# AAA PHENOMENOLOGY

Fabio Maltoni
CP3-UCLouvain

Wine & Cheese joint Exp/Th seminar
FNAL May, 6 2011

# AAA PHENOMENOLOGY

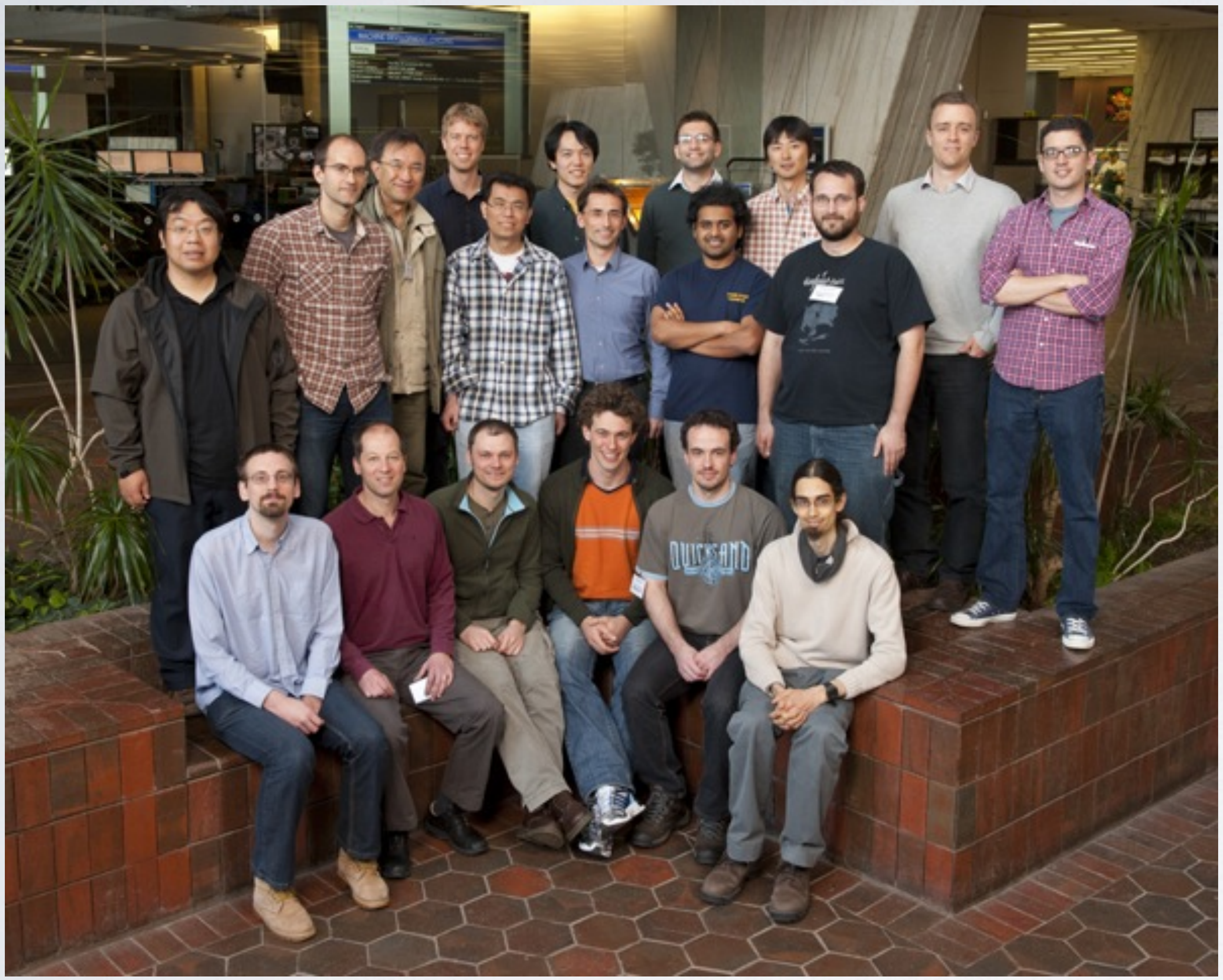
- AUTOMATIC
    - ACCURATE
        - AMAZING

new MC tools for hadron collider physics.

# PLAN

- Setting the stage: why do we need (accurate) predictions?
- 2003 ca : The first Monte Carlo revolution
- 2008 ca : The Loop revolution
- 2011 : The dawn of the AAA era

# COMMERCIAL



MadGraph
Spring 2011 Meeting

Thanks to all for the great work and fun!

# Discoveries at hadron colliders

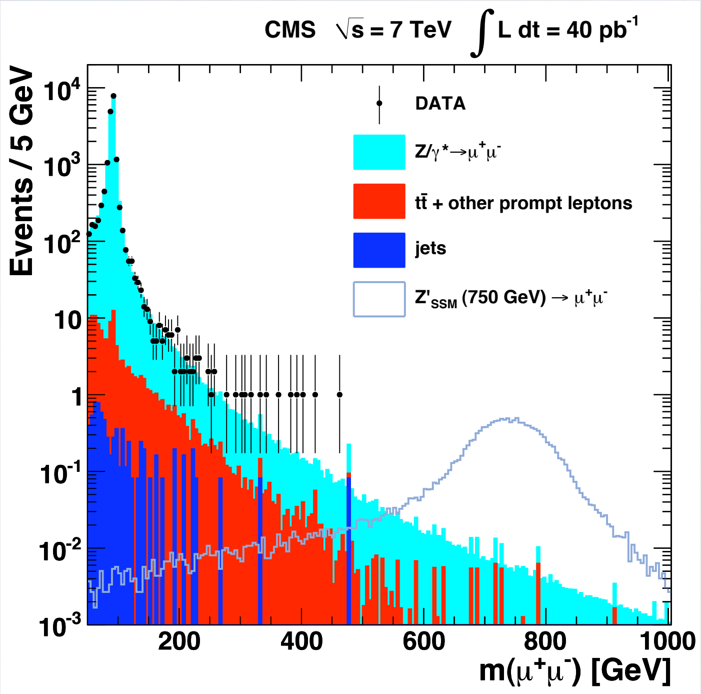
[MLM, 2008]

# Discoveries at hadron colliders

[MLM, 2008]

peak

$pp \to Z' \to e+e-$




"easy"

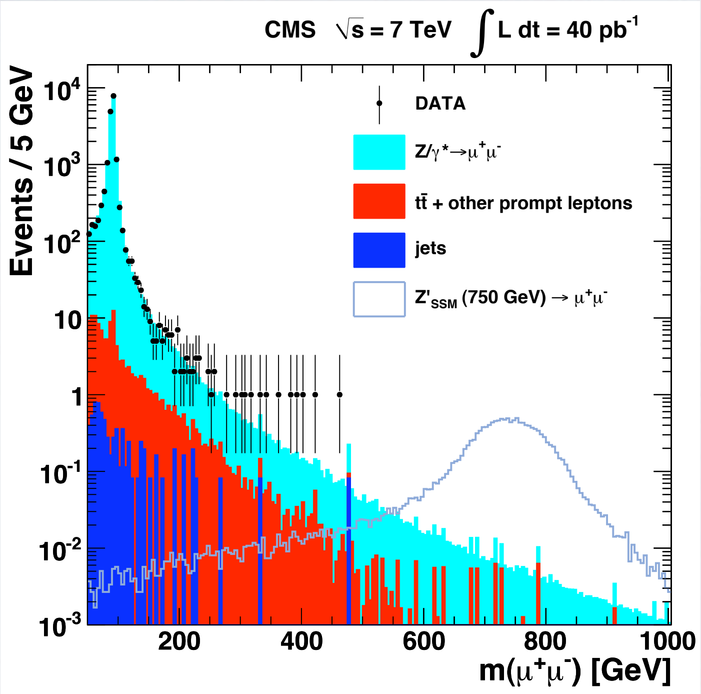
Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

# Discoveries at hadron colliders

[MLM, 2008]

peak

pp→Z'→e+e-

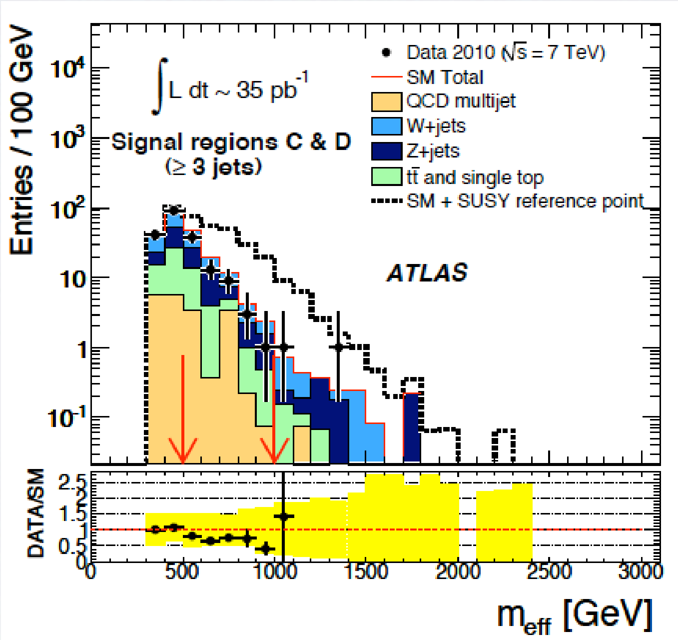



"easy"

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

shape

pp→g̃g̃,g̃q̃,q̃q̃→jets+ET




hard

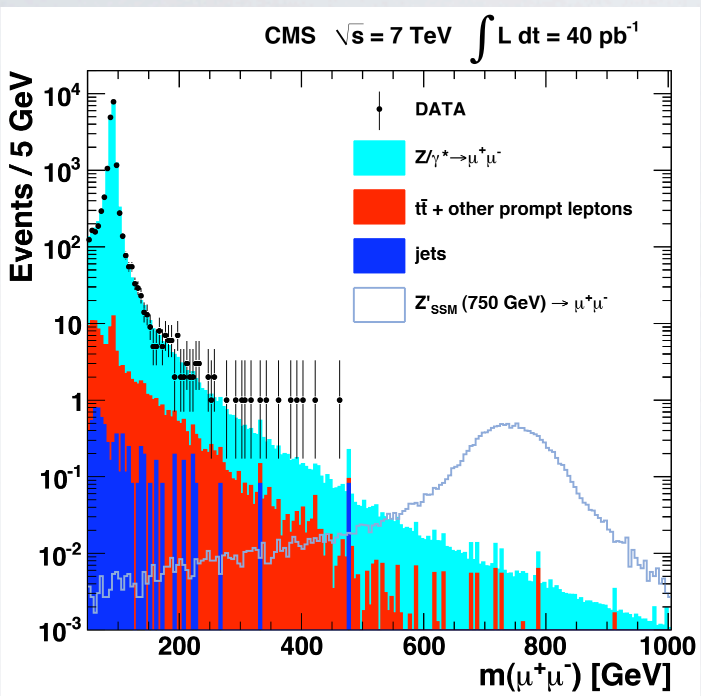
Background shapes needed. Flexible MC for both signal and backgroud tuned and validated with data.

# Discoveries at hadron colliders

[MLM, 2008]

peak

$pp \to Z' \to e^+e^-$

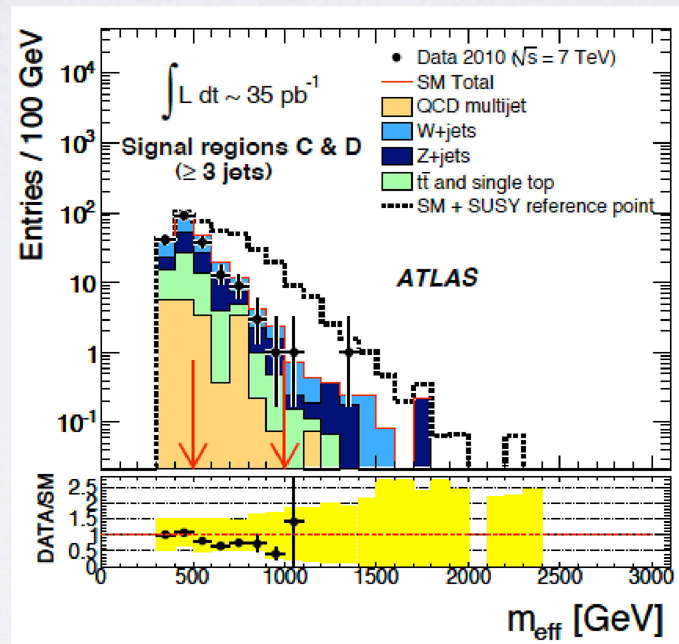



"easy"

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

shape

$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to$ jets+ET

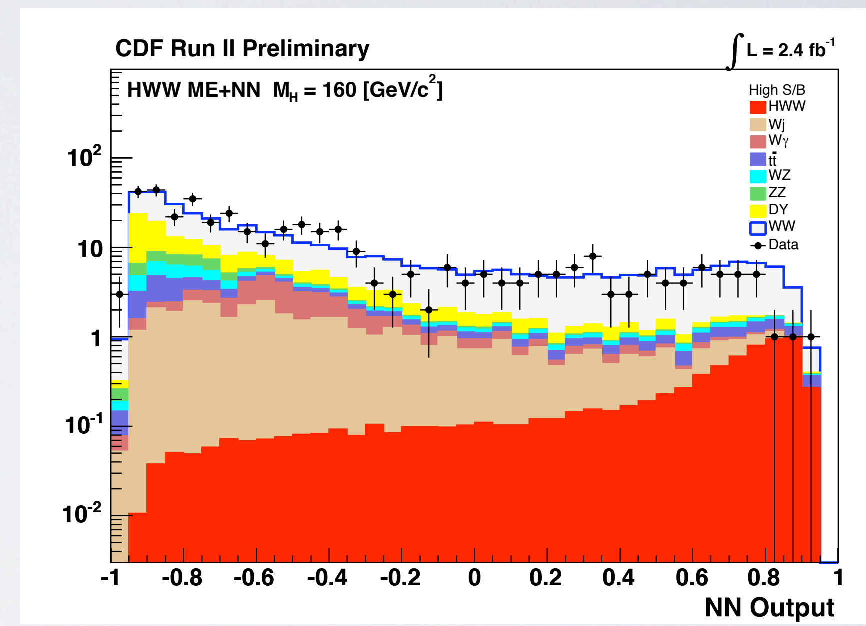



hard

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

rate

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




very hard

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

# TWO TEVATRON EXAMPLES

single top

Wjj

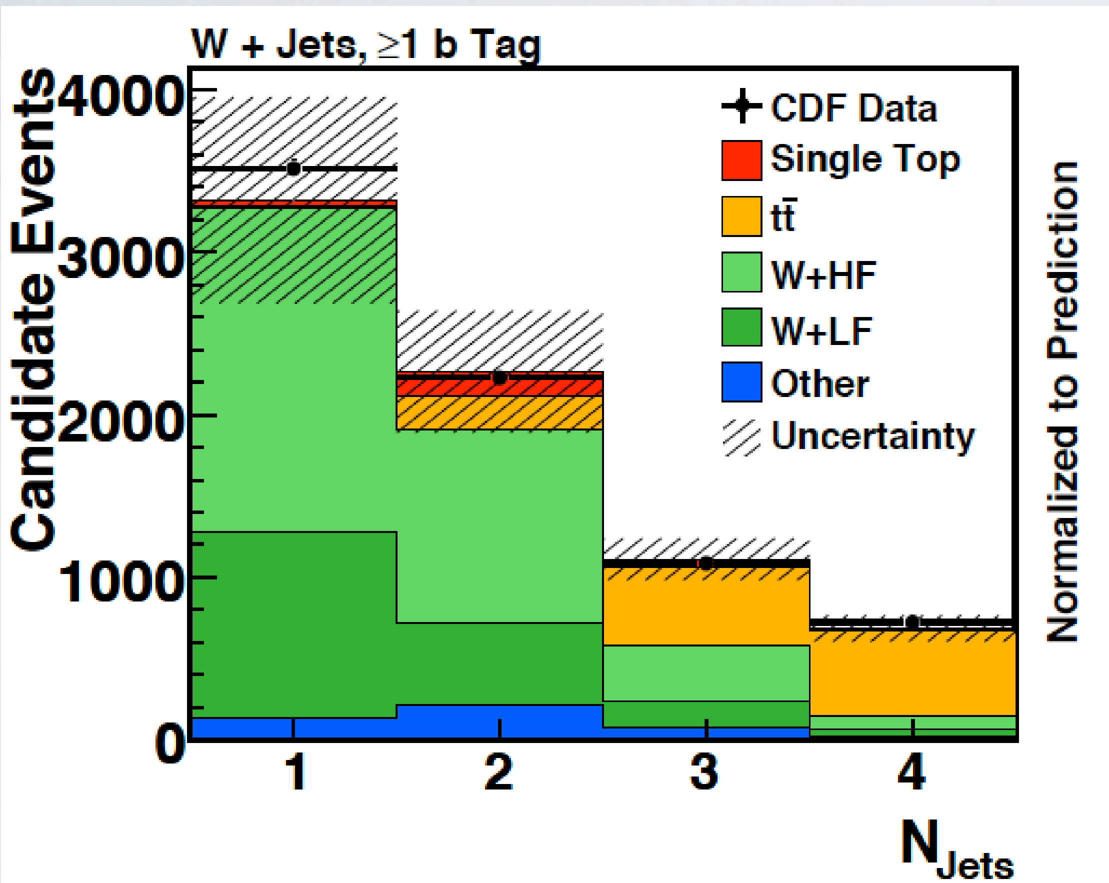
# TWO TEVATRON EXAMPLES

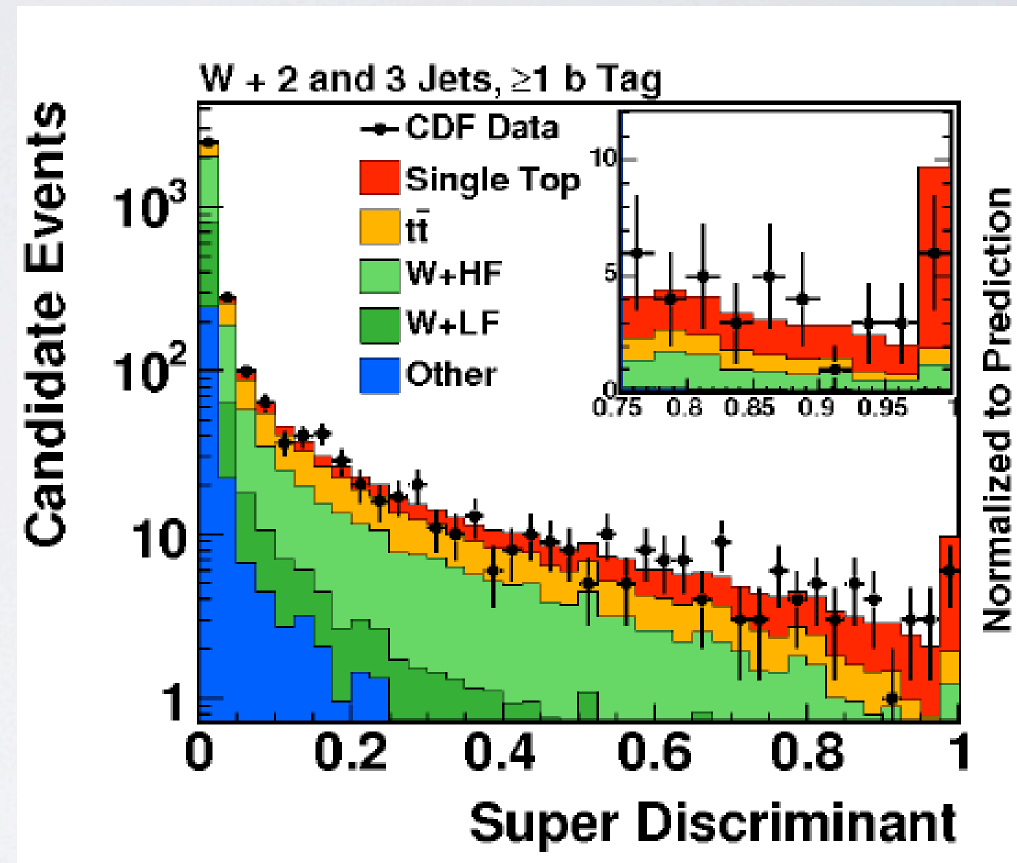
single top

Wjj

# SINGLE TOP

Well-known example of a "discovery" by CDF and D0 of the third kind:

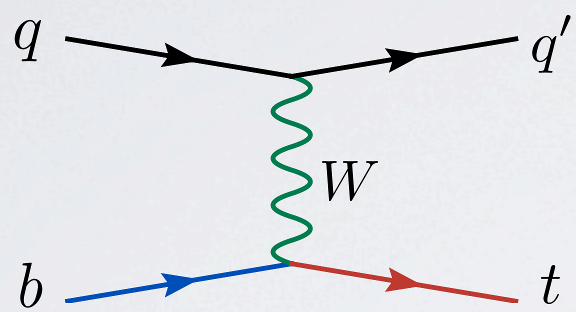


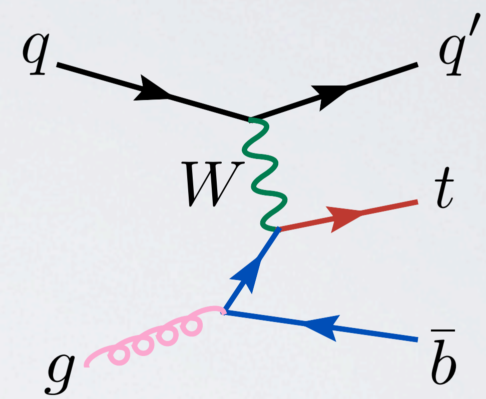

CDF 1004.1181

What was the accuracy of the predictions at the moment?

# SINGLE TOP




5-flavor scheme: "2 → 2"

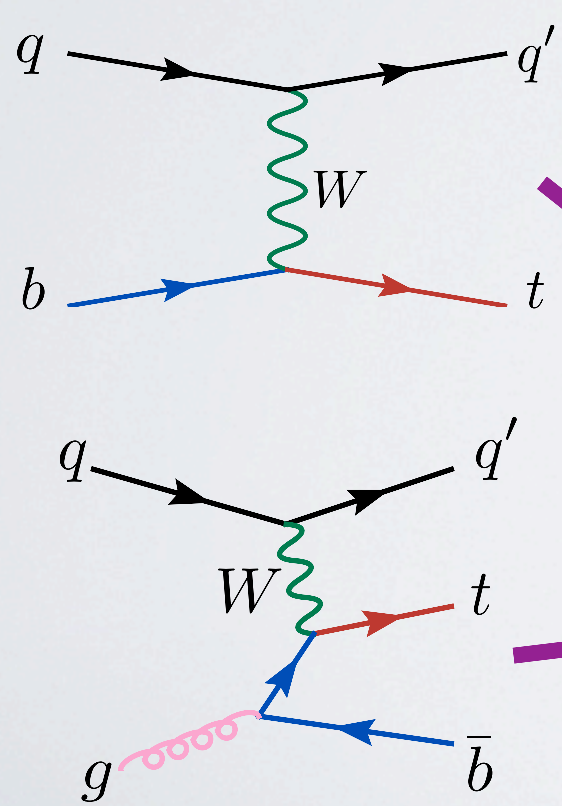



4-flavor scheme: "2 → 3"

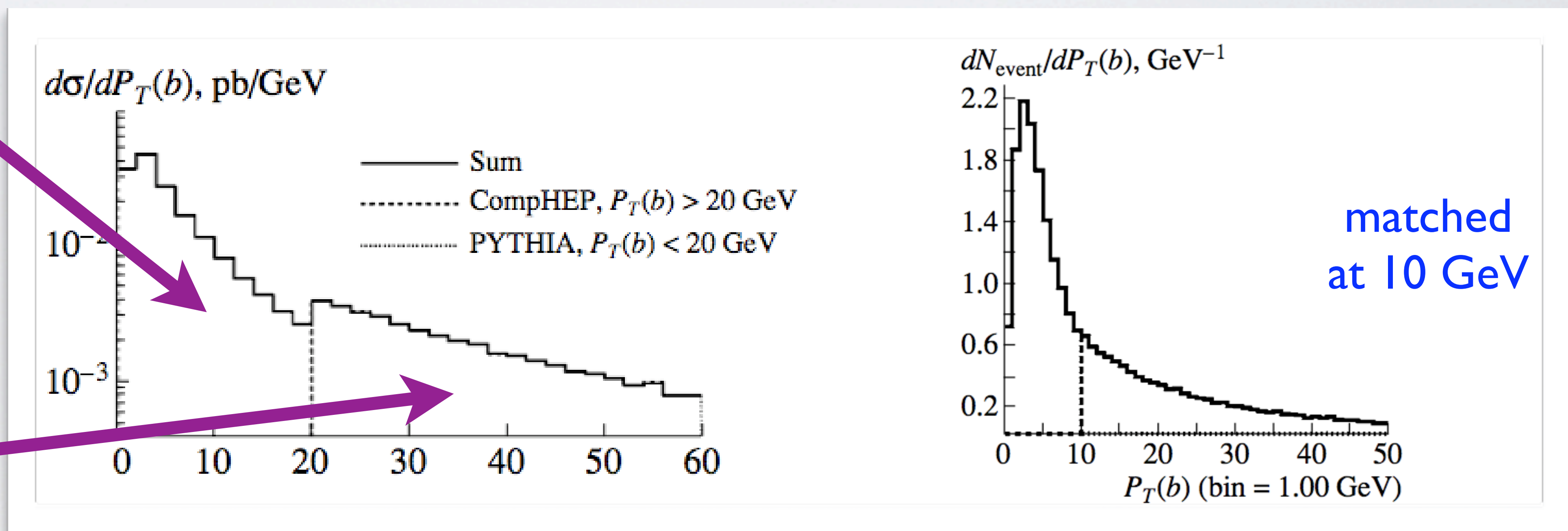
- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: they are resummed
  - available phase space
  - approximation by large logarithm

# SINGLE TOP

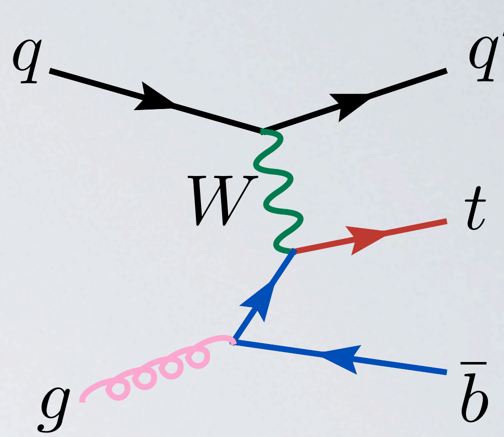
- At NLO, effects related to the spectator b only enter at this order and not well described by corresponding MC implementations.
- → separate regions according to $p_T(b)$ and use LO 5F (2 → 2)+ shower below and LO 4F (2 → 3) above




