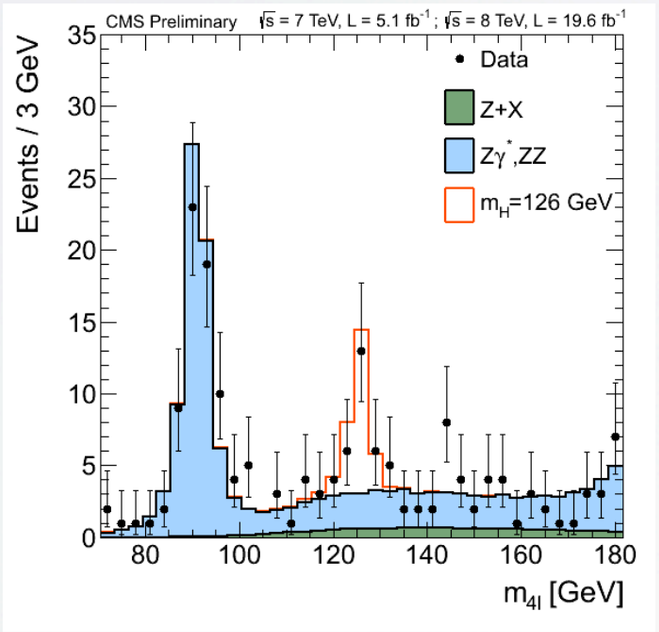

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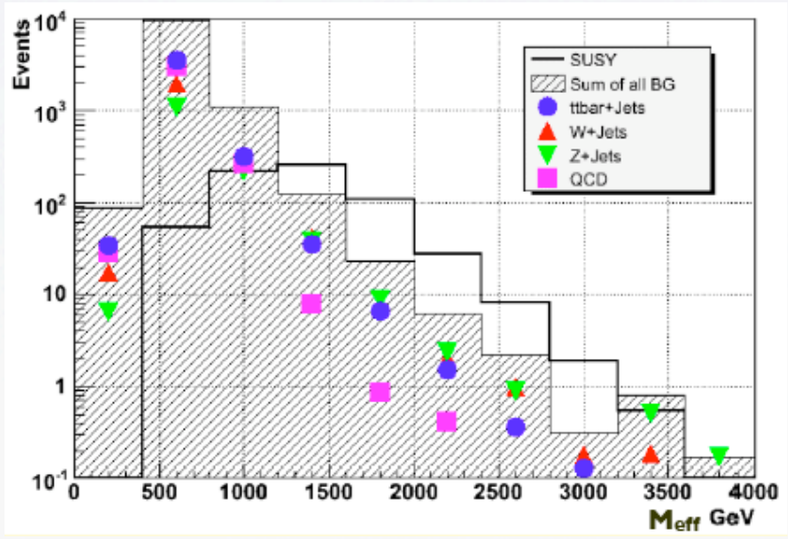
shape

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



hard

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

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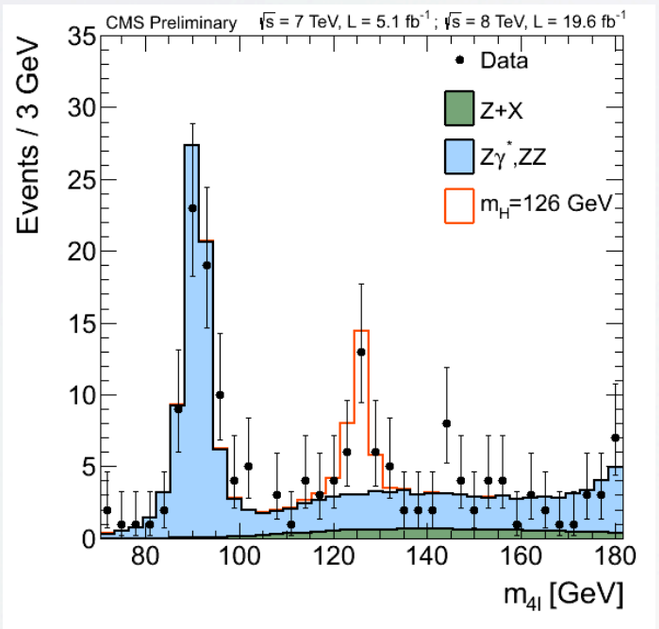

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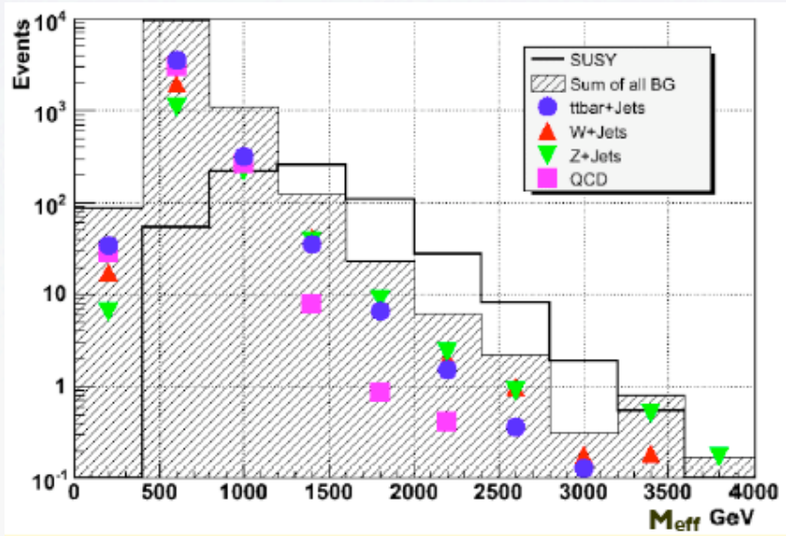

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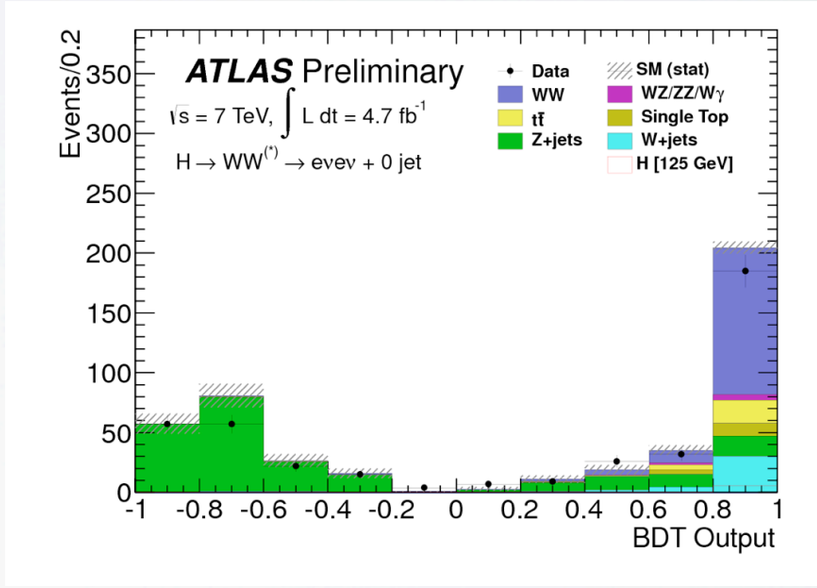
discriminant

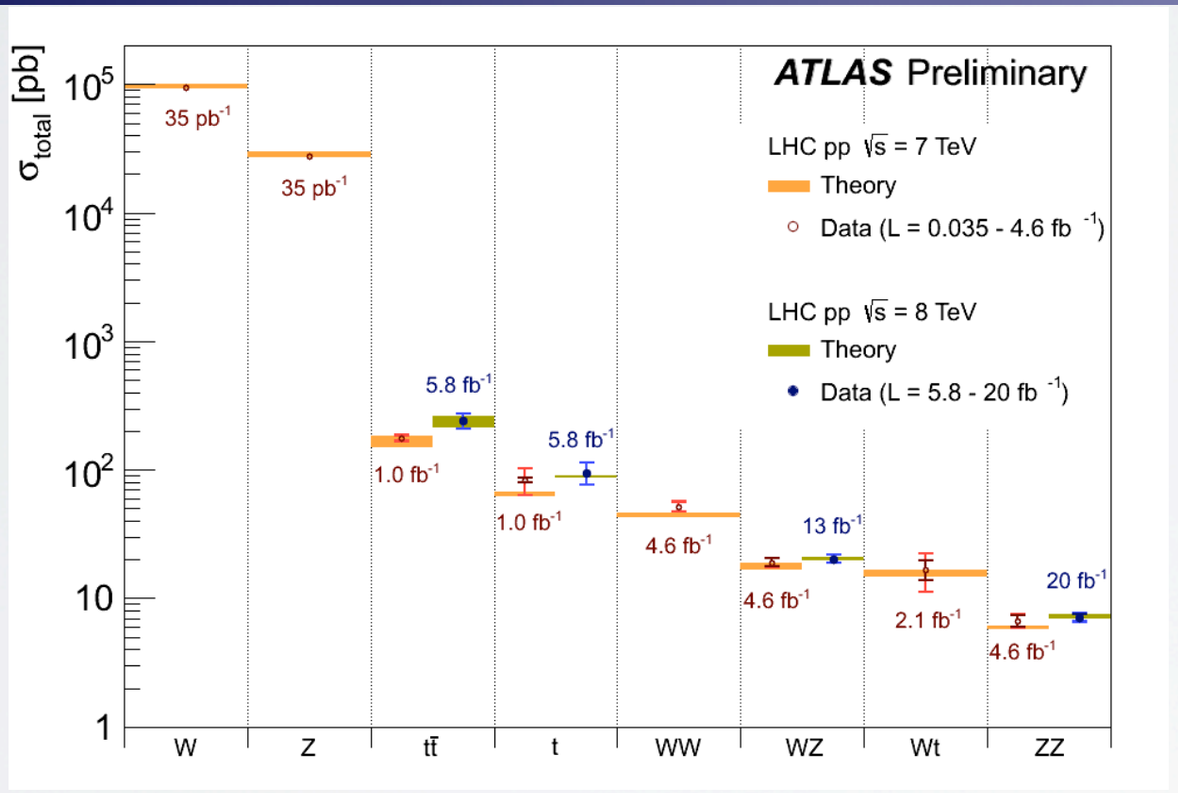
$pp \to H \to W^+W^-$

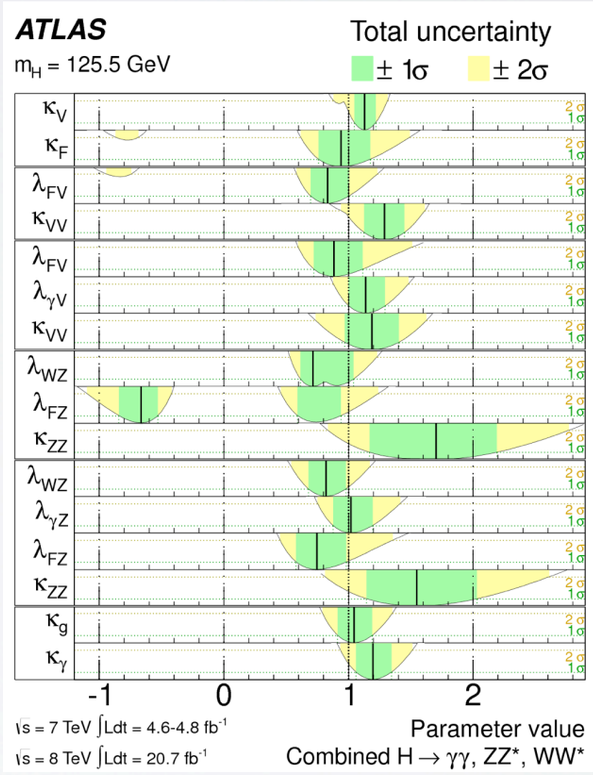


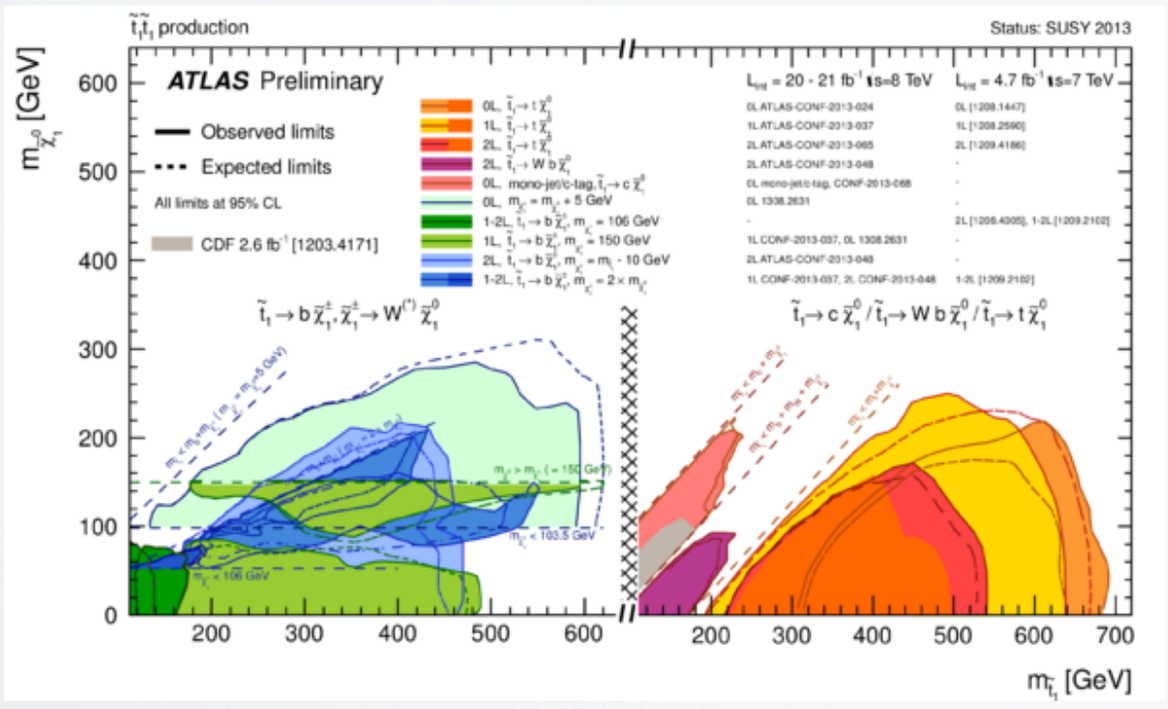
very hard

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

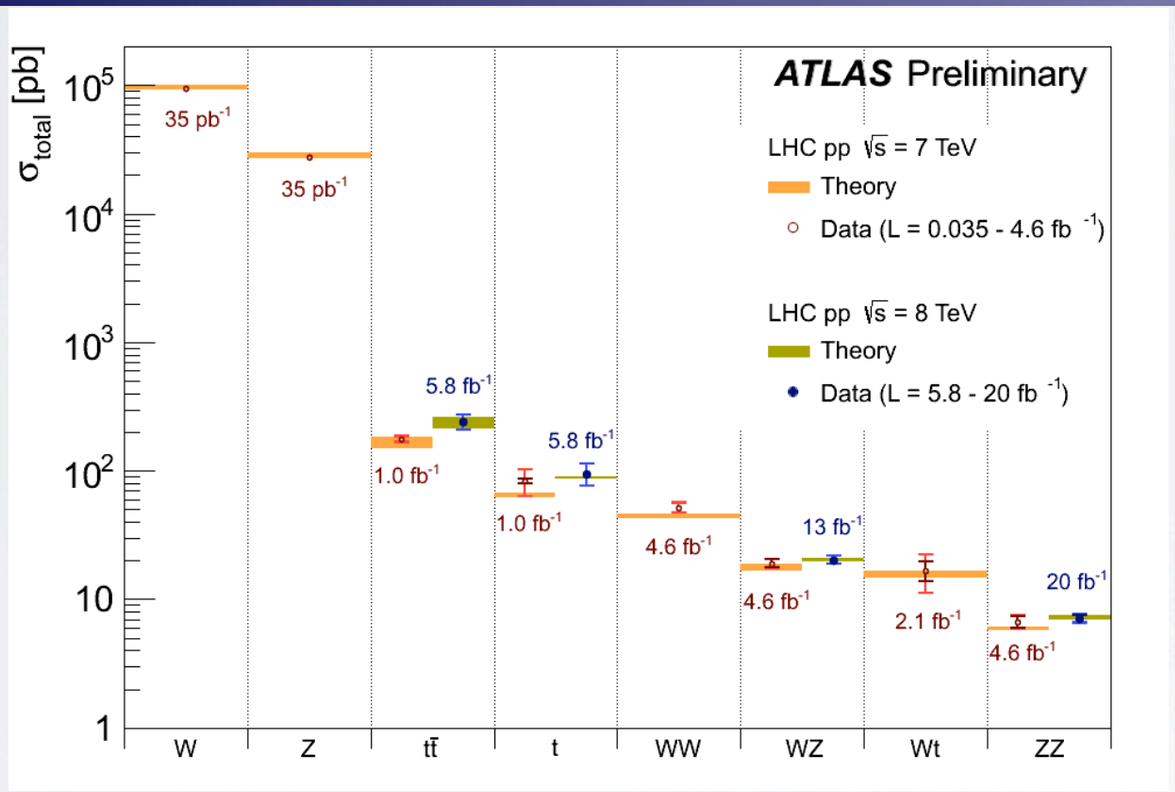
Wednesday 20 November 2013

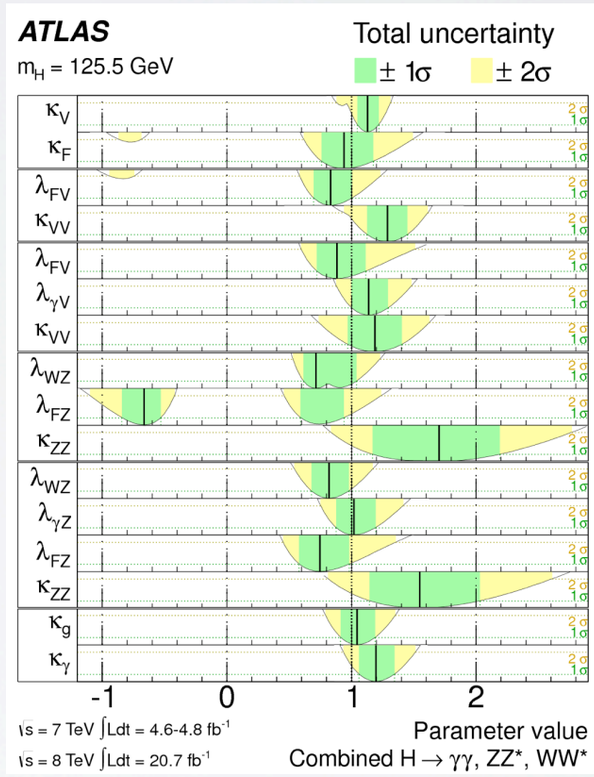

ATLAS Preliminary
LHC pp √s = 7 TeV
Theory
Data (L = 0.035 - 4.6 fb -1)
LHC pp √s = 8 TeV
Theory
Data (L = 5.8 - 20 fb -1)
σtotal [pb]
35 pb-1
35 pb-1
5.8 fb-1
1.0 fb-1
5.8 fb-1
1.0 fb-1
4.6 fb-1
13 fb-1
4.6 fb-1
2.1 fb-1
20 fb-1
4.6 fb-1
W
Z
tt̄
t
WW
WZ
Wt
ZZ


ATLAS
mH = 125.5 GeV
Total uncertainty
± 1σ
± 2σ
κV
κF
λFV
κVV
λFV
λγV
κVV
λWZ
λFZ
κZZ
λWZ
λγZ
λFZ
κZZ
κg
κγ
-1
0
1
2
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
Parameter value
Combined H → γγ, ZZ*, WW*

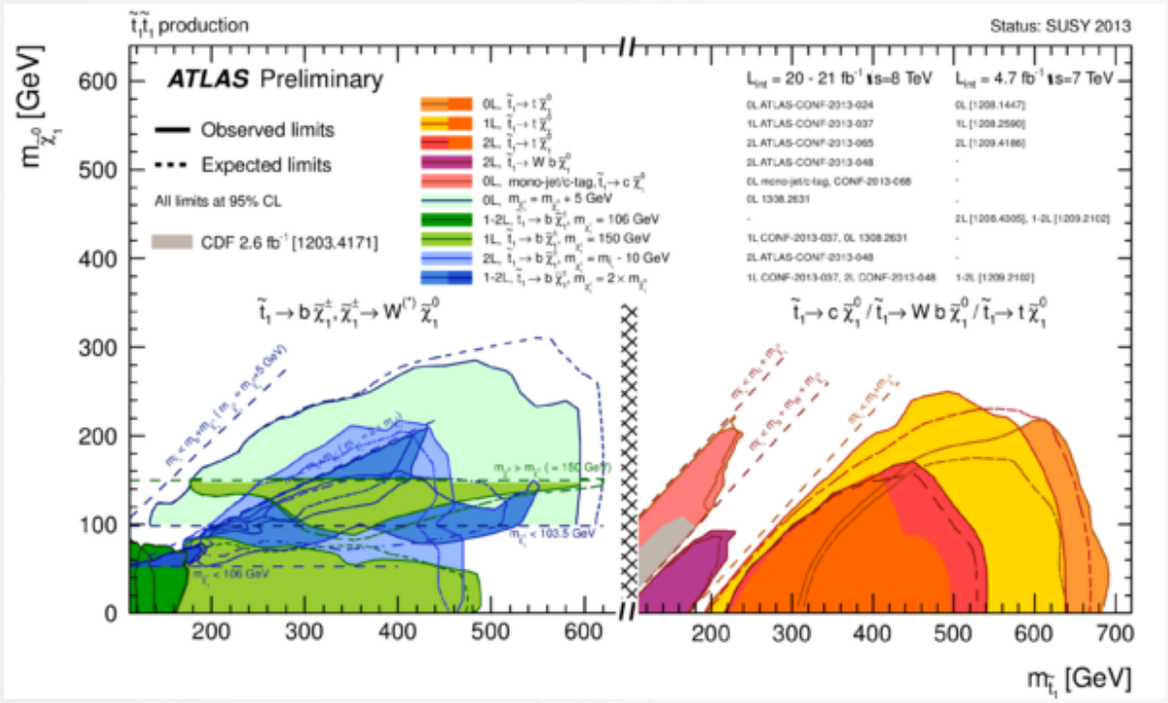

t̃1t̃1 production
Status: SUSY 2013
ATLAS Preliminary
Observed limits
Expected limits
All limits at 95% CL
CDF 2.6 fb-1 [1203.4171]
mχ̃10 [GeV]
mt̃1 [GeV]


ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)
ATLAS
Preliminary
Mass scale [TeV]





No sign of new physics (so far)!




MC developer

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

LHC MASTER FORMULA

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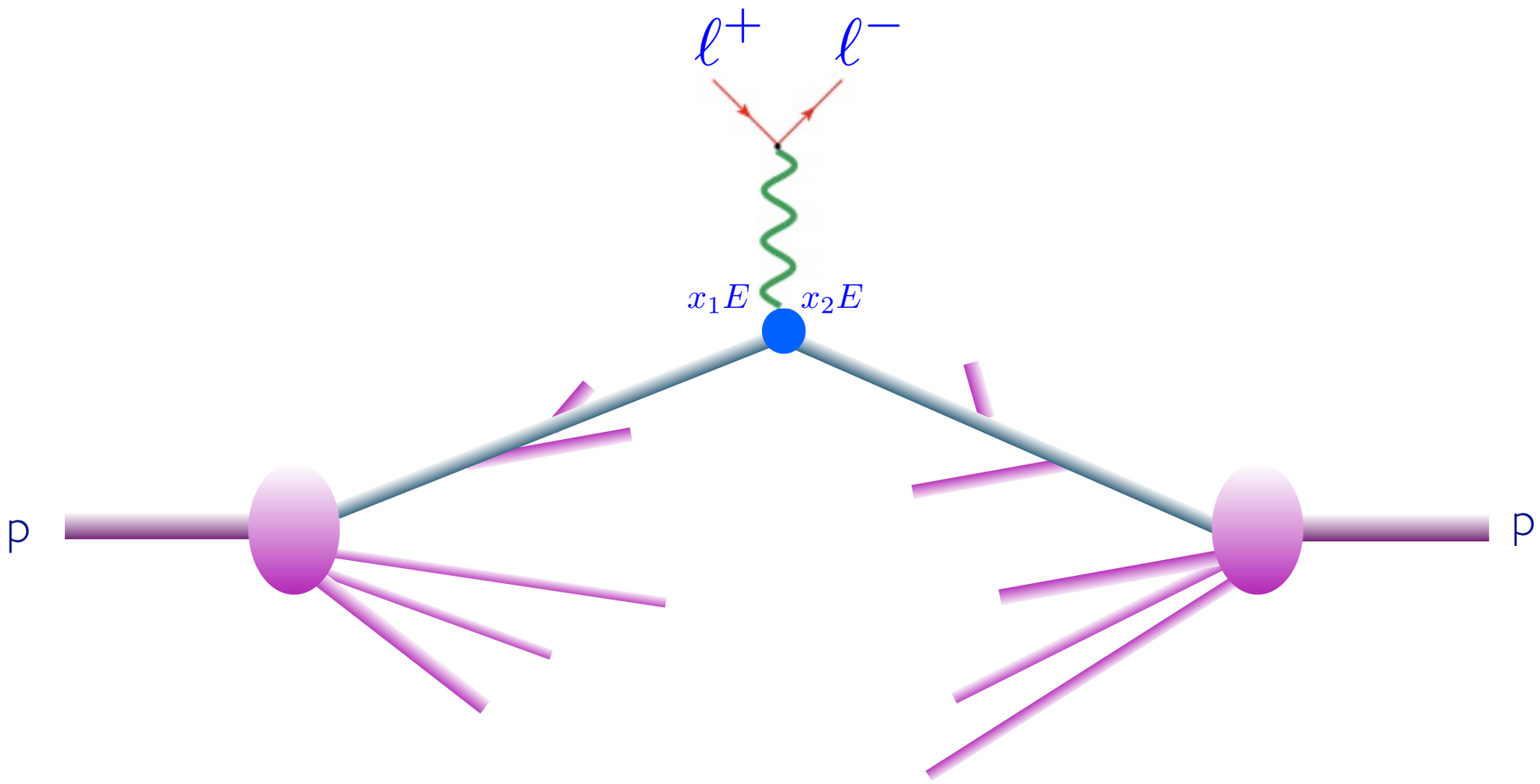

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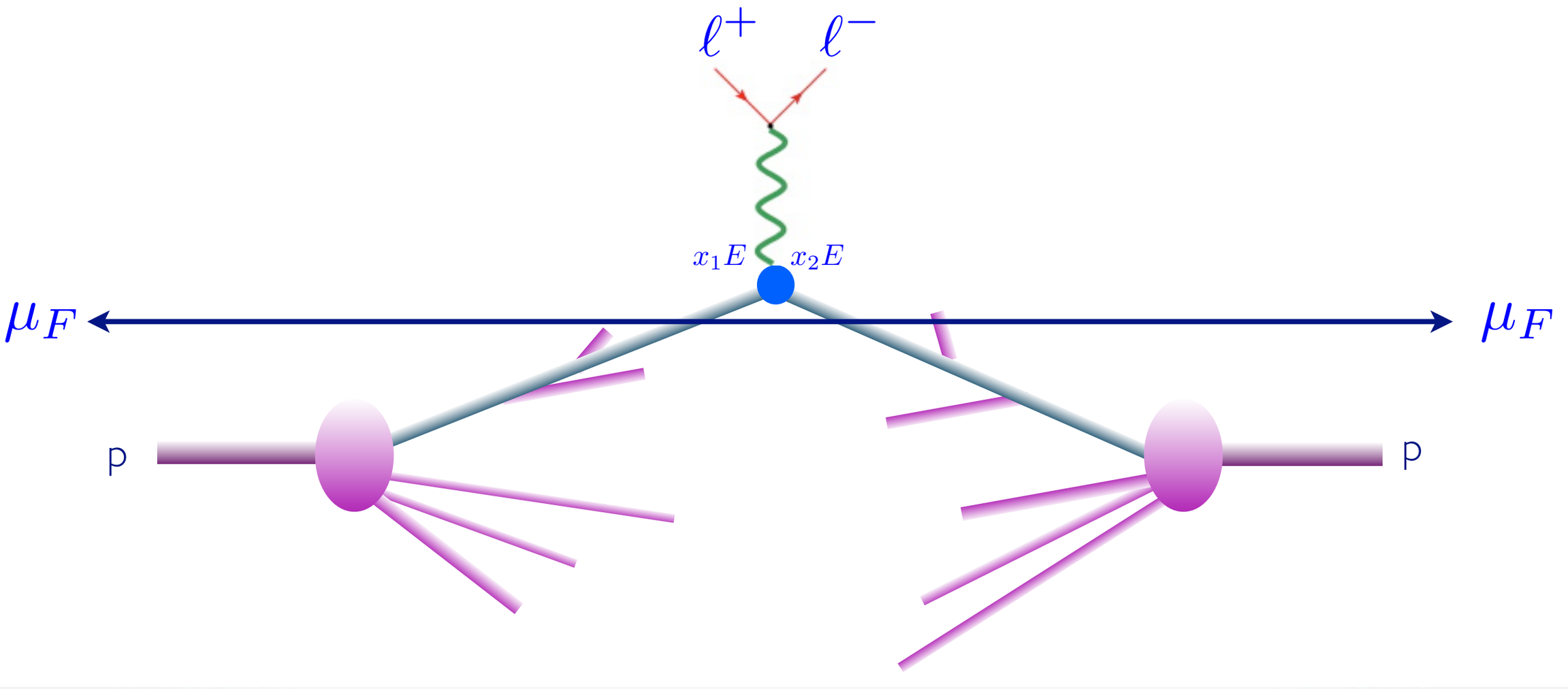

