QCD Basics for accurate LHC Physics

Lecture IV

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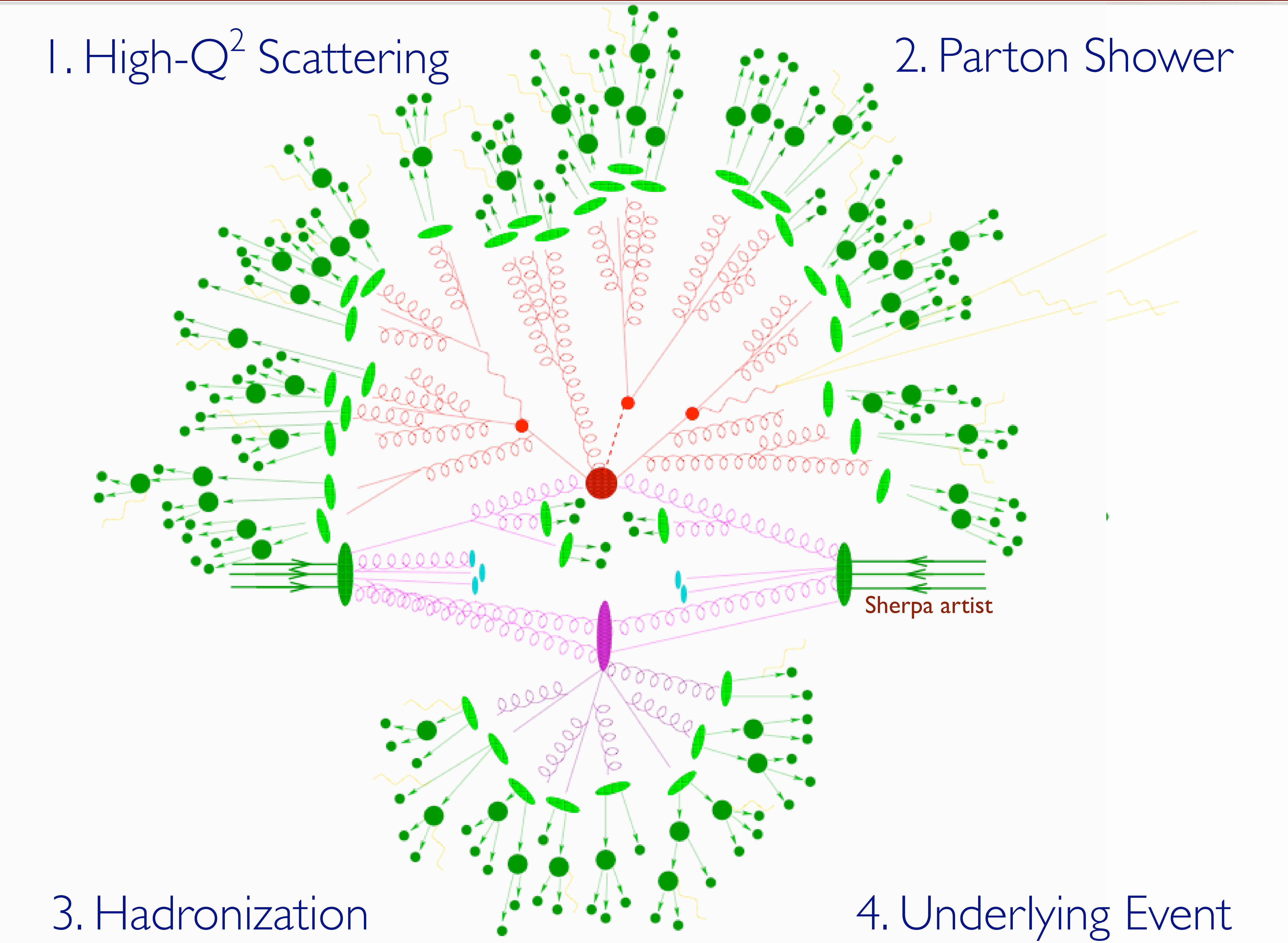
Claims and Aims

Four lectures:

1. Intro and QCD fundamentals
2. QCD in the final state
3. From accurate QCD to useful QCD
4. Advanced QCD with applications at the LHC

How do improve?

1. We reach NLO and NNLO accuracy — TH-Accurate
2. We include parton showers — EXP-Useful



1. High-Q^2 Scattering
2. Parton Shower
3. Hadronization
4. Underlying Event
Sherpa artist

Matrix Elements vs. Parton Showers

Matrix Elements vs. Parton Showers

ME

1. Fixed order calculation
2. Computationally expensive
3. Limited number of particles
4. Valid when partons are hard and well separated
5. Quantum interference correct
6. Needed for multi-jet description

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Shower MC

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Approaches are complementary: merge them!

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Approaches are complementary: merge them!

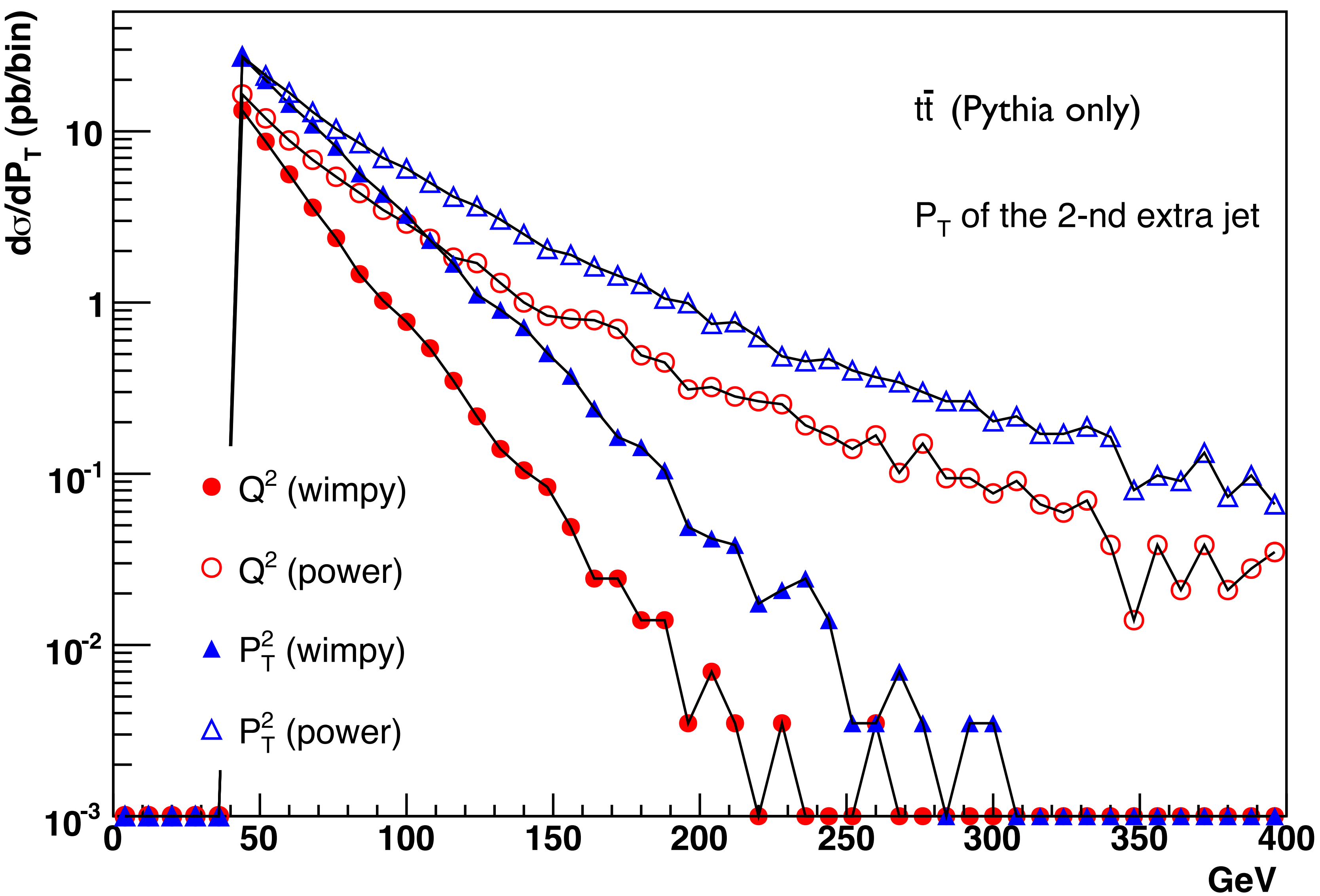
Difficulty: avoid double counting, ensure smooth distributions

TWO METHODS

- ME+PS : CKKW and MLM merging
- NLOwPS : MC@NLO and POWHEG

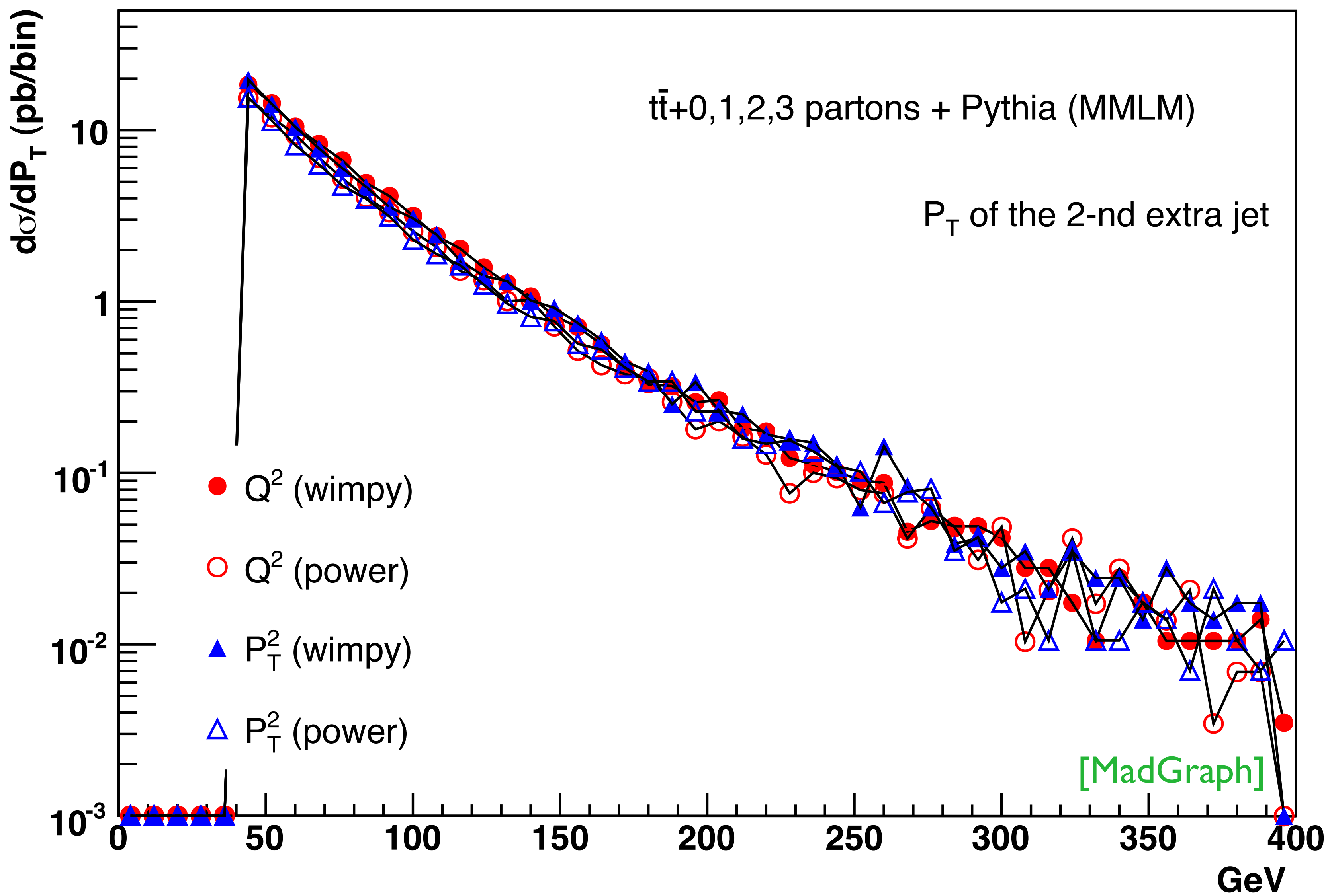
PS alone vs matched samples

In the soft-collinear approximation of Parton Shower MCs, parameters are used to tune the result ⇒ Large variation in results (small prediction power)



PS alone vs matched samples

In a matched sample these differences are irrelevant since the behavior at high pt is dominated by the matrix element.



Goal for ME-PS merging/matching

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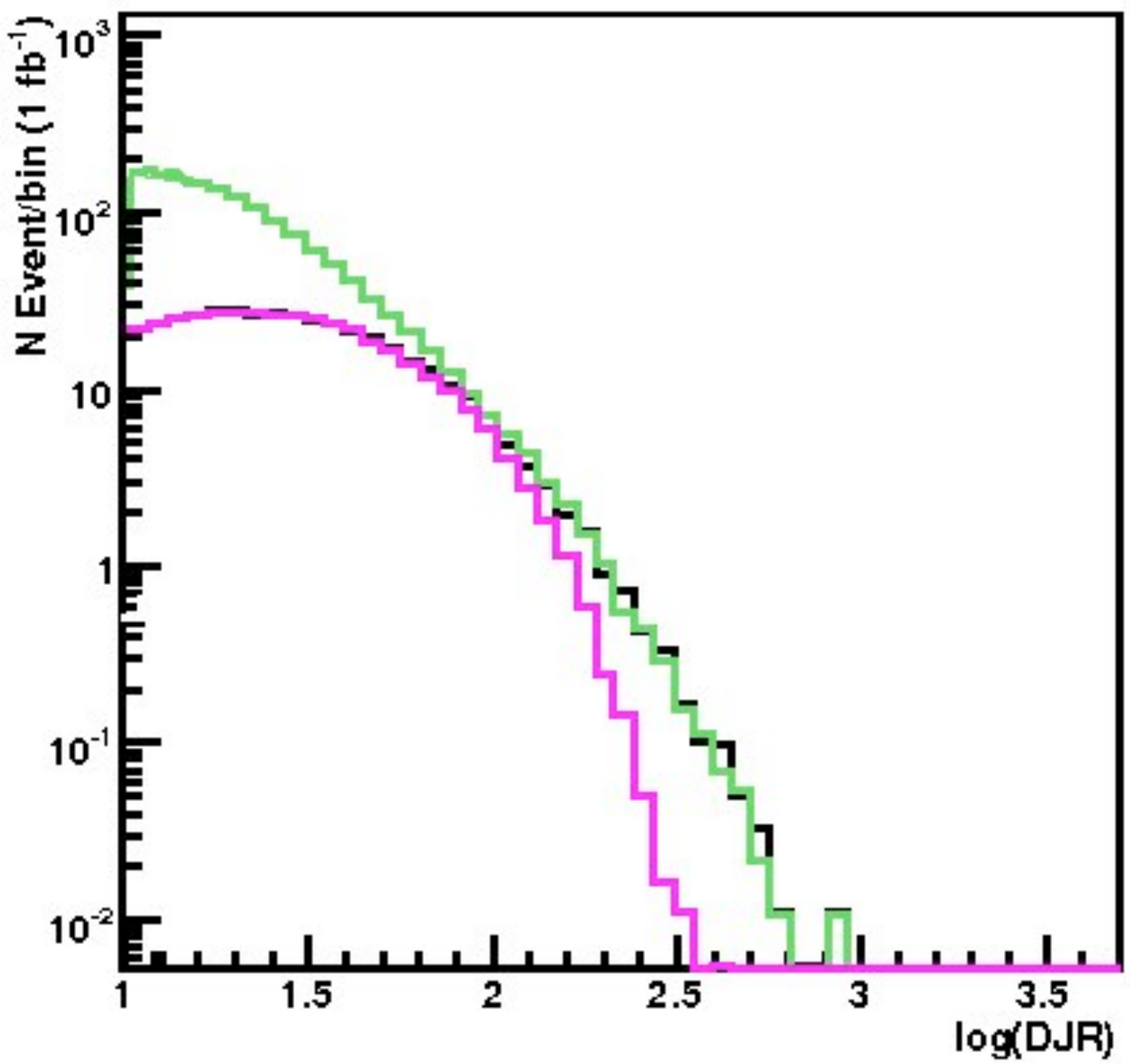

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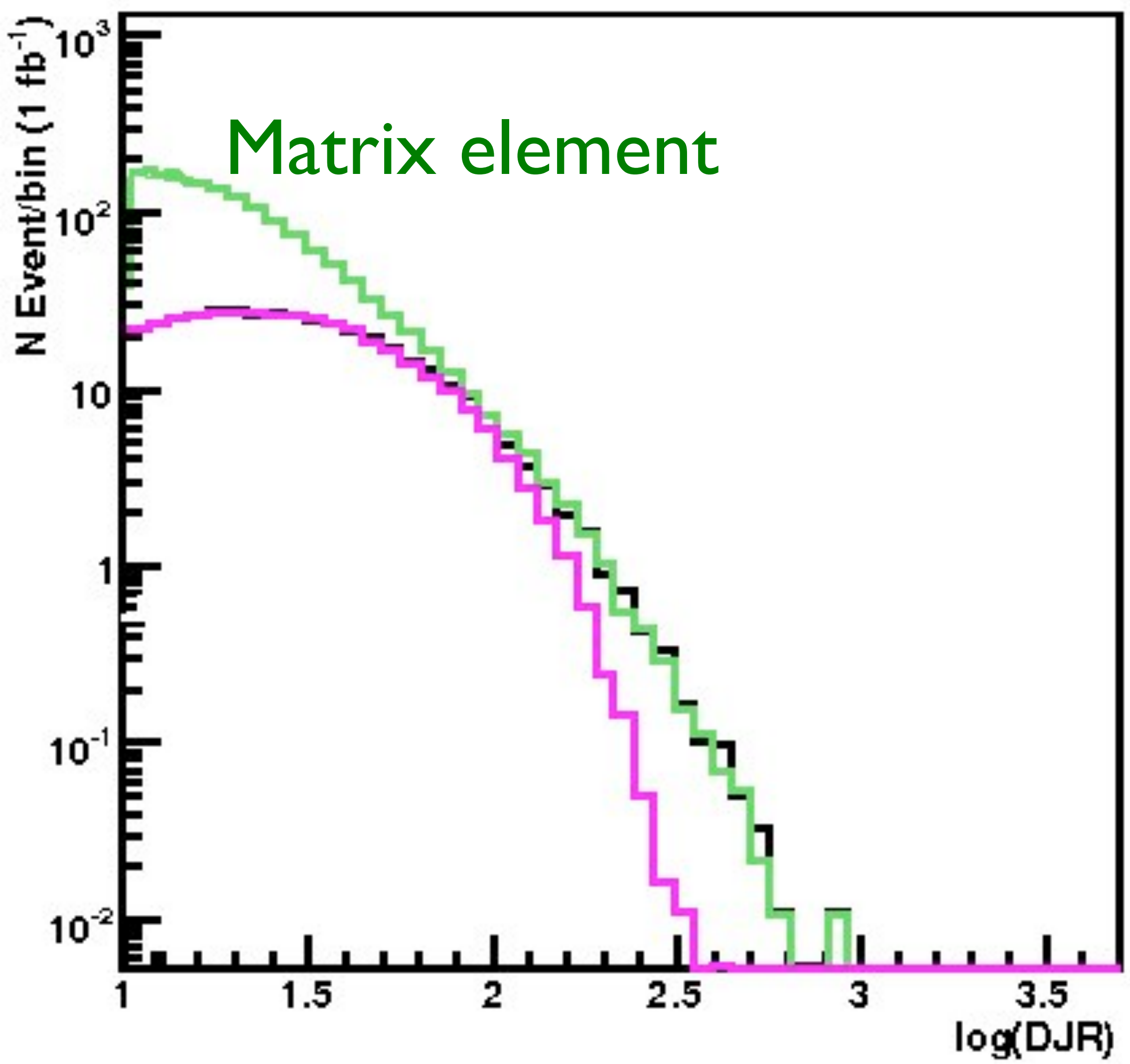

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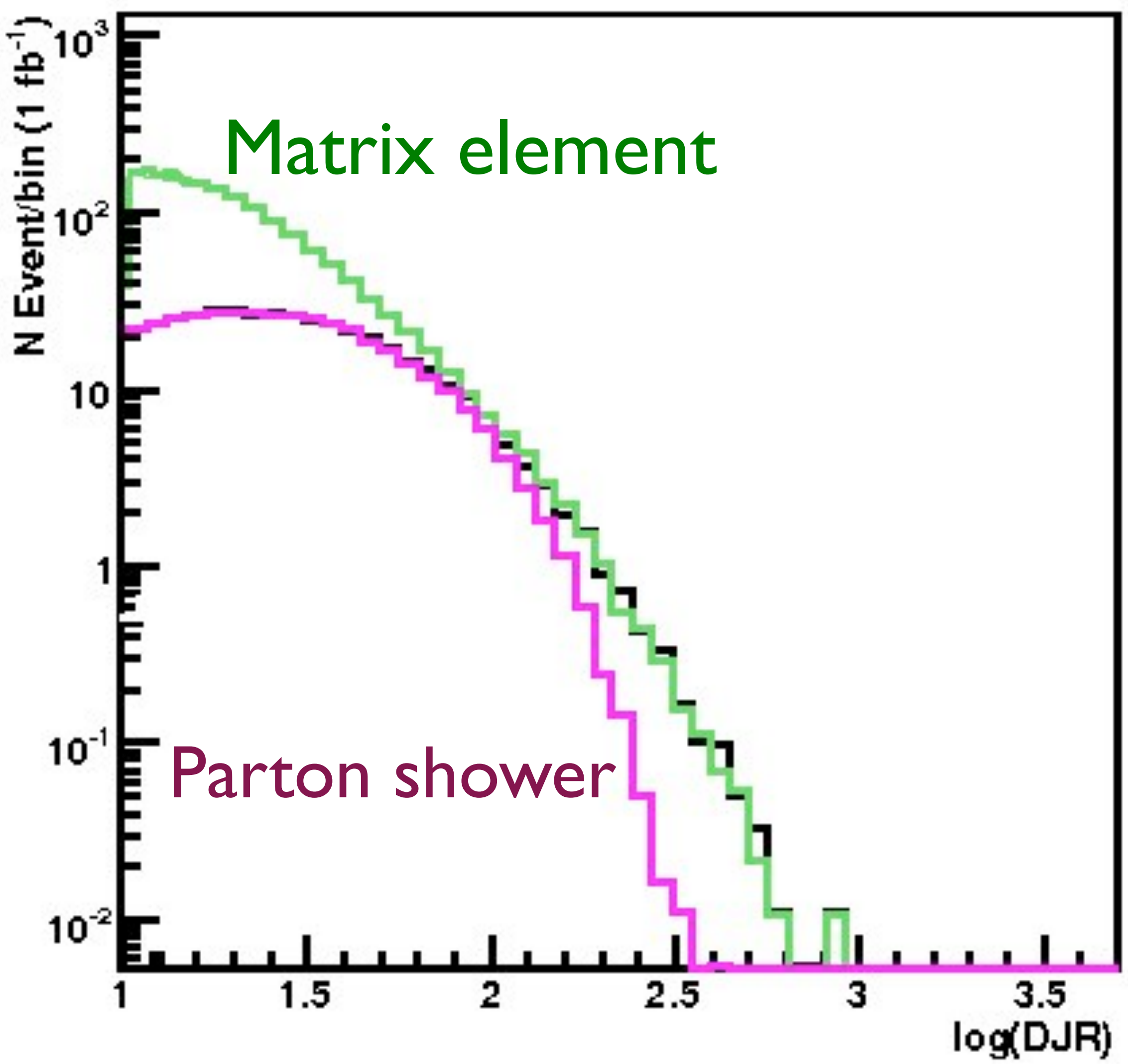

