Predictive Monte Carlo tools for the LHC

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Lecture III

PLAN

- Basics : LO predictions and event generation
- Fixed-order calculations : from NLO to NNLO
- Exclusive predictions : Parton Shower
- Merging ME+PS
- Matching NLO with PS

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- Matching NLO with PS

Today

NLO+PS matching

ME	Shower MC
1. Fixed order calculation	1. Resums logs to all orders
2. Computationally expensive	2. Computationally cheap
3. Limited number of particles	3. No limit on particle multiplicity
4. Valid when partons are hard and well separated	4. Valid when partons are collinear and/or soft
5. Quantum interference correct	5. Partial interference through angular ordering
6. Needed for multi-jet description	6. Needed for hadronization

Approaches are complementary: merge them!

Difficulty: avoid double counting, ensure smooth distributions

NLO+PS MATCHING

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No longer true at NLO!

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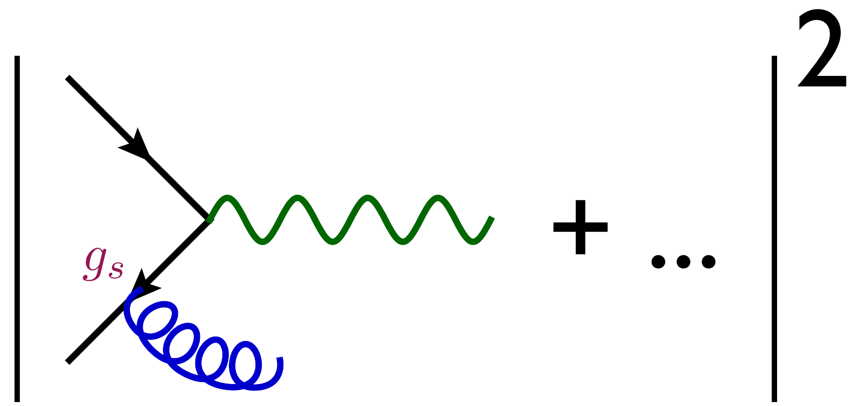
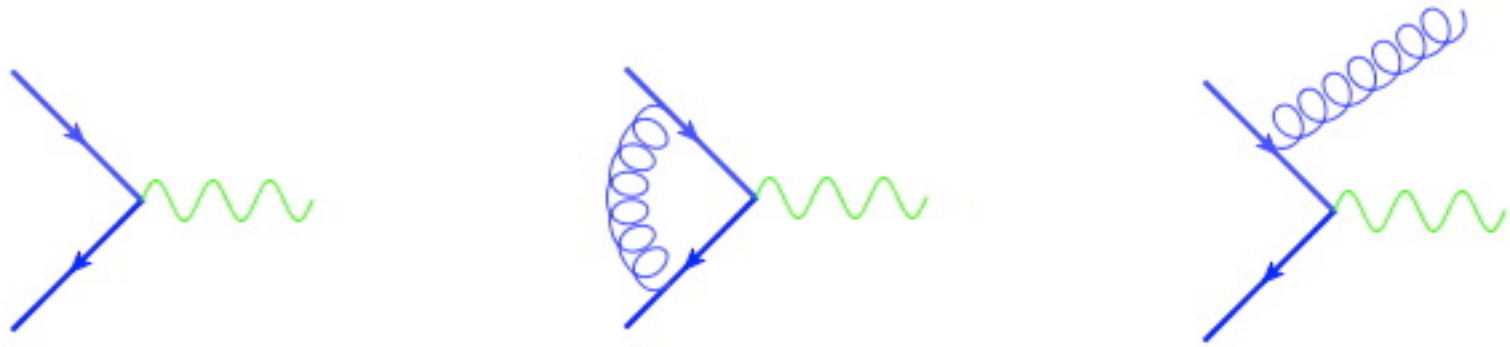
Difficulty: avoid double counting, ensure smooth distributions

At NLO



- We have to integrate the real emission over the **complete** phase-space of the one particle that can go soft or collinear to obtain the infra-red poles that will cancel against the virtual corrections
- We cannot use the same matching procedure: requiring that all partons should produce separate jets is not infrared safe
- We have to invent a new procedure to match NLO matrix elements with parton showers

Naive (wrong) approach



- In a fixed order calculation we have contributions with *m* final state particles and with *m*+1 final state particles

$$\sigma^{\rm NLO} \sim \int d^4\Phi_m\, B(\Phi_m) + \int d^4\Phi_m \int_{\rm loop} d^d l\, V(\Phi_m) + \int d^d\Phi_{m+1}\, R(\Phi_{m+1})$$

- We could try to shower them independently
- Let $I_{\rm MC}^{(k)}(O)$ be the parton shower spectrum for an observable O, showering from a k-body initial condition
- We can then try to shower the *m* and *m*+1 final states independently

$$\frac{d\sigma_{\rm NLOwPS}}{dO} = \left[d\Phi_m (B + \int_{\rm loop} V)\right] I_{\rm MC}^{(m)}(O) + \left[d\Phi_{m+1} R\right] I_{\rm MC}^{(m+1)}(O)$$

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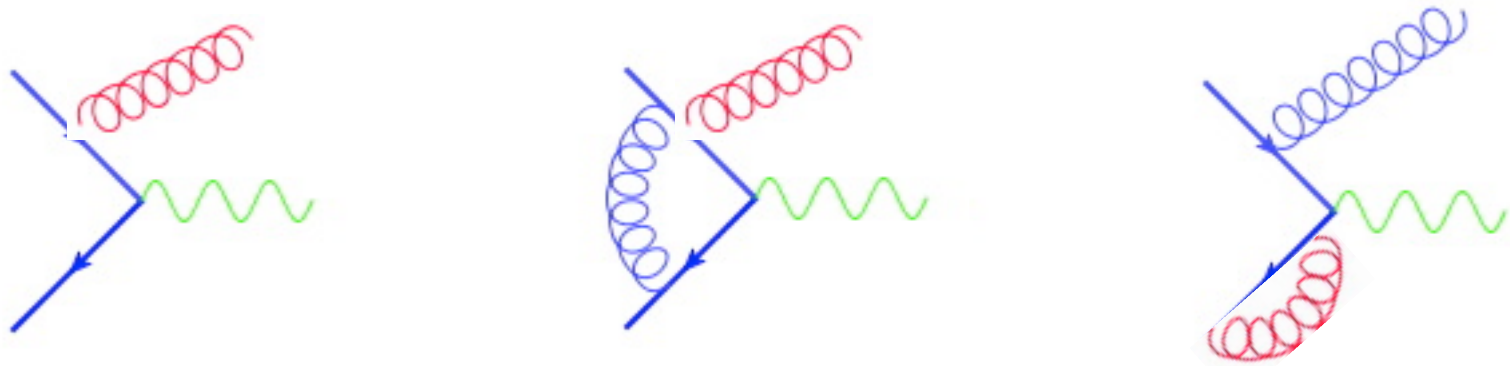

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Double counting

$$\frac{d\sigma_{\mathrm{NLOwPS}}}{dO} = \left[d\Phi_m (B + \int_{\mathrm{loop}} V)\right] I_{\mathrm{MC}}^{(m)}(O) + \left[d\Phi_{m+1} R\right] I_{\mathrm{MC}}^{(m+1)}(O)$$

- But this is wrong!
- If you expand this equation out up to NLO, there are more terms then there should be and the total rate does not come out correctly
- Schematically $I_{\mathrm{MC}}^{(k)}(O)$ for 0 and 1 emission is given by

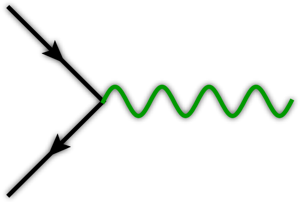
$$I_{\mathrm{MC}}^{(k)}(O) \sim \Delta_a(Q^2, Q_0^2) + \Delta_a(Q^2, t) \sum_{bc} dz \frac{dt}{t} \frac{d\phi}{2\pi} \frac{\alpha_s(t)}{2\pi} P_{a\to bc}(z)$$

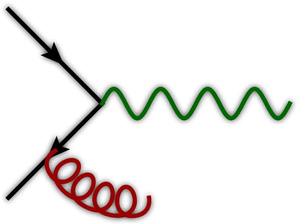
- And **Δ** is the Sudakov factor

$$\Delta_a(Q^2, t) = \exp\left[-\sum_{bc} \int_t^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_s(t')}{2\pi} P_{a\to bc}\right]$$

Sources of double counting

Parton shower

Born+Virtual: 

Real emission: 

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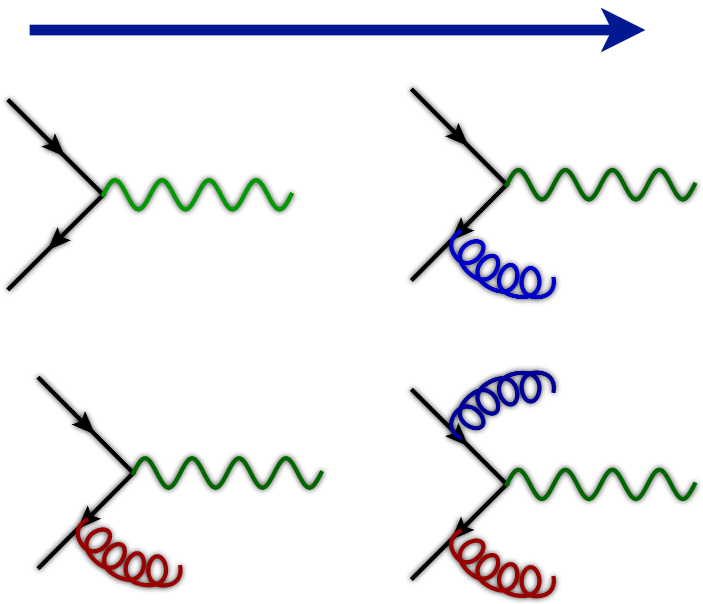

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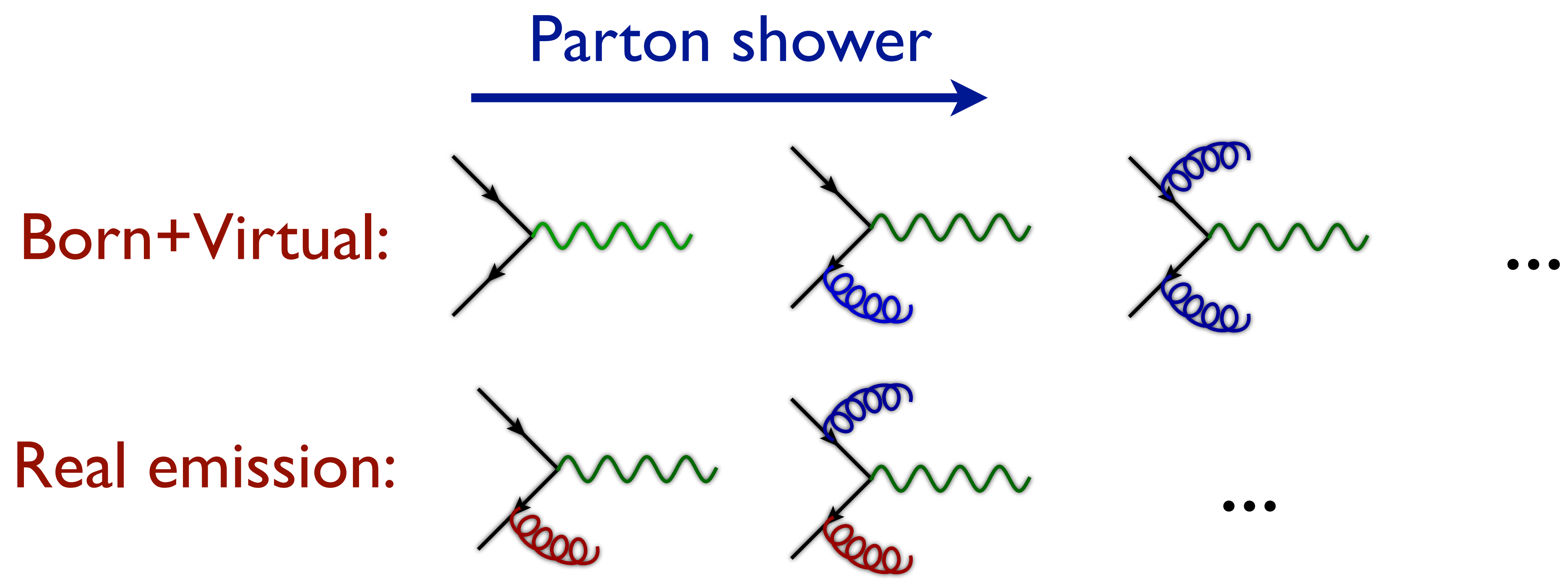

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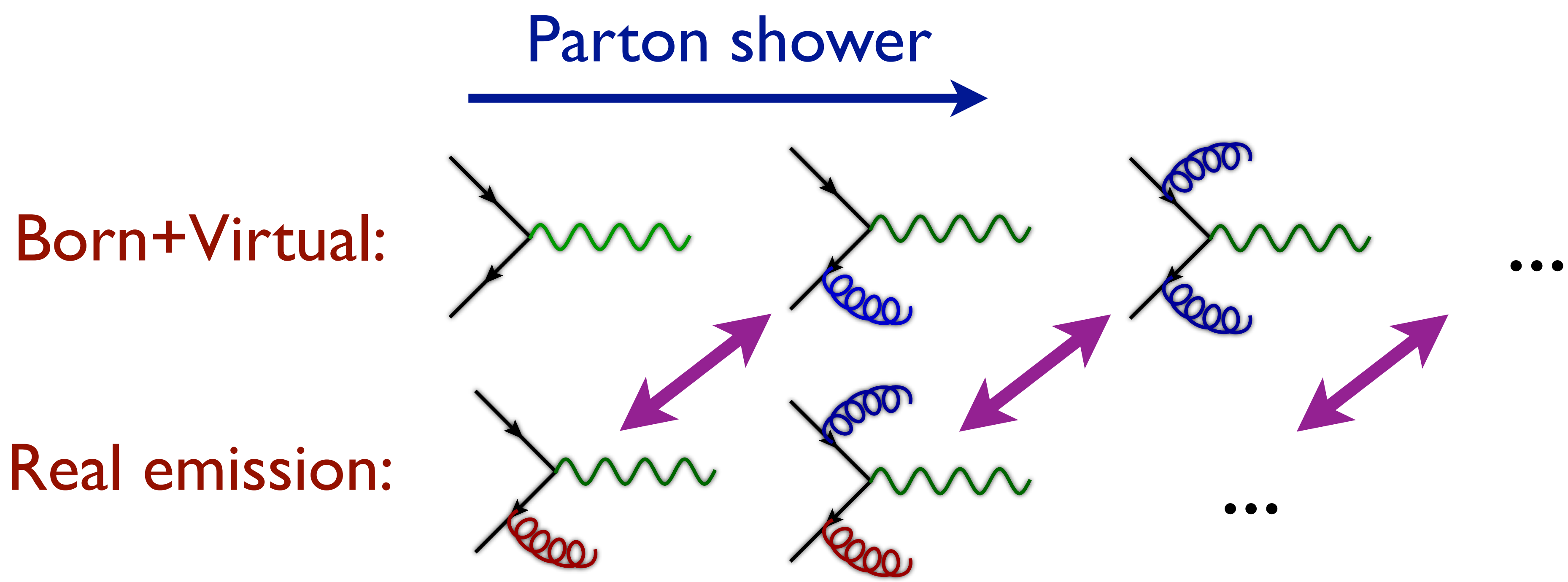

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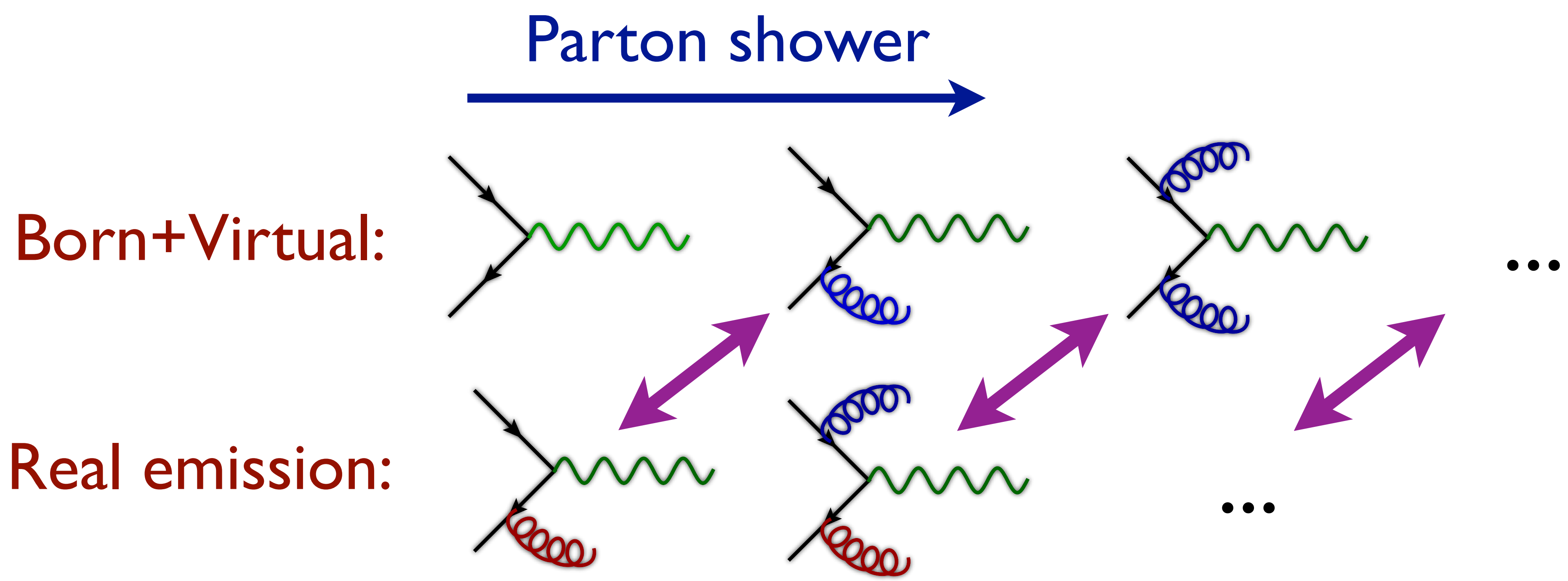


- There is double counting between the real emission matrix elements and the parton shower: the extra radiation can come from the matrix elements or the parton shower
- There is also an overlap between the virtual corrections and the Sudakov suppression in the zero-emission probability

Double counting in virtual/Sudakov

- The Sudakov factor Δ (which is responsible for the resummation of all the radiation in the shower) is the no-emission probability
- It's defined to be $\Delta = 1 - P$, where P is the probability for a branching to occur
- By using this conservation of probability in this way, Δ contains contributions from the virtual corrections implicitly
- Because at NLO the virtual corrections are already included via explicit matrix elements, Δ is double counting with the virtual corrections
- In fact, because the shower is unitary, what we are double counting in the real emission corrections is exactly equal to what we are double counting in the virtual corrections (but with opposite sign)!

Avoiding double counting

- There are two methods to circumvent this double counting
  - MC@NLO (Frixione & Webber)
  - POWHEG (Nason)

MC@NLO PROCEDURE

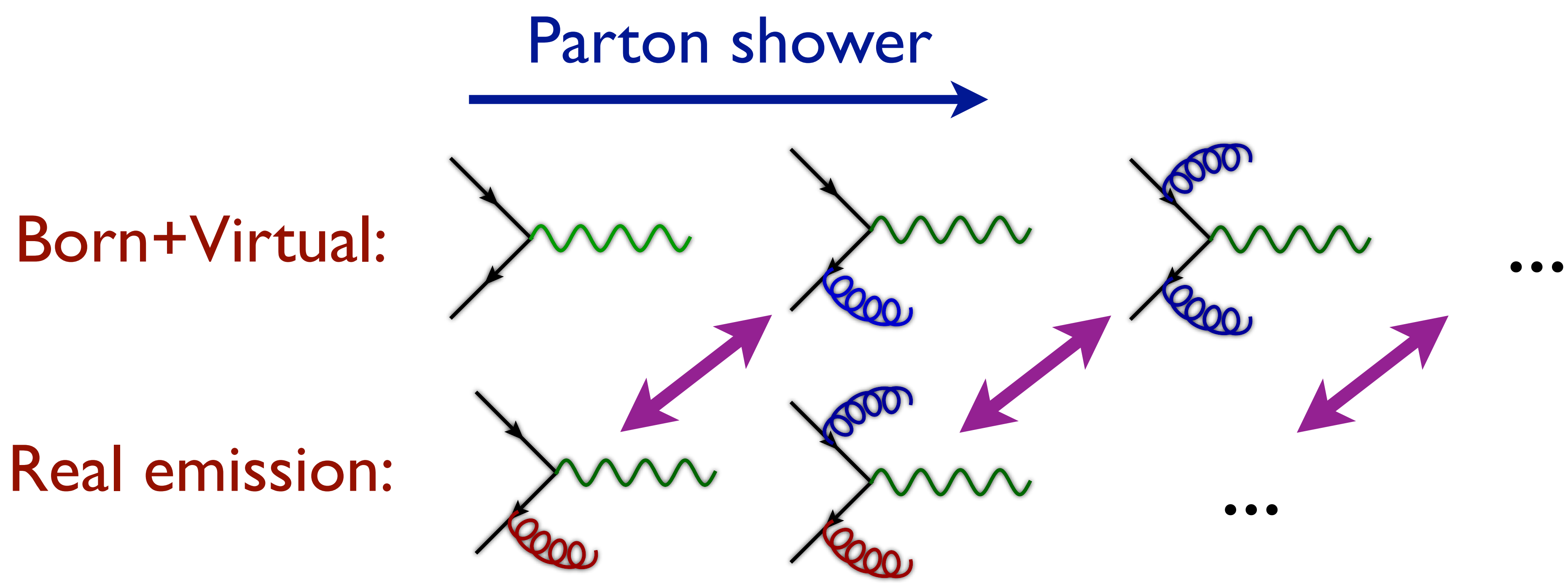
[Frixione & Webber (2002)]

- To remove the double counting, we can add and subtract the same term to the *m* and *m*+1 body configurations

$$\frac{d\sigma_{\mathrm{NLOwPS}}}{dO} = \left[d\Phi_m \left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC \right)\right] I_{\mathrm{MC}}^{(m)}(O) + \left[d\Phi_{m+1} (R - MC) \right] I_{\mathrm{MC}}^{(m+1)}(O)$$

- Where the *MC* are defined to be the contribution of the parton shower to get from the *m* body Born final state to the *m*+1 body real emission final state

MC@NLO PROCEDURE



$$\frac{d\sigma_{\mathrm{NLOwPS}}}{dO} = \left[d\Phi_m \left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC\right)\right] I_{\mathrm{MC}}^{(m)}(O)$$
$$+ \left[d\Phi_{m+1} (R - MC)\right] I_{\mathrm{MC}}^{(m+1)}(O)$$

- Double counting is explicitly removed by including the "shower subtraction terms"

MC@NLO PROPERTIES

- Good features of including the subtraction counter terms

  1. **Double counting avoided**: The rate expanded at NLO coincides with the total NLO cross section
  2. **Smooth matching**: MC@NLO coincides (in shape) with the parton shower in the soft/collinear region, while it agrees with the NLO in the hard region
  3. **Stability:** weights associated to different multiplicities are separately finite. The *MC* term has the same infrared behavior as the real emission (there is a subtlety for the soft divergence)

- Not so nice feature (for the developer not for the user..!)

