Software Tools in High Energy Physics

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Lecture 1 Review

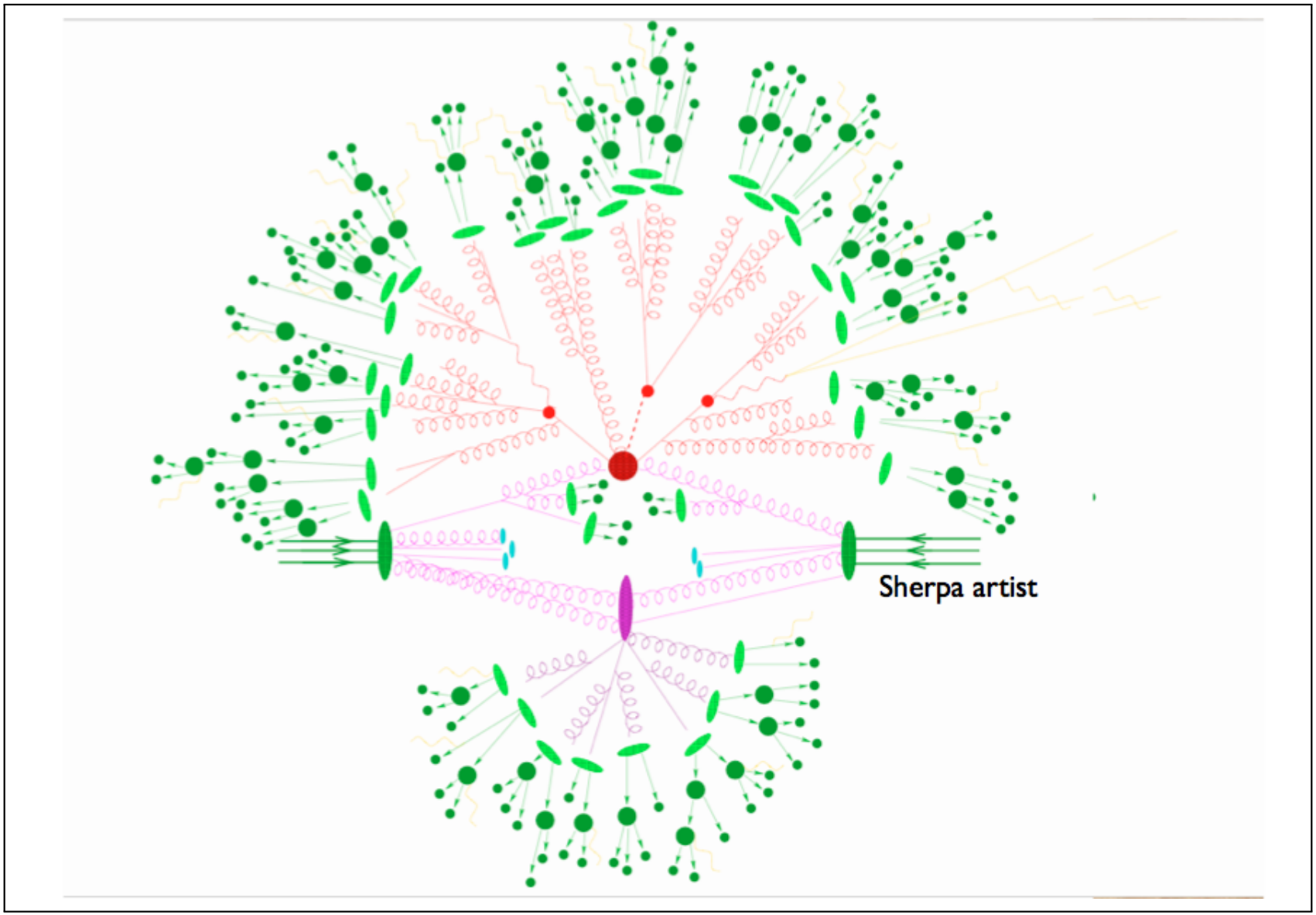
- Introduced Monte Carlo method of computing cross-sections
- Monte Carlo generates *unweighted events* (lists of four-vectors)
- Allows arbitrary phase space cuts
- Introduced Madgraph
  - Downloaded and installed
  - Made process (*Feynman diagrams*)
  - Computed cross-sections
  - Played with `run_card` settings

Lecture 2 Overview

1. Towards a realistic picture
   - Parton shower and hadronization with Pythia
   - Detector simulation with Delphes
2. Analyzing events
   - Standard event generator formats
   - Quick kinematics with ROOT
   - Sample analyses with ROOT

Towards a Realistic Picture

From Johan Alwall's slides



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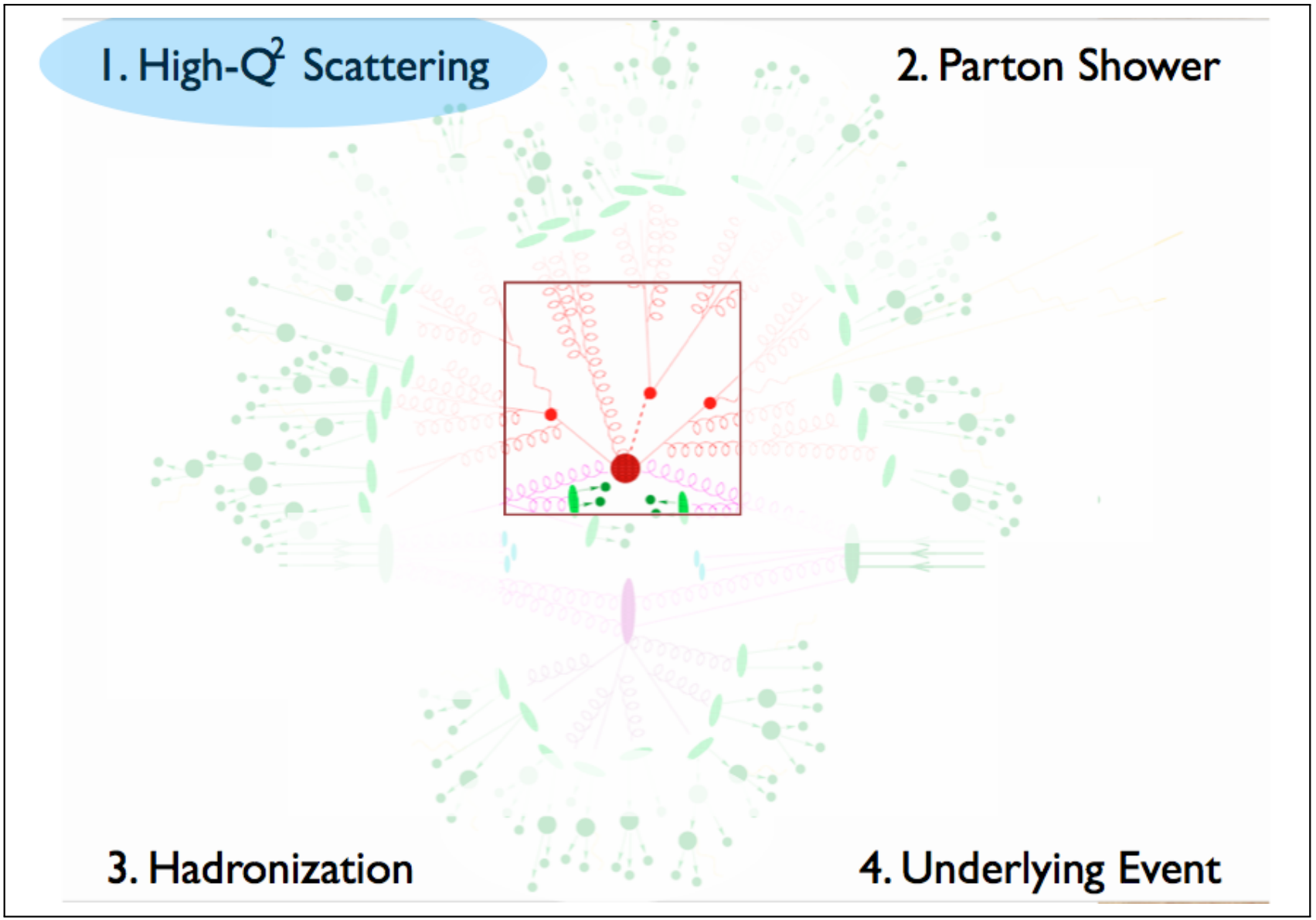

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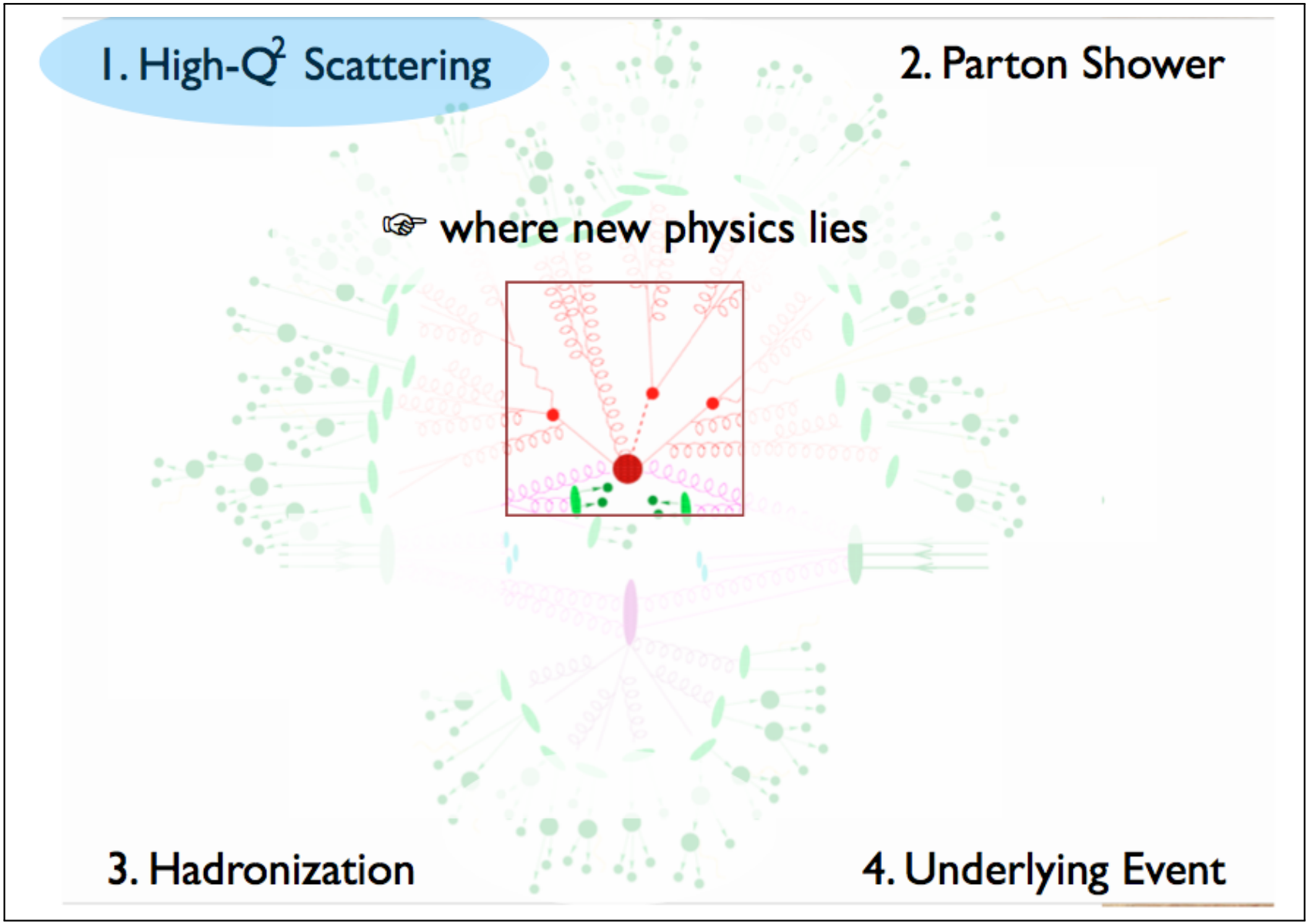


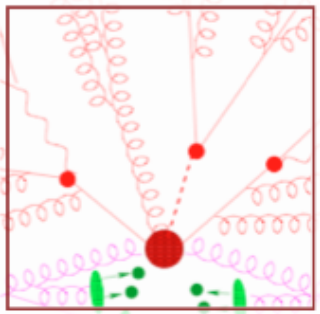
Towards a Realistic Picture

From Johan Alwall's slides

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



☞ process dependent

☞ first principles description

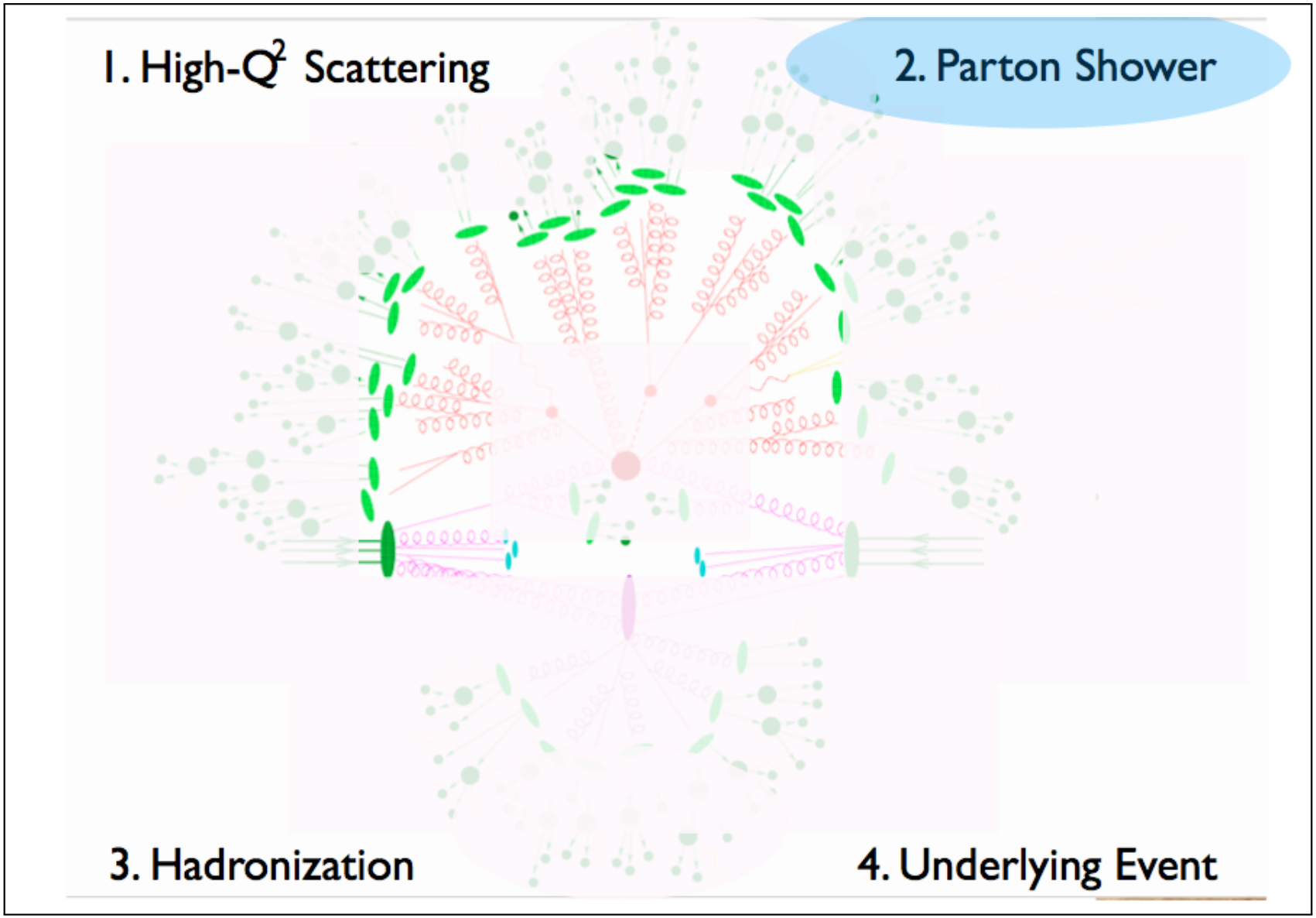
☞ it can be systematically improved

3. Hadronization

4. Underlying Event

Towards a Realistic Picture

From Johan Alwall's slides



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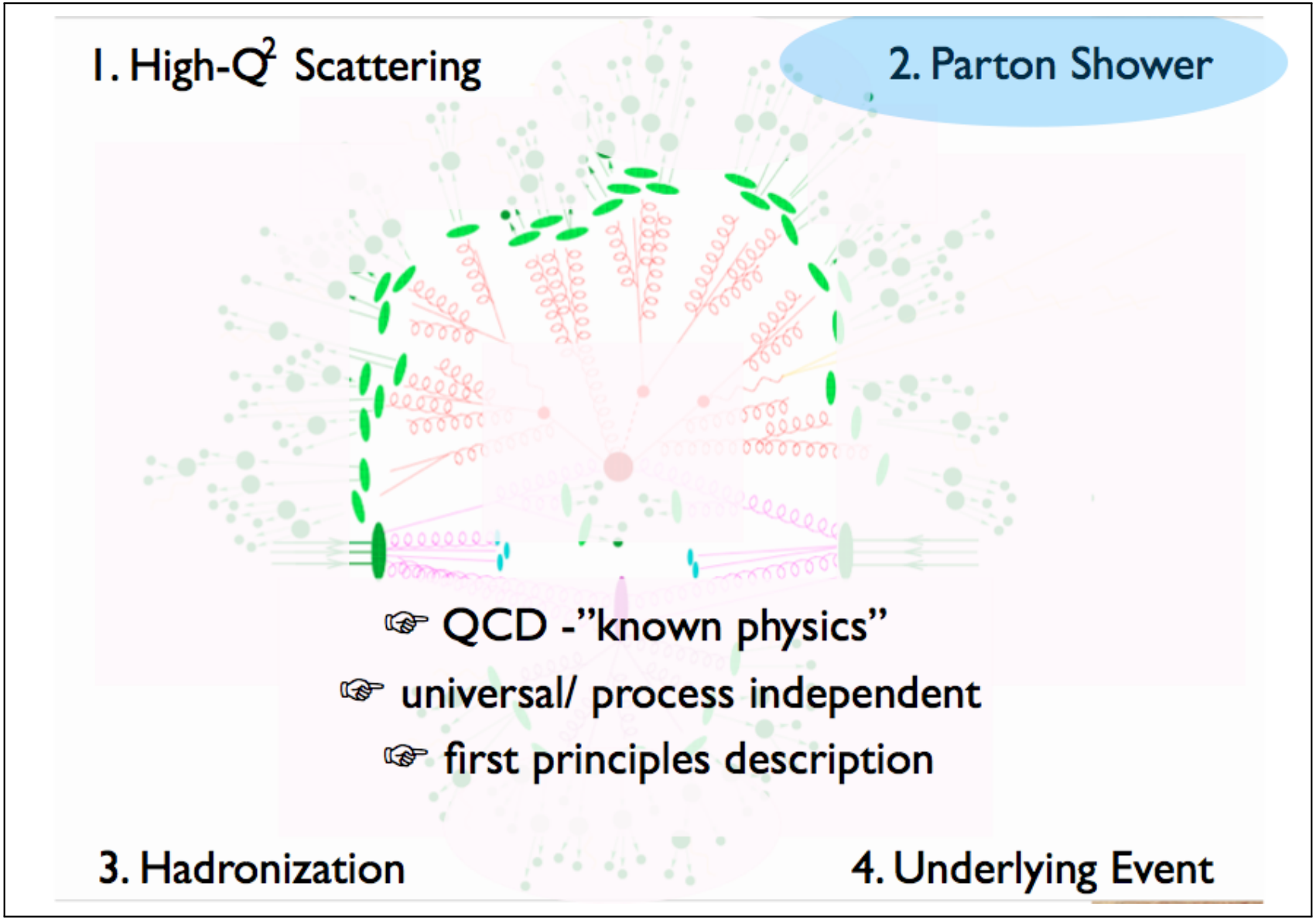

