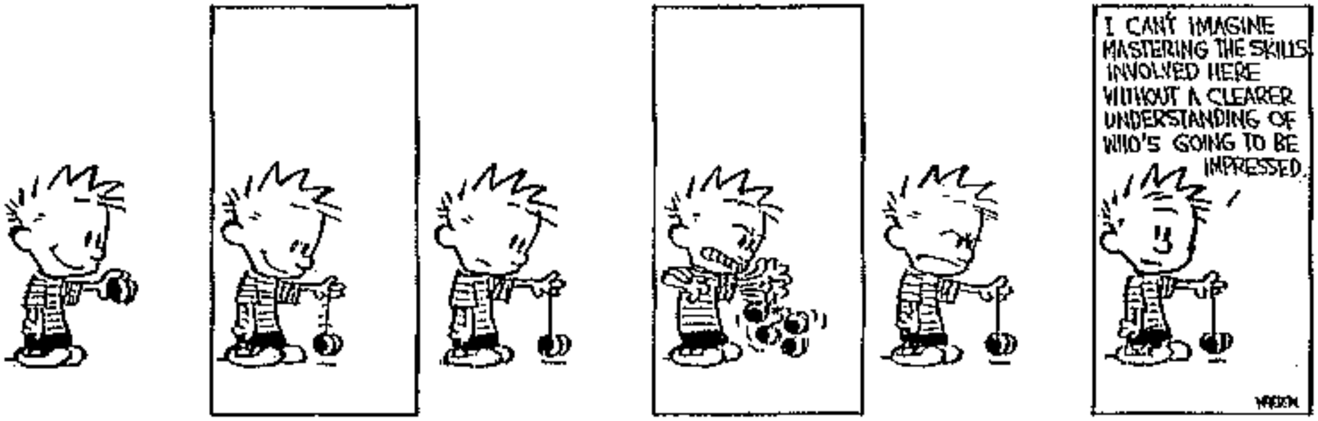
From Raw Data to Physics: Reconstruction and Analysis

Reconstruction: Tracking

Analysis: Measuring a lifetime



Why does tracking need to be done well?

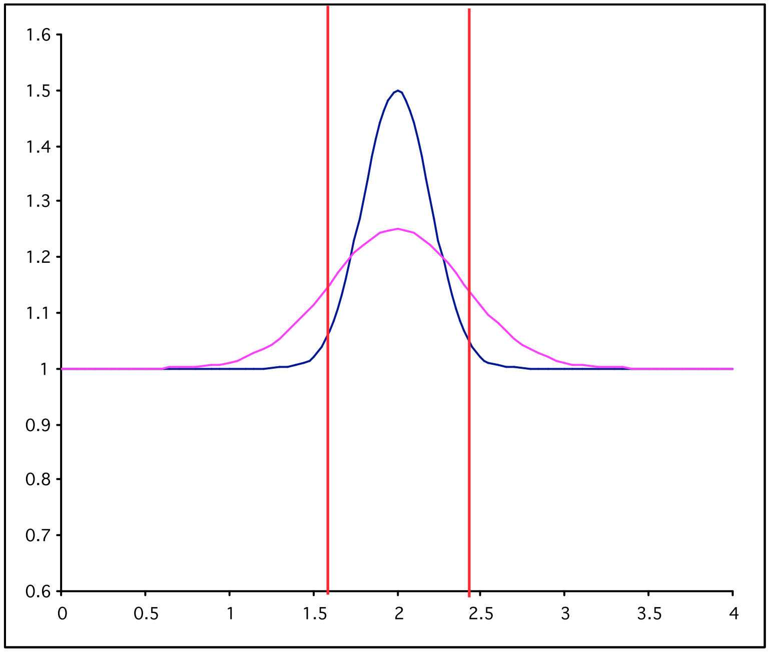
1) Tells you particles were created in an event