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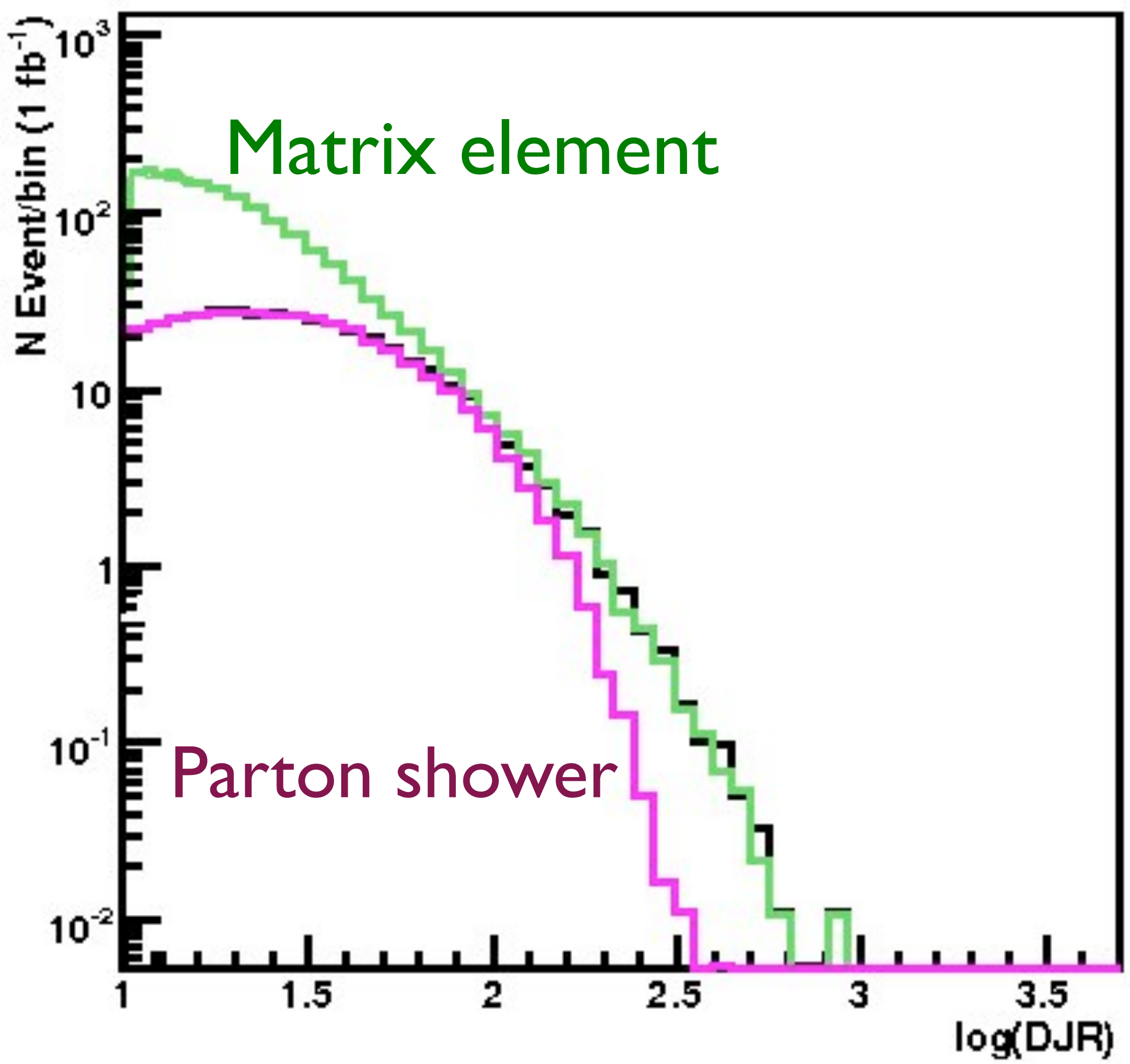

2nd QCD radiation jet in top pair production at the LHC

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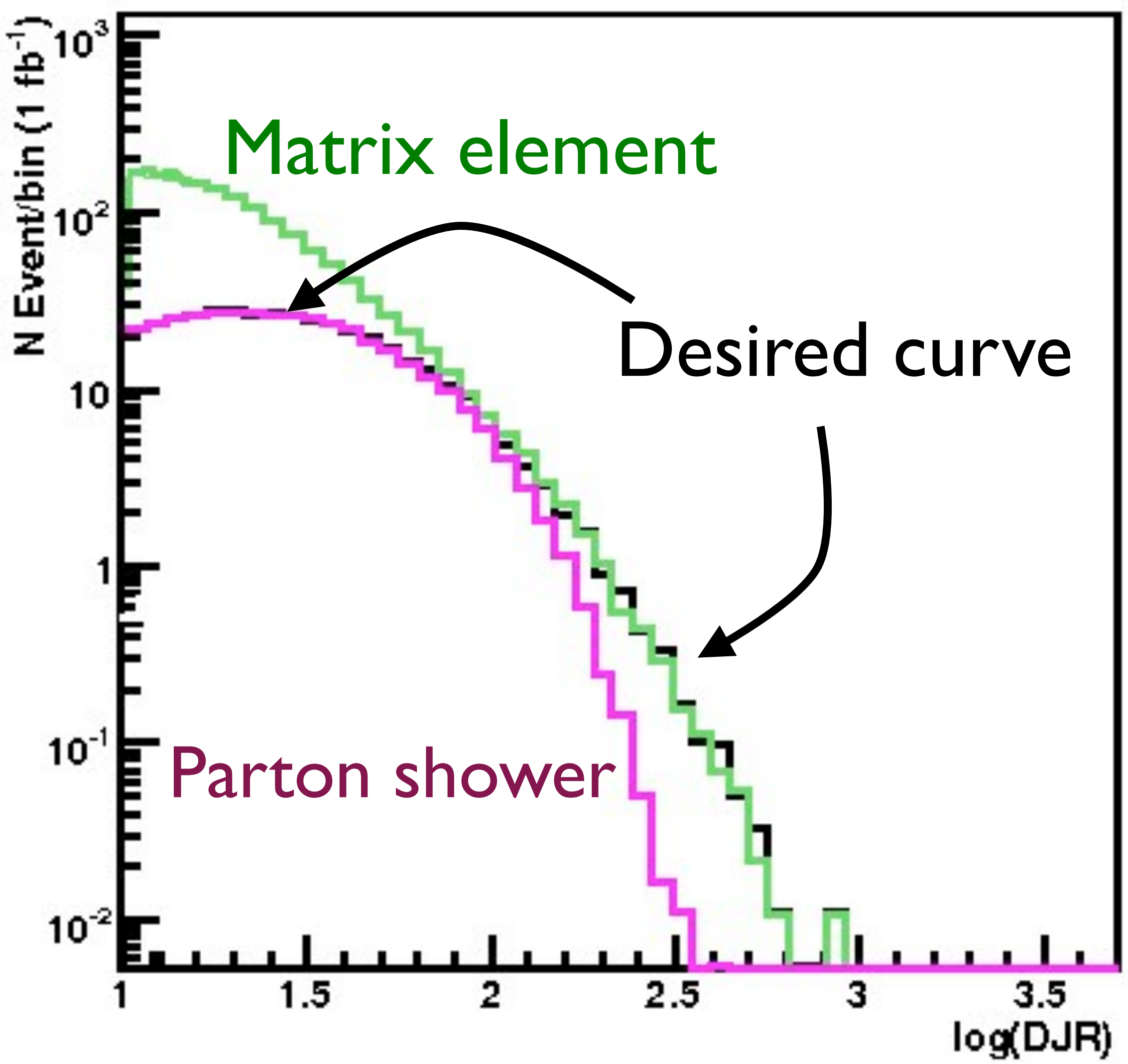

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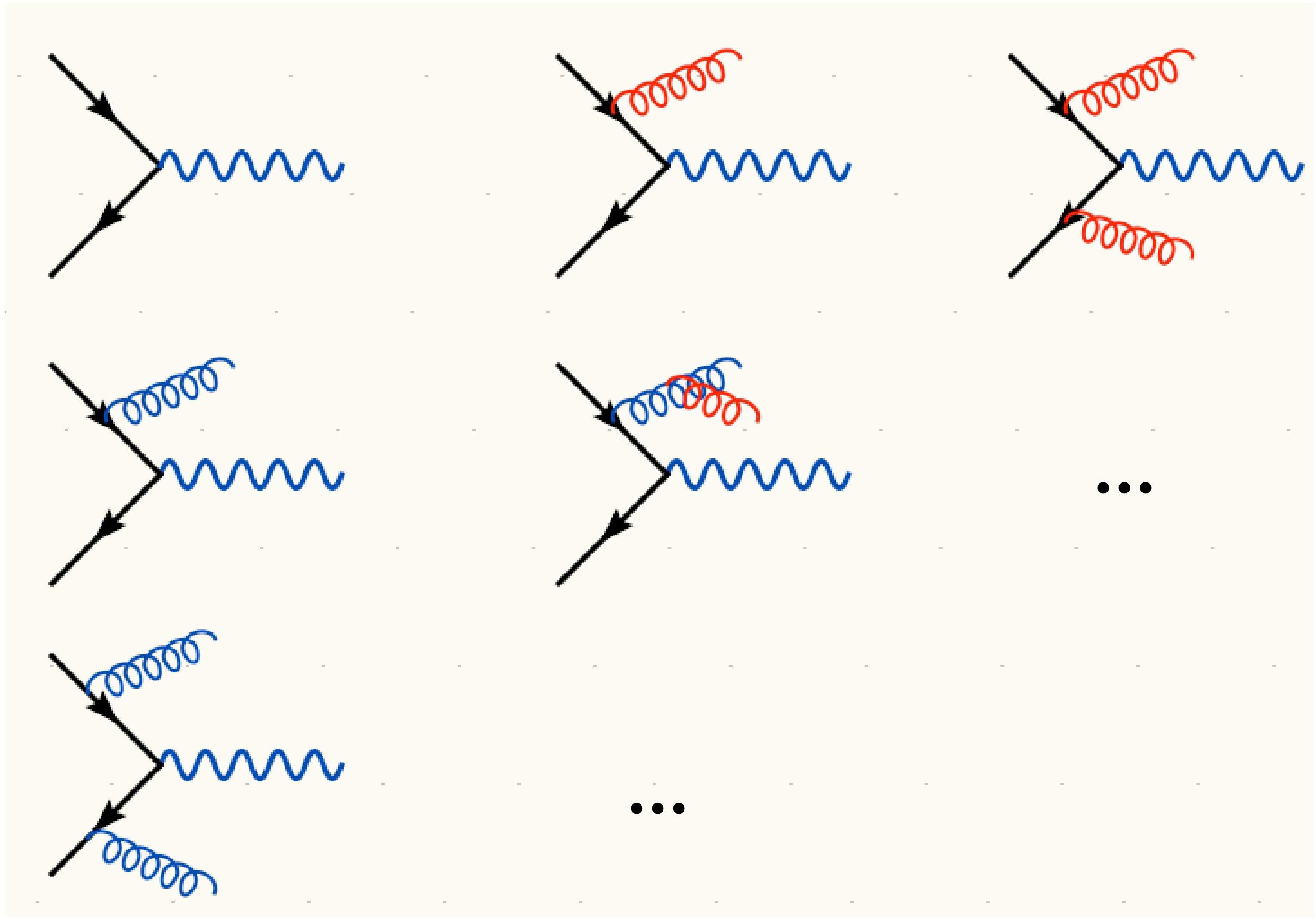
Merging ME with PS

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

PS →

ME ↓



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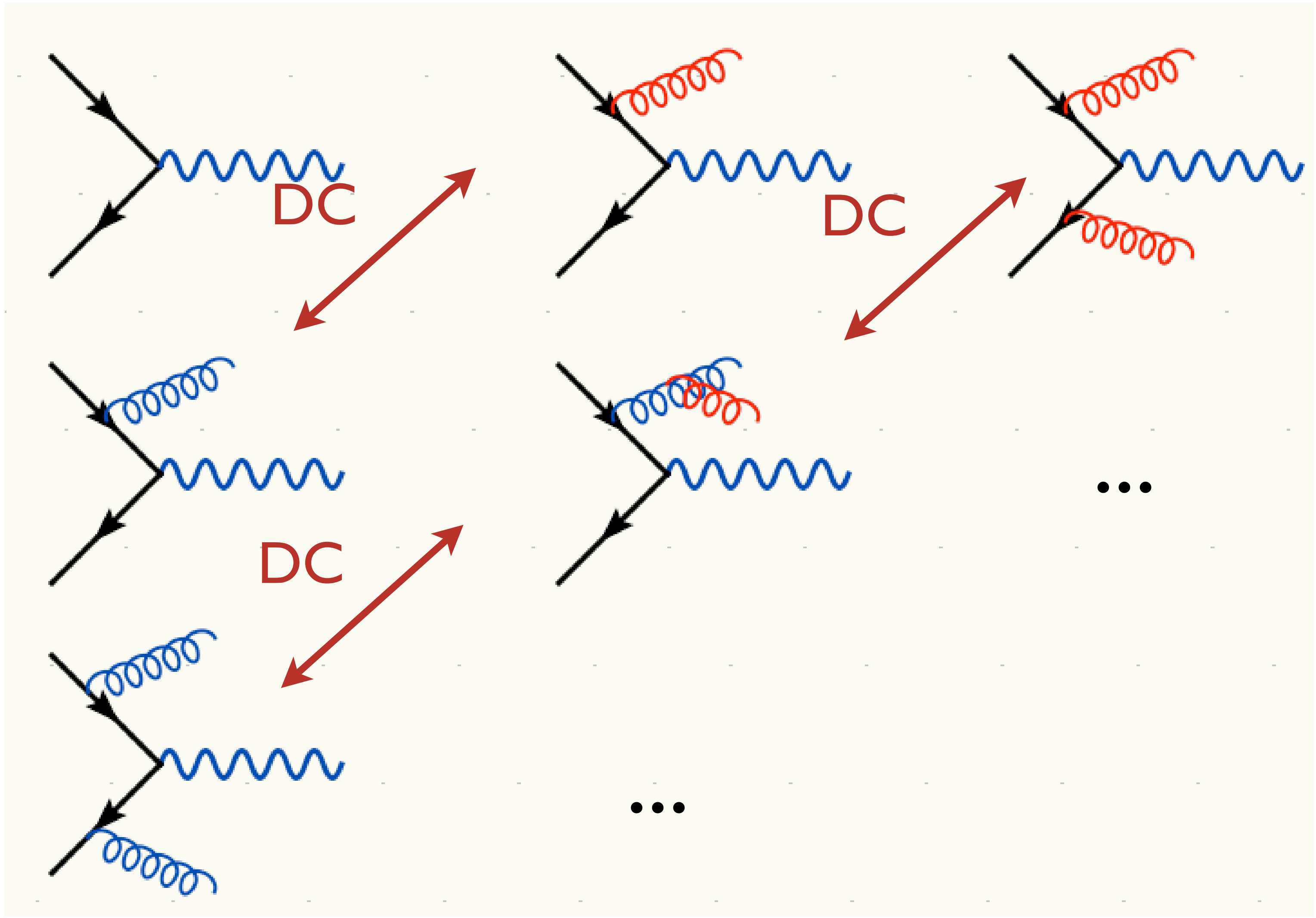

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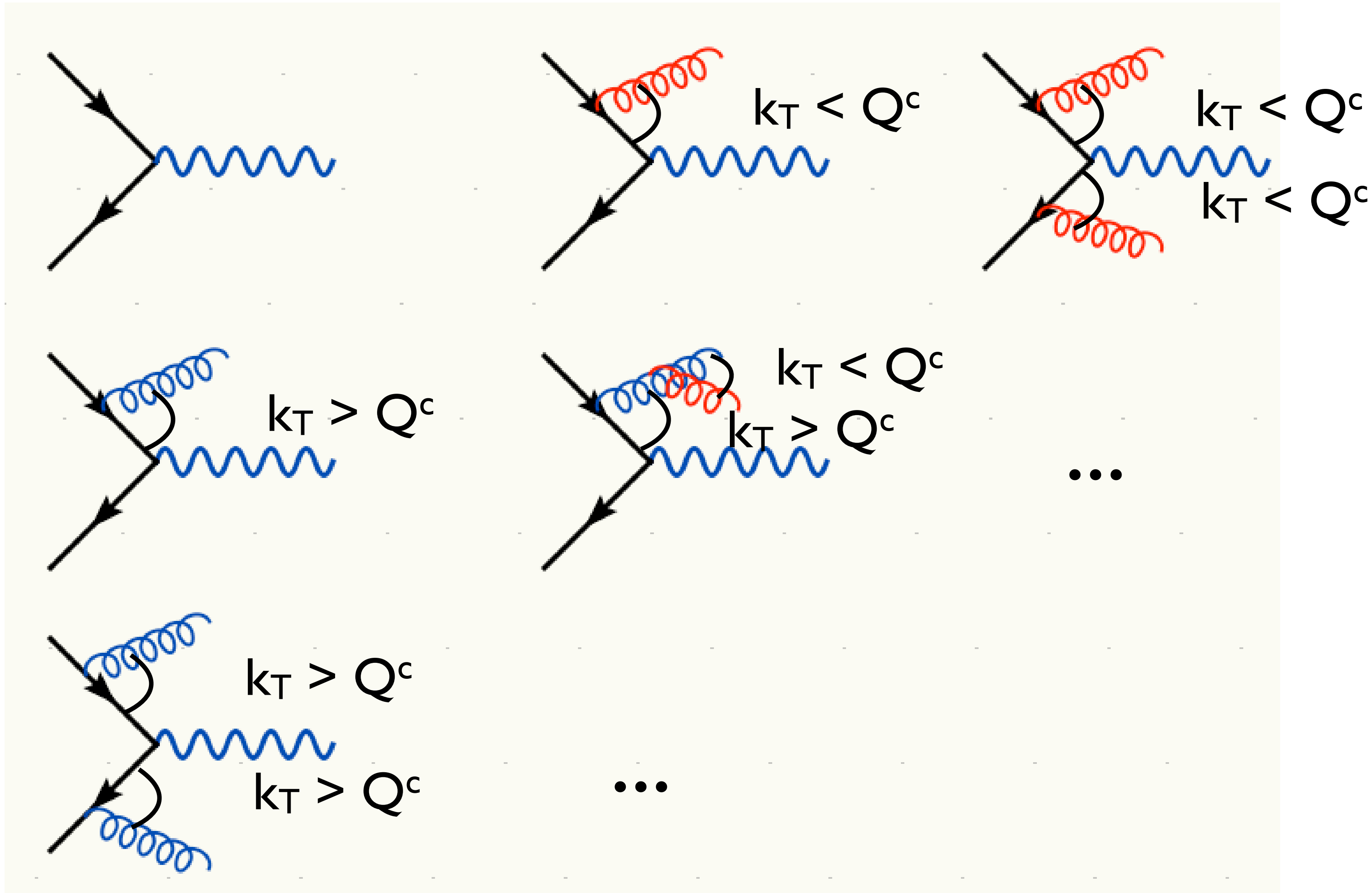

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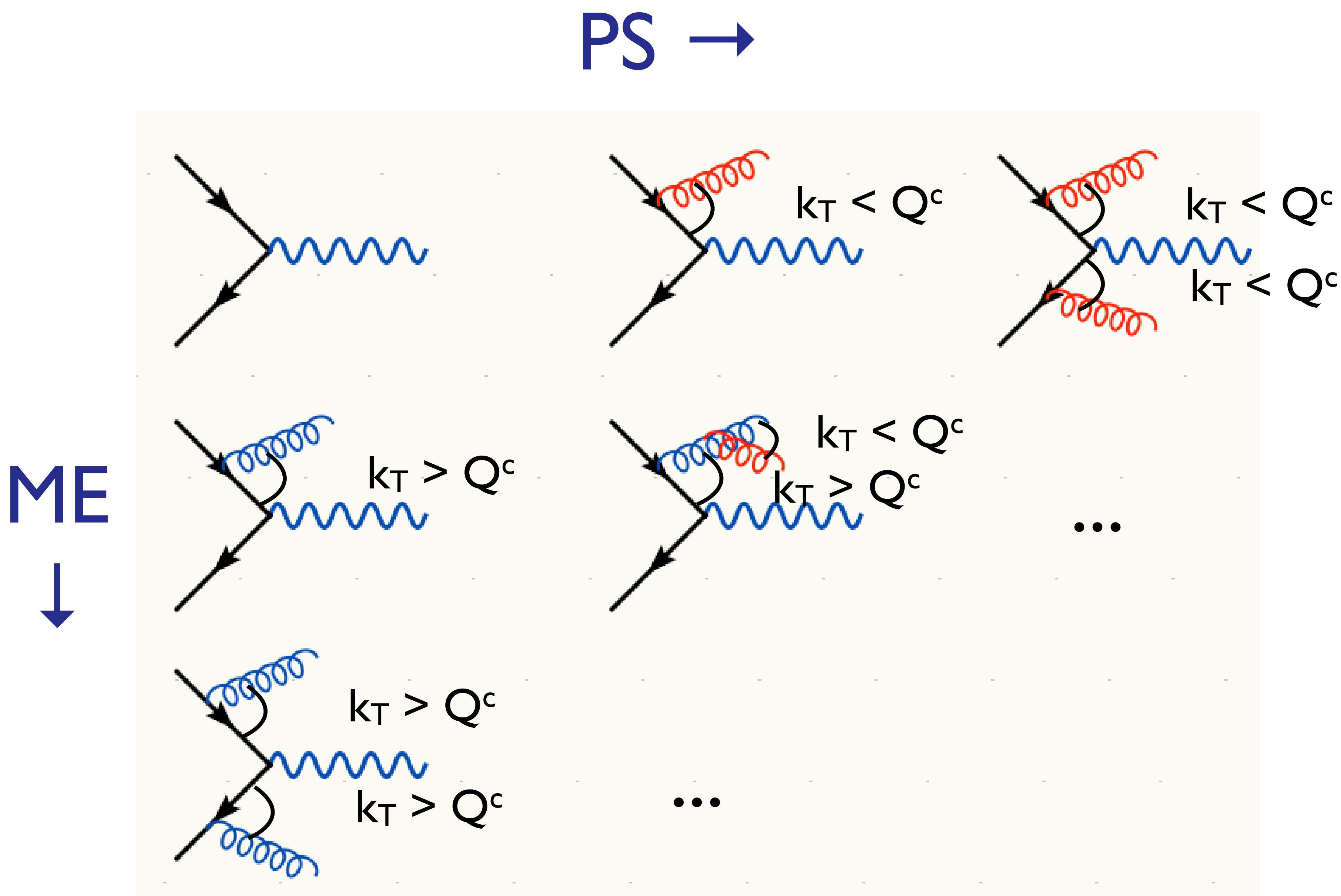
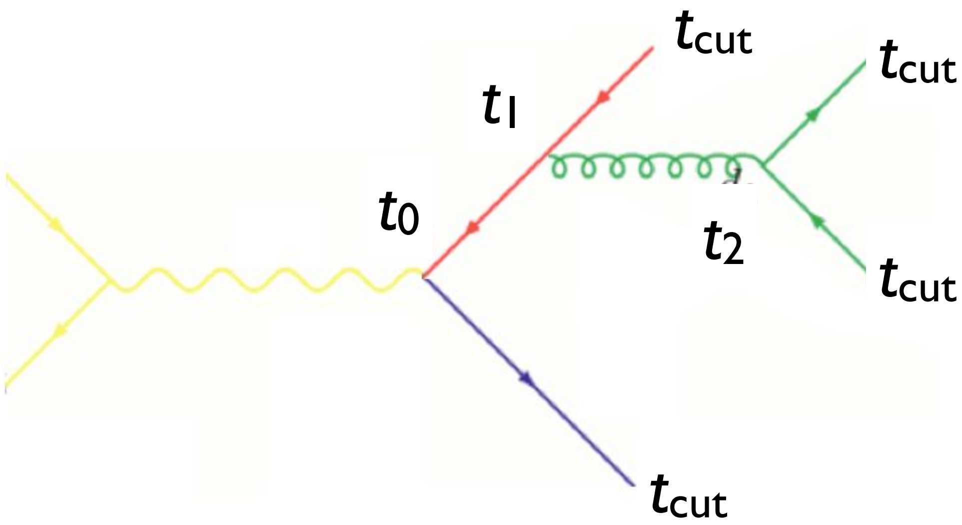


Double counting between ME and PS easily avoided using phase space cut between the two: PS below cutoff, ME above cutoff.