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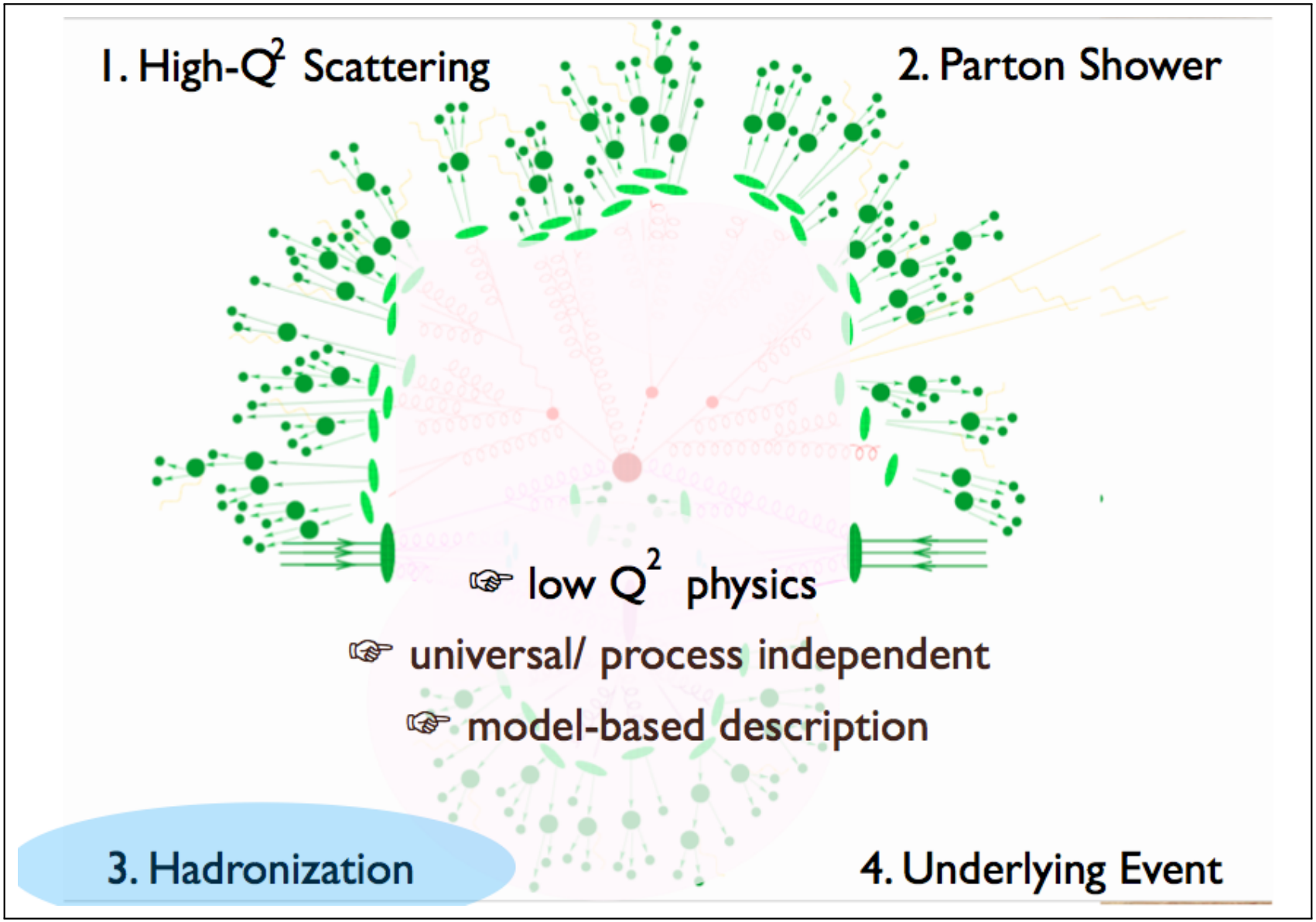

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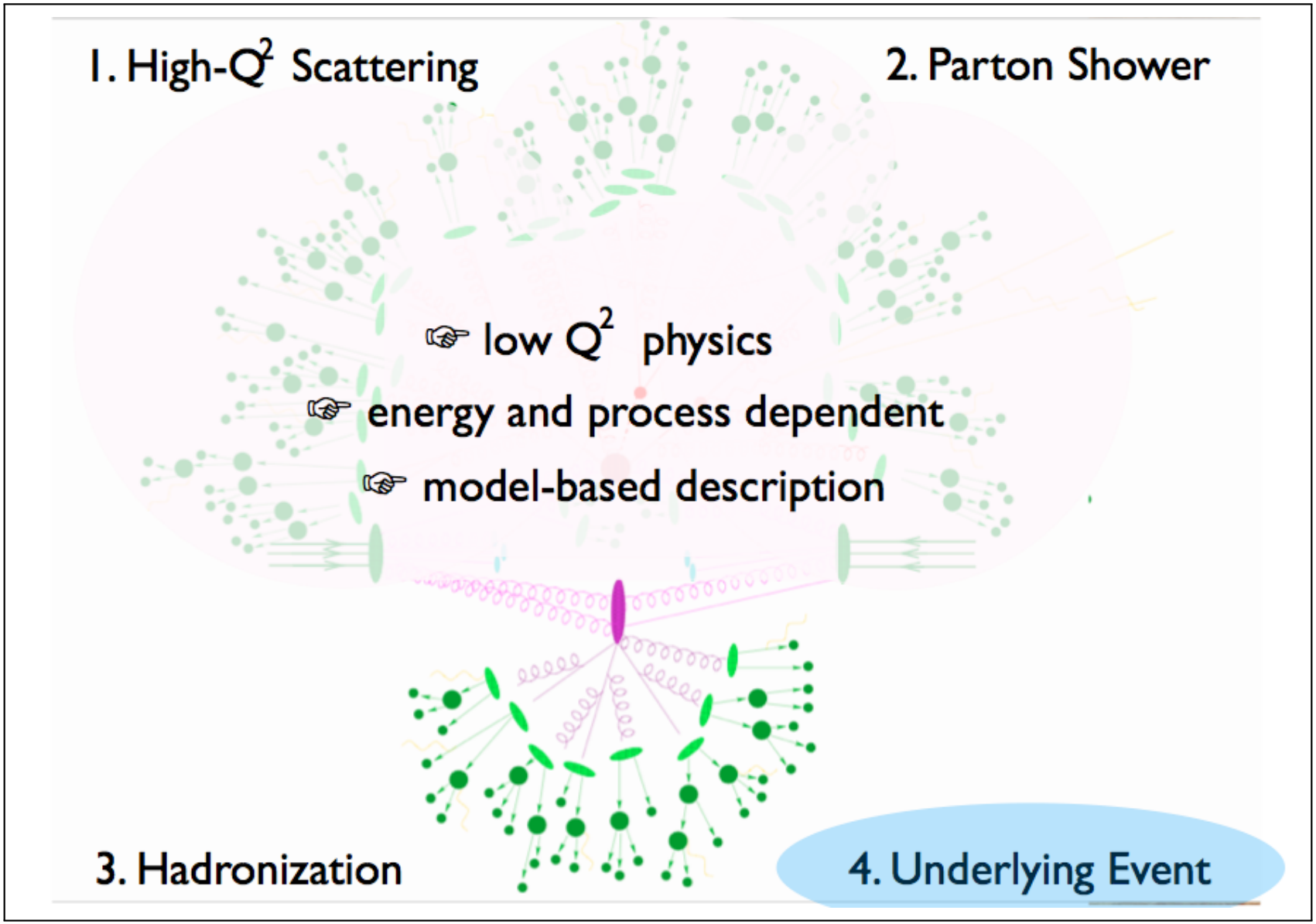

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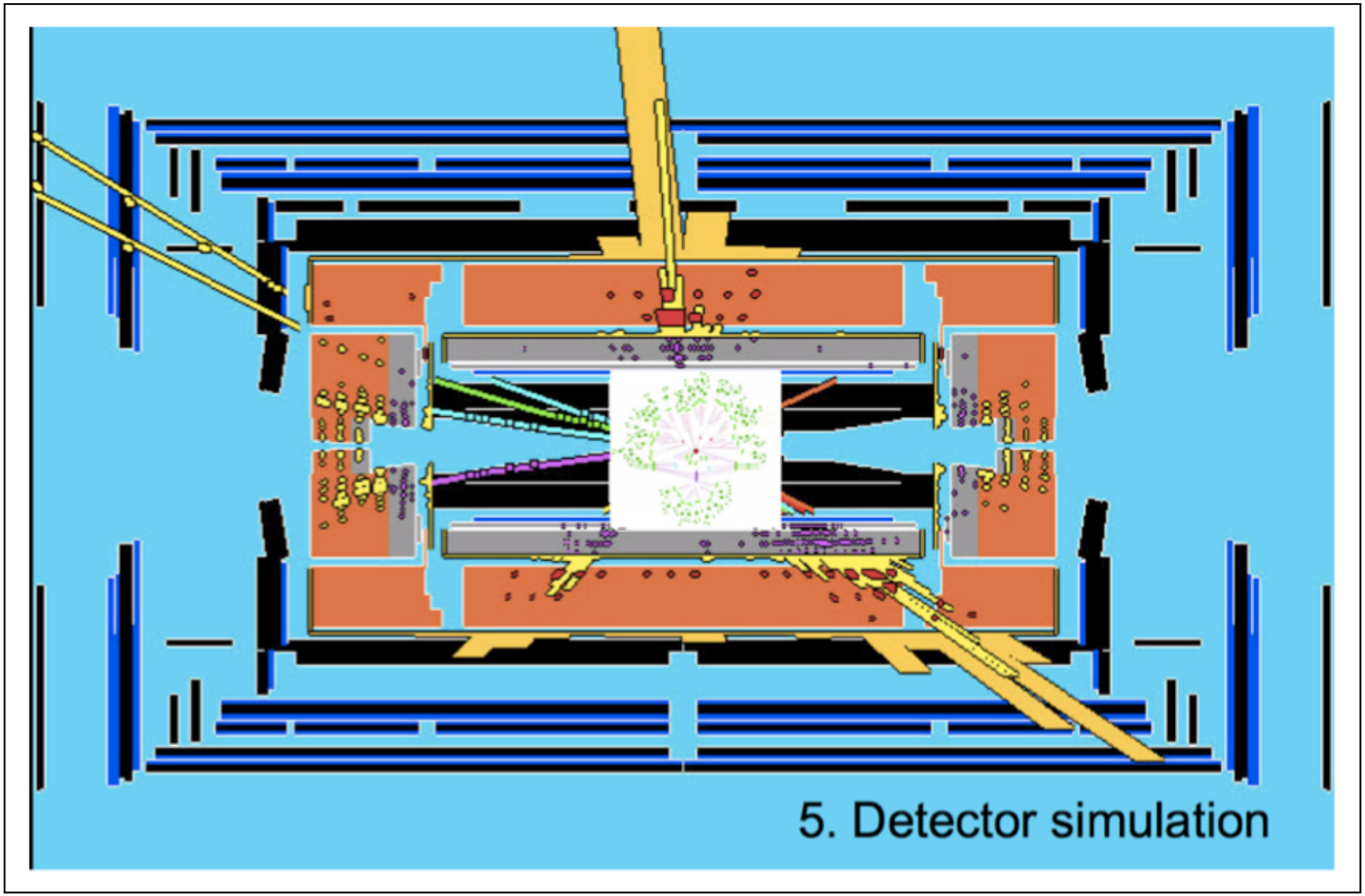

Madgraph

- So far we have used Madgraph to compute cross-sections
- Madgraph/Madevent generates hard scattering (*quarks, gluons, etc.*)
- In nature, we observe color singlet *hadrons*
- Use **Pythia** to go from partons to hadrons

Madgraph

- So far we have used Madgraph to compute cross-sections
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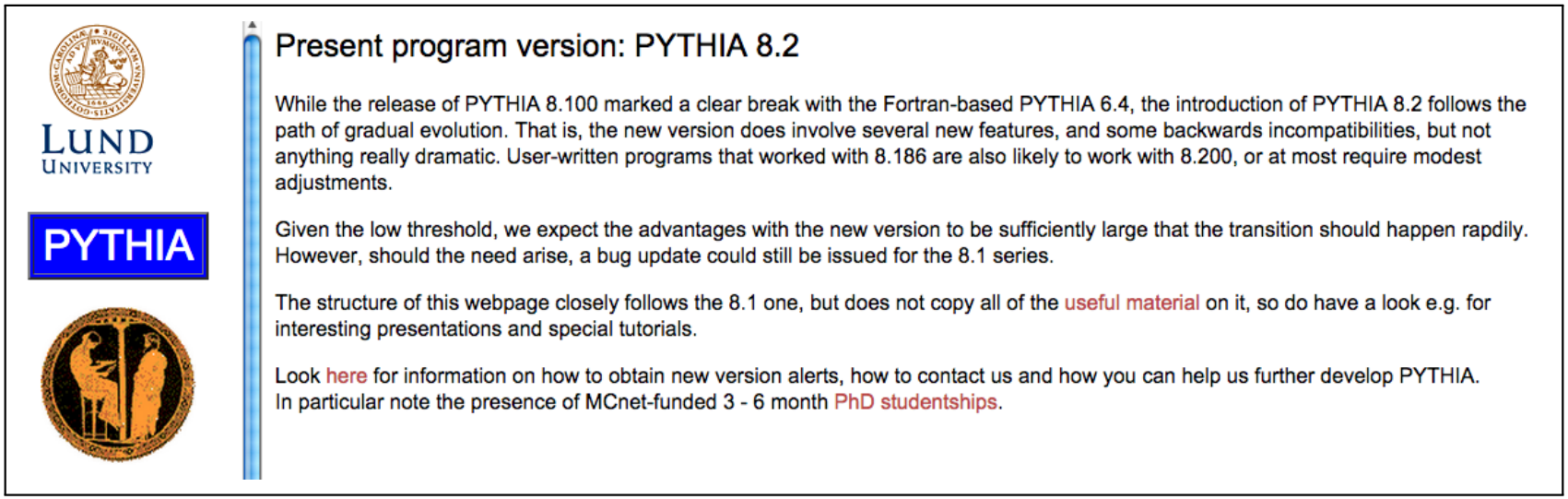
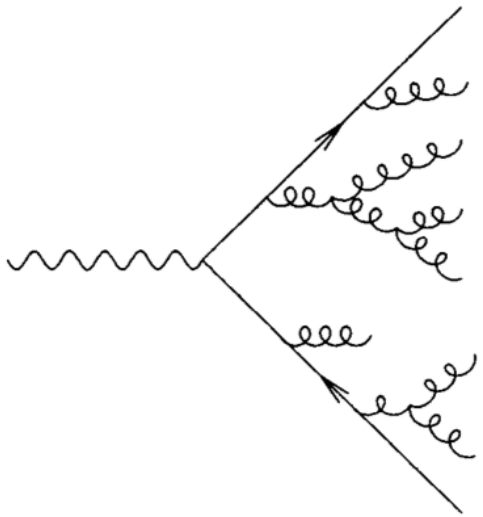
`http://home.thep.lu.se/~torbjorn/Pythia.html`



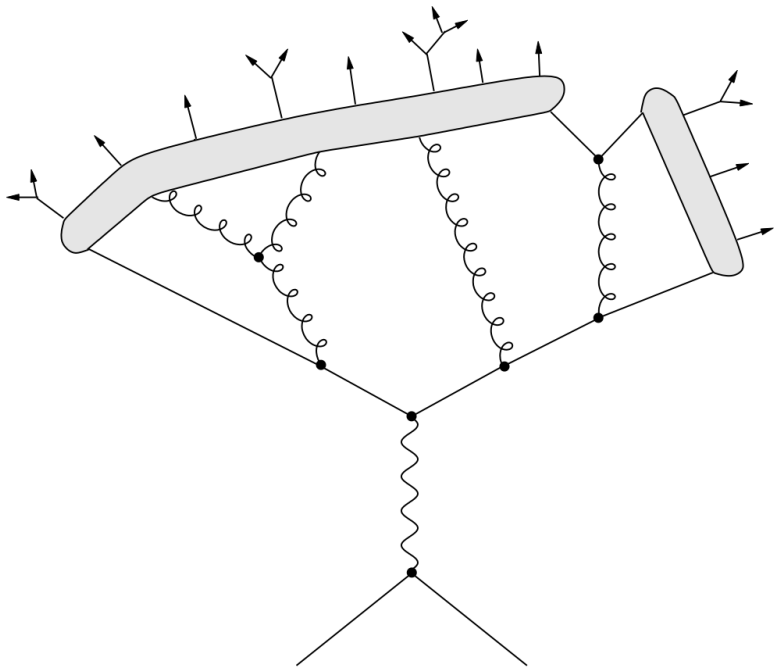
Pythia

- Standalone program
- Contains some (hard coded) matrix elements
- Implements *parton shower* and *hadronization model*
  - Successively applies splitting functions to partons
  - Evolves down from collision energy to Λ_{QCD}



Pythia

- Implements *parton shower* and *hadronization model*
  - Collects partons into hadrons
  - Phenomenologically-tuned model (non-perturbative process)
    (there are other models, *e.g.* see Herwig++)



See `http://pdg.lbl.gov/2014/reviews/rpp2014-rev-mc-event-gen.pdf`

Pythia

- Madgraph interfaces directly to Pythia 6
- Download via Madgraph interface

```
> ./bin/mg5
...
MG5_aMC> help install
```

Pythia

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```
> ./bin/mg5
...
MG5_aMC> help install
syntax:  install pythia-pgs|Delphes|MadAnalysis|
|ExRootAnalysis|update|Delphes2|SysCalc|Golem95
```

- Lists programs that interface directly to Madgraph
- (Delphes, MadAnalysis, and ExRootAnalysis will also be useful)

Pythia

```
MG5_aMC> install pythia-pgs
```

Pythia

```
MG5_aMC> install pythia-pgs

Downloading http://madgraph.phys.ucl.ac.be/Downloads/pythia-pgs_V2.4.3.

