MadGraph Tutorial

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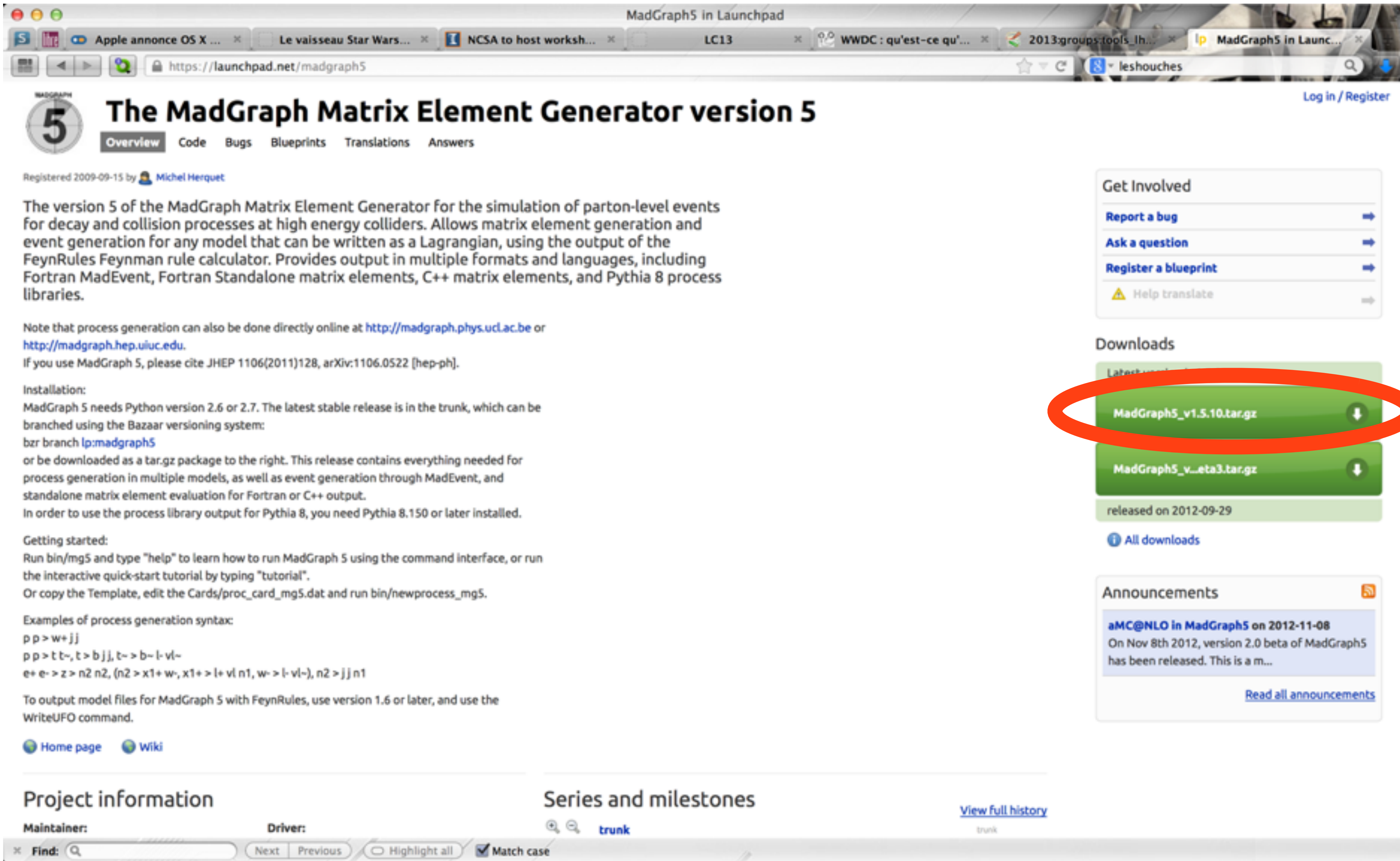
Exercise I: Install MadGraph 5!

- https://launchpad.net/madgraph5
- untar it (tar -xzpvf TUTO_model.tgz)
- launch it ($ ./bin/mg5)
- learn it!
  - ➡ Type tutorial and follow instructions

Install


MadGraph5 in Launchpad
Apple annonce OS X ...
Le vaisseau Star Wars...
NCSA to host worksh...
LC13
WWDC : qu'est-ce qu'...
2013:groups:tools_lh...
MadGraph5 in Launc...
https://launchpad.net/madgraph5
leshouches
Log in / Register
The MadGraph Matrix Element Generator version 5
Overview
Code
Bugs
Blueprints
Translations
Answers
Registered 2009-09-15 by Michel Herquet
The version 5 of the MadGraph Matrix Element Generator for the simulation of parton-level events for decay and collision processes at high energy colliders. Allows matrix element generation and event generation for any model that can be written as a Lagrangian, using the output of the FeynRules Feynman rule calculator. Provides output in multiple formats and languages, including Fortran MadEvent, Fortran Standalone matrix elements, C++ matrix elements, and Pythia 8 process libraries.
Note that process generation can also be done directly online at http://madgraph.phys.ucl.ac.be or http://madgraph.hep.uiuc.edu.
If you use MadGraph 5, please cite JHEP 1106(2011)128, arXiv:1106.0522 [hep-ph].
Installation:
MadGraph 5 needs Python version 2.6 or 2.7. The latest stable release is in the trunk, which can be branched using the Bazaar versioning system:
bzr branch lp:madgraph5
or be downloaded as a tar.gz package to the right. This release contains everything needed for process generation in multiple models, as well as event generation through MadEvent, and standalone matrix element evaluation for Fortran or C++ output.
In order to use the process library output for Pythia 8, you need Pythia 8.150 or later installed.
Getting started:
Run bin/mg5 and type "help" to learn how to run MadGraph 5 using the command interface, or run the interactive quick-start tutorial by typing "tutorial".
Or copy the Template, edit the Cards/proc_card_mg5.dat and run bin/newprocess_mg5.
Examples of process generation syntax:
p p > w+ j j
p p > t t~, t > b j j, t~ > b~ l- vl~
e+ e- > z > n2 n2, (n2 > x1+ w-, x1+ > l+ vl n1, w- > l- vl~), n2 > j j n1
To output model files for MadGraph 5 with FeynRules, use version 1.6 or later, and use the WriteUFO command.
Home page
Wiki
Get Involved
Report a bug
Ask a question
Register a blueprint
Help translate
Downloads
MadGraph5_v1.5.10.tar.gz
MadGraph5_v...eta3.tar.gz
released on 2012-09-29
All downloads
Announcements
aMC@NLO in MadGraph5 on 2012-11-08
On Nov 8th 2012, version 2.0 beta of MadGraph5 has been released. This is a m...
Read all announcements
Project information
Maintainer:
Driver:
Series and milestones
View full history
trunk
Find:
Next
Previous
Highlight all
Match case

Where to find help?

- Ask me/Celine
- Use the command "help" / "help XXX"
  - ➡ "help" tell you the next command that you need to do.
- Launchpad:
  - ➡ https://answers.launchpad.net/madgraph5
  - ➡ FAQ: https://answers.launchpad.net/madgraph5/+faqs

What are those cards?

- Read the Cards and identify what they do
  - ➡ param_card: model parameters
  - ➡ run_card: beam/run parameters and cuts
    - ✦ https://answers.launchpad.net/madgraph5/+faq/2014

Exercise II: Cards Meaning

- How do you change
  - ➡ top mass
  - ➡ top width
  - ➡ W mass
  - ➡ beam energy
  - ➡ pt cut on the lepton

Exercise III : Syntax

- What's the meaning of the order QED/QCD
- What's the difference between
  - ➡ p p > t t~
  - ➡ p p > t t~ QED=2
  - ➡ p p > t t~ QED=0
- Compute the cross-section for each of those

Exercise IV: Syntax

- Generate the cross-section and the distribution (invariant mass) for
  - ➡ p p > e+ e-
  - ➡ p p > z, z > e+ e-
  - ➡ p p > e+ e- $ z
  - ➡ p p > e+ e- / z

Hint :To plot automatically distributions:

mg5> install MadAnalysis

Exercise V: Automation

- Compute the cross-section for the top pair production for 3 different mass points.
  - ➡ Do NOT use the interactive interface
    - ✦ hint: you can edit the param_card/run_card via the "set" command [After the launch]
    - ✦ hint: All command [including answer to question] can be put in a file. (run ./bin/mg5 PATH_TO_FILE)

Exercise VI: Matching

1. Generate p p > w+ with 0 jets, 0,1 jets and 0,1,2 jets
   (Each on different computers - use the most powerful computer for 0,1,2 jets)
   a. Generate 20,000 events for a couple of different xqcut values.
   b. Compare the distributions (before and after Pythia) and cross sections (before and after Pythia) between the different processes, and between the different xqcut values.
   c. Summarize: How many jets do we need to simulate? What is a good xqcut value? How are the distributions affected?
2. Do the same exercise for matched squark production (p p > ur ur~ + 0,1 jets)
   a. Run with and without "$ go" - how does the result change?
   b. With "$ go", do the exercises a.-c. under 1. What is a good choice for matching scale?

See appendix slide if you do not know matching!

Matching

Merging ME with PS

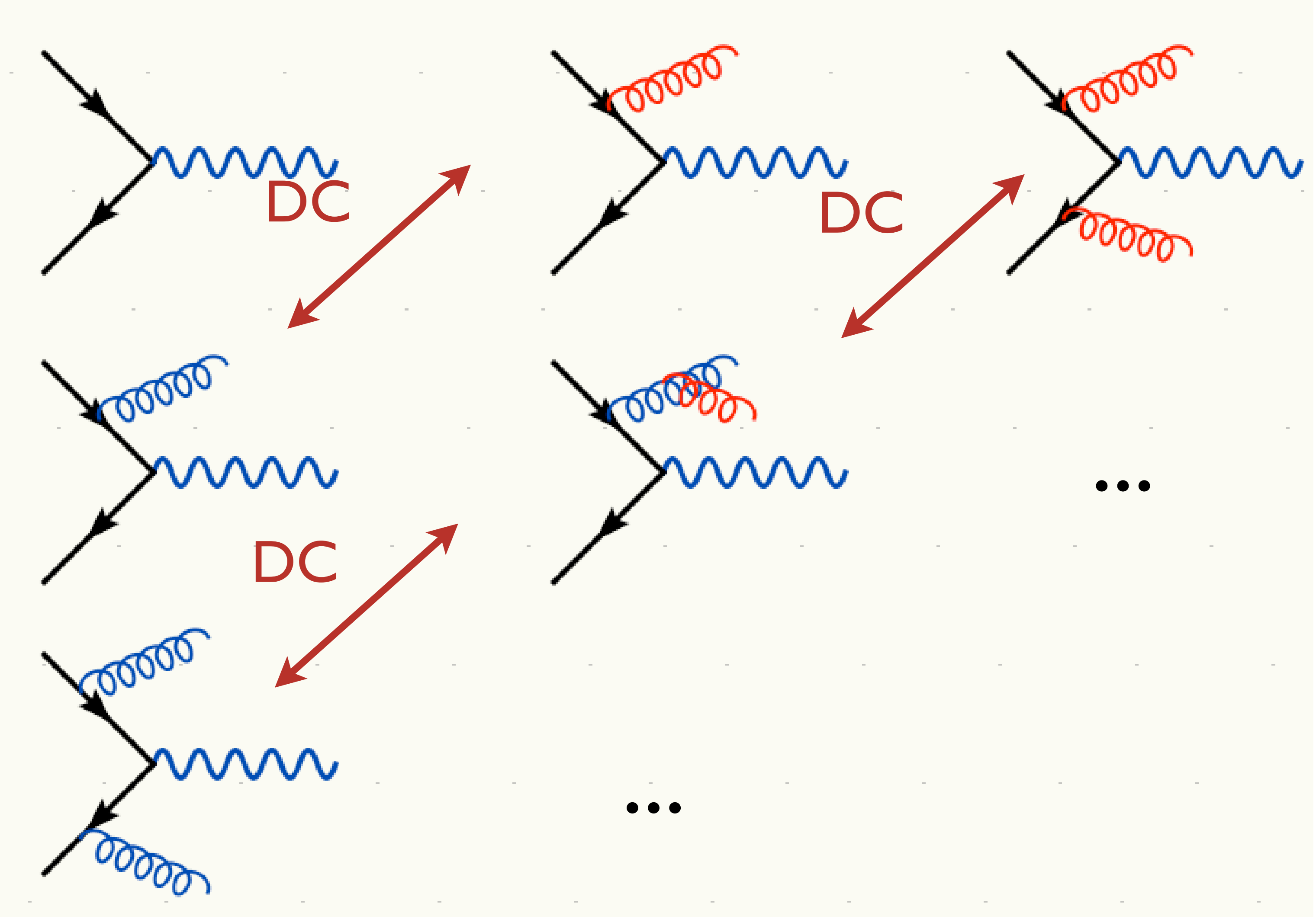
[Mangano]
[Catani, Krauss, Kuhn, Webber]

PS →

$pp \to W^+$

$pp \to W^+ j$ ME ↓

$pp \to W^+ jj$

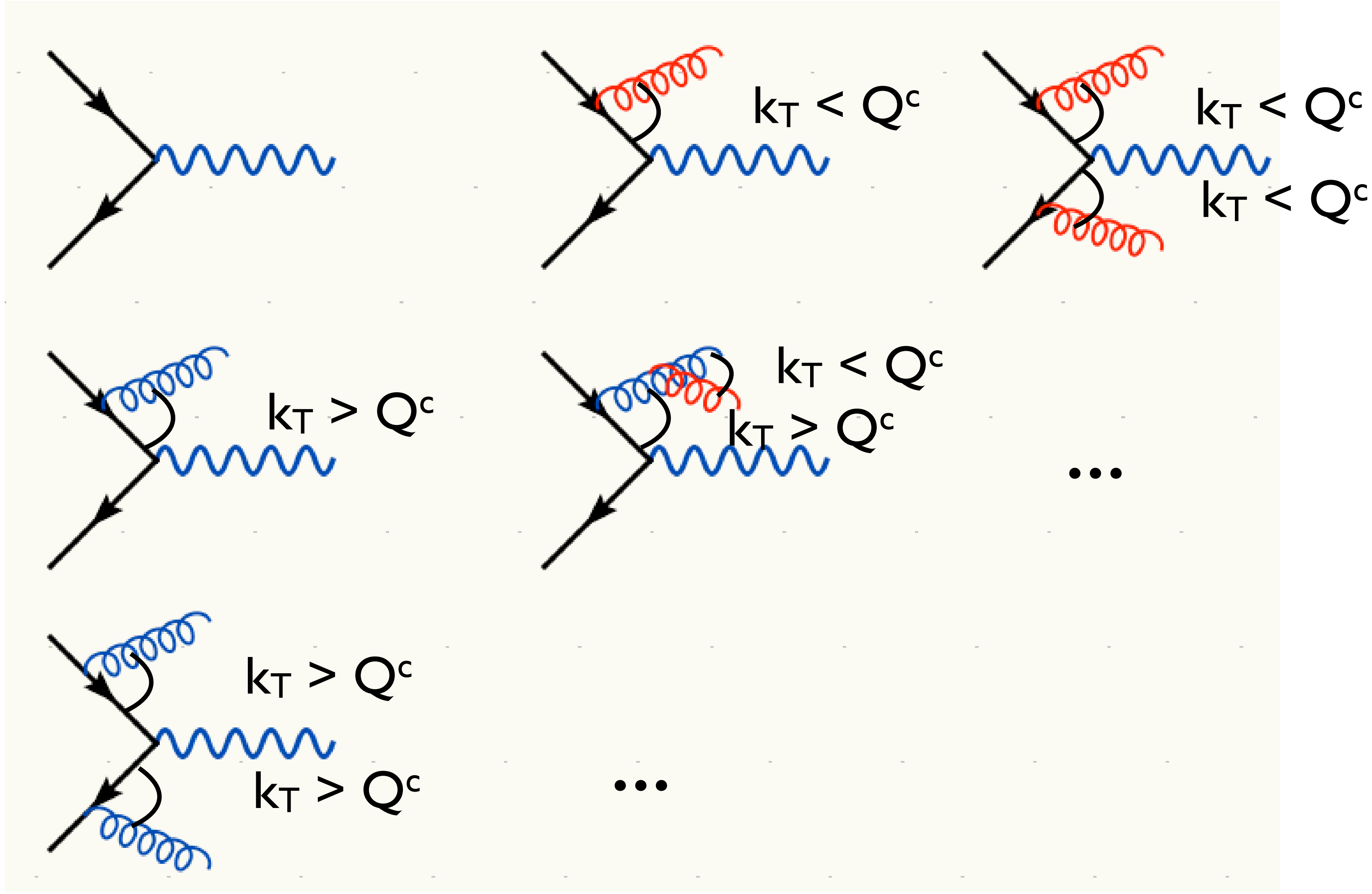


Merging ME with PS

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

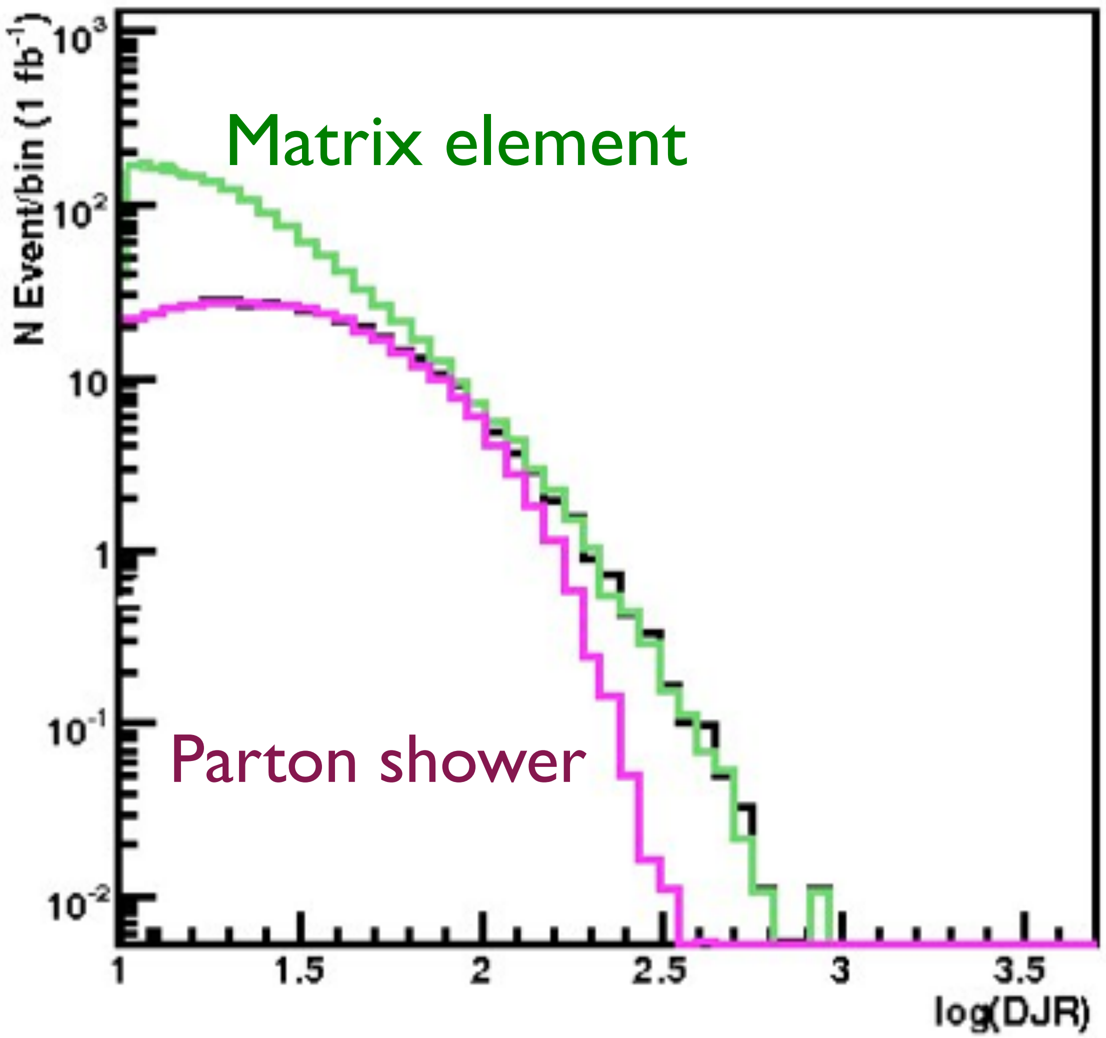
PS →

ME ↓



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

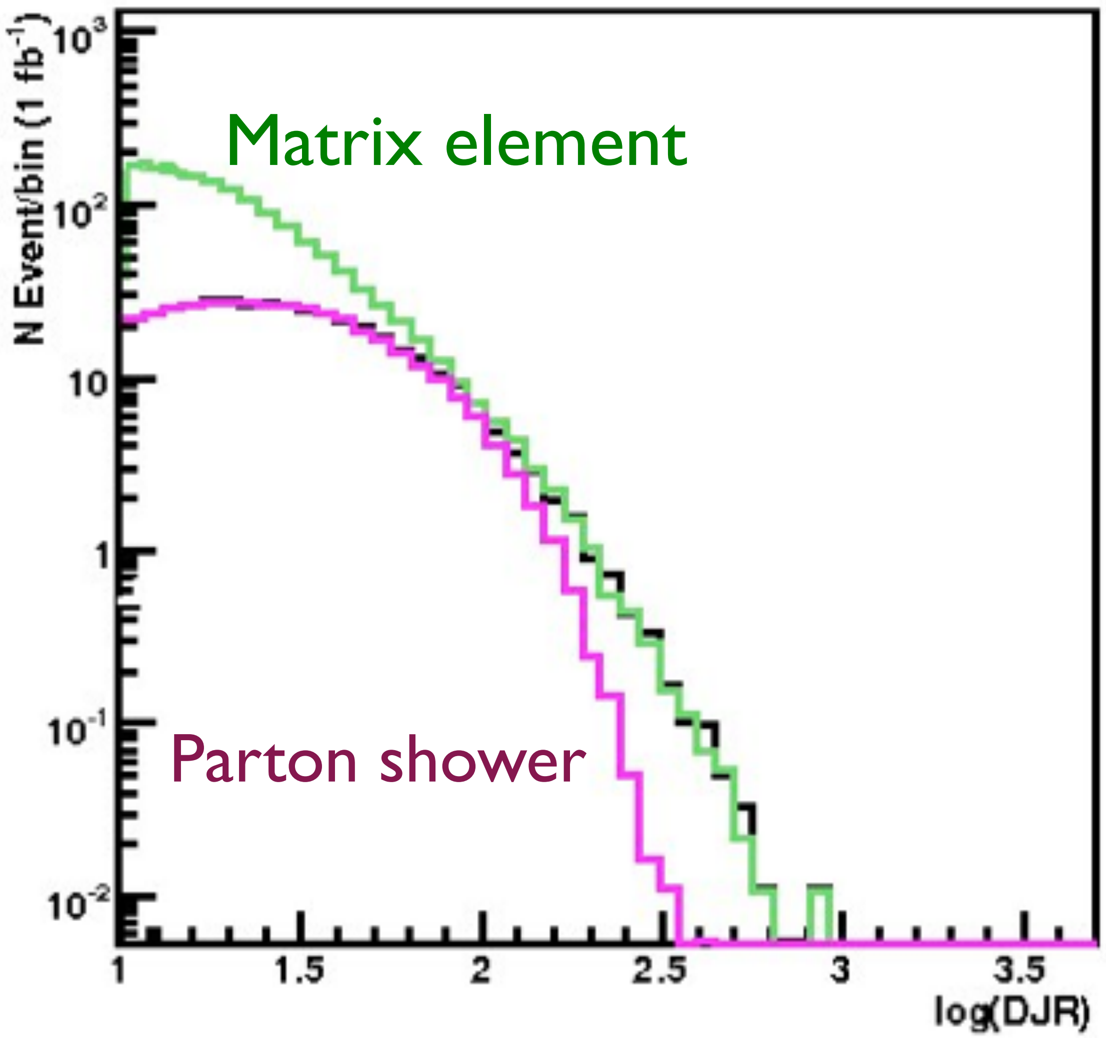
Goal for ME-PS merging/matching



2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

Goal for ME-PS merging/matching

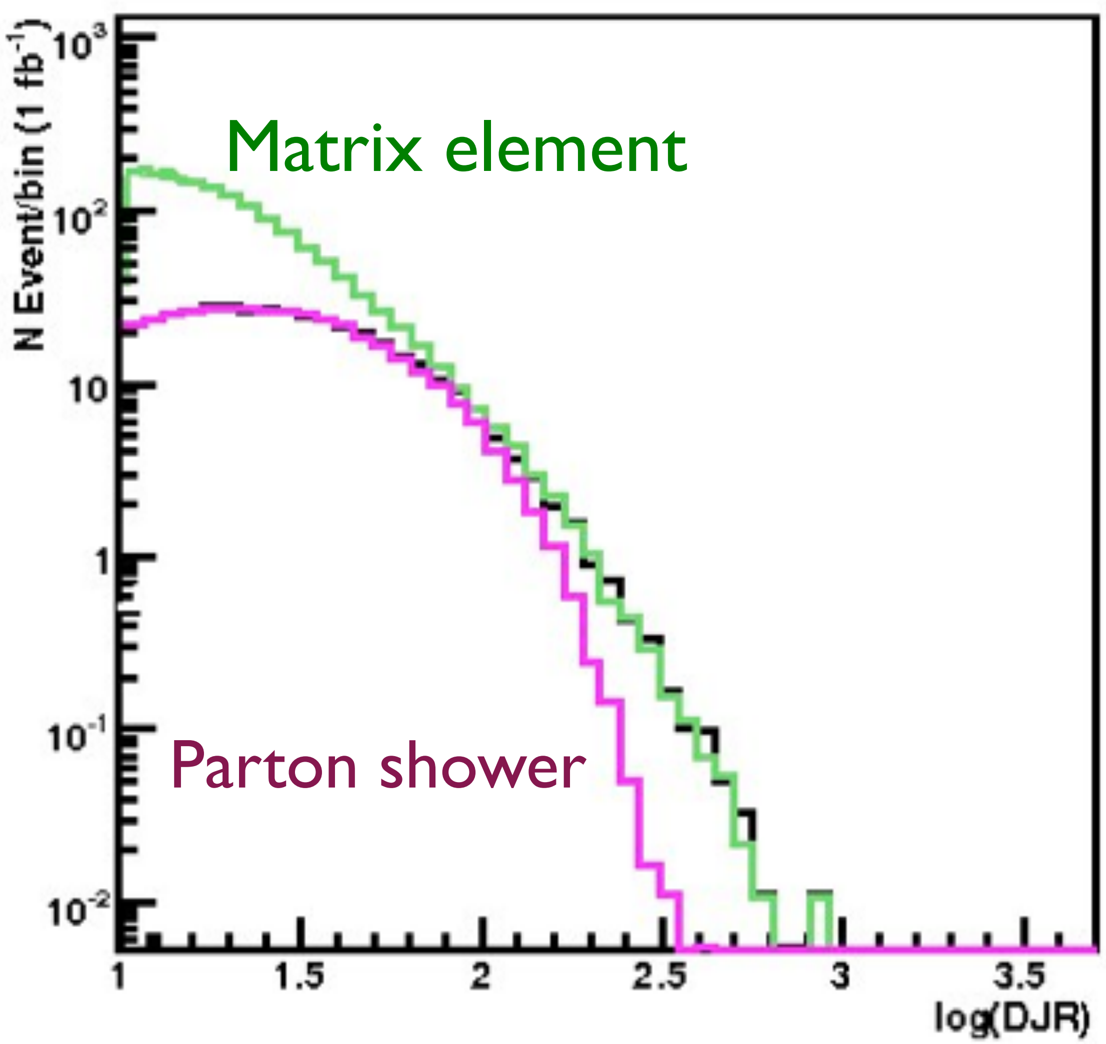
- Regularization of matrix element divergence



2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

Goal for ME-PS merging/matching

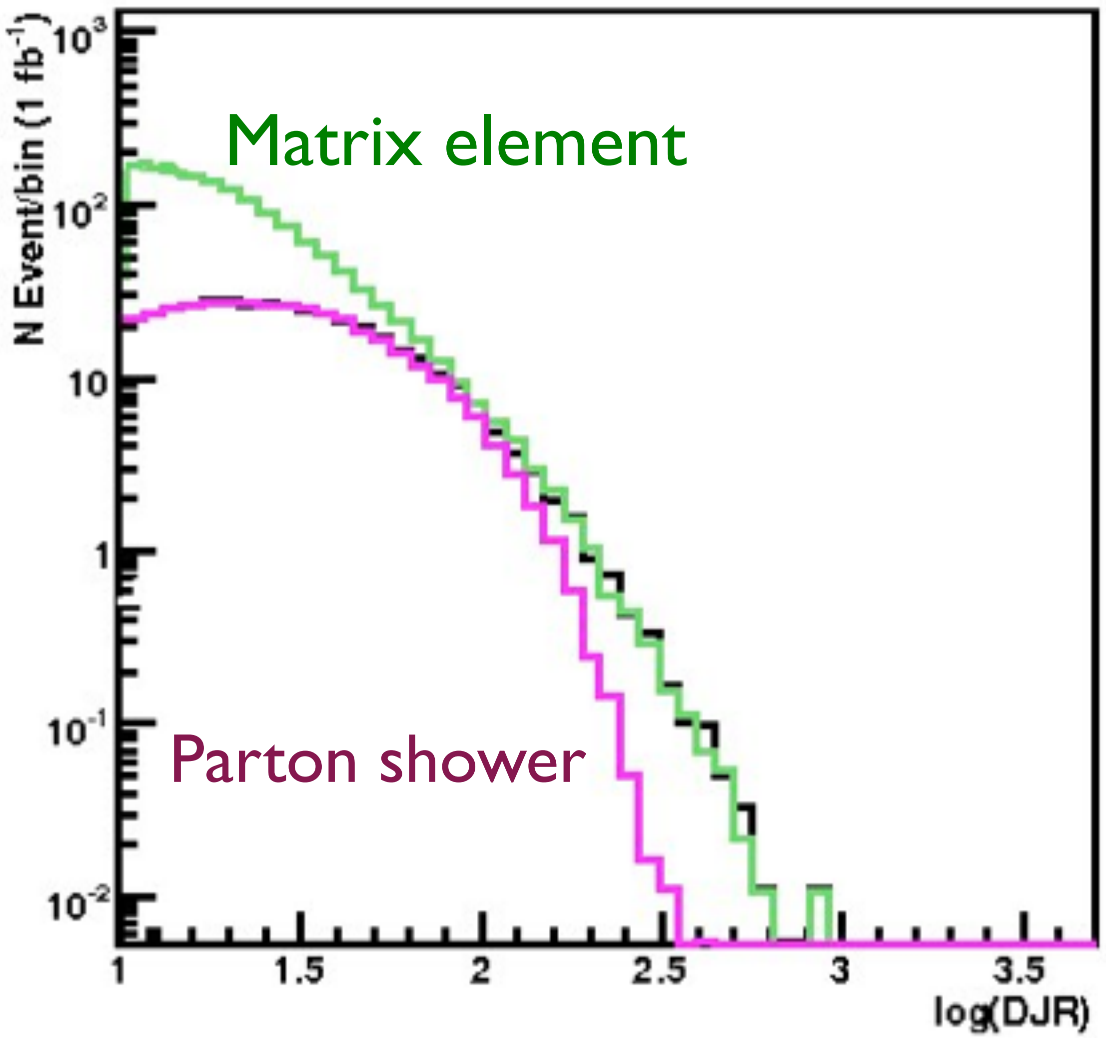
- Regularization of matrix element divergence
- Correction of the parton shower for large momenta



2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

Goal for ME-PS merging/matching

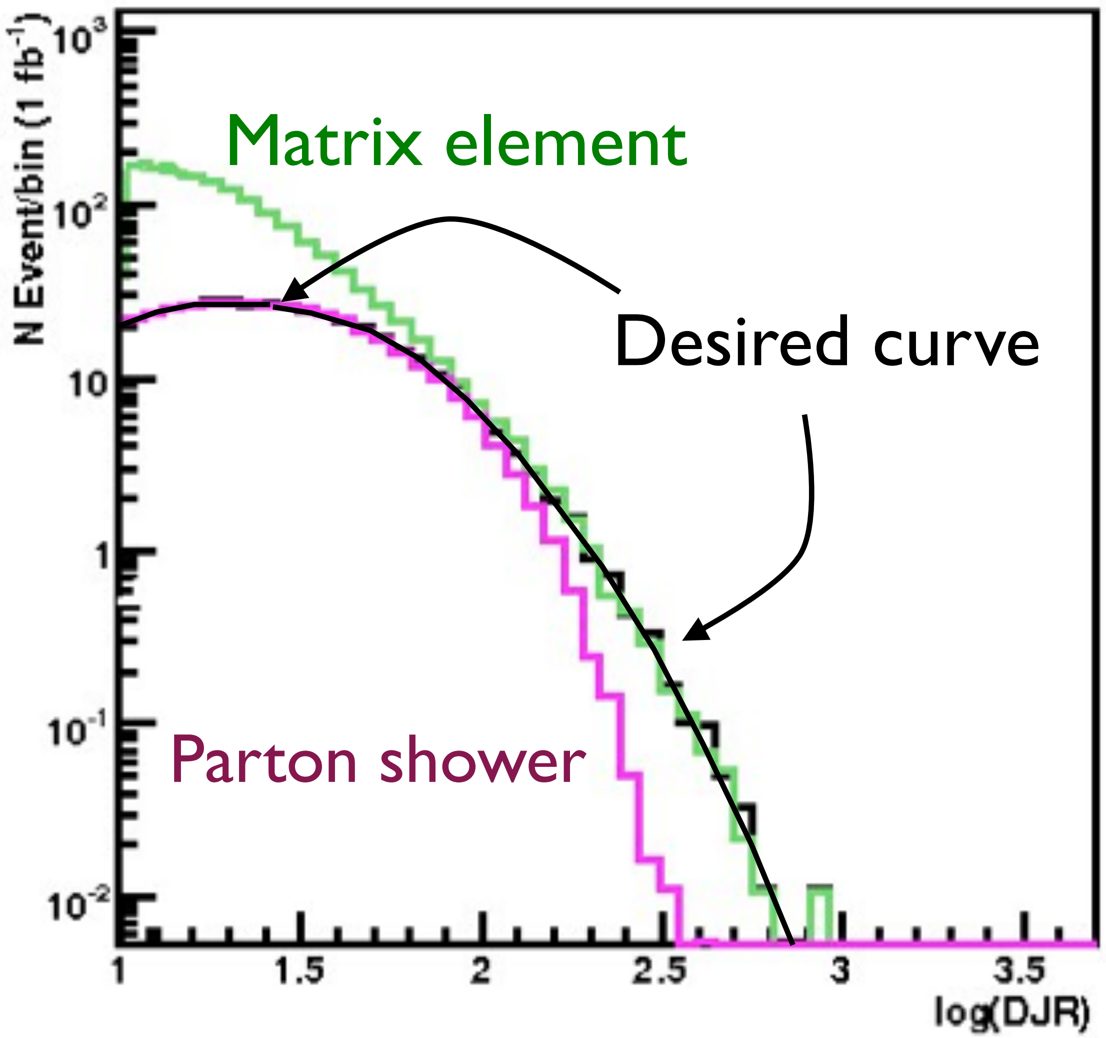
- Regularization of matrix element divergence
- Correction of the parton shower for large momenta
- Smooth jet distributions



2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

Goal for ME-PS merging/matching

- Regularization of matrix element divergence
- Correction of the parton shower for large momenta
- Smooth jet distributions



2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

MLM algorithm in a nutshell

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 corresponding 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 at a scale Q^{match}.
   If yes, keep the event. If no, reject the event. Q^{match} is called the *matching scale*.

Let's start

Exercises

1. Follow the built-in tutorial (type "tutorial" in mg5 shell)
2. Understand the cards
3. compare (diagram and cross-section)
   - ➡ p p > t t~
   - ➡ p p > t t~ QED=0
   - ➡ p p > t t~ QED=2
4. compare (distributions)
   - ➡ p p > e+ e-
   - ➡ p p > z, z > e+ e-
   - ➡ p p > e+ e- $ z
   - ➡ p p > e+ e- / z
5. compute the cross-section p p > t t~
   - ➡ for Mtop between 160 to 180 GeV
   - ➡ Do not use the interface!
6. matching generation
7. NLO

Solution

Exercise II: Cards Meaning

- How do you change
  - ➡ top mass
  - ➡ top width
  - ➡ W mass
  - ➡ beam energy
  - ➡ pt cut on the lepton

Param_card (top mass, top width, W mass)

Run_card (beam energy, pt cut on the lepton)

- top mass

```
#####################################
## INFORMATION FOR MASS
#####################################
Block mass
    6 1.730000e+02 # MT
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000 # d : 0.0
  2 0.000000 # u : 0.0
  3 0.000000 # s : 0.0
  4 0.000000 # c : 0.0
  11 0.000000 # e- : 0.0
  12 0.000000 # ve : 0.0
  13 0.000000 # mu- : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  21 0.000000 # g : 0.0
  22 0.000000 # a : 0.0
  24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```

- W mass

```
######################################
## INFORMATION FOR MASS
######################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000 # d : 0.0
  2 0.000000 # u : 0.0
  3 0.000000 # s : 0.0
  4 0.000000 # c : 0.0
  11 0.000000 # e- : 0.0
  12 0.000000 # ve : 0.0
  13 0.000000 # mu- : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  21 0.000000 # g : 0.0
  22 0.000000
  24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```

W Mass is an internal parameter!

