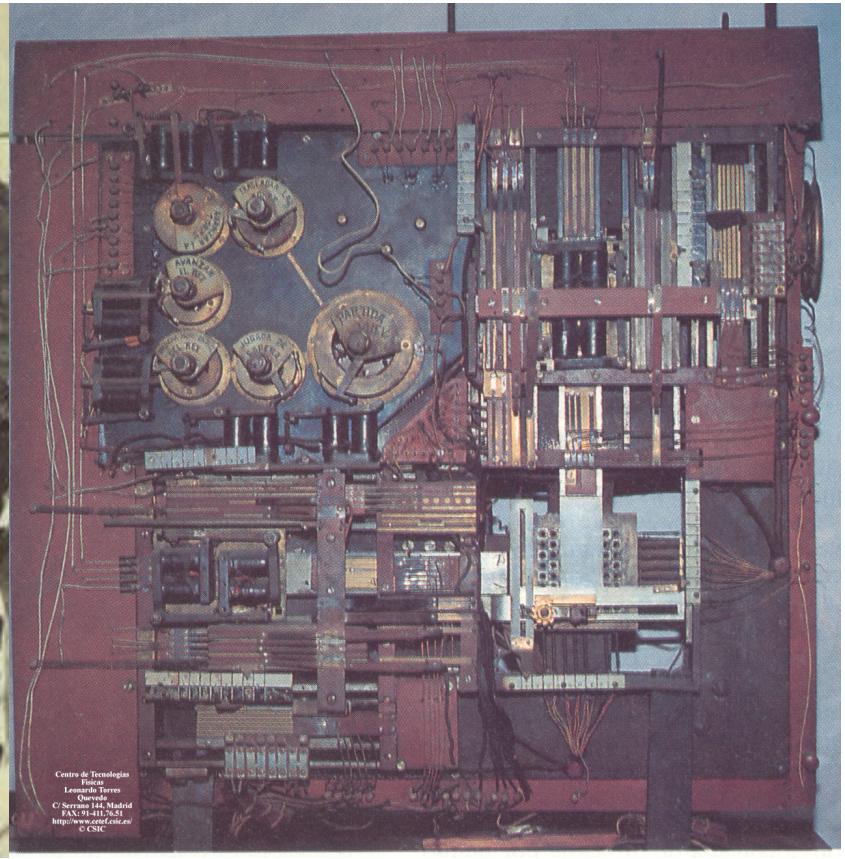
The Inner Workings of Checkmate



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♔ Contents

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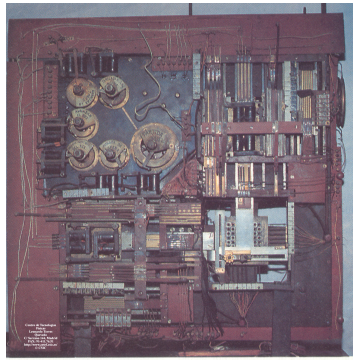
Checks Models At Terascale Energies



User Mode *(Program Flow)*

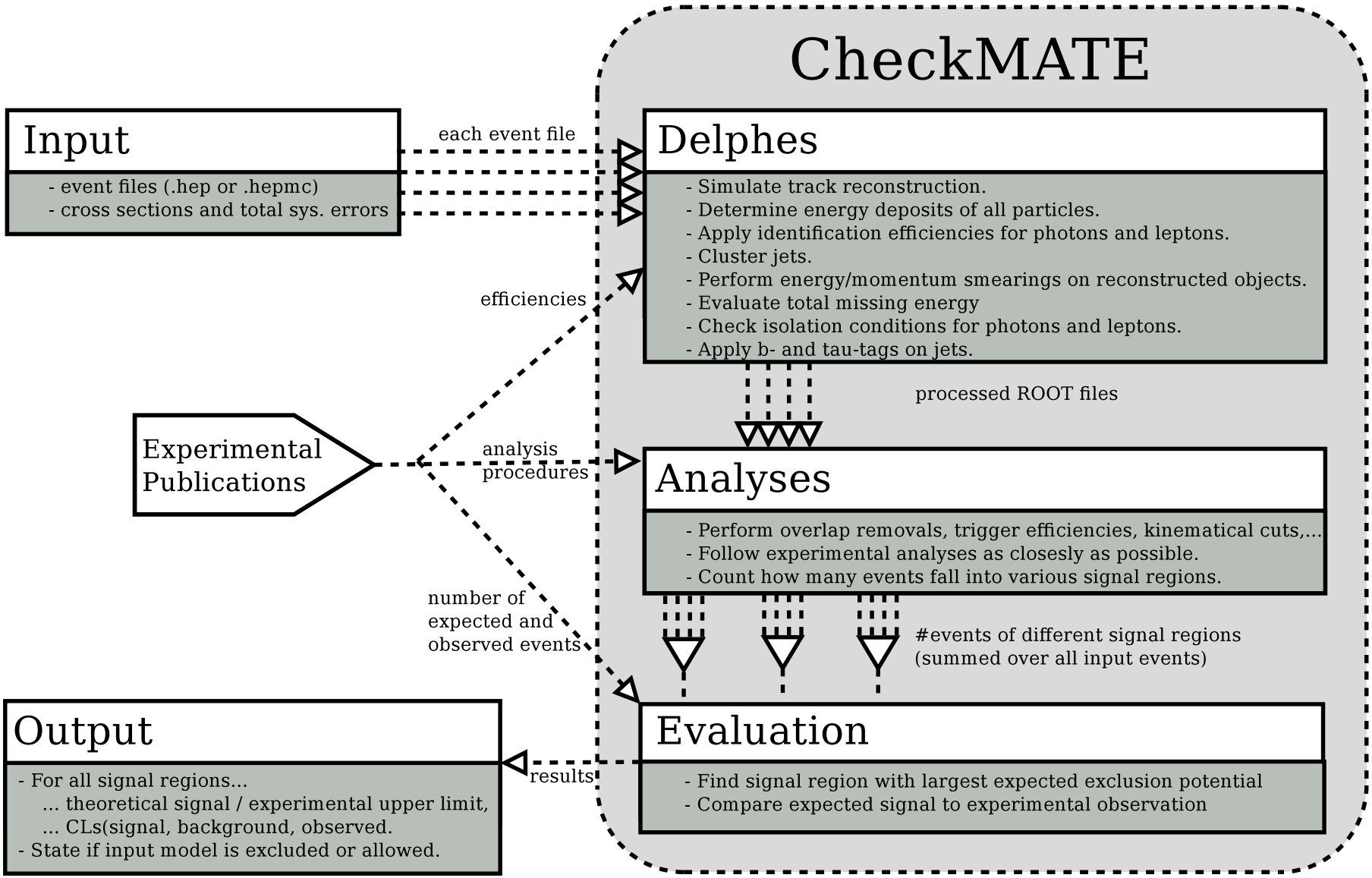
- ♙ Data Input
- ♕ Data Procession
- ♘ Data Output