% Total % Received % Xferd Average Speed Time Time Time Current

Dload Upload Total Spent Left Speed

100 2583k 100 2583k 0 0 460k 0 0:00:05 0:00:05 --:--:-- 516k

compile pythia-pgs.  This might takes a while.

...
```

Pythia

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MG5_aMC> install pythia-pgs

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100 2583k 100 2583k 0 0 460k 0 0:00:05 0:00:05 --:--:-- 516k

compile pythia-pgs.  This might takes a while.

...

Compilation succeeded
```

- Can take some time to download and compile
- Two main ways to run Pythia in Madgraph

Pythia

1. Choose option in interactive mode

```
MG5_aMC> launch MyDileptonProcess
```

Pythia

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MG5_aMC> launch MyDileptonProcess

generate_events run_01

The following switches determine which programs are run:

1 Run the pythia shower/hadronization:  pythia=OFF

2 Run PGS as detector simulator:  pgs=OFF

3 Run Delphes as detector simulator:  delphes=NOT INSTALLED
...
[0, 1, 2, 4, 5, auto, done, pythia=ON, pythia=OFF, ...][60s to answer]
```

Pythia

1 Choose option in interactive mode

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MG5_aMC> launch MyDileptonProcess

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> 1
```

Pythia

1 Choose option in interactive mode

```
> 1

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[0, 1, 2, 4, 5, auto, done, pythia=ON, pythia=OFF, ...][60s to answer]
```

- Madevent runs as before, but runs Pythia directly afterwards

Pythia

- Referring back to the results page (it automatically will open), there are now outputs from Pythia
- All outputs and results can be accessed from this page

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	1688 ± 4	10000	parton madevent	LHE	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	1687 ± 3.9	10000	parton madevent	LHE	remove run launch detector simulation
					pythia	LOG STDHEP LHE	remove run launch detector simulation

Main Page

2 Setting `pythia_card.dat` (by default there is no file with this name)

```
> cat Cards/pythia_card.dat

!...Parton showering on or off
MSTP(61)=1
MSTP(71)=1
!...Fragmentation/hadronization on or off
MSTJ(1)=1
!...Multiple interactions on or off
MSTP(81)=20
!...Don't stop execution after 10 errors
MSTU(21)=1
!...PDFset if MG set not supported by pythia-pgs package
LHAID= 10041
```

Pythia

- Pythia 6 commands can be found at `http://arxiv.org/abs/hep-ph/0603175`
- Very extensive (table of contents is 7 pages)
- *e.g.* initial state radiation (page 388)

> `MSTP(61)` : (D = 2) master switch for initial-state QCD and QED radiation.
> `= 0` : off.
> `= 1` : on for QCD radiation in hadronic events and QED radiation in leptonic ones. (Not implemented for `PYPTIS`, equivalent to 2.).
> `= 2` : on for QCD and QED radiation in hadronic events and QED radiation in leptonic ones.

- *e.g.* parton shower ordering virtuality-ordered vs. p_T-ordered shower
  - p_T-ordered: `MSTP(81) = 20`
  - Virtuality-ordered: `MSTP(81) = 0`

Pythia

- Once there is a file `pythia_card.dat` in the `Cards` directory, Pythia will run by default each time

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Main Page

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Main Page

- Log file gives details of Pythia run
- Other files contain events in various formats (will be discussed soon)

Pythia

- Let's look at the Pythia log file

Event listing (standard)

I	particle/jet	K(I,1)	K(I,2)	K(I,3)	K(I,4)	K(I,5)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!	21	2212	0	0	0	0.00000	0.00000	6499.99993	6500.00000	0.93827
2	!p+!	21	2212	0	0	0	0.00000	0.00000	-6499.99993	6500.00000	0.93827
3	!d!	21	1	1	0	0	0.14675	-0.02498	825.47280	825.47282	0.00000
4	!u!	21	2	2	0	0	0.86867	-3.97985	-105.59194	105.67048	0.00000
5	!ubar!	21	-2	3	0	0	1.04107	-4.67827	5.77979	7.50839	0.00000
6	!u!	21	2	4	0	0	-0.14586	-2.87055	-81.97518	82.02555	0.00000
7	!e+!	21	-11	0	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
8	!e-!	21	11	0	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
9	e+	1	-11	7	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
10	e-	1	11	8	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
11	(u)	A 12	2	3	28	28	-5.26201	1.59203	-20.55202	21.27716	0.33000
12	(ud_0)	V 11	2101	1	28	28	-0.28852	-0.35972	4841.80669	4841.80671	0.00000
13	(dbar)	A 12	-1	1	51	51	0.08152	0.52615	68.46652	68.46859	0.00000
14	(u)	V 11	2	1	51	51	0.06025	-0.14144	764.14130	764.14132	0.00000
15	(d)	A 12	1	2	54	54	-0.79088	1.70548	-12.41043	12.55201	0.00000
16	(ubar)	V 11	-2	2	54	54	0.26014	1.02056	-185.40059	185.40358	0.00000
17	(uu_1)	A 12	2203	2	61	61	-0.33793	1.25381	-6196.48436	6196.48449	0.00000
18	(g)	I 12	21	4	61	61	1.46715	-0.58123	0.26229	1.59973	0.00000
19	(g)	I 12	21	4	61	61	0.35358	0.55141	0.18871	0.68167	0.00000
20	(g)	I 12	21	3	61	61	3.03732	1.18607	3.01784	4.44290	0.00000
21	(g)	I 12	21	3	61	61	0.32773	0.01530	0.11583	0.34794	0.00000
22	(g)	I 12	21	3	61	61	1.17715	-0.35239	5.98445	6.10929	0.00000
23	(g)	I 12	21	3	61	61	-0.39935	0.21012	1.47506	1.54254	0.00000
24	(g)	I 12	21	3	61	61	0.49358	0.44806	10.46929	10.49050	0.00000
25	(g)	I 12	21	3	61	61	0.18070	0.20348	173.93094	173.93115	0.00000
26	(g)	I 12	21	3	61	61	-0.24432	-0.27848	51.49244	51.49377	0.00000
27	(d)	V 11	1	3	61	61	-1.01132	0.54963	569.69143	569.69268	0.33000

Pythia

- `particle/jet`: name of particle

(Pages 79 - 83 of the Pythia manual)

Event listing (standard)

I	particle/jet	K(I,1)	K(I,2)	K(I,3)	K(I,4)	K(I,5)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
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- `K(I,1)`: particle status

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24	(g)	I 12	21	3	61	61	0.49358	0.44806	10.46929	10.49050	0.00000
25	(g)	I 12	21	3	61	61	0.18070	0.20348	173.93094	173.93115	0.00000
26	(g)	I 12	21	3	61	61	-0.24432	-0.27848	51.49244	51.49377	0.00000
27	(d)	V 11	1	3	61	61	-1.01132	0.54963	569.69143	569.69268	0.33000

Pythia

- `K(I,2)`: PDG id

  (`http://pdg.lbl.gov/2014/reviews/rpp2014-rev-monte-carlo-numbering.pdf`)

Event listing (standard)

I	particle/jet	K(I,1)	K(I,2)	K(I,3)	K(I,4)	K(I,5)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!	21	2212	0	0	0	0.00000	0.00000	6499.99993	6500.00000	0.93827
2	!p+!	21	2212	0	0	0	0.00000	0.00000	-6499.99993	6500.00000	0.93827
3	!d!	21	1	1	0	0	0.14675	-0.02498	825.47280	825.47282	0.00000
4	!u!	21	2	2	0	0	0.86867	-3.97985	-105.59194	105.67048	0.00000
5	!ubar!	21	-2	3	0	0	1.04107	-4.67827	5.77979	7.50839	0.00000
6	!u!	21	2	4	0	0	-0.14586	-2.87055	-81.97518	82.02555	0.00000
7	!e+!	21	-11	0	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
8	!e-!	21	11	0	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
9	e+	1	-11	7	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
10	e-	1	11	8	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
11	(u)	A 12	2	3	28	28	-5.26201	1.59203	-20.55202	21.27716	0.33000
12	(ud_0)	V 11	2101	1	28	28	-0.28852	-0.35972	4841.80669	4841.80671	0.00000
13	(dbar)	A 12	-1	1	51	51	0.08152	0.52615	68.46652	68.46859	0.00000
14	(u)	V 11	2	1	51	51	0.06025	-0.14144	764.14130	764.14132	0.00000
15	(d)	A 12	1	2	54	54	-0.79088	1.70548	-12.41043	12.55201	0.00000
16	(ubar)	V 11	-2	2	54	54	0.26014	1.02056	-185.40059	185.40358	0.00000
17	(uu_1)	A 12	2203	2	61	61	-0.33793	1.25381	-6196.48436	6196.48449	0.00000
18	(g)	I 12	21	4	61	61	1.46715	-0.58123	0.26229	1.59973	0.00000
19	(g)	I 12	21	4	61	61	0.35358	0.55141	0.18871	0.68167	0.00000
20	(g)	I 12	21	3	61	61	3.03732	1.18607	3.01784	4.44290	0.00000
21	(g)	I 12	21	3	61	61	0.32773	0.01530	0.11583	0.34794	0.00000
22	(g)	I 12	21	3	61	61	1.17715	-0.35239	5.98445	6.10929	0.00000
23	(g)	I 12	21	3	61	61	-0.39935	0.21012	1.47506	1.54254	0.00000
24	(g)	I 12	21	3	61	61	0.49358	0.44806	10.46929	10.49050	0.00000
25	(g)	I 12	21	3	61	61	0.18070	0.20348	173.93094	173.93115	0.00000
26	(g)	I 12	21	3	61	61	-0.24432	-0.27848	51.49244	51.49377	0.00000
27	(d)	V 11	1	3	61	61	-1.01132	0.54963	569.69143	569.69268	0.33000

Pythia

- `K(I,3)`: line number of parent particle

Event listing (standard)

I	particle/jet	K(I,1)	K(I,2)	K(I,3)	K(I,4)	K(I,5)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!	21	2212	0	0	0	0.00000	0.00000	6499.99993	6500.00000	0.93827
2	!p+!	21	2212	0	0	0	0.00000	0.00000	-6499.99993	6500.00000	0.93827
3	!d!	21	1	1	0	0	0.14675	-0.02498	825.47280	825.47282	0.00000
4	!u!	21	2	2	0	0	0.86867	-3.97985	-105.59194	105.67048	0.00000
5	!ubar!	21	-2	3	0	0	1.04107	-4.67827	5.77979	7.50839	0.00000
6	!u!	21	2	4	0	0	-0.14586	-2.87055	-81.97518	82.02555	0.00000
7	!e+!	21	-11	0	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
8	!e-!	21	11	0	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
9	e+	1	-11	7	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
10	e-	1	11	8	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
11	(u)	A 12	2	3	28	28	-5.26201	1.59203	-20.55202	21.27716	0.33000
12	(ud_0)	V 11	2101	1	28	28	-0.28852	-0.35972	4841.80669	4841.80671	0.00000
13	(dbar)	A 12	-1	1	51	51	0.08152	0.52615	68.46652	68.46859	0.00000
14	(u)	V 11	2	1	51	51	0.06025	-0.14144	764.14130	764.14132	0.00000
15	(d)	A 12	1	2	54	54	-0.79088	1.70548	-12.41043	12.55201	0.00000
16	(ubar)	V 11	-2	2	54	54	0.26014	1.02056	-185.40059	185.40358	0.00000
17	(uu_1)	A 12	2203	2	61	61	-0.33793	1.25381	-6196.48436	6196.48449	0.00000
18	(g)	I 12	21	4	61	61	1.46715	-0.58123	0.26229	1.59973	0.00000
19	(g)	I 12	21	4	61	61	0.35358	0.55141	0.18871	0.68167	0.00000
20	(g)	I 12	21	3	61	61	3.03732	1.18607	3.01784	4.44290	0.00000
21	(g)	I 12	21	3	61	61	0.32773	0.01530	0.11583	0.34794	0.00000
22	(g)	I 12	21	3	61	61	1.17715	-0.35239	5.98445	6.10929	0.00000
23	(g)	I 12	21	3	61	61	-0.39935	0.21012	1.47506	1.54254	0.00000
24	(g)	I 12	21	3	61	61	0.49358	0.44806	10.46929	10.49050	0.00000
25	(g)	I 12	21	3	61	61	0.18070	0.20348	173.93094	173.93115	0.00000
26	(g)	I 12	21	3	61	61	-0.24432	-0.27848	51.49244	51.49377	0.00000
27	(d)	V 11	1	3	61	61	-1.01132	0.54963	569.69143	569.69268	0.33000

- `K(I,4)/K(I,5)`: line number of first/last daughter

Event listing (standard)

I	particle/jet	K(I,1)	K(I,2)	K(I,3)	K(I,4)	K(I,5)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!	21	2212	0	0	0	0.00000	0.00000	6499.99993	6500.00000	0.93827
2	!p+!	21	2212	0	0	0	0.00000	0.00000	-6499.99993	6500.00000	0.93827
3	!d!	21	1	1	0	0	0.14675	-0.02498	825.47280	825.47282	0.00000
4	!u!	21	2	2	0	0	0.86867	-3.97985	-105.59194	105.67048	0.00000
5	!ubar!	21	-2	3	0	0	1.04107	-4.67827	5.77979	7.50839	0.00000
6	!u!	21	2	4	0	0	-0.14586	-2.87055	-81.97518	82.02555	0.00000
7	!e+!	21	-11	0	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
8	!e-!	21	11	0	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
9	e+	1	-11	7	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
10	e-	1	11	8	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
11	(u)	A 12	2	3	28	28	-5.26201	1.59203	-20.55202	21.27716	0.33000
12	(ud_0)	V 11	2101	1	28	28	-0.28852	-0.35972	4841.80669	4841.80671	0.00000
13	(dbar)	A 12	-1	1	51	51	0.08152	0.52615	68.46652	68.46859	0.00000
14	(u)	V 11	2	1	51	51	0.06025	-0.14144	764.14130	764.14132	0.00000
15	(d)	A 12	1	2	54	54	-0.79088	1.70548	-12.41043	12.55201	0.00000
16	(ubar)	V 11	-2	2	54	54	0.26014	1.02056	-185.40059	185.40358	0.00000
17	(uu_1)	A 12	2203	2	61	61	-0.33793	1.25381	-6196.48436	6196.48449	0.00000
18	(g)	I 12	21	4	61	61	1.46715	-0.58123	0.26229	1.59973	0.00000
19	(g)	I 12	21	4	61	61	0.35358	0.55141	0.18871	0.68167	0.00000
20	(g)	I 12	21	3	61	61	3.03732	1.18607	3.01784	4.44290	0.00000
21	(g)	I 12	21	3	61	61	0.32773	0.01530	0.11583	0.34794	0.00000
22	(g)	I 12	21	3	61	61	1.17715	-0.35239	5.98445	6.10929	0.00000
23	(g)	I 12	21	3	61	61	-0.39935	0.21012	1.47506	1.54254	0.00000
24	(g)	I 12	21	3	61	61	0.49358	0.44806	10.46929	10.49050	0.00000
25	(g)	I 12	21	3	61	61	0.18070	0.20348	173.93094	173.93115	0.00000
26	(g)	I 12	21	3	61	61	-0.24432	-0.27848	51.49244	51.49377	0.00000
27	(d)	V 11	1	3	61	61	-1.01132	0.54963	569.69143	569.69268	0.33000

Pythia

- P: p_x, p_y, p_z, E, m

Event listing (standard)

I	particle/jet	K(I,1)	K(I,2)	K(I,3)	K(I,4)	K(I,5)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!	21	2212	0	0	0	0.00000	0.00000	6499.99993	6500.00000	0.93827
2	!p+!	21	2212	0	0	0	0.00000	0.00000	-6499.99993	6500.00000	0.93827
3	!d!	21	1	1	0	0	0.14675	-0.02498	825.47280	825.47282	0.00000
4	!u!	21	2	2	0	0	0.86867	-3.97985	-105.59194	105.67048	0.00000
5	!ubar!	21	-2	3	0	0	1.04107	-4.67827	5.77979	7.50839	0.00000
6	!u!	21	2	4	0	0	-0.14586	-2.87055	-81.97518	82.02555	0.00000
7	!e+!	21	-11	0	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
8	!e-!	21	11	0	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
9	e+	1	-11	7	0	0	-22.28091	-2.98586	-45.98123	51.18230	0.00051
10	e-	1	11	8	0	0	23.17612	-4.56296	-30.21416	38.35165	0.00051
11	(u)	A 12	2	3	28	28	-5.26201	1.59203	-20.55202	21.27716	0.33000
12	(ud_0)	V 11	2101	1	28	28	-0.28852	-0.35972	4841.80669	4841.80671	0.00000
13	(dbar)	A 12	-1	1	51	51	0.08152	0.52615	68.46652	68.46859	0.00000
14	(u)	V 11	2	1	51	51	0.06025	-0.14144	764.14130	764.14132	0.00000
15	(d)	A 12	1	2	54	54	-0.79088	1.70548	-12.41043	12.55201	0.00000
16	(ubar)	V 11	-2	2	54	54	0.26014	1.02056	-185.40059	185.40358	0.00000
17	(uu_1)	A 12	2203	2	61	61	-0.33793	1.25381	-6196.48436	6196.48449	0.00000
18	(g)	I 12	21	4	61	61	1.46715	-0.58123	0.26229	1.59973	0.00000
19	(g)	I 12	21	4	61	61	0.35358	0.55141	0.18871	0.68167	0.00000
20	(g)	I 12	21	3	61	61	3.03732	1.18607	3.01784	4.44290	0.00000
21	(g)	I 12	21	3	61	61	0.32773	0.01530	0.11583	0.34794	0.00000
22	(g)	I 12	21	3	61	61	1.17715	-0.35239	5.98445	6.10929	0.00000
23	(g)	I 12	21	3	61	61	-0.39935	0.21012	1.47506	1.54254	0.00000
24	(g)	I 12	21	3	61	61	0.49358	0.44806	10.46929	10.49050	0.00000
25	(g)	I 12	21	3	61	61	0.18070	0.20348	173.93094	173.93115	0.00000
26	(g)	I 12	21	3	61	61	-0.24432	-0.27848	51.49244	51.49377	0.00000
27	(d)	V 11	1	3	61	61	-1.01132	0.54963	569.69143	569.69268	0.33000