*Boos et al., Phys. At. Nucl. 69, 1317 (2006)*



# SINGLE TOP




- In 2009 NLO in 4F finally appeared [Campbell et al (2009)]
- Even though b quarks in the 4F (2 ➞ 3) scheme are more forward and softer, we expect to see more b's than in the 5F (2 ➞ 2)
- In 5F (2 ➞ 2) only a subset of real emission diagrams have a final state b quark. In any case the pT of the spectator b is a LO observable.
- Consider the "acceptance":

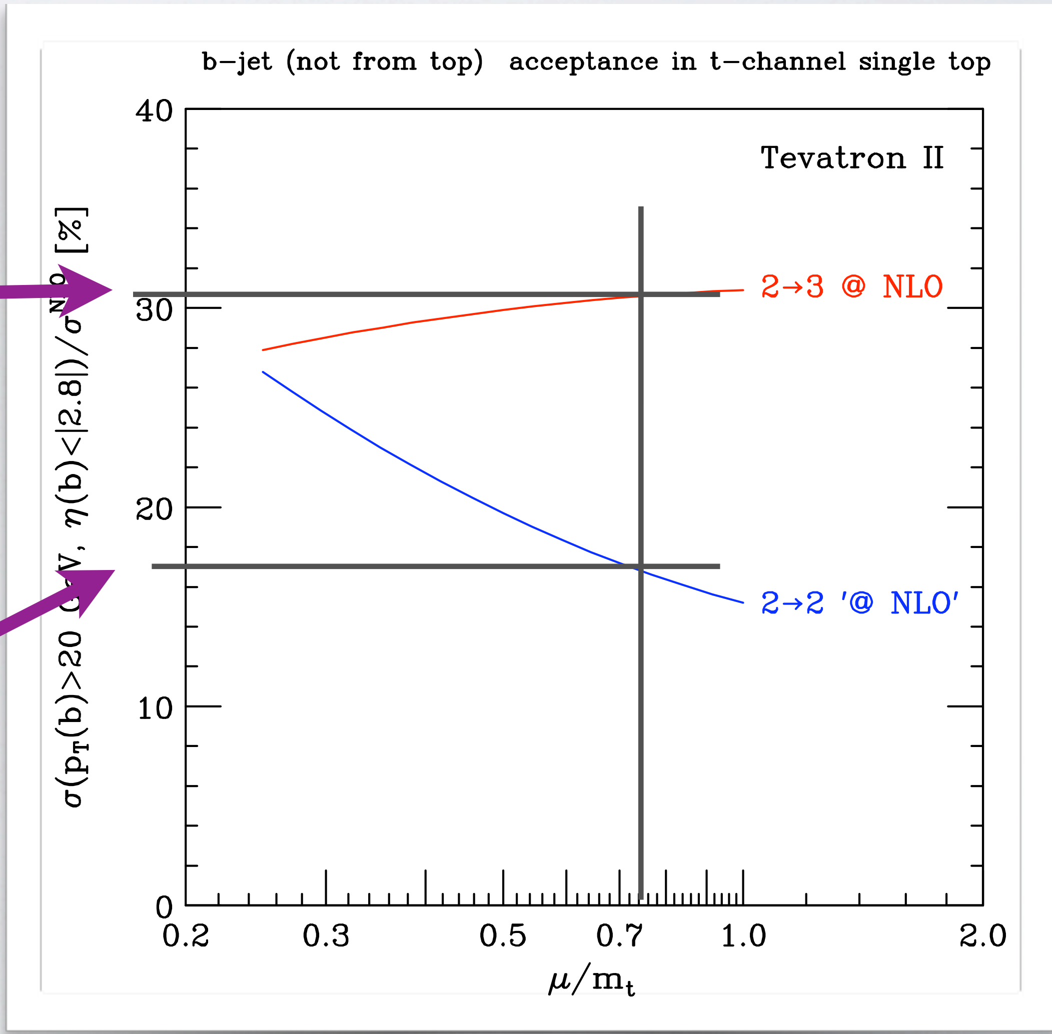
$$\frac{\sigma(|\eta(b)| < 2.5,\, p_T(b) > 20 \text{ GeV})}{\sigma_{\text{inclusive}}}$$

# SINGLE TOP

- In the Monte Carlo samples used by CDF (based on ZTOP), almost half as many b-jets (not from top decay) compared to best NLO predictions
  - What was the impact on the recent measurements for single top?
- DØ predictions were consistent with best theory prediction.

Best theory prediction: 30.5%

Value from ZTOP: 16.7%

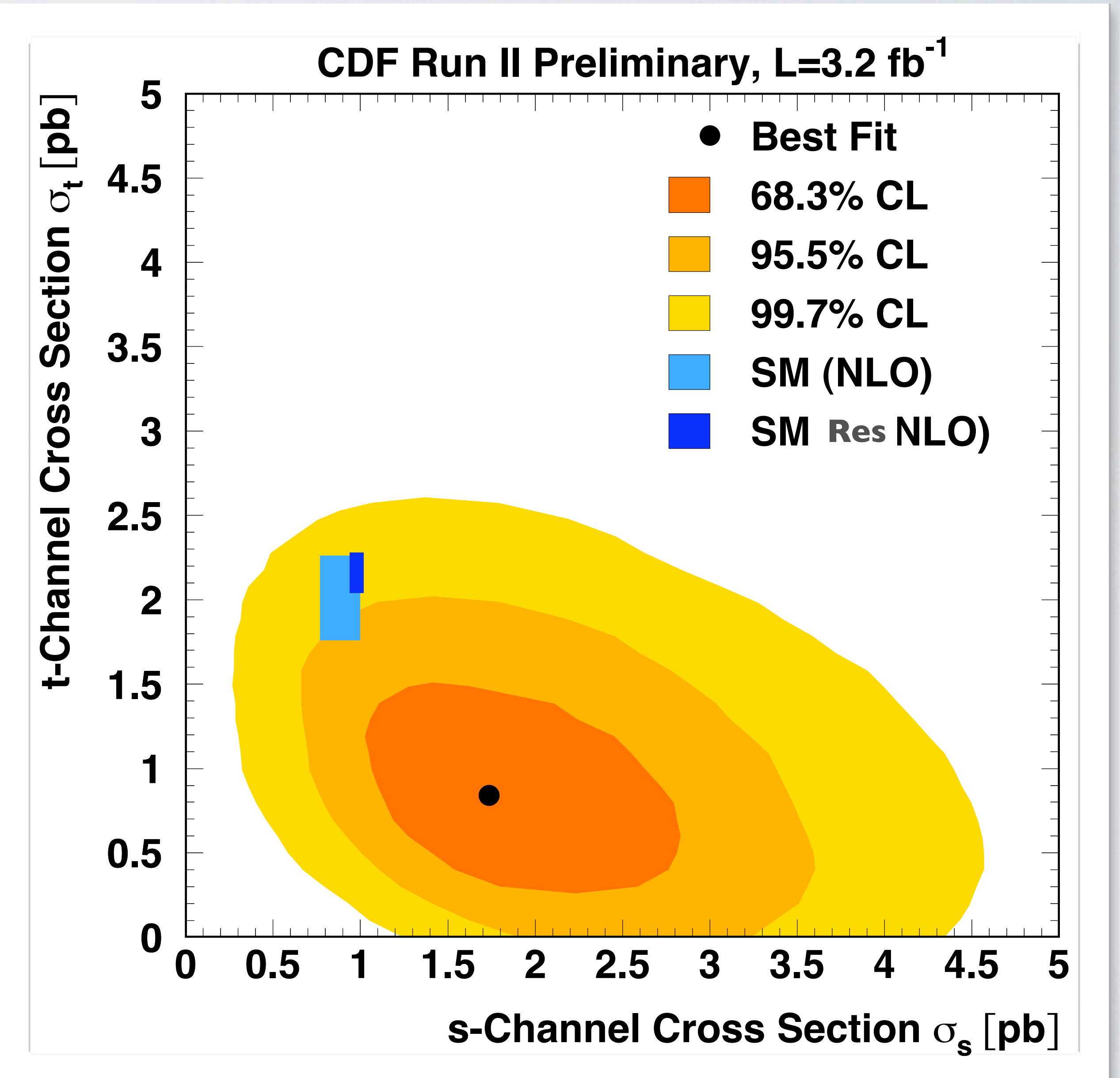


# SINGLE TOP

- Naively:

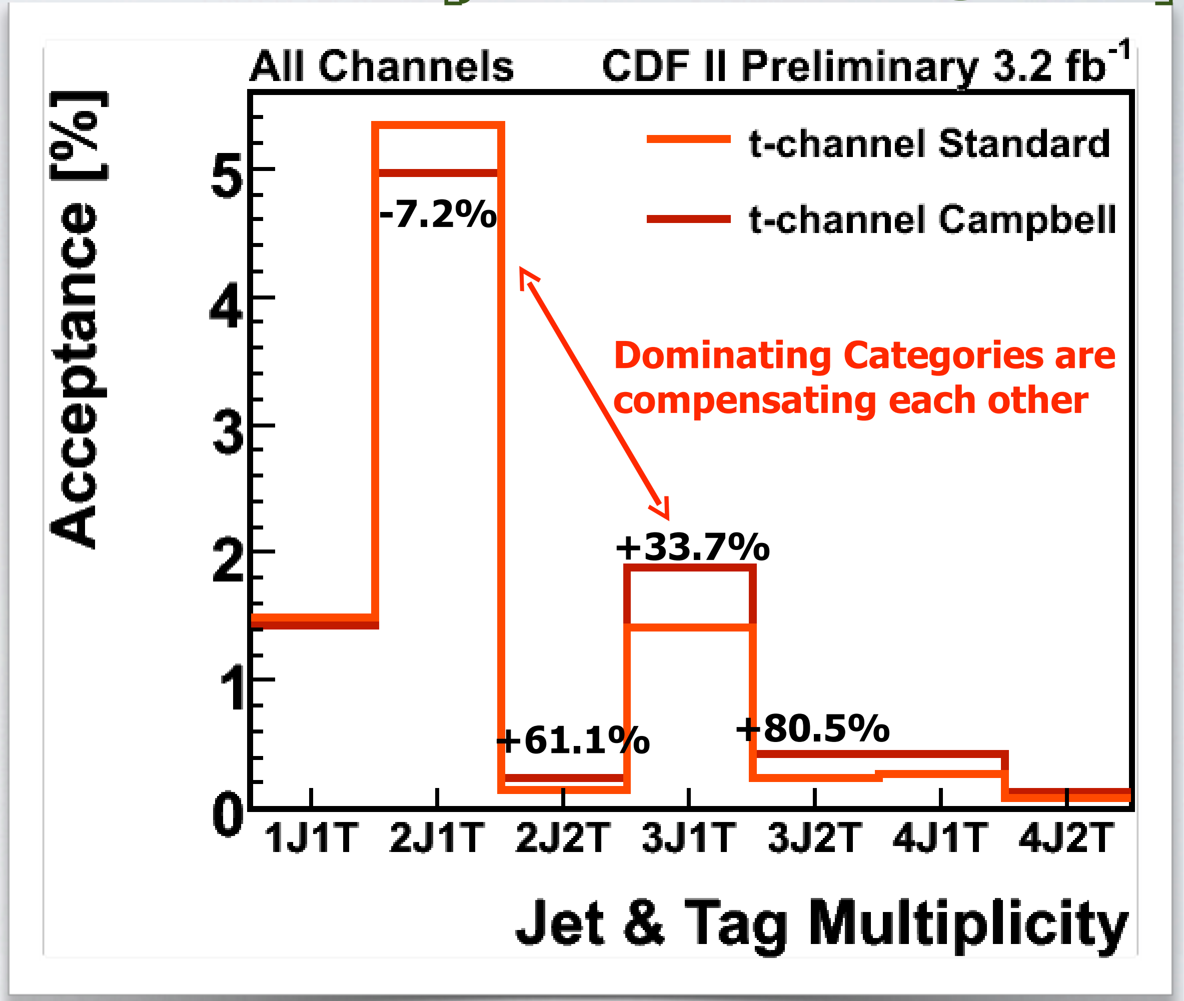
  Because

  - s-channel has one more b-jet in the final state compared to the 5 flavor t-channel, and
  - in the 4 flavor more t-channel events have the same # of b-jets as s-channel,
  - many t-channel events were assigned to the s-channel



# SINGLE TOP

[Jan Lueck et al. @ CDF]

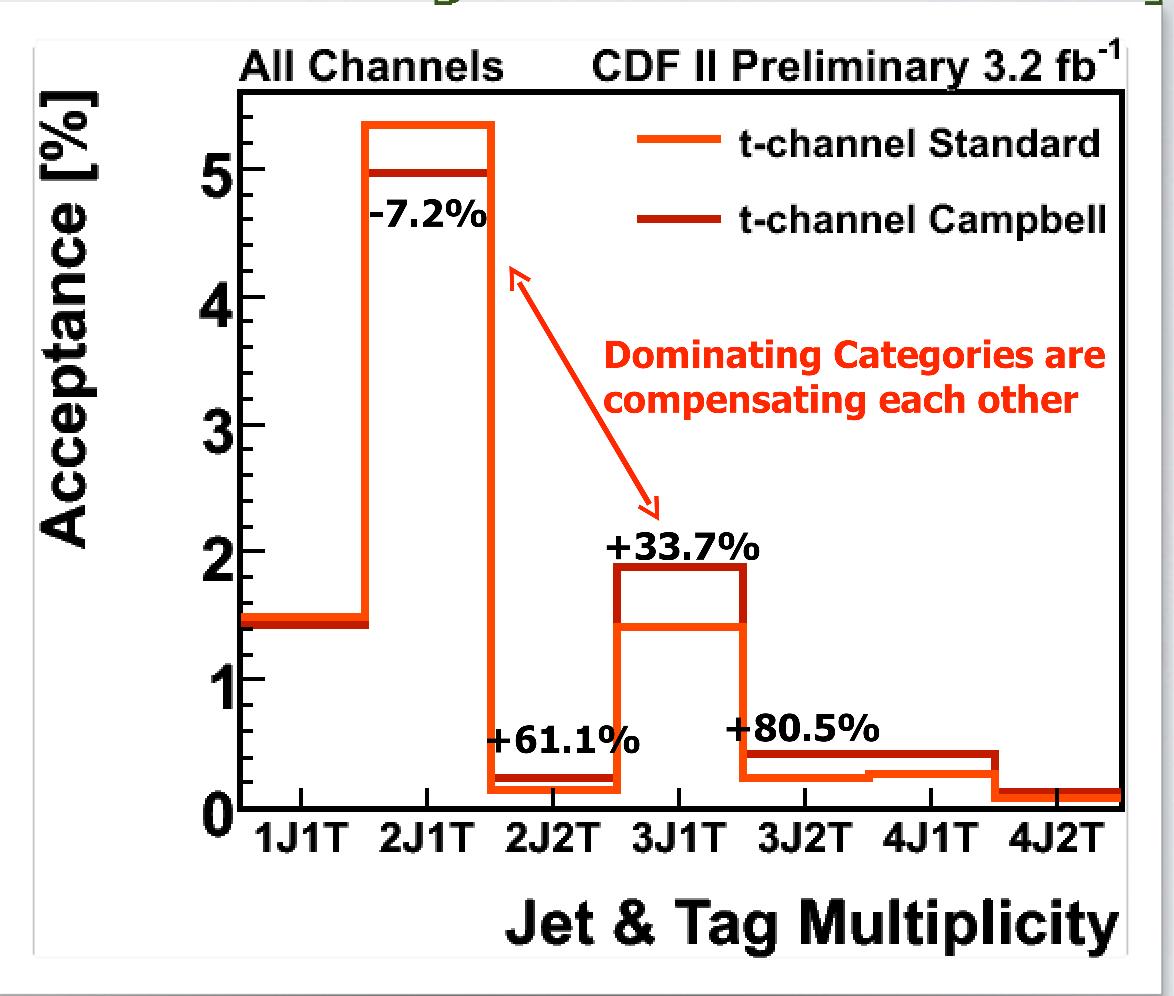



- In practice...
  It's slightly more complicated:

  Dominating categories are compensating each other.
  Large differences for channels with only minor contributions

# SINGLE TOP

[Jan Lueck et al. @ CDF]




- In practice...
  It's slightly more complicated:

  Dominating categories are compensating each other.
  Large differences for channels with only minor contributions

- UPSHOT: THERE IS AN ACCIDENTAL CANCELLATION.

  No final important effect!

# TWO TEVATRON EXAMPLES

single top

Wjj

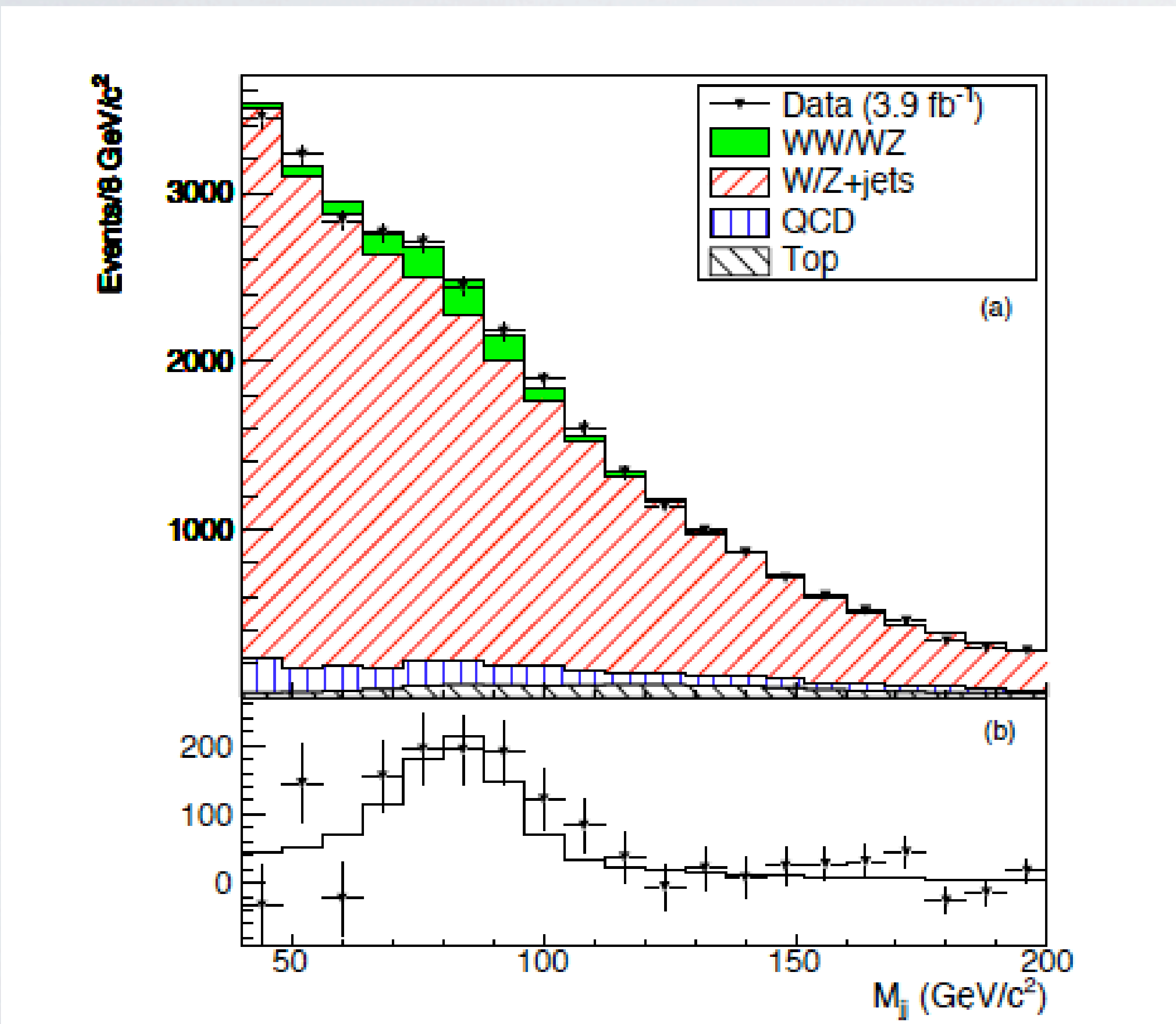
# TWO TEVATRON EXAMPLES

single top

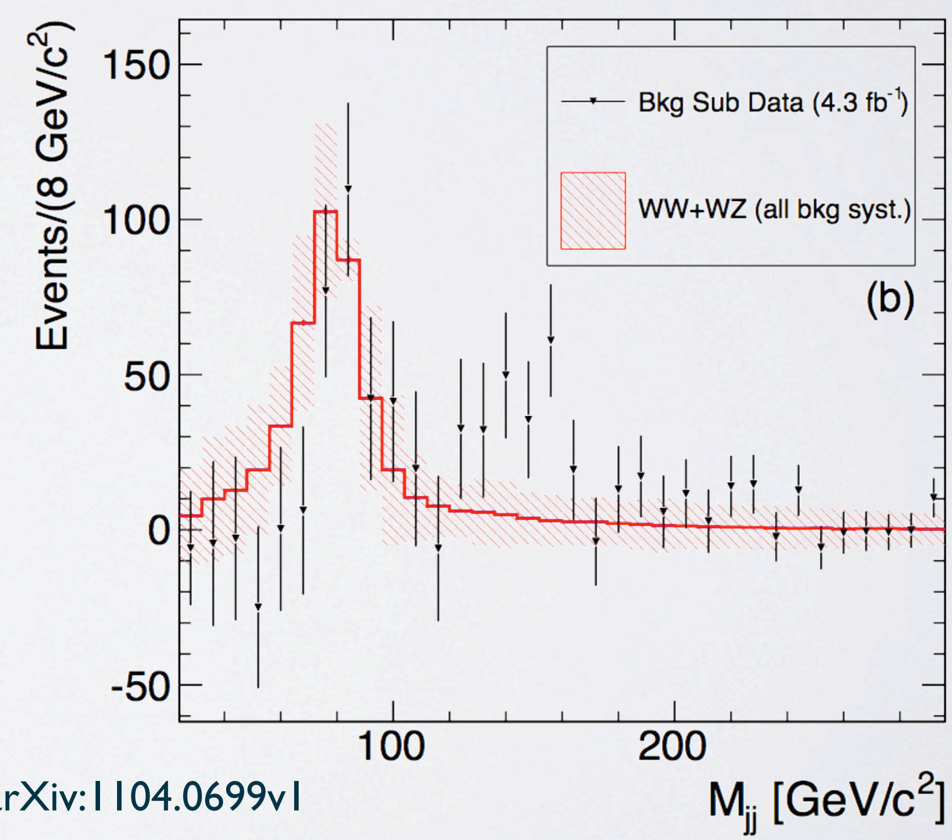
Wjj

# WJJ

CDF observes 3-σ deviation to the SM signal.




- New Physics, stat. fluctuations?
- Unreliable prediction?
  - ➥ W+jets treated at LO and distributions checked with MCFM!
  - ➥ Top background from theory.



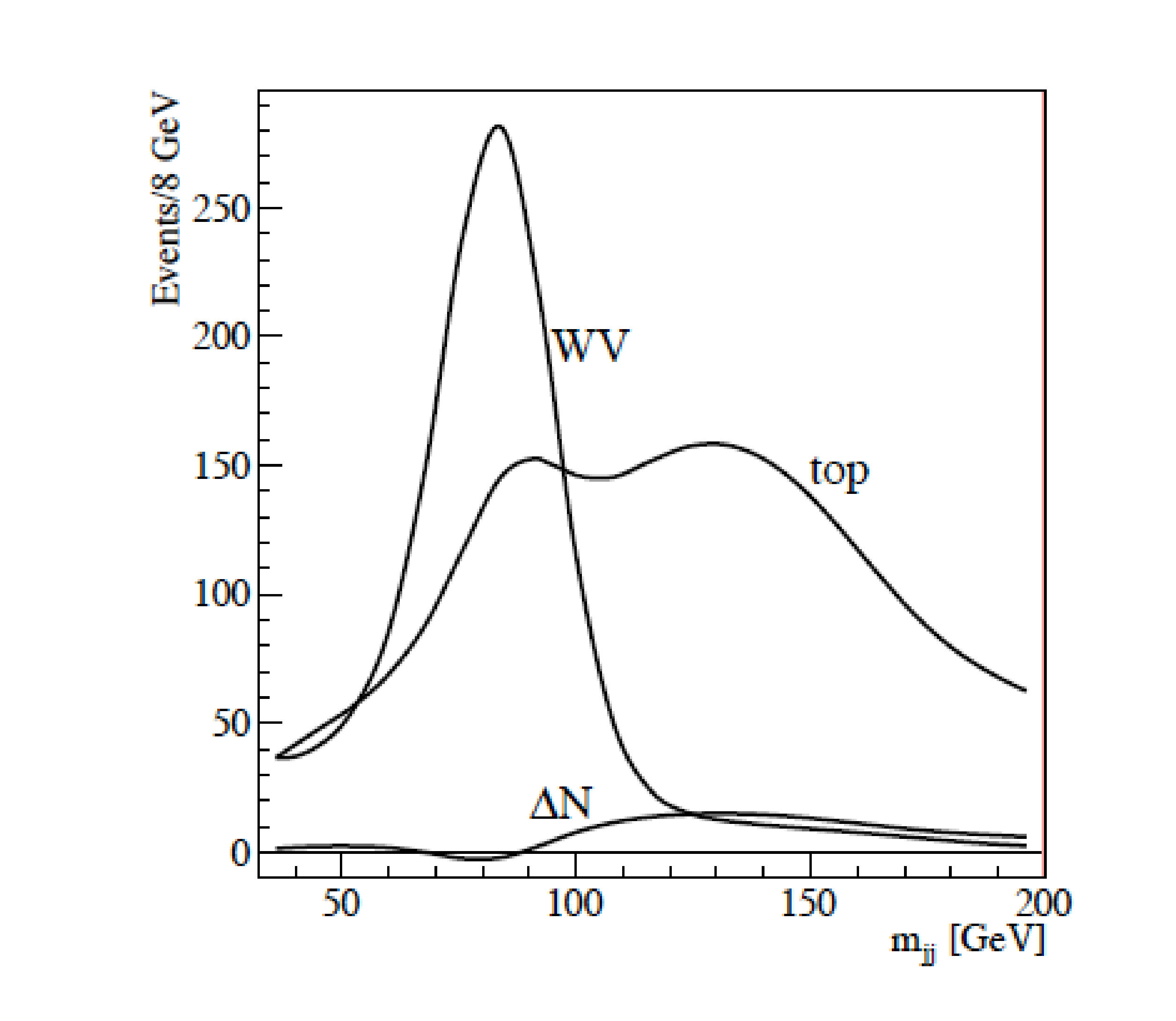

arXiv:1104.0699v1

# WJJ

More than **20 papers on BSM** interpretations in the last weeks.

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

related to top production and in particular to single top.