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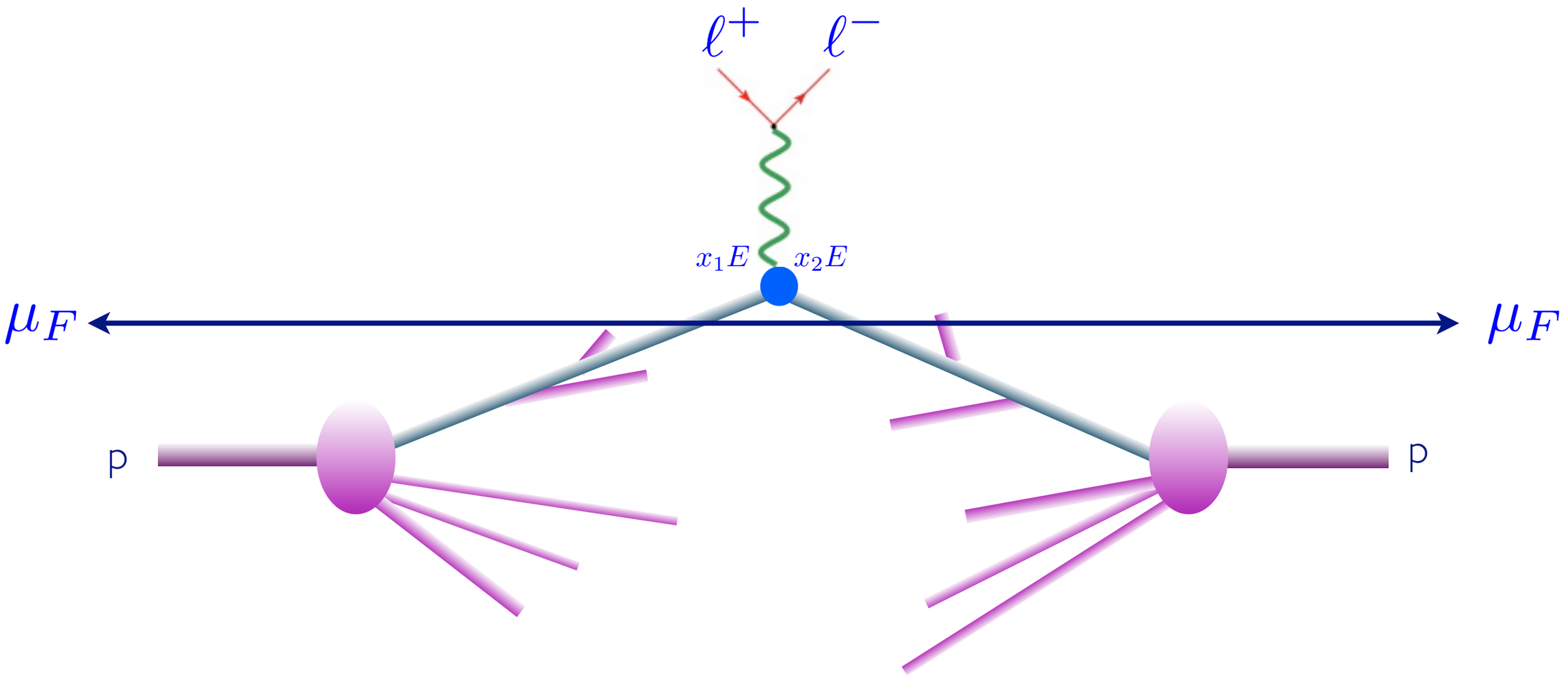

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

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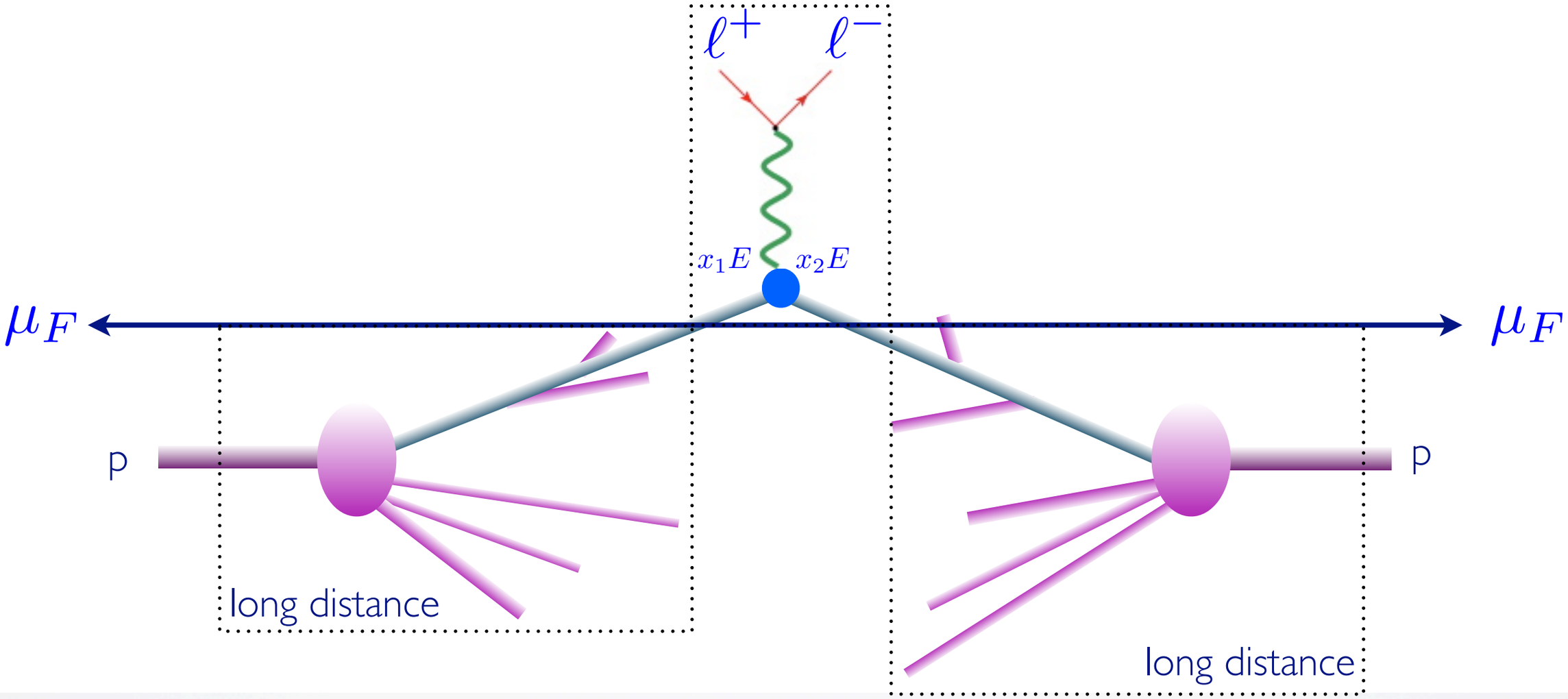

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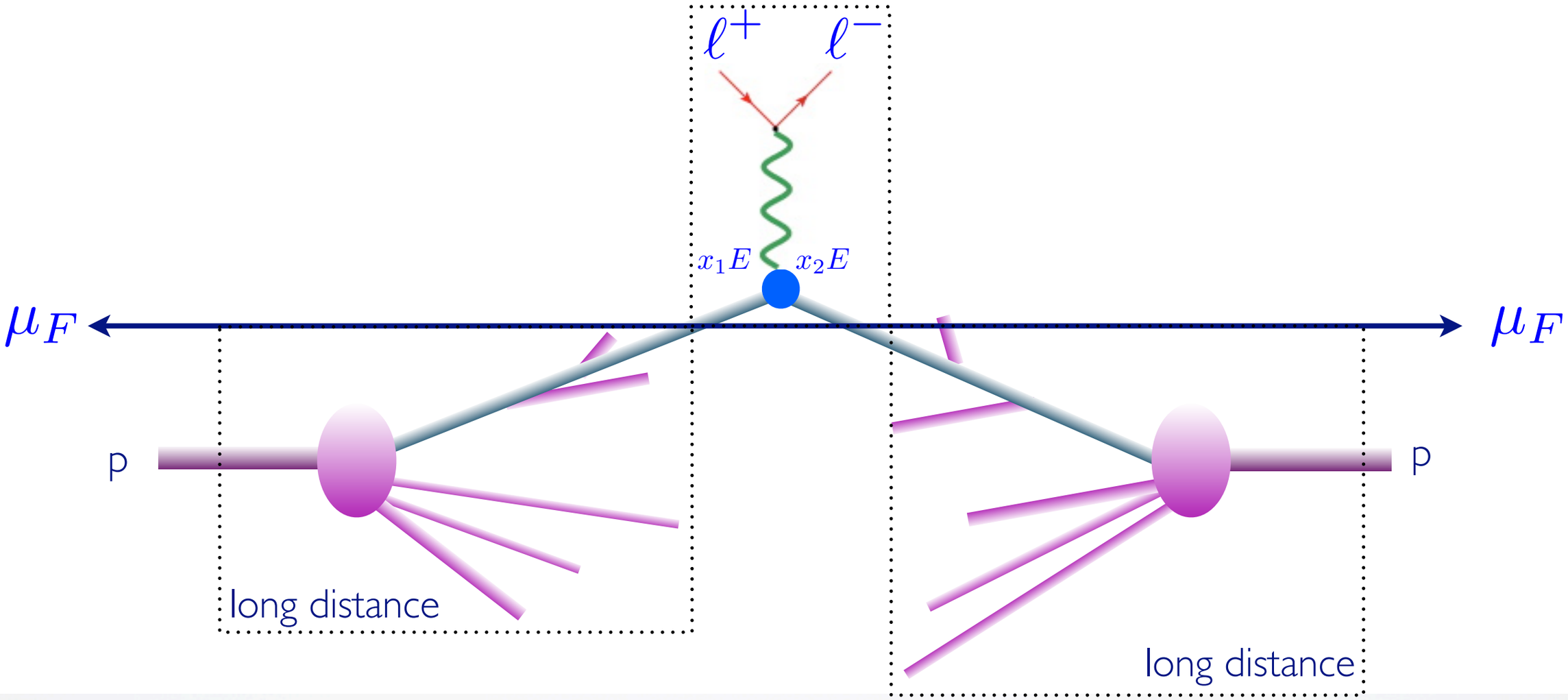

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Pheno/Th exploit this formula to provide accurate and flexible predictions from a given model (SM, MSSM,...)

HOW WE (USED TO) MAKE PREDICTIONS?

First way:

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

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

TH

- For high multiplicity use the tree-level results

Comments:

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

NLO BASICS

NLO contributions have three parts

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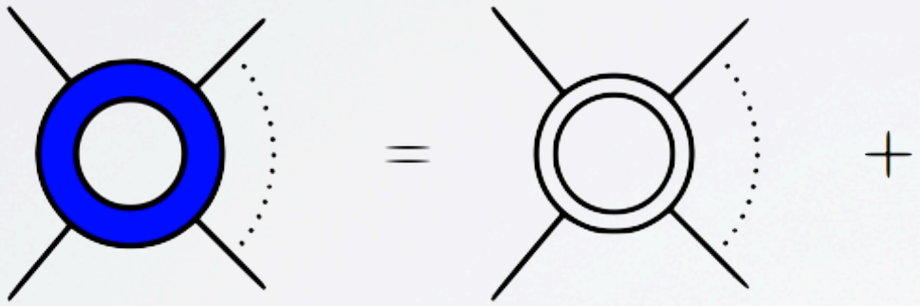

$$\sigma^{\rm NLO} = \int_m d^{(d)}\sigma^V +$$

Virtual part

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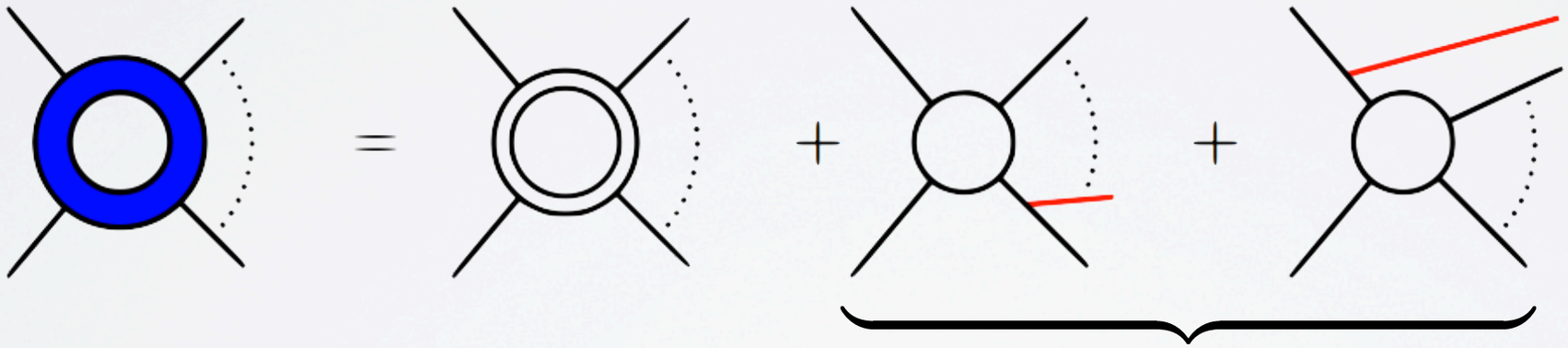
NLO contributions have three parts



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

Virtual part

Real emission part

NLO BASICS

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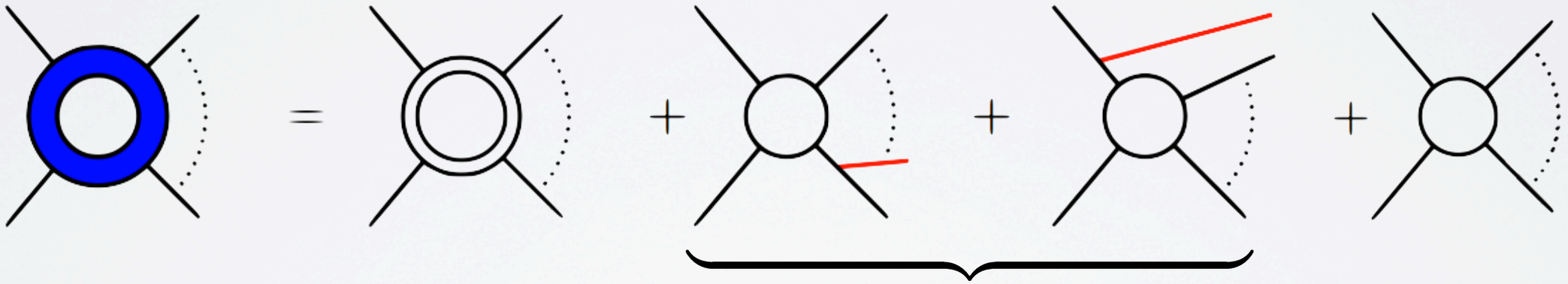

$$\sigma^{\rm NLO} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

Virtual part | Real emission part | Born

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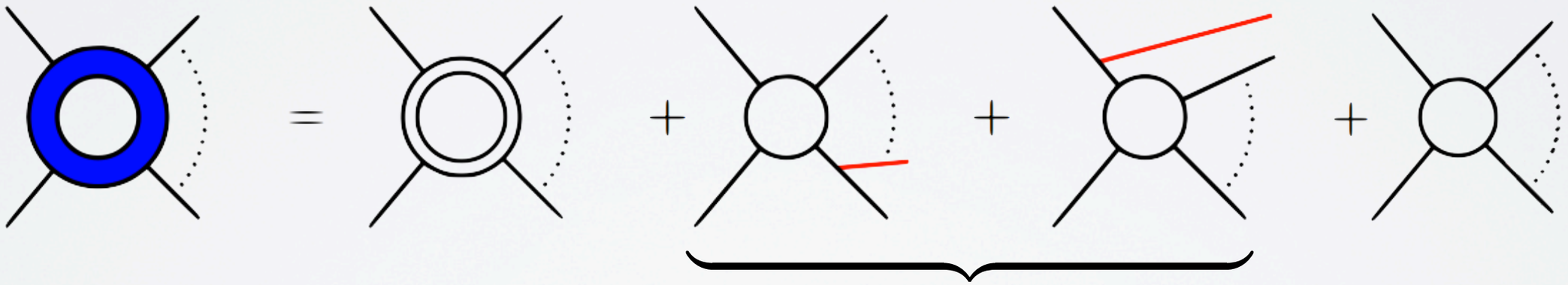

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Virtual part — Real emission part — Born

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

NLO BASICS

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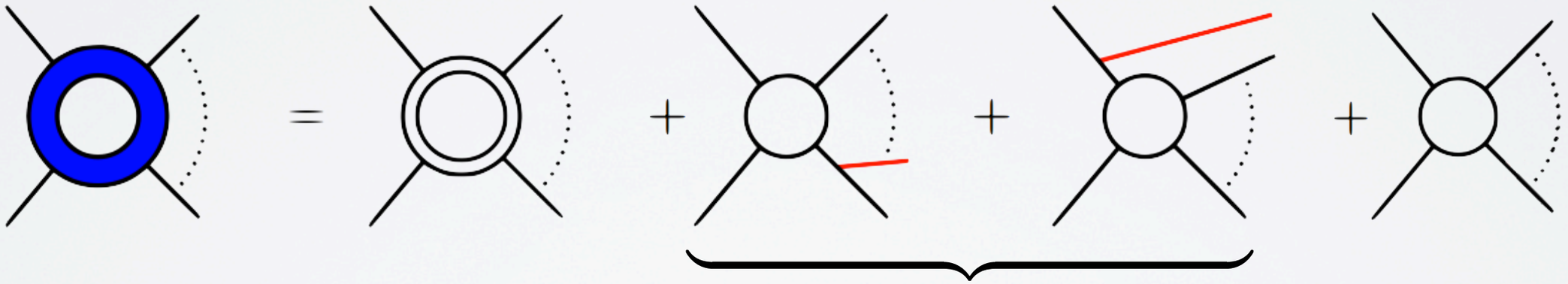

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The cost of a new prediction at NLO used to exceed 100k€.

LOOP TECHNIQUES

modified by the speaker

BEST EXAMPLE: MCFM

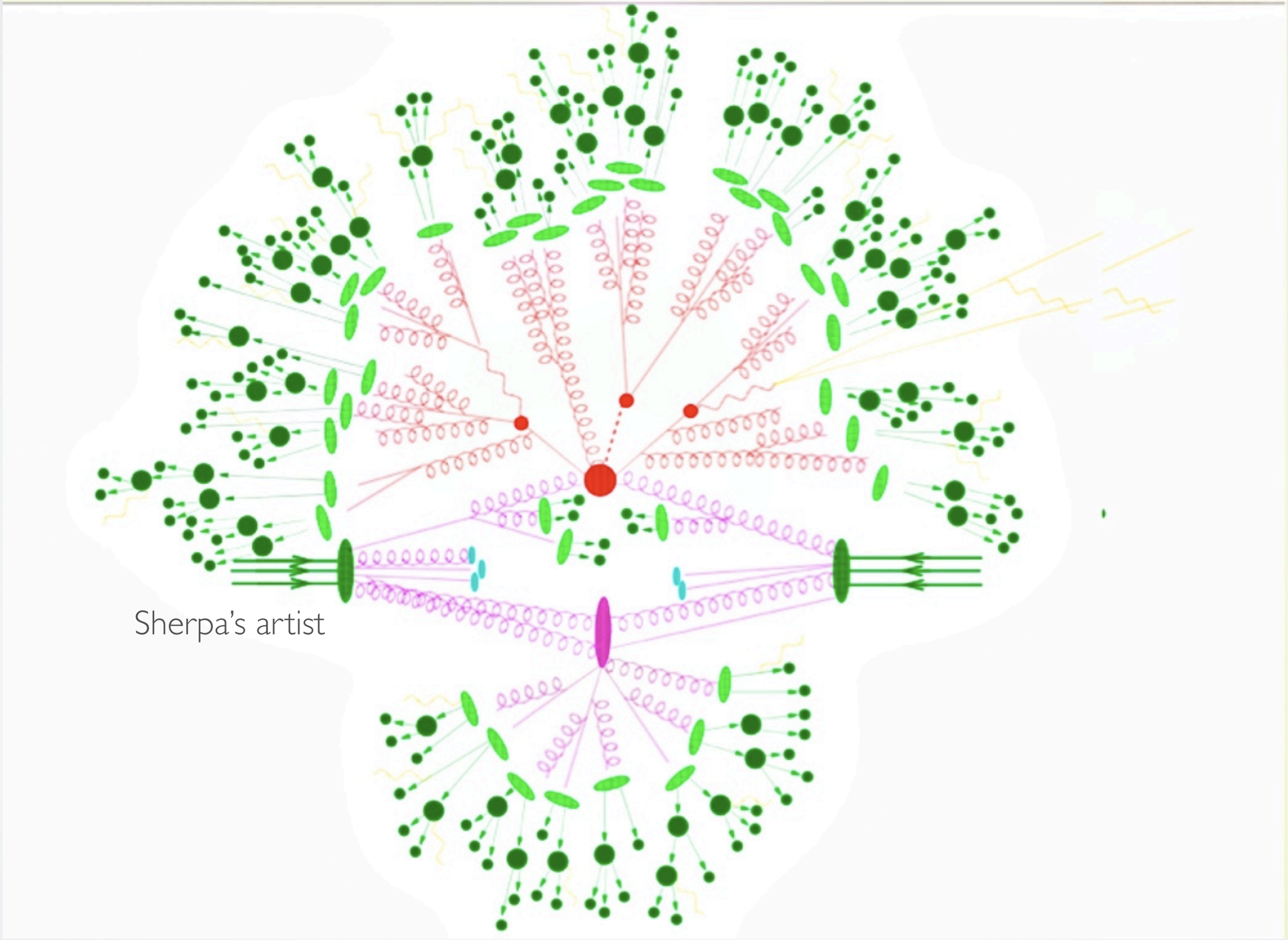
Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]

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	

- ☞ + recent additions, overall 30+ processes
- ☞ First results implemented in 1998 ...this is 13 years worth of work of several people **(~5M$)**
- ☞ Cross sections and parton-level distributions at NLO are provided
- ☞ One framework, however, each process implemented by hand.

Events at hadron colliders



Sherpa's artist

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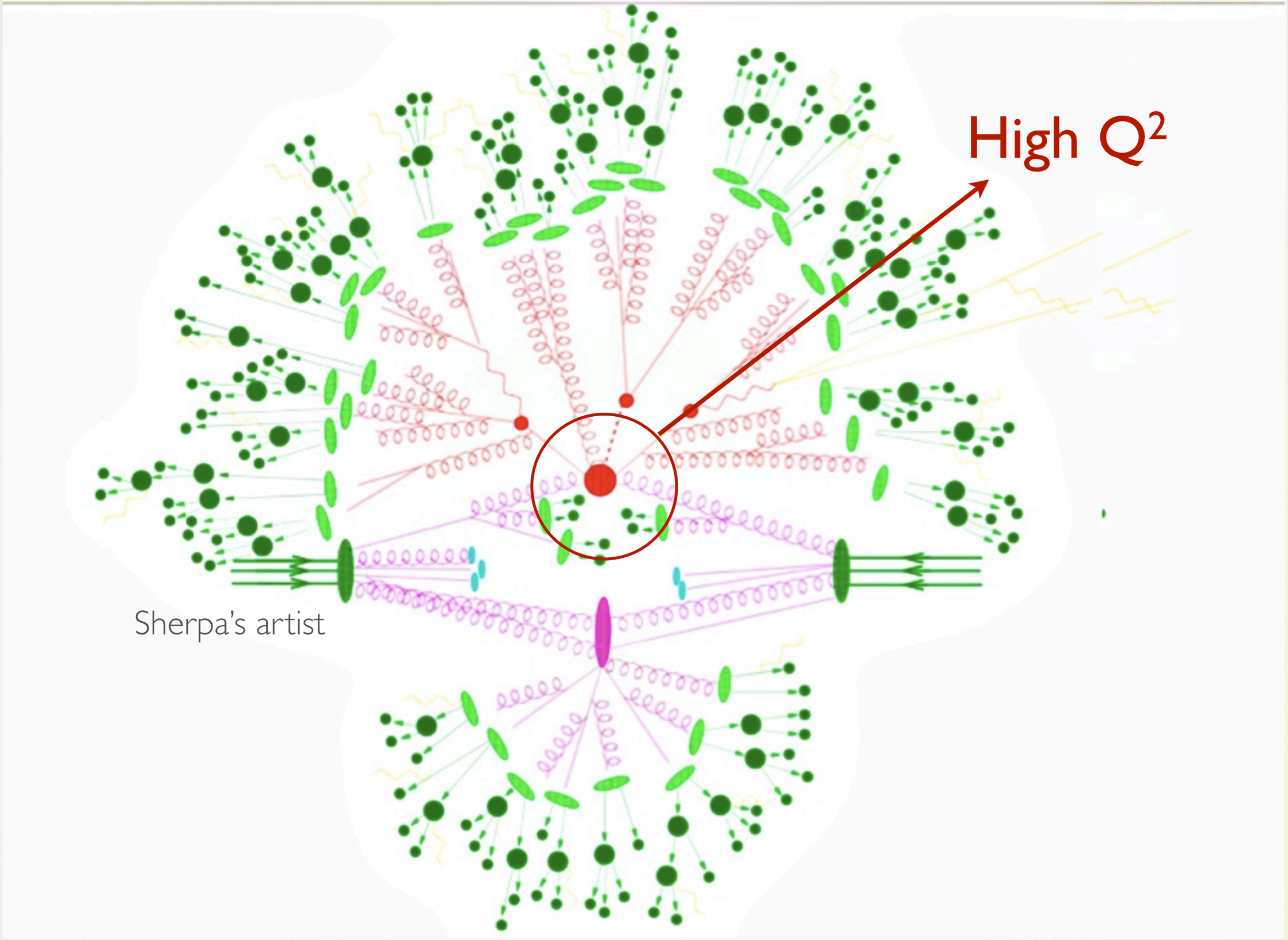

Sherpa's artist

HOW WE (USED TO) MAKE PREDICTIONS?

Second way:

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

EXP

Comments:

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

most known and used : PYTHIA, HERWIG, SHERPA

SM STATUS 10 YEARS AGO

pp → n particles

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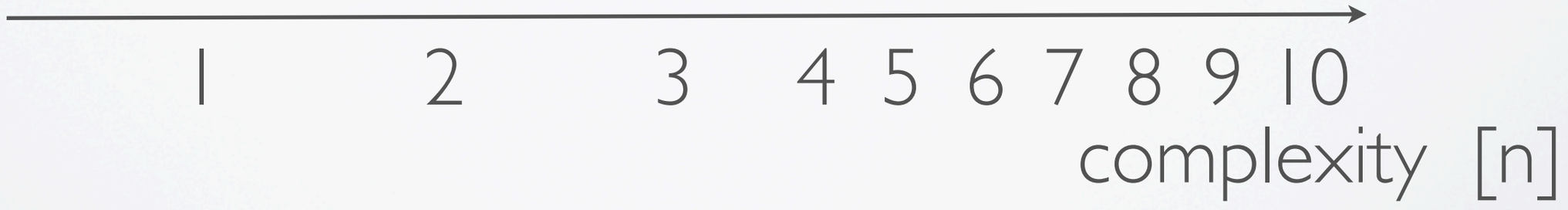