MG5 didn't use this value!

So you need to change MZ or Gf or alpha_EW

Exercise III: Syntax

- What's the meaning of the order QED/QCD
- What's the difference between
  - ➡ p p > t t~
  - ➡ p p > t t~ QED=2
  - ➡ p p > t t~ QED=0

Solution I : Syntax

- What's the meaning of the order QED/QCD
  - ➡ By default MG5 takes the lowest order in QED!
  - ➡ p p > t t~ => p p > t t~ QED=0
  - ➡ p p > t t~ QED=2
    - ✦ additional diagrams (photon/z exchange)

p p > t t~

Cross section (pb)
555 ± 0.84

p p > t t~ QED=2

Cross section (pb)
555.8 ± 0.91

No significant QED contribution

Exercise II: Syntax

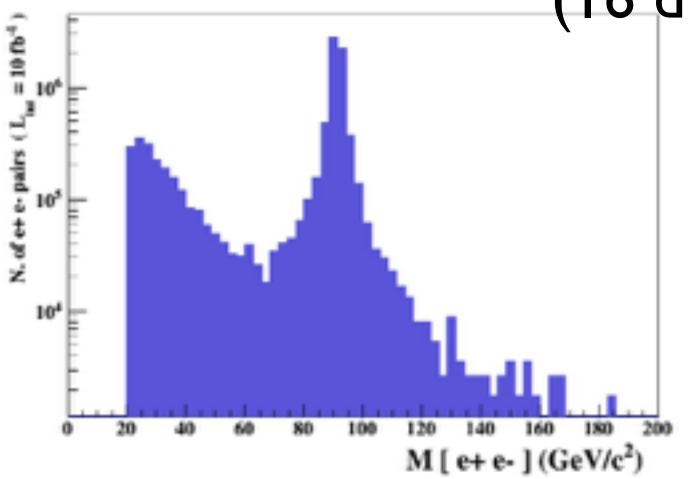
- Generate the cross-section and the distribution (invariant mass) for
  - ➡ p p > e+ e-
  - ➡ p p > z, z > e+ e-
  - ➡ p p > e+ e- $ z
  - ➡ p p > e+ e- / z

Hint :To have automatic distributions:

mg5> install MadAnalysis

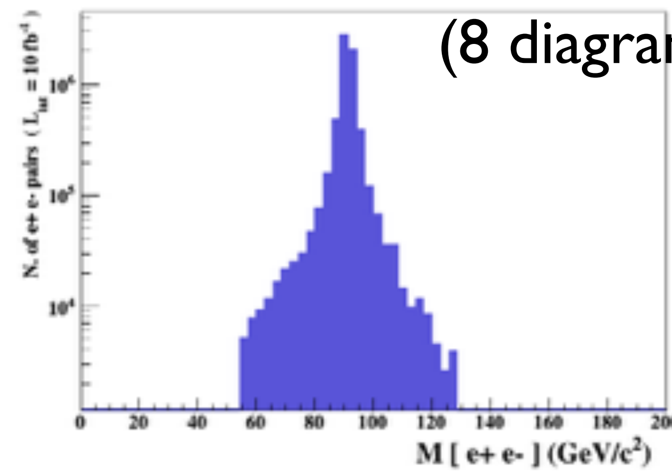
p p > e+ e-

(16 diagrams)



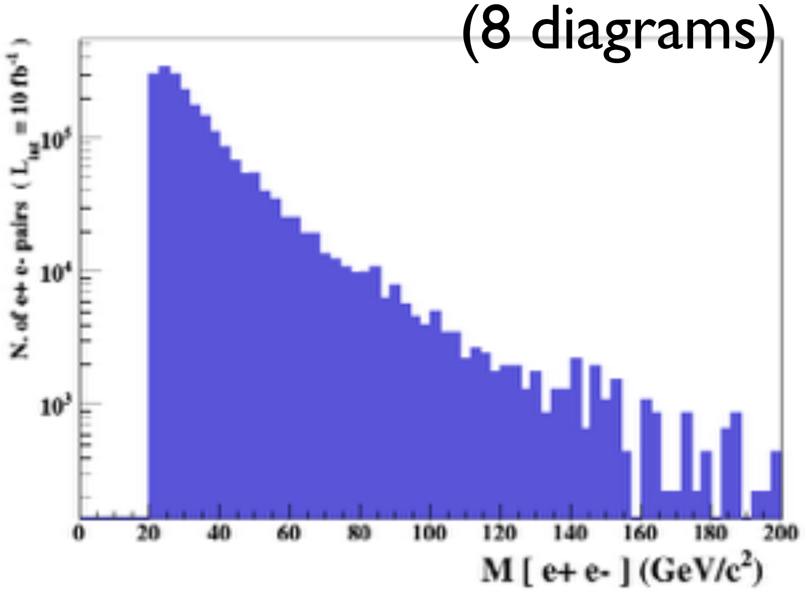
p p >z , z > e+ e-

(8 diagrams)



p p > e+ e- /z

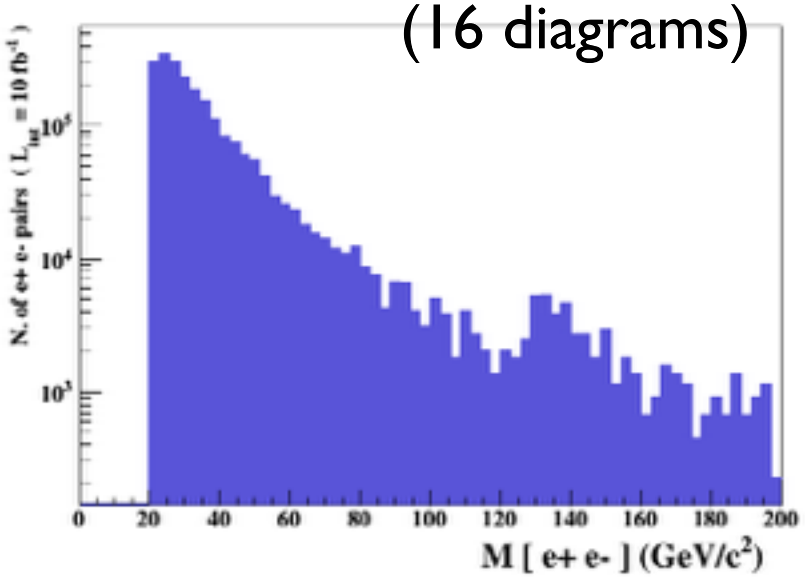
(8 diagrams)



No Z

p p > e+ e- $ z

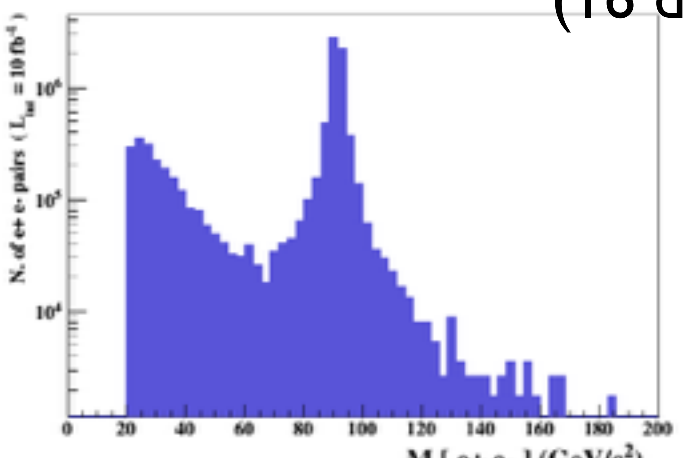
(16 diagrams)



Z- onshell veto

p p > e+ e-

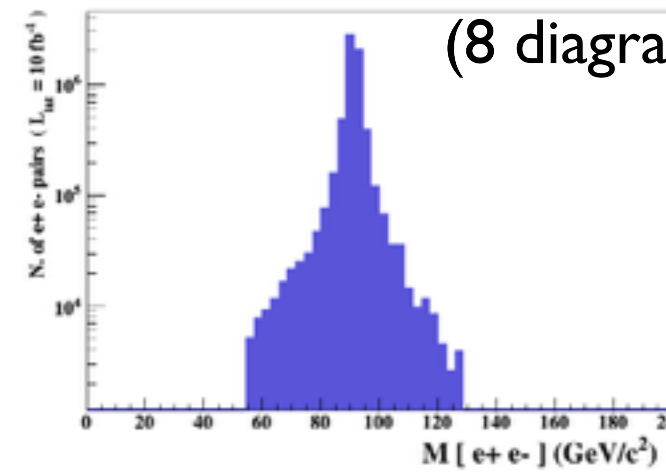
(16 diagrams)



Correct Distribution

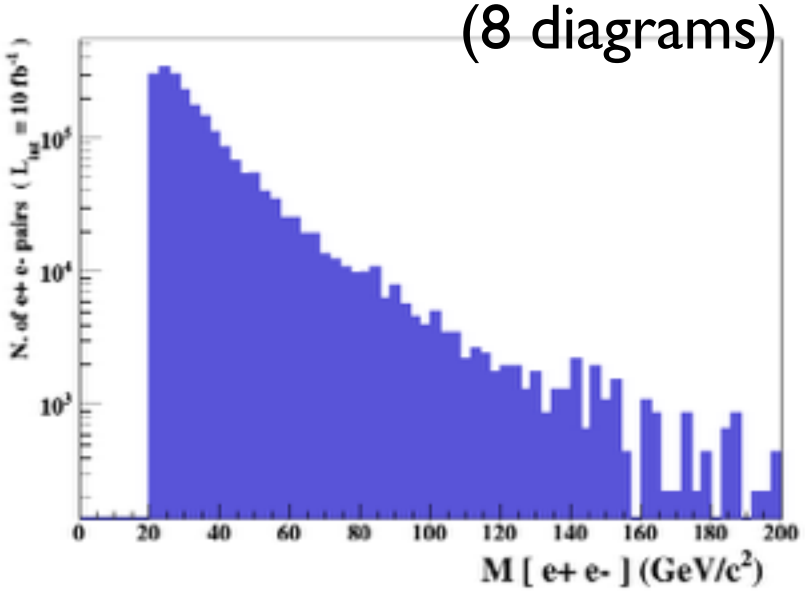
p p >z , z > e+ e-

(8 diagrams)



p p > e+ e- /z

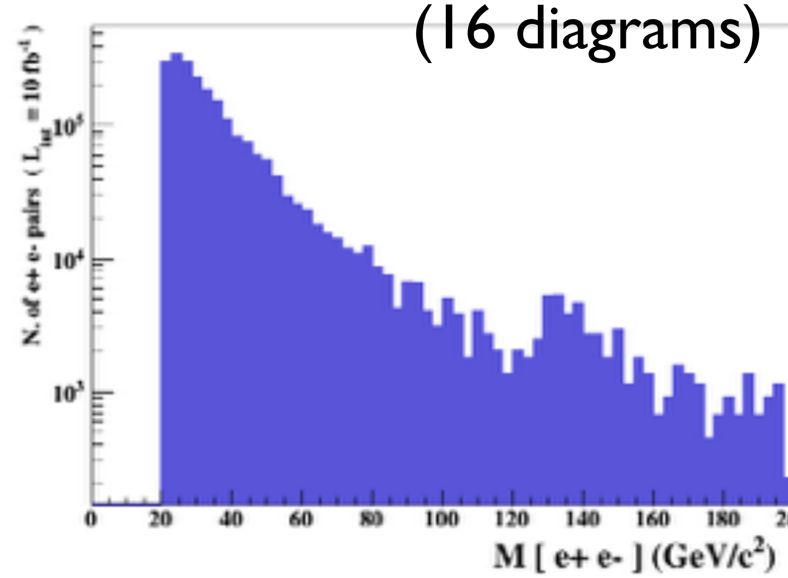
(8 diagrams)



No Z

p p > e+ e- $ z

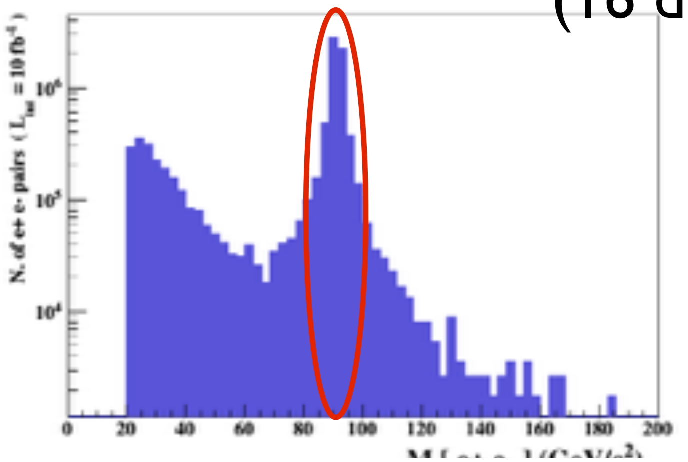
(16 diagrams)



Z- onshell veto

p p > e+ e-

(16 diagrams)

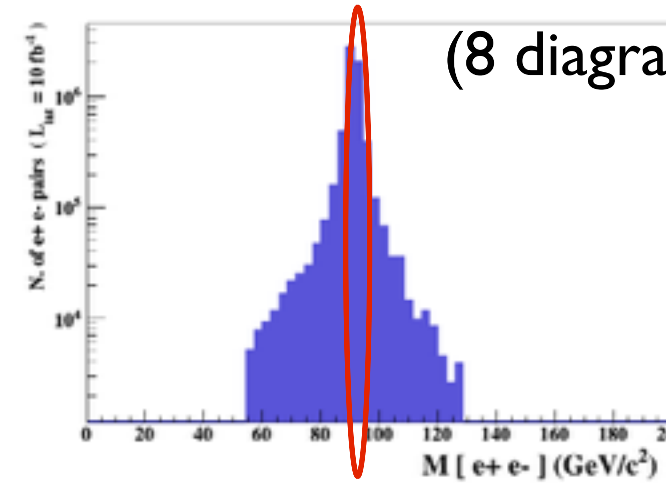


Correct Distribution

Z Peak

p p >z , z > e+ e-

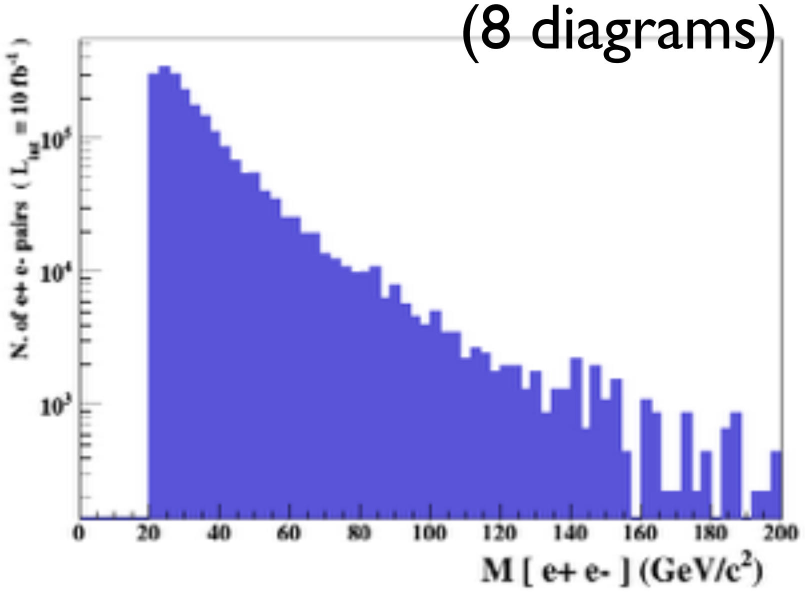
(8 diagrams)



p p > e+ e- /z

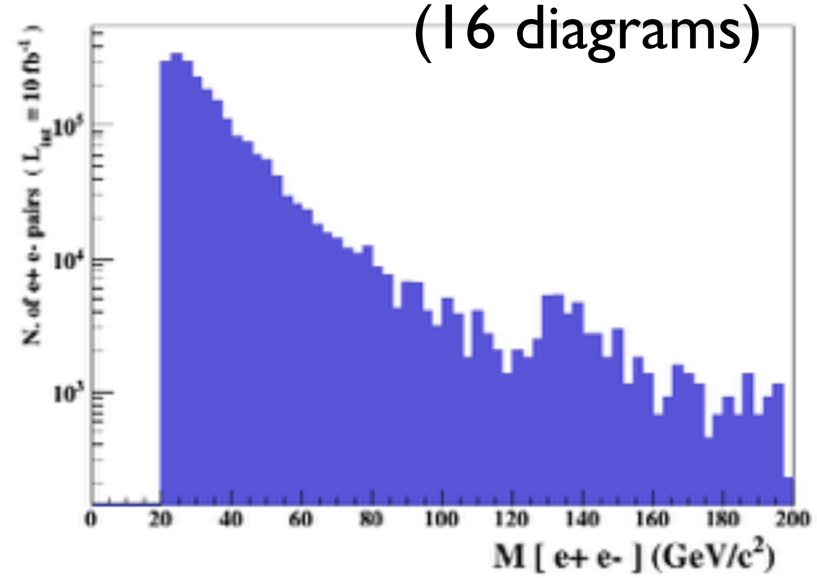
p p > e+ e- $ z

(8 diagrams)



NO Z Peak

(16 diagrams)

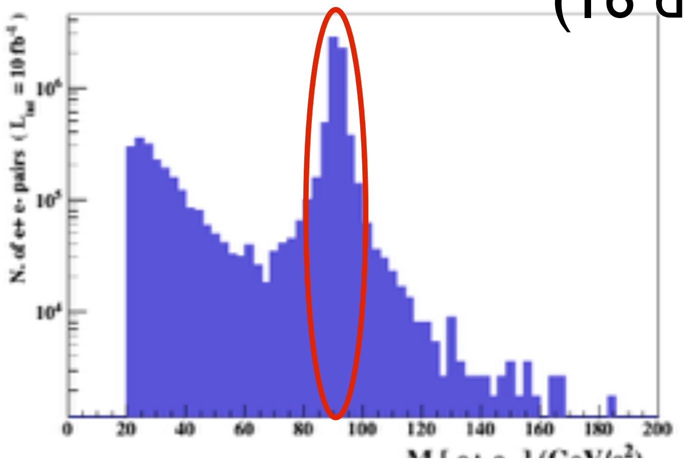


No Z

Z- onshell veto

p p > e+ e-

(16 diagrams)

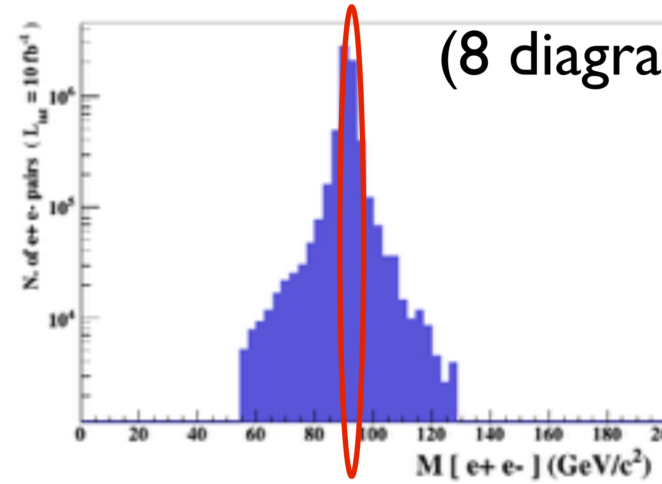


Correct Distribution

Z Peak

p p >z , z > e+ e-

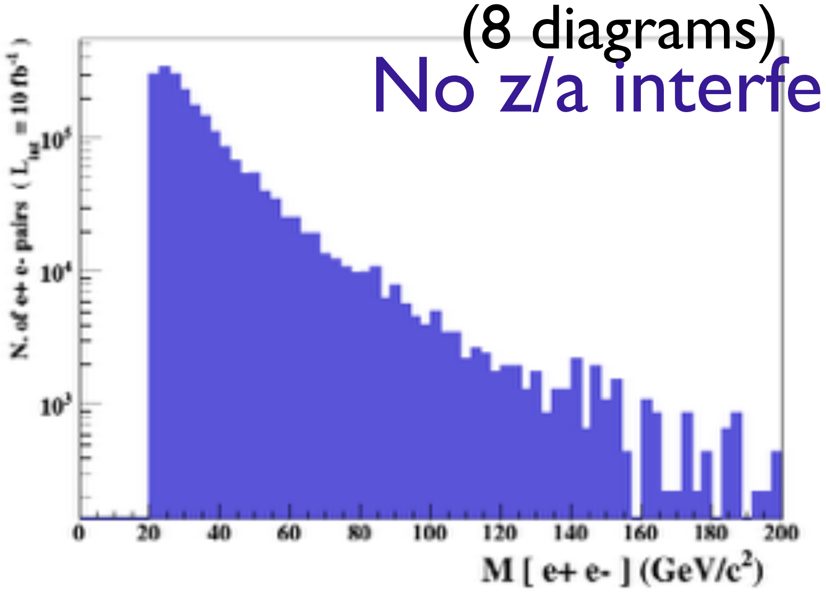
(8 diagrams)



p p > e+ e- /z

(8 diagrams)

No z/a interference



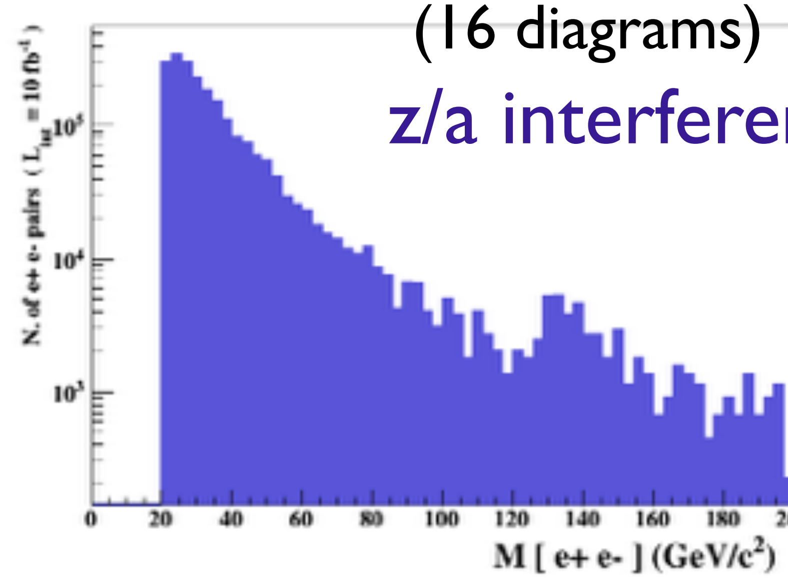
No Z

NO Z Peak

p p > e+ e- $ z

(16 diagrams)

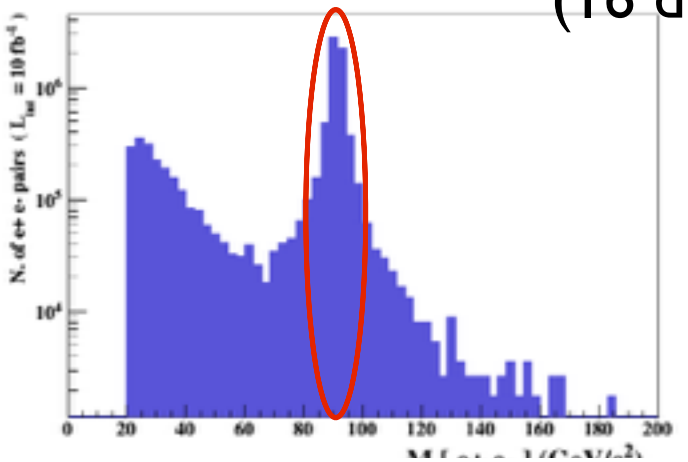
z/a interference



Z- onshell veto

p p > e+ e-

(16 diagrams)

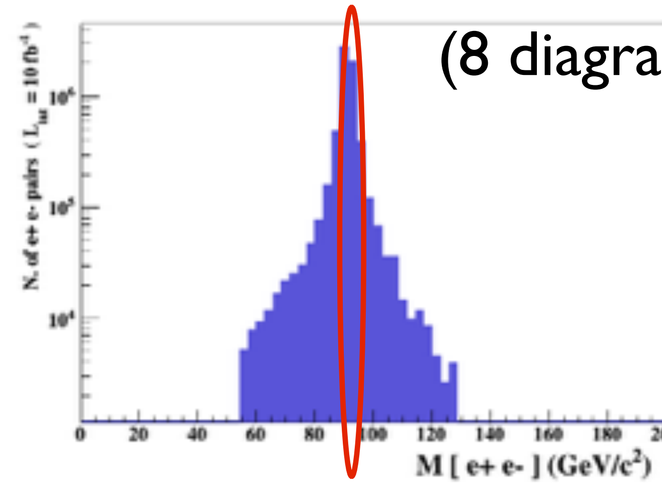


Correct Distribution

Z Peak

p p >z , z > e+ e-

(8 diagrams)



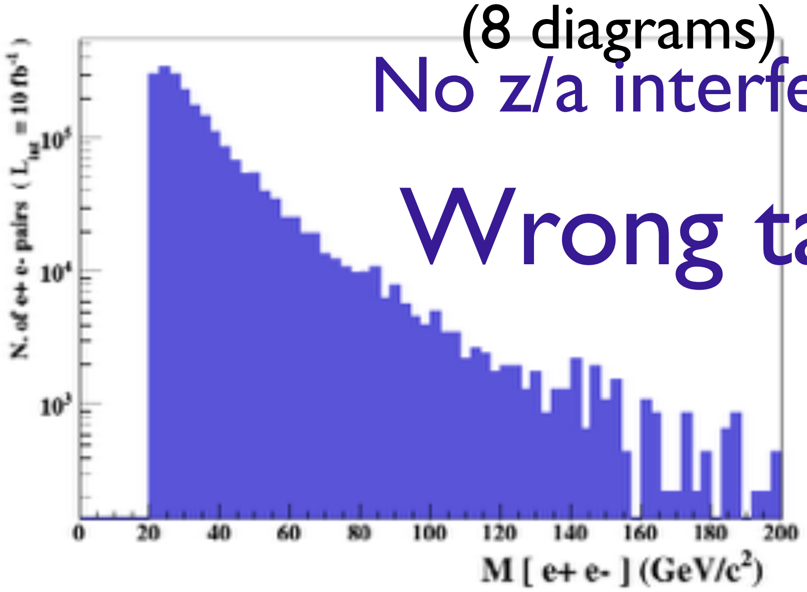
p p > e+ e- /z

(8 diagrams)

NO Z Peak

No z/a interference

Wrong tail



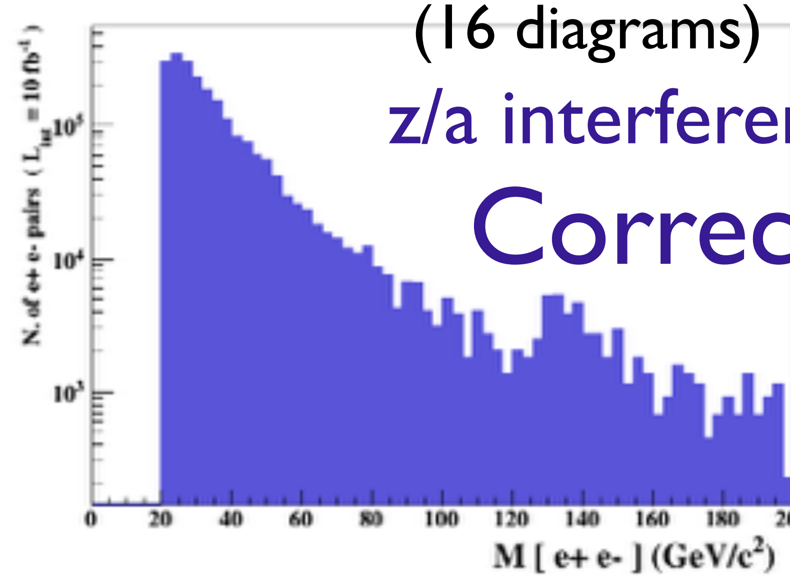
No Z

p p > e+ e- $ z

(16 diagrams)

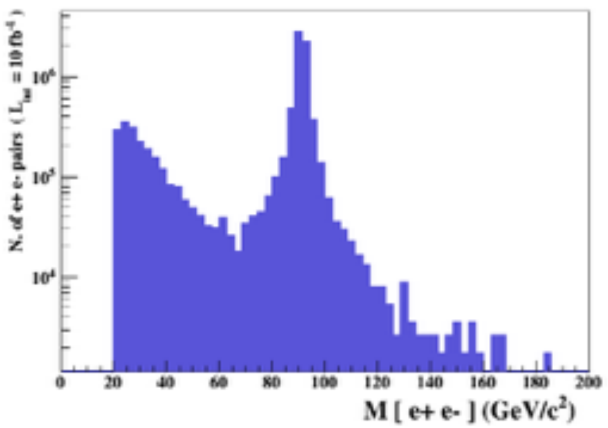
z/a interference

Correct tail



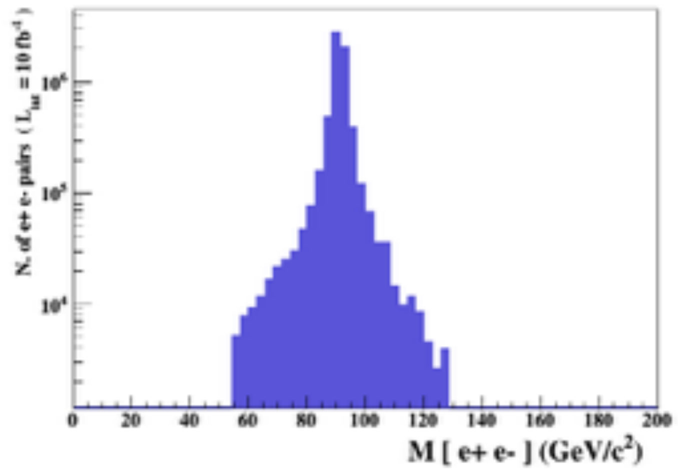
Z- onshell veto

p p > e+ e-   p p >z , z > e+ e-   p p > e+ e- $ z



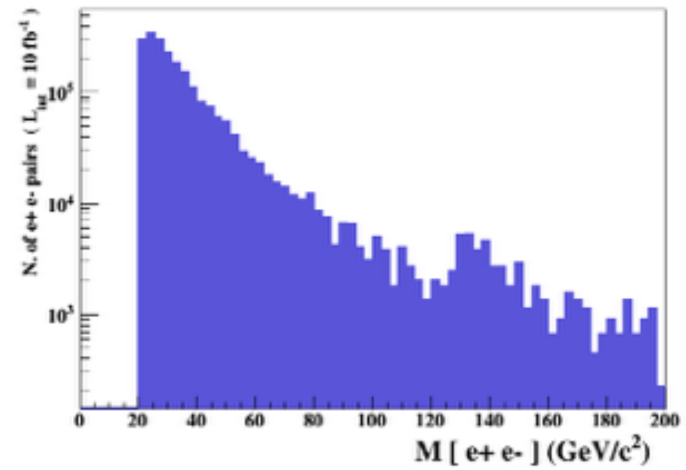
(16 diagrams)

=



(8 diagrams)

+



(16 diagrams)

Onshell cut: BW_cut

$$|M^* - M| < BW_{cut} * \Gamma$$

- The Physical distribution is (very close to) exact sum of the two other one.
- The "$" forbids the Z to be onshell but the photon invariant mass can be at MZ (i.e. on shell substraction).
- The "/" is to be avoid if possible since this leads to violation of gauge invariance.

WARNING

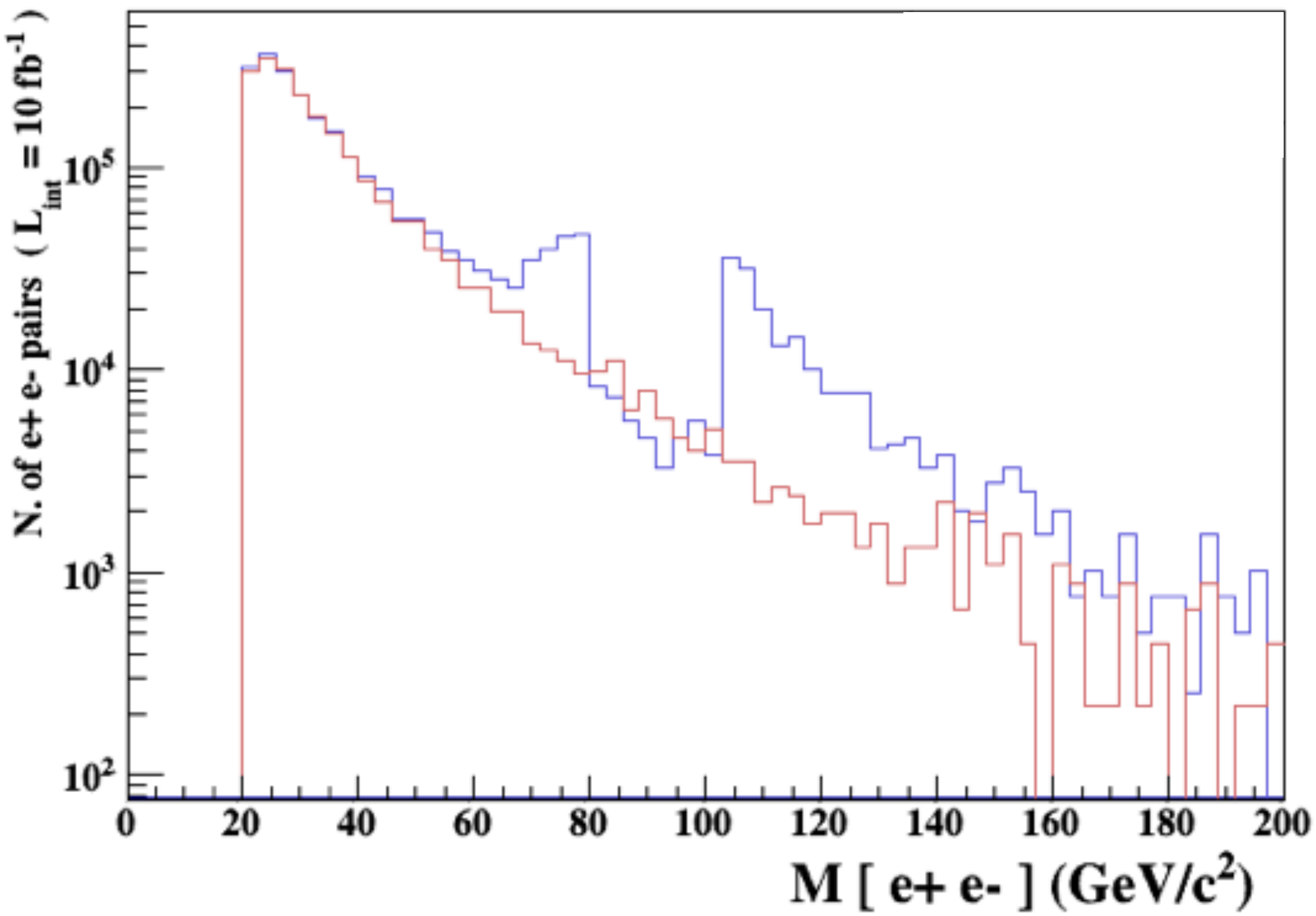
- NEXT SLIDE is generated with bw_cut =5
- This is TOO SMALL to have a physical meaning (15 the default value used in previous plot is better)
- This was done to illustrate more in detail how the "$" syntax works.