  1. **Parton shower dependence:** the form of the *MC* terms depends on what the parton shower does exactly. Need special subtraction terms for each parton shower to which we want to match

Double counting avoided

$$\frac{d\sigma_{\rm NLOwPS}}{dO} = \left[d\Phi_m (B + \int_{\rm loop} V + \int d\Phi_1 MC) \right] I_{\rm MC}^{(m)}(O) + \left[d\Phi_{m+1} (R - MC) \right] I_{\rm MC}^{(m+1)}(O)$$

- Expanded at NLO

$$I_{\rm MC}^{(m)}(O) dO = 1 - \int d\Phi_1 \frac{MC}{B} + d\Phi_1 \frac{MC}{B} + \ldots$$

$$d\sigma_{\rm NLOwPS} = \left[d\Phi_m (B + \int_{\rm loop} V + \int d\Phi_1 MC) \right] I_{\rm MC}^{(m)}(O) dO + \left[d\Phi_{m+1} (R - MC) \right] \simeq d\Phi_m (B + \int_{\rm loop} V) + d\Phi_{m+1} R = d\sigma_{\rm NLO}$$

Smooth matching

$$\frac{d\sigma_{\text{NLOwPS}}}{dO} = \left[d\Phi_m \left(B + \int_{\text{loop}} V + \int d\Phi_1 MC \right) \right] I_{\text{MC}}^{(m)}(O) + \left[d\Phi_{m+1} (R - MC) \right] I_{\text{MC}}^{(m+1)}(O)$$

- Smooth matching:
  - Soft/collinear region: $R \simeq MC \Rightarrow d\sigma_{\text{MC@NLO}} \sim I_{\text{MC}}^{(m)}(O) dO$
  - Hard region, shower effects suppressed, ie.

$$MC \simeq 0 \quad I_{\text{MC}}^{(m)}(O) \simeq 0 \quad I_{\text{MC}}^{(m+1)}(O) \simeq 1$$

$$\Rightarrow d\sigma_{\text{MC@NLO}} \sim d\Phi_{m+1} R$$

Stability & unweighting

$$\frac{d\sigma_{\rm NLOwPS}}{dO} = \left[d\Phi_m\left(B + \int_{\rm loop} V + \int d\Phi_1 MC\right)\right] I_{\rm MC}^{(m)}(O) + \left[d\Phi_{m+1}(R - MC)\right] I_{\rm MC}^{(m+1)}(O)$$

- The MC subtraction terms are defined to be what the shower does to get from the m to the m+1 body matrix elements. Therefore the cancellation of singularities is exact in the (R - MC) term: there is no mapping of the phase-space in going from events to counter events as we saw in the FKS subtraction

- The integral is bounded all over phase-space; we can therefore generate unweighted events!
  - "S-events" (which have m body kinematics)
  - "H-events" (which have m+1 body kinematics)

Negative weights

$$\frac{d\sigma_{\mathrm{NLOwPS}}}{dO} = \left[d\Phi_m\left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC\right)\right] I_{\mathrm{MC}}^{(m)}(O)$$
$$+ \left[d\Phi_{m+1}\left(R - MC\right)\right] I_{\mathrm{MC}}^{(m+1)}(O)$$

- We generate events for the two terms between the square brackets (S- and H-events) separately
- There is no guarantee that these contributions are separately positive (even though predictions for infra-red safe observables should always be positive!)
- Therefore, when we do event unweighting we can only unweight the events **up to a sign**. These signs should be taken into account when doing a physics analysis (i.e. making plots etc.)
- The events are only physical when they are showered.

Example : ttbar production

A NLO calculation always refers to an IR-safe observable.

An NLO code will, in general, be able to produce results for several quantities and distributions, only some of which will be at NLO accuracy.

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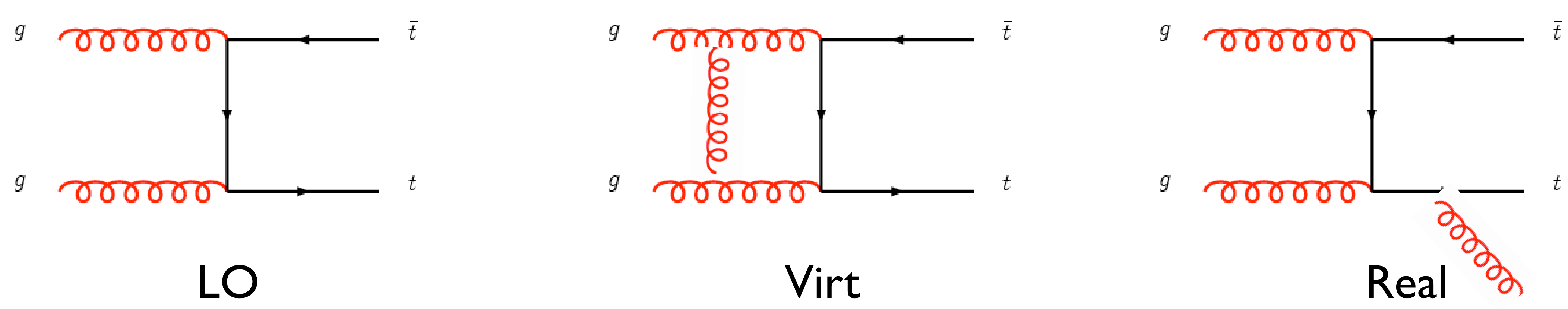
Example: Suppose we use the NLO code for pp → $t\bar{t}$



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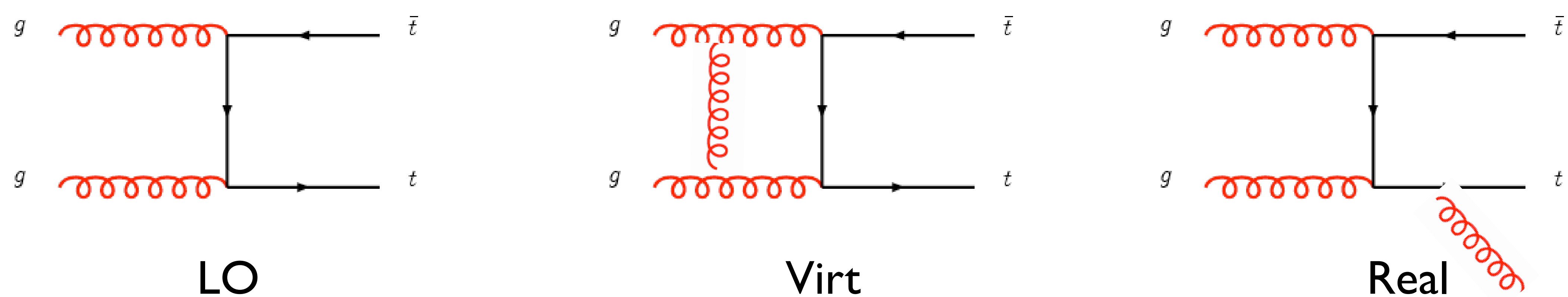

- ☞ Total cross section, $\sigma(tt)$
- ☞ P_T of one top quark
- ☞ P_T of the tt pair
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- ☞ tt invariant mass, m(tt)
- ☞ $\Delta\Phi(tt)$

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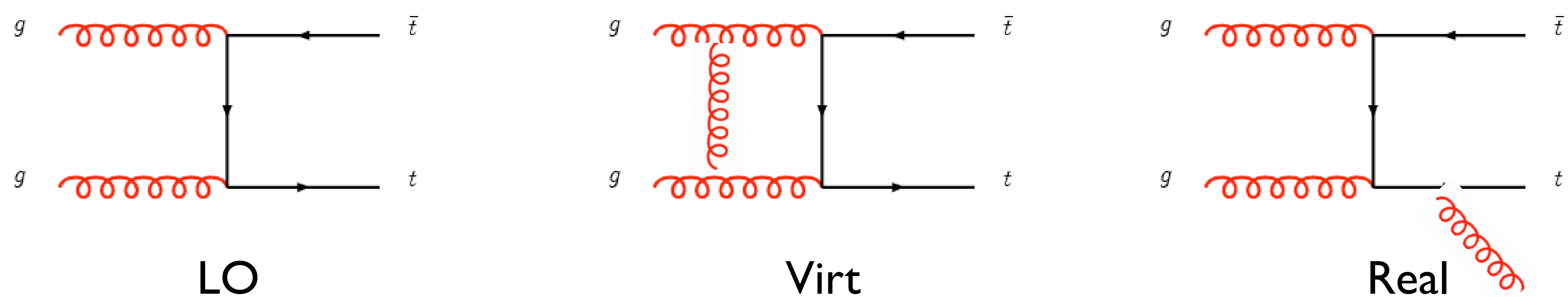

LO Virt Real

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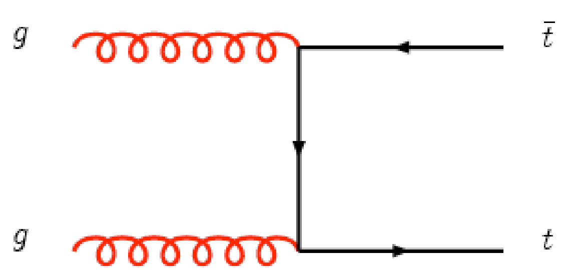
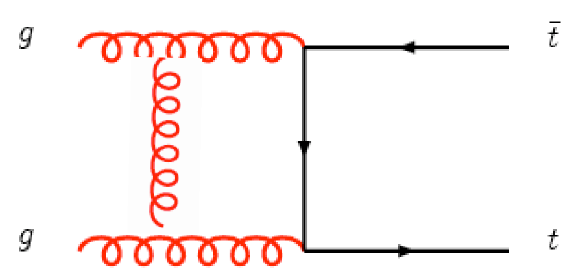
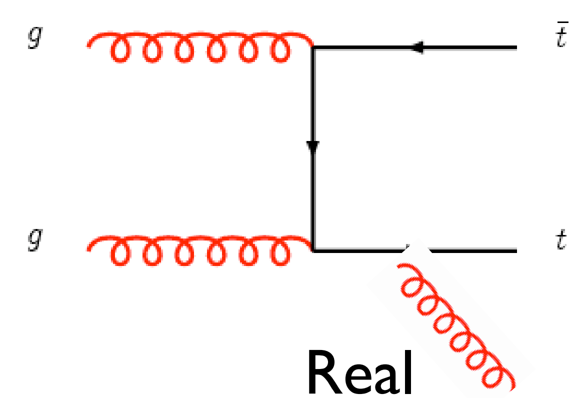


LO



Virt



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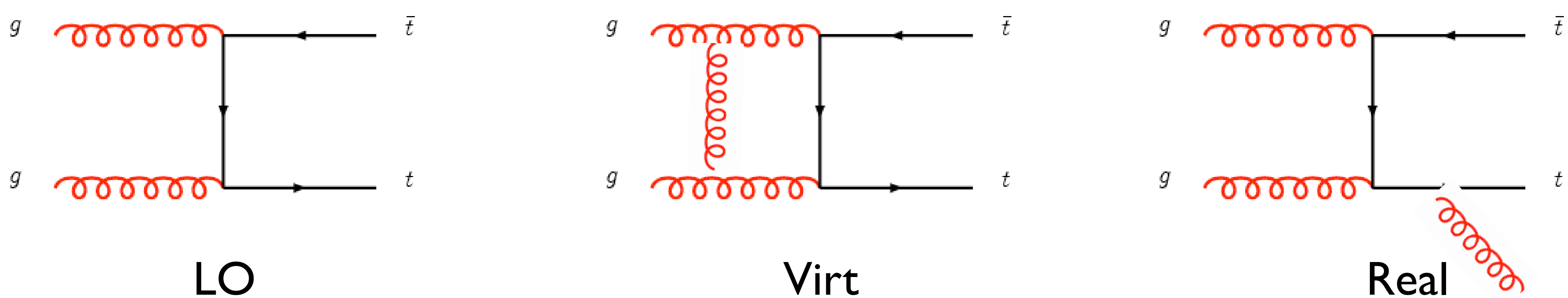

- ☞ Total cross section, $\sigma(t\bar{t})$ .... ✓
- ☞ P_T of one top quark .... ✓
- ☞ P_T of the $t\bar{t}$ pair .... ✗
- ☞ P_T of the jet
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- ☞ $\Delta\Phi(t\bar{t})$

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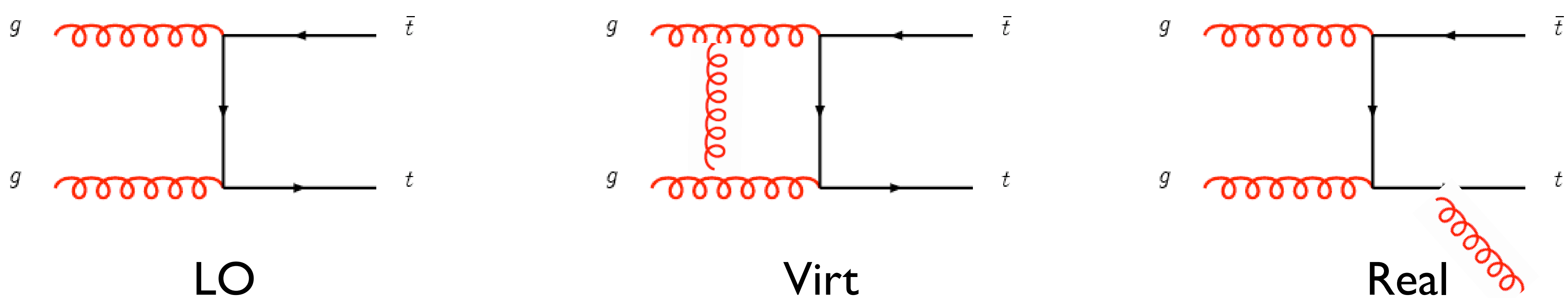

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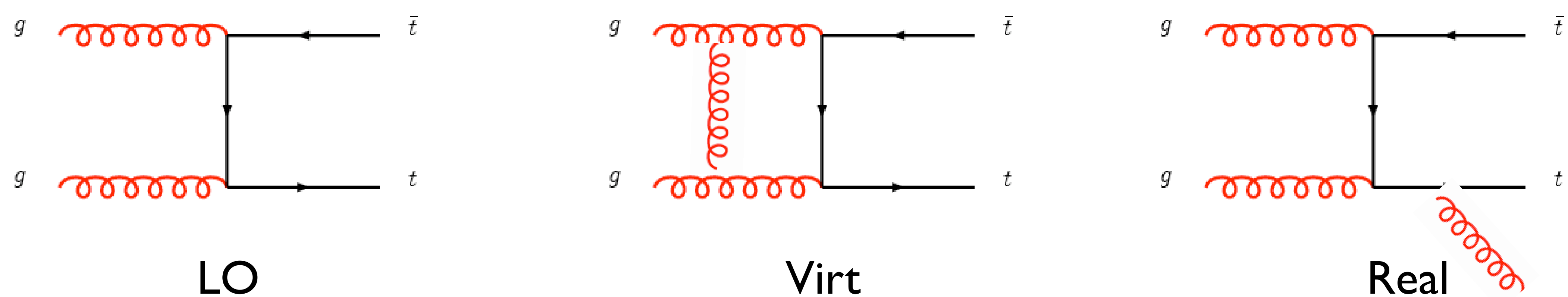

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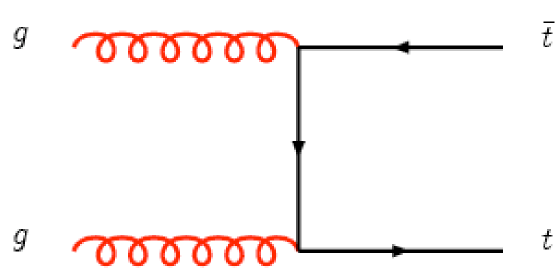

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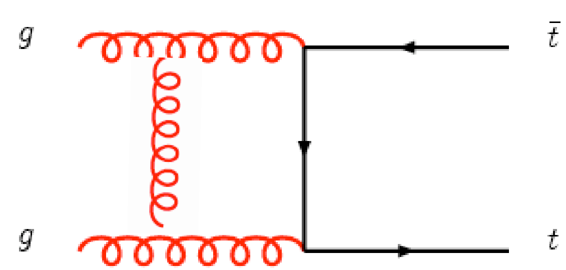

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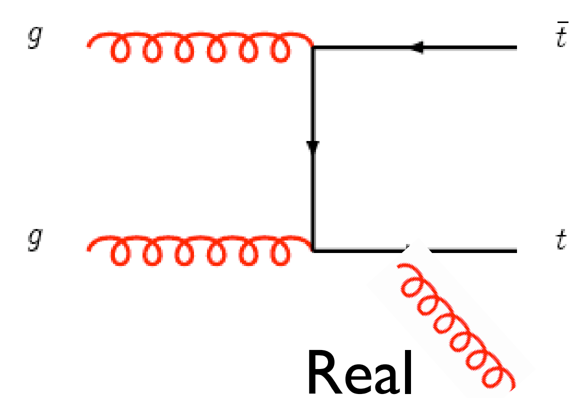

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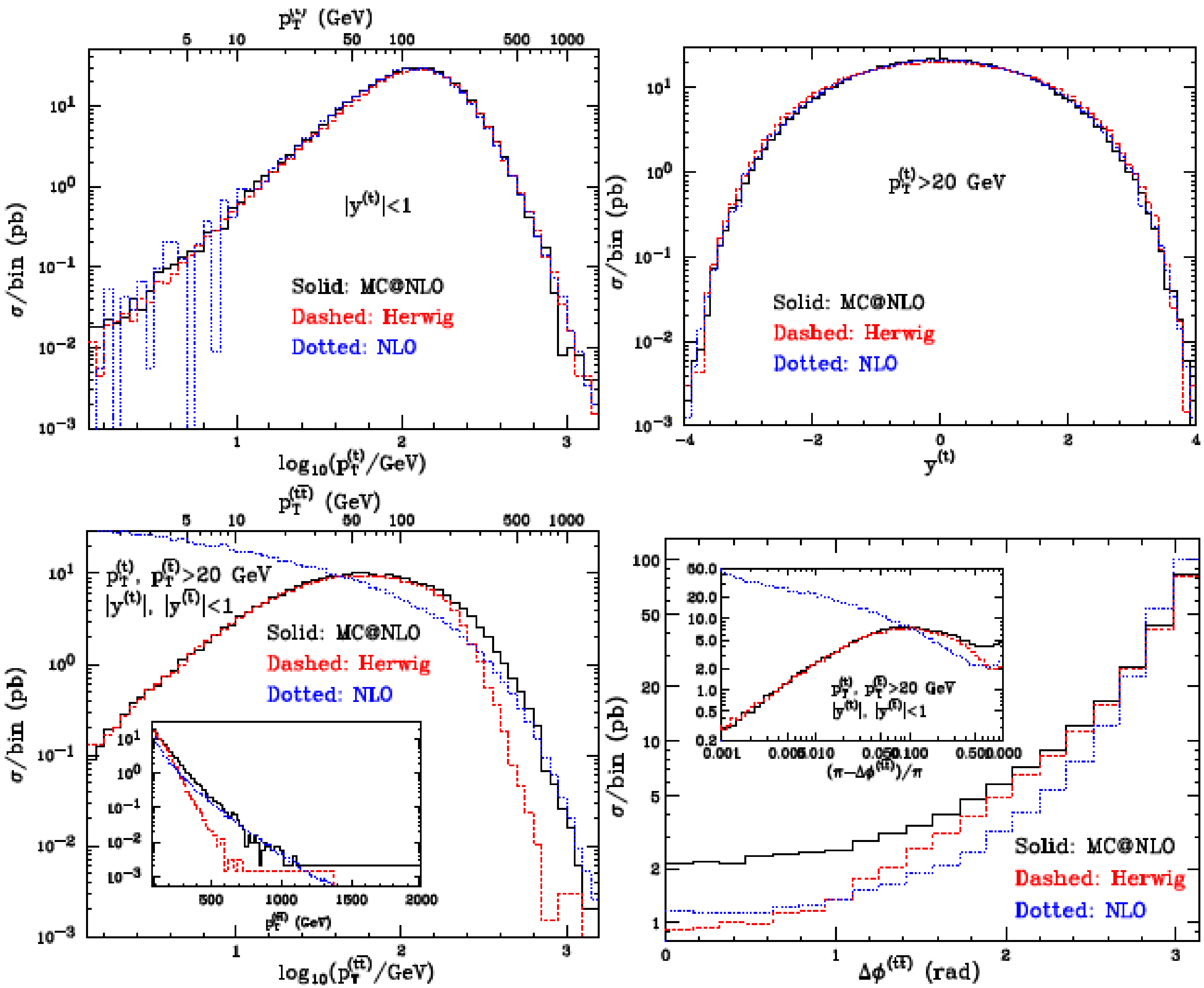

POWHEG

Nason (2004)

- Consider the probability of the first emission of a leg (inclusive over later emissions)

$$d\sigma = d\sigma_m d\Phi_m \left[\Delta(Q^2, Q_0^2) + \Delta(Q^2, t) \sum_{bc} dz \frac{dt}{t} \frac{d\phi}{2\pi} \frac{\alpha_\mathrm{S}}{2\pi} P_{a\to bc}(z) \right]$$

- In the notation used here, this is equivalent to

$$d\sigma = d\Phi_m \, B \left[\Delta(Q^2, Q_0^2) + \Delta(Q^2, t) d\Phi_{(+1)} \frac{MC}{B} \right]$$

- One could try to get NLO accuracy by replacing B with the NLO rate (integrated over the extra phase-space)

$$B \to B + V + \int d\Phi_{(+1)} \, R$$

- This naive definition is not correct: the radiation is still described only at leading logarithmic accuracy, which is not correct for hard emissions.

