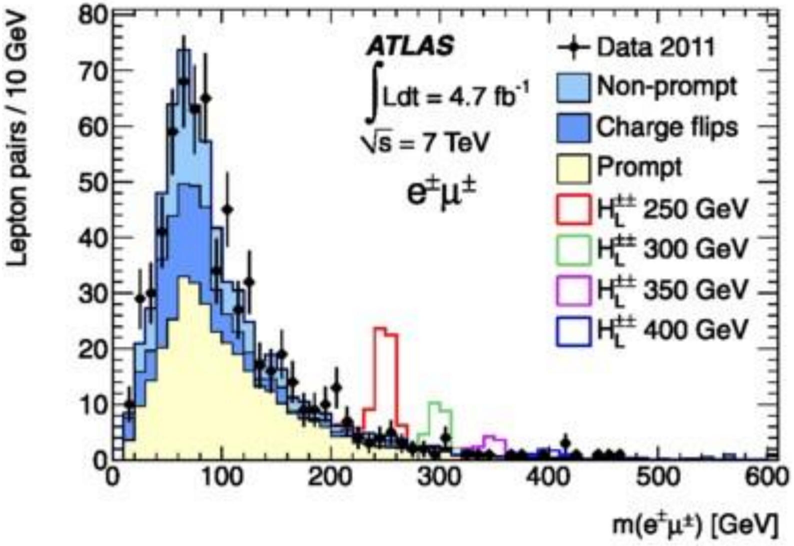
# FYST17 Lecture 7
# MC and Simulation

Thanks to M. Asai, T. Sjöstrand, J. Morris



**Suggested reading:** this is not well described in the book. Chap 9.4.3 in the statistics book has a few details. Better to follow a class with the world-famous Lund phenomenologists

# Today’s topics

- Simulation, Monte Carlo (MC) and why we use it
- MC generators
  - Examples
  - Different specialities
- Detector simulation
  - GEANT
- Performance, some examples

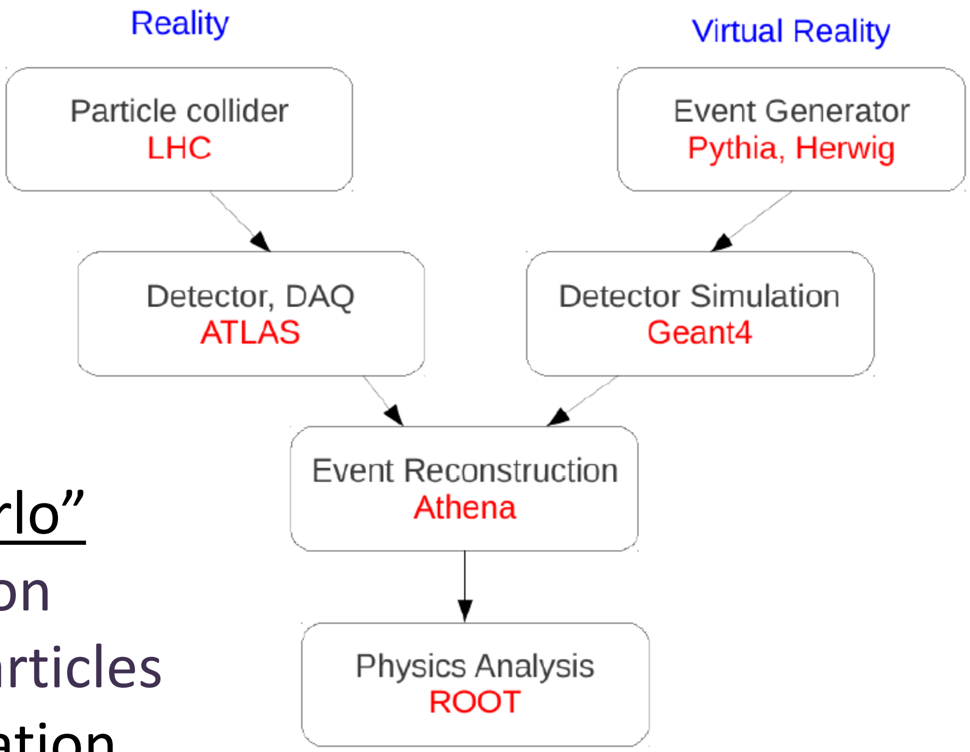
# Why simulation?

We want to be able to compare data to expectations

*”Virtual experiment”*

”Simulation” typically consists of two steps:

- <u>Event generation ”Monte Carlo”</u>
  - Calculations, hadronization
  - 4-vectors of final state particles
- <u>Detector simulation + digitization</u>
  - The particles’ paths through the detector material
  - Detector and electronic response



Reality

Virtual Reality

Particle collider
LHC

Event Generator
Pythia, Herwig

Detector, DAQ
ATLAS

Detector Simulation
Geant4

Event Reconstruction
Athena

Physics Analysis
ROOT

# Why simulation?

## Why use generators?

- Allows studies of complex multi-particle physics
- Allows studies of theoretical models
  - ⇒ What does a SUSY signal look like?

## Can be used to

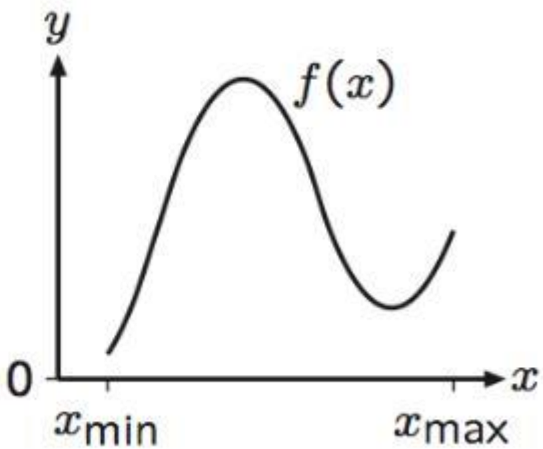
- Predict cross sections and topologies of various processes
  - ⇒ Feasibility study - Can we find the theoretical particle X?
- Simulate background processes to the signal of interest
  - ⇒ Can devise analysis strategies
- Study detector response
  - ⇒ Optimise trigger & detector selection cuts
- Study detector imperfections
  - ⇒ Can evaluate acceptance corrections

- Remove the effect of the apparatus from the measurement
  - ⇒ *Unfold* the data. Correcting the data for detector effects

Impossible to do analytically!

# The Monte Carlo method

”Monte Carlo” refers to any numerical method that uses random numbers in order to simulate probabilistic processes



Select x at random* according to f(x)

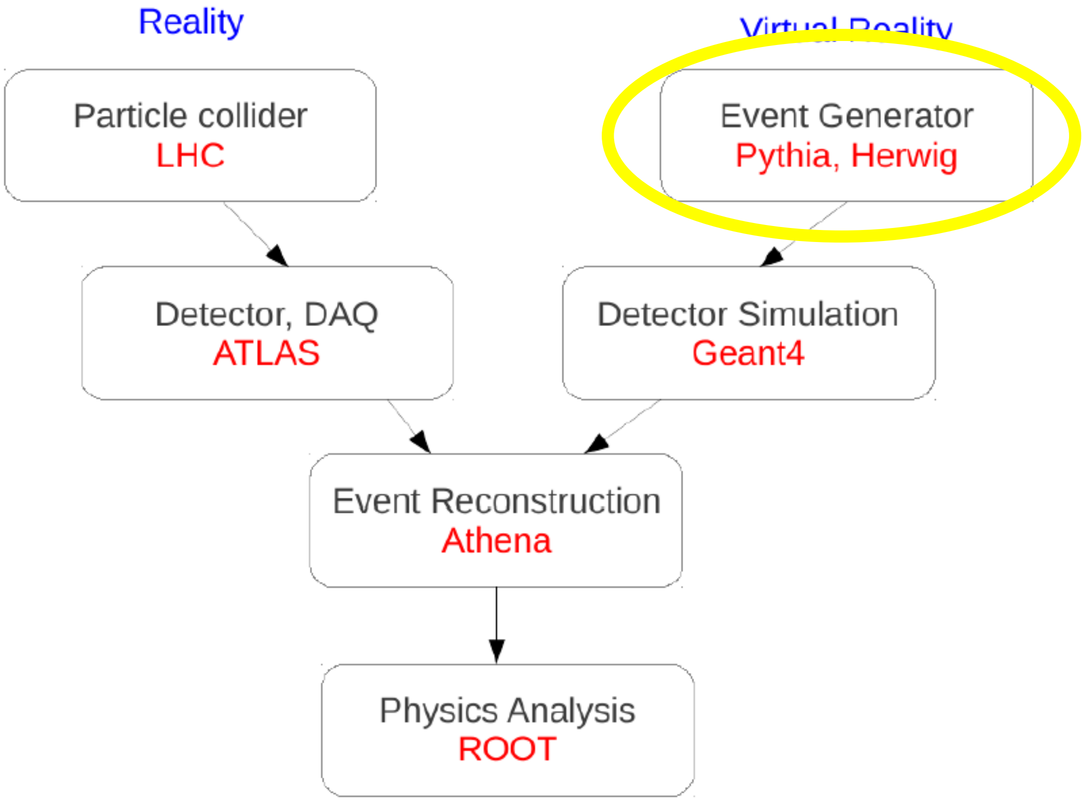
Integral $I = \int_{x1}^{x2} f(x)dx = (x_2 - x_1)\langle f(x)\rangle$

Draw N values from a uniform distribution:

$$I \approx I_N \equiv (x_2 - x_1)\frac{1}{N}\sum_{i=1}^{N} f(x_i)$$

Cross section randomly sampled over phase space. Method governed by the Central Limit Theorem: errors $\propto \frac{1}{\sqrt{N}}$

*In particle physics applications: Random numbers represent QM choices



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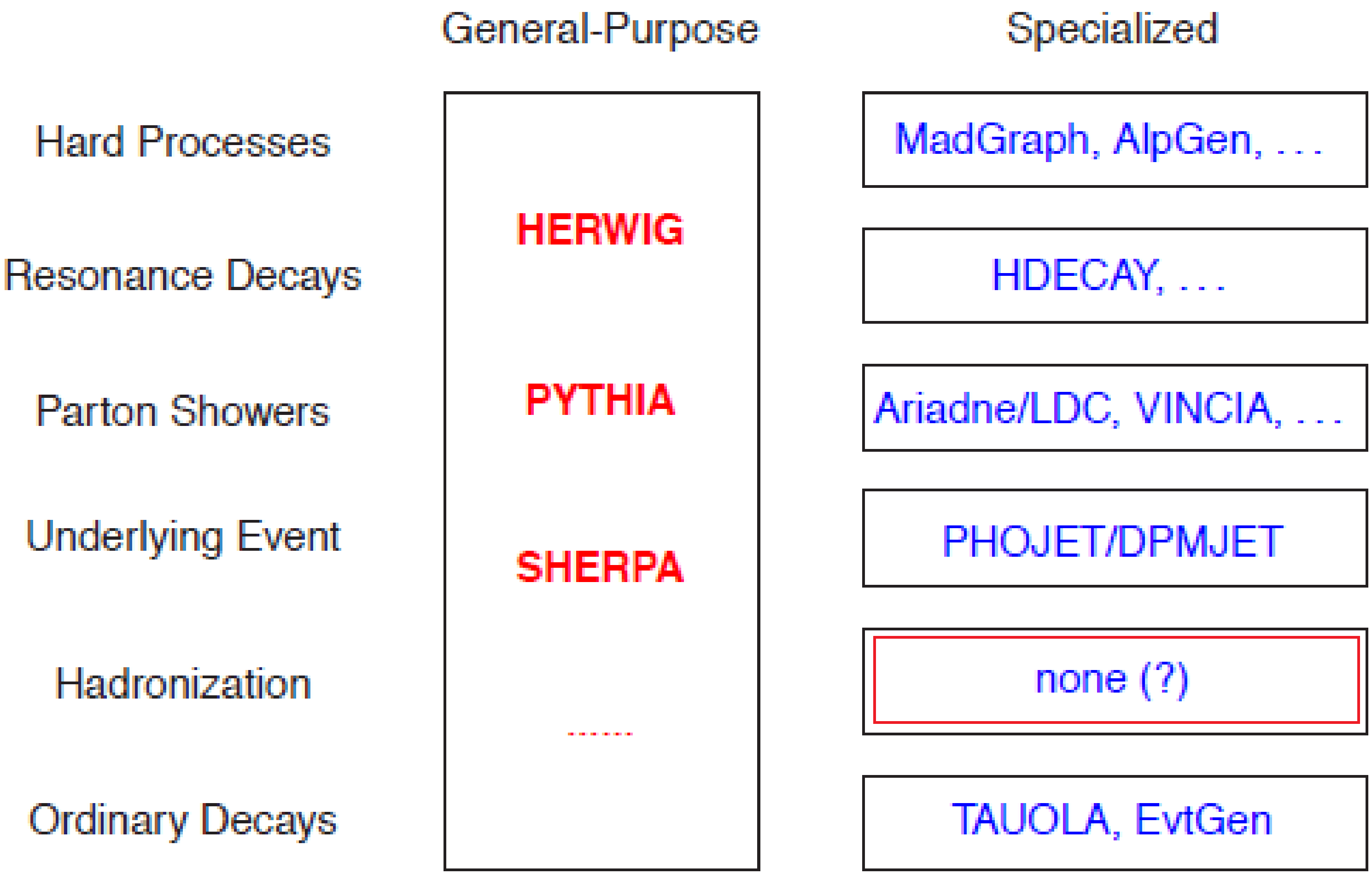
# Event generators



General-Purpose

Specialized

Hard Processes

Resonance Decays

Parton Showers

Underlying Event

Hadronization

Ordinary Decays

**HERWIG**

**PYTHIA**

**SHERPA**

……

MadGraph, AlpGen, . . .