See previous slide warning

p p > e+ e- / Z

(red curve)

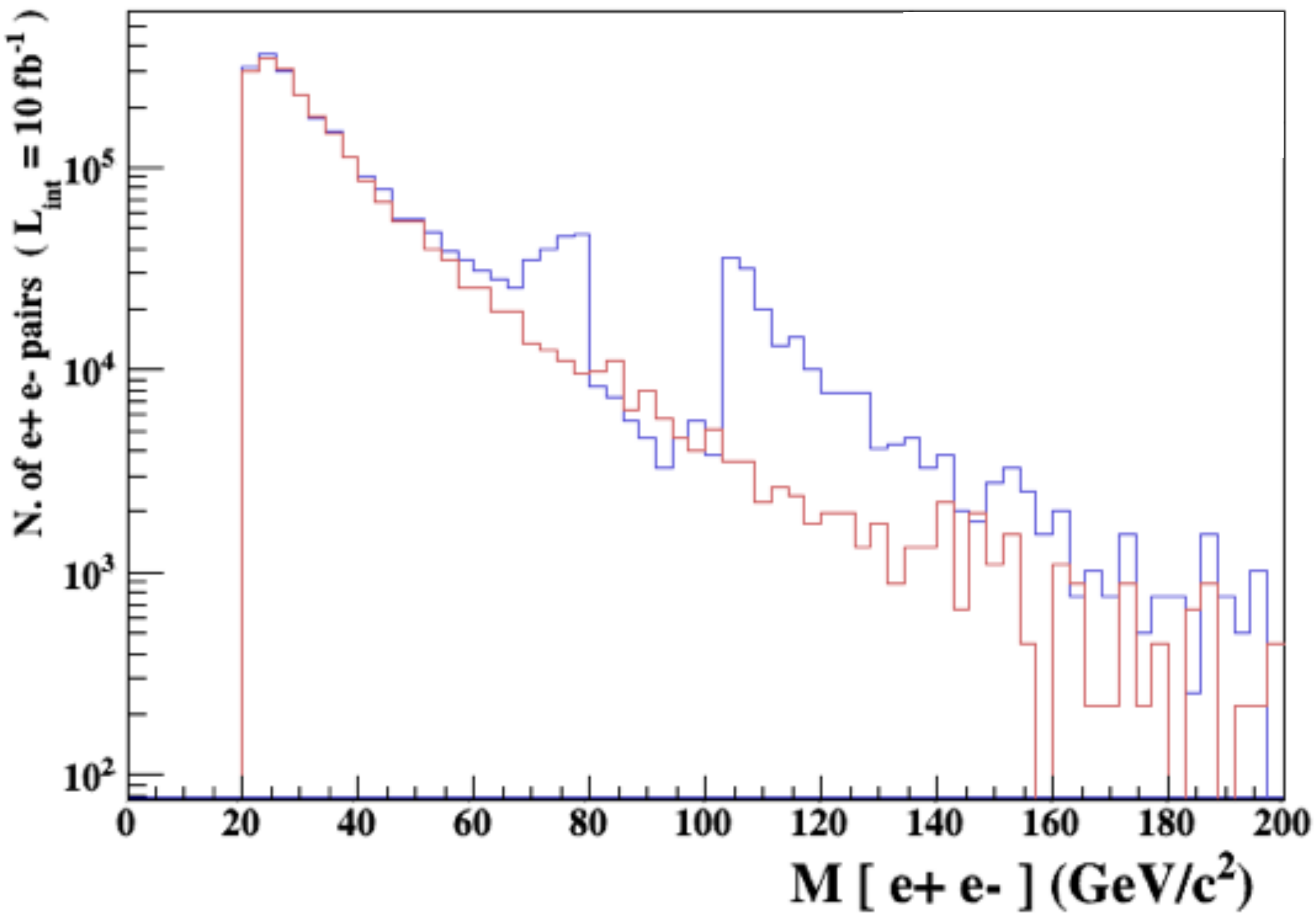
(blue curve)



See previous slide warning

p p > e+ e- / Z
(red curve)

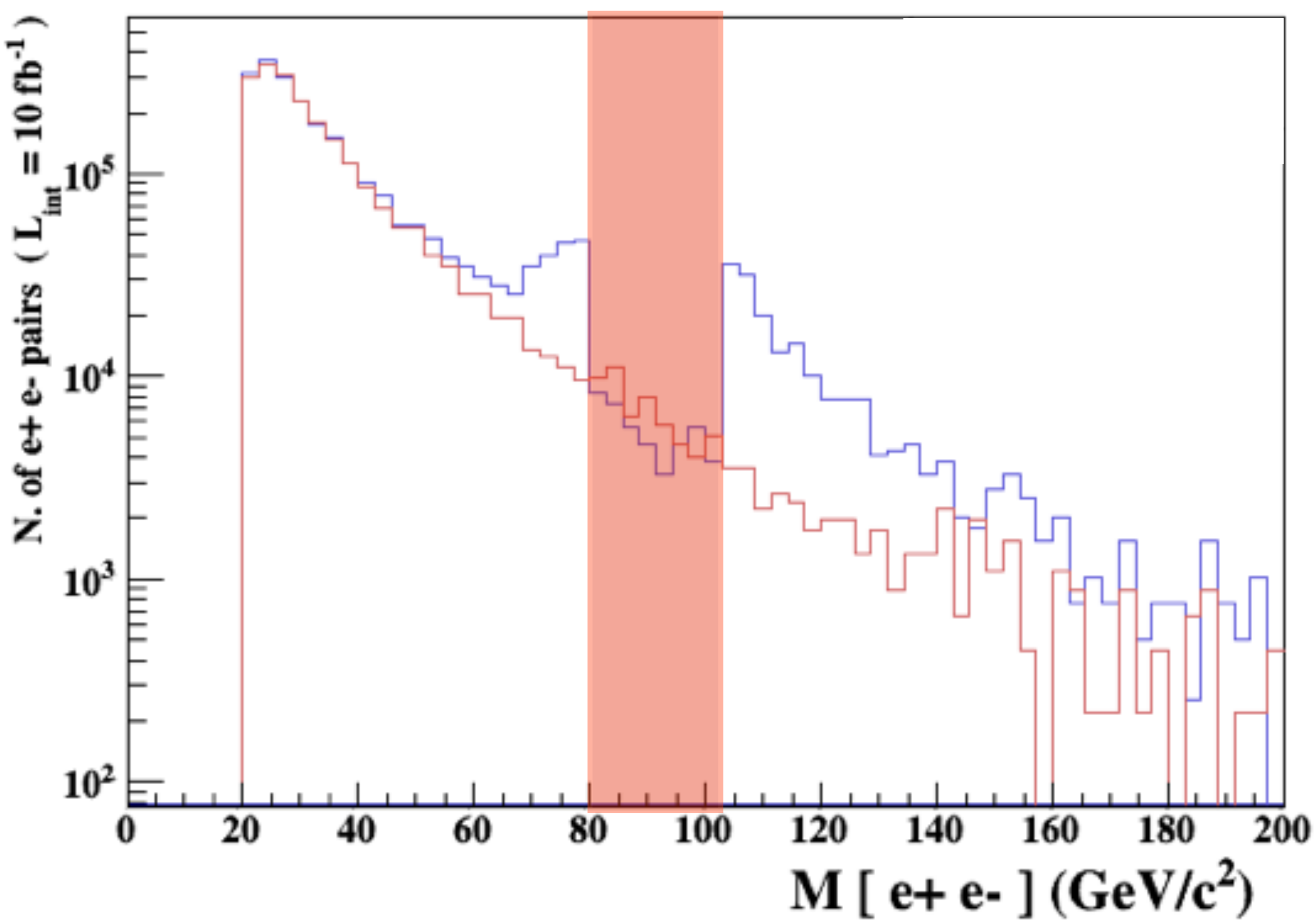
adding p p > e+ e- $ Z
(blue curve)



See previous slide warning

p p > e+ e- / Z
(red curve)

adding p p > e+ e- $ Z
(blue curve)



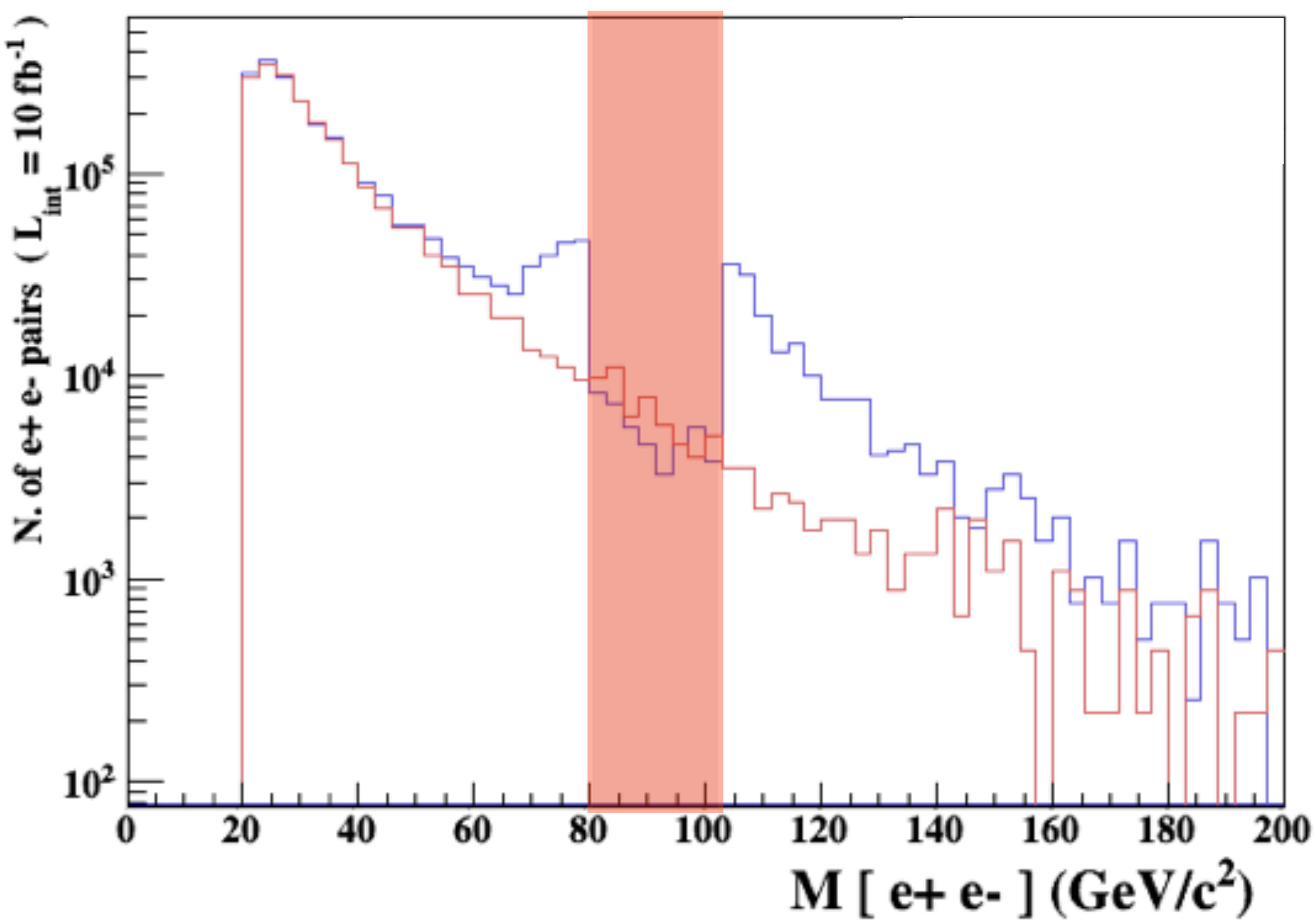
- Z onshell veto

5 times width area

See previous slide warning

p p > e+ e- / Z
(red curve)

adding p p > e+ e- $ Z
(blue curve)

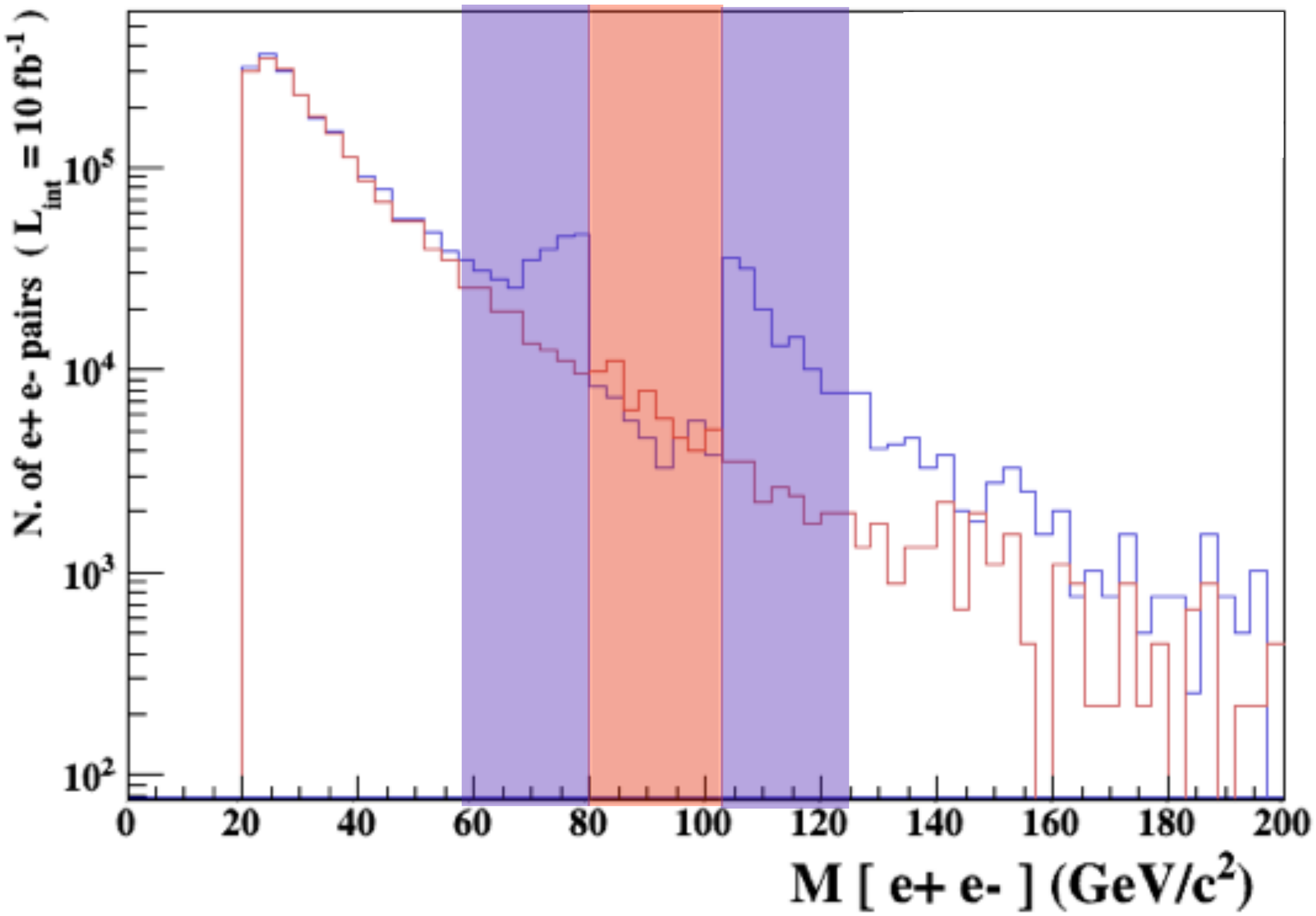


- Z onshell veto
- In veto area only photon contribution

5 times width area

See previous slide warning

p p > e+ e- / Z (red curve) adding p p > e+ e- $ Z (blue curve)



- Z onshell veto
- In veto area only photon contribution
- area sensitive to z-peak

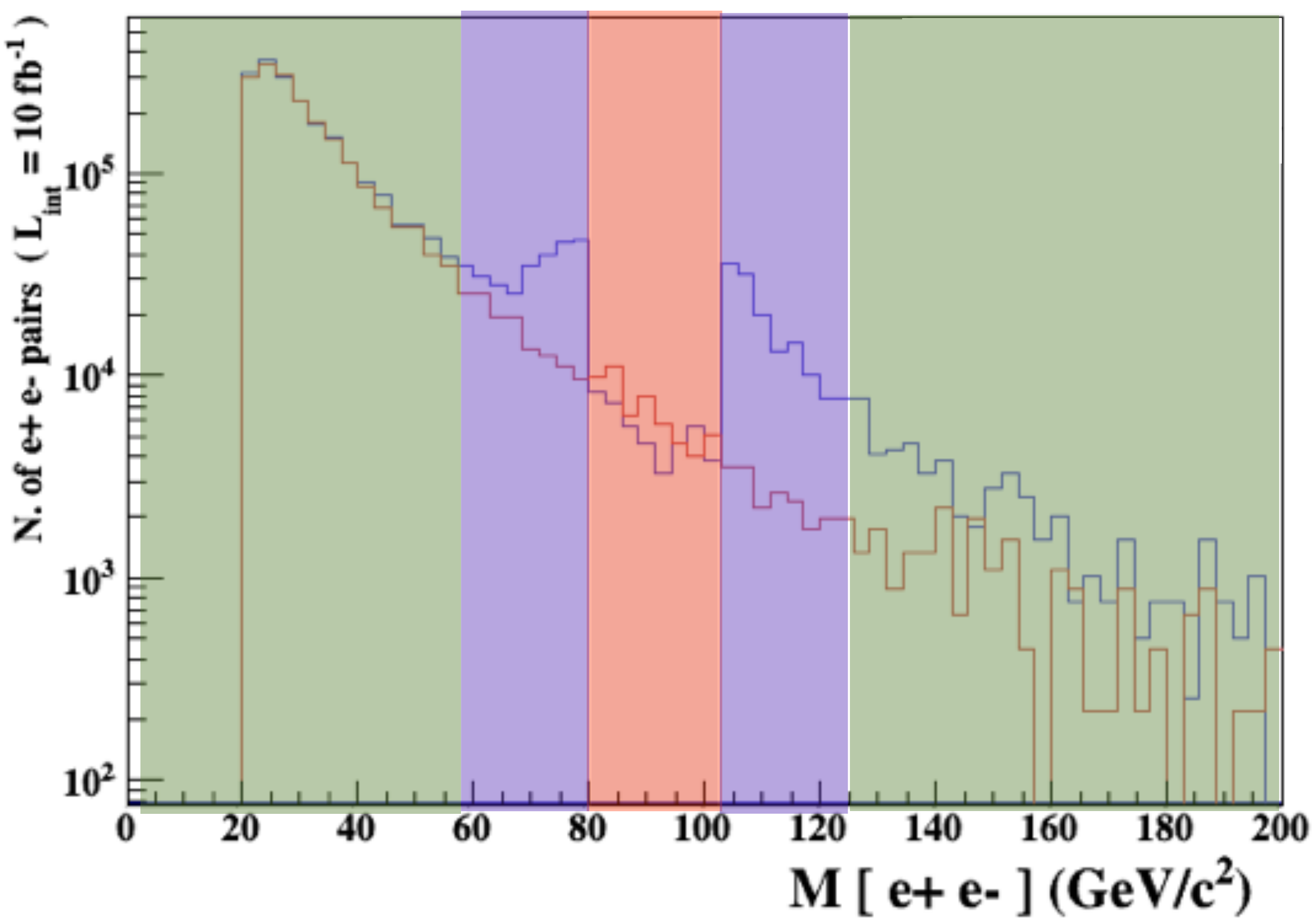
5 times width area

15 times width area

See previous slide warning

p p > e+ e- / Z
(red curve)

adding p p > e+ e- $ Z
(blue curve)



5 times width area

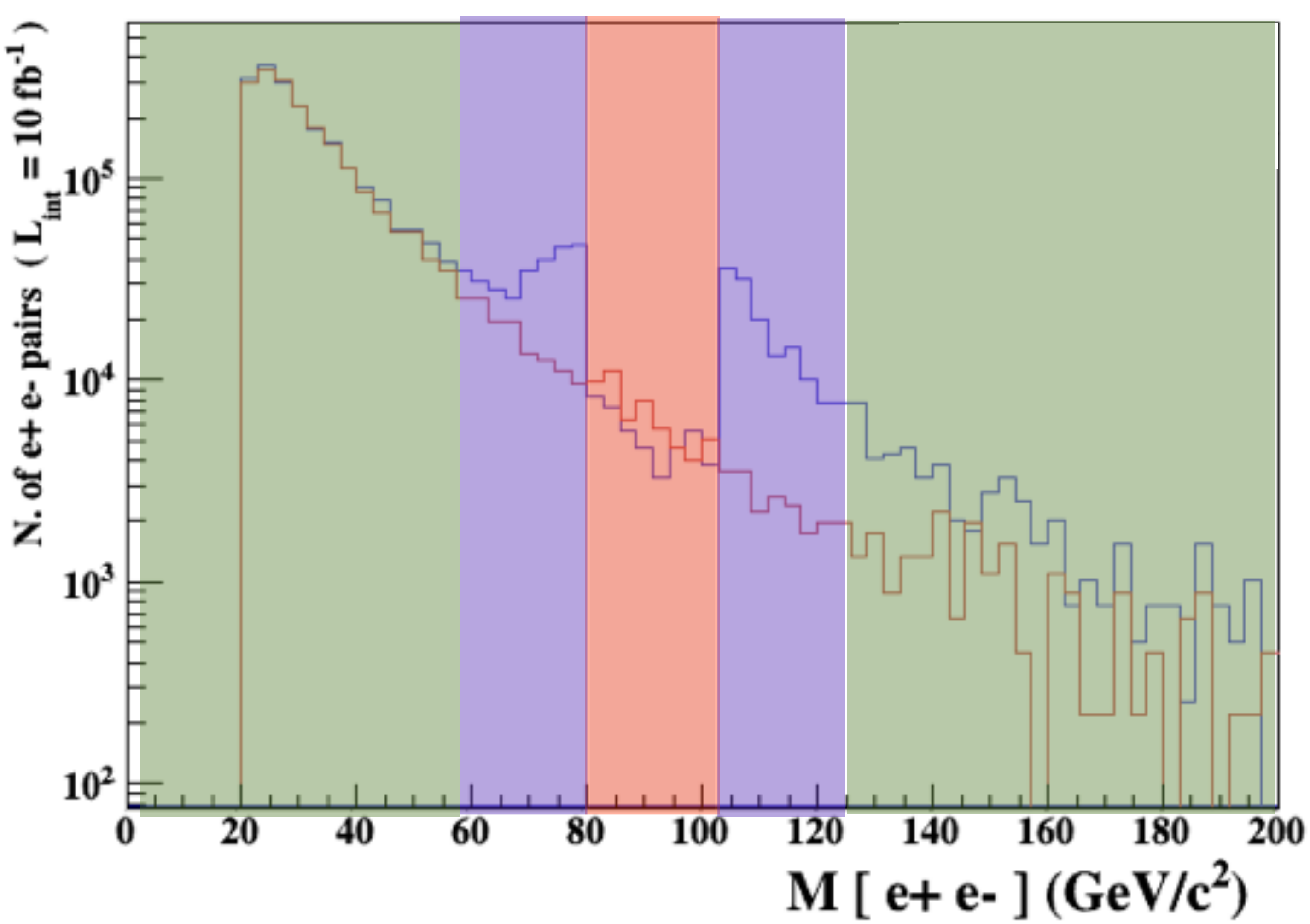
15 times width area

>15 times width area

- Z onshell veto
- In veto area only photon contribution
- area sensitive to z-peak
- very off-shell Z, the difference between the curve is due to interference which are need to be KEPT in simulation.

See previous slide warning

p p > e+ e- / Z (red curve) adding p p > e+ e- $ Z (blue curve)



- Z onshell veto
- In veto area only photon contribution
- area sensitive to z-peak
- very off-shell Z, the difference between the curve is due to interference which are need to be KEPT in simulation.

5 times width area

15 times width area

>15 times width area

The "$" can be use to split the sample in BG/SG area

- Syntax Like
  - ➡ p p > z > e+ e- (ask one S-channel z)
  - ➡ p p > e+ e- / z (forbids any z)
  - ➡ p p > e+ e- $$ z (forbids any z in s-channel)
- ARE NOT GAUGE INVARIANT !
- forgets diagram interference.
- can provides un-physical distributions.

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  - ➡ p p > z > e+ e- (ask one S-channel z)
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Avoid Those as much as possible!

- Syntax Like
  - `p p > z > e+ e-` (ask one S-channel z)
  - `p p > e+ e- / z` (forbids any z)
  - `p p > e+ e- $$ z` (forbids any z in s-channel)
- ARE NOT GAUGE INVARIANT !
- forgets diagram interference.
- can provides un-physical distributions.

Avoid Those as much as possible!

check physical meaning and gauge/Lorentz invariance if you do.

- Syntax like
  - p p > z, z > e+ e- (on-shell z decaying)
  - p p > e+ e- $ z (forbids s-channel z to be on-shell)
- Are linked to cut $|M^* - M| < BW_{cut} * \Gamma$
- Are more safer to use
- Prefer those syntax to the previous slides one

Exercise V: Automation

- Look at the cross-section for the previous process for 3 different mass points.
  - ➡ hint: you can edit the param_card/run_card via the "set" command [After the launch]
  - ➡ hint: All command [including answer to question] can be put in a file.

Exercise V: Automation

- File content:

```
import model sm
generate p p > t t~
output
launch
set mt 160
set wt Auto
done
launch
set mt 165
set wt Auto
launch
set mt 170
set wt Auto
launch
set mt 175
set wt Auto
launch
set mt 180
set wt Auto
launch
set mt 185
set wt Auto
```

- Run it by:
  - ./bin/mg5 PATH
    - (smarter than ./bin/mg5 < PATH)
- If an answer to a question is not present: Default is taken automatically

Excercise 5: Matching + Merging

- In run_card: put icckw=1
  - ➡ set the value for xqcut
- In pythia_card set a value for qcut

Exercise VI: Matching+Merging

	w+0j	w+1j	w+2j	w+3j
no matching	8.35E+04	1.58E+04	8.7E+03	3.5E+03

	1GeV	10GeV	20GeV	50GeV	100GeV	500GeV
w+0	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04
0+1	1.07E+05	9.09E+04	8.91E+04	8.61E+04	8.40E+04	8.35+04
0+1+2	1.12E+05	9.29E+04	9.03E+04	8.66E+04	8.44E+04	8.35E+04
0+1+2+3	1.20E+05	9.47E+04	9.07E+04	8.68E+04	8.40E+04	8.35E+04

Exercise VI: Matching+Merging

	w+0j	w+1j	w+2j	w+3j
no matching	8.35E+04	1.58E+04	8.7E+03	3.5E+03

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w+0	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04
0+1	1.07E+05	9.09E+04	8.91E+04	8.61E+04	8.40E+04	8.35+04
0+1+2	1.12E+05	9.29E+04	9.03E+04	8.66E+04	8.44E+04	8.35E+04
0+1+2+3	1.20E+05	9.47E+04	9.07E+04	8.68E+04	8.40E+04	8.35E+04

Slow → Fast

low efficiency → High efficiency

Exercise VI: Matching+Merging

	w+0j	w+1j	w+2j	w+3j
no matching	8.35E+04	1.58E+04	8.7E+03	3.5E+03

	1GeV	10GeV	20GeV	50GeV	100GeV	500GeV
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0+1+2	1.12E+05	9.29E+04	9.03E+04	8.66E+04	8.44E+04	8.35E+04
0+1+2+3	1.20E+05	9.47E+04	9.07E+04	8.68E+04	8.40E+04	8.35E+04

- No effect of the matching for 0 jet sample.

Exercise VI: Matching+Merging

	w+0j	w+1j	w+2j	w+3j
no matching	8.35E+04	1.58E+04	8.7E+03	3.5E+03

	1GeV	10GeV	20GeV	50GeV	100GeV	500GeV
w+0	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04
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0+1+2+3	1.20E+05	9.47E+04	9.07E+04	8.68E+04	8.40E+04	8.35E+04

- matching scale too high only the 0 jet sample contributes => all radiations are from pythia

Exercise VI: Matching+Merging

	w+0j	w+1j	w+2j	w+3j
no matching	8.35E+04	1.58E+04	8.7E+03	3.5E+03

	1GeV	10GeV	20GeV	50GeV	100GeV	500GeV
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0+1+2	1.12E+05	9.29E+04	9.03E+04	8.66E+04	8.44E+04	8.35E+04
0+1+2+3	1.20E+05	9.47E+04	9.07E+04	8.68E+04	8.40E+04	8.35E+04

- matching scale too low. Only highest multiplicity sample contributes and low efficiency

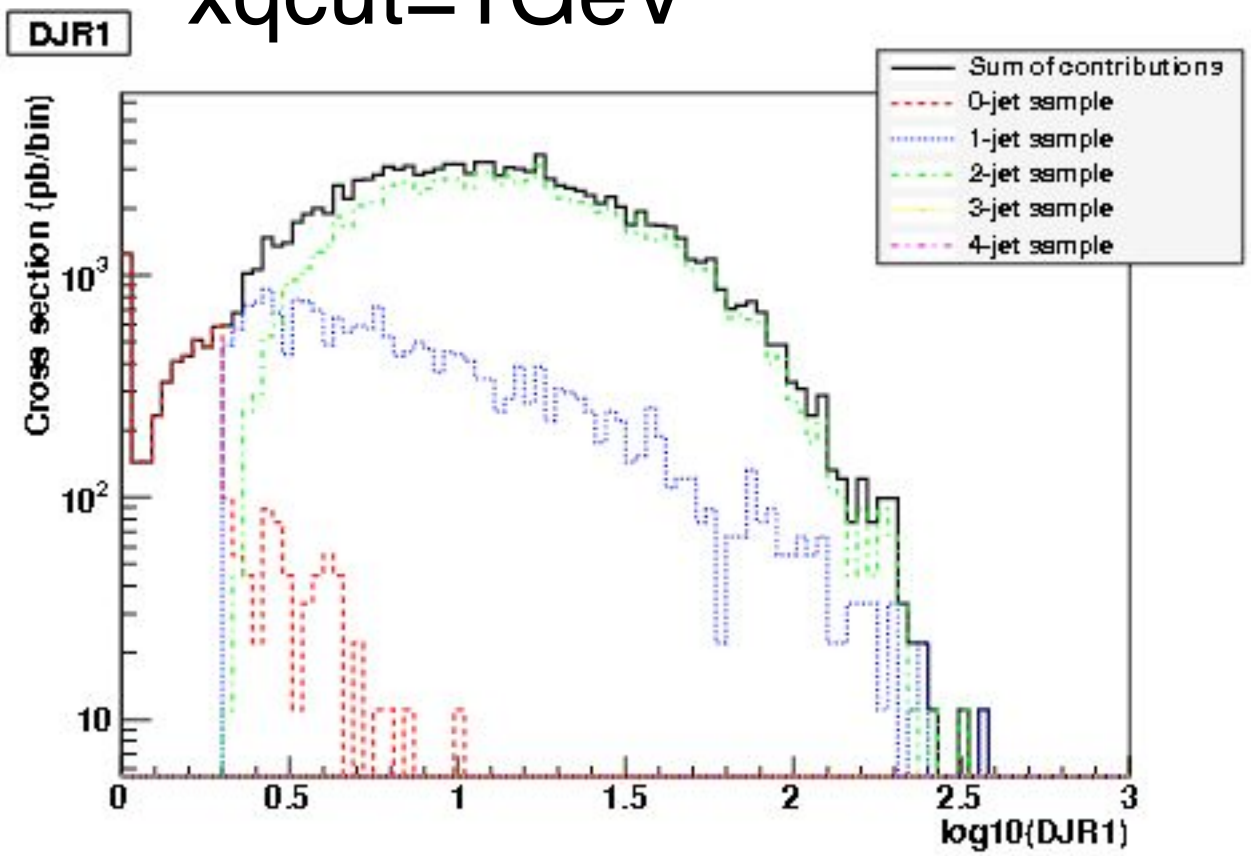
Exercise VI: Matching+Merging

	w+0j	w+1j	w+2j	w+3j
no matching	8.35E+04	1.58E+04	8.7E+03	3.5E+03

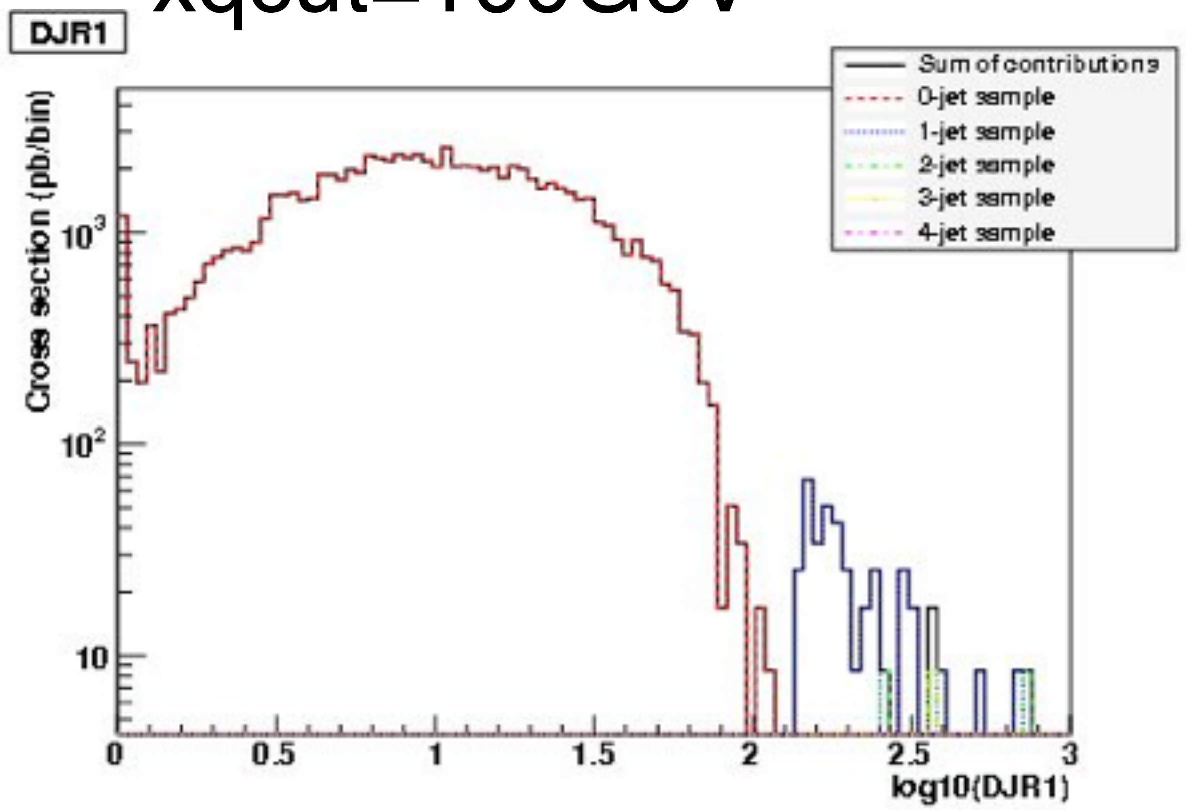
	1GeV	10GeV	20GeV	50GeV	100GeV	500GeV
w+0	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04
0+1	1.07E+05	9.09E+04	8.91E+04	8.61E+04	8.40E+04	8.35+04
0+1+2	1.12E+05	9.29E+04	9.03E+04	8.66E+04	8.44E+04	8.35E+04
0+1+2+3	1.20E+05	9.47E+04	9.07E+04	8.68E+04	8.40E+04	8.35E+04

- Wrong differential rate plot. so to discard.