POWHEG

- This is double counting.
  To see this, expand the equation up to the first emission
  $$d\Phi_B \left[B + V + \int d\Phi_{(+1)} R\right] \left[1 - \int d\Phi_{(+1)} \frac{MC}{B} + d\Phi_{(+1)} \frac{MC}{B}\right]$$
  which is not equal to the NLO

- In order to avoid double counting, one should replace the definition of the Sudakov form factor with the following:

$$\Delta(Q^2, Q_0^2) = \exp\left[-\int_{Q_0^2}^{Q^2} d\Phi_{(+1)} \frac{MC}{B}\right] \to \tilde{\Delta}(Q^2, Q_0^2) = \exp\left[-\int_{Q_0^2}^{Q^2} d\Phi_{(+1)} \frac{R}{B}\right]$$

  corresponding to a modified differential branching probability

$$d\tilde{p} = d\Phi_{(+1)} R/B$$

- Therefore we find for the POWHEG differential cross section

$$d\sigma_{\text{POWHEG}} = d\Phi_B \left[B + V + \int d\Phi_{(+1)} R\right] \left[\tilde{\Delta}(Q^2, Q_0^2) + \tilde{\Delta}(Q^2, t)\ d\Phi_{(+1)} \frac{R}{B}\right]$$

Properties

$$d\sigma_{\text{POWHEG}} = d\Phi_B \left[B + V + \int d\Phi_{(+1)} R \right] \left[\tilde{\Delta}(Q^2, Q_0^2) + \tilde{\Delta}(Q^2, t)\; d\Phi_{(+1)} \frac{R}{B} \right]$$

- The term in the square brackets integrates to one (integrated over the extra parton phase-space between scales Q_0^2 and Q^2)
  (this can also be understood as unitarity of the shower below scale t)
  POWHEG cross section is normalized to the NLO

- Expand up to the first-emission level:

  $$d\sigma_{\text{POWHEG}} = d\Phi_B \left[B + V + \int d\Phi_{(+1)} R \right] \left[1 - \int d\Phi_{(+1)} \frac{R}{B} + d\Phi_{(+1)} \frac{R}{B} \right] = d\sigma_{\text{NLO}}$$

  so double counting is avoided

- Its structure is identical an ordinary shower, with normalization rescaled by a global K-factor and a different Sudakov for the first emission: no negative weights are involved.

MC@NLO and POWHEG

MC@NLO and POWHEG

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

MC@NLO AND POWHEG

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

integrates to 1 (unitarity)

MC@NLO and POWHEG

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

integrates to 1 (unitarity)

with

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

Full cross section at fixed Born kinematics (If F=1).

$$R(\Phi_R) = R^s(\Phi_R) + R^f(\Phi_R)$$

MC@NLO AND POWHEG

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

integrates to 1 (unitarity)

with

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

Full cross section at fixed Born kinematics (If F=1).

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This formula is valid both for both MC@NLO and POWHEG

MC@NLO AND POWHEG

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

integrates to 1 (unitarity)

with

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

Full cross section at fixed Born kinematics (If F=1).

$$R(\Phi_R) = R^s(\Phi_R) + R^f(\Phi_R)$$

This formula is valid both for both MC@NLO and POWHEG

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

Needs exact mapping (ΦB,ΦR) →Φ

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

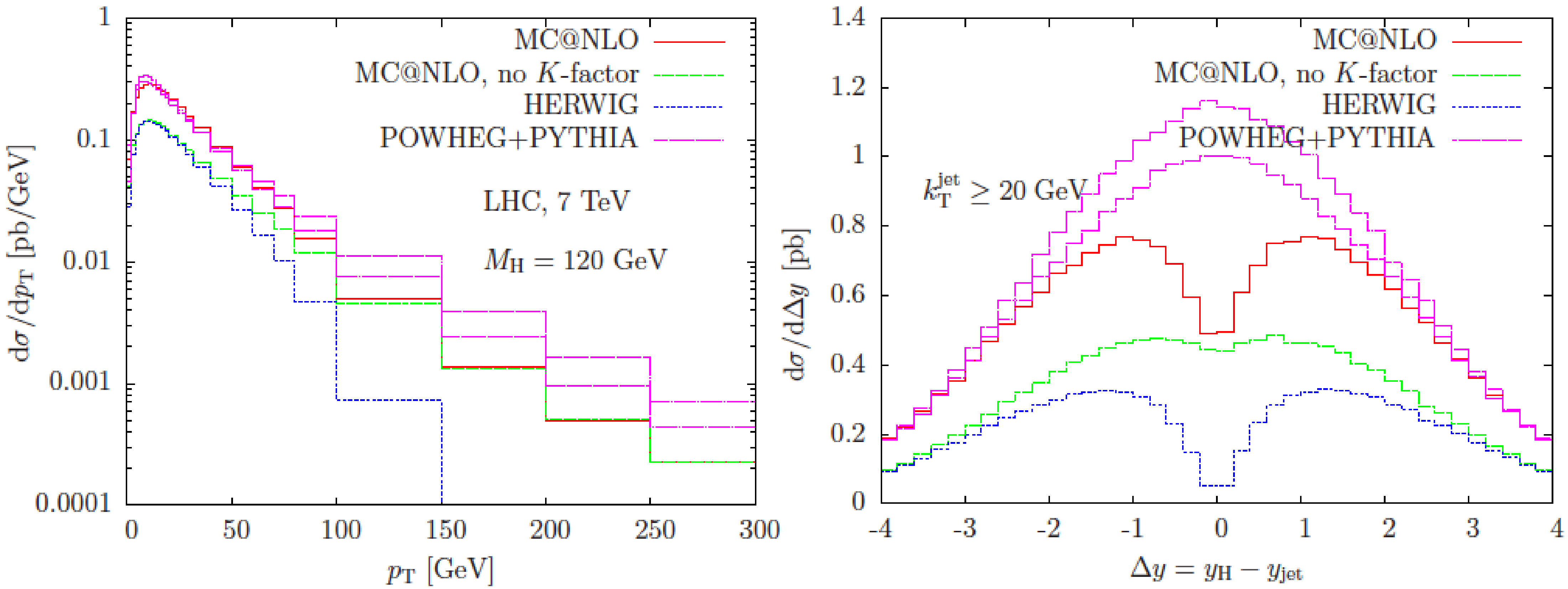
F=1 = Exponentiates the Real. It can be damped by hand.

MC@NLO and POWHEG

	MC@NLO	POWHEG
MC@NLO does not exponentiate the non-singular part of the real emission amplitudes	☺	☹
MC@NLO does not require any tricks for treating Born zeros	☺	☹
POWHEG is independent from the parton shower (although, in general the shower should be a truncated vetoed)	☹	☺
POWHEG is (almost) negative weighted events free	☹	☺
Automation of the method: http://amcatnlo.cern.ch http://powhegbox.mib.infn.it/	☺	☺

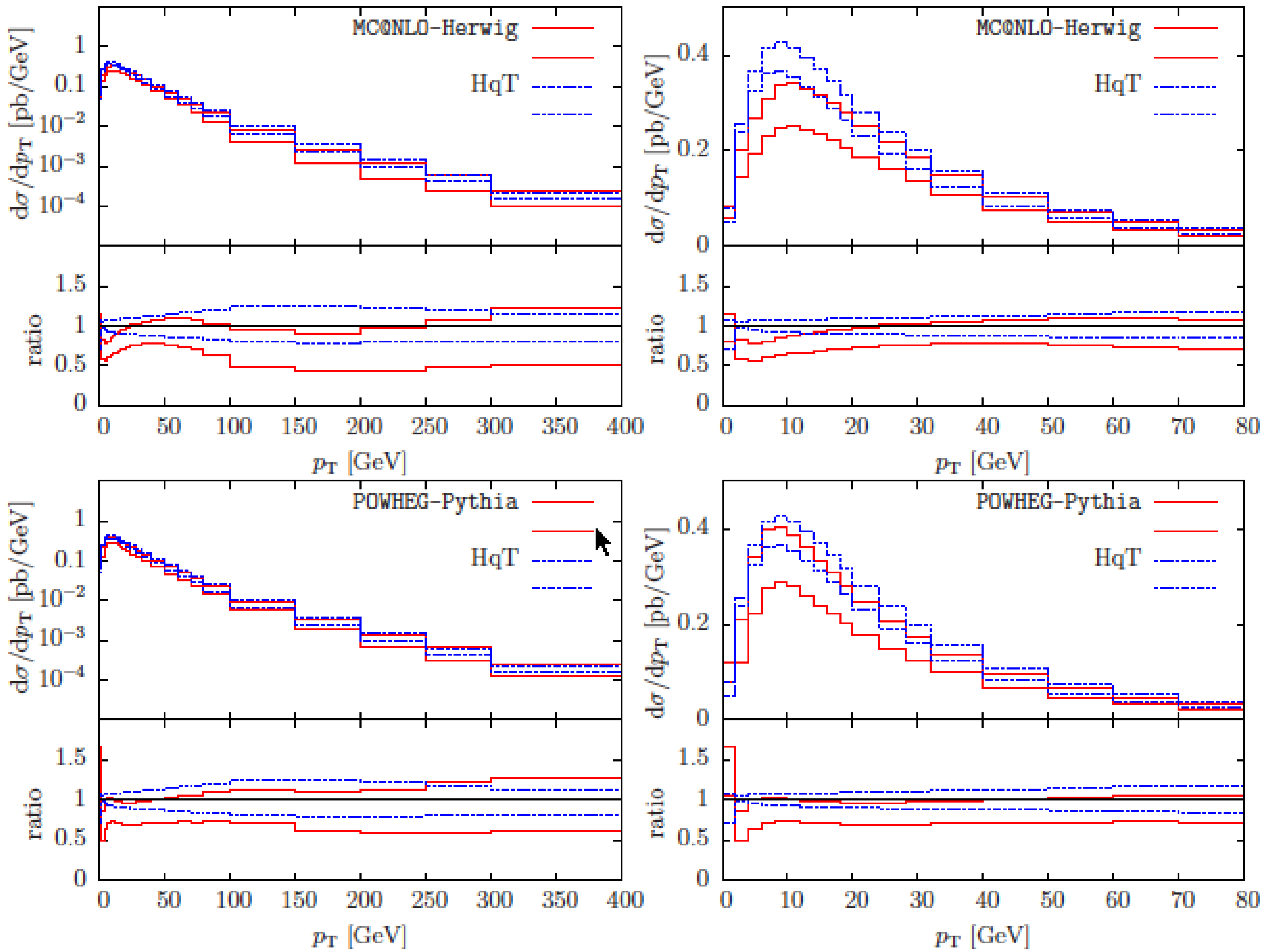
MC@NLO and POWHEG

Nason and Webber 2012



Pt of the Higgs in ggH

MC@NLO and POWHEG



Summary

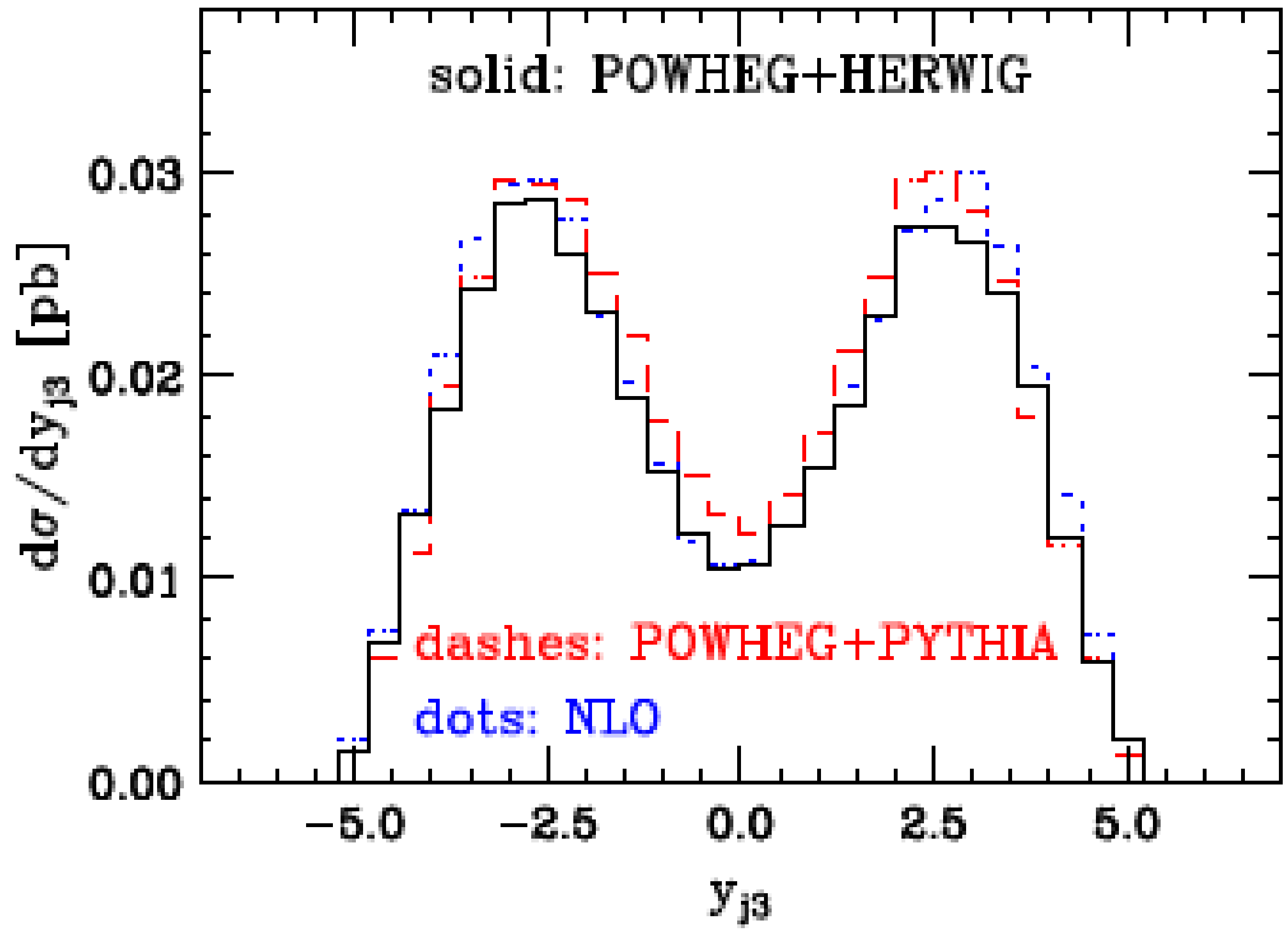
- We want to match NLO computations to parton showers to keep the good features of both approximations
  - In the MC@NLO method:
    by including the shower subtraction terms in our process we avoid double counting between NLO processes and parton showers
  - In the POWHEG method:
    apply an overall K-factor, and modify the (Sudakov of the) first emission to fill the hard region of phase-space according to the real-emission matrix elements
- First studies to combine NLO+PS matching with ME+PS merging have been made, but nothing 100% satisfactory has come out yet...

State of the Art

POWHEG BOX

Public framework to promote any NLO calculation into NLO+PS via the POWHEG method. Several processes implemented and available now:

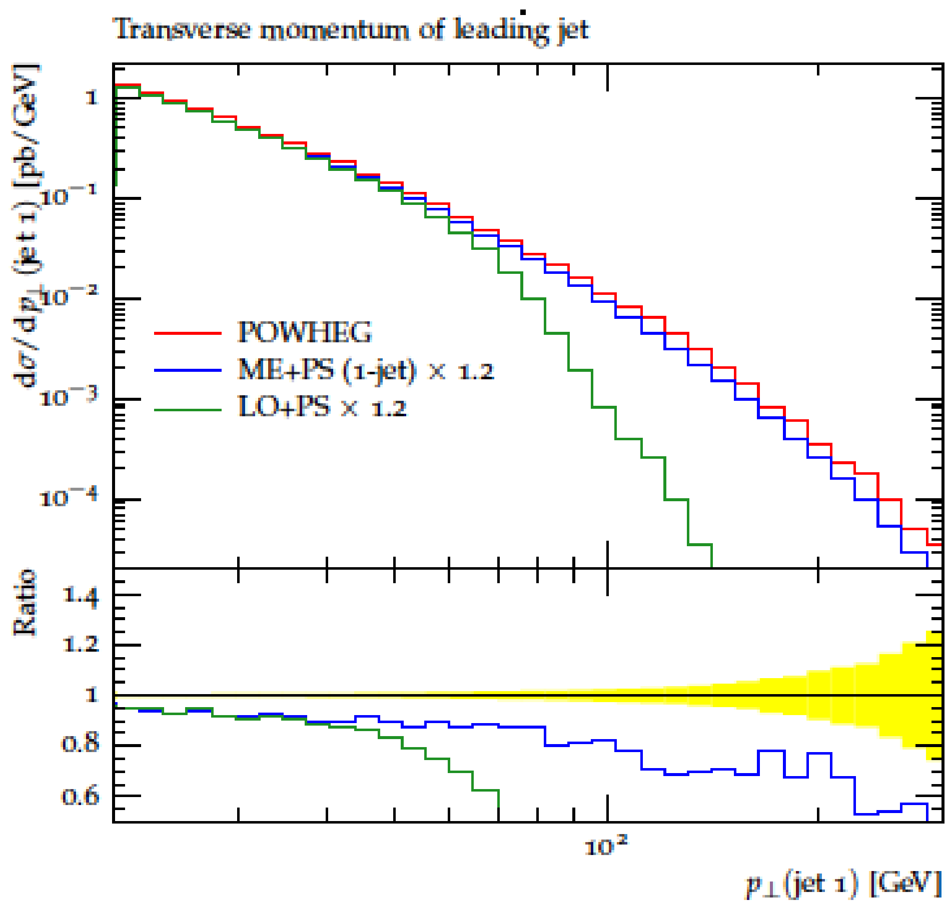
- jj, QQ
- W, Z inclusive
- Wj,Zj
- Zjj
- Wbb
- WW,WZ,ZZ
- W±W±jj
- single top
- H (with hvq loops)
- Hj, Hjj
- VBF
- tH^+



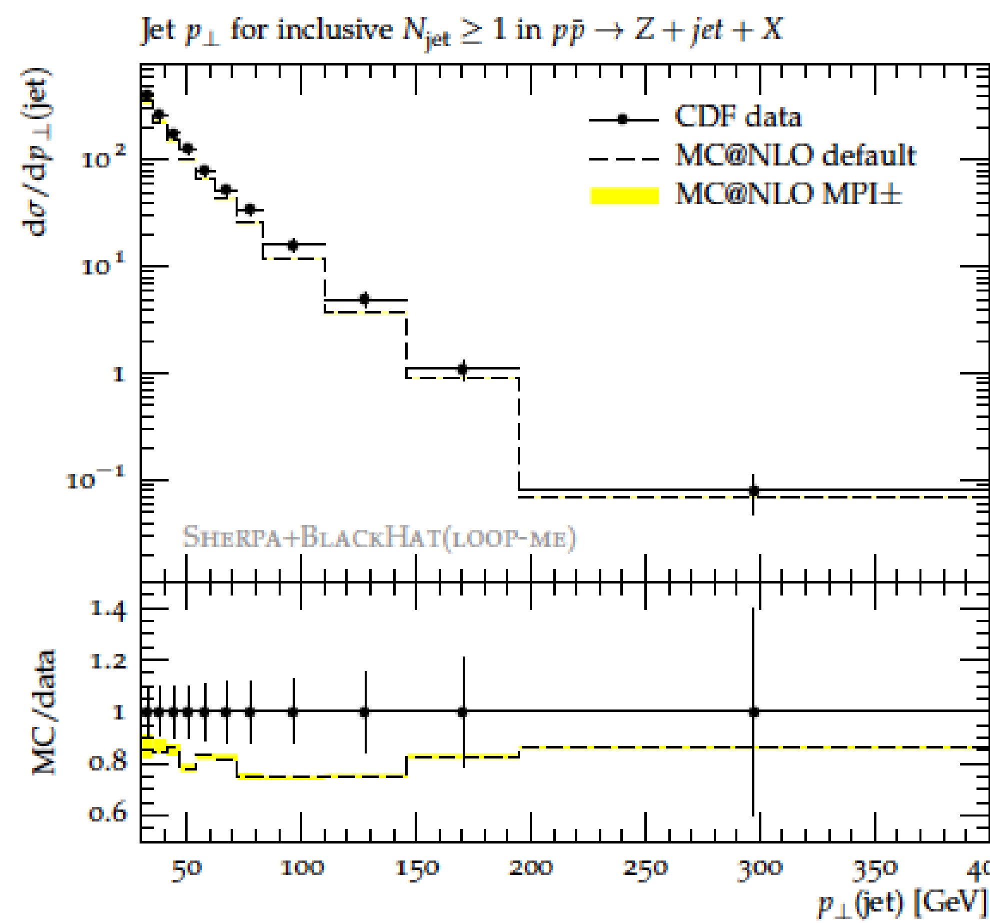
pp→Hjj

SHERPA

SHERPA has implemented both MC@NLO and POWHEG methods. It uses external loop amplitudes, while the rest is automatic. Several processes available now in particular with extra jets.