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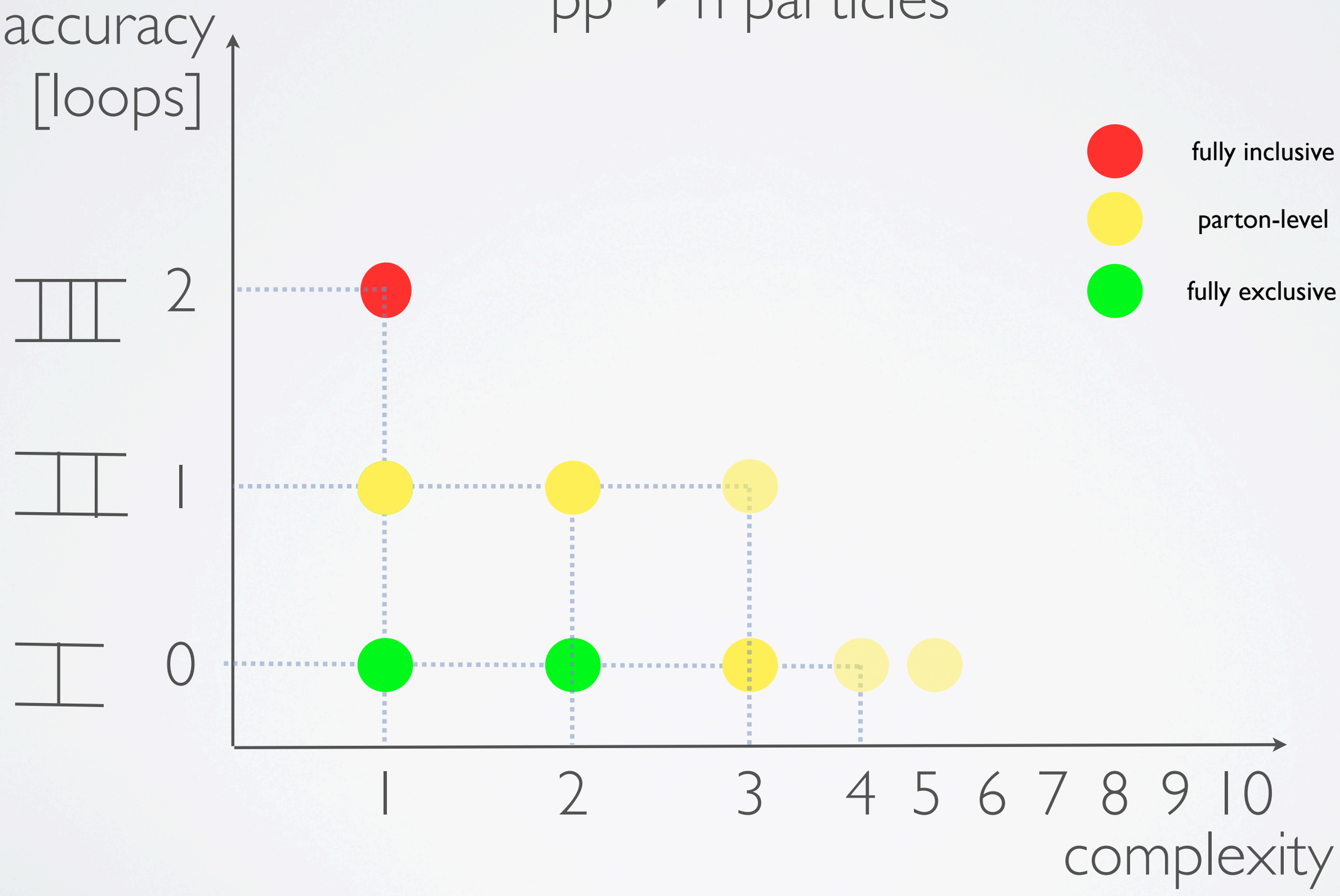
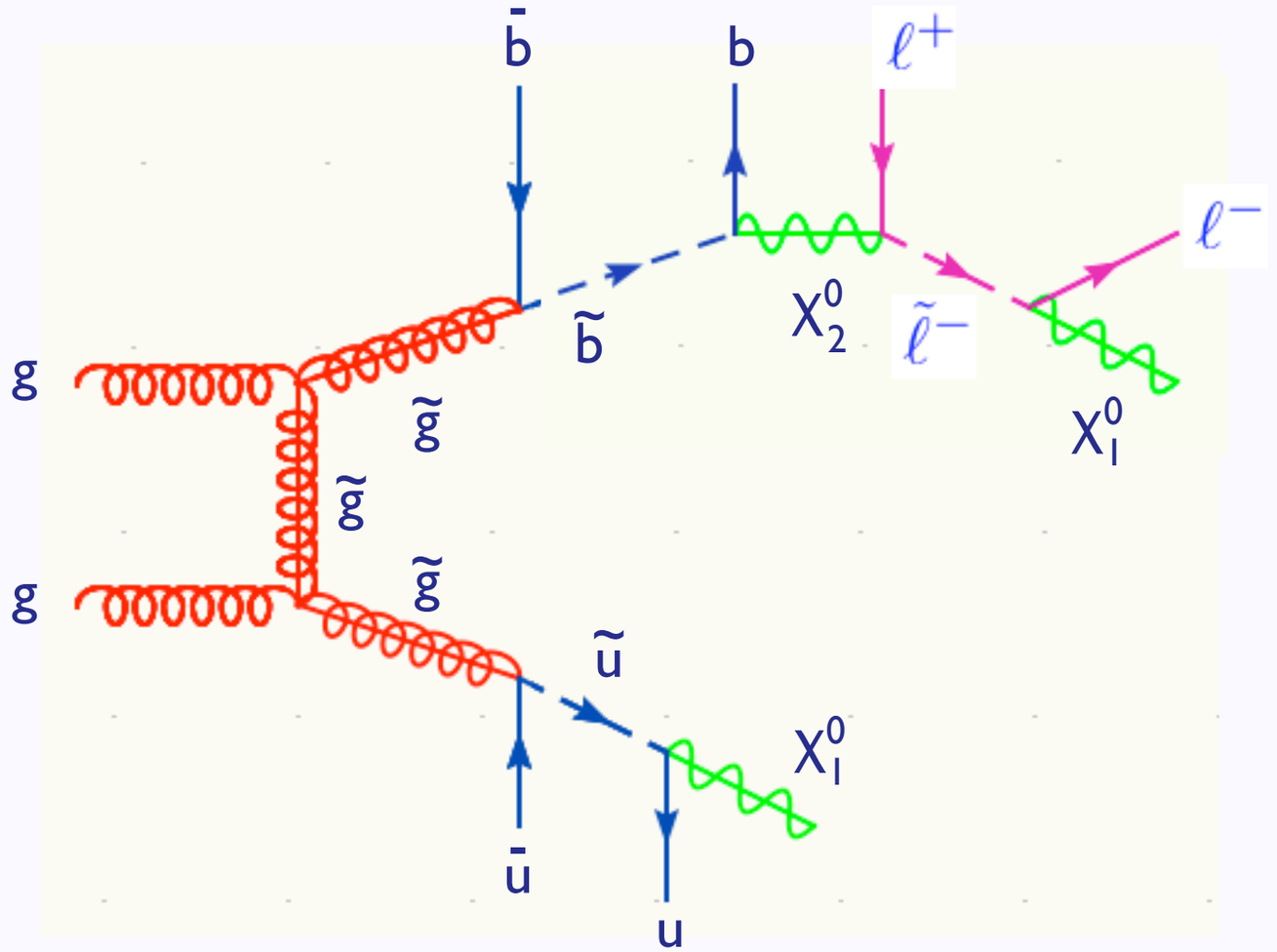
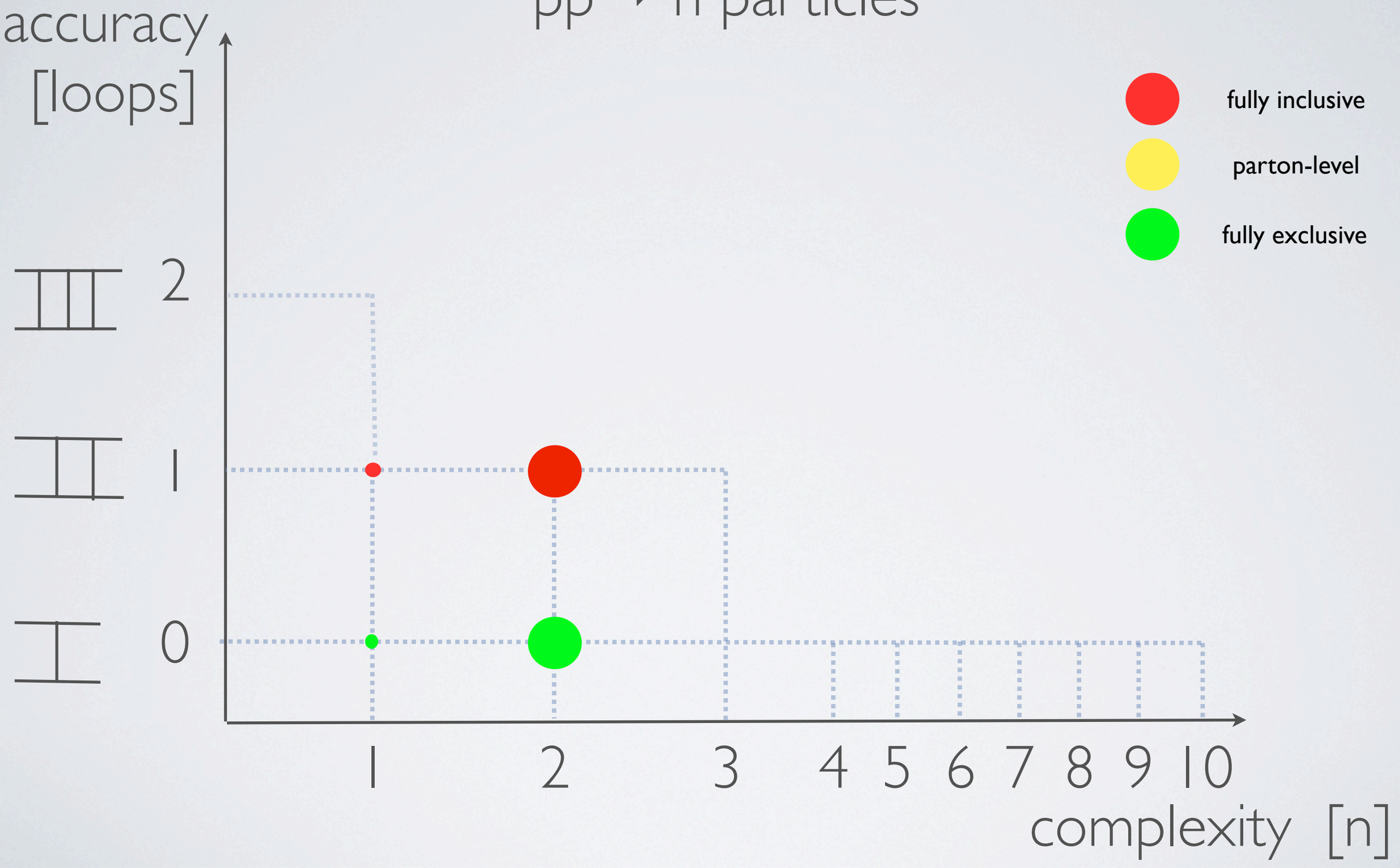


WHAT ABOUT NEW PHYSICS?



BSM (=SUSY)STATUS 10 YEARS AGO

pp → n particles



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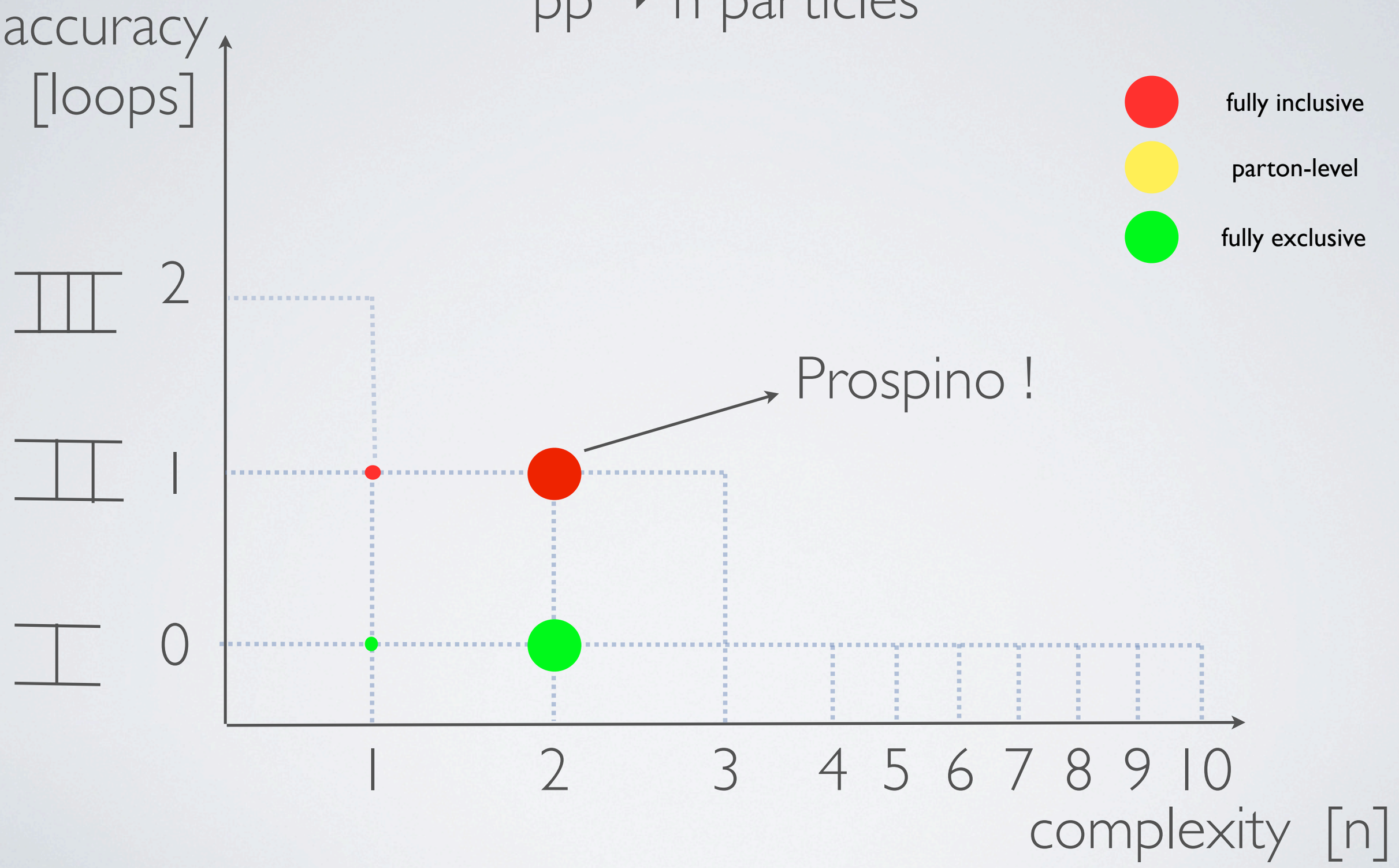

TH/EXP INTERACTIONS ANTE LHC

TH

Idea

TH/EXP INTERACTIONS ANTE LHC

TH

Idea

Lagrangian

Feyn. Rules

Amplitudes

x secs

Paper

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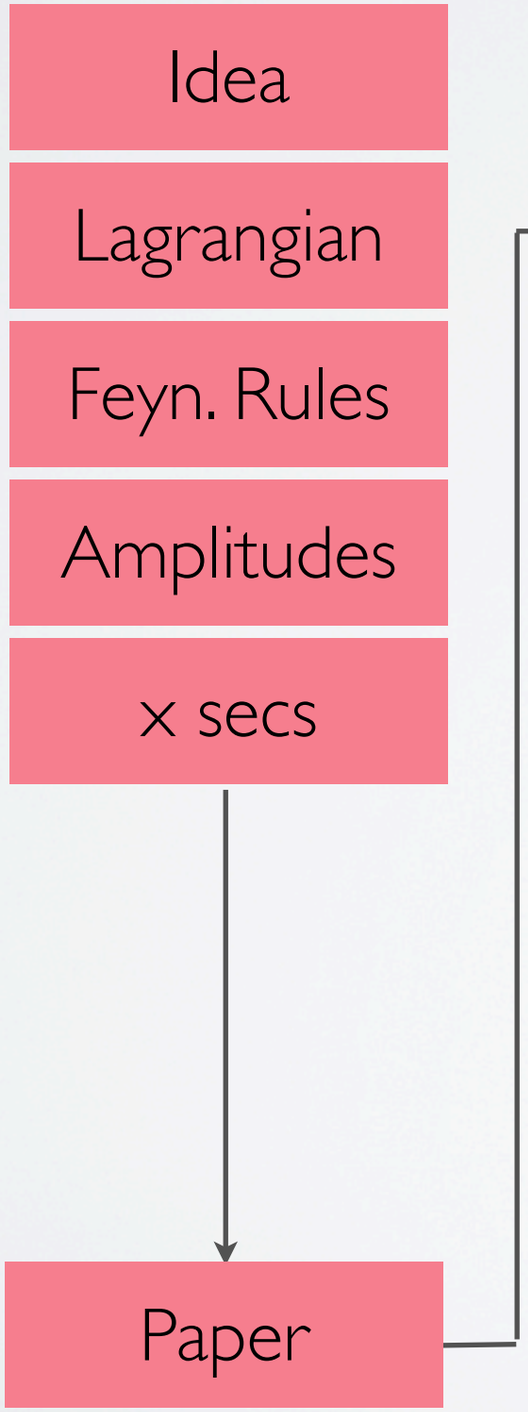

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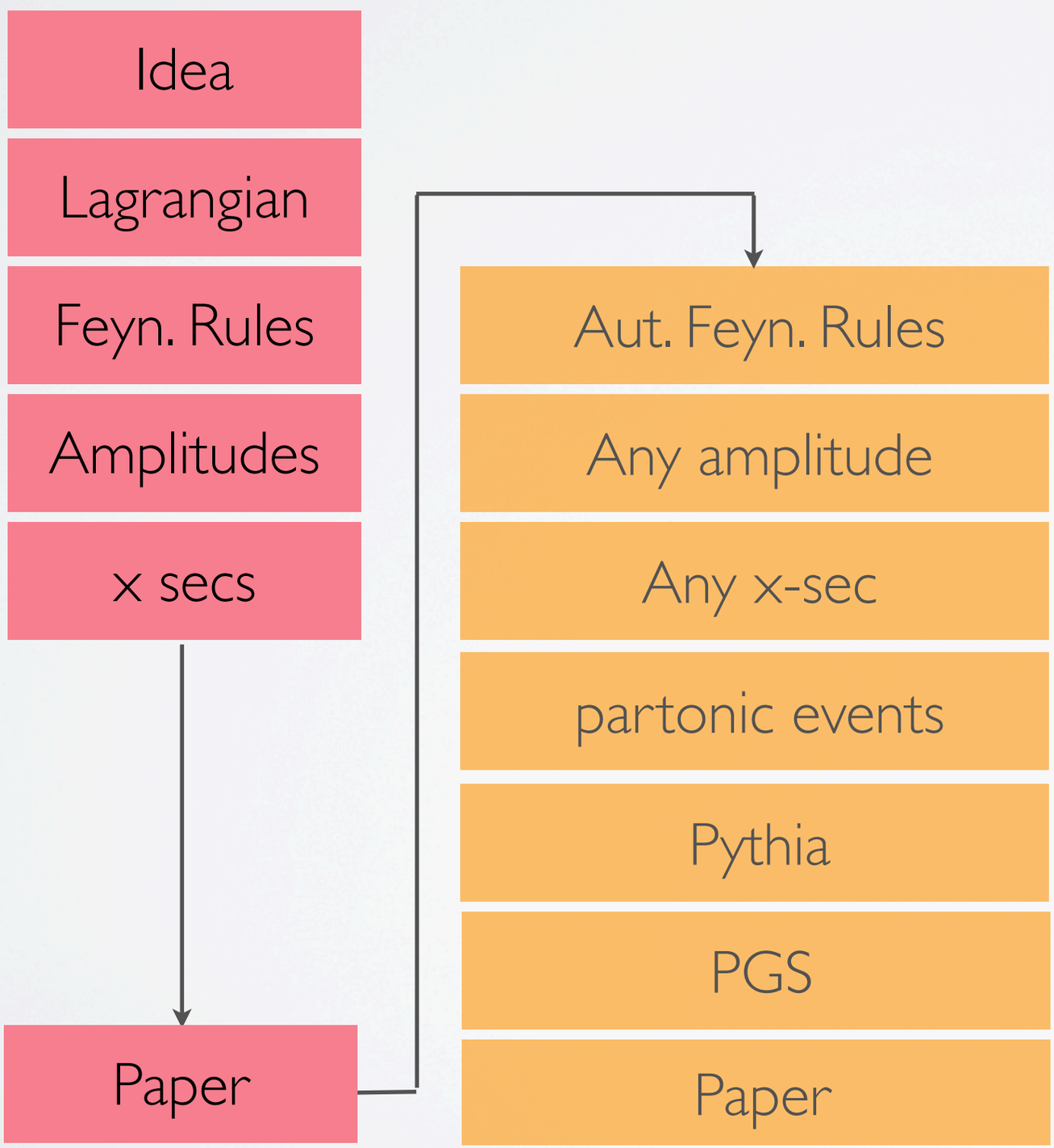

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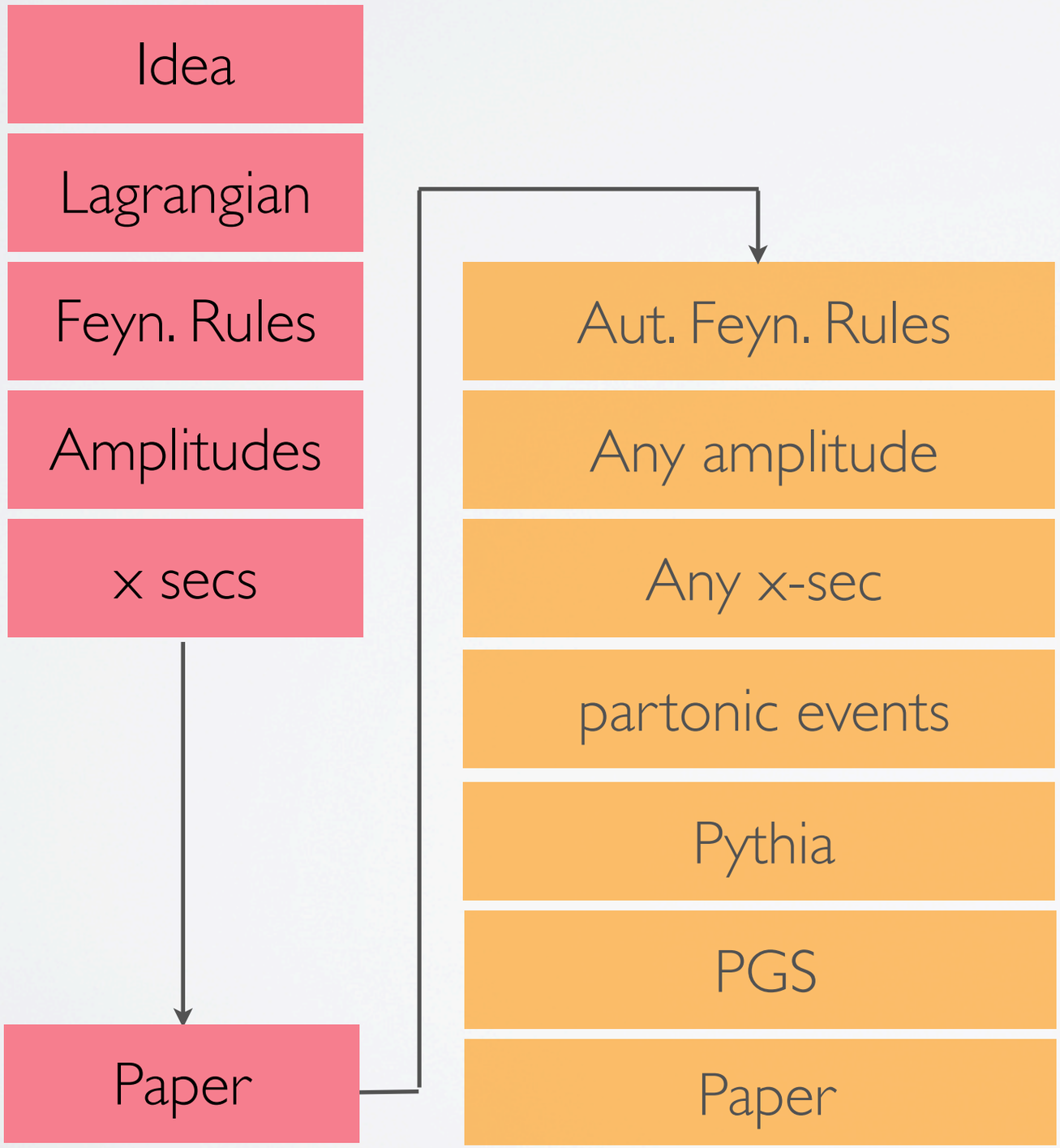

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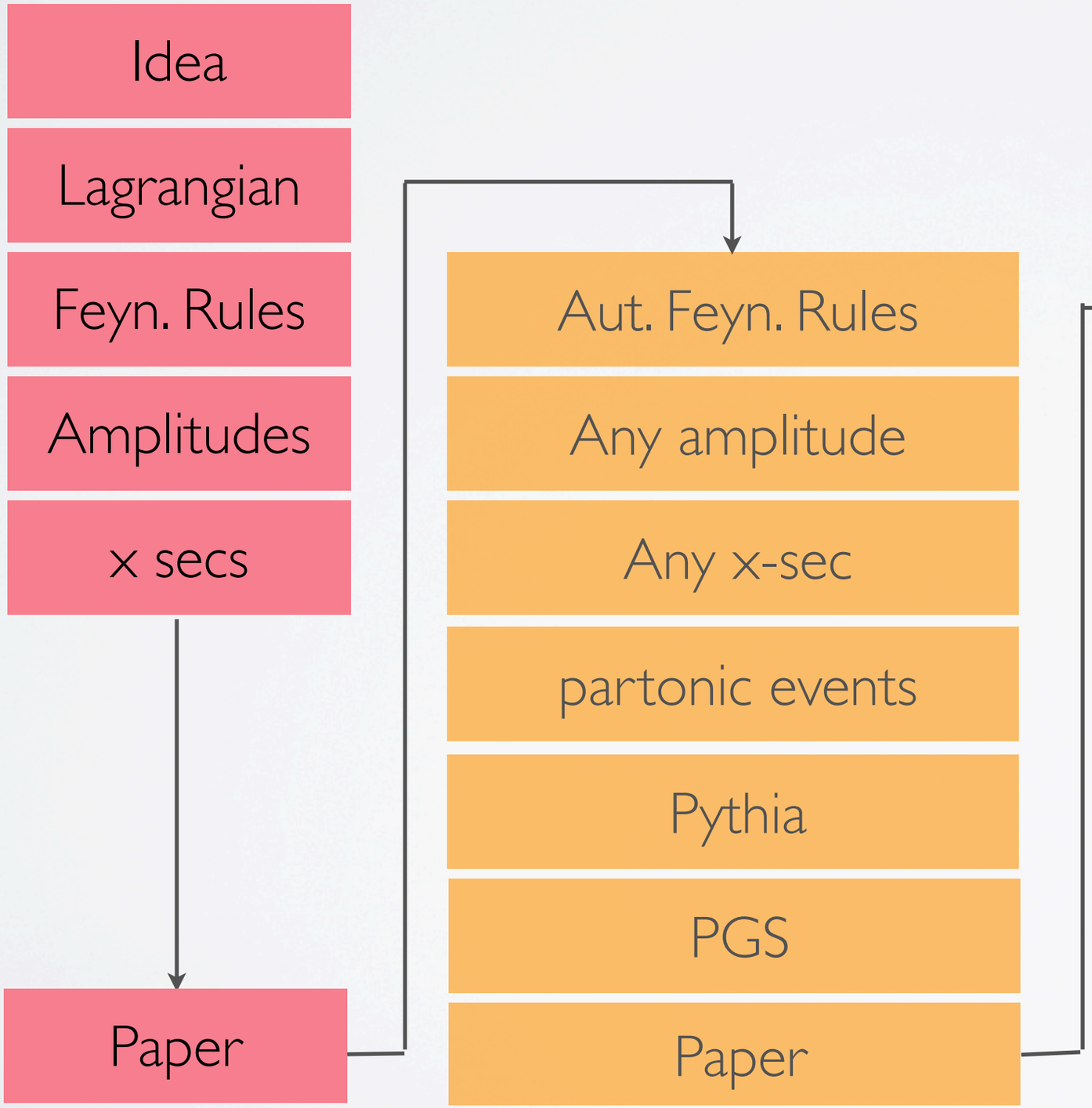
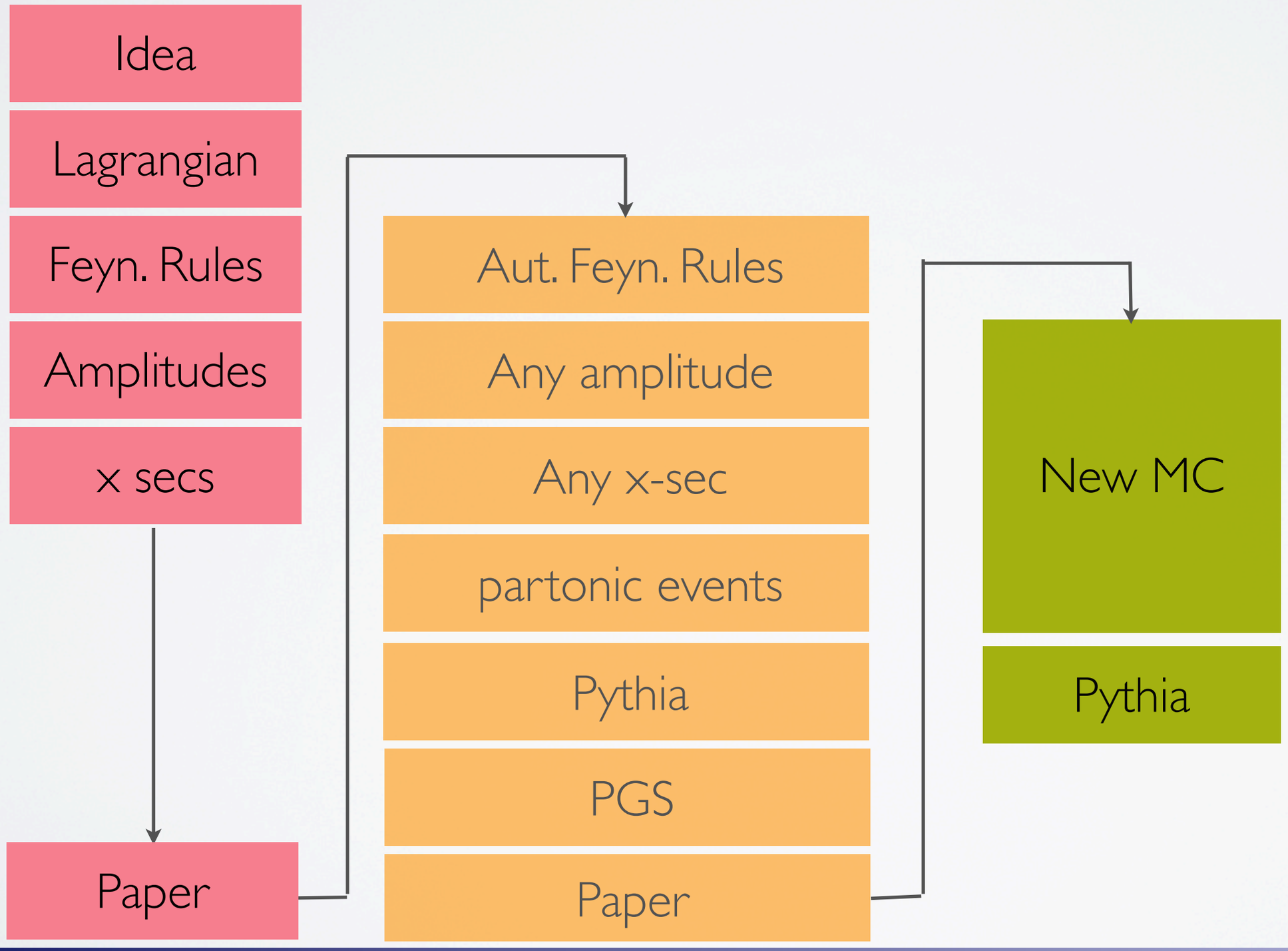
TH | PHENO | EXP



TH/EXP INTERACTIONS ANTE LHC

TH | PHENO | EXP



TH/EXP INTERACTIONS ANTE LHC

TH

Idea

Lagrangian

Feyn. Rules

Amplitudes

x secs

Paper

PHENO

Aut. Feyn. Rules

Any amplitude

Any x-sec

partonic events

Pythia

PGS

Paper

New MC

Pythia

EXP

Amps 2→2

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Amps 2→2

New Pythia

Detec. Sim.

Paper

Data

BSM TH/EXP INTERACTIONS : THE OLD WAY

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

"GAP ANALYSIS" (ANTE LHC)

We would like to:

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

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OK?