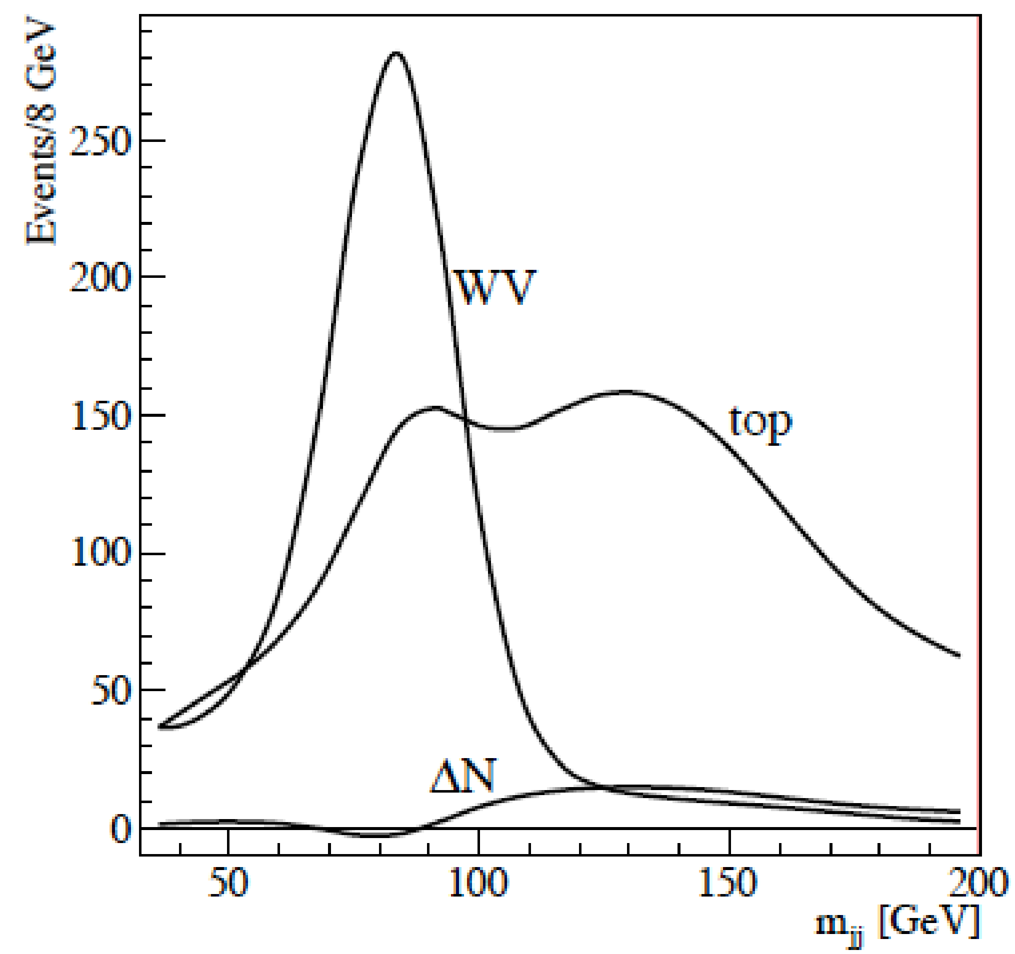


# WJJ

More than **20 papers on BSM** interpretations in the last weeks.

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

related to top production and in particular to single top.




UPSHOT: Inconclusive at the moment.
Need more investigation. Certainly interesting testing ground of our strategies/capabilities of finding new effects.

# MOTIVATION : SUMMARY

# MOTIVATION : SUMMARY

- Reliable and experimental friendly predictions for collider physics range from being very useful to strictly necessary.

# MOTIVATION : SUMMARY

- Reliable and experimental friendly predictions for collider physics range from being very useful to strictly necessary.
- Confidence on possible excesses, evidences and eventually discoveries builds upon an intense (and often non-linear) process of description/prediction of data via MC's.

# MOTIVATION : SUMMARY

- Reliable and experimental friendly predictions for collider physics range from being very useful to strictly necessary.
- Confidence on possible excesses, evidences and eventually discoveries builds upon an intense (and often non-linear) process of description/prediction of data via MC's.
- Measurements and exclusions always rely on accurate predictions.

# MOTIVATION : SUMMARY

- Reliable and experimental friendly predictions for collider physics range from being very useful to strictly necessary.
- Confidence on possible excesses, evidences and eventually discoveries builds upon an intense (and often non-linear) process of description/prediction of data via MC's.
- Measurements and exclusions always rely on accurate predictions.
- Predictions for both SM and BSM on the same ground.

# A MC MOTTO

Ability

of making good (simulated) data

is as important as that

of taking good (real) data

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

# Master QCD formula

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

Two ingredients necessary:

1. Parton Distribution functions (from exp, but evolution from th).
2. Short distance coefficients as an expansion in $\alpha_S$ (from th).

# HOW WE (USED TO) MAKE PREDICTIONS?

## First way:

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

TH

- For high multeplicity 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
5. Cost of a new prediction at NLO can easily exceed 100k$.

# BEST EXAMPLE: MCFM

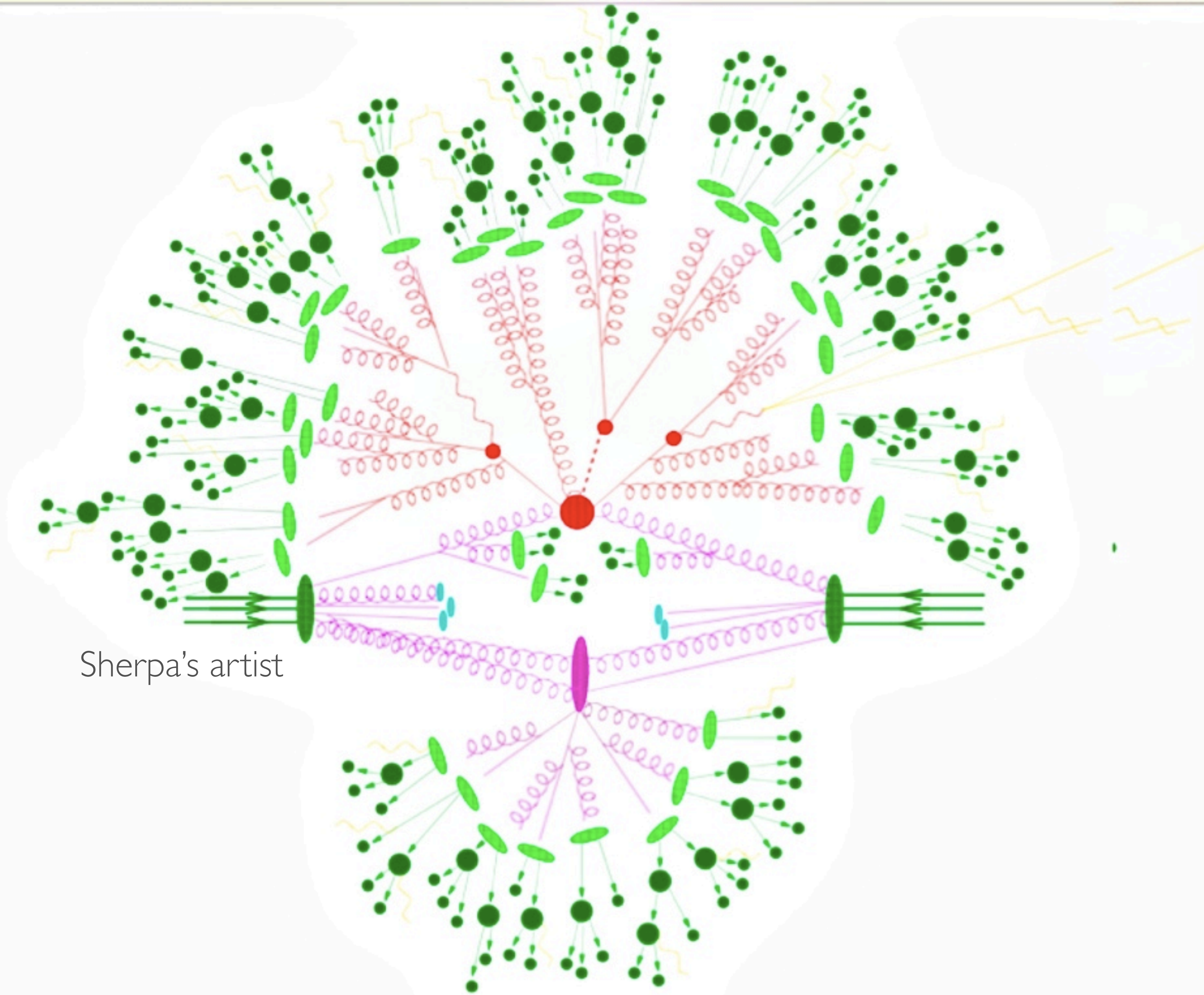
Downloadable general purpose NLO code (Campbell & Ellis+ collaborators)

| Final state | Notes | Reference |
|---|---|---|
| W/Z | | |
| diboson (W/Z/γ) | photon fragmentation, anomalous couplings | hep-ph/9905386, arXiv:1105.0020 |
| Wbb | massless b-quark massive b quark | hep-ph/9810489 arXiv:1011.6647 |
| Zbb | massless b-quark | hep-ph/0006304 |
| W/Z+1 jet | | |
| W/Z+2 jets | | hep-ph/0202176, hep-ph/0308195 |
| Wc | massive c-quark | hep-ph/0506289 |
| Zb | 5-flavour scheme | hep-ph/0312024 |
| Zb+jet | 5-flavour scheme | hep-ph/0510362 |

| 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 | |

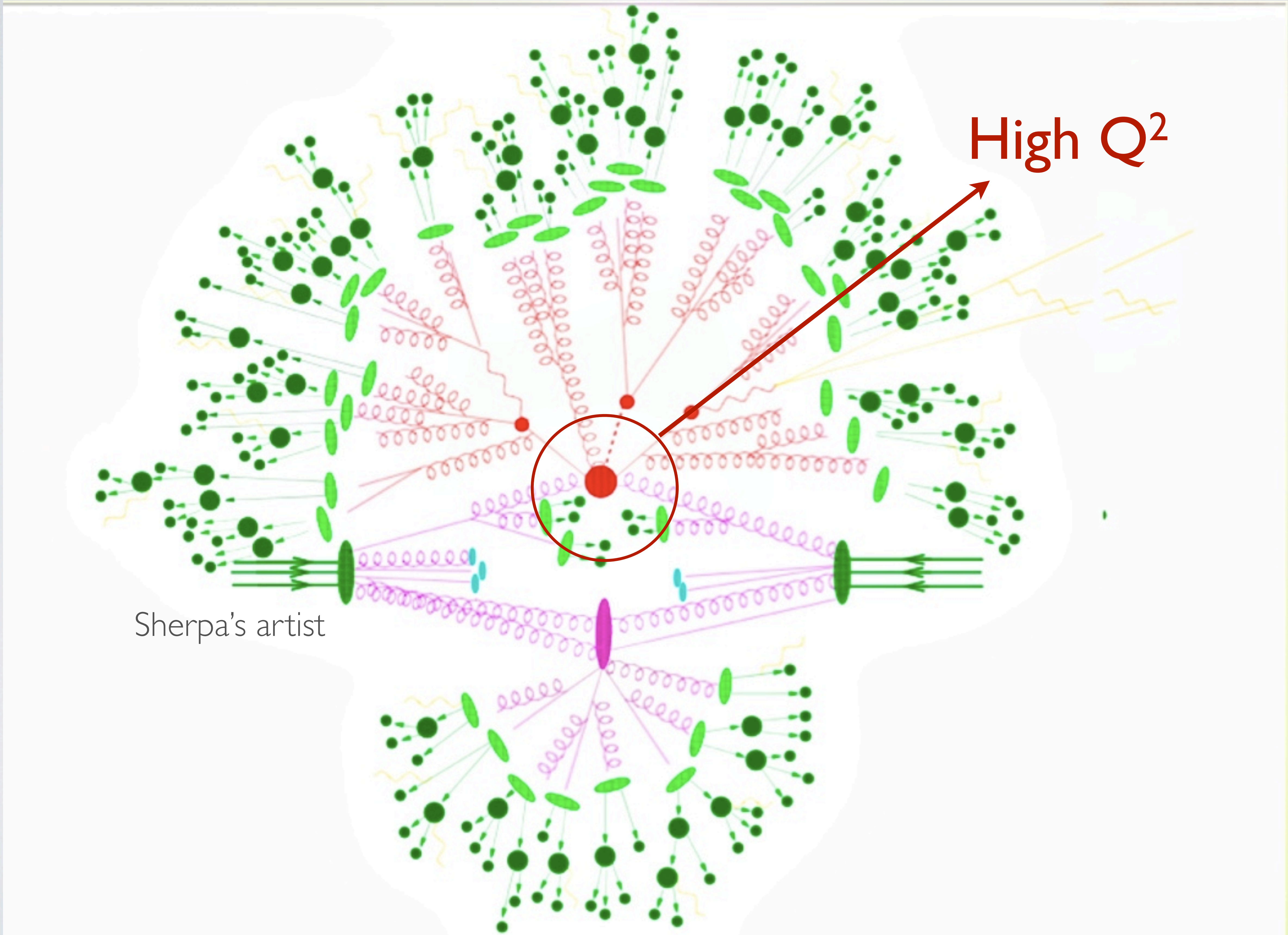
- First results implemented in 1998 ...this is 13 years worth of work of several people (~3-5M$)
- Now extended to many more processes Wc, WQJ, ZQJ,...
- Cross sections and distributions at NLO are provided
- One general framework. However, each process implemented by hand.

# Events at hadron colliders



Sherpa's artist

# Events at hadron colliders



# 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

# SM STATUS : BEFORE 2003

pp→ n particles

# SM STATUS : BEFORE 2003

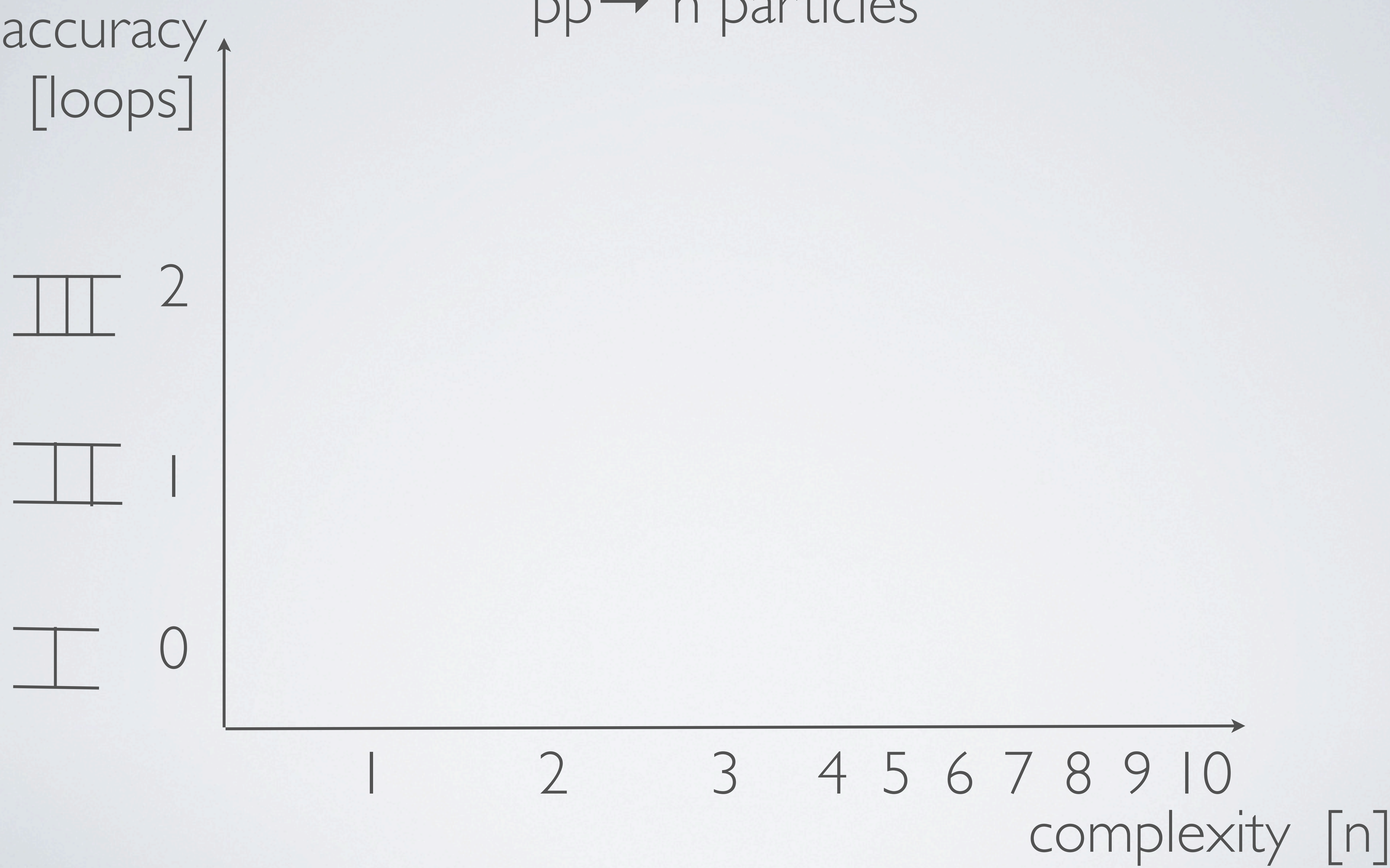
pp→ n particles

1 2 3 4 5 6 7 8 9 10

complexity [n]

# SM STATUS : BEFORE 2003

pp → n particles

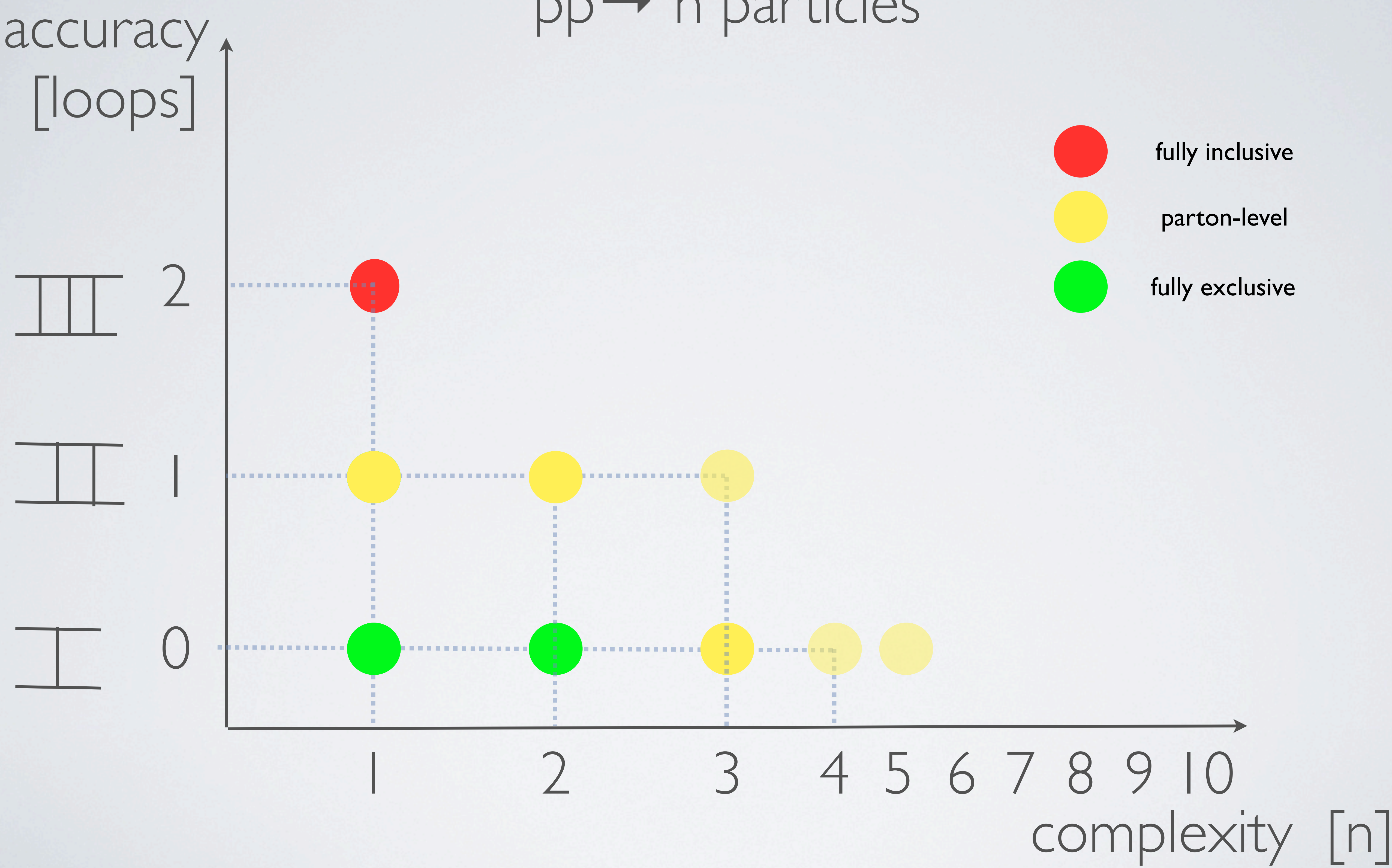


# SM STATUS : BEFORE 2003

pp→ n particles

# SM STATUS : BEFORE 2003

pp→ n particles



# THE (CIRCA) 2003 MC REVOLUTION

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

# ME vs PS

| ME | 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 |

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

# ME vs PS

| ME | 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 |

Approaches are complementary: merge them!

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

# ME vs PS

| ME | 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 |

Approaches are complementary: merge them!

Difficulty: avoid double counting

# HOW TO IMPROVE OUR PREDICTIONS?

Current trend: TH & EXP

Match fixed-order calculations and parton showers to obtain the most accurate predictions in a detector simulation friendly way!

Two directions:

1. Get fully exclusive description of many parton events correct at LO (LL) in all the phase space. **ME+PS**

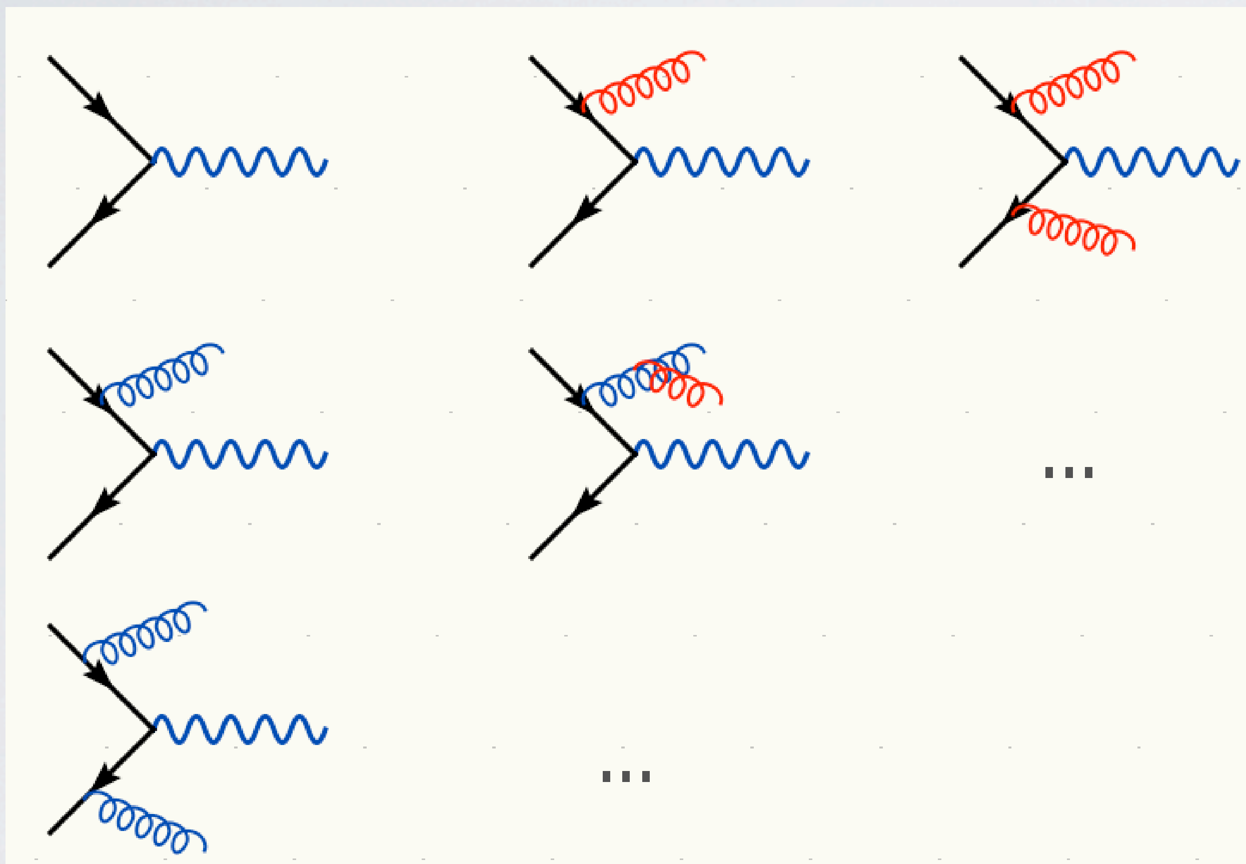
2. Get fully exclusive description of events correct at NLO in the normalization and distributions. **NLOwPS**