Merging ME with PS

- So double counting no problem, but what about getting smooth distributions that are independent of the precise value of Q^c?
- Below cutoff, distribution is given by PS
  - need to make ME look like PS near cutoff
- Let's take another look at the PS!

Merging ME with PS



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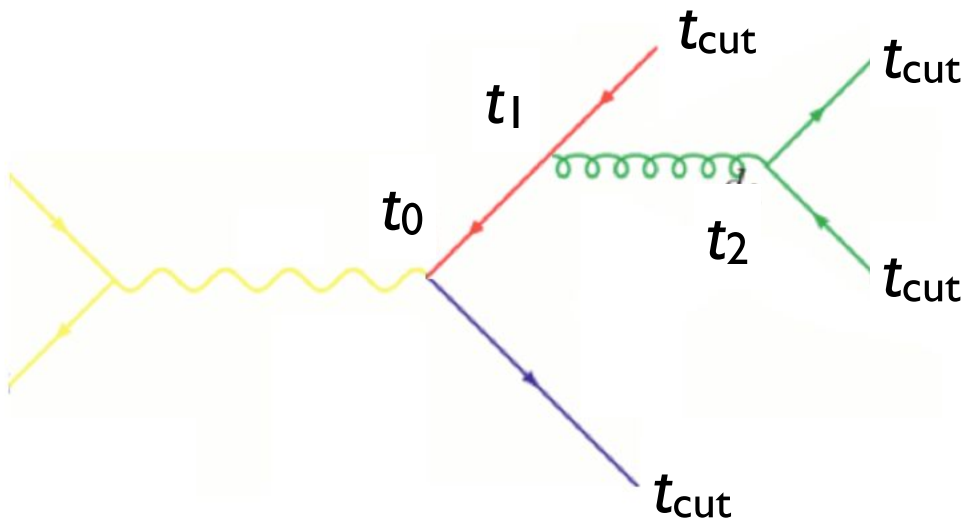

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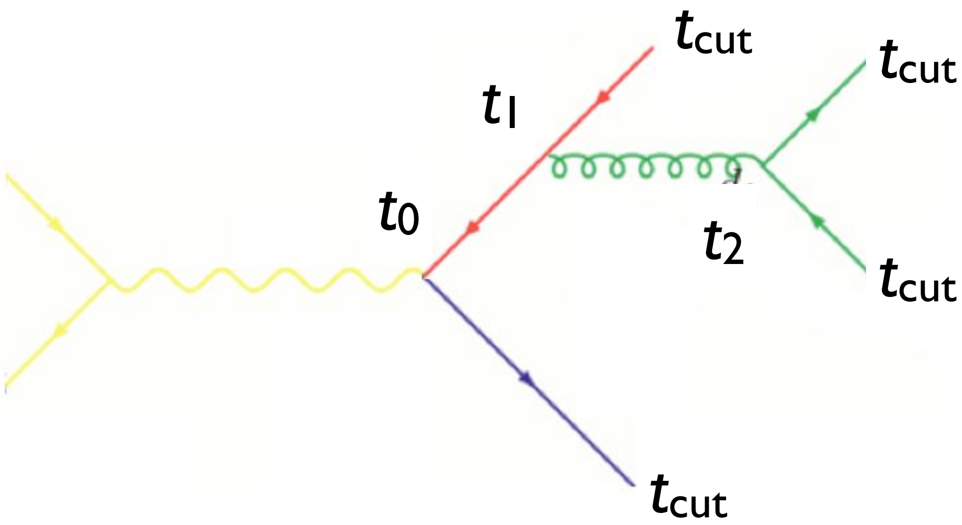

- How does the PS generate the configuration above?
- Probability for the splitting at t_1 is given by

$$(\Delta_q(t_1, t_0))^2 \frac{\alpha_s(t_1)}{2\pi} P_{gq}(z)$$

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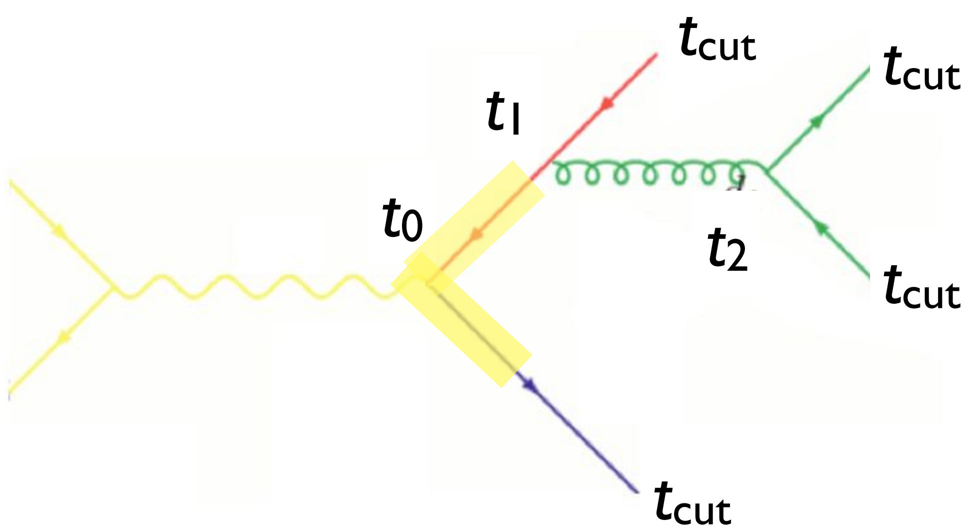

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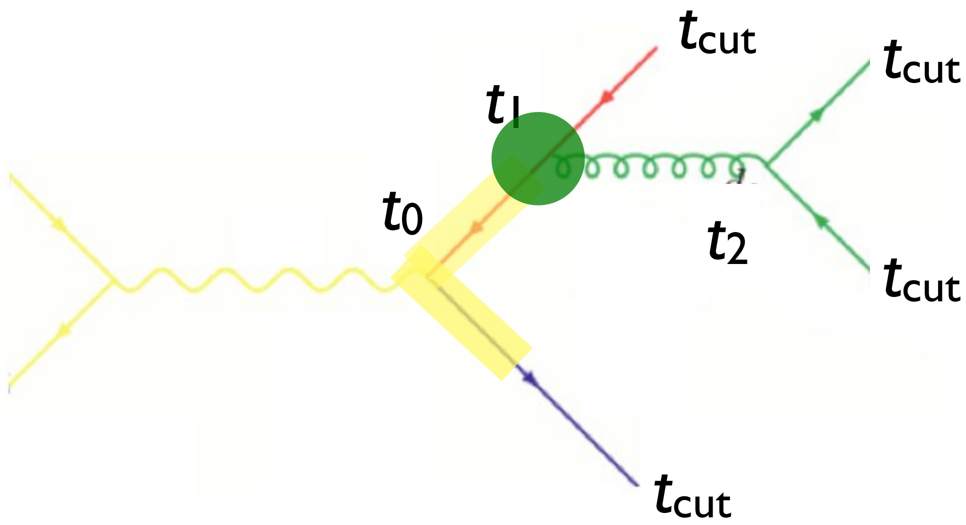

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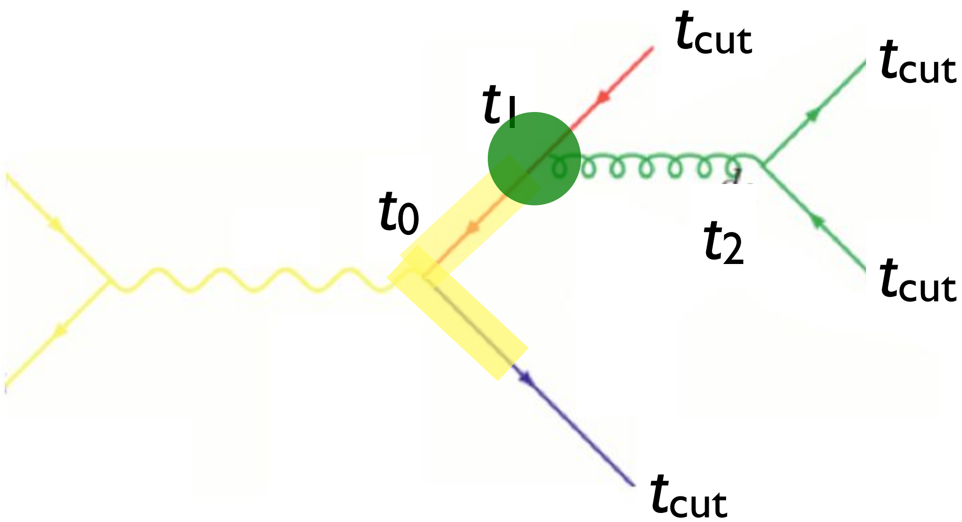

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and for the whole tree

$$(\Delta_q(t_{\rm cut},t_0))^2 \Delta_g(t_2,t_1)(\Delta_q({\rm cut},t_2))^2 \frac{\alpha_s(t_1)}{2\pi} P_{gq}(z) \frac{\alpha_s(t_2)}{2\pi} P_{qg}(z')$$

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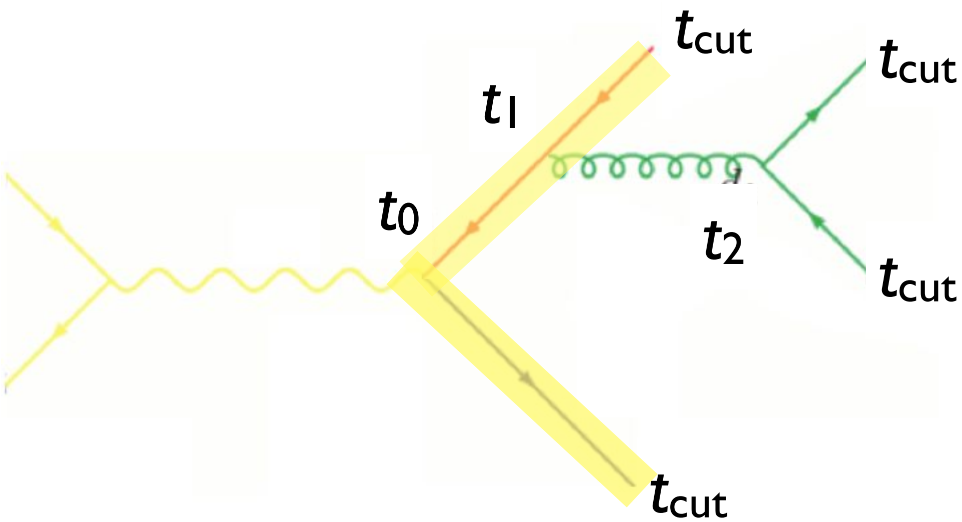

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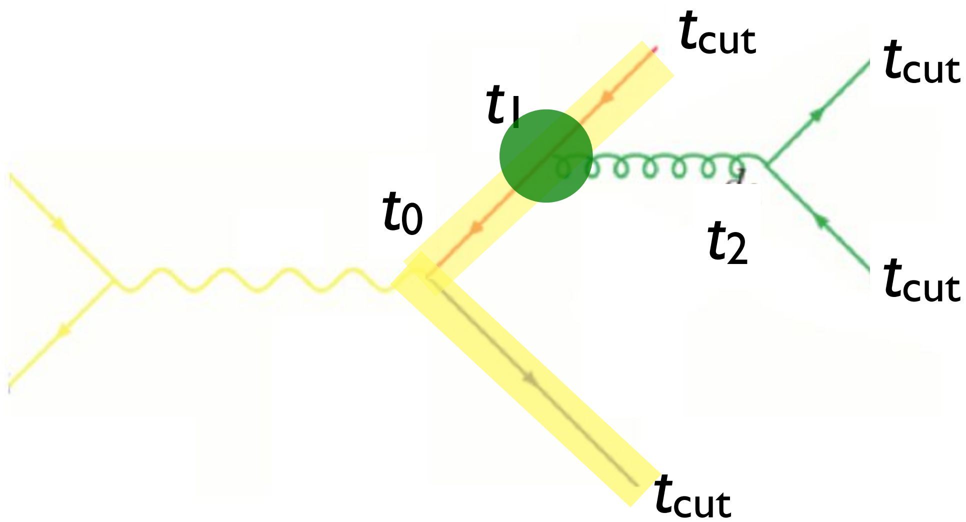

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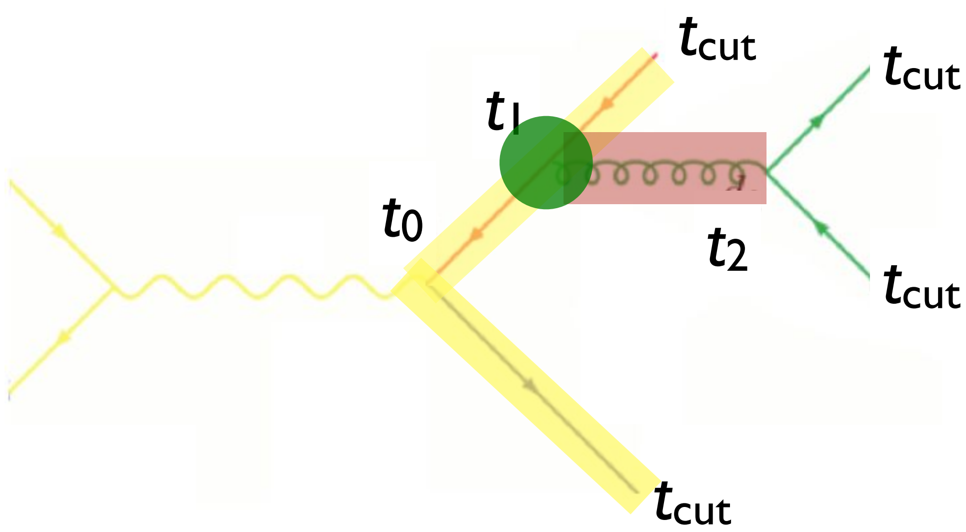

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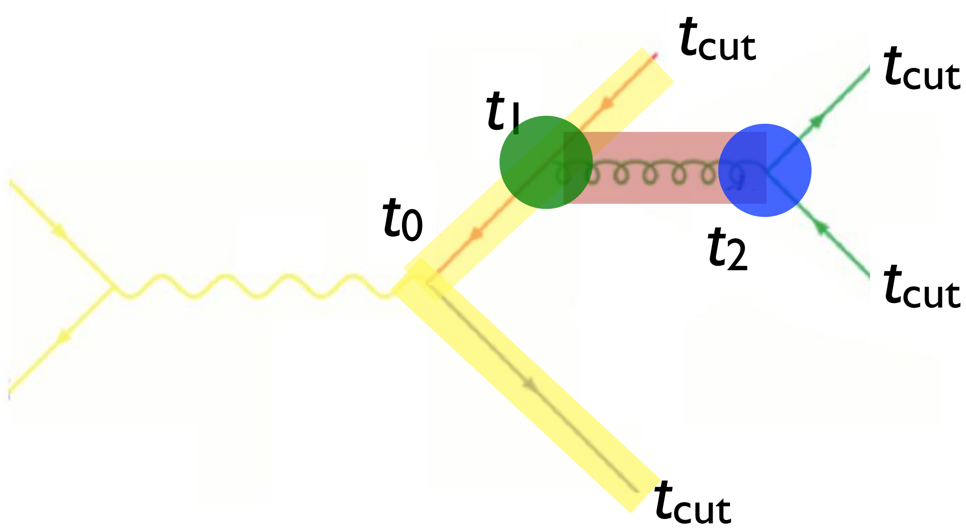

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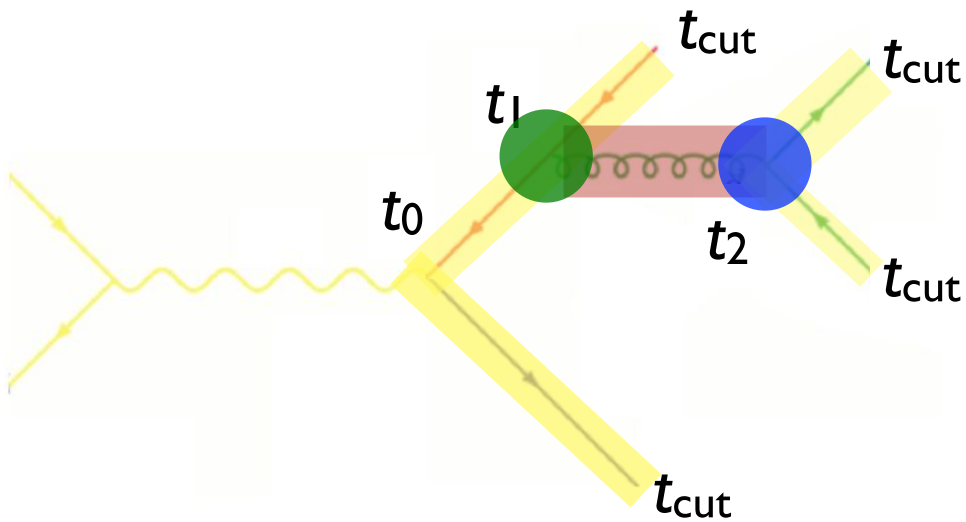

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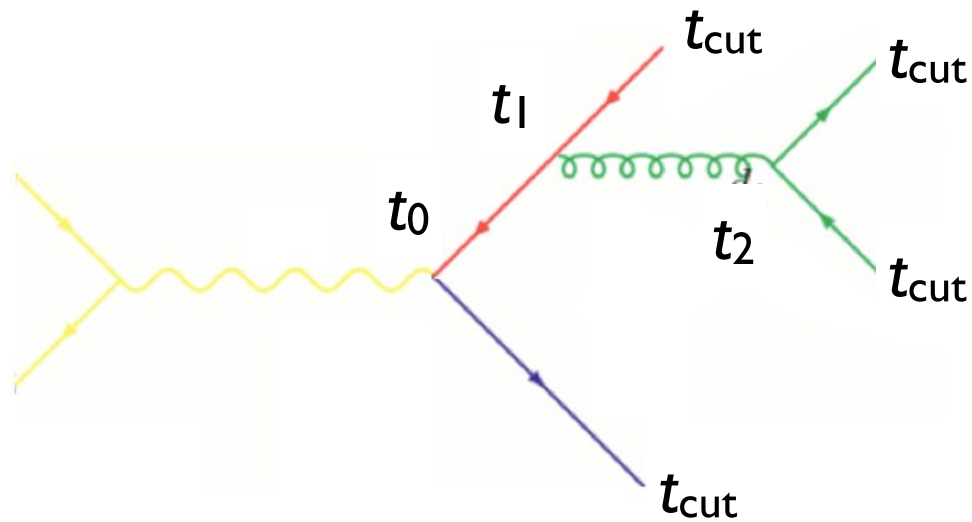

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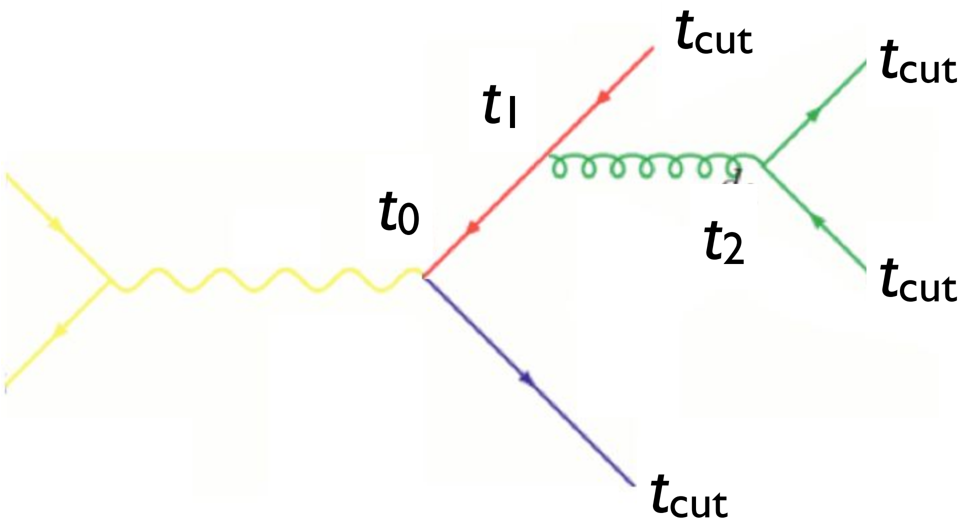

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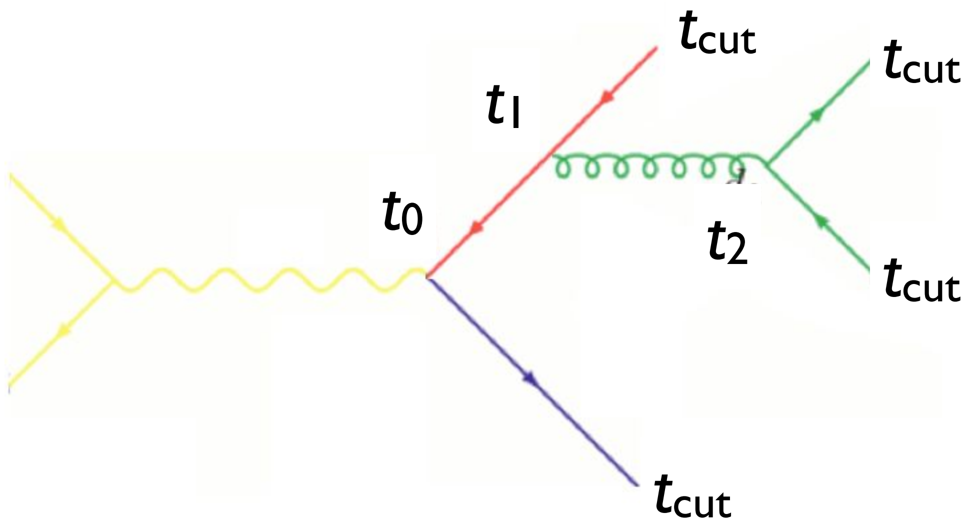