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We would like to:

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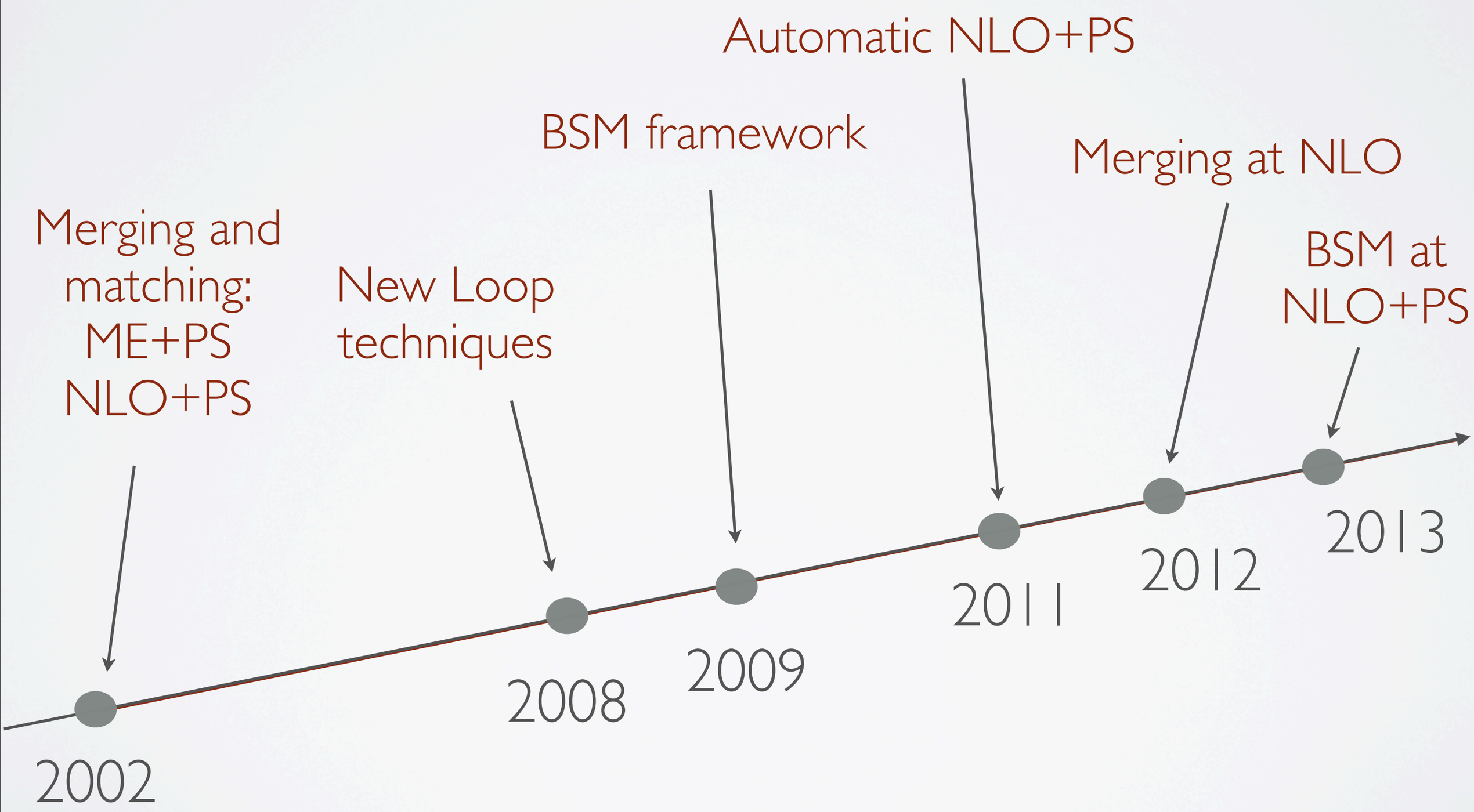
PREDICTIVE MC (SIMPLIFIED) PROGRESS



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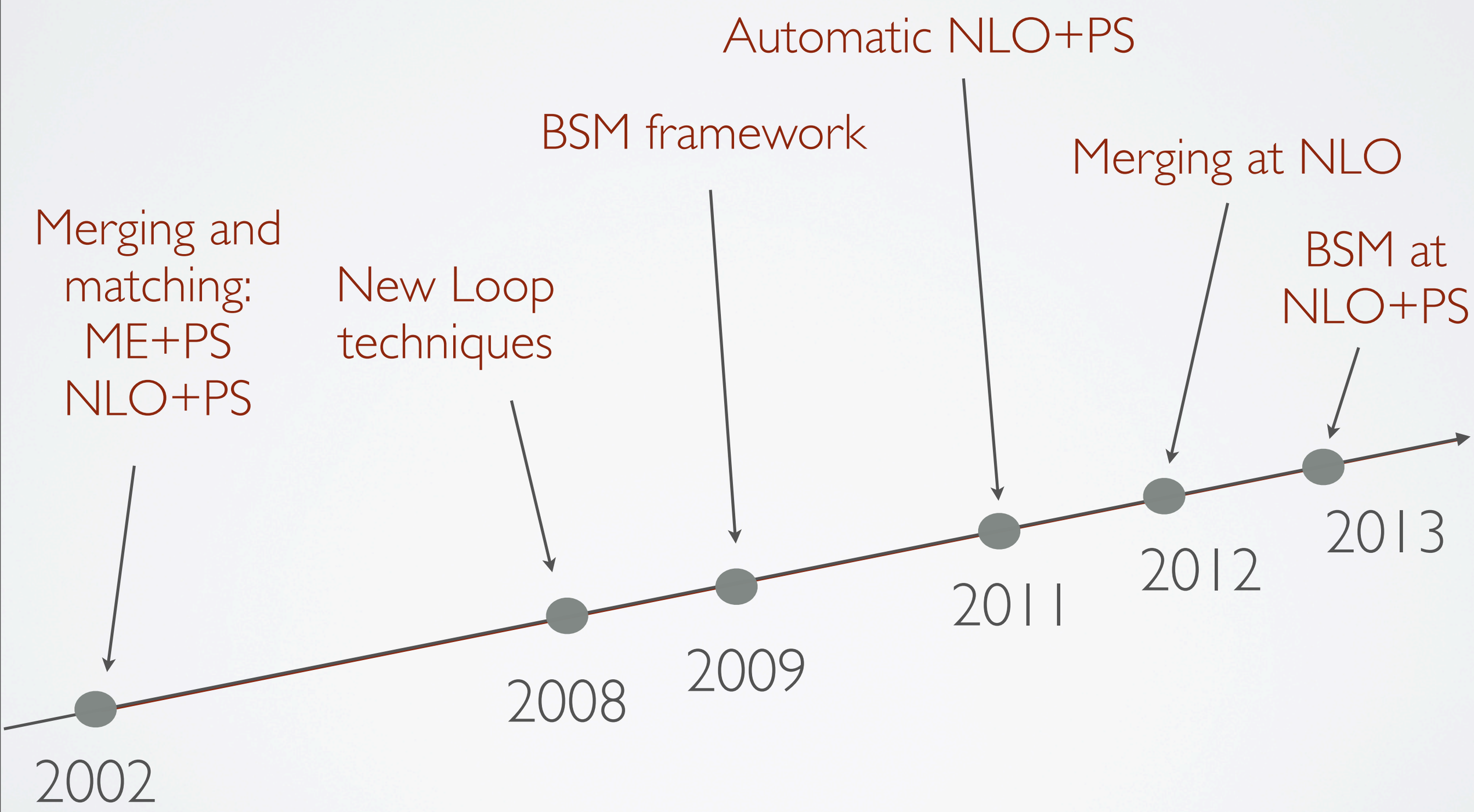

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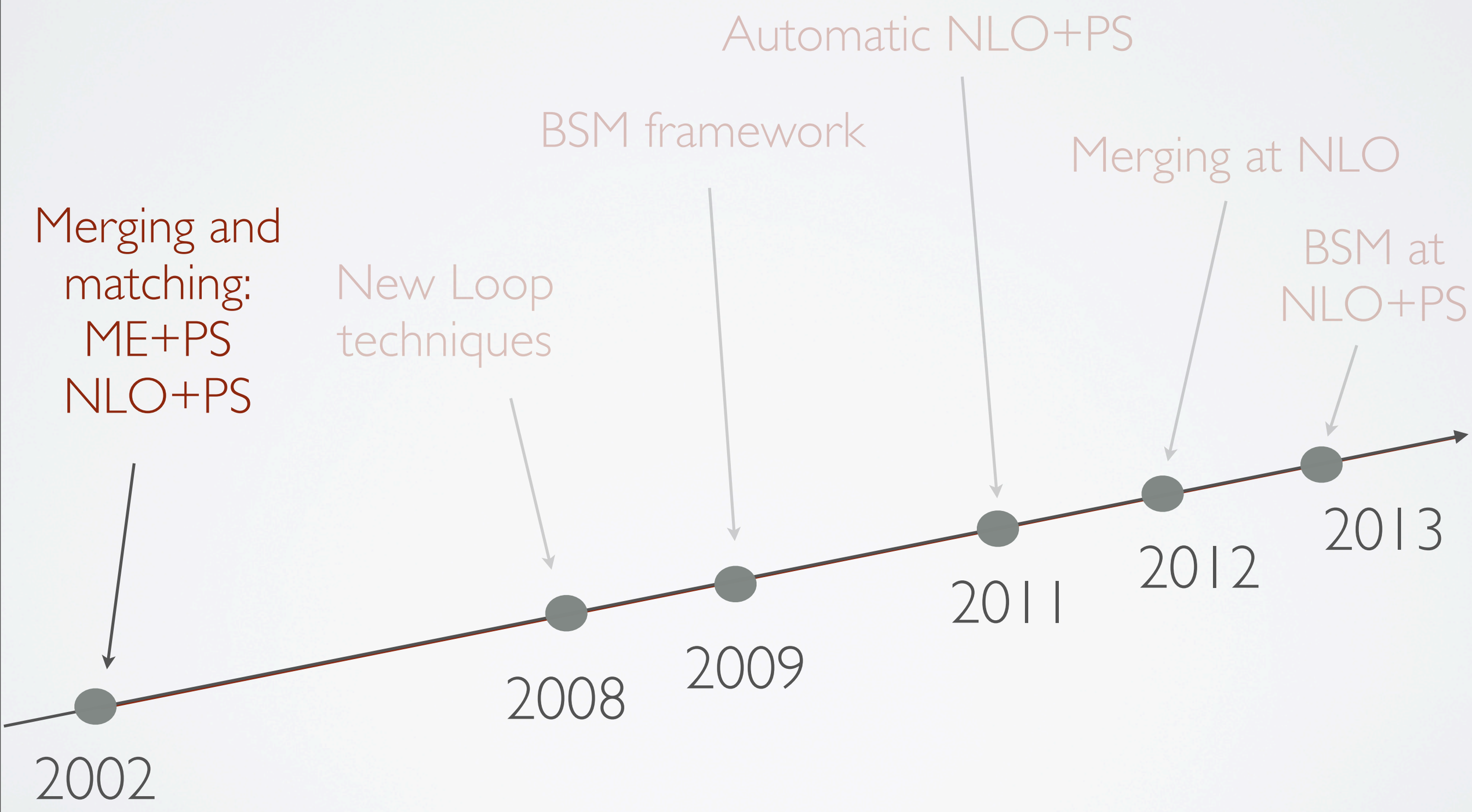

ME WITH PS

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

Matrix Element

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

Shower MC

1. hadron-level description
2. resums large logs
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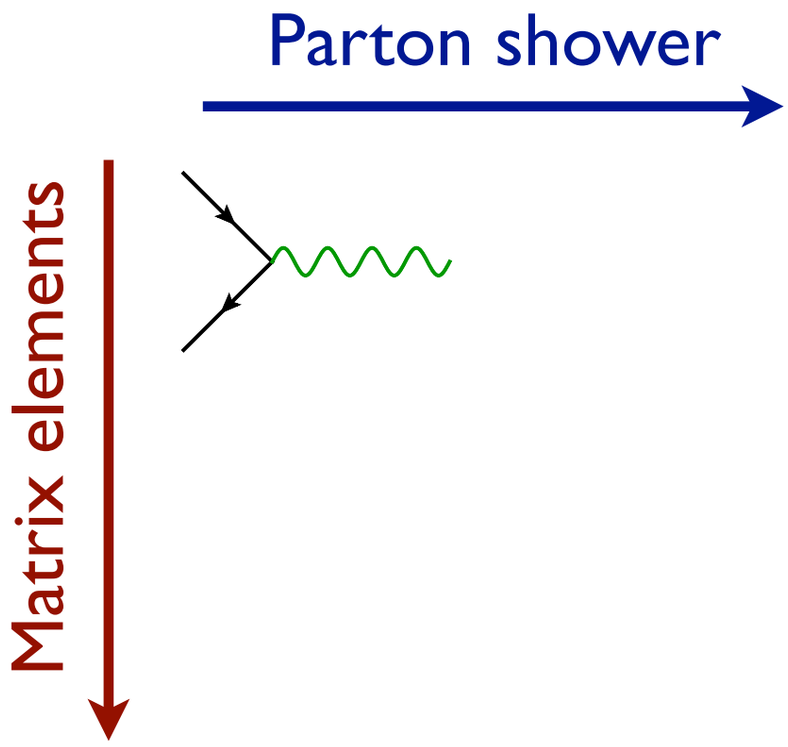
Approaches are complementary: merge them!

Difficulty: avoid double counting

Merging fixed order with PS



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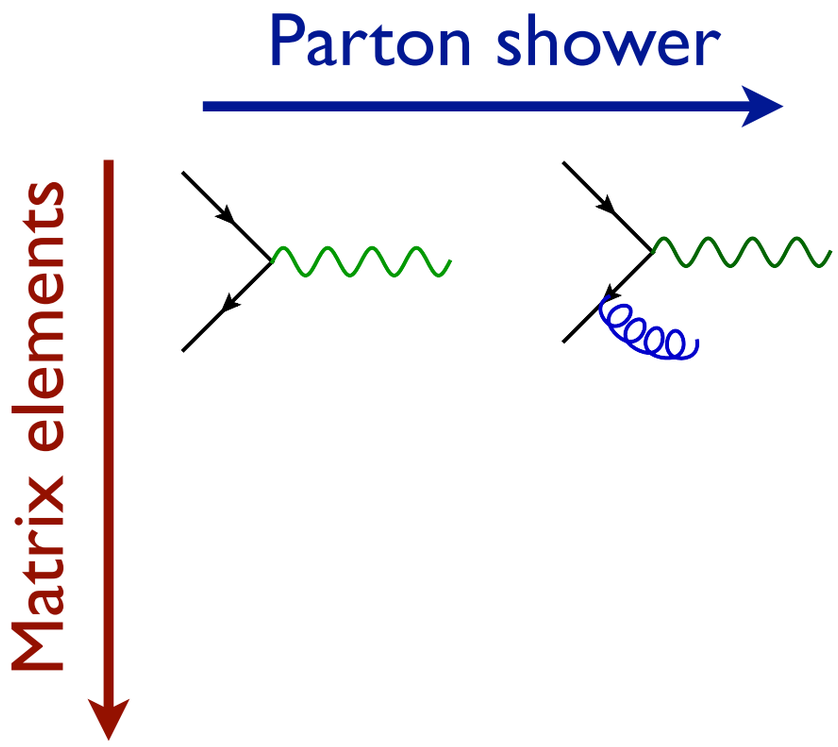

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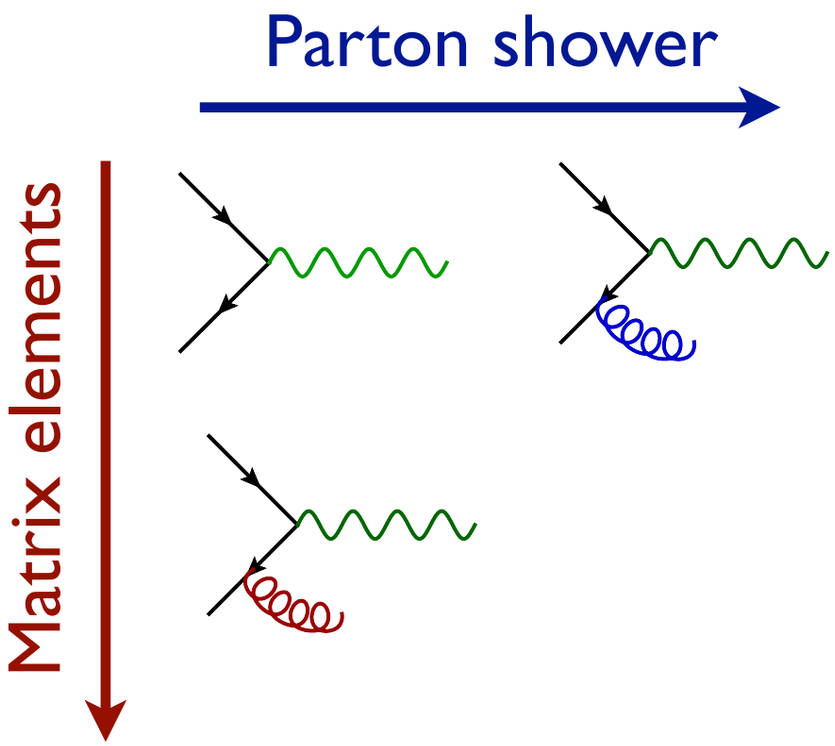

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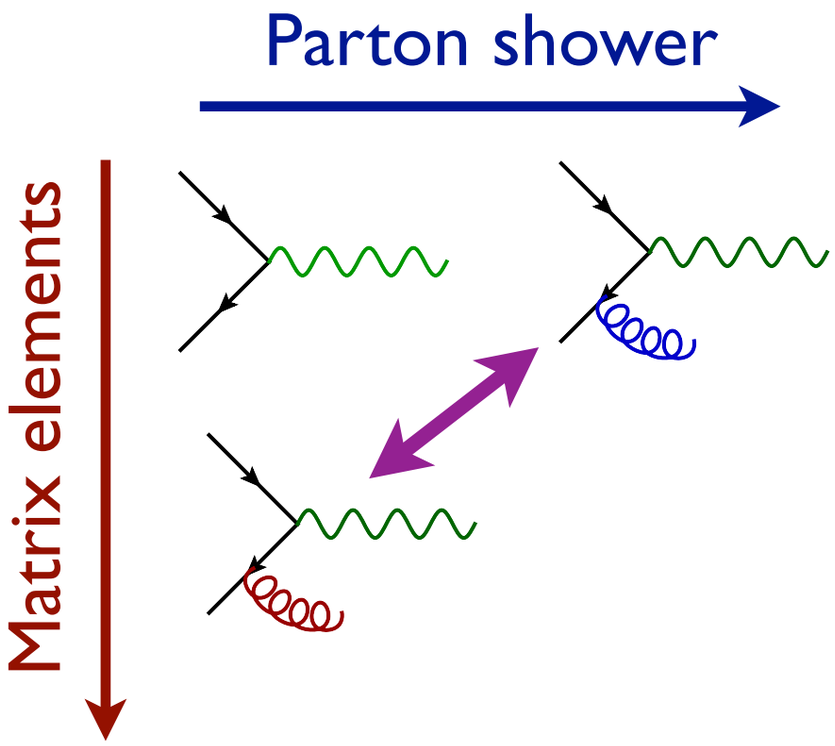

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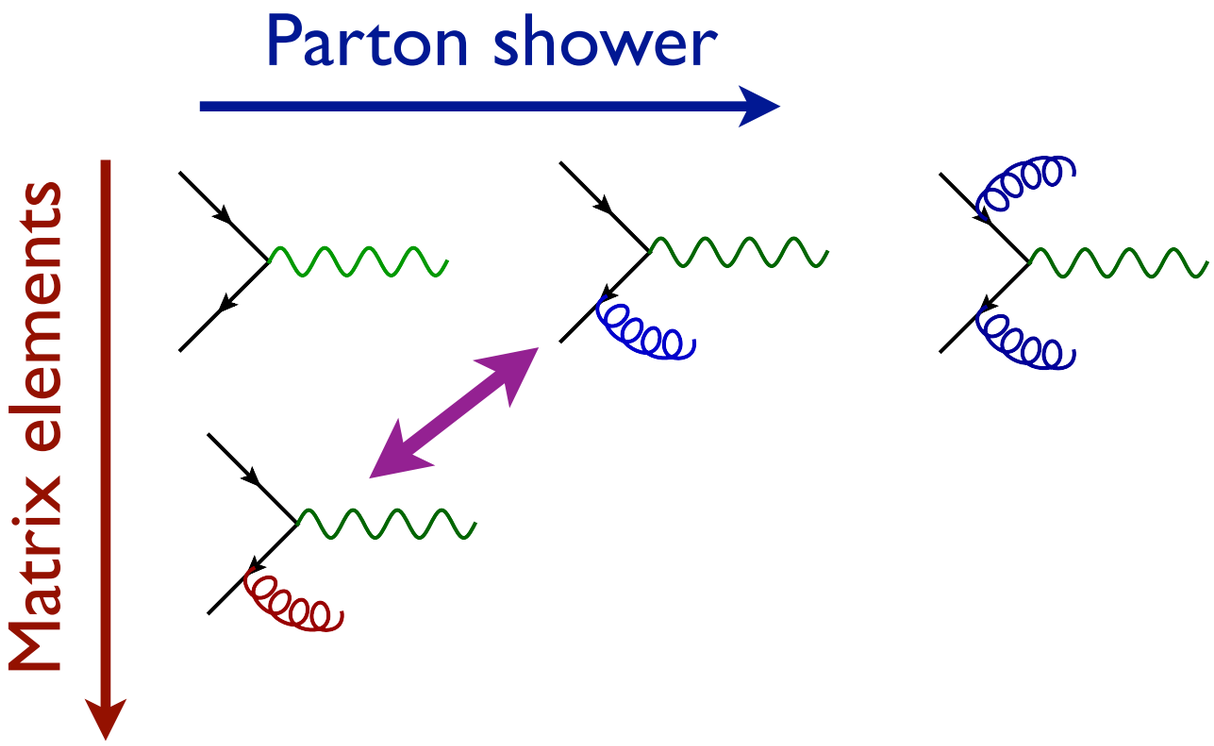

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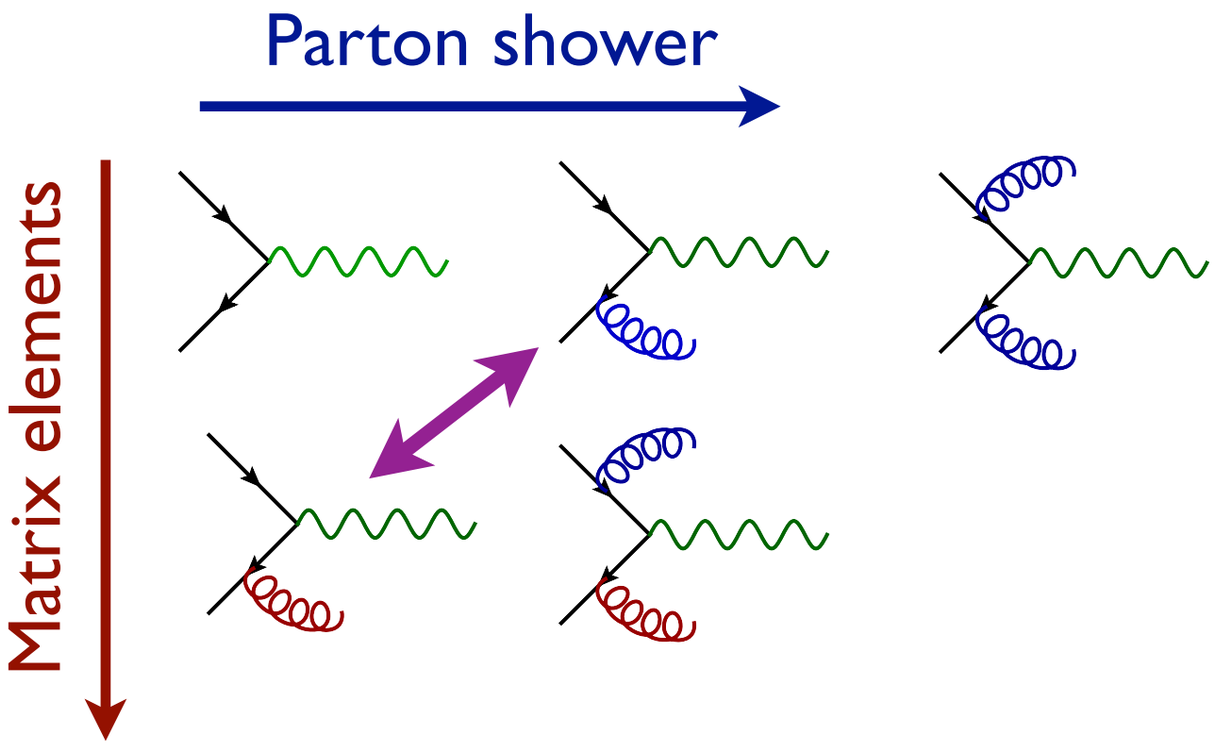

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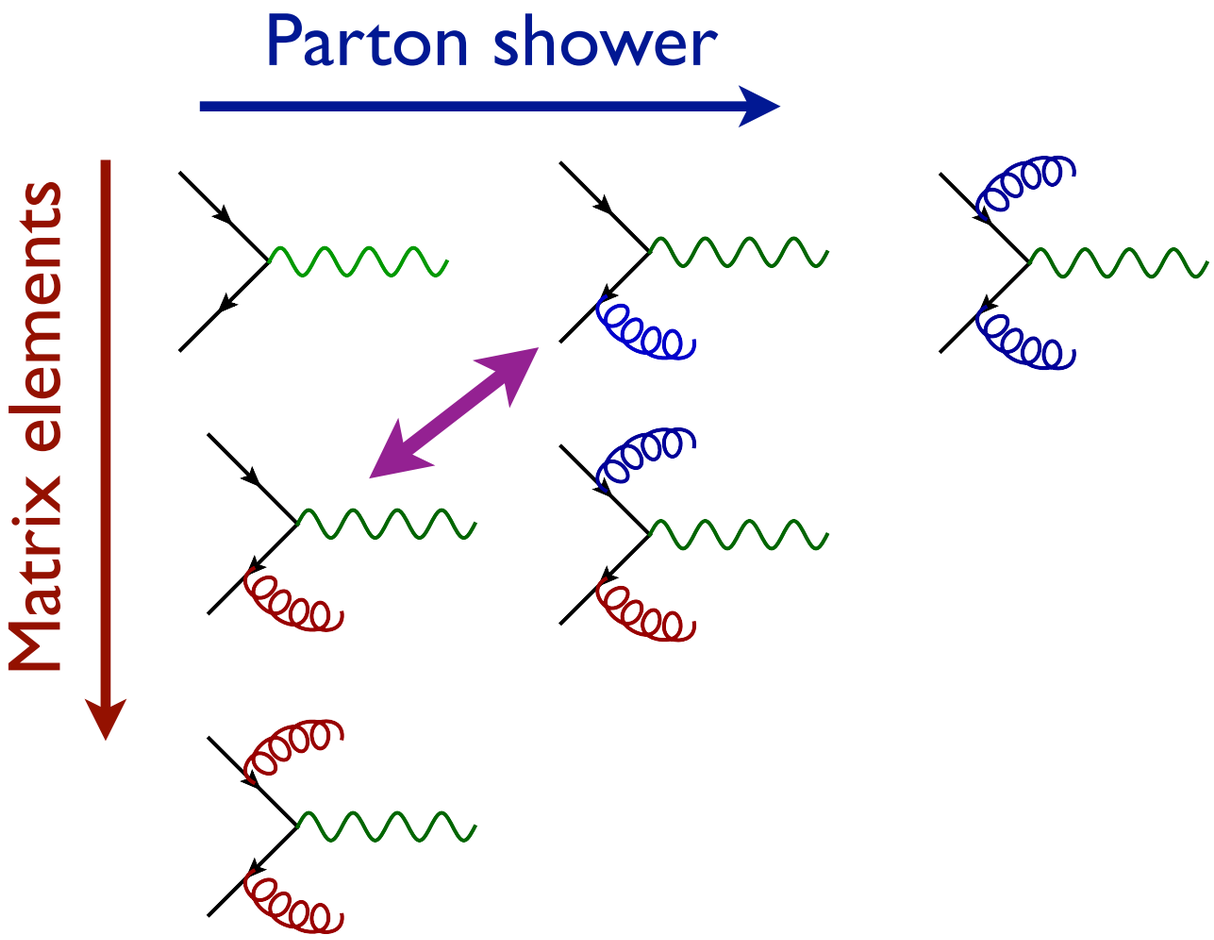

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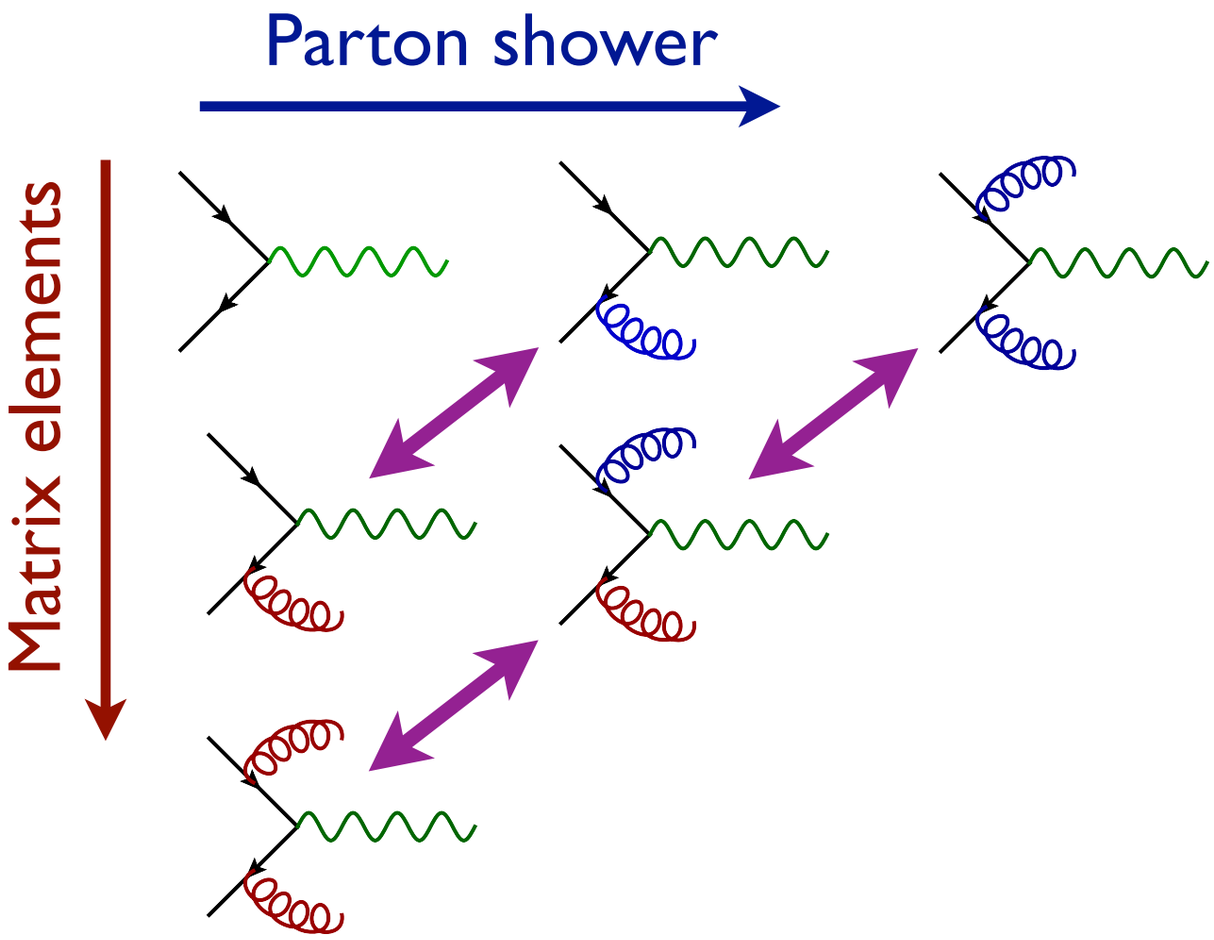

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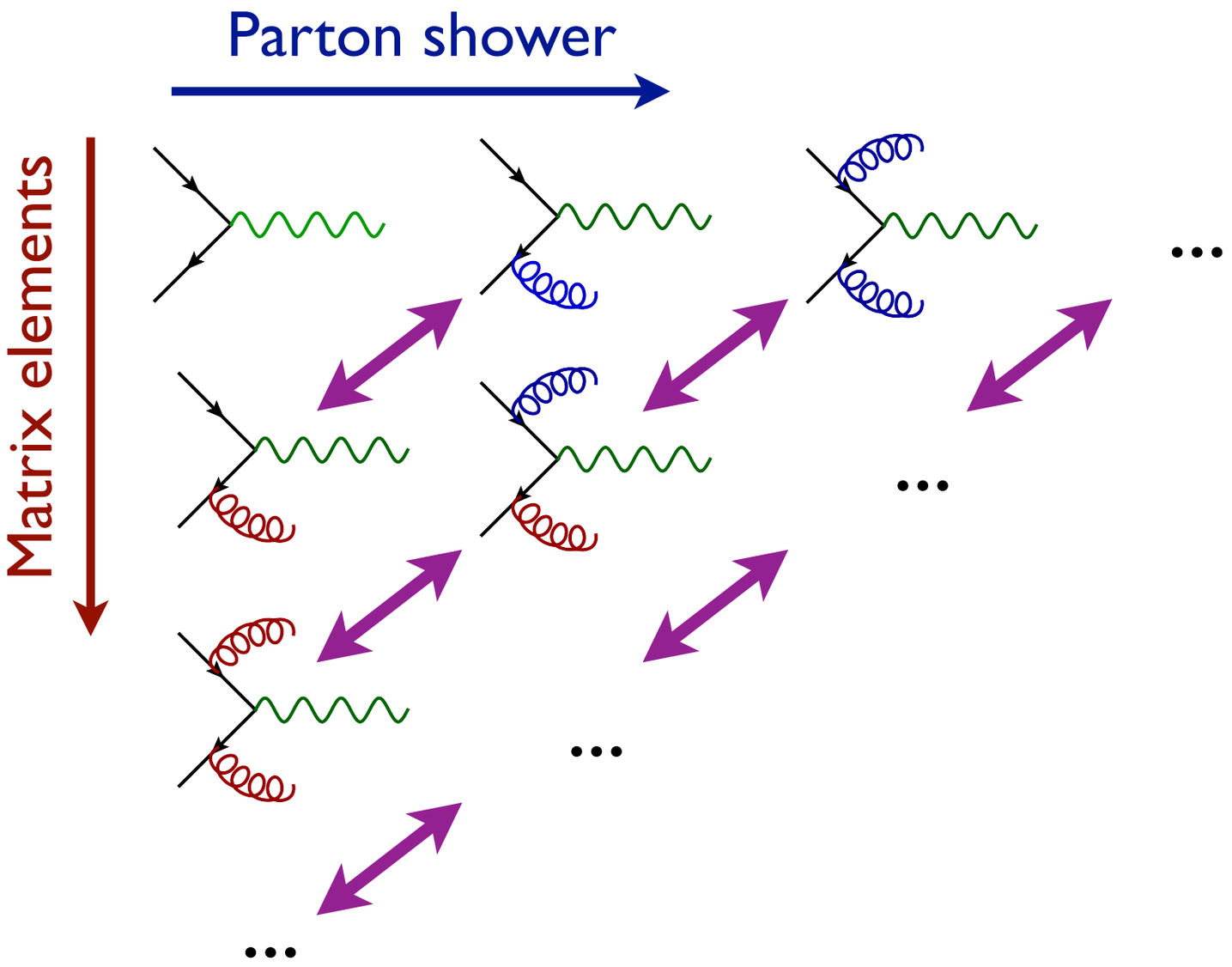