W



Z+1 jet

Friday 4 May 2012

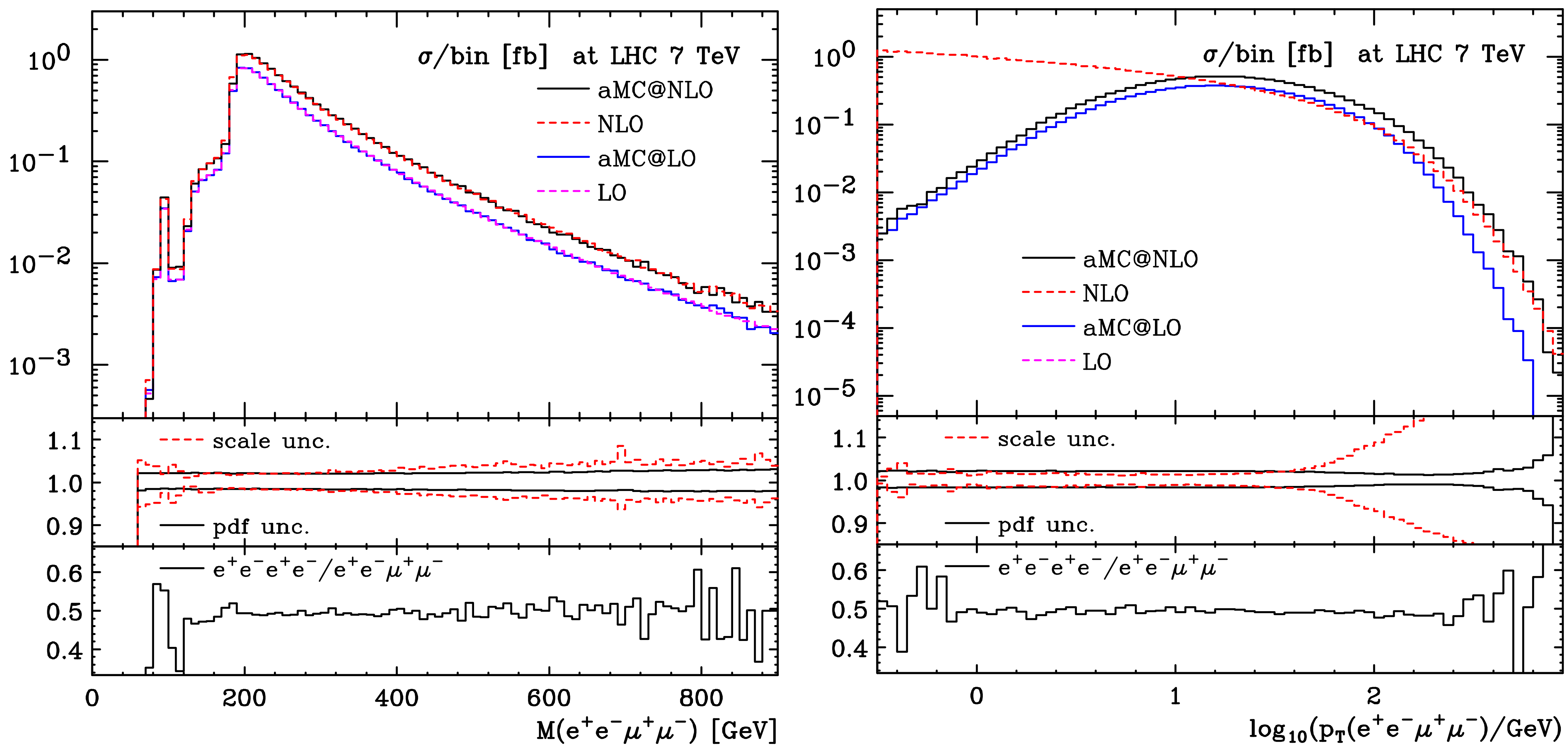
aMC@NLO

Fully automatic implementation of the MC@NLO method using MadLoop and MadFKS.

- Large class of processes available as they can be generated automatically.
- Automatic scale and PDF uncertainties without need of rerunning.
- NLO+PS for processes with n-jets tested and validated.
- Public release coming via MG5 soon..

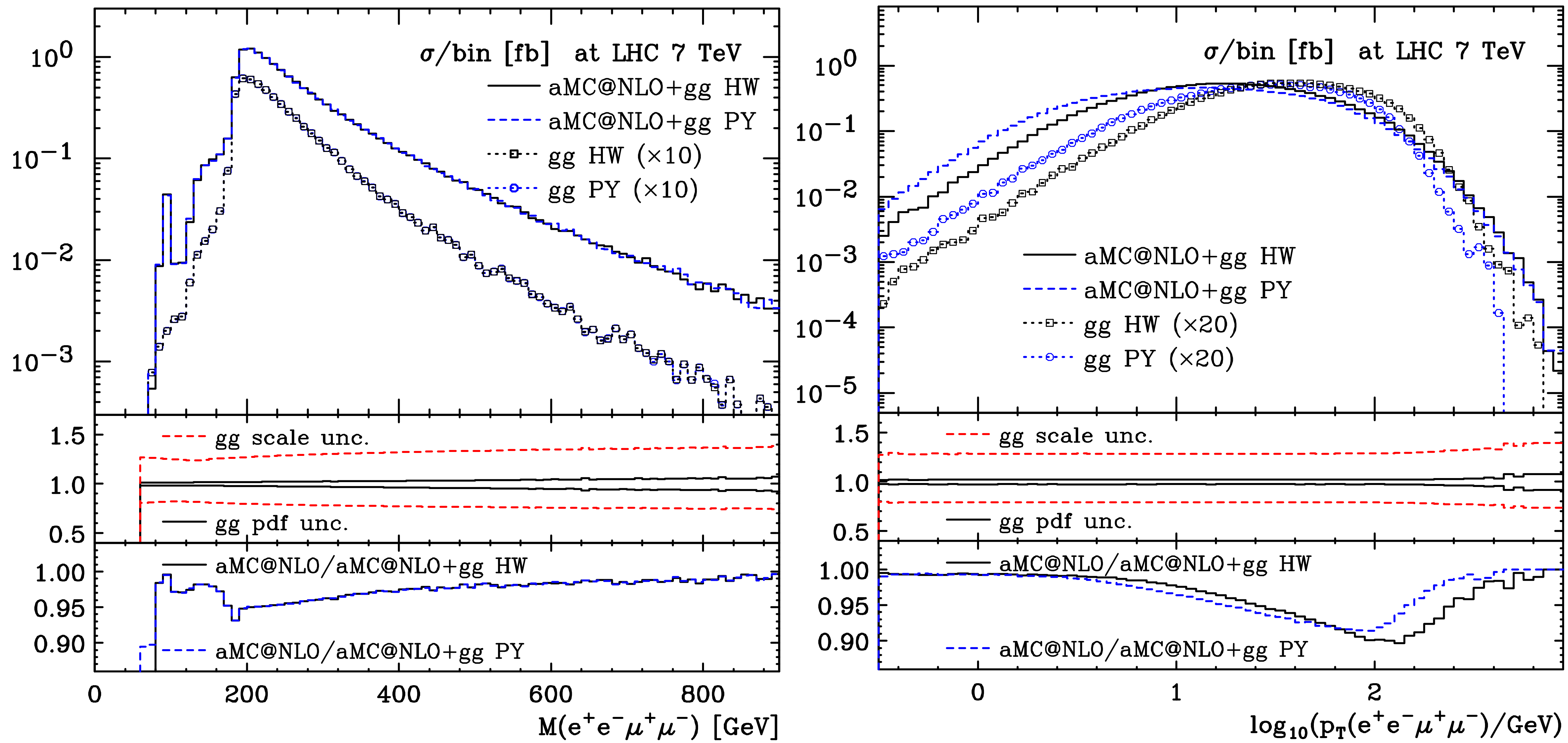
Let's see a few examples in detail...

Four-lepton production



- 4-lepton invariant mass is almost insensitive to parton shower effects. 4-lepton transverse moment is extremely sensitive
- Including scale uncertainties

Four-lepton production



- Differences between Herwig (black) and Pythia (blue) showers large in the Sudakov suppressed region (much larger than the scale uncertainties)
- Contributions from gg initial state (formally NNLO) are of 5-10%

PP → HTT/ATT

- Top pair production in association with a (pseudo-)scalar Higgs boson
- Three scenarios

  I) scalar Higgs H, with m_H = 120 GeV

  II) pseudo-scalar Higgs A, with m_A = 120 GeV

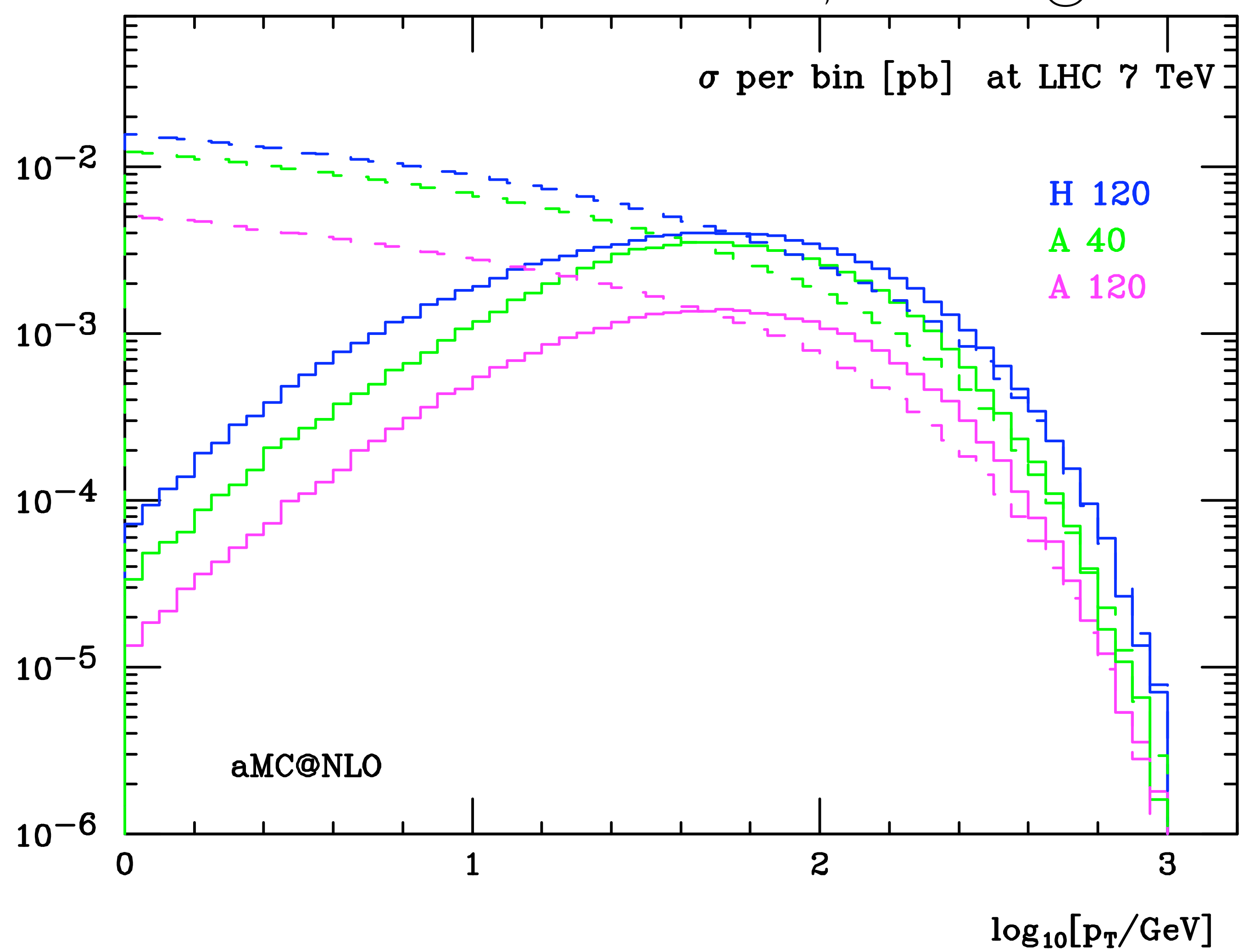
  III) pseudo-scalar Higgs A, with m_A = 40 GeV

- SM-like Yukawa coupling, $y_t/\sqrt{2}=m_t/v$
- Renormalization and factorization scales $\mu_F = \mu_R = \left(m_T^t m_T^{\bar{t}} m_T^{H/A}\right)^{\frac{1}{3}}$ with $m_T = \sqrt{m^2 + p_T^2}$ and $m_t^{pole} = m_t^{MS} = 172.5 \text{ GeV}$
- Note: first time that pp → ttA has been computed beyond LO

PP → HTT/ATT

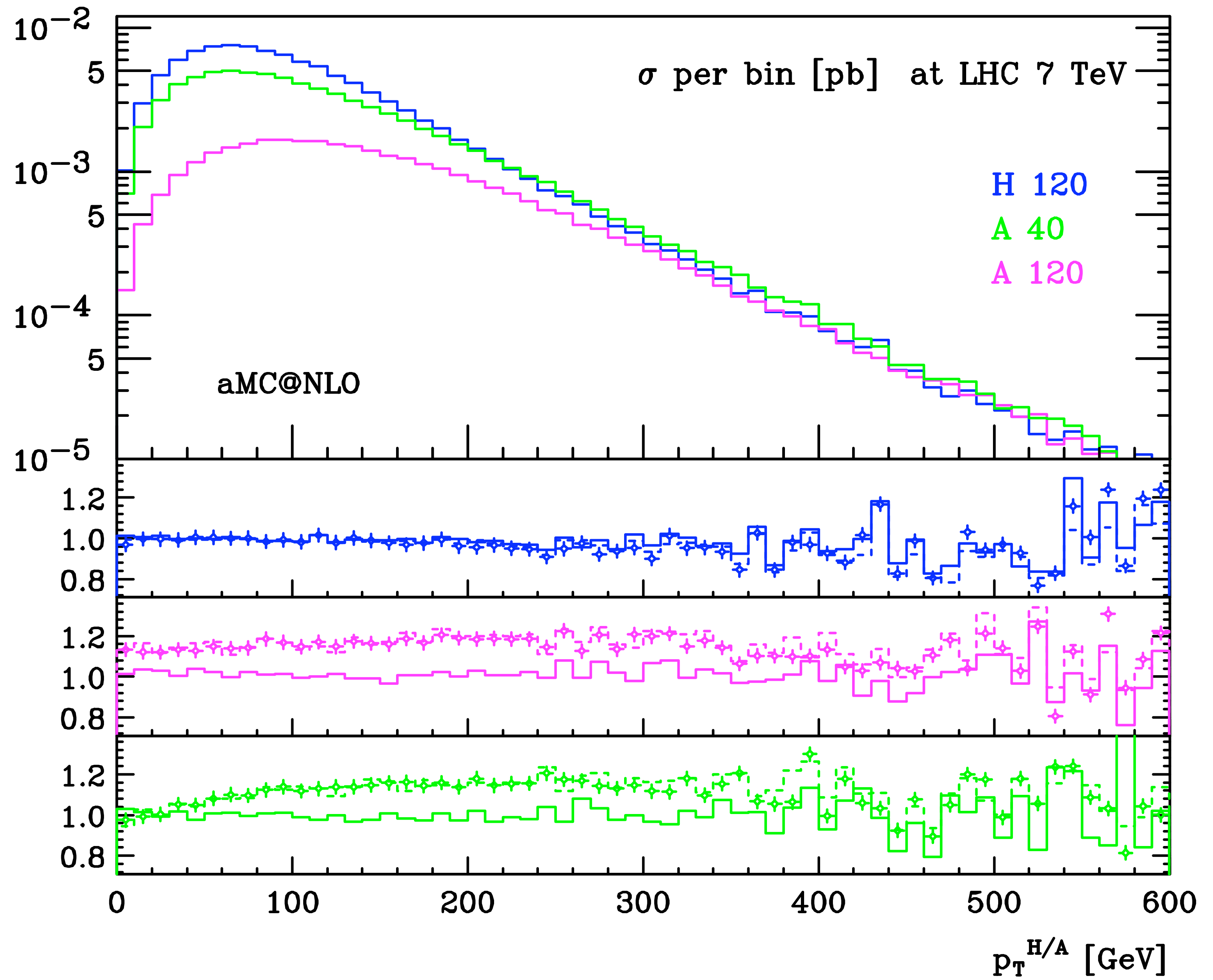
- Three particle transverse momentum, p_T(H/A t tbar), is obviously sensitive to the impact of the parton shower
- Infrared sensitive observable at the pure-NLO level for $p_T \to 0$
- aMC@NLO displays the usual Sudakov suppression
- At large p_T's the two descriptions coincide in shape and rate

Dashed: NLO, Solid: aMC@NLO



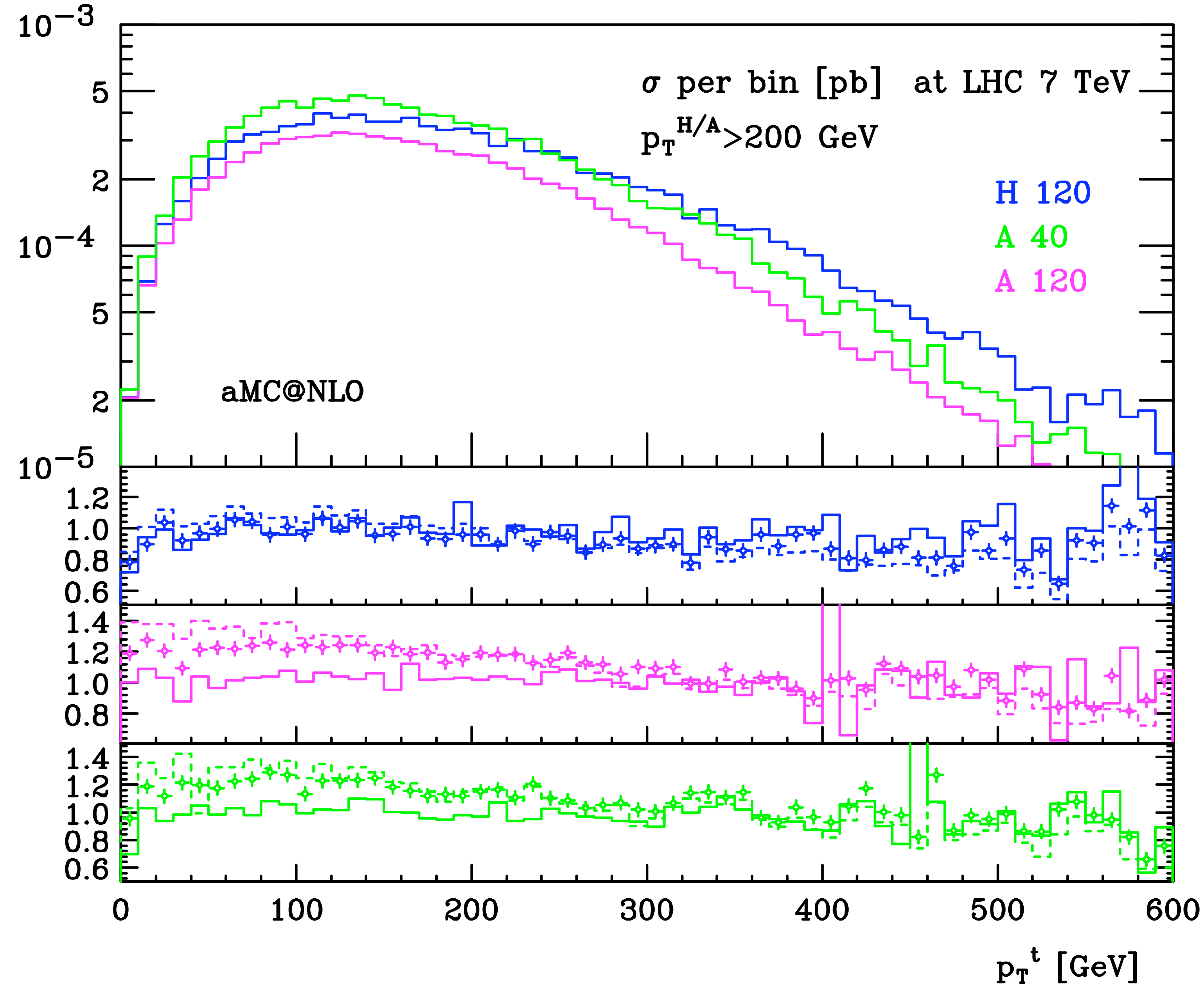
PP → HTT/ATT

- Transverse momentum of the Higgs boson
- Lower panels show the ratio with LO (dotted), NLO (solid) and aMC@LO (crosses)
- Corrections are small and fairly constant
- At large p_T, scalar and pseudo-scalar production coincide: boosted Higgs scenario [Butterworth et al., Plehn et al.] should work equally well for pseudo-scalar Higgs