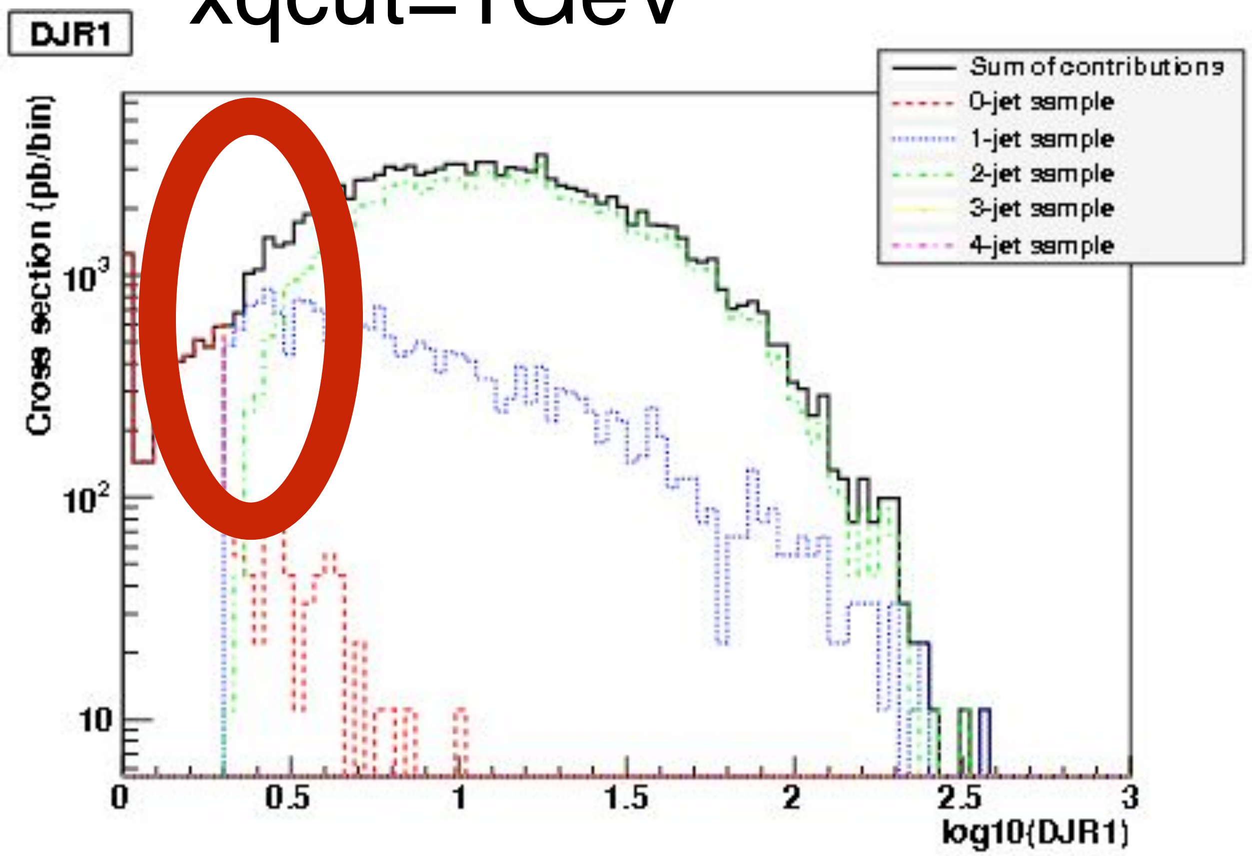
xqcut=1GeV



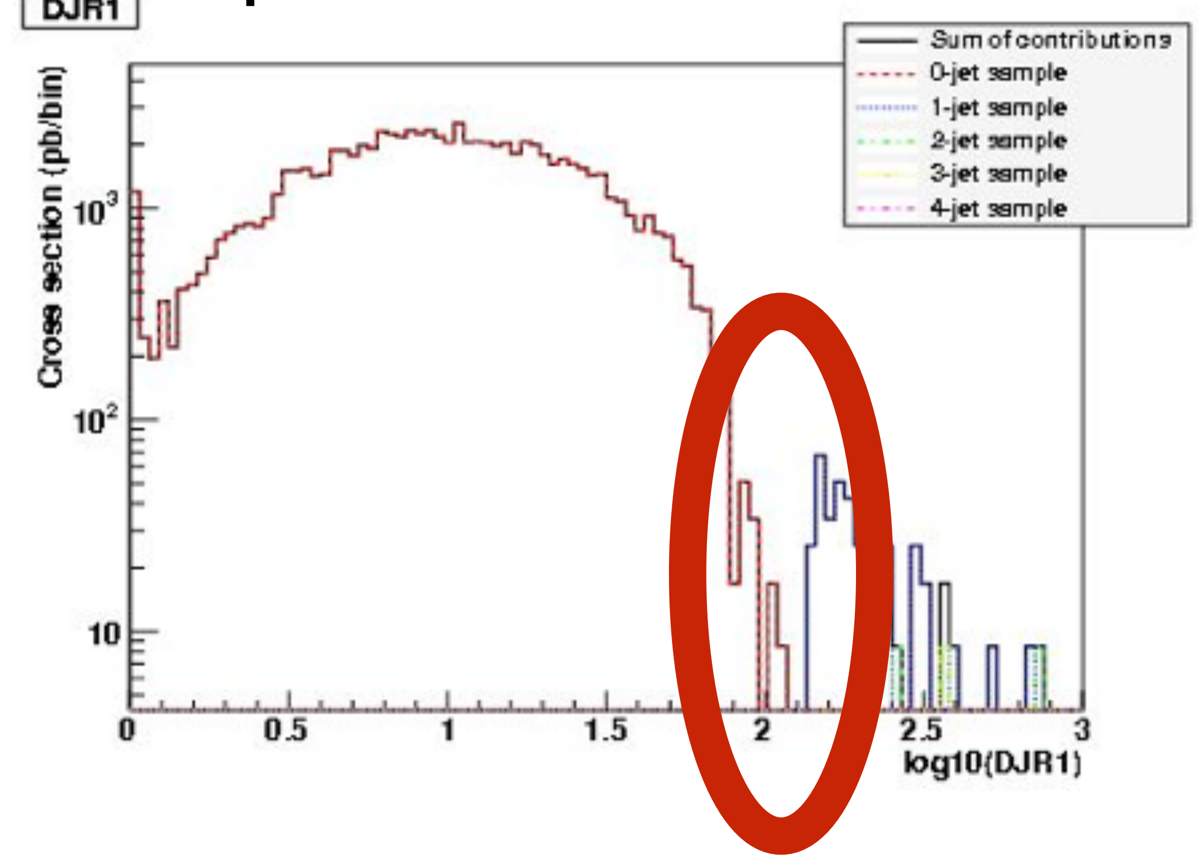
xqcut=100GeV



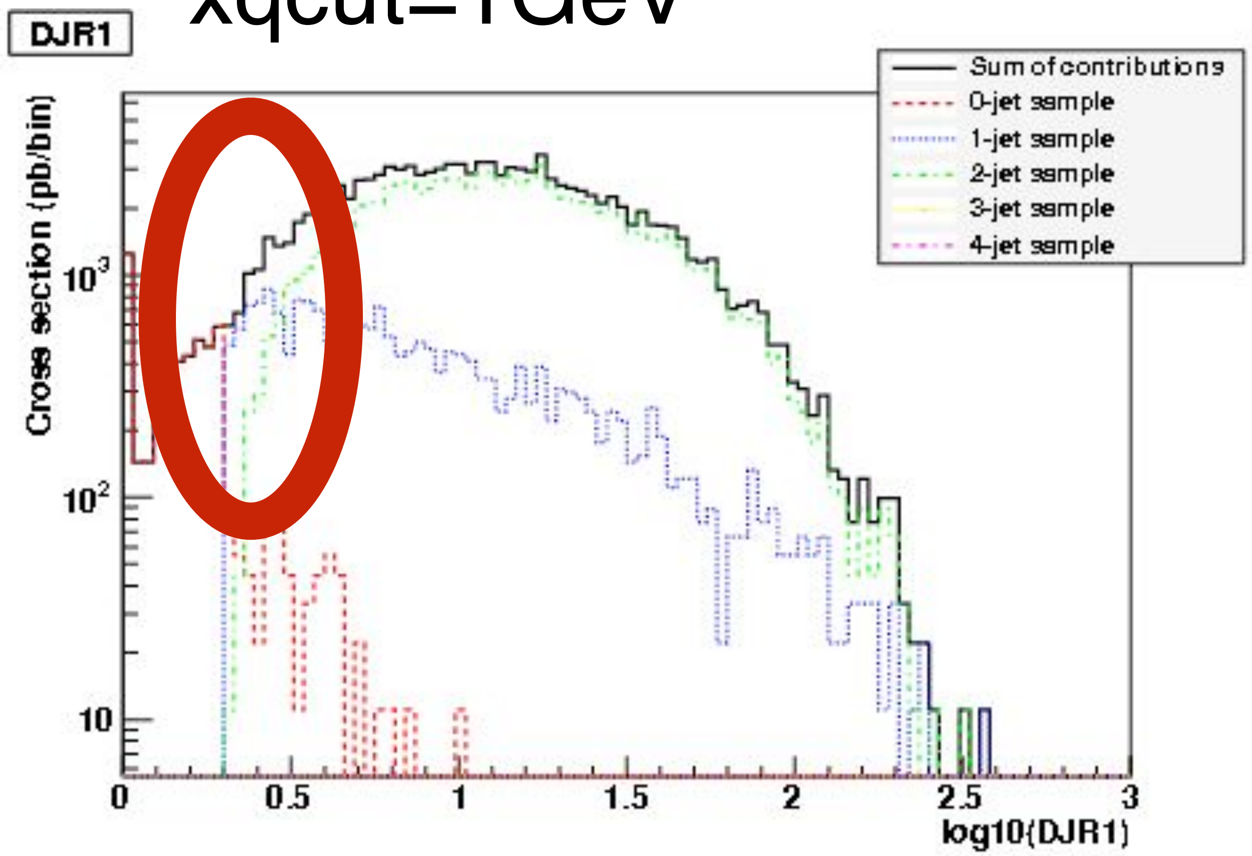
xqcut=1GeV



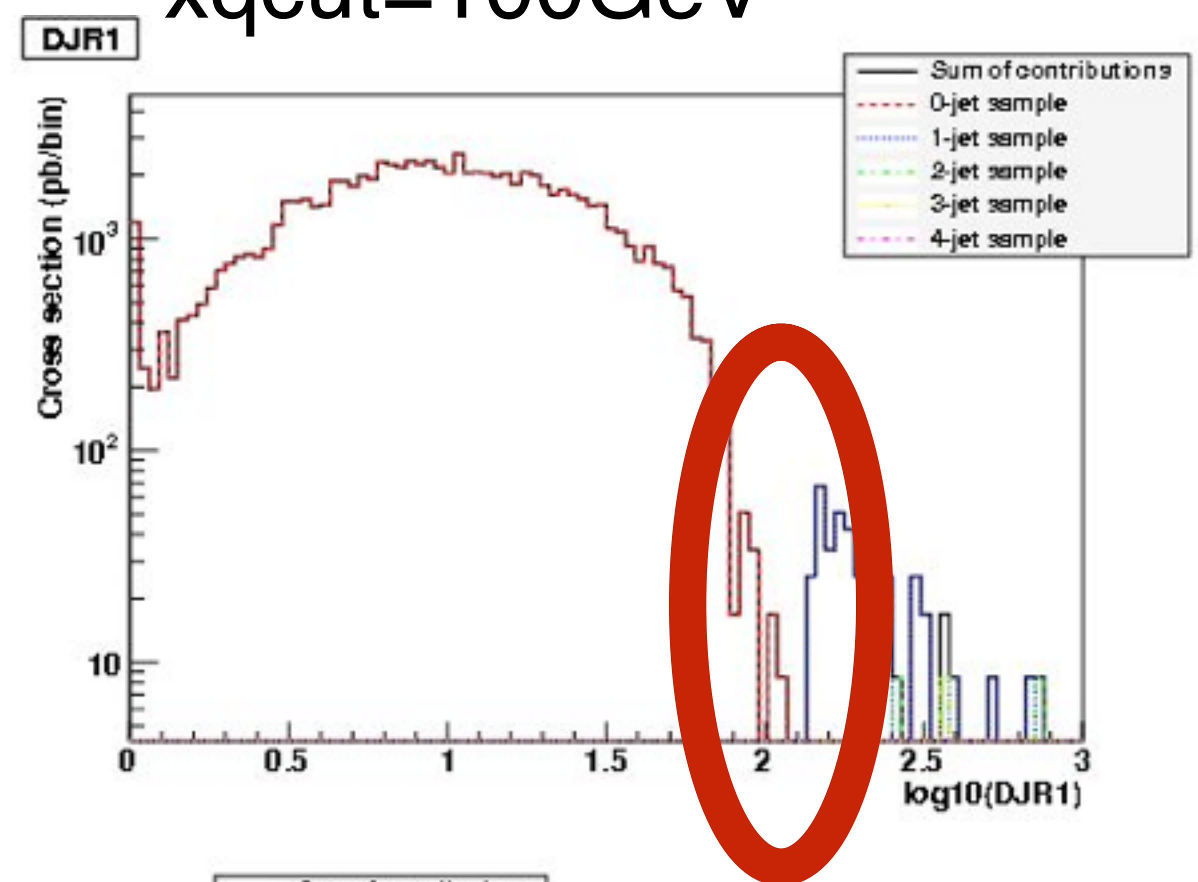
xqcut=100GeV

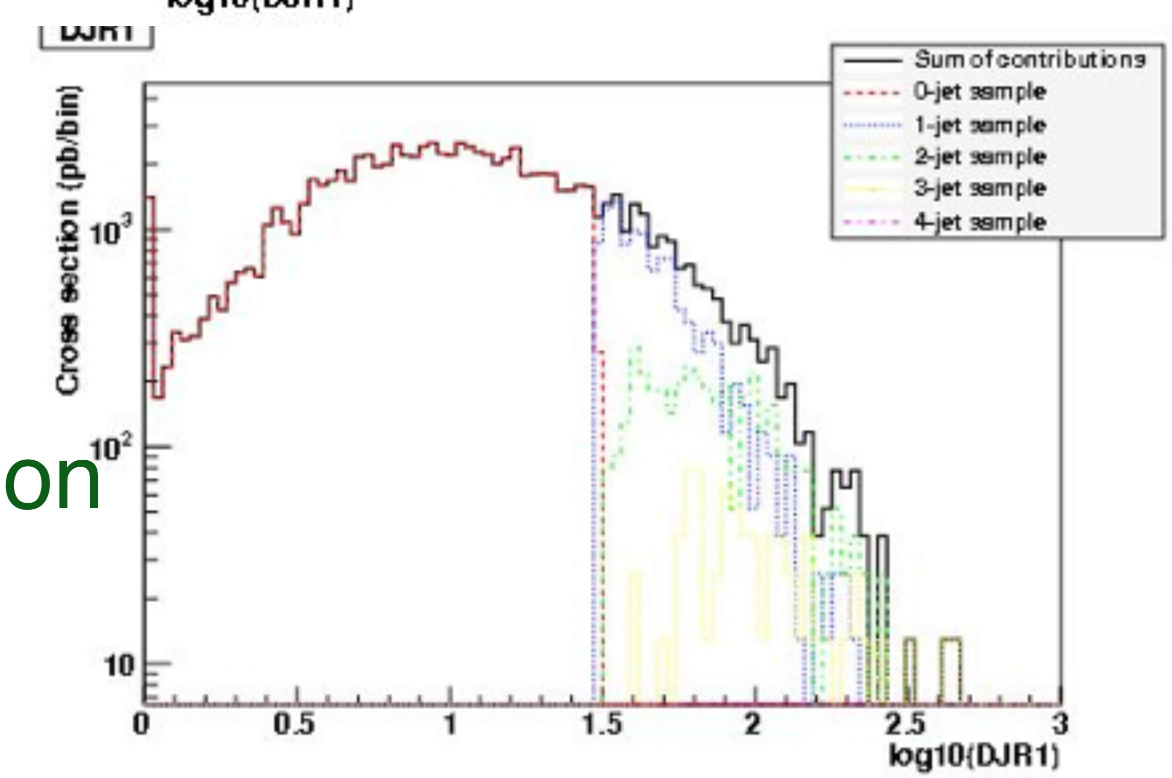


xqcut=1GeV



xqcut=100GeV





xqcut=20GeV

smooth transition

Exercise VI: Matching+Merging

	w+0j	w+1j	w+2j	w+3j
no matching	8.35E+04	1.58E+04	8.7E+03	3.5E+03

	1GeV	10GeV	20GeV	50GeV	100GeV	500GeV
w+0	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04	8.35E+04
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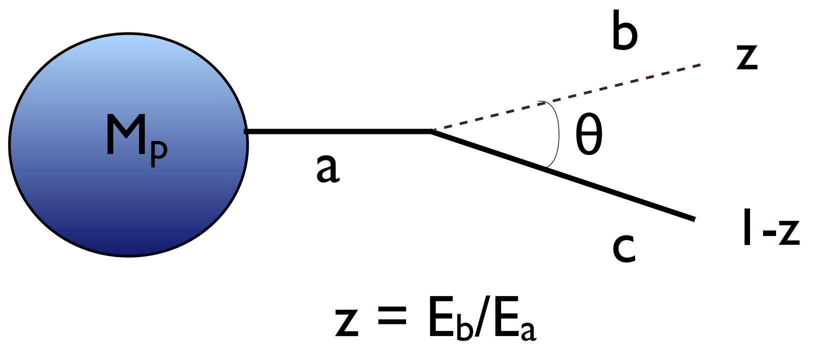
0+1+2	1.12E+05	9.29E+04	9.03E+04	8.66E+04	8.44E+04	8.35E+04
0+1+2+3	1.20E+05	9.47E+04	9.07E+04	8.68E+04	8.40E+04	8.35E+04

- Relatively stable cross-section! Important check.
- Close to the unmatched 0j cross-section

Matching Appendix

Matrix elements involving q →q g or g → gg are strongly enhanced when the final state particles are close in the phase space:

$$\frac{1}{(p_b+p_c)^2} \simeq \frac{1}{2E_bE_c(1-\cos\theta)} = \frac{1}{t}$$



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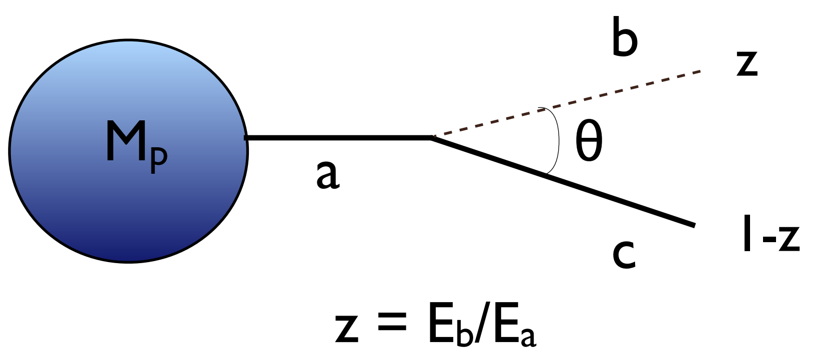
soft



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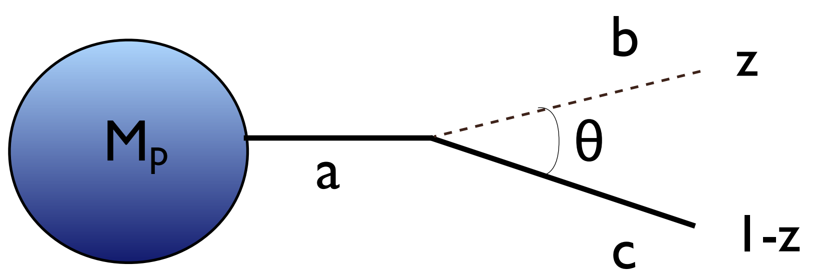
soft and collinear

divergencies



$z = E_b/E_a$

Matrix elements involving q →q g or g → gg are strongly enhanced when the final state particles are close in the phase space:

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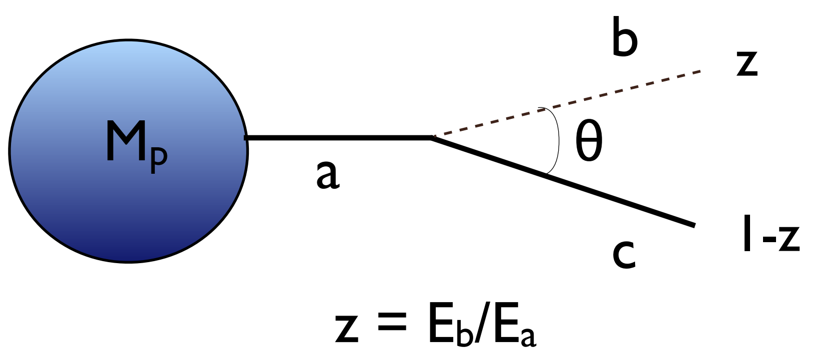

soft and collinear

divergencies

Collinear factorization:

$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \simeq |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

when θ is small.

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

Matrix Elements vs. Parton Showers

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

Matrix Elements vs. Parton Showers

ME	Shower MC
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	1. Resums logs to all orders 2. Computationally cheap 3. No limit on particle multiplicity 4. Valid when partons are collinear and/or soft 5. Partial interference through angular ordering 6. Needed for hadronization

Approaches are complementary: merge them!

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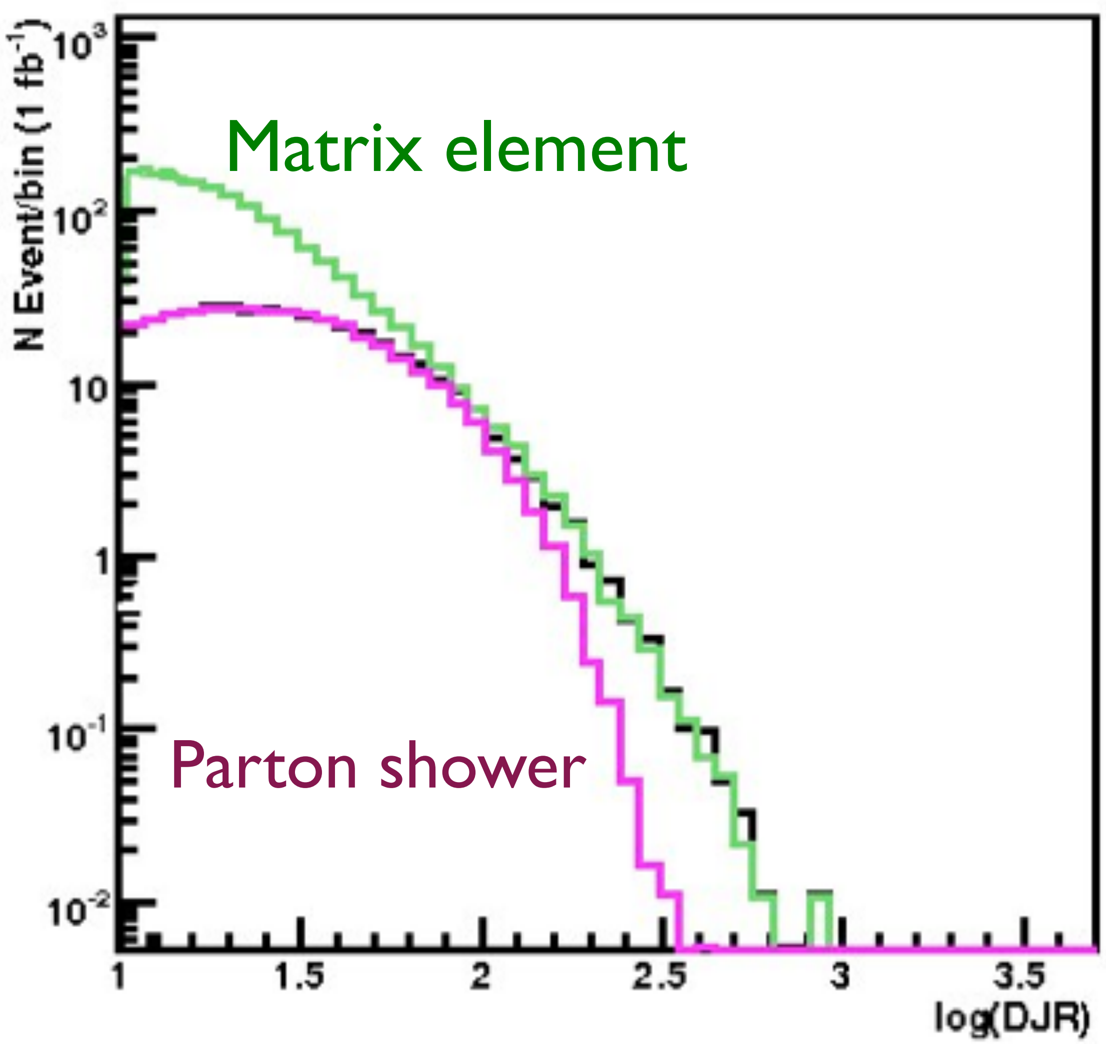
4. Valid when partons are collinear and/or soft
5. Partial interference through angular ordering
6. Needed for hadronization

Approaches are complementary: merge them!

Difficulty: avoid double counting, ensure smooth distributions

Goal for ME-PS merging/matching

- Regularization of matrix element divergence
- Correction of the parton shower for large momenta
- Smooth jet distributions



2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

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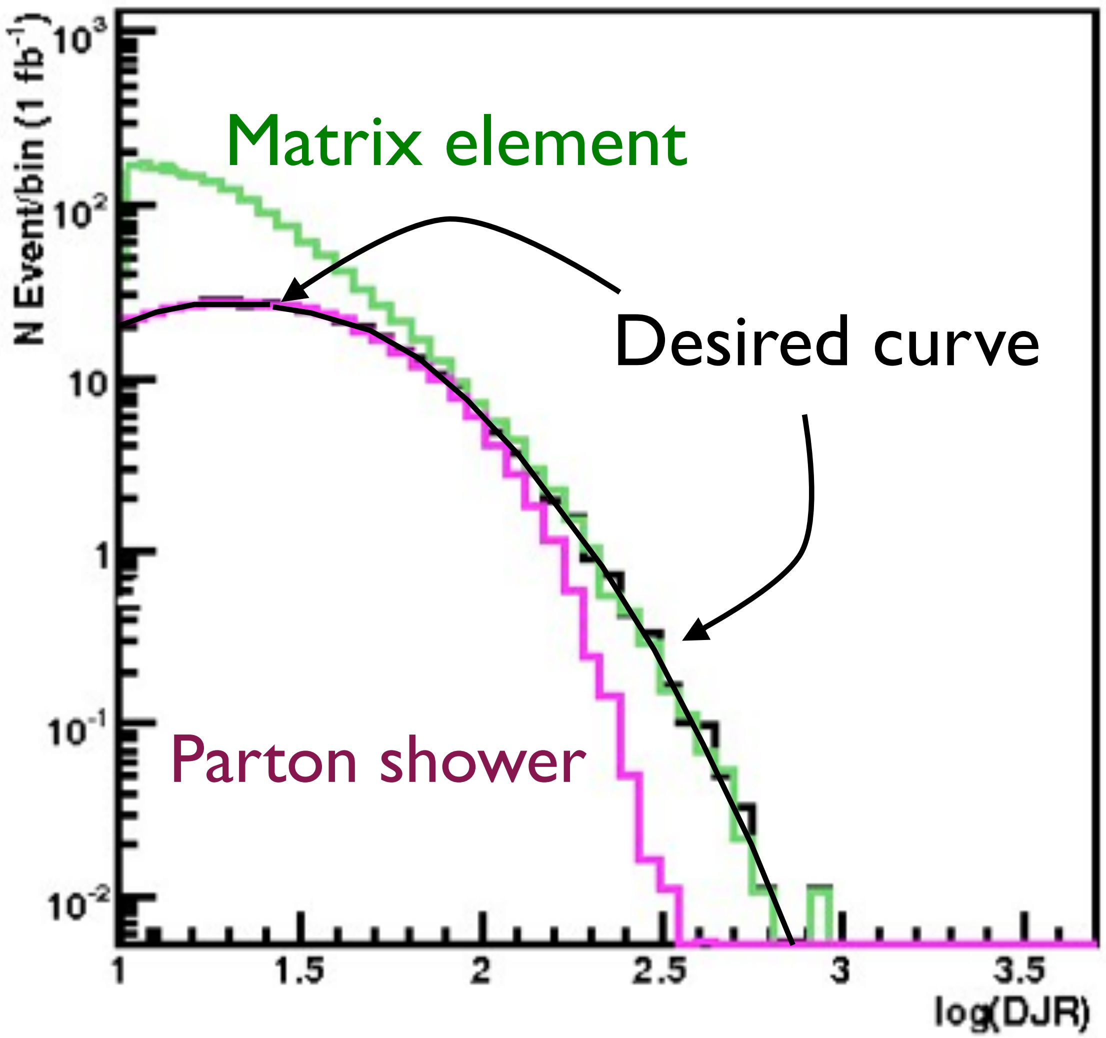
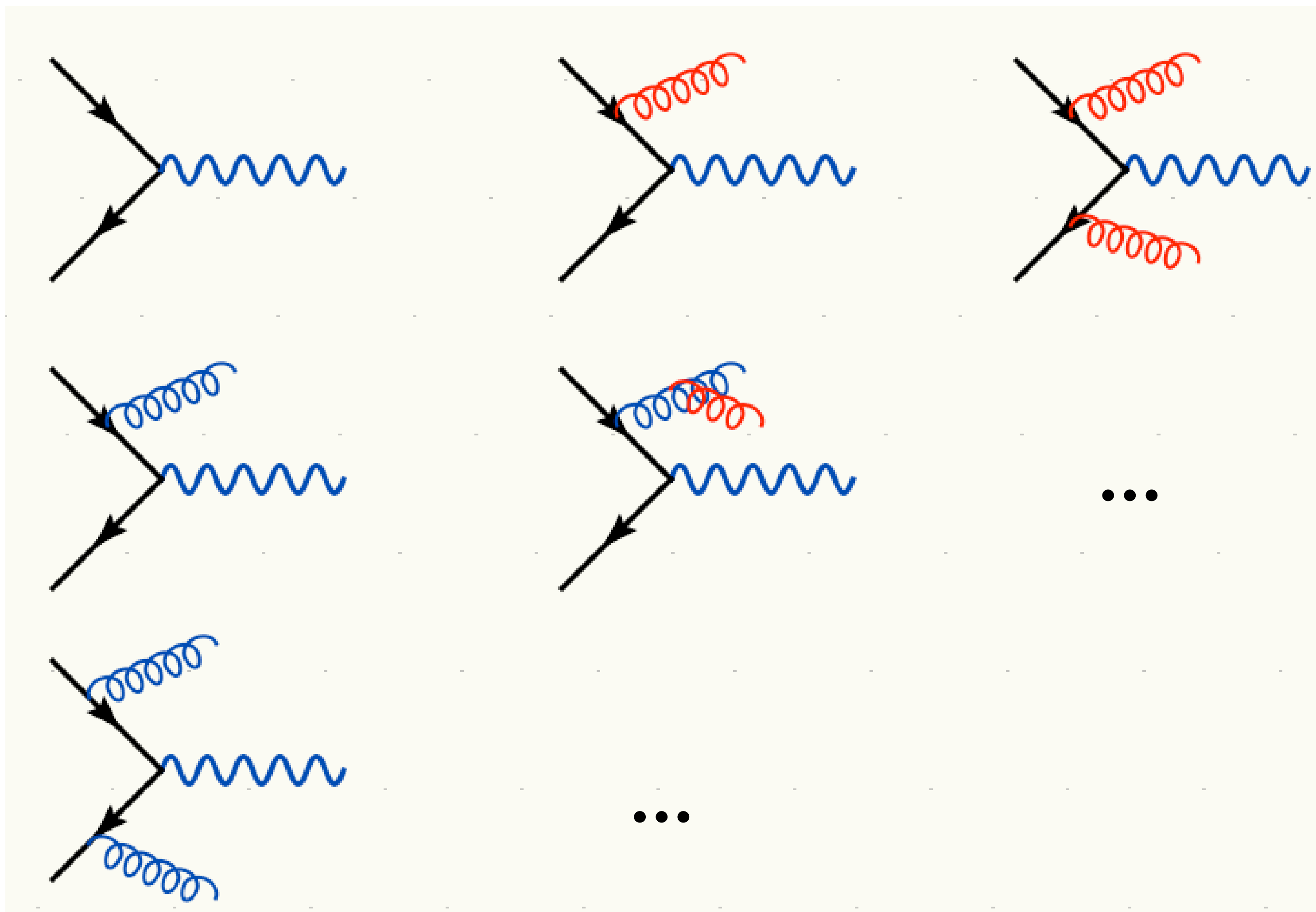


2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

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

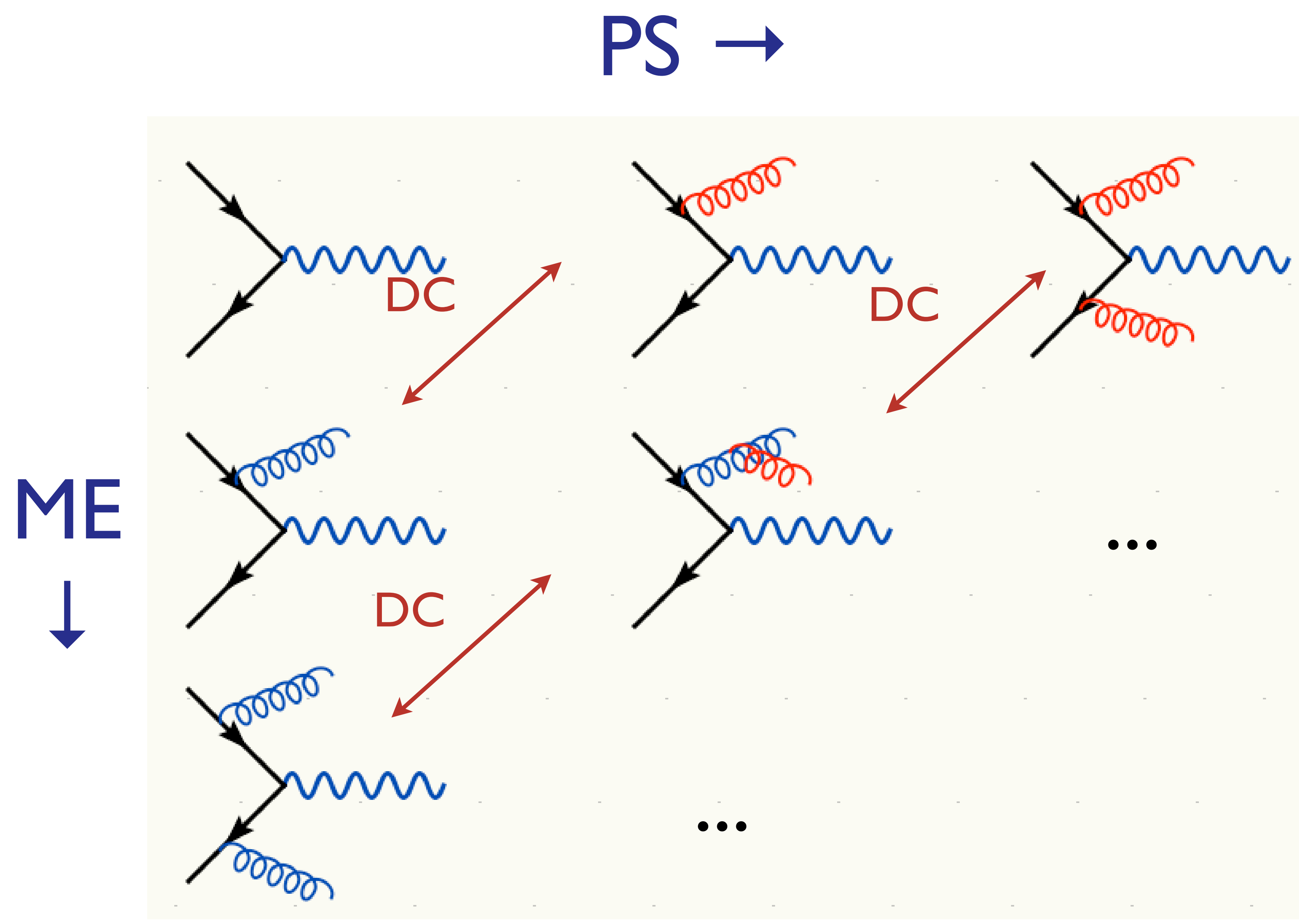
PS →

ME ↓



Merging ME with PS

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



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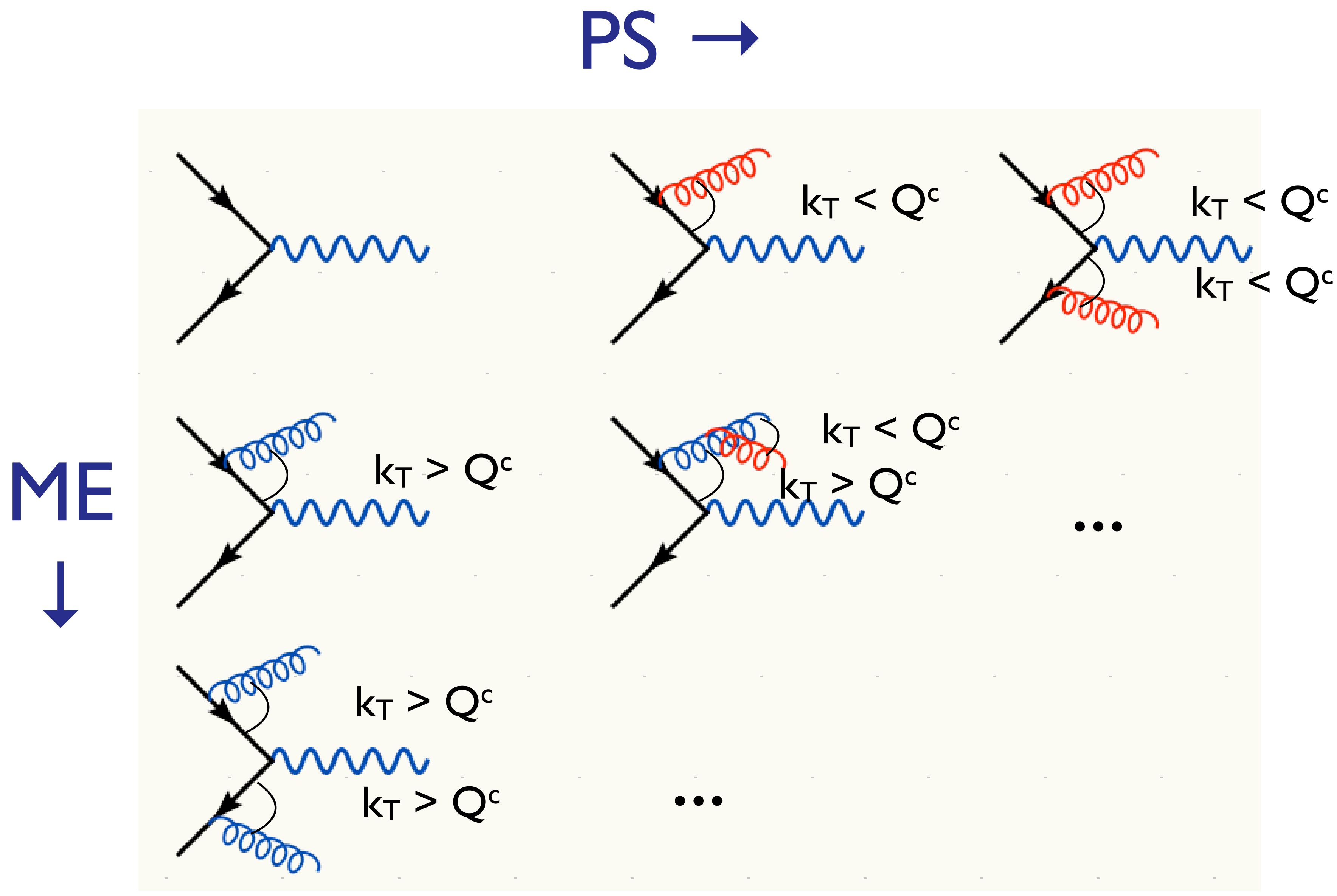