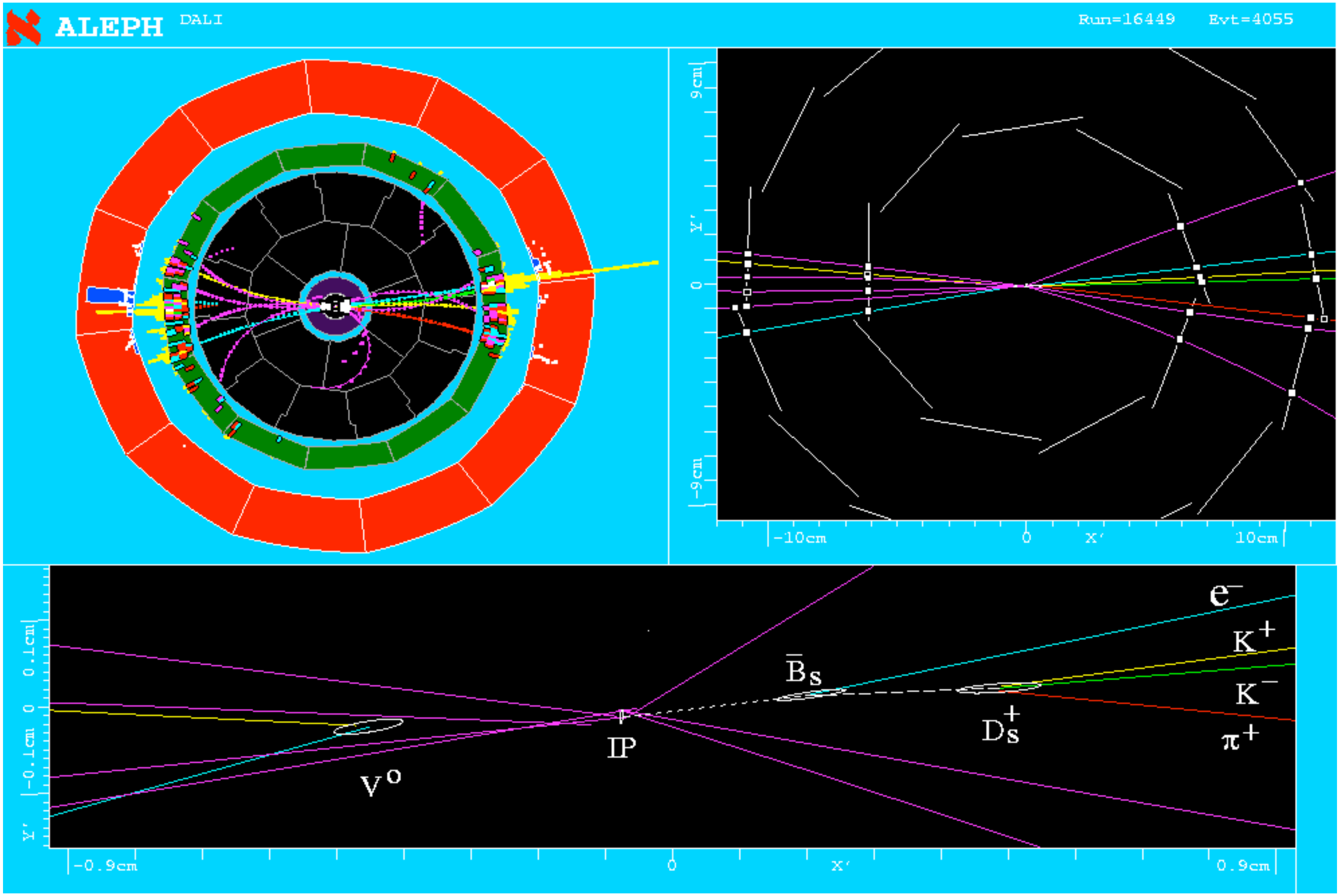
2) Allows you to measure their momentum

- Direction and magnitude
- Combine these to look for decays with known masses
- Only final particles are visible!