HDECAY, . . .

Ariadne/LDC, VINCIA, . . .

PHOJET/DPMJET

none (?)

TAUOLA, EvtGen

Specialized often best at given task, but need General-Purpose core

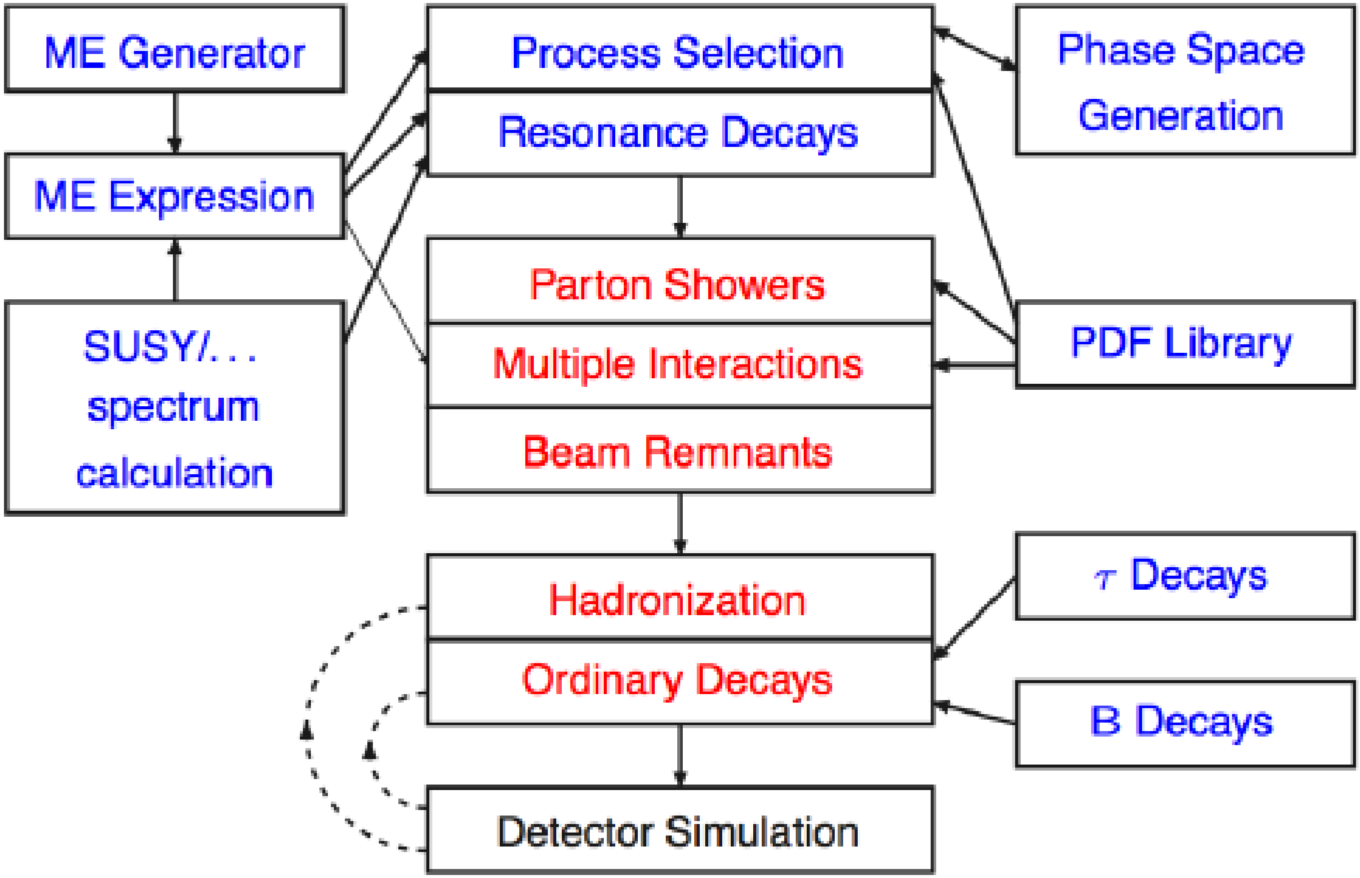
# Event generators

From Lund U phenomenology group!

| | General-Purpose | Specialized |
|---|---|---|
| Hard Processes | **HERWIG**<br>**PYTHIA**<br>**SHERPA**<br>....... | MadGraph, AlpGen, . . . |
| Resonance Decays | | HDECAY, . . . |
| Parton Showers | | Ariadne/LDC, VINCIA, . . . |
| Underlying Event | | PHOJET/DPMJET |
| Hadronization | | none (?) |
| Ordinary Decays | | TAUOLA, EvtGen |

Specialized often best at given task, but need General-Purpose core

# What they do

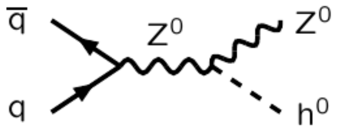


Several standardized interfaces!

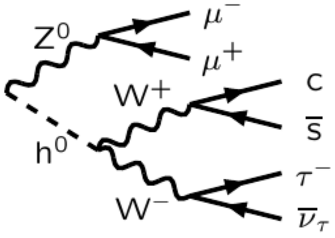
# Monte Carlo generation

**Matrix elements (ME):**

1) Hard subprocess:
$|\mathcal{M}|^2$, Breit-Wigners,
parton densities.

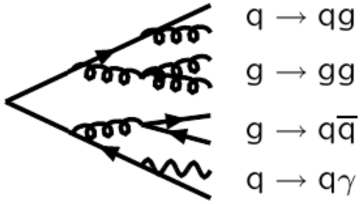


2) Resonance decays:
includes correlations.

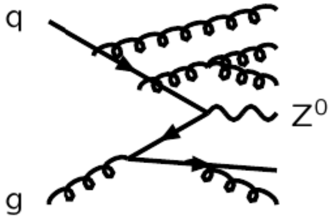


**Parton Showers (PS):**

3) Final-state parton showers.

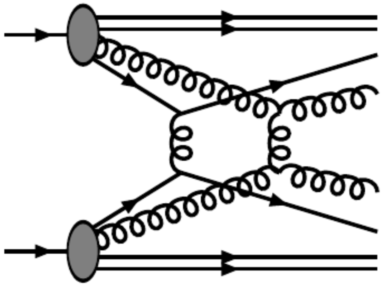


4) Initial-state parton showers.

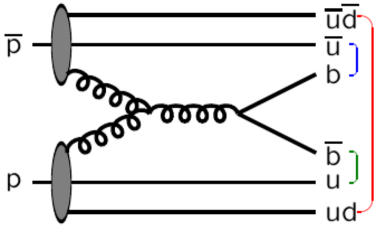


# Monte Carlo generation

5) Multiple parton–parton interactions.

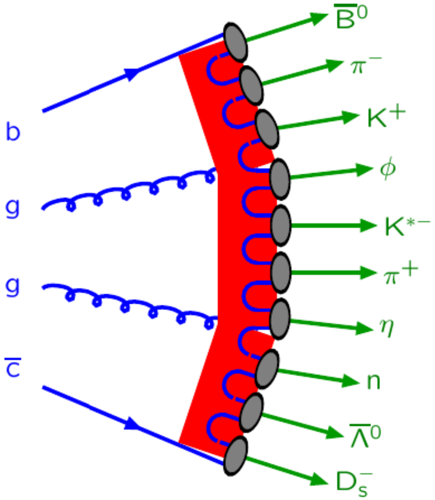


6) Beam remnants, with colour connections.



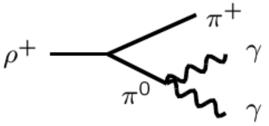
5) + 6) = Underlying Event

**7) Hadronization**

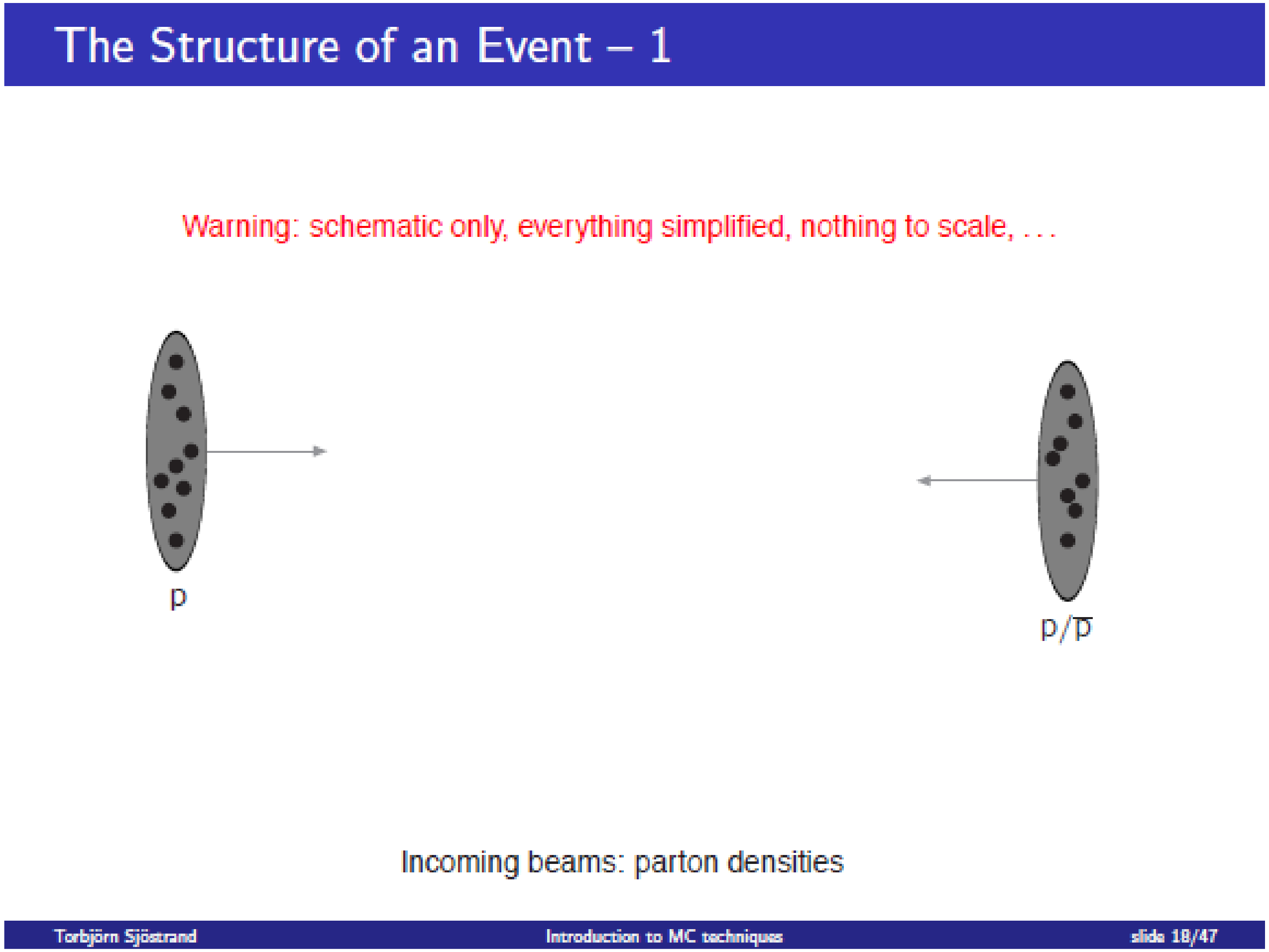


**8) Ordinary decays**:

hadronic, $\tau$, charm, . . .