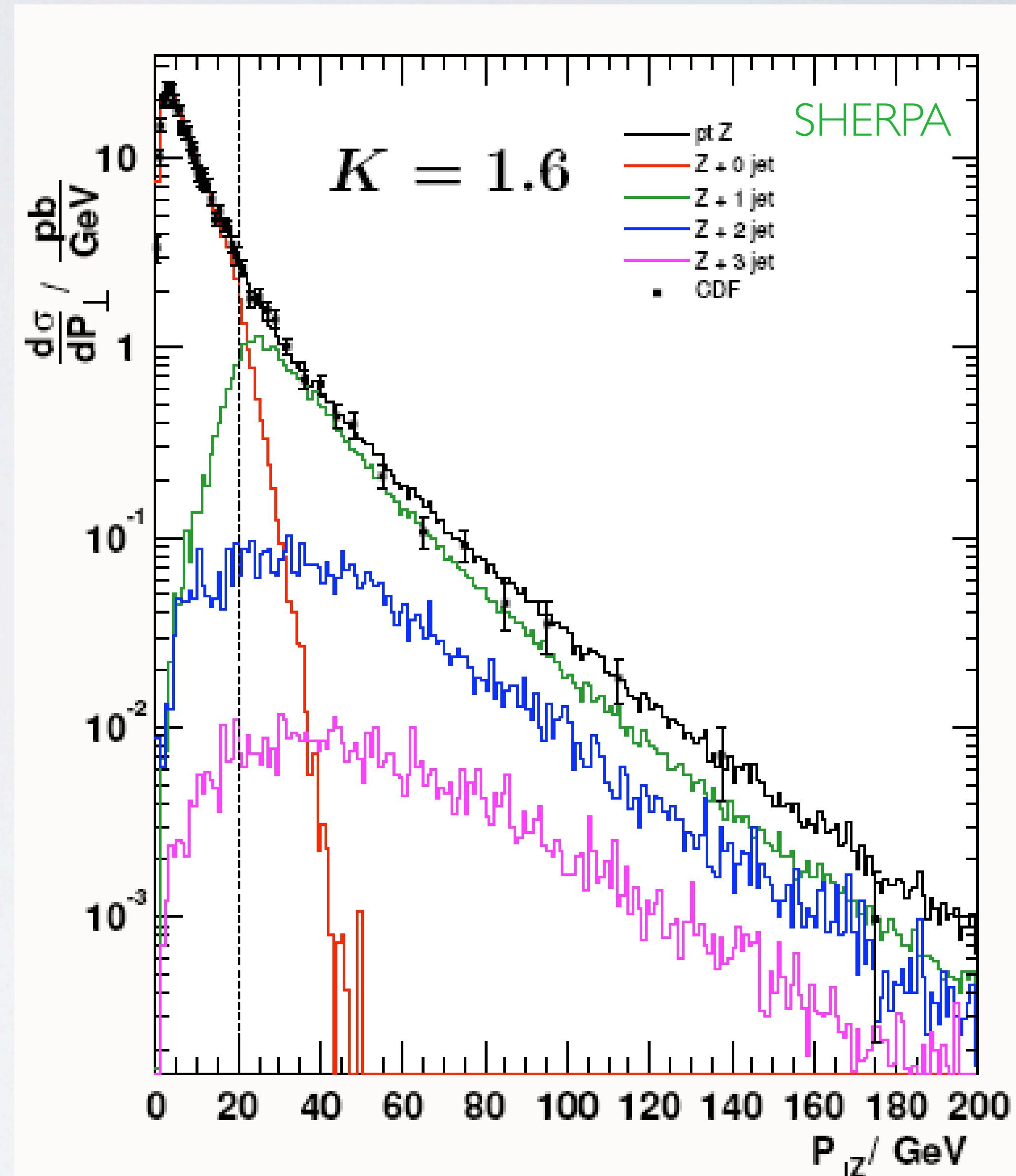
# Merging fixed order with PS

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

PS →

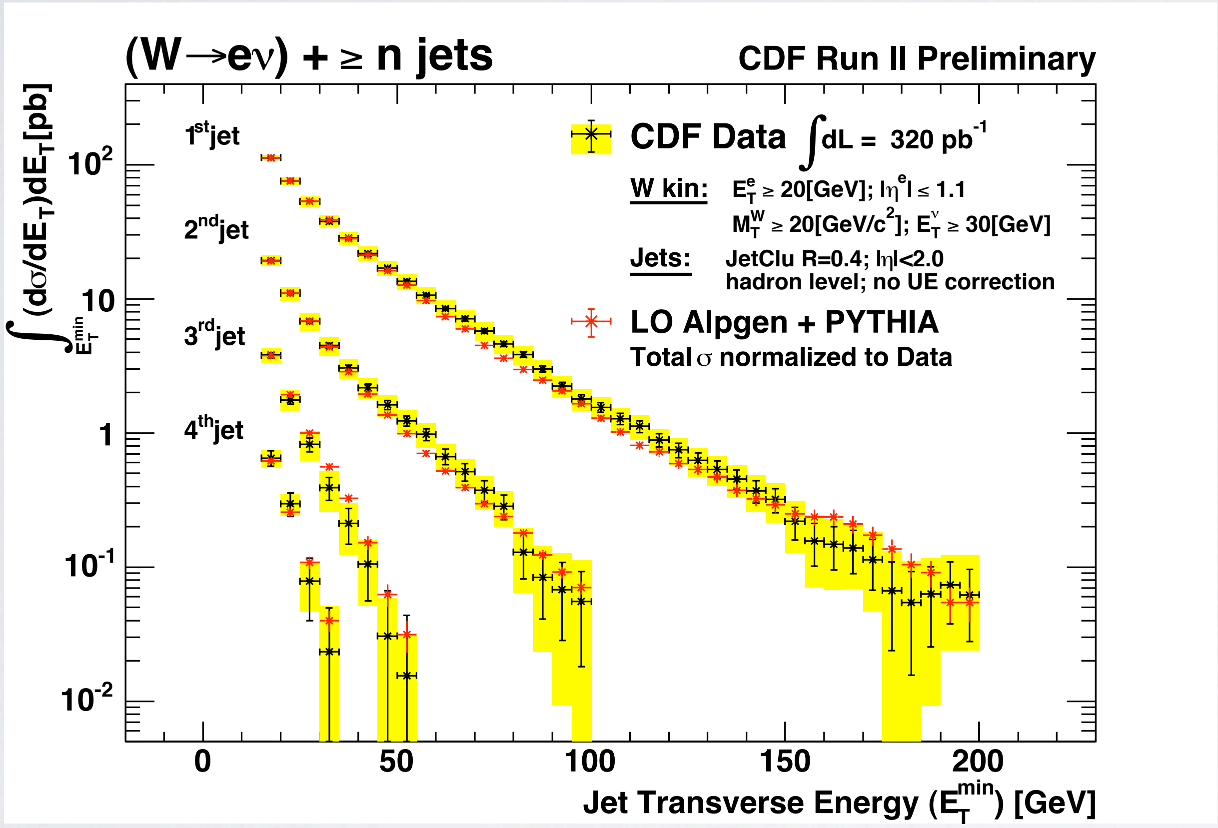
ME ↓

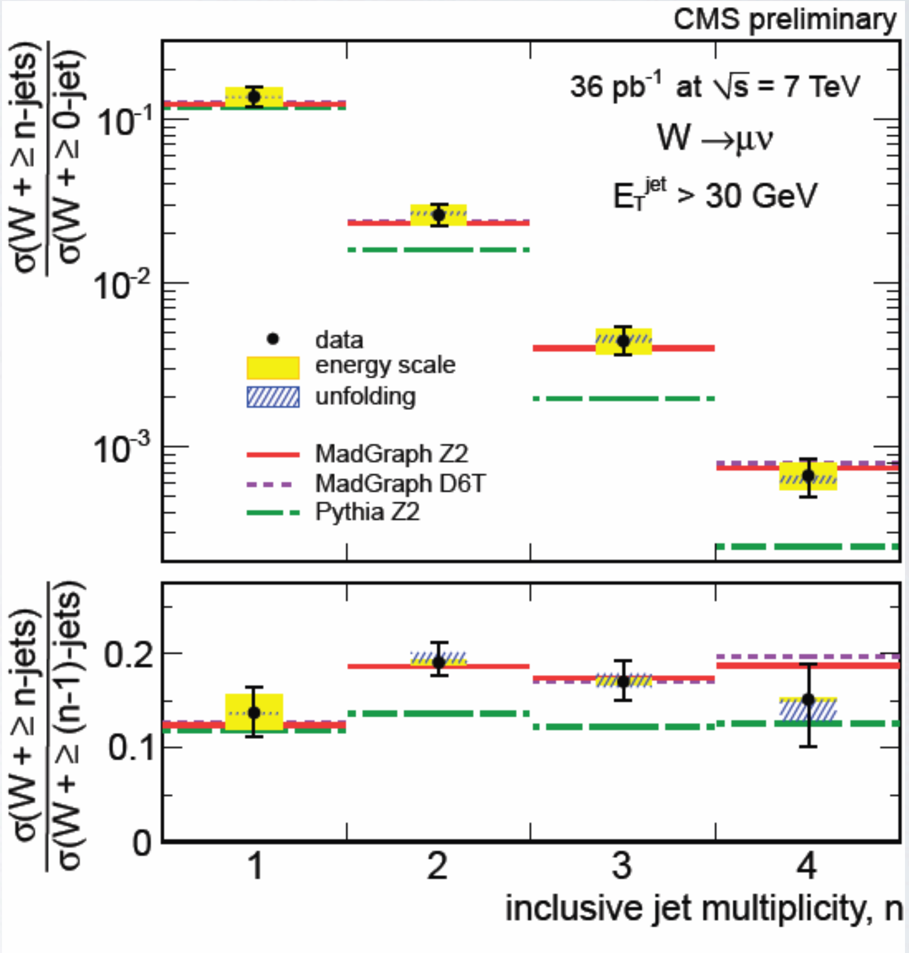



Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample.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

# W+JETS FROM TEVATRON TO LHC



# NLOwPS

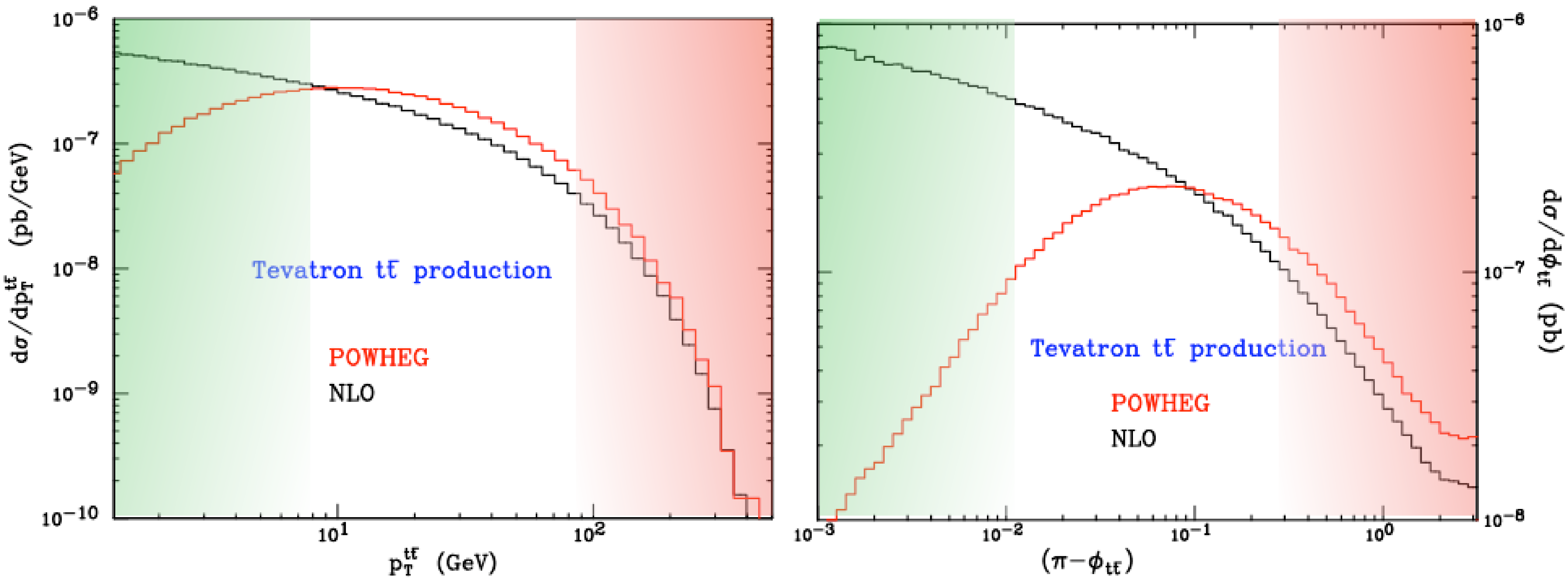
Problem of double counting becomes even more severe at NLO
* Real emission from NLO and PS has to be counted once
* Virtual contributions in the NLO and Sudakov should not overlap

Current available (and working) solutions:

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

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

# TTBAR : NLOWPS VS NLO



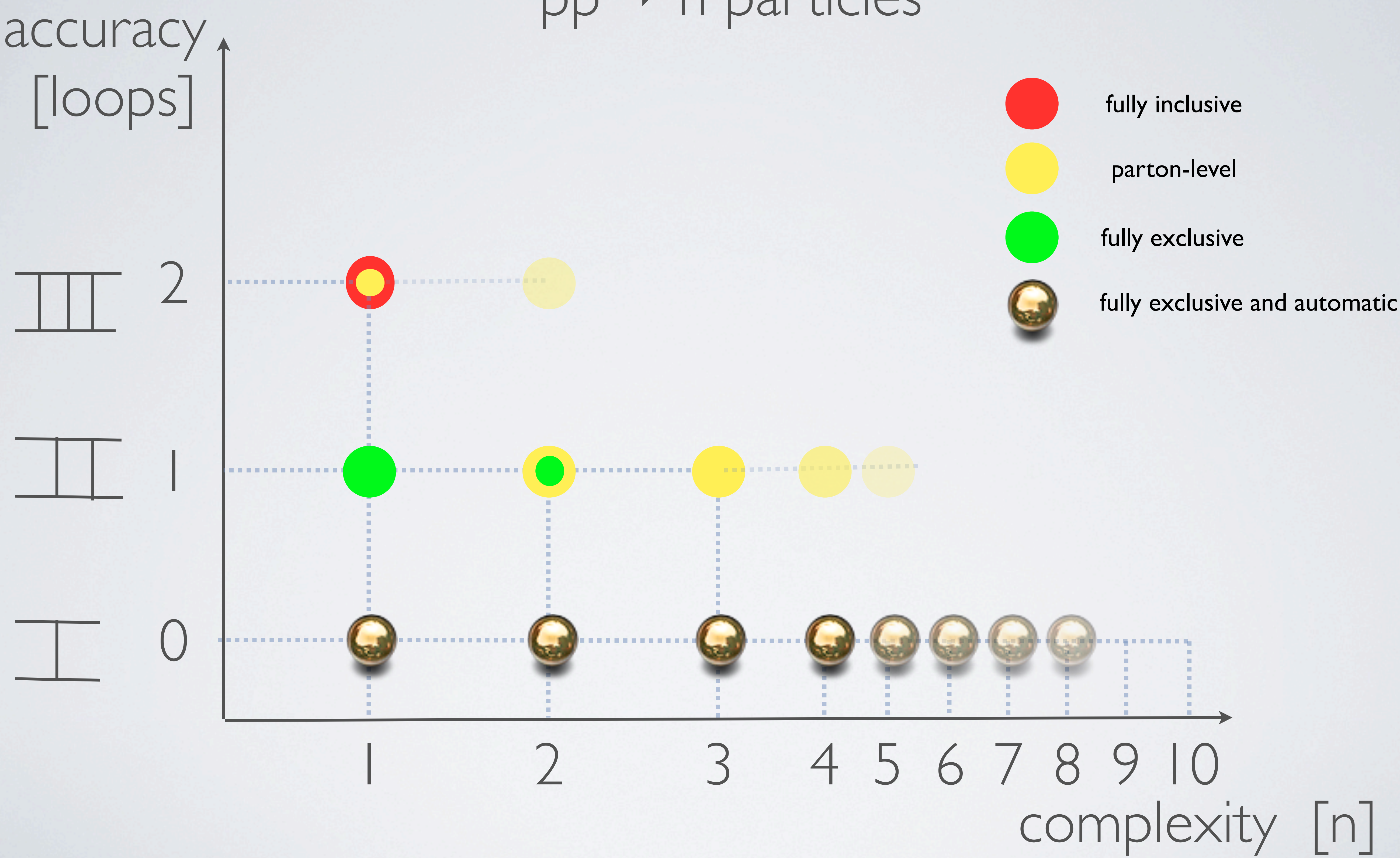

- Soft/Collinear resummation of the $p_T$(tt) →0 region.
- At high $p_T$(tt) it approaches the tt+parton (tree-level) result.
- When Φ(tt)→0 (Φ(tt)→ π) the emitted radiation is hard (soft).
- Normalization is FIXED and non trivial!!

# SM STATUS : SINCE 2007

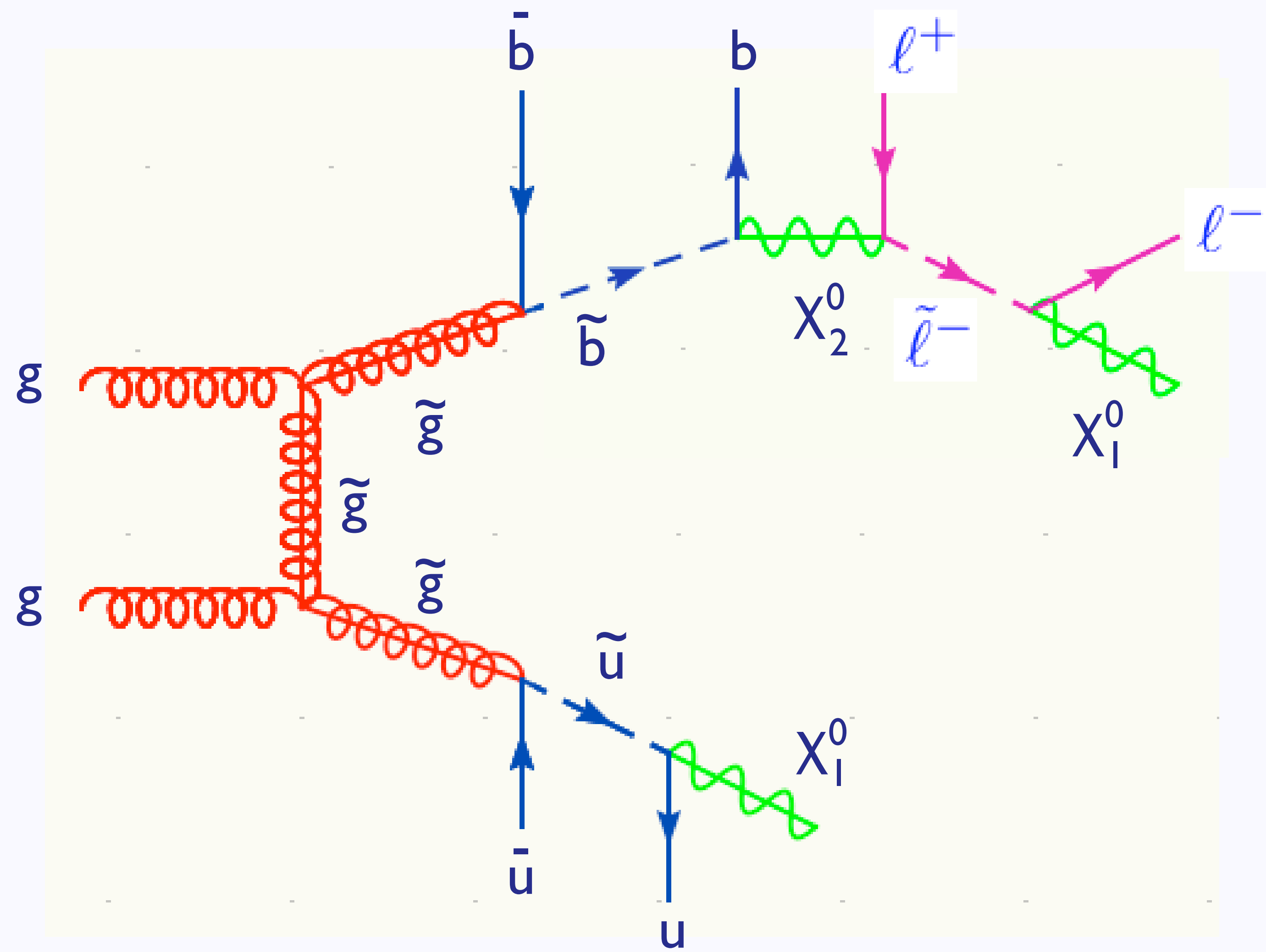
pp→ n particles

# SM STATUS : SINCE 2007

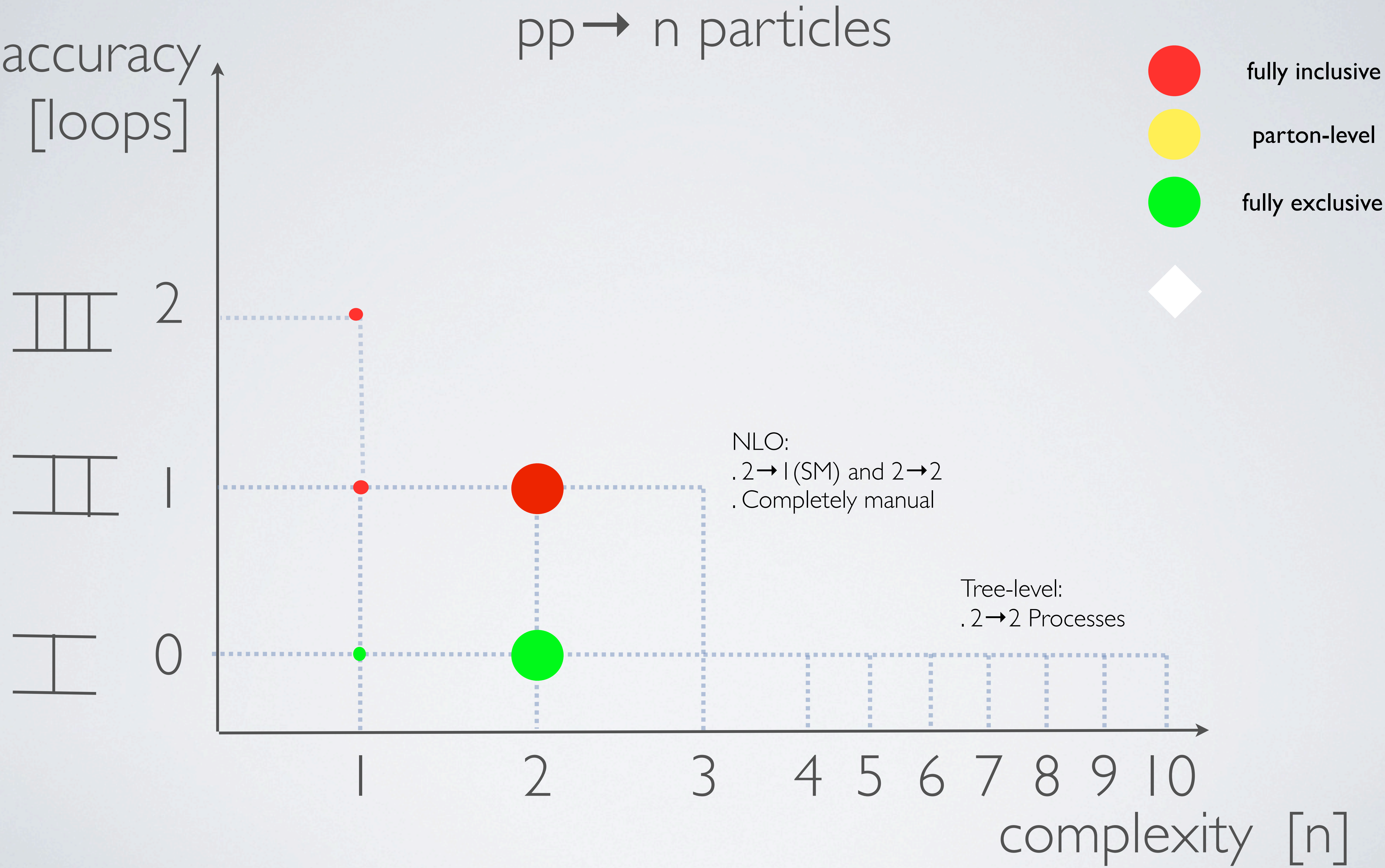
pp → n particles



# WHAT ABOUT NEW PHYSICS?



# BSM (=SUSY) STATUS : BEFORE 2003



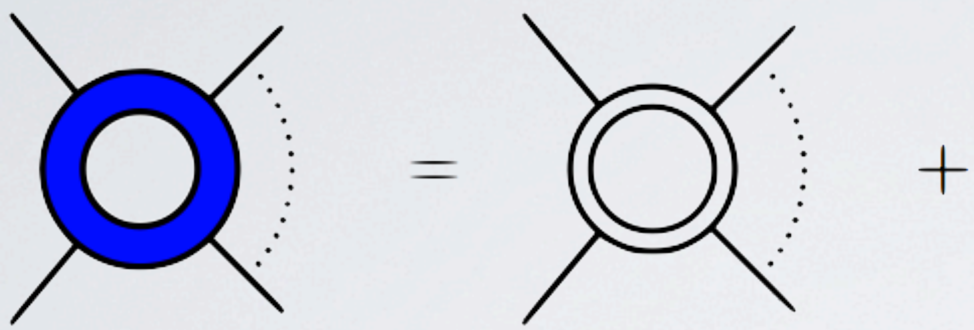
# The circa 2008 LOOP revolution

# NLO BASICS

NLO contributions have three parts

# NLO BASICS

NLO contributions have three parts



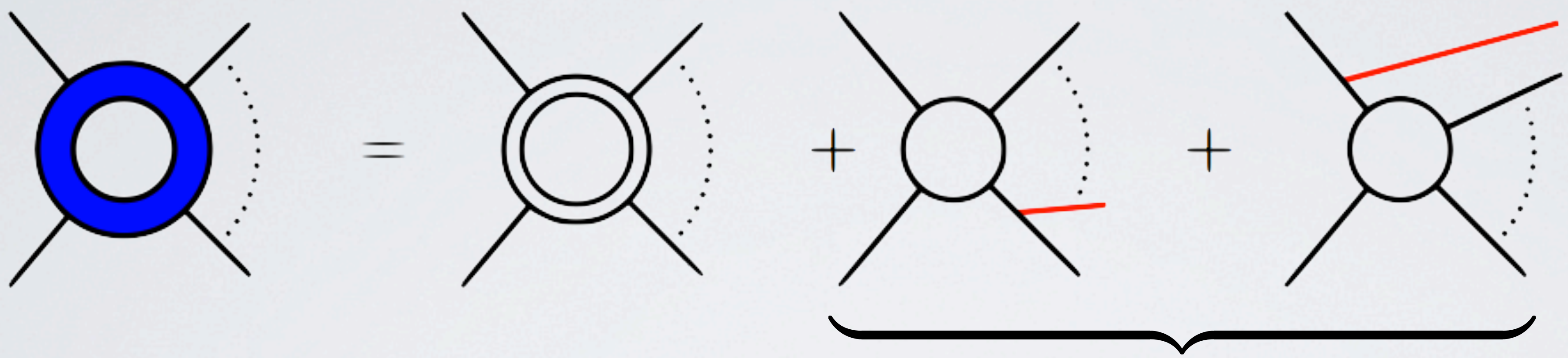

$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V +$$

Virtual part

- Current bottleneck of NLO computations
- Algorithms for automation known in principle but not yet efficiently implemented
- This work brings automation using MadGraph and CutTools interfaced through MadLoop.