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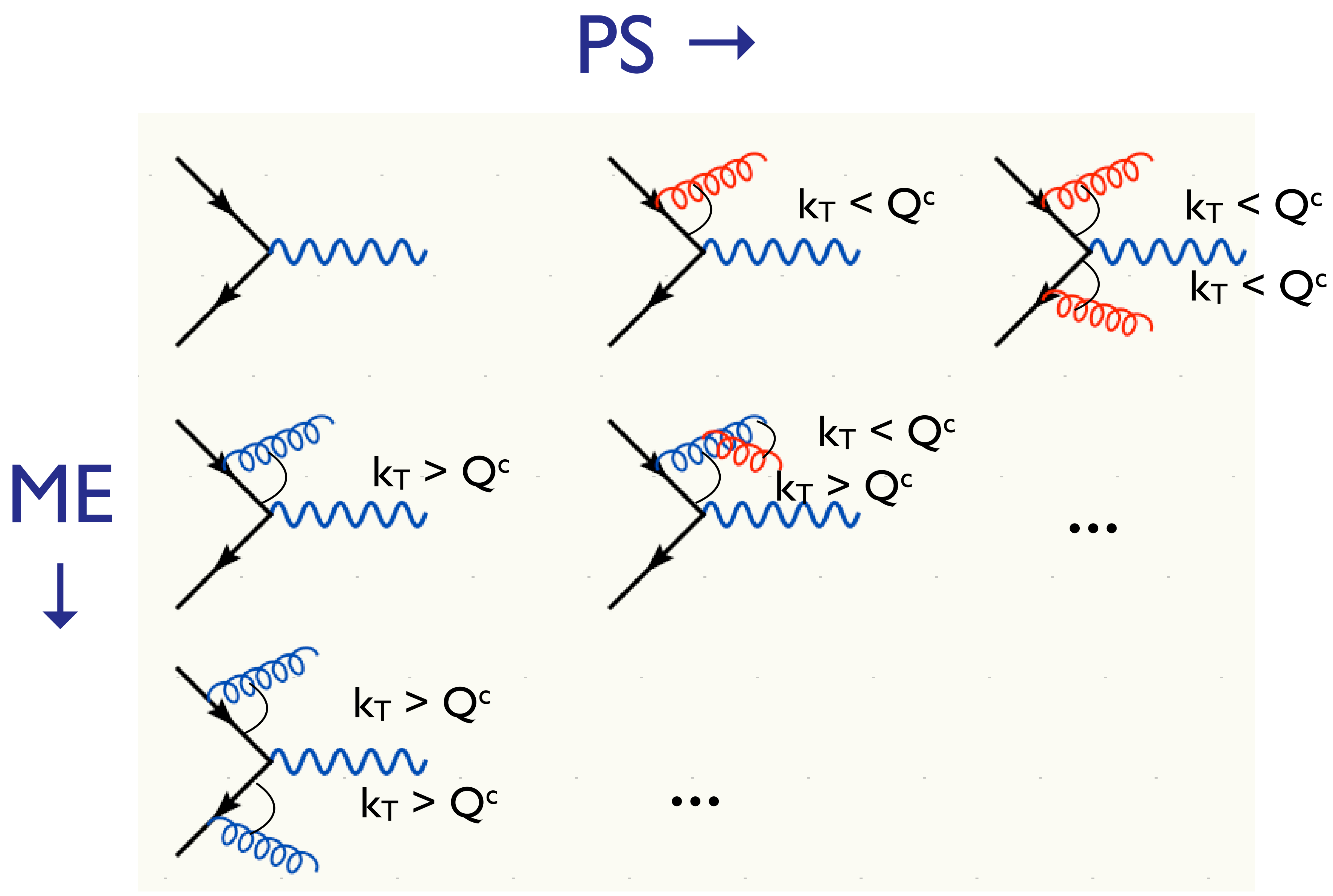
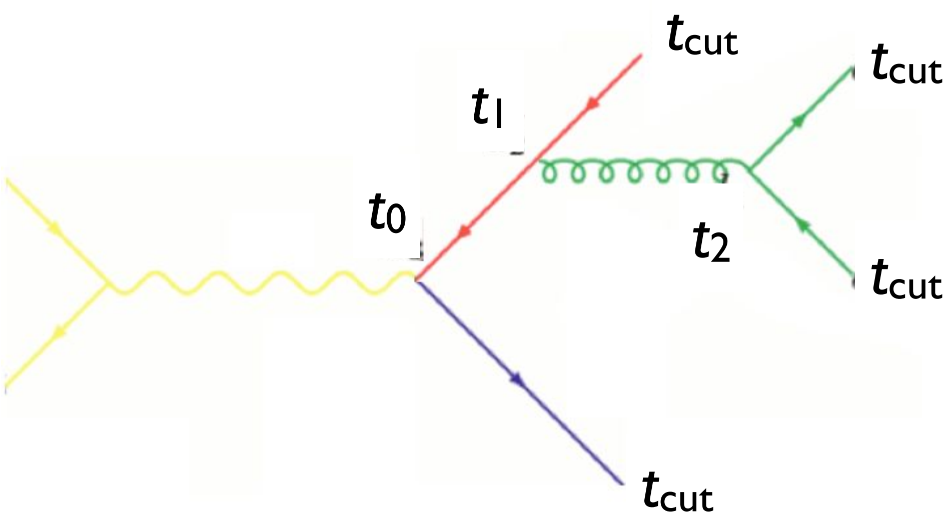


Double counting between ME and PS easily avoided using phase space cut between the two: PS below cutoff, ME above cutoff.

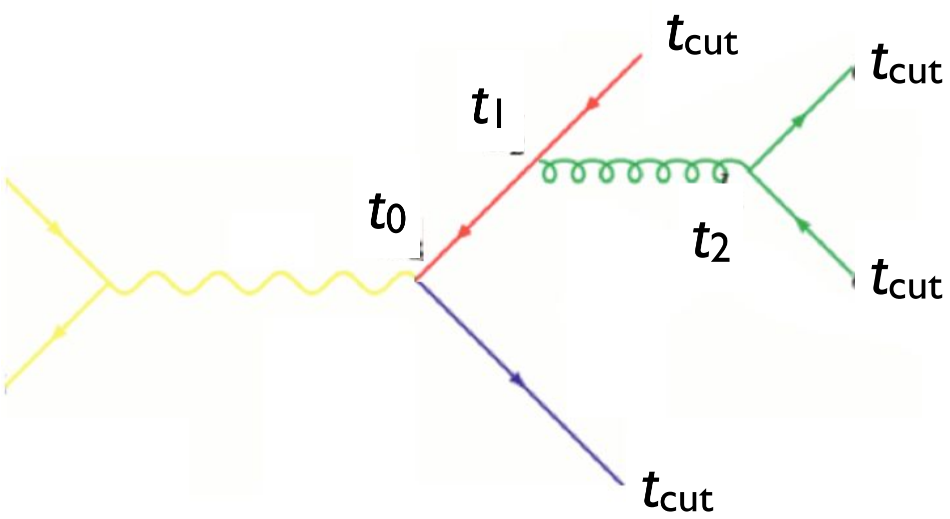
Merging ME with PS

- So double counting problem easily solved, 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!

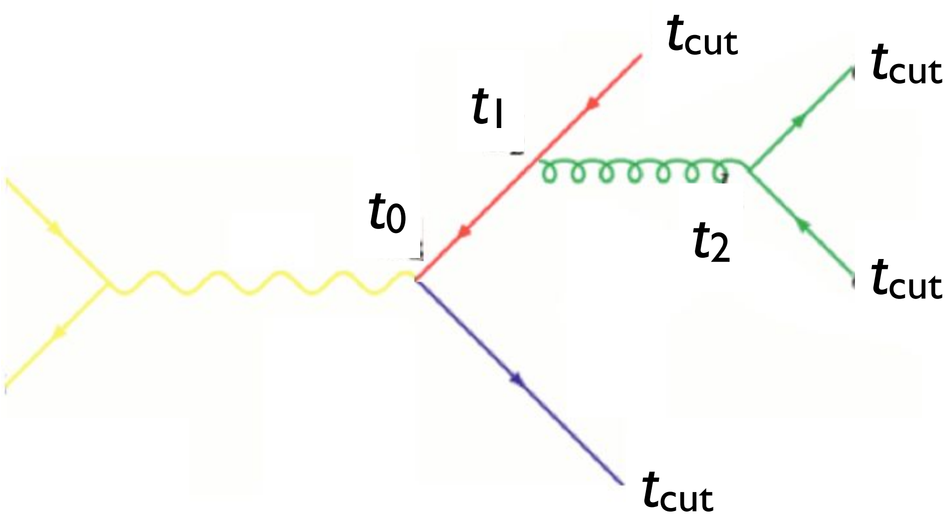
Merging ME with PS



Merging ME with PS



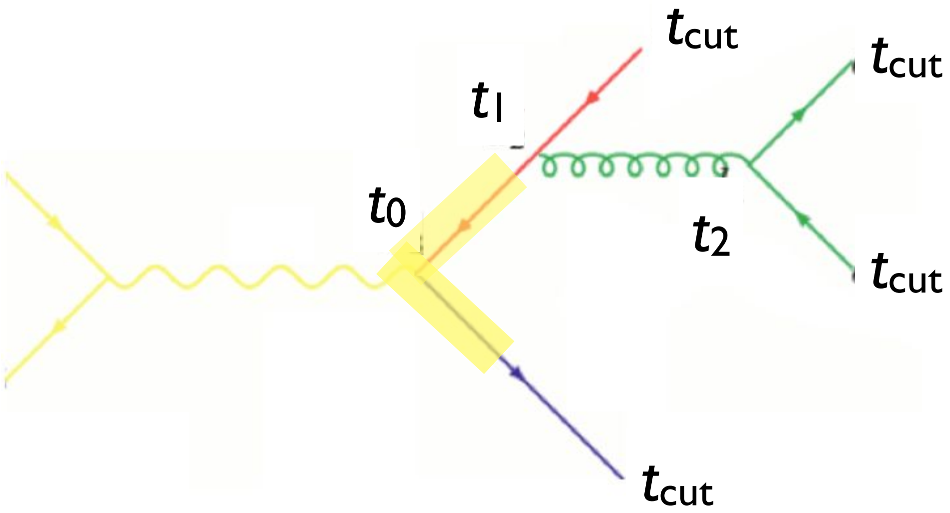
- How does the PS generate the configuration above?



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

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

Merging ME with PS



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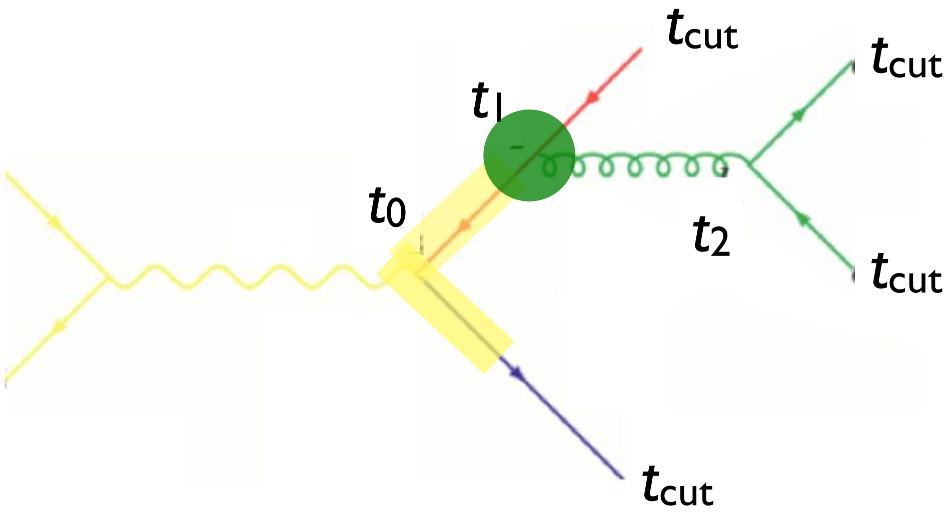

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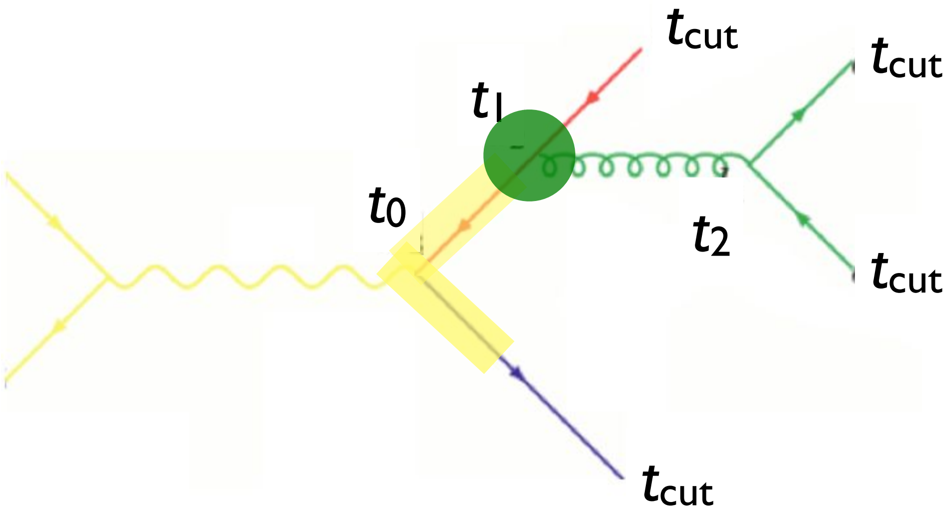

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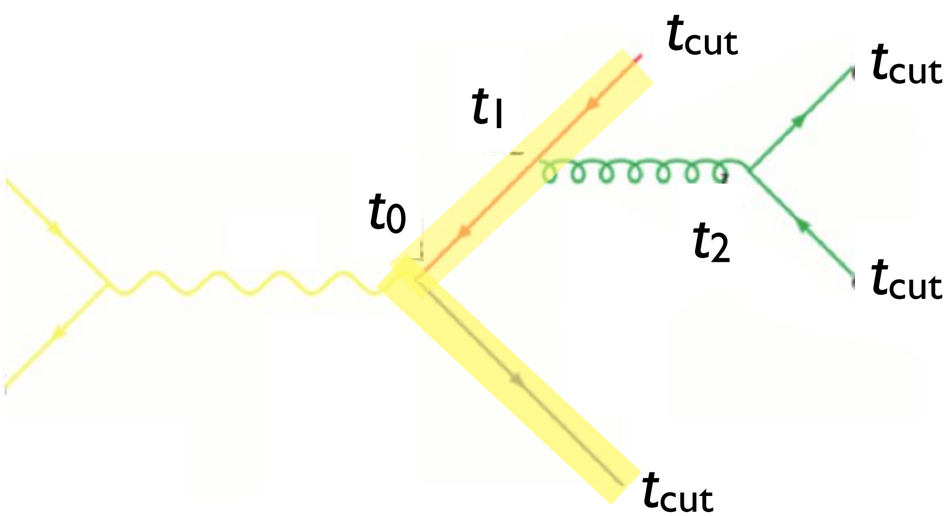
- Probability for the splitting at t_1 is given by

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

and for the whole tree

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

Merging ME with PS



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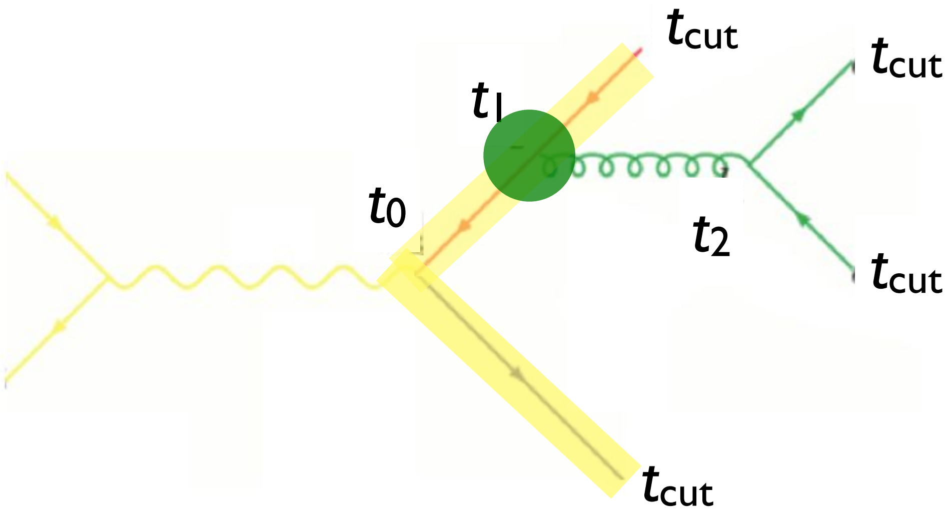
$$(\Delta_q(t_1, t_0))^2 \frac{\alpha_s(t_1)}{2\pi} P_{gq}(z)$$

and for the whole tree

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



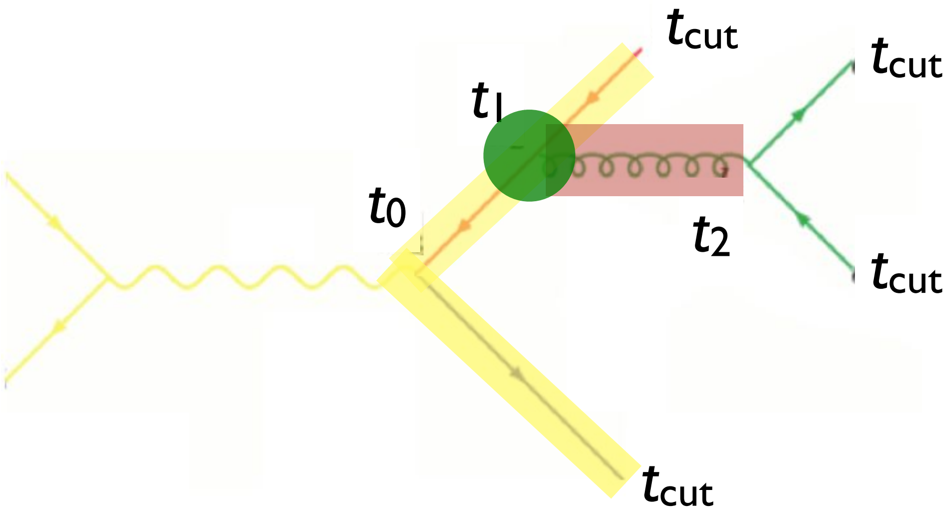
- How does the PS generate the configuration above?
- Probability for the splitting at t_1 is given by

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

and for the whole tree

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

Merging ME with PS



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

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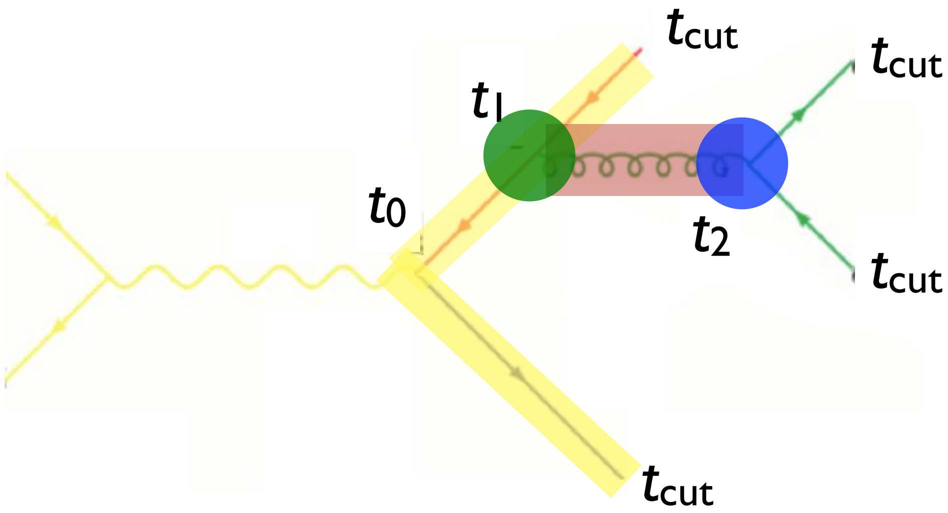

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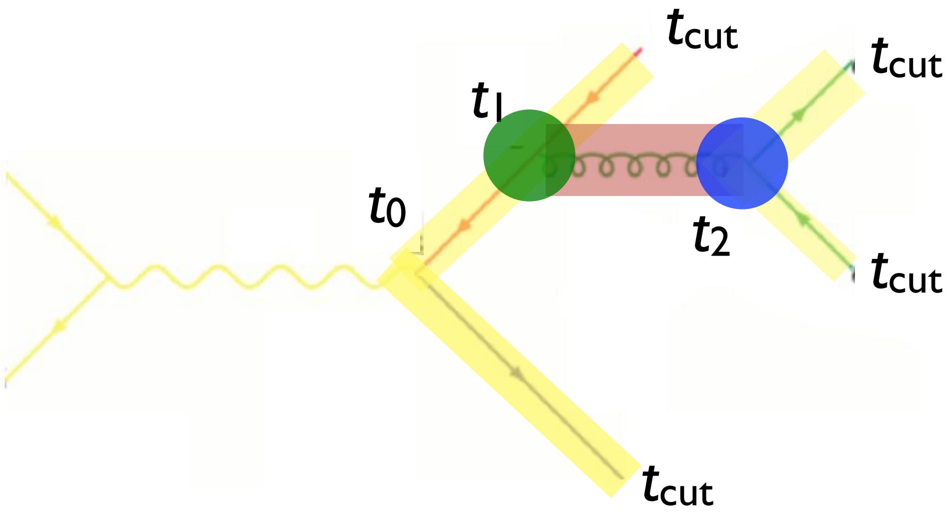

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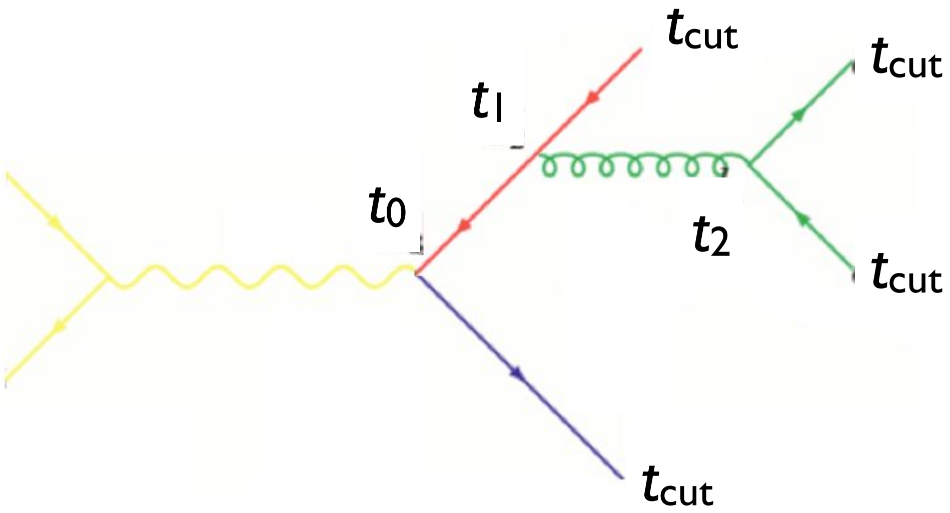

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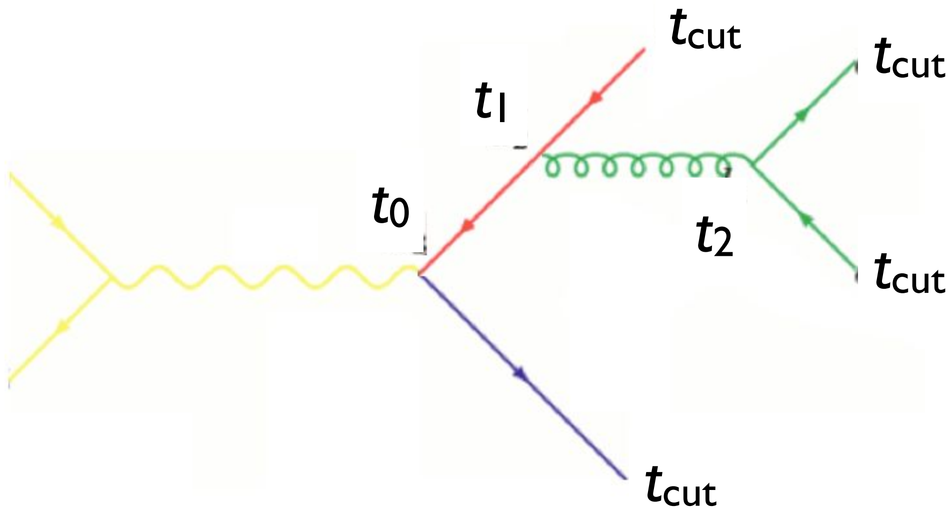

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Corresponds to the matrix element
BUT with α_s evaluated at the scale of each splitting

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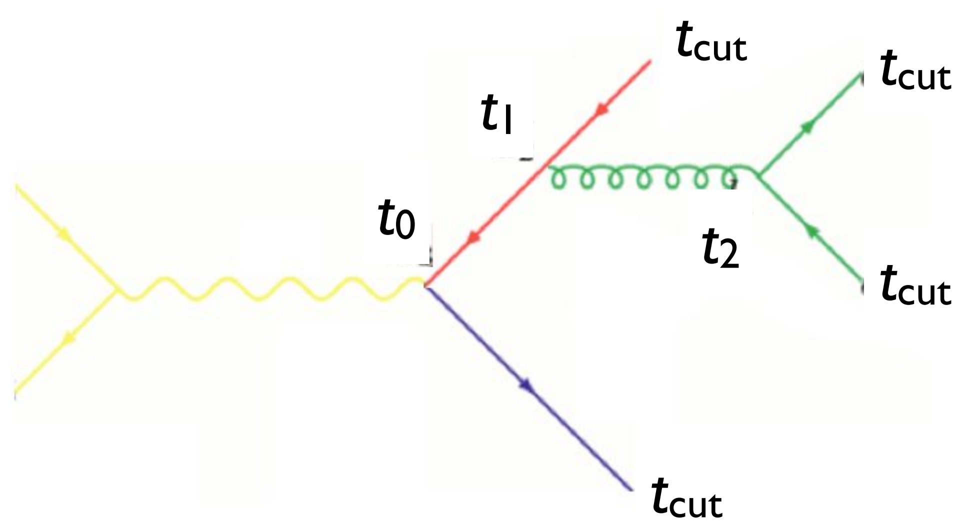

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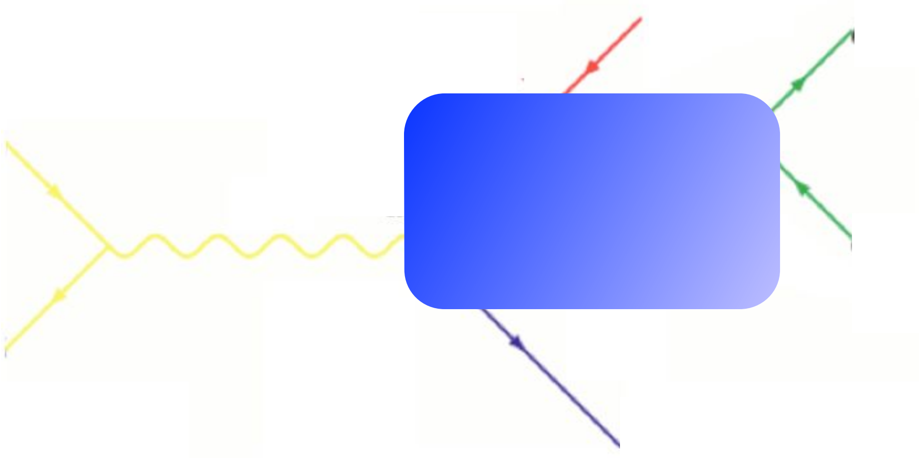
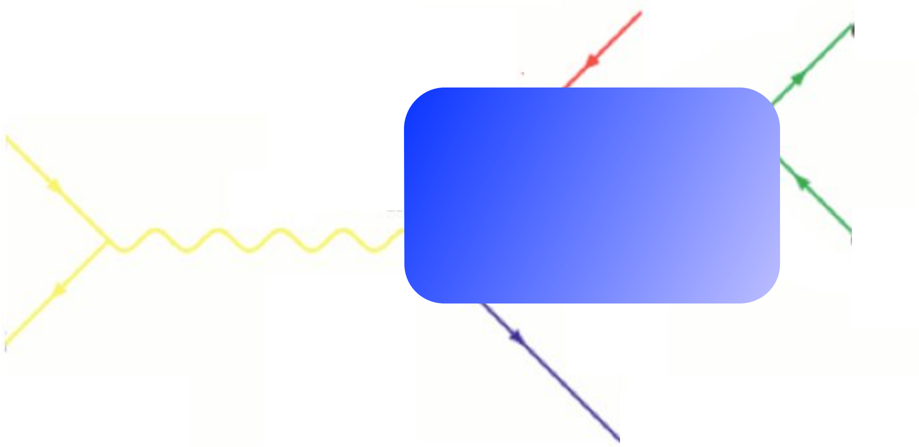
Sudakov suppression due to disallowing additional radiation above the scale t_{cut}

Merging ME with PS



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



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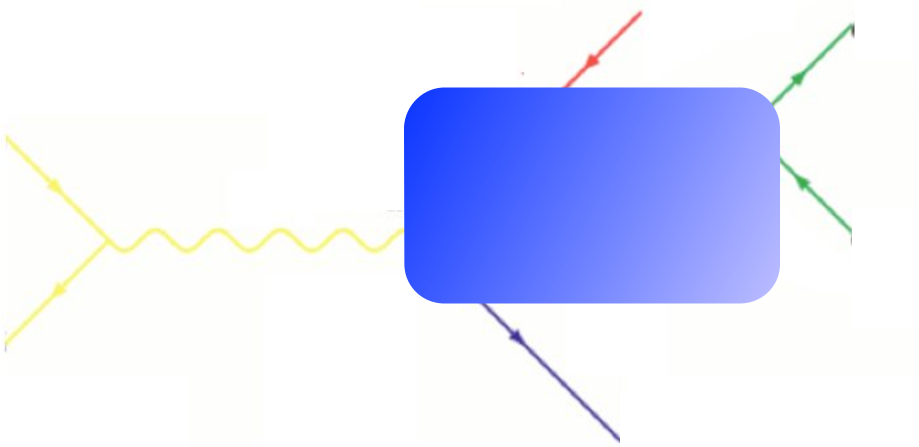

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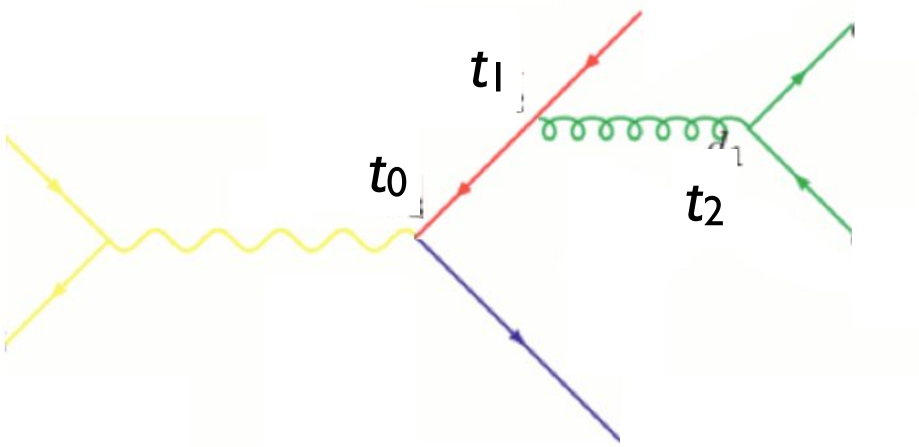

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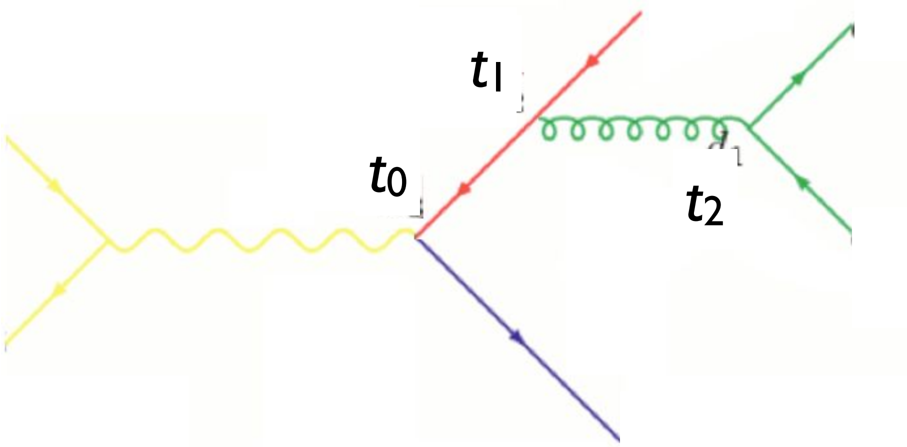

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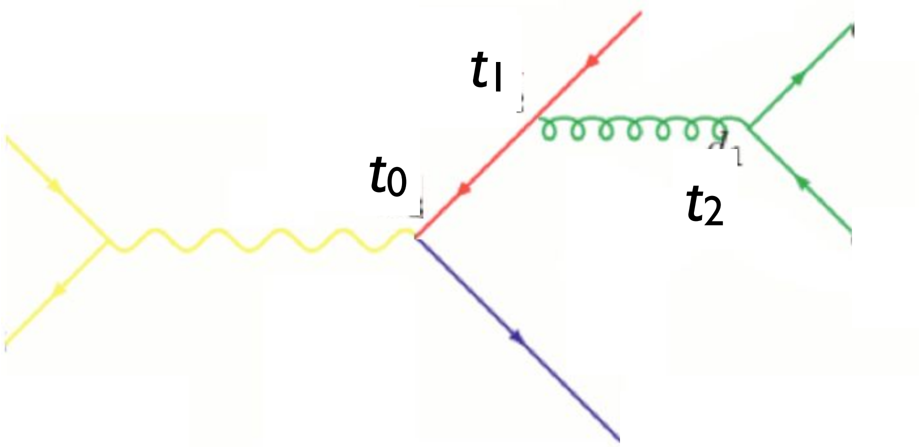