Generation Chain

Madgraph

Madevent

Pythia

- Creates directory with diagrams and amplitudes
- Generates hard scatter events (output: four vectors)
- Shower/hadronizes (output: four vectors)

Generation Chain

Madgraph

Madevent

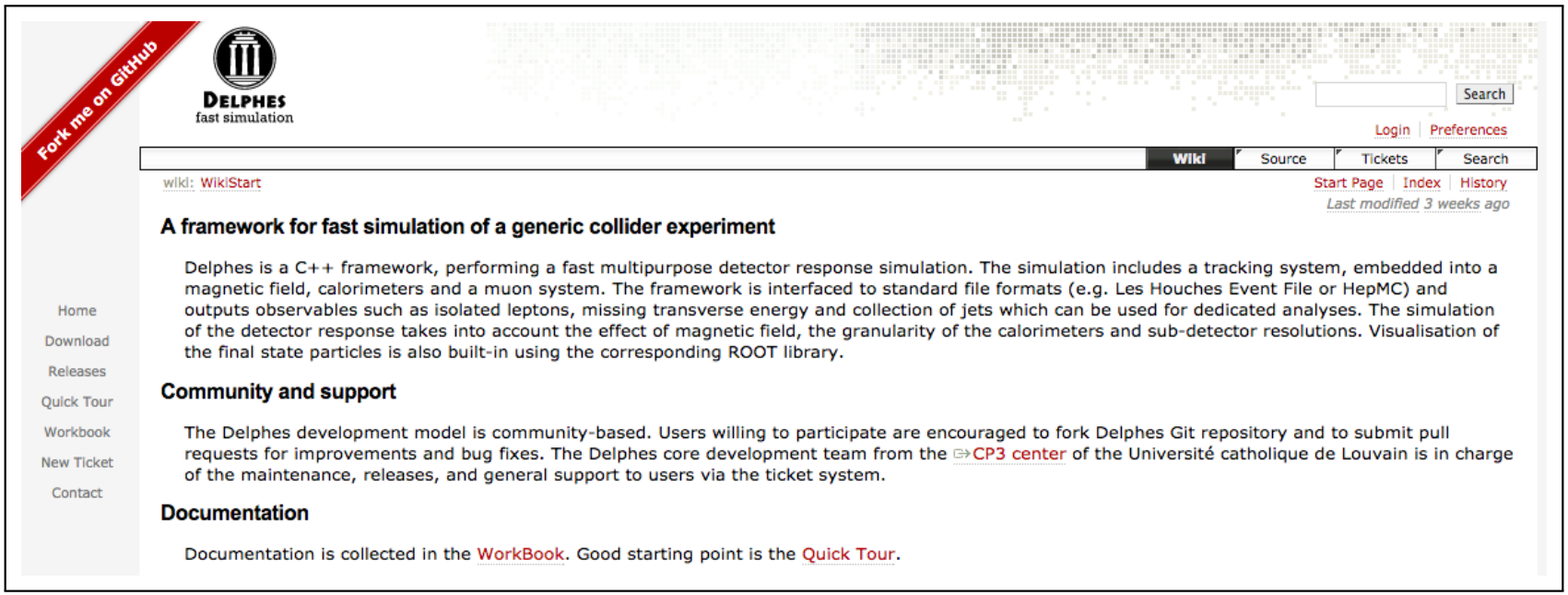
Pythia

Delphes

- Creates directory with diagrams and amplitudes
- Generates hard scatter events (output: four vectors)
- Shower/hadronizes (output: four vectors)
- Simulates detector response (output: physics objects)

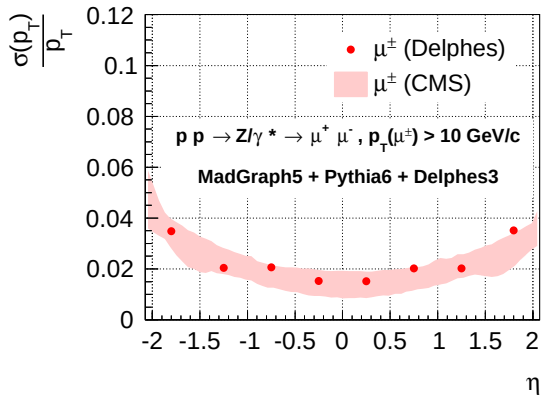
Delphes

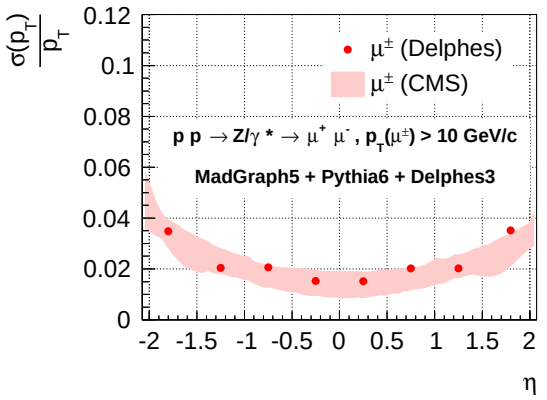
- Standalone program (`https://cp3.irmp.ucl.ac.be/projects/delphes`)
- Directly interfaces with Madgraph
- Can read in Madgraph output, Pythia output, etc.
- Thorough description in paper (`http://arxiv.org/abs/1307.6346`)



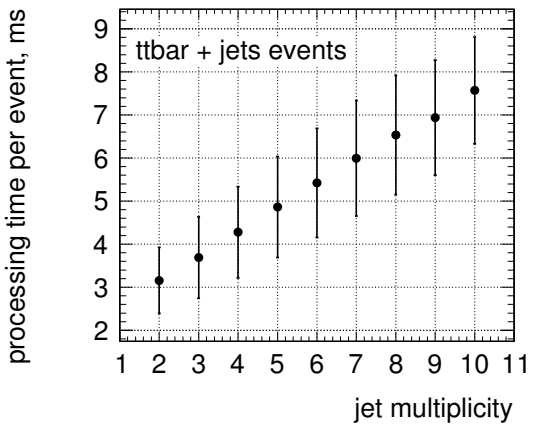
Delphes

- Some excerpts from the paper
  - Has been validated





  - Has been optimized for speed (much faster than full detector simulations)



Delphes

- Installing follows the same procedure as Pythia

```
MG5_aMC> install Delphes

Downloading http://cp3.irmp.ucl.ac.be/downloads/Delphes-3-current...

...

>> Building DelphesSTDHEP

Compilation succeeded
```

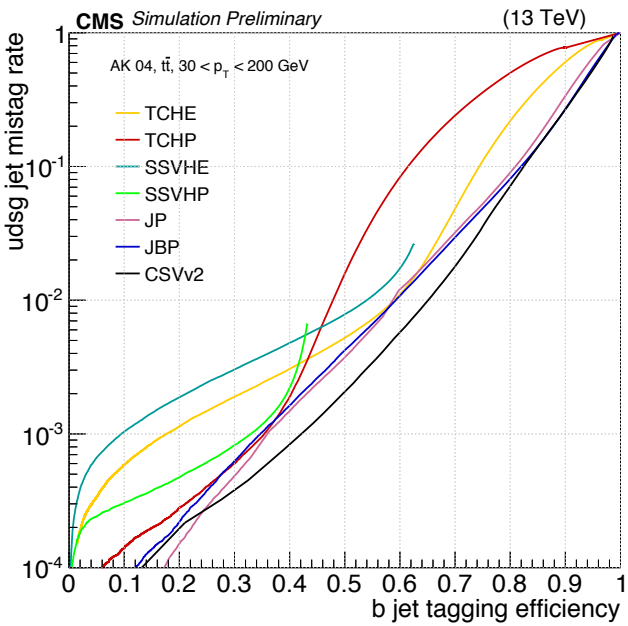
Delphes

- Can run Delphes interactively or by card `delphes_card.dat` (same as with Pythia)
- Contains simple parameterization of detector response
- Realistically clusters jets (uses Fastjet program)

```
module FastJetFinder FastJetFinder {
  set InputArray EFlowMerger/eflow
  set OutputArray jets
  # algorithm:  ..., 4 kt, 5 Cambridge/Aachen, 6 antikt
  set JetAlgorithm 6
  set ParameterR 0.5
  set JetPTMin 20.0
}
```

Delphes (aside)

- *b*-tagging
  - For each jet, one applies an algorithm to tell if the jet is a *b*-jet
  - The "*b*-jet tagging efficiency" tells you the probability to call it a *b* (when it is really a *b*)
  - The "mistag rate" tells you the probability to call it a *b* (when it is really **not** a *b*)



- "ROC" curve plots efficiency vs. mistag rate
- Depends on η and p_T

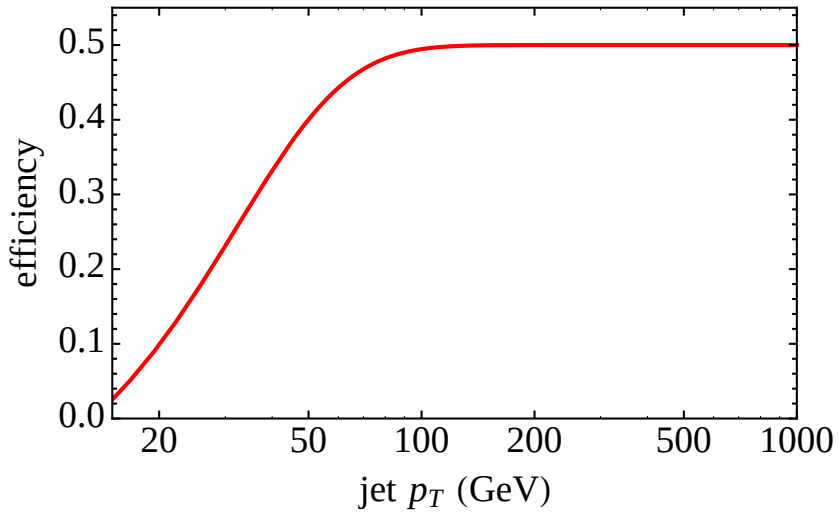
Delphes (aside)

- *b*-tagging parameterization in Delphes
  - jet mistagging rate

```
add EfficiencyFormula {0} {0.001}
```

  - *b*-jet tagging rate (simplified example)

```
add EfficiencyFormula {5} { (abs(eta) <= 2.5)
                          * (0.5*tanh(pt*0.03 - 0.4))
                          + (abs(eta) > 2.5) * (0.000)}
```



Delphes

- Delphes output now included in results page

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	1688 ± 4	10000	parton madevent	LHE	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	1687 ± 3.9	10000	parton madevent	LHE	remove run launch detector simulation
					pythia	LOG STDHEP LHE	remove run launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	1690 ± 4	10000	parton madevent	LHE	remove run launch detector simulation
					pythia	LOG STDHEP LHE	remove run launch detector simulation
					delphes	LOG LHCO rootfile	remove run

Main Page

Delphes

- Delphes output now included in results page

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	1688 ± 4	10000	parton madevent	LHE	remove run / launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	1687 ± 3.9	10000	parton madevent	LHE	remove run / launch detector simulation
					pythia	LOG STDHEP LHE	remove run / launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	1690 ± 4	10000	parton madevent	LHE	remove run / launch detector simulation
					pythia	LOG STDHEP LHE	remove run / launch detector simulation
					delphes	LOG LHCO rootfile	remove run

Main Page

- Can also run Pythia or Delphes on existing runs

Delphes

- Delphes output now included in results page

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	1688 ± 4	10000	parton madevent	LHE	remove run / launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	1687 ± 3.9	10000	parton madevent	LHE	remove run / launch detector simulation
					pythia	LOG STDHEP LHE	remove run / launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	1690 ± 4	10000	parton madevent	LHE	remove run / launch detector simulation
					pythia	LOG STDHEP LHE	remove run / launch detector simulation
					delphes	LOG LHCO rootfile	remove run

Main Page

- Can also run Pythia or Delphes on existing runs

Madgraph Output

- Let's look at the format of the events that Madgraph creates
- From process directory, events are stored in

```
> cd Events/
> ls
run_01      run_02      run_03                    (Each separate run we generated)
> cd run_01/
> ls
```

```
run_01_tag_1_banner.txt
```

```
events.lhe.gz
```

```
unweighted_events.lhe.gz
```

Madgraph Output

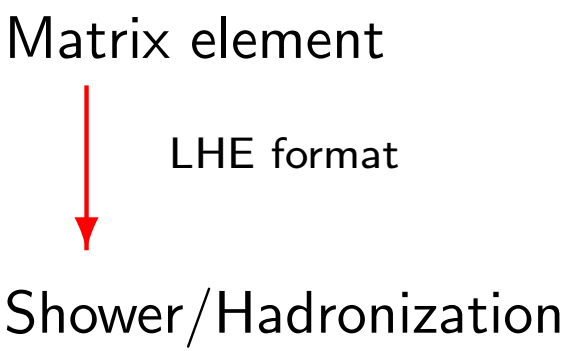
- Let's look at the format of the events that Madgraph creates
- From process directory, events are stored in

```
> cd Events/
> ls
run_01      run_02      run_03                    (Each separate run we generated)
> cd run_01/
> ls
```

`run_01_tag_1_banner.txt`	▶ Record of all run settings
`events.lhe.gz`	▶ List of *weighted* events
`unweighted_events.lhe.gz`	▶ List of *unweighted* events

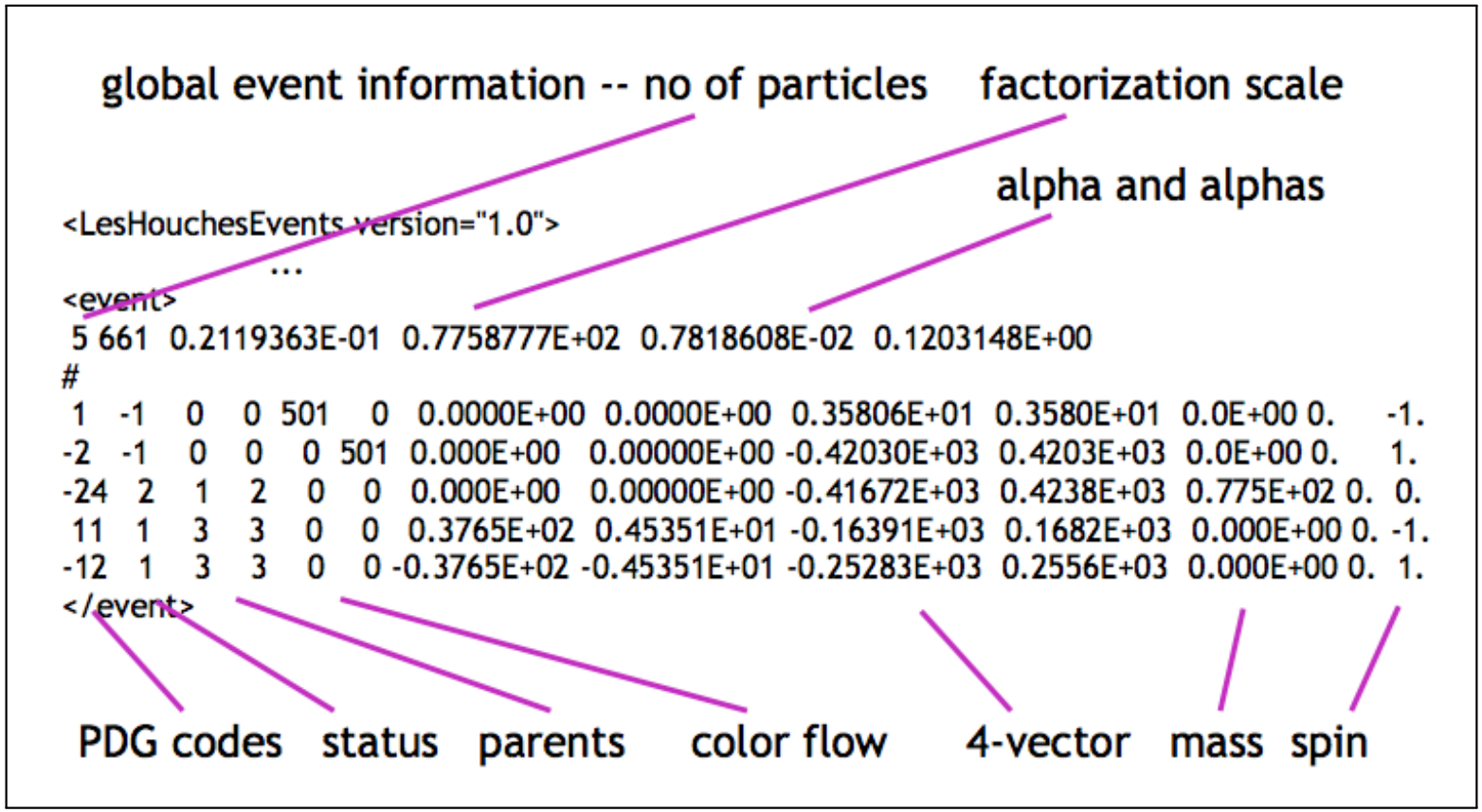
Madgraph Output

- Events in *LHE format*
  - Les Houches Event Files, *hep-ph/0609017*
  - Standard format used by all MC generators
  - Can interchange programs for matrix element vs. parton shower
  - *e.g.* Madgraph $\rightarrow$ Herwig++, WHIZARD $\rightarrow$ Pythia 8, etc.