# 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

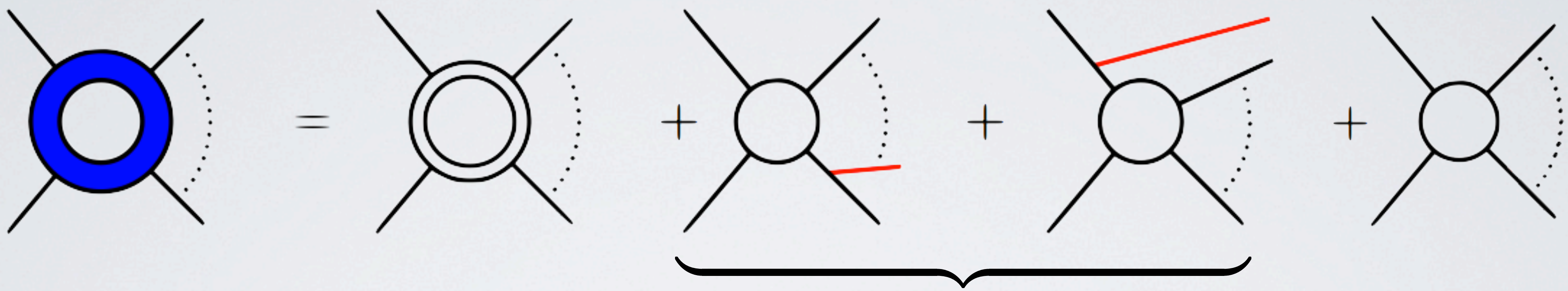
- Current bottleneck of NLO computations
- Algorithms for automation known in principle but not yet efficiently implemented
- This work brings automation using MadGraph and CutTools interfaced through MadLoop.

### Real emission part

- Automated for different methods
- Challenge is the systematic extraction of singularities
- MadFKS using the FKS subtraction method successfully implemented on MGv4

# NLO BASICS

## NLO contributions have three parts



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

### Virtual part

- Current bottleneck of NLO computations
- Algorithms for automation known in principle but not yet efficiently implemented
- This work brings automation using MadGraph and CutTools interfaced through MadLoop.

### Real emission part

- Automated for different methods
- Challenge is the systematic extraction of singularities
- MadFKS using the FKS subtraction method successfully implemented on MGv4

# ESTABLISHED LOOP TECNHIQUES

For the calculation of one-loop matrix elements, several methods are now established :

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

[Bern, Dixon, Dunbar, Kosower, hep-ph/9403226 + ....; Ellis, Giele, Kunszt 0708.2398, +Melnikov 0806.3467]

- Integrand Reduction (ex. CutTools, Samurai)

[Ossola, Papadopolulos, Pittau, hep-ph/0609007; del Aguila, Pittau, hep-ph/0404120; Mastrolia, Ossola, Reiter, Tramontano, 1006.0710]

- Tensor Reduction (ex. Golem)

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

# SUBTRACTION TERMS

IR divergences are dealt with using subtraction terms

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

$$\Downarrow$$

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

- Add local counterterms to make each of the two integrals separately finite.

# ESTABLISHED SUB TECHNIQUES

For the calculation of one-loop matrix elements, several methods are now established :

- Dipoles (ex. MadDipoles, AutoDipole, )
[Catani, Seymour, hep-ph/9605323+..]

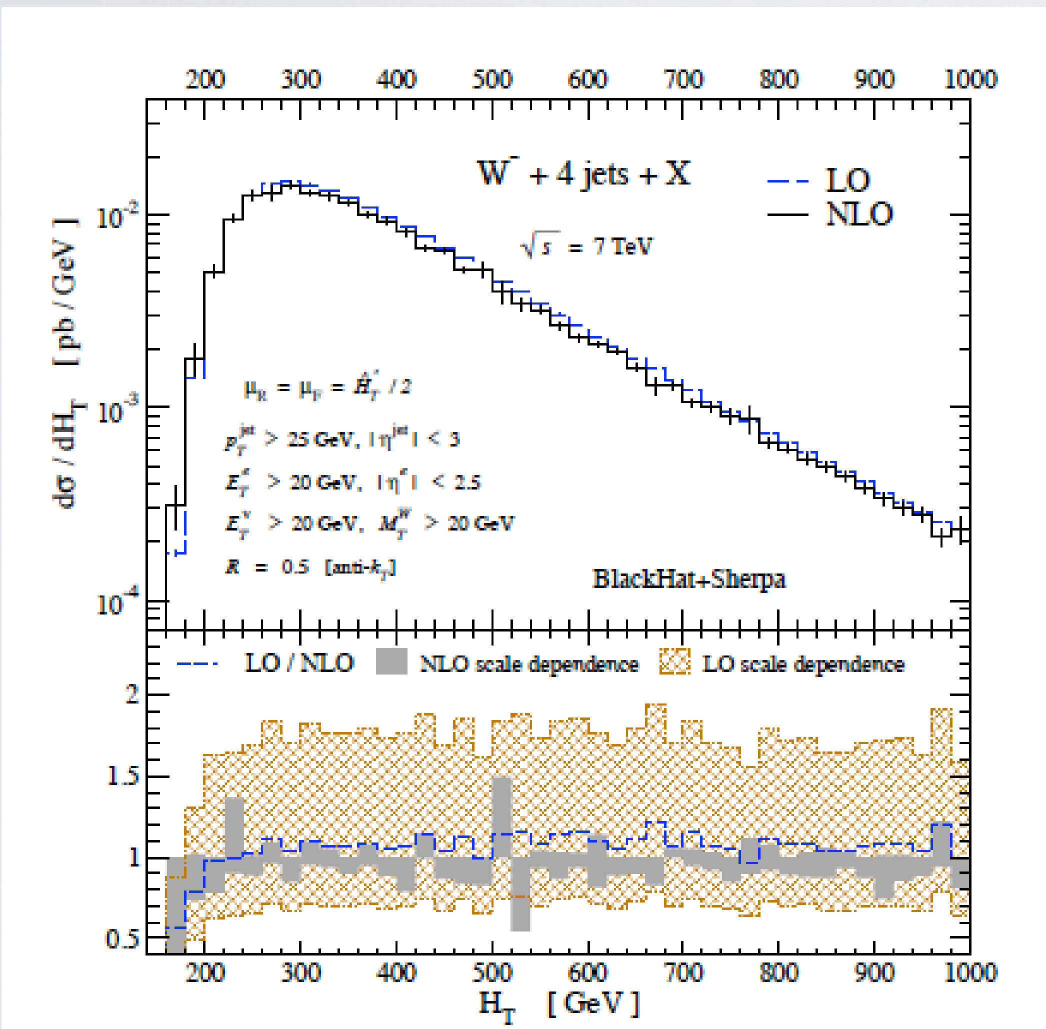
- Antenna (ex. Vincia...)
[Kosower hep-ph/9720213]

- Residue (ex. MadFKS)
[Frixione, Kunszt, Signer, hep-ph/9512328]

# GUINNESS WR NLO CALCULATIONS

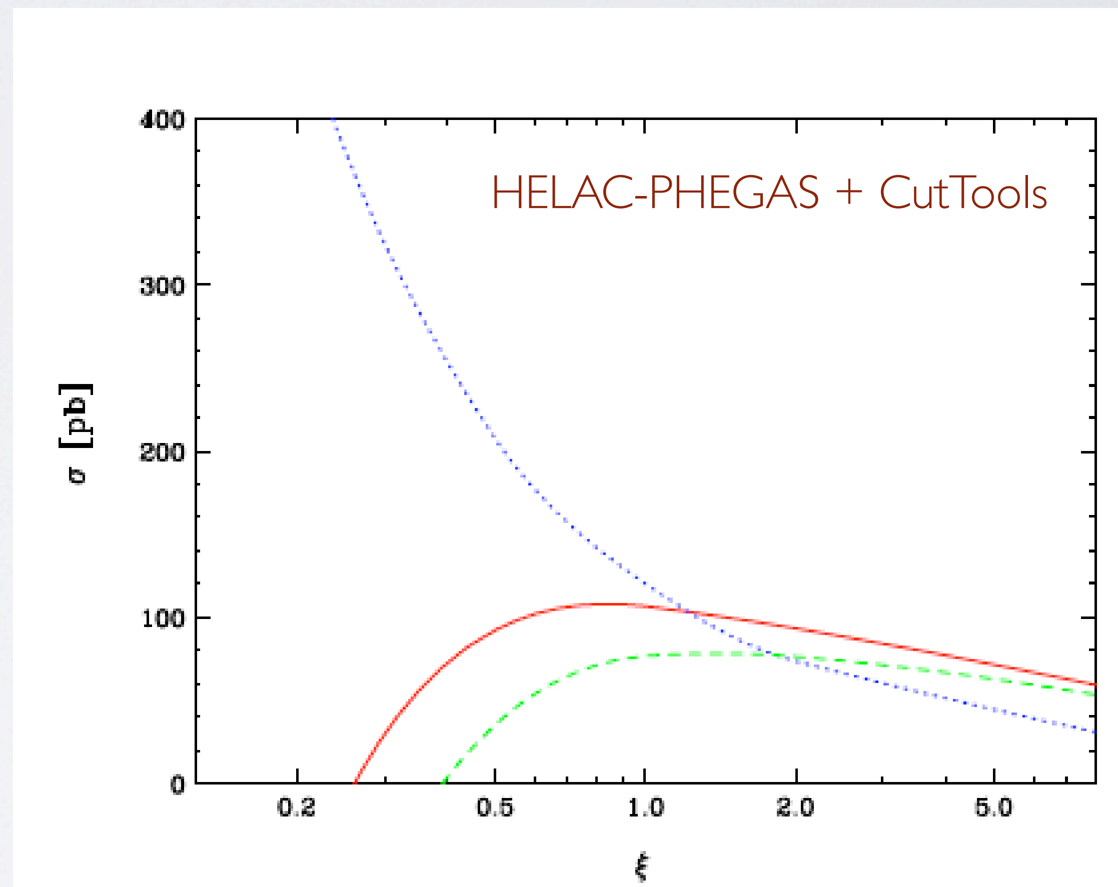
## W+4 jets

[Berger et al., 1009.2338]




## tt+2jets

[Bevilacqua et al., 1002.4009]




Both based on unitarity methods and recursive relations for trees.

# One indicator of NLO progress

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

Slide from L. Dixon

# NLO : SUMMARY

- Many established techniques to make NLO computations
- Some of them are more efficient/general than others.
- Impressive progress and results now make NLO calculations for specific processes a normal (though boring) activity.

## ARE WE THERE YET?

# The dawn of the AAA era

1. NEW Approach to BSM Phenomenology
2. Fully Automatic NLOwPS

# The dawn of the AAA era

1. NEW Approach to BSM Phenomenology
2. Fully Automatic NLOwPS

# WHY AUTOMATIC?

- Cost saving

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

# WHY AUTOMATIC?

- 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.

# WHY AUTOMATIC?

- Cost saving

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

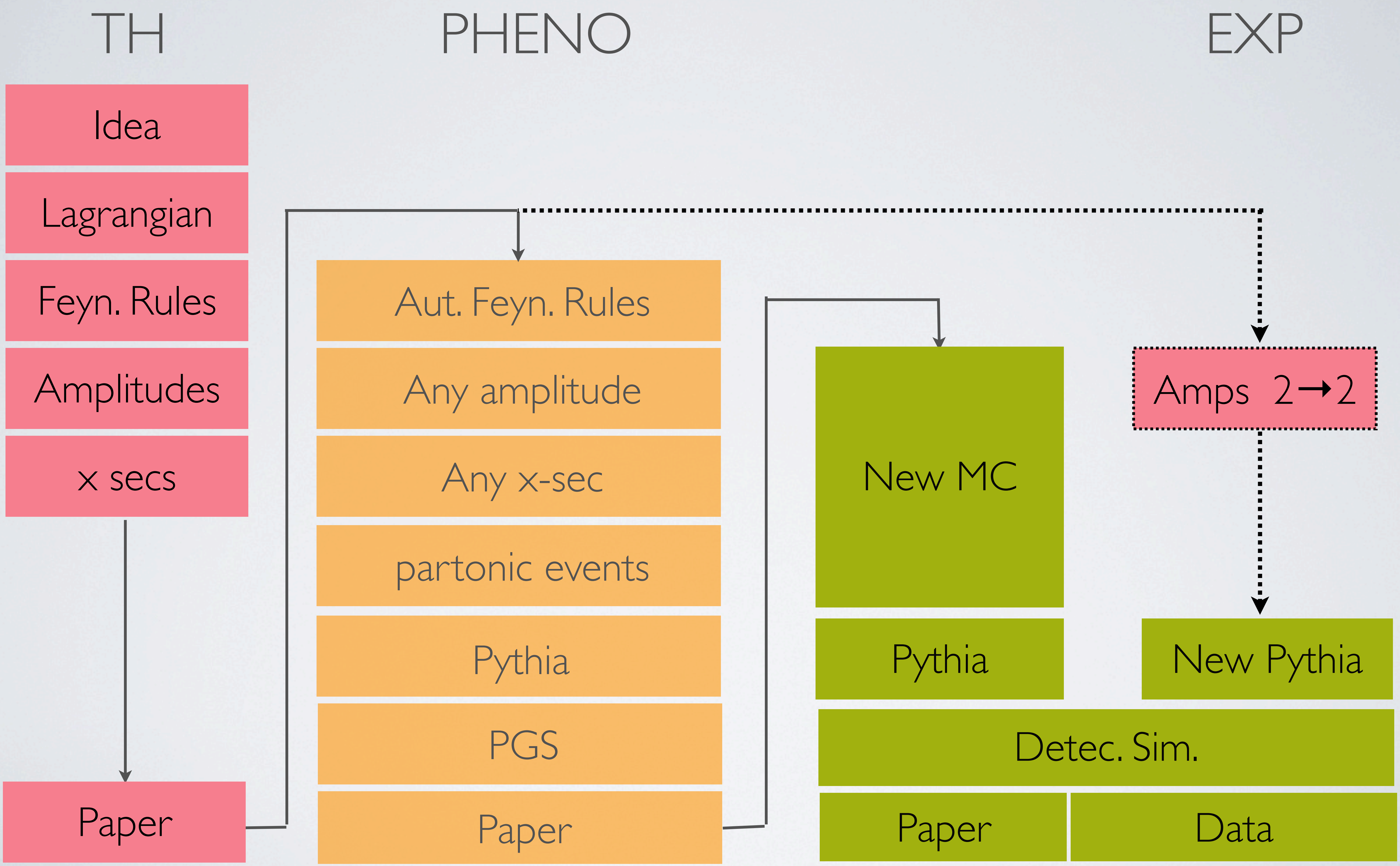
- Robustness

  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.

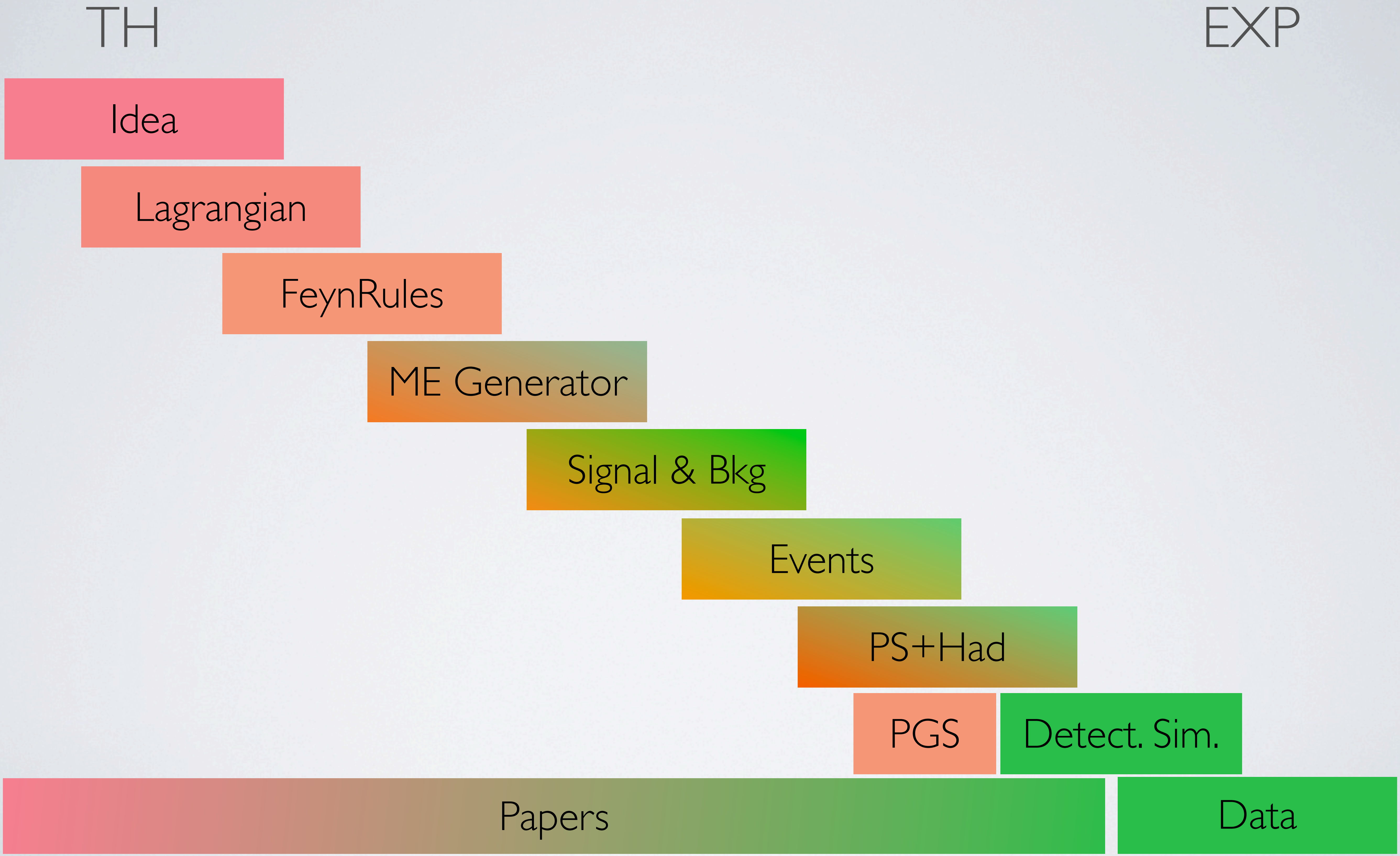
# A Roadmap (with roadblocks) for BSM



# A Roadmap (with roadblocks) for BSM

| TH | PHENO | EXP |
|---|---|---|
| Idea | | |
| Lagrangian | | |
| | Aut. Feyn. Rules | |
| | Any amplitude | |
| | Any x-sec | |
| | partonic events | |
| | | Pythia |
| | | Detec. Sim. |
| | | Data |

# A Roadmap for BSM @ the LHC



# A Roadmap for BSM @ the LHC

TH

EXP

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

Events

PS+Had

PGS

Detect. Sim.

Papers

Data

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

# A Roadmap for BSM @ the LHC

TH

EXP

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

Events

PS+Had

PGS

Detect. Sim.

Papers

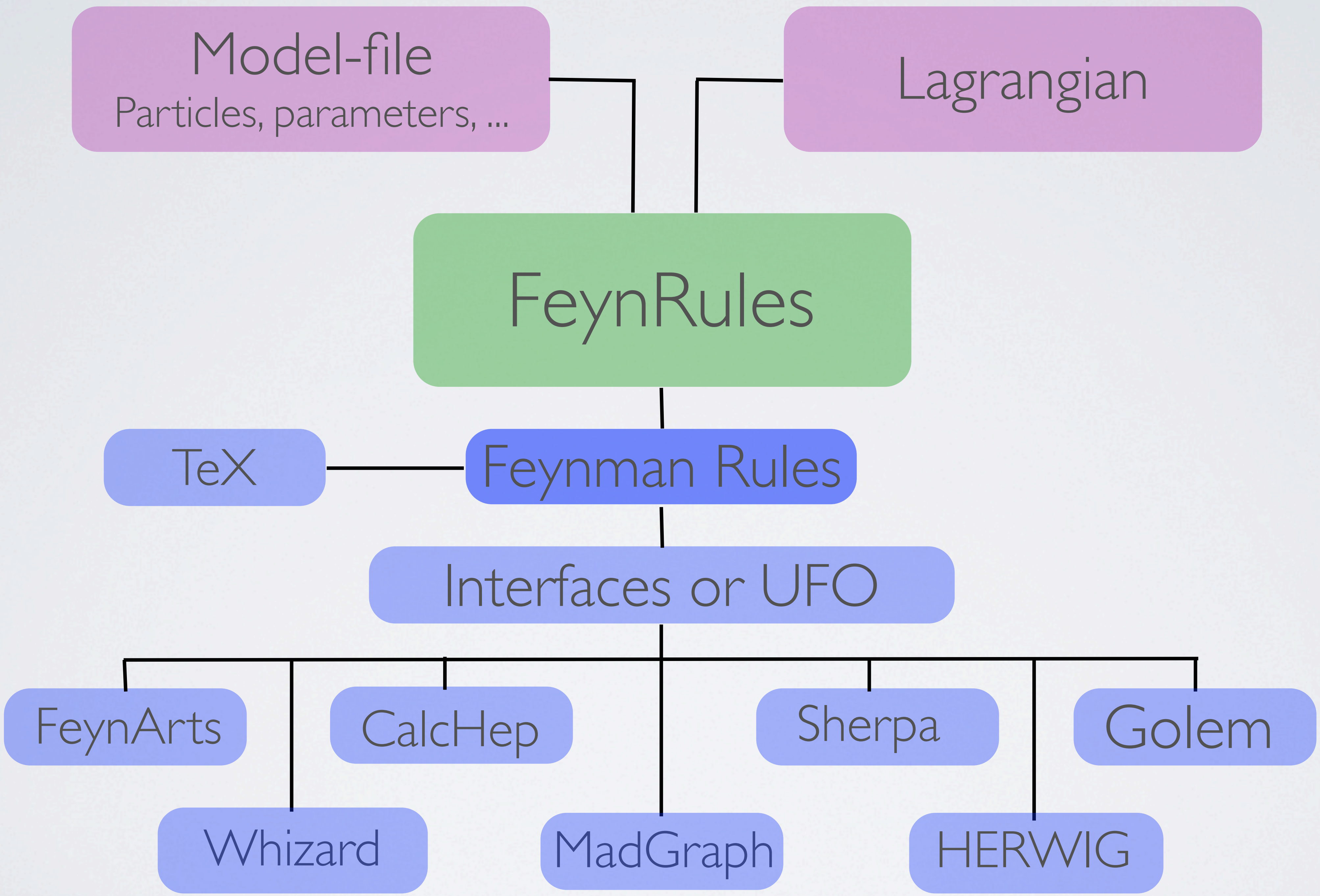
Data

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

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

# THE FEYNRULES PROJECT

[Christensen, Duhr, 2008; Christensen, et al.2009]



# THE FEYNRULES PROJECT

**Available models**

| | |
|---|---|
| Standard Model | The SM implementation of FeynRules, included into the distribution of the FeynRules package. |
| Simple extensions of the SM (9) | Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars. |
| Supersymmetric Models (4) | Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more. |
| Extra-dimensional Models (4) | Extensions of the SM including KK excitations of the SM particles. |
| Strongly coupled and effective field theories (4) | Including Technicolor, Little Higgs, as well as SM higher-dimensional operators. |
| Miscellaneous (0) | |

# THE FEYNRULES PROJECT

**Available models**

| | |
|---|---|
| Standard Model | The SM implementation of FeynRules, included into the distribution of the FeynRules package. |
| Simple extensions of the SM (9) | Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars. |
| Supersymmetric Models (4) | Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more. |
| Extra-din | |
| Strongly theories | |
| Miscellan | |

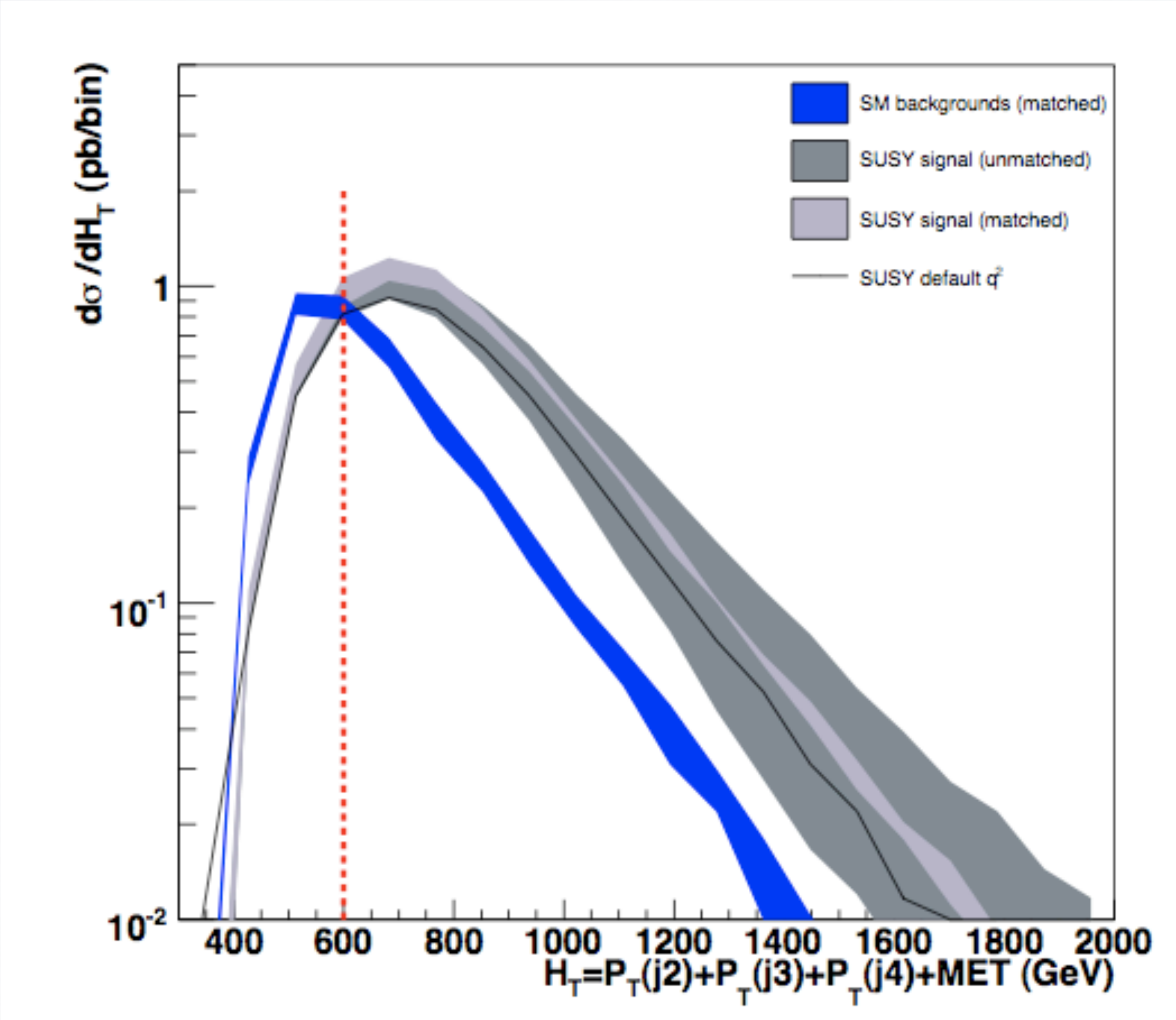
| Model | Short Description | Contact | Status |
|---|---|---|---|
| Higgs effective theory | An add-on for the SM implementation containing the dimension 5 gluon fusion operator. | C. Duhr | **Available** |
| 4th generation model | A fourth generation model including a t' and a b' | C. Duhr | **Available** |
| Standard model + Scalars | The SM, together with a set of singlet scalar particles coupling only to the SM Higgs, and allowing it to decay invisibly into this new scalar sector. | C. Duhr | **Available** |
| Hidden Abelian Higgs Model | A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings. | C. Duhr | **Available** |
| Hill Model | A model with an unusual extension of the SM Higgs sector. | P. de Aquino, C. Duhr | **Available** |
| The general 2HDM | The most general 2HDM, including all flavor violation and mixing terms. | C. Duhr, M. Herquet | **Available** |
| Triplet diquarks | The SM plus triplet diquark scalars. | J. Alwall, C. Duhr | **Available** |
| Sextet diquarks | The SM plus sextet diquark scalars. | J. Alwall, C. Duhr | **Available** |