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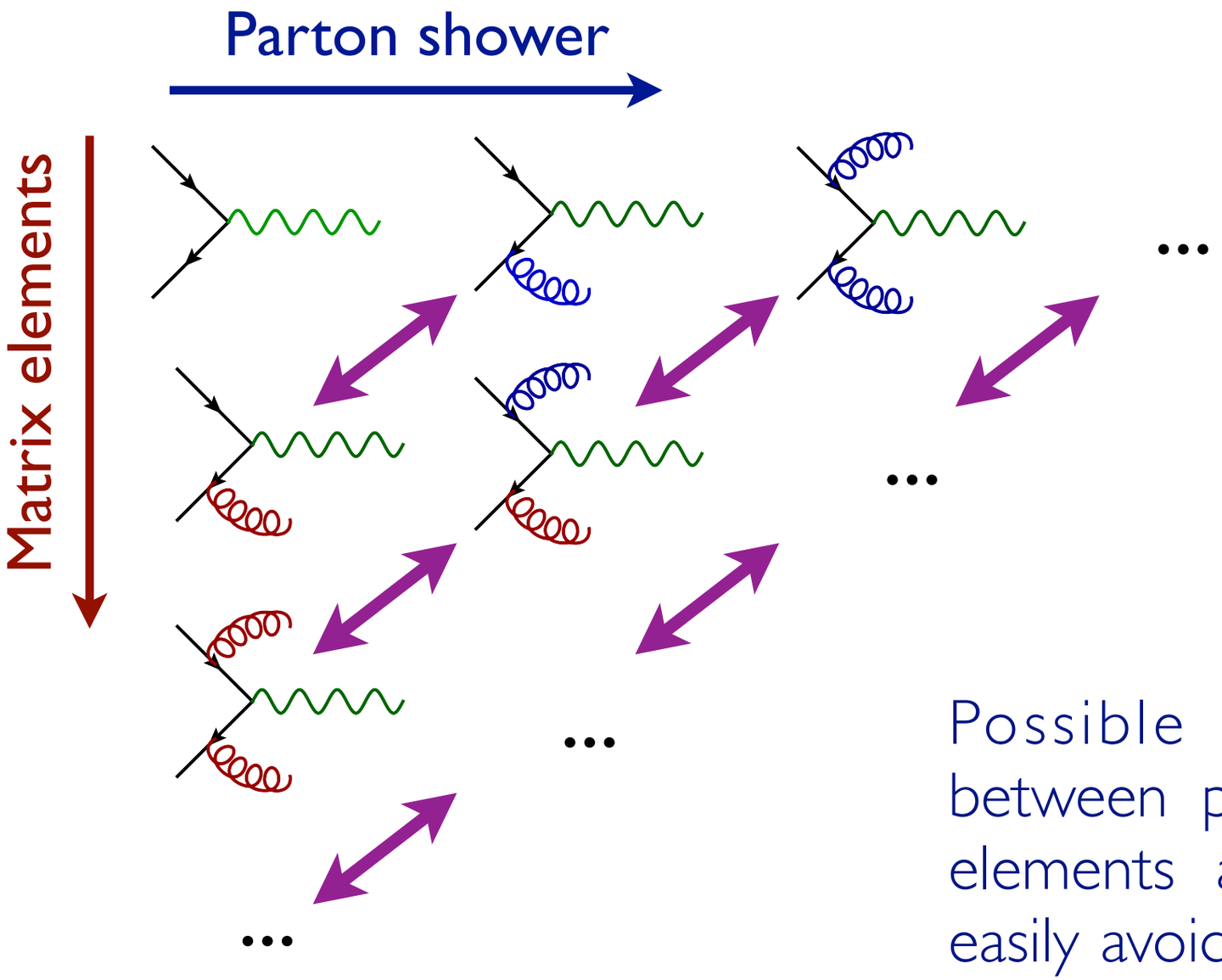

Possible double counting between partons from matrix elements and parton shower easily avoided by applying a cut in phase space

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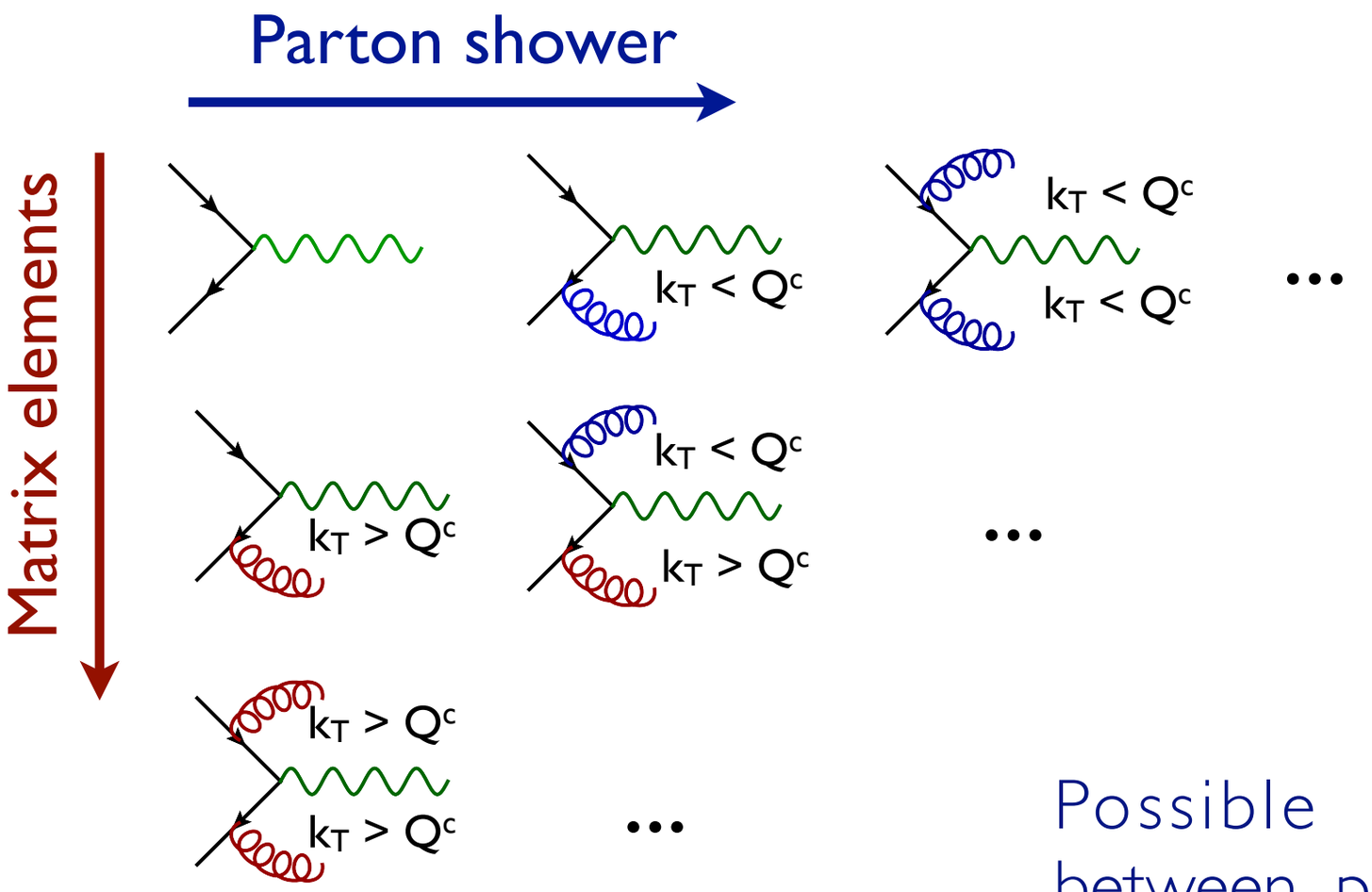

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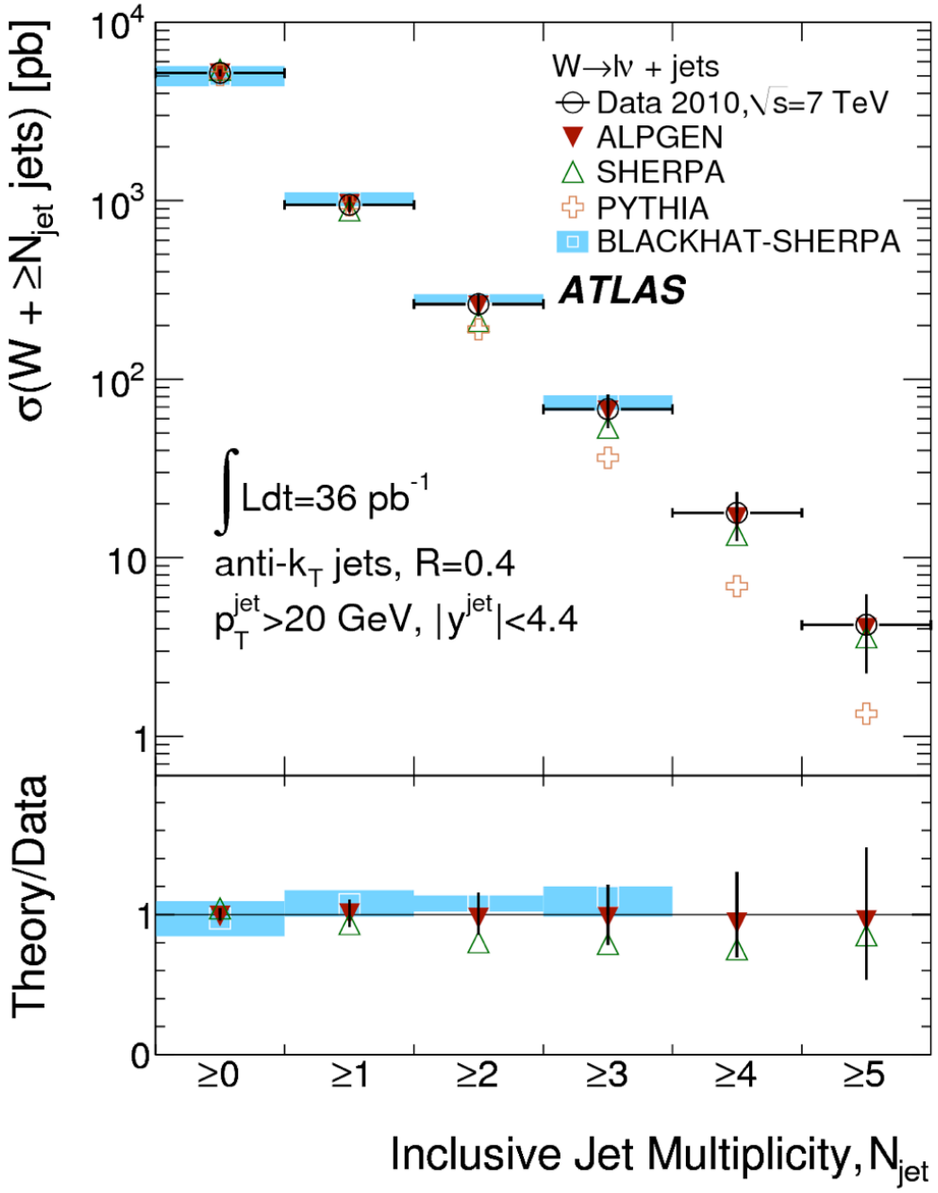
V+JETS AT THE LHC



Working amazingly well!

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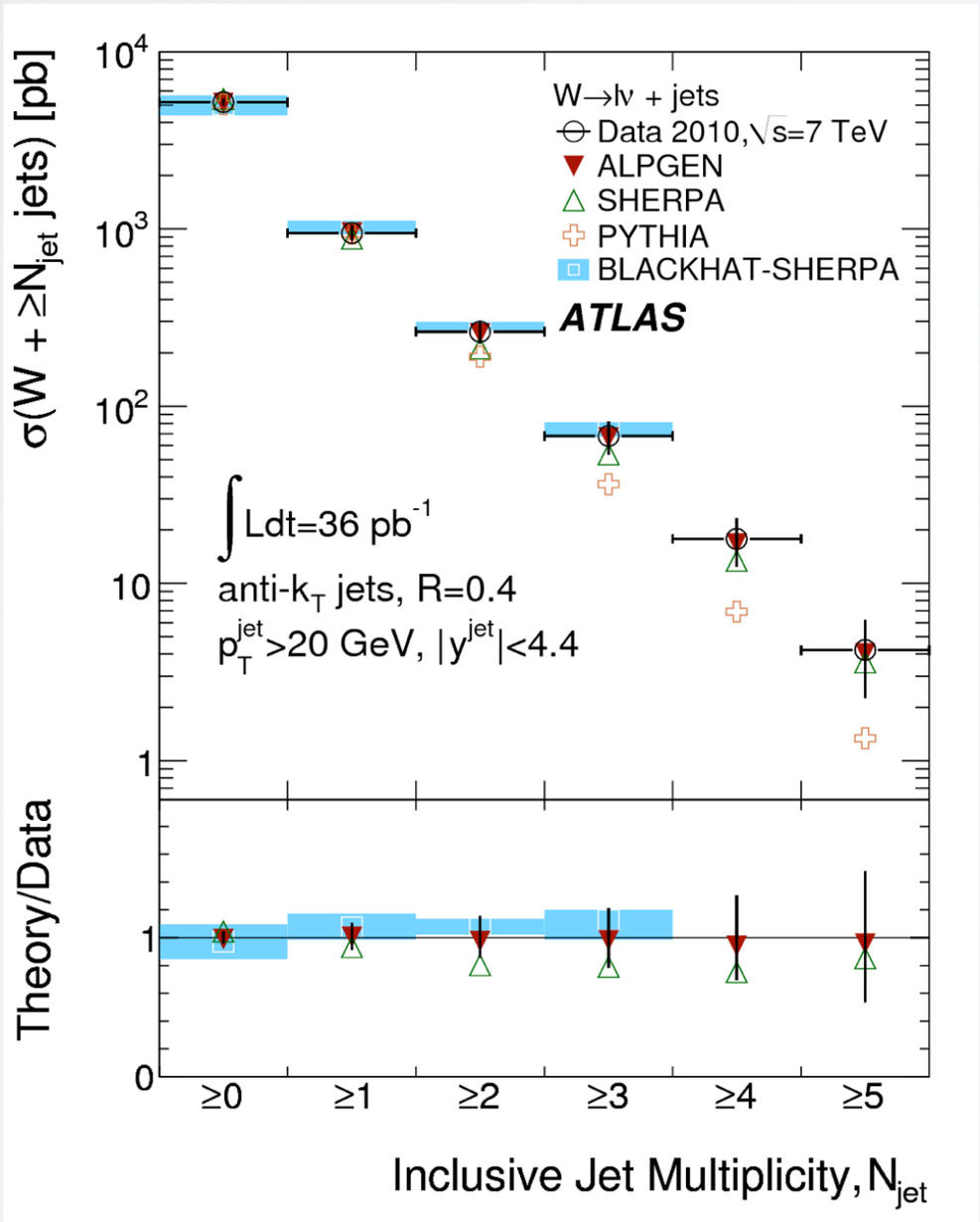

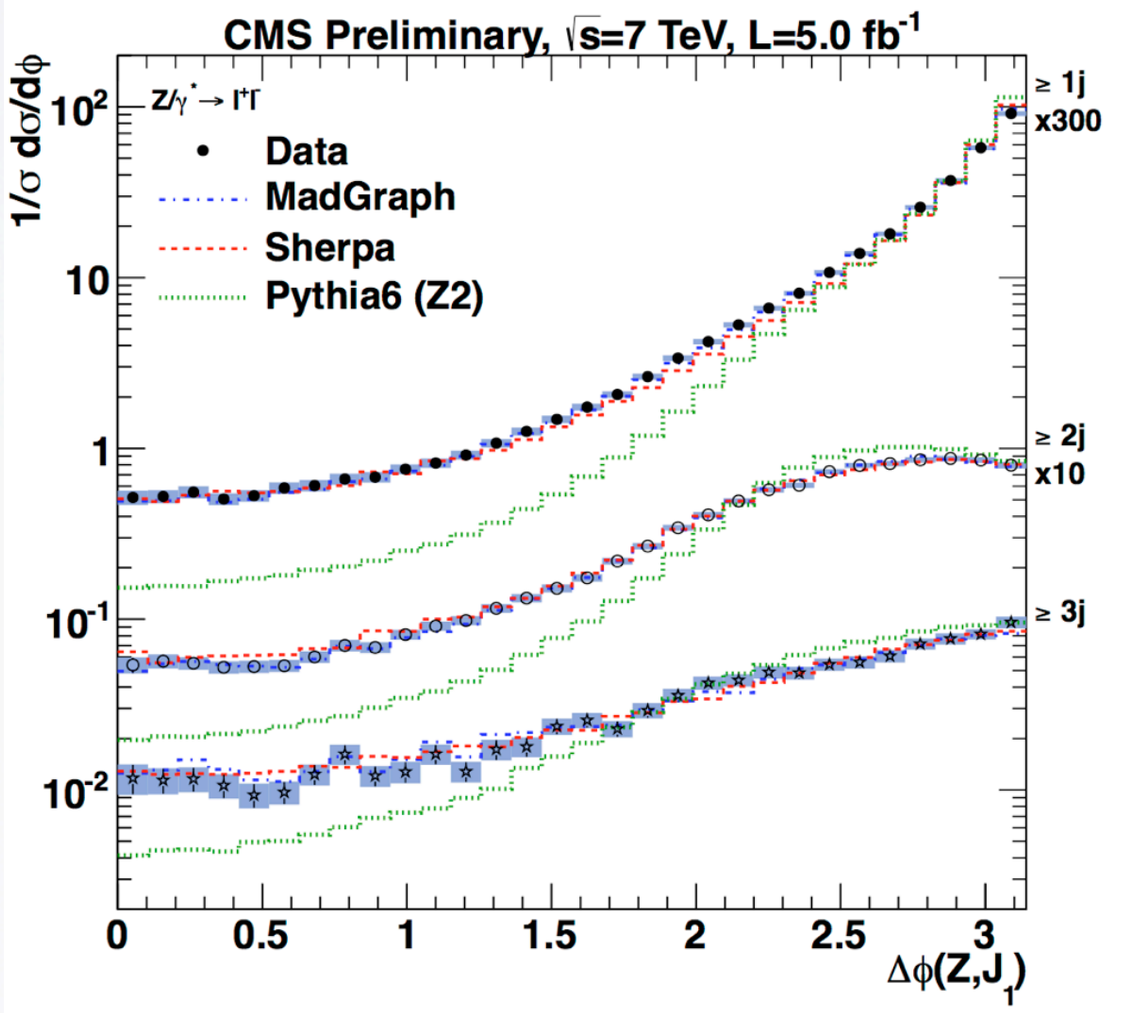

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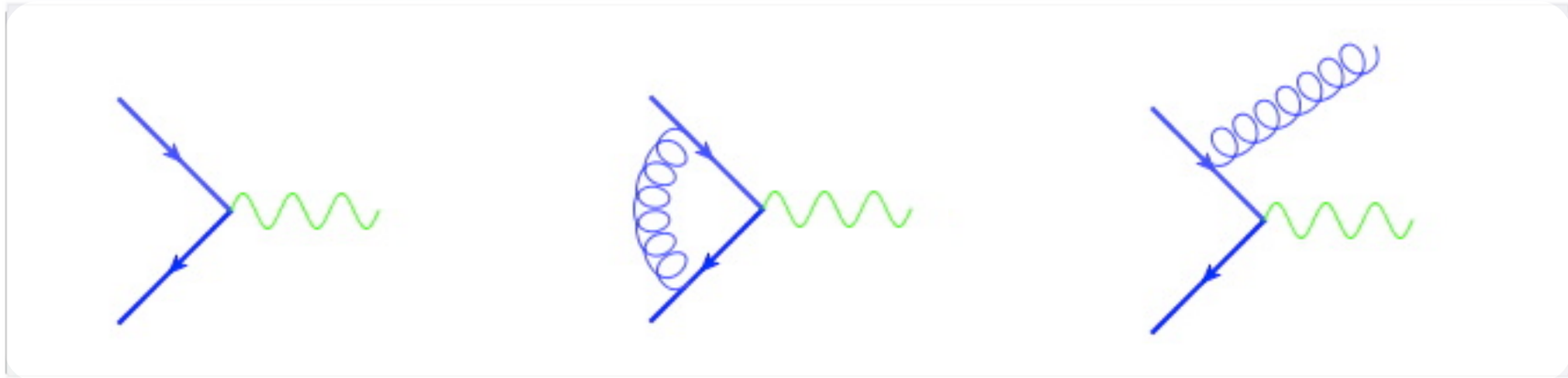
WHAT ABOUT NLO?



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

This simple approach does not work:

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

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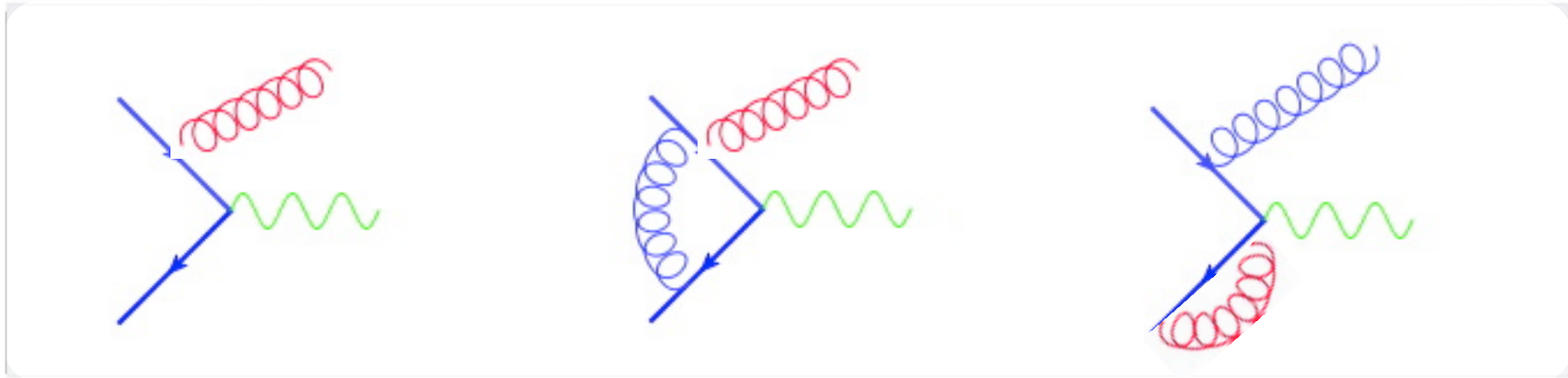

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NLO+PS IN A NUTSHELL

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

integrates to 1 (unitarity)

with

$$\bar{B}^s = B(\Phi_B) + \left[V(\Phi_B) + \int \mathrm{d}\Phi_{R|B} R^s(\Phi_{R|B}) \right]$$

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: $R^{\mathrm{s}}(\Phi) = P(\Phi_{R|B})\, B(\Phi_B)$

Needs exact mapping $(\Phi_B,\Phi_R) \rightarrow \Phi$

POWHEG: $R^{\mathrm{s}}(\Phi) = F R(\Phi)\,, R^{\mathrm{f}}(\Phi) = (1-F) R(\Phi)$

F=1 = Exponentiates the Real.
It can be damped by hand.

MC@NLO AND POWHEG

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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 and HERWIG
- Generates only* positive unit weights.

- Can use existing NLO results via the POWHEG-Box [Aioli, Nason, Oleari, Re et al. 2009]

AUTOMATION

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GENIUS: 1% INSPIRATION AND 99% PERSPIRATION.

[Thomas Edison]

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TRUE, BUT PERSPIRATION CAN BE AUTOMATED!

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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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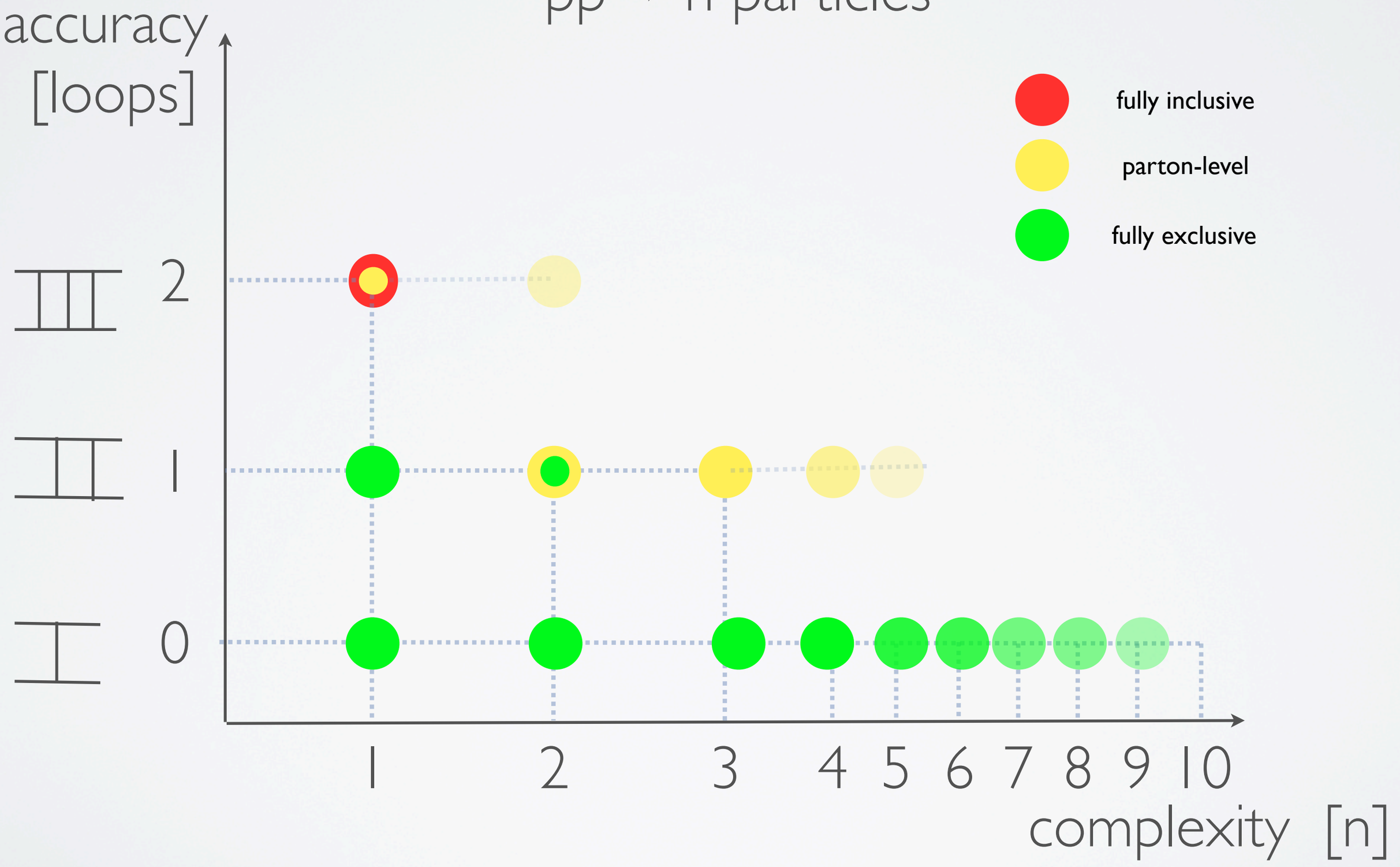
WIDE ACCESSIBILITY

One framework for all. Available to everybody for an unlimited set of applications for all. Augmented TH/EXP collaboration.