Madgraph Output

- Events in *LHE format*
  - Les Houches Event Files, *hep-ph/0609017*



http://www.physics.uci.edu/~tanedo/files/notes/ColliderMadgraph.pdf

Pythia Output

- Let's look at the output Pythia provides

```
> cd Events/run_02
> ls
```

```
run_02_tag_1_banner.txt

events.lhe.gz

unweighted_events.lhe.gz

tag_1_pythia.log

tag_1_pythia_syst.dat.gz

tag_1_pythia_events.lhe.gz

tag_1_pythia_events.hep.gz
```

Pythia Output

- Let's look at the output Pythia provides

```
> cd Events/run_02
> ls
```

`run_02_tag_1_banner.txt`	Record of all run settings
`events.lhe.gz`	List of weighted events
`unweighted_events.lhe.gz`	List of unweighted events
`tag_1_pythia.log`	Log of Pythia run
`tag_1_pythia_syst.dat.gz`	Pythia systematics
`tag_1_pythia_events.lhe.gz`	Pythia events in *LHE format*
`tag_1_pythia_events.hep.gz`	Pythia events in *HEP format*

Pythia Output

- Comparing file sizes

```
75M tag_1_pythia_events.hep.gz

1.7M tag_1_pythia_events.lhe.gz
```

Pythia Output

- Comparing file sizes

```
75M tag_1_pythia_events.hep.gz

1.7M tag_1_pythia_events.lhe.gz
```

- HEP contains all of the information
- The LHE is condensed (**do not use this for analysis**)

Pythia Output

- The LHE is condensed (**do not use this for analysis**)

```
<event>
  8 100  0.10000000E+01  0.00000000E+00  0.00000000E+00  0.00000000E+00
      -2 -1   0   0 0 0  0.21473741E+01  0.43598572E+01  0.21395160E+03  0.21400679E+03  0.00000000E+00 0. 0.
       2 -1   0   0 0 0  0.81102107E+01  0.44423865E+02  0.38115393E+02  0.59093472E+02  0.00000000E+00 0. 0.
      23  2   1   1 0 0  0.10257585E+02  0.48783722E+02  0.25206699E+03  0.27310026E+03  0.92525215E+02 0. 0.
     -11  2   3   3 0 0 -0.32055152E+02  0.17717650E+02  0.38345025E+02  0.53026303E+02  0.51000000E-03 0. 0.
      11  2   3   3 0 0  0.42312737E+02  0.31066072E+02  0.21372197E+03  0.22007396E+03  0.51000000E-03 0. 0.
     -11  1   0   0 0 0 -0.32049869E+02  0.17715584E+02  0.38340792E+02  0.53019358E+02  0.51000000E-03 0. 0.
      11  1   0   0 0 0  0.42312686E+02  0.31066035E+02  0.21372171E+03  0.22007370E+03  0.51000000E-03 0. 0.
      21  1   0   0 0 0 -0.41042640E+01 -0.37984421E+02 -0.54799213E+01  0.38860106E+02  0.45185273E+01 0. 0.
</event>
```

- Column 1: PDG id [PDG link]
- Column 2: -1 = incoming, 2 = intermediate, 1 = final state
- Columns 3, 4: mother particle(s)
- Columns 5, 6: color flow
- Columns 7 - 11: p_x, p_y, p_z, E, m

Delphes Output

- Let's look at the output Delphes provides

```
> cd Events/run_02
> ls

    ...

    tag_1_delphes_events.root

    tag_1_delphes.log

    tag_1_delphes_events.lhco.gz
```

Delphes Output

- Let's look at the output Delphes provides

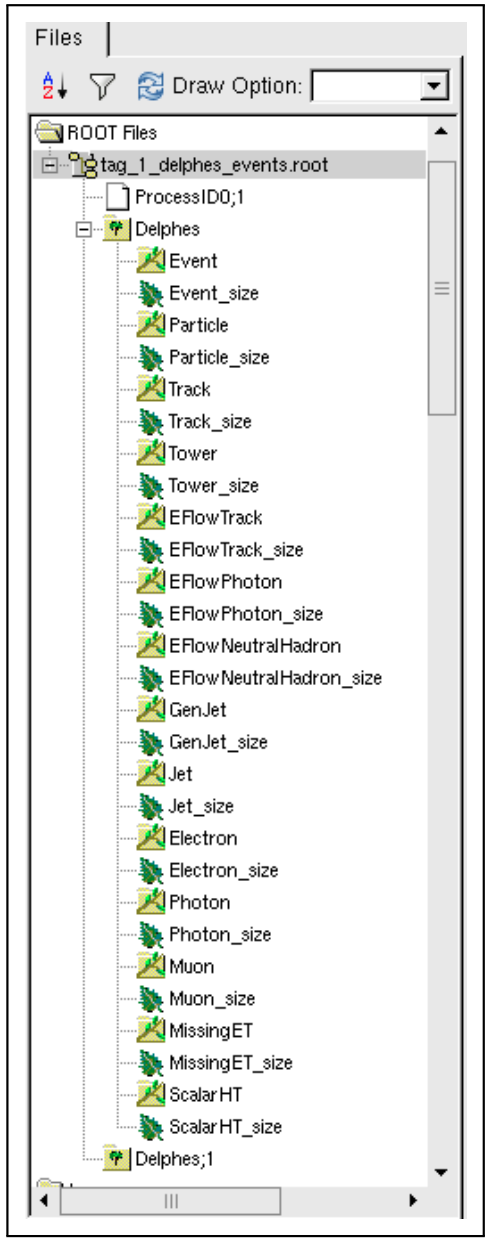
```
> cd Events/run_02
> ls
```

```
...
```

`tag_1_delphes_events.root`	▶ Delphes events in *ROOT* format
`tag_1_delphes.log`	▶ Log of Delphes run
`tag_1_delphes_events.lhco.gz`	▶ Delphes events in *LHCO* format

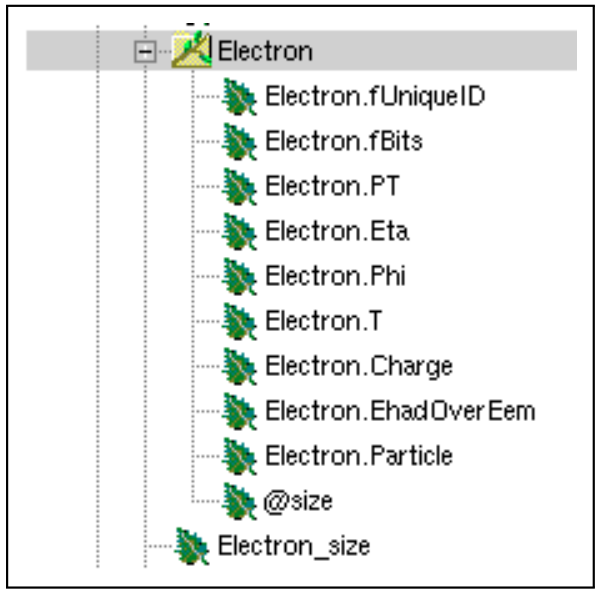
Delphes Output

- Inside the ROOT file
- Physics objects are:
  - Jets
  - Electrons
  - Photons
  - Muons
  - Missing E_T
  - Scalar H_T
- Can be used directly in analyses
- Using ROOT file one can make quick sanity checks



Delphes Output

- *e.g.* electron variables
  - number of electrons per event
  - transverse momentum p_T
  - pseudorapidity η
  - azimuthal angle ϕ



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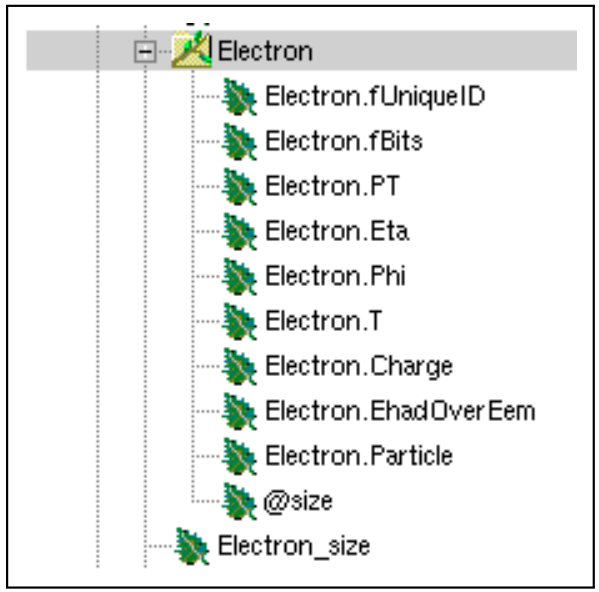
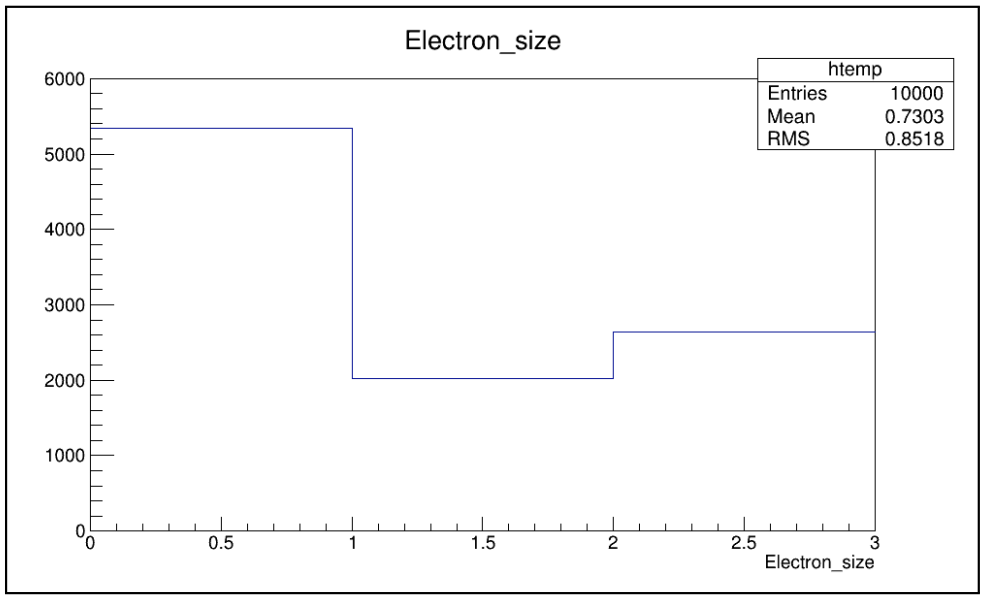
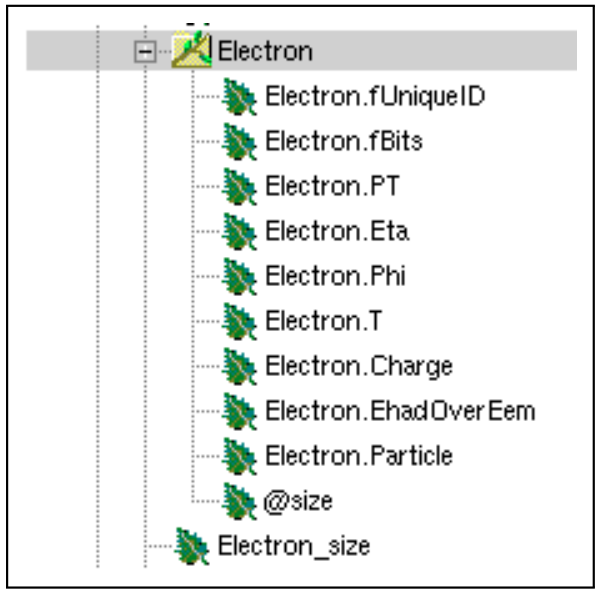
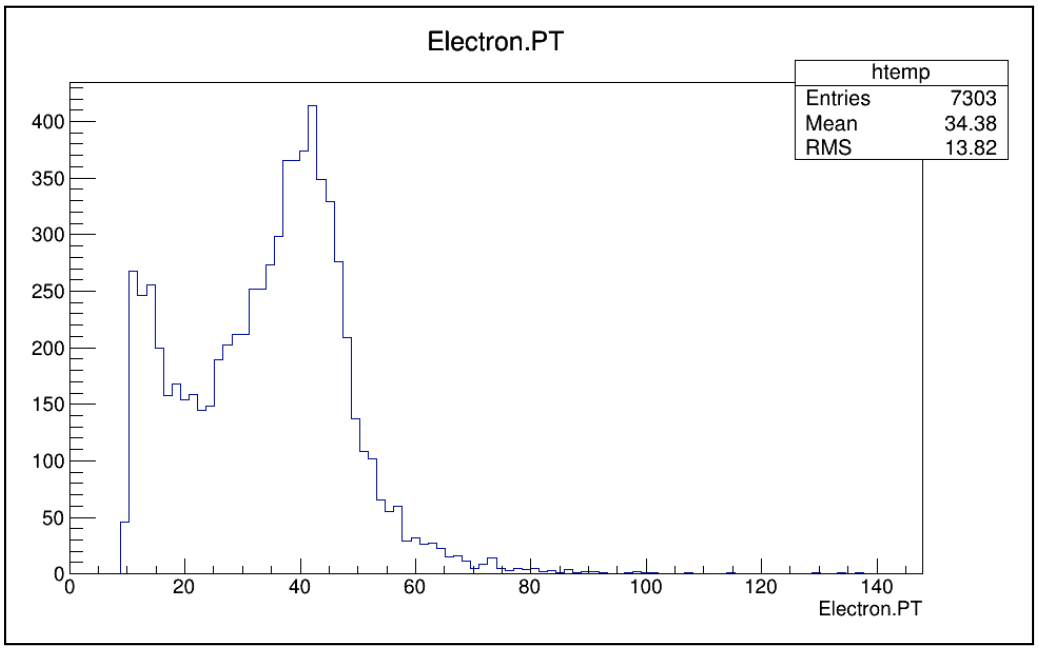




Delphes Output

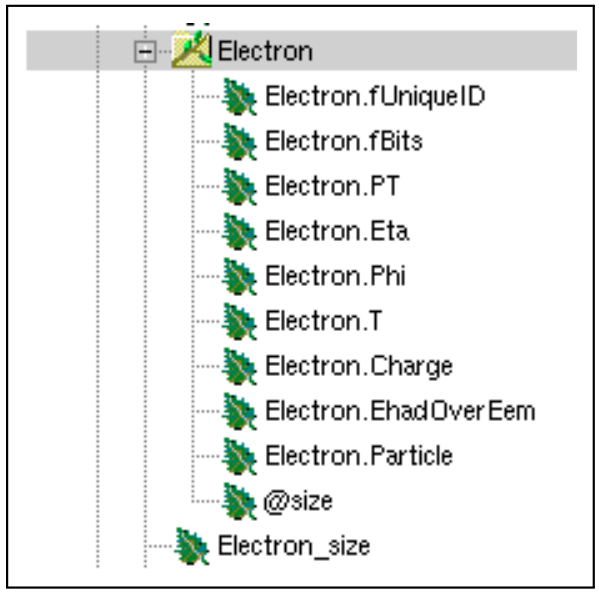
- *e.g.* electron variables
  - **transverse momentum** p_T
- *After* detector simulation
- As expected, we see Z and γ^* contributions

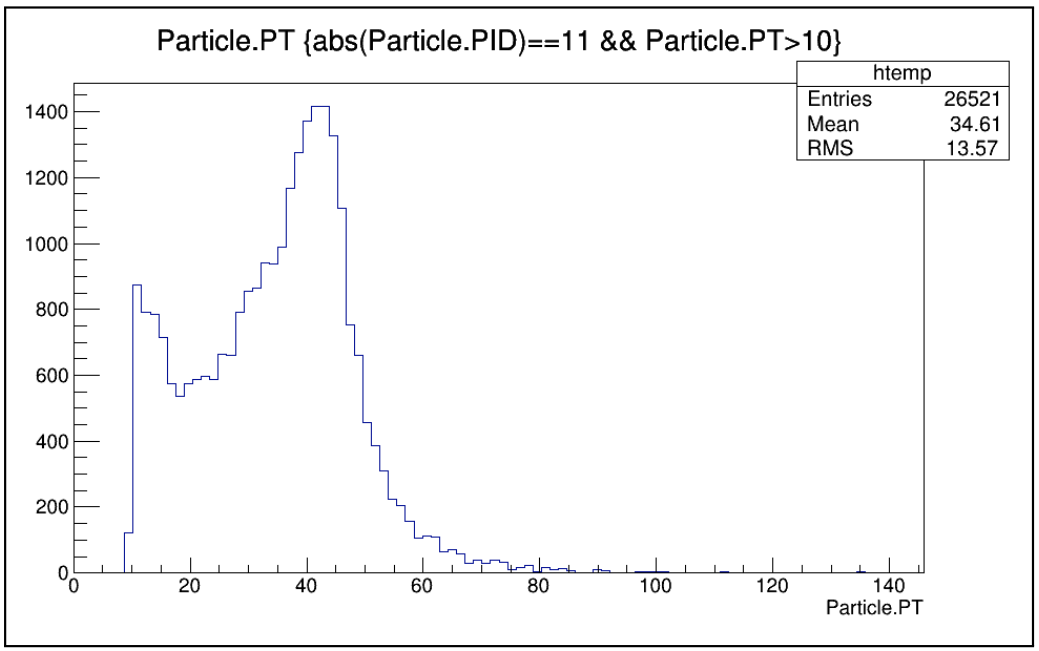




Delphes Output

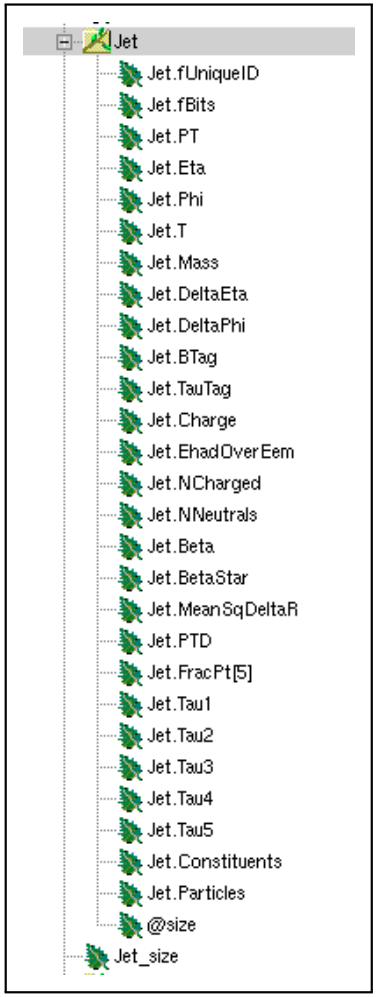
- *e.g.* electron variables
  - **transverse momentum** p_T
- *Before* detector simulation
- Shape not modified much due to detector





Delphes Output

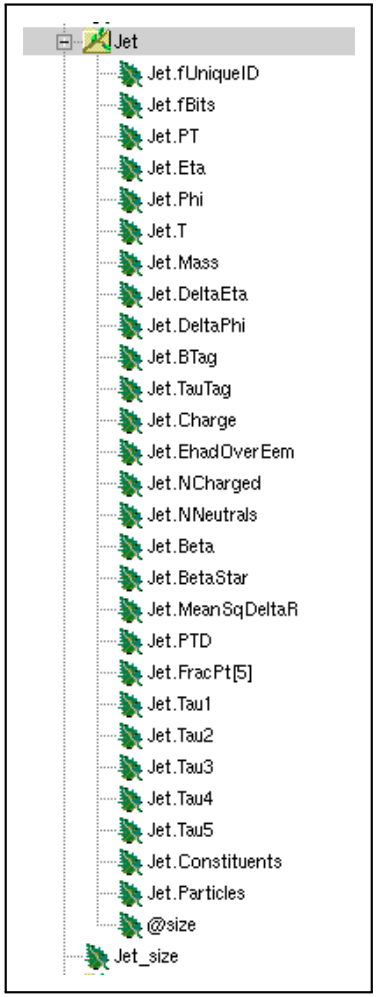
- Jets have additional descriptors
  - `Jet.BTag` includes flags on whether a jet was b-tagged
  - `Jet.TauTag` includes flags on whether a jet was τ-tagged
  - `Jet.TauN` are substructure variables used for boosted boson tagging



Delphes Output

Short case study: let's do some sanity checks

- The process is $pp \to \ell^+\ell^-$
- No quarks/gluons in the matrix element
- Do we expect to see any jets?