Dev Mode *(Program Code)*

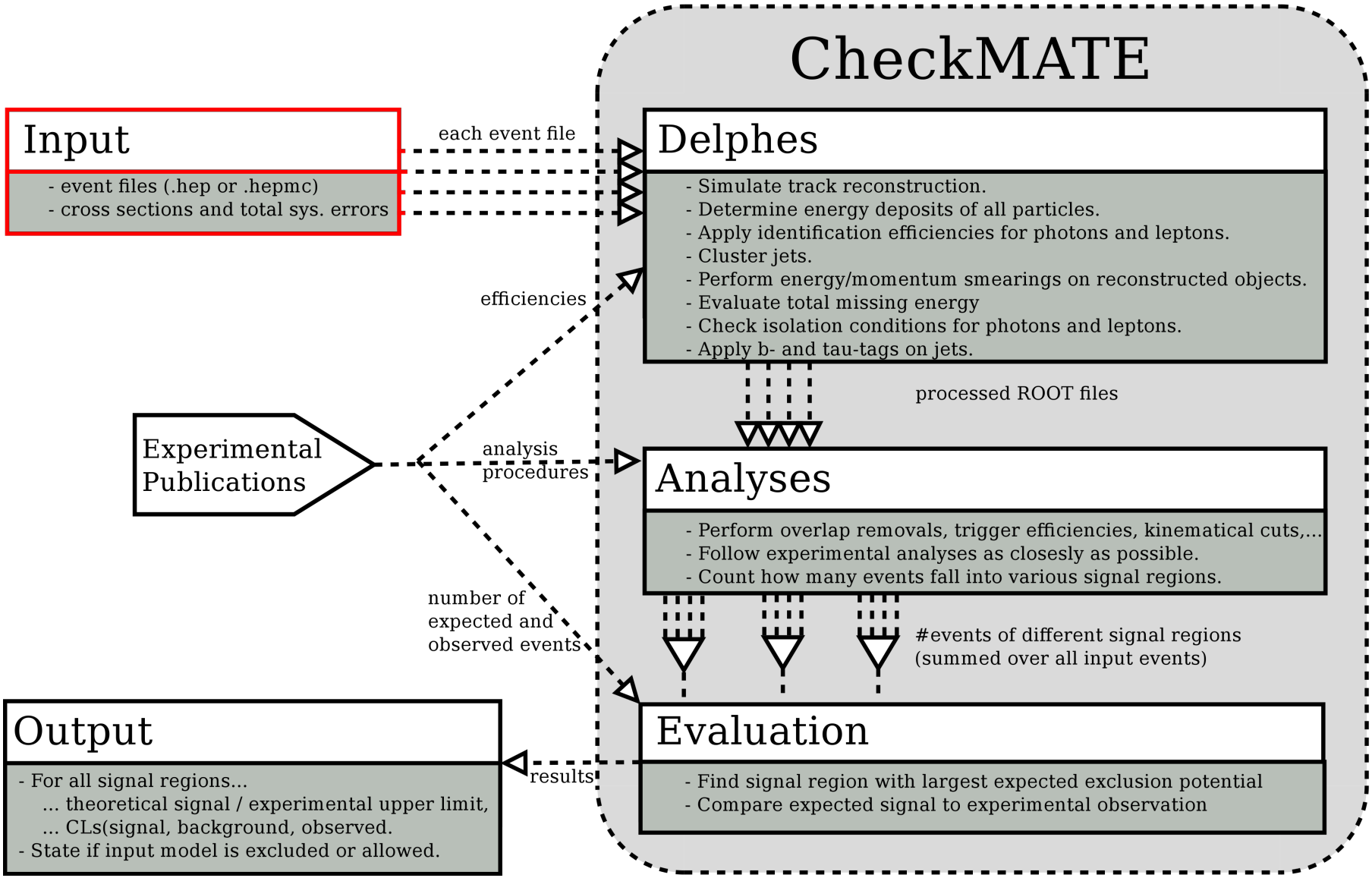
- General Structure ♘
- Analysis Setup ♖
- Analysis Coding ♗

♕ Part A: User Mode ♕

Overview: Data Flow



Input


CheckMATE
Input
- event files (.hep or .hepmc)
- cross sections and total sys. errors
each event file
Delphes
- Simulate track reconstruction.
- Determine energy deposits of all particles.
- Apply identification efficiencies for photons and leptons.
- Cluster jets.
- Perform energy/momentum smearings on reconstructed objects.
- Evaluate total missing energy
- Check isolation conditions for photons and leptons.
- Apply b- and tau-tags on jets.
efficiencies
processed ROOT files
Experimental Publications
analysis procedures
Analyses
- Perform overlap removals, trigger efficiencies, kinematical cuts,...
- Follow experimental analyses as closesly as possible.
- Count how many events fall into various signal regions.
number of expected and observed events
#events of different signal regions (summed over all input events)
Output
- For all signal regions...
... theoretical signal / experimental upper limit,
... CLs(signal, background, observed.
- State if input model is excluded or allowed.
results
Evaluation
- Find signal region with largest expected exclusion potential
- Compare expected signal to experimental observation