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Sudakov suppression due to disallowing additional radiation above the scale t_{cut}

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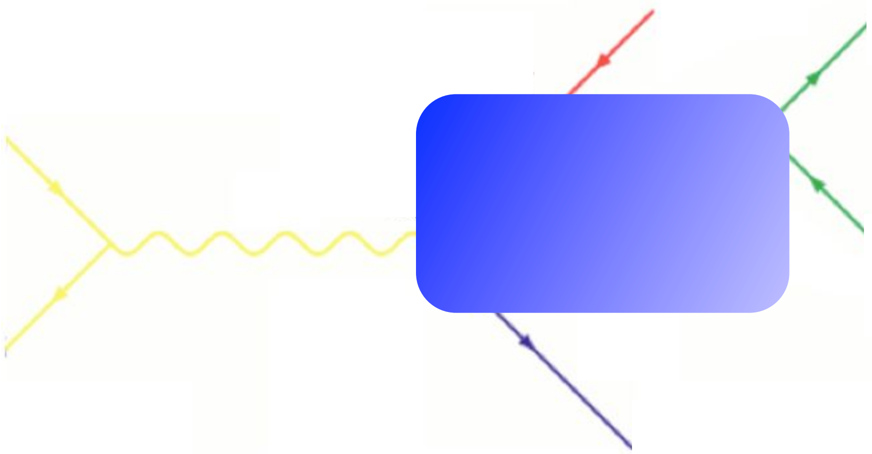
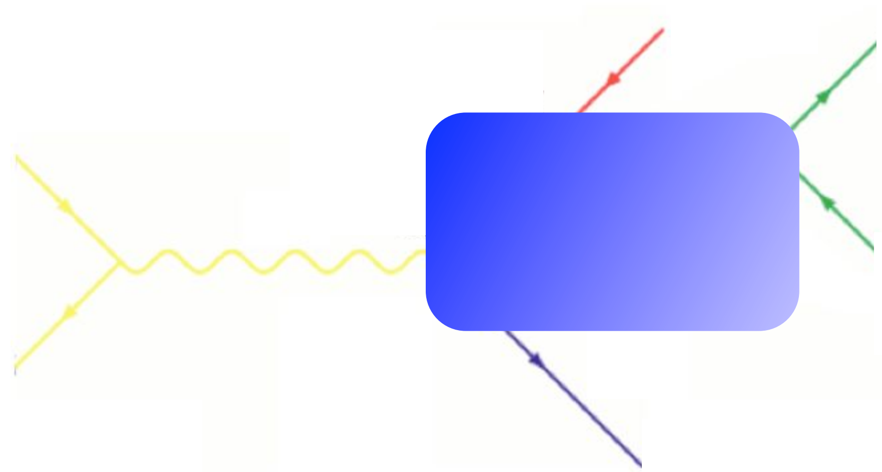


$$|\mathcal{M}|^2(\hat{s}, p_3, p_4, \ldots)$$

MERGING ME WITH PS



$$|\mathcal{M}|^2(\hat{s}, p_3, p_4, \dots)$$

- To get an equivalent treatment of the corresponding matrix element, do as follows:
  1. Cluster the event using some clustering algorithm
     - this gives us a corresponding "parton shower history"
  2. Reweight α_s in each clustering vertex with the clustering scale
     $$|\mathcal{M}|^2 \to |\mathcal{M}|^2 \frac{\alpha_s(t_1)}{\alpha_s(t_0)} \frac{\alpha_s(t_2)}{\alpha_s(t_0)}$$
  3. Use some algorithm to apply the equivalent Sudakov suppression

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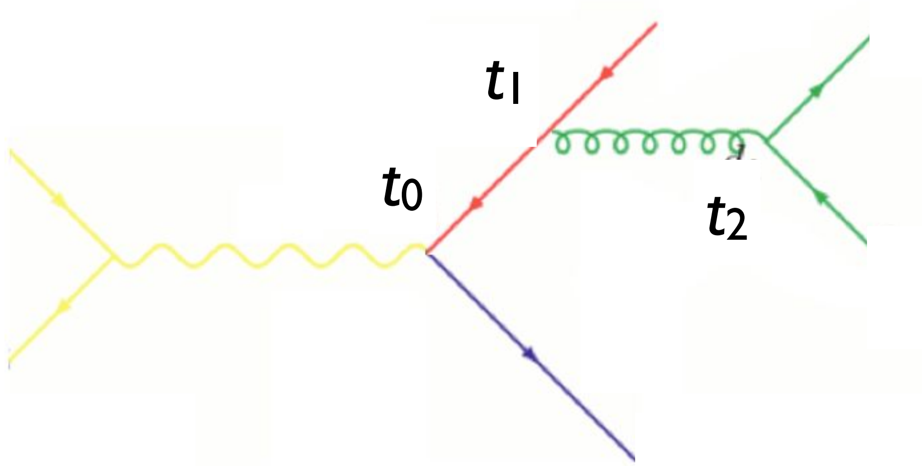

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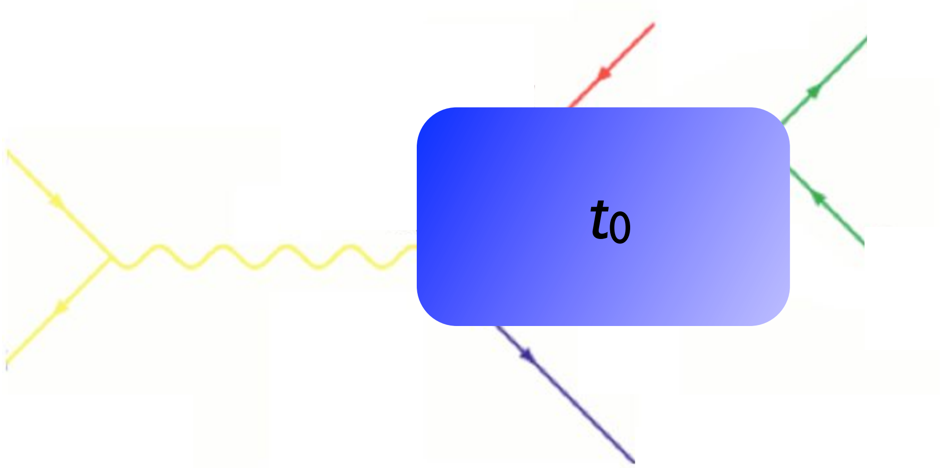
MLM MATCHING

[M.L. Mangano, 2002, 2006]
[J.Alwall et al 2007, 2008]

- The simplest way to do the Sudakov suppression is to run the shower on the event, starting from t_0!



- If hardest shower emission scale $k_{T1} > t_{cut}$, reject the event, if all $k_{T1,2,3} < t_{cut}$, keep the event
- The probability for this is so the internal structure of the shower history is ignored. In practice, this approximation is still pretty good.
- Allows matching with any shower, without modifications!

MLM matching

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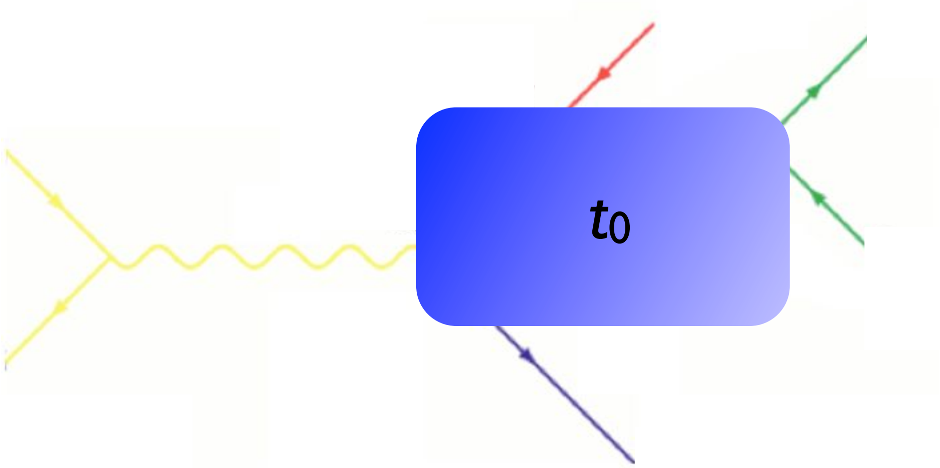

- If hardest shower emission scale $k_{T1} > t_{cut}$, reject the event, if all $k_{T1,2,3} < t_{cut}$, keep the event
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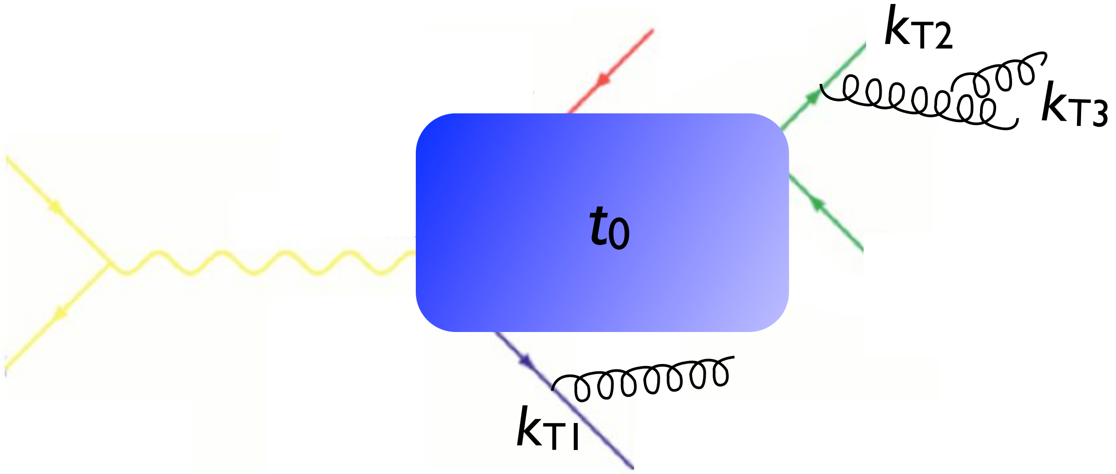

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MLM matching schemes in MadGraph

MLM matching schemes in MadGraph

- We have a number of choices to make in the above procedure. The most important are:

1. The clustering scheme used to determine the parton shower history of the ME event
2. What to use for the scale t_0 (factorization scale)
3. How to divide the phase space between parton showers and matrix elements

MLM matching schemes in MadGraph

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  2. What to use for the scale t_0 (factorization scale)
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- In MadGraph and the MadGraph-Pythia interface, there are three different schemes implemented:
  a. Cone jet scheme (original MLM scheme from AlpGen)
  b. k_T-jet MLM scheme
  c. "Shower-k_T" scheme

MLM matching schemes in MadGraph

1. The default clustering scheme used inside MadGraph to determine the parton shower history is the Durham k_T scheme. For e^+e^-:

$$k^2_{Tij} = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$$

and for hadron collisions, the minimum of:

$$k_{Ti\mathrm{beam}} = m_i^2 + p_{Ti}^2 = (E_i + p_{zi})(E_i - p_{zi})$$

and

$$k^2_{Tij} = \min(p^2_{Ti}, p^2_{Tj})R_{ij}$$

with

$$R_{ij} = 2[\cosh(y_i - y_j) - \cos(\phi_i - \phi_j)] \simeq (\Delta y)^2 + (\Delta\phi)^2$$

2. Find the smallest k_{Tij} (or $k_{Ti\mathrm{beam}}$), combine partons *i* and *j* (or *i* and the beam), and continue until you reach a 2 → 2 (or 2 → 1)

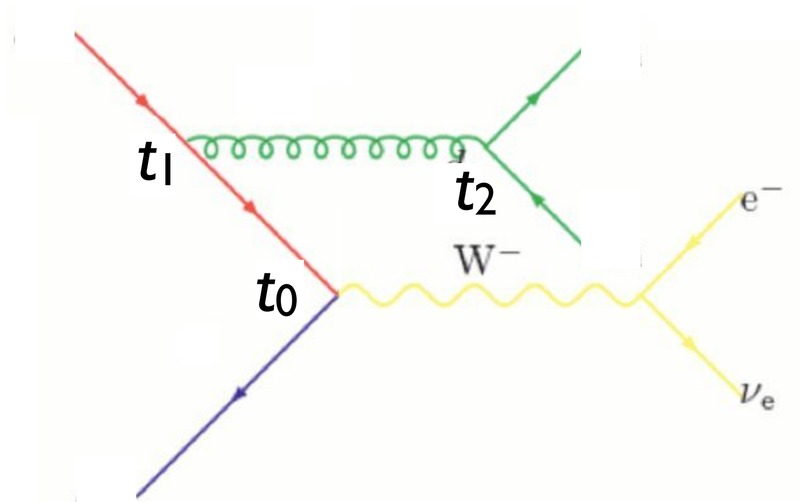
MLM matching schemes in MadGraph

Additional notes:

- MadGraph only allows clustering according to valid diagrams in the process. This means that, e.g., two quarks or quark-antiquark of different flavor are never clustered, and the clustering always gives a physically allowed parton shower history.
- For on-shell s-channel propagators, the clustering value is the invariant mass.
- If there is an on-shell propagator in the diagram, only clustering according to diagrams with this propagator is allowed.

MLM matching schemes in MadGraph

2. The clustering provides a convenient choice for factorization scale t_0:



Cluster back to the 2 → 2 (here $q\bar{q} \to W^- g$) system, and use the W boson transverse mass in that system.

- Special treatment (still beta) for
  - ➡ Processes with final-state b quarks that are considered as heavy particles (the 4-flavor scheme)
  - ➡ Processes with t-channel color singlet exchange, e.g. weak boson fusion processes.

MLM matching schemes in MadGraph

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3. How to divide the phase space between PS and ME:
   This is where the different schemes differ!

MLM matching schemes in MadGraph

3. How to divide the phase space between PS and ME:
   This is where the different schemes differ!
   a. Cone jet MLM scheme:
      - Use cuts in p_T (p_T^{ME})and ΔR between partons in ME
      - Cluster events after parton shower using a cone jet algorithm with the same ΔR and $p_T^{match} > p_T^{ME}$
      - Keep event if all jets are matched to ME partons (i.e., all ME partons are within ΔR of a jet)

MLM matching schemes in MadGraph

3. How to divide the phase space between PS and ME:
   This is where the different schemes differ!
   a. Cone jet MLM scheme:
      - Use cuts in p_T (p_T^{ME})and ΔR between partons in ME
      - Cluster events after parton shower using a cone jet algorithm with the same ΔR and $p_T^{match} > p_T^{ME}$
      - Keep event if all jets are matched to ME partons (i.e., all ME partons are within ΔR of a jet)
   b. k_T-jet MLM scheme:
      - Use cut in the Durham k_T in ME
      - Cluster events after parton shower using the same k_T clustering algorithm into k_T jets with $k_T^{match} > k_T^{ME}$
      - Keep event if all jets are matched to ME partons (i.e., all partons are within k_T^{match} to a jet)

MLM matching schemes in MadGraph

3. How to divide the phase space between PS and ME:
   This is where the different schemes differ!
   c. Shower-k_T scheme:
      - Use cut in the Durham k_T in ME
      - After parton shower, get information from the PS generator about the k_T^{PS} of the hardest shower emission
      - Keep event if $k_T^{PS} < k_T^{match}$

Summary of MLM algorithm

1. Generate ME events (with different parton multiplicities) using parton-level cuts ($p_T^{ME}/\Delta R$ or k_T^{ME})
2. Cluster each event and reweight α_s and PDFs based on the scales in the clustering vertices
3. Run the parton shower with starting scale $t_0 = m_T$.
4. Check that the number of jets after parton shower is the same as ME partons, and that all jets after parton shower are matched to the ME partons (using one of the schemes in the last slides) at a scale Q^{match}. If yes, keep the event. If no, reject the event. Q^{match} is called the *matching scale*.

One more subtlety: the highest multiplicity sample

Highest multiplicity sample

- For the highest jet multiplicity that we generate with the matrix element, we need to allow additional jets above the matching scale Q^{match}., since we will otherwise not get a jet-inclusive description.
- However, we need to reject events with additional jets above the scale of the softest ME parton to avoid double counting.
- For the k_T MLM and shower-kT schemes, the clustering scales of the ME partons are communicated to Pythia using an additional line in the LHE event file written by MadEvent.

How to do matching in MadGraph +Pythia

Example: Simulation of pp→W with 0, 1, 2 jets (possible on a laptop!)

```
mg5> generate p p > w+, w+ > l+ vl @0
mg5> add process p p > w+ j, w+ > l+ vl @1
mg5> add process p p > w+ j j, w+ > l+ vl @2
mg5> output
```

```
In run_card.dat:
…
  1 = ickkw
…
  0 = ptj
…
 15 = xqcut
```

- 1 = ickkw: Matching on
- 0 = ptj: No cone matching
- 15 = xqcut: k_T matching scale

Matching automatically done when run through MadEvent and Pythia!

How to do matching in MadGraph +Pythia

- By default, k_T-MLM matching is run if xqcut > 0, with the matching scale QCUT = max(xqcut*1.4, xqcut+10)
- For shower-kT, by default QCUT = xqcut
- If you want to change the Pythia setting for matching scale or switch to shower-k_T matching:

```
In pythia_card.dat:
…
! This sets the matching scale, needs to be > xqcut
QCUT = 30
! This switches from kT-MLM to shower-kT matching
! Note that MSTP(81)>=20 needed (pT-ordered shower)
SHOWERKT = T
```

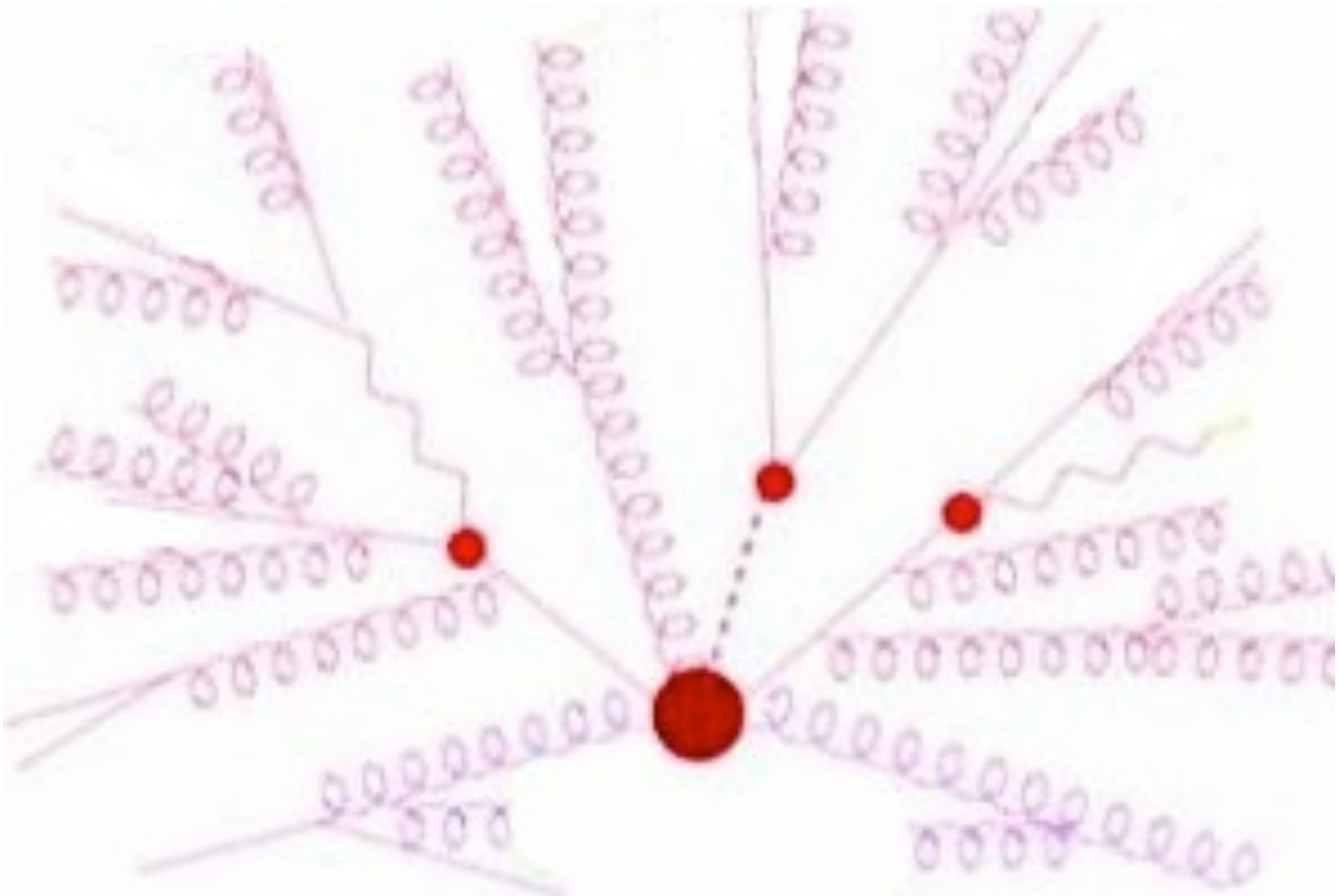
How to do validate the matching

- The matched cross section is found at the end of the Pythia log file
- The matched cross section (for X+0,1,... jets) should be close to the unmatched cross section for the 0-jet sample
- The matching scale (QCUT) should typically be chosen around 1/6-1/3 x hard scale (so xqcut correspondingly lower)
- The differential jet rate plots should be smooth
- When QCUT is varied (within the region of validity), the matched cross section should not vary significantly

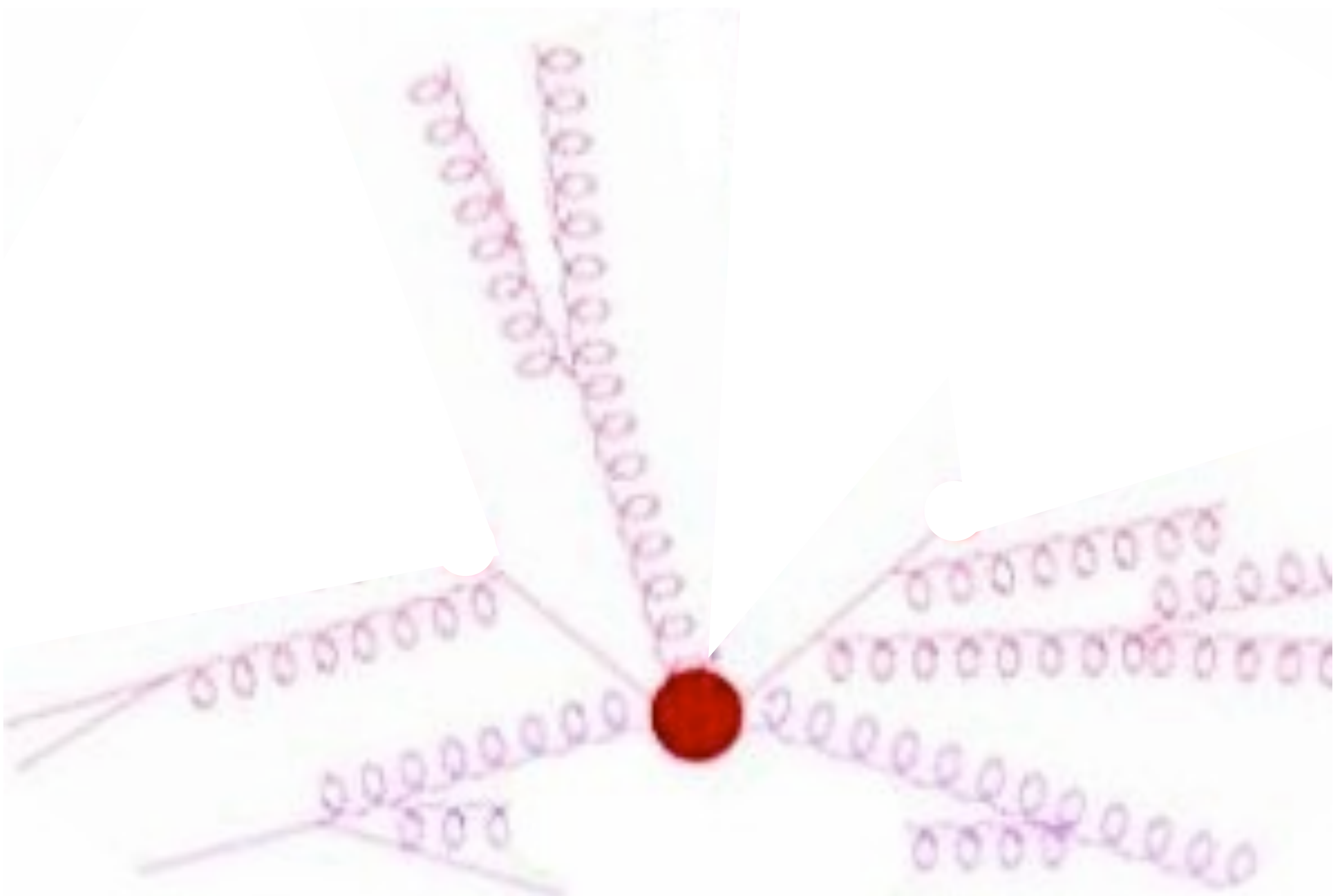
“Differential jet rate plots”?

