Generators

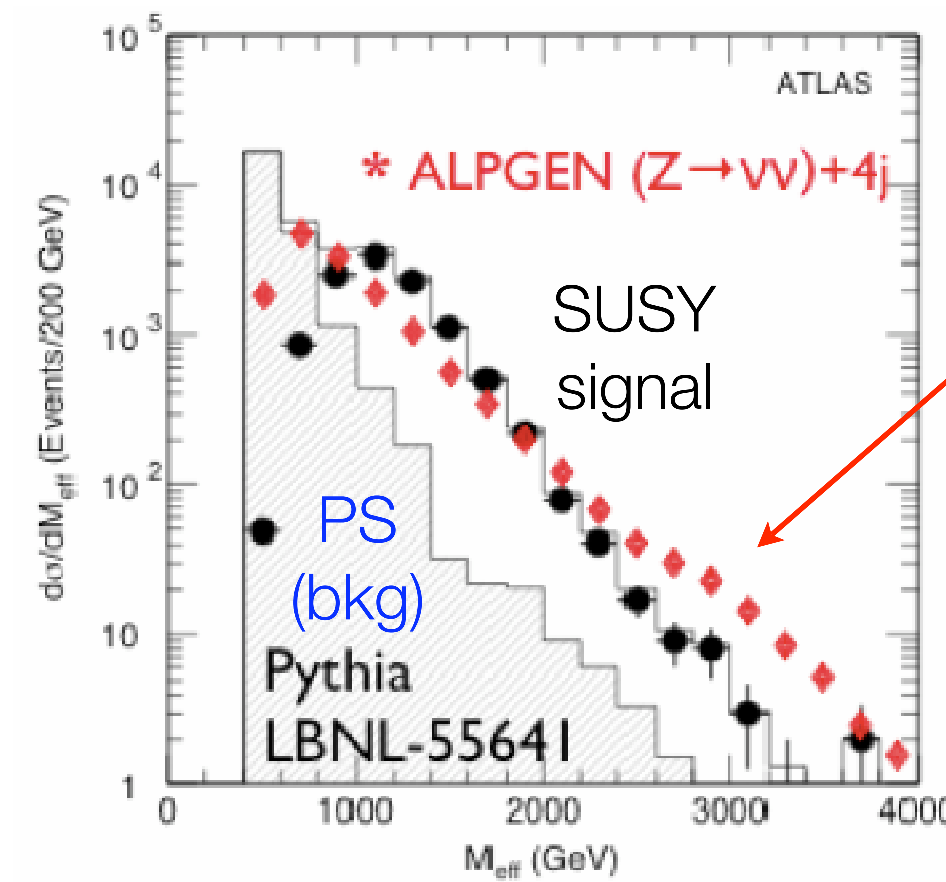
Lecture 2: Modern parton showers and higher orders

John Campbell, Fermilab

Recap

- By construction, a parton shower is correct only for successive branchings that are collinear or soft (i.e. only leading/next-to-leading logs).

- Should therefore take care when describing final states in which there is either manifestly multiple hard radiation, or its effects might be important.
  - example: simulation of background to a SUSY search in the ATLAS TDR.



improved background calculation

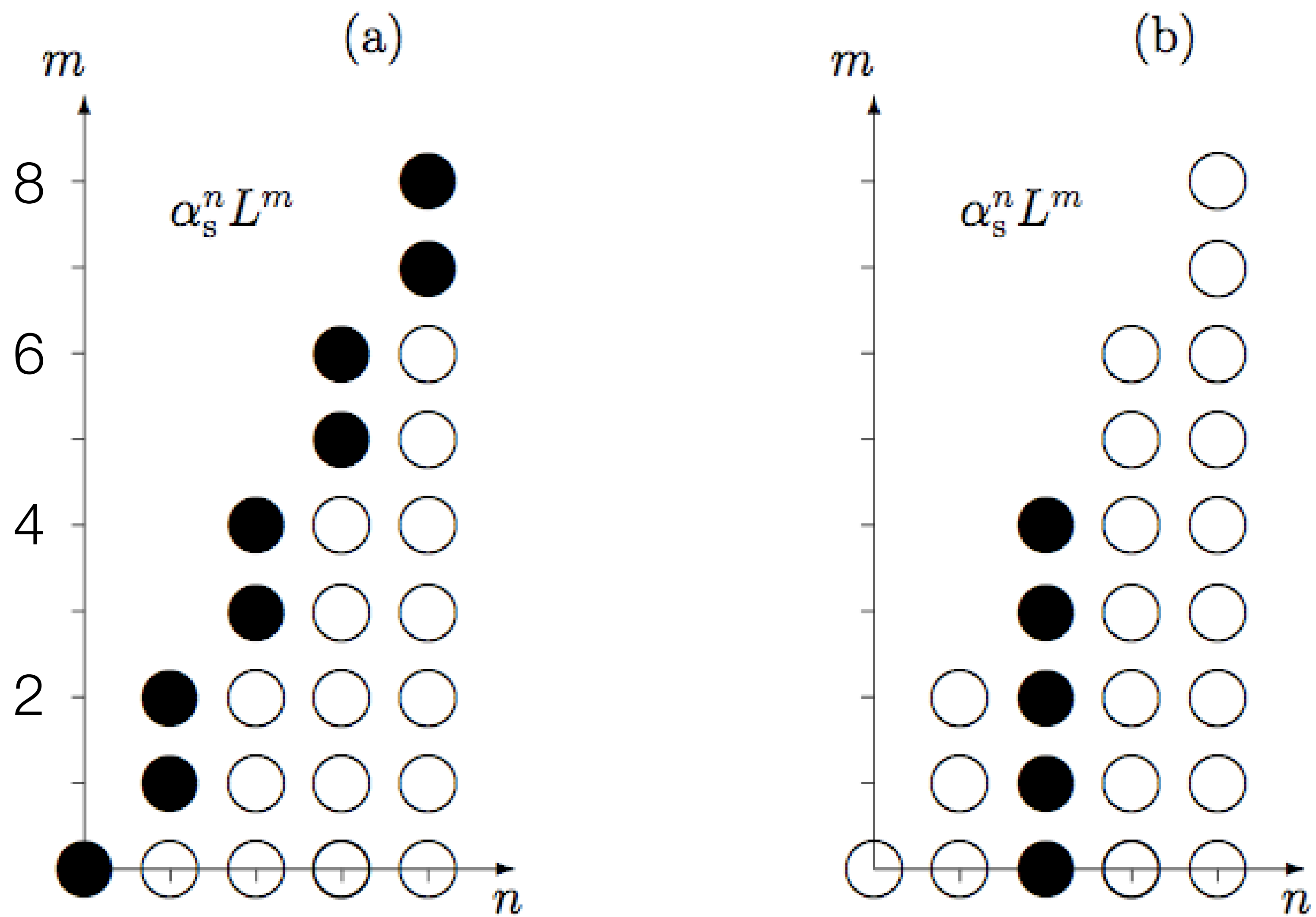
$$M_{\text{eff}} = \Sigma_i |p_{T(i)}| + \not{E}_T$$

- Higher-order corrections are not included.

- Uncertainty can only be estimated by comparison with data and/or between different parton shower implementations.
  - exact details of each shower differ, possibility for significant differences.

Parton shower extensions

- As simplest example, consider Drell-Yan process: $pp \to Z\ (+n \text{ jets})$
  (one power of α_s per jet)



accuracy of NLL parton shower

accuracy of tree-level Z+2 jet calculation

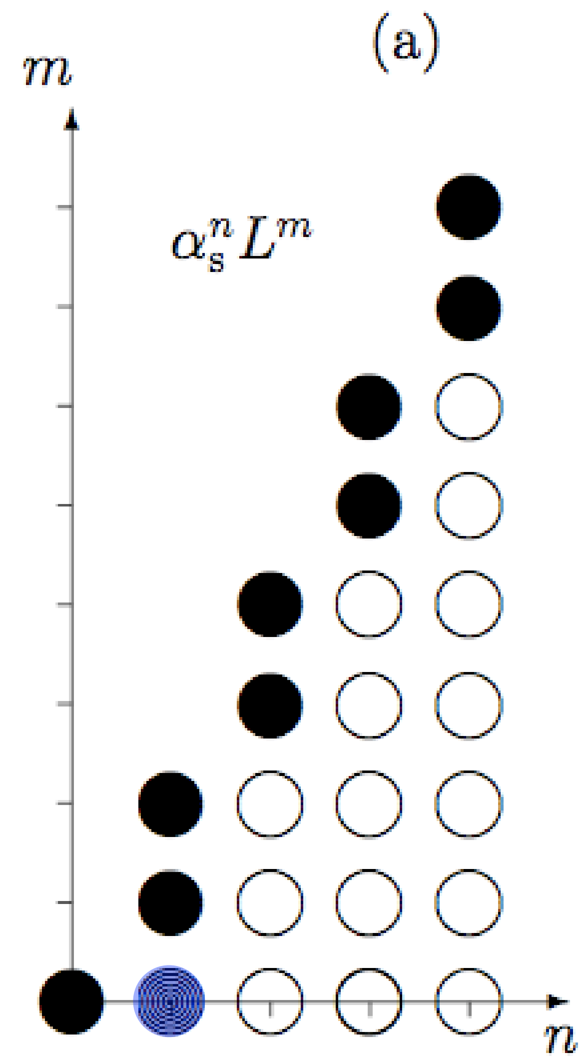
c.f. earlier, leading log: $\alpha_s^n L^{2n}$

How can parton shower recover more of fixed-order accuracy?

Tree-level matching

- Use exact matrix elements for the first/hardest emission from the parton shower instead of approximate form.
- Captures one extra term in the expansion
  - but not completely correctly
  - real radiation is taken into account but not virtual (loop diagram) contributions
- Hence shape improved for observables dominated by low-multiplicity emission, but overall normalization same as before.