♔ Input: Minimal Case

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```
[Mandatory Parameters]
Name: My_New_Run
Analyses: atlas_conf_2013_047

[gluinogluino]
XSect: 3.53*FB
XSectErr: 1e-5*PB
Events: testfile.hep
```

Required

- Name
- At least one analysis
- At least one `[process]` with at least one item in `Events` (.hep or .hepmc), one total cross section and a total estimate on the *systematic* error

♔ Input: Extended Cases


```
[Mandatory Parameters]
Name: My_New_Extended_Run
Analyses: atlas_conf_2013_035,
          atlas_conf_2013_049,
          atlas_conf_2013_047,
          atlas_conf_2013_089

[gluinogluino]
XSect: 3.53*FB
XSectErr: 1e-5*PB
Events: gg.hep
```

Optional

- More analyses (Delphes still runs only once but then the analyses are processed one by one)

♔ Input: Extended Cases


```
[Mandatory Parameters]
Name: My_New_Extended_Run
Analyses: atlas_conf_2013_047

[gluinogluino]
XSect: 3.53*FB
XSectErr: 1e-5*PB
Events: gg.hep, gg2.hepmc
```

Optional

- Many event files for one process (are processed one by one, normalised *in total* to the given cross section)

♔ Input: Extended Cases


```
[...]

[gluinogluino]
XSect: 3.53*FB
XSectErr: 1e-5*PB
Events: gg.hep

[squarksquark]
XSect: 4.64*FB
XSectErr: 2e-5*PB
Events: ss.hep
```

Optional

- Events for different processes with individual cross sections and errors (are processed one by one, normalised events *independently added* in the end)

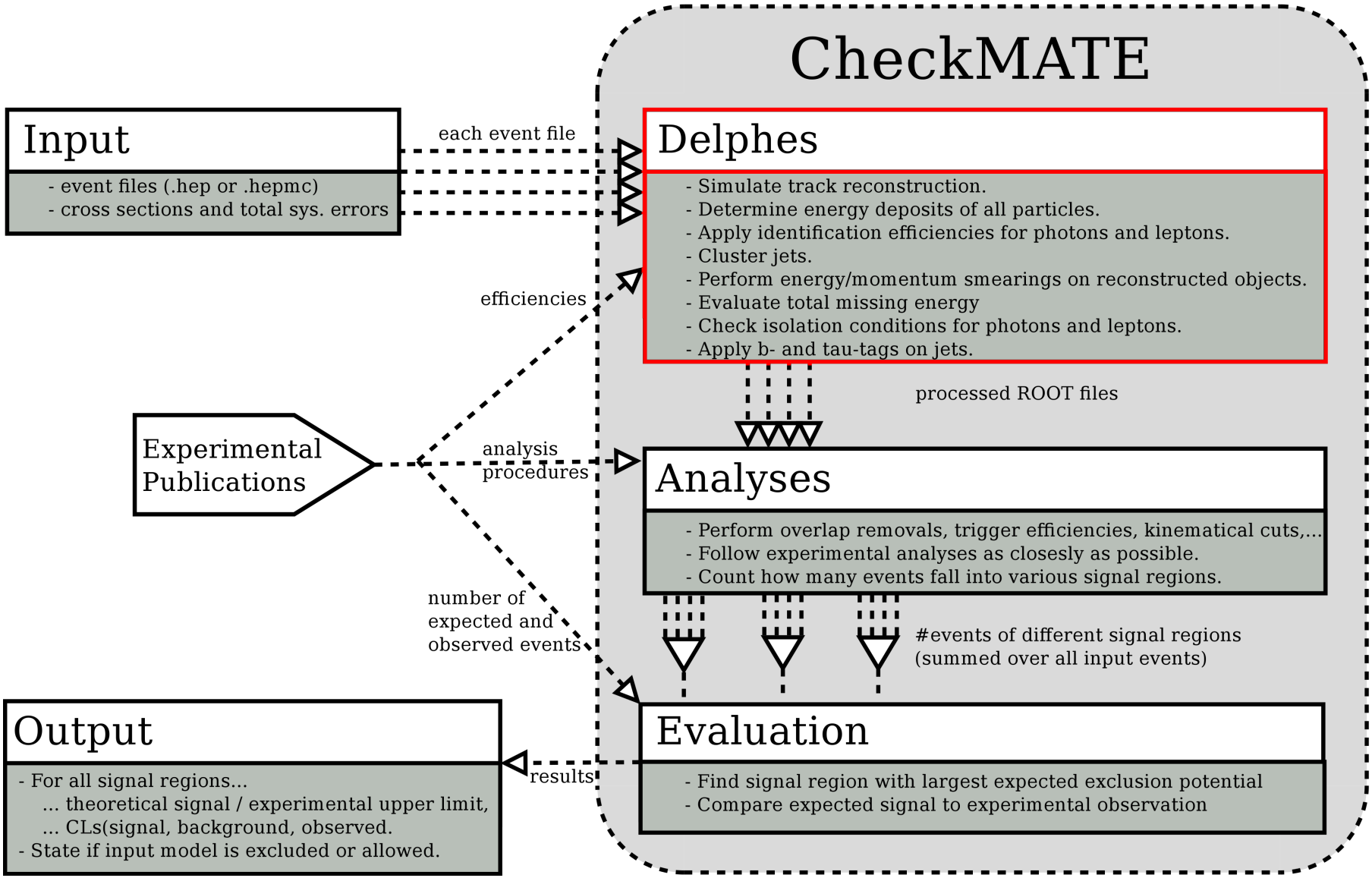
♔ Input: Extended Cases


```
[...]