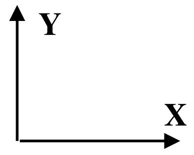
3) Allows you to measure spatial trajectories

- Combine to look for separated vertices, indicating particles with long lifetimes




ALEPH
DALI
Run=16449
Evt=4055
9cm
Y'
0
-9cm
-10cm
0
X'
10cm
e⁻
K⁺
K⁻
π⁺
B̄s
Ds⁺
IP
V⁰
0.1cm
0
-0.1cm
Y'
-0.9cm
0
X'
0.9cm

Track Fitting



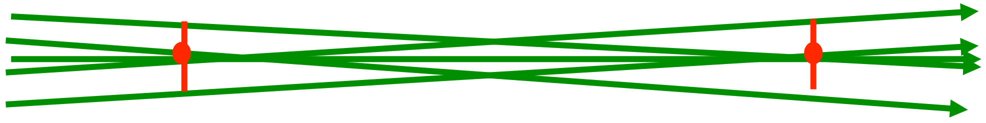
1D straight line as simple case

Two perfect hits

- Away from interaction point
- With no measurement uncertainty
- Just draw a line through them and extrapolate

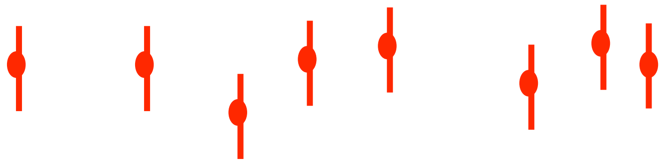
Imperfect measurements give less precise results

- The farther you go, the less you know



Smaller errors, more points help constrain the possibilities

How to find the best track from a large set of points?



How to fit quantitatively?

Parameterize track: $y(x) = \theta x + d$

- Two measurements, two parameters => OK

Best track?

- Consistency with measurements represented by $\chi^2 = \sum_{i=1}^{n_{hits}} \frac{\left(y_i - y(x_i)\right)^2}{\sigma_i^2}$

  Sum of normalized errors squared

Position of i^{th} hit

Predicted track position at i^{th} hit

Accuracy of measurement

- This is directly a function of our parameters:

$$\chi^2 = \sum_{i=1}^{n_{hits}} \frac{\left(y_i - \theta x_i - d\right)^2}{\sigma_i^2}$$

- The best track has the smallest normalized error
- So minimize in the usual way:

$$\frac{\partial \chi^2}{\partial \theta} = 0 \qquad \frac{\partial \chi^2}{\partial d} = 0$$

$$\frac{\partial \chi^2}{\partial \theta} = 2\sum \frac{\left(y_i - \theta x_i - d\right)}{\sigma_i^2}\left(-x_i\right)$$

$$0 = \left(\sum \frac{y_i x_i}{\sigma_i^2}\right) - \left(\sum \frac{x_i}{\sigma_i^2}\right) d - \left(\sum \frac{x_i^2}{\sigma_i^2}\right)\theta$$

$$\frac{\partial \chi^2}{\partial d} = 2\sum \frac{\left(y_i - \theta x_i - d\right)}{\sigma_i^2}(-1)$$

$$0 = \left(\sum \frac{y_i}{\sigma_i^2}\right) - \left(\sum \frac{1}{\sigma_i^2}\right) d - \left(\sum \frac{x_i}{\sigma_i^2}\right)\theta$$

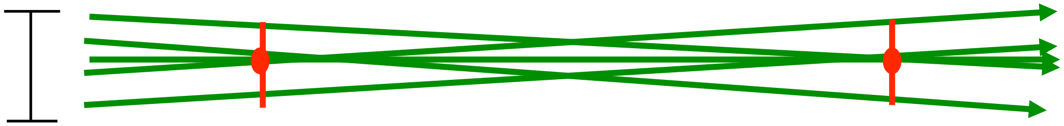
<u>Two</u> equations in <u>two</u> unknowns

- Terms in () are constants calculated from measurement, detector geometry

Generalizes nicely to 3D, helical tracks with 5 parameters

- Five equations in five unknowns

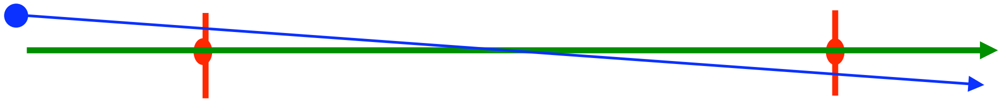
With a little more work, can calculate expected errors on θ, d