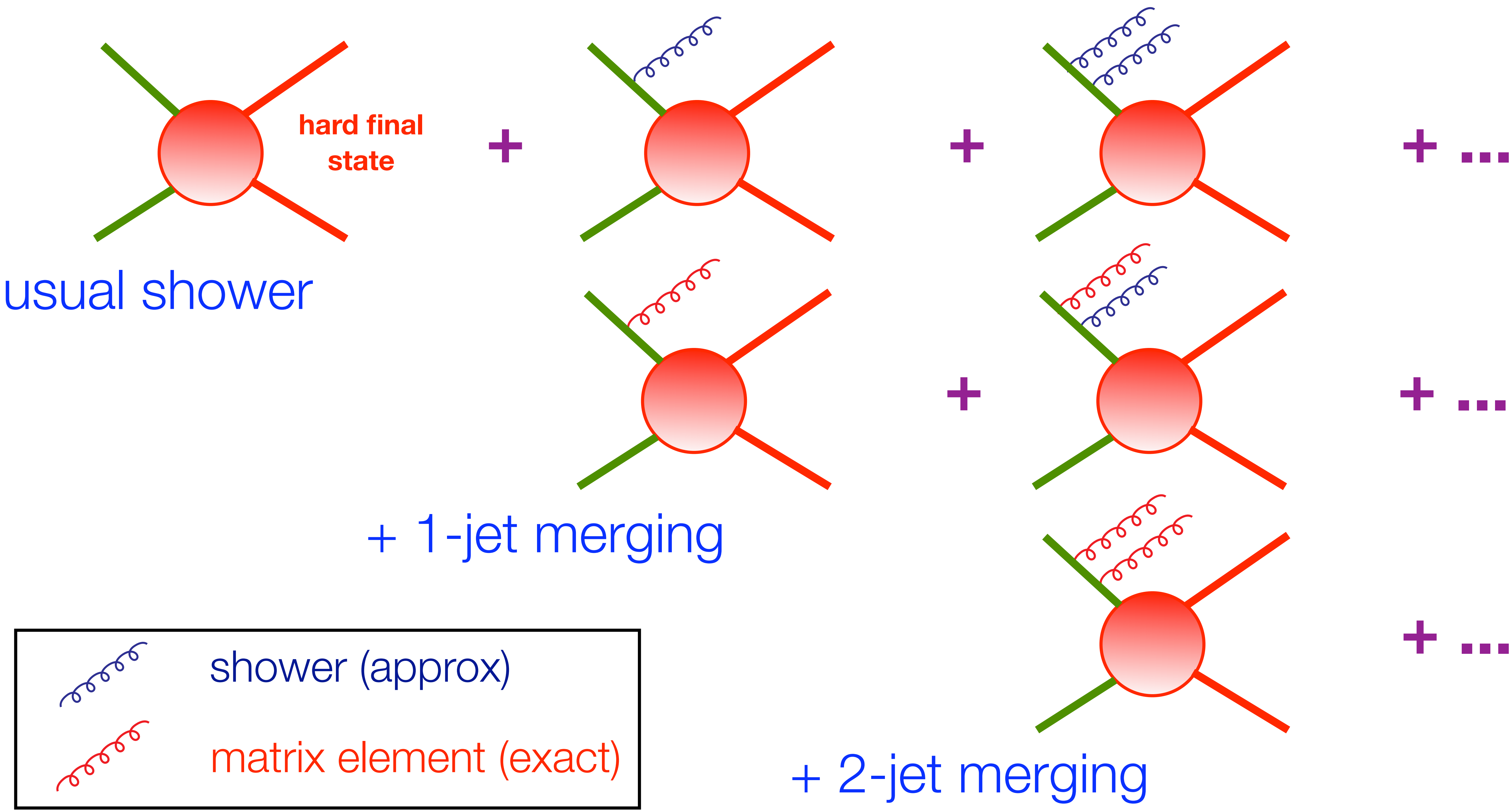
Mostly historical, not a feature of modern generators



PS + one matched emission

Multi-jet merging in pictures

- Merging: include more exact matrix elements as initial hard scatters, with merging scale determining transition from approx. to exact MEs.



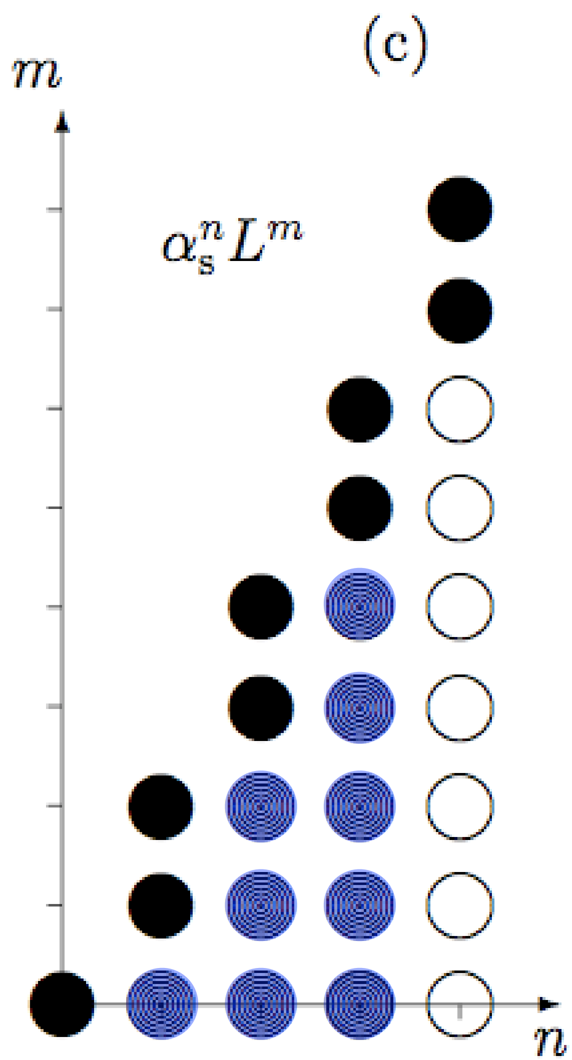
Multi-jet merging

- Perform matrix element corrections to multiple emissions
- Introduces an unphysical merging scale in order to perform corrections for each jet multiplicity
  - again, impact only on shapes of relevant distributions - for observables up to the number of jet samples merged
  - again, no possible improvement in rate
- Various techniques for combining samples without overcounting in shower:
  - CKKW (Catani, Krauss, Kuhn, Webber) CKKW-L (Lönnblad)

    SHERPA

  - MLM (Mangano)

    ALPGEN

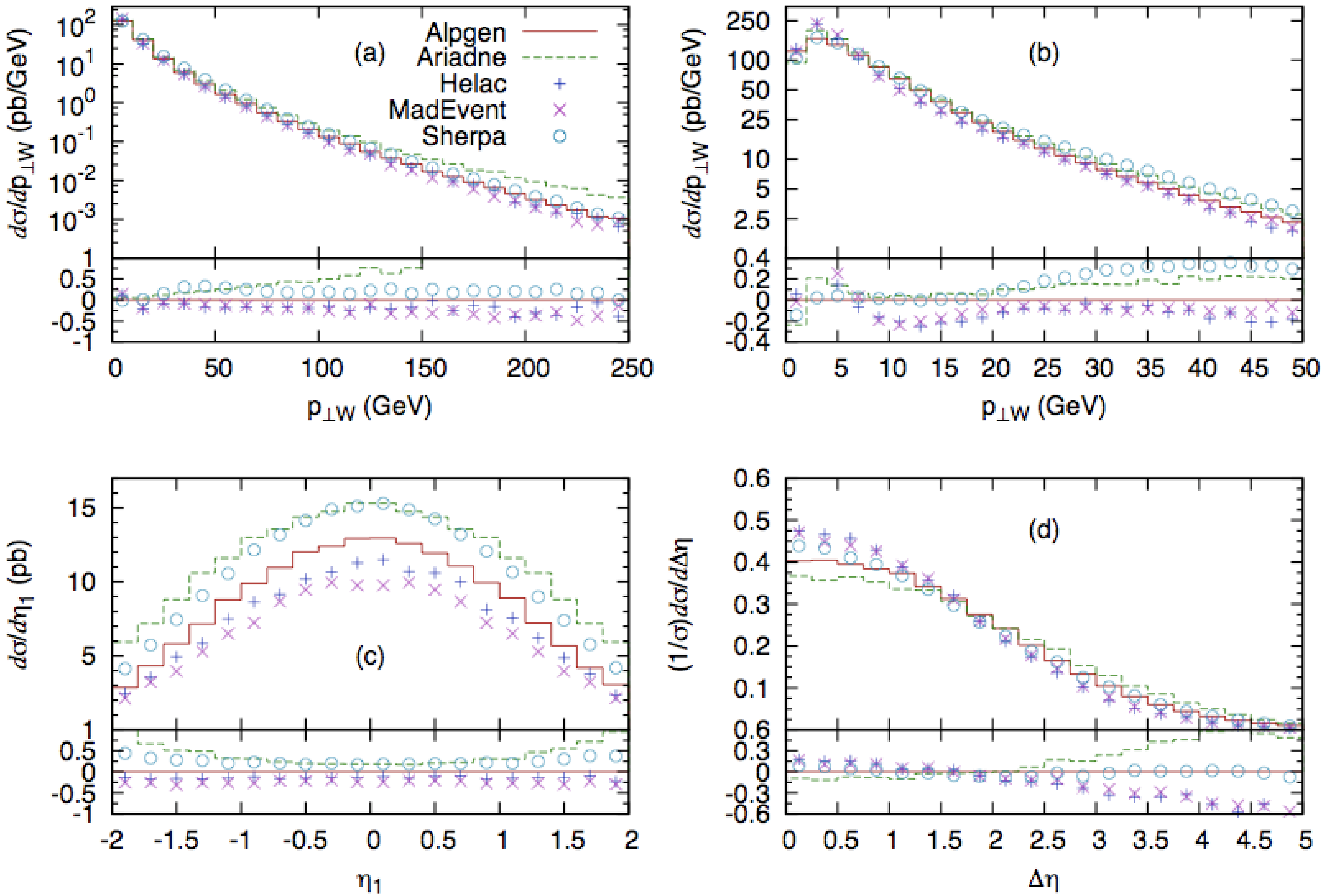


PS + multi-jet merging for up to 3 jets

Comparison of merging techniques

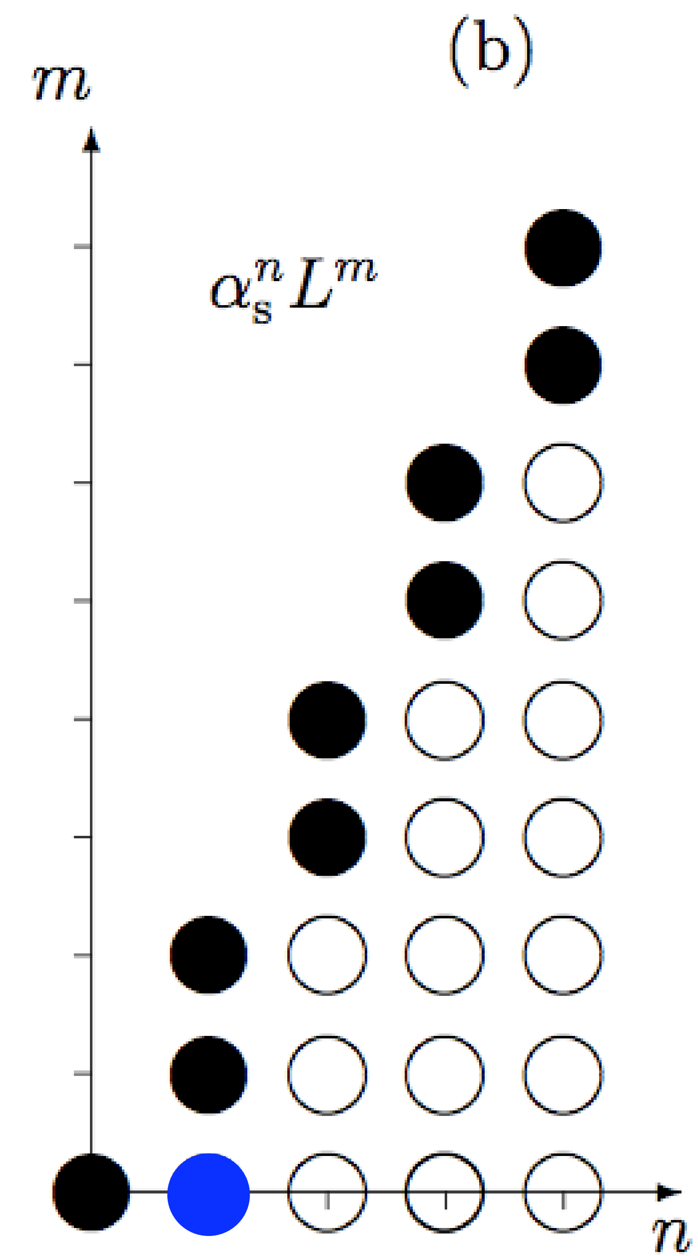
Alwall et al. (2007)