[Optional Parameters]
SkipEvaluation: True
FullCLs: True
OutputExists: Add

[...]
```

Many extra options / arguments, most importantly

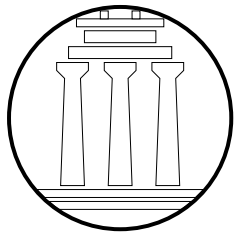
- Skip parts in CheckMATE (for debugging)
- Calculate full CLs for each SR (See later)
- Add events to an already processed CheckMATE run (either add statistics to a known process or add events from a new process)
- ...

Step 1: Delphes



Delphes 3.0.10 Standard

- Simulates track reconstruction
- Determines energy deposits of all particles
- Applies identification efficiencies for photons and leptons
- Clusters jets
- Performs energy/momentum smearings of all reconstructed objects
- Evaluates total missing energy
- Checks isolation conditions for photons and leptons
- Applies b-/ tau-tag on jets



DELPHES
fast simulation

Extra Features / Improvements

- → Wait for Jamie's Talk

Delphes within CheckMATE

Input and Setup

- The user has declared, which analyses should be considered
- Every analysis comes with a list of required objects:
  - Efficiency and isolation for electrons, muons and photons
  - Parameters for jet algorithm (p_{min}^T, ΔR)
  - If/Which τ IDs are used
  - If/Which b IDs are used
- CheckMATE will *automatically* find and merge all analyses' settings, load the required Delphes modules and runs on each input event file *once*, regardless of the number of analyses

♔ Delphes within CheckMATE