# Slides from Torbjörn Sjöstrand



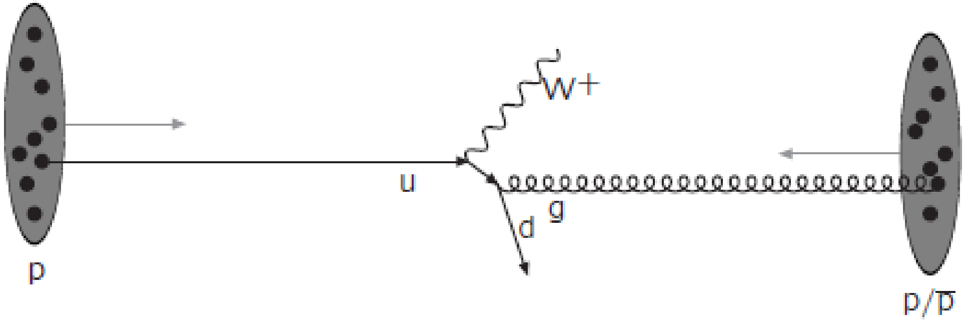
## The Structure of an Event – 1

Warning: schematic only, everything simplified, nothing to scale, . . .

Incoming beams: parton densities

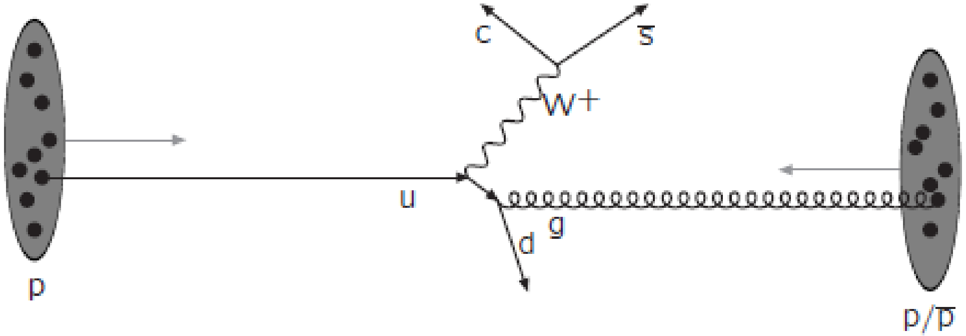
Torbjörn Sjöstrand Introduction to MC techniques slide 18/47

# The Structure of an Event – 2



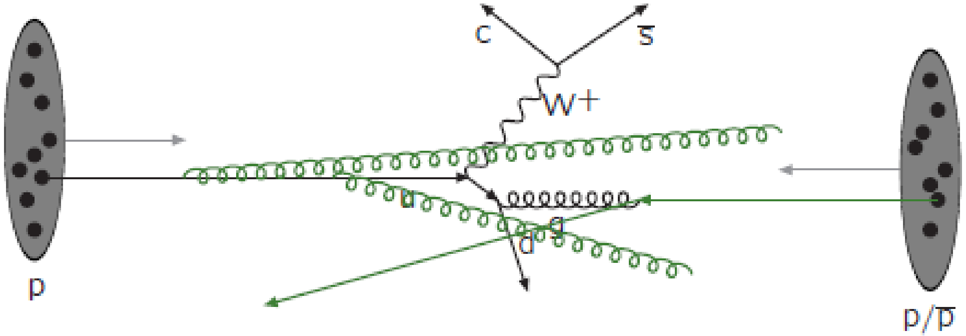
Hard subprocess: described by matrix elements

# The Structure of an Event – 3



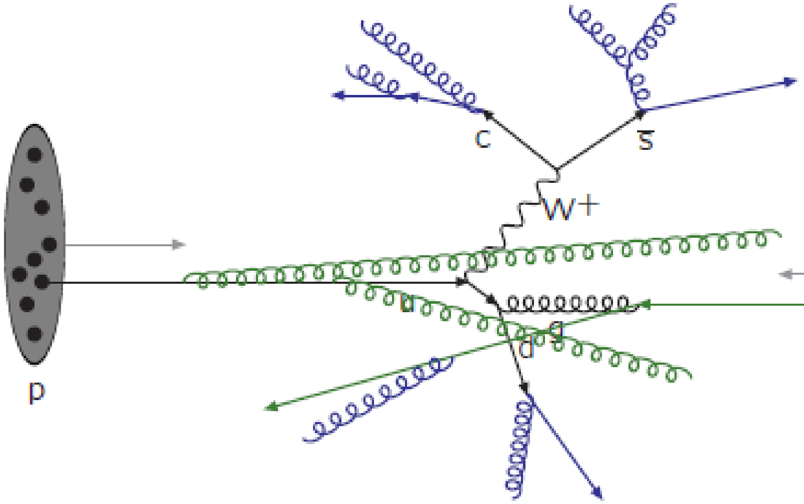
Resonance decays: correlated with hard subprocess

# The Structure of an Event – 4

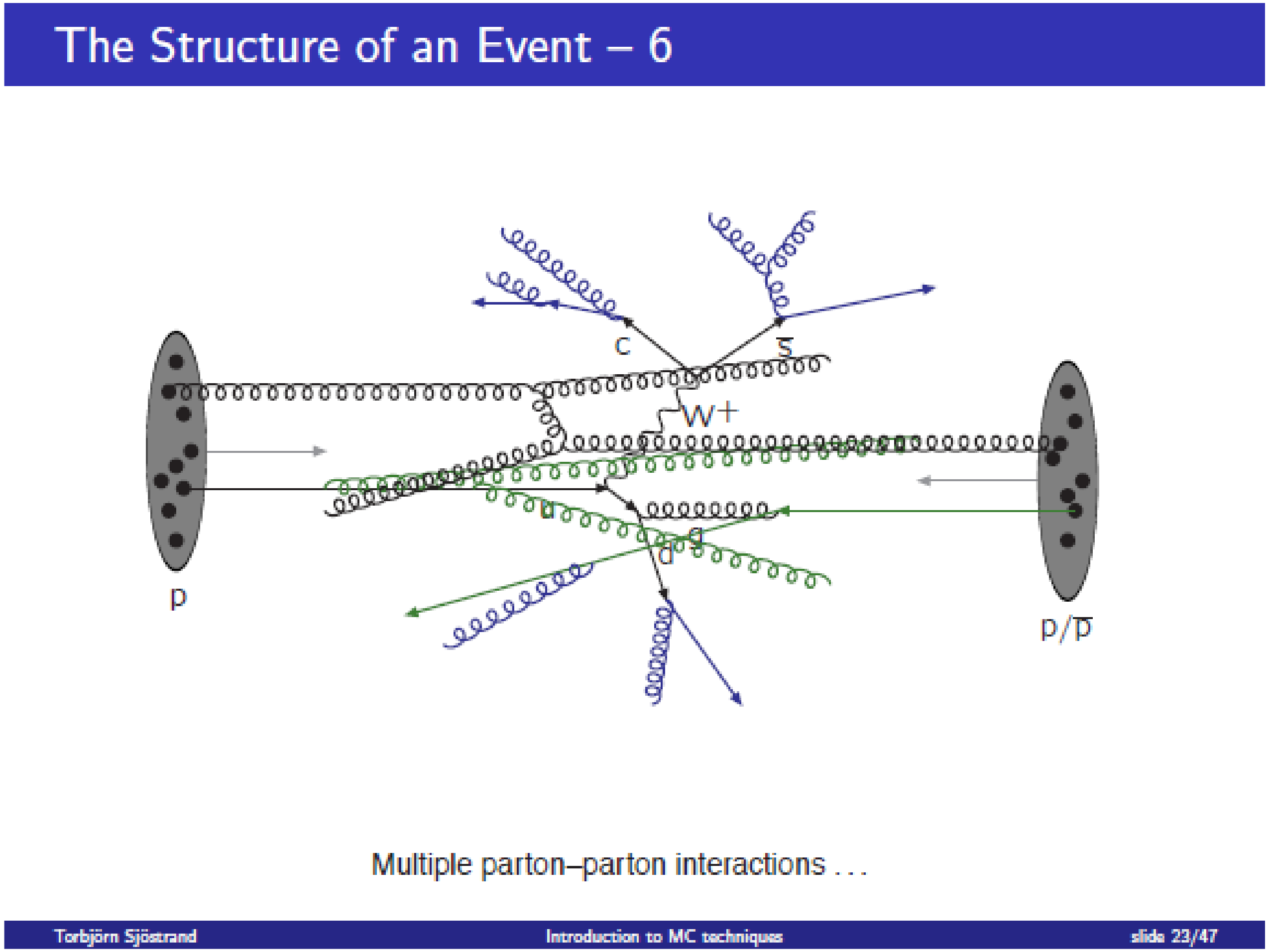


Initial-state radiation: spacelike parton showers

# The Structure of an Event – 5



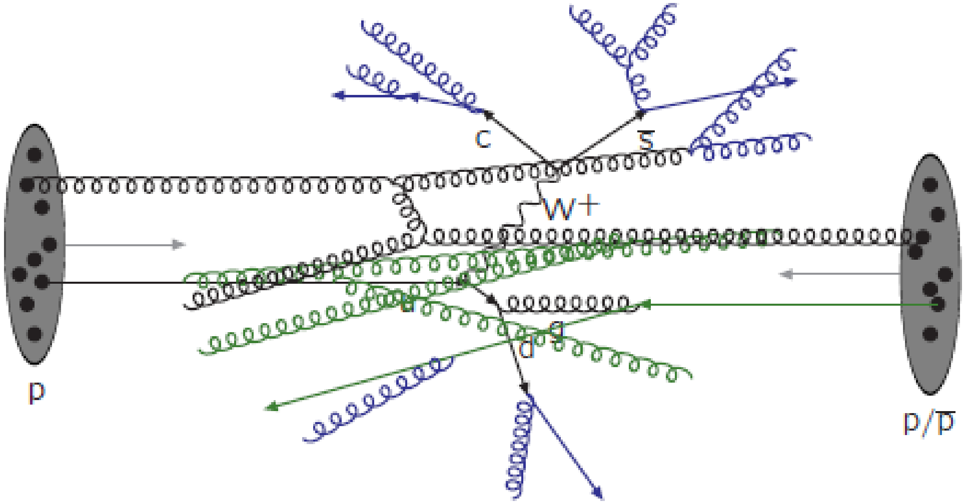
Final-state radiation: timelike parton showers



# The Structure of an Event – 6

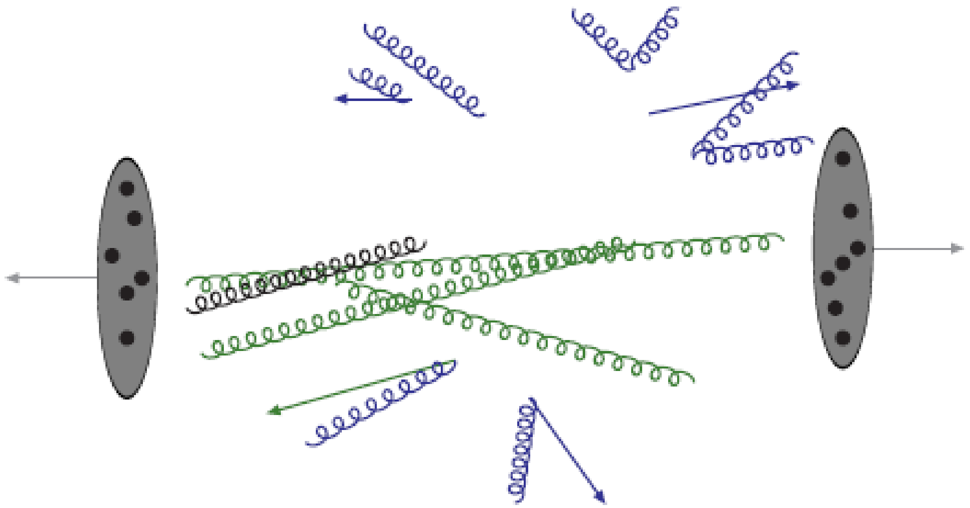
Multiple parton–parton interactions . . .