Tevatron



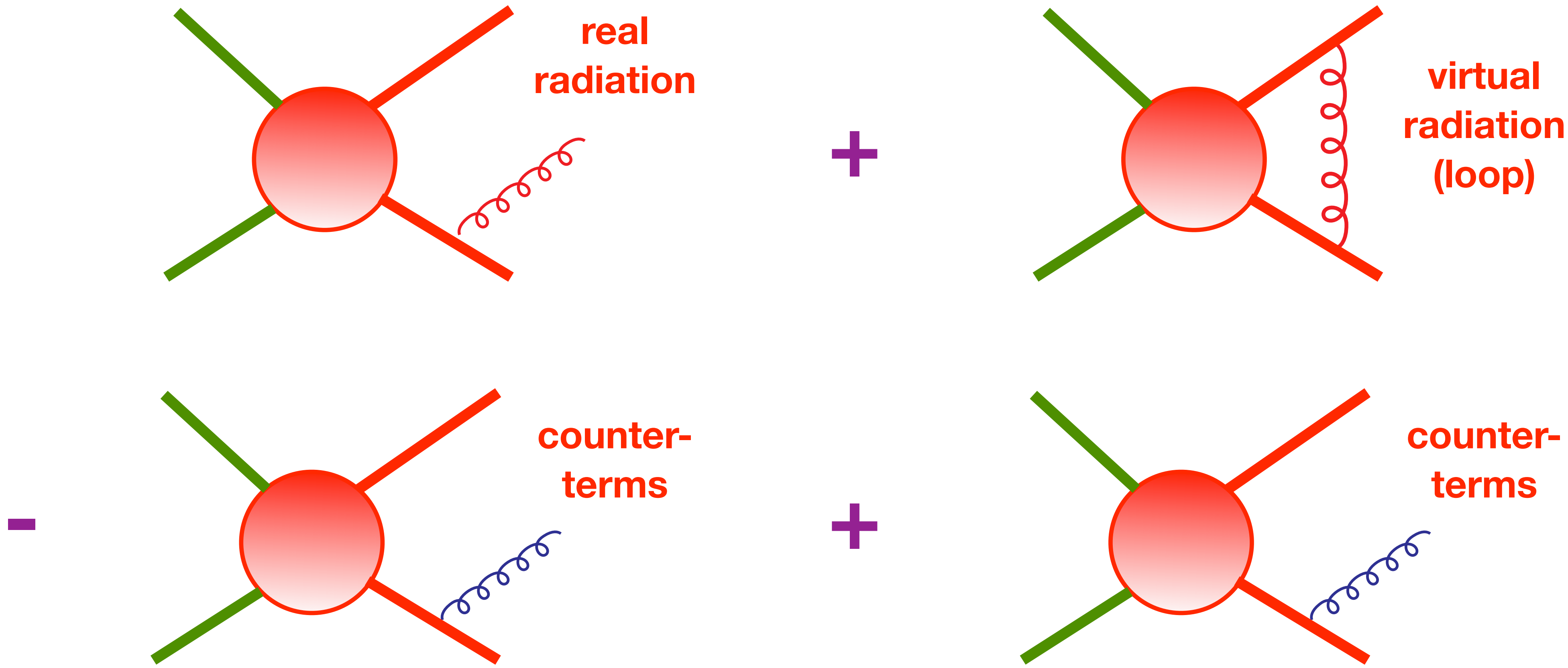
Limits of merging approaches

- Even after adding additional hard radiation by merging methods, overall normalization of cross section remains a leading order estimate
  - usual disadvantages, such as sensitivity to scale choices.
- Natural question: how to obtain NLO accuracy with a parton shower?
- Many NLO parton-level predictions available - but without parton shower benefits.
- Obvious problem:
  - NLO already includes one extra parton emission.
  - the hard part of this can be matched as before.
  - the soft/collinear part contains singularities that must be extracted in a particular way (e.g. subtraction).



PS + NLO inclusive

Reminder: general structure of NLO

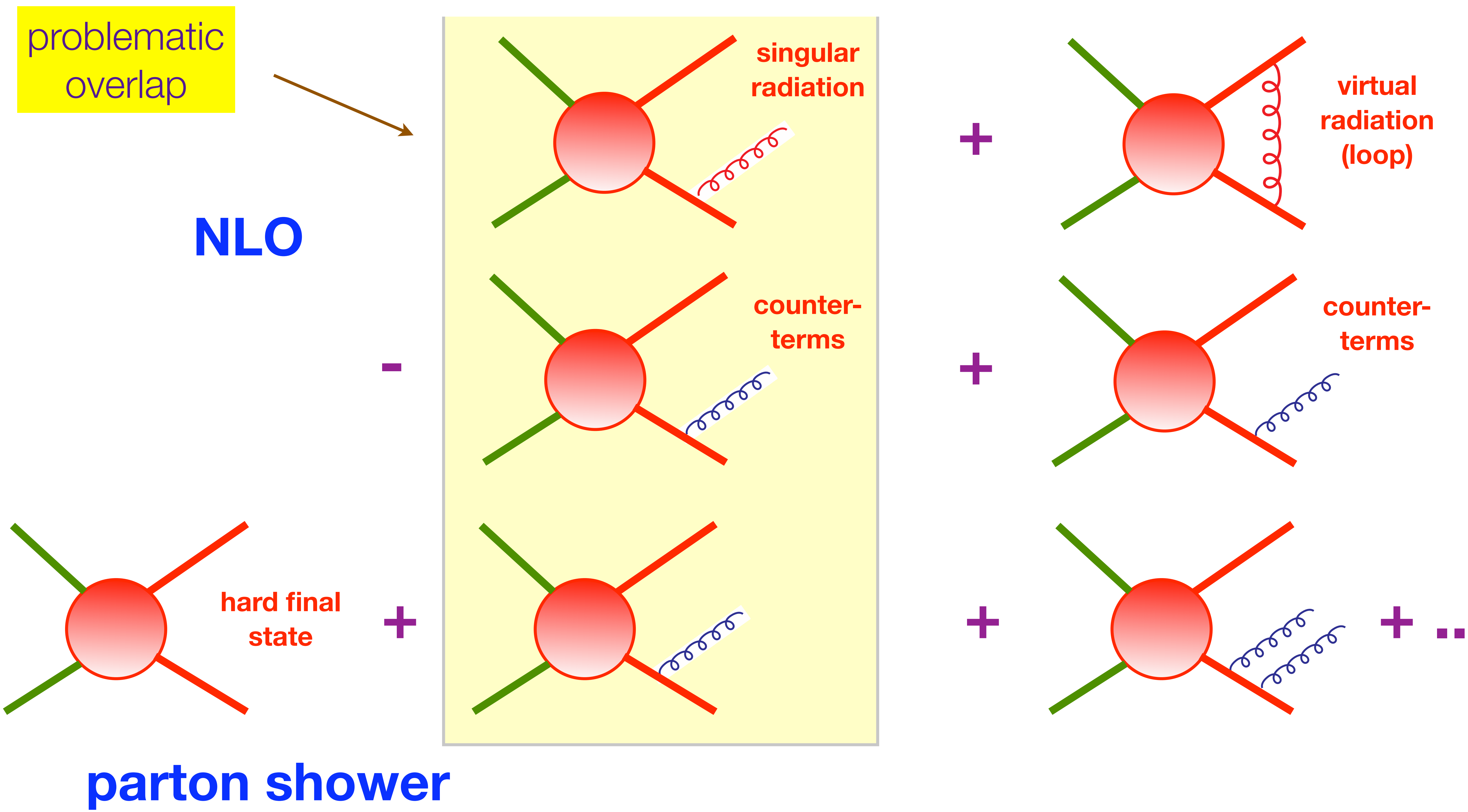


soft/collinear singularities cancelled numerically

singularities cancelled analytically

- Schematic picture of subtraction method for NLO calculations.
- In general: many subtractions (“counter-events”) for each real radiation event.
- How can this be combined with a shower?

NLO+parton shower overlap

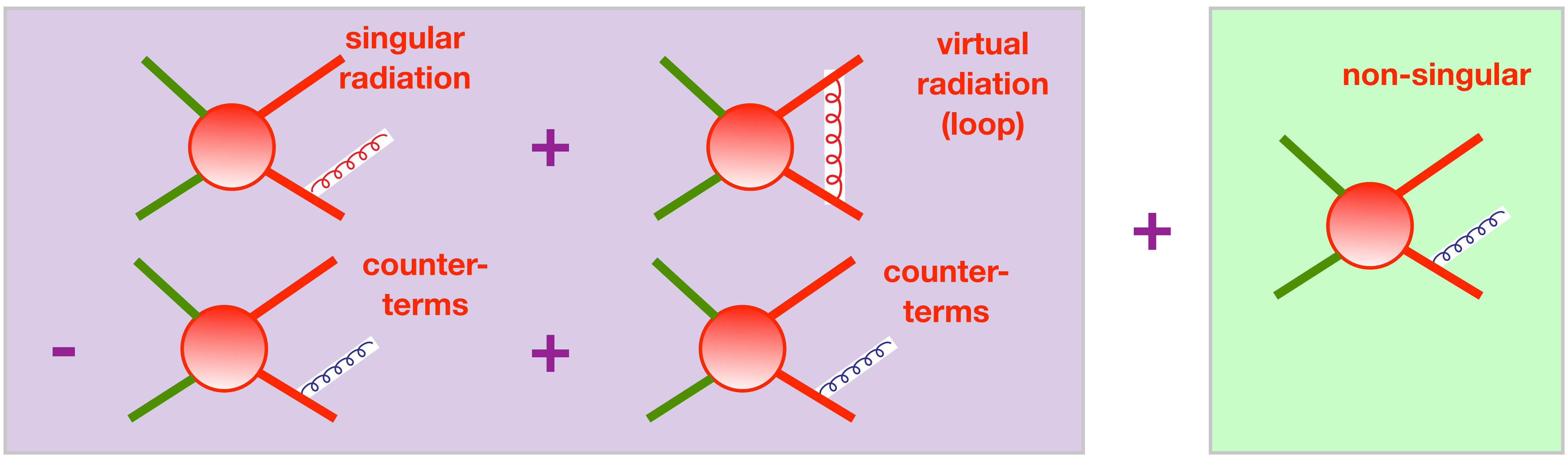


Schematic shower and NLO

- Usual parton shower: $d\sigma^{PS} = d\Phi_0 B(\Phi_0) \times \Big[\text{shower}\Big]$

  (Born level exact matrix element, shower generates the emissions)

- At NLO, group into Born-like and non-singular radiation terms:



$$d\sigma^{NLO} = d\Phi_0 \bar{B}(\Phi_0) + d\Phi_1 N(\Phi_1)$$

Born-like non-singular

Matching strategies

- Two main methods: as introduced by POWHEG and MC@NLO.
- POWHEG (Frixione, Nason, Oleari)
  - singular emission = complete real emission expression
  - non-singular emission = 0

$$\mathrm{d}\sigma^{POWHEG} = \mathrm{d}\Phi_0 \bar{B}(\Phi_0) \times \Big[\text{shower}\Big]$$