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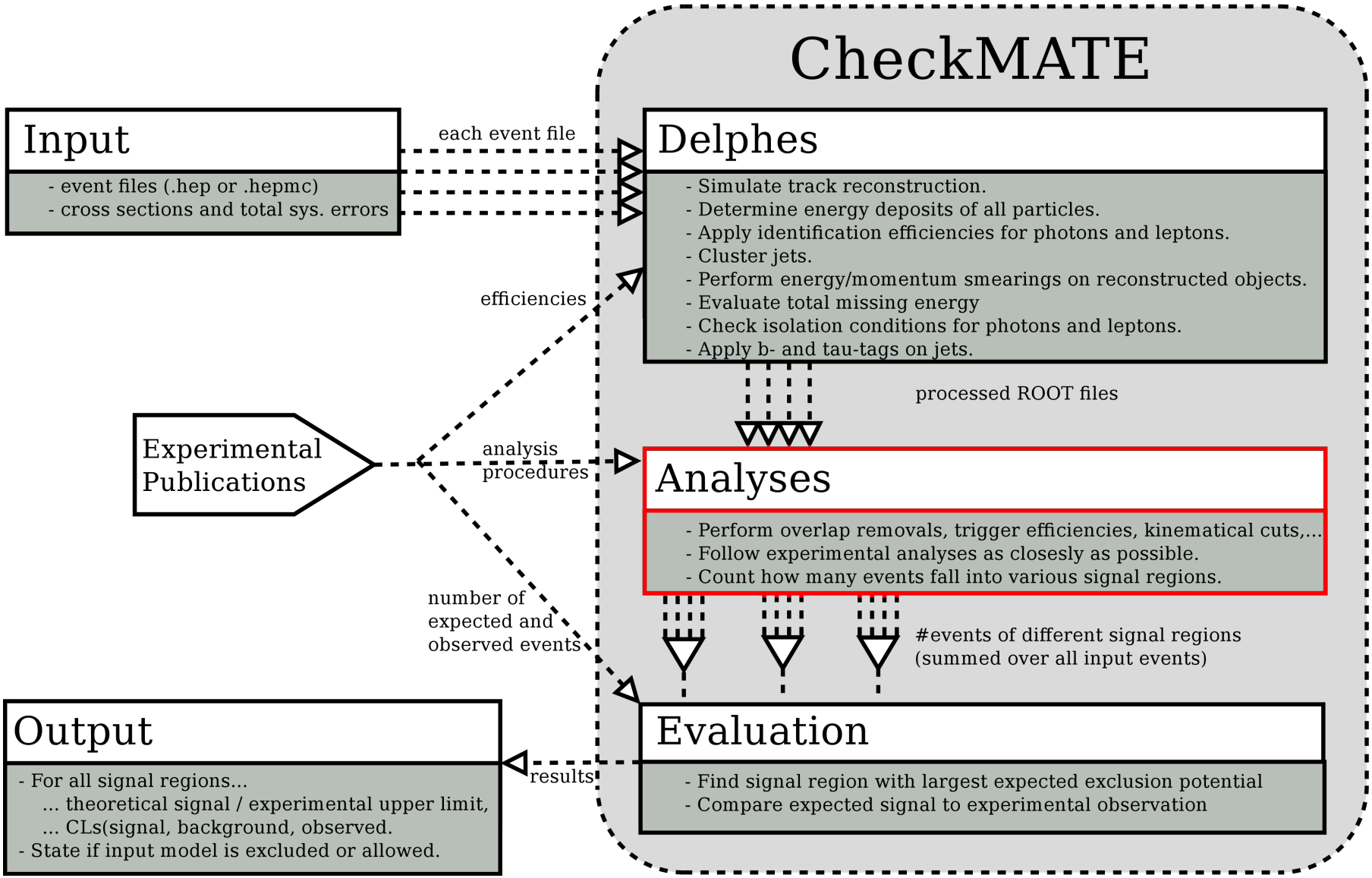
  - If/Which τ IDs are used
  - If/Which b IDs are used
- CheckMATE will *automatically* find and merge all analyses' settings, load the required Delphes modules and runs on each input event file *once*, regardless of the number of analyses

Output

- Delphes produces a ROOT output file for each input event file
- These are automatically processed by further CheckMATE units, but can be examined by user if desired

Step 2: Analyses



Analyses

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A CheckMATE analysis does the following

- Choose the objects of interest (leptons, jets,...)
- Filter objects (efficiency and isolation flags, kinematical cuts, overlap removals, ...)
- Check event vetoes (Too many/few objects, trigger efficiencies, ...)
- Check various signal region criteria (total $\not{E}_T$, # and energy of objects, ...)
- Count number of input events that fall into each signal region

♔ Analyses

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- ♙ Check various signal region criteria (total $\not{E}_T$, # and energy of objects, ...)
- ♙ Count number of input events that fall into each signal region

Output

- ♙ For each input file, store general information and
- ♙ for each SR, store Σ (weights) and Σ(weights^2) for the input events that passed the respective signal region cuts

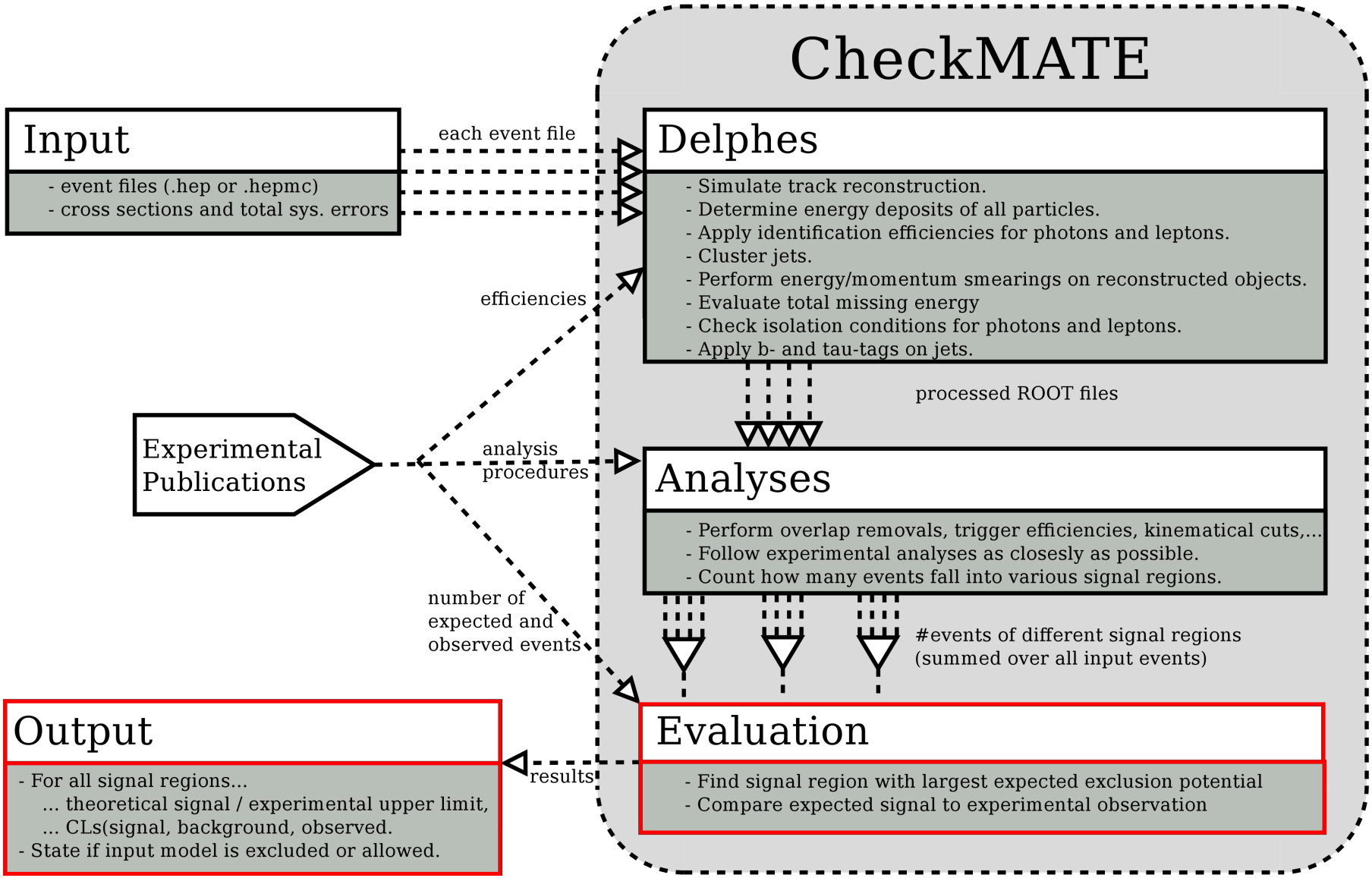
Example Output