# The Structure of an Event – 7



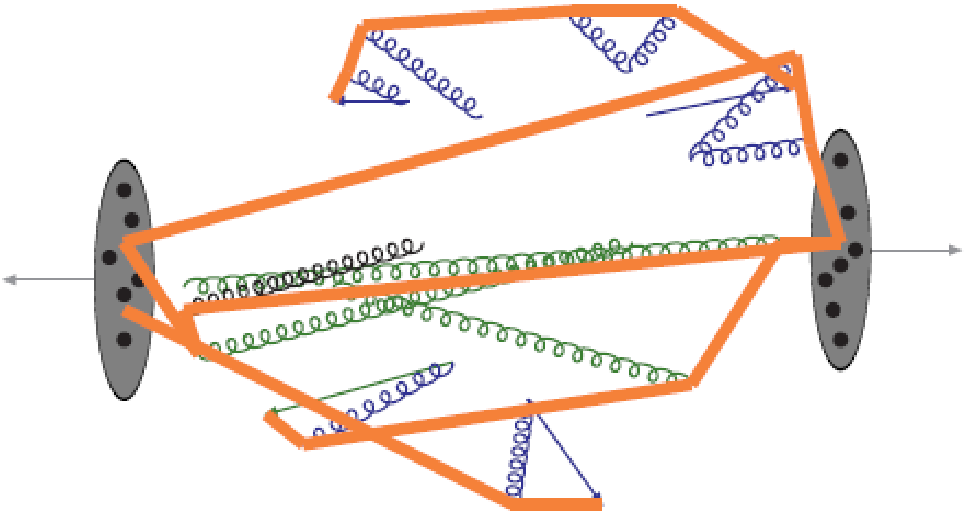
. . . with its initial- and final-state radiation

# The Structure of an Event – 8



Beam remnants and other outgoing partons

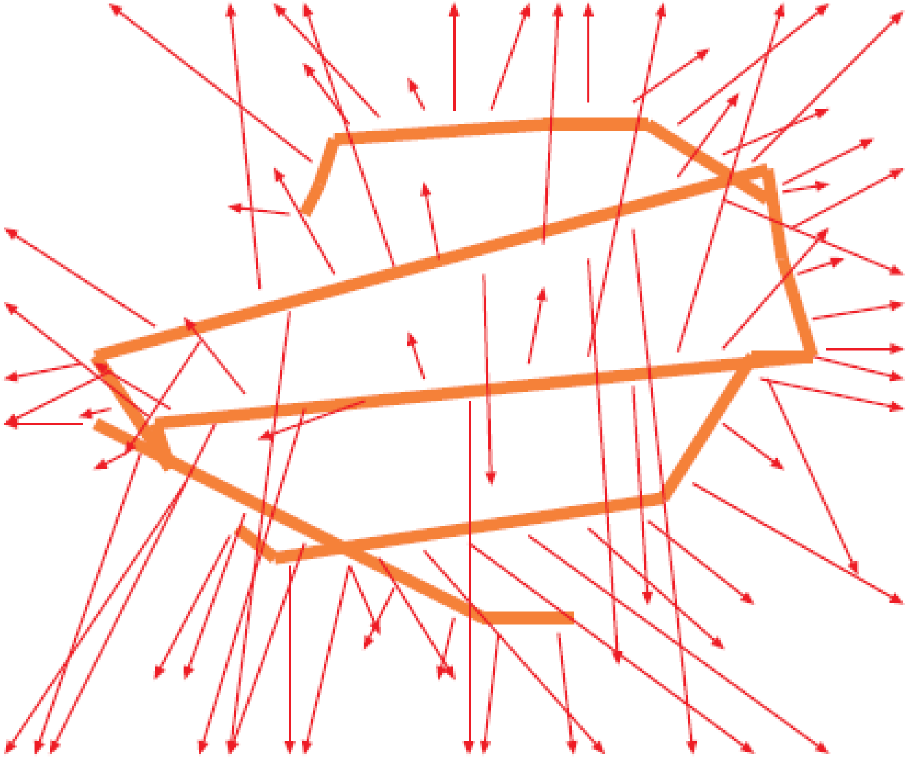
# The Structure of an Event – 9



Everything is connected by colour confinement strings

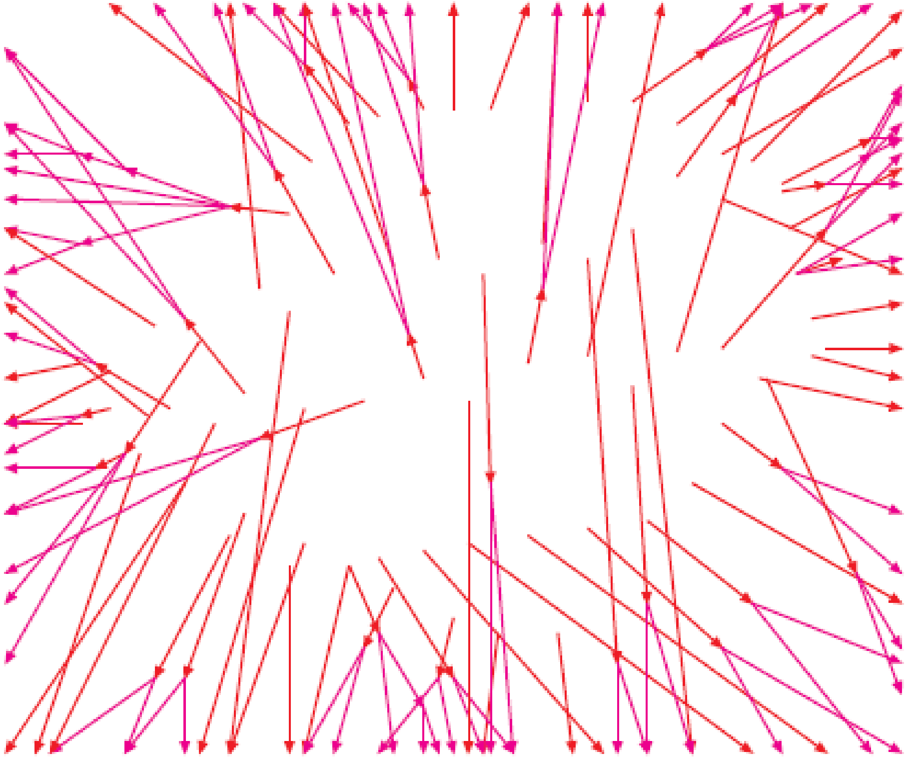
Recall! Not to scale: strings are of hadronic widths

# The Structure of an Event – 10



The strings fragment to produce primary hadrons

# The Structure of an Event – 11

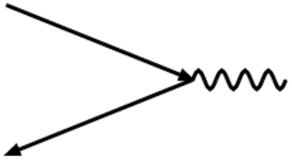


Many hadrons are unstable and decay further

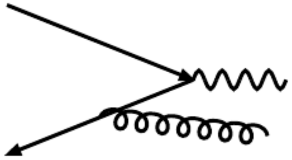
# Matrix Element calculation

Normally done to LO or NLO

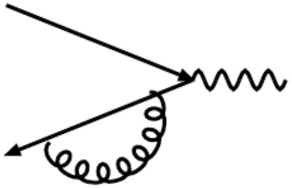
I. Lowest order,
$\mathcal{O}(\alpha_{\mathrm{em}})$:
$q\overline{q} \rightarrow Z^0$



II. First-order real,
$\mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$:
$q\overline{q} \rightarrow Z^0 g$ etc.

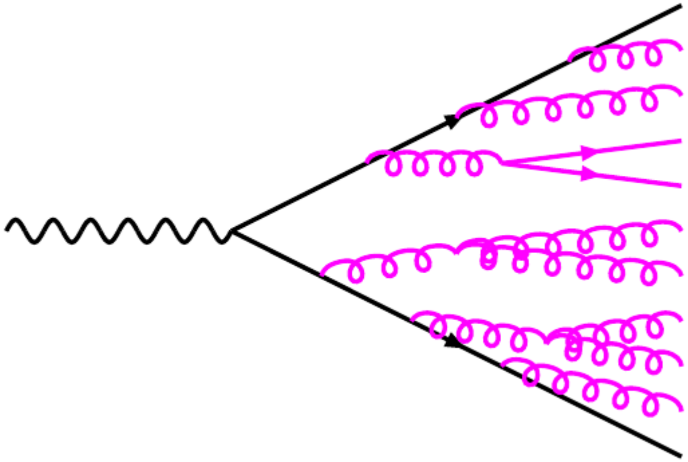


III. First-order virtual,
$\mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$:
$q\overline{q} \rightarrow Z^0$ with loops



- Higher order corrections are important:
  - Normalisation and shape of kinematic distributions
  - Multiplicity of objects like jets
- Higher order corrections are hard to calculate and CPU intensive
- Several programs that will do the calculation
  - Different calculation techniques
  - Different assumptions
  - Different results
  - $\Rightarrow$ Theoretical modelling uncertainty

# Parton showering



- Need to go from 2→2 scattering to 100's of particles
  - A particle can decay into more particles
  - A particle can emit another particle
  - All controlled by random numbers
- Parton shower evolution is a probabilistic process
  - Occurs with unit total probability

# Parton Showering

## 2 Common approaches to parton showering

- Need to avoid divergences and infinities in calculations
  - See your QCD course for why these occur
  - Solution requires the final state partons to be ordered
- There are 2 common approaches to do this
- PYTHIA : $Q^2 = m^2$
  - The parton with the highest $p_{\mathrm{T}}$ is calculated first
- HERWIG : $Q^2 \approx E^2\left(1 - \cos\left(\theta\right)\right)$
  - The parton with the largest angle is calculated first

## This represents a theoretical modelling uncertainty

- Both provide a good description of data but which is correct?
  - Neither is correct, but nature is unknown, we only have models
- All physics measurements need to take this into account
  - Expect to see a parton shower systematic for every result
  - Use both methods for calculation of physics result
  - Difference between results is a theoretical modelling systematic

# Hadronization

## Going from partons to hadrons

- Partons are not observed directly in nature, only hadrons
- Hadronisation occurs at low energy scales
    - Perturbation theory is not valid
    - Cannot calculate this process from first principals
- Require models to simulate what happens
- 2 common approaches are used
    - Pythia : Lund string model
    - Herwig : Cluster model

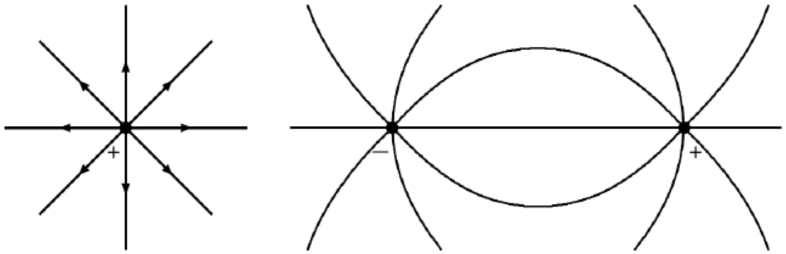
## This is another theoretical modelling uncertainty

- Similar type of uncertainty as for parton showering
    - We don't know exactly how nature works
    - We have 2 reasonable models
    - Calculate physics result using each method
    - Difference is a theoretical modelling systematic