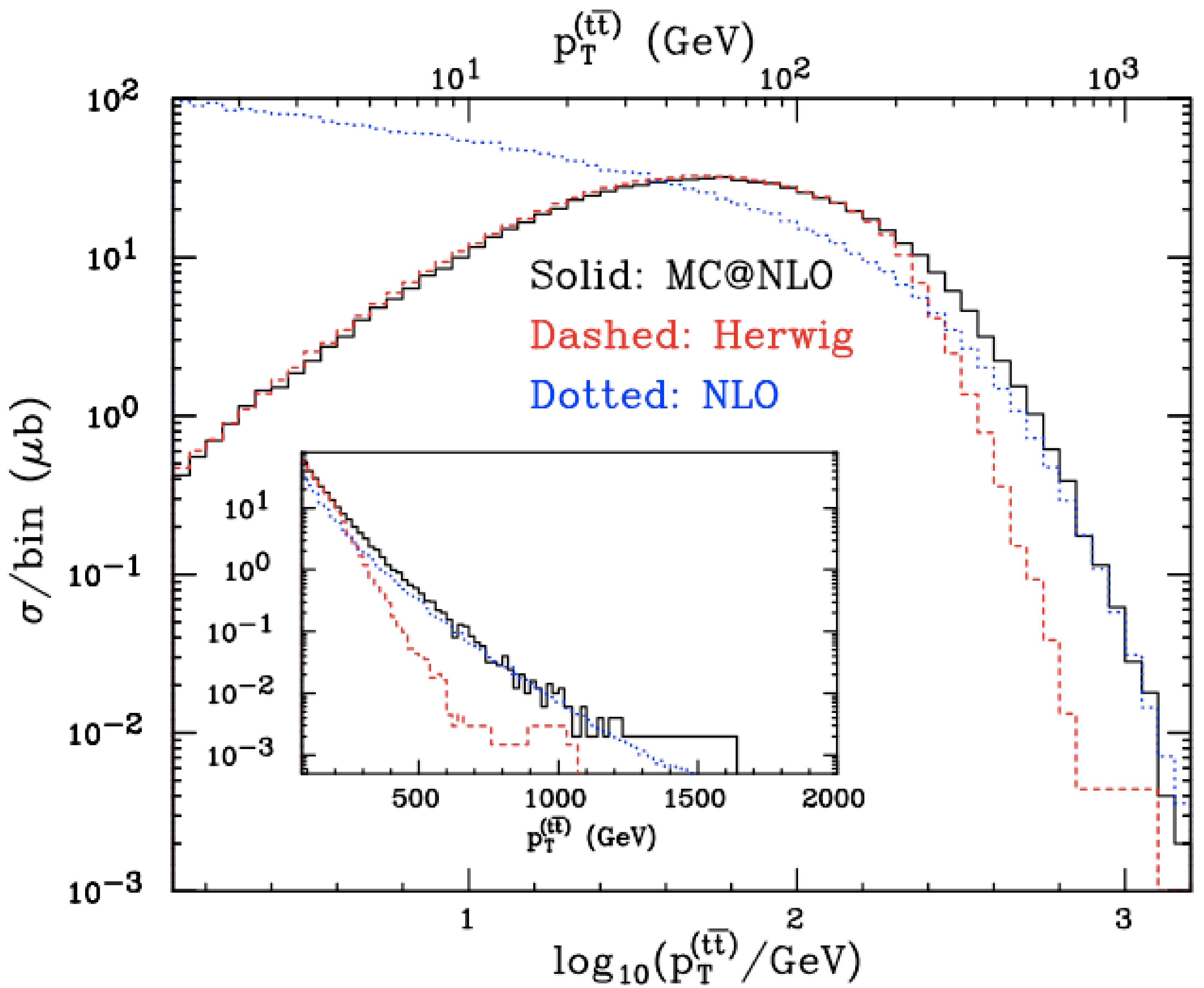
  - “local K-factor”, real exponentiated in Sudakov, positive-weight generator.
- MC@NLO (Frixione, Webber)
  - singular emission = subtraction term generated by shower kernel
  - non-singular emission = complete real emission - shower kernel

$$\mathrm{d}\sigma^{MC@NLO} = \mathrm{d}\Phi_0 \bar{B}'(\Phi_0) \times \Big[\text{shower}\Big] + \Big[\text{real} - \text{shower kernel}\Big]$$

  - usual Sudakov factor but possibility of negative weights.

NLO + PS demonstration: MC@NLO

- First real matching of a parton shower (HERWIG) onto a NLO calculation.



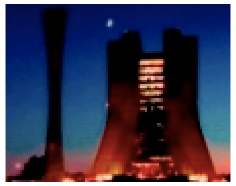
transverse momentum of top pairs, from MC@NLO

Frixione and Webber (2003)

MC@NLO

Frixione, Stoeckli, Torrielli, Webber, White

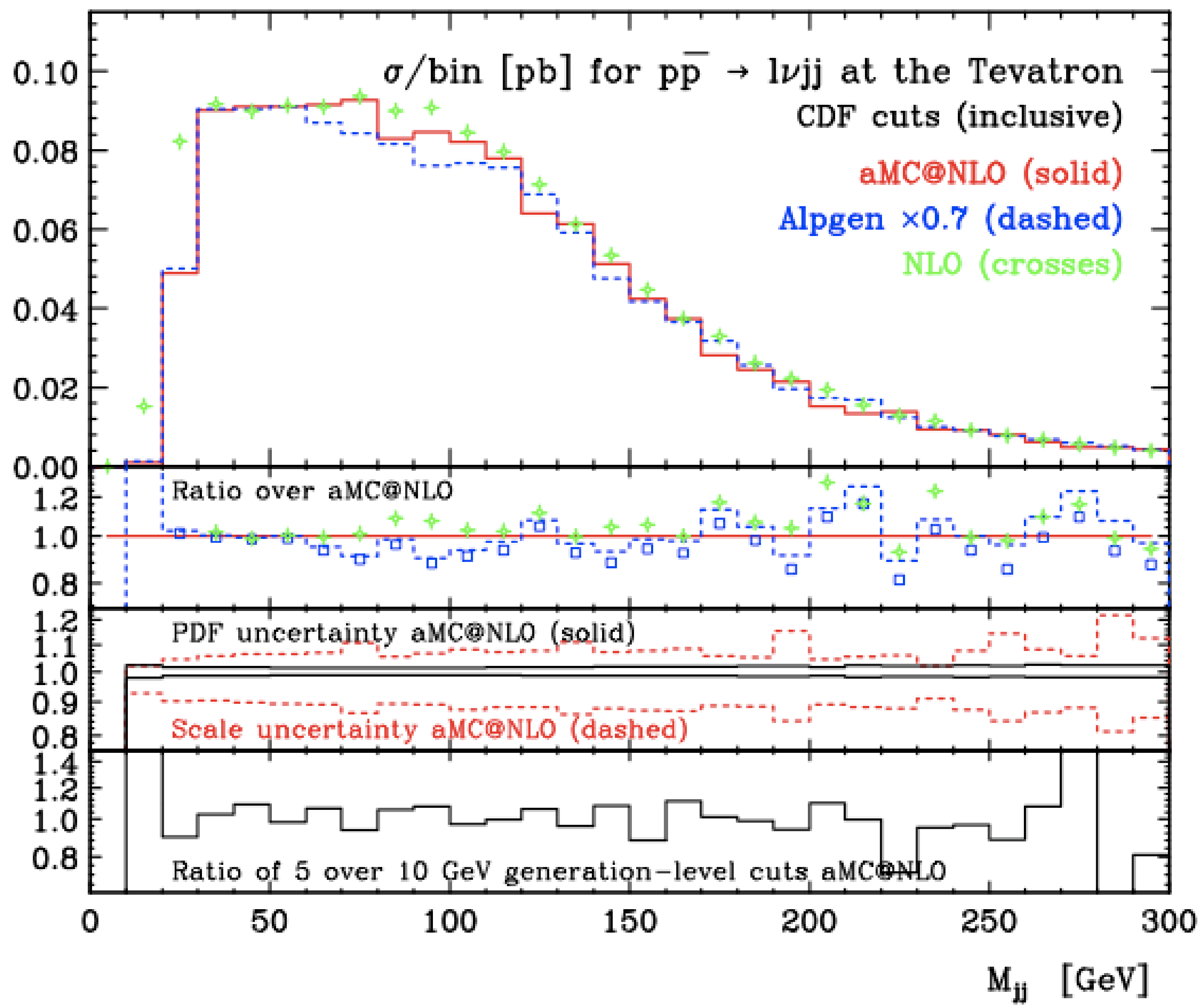
- Stand-alone Fortran package, compatible with HERWIG or HERWIG++.
- Available final states:
  - single boson (W/Z/Higgs)
  - vector boson pairs
  - heavy quark pairs
  - single top (s, t, Wt channels)
  - associated Higgs production
- Spin correlations included except in ZZ decay.
- NLO corrections in production only (i.e. not in decays).
- Implementation of new processes by hand.



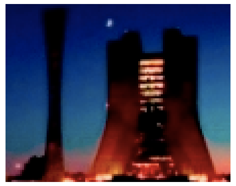
aMC@NLO

Alwall, Artoisenet, Frederix, Frixione, Fuks, Hirschi, Maltoni, Mattelaer, Pittau, Serret, Stelzer, Torrielli, Zaro

- Automated MC@NLO
- Parton shower matching performed generically
  - already applied to:
    - ZZ
    - Zbb
    - Wbb
    - W+2 jets

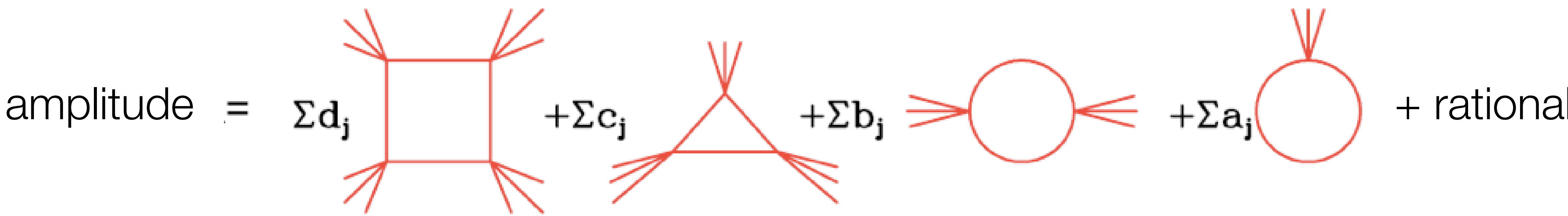


- One-loop matrix elements also computed in an automated fashion (Madloop).

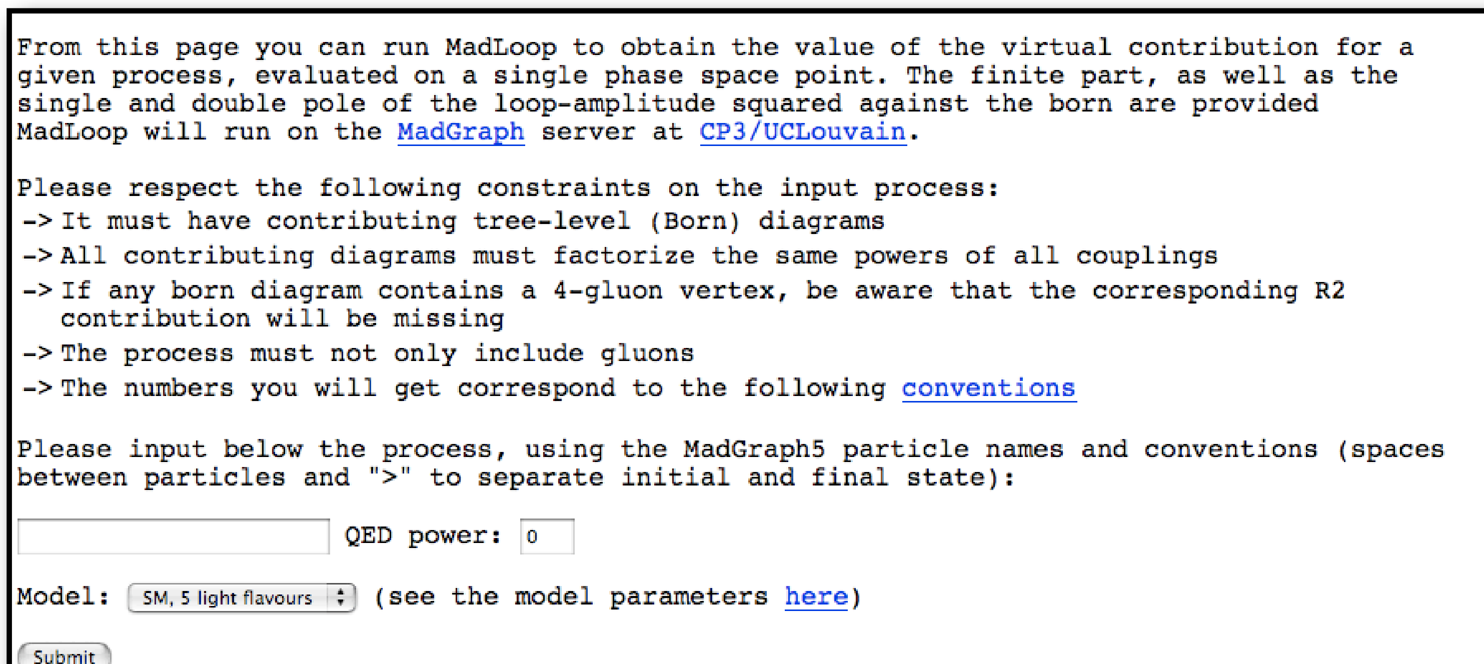


MadLoop

- One-loop matrix element calculator using numerical D-dimensional unitarity
  - recycles tree-level amplitudes into loops
  - determination of one-loop integral coefficients and rational terms using OPP method (Ossola, Pittau, Papodopoulos)



- Also, very useful tool for cross-checks of analytic results.