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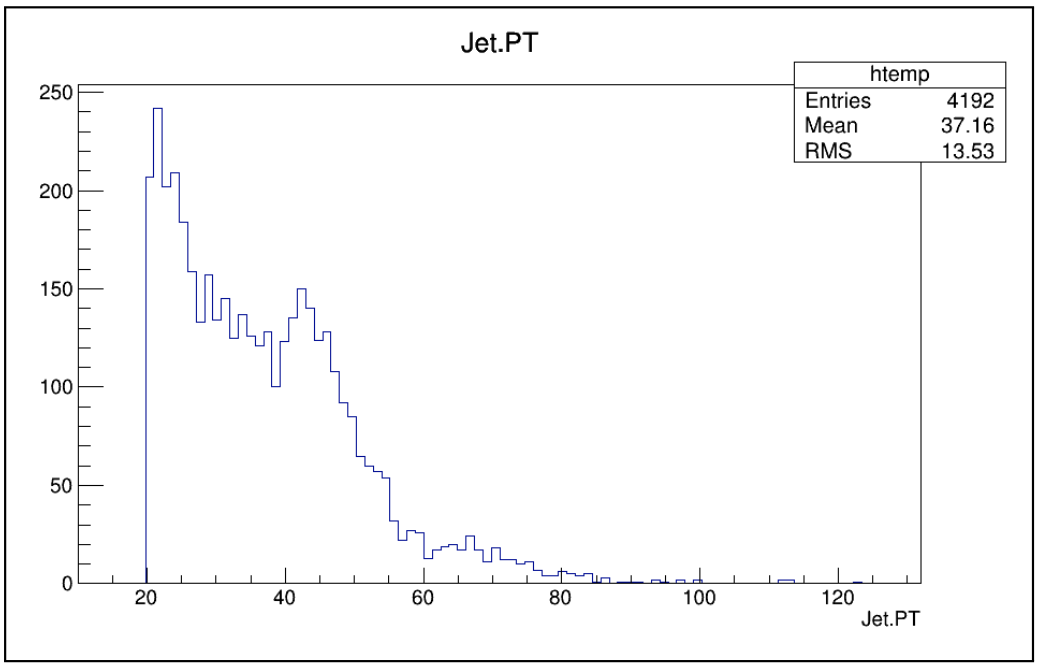
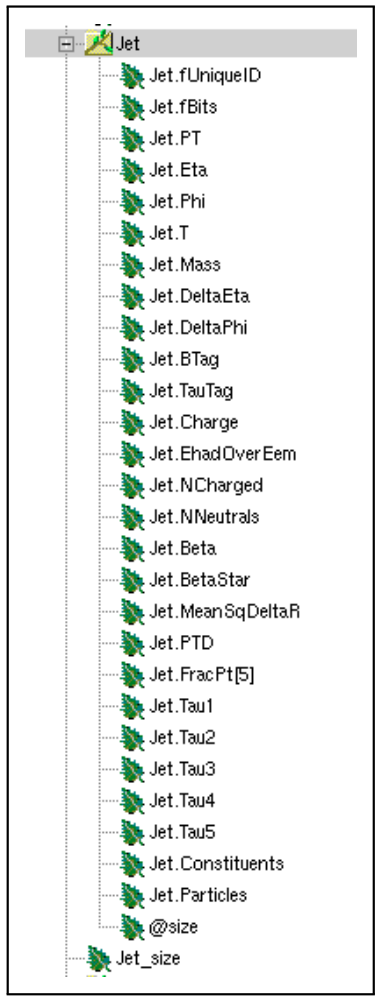
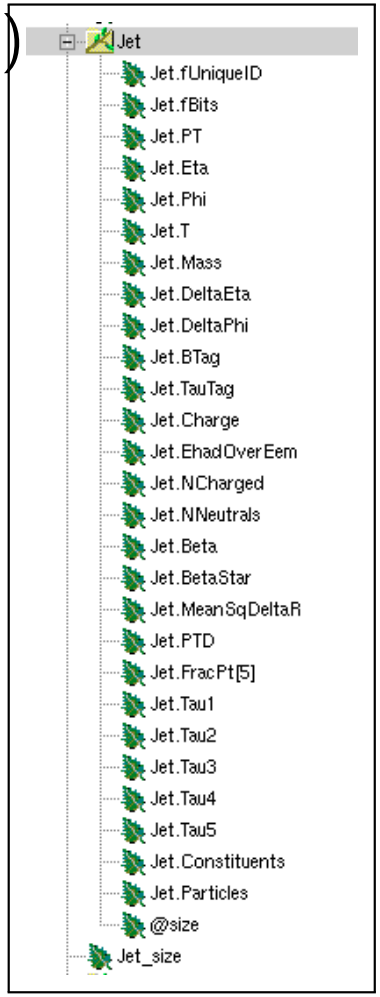




Delphes Output

- Can radiate jets off of the beams (*initial state radiation*)
- Let's turn off ISR in Pythia and regenerate events



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> cat Cards/pythia_card.dat
MSTP(61)=0
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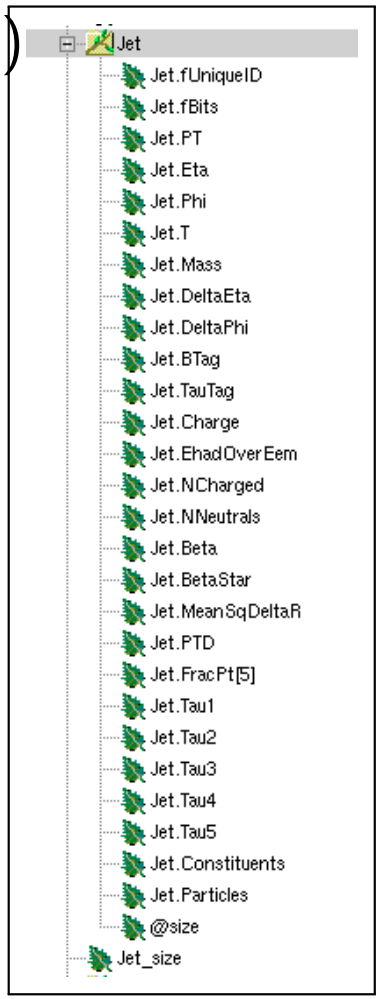

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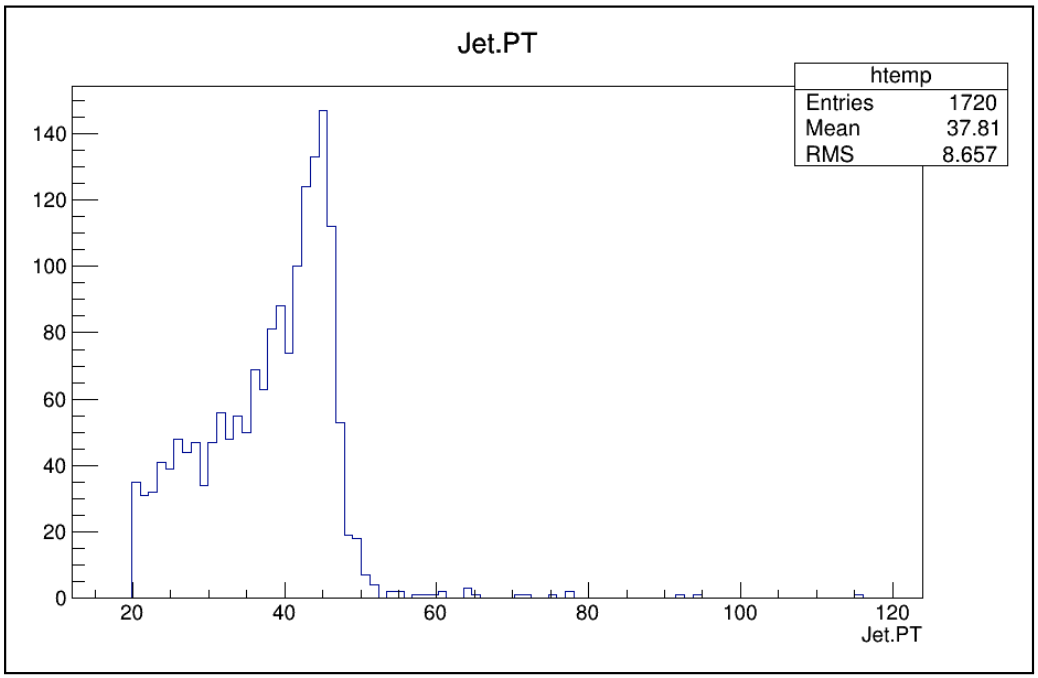
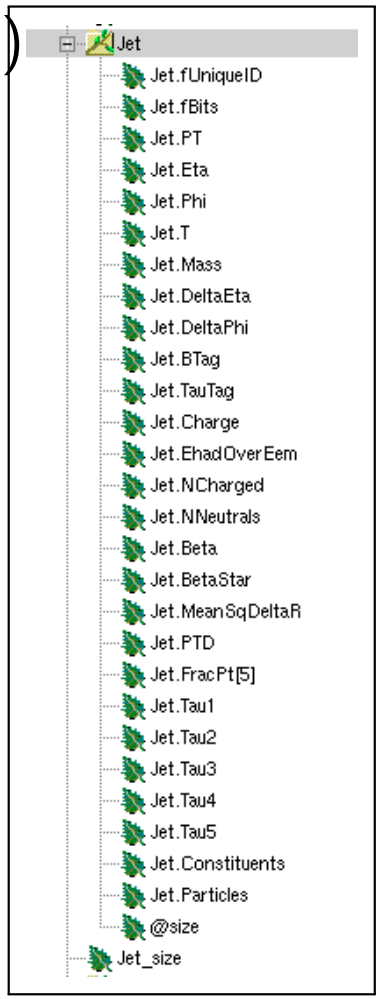
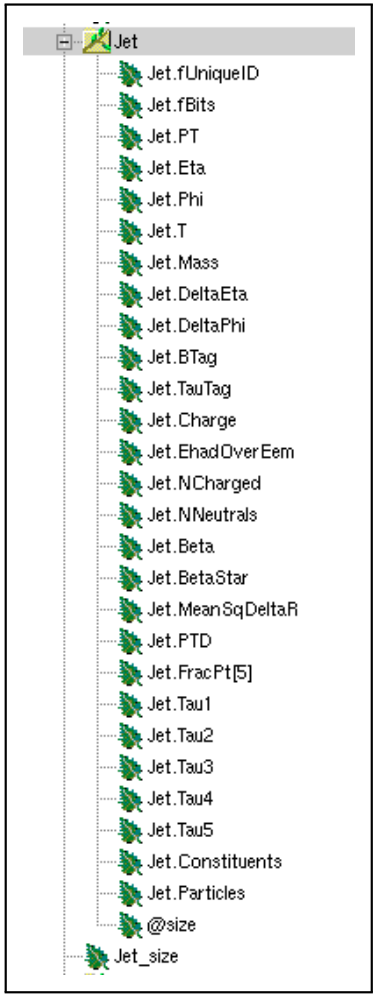




Delphes Output

- Removed about half of jets
- Let's turn off FSR (*final state radiation*)



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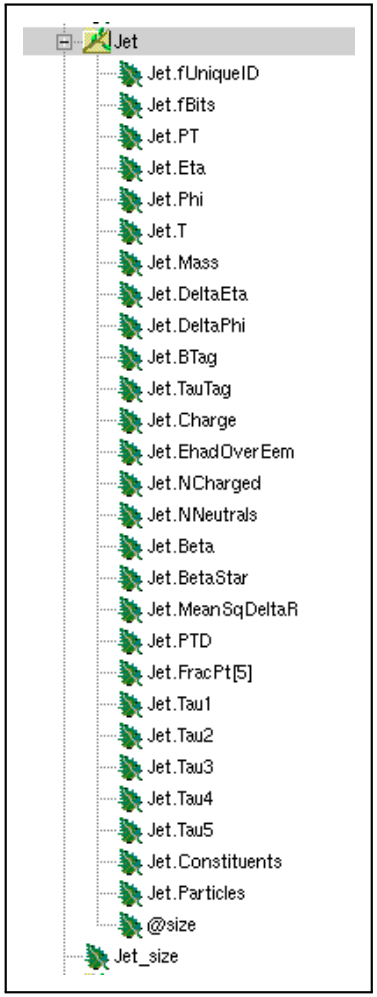

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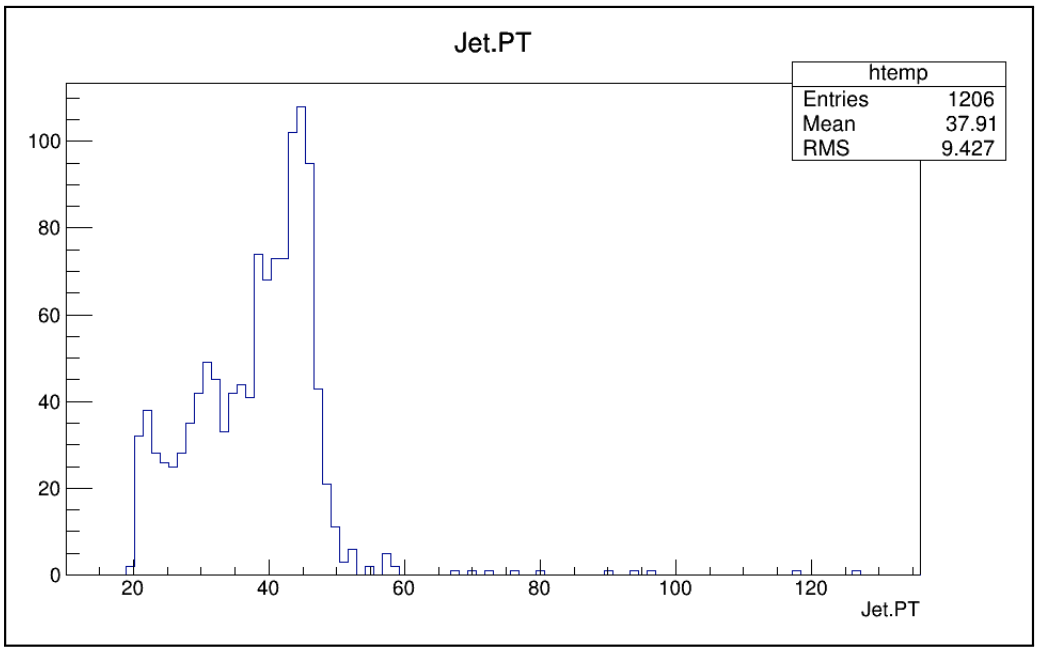
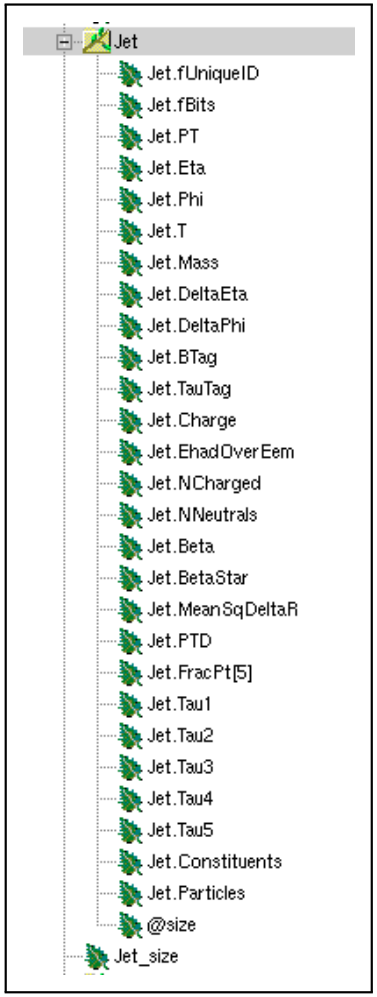
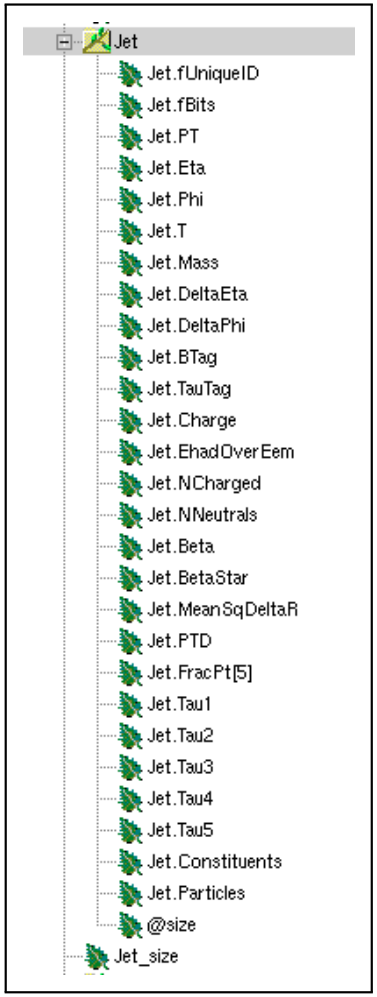




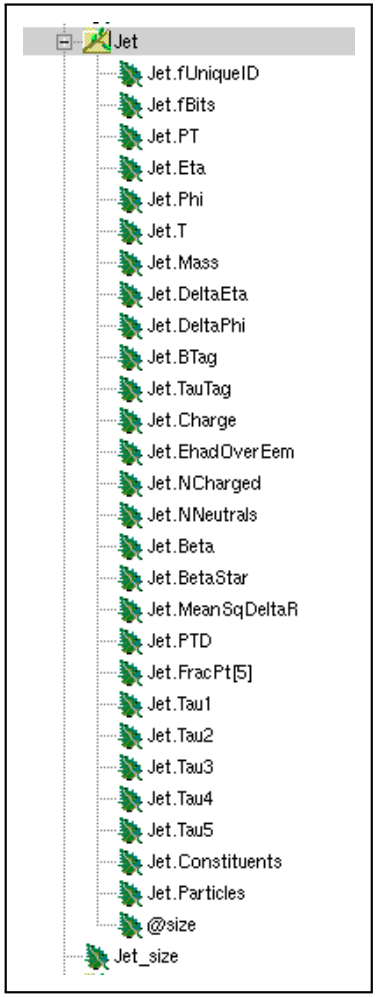
Delphes Output

- Where are the extra jets from?