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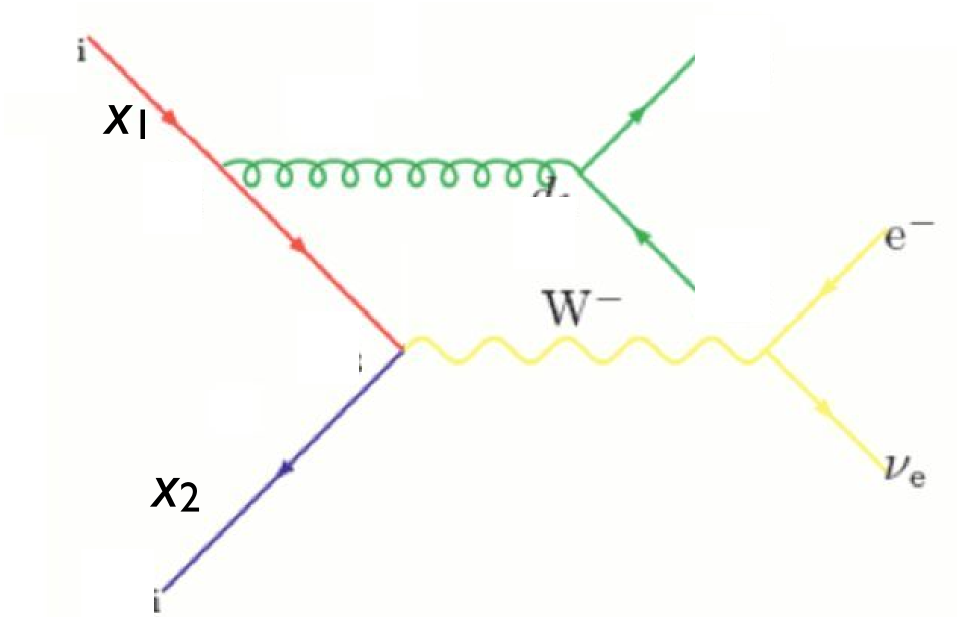
3. Use some algorithm to apply the equivalent Sudakov suppression $(\Delta_q(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q(_{\text{cut}}, t_2))^2$

Matching for initial state radiation



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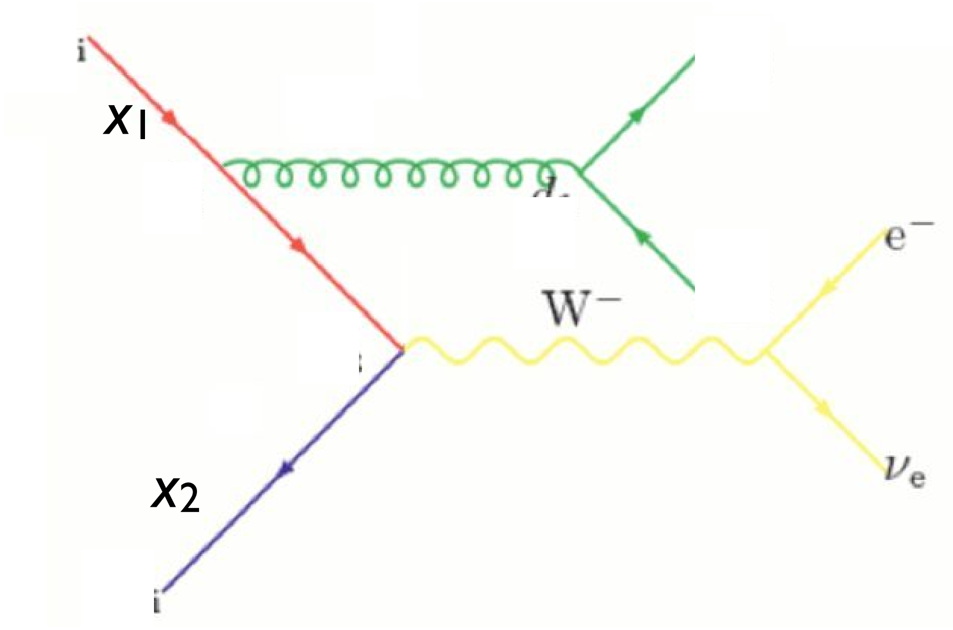

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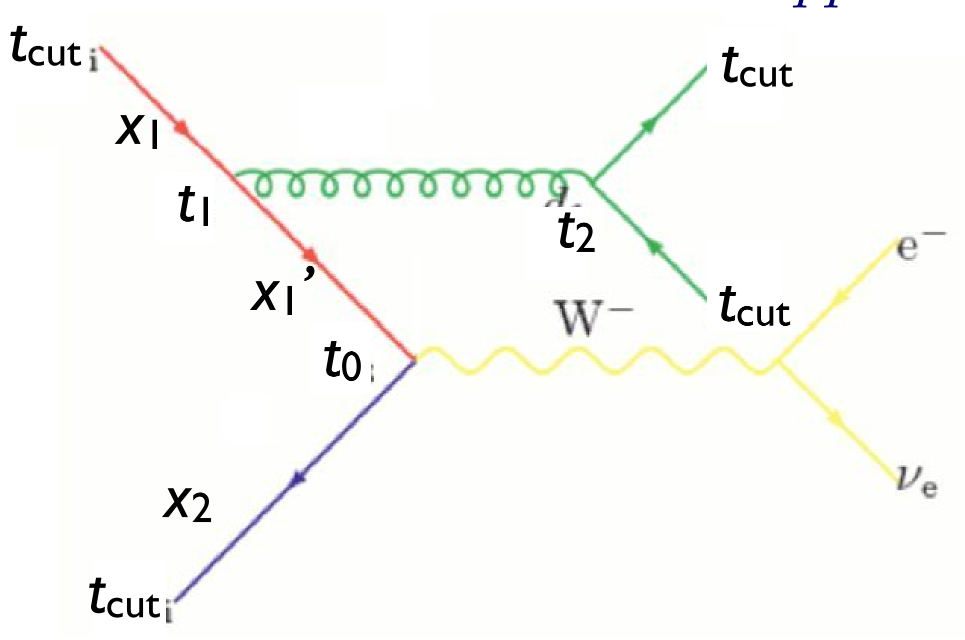

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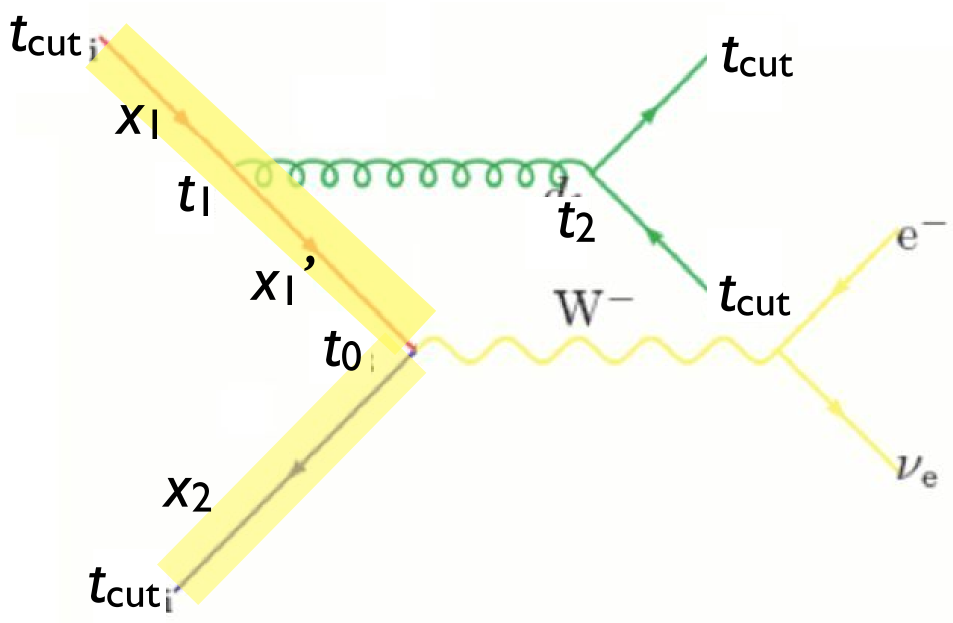

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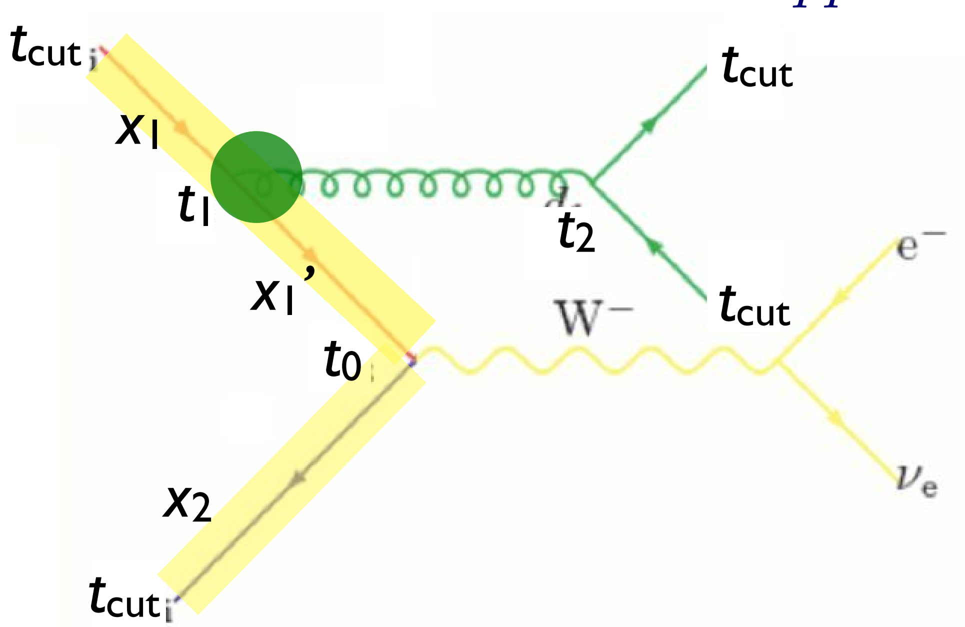

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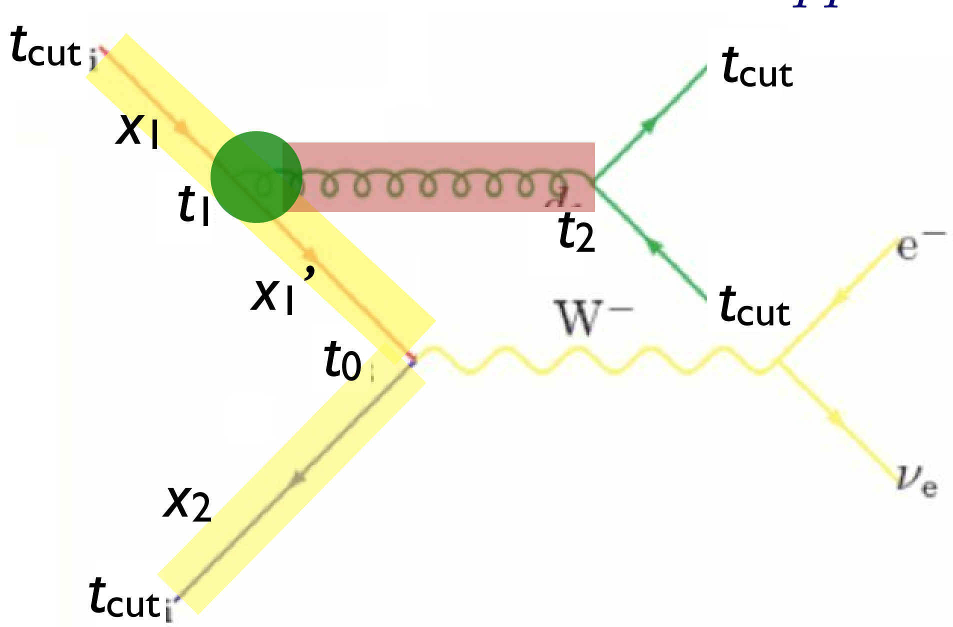

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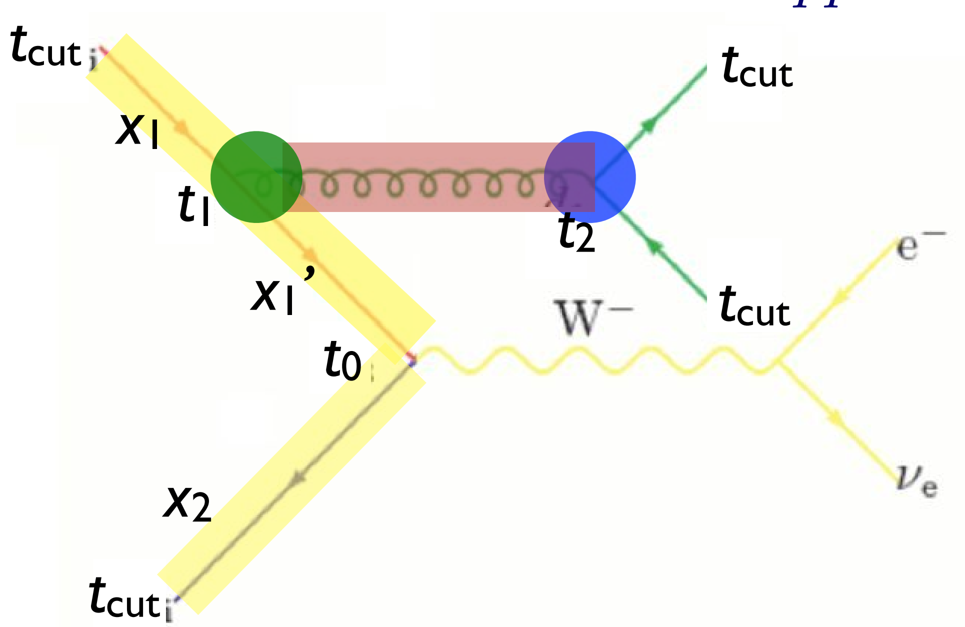

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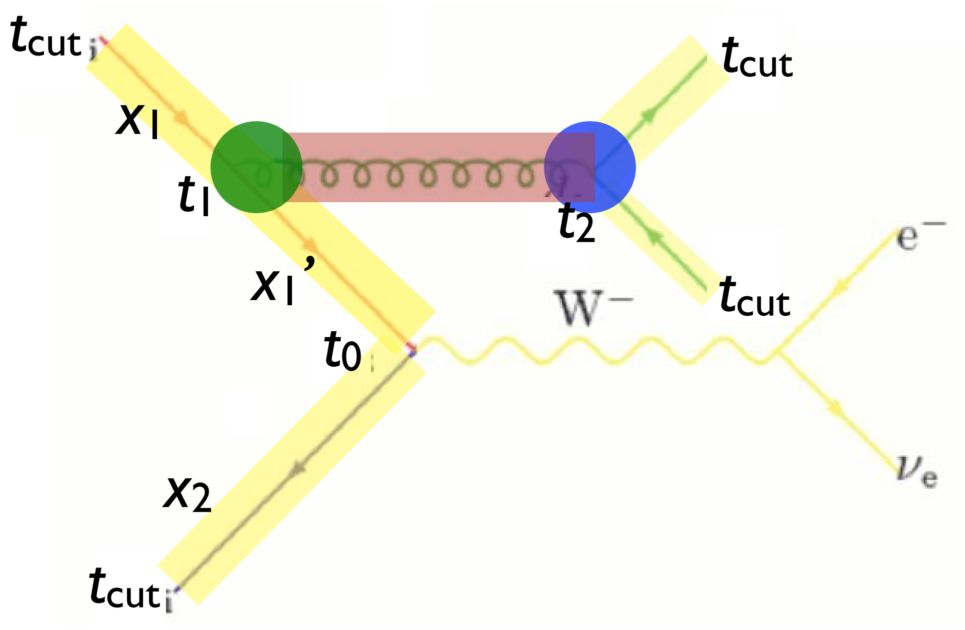

$$(\Delta_{Iq}(t_{\rm cut},t_0))^2\Delta_g(t_2,t_1)(\Delta_q(t_{\rm cut},t_2))^2\frac{\alpha_s(t_1)}{2\pi}\frac{P_{gq}(z)}{z}\frac{f_q(x_1,t_1)}{f_q(x'_1,t_1)}\frac{\alpha_s(t_2)}{2\pi}P_{qg}(z')$$
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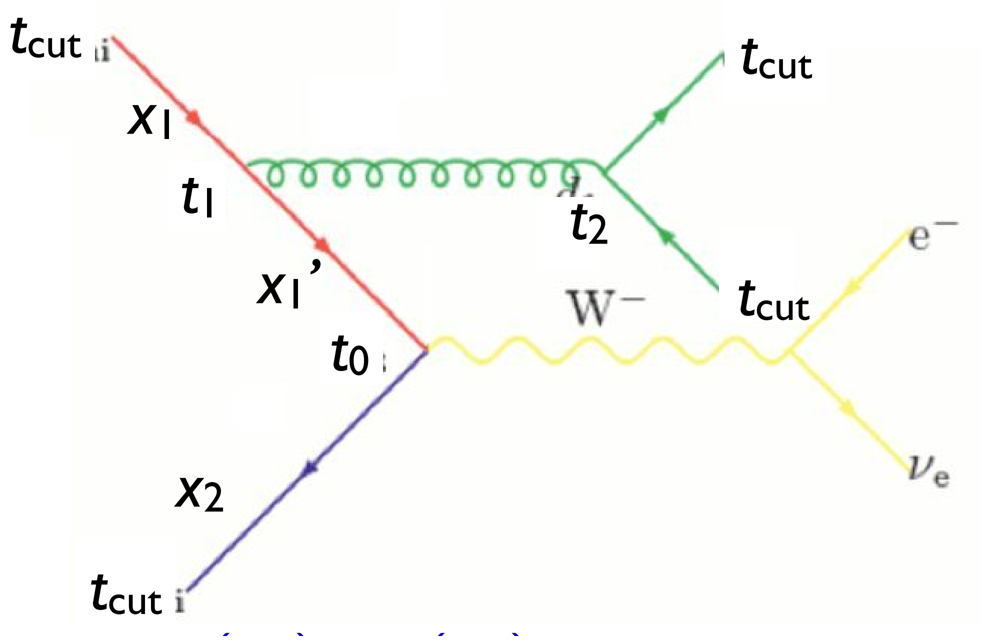

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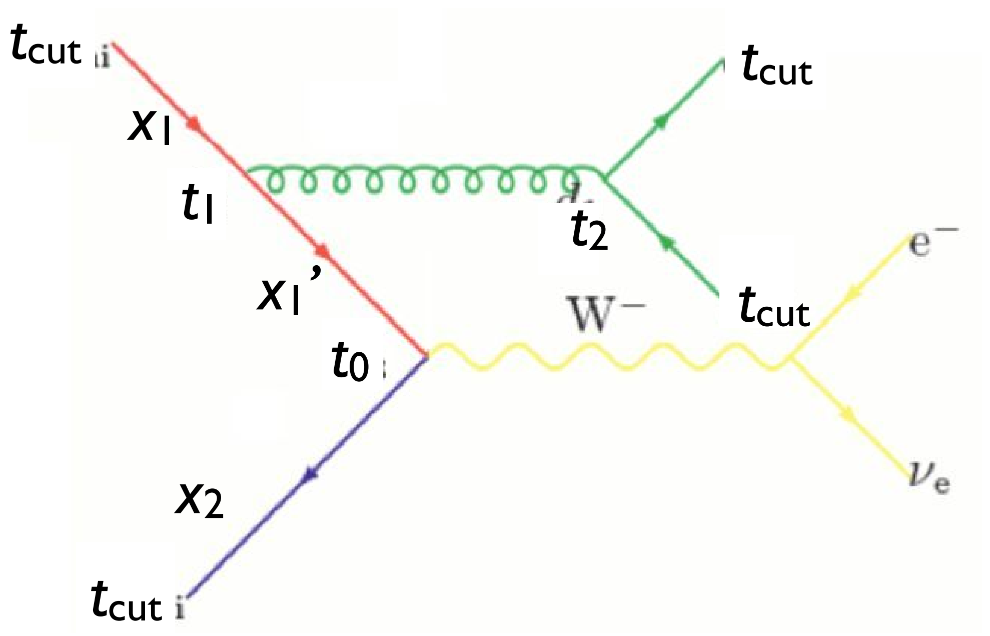
ME with α_s evaluated at the scale of each splitting



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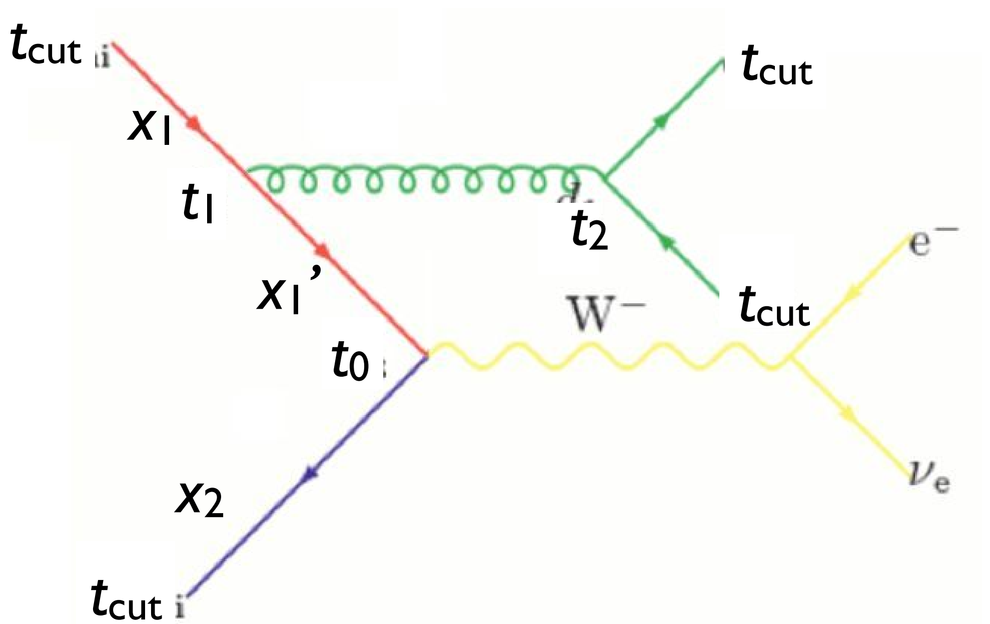
PDF reweighting



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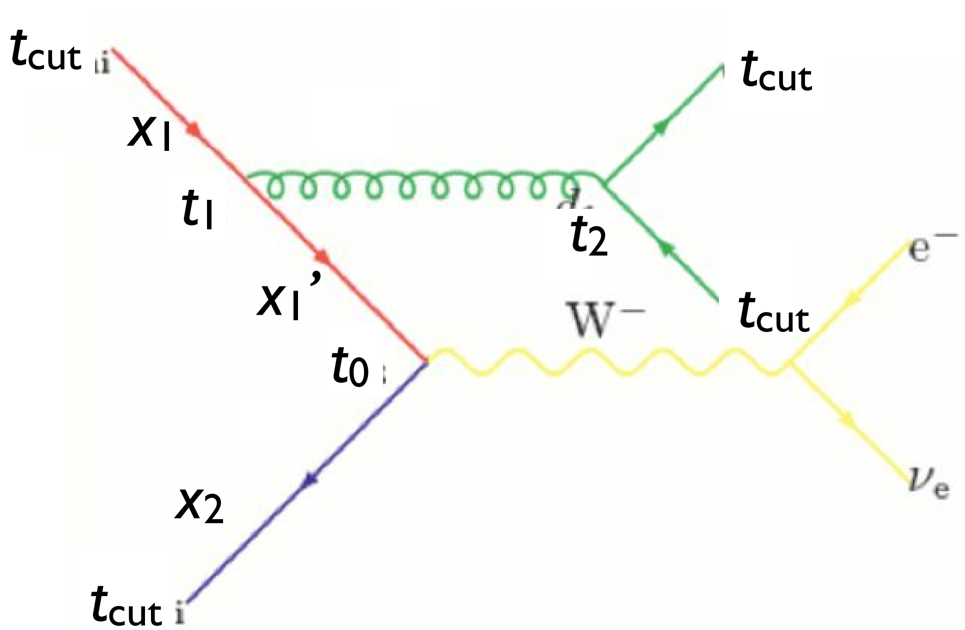
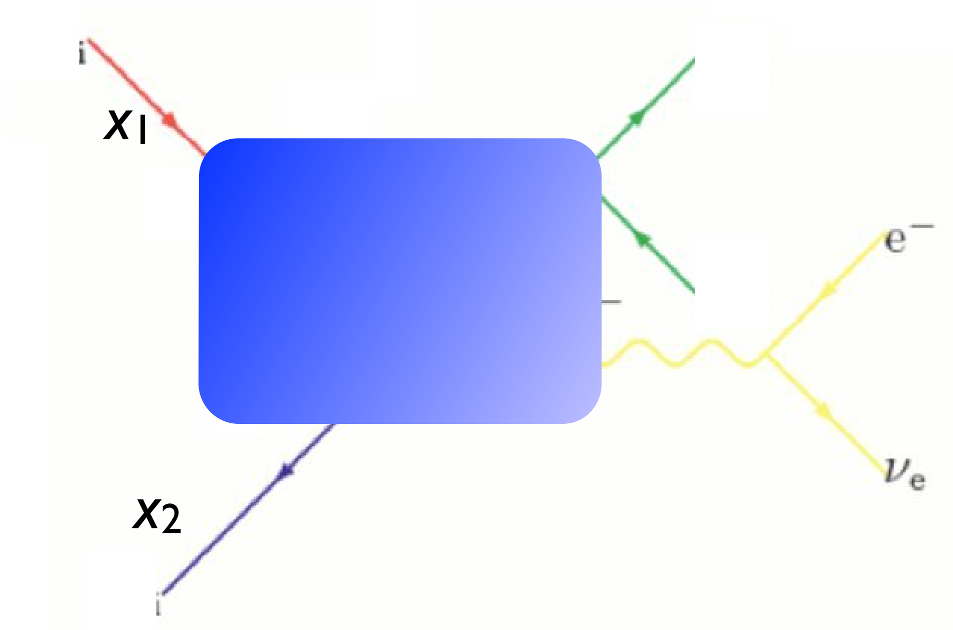
PDF reweighting

Sudakov suppression due to non-branching above scale $t_{\rm cut}$

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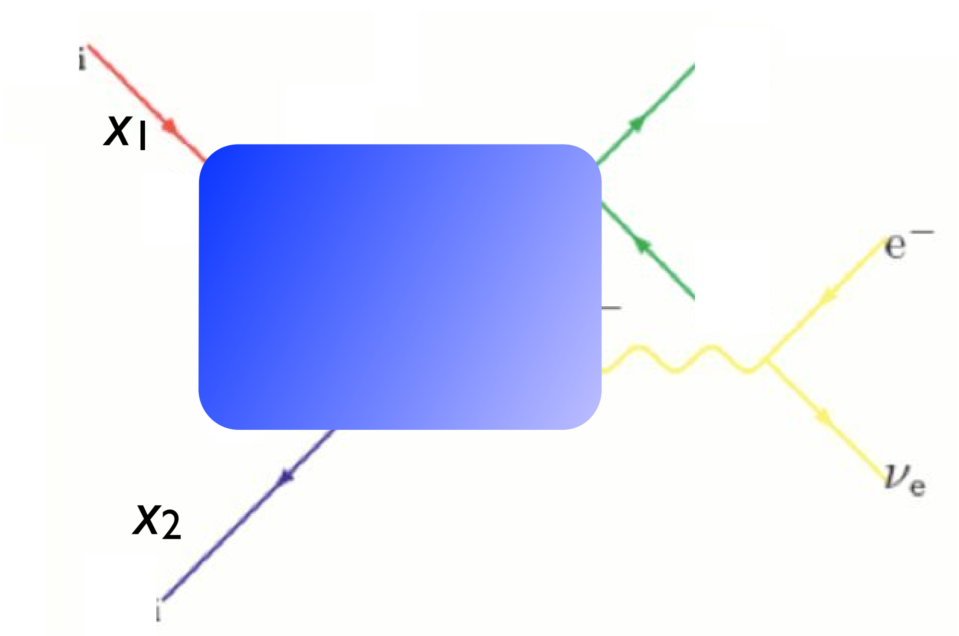
i

- Again, use a clustering scheme to get a parton shower history



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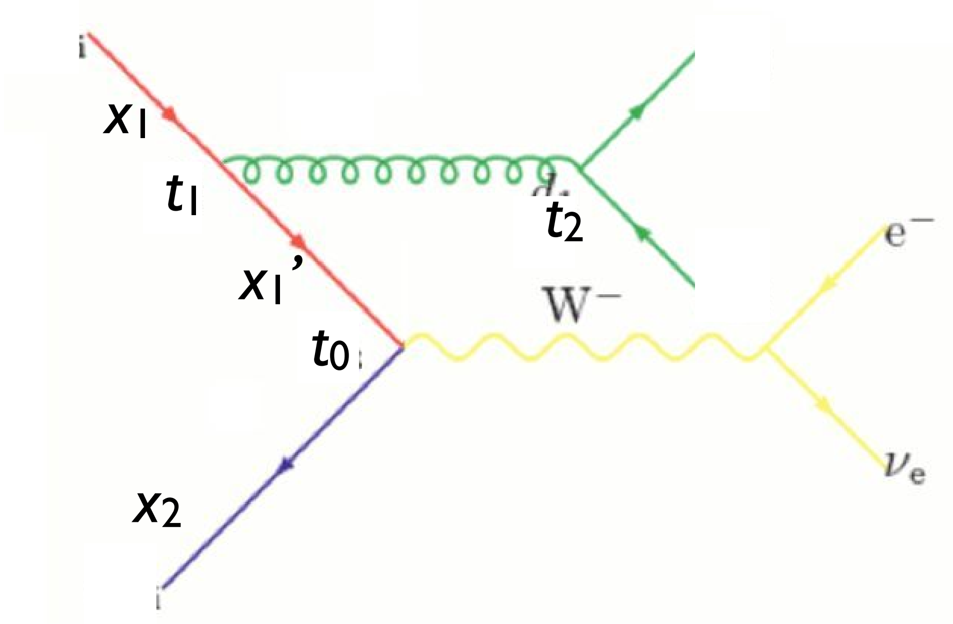

Matching for initial state radiation

- Again, use a clustering scheme to get a parton shower history
- Now, reweight both due to α_s and PDF

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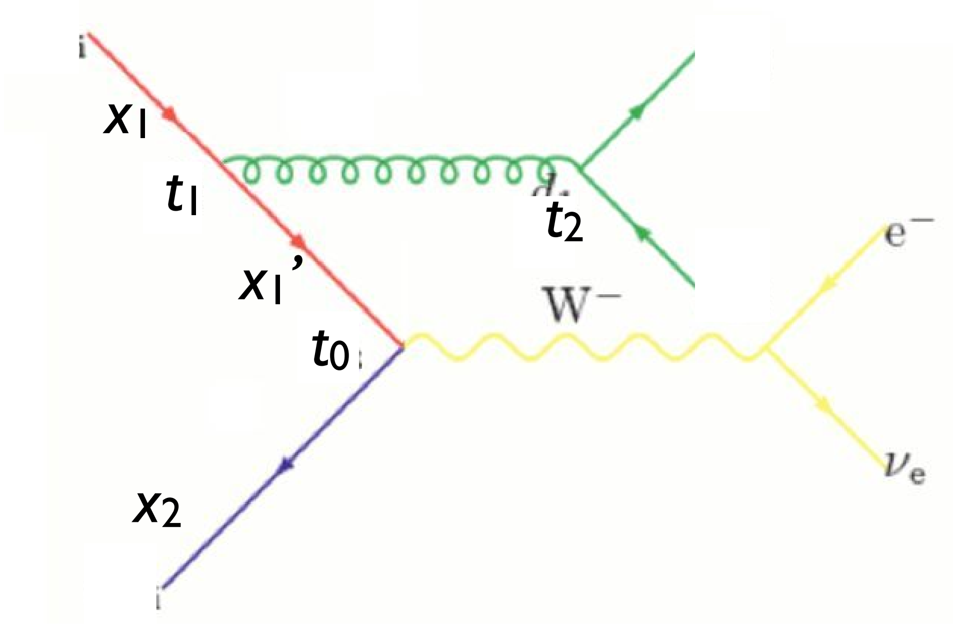

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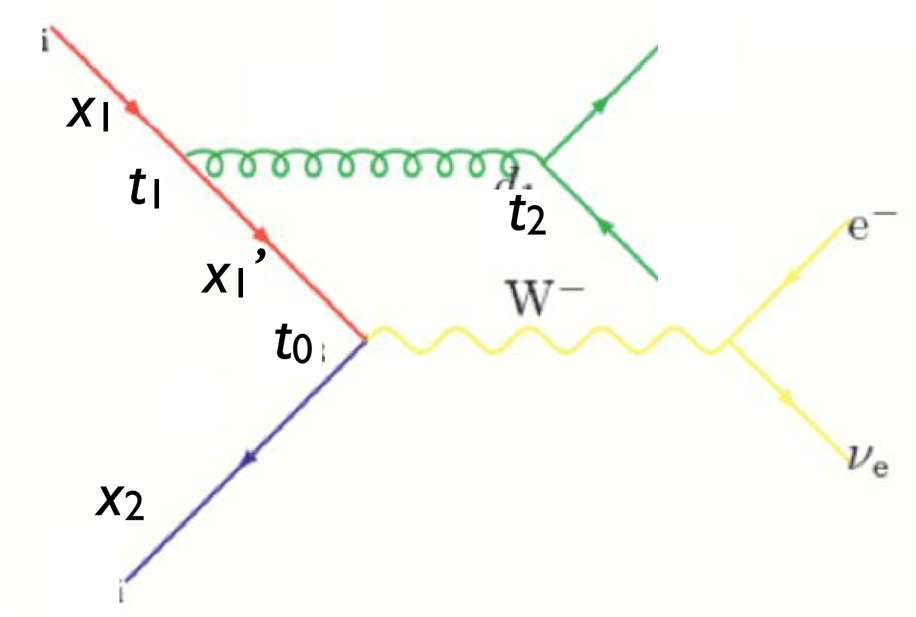
- Remember to use first clustering scale on each side for PDF scale:

$$\mathcal{P}_{\text{event}} = \hat{\sigma}(x_1, x_2, p_3, p_4, \ldots) f_q(x_1, t_1) f_{\bar{q}}(x_2, t_0)$$



K_T clustering schemes

The default clustering scheme used (in MG/Sherpa/AlpGen)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:

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

and

$$k^2_{Tij} = \max(m_i^2, m_2^2) + \min(p^2_{Ti}, p^2_{Tj})R_{ij}$$

with

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

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) scattering.

Matching schemes

- We still haven't specified how to apply the Sudakov reweighting to the matrix element
- Three general schemes available in the literature:
  - ➡ CKKW scheme [Catani,Krauss,Kuhn,Webber 2001; Krauss 2002]
  - ➡ Lönnblad scheme (or CKKW-L) [Lönnblad 2002]
  - ➡ MLM scheme [Mangano *unpublished* 2002; Mangano et al. 2007]

CKKW matching

[Catani, Krauss, Kuhn, Webber 2001]
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$$(\Delta_{Iq}(t_{\rm cut}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q(t_{\rm cut}, t_2))^2$$

analytically, using the best available (NLL) Sudakovs.