From this page you can run MadLoop to obtain the value of the virtual contribution for a given process, evaluated on a single phase space point. The finite part, as well as the single and double pole of the loop-amplitude squared against the born are provided MadLoop will run on the MadGraph server at CP3/UCLouvain.

Please respect the following constraints on the input process:
-> It must have contributing tree-level (Born) diagrams
-> All contributing diagrams must factorize the same powers of all couplings
-> If any born diagram contains a 4-gluon vertex, be aware that the corresponding R2 contribution will be missing
-> The process must not only include gluons
-> The numbers you will get correspond to the following conventions

Please input below the process, using the MadGraph5 particle names and conventions (spaces between particles and ">" to separate initial and final state):

QED power: 0

Model: SM, 5 light flavours (see the model parameters here)

Submit

Madloop results

	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

Impressive list of NLO calculations

2 weeks
x 150 nodes

(this mode of running not yet public)

POWHEG

- Stand-alone Fortran package, compatible with any shower.
- Available final states:
  - single boson (W/Z/Higgs)
  - vector boson pairs
  - heavy quark pairs
  - single top (s, t, Wt channels)
  - dijets
  - vector boson + jet, Z+2 jets
  - Higgs + 1 or 2 jets
  - Wbb
  - top pair + jet / H / Z

Many of these thanks to POWHEG-BOX.

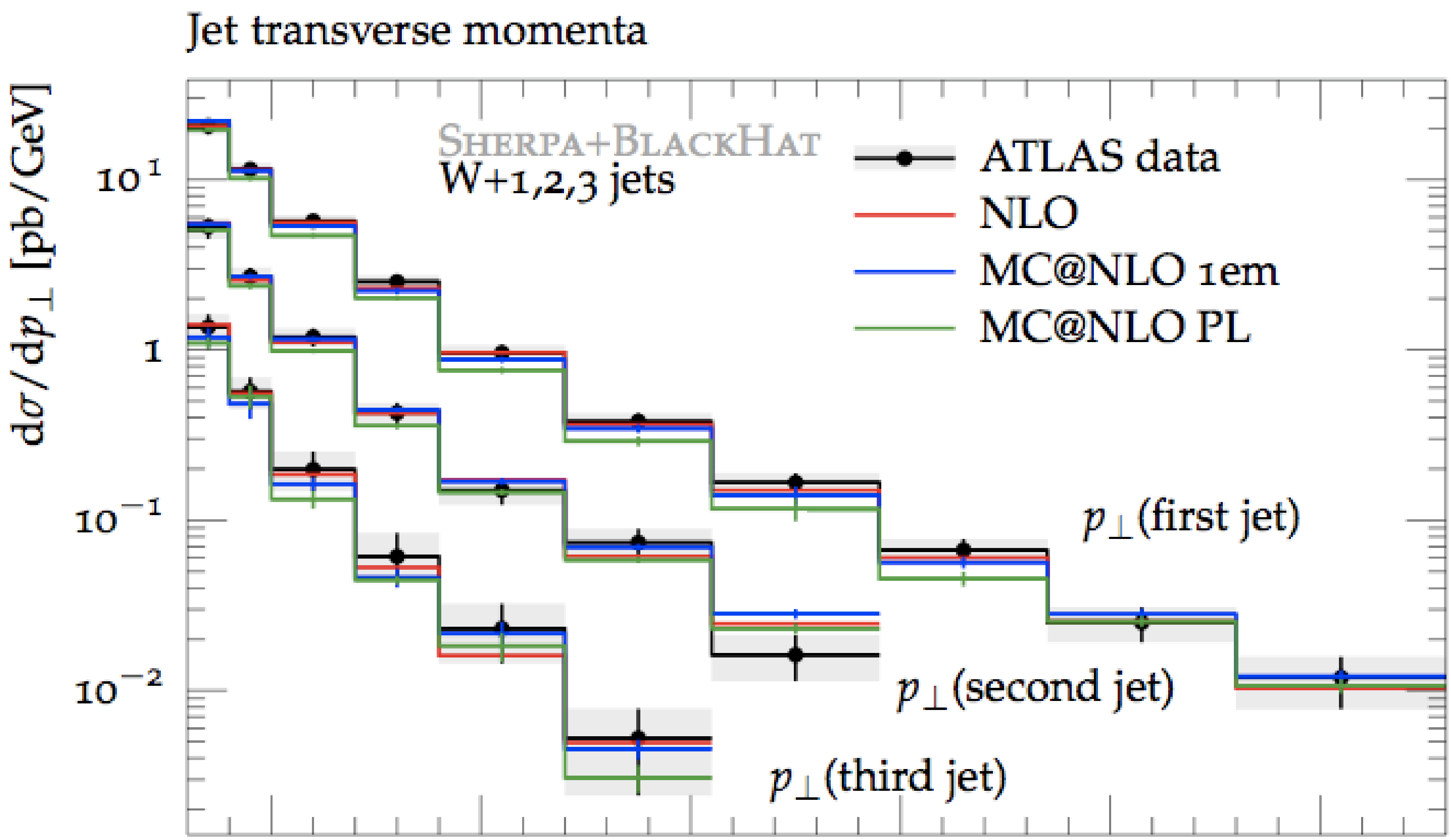
Alioli, Hamilton, Nason, Oleari, Re

simple way for theorists to incorporate latest parton-level NLO calculations.

SHERPA

- POWHEG and MC@NLO methods also used in SHERPA.
- Recent application to W+1,2,3 jets.