Delphes Output

- Where are the extra jets from?
- Could it be from mistaking electrons to be jets?
- Test by counting electrons and jets



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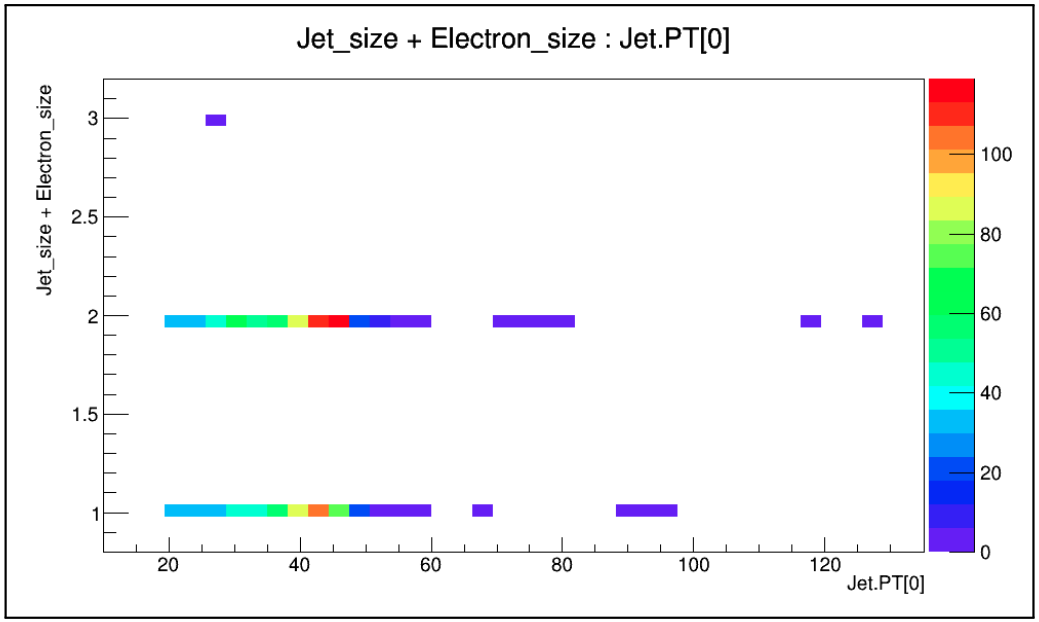

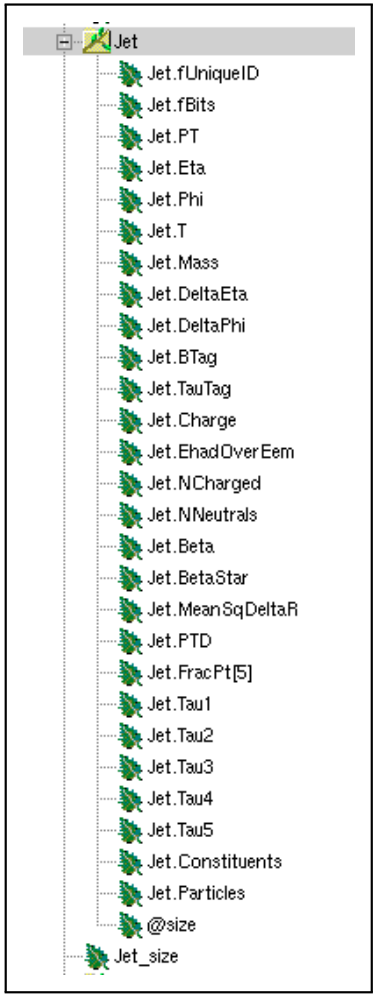

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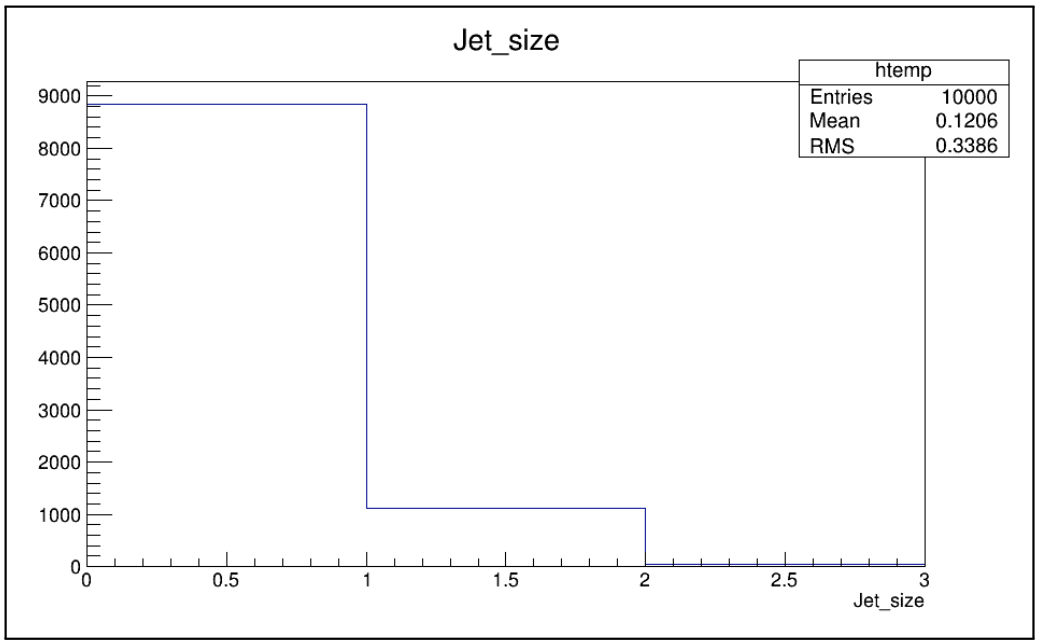

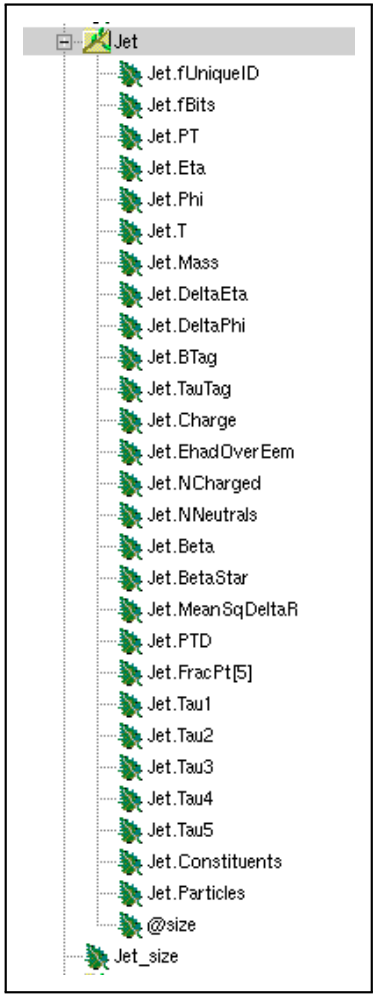

Delphes Output

- The other output format is LHC Olympics (LHCO)
- Simplified text output that lists objects
- Description at `http://madgraph.phys.ucl.ac.be/Manual/lhco.html`
- Below is a sample event

#	typ	eta	phi	pt	jmass	ntrk	btag	had/em
0		103	2563					
1	2	-1.219	4.739	449.95	0.11	1.0	0.0	12.15
2	4	-1.729	1.557	687.76	592.46	37.0	0.0	4.41
3	4	-0.829	2.540	67.26	20.33	5.0	0.0	3.55
4	6	0.000	4.857	275.16	0.00	0.0	0.0	0.00

MadAnalysis

- Now we switch from formats to how to analyze events
- Another useful tool for quick checks (and simple analyses) is MadAnalysis

```
MG5_aMC> install MadAnalysis
Downloading http://madgraph.hep.uiuc.edu/Downloads/MadAnalysis...
...
Compilation succeeded
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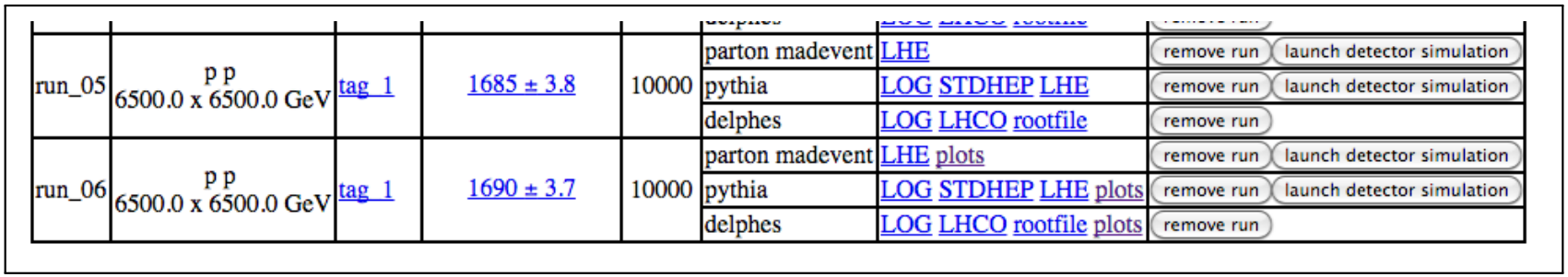

run_05	p p 6500.0 x 6500.0 GeV	tag_1	1685 ± 3.8	10000	parton madevent	LHE	remove run / launch detector simulation
					pythia	LOG STDHEP LHE	remove run / launch detector simulation
					delphes	LOG LHCO rootfile	remove run
run_06	p p 6500.0 x 6500.0 GeV	tag_1	1690 ± 3.7	10000	parton madevent	LHE plots	remove run / launch detector simulation
					pythia	LOG STDHEP LHE plots	remove run / launch detector simulation
					delphes	LOG LHCO rootfile plots	remove run

- Select `plots` to see MadAnalysis pages

MadAnalysis

- MadAnalysis creates and draws histograms for observables
- All viewable on the `plots` page

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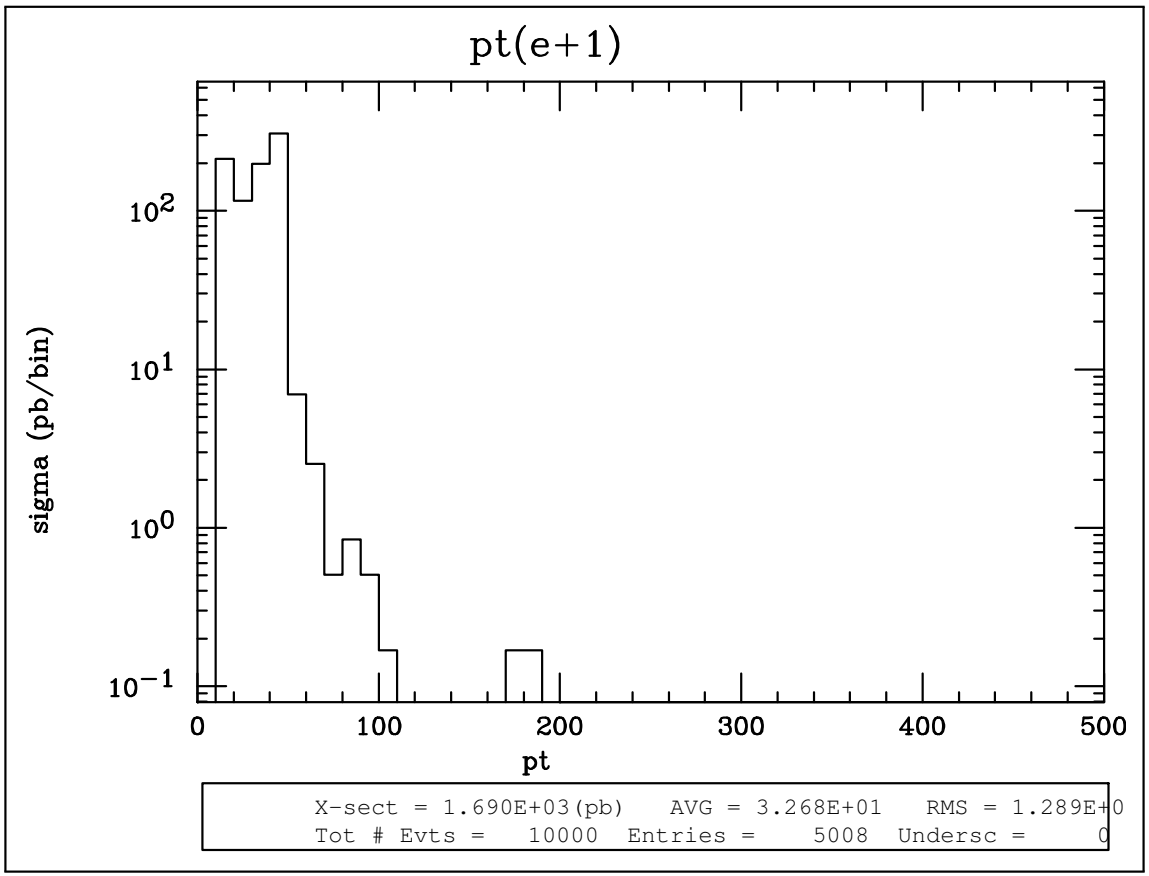
At parton-level



MadAnalysis

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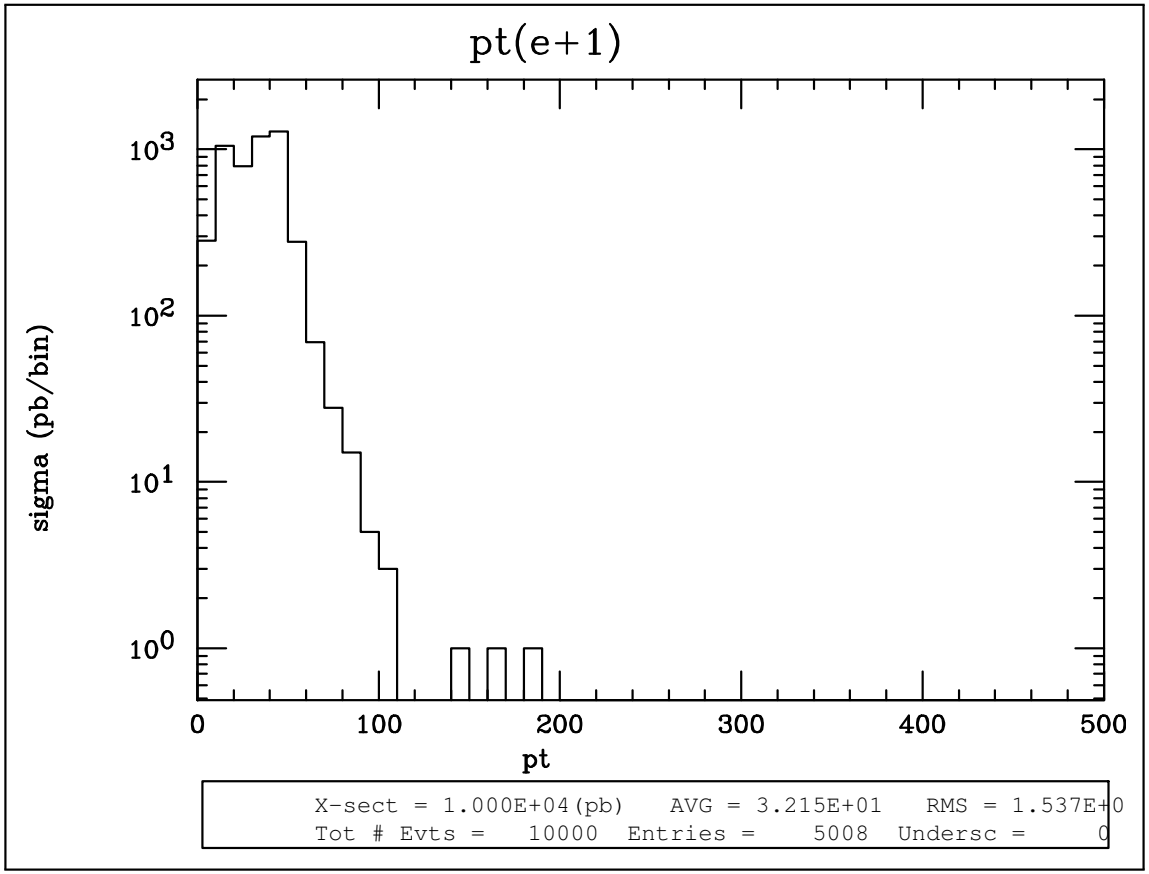
- All viewable on the `plots` page

At pythia-level



MadAnalysis

- MadAnalysis creates and draws histograms for observables
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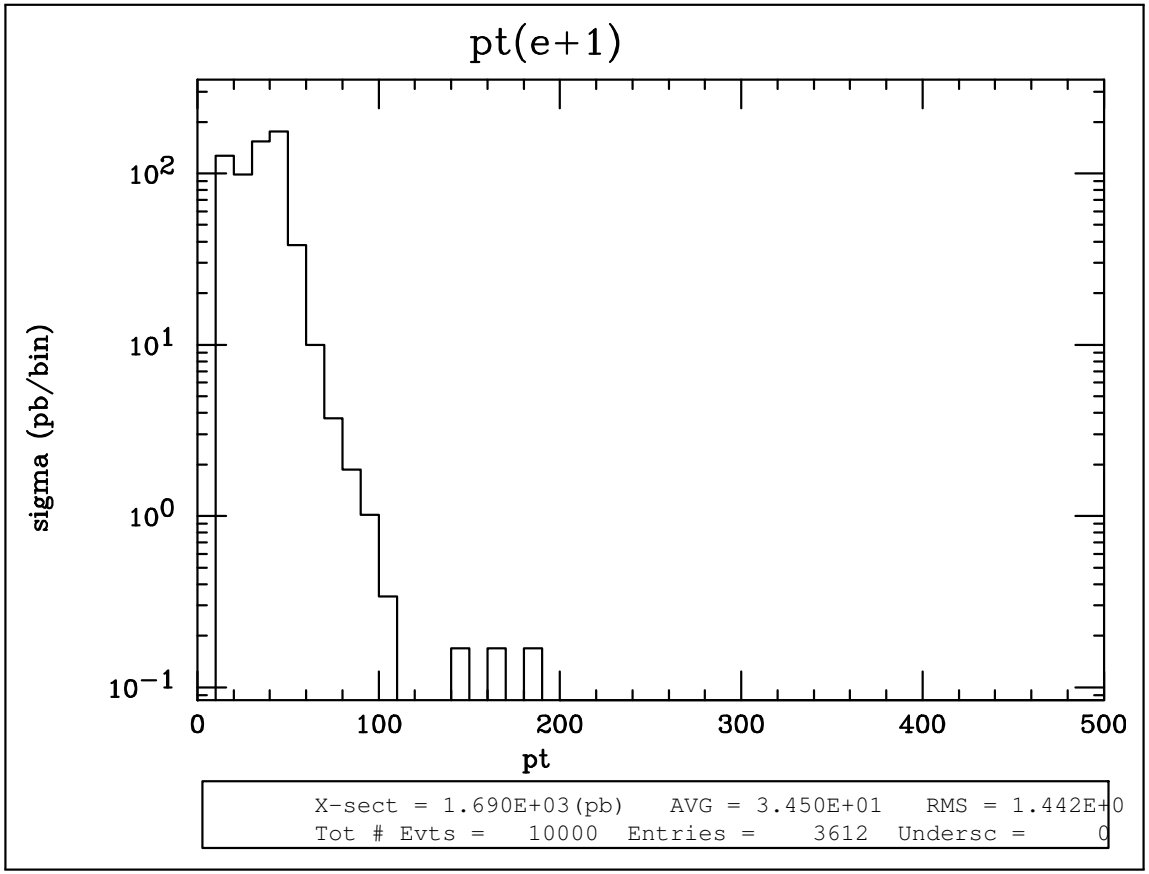
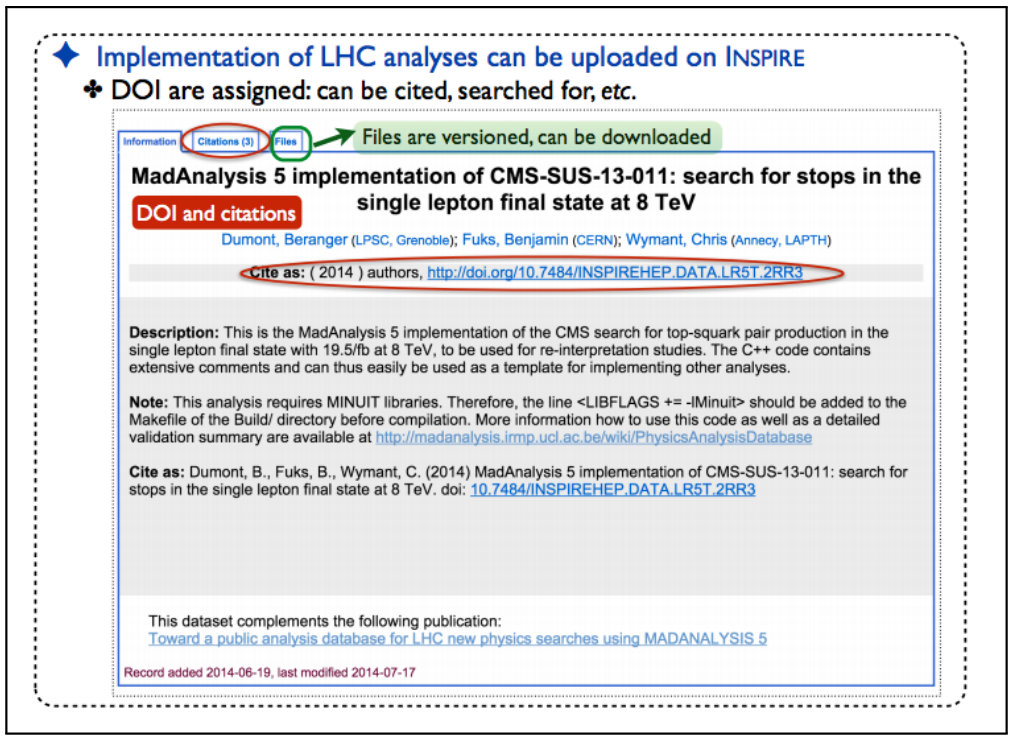
At detector-level



MadAnalysis

- Histograms can be chosen in `Cards/plot_card.dat`
- MadAnalysis has undergone updates recently (See MC4BSM slides for details)
- Now can be used to *recast* LHC results



Recasting Results *(aside)*

- Say you propose a new model with

  ψ heavy colored fermion

  ϕ light neutral scalar

- And the decay $\psi \to t\phi$
- How to set limits on ψ?

Recasting Results *(aside)*

- Say you propose a new model with

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- And the decay $\psi \to t\phi$
- How to set limits on ψ?
  - You note there are very similar searches already done
  - There are SUSY searches for $\tilde{t} \to t\chi$
  - Backgrounds are the same
  - Signal is similar, but *not* the same

Recasting Results *(aside)*

ψ heavy colored fermion

ϕ light neutral scalar

- Need *efficiency* of signal

$$\epsilon = \frac{N \text{ passing cuts}}{N \text{ total}}$$

- If detector simulation is accurate then can compute ϵ with Monte Carlo
- Can recast published LHC results to set limits on your model

(having good detector simulation is very useful)

MadAnalysis

- Library of LHC results found at
  `http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase`
- Includes links to Inspire pages (*e.g.*
  `http://inspirehep.net/record/1325001/`)
- Launchpad page for help (`https://launchpad.net/madanalysis5`)
- There are competing programs including:
  - **CheckMATE** (`https://checkmate.hepforge.org/`)
  - **ATOM/Fastlim** (`http://fastlim.web.cern.ch/fastlim/`)

Using ROOT for Analysis

- To do an analysis yourself there are two main options: ROOT and Mathematica
- Allow you to construct a *cut flow*
  - Loop over events
  - For each event compute a number of observables
  - Keep or reject event based on values
  - Count number of events passing
- ROOT is a C++ library, but also contains an interpreter
- Interpreter allows quick access to the data

Using ROOT for Analysis