- The “differential jet rates” are simply the clustering scales in k_T jet clustering
- The 0→1 diff. jet rate (DJR1) is the p_T of the last remaining jet after clustering
- The 1→2 diff. jet rate (DJR2) is the smallest of the p_T of the 2nd last remaining jet and the k_T between the 2nd jet and the 1st jet
- Note that only radiated jets (not jets from decays) are included in the jet rate plots

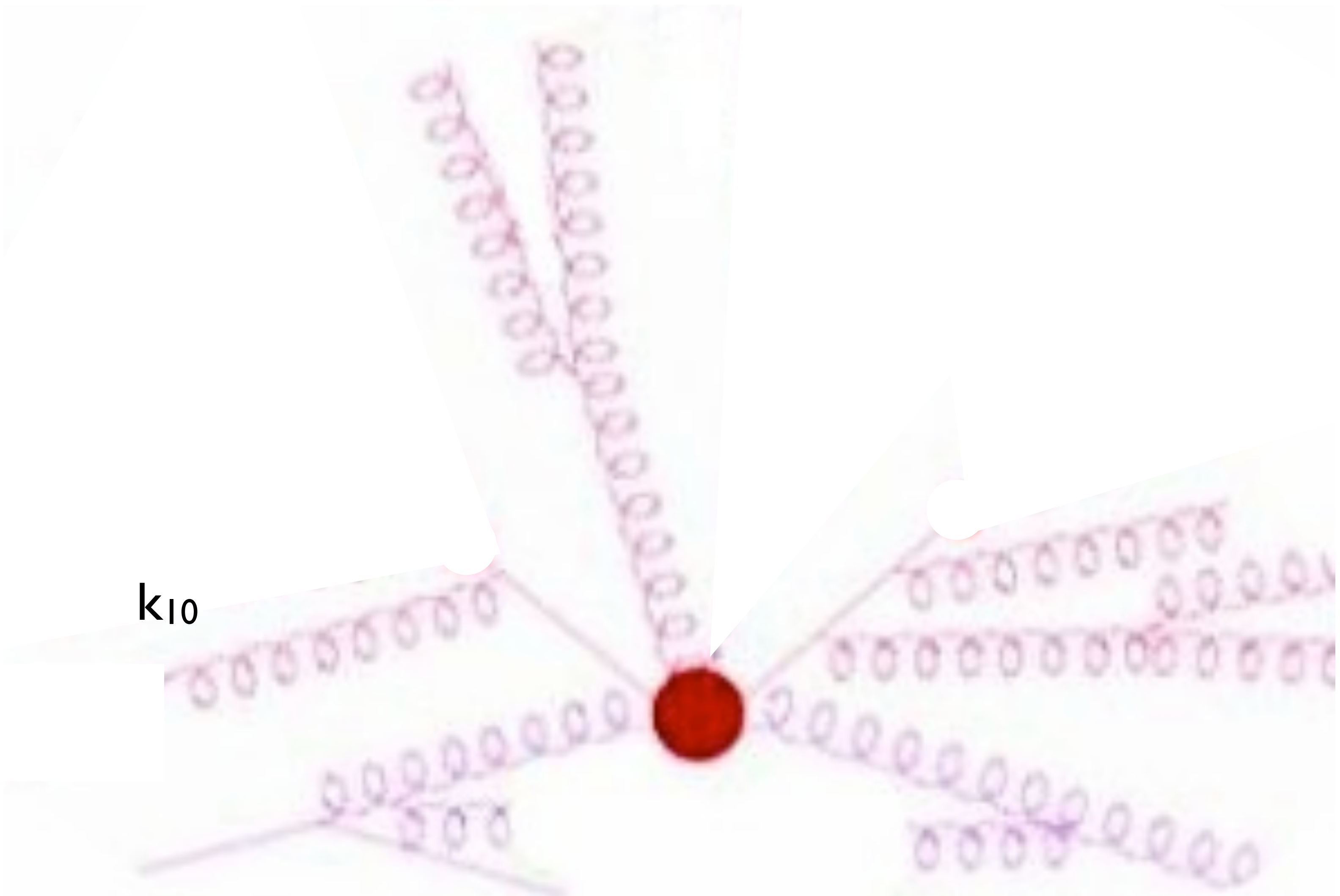
“Differential jet rate plots”?



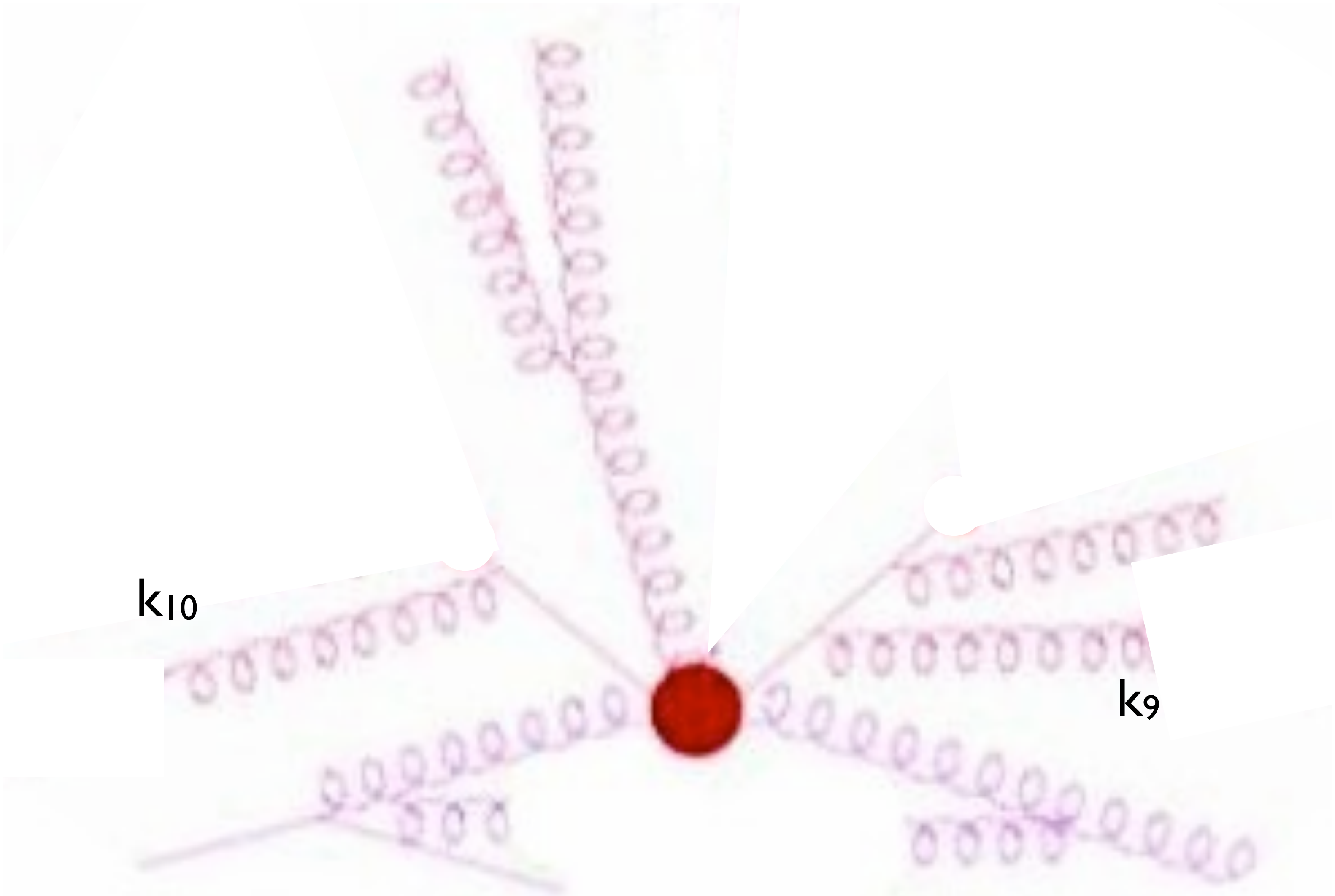
“Differential jet rate plots”?



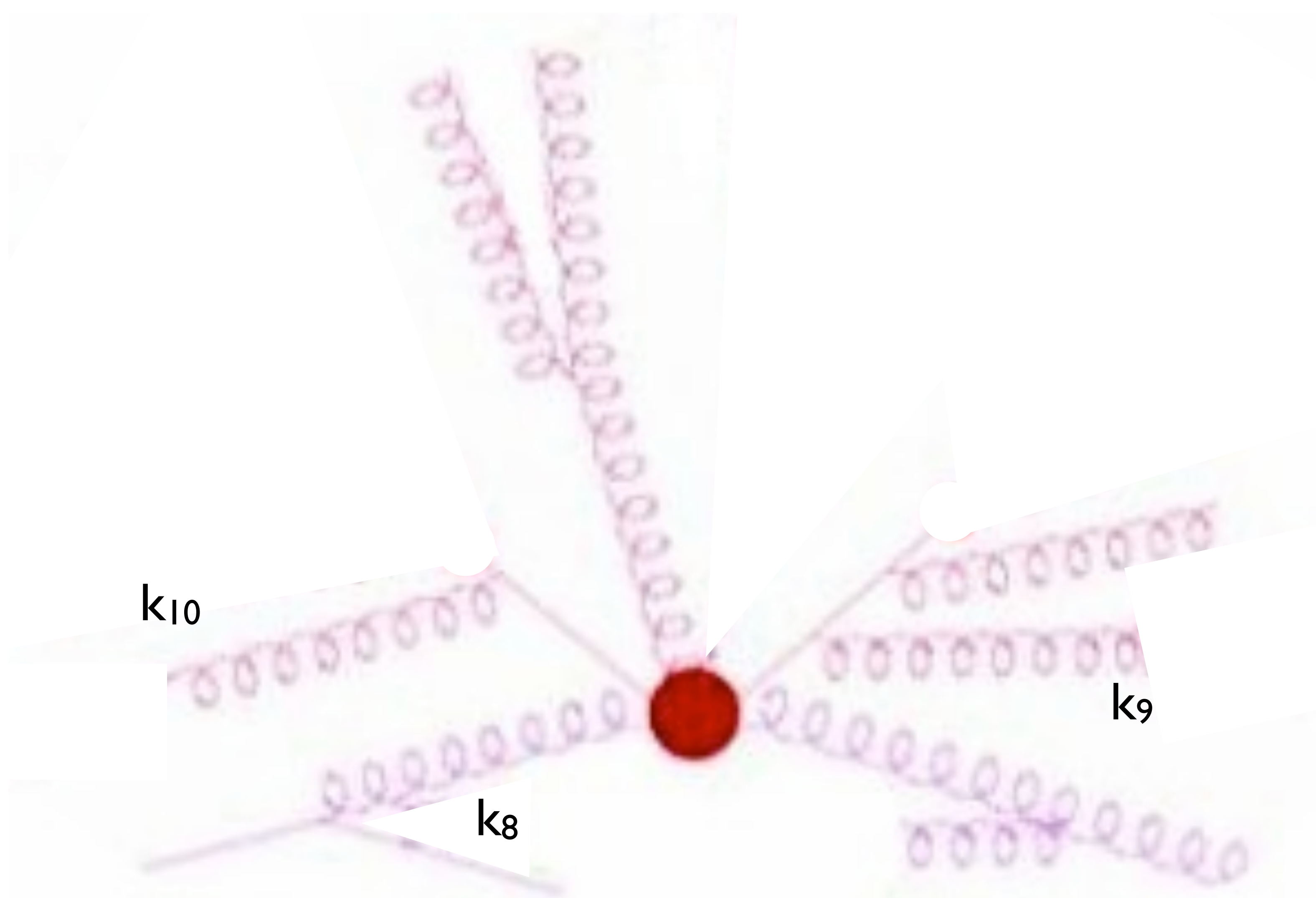
“Differential jet rate plots”?



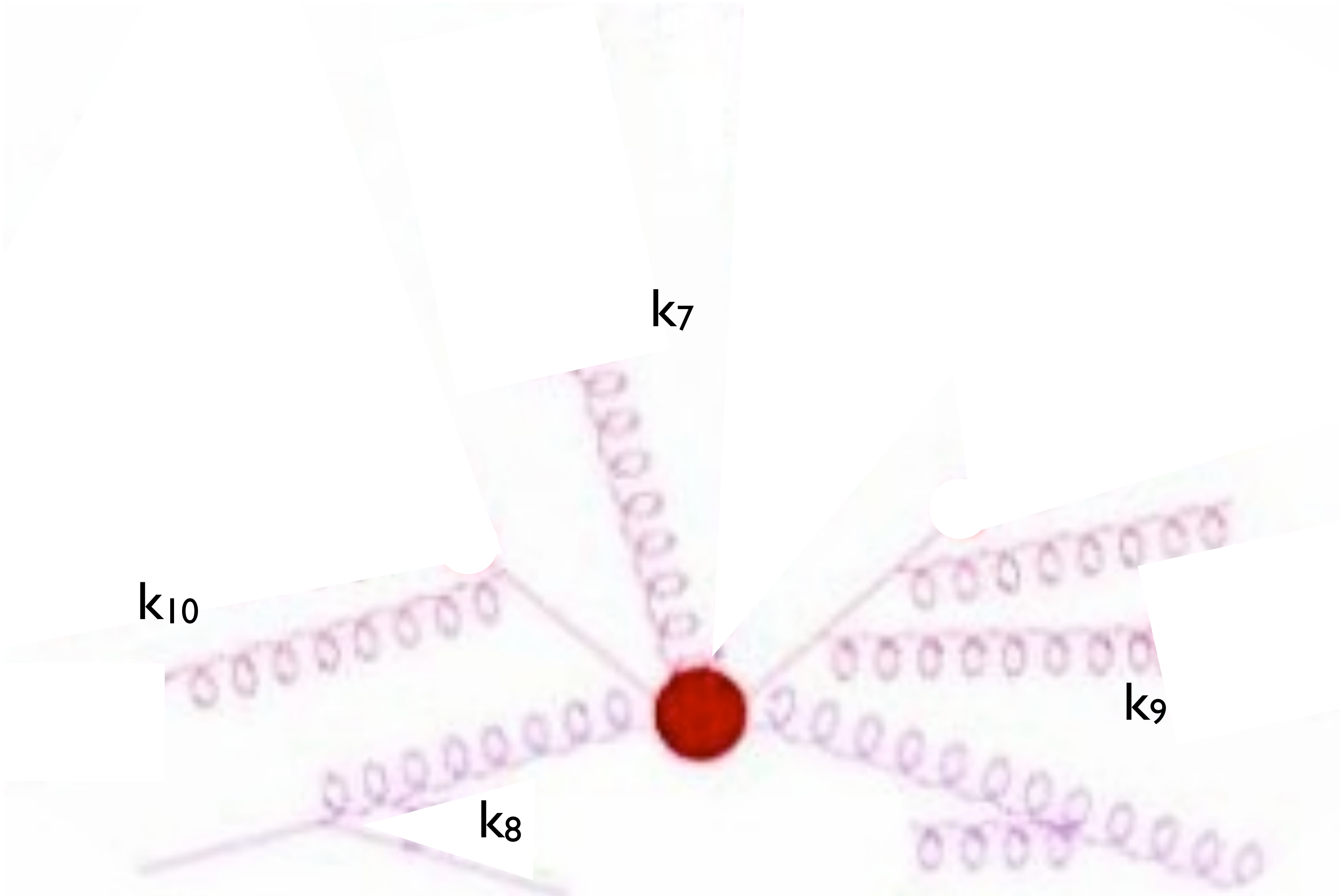
“Differential jet rate plots”?



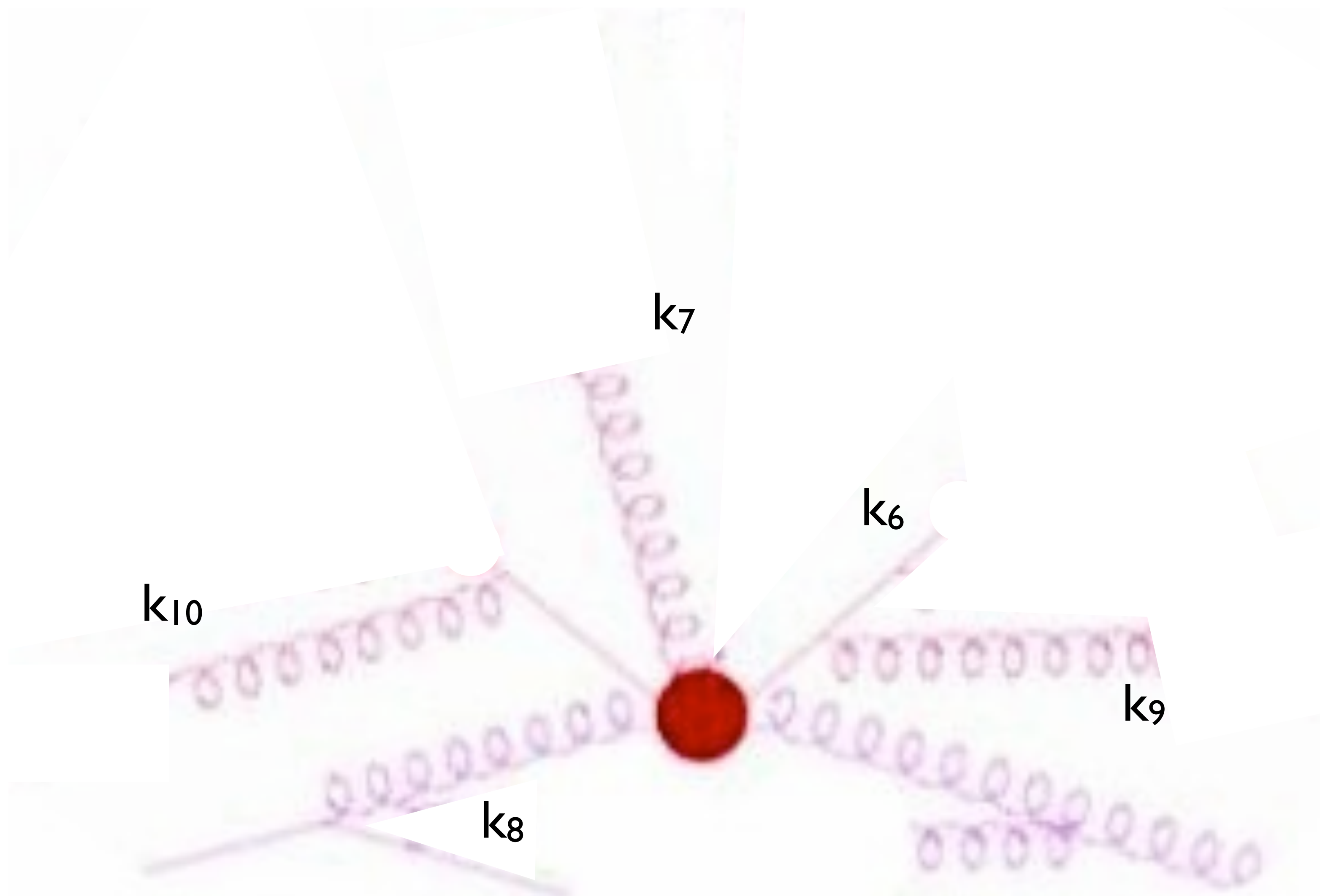
“Differential jet rate plots”?



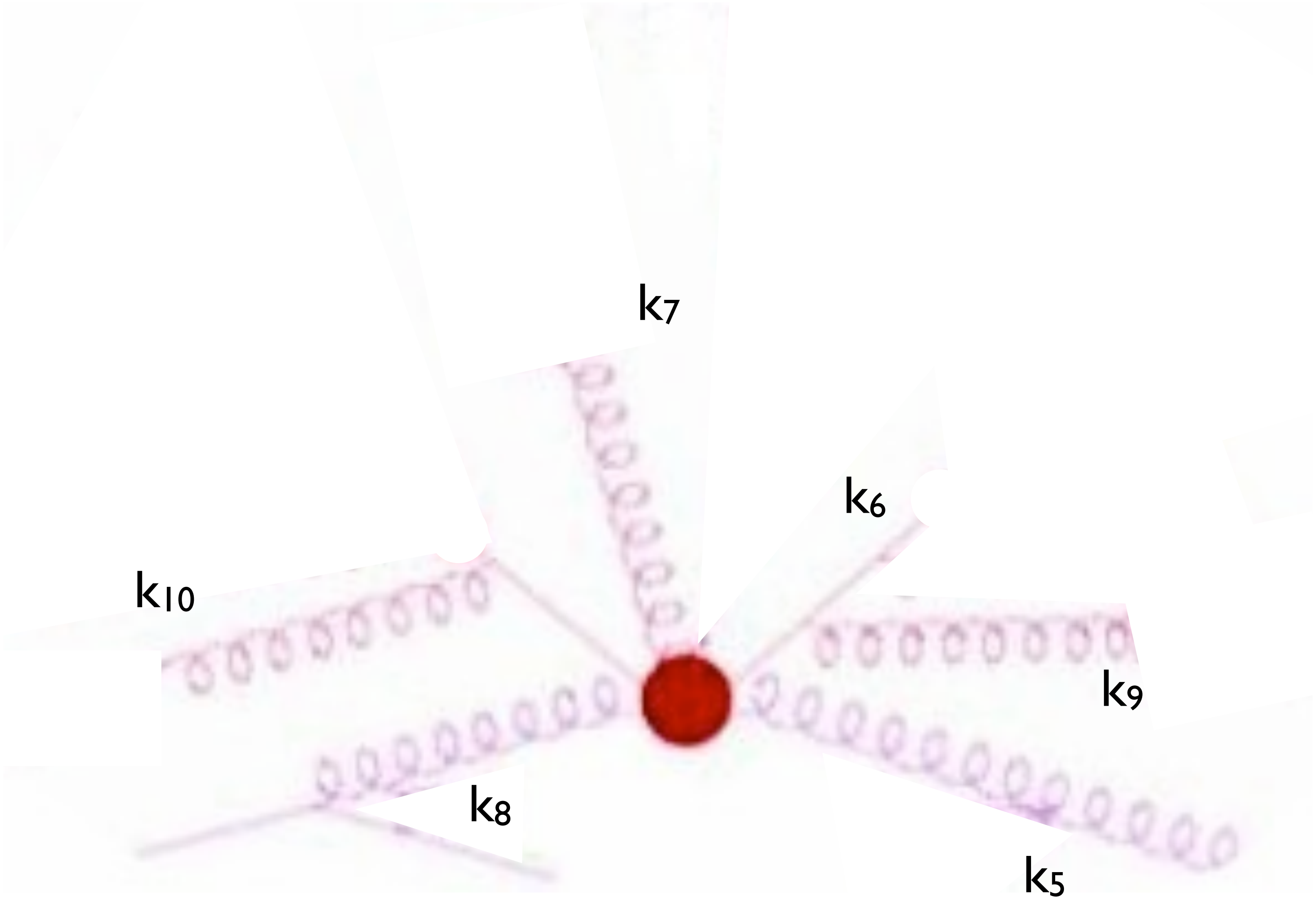
“Differential jet rate plots”?