Höche, Krauss, Schönherr, Siegert

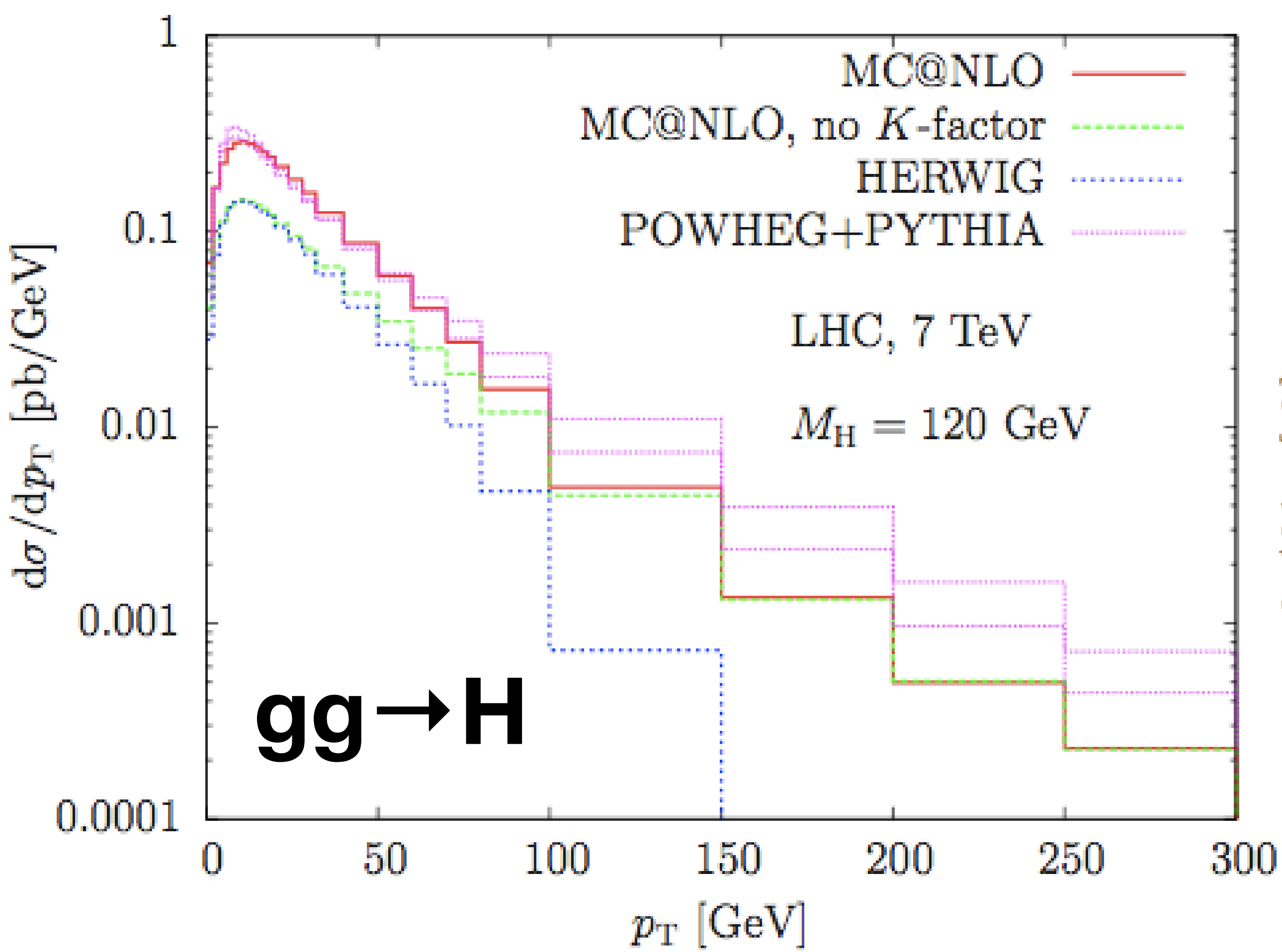


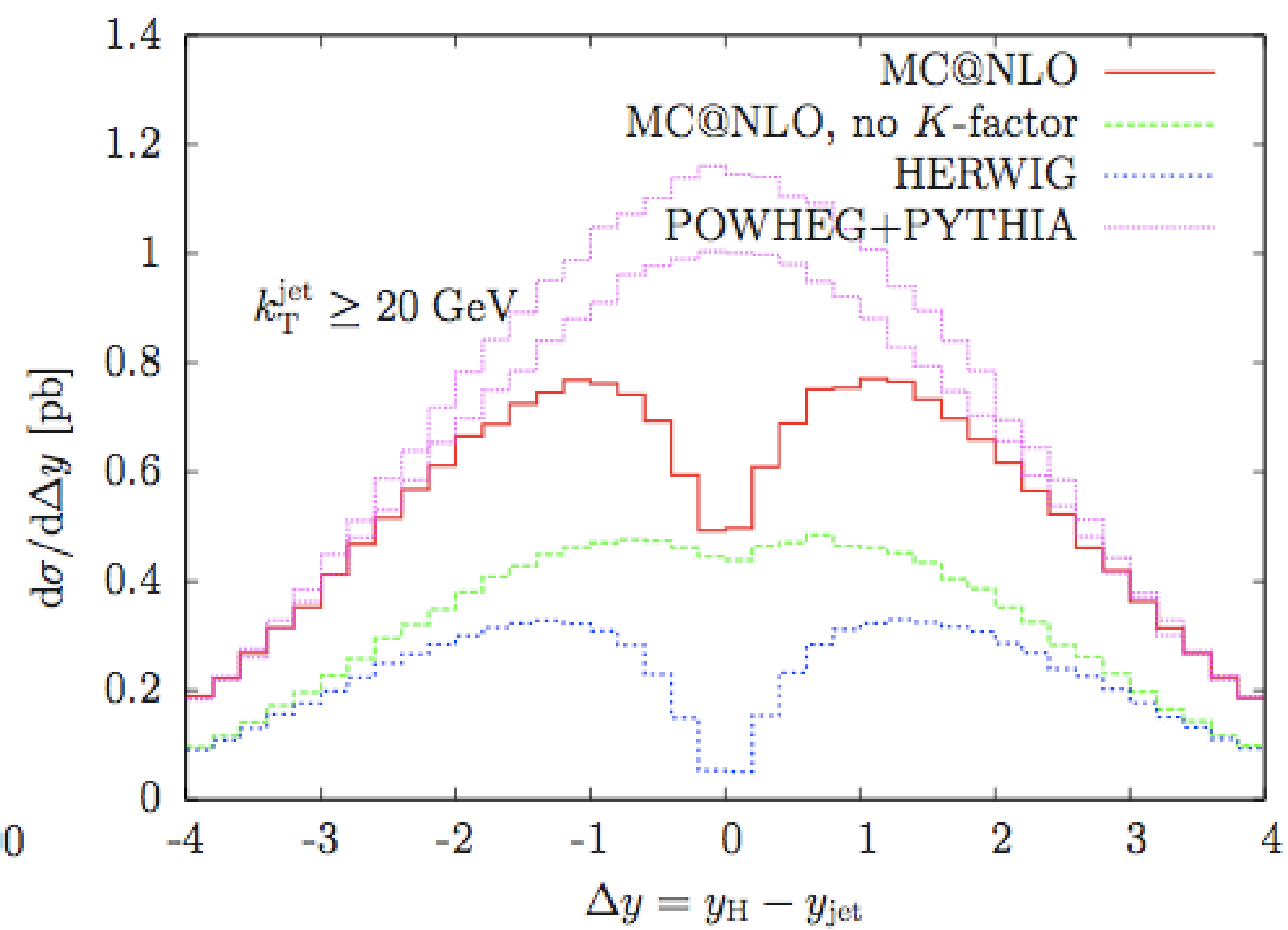
- Smooth interpolation between POWHEG, MC@NLO procedures.

NLO matching differences

- Real differences that may be useful and/or serve as a warning.

see: Nason and Webber, arXiv:1202.1251





differences at high p_T, but NNLO corrections large there

very different, reminder of sensitivity to NNLO effects

Beyond MC@NLO and POWHEG

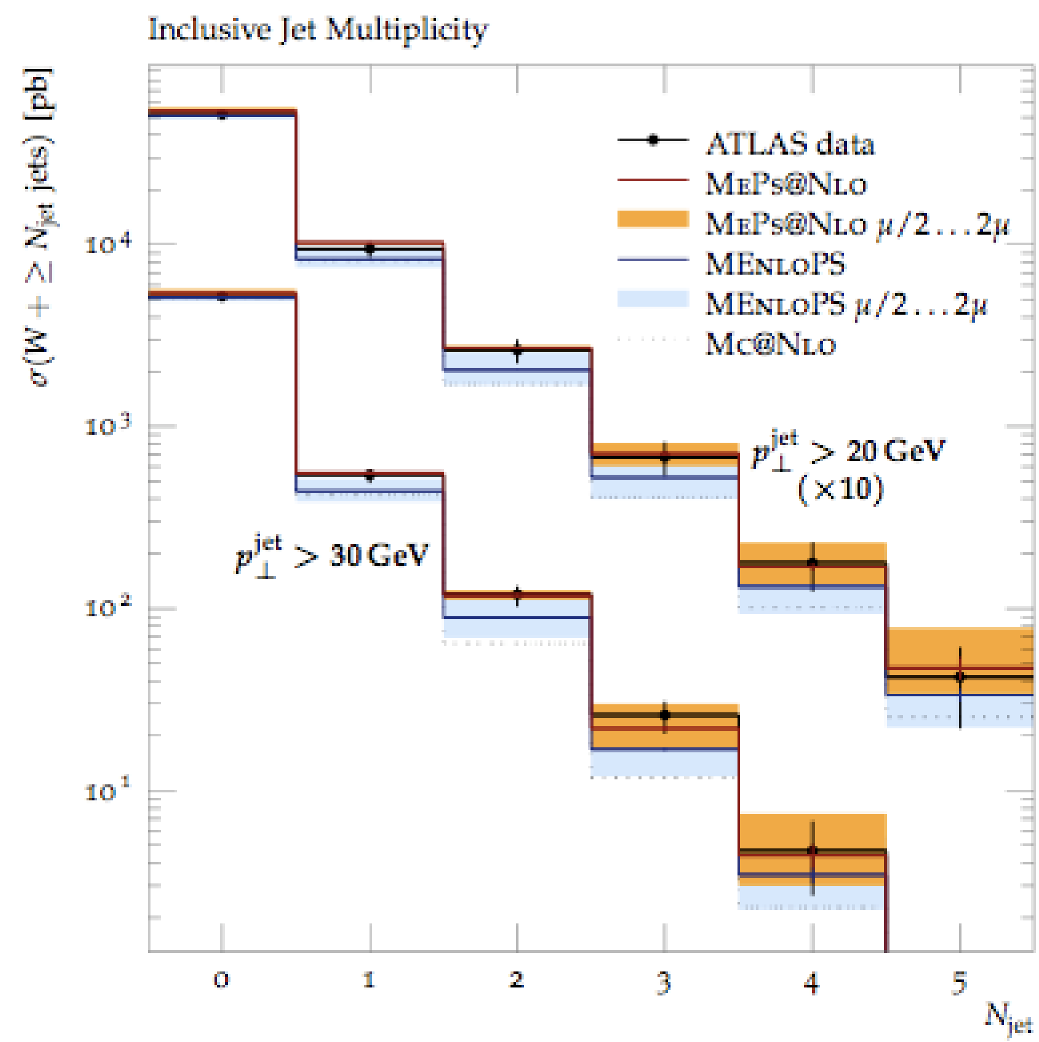
- NLO inclusive cross section, exact matrix elements for further jets.
  - "MENLOPS" and "ME&TS".

    Hamilton, Nason;
    Höche, Krauss, Schönherr, Siegert

- NLO precision for each jet emission: merging samples that are each matched to correct NLO
  - "MEPS@NLO"

    Höche, Krauss, Schönherr, Siegert

- Very recent developments and ongoing intense activity.



MENLOPS: W+0 jet NLO, W+1,2,3,4 LO

MEPS@NLO: W+0,1,2 jets NLO, W+3,4 LO

Parton showers beyond NLO

- Next frontier: parton shower + NNLO?
- Problem: even parton level NNLO predictions scarce.

Drell-Yan, Higgs (all except ttH), diphotons	hadron colliders
2- and 3-jet production	lepton colliders

- Many advantages at NNLO:
  - normalization of a cross section begins to be trustworthy at NLO,
  - associated theoretical uncertainty only reasonably estimated at NNLO.
- Reasons for scarcity:
  - ingredients for a NNLO calculation are similar to, but more complicated than, those that enter at NLO
  - no generic, well-established procedure for dealing with singularities.

NNLO complexity

- One way to envision the different NNLO contributions is to consider all possible cuts of a 3-loop diagram.

- Example: 3-jet production in e^+e^- annihilation.

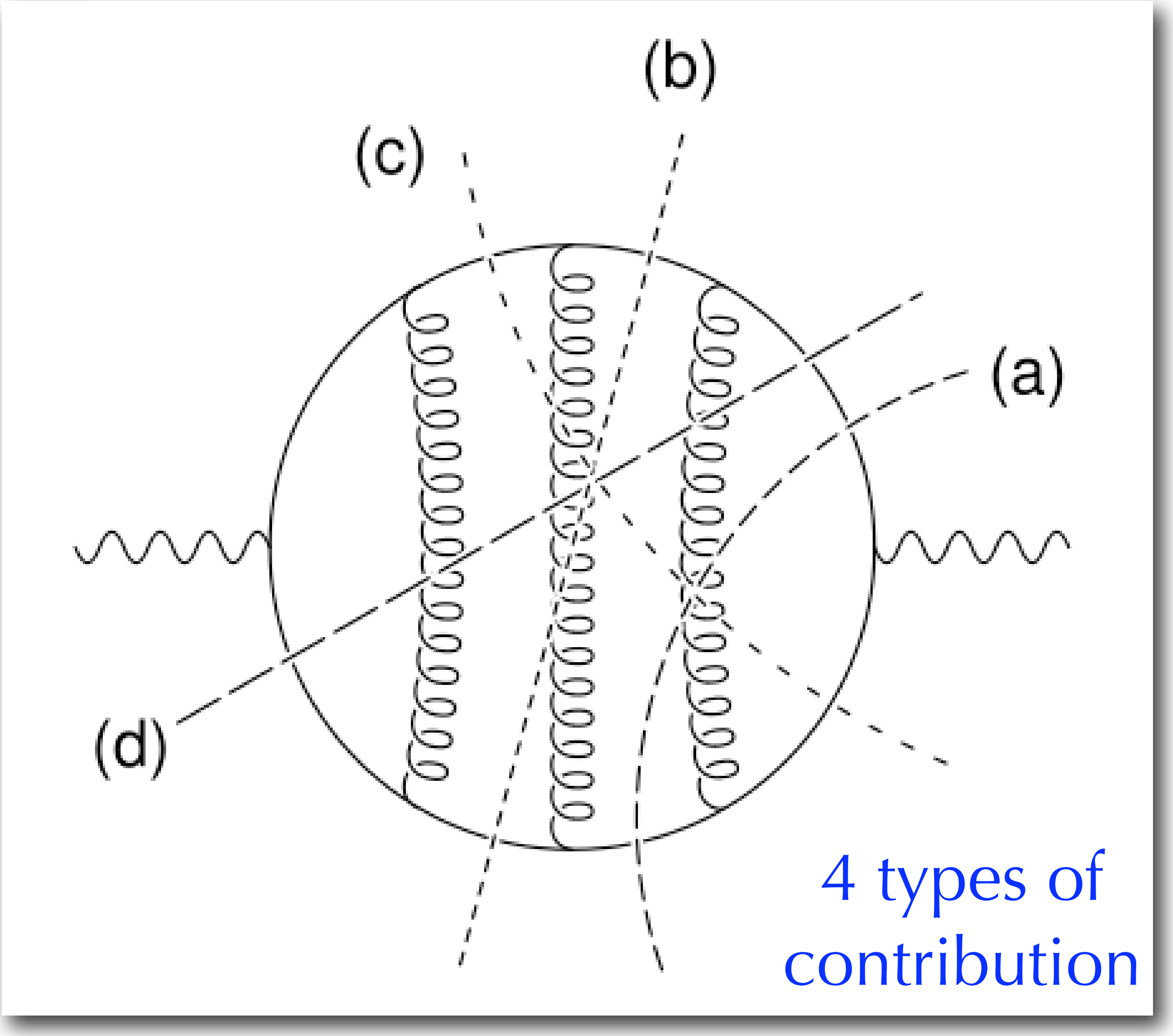
  (a) 2-loop virtual diagrams.