# THE FEYNRULES PROJECT

- Public database, user driven, easy legacy
- All automatic ME generators supported
- Unprecedented validation and robustness
- It can be systematically improved/extended
- Superfield notation, higher spin-particles,
- User driven easy new functionalities (eg, NLO)

# SUSY multijet final states

[Alwall, de Visscher, FM, 2009]

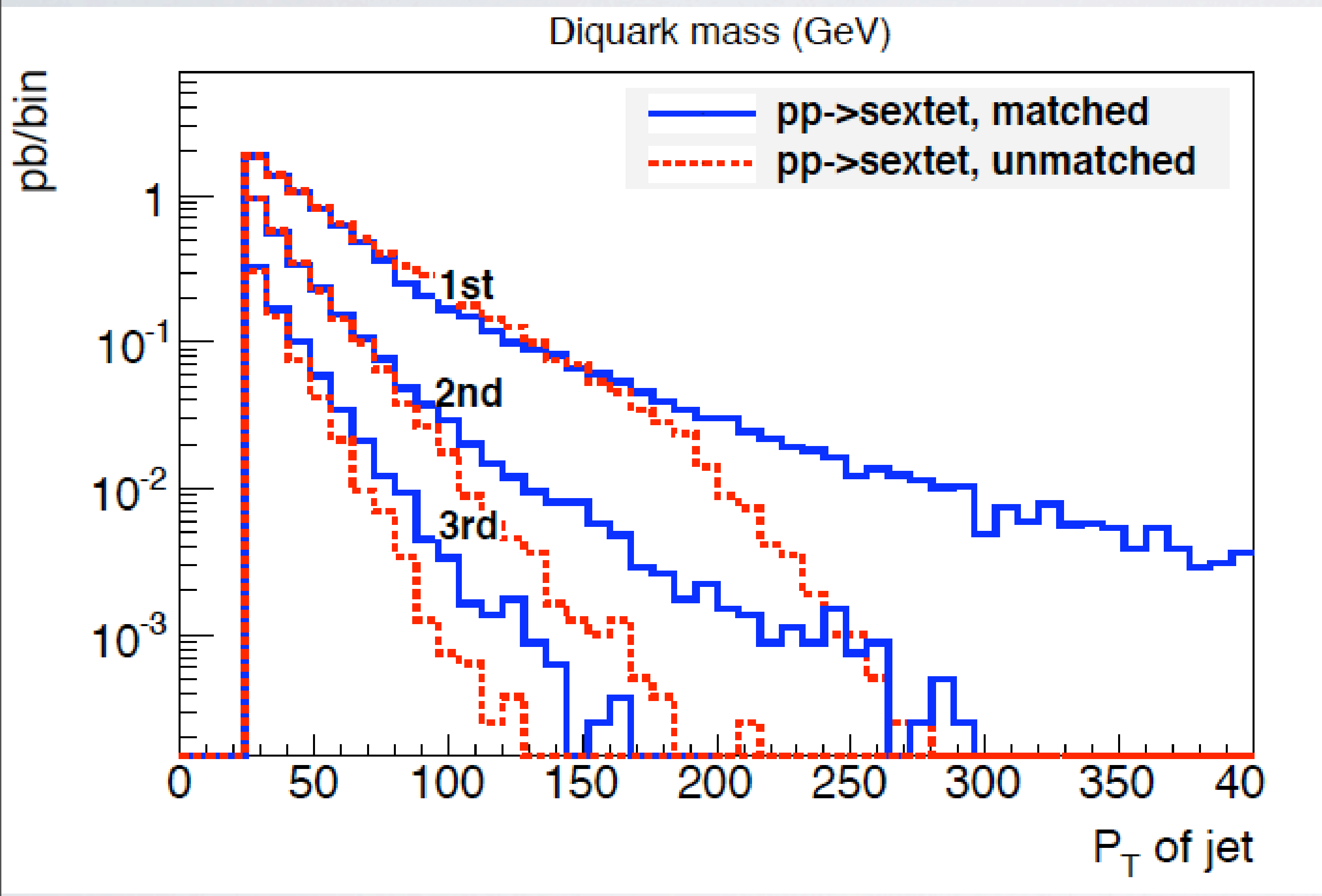



Both signal and background matched!

Sizable reduction of the uncertainties. Overall picture unchanged for SPS1a.

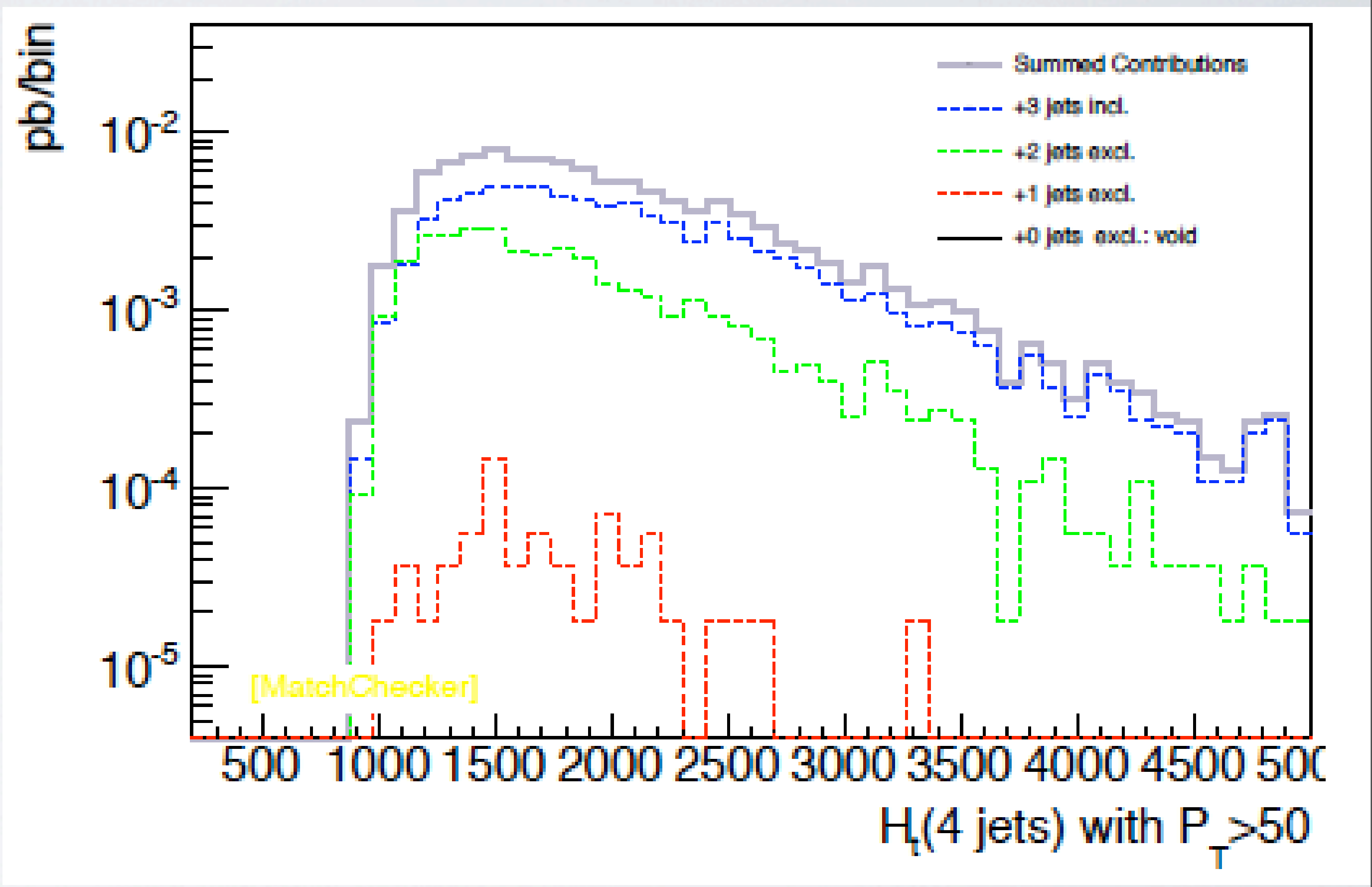
# ANY BSM MULTIJET FINAL STATES

pp→X6 +jets



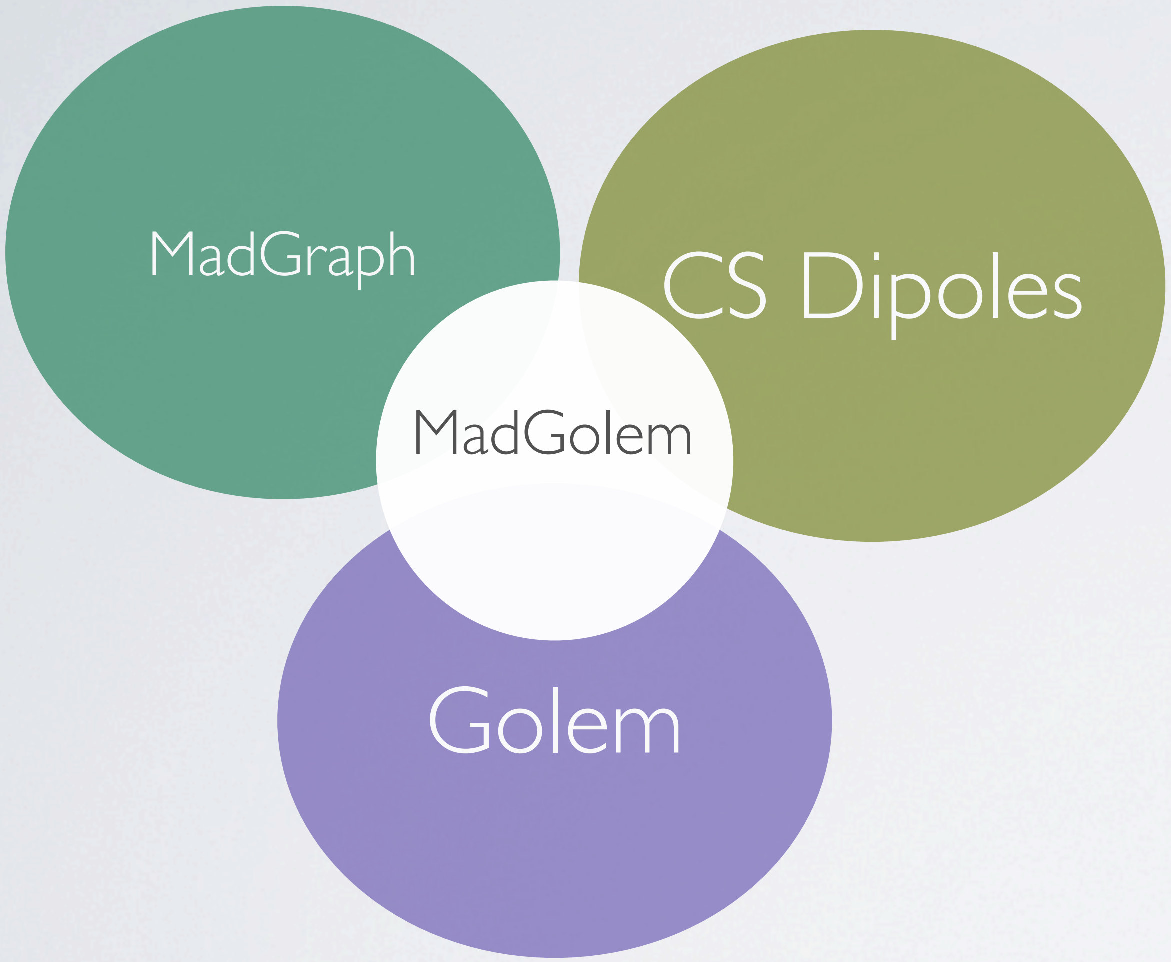

[Alwall 2011]

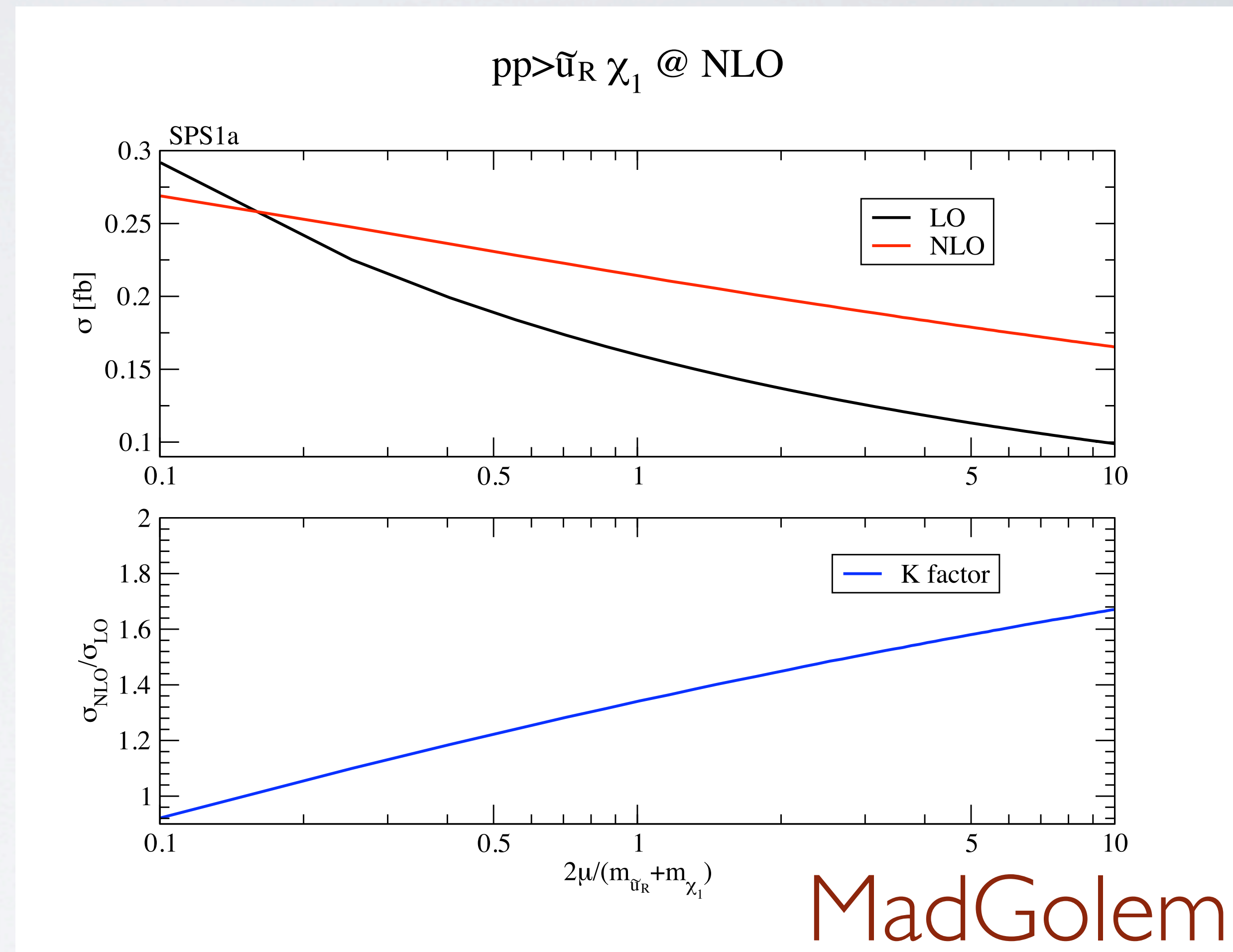
pp→Graviton (ADD&RS) +jets




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

# FIRST STEPS TOWARDS AUTOMATIC SUSY AT NLO



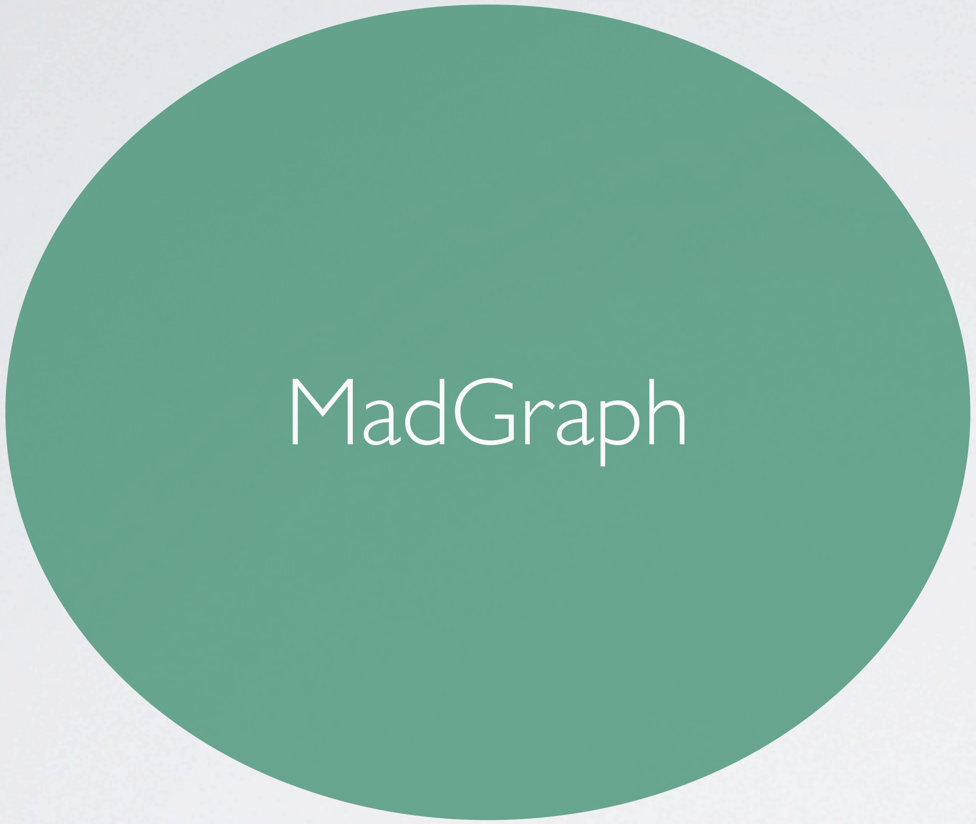

* Dorival Gon,calves Netto, ITP, Univ. Heidelberg
* Fabian Gross, ITP, Univ. Heidelberg
* David Lopez Val, ITP, Univ. Heidelberg
* Kentarou Mawatari, Vrije Univ. Brussels
* Tilman Plehn, ITP, Univ. Heidelberg
* Ioan Wigmore, SUPA, Univ. Edinburgh

# THE DAWN OF THE AAA ERA

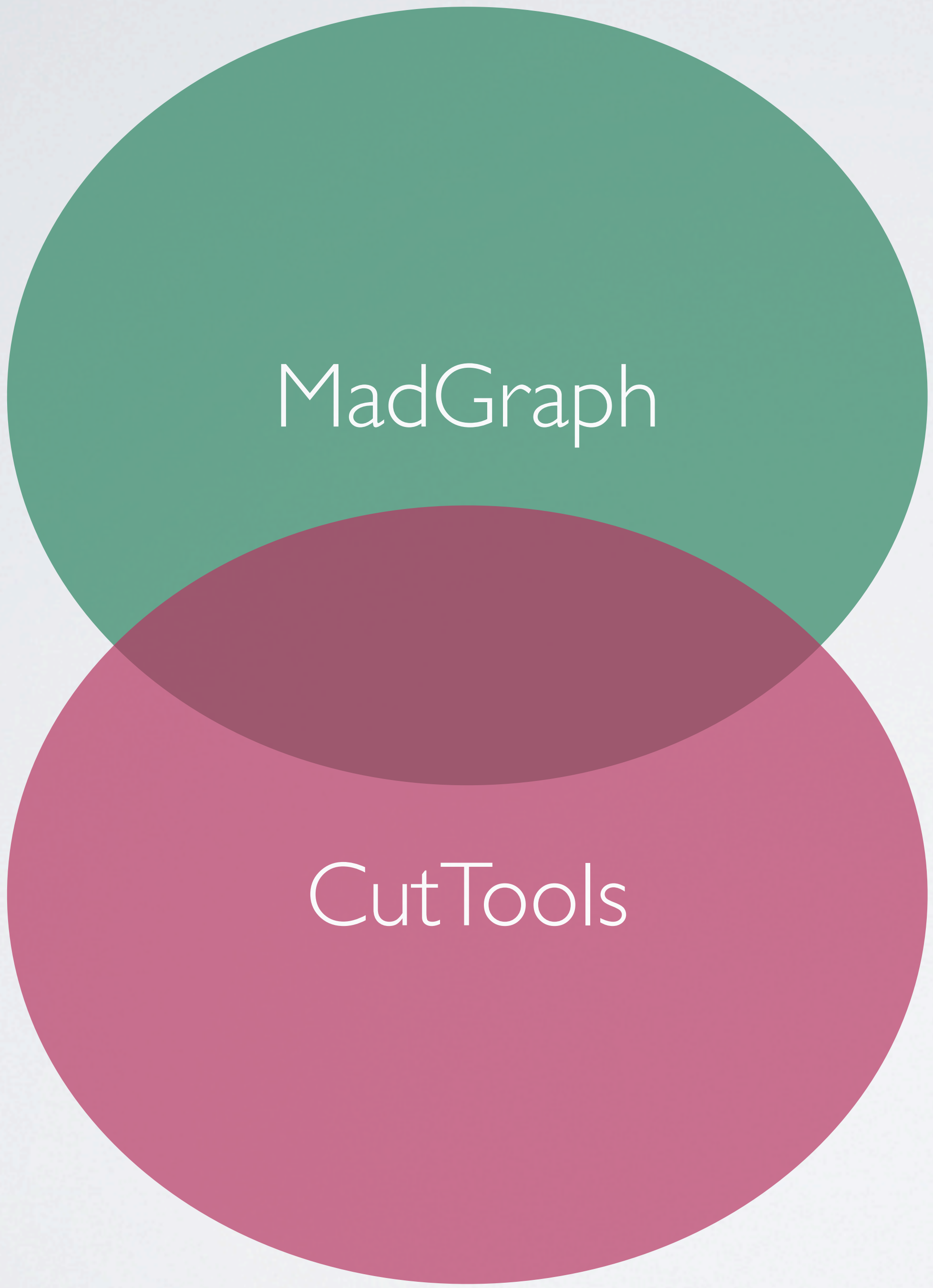
1. NEW Approach to BSM Phenomenology
2. Fully Automatic NLOwPS