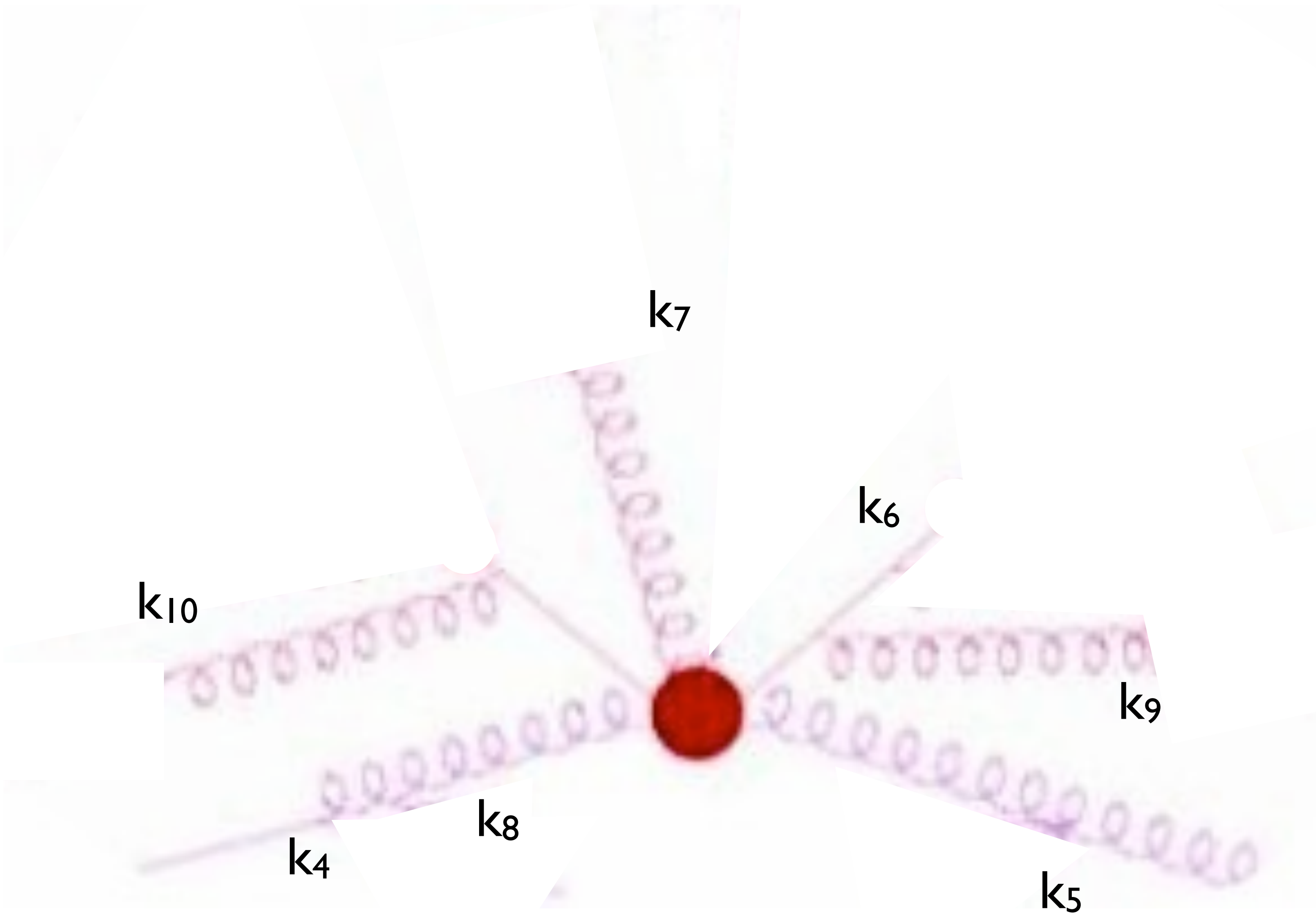
"Differential jet rate plots"?



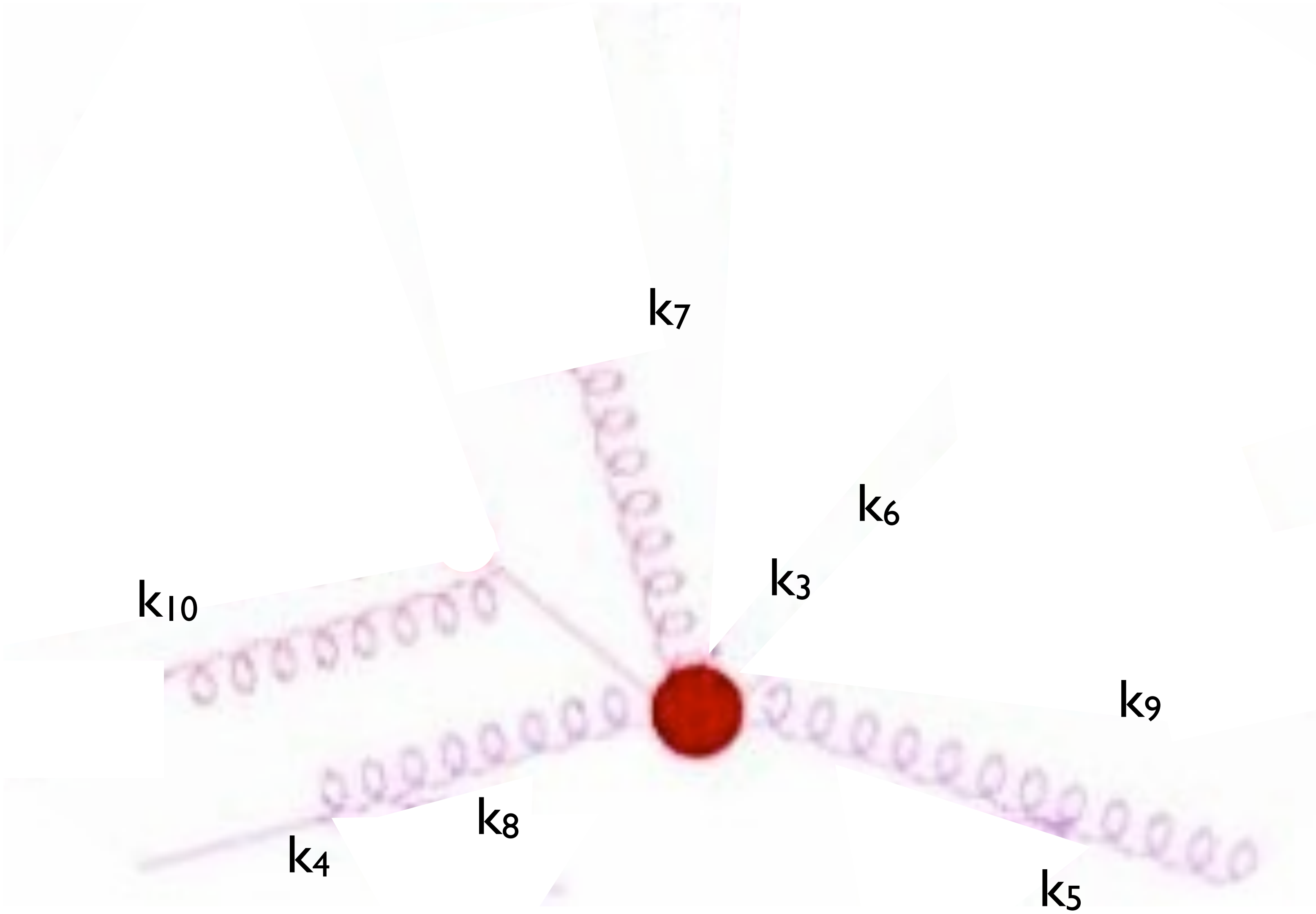
“Differential jet rate plots”?



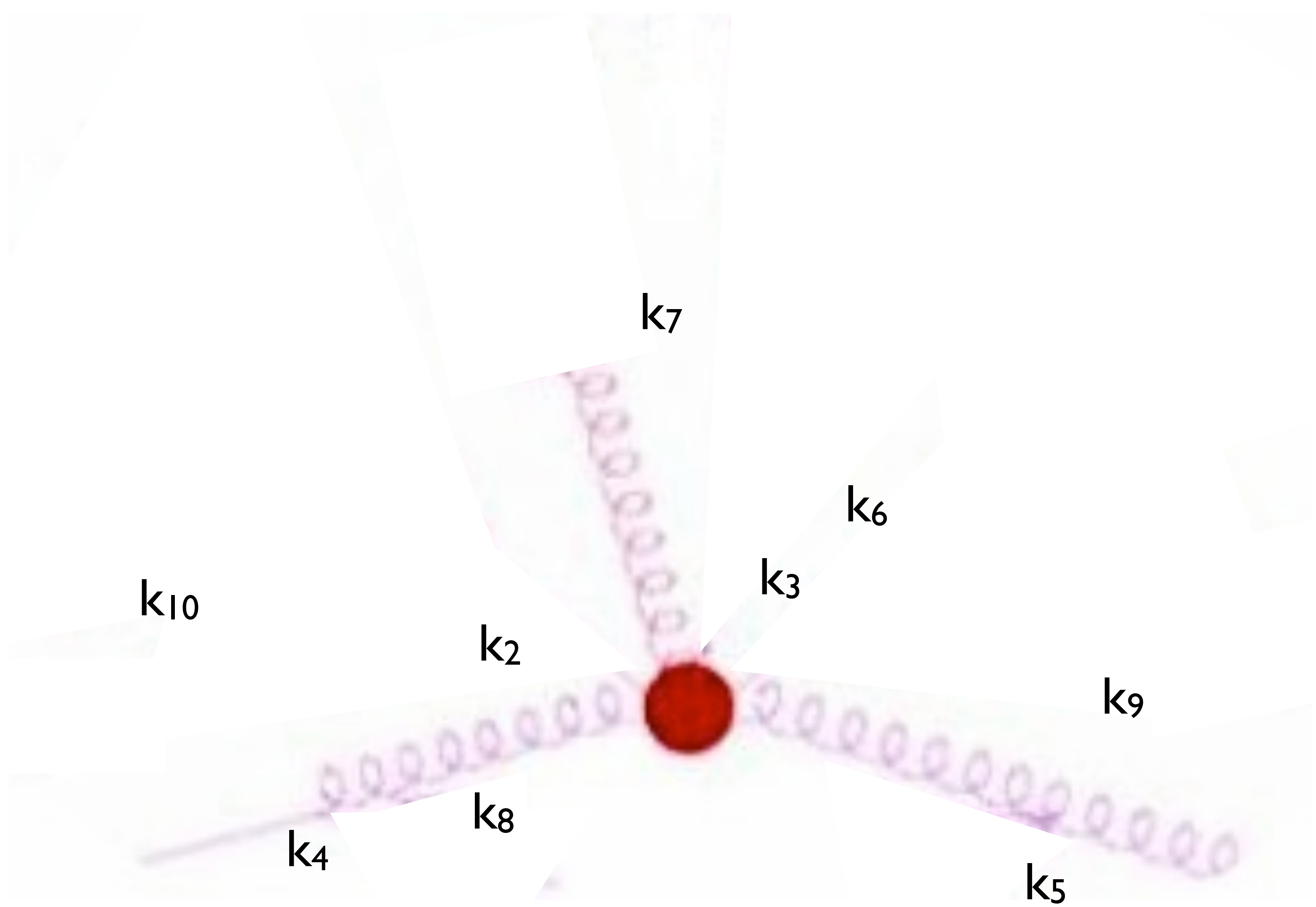
“Differential jet rate plots”?



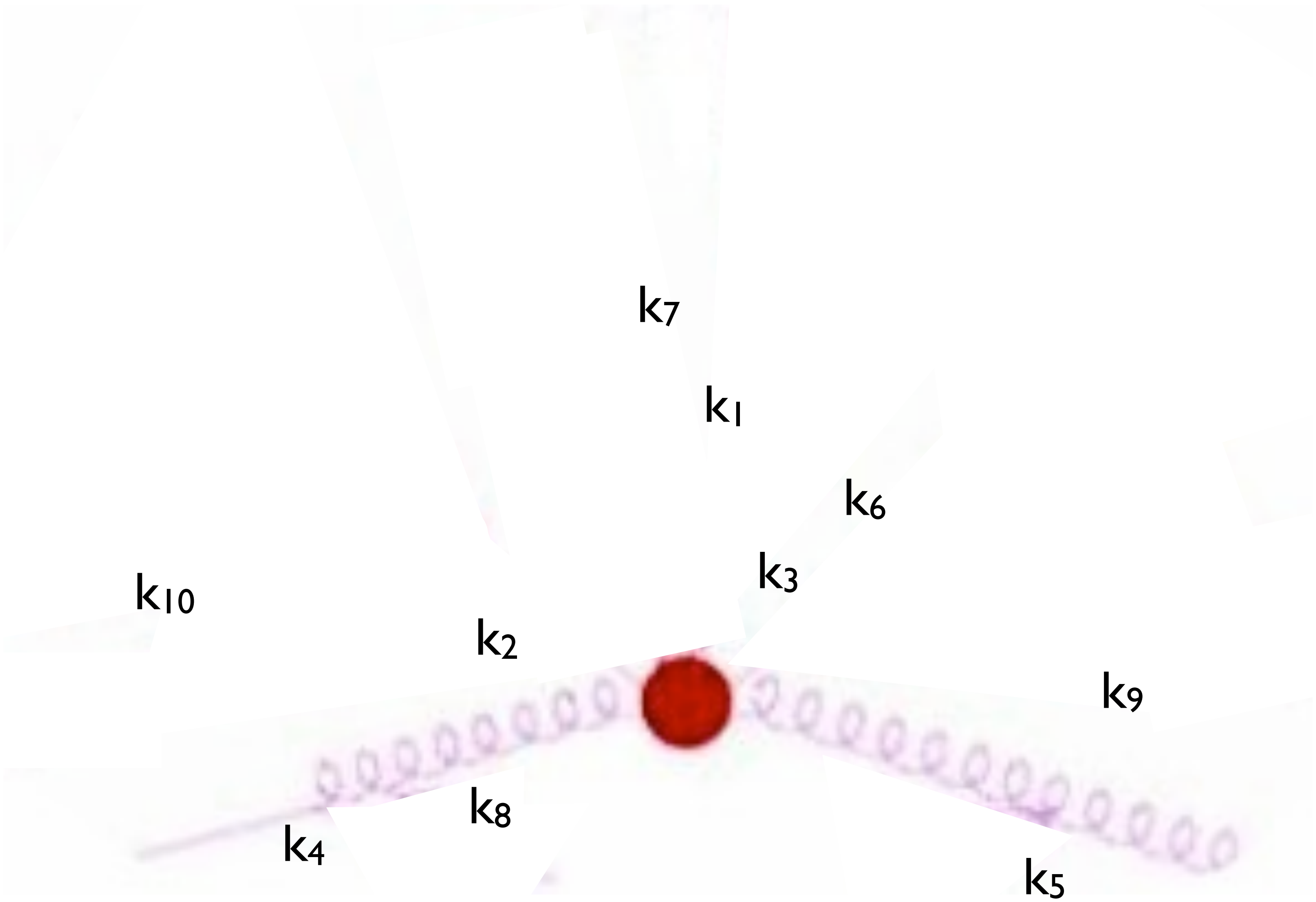
“Differential jet rate plots”?



"Differential jet rate plots"?



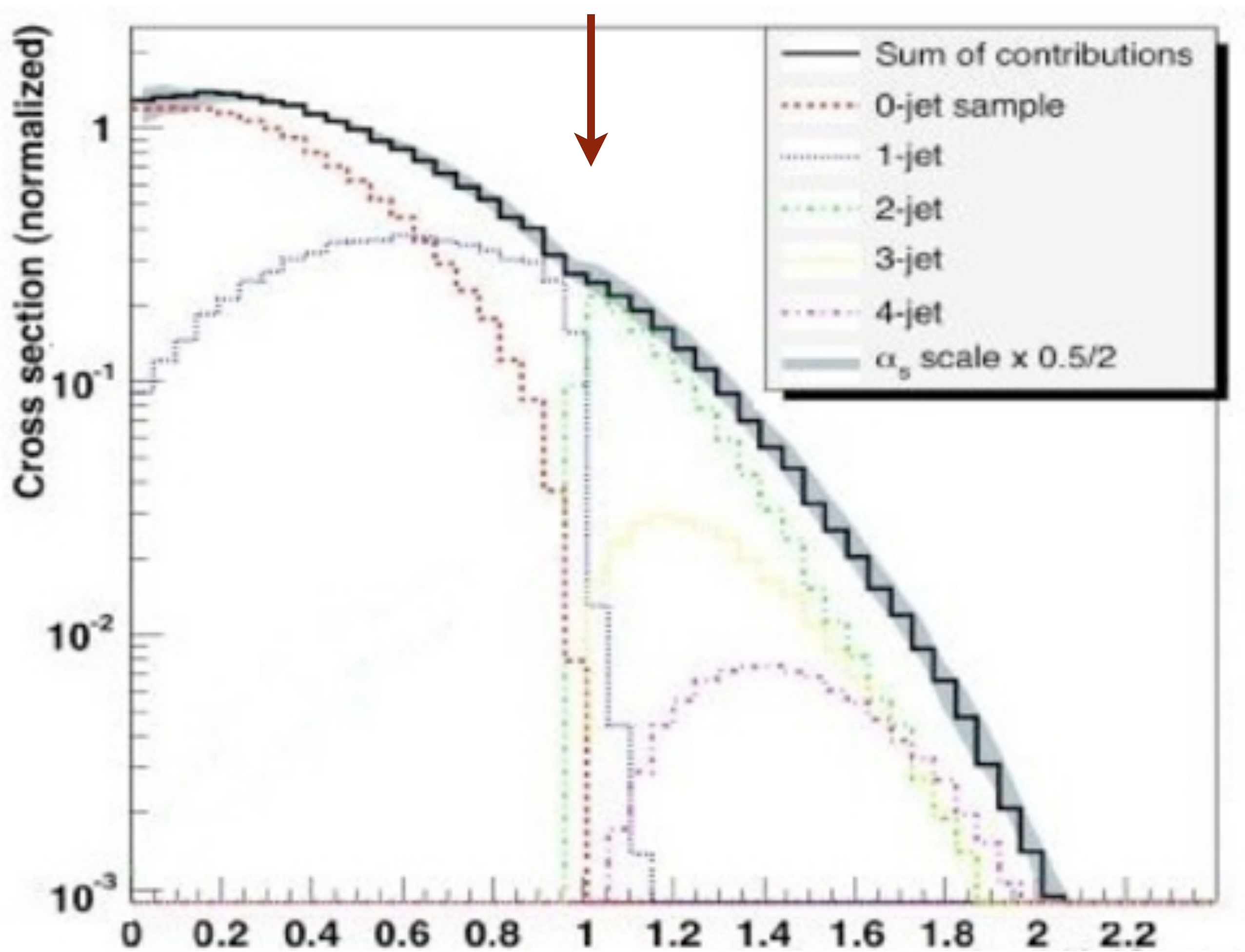
“Differential jet rate plots”?