```
# ATLAS
# ATLAS-CONF-2013-047
# 0 leptons, 2-6 jets, etmiss
# sqrt(s) = 8 TeV
# int(L) = 20.3 fb^-1

Inputfile:          /hdd/results/cMSSM/delphes/000_delphes.root
XSect:              4.35 fb
 Error:             1.22086 fb
MCEvents:           5000
 SumOfWeights:      5000
 SumOfWeights2:     5000
 NormEvents:        87.9518

SR   Sum_W   Sum_W2   Acc      N_Norm
AL   1315    1315     0.263    23.1313
AM   71      71       0.0142   1.24892
BM   98      98       0.0196   1.72385
BT   2       2        0.0004   0.0351807
CM   505     505      0.101    8.88313
CT   9       9        0.0018   0.158313
D    184     184      0.0368   3.23663
EL   613     613      0.1226   10.7829
EM   398     398      0.0796   7.00096
ET   149     149      0.0298   2.62096
```

Step 3: Evaluation



♔ Combination to get $S \pm \Delta S$

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Combine within each process p with given σ^p, $\Delta\sigma^p$

- Determine $\sum$ weights over all input files for p
- Normalise w.r.t $\mathcal{L}\sigma^p$ for S^p
- Determine normalised $\sqrt{\sum \text{weights}^2}$ for ΔS^p_{stat}
- Use $\mathcal{L}\Delta\sigma^p$ for ΔS^p_{sys}

♔ Combination to get $S \pm \Delta S$

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Combine different processes

- Use $S = \sum_p S^p$
- Use $\Delta S_{\text{stat/sys}} = \sqrt{\sum_p (\Delta S^p_{\text{stat/sys}})^2}$
- Use $\Delta S = \sqrt{\Delta S^2_{\text{stat}} + \Delta S^2_{\text{sys}}}$

Combination to get $S \pm \Delta S$

Combine within each process p with given σ^p, $\Delta\sigma^p$

- Determine $\sum$ weights over all input files for p
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Output

- A table with, for each signal region, a list of all the above numbers

Example Output

Prefix	N_TotMC	AL	stat	sys	AM	stat	sys	BM	stat	sys	BT	stat
Process: gluino_pair												
000	10000.00	31.99	0.60	3.94	3.94	0.21	0.49	5.33	0.24	0.66	0.39	0.07
001	10000.00	32.84	0.61	4.04	4.04	0.21	0.50	5.49	0.25	0.68	0.41	0.07
Tot	20000.00	32.41	0.43	3.99	3.99	0.15	0.49	5.41	0.17	0.67	0.40	0.05
Process: gluino_squark												
002	10000.00	4.99	0.10	0.93	1.34	0.05	0.25	1.92	0.06	0.36	0.47	0.03
003	10000.00	5.00	0.10	0.93	1.43	0.05	0.27	1.92	0.06	0.36	0.42	0.03
Tot	20000.00	4.99	0.07	0.93	1.38	0.04	0.26	1.92	0.04	0.36	0.44	0.02
Tot	40000.00	37.41	0.43	4.10	5.37	0.15	0.56	7.33	0.18	0.76	0.84	0.05

Evaluation

Input and Setup

- We have number of expected signal $S \pm \Delta S$ in each signal region
- CheckMATE has a reference card with experimental results:
  - observed events O
  - expected background plus uncertainty $B \pm \Delta B$
  - (in most cases) translated 95% upper limit on signal S_{max}^{95}

User can choose

- Directly compare S to S_{max}^{95}
- If $r^{c} = \frac{S-2\Delta S}{S_{\text{max}}^{95}} > 1$: Excluded!
- Quick and easy for limit setting

- Evaluate $\text{CL}_s(O, B, \Delta B, S, \Delta S)$
- If $\text{CL}_s < 0.05$: Excluded!
- Slower, but limits can be set to different confidence levels

♔ Evaluation

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Input and Setup

- We have number of expected signal $S \pm \Delta S$ in each signal region
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  - observed events O
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  - (in most cases) translated 95% upper limit on signal S^{95}_{max}

User can choose

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- Quick and easy for limit setting

- Evaluate $\text{CL}_s(O, B, \Delta B, S, \Delta S)$
- If $\text{CL}_s < 0.05$: Excluded!
- Slower, but limits can be set to different confidence levels

Result

- Choose signal region with strongest *expected* exclusion ($O = B$)
- Use its *observed* result to state final "excluded" or "allowed"

ATLAS Reference

Signal Region	**A-loose**	**A-medium**	**B-medium**	**B-tight**
Total bkg	4700 ± 500	122 ± 18	33 ± 7	2.4 ± 1.4
Observed	5333	135	29	4
S^{95}_{obs}	1341.2	51.3	14.9	6.7
S^{95}_{exp}	$1135.0^{+332.7}_{-291.5}$	$42.7^{+15.5}_{-11.4}$	$17.0^{+6.6}_{-4.6}$	$5.8^{+2.9}_{-1.8}$

Example

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atlas_conf_2013_047_r_limits

SR	S	dS_stat	dS_sys	dS_tot	S95_obs	S95_exp	r^c_obs	r^c_exp
AL	37.36	0.61	4.10	4.15	1341.20	1135.00	0.02	0.03
AM	5.34	0.22	0.55	0.59	51.30	42.70	0.08	0.10
BM	7.41	0.25	0.77	0.81	14.90	17.00	0.39	0.34
BT	0.86	0.07	0.10	0.12	6.70	5.80	0.09	0.11
CM	17.82	0.43	1.99	2.04	81.20	72.90	0.17	0.19
CT	2.40	0.12	0.28	0.31	2.40	3.30	0.75	0.54
D	12.14	0.34	1.29	1.33	15.50	13.60	0.61	0.70
EL	21.26	0.46	2.35	2.39	92.40	57.30	0.18	0.29
EM	16.14	0.40	1.79	1.83	28.60	21.40	0.44	0.59
ET	7.95	0.28	0.87	0.91	8.30	6.50	0.74	0.95

Example

ATLAS Reference

Signal Region	A-loose	A-medium	B-medium	B-tight
Total bkg	4700 ± 500	122 ± 18	33 ± 7	2.4 ± 1.4
Observed	5333	135	29	4
S^{95}_{obs}	1341.2	51.3	14.9	6.7
S^{95}_{exp}	$1135.0^{+332.7}_{-291.5}$	$42.7^{+15.5}_{-11.4}$	$17.0^{+6.6}_{-4.6}$	$5.8^{+2.9}_{-1.8}$

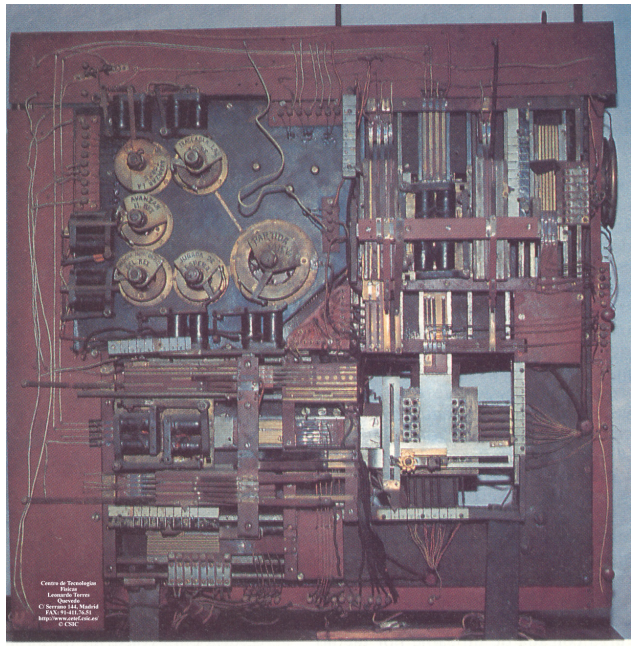
Result