“Most likely” that <u>real</u> d (Y intercept) is within this band of $\pm\sigma_d$

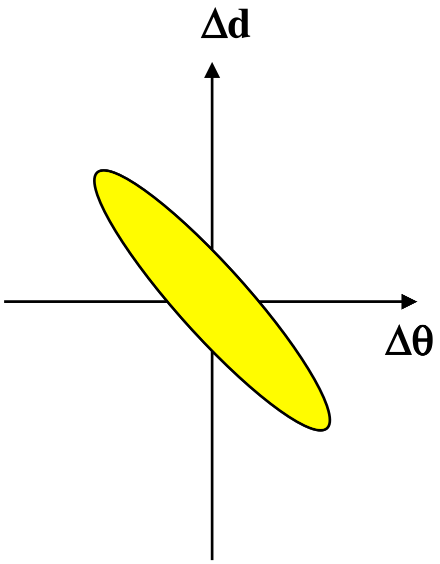
Similar θ error, where θ_{real} is most likely within $\pm\sigma_\theta$ of best value

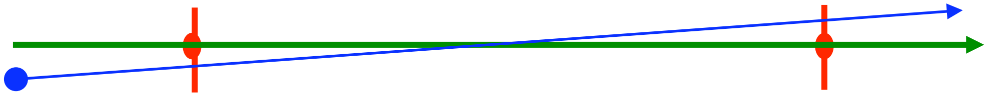
Note that the errors are <u>correlated</u>:



Δd = “+” - $0 > 0$

$\Delta\theta$ = “-” - $0 < 0$

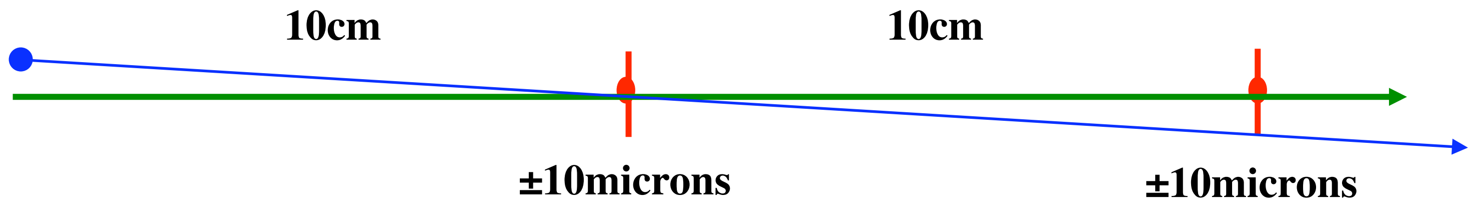




Δd = “-” - $0 < 0$

$\Delta\theta$ = “+” - $0 > 0$

Typical size of errors



Error on position is about ±10 microns

By similar triangles

Error on angle is about ±0.1 milliradians (±0.002 degrees)

Satisfyingly small errors!

Allows separation of tracks that come from different particle decays

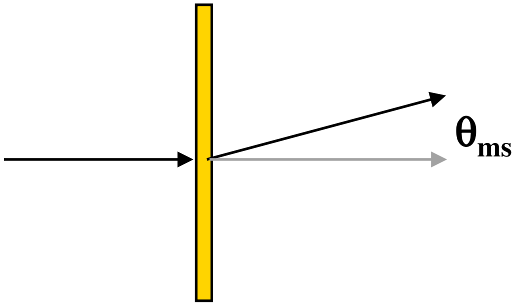
But how to we “see” particles?

- Charged particles pass through matter,
- ionize some atoms, leaving energy
- which we can sense electronically.