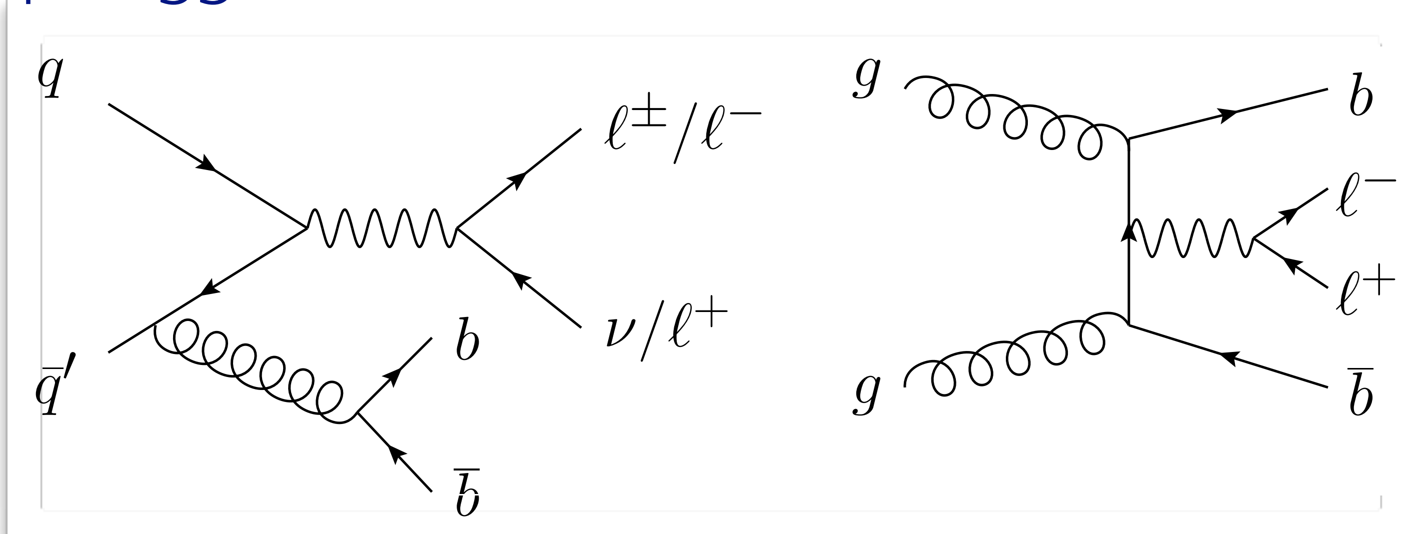
PP → HTT/ATT

- Boosted Higgs: $p_T^{H/A}$ > 200 GeV
- Transverse momentum of the top quark
- Corrections compared to (MC@)LO are significant and cannot be approximated by a constant K-factor



pp → Wbb/Zbb

- Background to pp → HW/HZ, H → bb
- 4 Flavor scheme calculations
    - Massive b quarks
    - No initial state b quarks
    - Born is finite: no generation cuts are needed

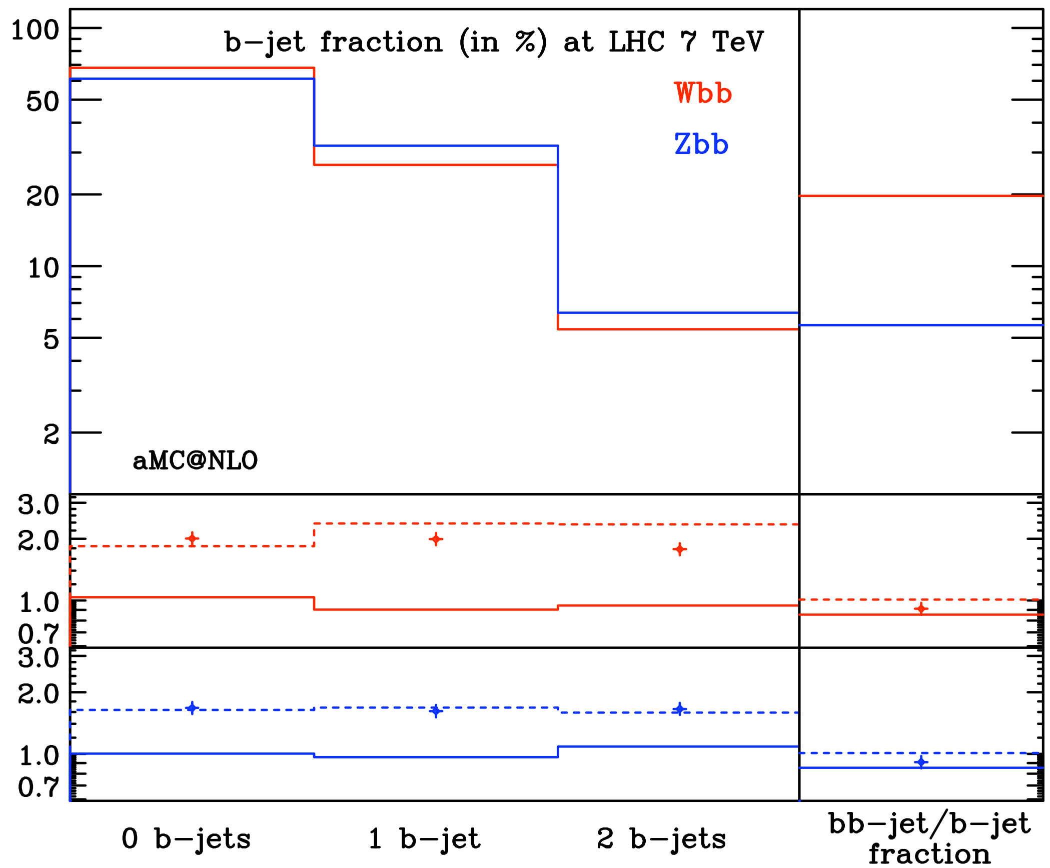


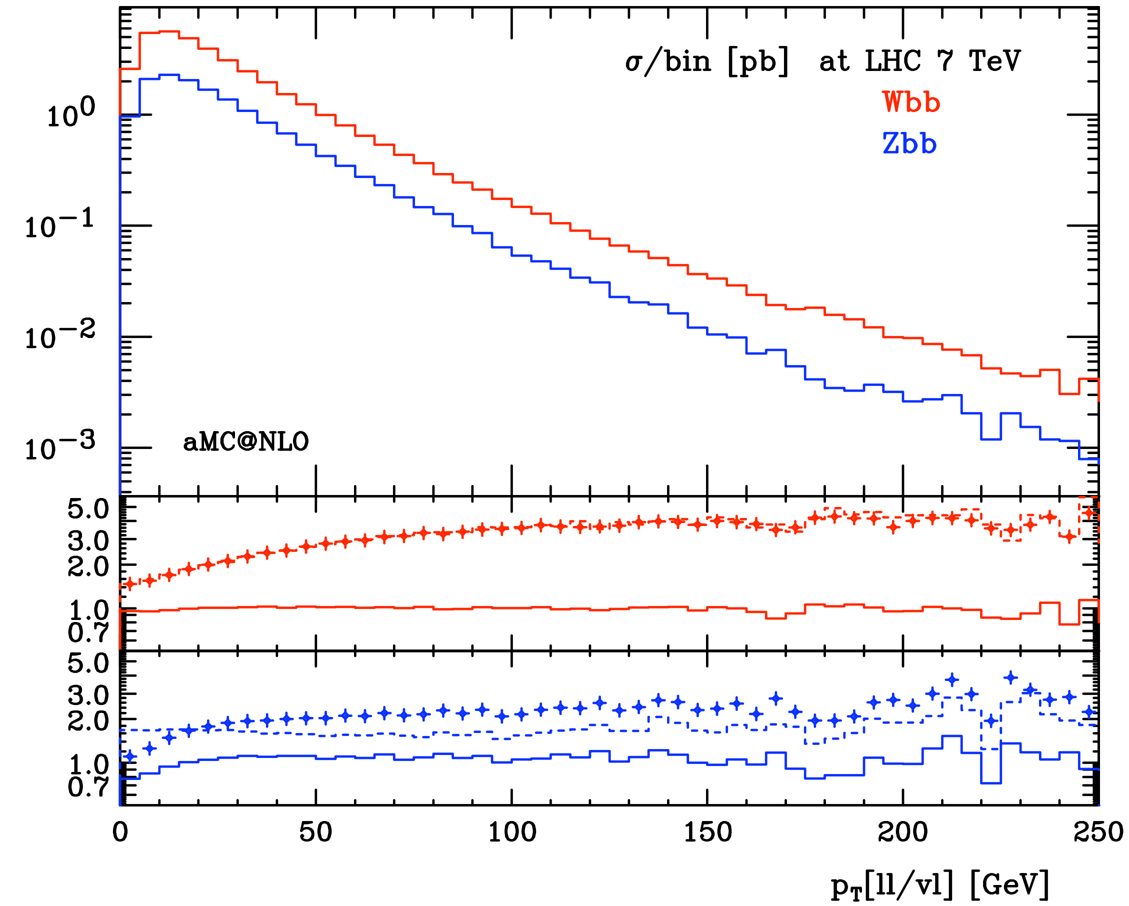
- At LO, Wbb is purely qq induced, while Zbb has also contributions from gg initial states
- Cross sections for Zbb and Wbb are similar at LHC 7 TeV

	Cross section (pb)					
	Tevatron $\sqrt{s}$ =1.96 TeV			LHC $\sqrt{s}$ =7 TeV		
	LO	NLO	K factor	LO	NLO	K factor
$\ell\nu b\bar{b}$	4.63	8.04	1.74	19.4	38.9	2.01
$\ell^+\ell^- b\bar{b}$	0.860	1.509	1.75	9.66	16.1	1.67

pp → Wbb/Zbb

aMC@NLO team

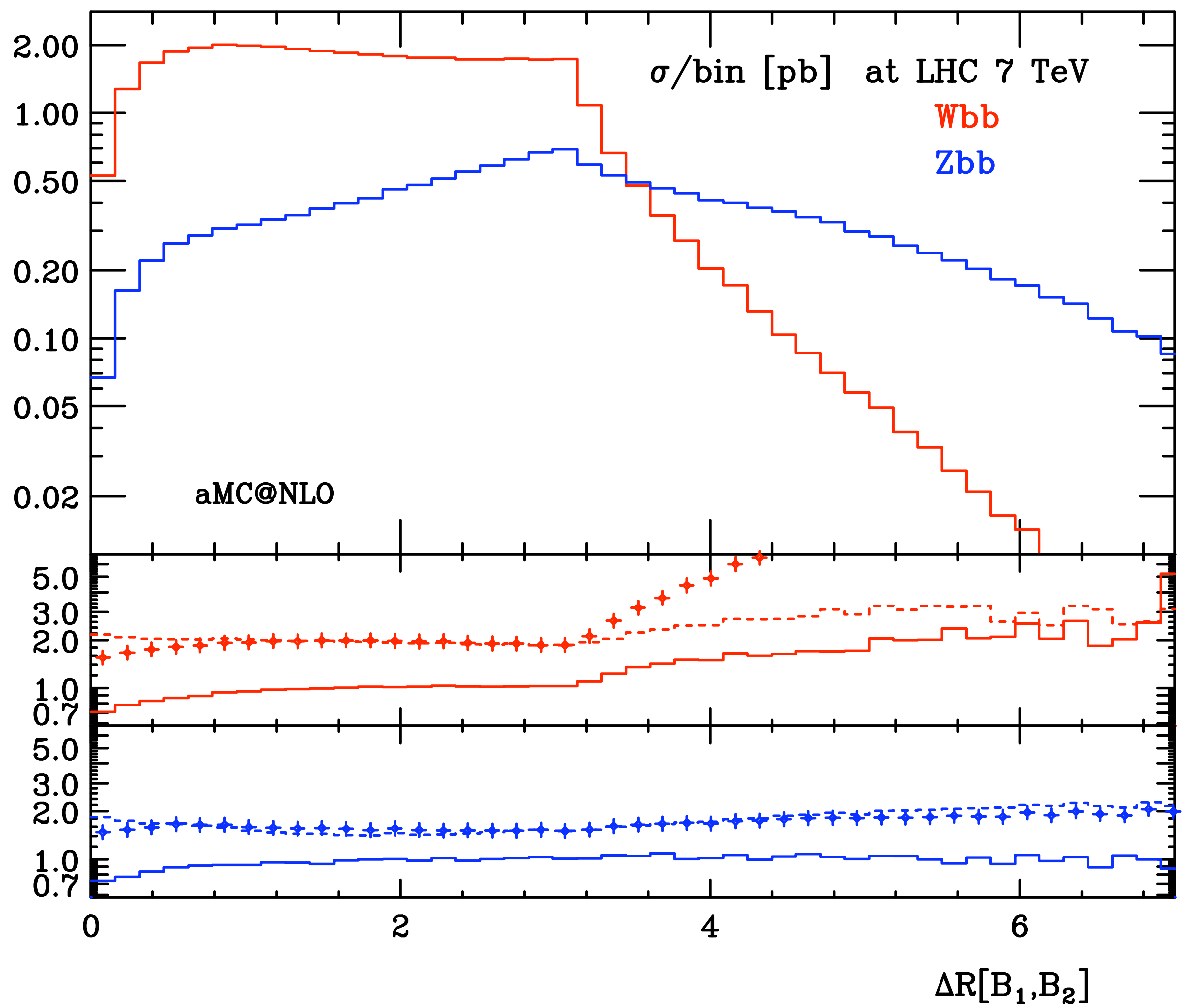




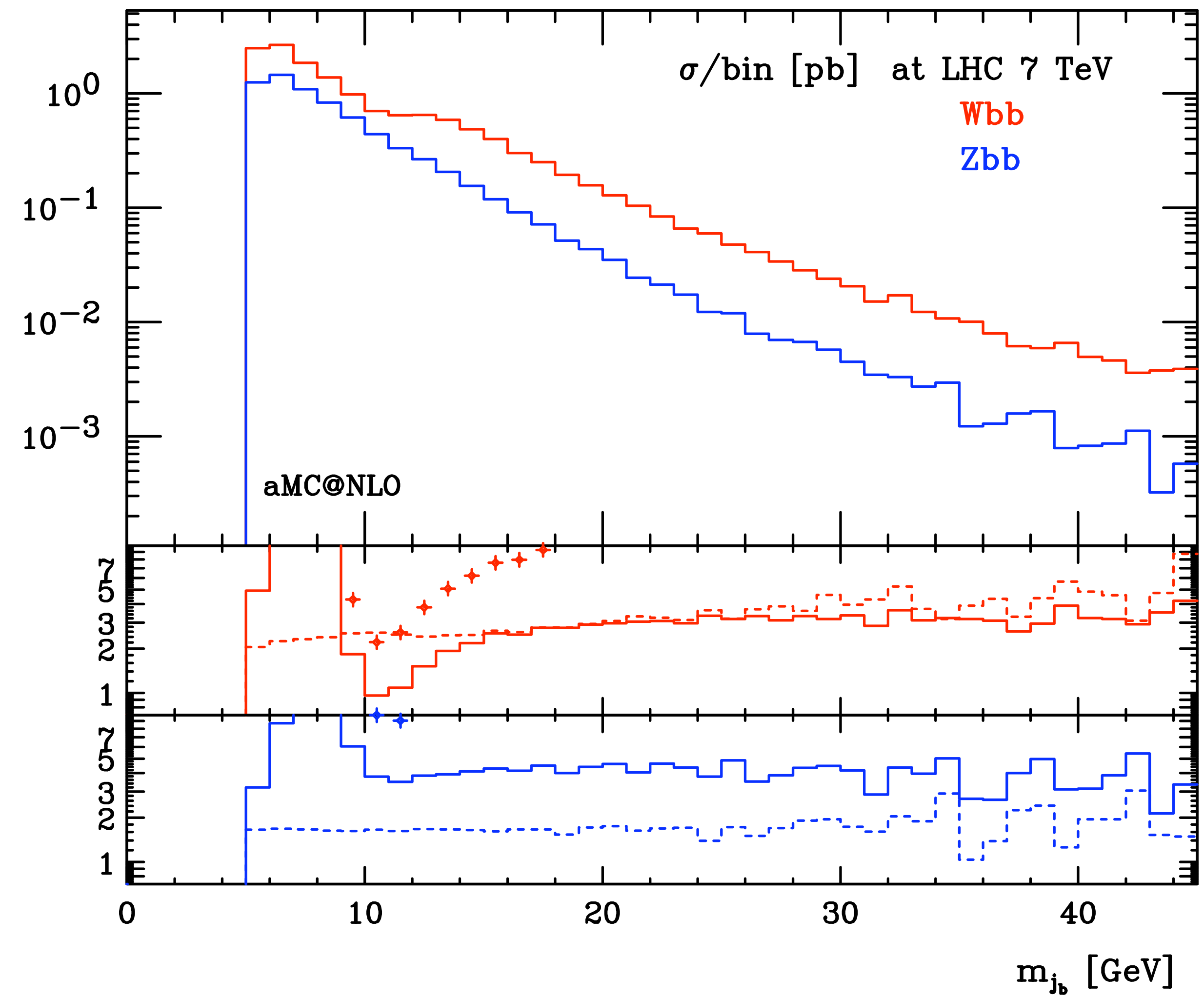
- In Wbb, ~20% of b-jets are bb-jets; for Zbb only ~6%
  - Jets defined with anti-k_T and R=0.5, with p_T(j)>20 GeV and |η|<2.5
- Lower panels show the ratio of aMC@NLO with LO (crosses), NLO (solid) and aMC@LO (dotted)
- NLO and aMC@NLO very similar and consistent

pp → Wbb/Zbb

Distance between B-mesons

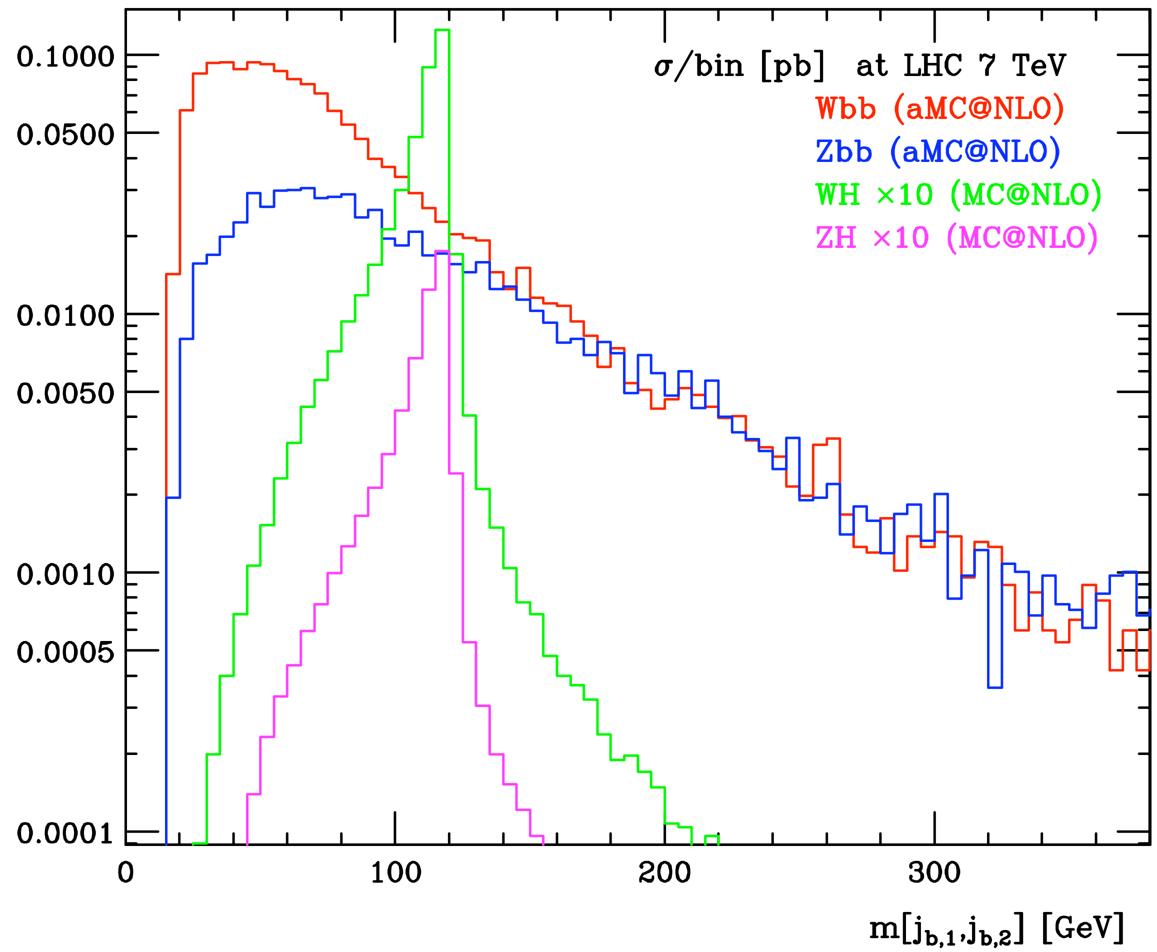


b-jet mass



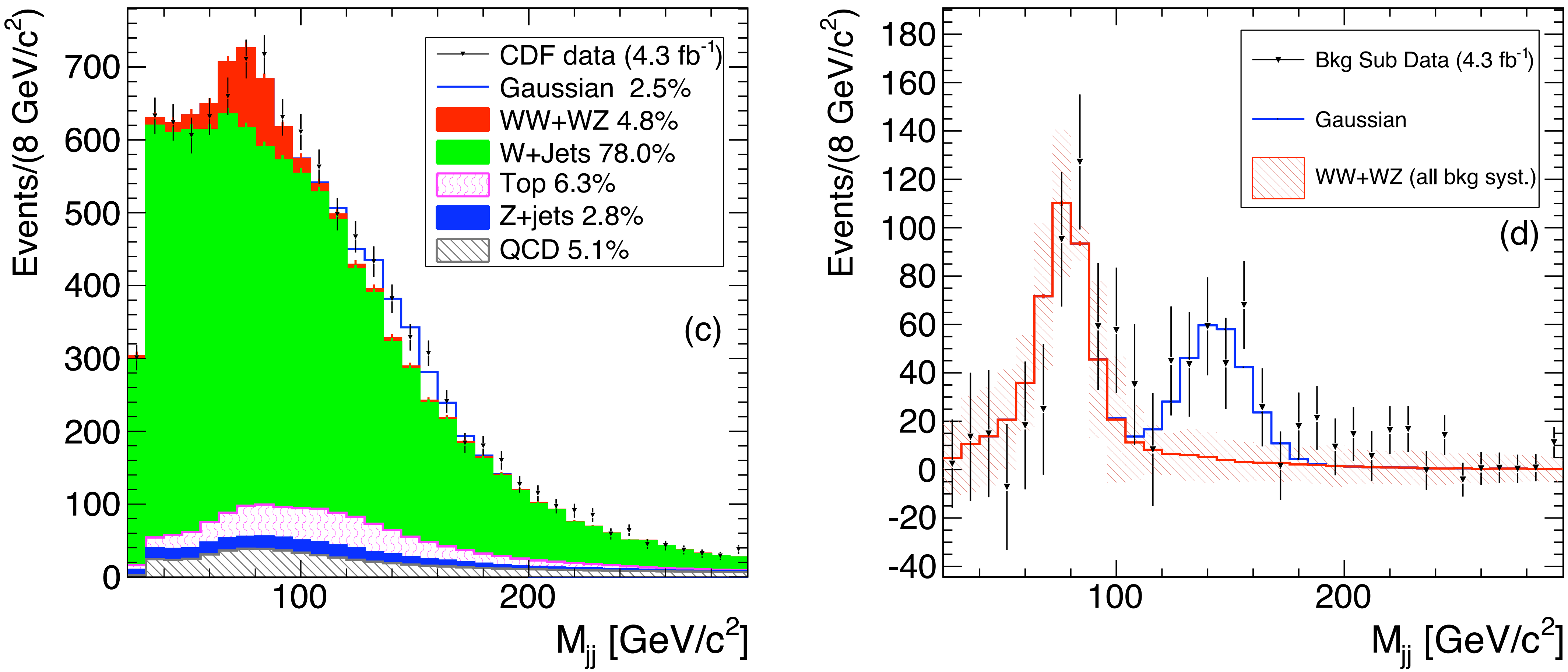
- For some observables NLO effects are large and/or parton showering has large effects