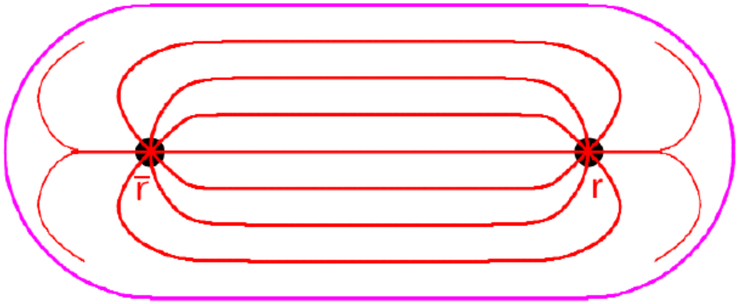
# Hadronization

The Lund String model:

- In QED field lines go all the way to infinity
- Photons do not interact with each other



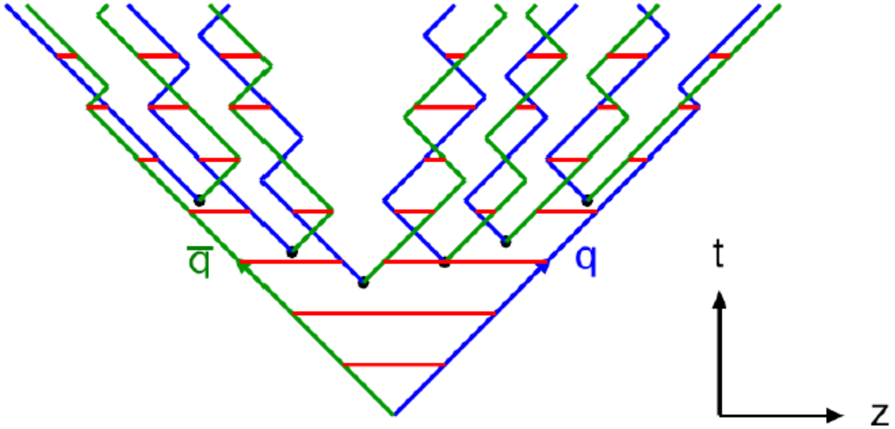
- In QCD, for large charge separation, field lines seem to be compressed into tube-like regions ⇒ string(s)
- Self-interaction among soft gluons in the vacuum



# Hadronization

The Lund String model:

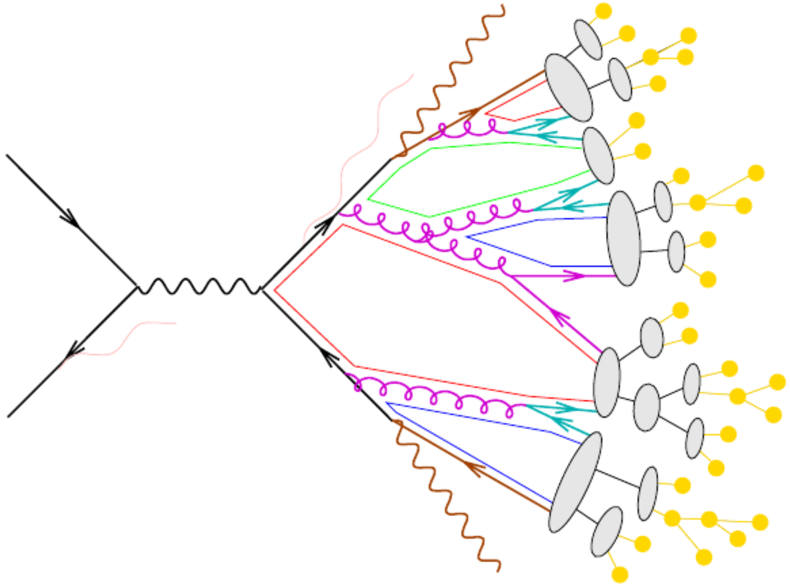
- The strings connecting the 2 partons breaks as they move apart
- Fragmentation starts in the middle and spreads out



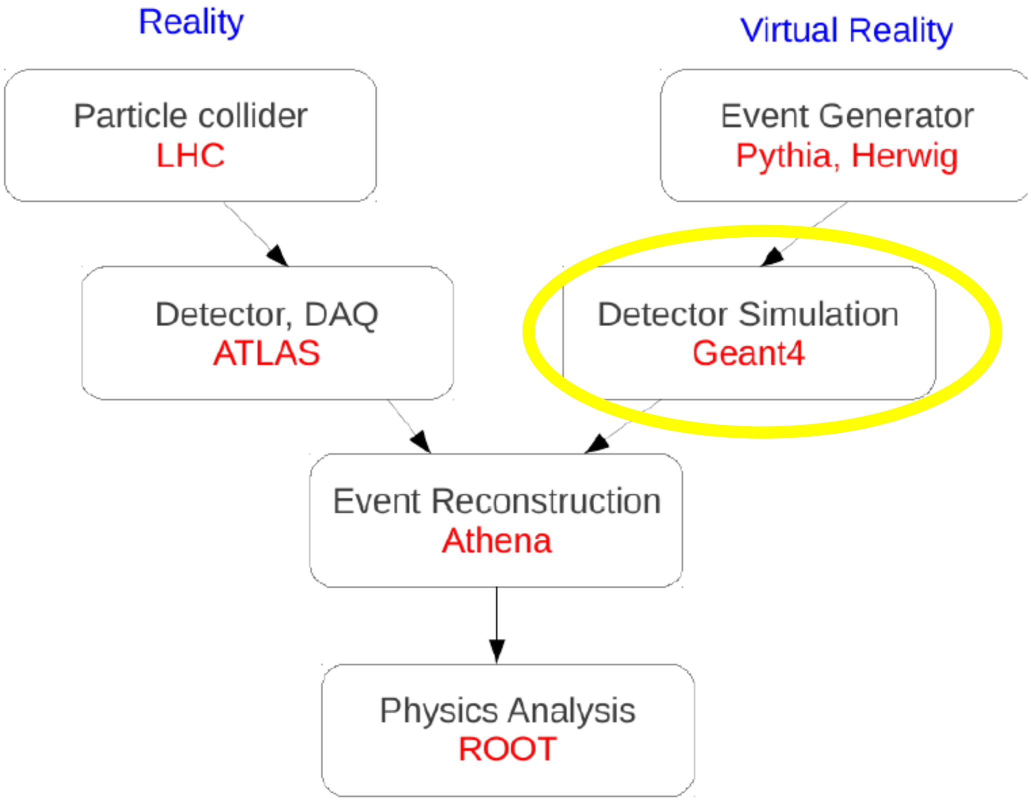
- The breakup vertices become causally disconnected
- This is governed by many internal parameters
- Implemented by the PYTHIA MC program

# Hadronization

The Cluster model:



- Pre-confinement colour flow is local
- Forced $g \to q\bar{q}$ branchings
- Colour singlet clusters are formed
- Clusters decay isotropically to hadrons
- Relatively few internal parameters
- Implemented by the HERWIG MC program



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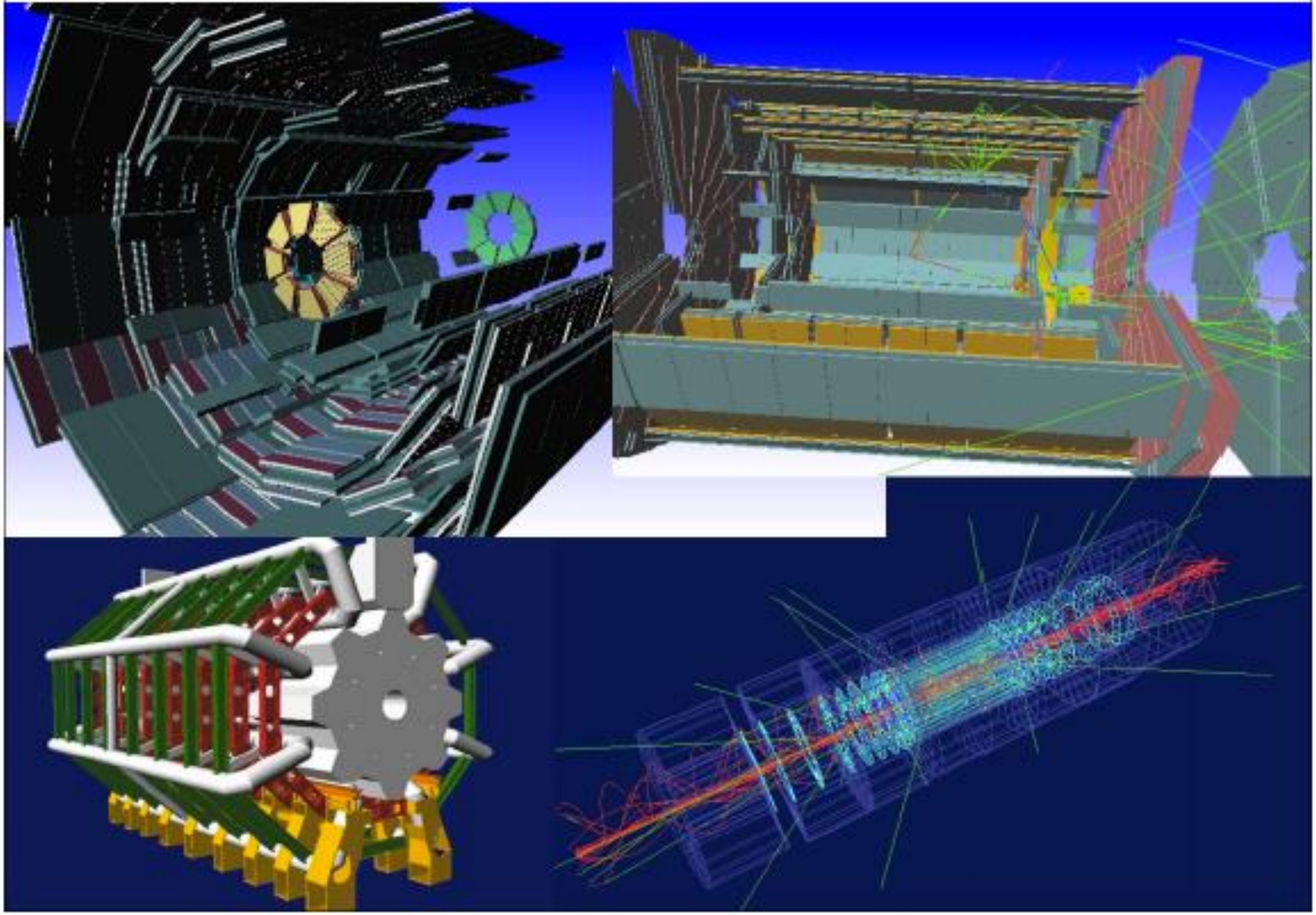
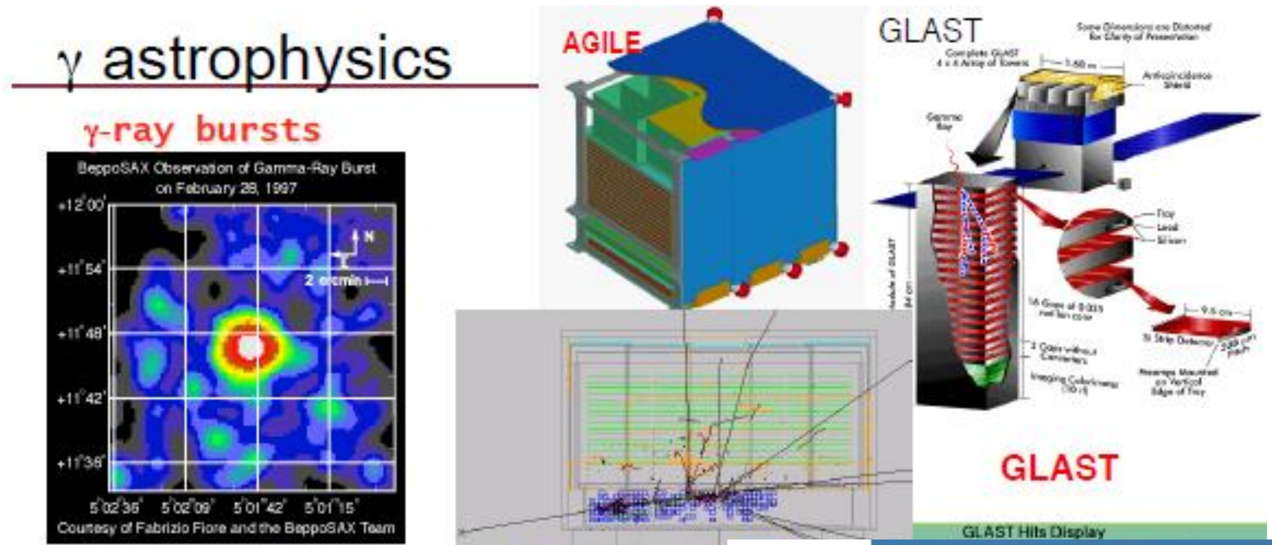
# Detector simulation