SM STATUS ANTE LHC

pp → n particles



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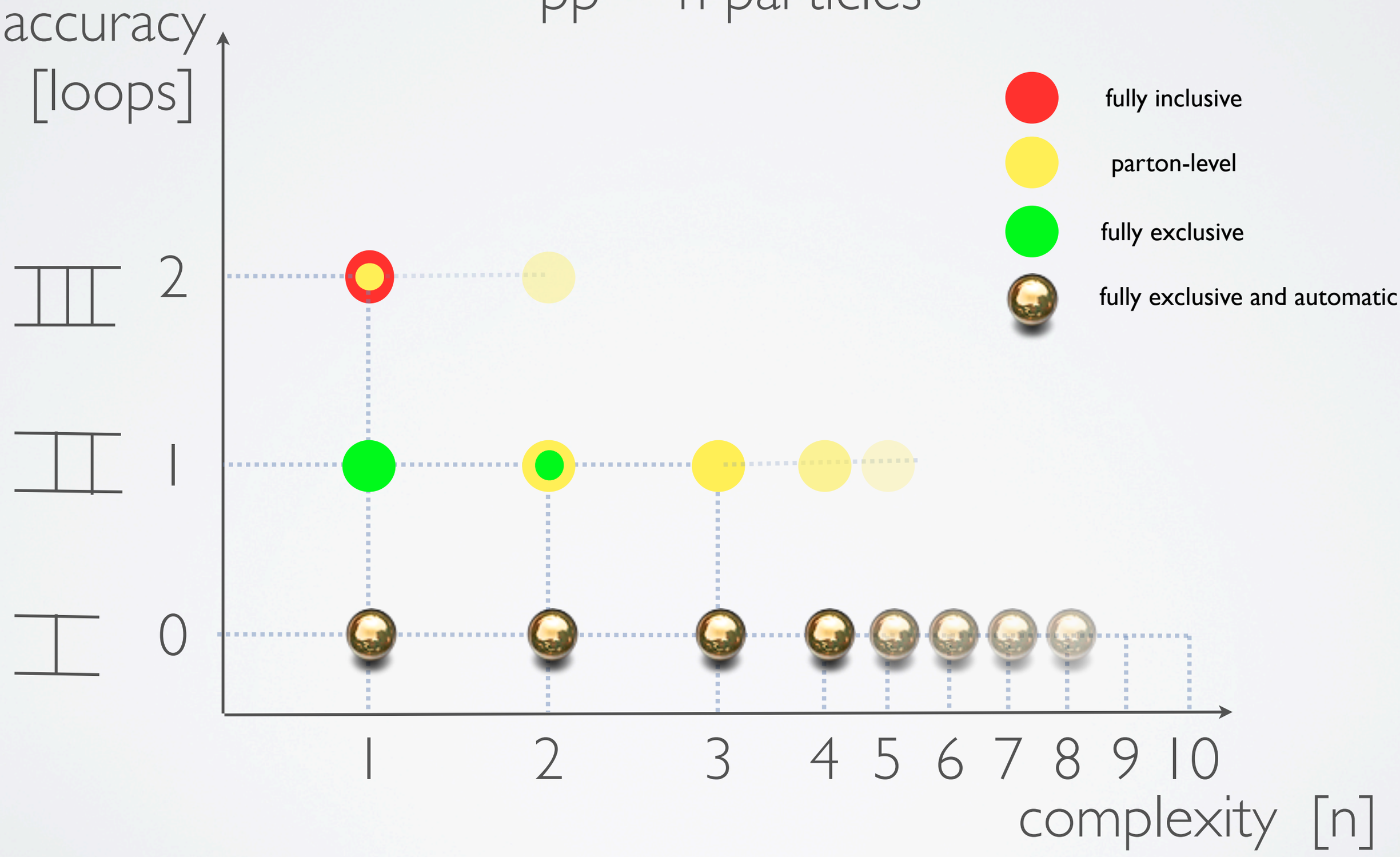
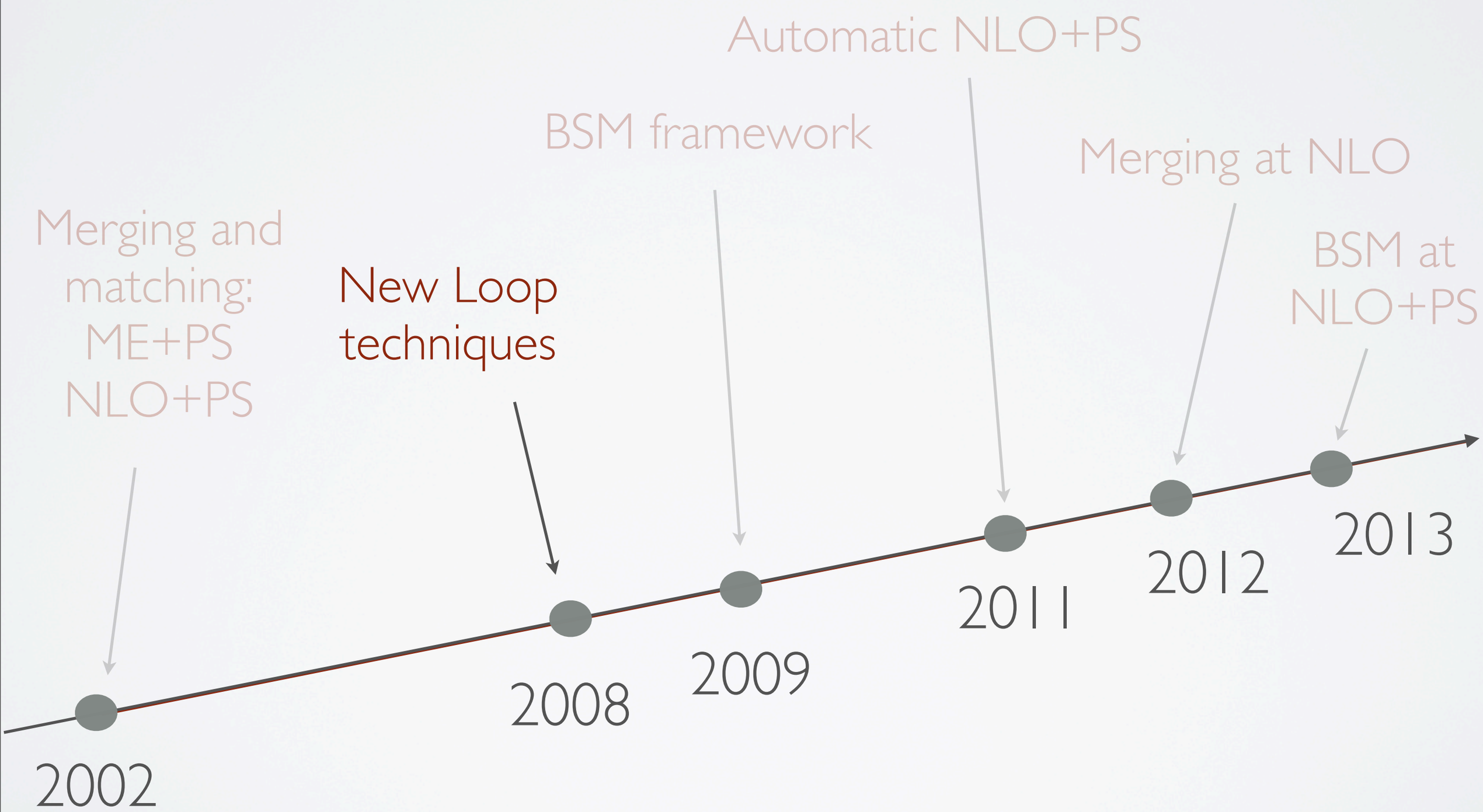


PREDICTIVE MC (SIMPLIFIED) PROGRESS



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, GoSam)

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

Predictions at NLO

modified by the speaker

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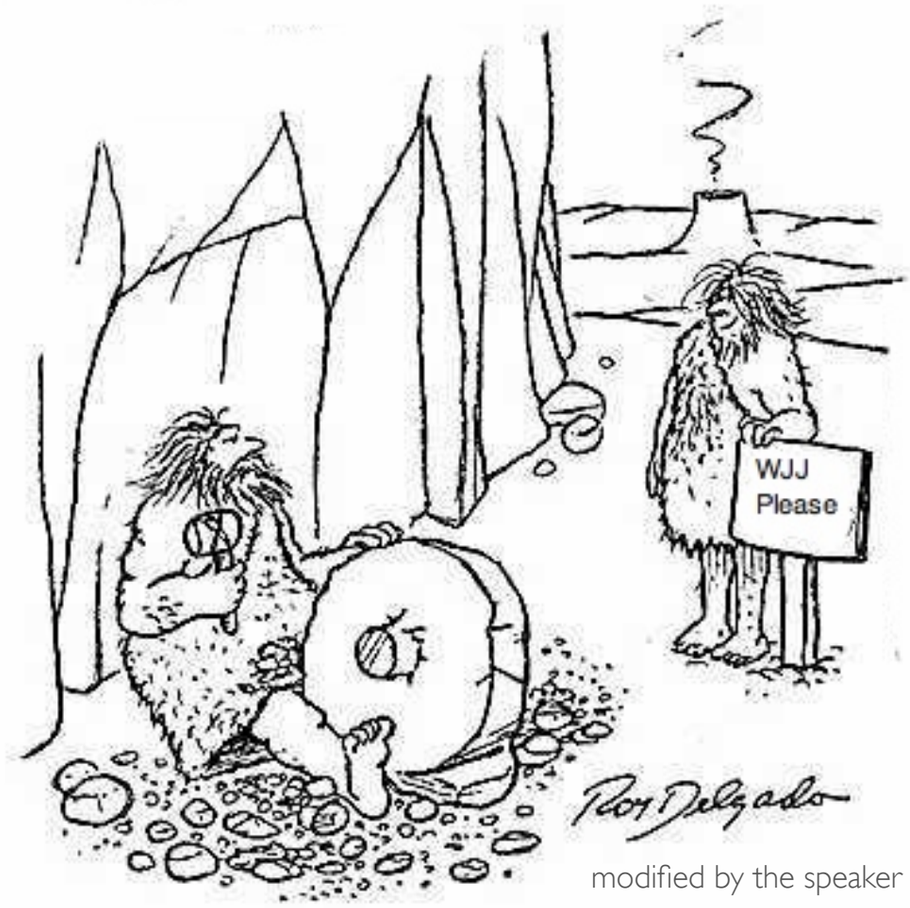

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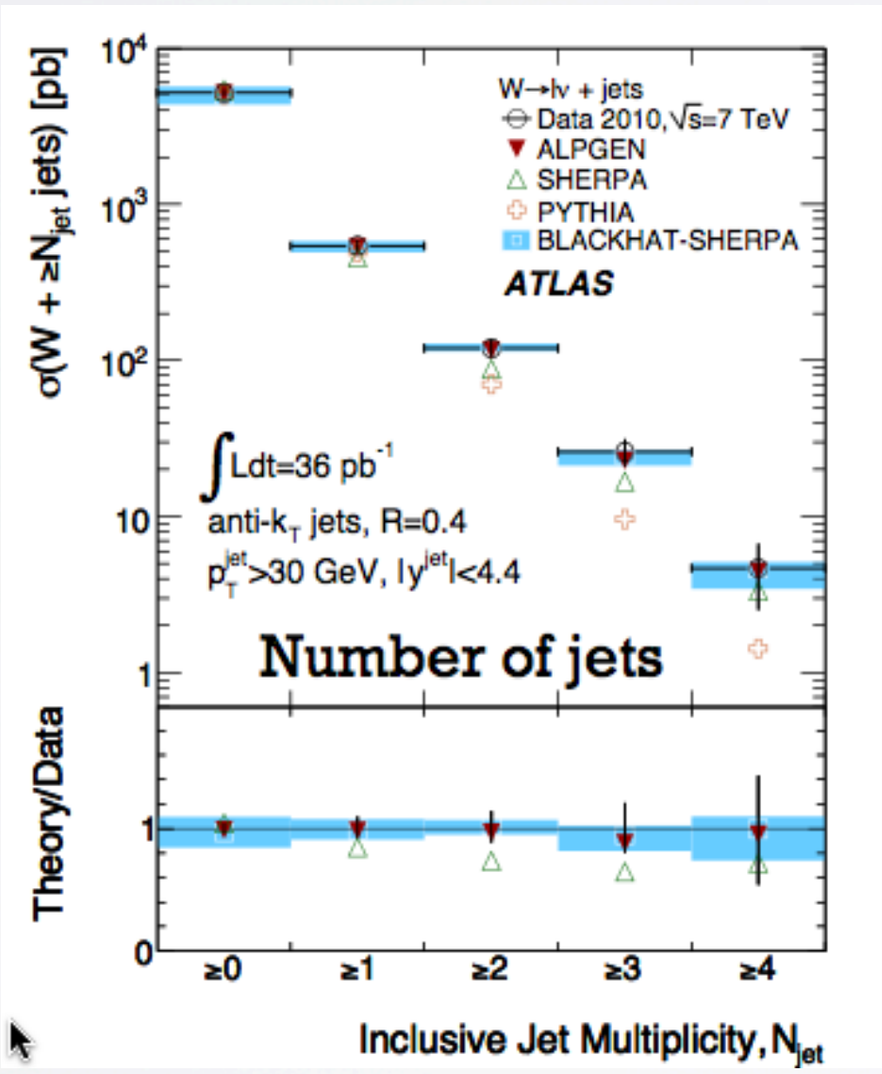
Thanks to new amazing results, some of them inspired by string theory developments, now the computation of loops has been extended to high-multiplicity processes or/and automated.

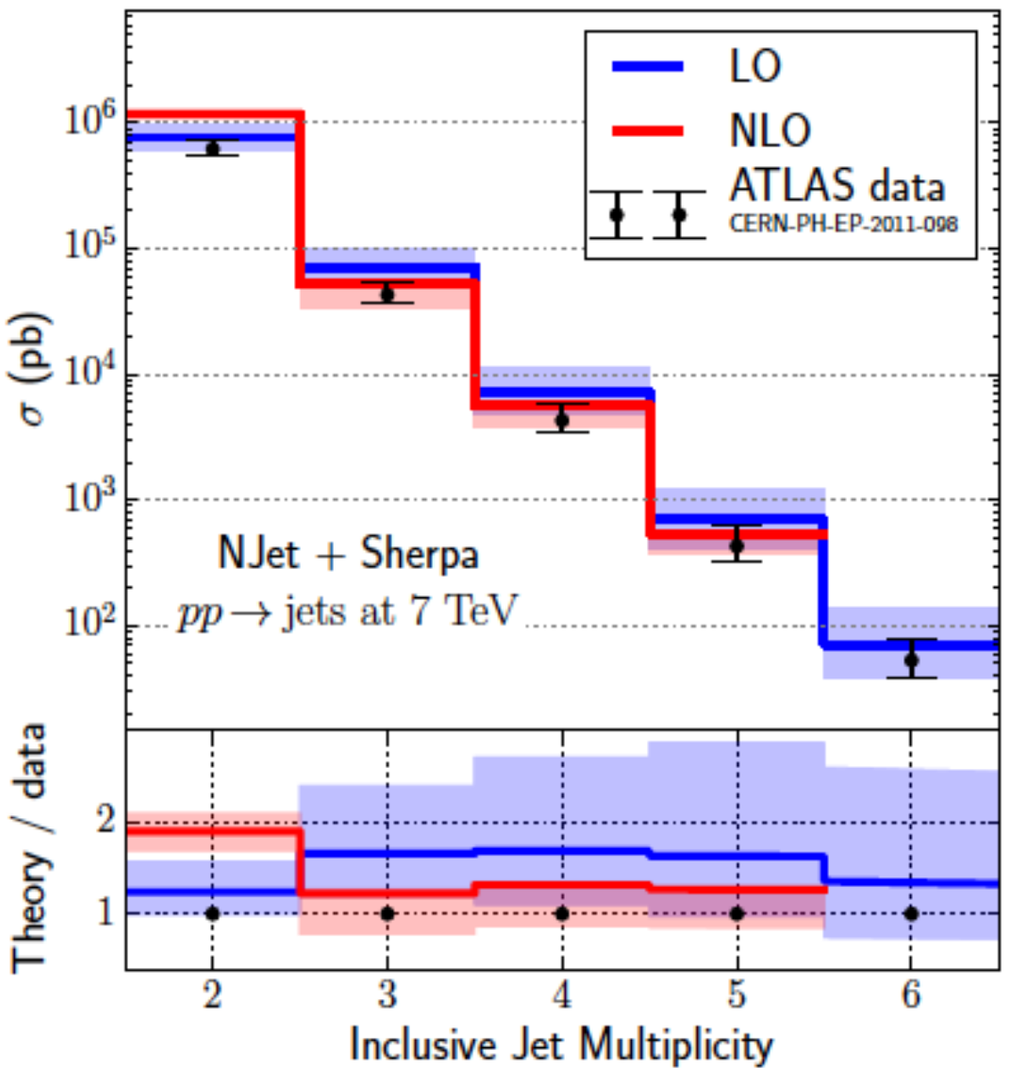
COMPARISON WITH DATA

W+5 jets



[Bern et al., 1304.1253]

5 jets



[Badger et al. 1309.6585]

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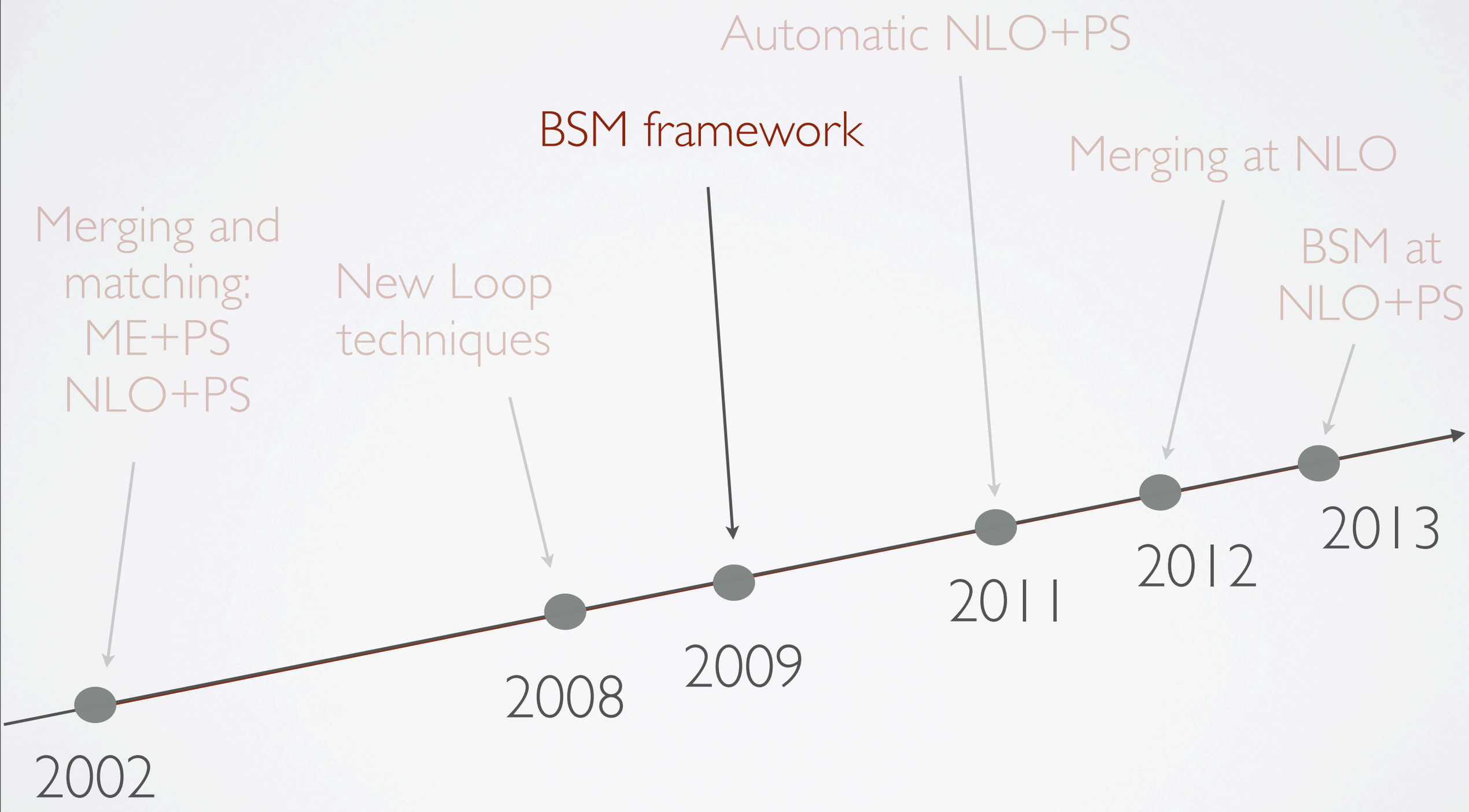

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- Physics and software validations streamlined
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

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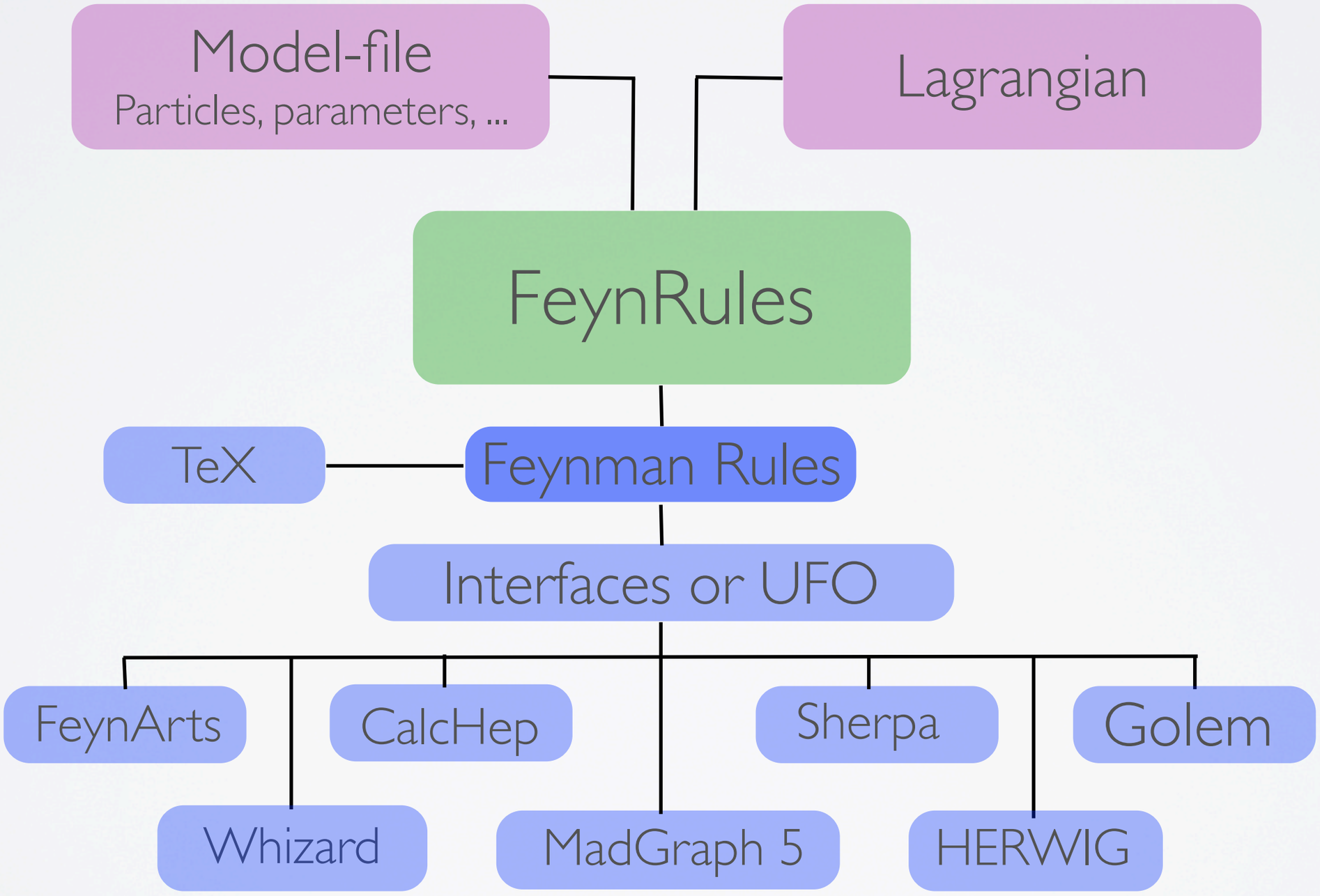
Complete automatization LO (and now NLO) calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics.

THE FEYNRULES PROJECT

[Alloul, Christensen, Degrande, Duhr, Fuks]



THE FEYNRULES PROJECT

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (18)	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models (5)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories (8)	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous (0)	

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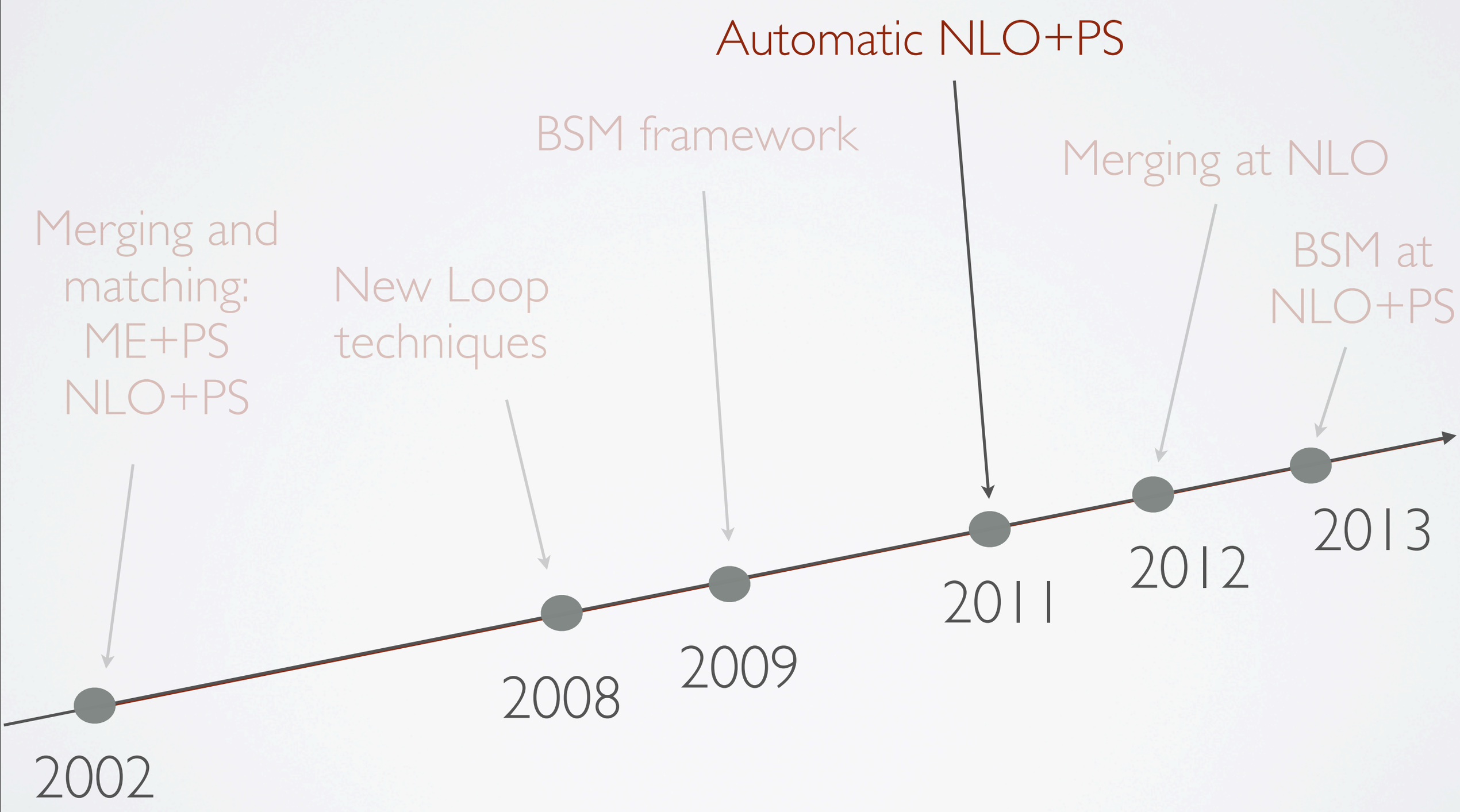
Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (18)	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models (5)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly theories	
Miscellan	

Model	Short Description	Contact	Status
Axigluon model	The SM plus a scalar gluon field.	S. Krastanov	**Available**
DY SM extension	The SM plus new spin-0, -1, and -2 bosons that contribute to Drell-Yan production of leptons at the LHC.	N. Christensen	**Available**
FCNC Higgs interactions	The SM plus higher-dimensional flavor changing Higgs interactions.	S. Krastanov	**Available**
Fourth generation model	A fourth generation model including a t' and a b'	C. Duhr	**Available**
General 2HDM	The most general 2HDM, including all flavor violation and mixing terms.	C. Duhr, M. Herquet	**Available**
Hidden Abelian Higgs Model	A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings.	C. Duhr	**Available**
HiggsCharacterisation	The model file for the spin/parity characterisation of a 125 GeV resonance.	P. de Aquino, K. Mawatari	**Available**
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	**Available**
Higgs Effective Lagrangian	Higgs effective Lagrangian including operators up-to dimension 6.	A. Alloul, B. Fuks and V. Sanz	**Available**
Hill Model	A model with an unusual extension of the SM Higgs sector.	P. de Aquino, C. Duhr	**Available**
Inert Doublet Model	A model with an additional complex scalar SU(2)L doublet and an unbroken Z2 symmetry under which all SM particles are even while the extra doublet is odd.	A. Goudelis, B. Herrmann, O. Stal	**Available**
Minimal Zp models	The minimal Z' extension of the SM.	L. Basso	**Available**
Monotops	The SM plus monotop effective Lagrangian.	B. Fuks	**Available**
Sextet diquarks	The SM plus sextet diquark scalars.	J. Alwall, C. Duhr	**Available**
Standard model + Scalars	The SM, together with a set of singlet scalar particles coupling only to the SM Higgs, and allowing it to decay invisibly into this new scalar sector.	C. Duhr	**Available**
Triplet diquarks	The SM plus triplet diquark scalars.	J. Alwall, C. Duhr	**Available**