```
MG5_aMC> install ExRootAnalysis
```

Using ROOT for Analysis

```
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Downloading http://madgraph.hep.uiuc.edu/Downloads/ExRootAnalysis...

...

Compilation succeeded
```

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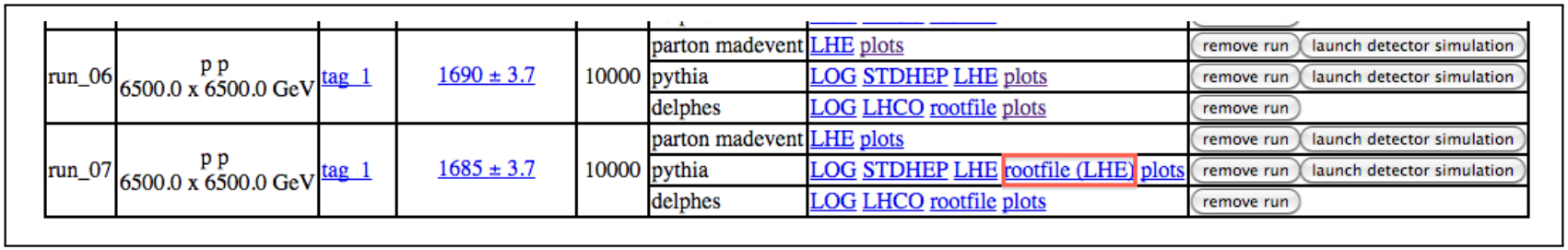


run_06	p p 6500.0 x 6500.0 GeV	tag_1	1690 ± 3.7	10000	parton madevent	LHE plots	remove run launch detector simulation
					pythia	LOG STDHEP LHE plots	remove run launch detector simulation
					delphes	LOG LHCO rootfile plots	remove run
run_07	p p 6500.0 x 6500.0 GeV	tag_1	1685 ± 3.7	10000	parton madevent	LHE plots	remove run launch detector simulation
					pythia	LOG STDHEP LHE rootfile (LHE) plots	remove run launch detector simulation
					delphes	LOG LHCO rootfile plots	remove run

- Converts LHE files to ROOT format
- In `ExRootAnalysis` there are programs to convert to ROOT from LHE, HEP, and LHCO

Using ROOT for Analysis

- Quick view of kinematics

```
> root events.root

root [0] .ls
```

Using ROOT for Analysis

- Quick view of kinematics

```
> root events.root

root [0] .ls                                    (lists what is loaded into ROOT)

TFile* events.root

KEY: TTree Delphes;1 Analysis tree
```

Using ROOT for Analysis

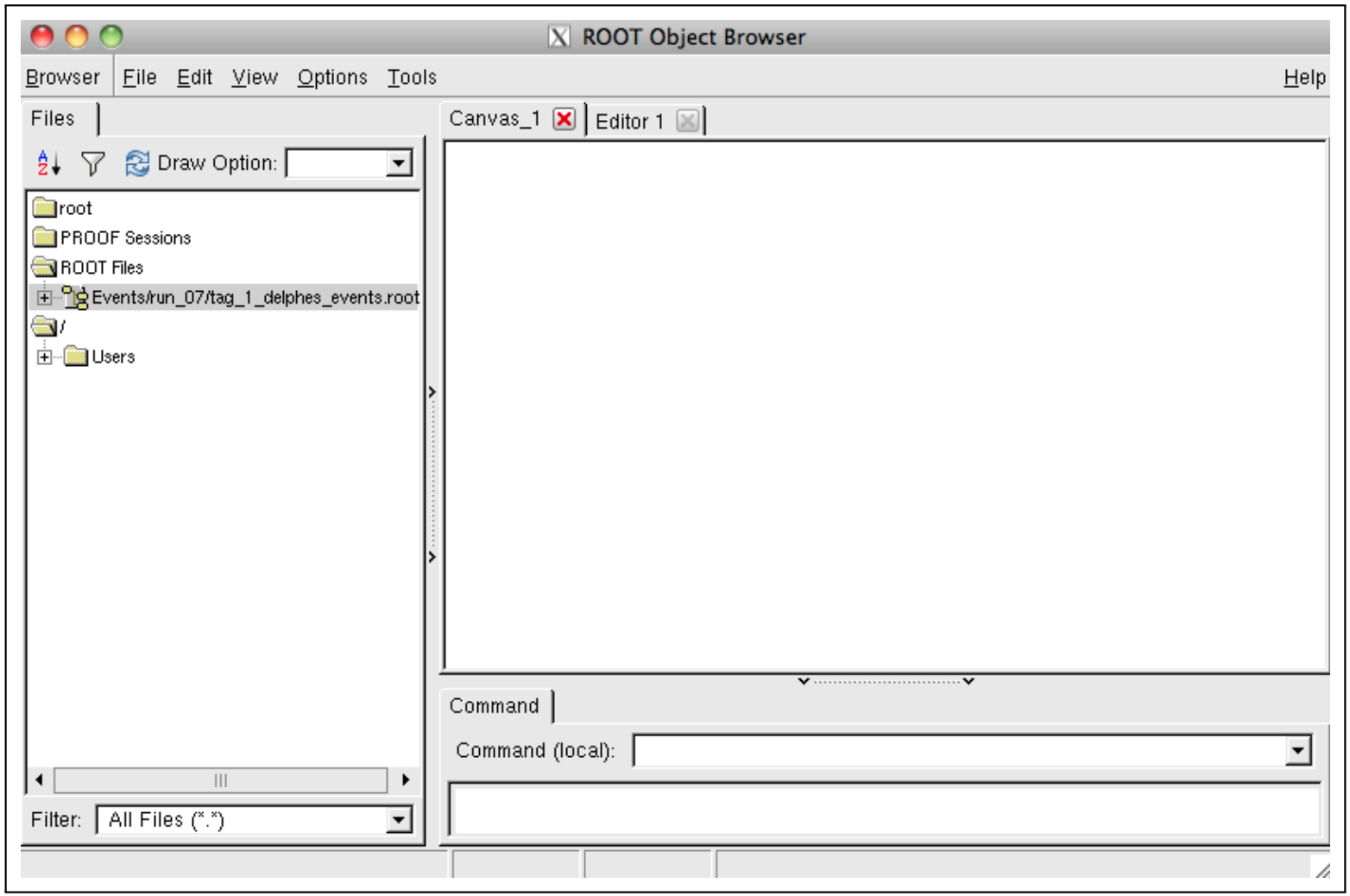
- Quick view of kinematics

```
> root events.root

root [0] .ls                                   (lists what is loaded into ROOT)

TFile* events.root

KEY: TTree Delphes;1 Analysis tree

root [1] TBrowser b;
```

- Opens up graphical interface to look through `TTree`

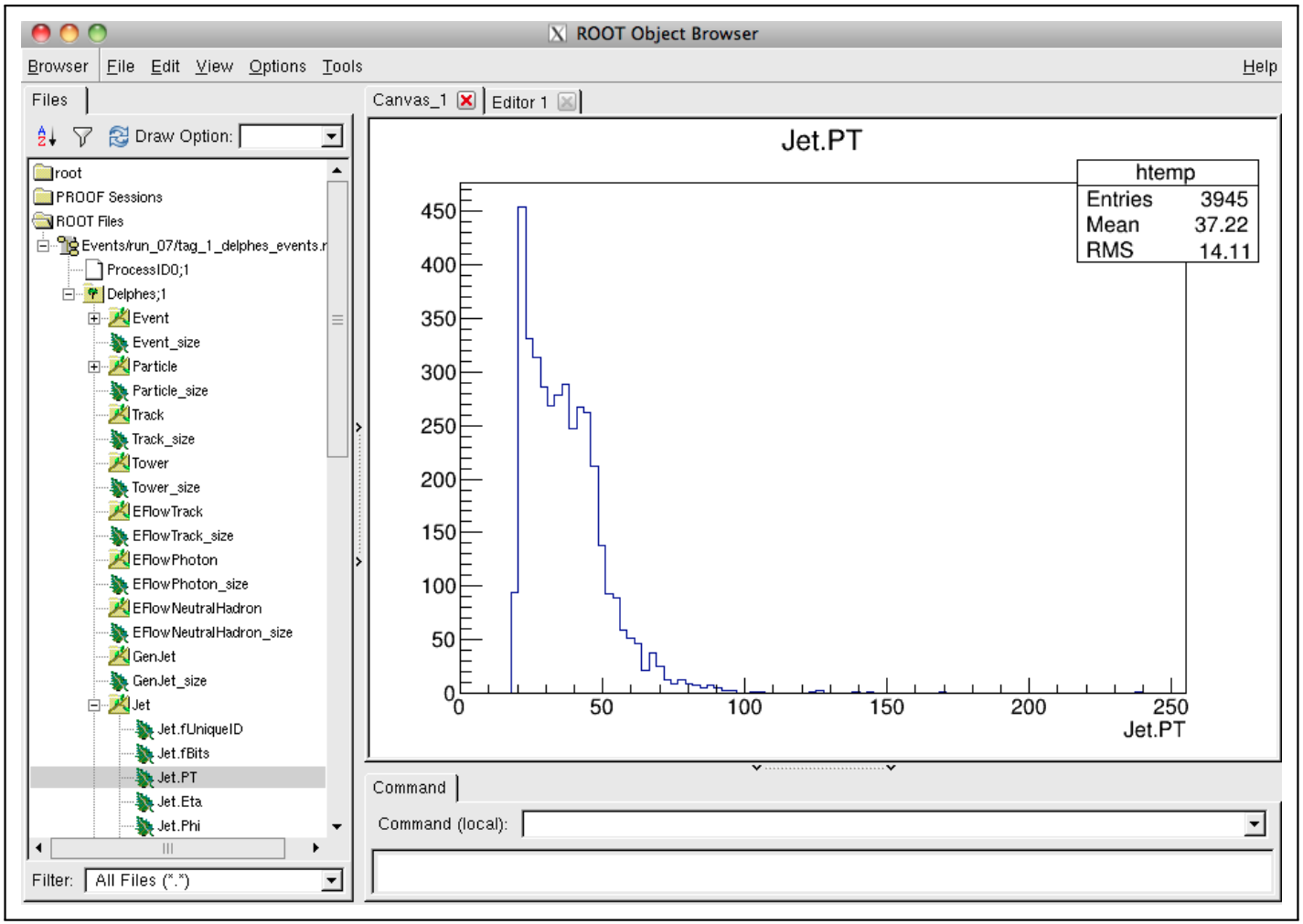
Using ROOT for Analysis

- Using `TBrowser`



Using ROOT for Analysis

- Can view basic kinematic observables



Using ROOT for Analysis

- Can do the same thing directly from interpreter

```
root [2] Delphes->Draw(``Jet.PT'');
```

- Can specify functions of variables

```
root [3] Delphes->Draw(``sqrt(Jet.PT**2 + Jet.Mass**2)'');
```

- Can make simple cuts on variables

```
root [4] Delphes->Draw(``Jet.Mass'',``Jet.PT>50'');
```

- Can make two-dimensional histograms

```
root [5] Delphes->Draw(``Jet.PT : Jet.Mass'');
```

Using ROOT for Analysis

- For more complicated analyses (and cut flows), need to write a script
- Can get template by

```
root [5] Delphes->MakeSelector(``MyTemplate'');
```

- Files `MyTemplate.h` and `MyTemplate.C` are created
- Instructions for running in `MyTemplate.C`

Using ROOT for Analysis

- For more complicated analyses (and cut flows), need to write a script
- Can get template by

```
root [5] Delphes->MakeSelector(''MyTemplate'');
```

- Files `MyTemplate.h` and `MyTemplate.C` are created
- Instructions for running in `MyTemplate.C`
- Write code inside `MyTemplate.C`
- Run as

```
> root events.root

root [0] Delphes->Process(''MyTemplate.C'');
```

Lecture 2 Review

- Installed Pythia via Madgraph interface
- Took parton-level Madgraph events and showered and hadronized them
- Installed Delphes via Madgraph interface
- Input final state particles into Delphes to simulate detector response
- Used ROOT to analyze physics objects from Delphes