- Next step is simulating the particles paths through the detector:
  - Tracking chambers, calorimeters, muon system
  - but also cables, cooling pipes etc
  - and also faulty detector modules/electronics!
- Takes time: need to simulate all interactions, ionization, energy deposits, secondary interactions and decays, scattering …
- Mostly used: **GEANT4** a C++ program. Takes as input 4-vectors from event generators and outputs ”raw data”
- Takes up to 10 mins/event! Short-cut ***Fast simulation***: Smear the 4-vectors instead of calorimeter simulation

# Geant4 in High Energy Physics (ATLAS at LHC)



# Not just used in high energy physics

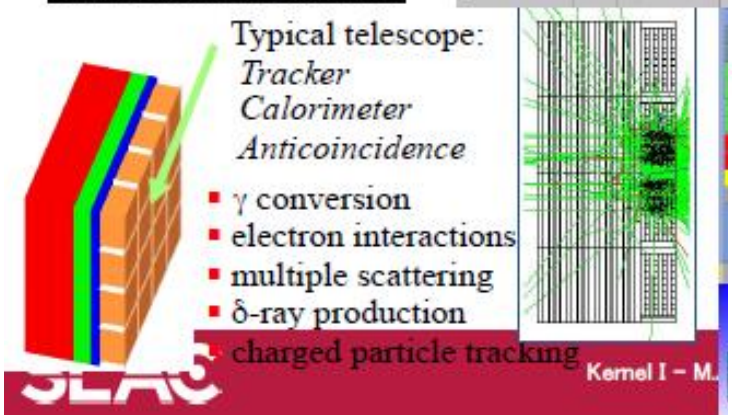


γ astrophysics

γ-ray bursts

BeppoSAX Observation of Gamma-Ray Burst on February 28, 1997

Courtesy of Fabrizio Fiore and the BeppoSAX Team



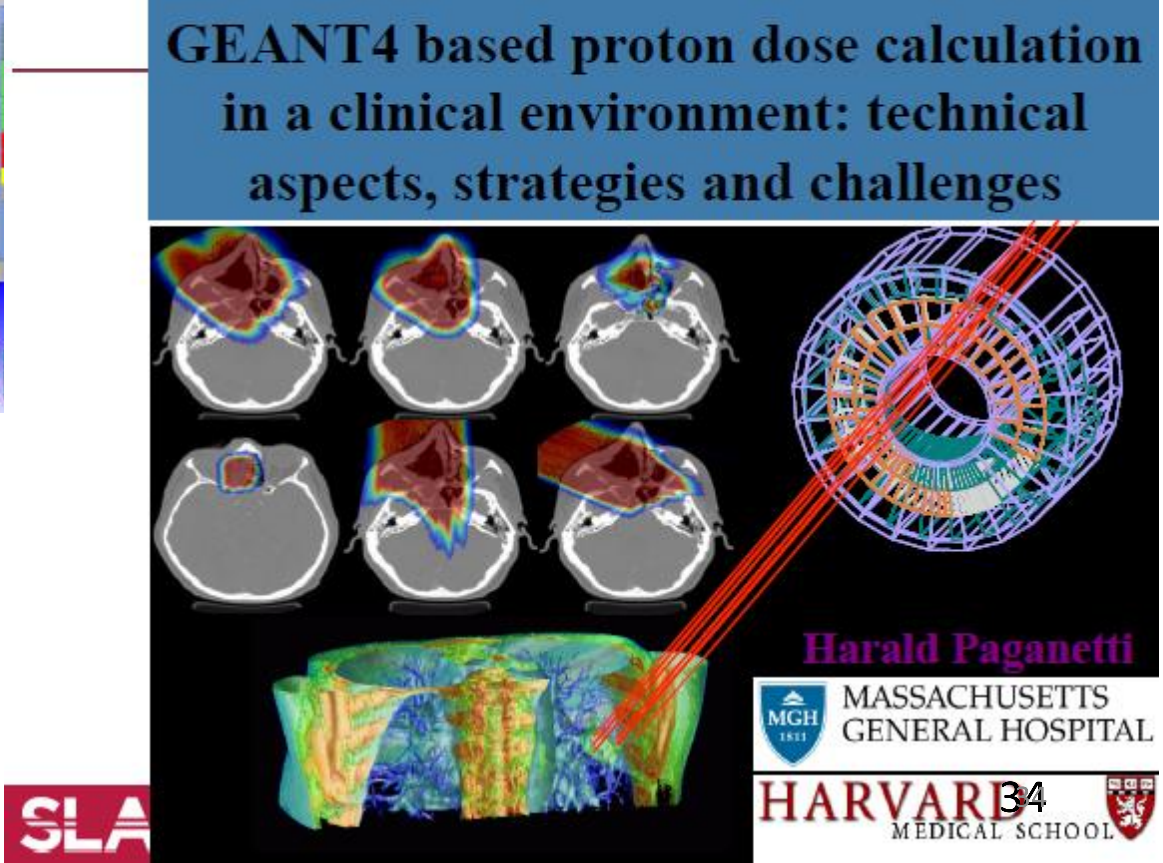
Typical telescope:

*Tracker*

*Calorimeter*

*Anticoincidence*

- γ conversion
- electron interactions
- multiple scattering
- δ-ray production
- charged particle tracking



**GEANT4 based proton dose calculation in a clinical environment: technical aspects, strategies and challenges**

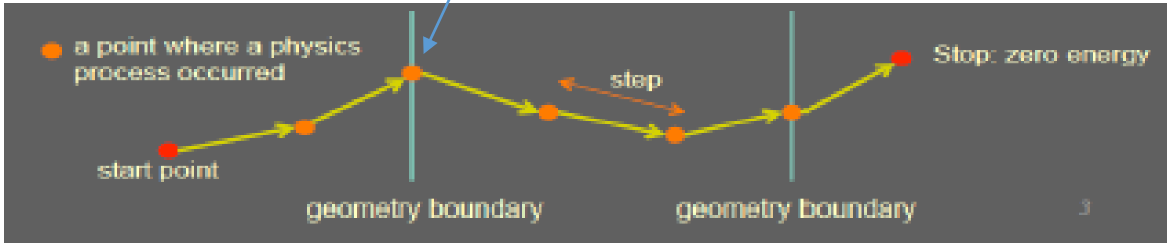
**Harald Paganetti**

MASSACHUSETTS GENERAL HOSPITAL

HARVARD MEDICAL SCHOOL

# How does it Work ?

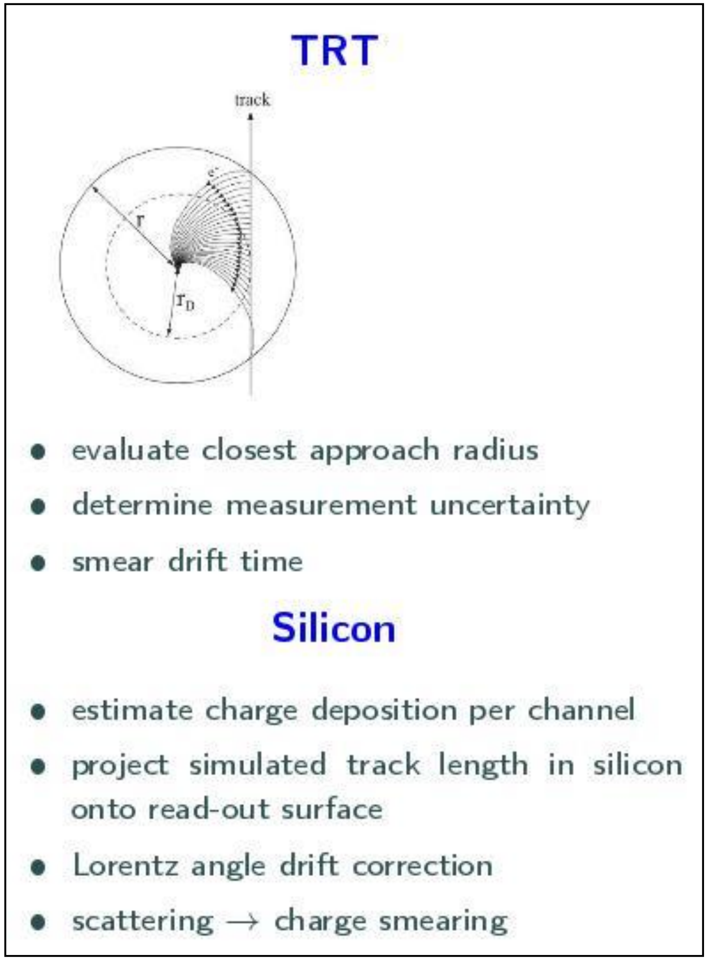
- Treat one particle at the time
- Treat a particle in **steps**



+ a photon?

- For each step
  - the step length is determined by the cross sections of the physics processes and the geometrical boundaries; if new particles are created, add them to the list of particles to be transported;
  - local energy deposit; effect of magnetic and electric fields;
  - if the particle is destroyed by the interaction, or it reaches the end of the apparatus, or its energy is below a (tracking) threshold, then the simulation of this particle is over;
    else continue with another step.
- Output - new particles created (indirect)
  - local **energy deposits** throughout the detector (direct)

# Digitization



**TRT**

- evaluate closest approach radius
- determine measurement uncertainty
- smear drift time

**Silicon**

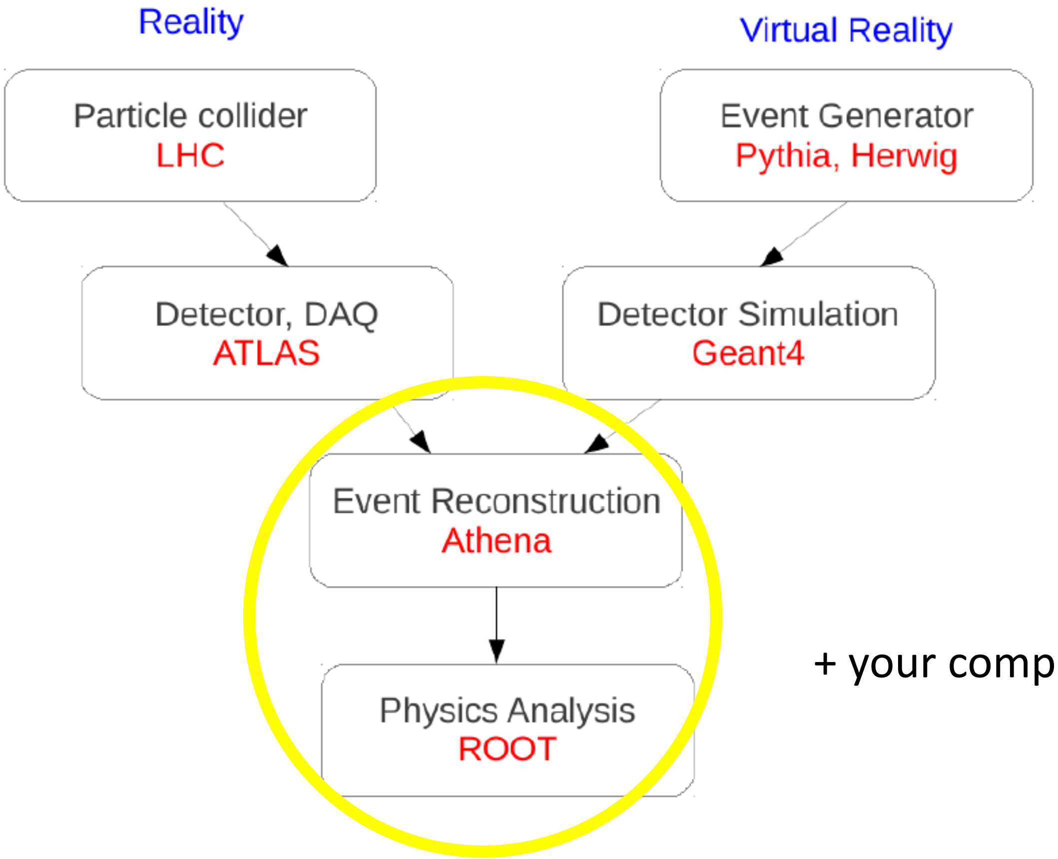
- estimate charge deposition per channel
- project simulated track length in silicon onto read-out surface
- Lorentz angle drift correction
- scattering → charge smearing