More ionization => more signal => more precision

=> more energy loss

Multiple Scattering

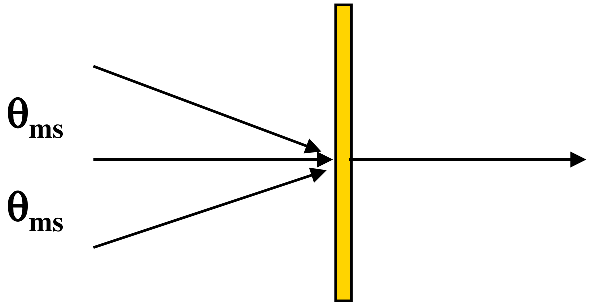


Charged particles passing through matter "scatter" by a random angle

$$\sqrt{\langle \theta_{ms}^2 \rangle} = \frac{15\,MeV/c}{\beta p}\sqrt{\frac{\text{thickness}}{X_{rad}}}$$

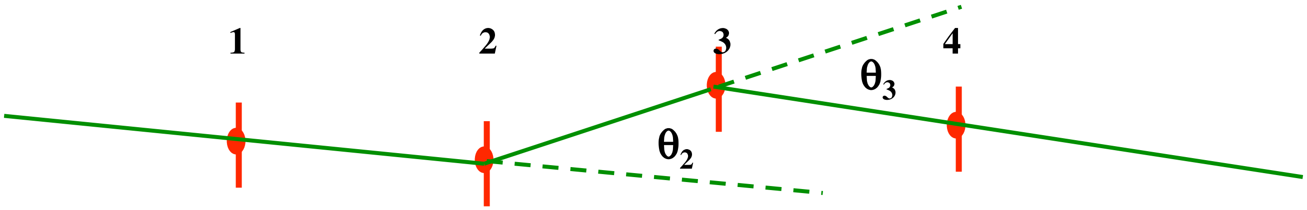
300µ Si   RMS ♠ 0.9 milliradians / βp

1mm Be RMS ♠ 0.8 milliradians / βp



Also leads to position errors

So?



Fitting points 3 & 4 no longer measures angle at IP

Track already scattered by random angles θ_1, θ_2,θ_3

Track has more parameters

$$y(x) = d + \theta x + \theta_1 (x - x_1)\Theta(x - x_1)$$
$$+ \theta_2 (x - x_2)\Theta(x - x_2) + \theta_3 (x - x_3)\Theta(x - x_3) + \ldots$$

1 if $x\text{-}x_3 > 0$, otherwise 0

If we knew θ_1, $\theta_{2,\ldots}$ we'd know entire trajectory

Can we measure those angles?

θ_2 roughly given by y_1, y_2, y_3

Just a more complex χ^2 equation?

$\sqrt{\langle \theta_{ms}^2 \rangle}$ **acts like a measurement**

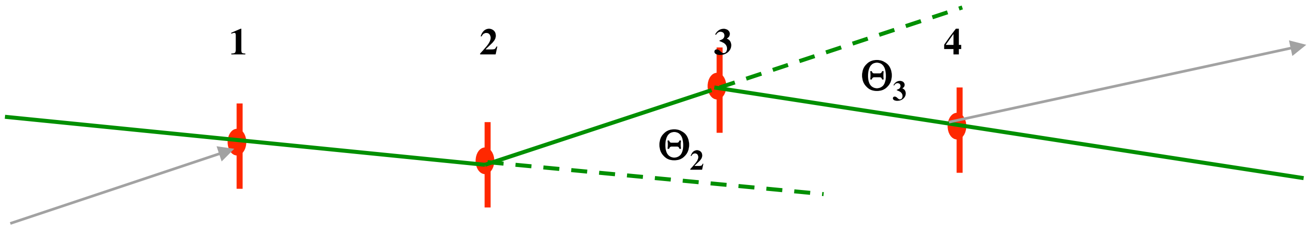
"I'd be surprised if it was larger than $0 \pm \frac{15 MeV/c}{\beta p} \sqrt{\frac{L}{X_{rad}}}$

"Add information" to fit by adding new terms to χ^2

$$\chi^2 = \chi_{old}^2 + \sum_i \frac{\theta_i^2}{\sigma_{ms}^2}$$

N measurements from planes (say 100)