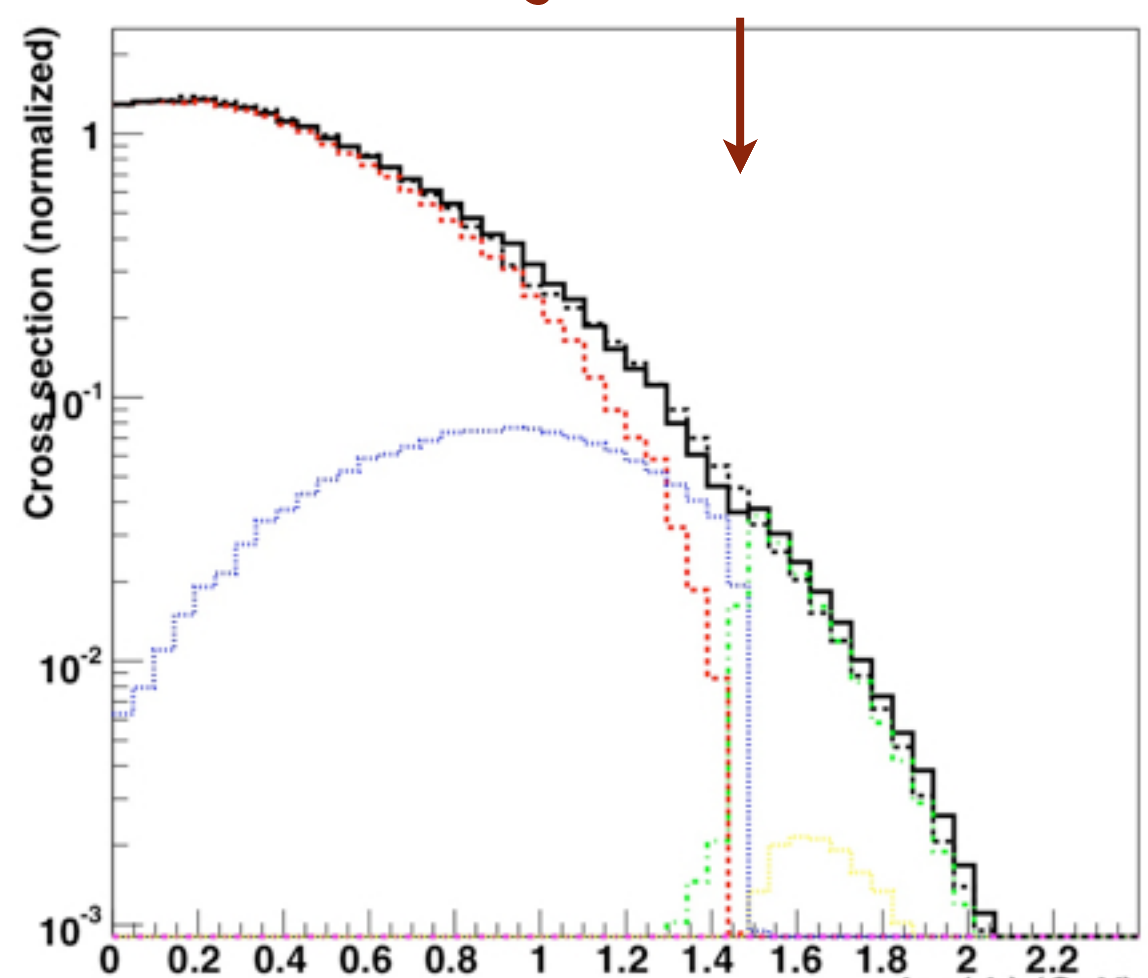
Matching results

W+jets production at the Tevatron for MadGraph+Pythia
(kT-jet MLM scheme)

Q^{match} = 10 GeV



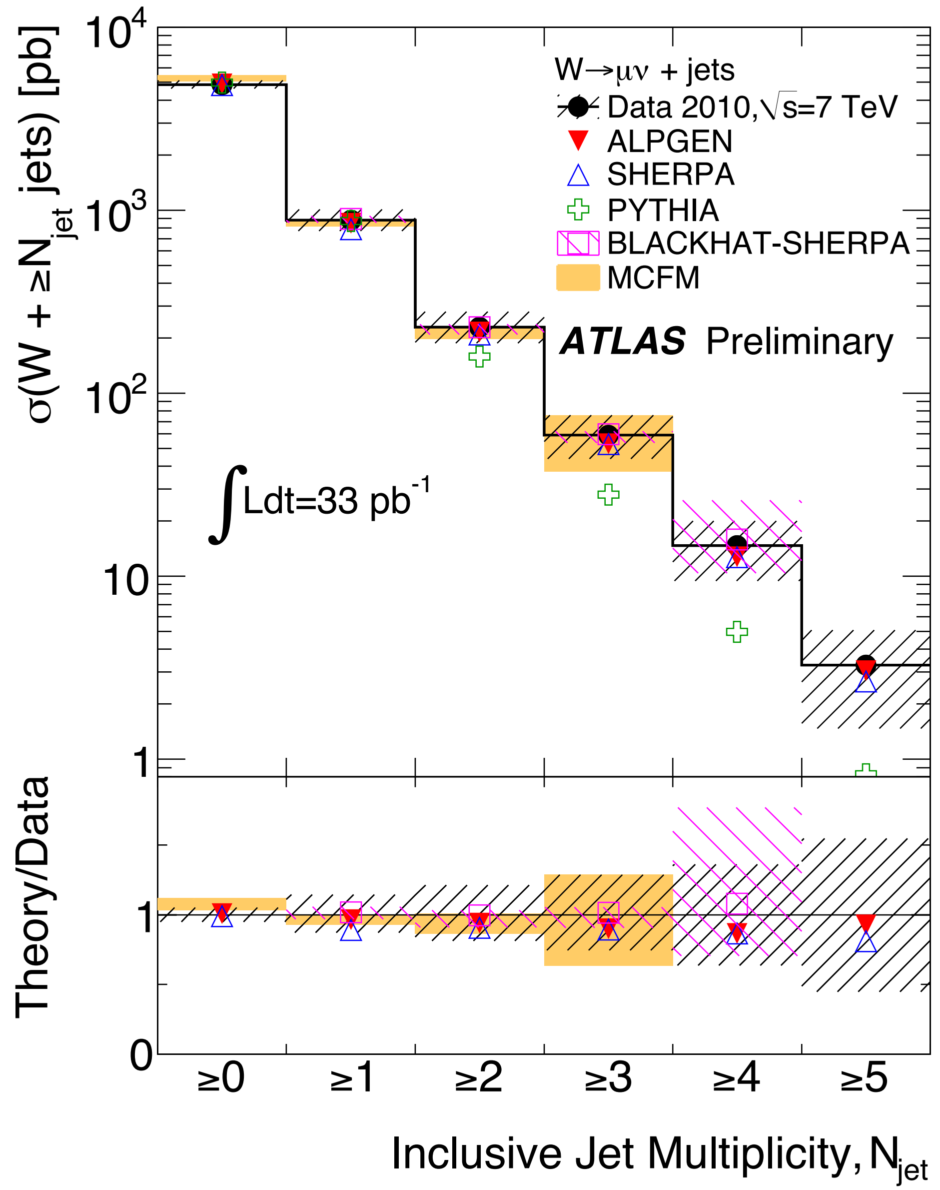
Q^{match} = 30 GeV

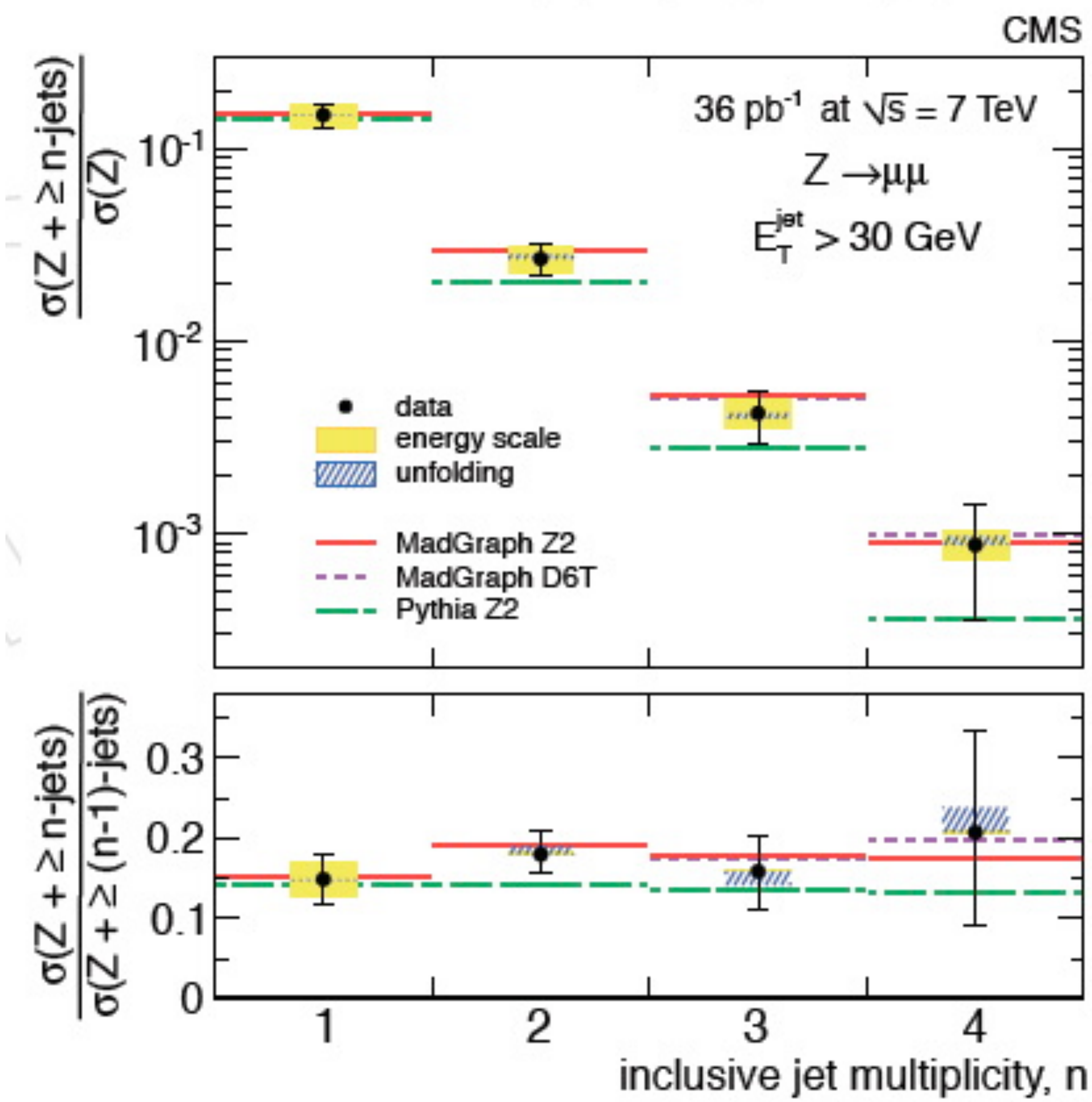


log(Differential jet rate for 1 → 2 radiated jets ~ pT(2nd jet))

Jet distributions smooth, and stable when we vary the matching scale!

TH/EXP comparison at the LHC





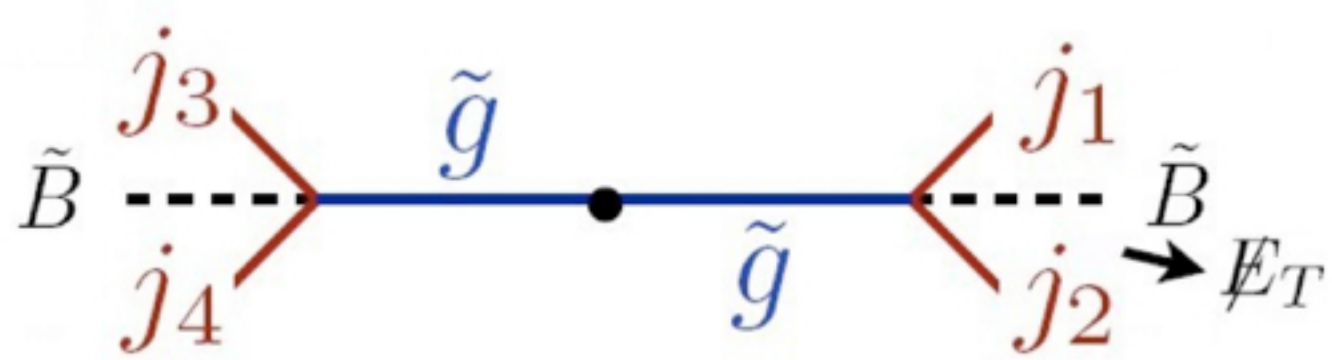
Matching in New Physics production

Alwall, de Visscher, FM [arXiv:0810.5350]

- We know that matching of ME+PS is vital for jet production in SM backgrounds
- But is it relevant for heavy BSM particle production?
  - ➡ Very hard jets from decays
  - ➡ Parton showers expected to be more accurate for larger masses
- Using gluino and squark production as example
- Turns out there are many cases where matching is necessary for precise description!

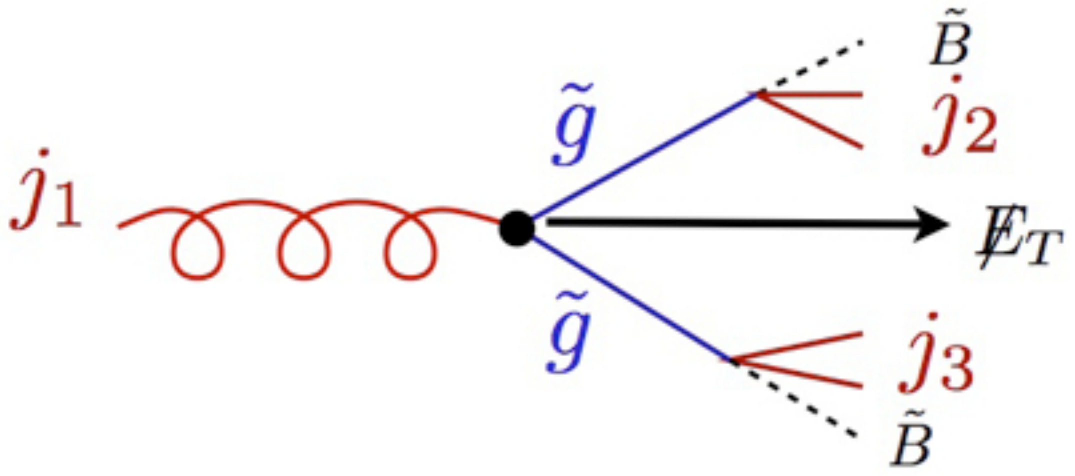
Example

- Example: Gluinos that decay to two quarks+LSP with free ratio of gluino/LSP mass
- Special difficulty when decay products nearly mass-degenerate with produced particle
- No (small) missing transverse energy in decay



Example

- Example: Gluinos that decay to two quarks+LSP with free ratio of gluino/LSP mass
- Special difficulty when decay products nearly mass-degenerate with produced particle
- No (small) missing transverse energy in decay
    - ➡ Need recoil agains ISR jet!



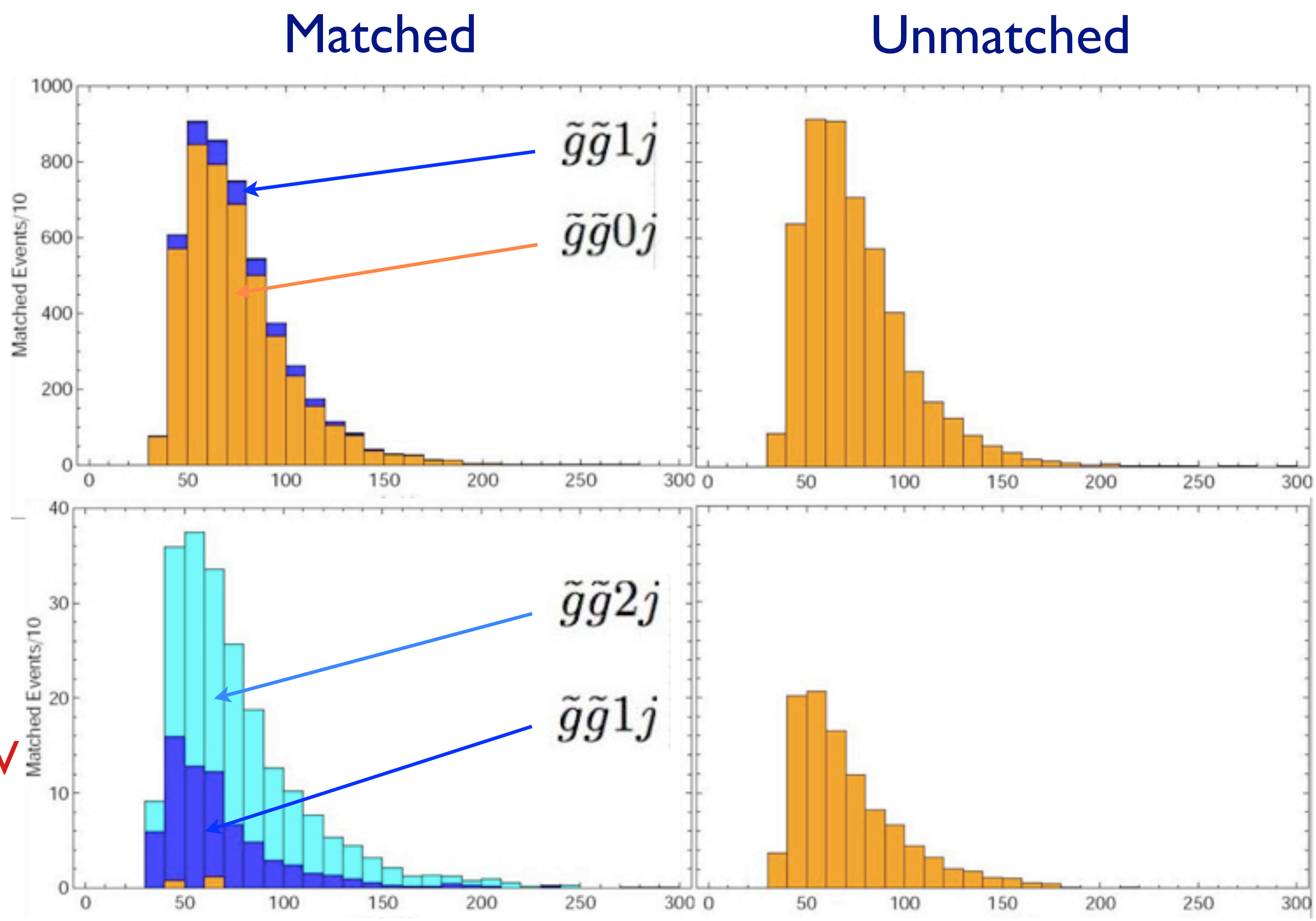
Example

$M_{\tilde{g}}$ = 150 GeV

M_{LSP} = 40 GeV

$M_{\tilde{g}}$ = 150 GeV

M_{LSP} = 130 GeV

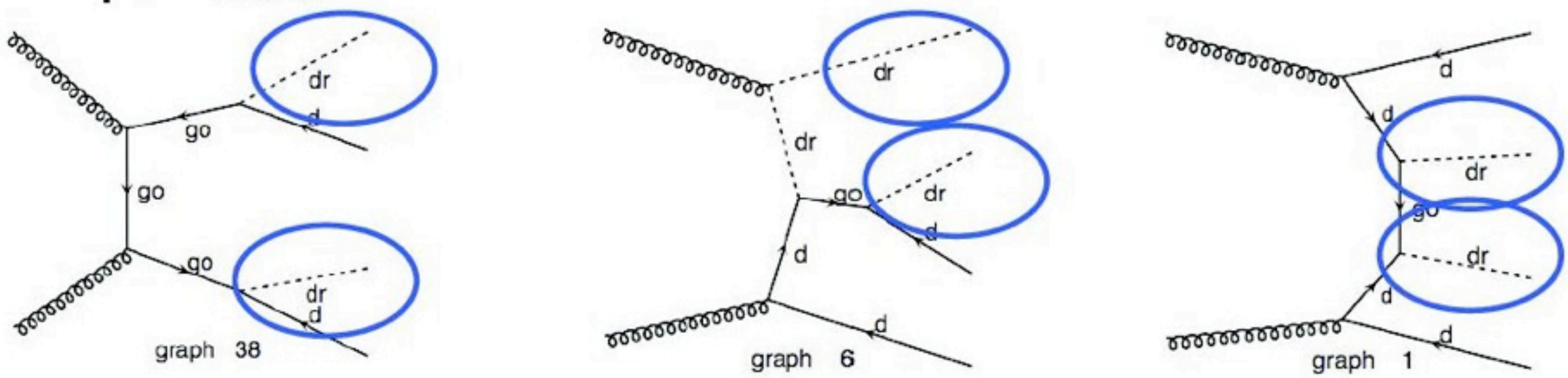


$p_T(j1)$ in GeV at the Tevatron, after 2-jet and missing E_T cuts

Double counting of decays

- Special difficulty in e.g. SUSY matching:
  Double counting of decays to jets!

Example: $\tilde{q}\tilde{q}jj$



Double counting of decays

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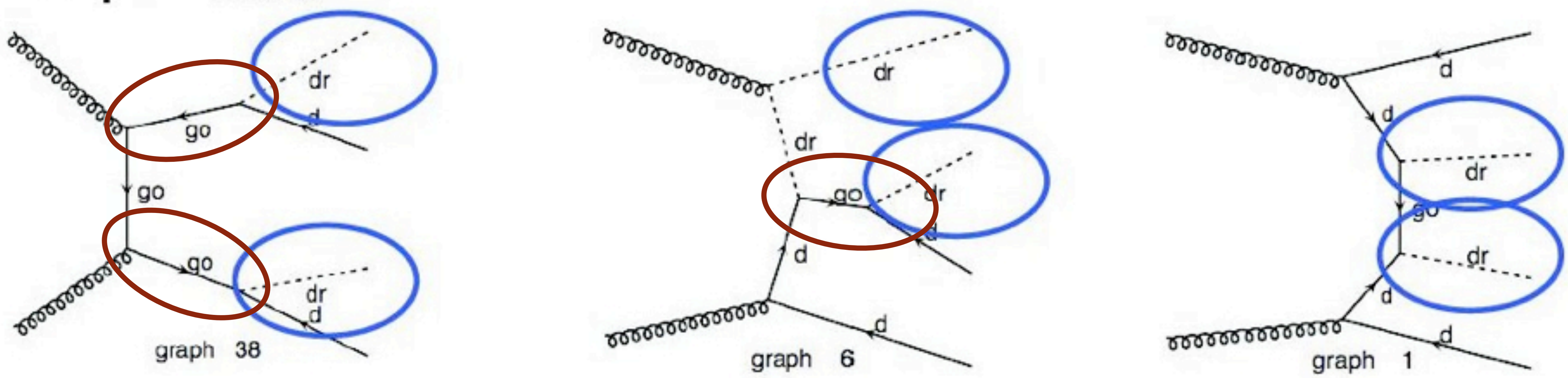
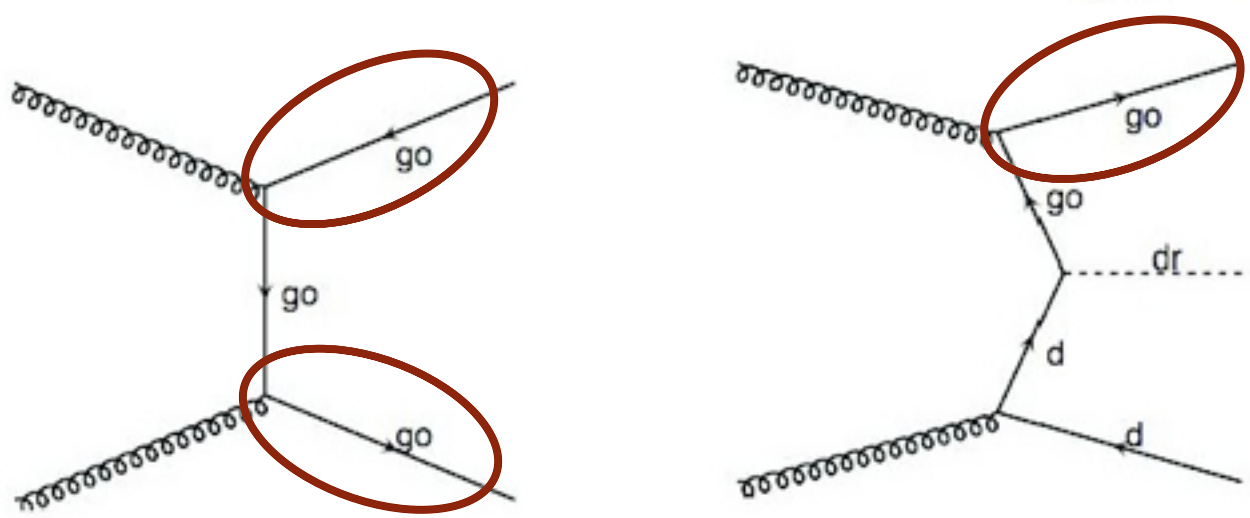
Example: $\tilde{q}\tilde{q}jj$





Decays double-counted with on-shell gluino production and subsequent decay

DOUBLE COUNTING OF DECAYS

- This has been solved in recent versions of MadGraph 5 by the new "$" syntax

```
mg5> import model_v4 mssm
mg5> generate p p > dr dr~ j j $ go
```

- This removes any on-shell gluinos from the event generation (where on-shell is defined as $m \pm n \cdot \Gamma$ with n set by `bwcutoff` in the run_card.dat)

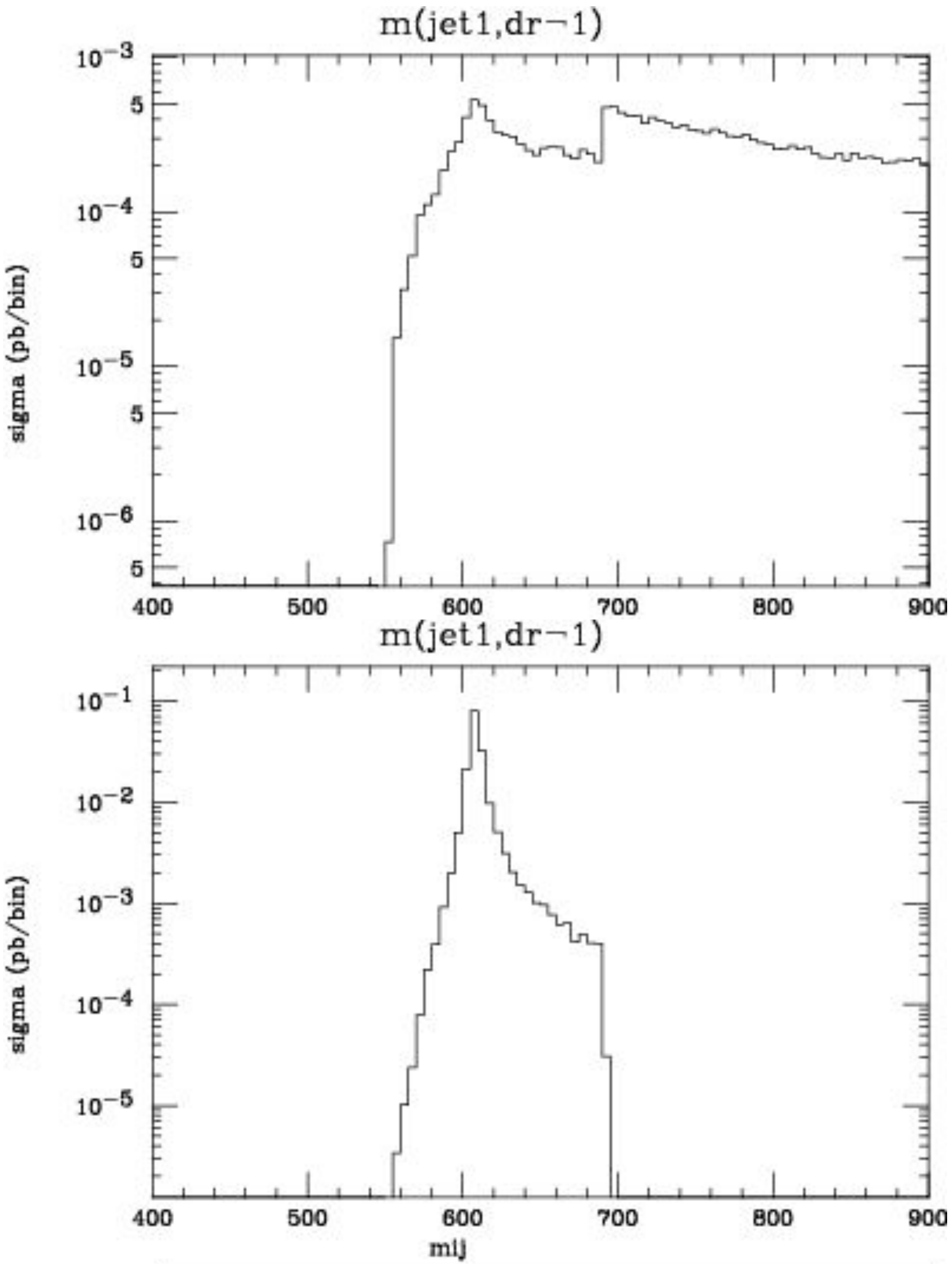
- The corresponding region is exactly filled if you run gluino production with gluinos decaying to dr j (using the same `bwcutoff`).