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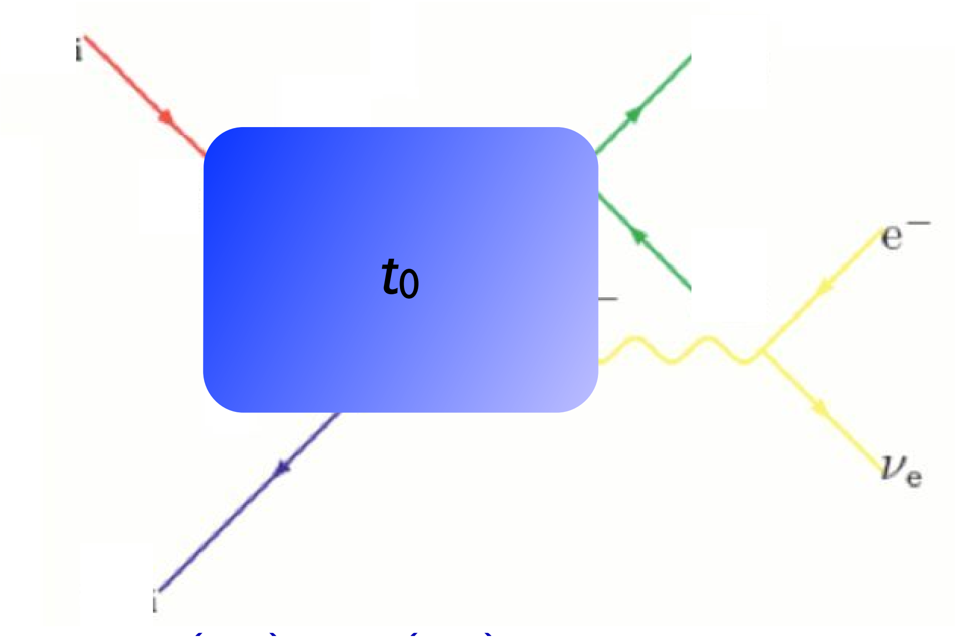

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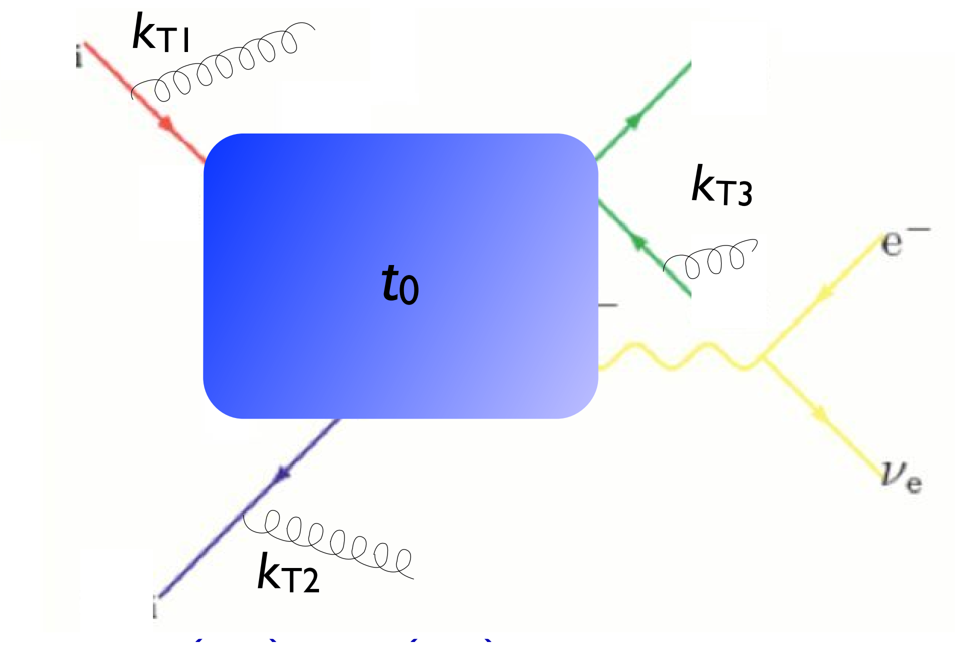

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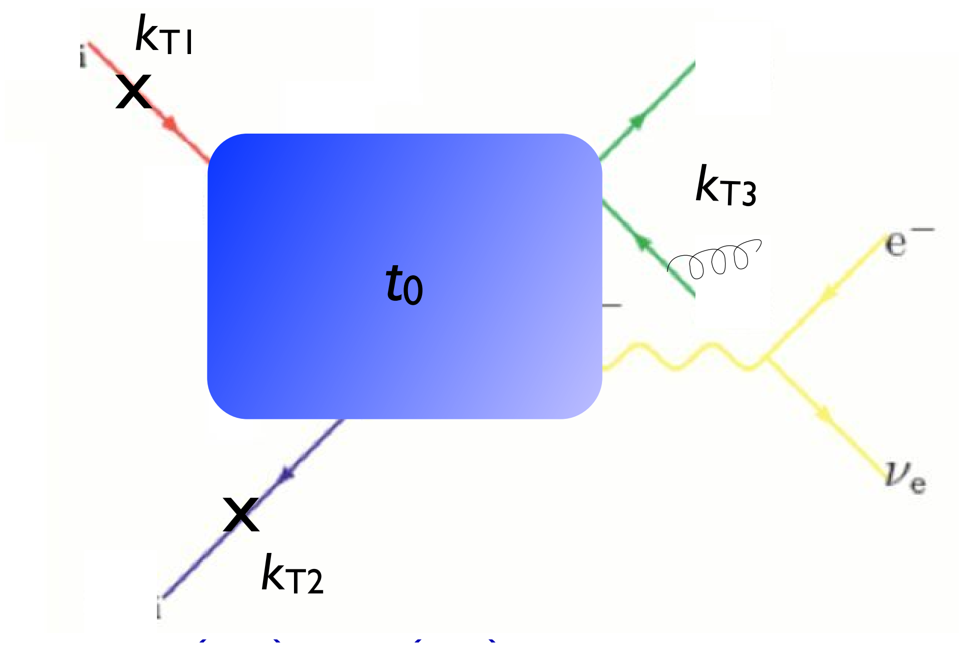
- Apply the required Sudakov suppression

$$(\Delta_{Iq}(t_{\rm cut},t_0))^2\Delta_g(t_2,t_1)(\Delta_q(t_{\rm cut},t_2))^2$$

  analytically, using the best available (NLL) Sudakovs.
- Perform "truncated showering": Run the parton shower starting at t_0, but forbid any showers above the cutoff scale $t_{\rm cut}$.



CKKW matching

[Catani, Krauss, Kuhn, Webber 2001]
[Krauss 2002]

- Apply the required Sudakov suppression

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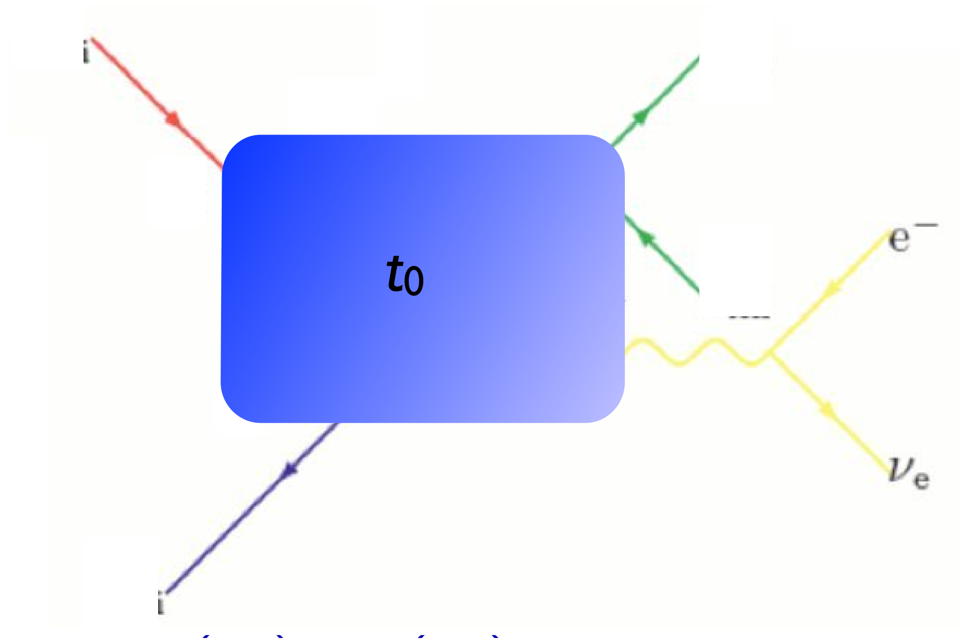
analytically, using the best available (NLL) Sudakovs.

- Perform "truncated showering": Run the parton shower starting at t_0, but forbid any showers above the cutoff scale $t_{\rm cut}$.

✓ Best theoretical treatment of matrix element
- Requires dedicated PS implementation
- Mismatch between analytical Sudakov and (non-NLL) shower
- Implemented in Sherpa (v. 1.1)

CKKW-L matching

[Lönnblad 2002]
[Hoeche et al. 2009]



CKKW-L matching

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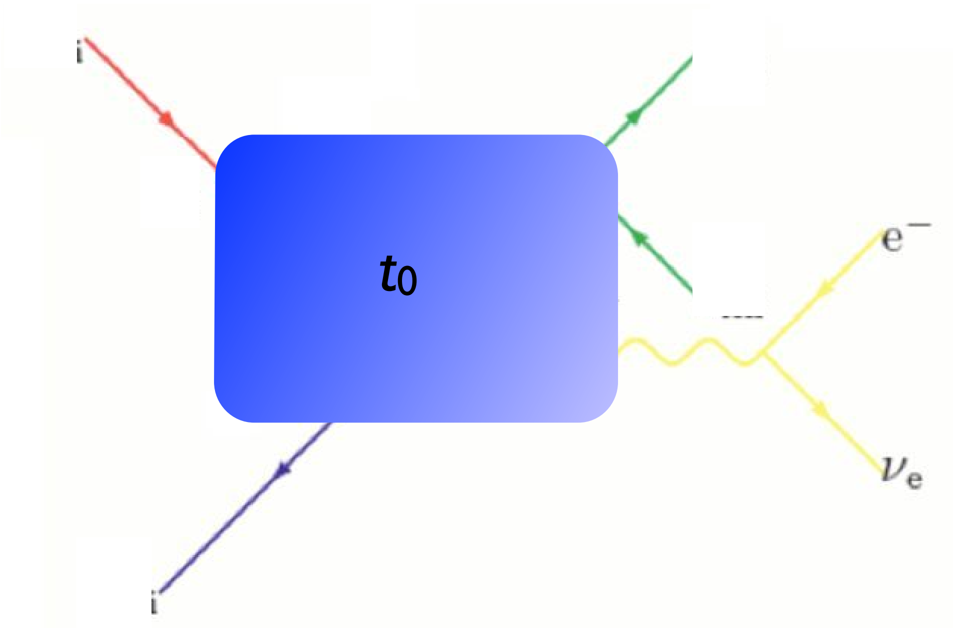

- Cluster back to "parton shower history"

CKKW-L matching

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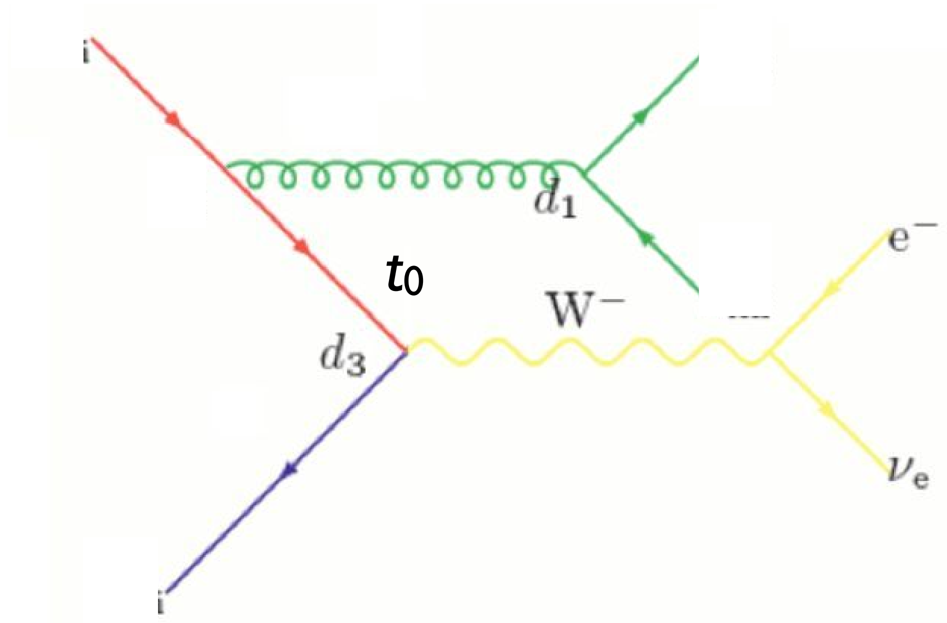
[Hoeche et al. 2009]



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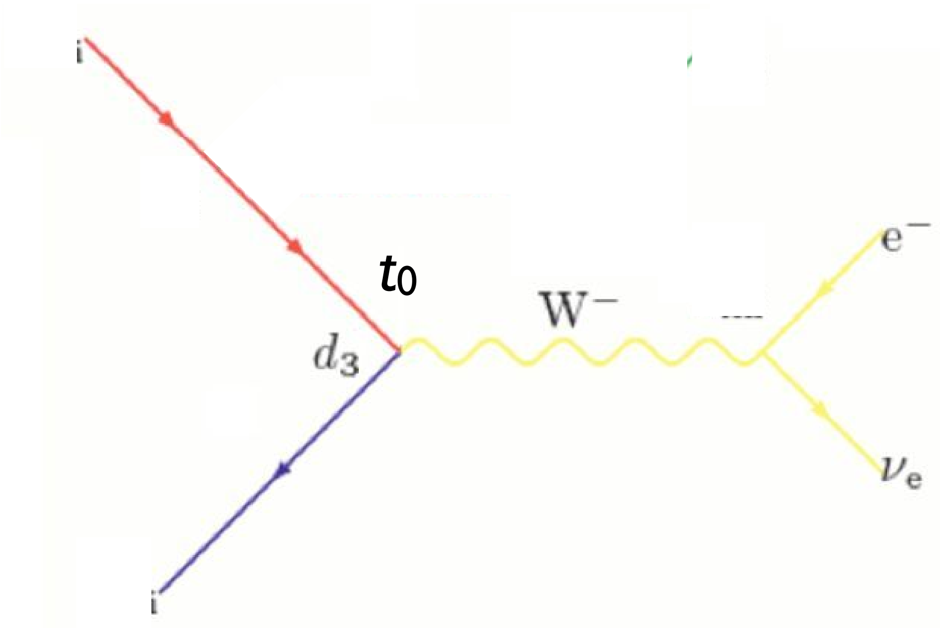

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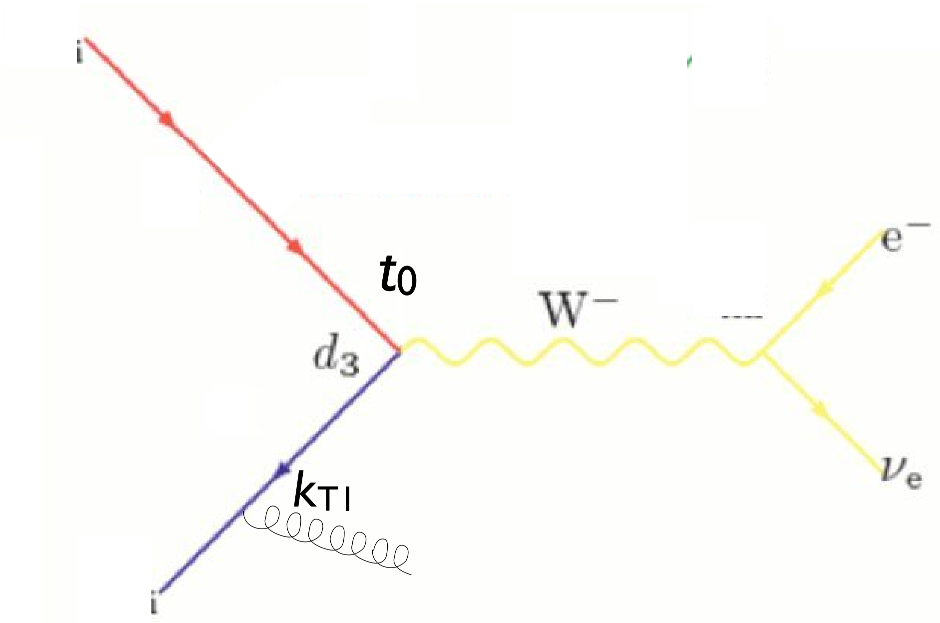

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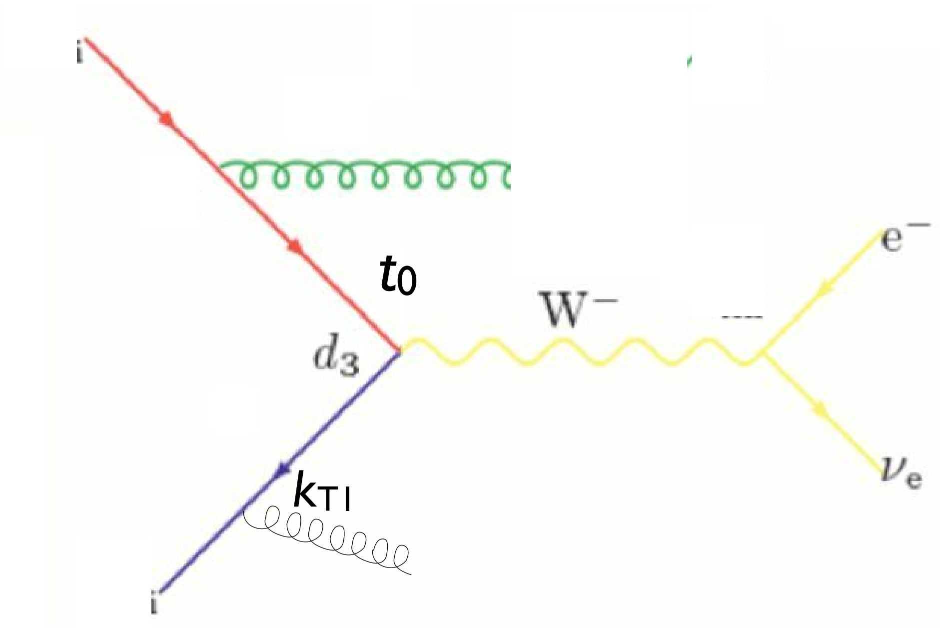

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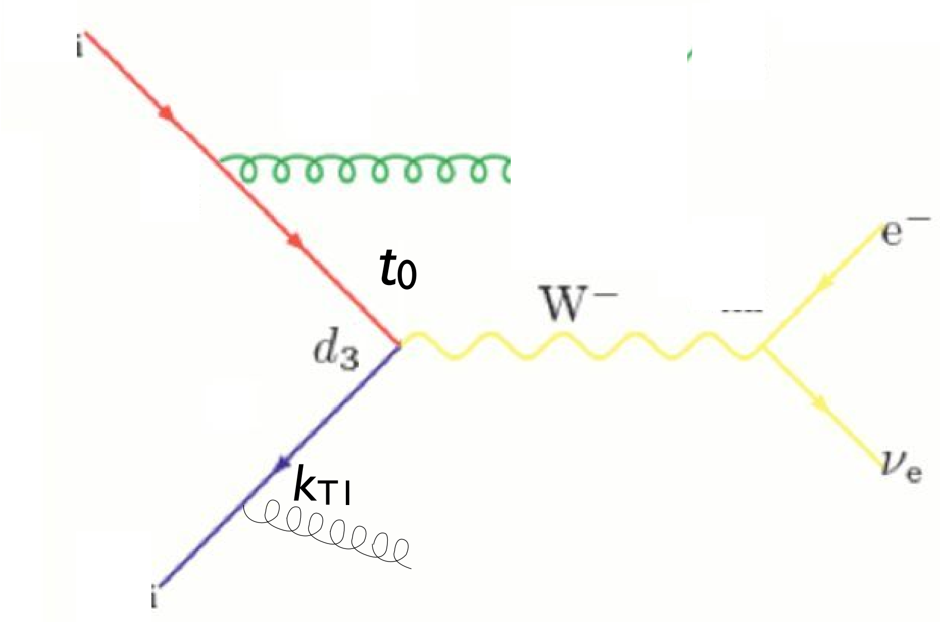

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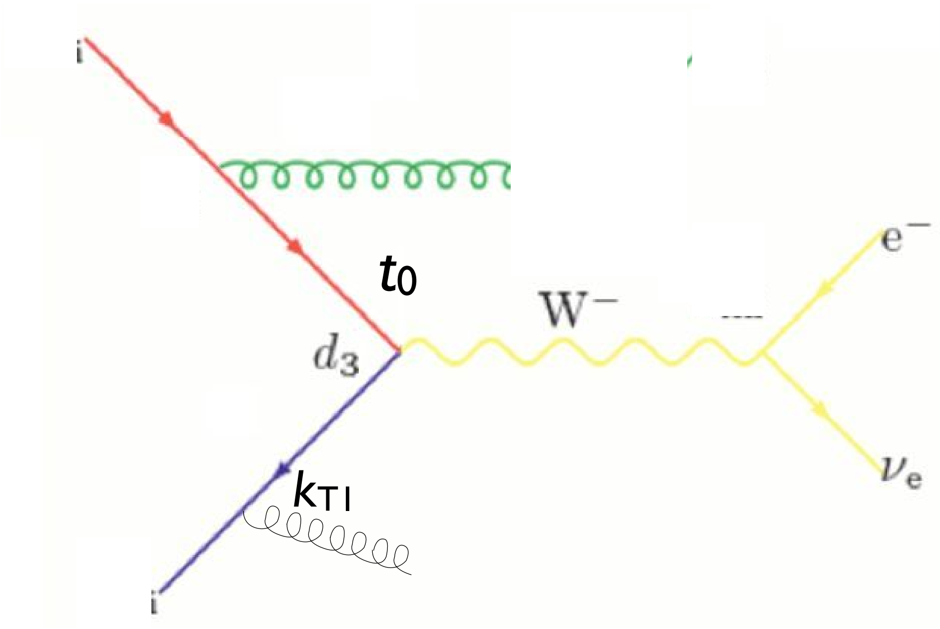

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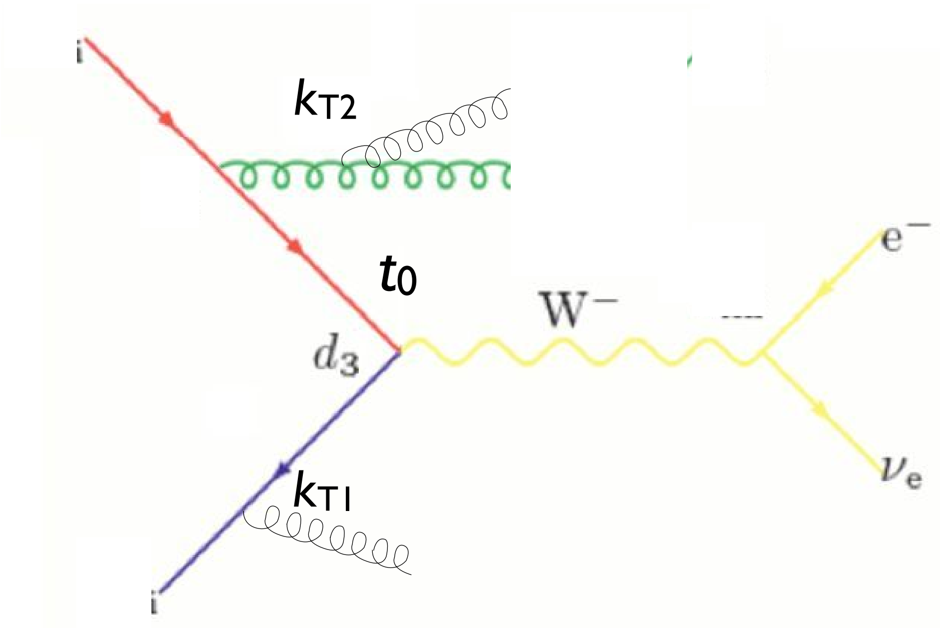

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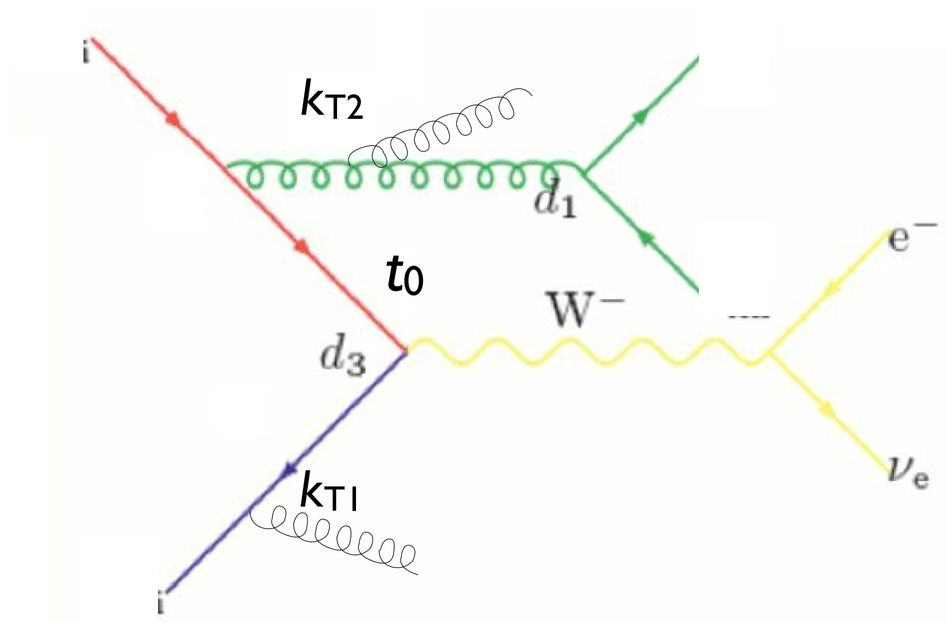

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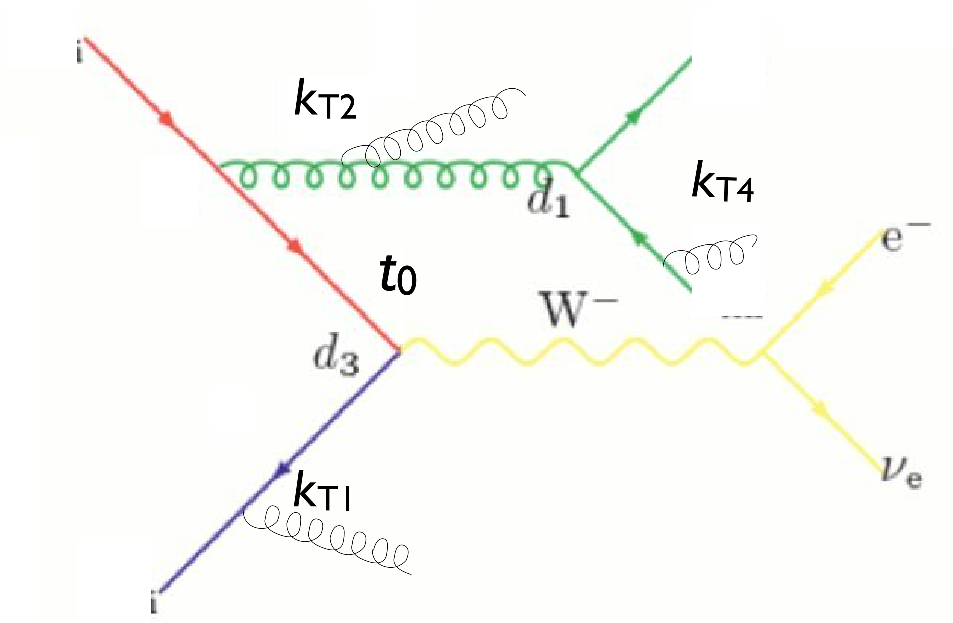

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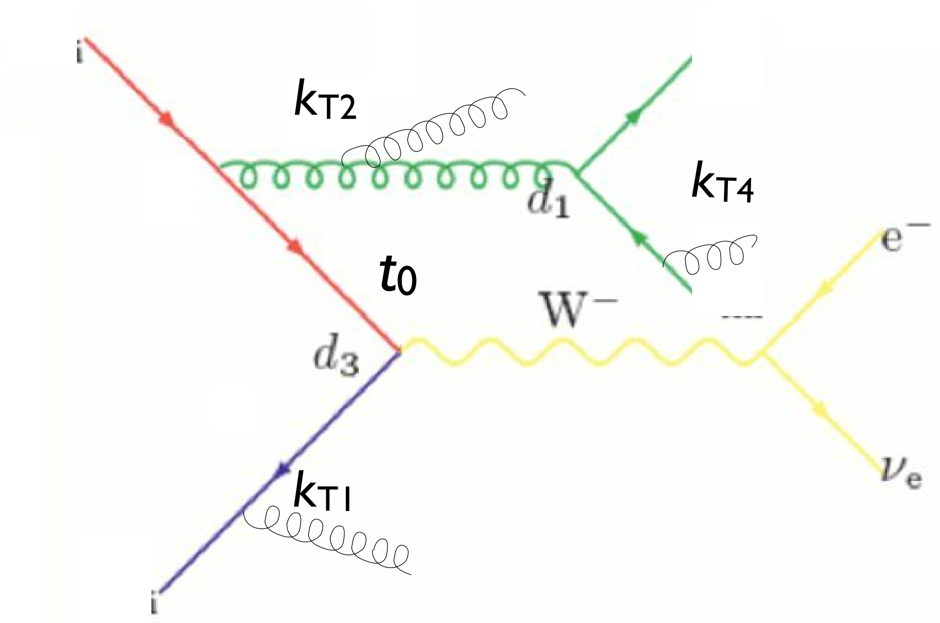

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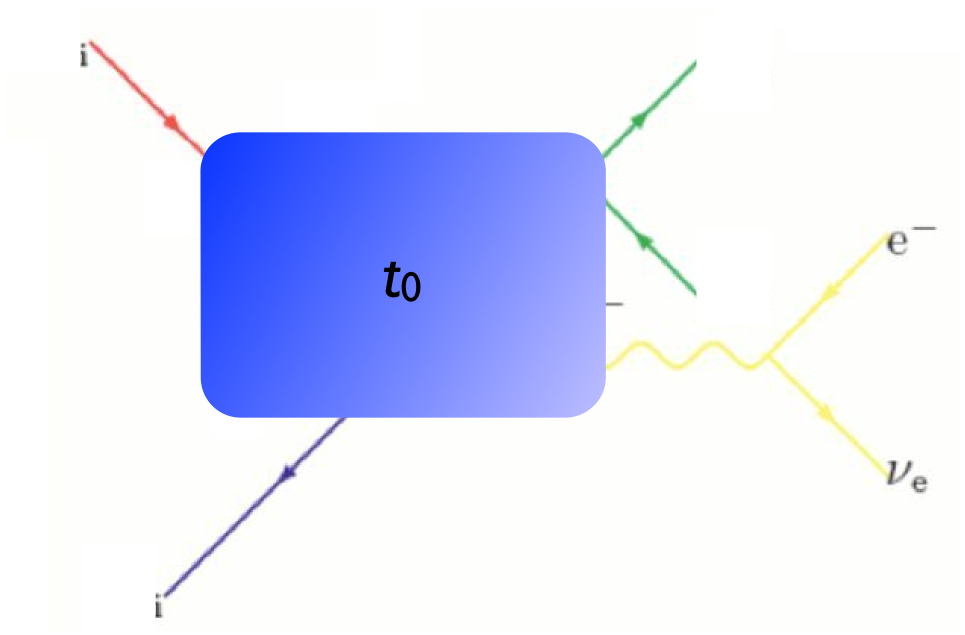
✓ Automatic agreement between Sudakov and shower

- Requires dedicated PS implementation
  - ➡ Need multiple implementations to compare between showers
- Implemented in Ariadne, Sherpa (v. 1.2), and Pythia 8

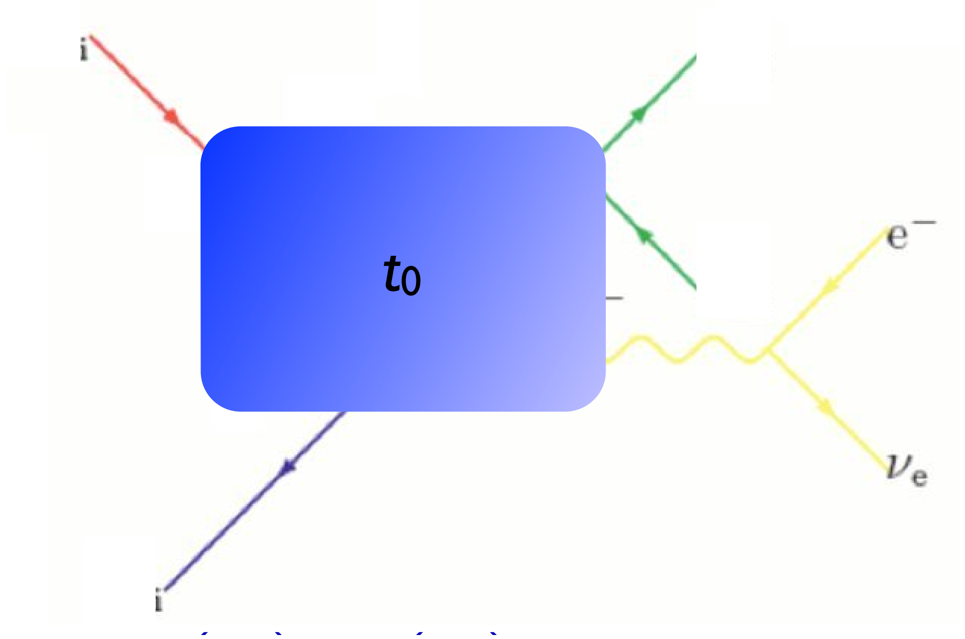
[M.L. Mangano, ~2002, 2007]
[J.A. et al 2007, 2008]



MLM matching

[M.L. Mangano, ~2002, 2007]
[J.A. et al 2007, 2008]

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



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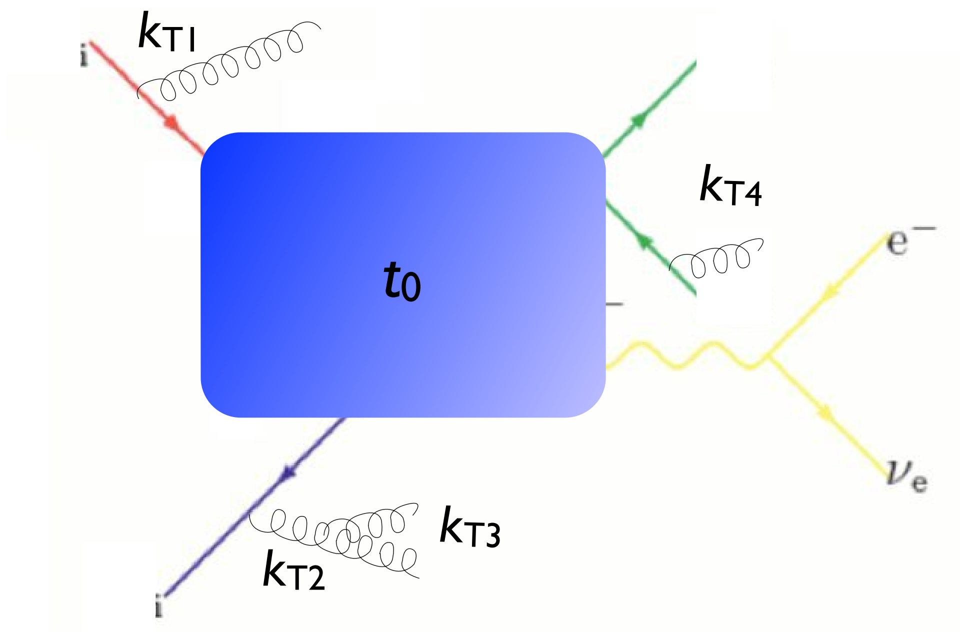

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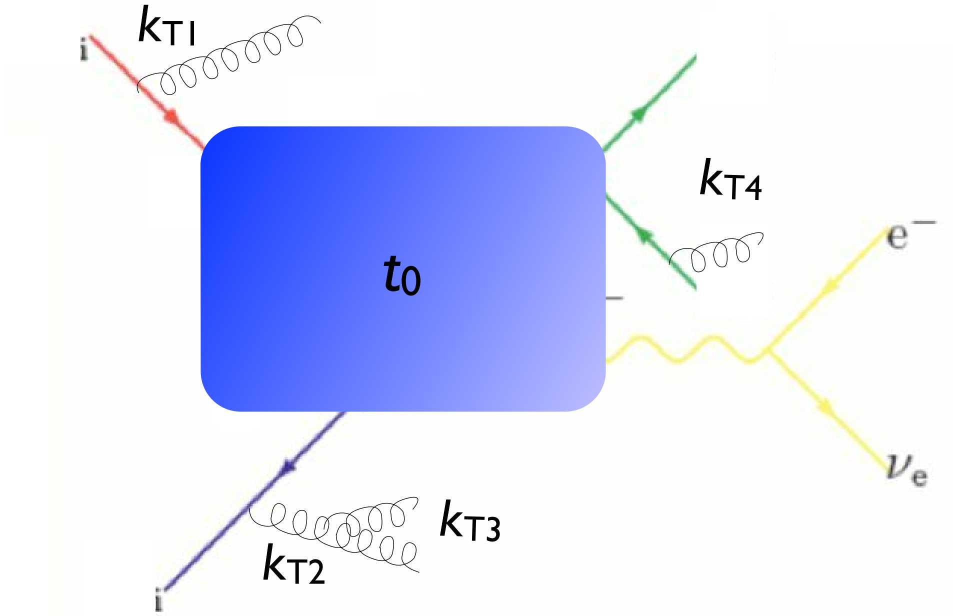

- Perform jet clustering after PS - if hardest jet $k_{T1} > t_{cut}$ or there are jets not matched to partons, reject the event

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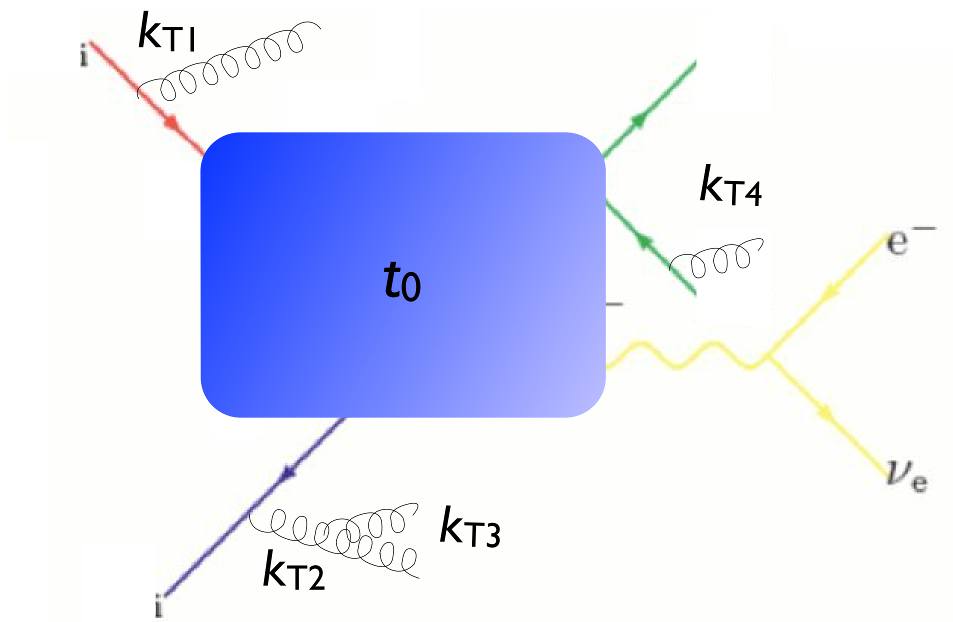