# THE aMC@NLO JOINT VENTURE

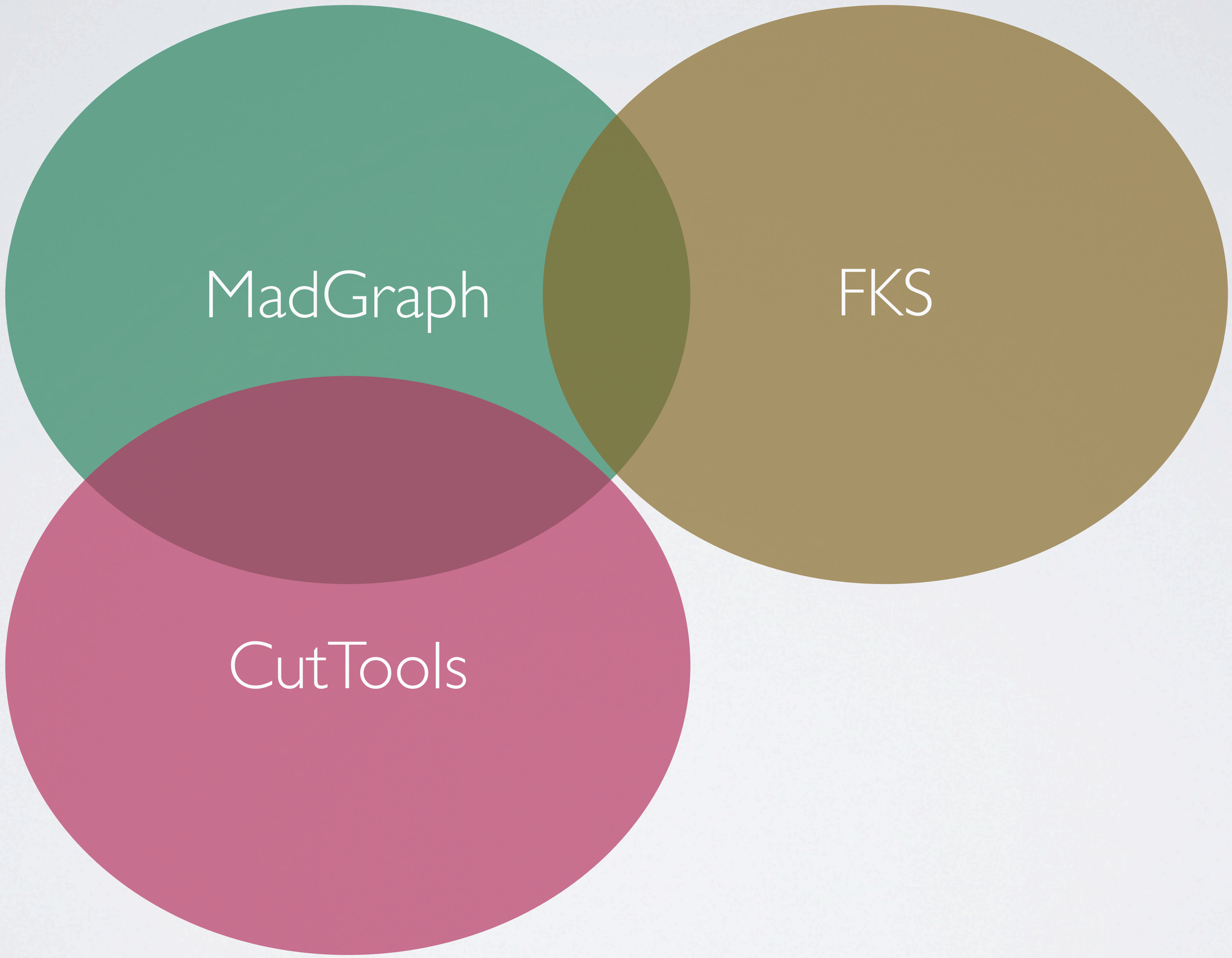
# THE aMC@NLO JOINT VENTURE



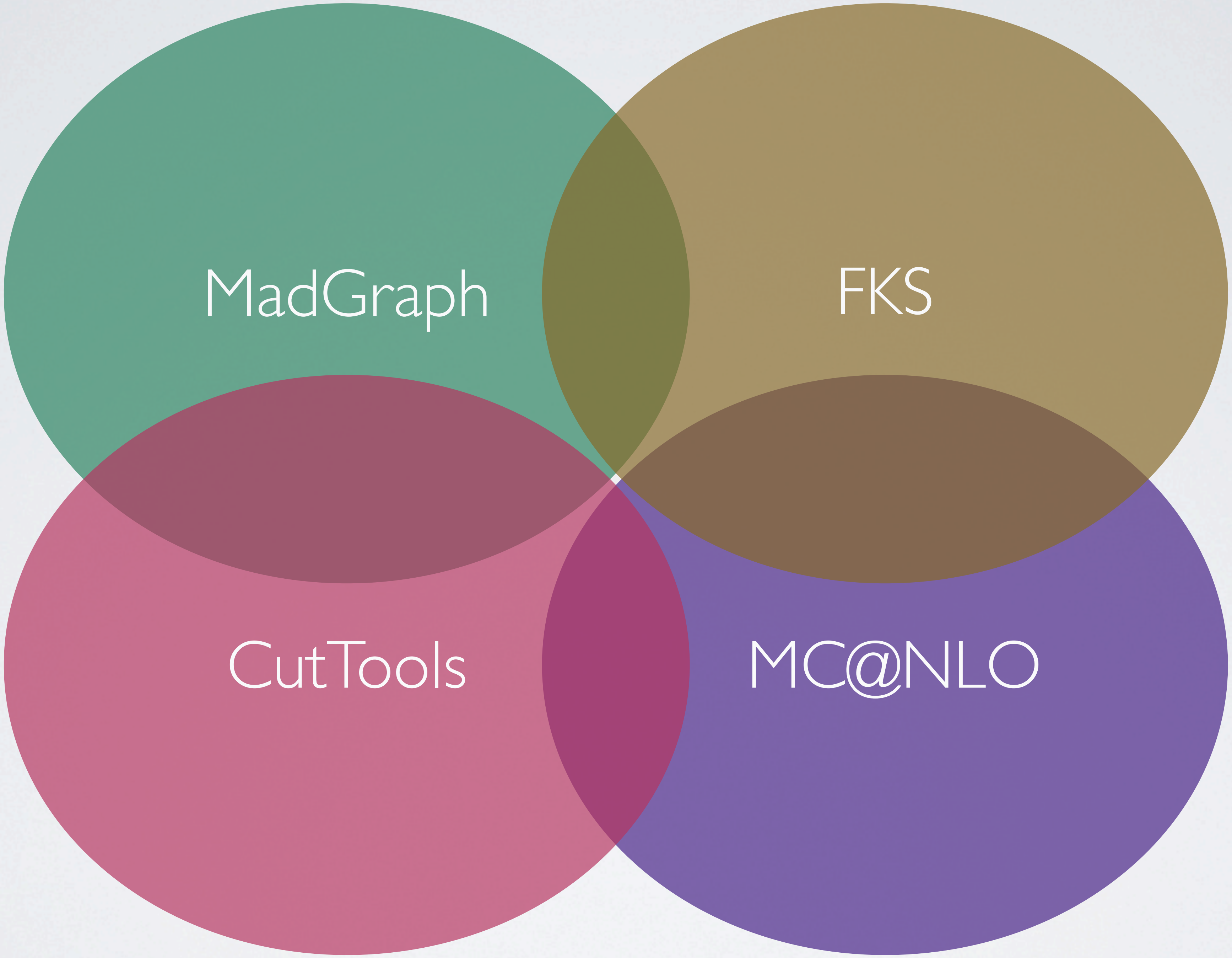
# THE aMC@NLO JOINT VENTURE



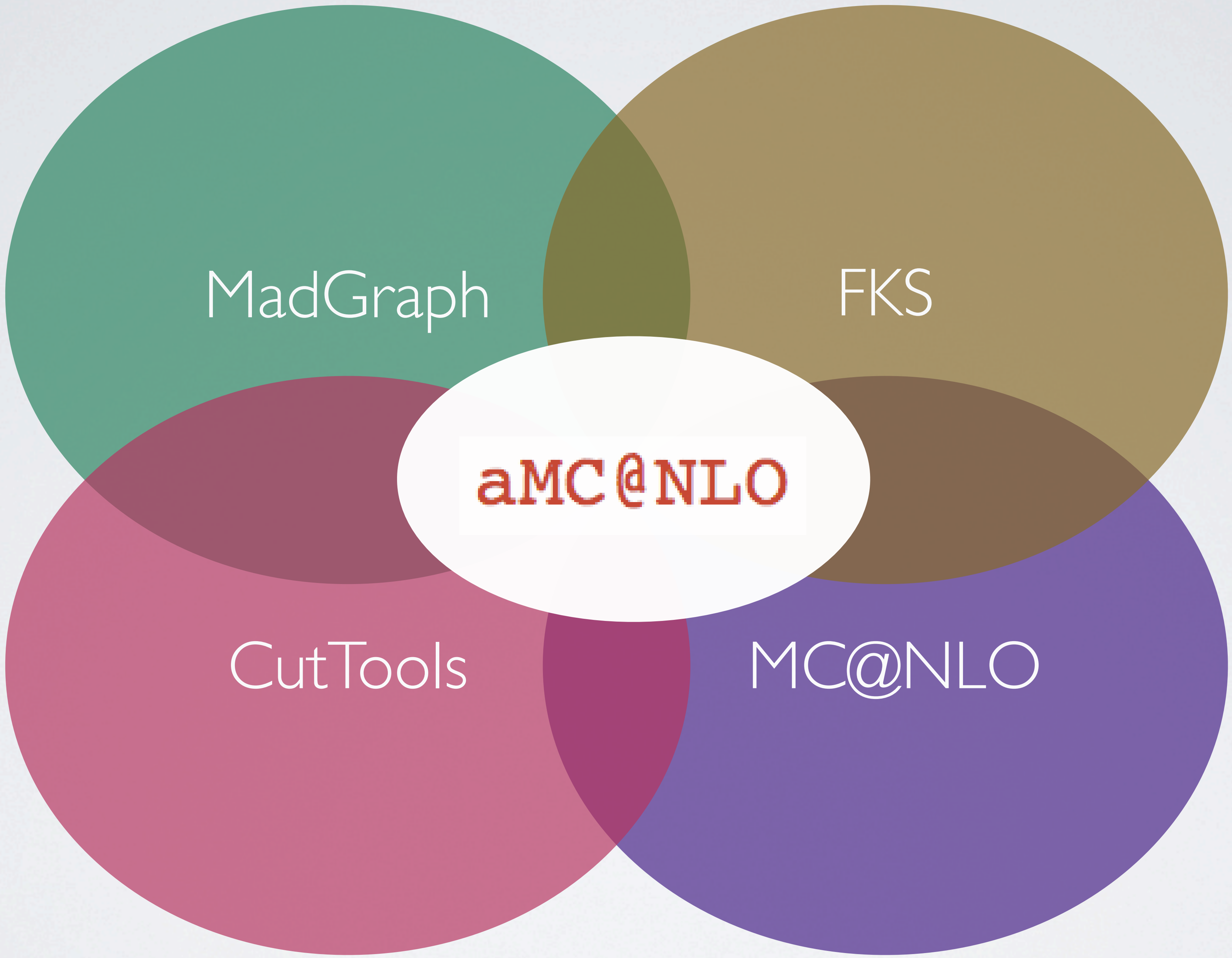
# THE aMC@NLO JOINT VENTURE



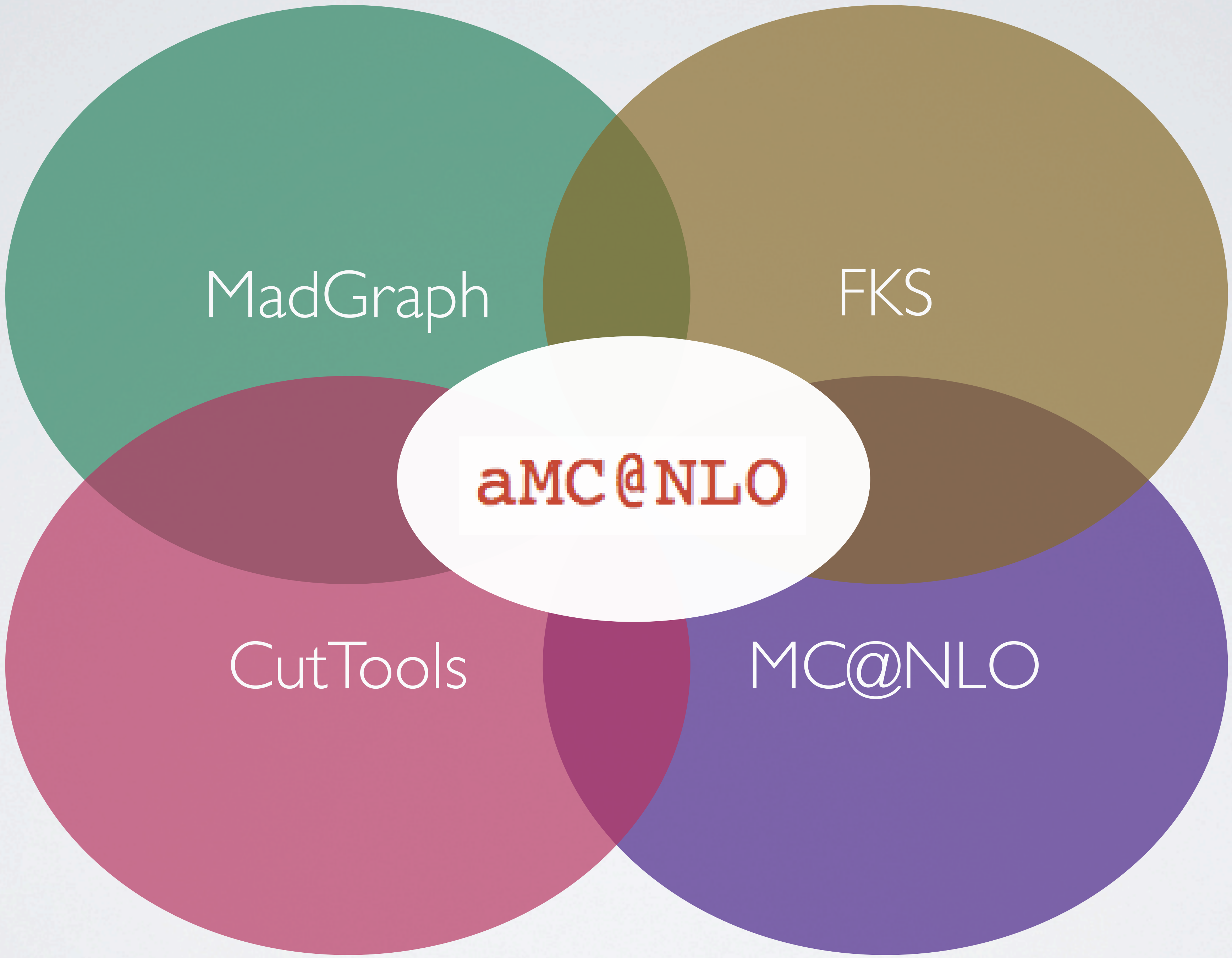
# THE aMC@NLO JOINT VENTURE



# THE aMC@NLO JOINT VENTURE



# THE aMC@NLO JOINT VENTURE




http://amcatnlo.cern.ch

# AUTOMATIC NLO IN SM

## MADLOOP+MADFKS

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

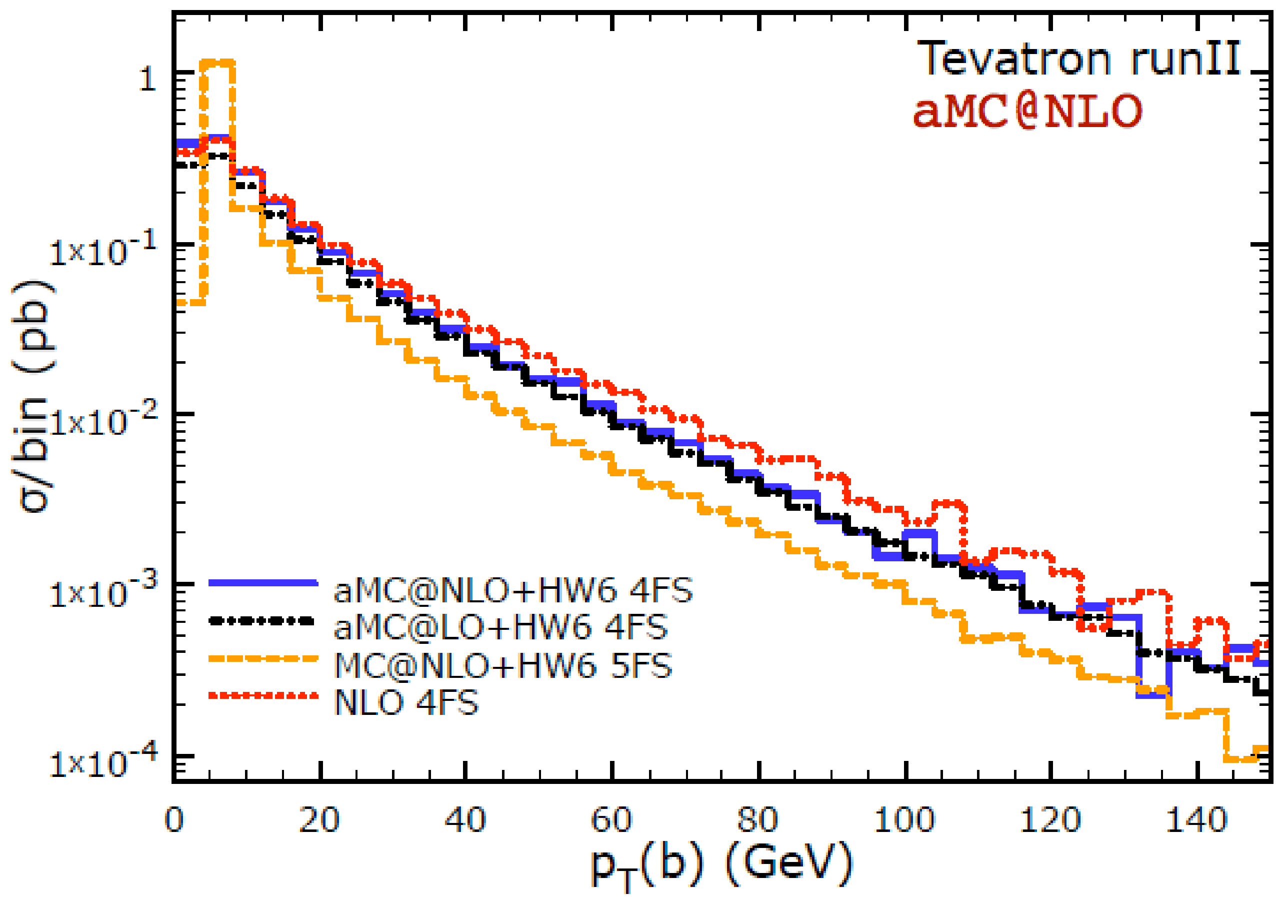
- Total cross sections at the LHC for 26 sample procs
- Very loose cuts just when needed
- Running time: Two weeks on a 150+ node cluster
- Proof of efficient EPS handling with ttZ.
- Successful cross-check against known results (and bugs found in other NLO codes Zjj, W+W+jj)

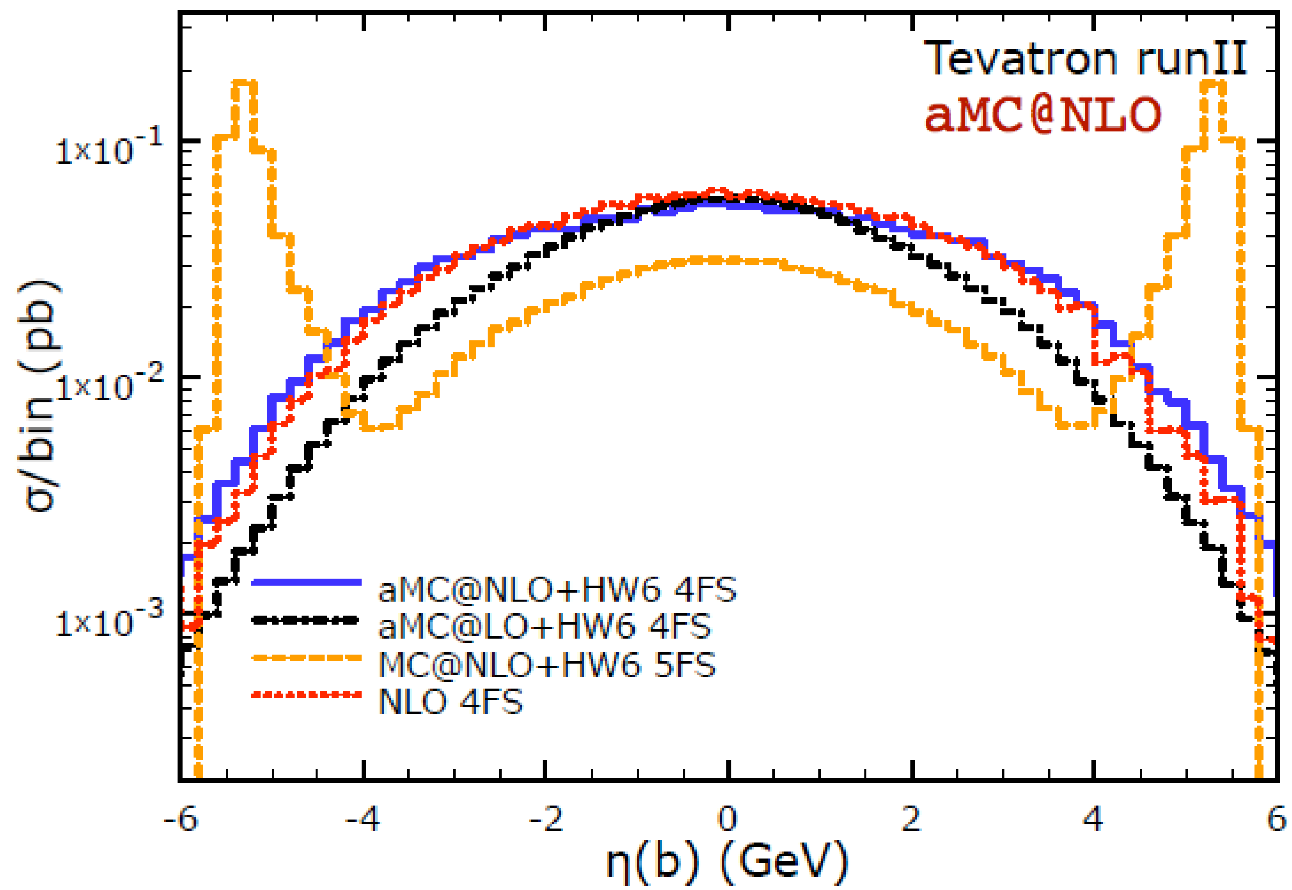
| | Process | $\mu$ | $n_{lf}$ | Cross section (pb) LO | NLO |
|---|---|---|---|---|---|
| a.1 | $pp\to t\bar{t}$ | $m_{top}$ | 5 | $123.76\pm0.05$ | $162.08\pm0.12$ |
| a.2 | $pp\to tj$ | $m_{top}$ | 5 | $34.78\pm0.03$ | $41.03\pm0.07$ |
| a.3 | $pp\to tjj$ | $m_{top}$ | 5 | $11.851\pm0.006$ | $13.71\pm0.02$ |
| a.4 | $pp\to t\bar{b}j$ | $m_{top}/4$ | 4 | $25.62\pm0.01$ | $30.96\pm0.06$ |
| a.5 | $pp\to t\bar{b}jj$ | $m_{top}/4$ | 4 | $8.195\pm0.002$ | $8.91\pm0.01$ |
| b.1 | $pp\to(W^+\to)e^+\nu_e$ | $m_W$ | 5 | $5072.5\pm2.9$ | $6146.2\pm9.8$ |
| b.2 | $pp\to(W^+\to)e^+\nu_e\,j$ | $m_W$ | 5 | $828.4\pm0.8$ | $1065.3\pm1.8$ |
| b.3 | $pp\to(W^+\to)e^+\nu_e\,jj$ | $m_W$ | 5 | $298.8\pm0.4$ | $300.3\pm0.6$ |
| b.4 | $pp\to(\gamma^*/Z\to)e^+e^-$ | $m_Z$ | 5 | $1007.0\pm0.1$ | $1170.0\pm2.4$ |
| b.5 | $pp\to(\gamma^*/Z\to)e^+e^-\,j$ | $m_Z$ | 5 | $156.11\pm0.03$ | $203.0\pm0.2$ |
| b.6 | $pp\to(\gamma^*/Z\to)e^+e^-\,jj$ | $m_Z$ | 5 | $54.24\pm0.02$ | $56.69\pm0.07$ |
| c.1 | $pp\to(W^+\to)e^+\nu_e b\bar{b}$ | $m_W+2m_b$ | 4 | $11.557\pm0.005$ | $22.95\pm0.07$ |
| c.2 | $pp\to(W^+\to)e^+\nu_e t\bar{t}$ | $m_W+2m_{top}$ | 5 | $0.009415\pm0.000003$ | $0.01159\pm0.00001$ |
| c.3 | $pp\to(\gamma^*/Z\to)e^+e^-b\bar{b}$ | $m_Z+2m_b$ | 4 | $9.459\pm0.004$ | $15.31\pm0.03$ |
| c.4 | $pp\to(\gamma^*/Z\to)e^+e^-t\bar{t}$ | $m_Z+2m_{top}$ | 5 | $0.0035131\pm0.0000004$ | $0.004876\pm0.000002$ |
| c.5 | $pp\to\gamma t\bar{t}$ | $2m_{top}$ | 5 | $0.2906\pm0.0001$ | $0.4169\pm0.0003$ |
| d.1 | $pp\to W^+W^-$ | $2m_W$ | 4 | $29.976\pm0.004$ | $43.92\pm0.03$ |
| d.2 | $pp\to W^+W^-\,j$ | $2m_W$ | 4 | $11.613\pm0.002$ | $15.174\pm0.008$ |
| d.3 | $pp\to W^+W^+\,jj$ | $2m_W$ | 4 | $0.07048\pm0.00004$ | $0.1377\pm0.0005$ |
| e.1 | $pp\to HW^+$ | $m_W+m_H$ | 5 | $0.3428\pm0.0003$ | $0.4455\pm0.0003$ |
| e.2 | $pp\to HW^+\,j$ | $m_W+m_H$ | 5 | $0.1223\pm0.0001$ | $0.1501\pm0.0002$ |
| e.3 | $pp\to HZ$ | $m_Z+m_H$ | 5 | $0.2781\pm0.0001$ | $0.3659\pm0.0002$ |
| e.4 | $pp\to HZ\,j$ | $m_Z+m_H$ | 5 | $0.0988\pm0.0001$ | $0.1237\pm0.0001$ |
| e.5 | $pp\to Ht\bar{t}$ | $m_{top}+m_H$ | 5 | $0.08896\pm0.00001$ | $0.09869\pm0.00003$ |
| e.6 | $pp\to Hb\bar{b}$ | $m_b+m_H$ | 4 | $0.16510\pm0.00009$ | $0.2099\pm0.0006$ |
| e.7 | $pp\to Hjj$ | $m_H$ | 5 | $1.104\pm0.002$ | $1.036\pm0.002$ |

# FIRST aMC@NLO APPLICATIONS

tbj  ZZ→4l  (W→eν)bb  ttH/ttA

Calculation at NLO in the 4FS done in [Campbell, Frederix, FM, Tramontano, 0903.0005]. Virtuals taken from the above reference.