Signal + background



Using (a)MC@NLO both signal and background for Vector boson production in association with a Higgs boson (where the Higgs decays to b anti-b) can be produced at the same NLO accuracy, including showering and hadronization effects

Wjj at CDF

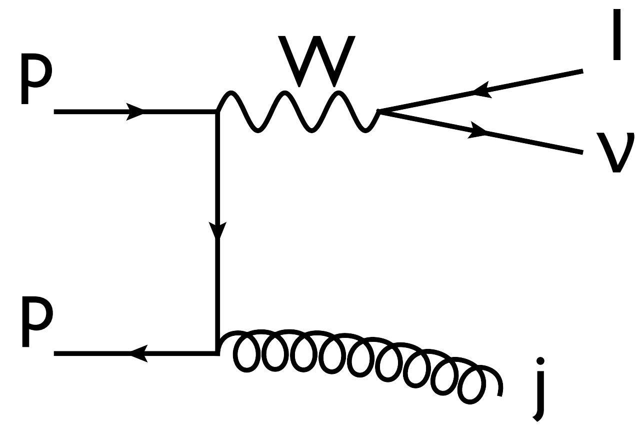


- In April CDF reported an excess of events with 3.2 standard deviation significance in the dijet invariant mass distribution (with invariant mass 130-160 GeV) for Wjj events
- The update in June (using 7.3 fb^{-1} of data) increased significance of the excess to 4.1 standard deviations

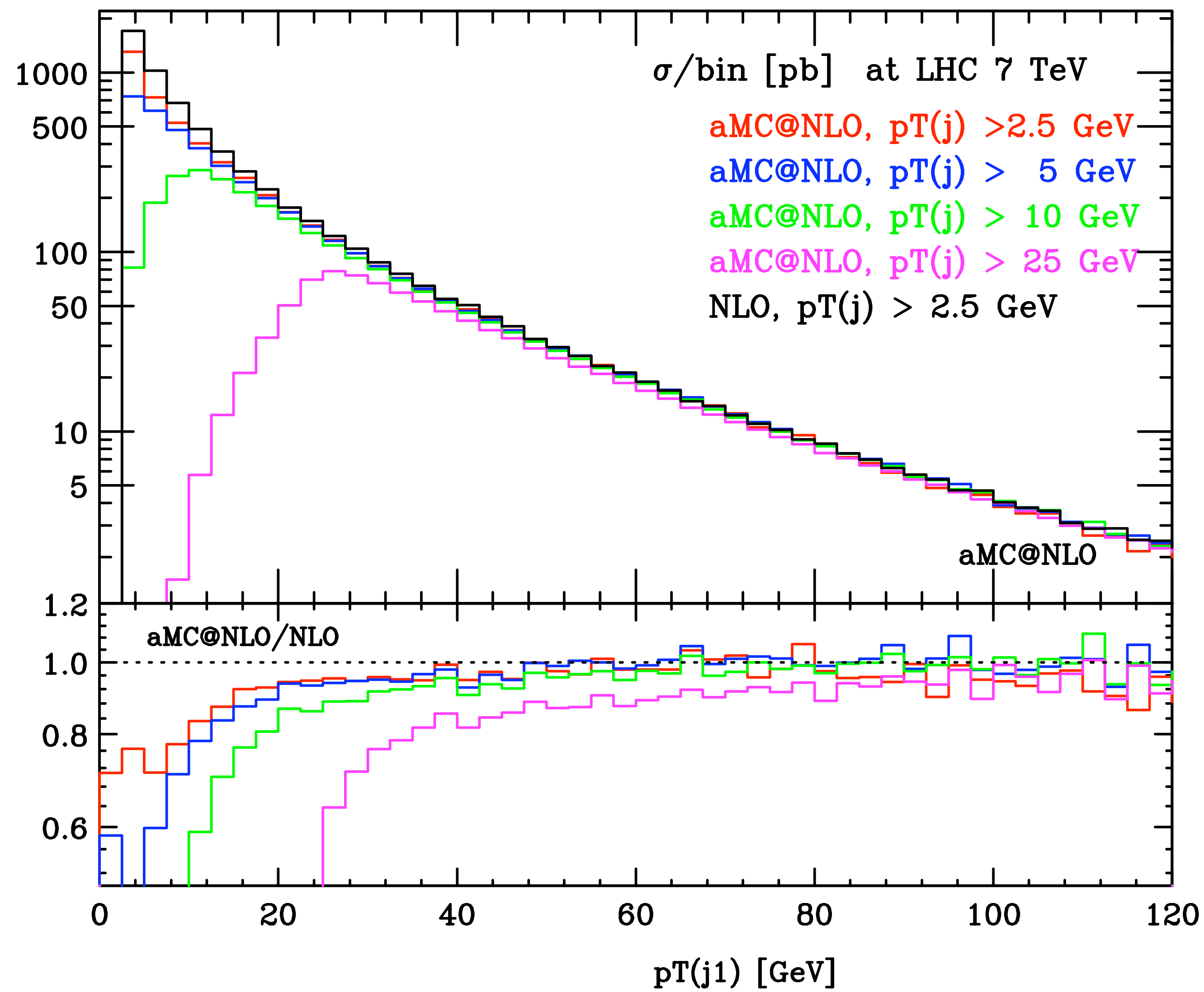
Computational challenge

- At the time, first process with so many scales and possible (IR) divergences is matched to a parton shower at NLO accuracy
- Start with W+1j production to validate processes which need cuts at the matrix-element level
- To check the insensitivity to this cut:
  - generate a couple of event samples with different cuts and show that the distributions after analysis cuts are statistically equivalent

PP → WJ



- For W+1j the easiest cut would be in on the p_T of the W boson
- However, for validation purposes it is more appropriate to apply this cut on the jet instead (because that is what we'll be doing in W+2j). Same at LO, but different at NLO



- Different cuts at generation level yield the same distributions at analysis level if the analysis level cut is 3-4 times larger

pp → Wjj
Set-up

- Two event samples with 5 GeV and 10 GeV p_T cuts on the jets at generation level, respectively, each with 10 million unweighted events
- Renormalization and factorization scales equal to $\mu_R = \mu_F = H_T/2$

$$2\mu_R = 2\mu_F = H_T = \sqrt{(p_{T,l\nu}^2 + m_{l\nu}^2)} + \sum |p_{T,i}|$$

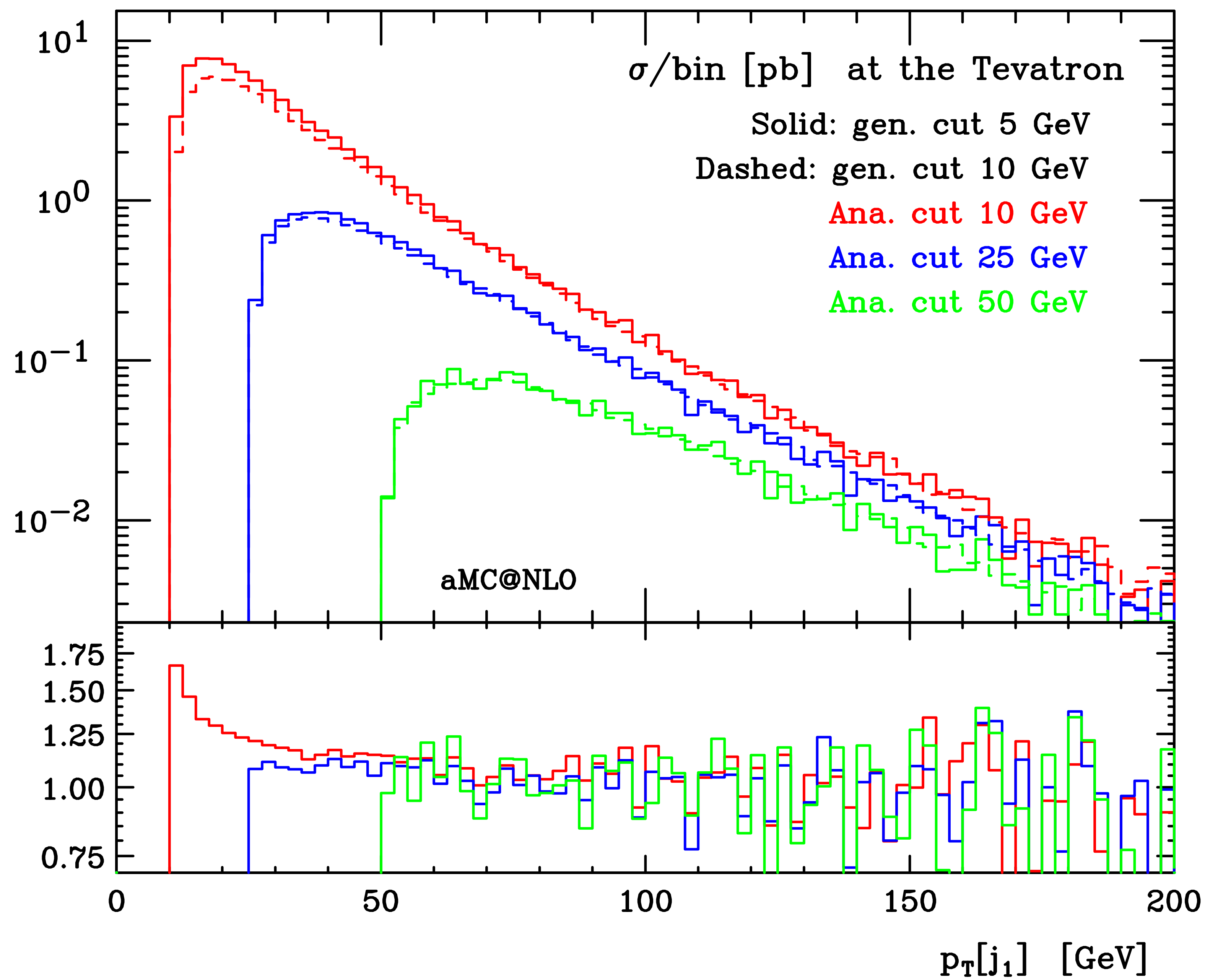
  where sum is over the 2 or 3 partons (and the matrix element level)

- Jets are defined with anti-k_T and R=0.4
- MSTW2008(N)LO PDF set for the (N)LO predictions (with $\alpha_s(m_Z)$ from PDF set using (2)1-loop running)
- $m_W = 80.419$ GeV,
  $G_F = 1.16639 \cdot 10^{-5}$ GeV^{-2},
  $\alpha^{-1} = 132.507$,
  $\Gamma_W = 2.0476$ GeV

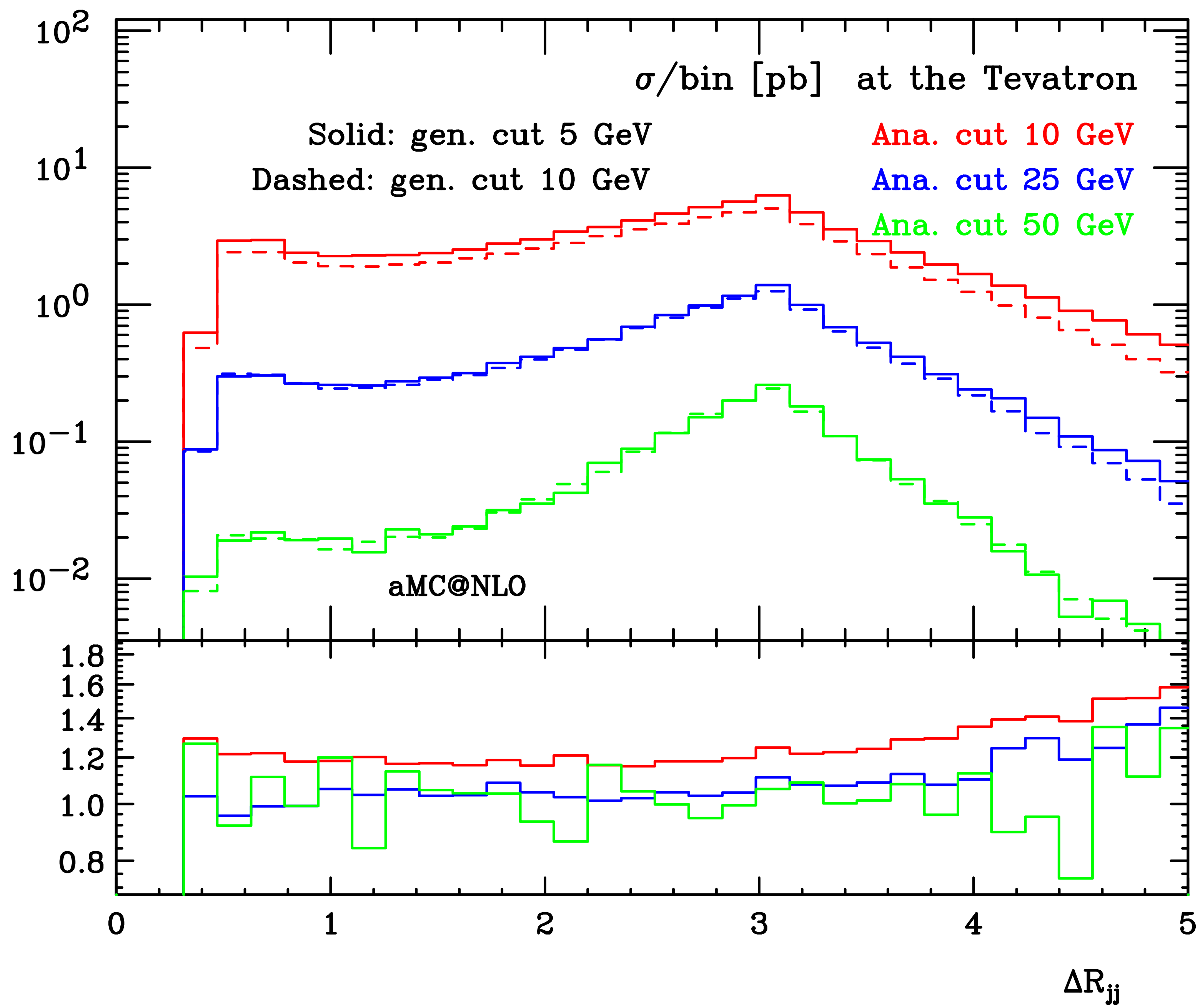
pp → Wjj

Validation

- The two generation level cuts agree for high enough momenta (or harder analysis cuts)
- Middle plot shows ratio of NLO (solid), LO (dotted) and LOwPS (dashed) over aMC@NLO
- Good agreement with (N) LO, slight difference in shape
- Tails have low statistics, in particular for the 5 GeV generation cuts



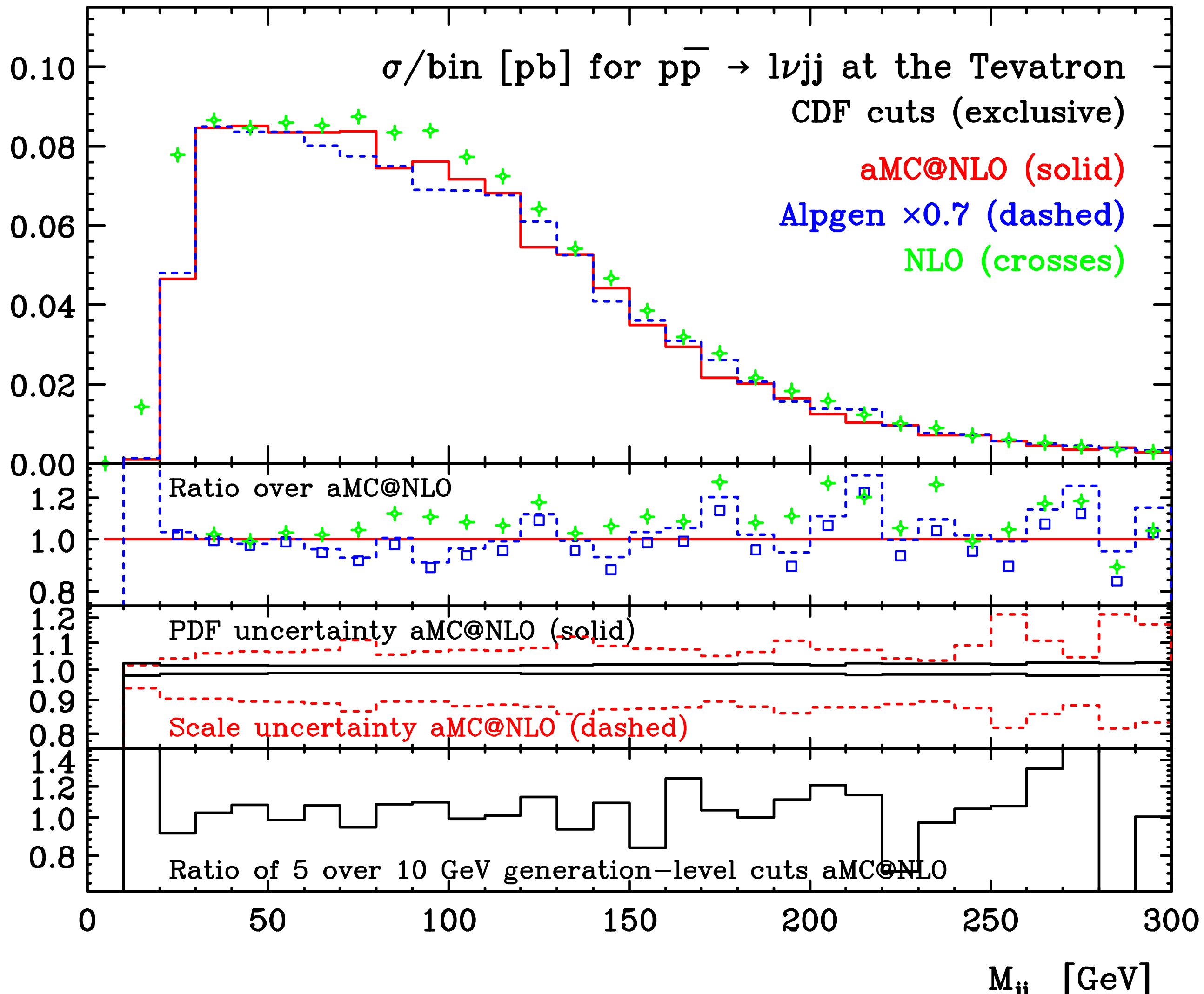
PP → WJJ
Validation - III

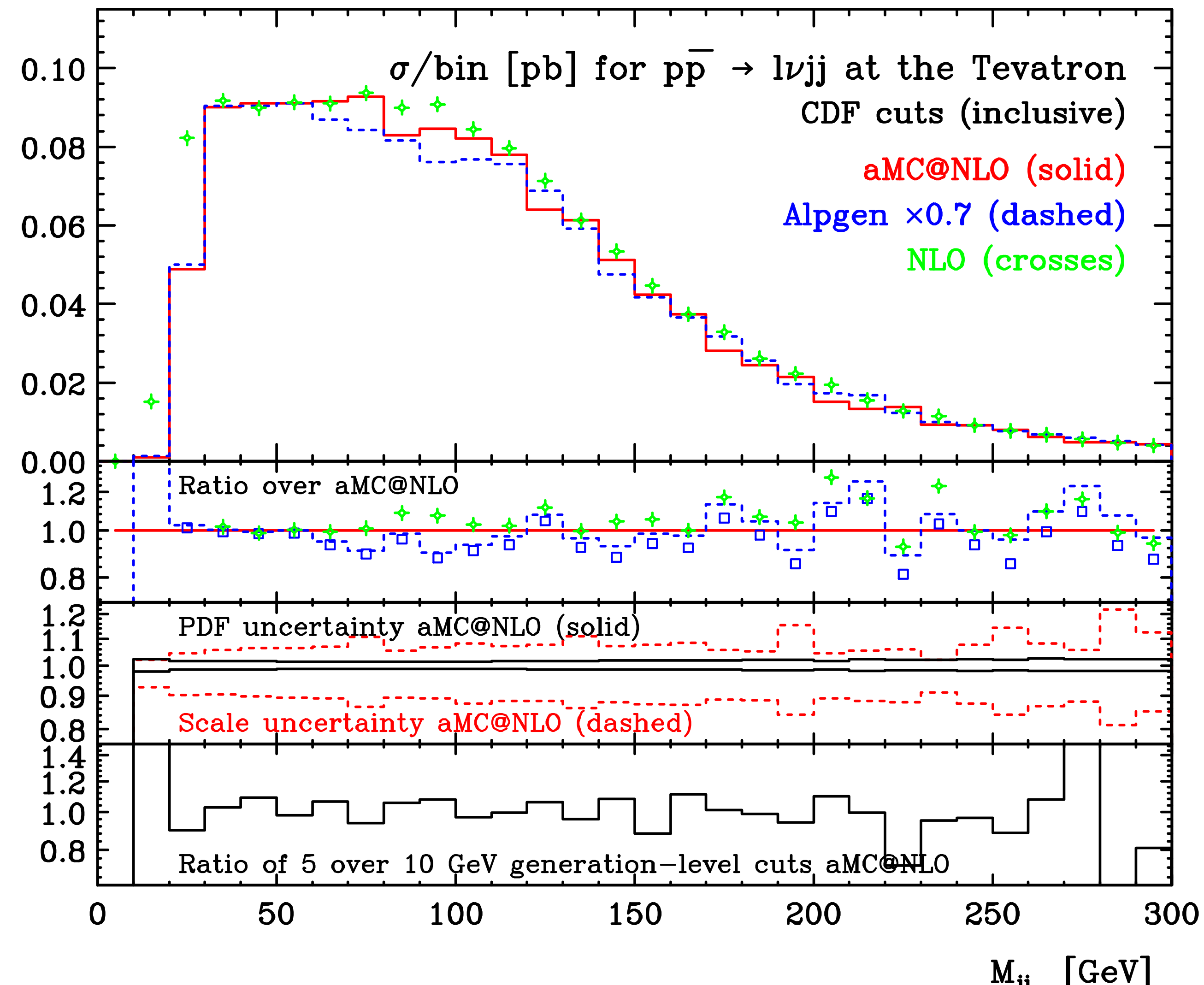


- Distance between the jets
- A small bias remains at 25 GeV analysis in the tail of the distribution, but reduced a lot from lower cuts analysis cuts
  - 5 GeV sample probably ok, 10 GeV gen. cut is a bit too hard
- Of all distributions we have looked at, this one shows the largest bias due to generation cut