- Perform jet clustering after PS - if hardest jet $k_{T1} > t_{cut}$ or there are jets not matched to partons, reject the event
- The resulting Sudakov suppression from the procedure is

$$(\Delta_{Iq}(t_{\rm cut}, t_0))^2(\Delta_q(t_{\rm cut}, t_0))^2$$

which turns out to be a good enough approximation of the correct expression $$(\Delta_{Iq}(t_{\rm cut}, t_0))^2\Delta_g(t_2, t_1)(\Delta_q(t_{\rm cut}, t_2))^2$$

MLM matching

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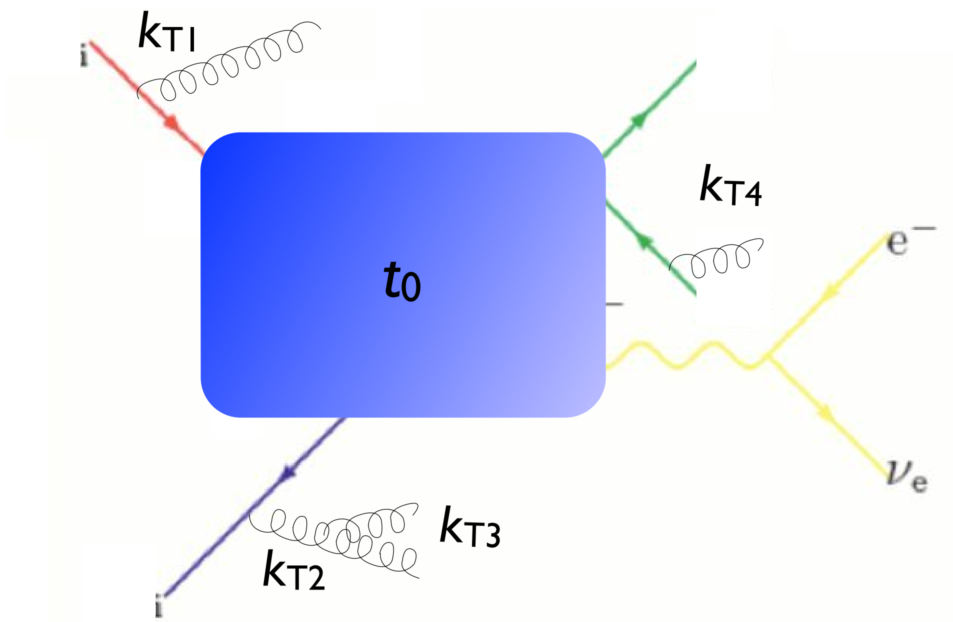


- Perform jet clustering after PS - if hardest jet $k_{T1} > t_{cut}$ or there are jets not matched to partons, reject the event
  - ✓ Simplest available scheme
  - ✓ Allows matching with any shower, without modification
  - ➡ Sudakov suppression not exact, minor mismatch with shower
  - Implemented in AlpGen, HELAC, MadGraph+Pythia 6

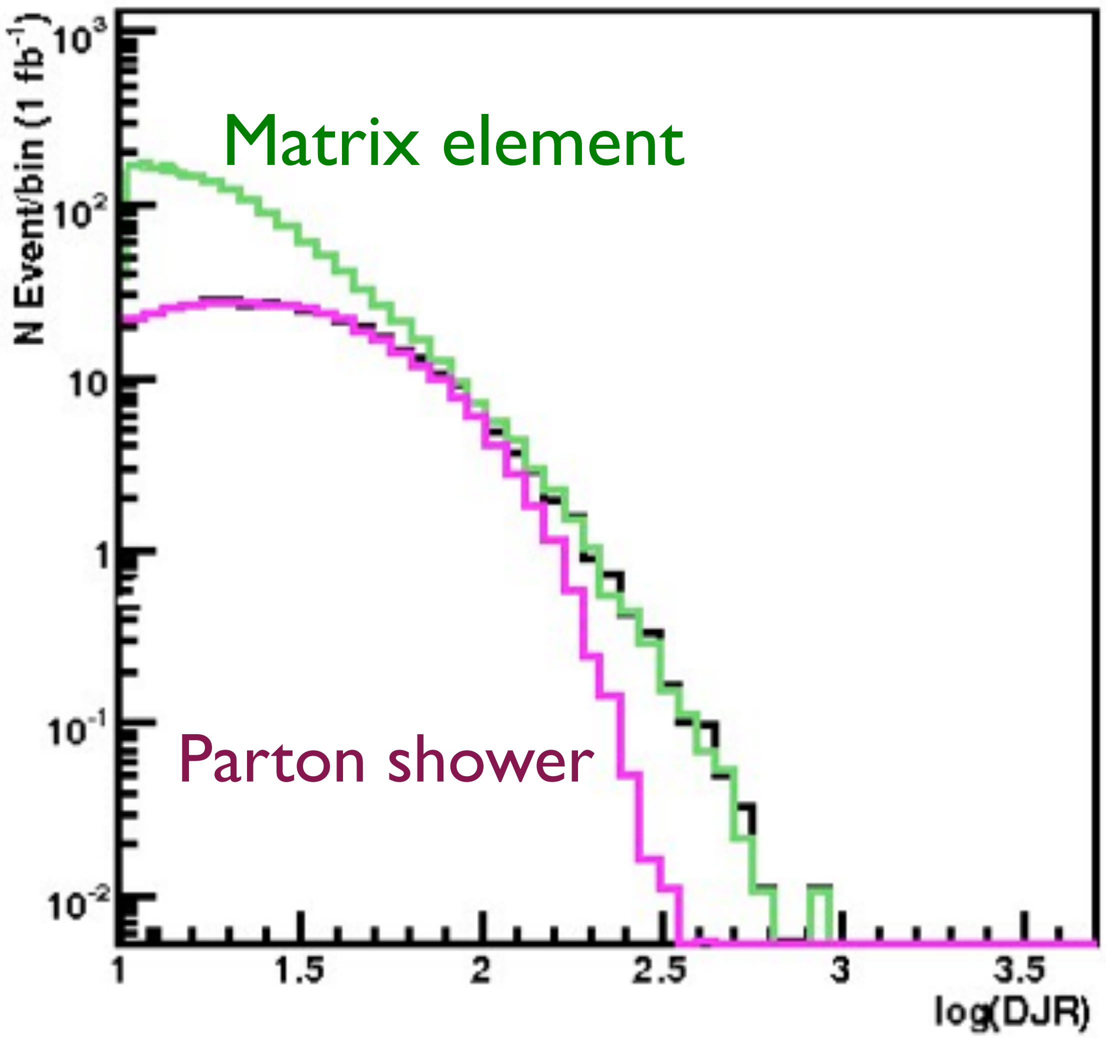
Highest multiplicity sample

- In the previous, assumed we can simulate all parton multiplicities by the ME
- In practice, we can only do limited number of final-state partons with matrix element (up to 4-5 or so)
- For the highest jet multiplicity that we generate with the matrix element, we need to allow additional jets above the matching scale t_{cut}, since we will otherwise not get a jet-inclusive description – but still can't allow PS radiation harder than the ME partons

➡ Need to replace t_{cut} by the clustering scale for the softest ME parton for the highest multiplicity

Back to the “matching goal”

- Regularization of matrix element divergence
- Correction of the parton shower for large momenta
- Smooth jet distributions



2nd QCD radiation jet in top pair production at the LHC, using MadGraph + Pythia

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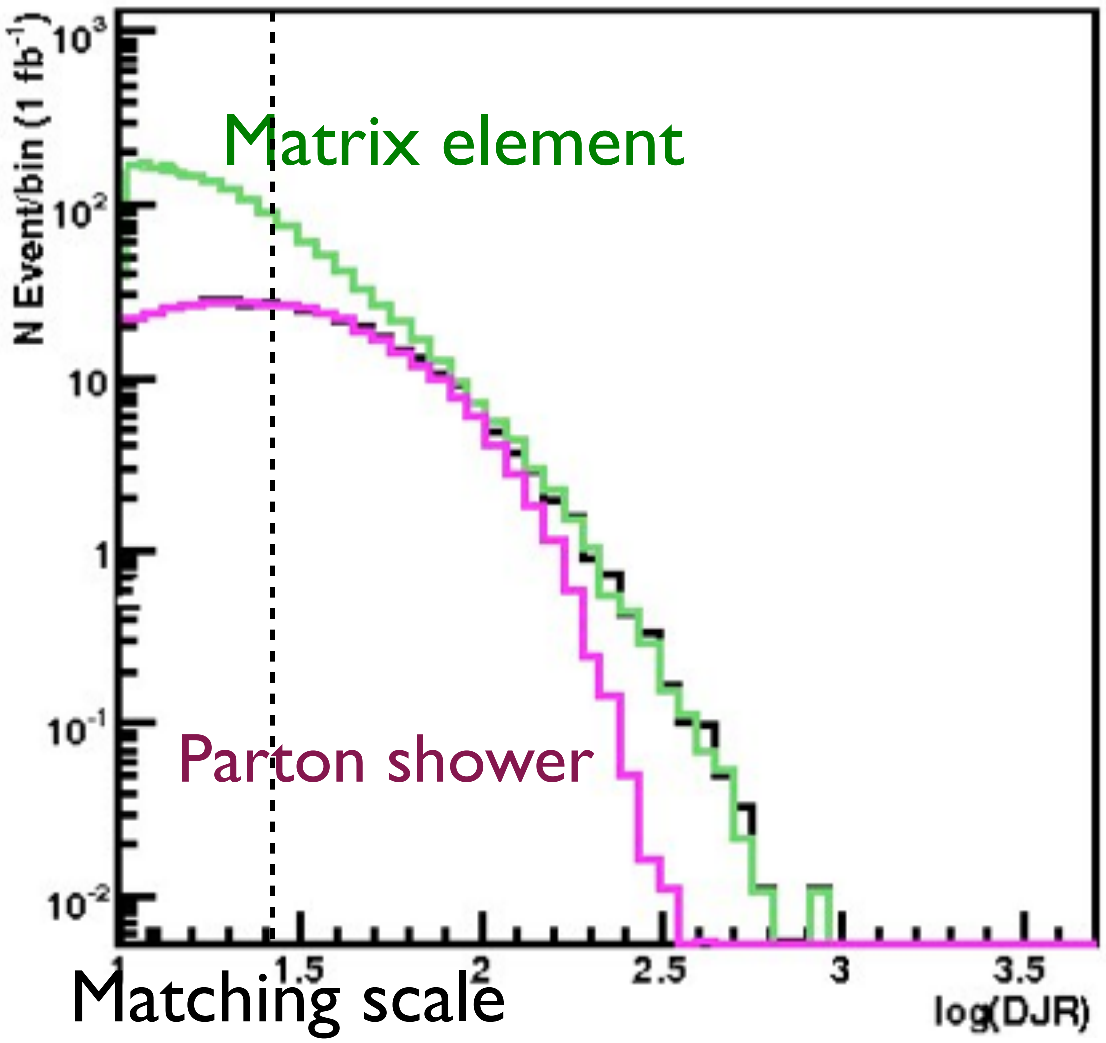

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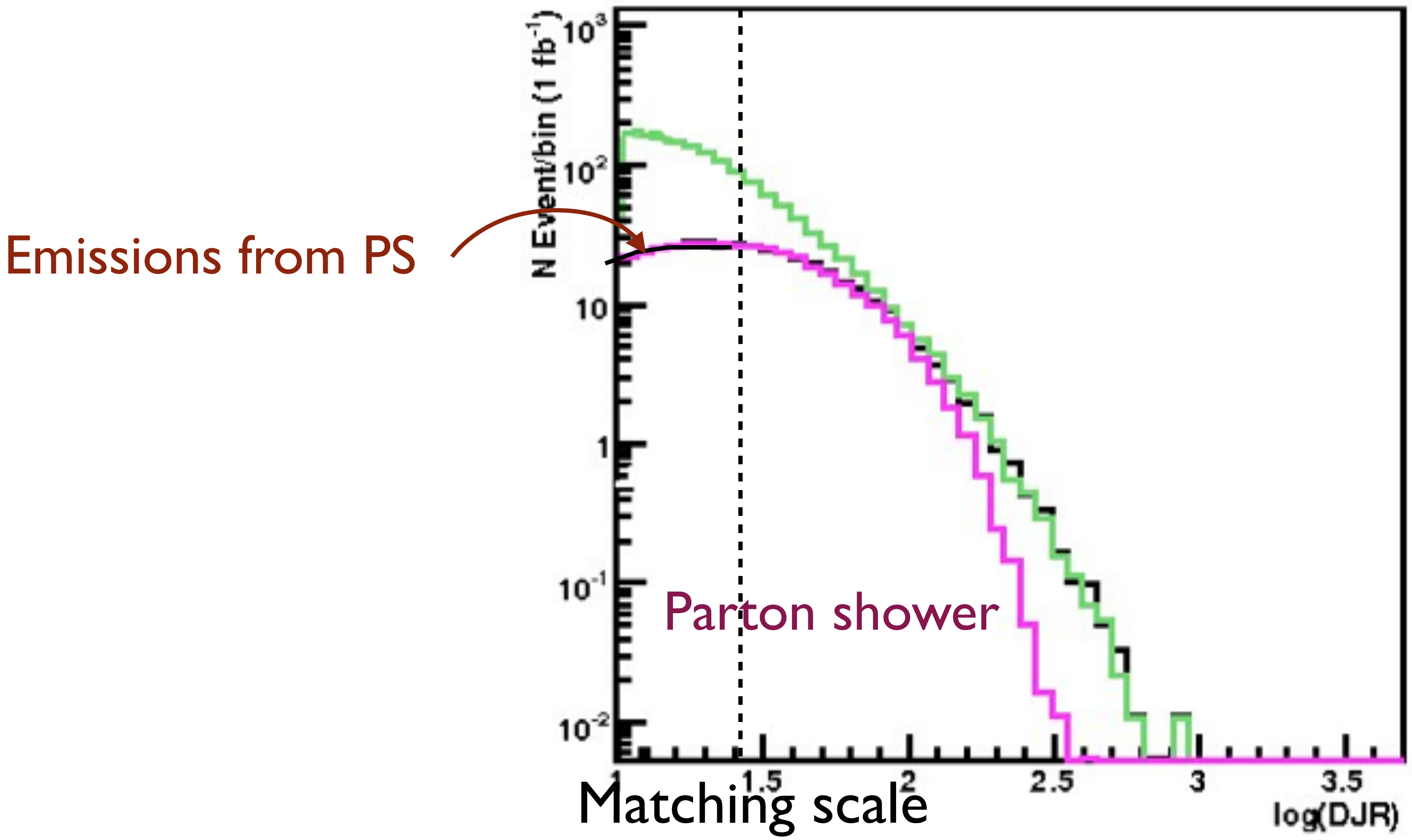

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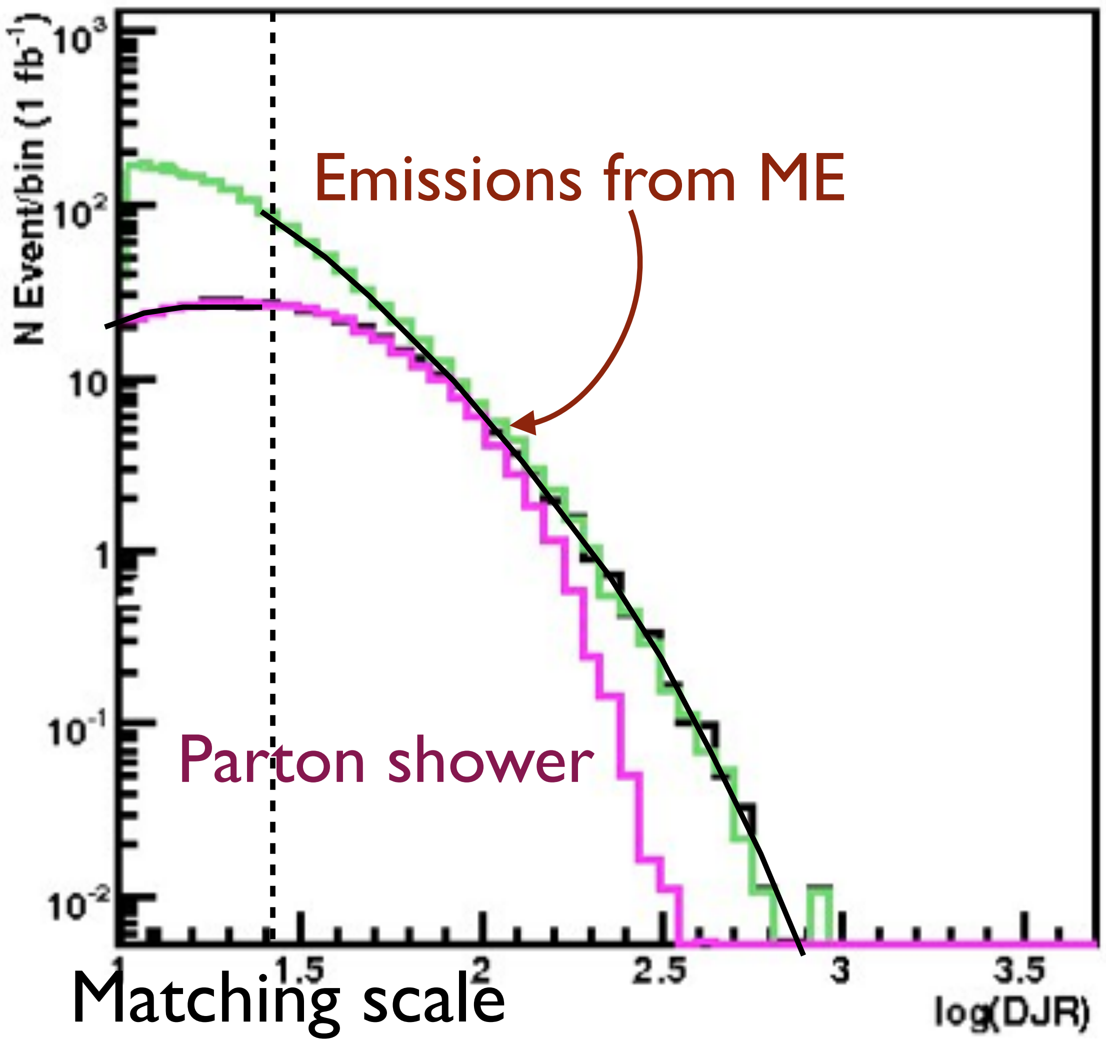

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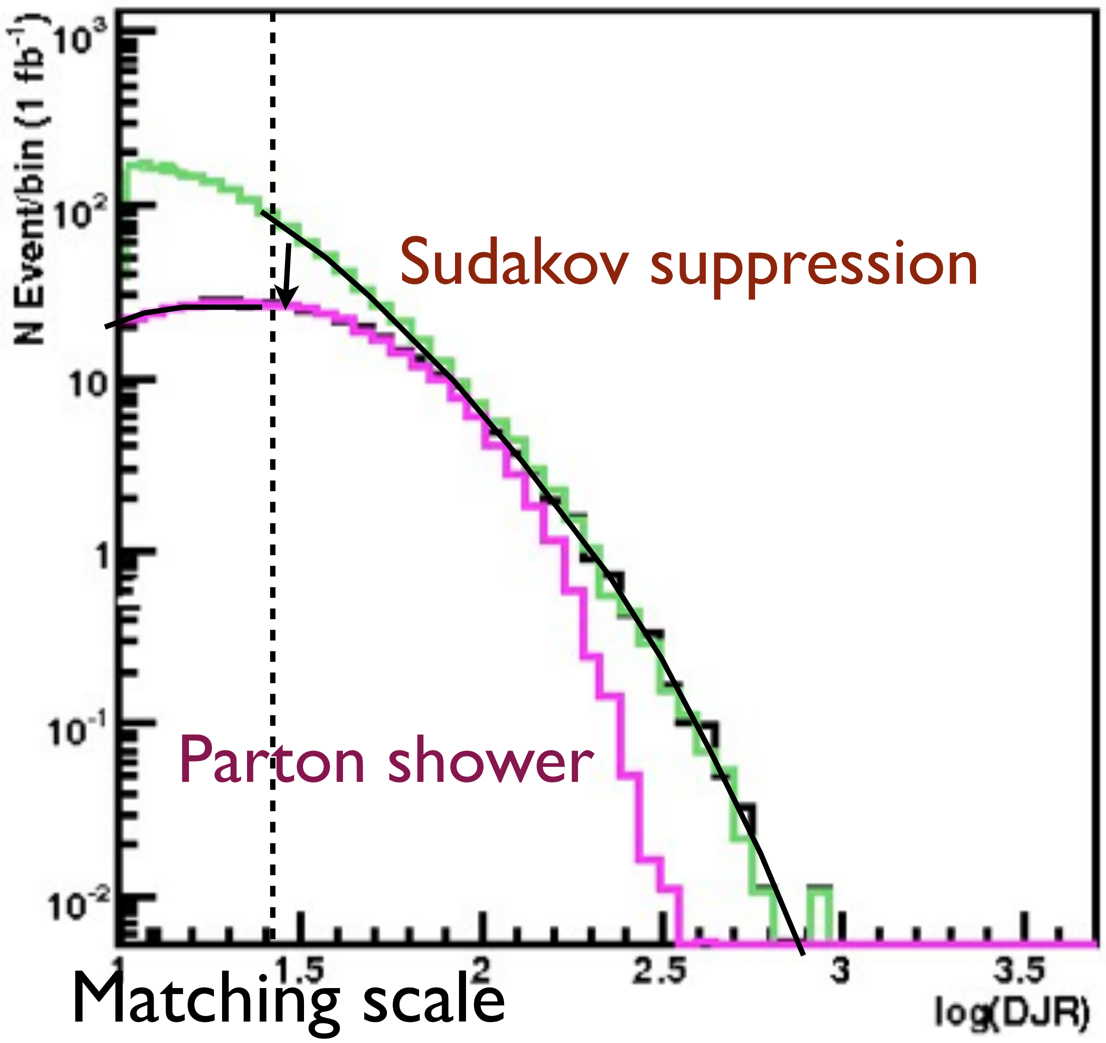

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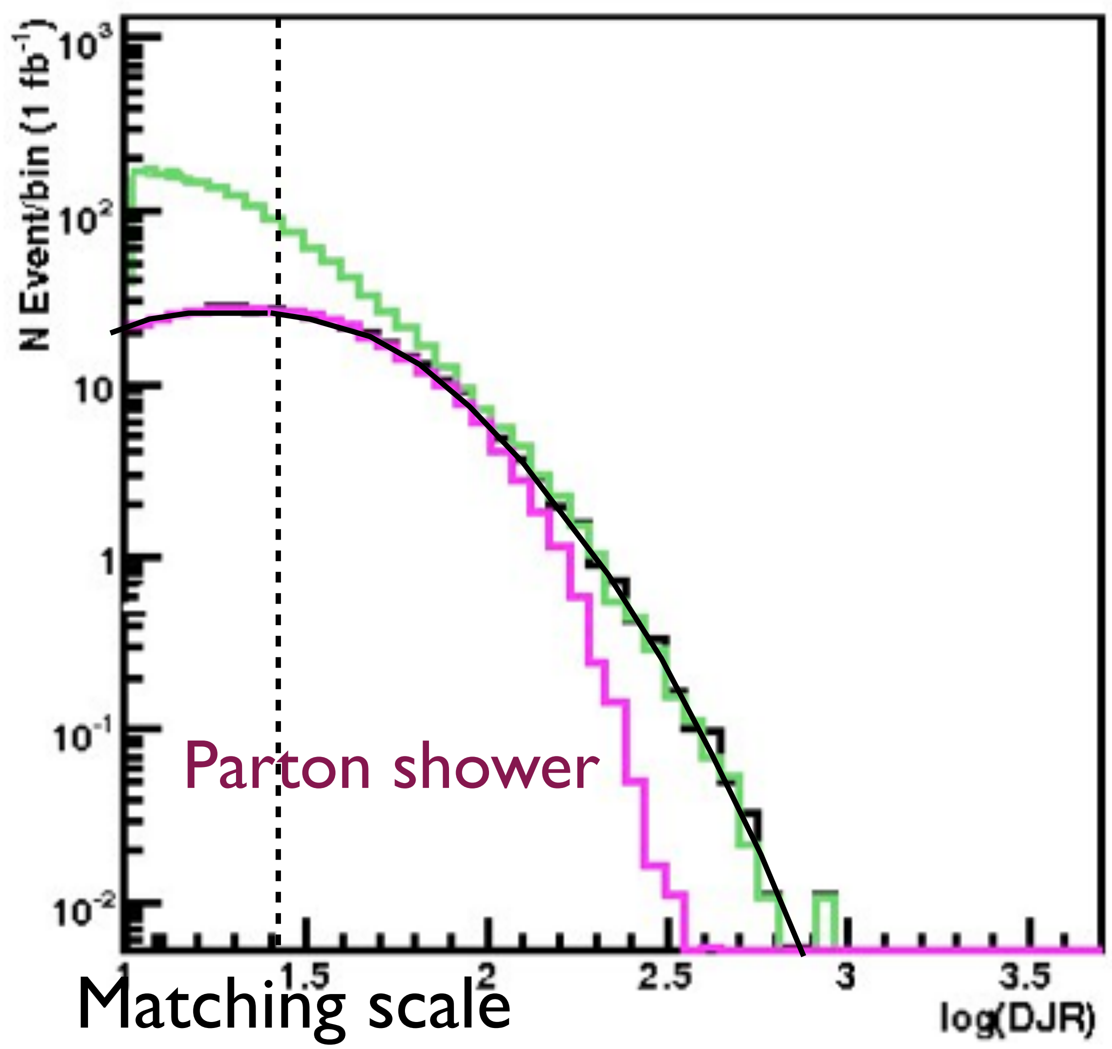

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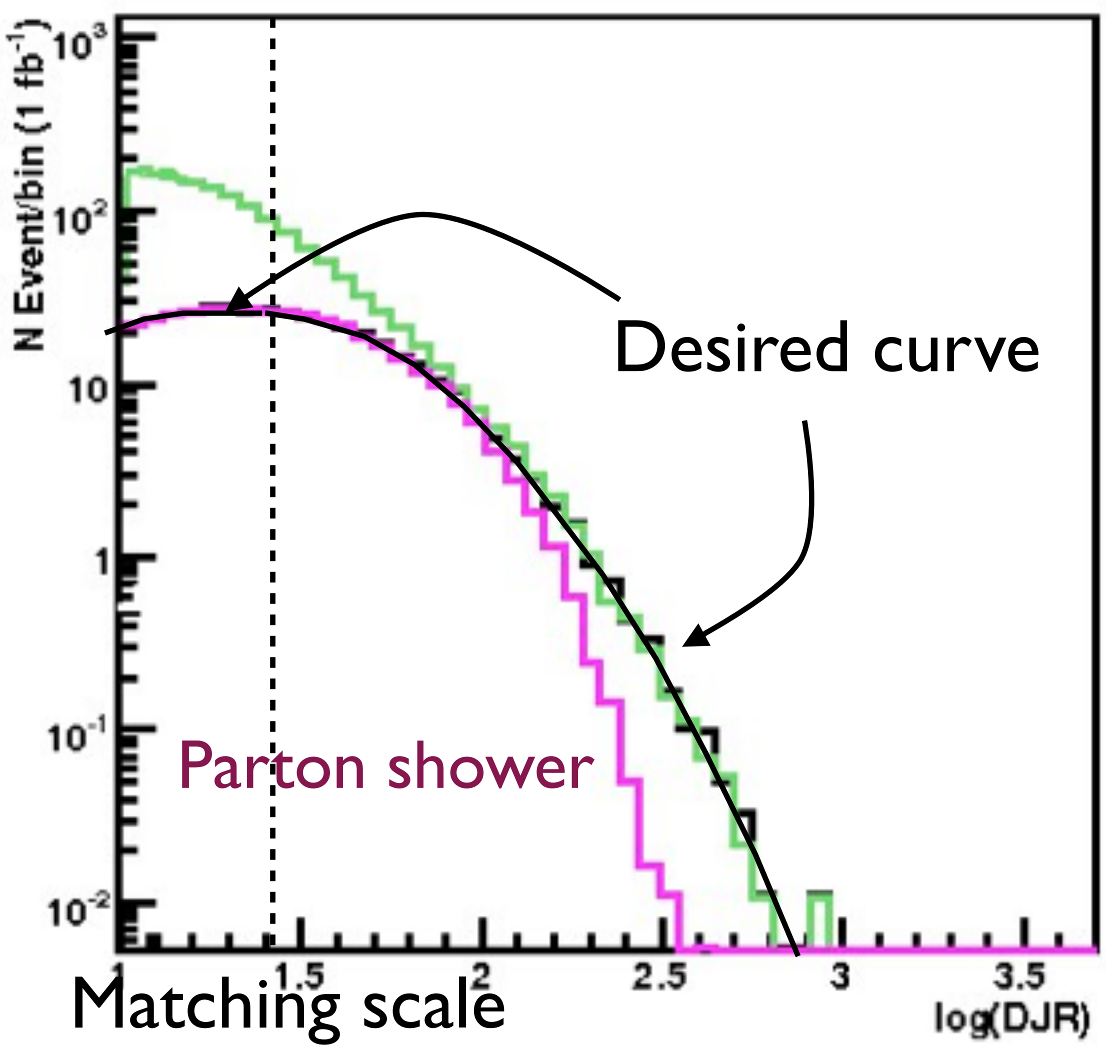

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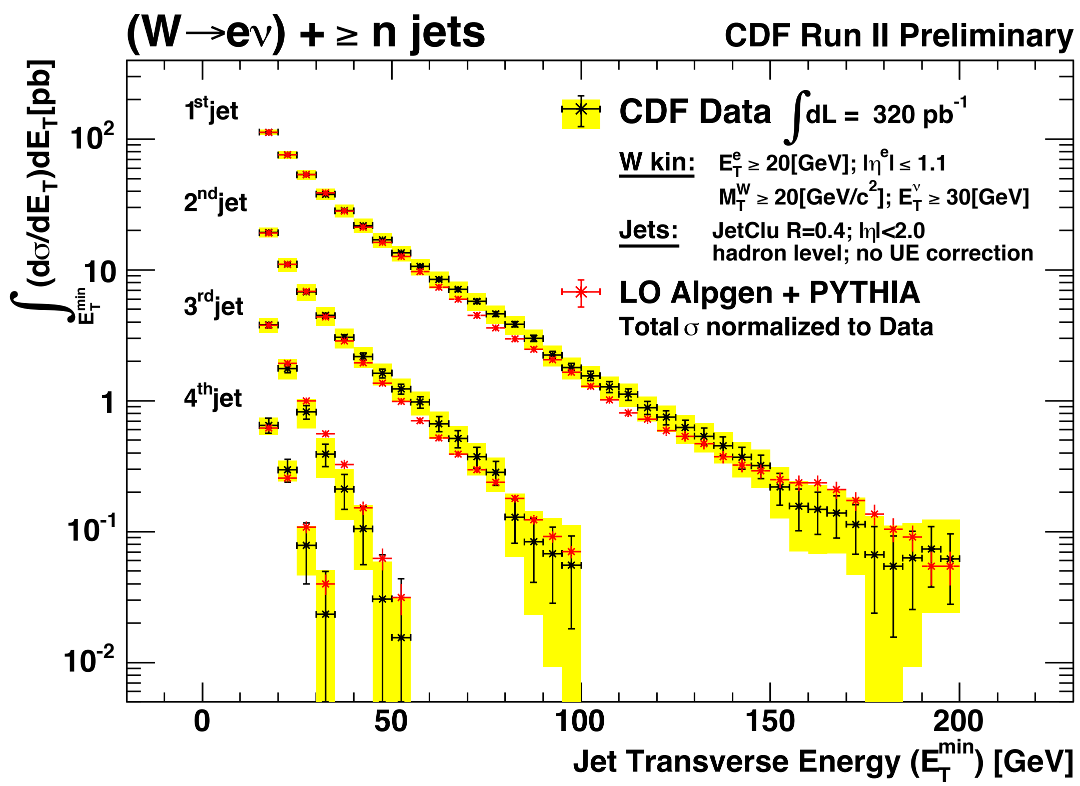
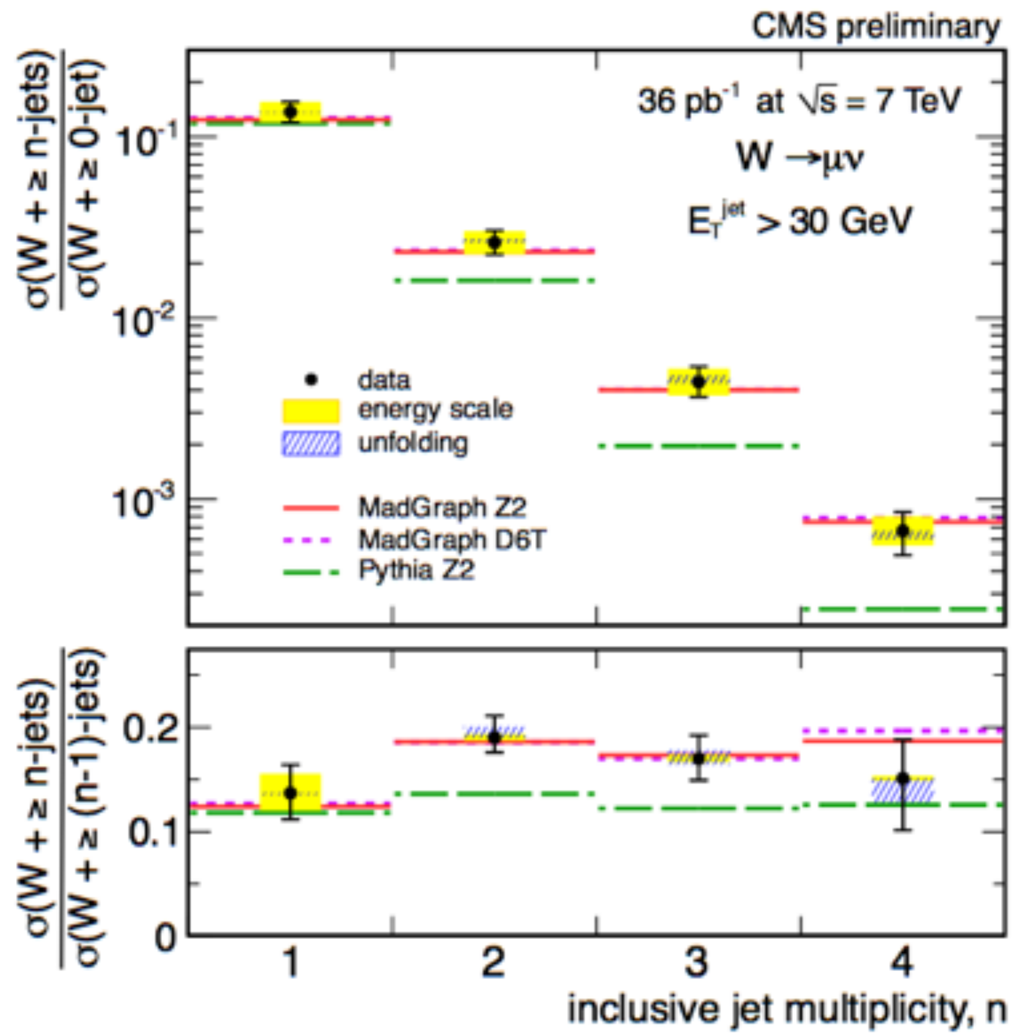
Summary of Matching Procedure

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. Apply Sudakov factors to account for the required non-radiation above clustering cutoff scale and generate parton shower emissions below clustering cutoff:
   a. (CKKW) Analytical Sudakovs + truncated showers
   b. (CKKW-L) Sudakovs from truncated showers
   c. (MLM) Sudakovs from reclustered shower emissions

Comparing to experiment: W+jets





- Very good agreement at Tevatron (left) and LHC (right)
- Matched samples obtained via different matching schemes (MLM and CKKW) consistent within the expected uncertaintes.
- Pure parton shower (Pythia) doesn't describe the data beyond 1st jet.