```
Result: Allowed
Result for r: r_max = 0.74
SR: atlas_conf_2013_047 - ET
```

atlas_conf_2013_047_r_limits

SR	S	dS_stat	dS_sys	dS_tot	S95_obs	S95_exp	r^c_obs	r^c_exp
AL	37.36	0.61	4.10	4.15	1341.20	1135.00	0.02	0.03
AM	5.34	0.22	0.55	0.59	51.30	42.70	0.08	0.10
BM	7.41	0.25	0.77	0.81	14.90	17.00	0.39	0.34
BT	0.86	0.07	0.10	0.12	6.70	5.80	0.09	0.11
CM	17.82	0.43	1.99	2.04	81.20	72.90	0.17	0.19
CT	2.40	0.12	0.28	0.31	2.40	3.30	0.75	0.54
D	12.14	0.34	1.29	1.33	15.50	13.60	0.61	0.70
EL	21.26	0.46	2.35	2.39	92.40	57.30	0.18	0.29
EM	16.14	0.40	1.79	1.83	28.60	21.40	0.44	0.59
ET	7.95	0.28	0.87	0.91	8.30	6.50	0.74	0.95

♕ Part B: Dev Mode ♕



♔ How does the code work?

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What is needed to understand all of the code?

- General Input/Output routines are written in Python 2.7
- Delphes is written in C++ using ROOT libraries
- Analysis code is written in C++ using ROOT libraries (see later)
- Evaluation is done in Python (linking to PyROOT/RooStat for CLs)
- Compilation scripts are created using Autotools
- Experimental data is stored in Python and human readable textfiles

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What is needed to add analyses?

♔ How does the code work?

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- Compilation scripts are created using Autotools
- Experimental data is stored in Python and human readable textfiles

What is needed to add analyses?

- Ability to answer questions
- Some understanding of C++

Running the Analysis Manager

- Run `make AnalysisManager; /bin/AnalysisManager`

```
 ____ _                 _    __  __    _  _____ _____
/ ___| |__   ___  ___| | _|  \/  |  / \|_   _| ____|
| |   | '_ \ / _ \/ __| |/ / |\/| | / _ \ | | |  _|
| |___| | | |  __/ (__|   <| |  | |/ ___ \| | | |___
 \____|_| |_|\___|\___|_|\_\_|  |_/_/   \_\_| |_____|

                  /\  _  _ |   _. _  |\/| _  _  _  _  _ _
                 /--\| )(_||\/_)|_)  |  |(_|| )(_|(_)(-|
                           /                      _/

What do you want?
  -(l)ist all analyses,
  -(a)dd a new analysis to CheckMATE,
  -(r)emove an analysis from CheckMATE]
```

The Analysis Manager

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```
    1
#########################################################################################
##Name                 NSR  Description                                          Lumi  CR?  #
# atlas_1210_2979      1    ATLAS, WW measurement with 2 leptons (7TeV)           4.6   no  #
# atlas_1308_2631      6    ATLAS, 0 leptons + 2 b-jets + etmiss                 20.1  yes #
# atlas_1402_7029      20   ATLAS, 3 leptons + etmiss (chargino+neutralino)      20.3  no  #
# atlas_1403_4853      12   ATLAS, 2 leptons + etmiss (direct stop)              20.3  no  #
# atlas_1403_5294      13   ATLAS, 2 leptons + etmiss, (SUSY electroweak)        20.3  yes #
# atlas_1404_2500      5    ATLAS, Same sign dilepton or 3l                      20.3  no  #
# atlas_1407_0583      27   ATLAS, 1 lepton + (b-)jets + etmiss (stop)           20.3  no  #
# atlas_1407_0600      9    ATLAS, 3 b-jets + 0-1 lepton + etmiss                20.1  no  #
# atlas_1407_0608      3    ATLAS, Monojet or charm jet (stop)                   20.3  no  #
# atlas_conf_2012_104  2    ATLAS, 1 lepton + >= 4 jets + etmiss                  5.8  yes #
# atlas_conf_2012_147  4    ATLAS, Monojet + etmiss                              10.0  yes #
# atlas_conf_2013_021  4    ATLAS, WZ standard model (3 leptons + etmiss)        13.0  no  #
# atlas_conf_2013_024  3    ATLAS, 0 leptons + 6 (2 b-)jets + etmiss             20.5  yes #
# atlas_conf_2013_031  2    ATLAS: Higgs spin measurement (WW)                   20.7  no  #
# atlas_conf_2013_036  5    ATLAS: 4 leptons + etmiss                            20.7  no  #
# atlas_conf_2013_037  6    ATLAS, 1 lepton + (b-)jets + etmiss (stop)           20.7  no  #
# atlas_conf_2013_047  10   ATLAS, 0 leptons + 2-6 jets + etmiss                  20.3  yes #
# atlas_conf_2013_049  9    ATLAS, 2 leptons + etmiss                            20.3  yes #
# atlas_conf_2013_061  9    ATLAS, 0-1 leptons + >= 3 b-jets + etmiss            20.1  yes #
# atlas_conf_2013_062  19   ATLAS: 1-2 leptons + 3-6 jets + etmiss               20.1  yes #
# atlas_conf_2013_089  12   ATLAS, 2 leptons (razor)                            20.3  yes #
# atlas_conf_2014_014  1    ATLAS, 2 leptons + b-jets (stop)                     20.3  yes #
# atlas_conf_2014_033  3    ATLAS, WW standard model measurement                 20.3  yes #
# cms_1303_2985        59   CMS, alpha_T + b-jets                                11.7  yes #
# cms_1301_4698_WW     1    CMS, WW standard model measurement                   3.5   no  #
# cms_1306_1126_WW     1    CMS, WW standard model measurement (7TeV             4.9   no  #
# cms_smp_12_006       4    CMS, WZ standard model (3 leptons + etmiss)          19.6  no  #
# cms_sus_12_019       2    CMS, 2 leptons, >= 2 jets + etmiss (dilep edge)      19.4  no  #
#########################################################################################
```