Before we are ready to run the same reconstruction algorithms as on data, the GEANT output needs to be ***digitized***

That is, converting the simulated hits in detectors into signals in read-out electronics

Also trigger simulation can be done at this level

Time consumption dominated by inner detector (most channels)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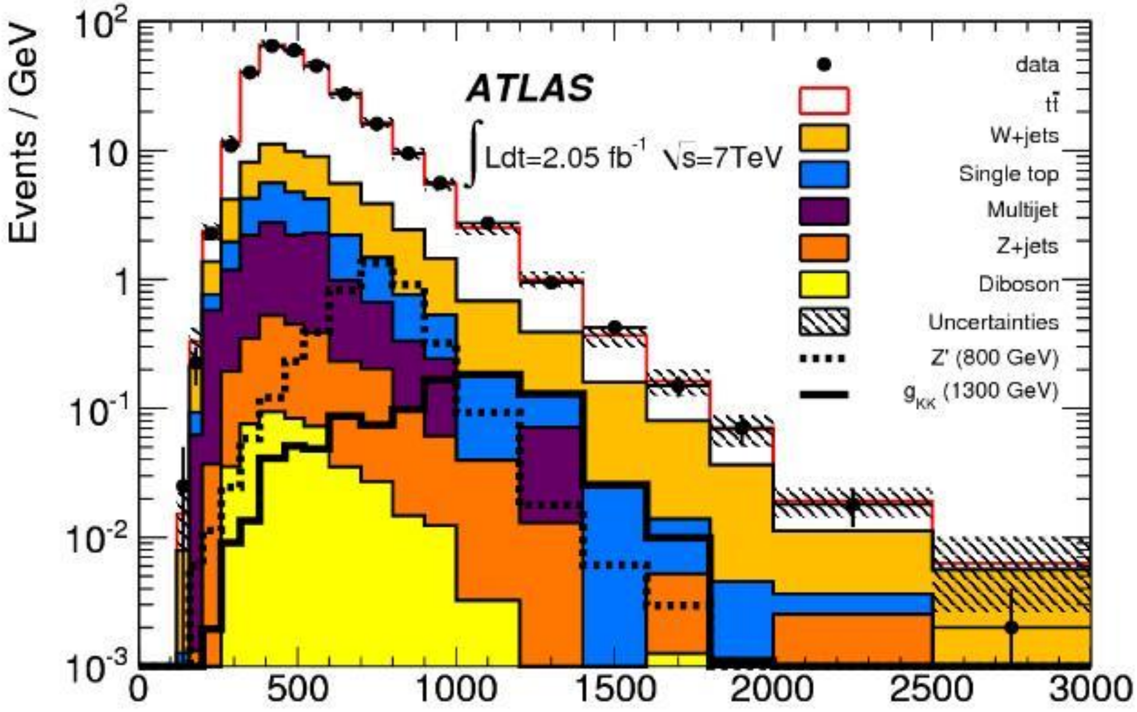
+ your computer exercise

# Putting it all together

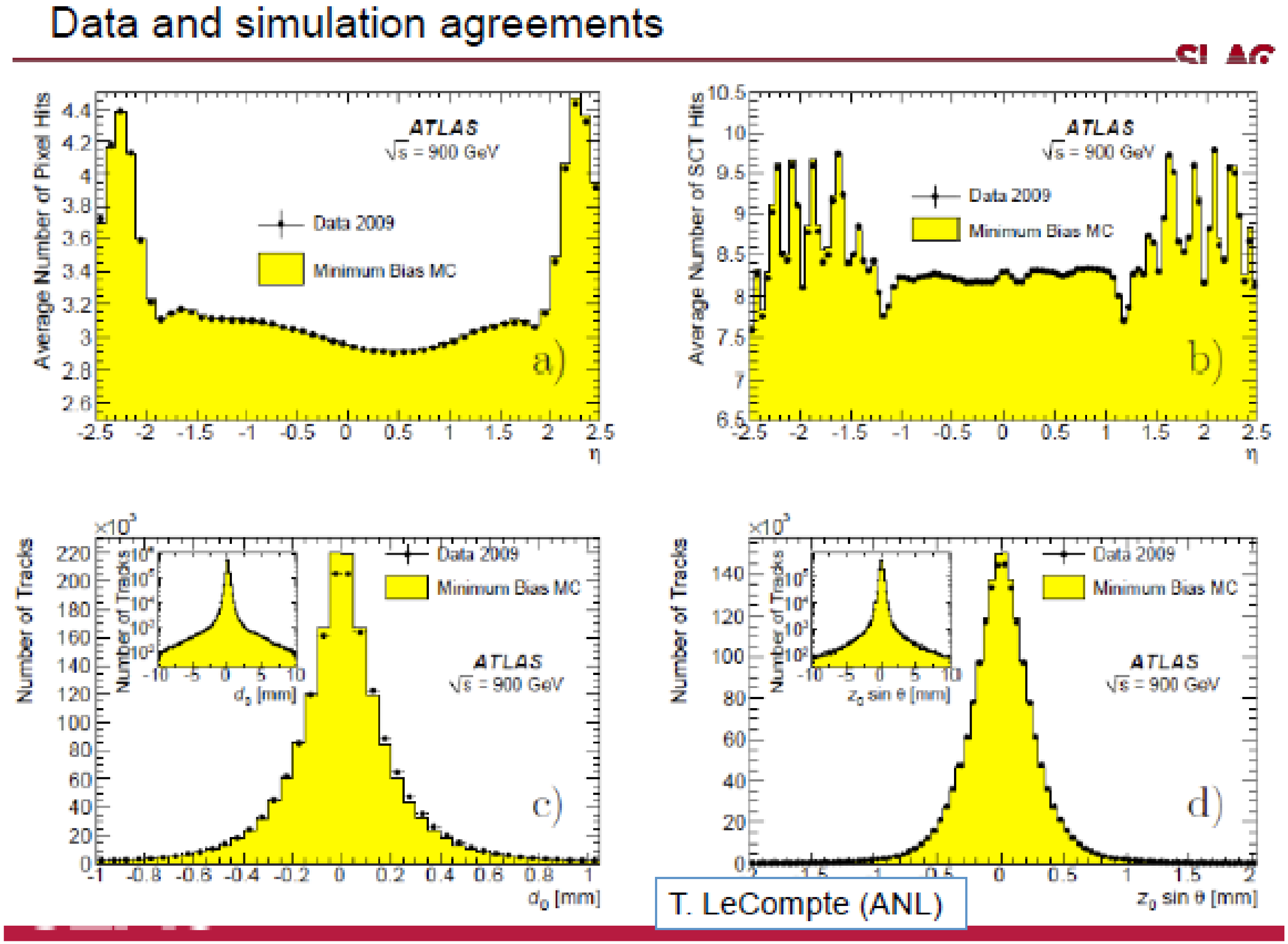
MC is not the truth! – tests/validation necessary

Some features are time-dependent ie amount of pile-up, technical problems with the detector, center of mass energy etc