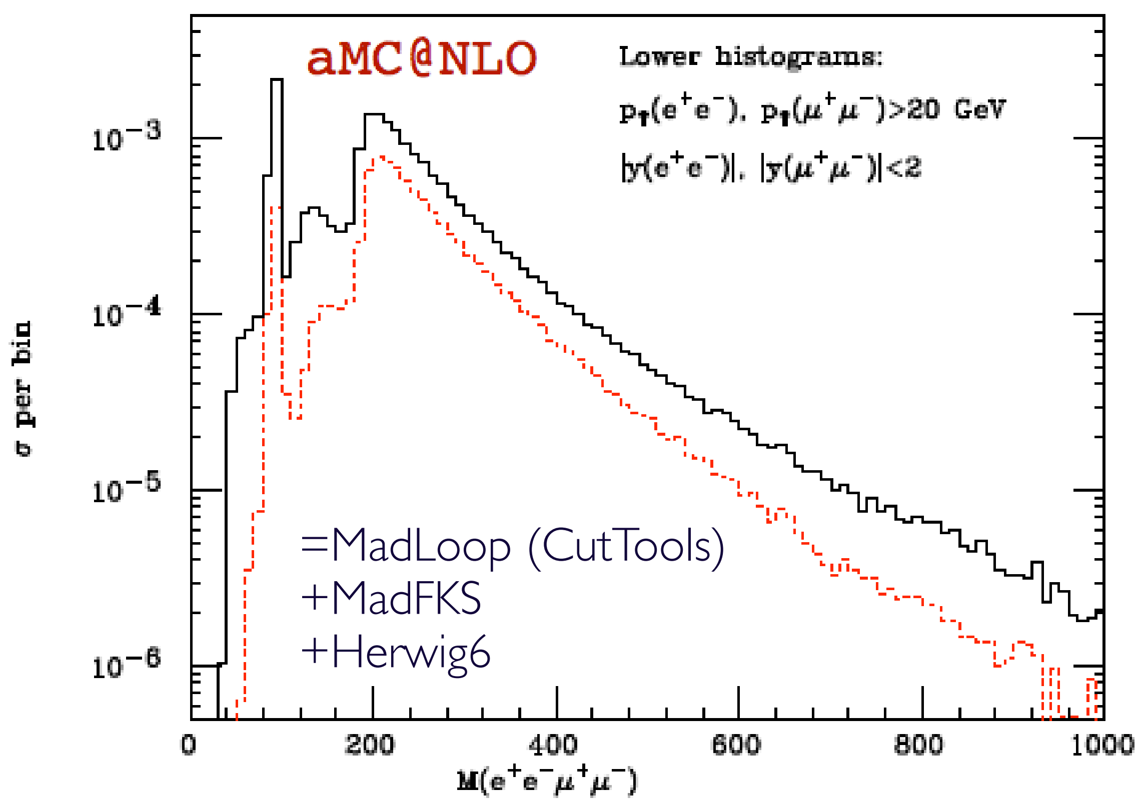


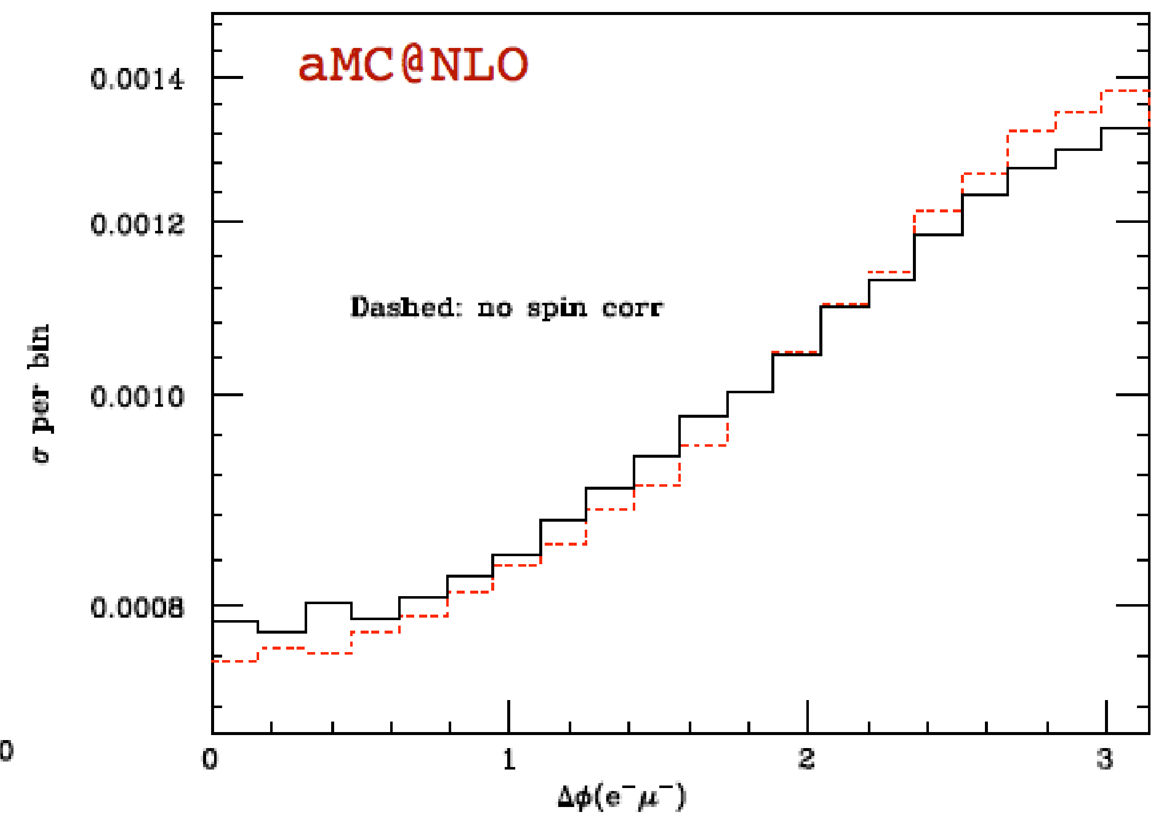



# FIRST aMC@NLO APPLICATIONS

tbj ZZ→4l (W→eν)bb ttH/ttA

NLO calculation includes $\gamma^*/Z$ interference and full spin correlations. Equivalent at pure NLO to MCFM.

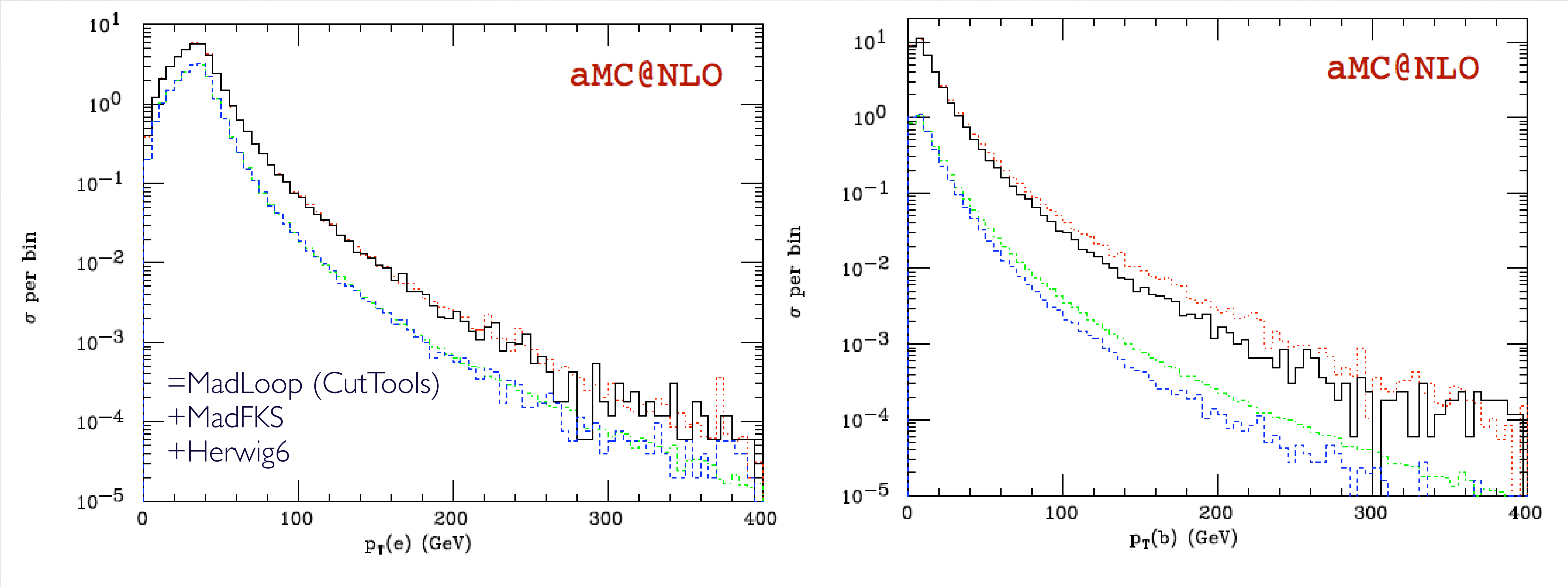


# FIRST aMC@NLO APPLICATIONS

tbj ZZ→4l (W→eν)bb ttH/ttA

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

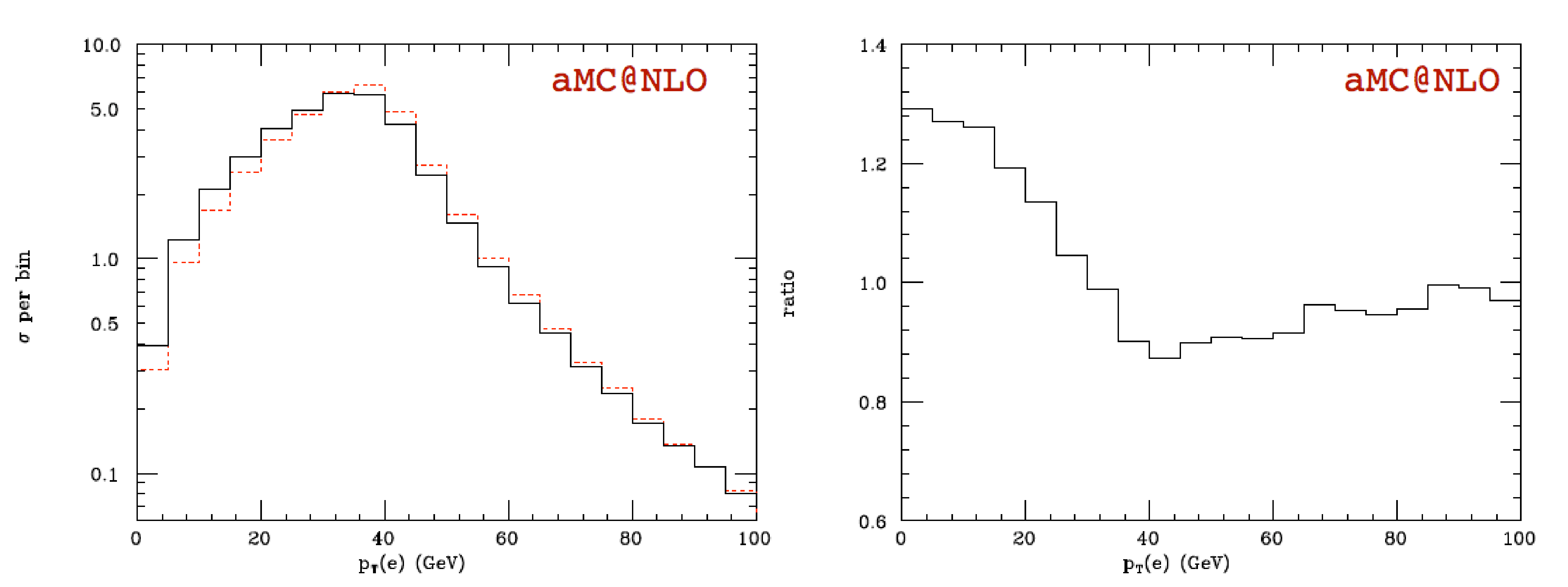



Solid: aMC@NLO Dashed: aMC@LO Dotted: NLO Dotdashed: LO

# FIRST aMC@NLO APPLICATIONS

tbj     ZZ→4l     (W→eν)bb     ttH/ttA

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



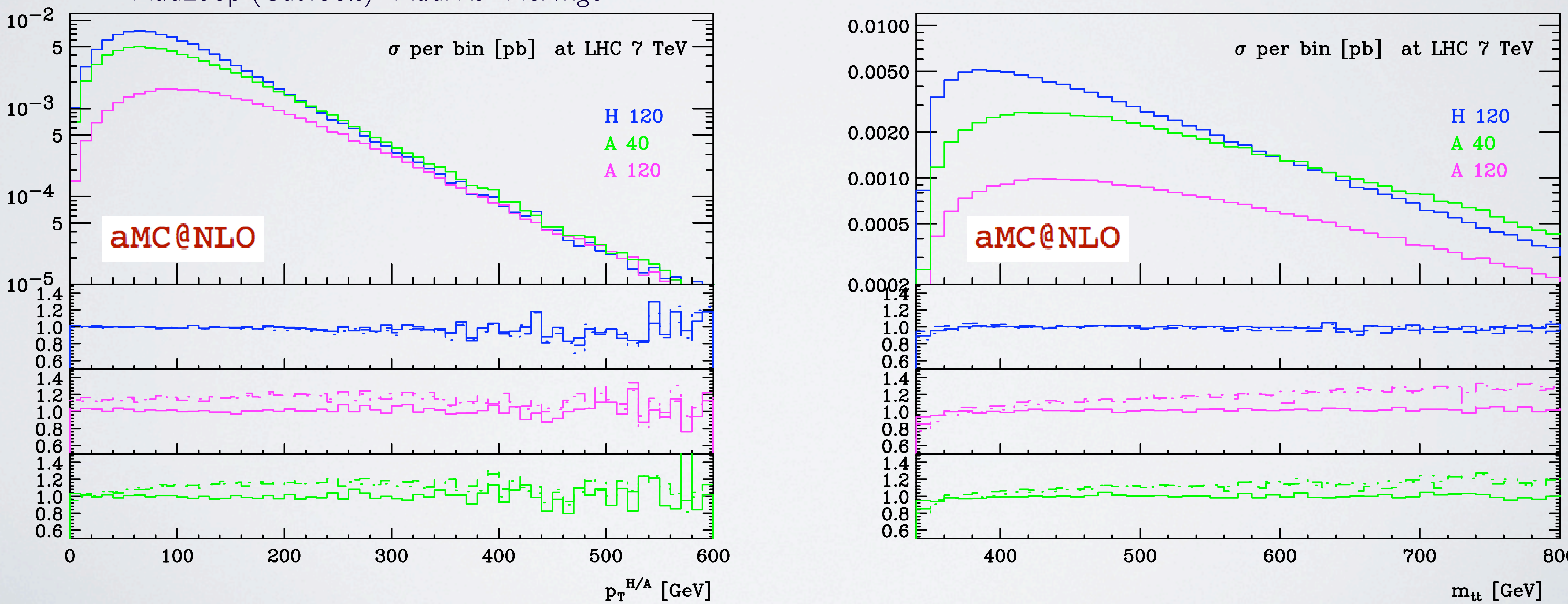

Solid: w/ spin correlations     Dashed: w/o spin correlations

# FIRST aMC@NLO APPLICATIONS

tbj ZZ→4l (W→eν)bb **ttH/ttA**

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

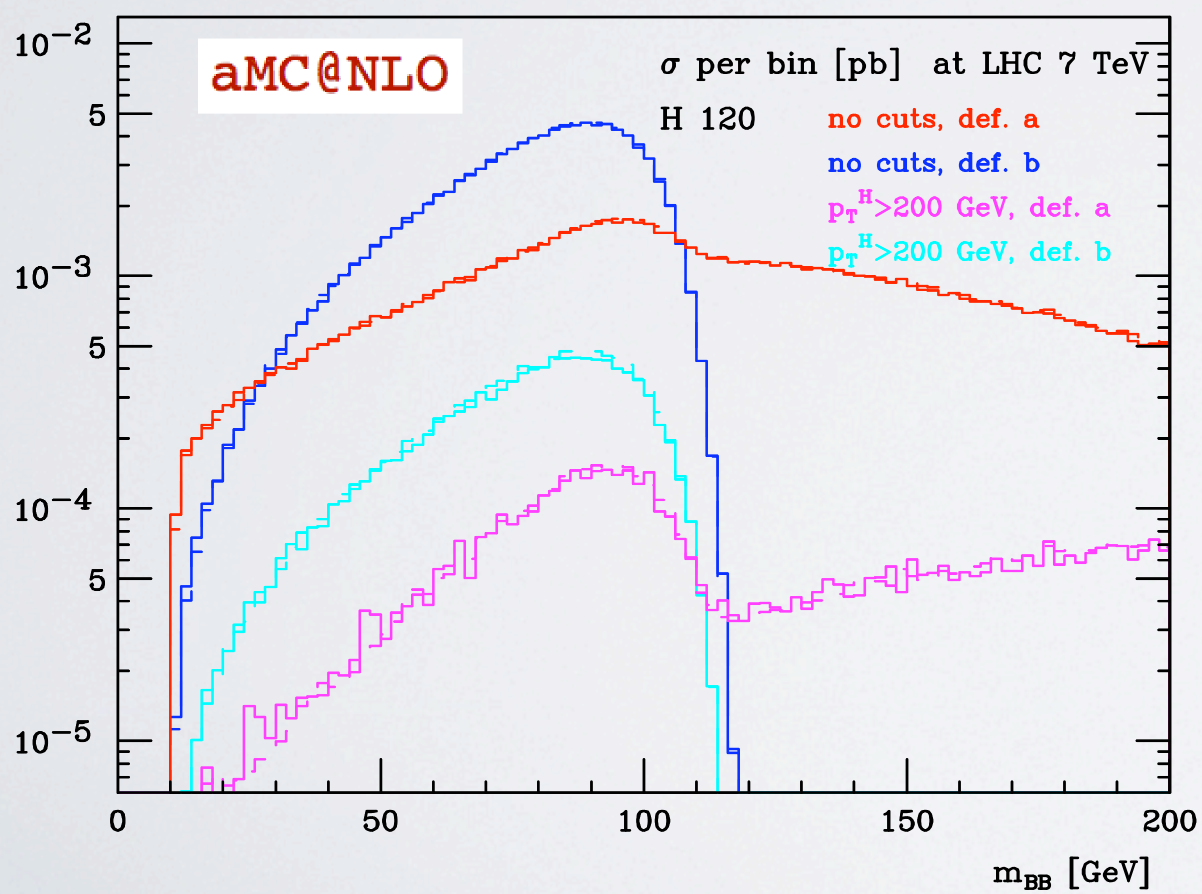
MadLoop (CutTools)+MadFKS+Herwig6

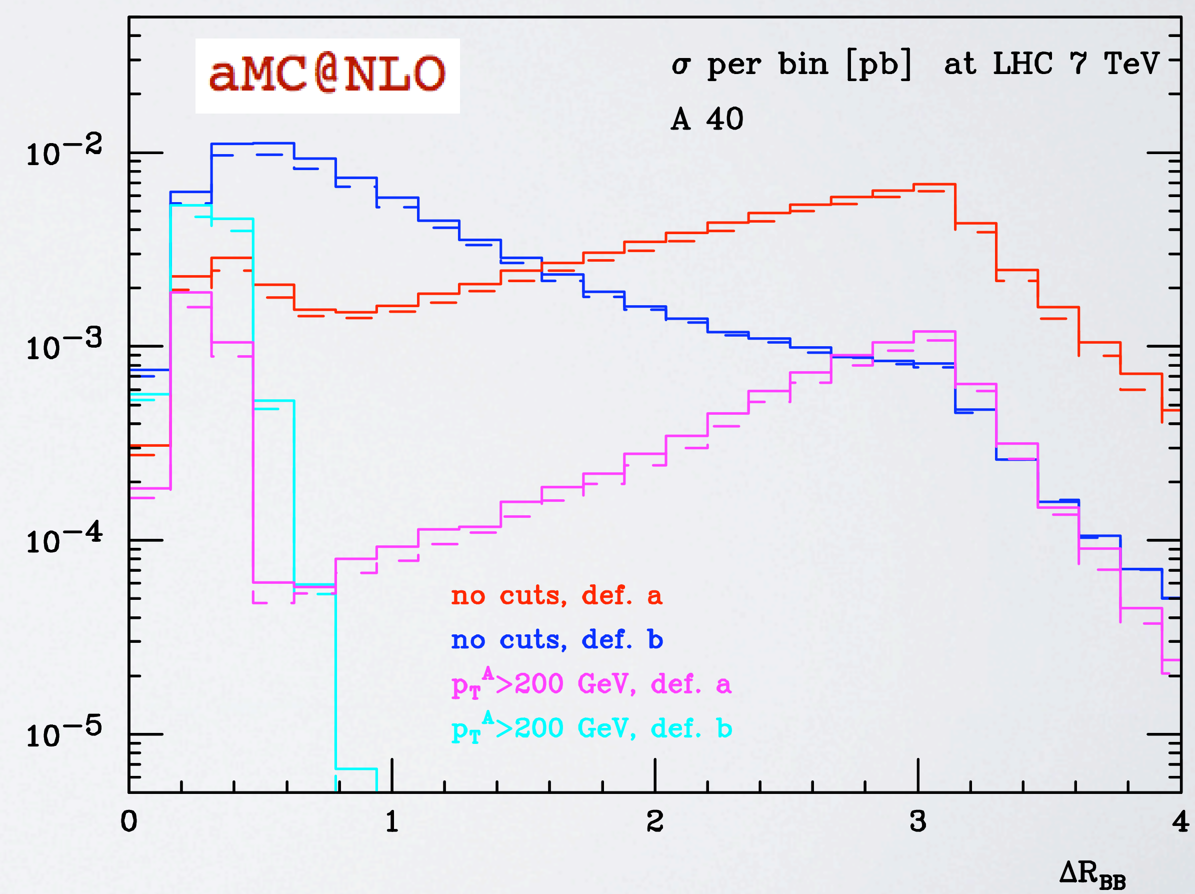


# FIRST aMC@NLO APPLICATIONS

tbj  ZZ→4l  (W→eν)bb  ttH/ttA

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



# aMC@NLO PROSPECTS

- "99%" of the elements needed to calculate QCD corrections for SM processes are present. The missing bits will be included in MadGraph 5.
- QCD+EW corrections possible but need more work on MadLoop.
- Automatic loop computations in BSM need new elements. Work is in progress to automate them.
- Analytic/numeric loop amplitudes from other codes can be easily interfaced via the Binoth Les Houches Accord, SM or BSM.
- Use of the code will be made public via the web asap. Codes for processes will follow. And then Meta code public in MadGraph 5.

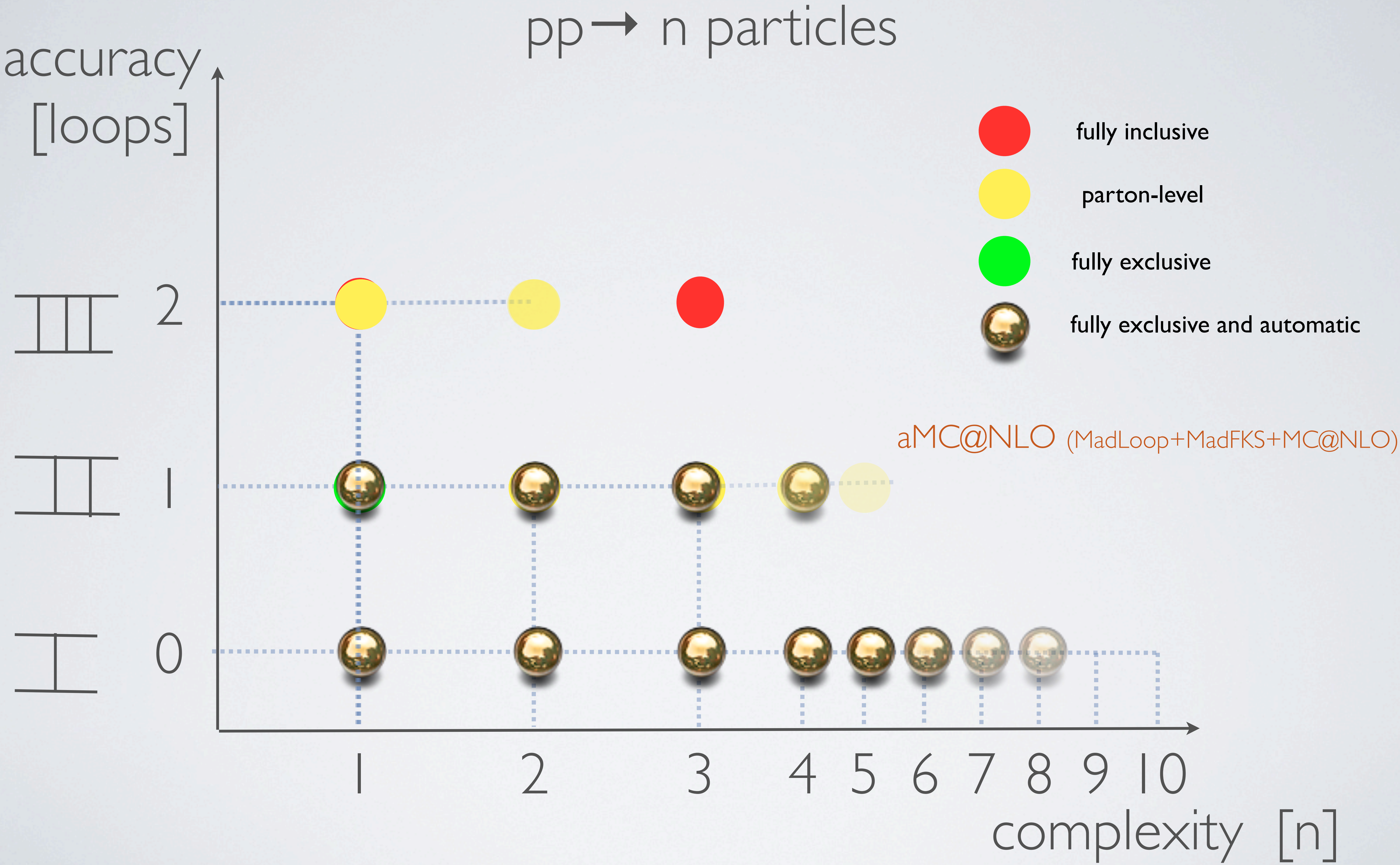
# AMAZING MG4/MG5 NEW POSSIBILITIES

- Unlimited BSM model inheritance from FeynRules
- MC based on GPU's [Kanzaki, Hagiwara, Rainwater, Stelzer, Takeushi, 2010]
- Dark Matter relic abundance calculator tools for BSM
  [Backovic Kong, McCaskeyet, 2011]
- Library of BSM Matrix-element processes for any model can be automatically generated and included in Pythia 8 [Alwall et al. 2011]
- Long Decay chains possible [Alwall et al. 2011]
- Matrix Element Reweighting analysis techniques available automatically for any process [Artoisenet, Lemaitre,FM, Mattelaer, 2010]

# STATUS : SINCE THIS WEEK

pp→ n particles

# STATUS : SINCE THIS WEEK



# CONCLUSIONS

# CONCLUSIONS

- The need for better description and more reliable predictions for SM processes for the LHC has motivated a significant increase of theoretical and phenomenological activity in the last years, leading to several important achievements.

# CONCLUSIONS

- The need for better description and more reliable predictions for SM processes for the LHC has motivated a significant increase of theoretical and phenomenological activity in the last years, leading to several important achievements.

- A new generation of tools and techniques is now available. Full automation of computations at fixed order as well as their the matching to parton-shower both at tree-level and at NLO has been proven.

# *Long-term outlook*

- It seems clear that performing NLO calculations on a case-by-case basis is not the way of the future
- An automated approach, combining algebraic and numerical recipes, appears both promising (in terms of physics output) and feasible
    - Perhaps one day we'll have an ALPGEN@NLO or MadLoop
- However, even if such ambitious projects can be realized, the story does not end there
    - interpretation and grooming of results will still be very process-specific
    - jet-clustering, photon fragmentation, threshold effects, resummation and more will need to be considered

John Campbell talk at KITP 2004

# Long-term outlook

- It seems clear that performing NLO calculations on a case-by-case basis is not the way of the future
- An automated approach, combining algebraic and numerical recipes, appears both promising (in terms of physics output) and feasible
  - Perhaps one day we'll have an ALPGEN@NLO or MadLoop
- However, even if such ambitious projects can be realized, the story does not end there
  - interpretation and grooming of results will still be very process-specific
  - jet-clustering, photon fragmentation, threshold effects, resummation and more will need to be considered

John Campbell talk at KITP 2004

# CONCLUSIONS

- The need for better description and more reliable predictions for SM processes for the LHC has motivated a significant increase of theoretical and phenomenological activity in the last years, leading to several important achievements.

- A new generation of tools and techniques is now available. Full automation of computations at fixed order as well as their the matching to parton-shower both at tree-level and at NLO has been proven.

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

- Integrated EXP/TH community....

# THE AAA MOTTO

Free to Pheno

# CREDITS

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