Adding an analysis

```
    a
This will collect all necessary information to create a full analysis and
Takes care for the creation and implementation of the source files into the code.
Please answer the following questions.
Attention: Your input is NOT saved before you finish this questionnaire!

1. General Information to build analysis
  Analysis Name:
    ATLAS_1234_5678
  Description (short, one line):
    ATLAS: many leptons, few jets
  Description (long, multiple lines, finish with ';;' on a new line):
    ATLAS
    many leptons, few jets
    sqrt(s) = 9 TeV
    int(L) = 42 fb^-1
    ;;
  Luminosity (in fb^-1):
    42
  Do you plan to implement control regions to that analysis? [(y)es, (n)o)
    n
```

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universitätbonn

Adding an analysis

```
2. Information on Signal Regions
  List all signal regions (one per line, finish with ';;' on a new line):
    1l
    2l
    ;;
  [...]
  You now have to add the numbers for each of the given signal regions.
    1l
      obs:
        100
      bkg:
        90
      bkg_err:
        15
      S95_obs:
        25
      S95_exp:
        20
    2l
      obs:
        200
      bkg:
        180
      bkg_err:
        30
      S95_obs:
        45
      S95_exp:
        35
```

Adding an analysis

```
3. Settings for Detector Simulation
3.1: Miscellaneous
  To which experiment does the analysis correspond? (A)TLAS, (C)MS
    A
3.2: Electron Isolation
  Do you need any particular isolation criterion? [(y)es, (n)o]
    y
  Isolation 1:
    Which objects should be considered for isolation? [(t)racks, (c)alo objects?
      t
    What is the minimum pt of a surrounding object to be used for isolation? [in GeV]
      5
    What is the dR used for isolation?
      0.4
    Is there an absolute or a relative upper limit for the surrounding pt? [(a)bsolute, (r)elative]
      a
    What is the maximum surrounding pt used for isolation [in GeV]?
      20

  Do you need more isolation criteria? [(y)es, (n)o]
    n
3.3: Muon Isolation
  Do you need any particular isolation criterion? [(y)es, (n)o]
    n
3.4: Photon Isolation
  Do you need any particular isolation criterion? [(y)es, (n)o]
    n
```

Adding an analysis

```
3.5: Jets
  Which dR cone radius do you want to use for the FastJet algorithm?
    0.4
  What is the minimum pt of a jet? [in GeV]
    10
  Do you need a separate, extra type of jet? [(y)es, (n)o]
    n
  Do you want to use b-tagging? [(y)es, (n)o]
    y

  b-Tagging 1:
    What is the signal efficiency to tag a b-jet? [in %]
      70
  Do you need more b tags? [(y)es, (n)o]
    y

  b-Tagging 2:
    What is the signal efficiency to tag a b-jet? [in %]
      40
  Do you need more b tags? [(y)es, (n)o]
    n

  Do you want to use tau-tagging? [(y)es, (n)o]
    n
```

Adding an analysis

```
   - Variable values saved in /hdd/Tools/CheckMATE/data/ATLAS_1234_5678_var.j
   - Created source file  /hdd/Tools/CheckMATE/tools/analysis/src/ATLAS_1234_5678.cc
   - Created header file  /hdd/Tools/CheckMATE/tools/analysis/include/ATLAS_1234_5678.h
   - Updated Makefile
   - Updated main source  main.cc
   - Reference file created
   - List of analyses updated
Analysis ATLAS_1234_5678 has been added successfully!
```

And that's it!

- A simple `make` will add the analysis to the framework
- Of course, the actual analysis code still has to be written by the user (imagine if this could be automatised...)

The Analysis Code

Generalities

- All analyses inherit their from a common `AnalysisBase` class
- This class takes care of lots of the technical details, i.e. it
  1. automatically reads the Delphes tree and provides vectors of `Muons`, `ElecronsTight`, `Jets`,... and missing ET
  2. dictates a simple structure similar to Rivet (procedure for the start, procedure for each event, procedure for the end)
  3. comes along with many standard functions (overlap removals, isolation checks, kinematical cuts, ...)
  4. provides very simple way of counting signal events

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  3. comes along with many standard functions (overlap removals, isolation checks, kinematical cuts, ...)
  4. provides very simple way of counting signal events
- The user only has to write the lines which
  1. choose and cut on the right objects
  2. perform lots of tests the event has to pass to not be vetoed
  3. if the event fulfills all criteria for signal region X, call line `countSignalEvent('X');`. That's all

Some example lines


```
void Atlas_conf_2013_047::analyze() {
  missingET->addMuons(muonsCombined);
  electronsLoose = filterPhaseSpace(electronsLoose, 10., -2.47, 2.47);
  muonsCombined = filterPhaseSpace(muonsCombined, 10., -2.4, 2.4);
  jets = filterPhaseSpace(jets, 20., -2.8, 2.8);

  ...

  jets = overlapRemoval(jets, electronsLoose, 0.2);
  electronsLoose = overlapRemoval(electronsLoose, jets, 0.4);
  if(!electronsLoose.empty())
    return;

  ...

  double HT = 0.;
  for(int j = 0; j < jets.size(); j++)
    HT += jets[j]->PT;
  double mEffInc = missingET->P4().Et() + HT;

  mEffA = missingET->P4().Et() + jets[0]->PT + jets[1]->PT;
  if (missingET->P4().Et()/mEffA > 0.2) {
    countCutflowEvent("AL1");
    if (mEffInc > 1000.)
      countSignalEvent("AL");
  }
  ...
```

Summary

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User Mode

- Input: Event files, cross sections and expected systematic errors
- CheckMATE consequtively runs Delphes, performs the analyses and statistically evaluates the results
- It stores lots of intermediate results for the user to check and process otherwise
- Output: “Allowed” or “Excluded” in its most simple form

Dev Mode

- Code is transparently written in Python and C++
- AnalysisManager makes definition of new analyses simple
- AnalysisBase class makes coding of new analyses simple too