Need to update (and test!) the simulation regularly

# Minimum bias events

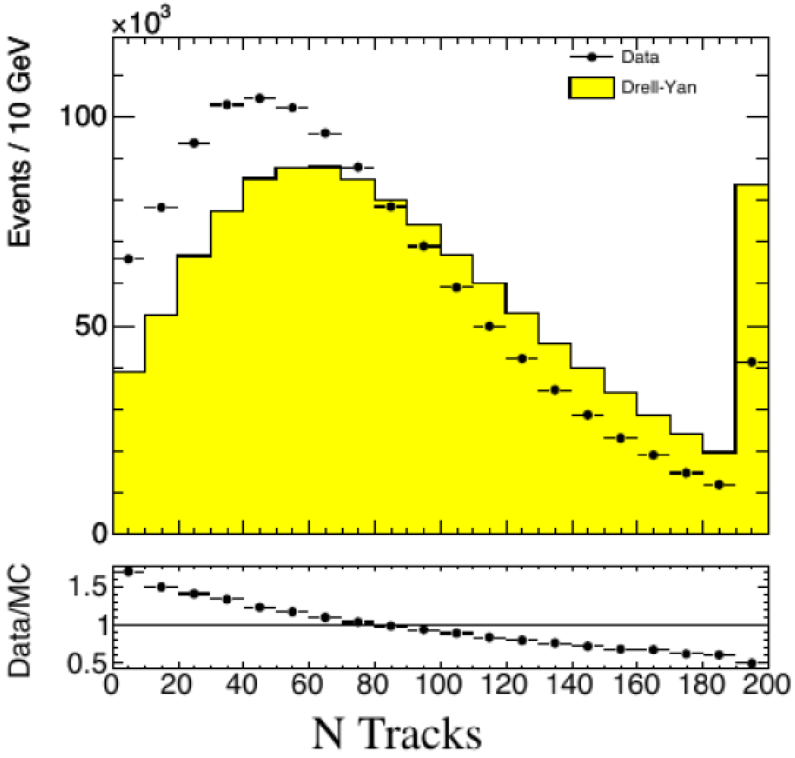


Data and simulation agreements

T. LeCompte (ANL)

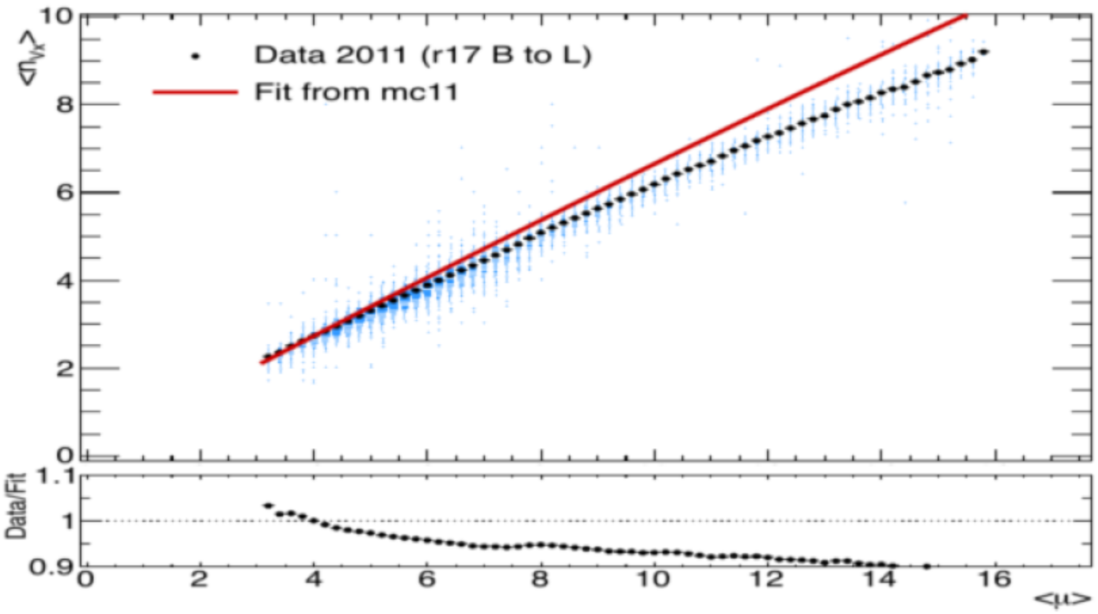
# It doesn’t always work

## Number of tracks (ATLAS)



# Re-weighting effect of pile-up

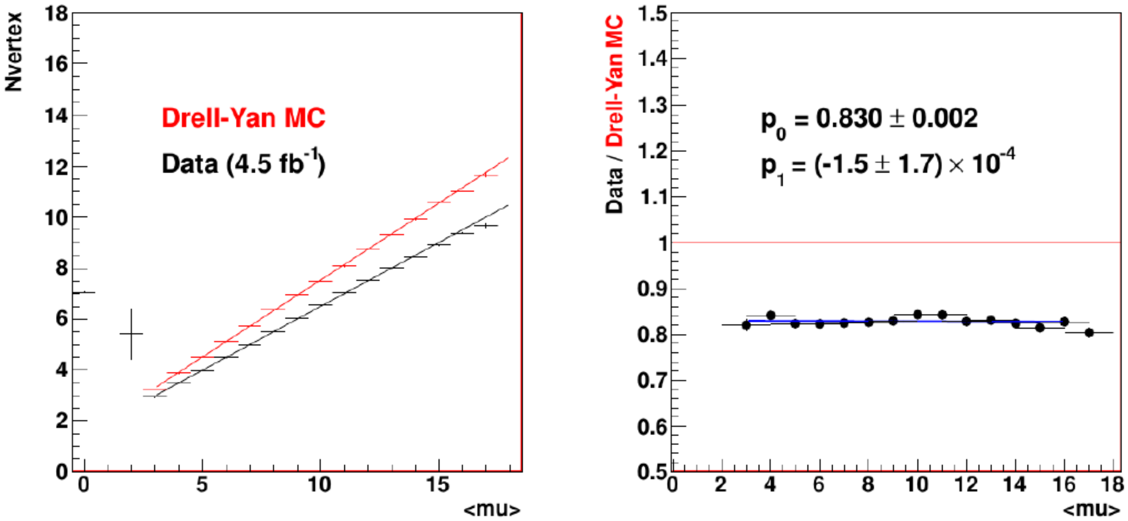
N vertices Vs average N interactions per bunch crossing



- Classic *ATLAS* example of MC not describing data accurately
- This shows that the MC gets the number of vertices wrong
  - Problem simulating proton bunches with $10^{11}$ protons
  - Understandably a very difficult task!
- Unfortunately this has big effects for many distributions

# Re-weighting the MC

## Need to determine re-weighting factors



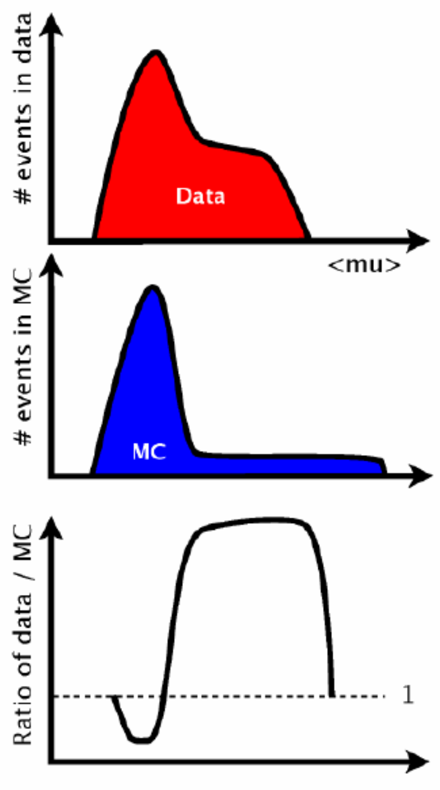
(a) Data-MC comparison

(b) Fit of the ratio of the distributions in (a)

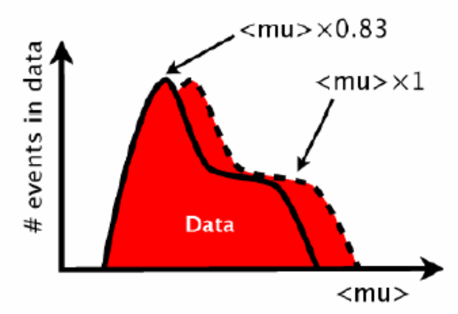
- Divide Data by MC to determine correction
- In this case, fit the ratio and determine a weight
- Use this weight for each MC event
  - histogram → Fill(x, weight);

# Re-weighting the MC

## Illustration of re-weighting procedure



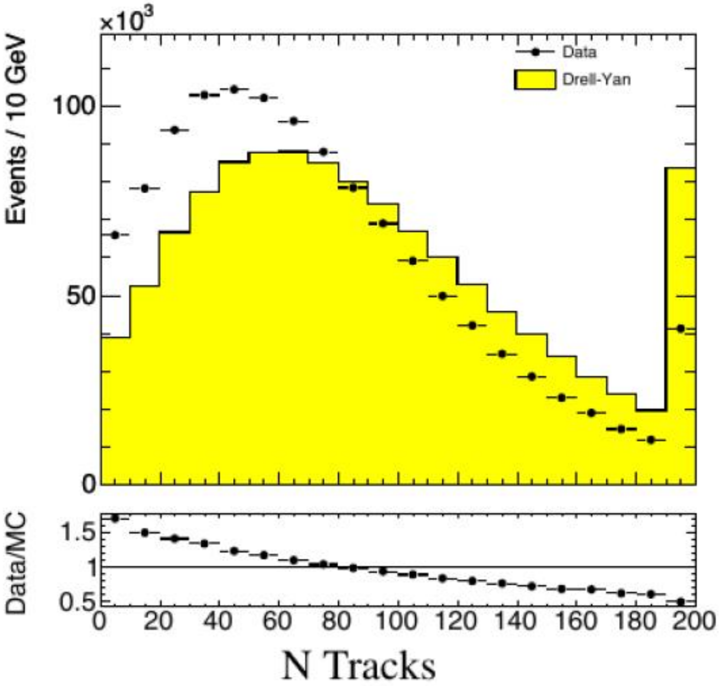
(a) Reweight procedure



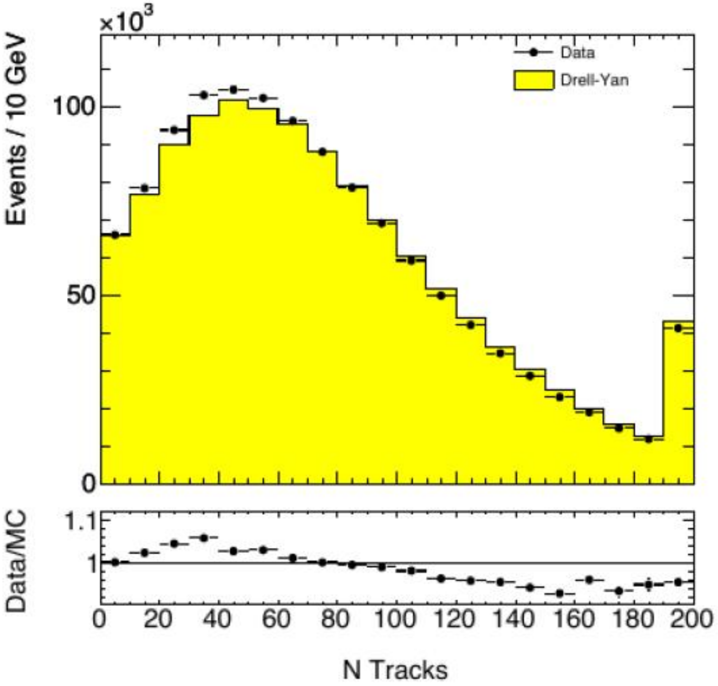
(b) Rescale procedure

Pile-up for instance , is hard to get right, we only know the exact conditions *after* data-taking is over

# After reweighting the agreement is much better
# Main problem is understanding the number of vertices

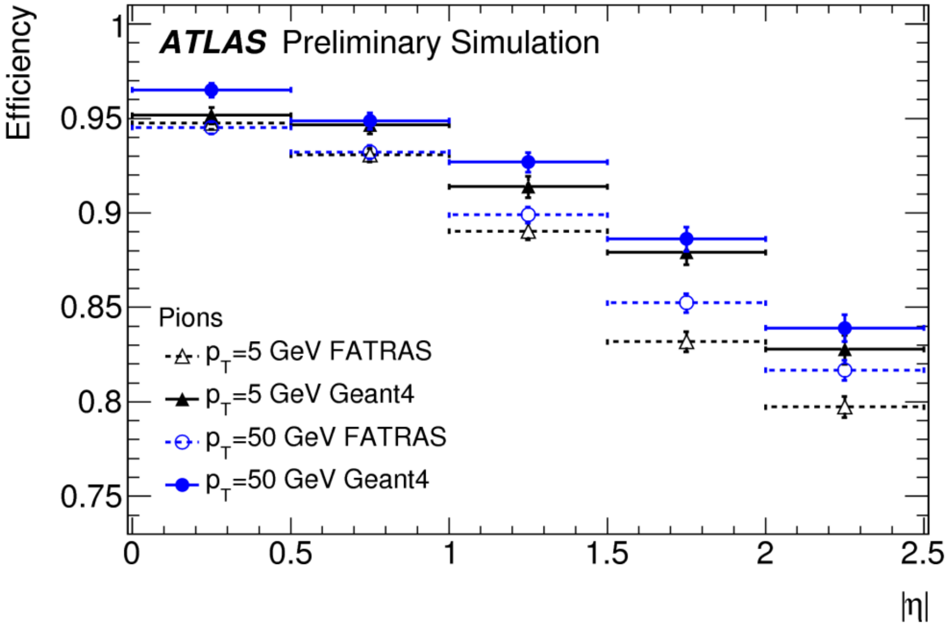


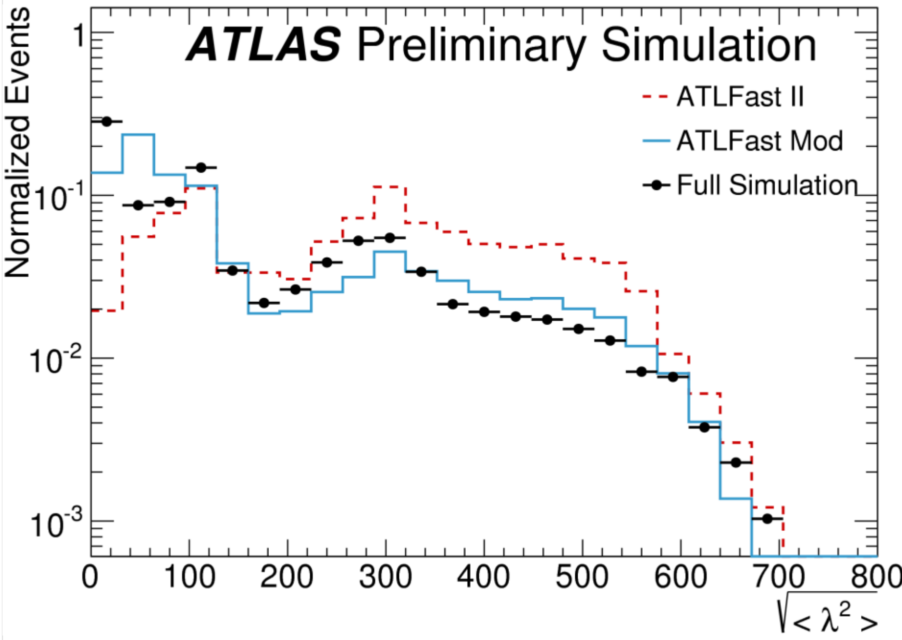
(a) ⟨$\mu$⟩ rescale factor= 1 (no rescale)



(b) ⟨$\mu$⟩ rescale factor= 0.83

# Fast vs full simulation





Although less meticulous, the fast simulation can be easily tuned to GEANT – or to data!

# Summary

- Most processes are impractical or impossible to calculate analytically
  - Therefore we use simulation to prepare for analysis

- Two steps: event generation (the physics process) and detector simulation (interaction with materials + electronics)
  - Several choices when it comes to event generators. Each have the pros and cons
  - Detector simulation = GEANT4 + digitization code
  - PYTHIA is a Lund product. You can try it yourself at: [http://home.thep.lu.se/~torbjorn/Pythia.html](http://home.thep.lu.se/~torbjorn/Pythia.html)

- It works! Many good comparisons between data and MC gives us confidence that we should notice the first non-SM physics!