PREDICTIVE MC (SIMPLIFIED) PROGRESS



NEW CODES FOR AUTOMATIC LOOP AMPLITUDES

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

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

NEW NLO+PS FRAMEWORKS

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

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

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

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

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

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

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

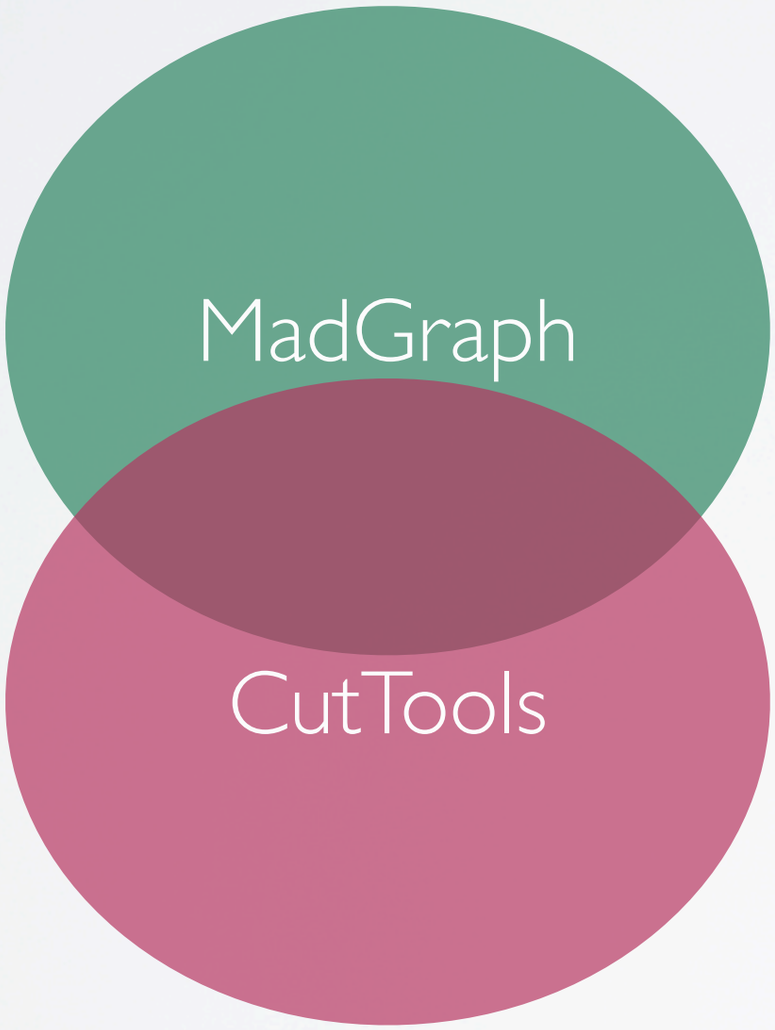
  HELAC-NLO + POWHEG-Box

THE aMC@NLO JOINT VENTURE

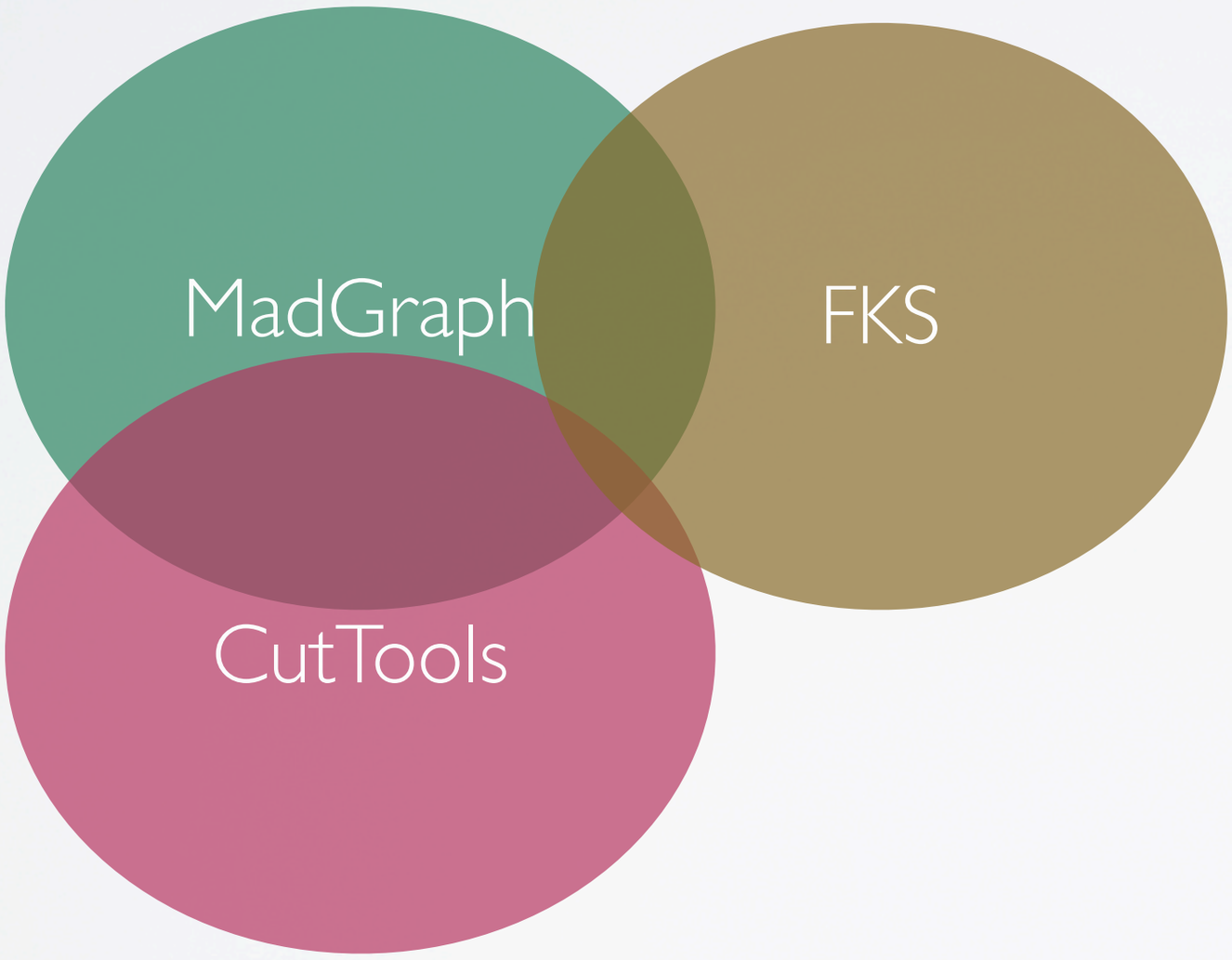
THE aMC@NLO JOINT VENTURE

MadGraph

THE aMC@NLO JOINT VENTURE



THE aMC@NLO JOINT VENTURE



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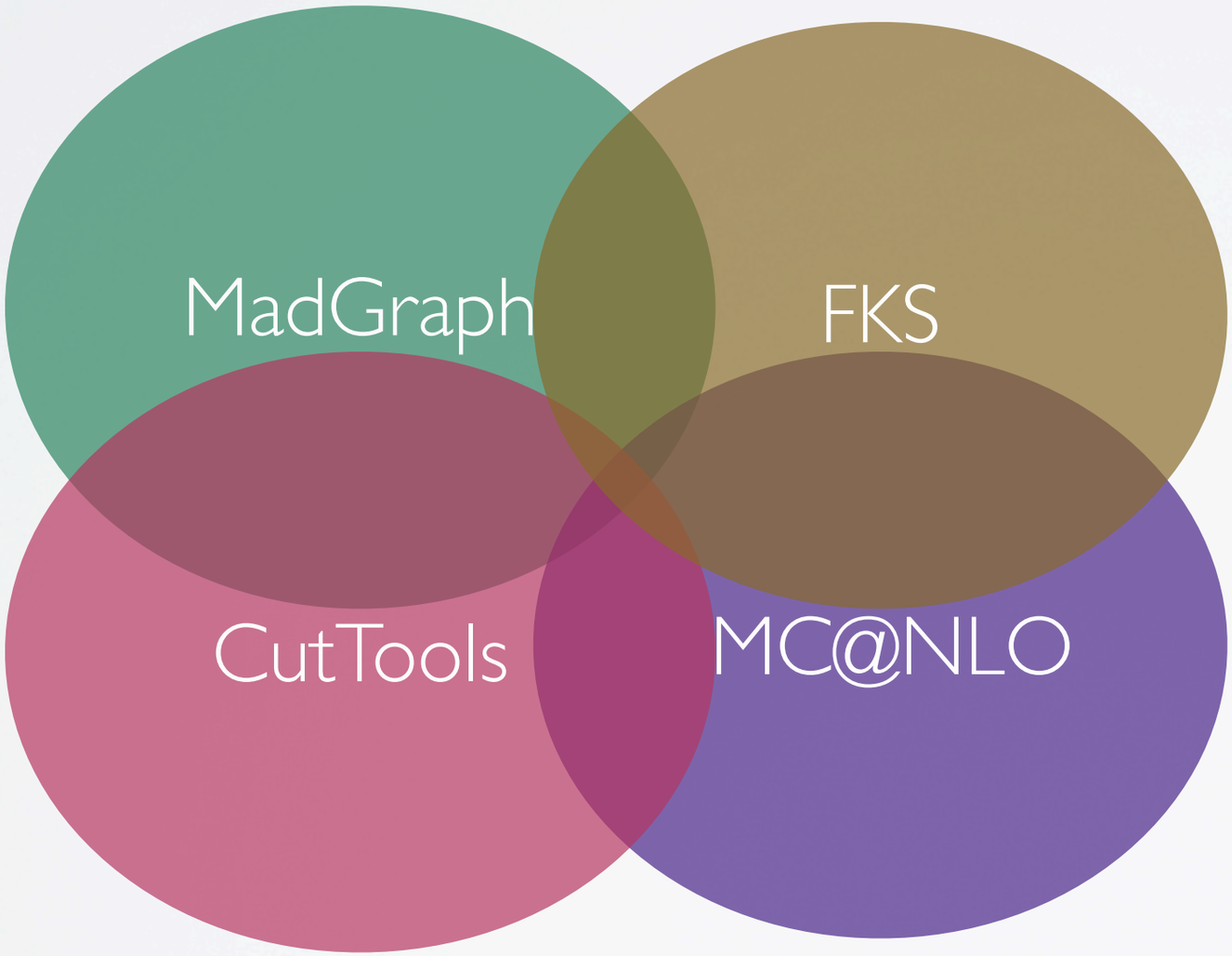

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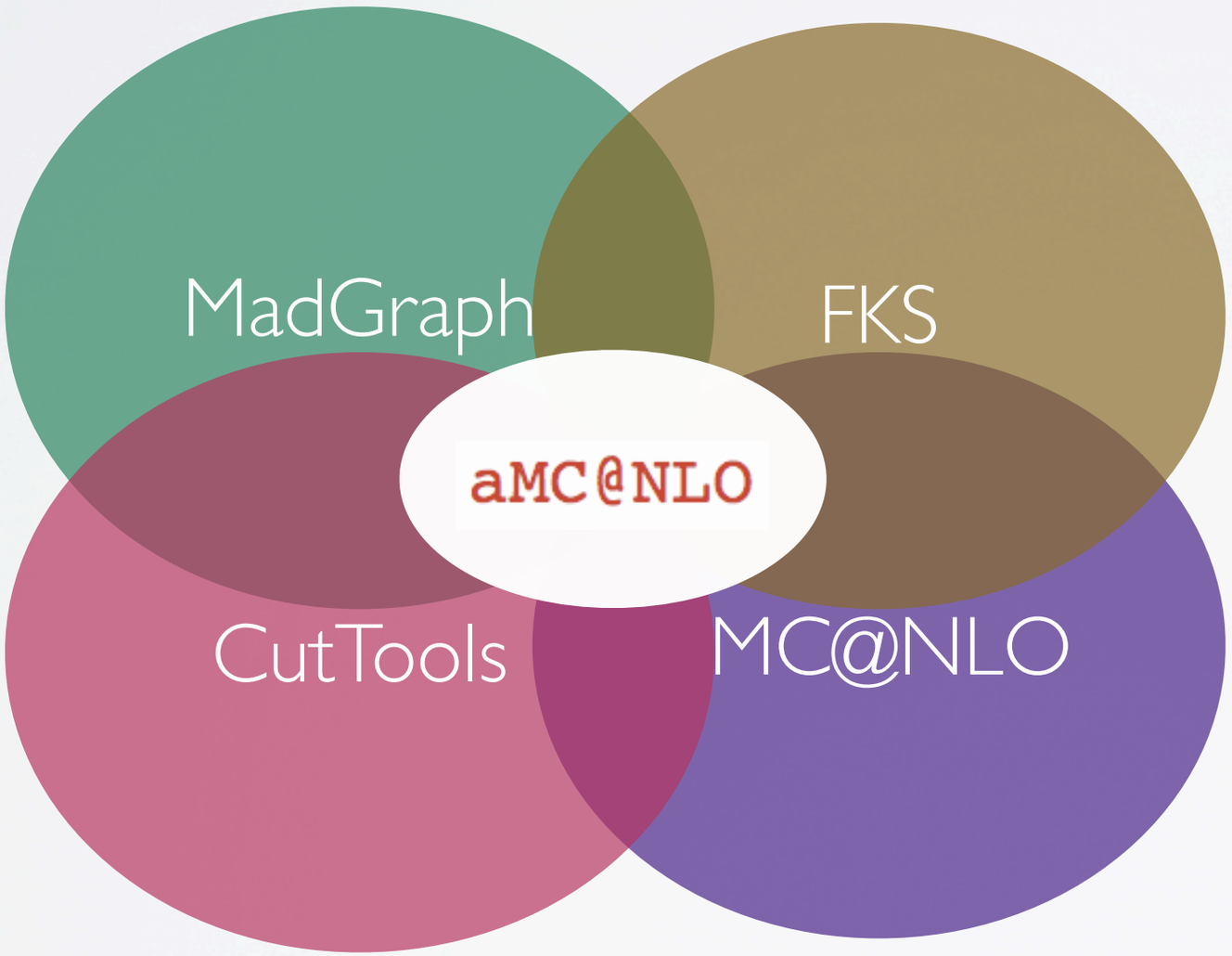
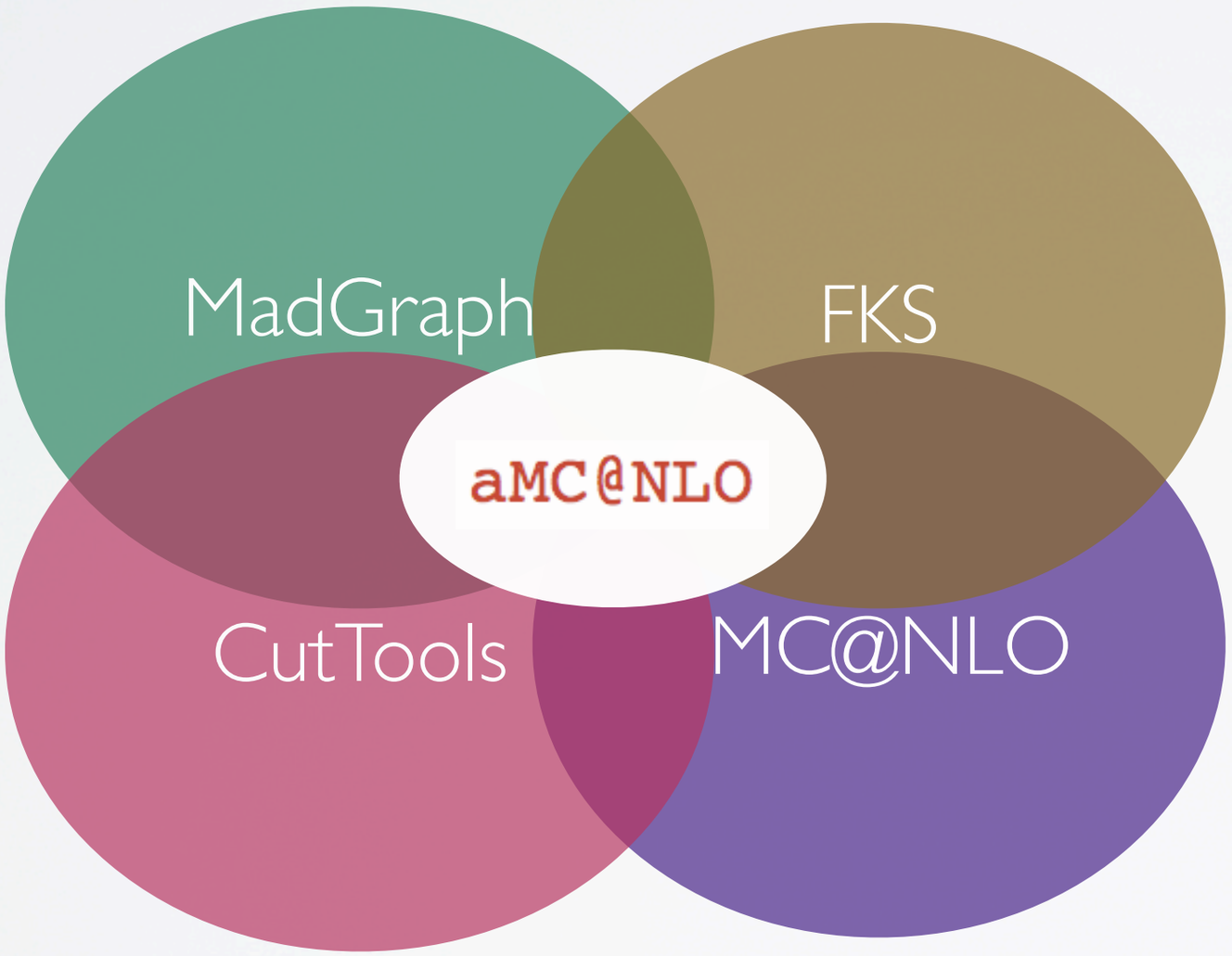


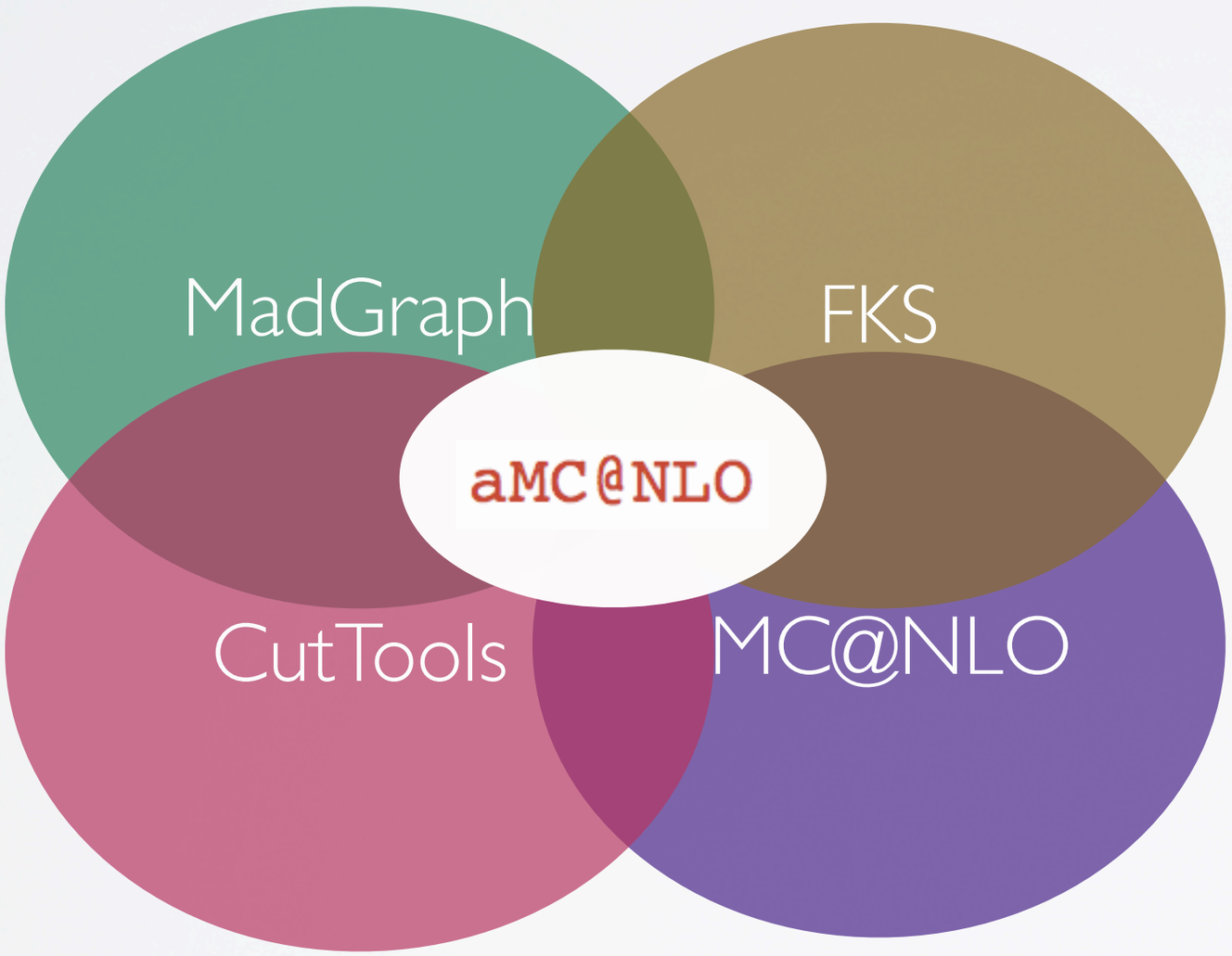
THE aMC@NLO JOINT VENTURE



Modular structure:

- MadLoop or External Tool (via Binoth LH accord)
- MadFKS
- MC@NLO counterterms
- Interfaced to Herwig++ and Pythia8

THE aMC@NLO JOINT VENTURE



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http://amcatnlo.cern.ch

AUTOMATIC NLO+PS IN 2011

[Hirshi, Frederix, Frixione, FM, Torrielli,].

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

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

AUTOMATIC MC'S AT NLO

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

```
./bin/mg5
> define Wpm = W+ W-
> generate p p > t t~ Wpm [QCD]
> output ttw
> launch
```

or

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

where heavy states can also be decayed keeping spin correlations.

AUTOMATIC NLO IN SM (2013)

- ~15 NLO publications since 2011
- Public release of aMC@NLO (beta) 8 Nov 2012
- Improved functionalities (OpenLoops method, automatic uncertainties, Pythia8 interface, speed-up)
- Running/validating now a wide range of **sample** SM processes:

Process	Vector boson +jets
a.1	$pp \to W^{\pm}$
a.2	$pp \to W^{\pm} j$
a.3	$pp \to W^{\pm} jj$
a.4	$pp \to Z$
a.5	$pp \to Z j$
a.6	$pp \to Z jj$
a.7	$pp \to \gamma j$
a.8	$pp \to \gamma jj$

Process	Vector boson pair +jets
b.1	$pp \to W^+W^-$
b.2	$pp \to ZZ$
b.3	$pp \to ZW^{\pm}$
b.4	$pp \to \gamma\gamma$
b.5	$pp \to \gamma Z$
b.6	$pp \to \gamma W^{\pm}$
b.7	$pp \to W^+W^- j$
b.8	$pp \to ZZ j$
b.9	$pp \to ZW^{\pm} j$
b.10	$pp \to \gamma\gamma j$
b.11	$pp \to \gamma Z j$
b.12	$pp \to \gamma W^{\pm} j$
b.13	$pp \to W^+W^- jj$
b.14	$pp \to W^+W^+ jj$
b.15	$pp \to ZZ jj$
b.16	$pp \to ZW^{\pm} jj$
b.17	$pp \to \gamma\gamma jj$
b.18	$pp \to \gamma Z jj$
b.19	$pp \to \gamma W^{\pm} jj$

Process	Multi Vector boson production
c.1	$pp \to W^{\pm}W^{\pm}W^{\mp}$
c.2	$pp \to ZW^-W^+$
c.3	$pp \to ZZW^{\pm}$
c.4	$pp \to ZZZ$
c.5	$pp \to \gamma W^-W^+$
c.6	$pp \to \gamma\gamma W^{\pm}$
c.7	$pp \to \gamma ZW^{\pm}$
c.8	$pp \to \gamma ZZ$
c.9	$pp \to \gamma\gamma Z$
c.10	$pp \to \gamma\gamma\gamma$
c.11	$pp \to W^{\pm}W^{\pm}W^{\mp}W^{\mp}$

Process	heavy quarks and jets
d.1	$pp \to jj$
d.2*	$pp \to jjj$
d.3	$pp \to b\bar{b}$
d.4	$pp \to b\bar{b}j$
d.5*	$pp \to b\bar{b}jj$
d.6	$pp \to b\bar{b}b\bar{b}$
d.7	$pp \to t\bar{t}$
d.8	$pp \to t\bar{t}j$
d.9*	$pp \to t\bar{t}jj$
d.10	$pp \to t\bar{t}t\bar{t}$
d.11	$pp \to t\bar{t}b\bar{b}$
d.12	$pp \to t\bar{b}$
d.13	$pp \to t\bar{b}j$
d.14	$pp \to t\bar{b}jj$

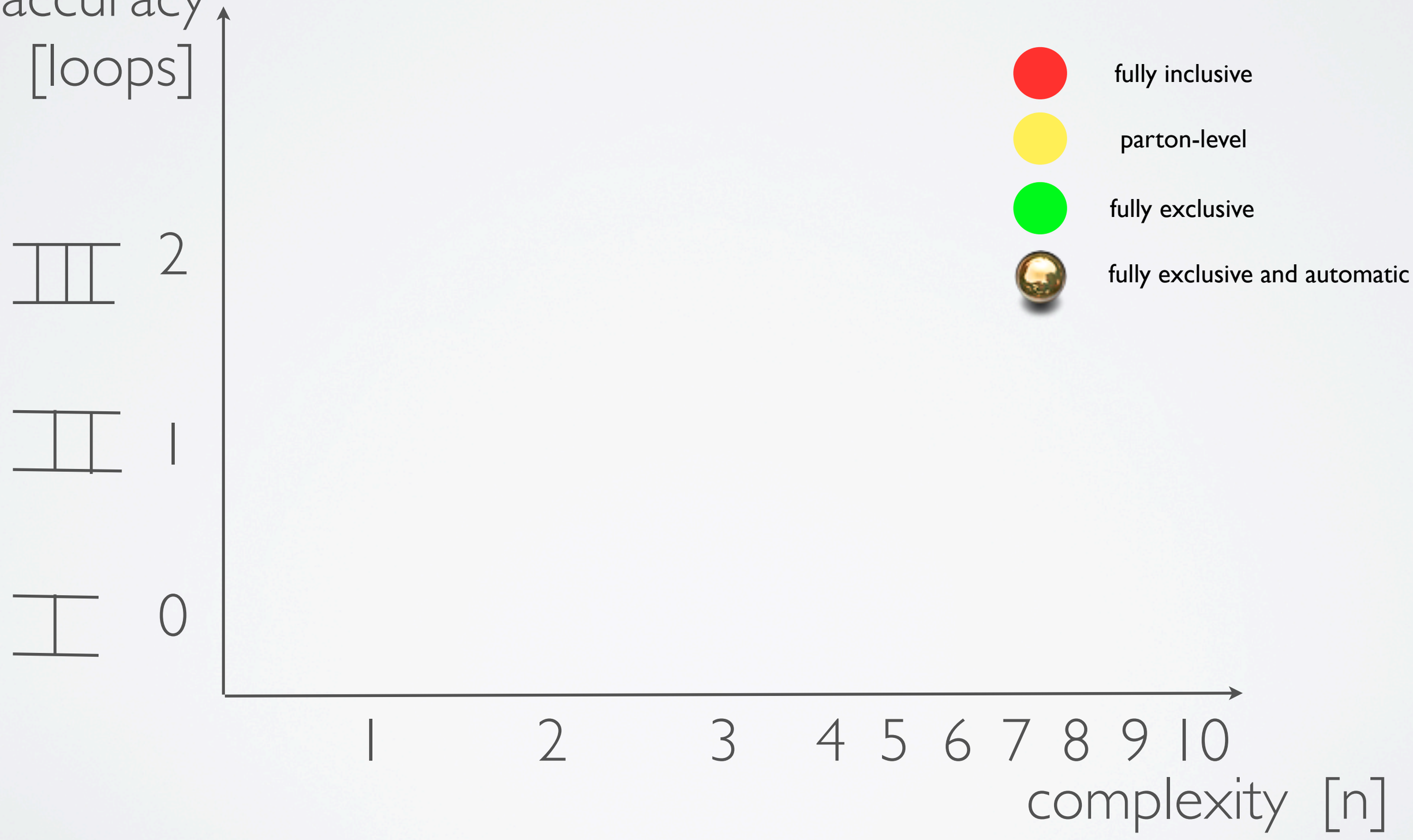
Process	Heavy quarks + vector bosons
e.1	$pp \to W^{\pm} b\bar{b}$
e.2	$pp \to Z b\bar{b}$
e.3	$pp \to \gamma b\bar{b}$
e.4	$pp \to W^{\pm} b\bar{b} j$
e.5*	$pp \to Z b\bar{b} j$
e.6*	$pp \to \gamma b\bar{b} j$
e.7	$pp \to t\bar{t} W^{\pm}$
e.8	$pp \to t\bar{t} Z$
e.9	$pp \to t\bar{t}\gamma$
e.10	$pp \to t\bar{t} W^{\pm} j$
e.11*	$pp \to t\bar{t} Zj$
e.12*	$pp \to t\bar{t}\gamma j$
e.13	$pp \to t\bar{t} W^-W^+$
e.14	$pp \to t\bar{t} W^{\pm} Z$
e.15	$pp \to t\bar{t} W^{\pm}\gamma$
e.16*	$pp \to t\bar{t} ZZ$
e.17*	$pp \to t\bar{t} Z\gamma$
e.18*	$pp \to t\bar{t}\gamma\gamma$

Process	Higgs production
f.1	$pp \to H$ (HEFT)
f.2	$pp \to Hj$ (HEFT)
f.3	$pp \to Hjj$ (HEFT)
f.4	$pp \to Hjj$ (VBF)
f.5	$pp \to Hjjj$ (VBF)
f.6	$pp \to HW^{\pm}$
f.7	$pp \to HW^{\pm} j$
f.8	$pp \to HW^{\pm} jj$
f.12	$pp \to HZ$
f.13	$pp \to HZ j$
f.14	$pp \to HZ jj$
f.15	$pp \to Ht\bar{t}$
f.16	$pp \to Htbj$
f.17	$pp \to Hb\bar{b}$

Release of MadGraph5_aMC@NLO before the end of the year !