  (b) 1-loop squared.

  (c) interference of 1-loop and tree, both with extra parton → infrared singularities (easy)

  (d) tree with two extra partons → [infrared singularities]^2

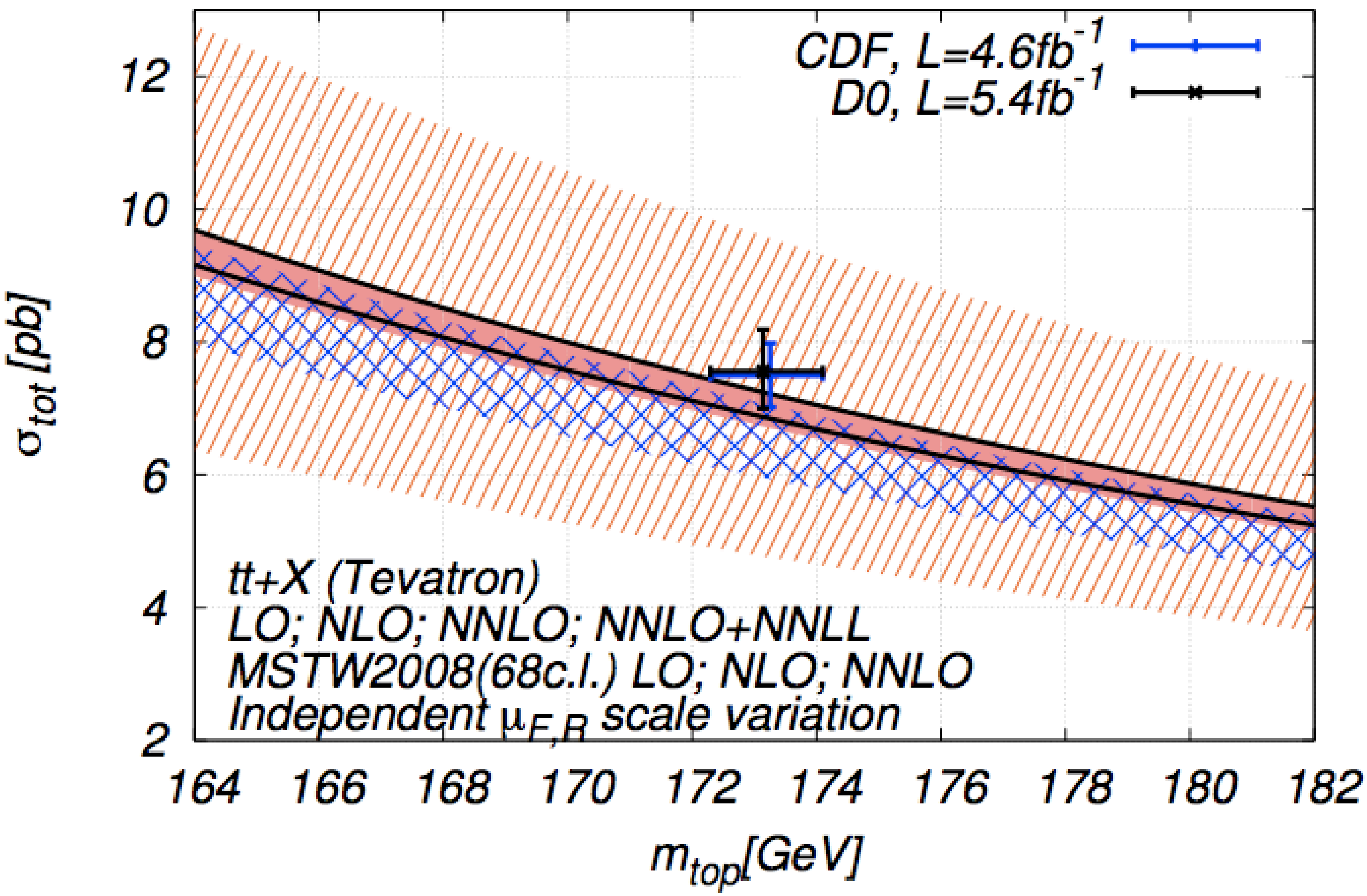
- At present, no universal procedure (like dipole subtraction) formulated for dealing with (d)



NNLO development

- This summer, first NNLO hadron collider calculation with color in the final state
  - quark-initiated top pair production (good for Tevatron, not so much LHC).
  - not differential, but cross-section only.

Barnreuther, Czakon, Mitov



decreasing error bands:

LO

NLO

NNLO

NNLO + NNLL

(resummation)

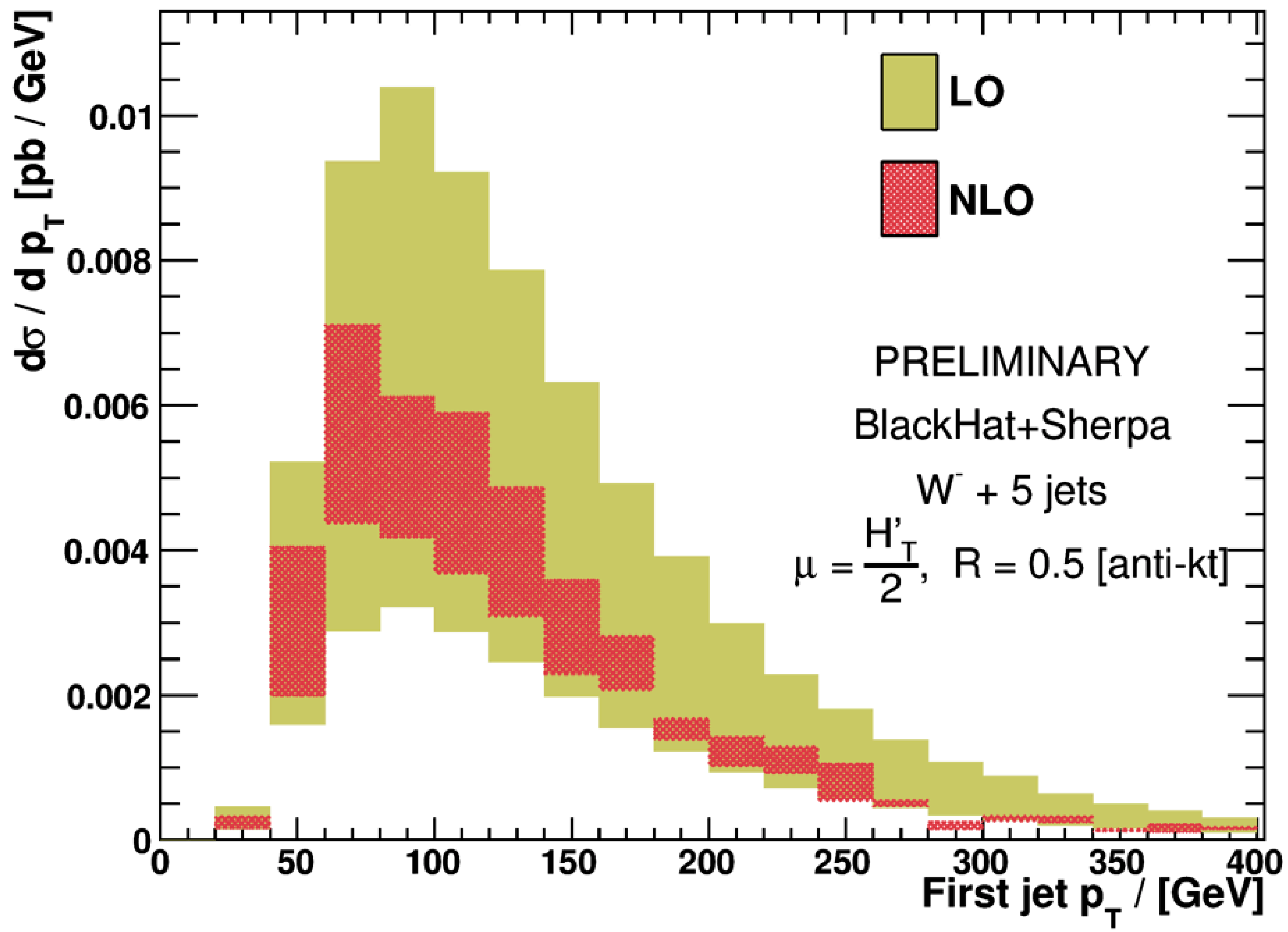
Parton-level NLO

- NLO accuracy combined with parton shower often best option when available
  - not always possible, e.g. no analytic calculation interfaced and generic numerical approaches too slow
  - further refinements implemented first at parton-level, e.g. spin correlations
- Automated 1-loop approaches
  - HELAC-NLO: e.g. tt+2 jets, tttt — Bevilacqua et al
  - GoSam: e.g. WW+2 jets — Cullen et al
- Other tools:
  - MCFM: W/Z+2 jets, Wbb, Zbb, diboson, top processes — JC, Ellis, Williams
  - VBFNLO: double and triple boson production, VBF — Arnold et al
  - NLOJET++: two and three jet production — Nagy
  - Rocket/MCFM+: W+3 jets, WW+jet — Melia et al
  - Blackhat: 4 jets, W/Z + up to 4 jets, photon+jets — Bern et al

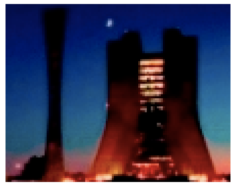
Blackhat+SHERPA

- One of the main tools pushing the boundaries of NLO computations.
- On-shell methods for loops (similar to MadLoop), SHERPA for real emissions.
- No public code available, but event n-tuples on request.

W+5 jets



Bern, Diana, Dixon, Febres Cordero, Höche, Ita, Kosower, Maître, Ozeren



MCFM

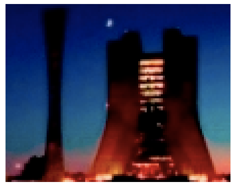
- Fortran code MCFM: “one-stop shopping” for many NLO predictions.

  http://mcfm.fnal.gov (v6.3, August 2012)

  JC, R. K. Ellis, C. Williams (main authors)
  F. Caola, R. Frederix, H. Hartanto F. Maltoni, F. Tramontano, S. Willenbrock

- Standard Model processes involving photons,W,Z + jets, top quarks, Higgs.
- Decays of unstable particles are included, maintaining spin correlations and (sometimes) including NLO effects.
- Photon fragmentation and realistic isolation included.
- Cross sections and differential distributions, flexible cuts.

- Analytic helicity amplitudes calculated from scratch or taken from literature.
- Slightly-modified implementation of Catani-Seymour dipole subtraction.