pp → Wjj
Dijet invariant mass

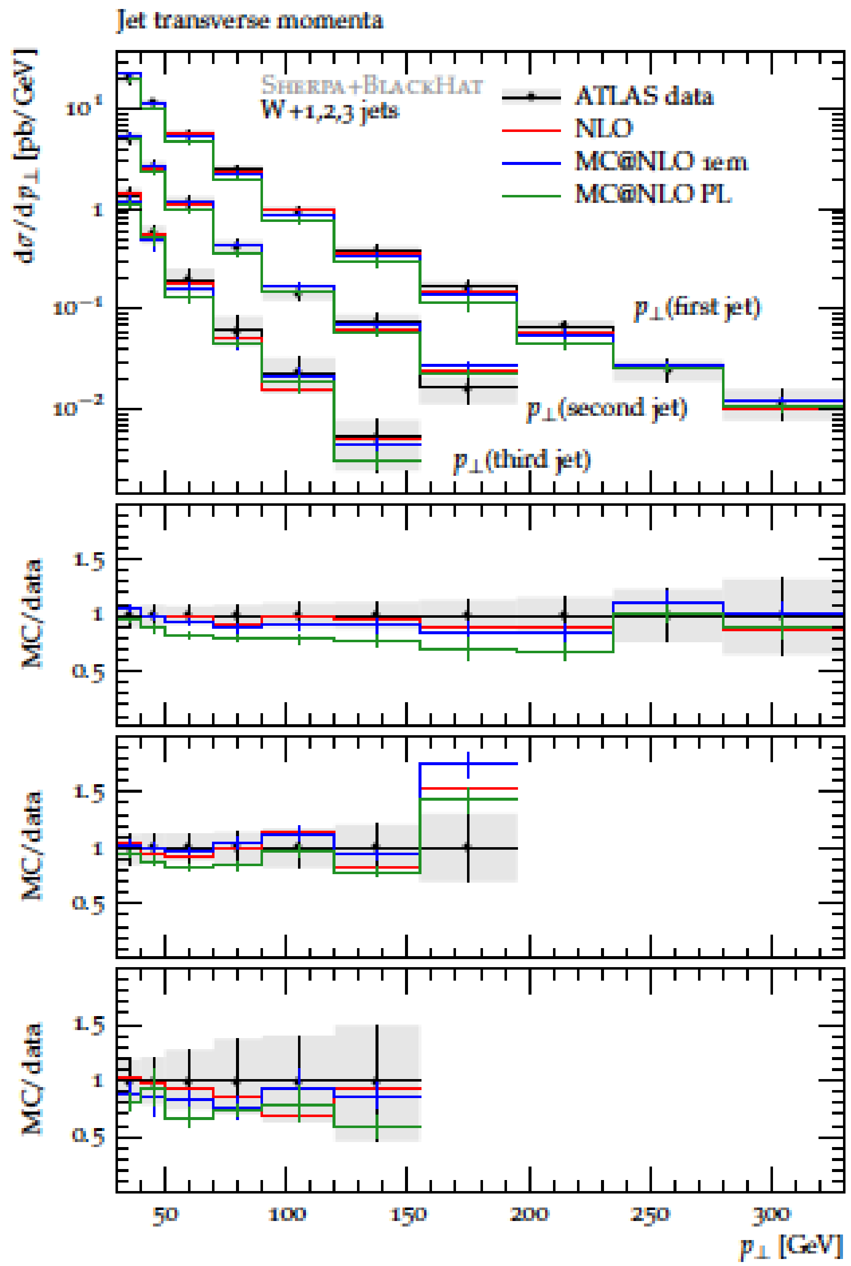
- Dijet invariant mass with/without jet veto
- This is the distribution in which CDF found an excess of events around 130-160 GeV
- No differences in shape between the 5 and 10 GeV generation level cuts
- No sign of enhancement over (N)LO or LOwPS in the mass range 130-160 GeV



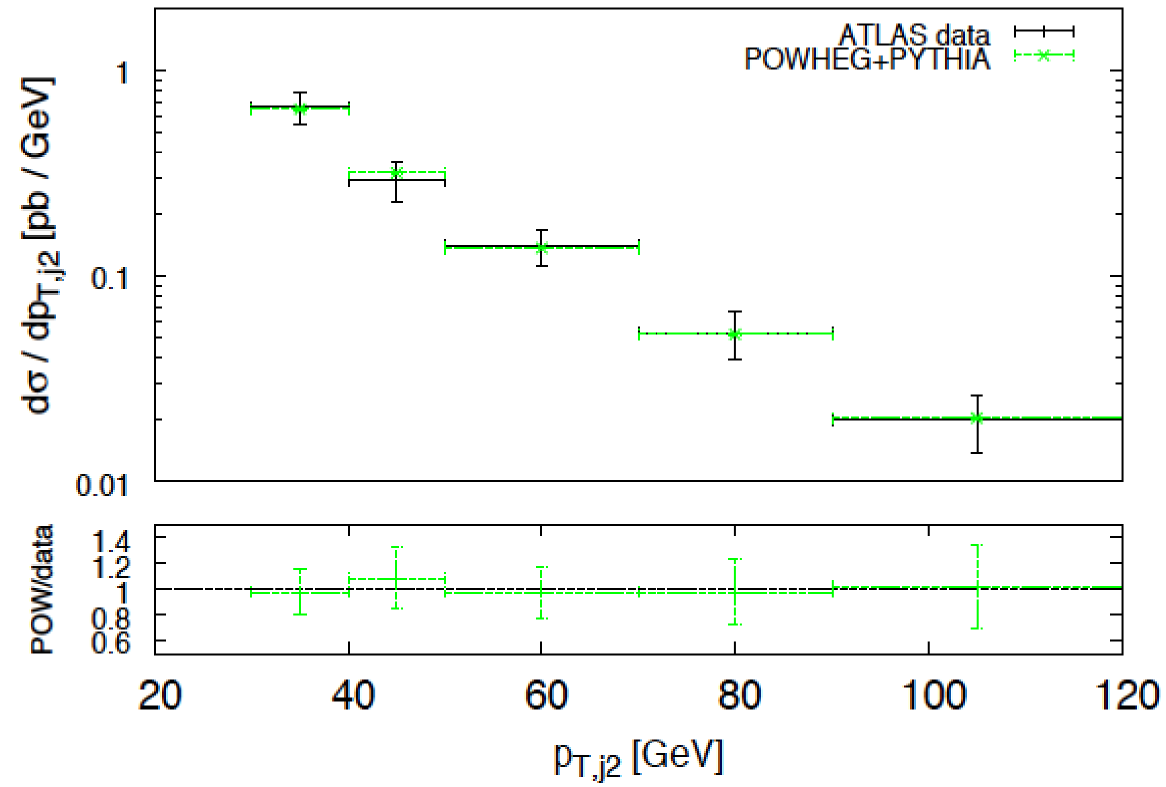


RF, Frixione, Hirschi, maltoni, Pittau & Torrielli (2011)

Other recent results for V+jets



W+1/2/3jets in the SHERPA
Hoeche et al, 1201. 5882



Z+2jets in the POWHEG BOX
E. Re, 1204.5433

NLO+PS

"Best" tools when NLO calculation is available (i.e. low jet multiplicity).

* Main points:
  * NLO+PS provide a consistent to include K-factors into MC's
  * Scale dependence is meaningful
  * Allows a correct estimates of the PDF errors.
  * Non-trivial dynamics beyond LO included for the first time.

N.B. : The above is true for observables which are at NLO to start with!!!

* Current developments:
  * Upgrading of all available NLO computations to MC's in progress
  * Extendable to BSM without hurdles.
  * No merging with different multiplicities available yet (CKKW@NLO)

SM Status circa 2002

$pp \to$ n particles

SM Status circa 2002

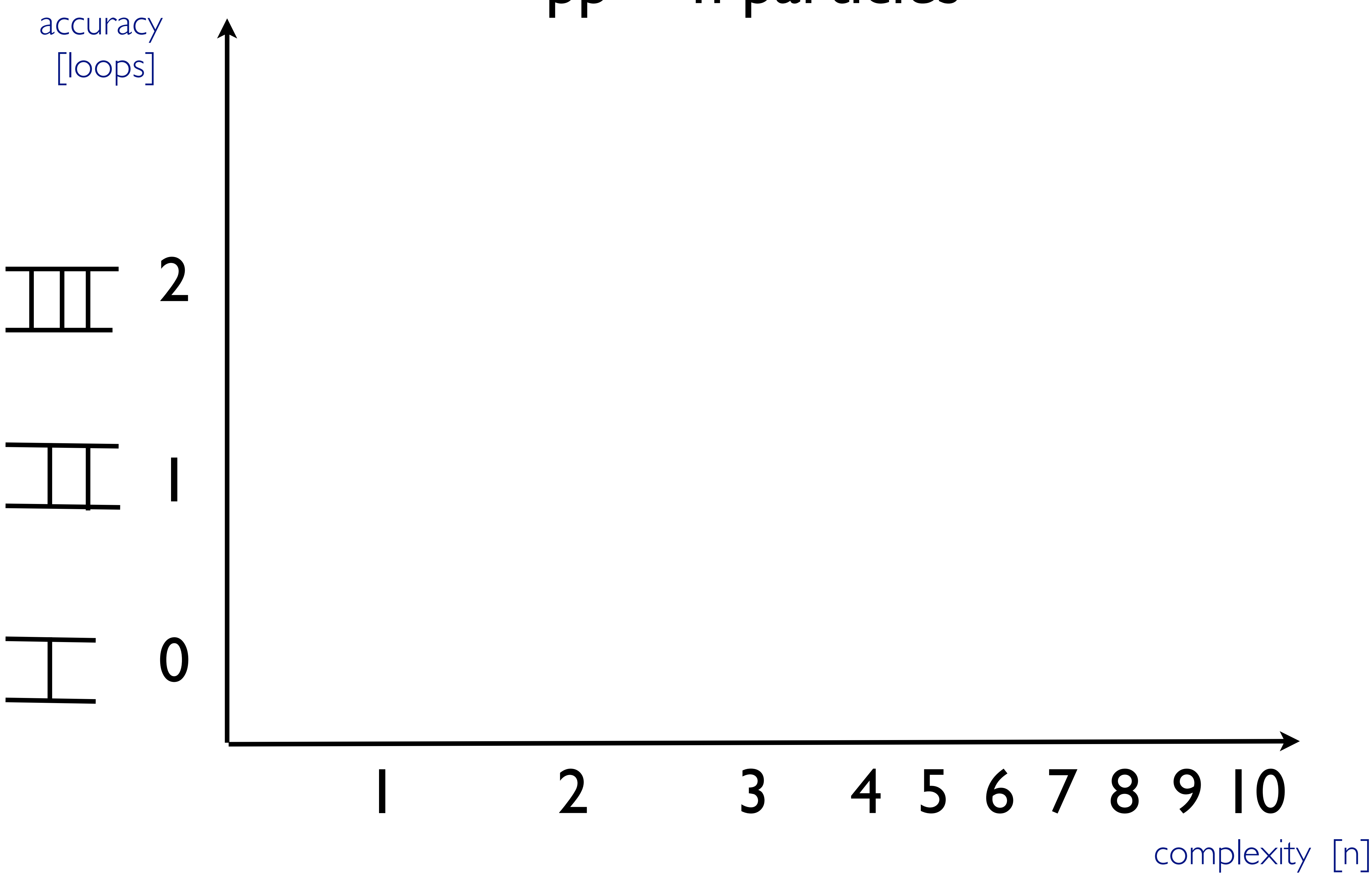
pp → n particles

1 2 3 4 5 6 7 8 9 10

complexity [n]