SM STATUS : YEAR 2011

pp → n particles



- fully inclusive
- parton-level
- fully exclusive
- fully exclusive and automatic

SM STATUS : YEAR 2011

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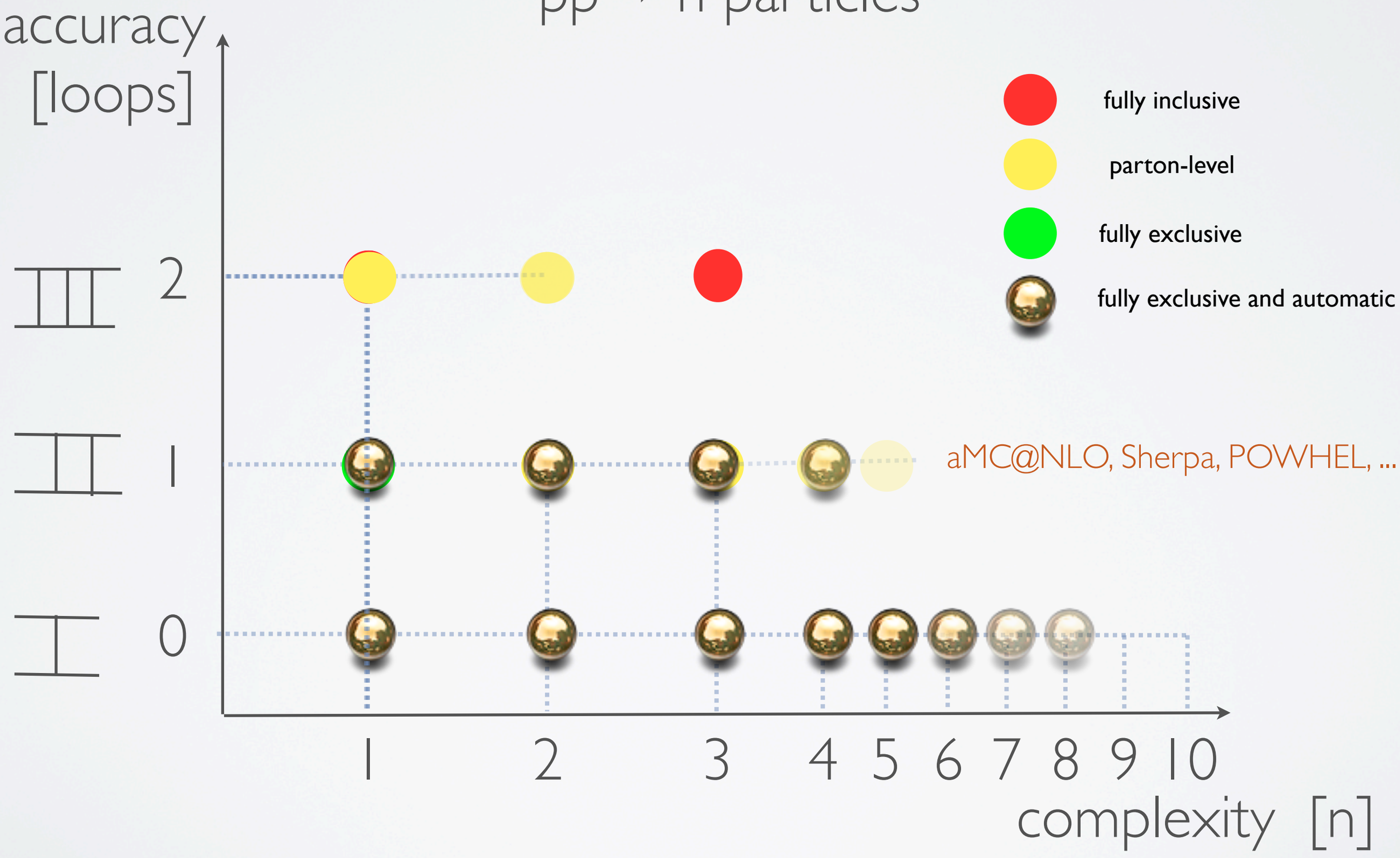


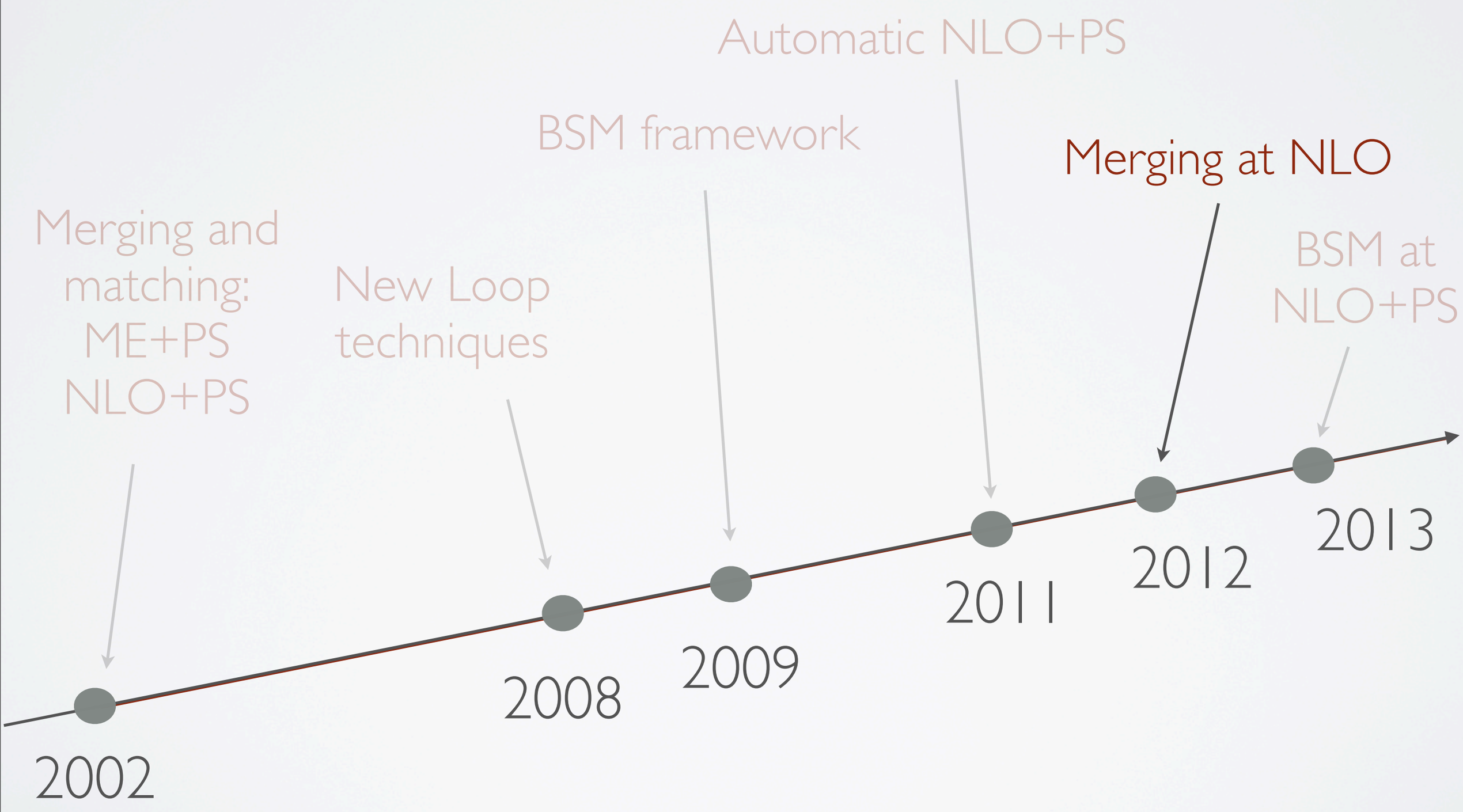
BOTTOM LINE

NNLO and NLO+PS stay to the LHC era

as

NLO and LO+PS stayed to the Tevatron era

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

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

FxFx approach (with MC@NLO) : Frederix and Frixione 1209.6215

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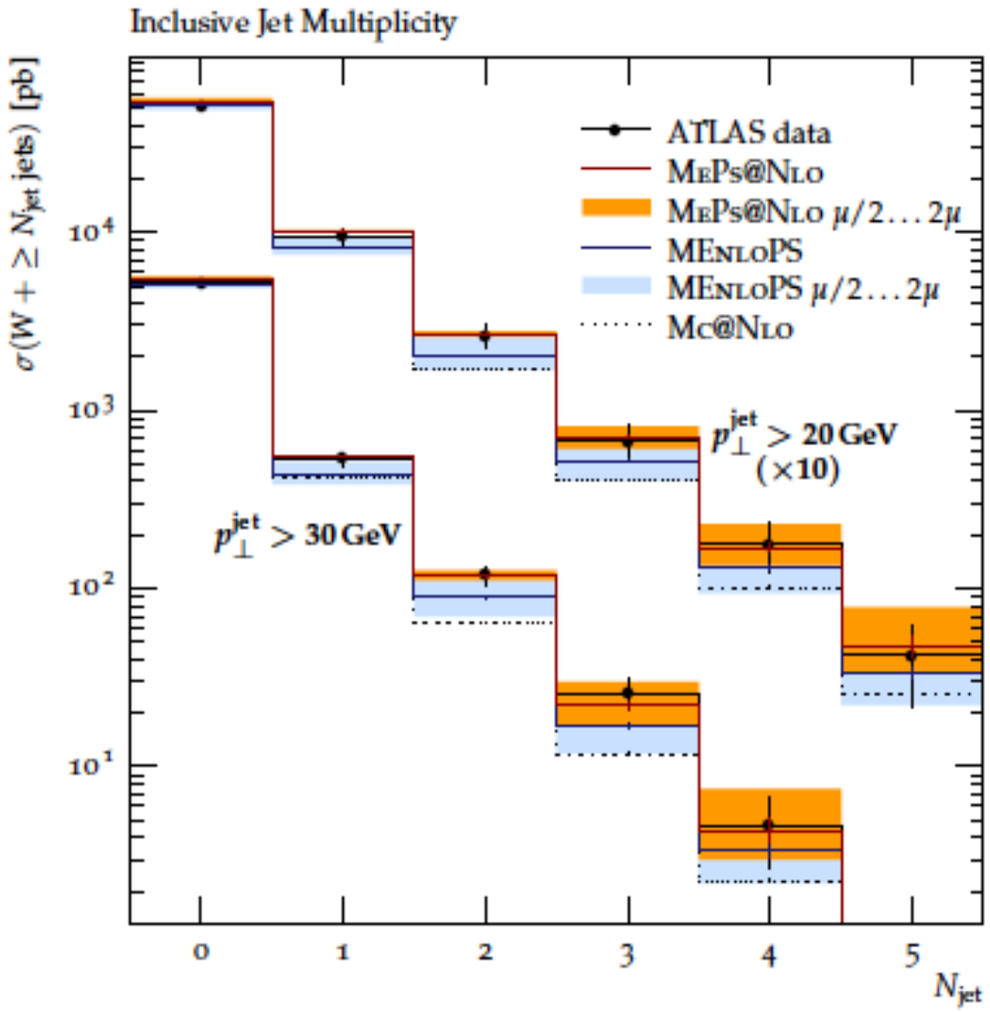
The wave function of the merging at NLO effort has collapsed in 2012

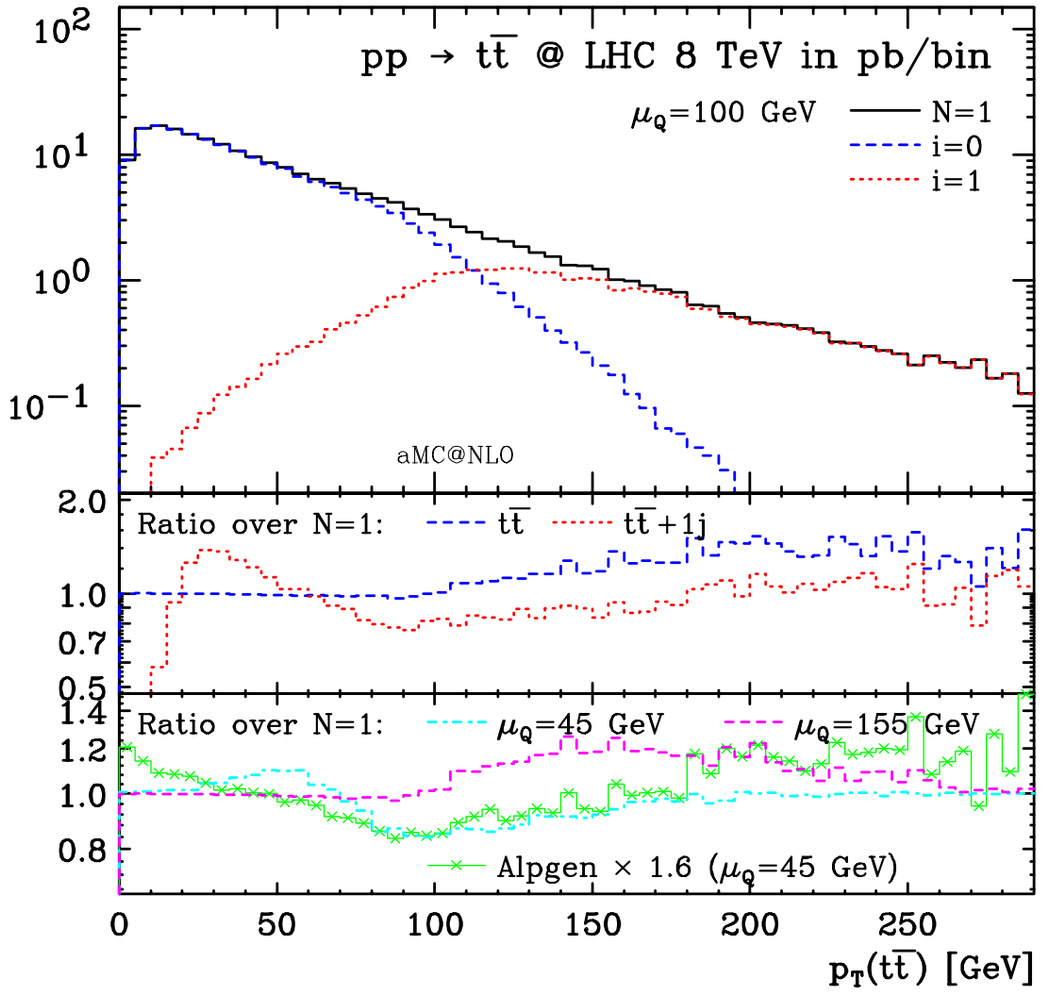
MULTI-JET MERGING @ NLO

[Hoeche et al., 1207.5030]



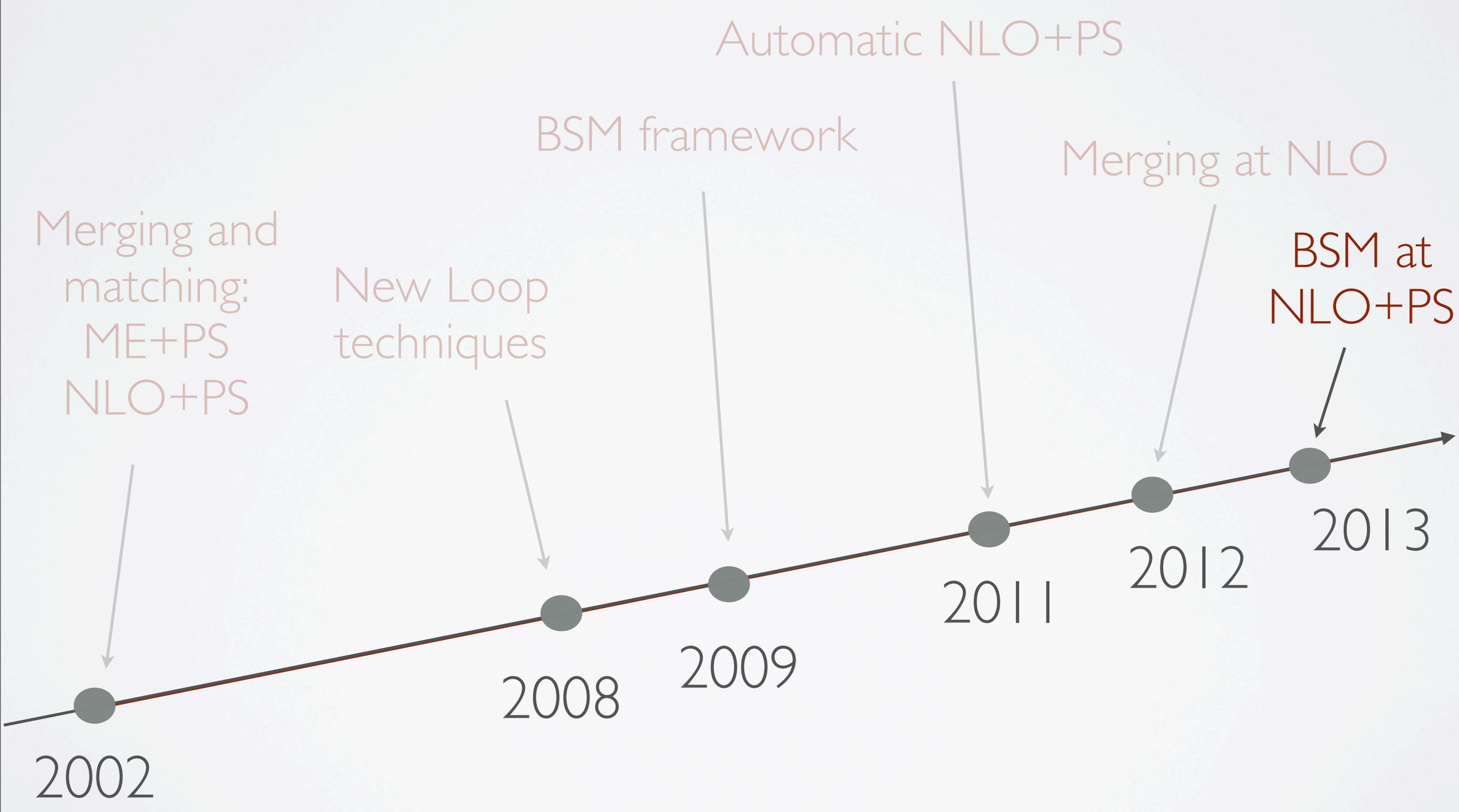
- Jet rates
- Up to 3 extra jets at NLO
- Various approaches give consistent results

[Frederix, Frixione, 1209.6215]

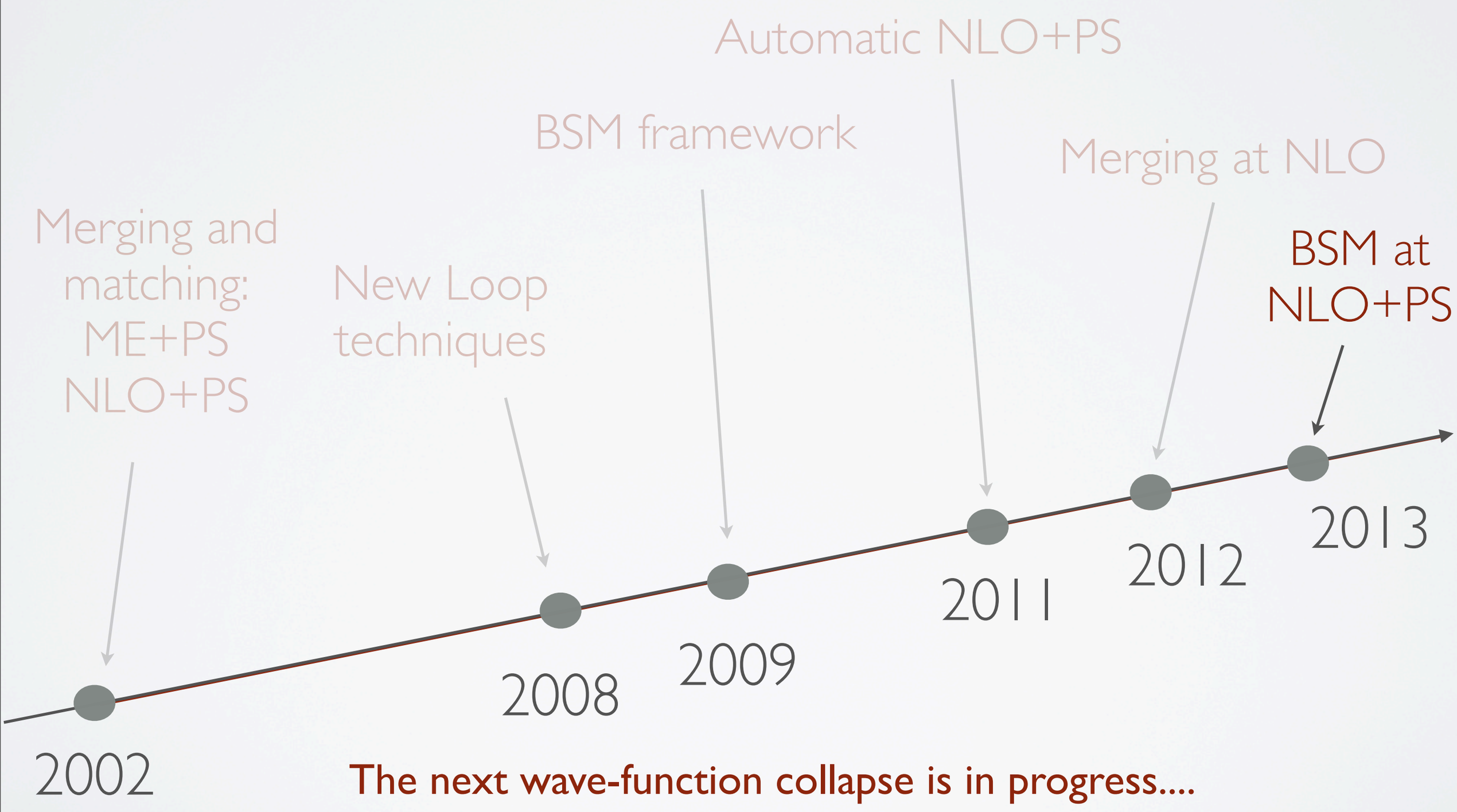


- Differential jet rates
- Matching up to 1 extra jet at NLO
- Method works for H+jets and W+jets equally well.

PREDICTIVE MC (SIMPLIFIED) PROGRESS



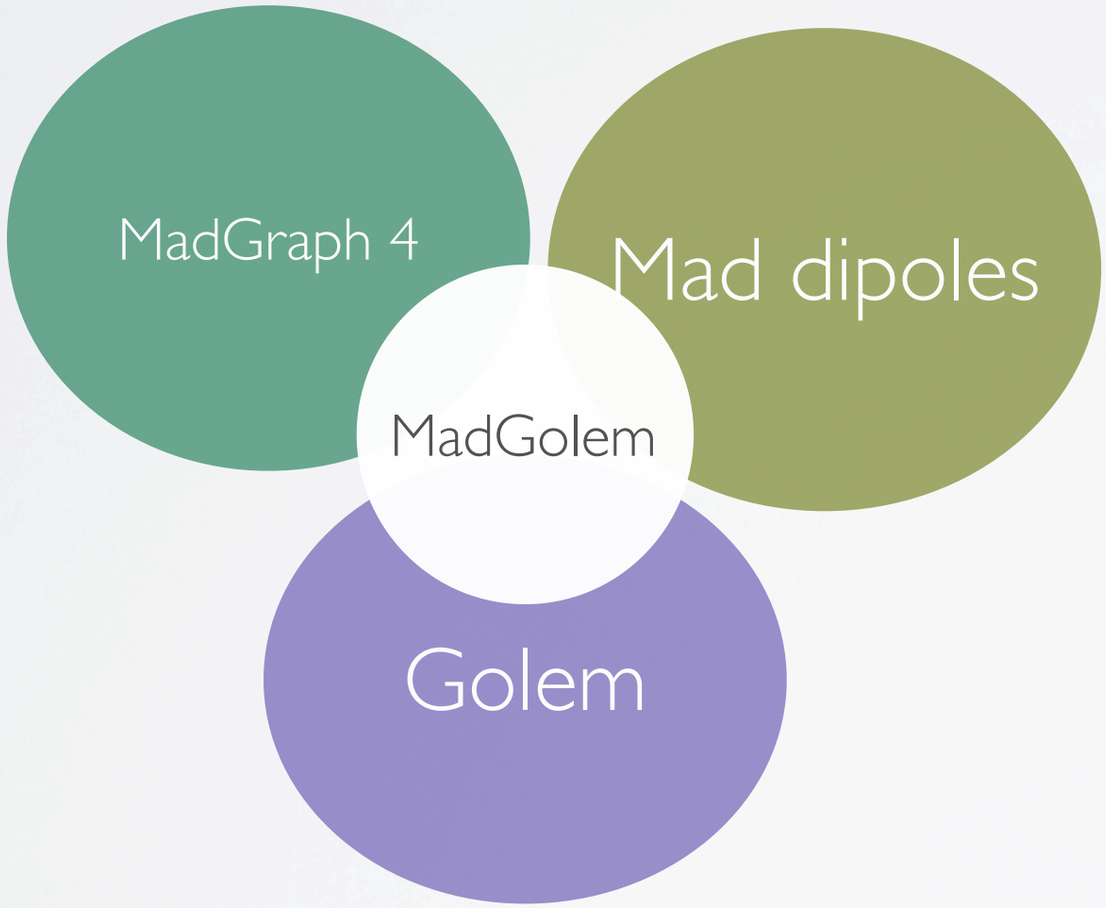
PREDICTIVE MC (SIMPLIFIED) PROGRESS

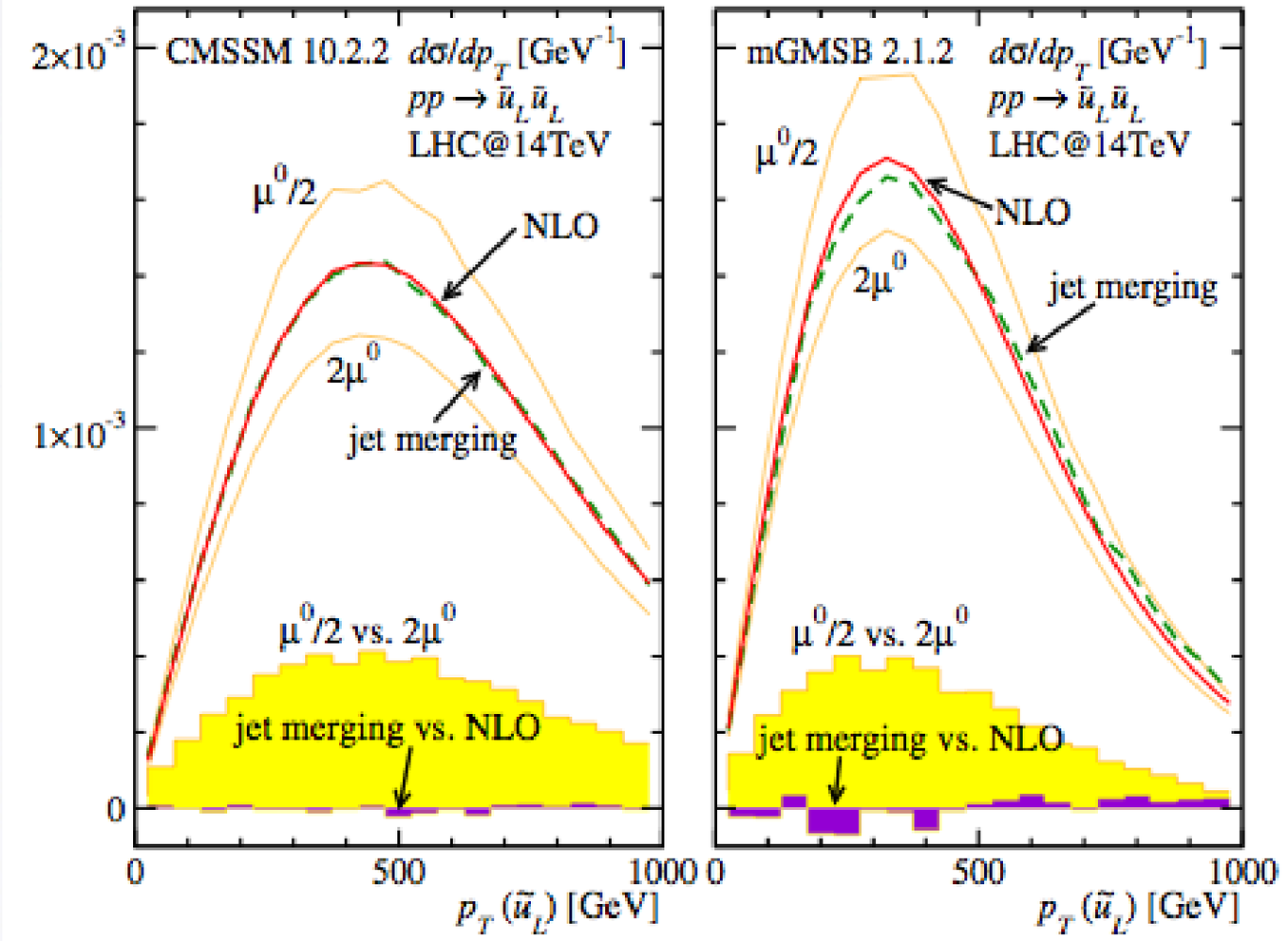


The next wave-function collapse is in progress....

AUTOMATIC SUSY AT NLO WITH MADGOLEM

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

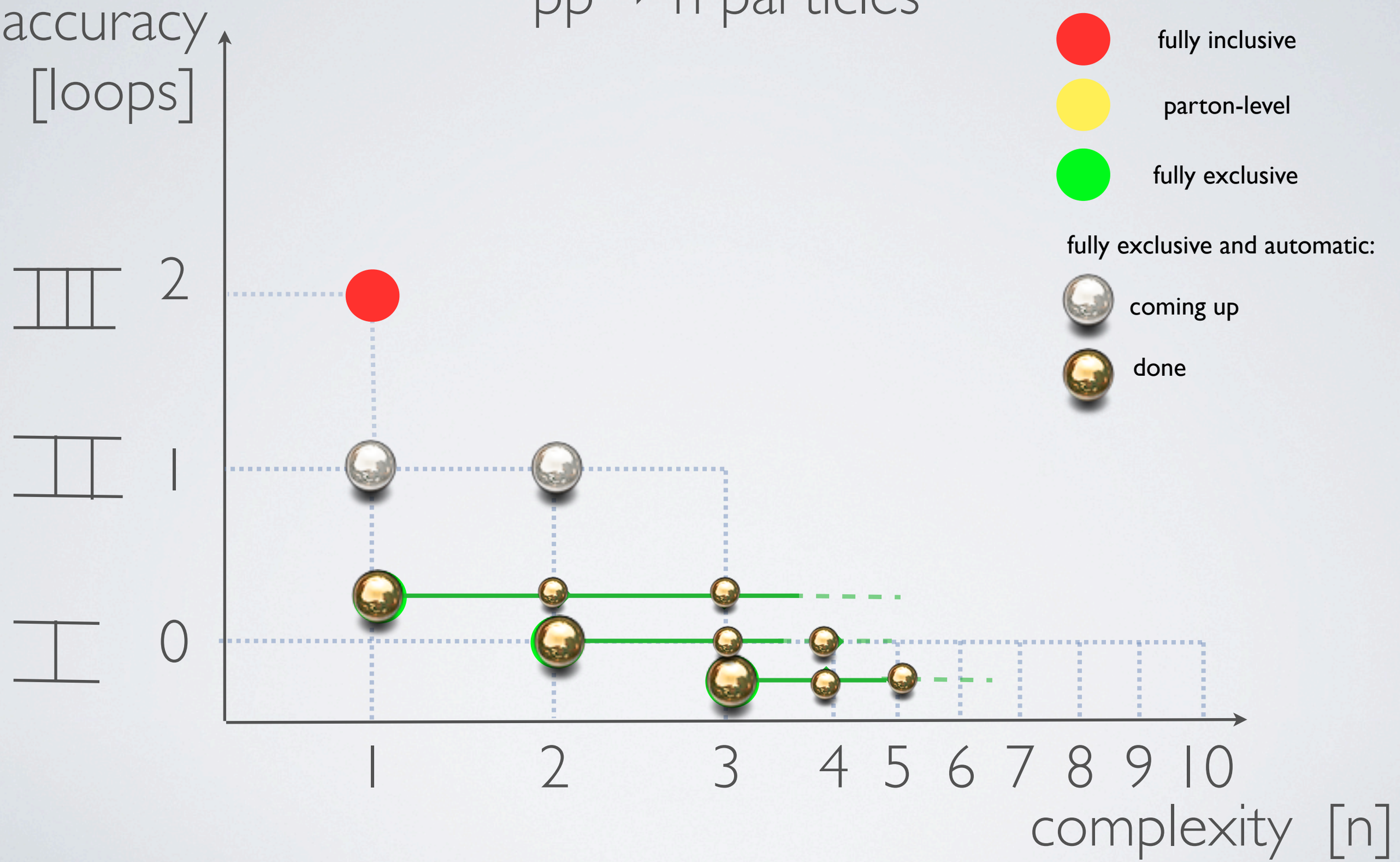




- All pp to sparticle-sparticle channels available
- No events, but completely differential in partonic observables.
- Shapes very similar to those obtained with ME+PS merging at LO.

BSM STATUS AND OUTLOOK

pp → n particles



WHAT'S NEXT

- Automation of high-parton multiplicity final states

  [e.g., Becker et al, 1111.1733,....]

- Automation of EW corrections

  [e.g., Actis et al, 1211.6316,....]

- Process-independent algorithms for NNLO

  [e.g., Czakon et al. 13036254, Currie et al. 1310.3993, Boughezal, 1202.6216,...]

- NNLO+PS

  [e.g., Alioli et al, 1311.0286]

- ....

CONCLUSIONS

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

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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.

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

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

- **A**ugmented EXP/TH interactions in the new framework and not limited anymore by the burden of heavy/long and inefficient calculations...

Automation

Accurate

Augmented

AAA

Automation

Accurate

Augmented

AAA PHENOMENOLOGY AT THE LHC

Free to Pheno