Double counting of decays

Invariant mass distributions of d_r squark and d quark

p p > dr dr~ d $ go

p p > dr go, go > dr~ d



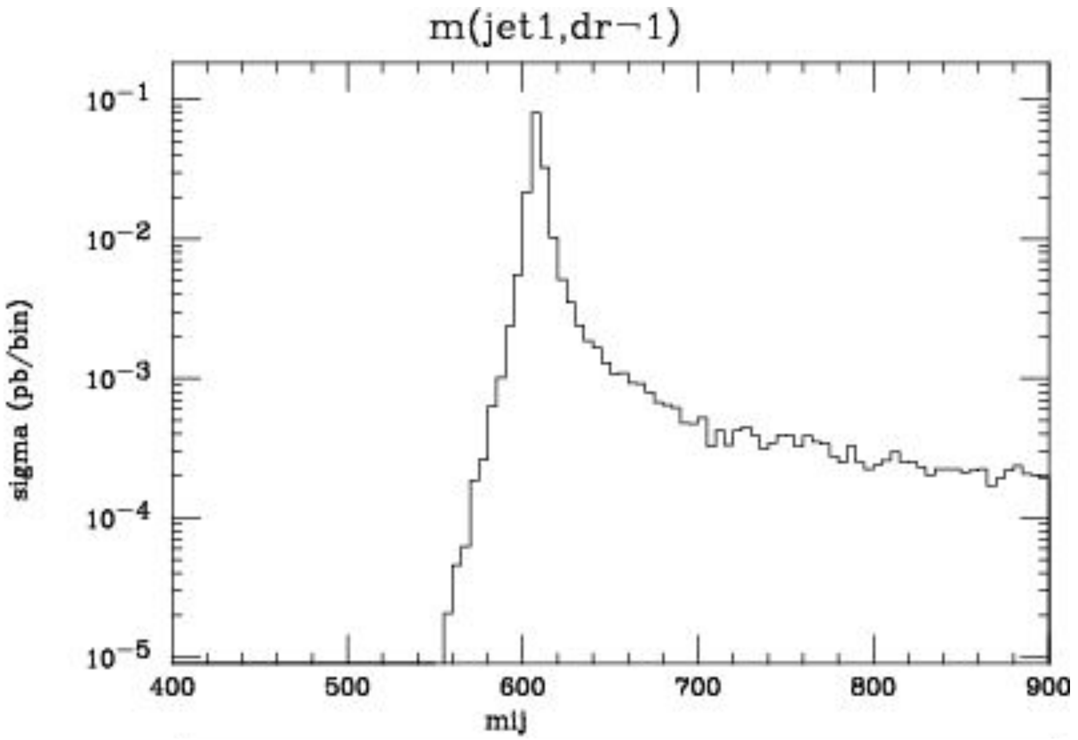
Double counting of decays

Invariant mass distributions of d_r squark and d quark

p p > dr dr~ d $ go

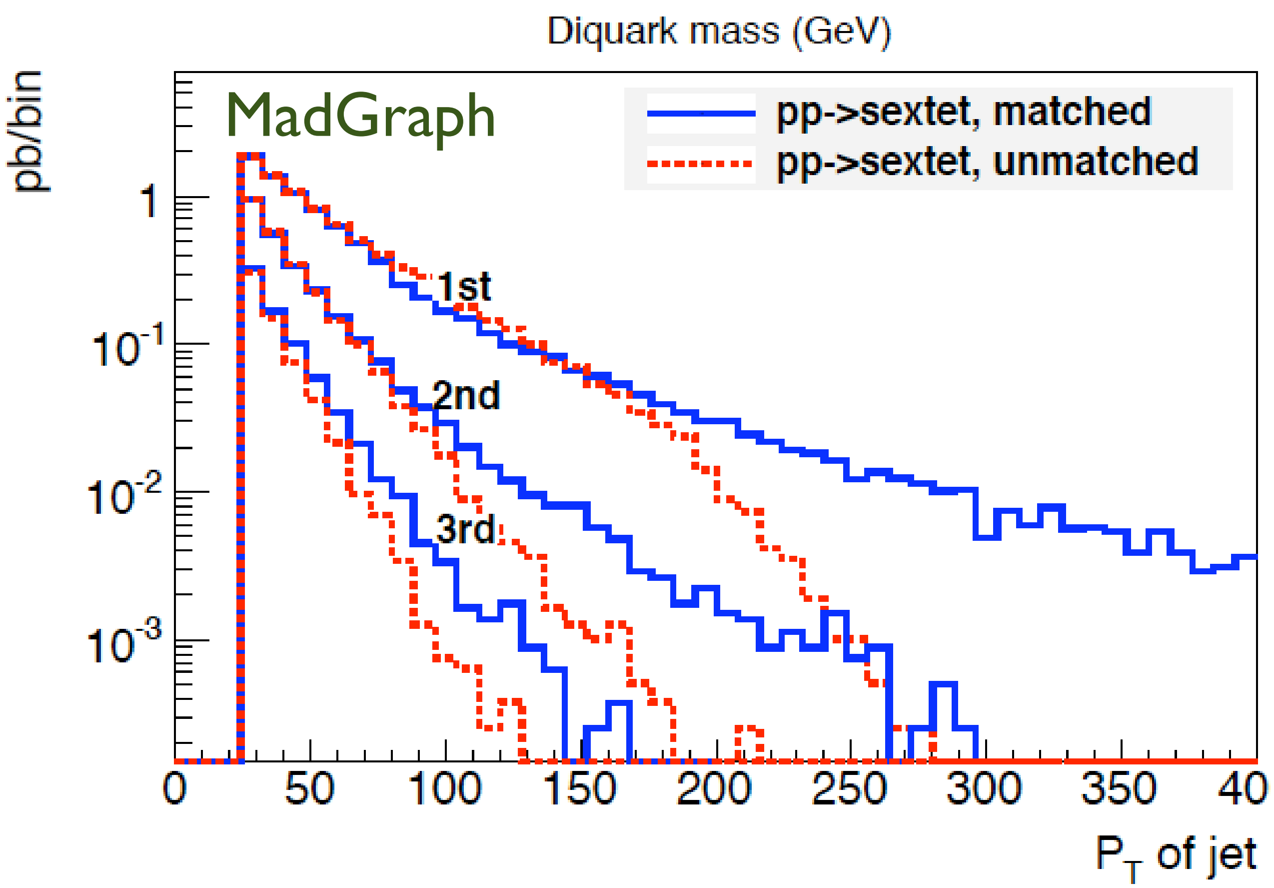
+

p p > dr go, go > dr~ d



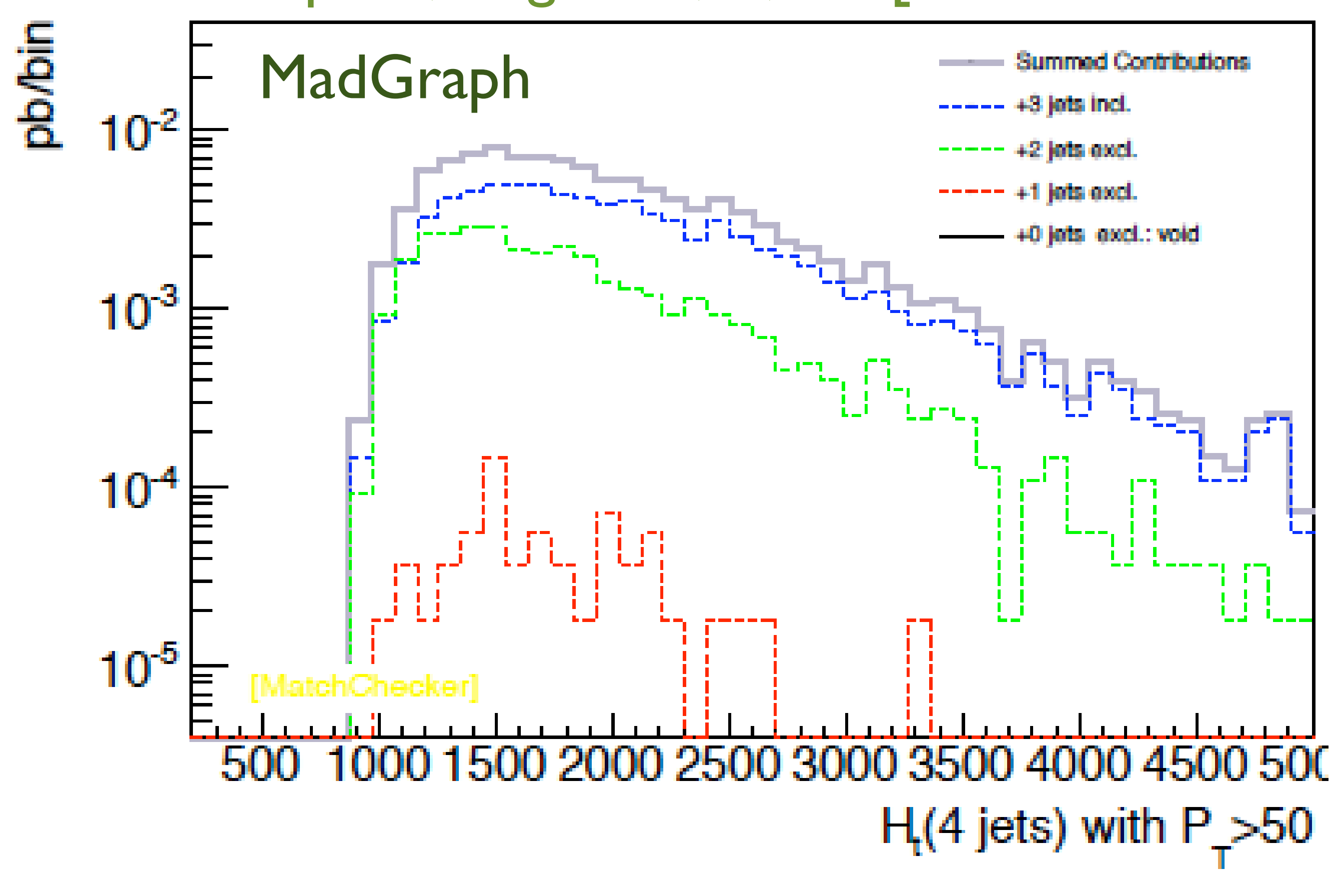
Example: BSM multijet final states

pp→X6 +jets



pp→Graviton (ADD&RS) +jets

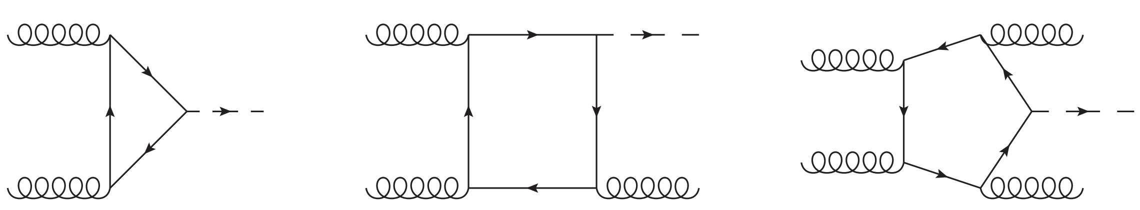
de Aquino, Hagiwara, Li, FM [arXiv:1101.5499]

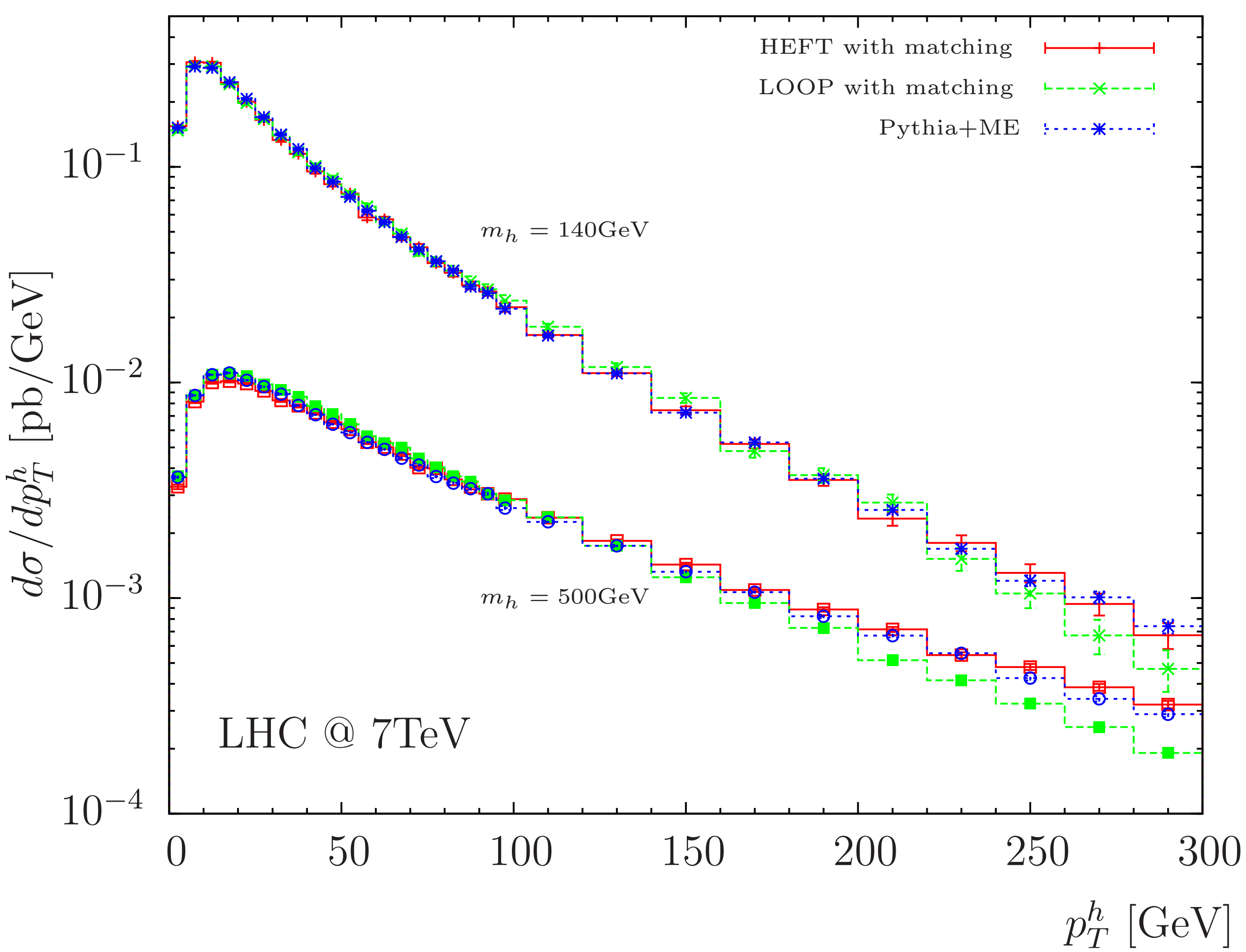


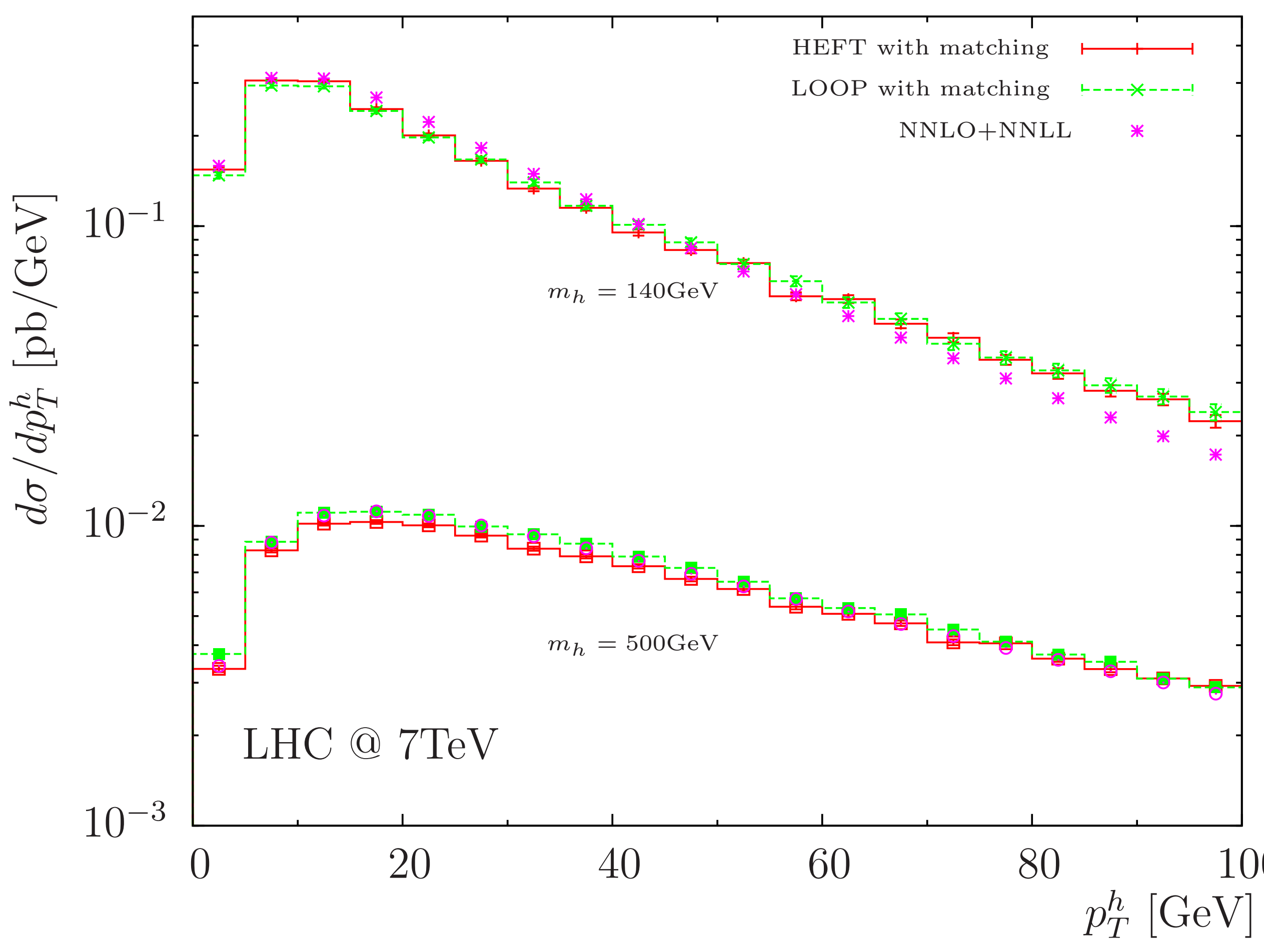
New Physics models can be easily included in Matrix Element generators via FeynRules and results automatically for multi-jet inclusive final state obtained at the same level of accuracy that for the SM.

The power of matching: loop effects in H+jets

Alwall, Li, FM [arXiv:1110.1728]



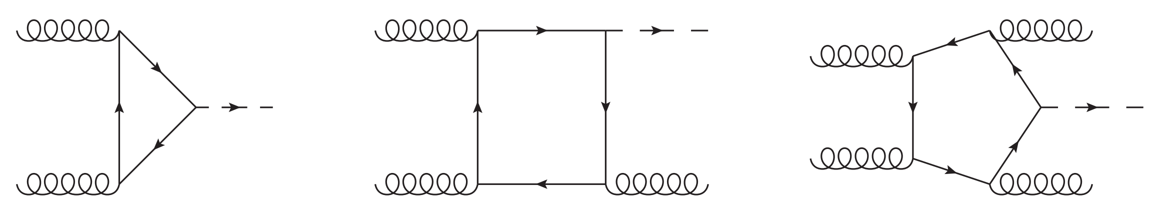




Matched samples can be obtained easily. They agree pretty well with HqT predictions.

THE POWER OF MATCHING: LOOP EFFECTS IN H+JETS

Alwall, Li, FM [arXiv:1110.1728]



While finite mass effects are small for SM Higgs, for a SUSY Higgs they are very important and the HEFT approximation is a very bad one.