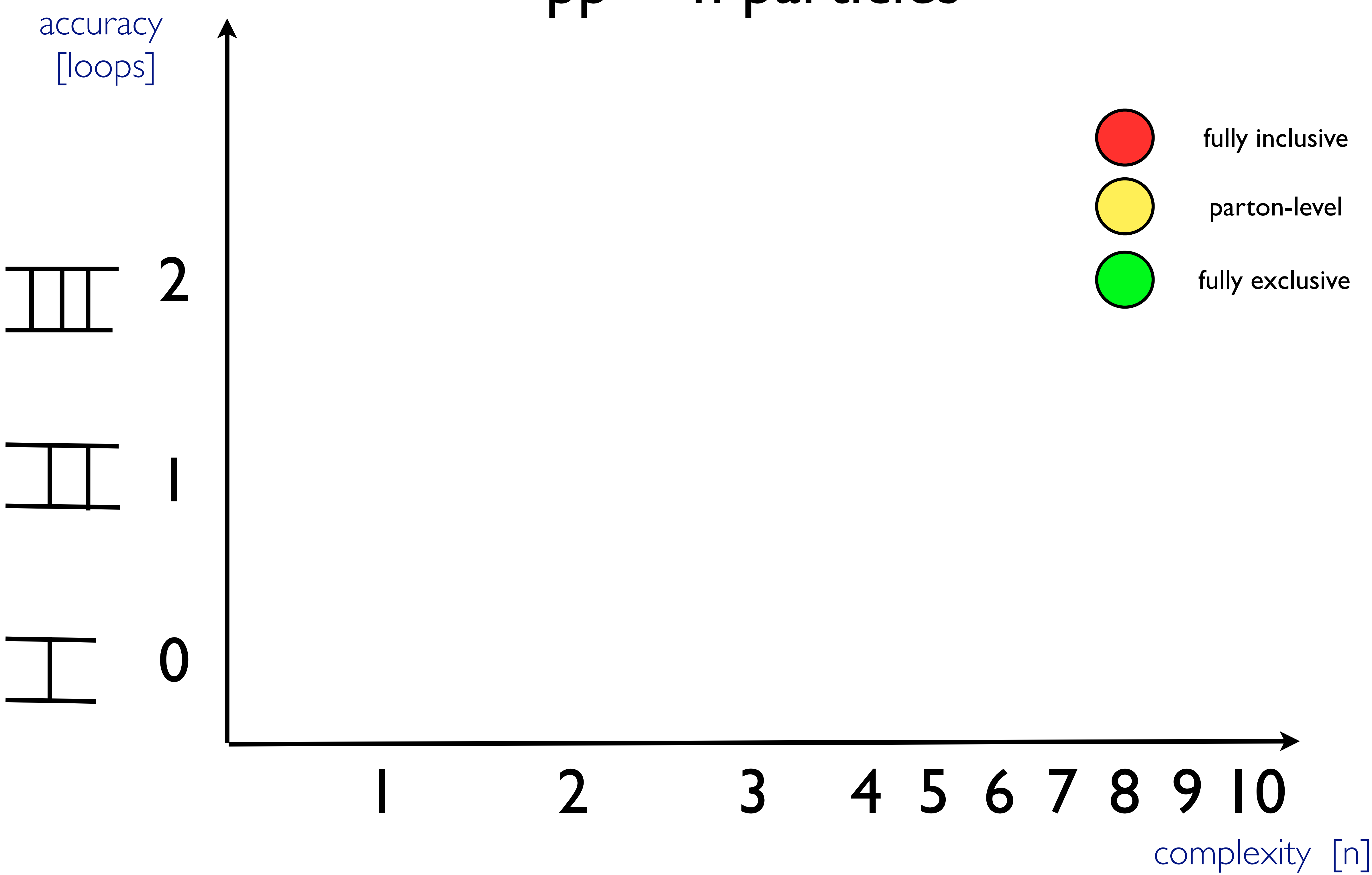
SM Status circa 2002

pp→ n particles



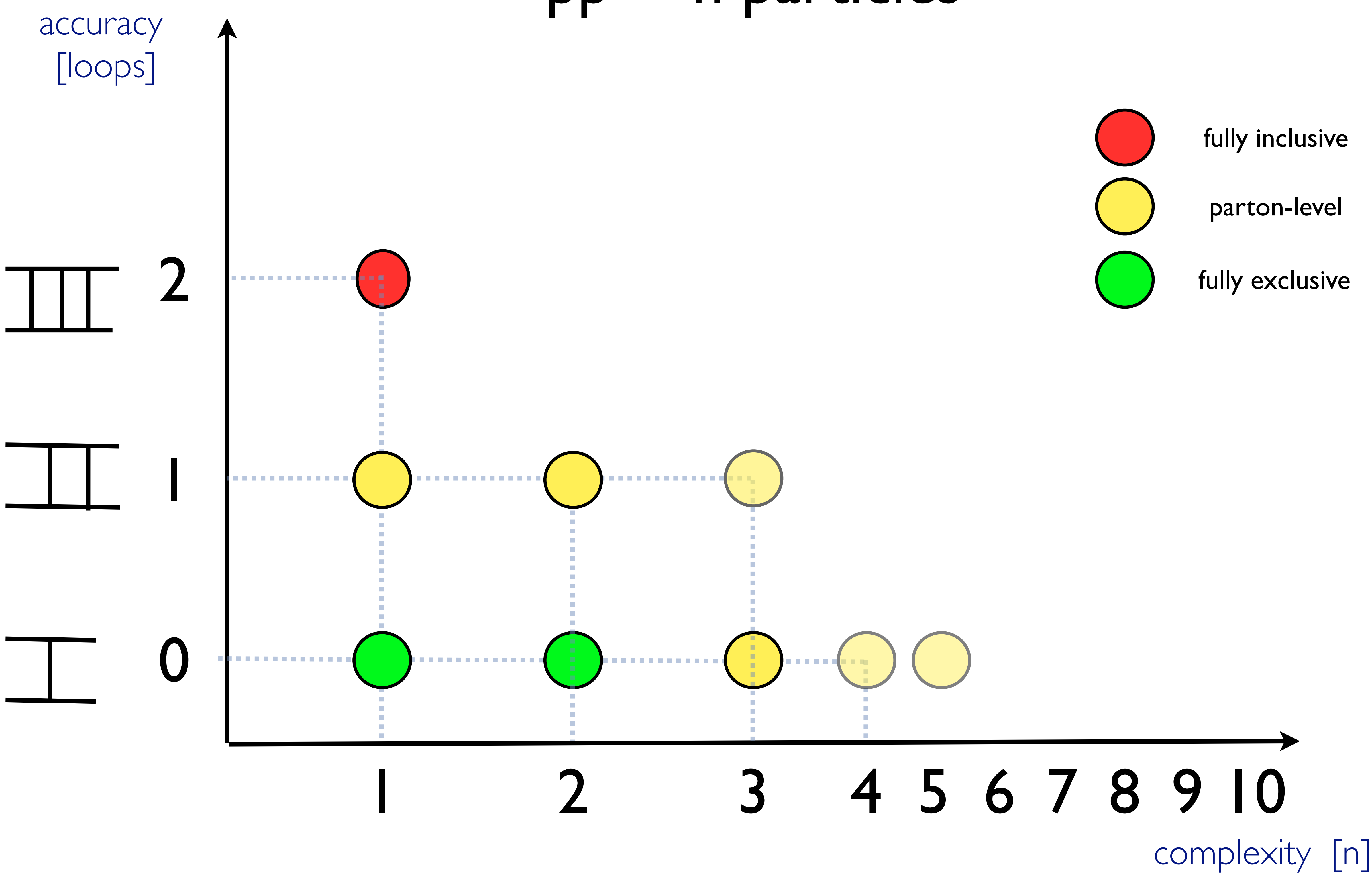
SM Status circa 2002

pp→ n particles



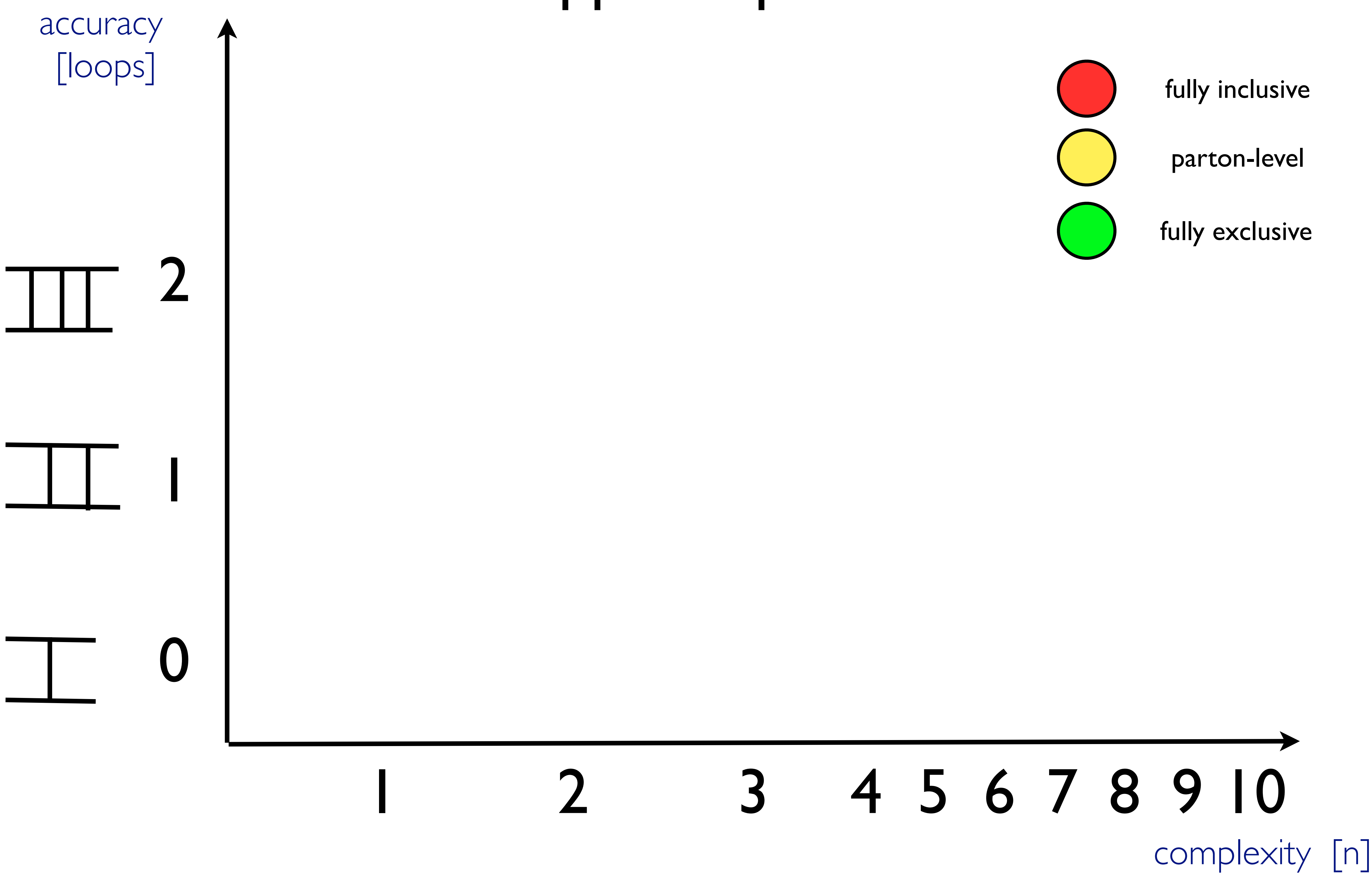
SM Status CIRCA 2002

pp → n particles



SM Status : since 2007

pp→ n particles



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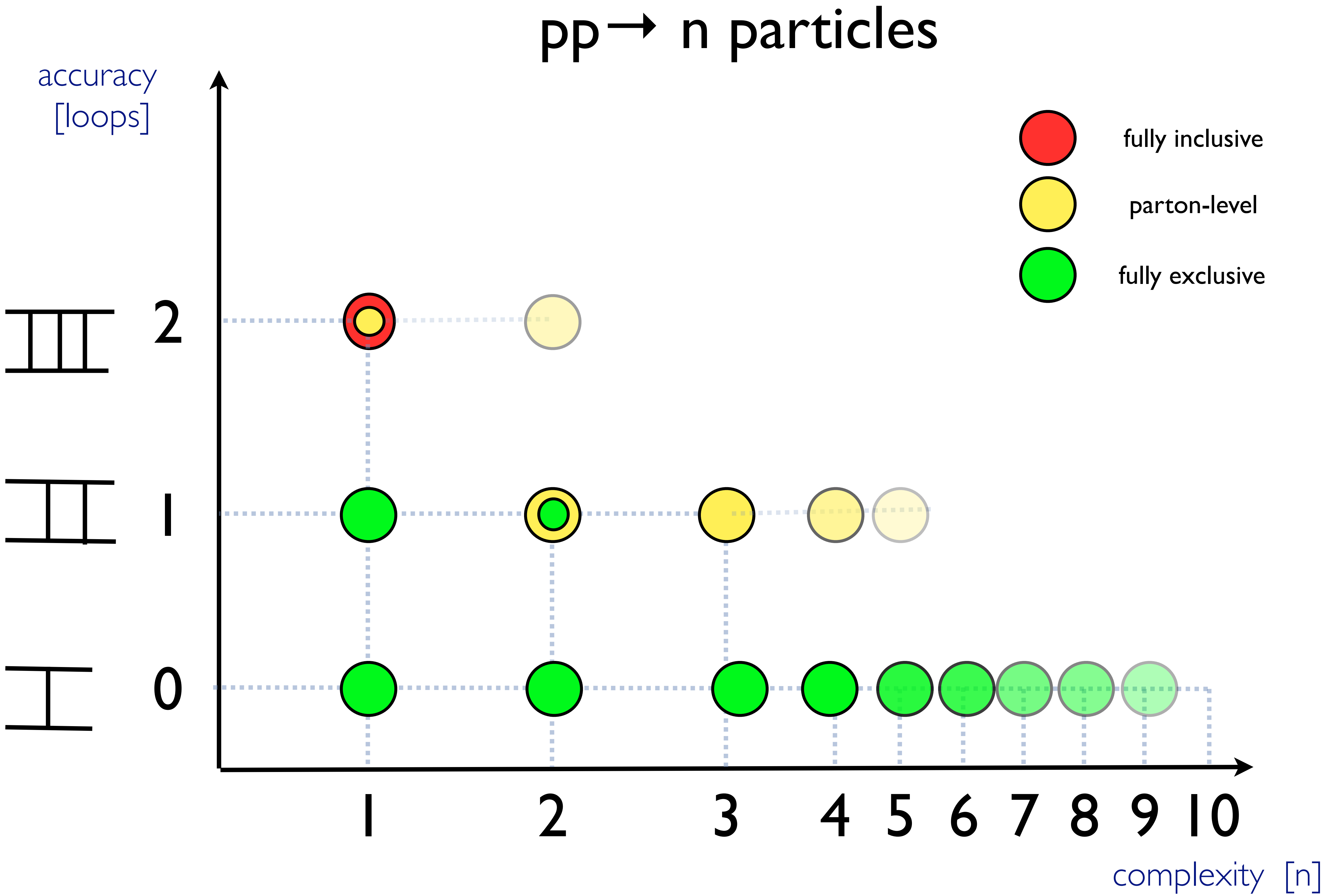

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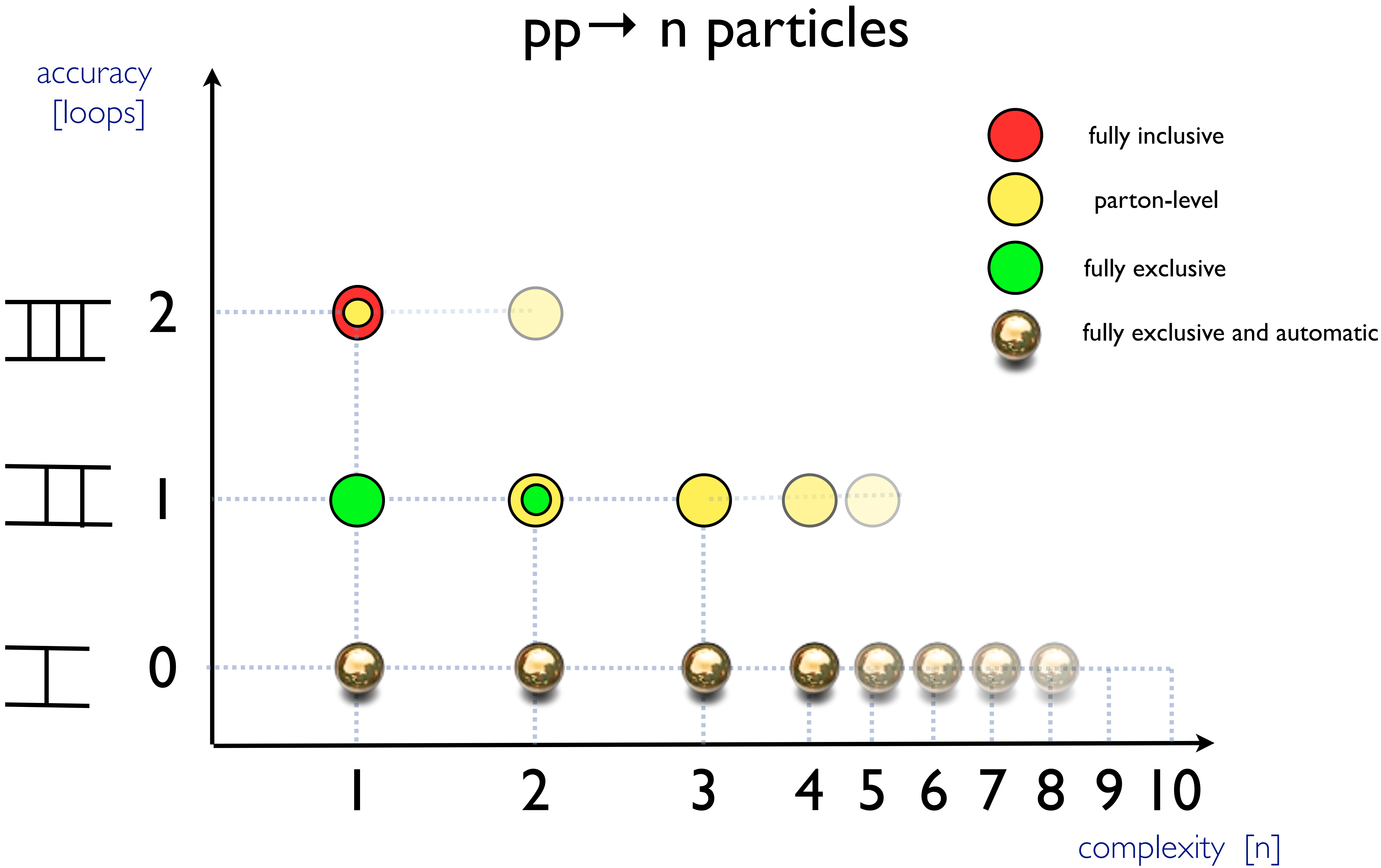
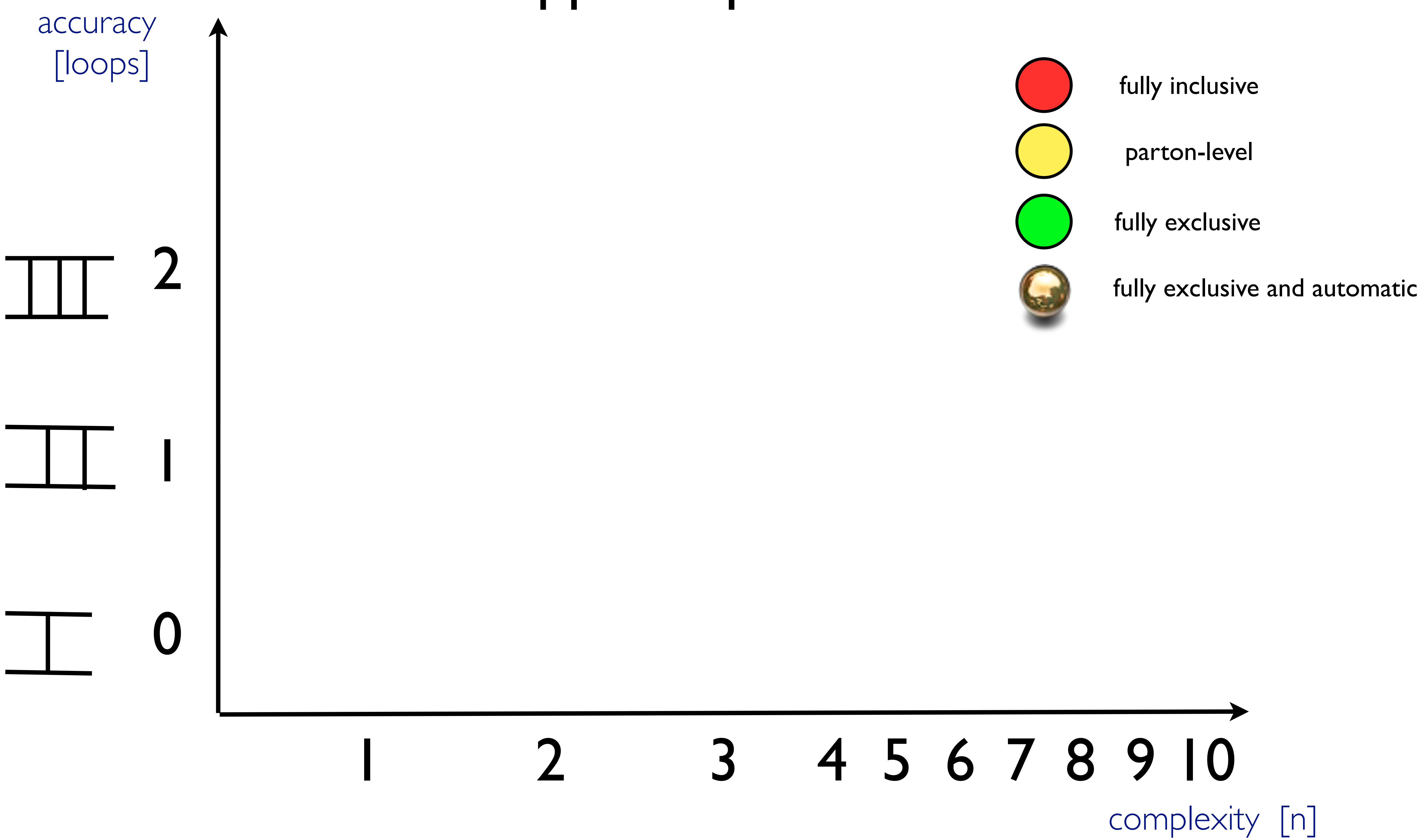


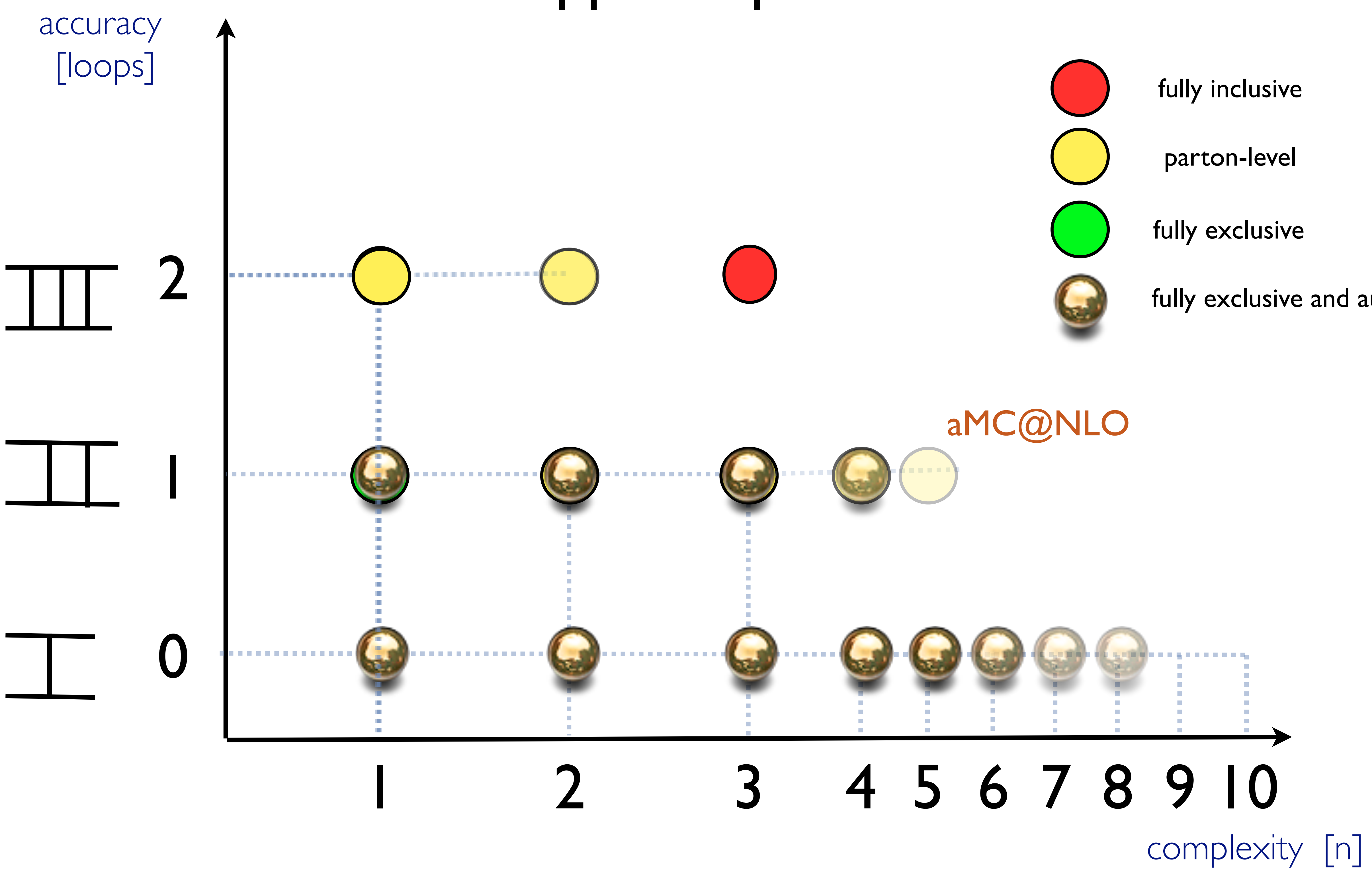
SM Status: now

pp→ n particles

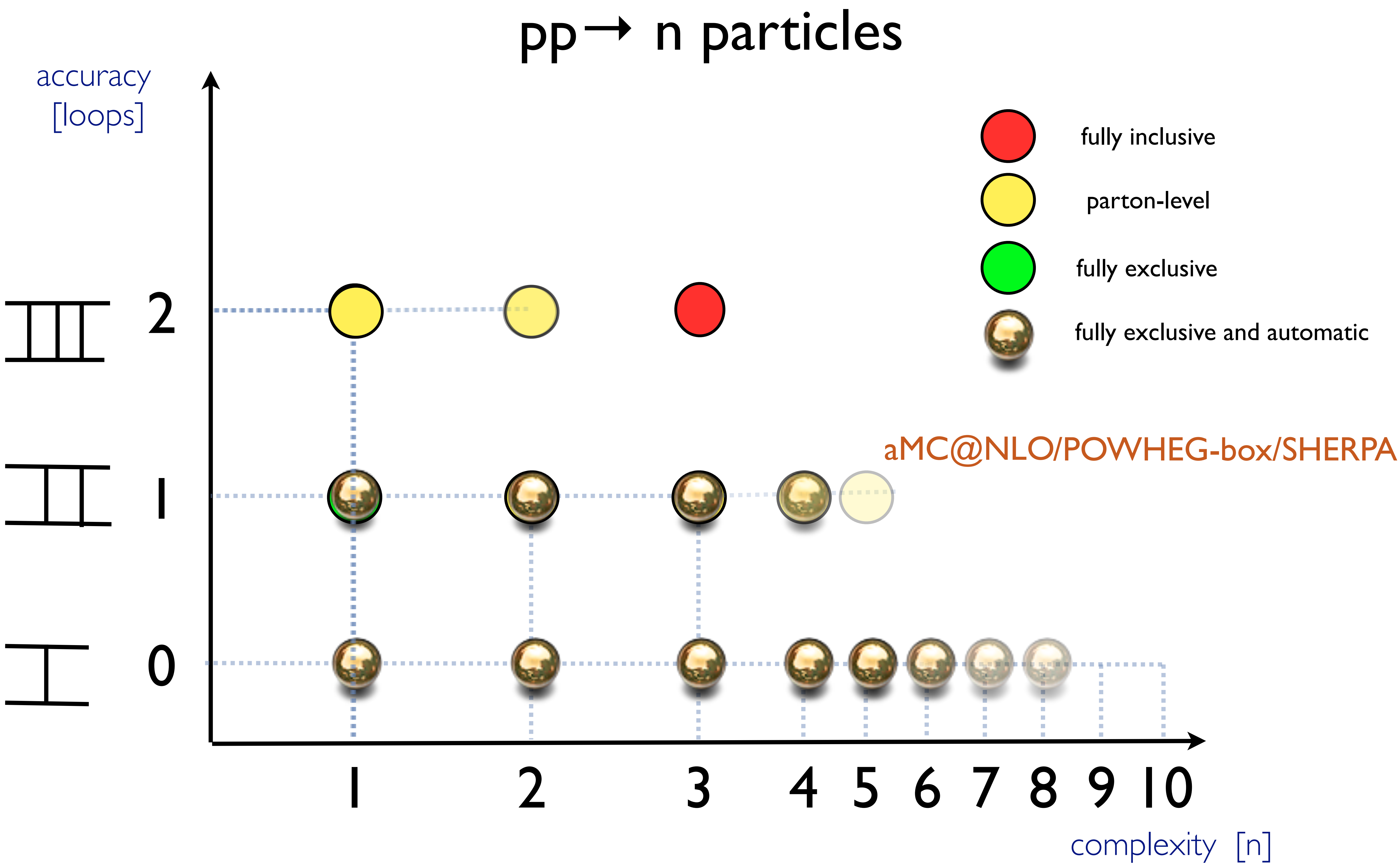


SM STATUS: NOW

pp→ n particles



SM Status: now



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 in the field of QCD and MC's.
- A new generation of tools and techniques is now available.
- A complete set of NLO computations is available, even in fully automatic form. Several NNLO results are being used already now and will be extended in the future.
- New techniques and codes available for interfacing at LO and NLO computations at fixed order to parton-shower has been proven for SM (and BSM).
- Unprecedented accuracy and flexibility achieved.
- EXP/TH interactions enhanced by a new framework where exps and theos speak the same language.

Credits

To organize this presentation I have benefited from lectures (and actual slides), talks and discussions with many people.
In particular:

- Mike Seymour (MC basics)
- Claude Duhr (FeynRules)
- Johan Alwall (ME+PS merging)
- Rikkert Frederix, Paolo Torrielli (NLO+PS)
- Stefano Frixione, Michelangelo Mangano, Paolo Nason (for QCD, PS, LO, NLO, and more...)
- ....

Whom I all warmly thank!!