Radiation in top quark decay

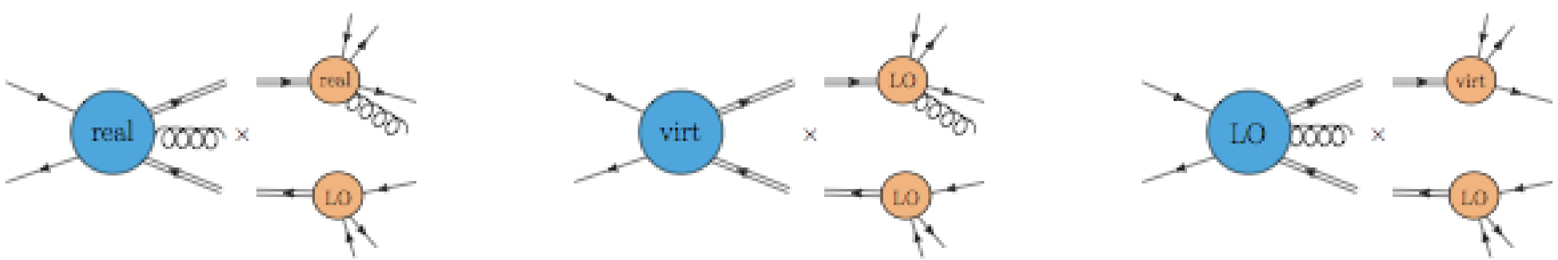
- Effect not included in current parton showers: NLO radiation in decay.
- Small width Γt/mt < 1% → factorization of production and decay

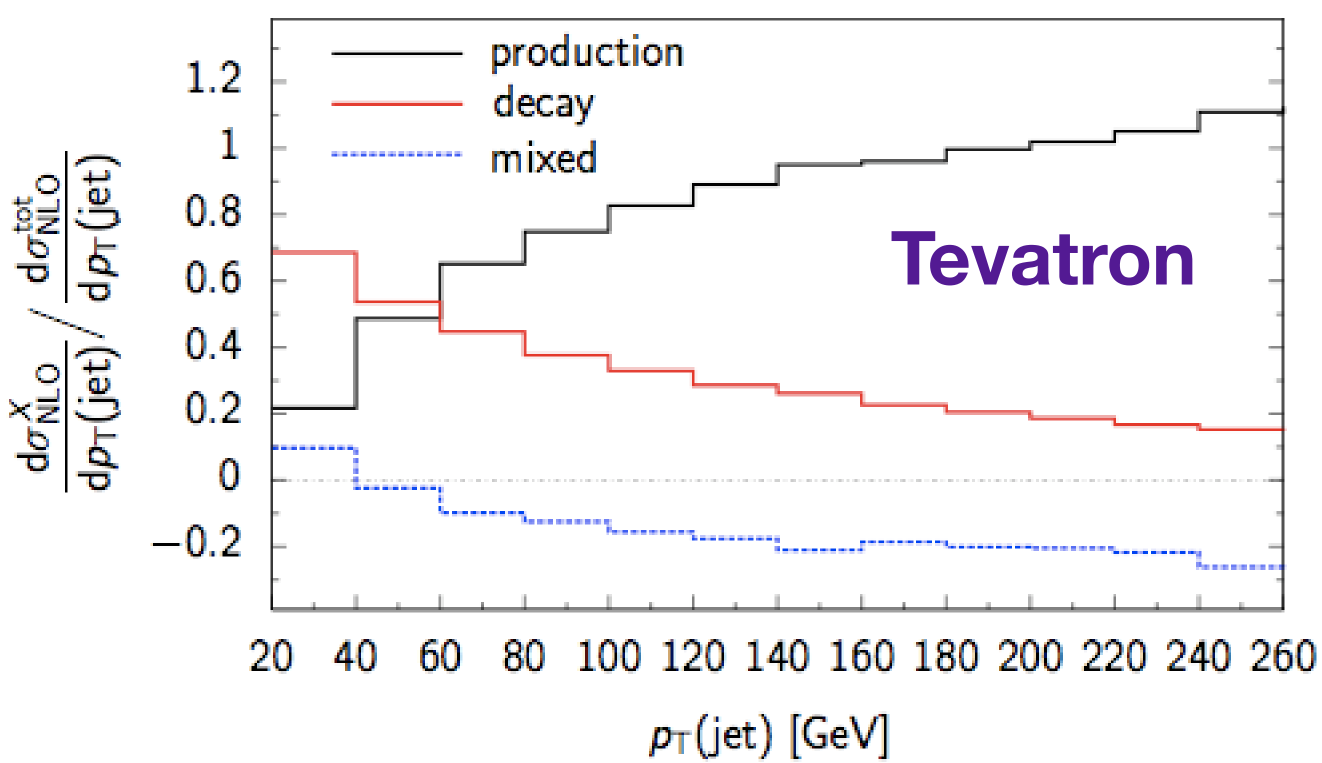
tt+jet

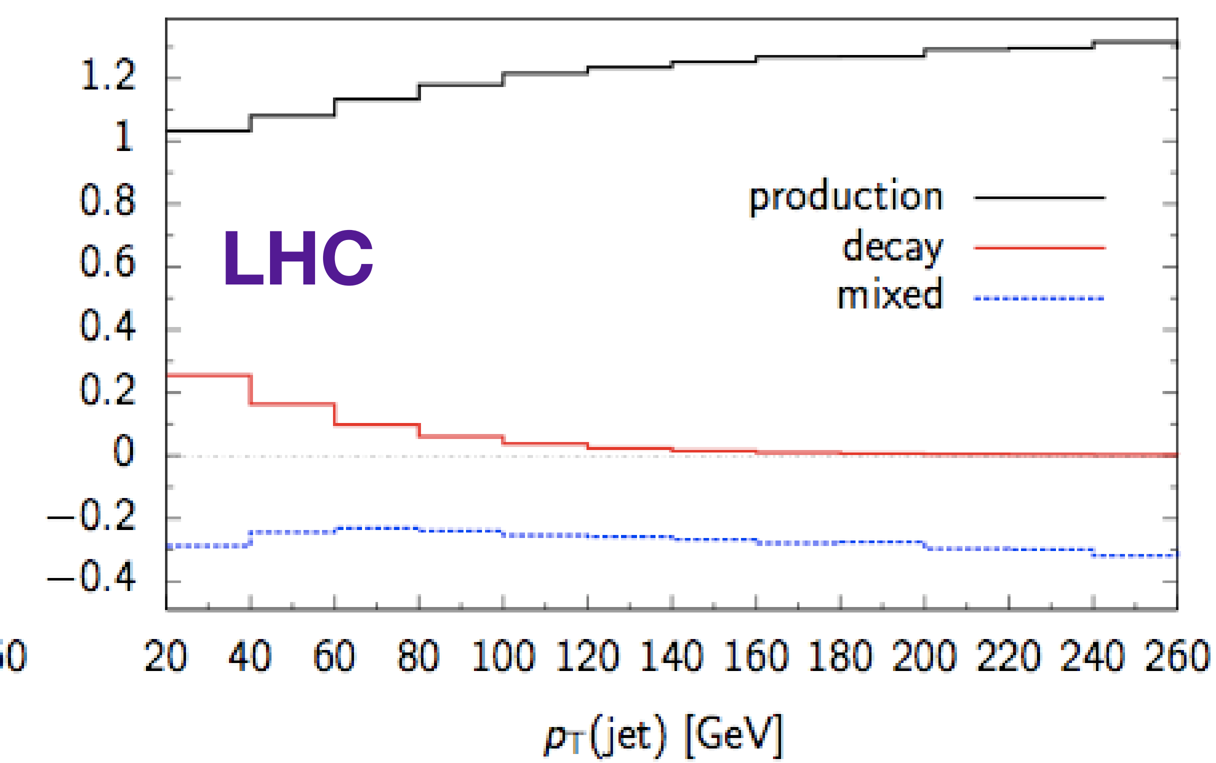
Melnikov, Scharf, Schulze

(a) jet emission in production (b) jet emission in decay

Radiation in decay important!







Higher orders: reminder

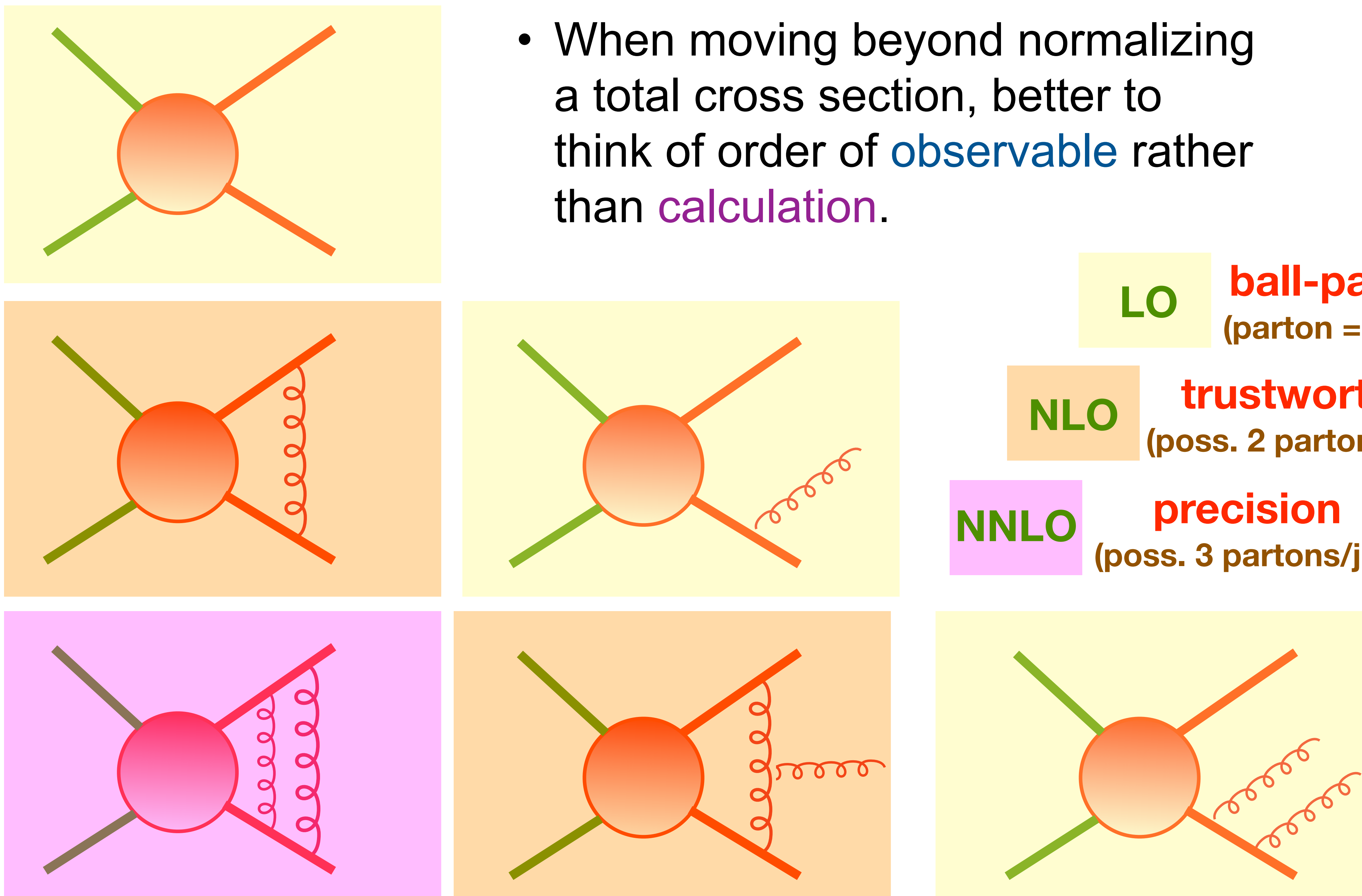
- Orders of calculation populate different jet bins at differing orders of accuracy.

- When moving beyond normalizing a total cross section, better to think of order of observable rather than calculation.

LO N-jet calculation

NLO N-jet

NNLO N-jet



N-jet kinematics | **(N+1)-jet** | **(N+2)-jet**

LO — **ball-park** (parton = jet)

NLO — **trustworthy** (poss. 2 partons/jet)

NNLO — **precision** (poss. 3 partons/jet)

Summary

- Modern parton showers come in many flavors
  - multi-jet merged samples (MLM, CKKW)
  - NLO matched for first emission (MC@NLO, POWHEG)
  - NLO matched for first emission, multi-jet merged (ME&TS, MENLOPS)
  - NLO matched for many jets (MEPS@NLO)
- Availability and maturity of predictions in that order.

- Developments at the parton level too
  - refinements of NLO that will eventually make their way into the PS
  - beginning of NNLO for colored final states

- Many tools: always pros and cons; know limitations before making conclusions!