N+2 unknowns (d, θ, plus N scattering angles)



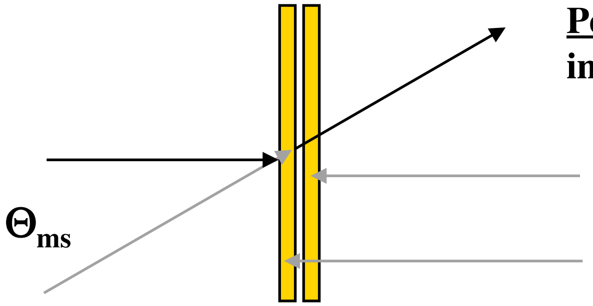
Can't see first, last scattering angles; can only extrapolate outside

Hence ignore θ_1, θ_N

Now all we have to do is solve 100 equations in 100 unknowns...

Nobody cares about θ_N

But θ_1 effects accuracy of d



Θ_{ms}

<u>Perfect</u> measurement out here in tracking chamber

300 μ Si plane

1 mm Be pipe

θ_{ms} => 1.2 milliradian/βp error on θ

@10 cm, leads to 120μ/βp error on d

$$\sigma_d \approx 10\mu \oplus \frac{120\mu}{\beta p}$$

In spite of

- N=100 chambers,
- complicated programs
- and inverting 100x100 matrices

“Kalman fit”?

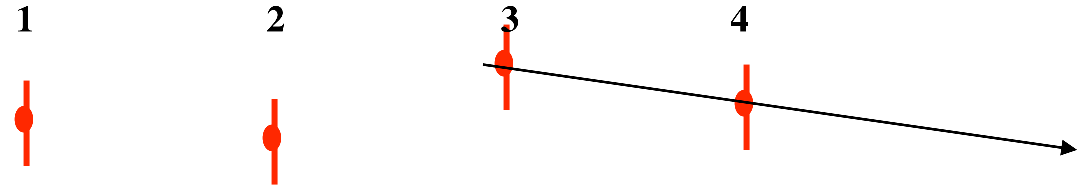
(ref: Brillion)

Computational expensive to calculate solutions with 100 angles

Computer time grows like O(N^3), with N large

And we’re not really interested in all those angles anyway

Instead, approximate, working inward N times:



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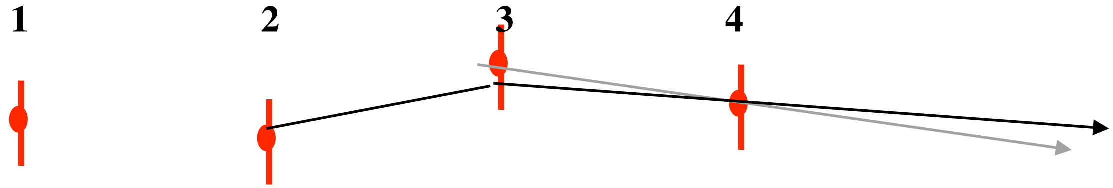

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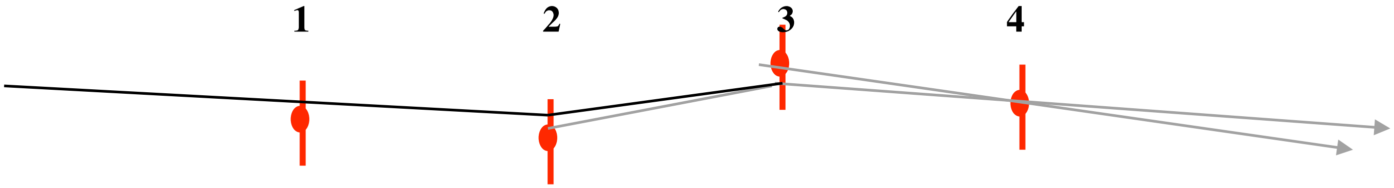


This is O(N) computations

May need to repeat once or twice to use good starting estimate

Each one a little more complex

But still results in a large net savings of CPU time

Moral: Consider what you <u>really</u> want to know

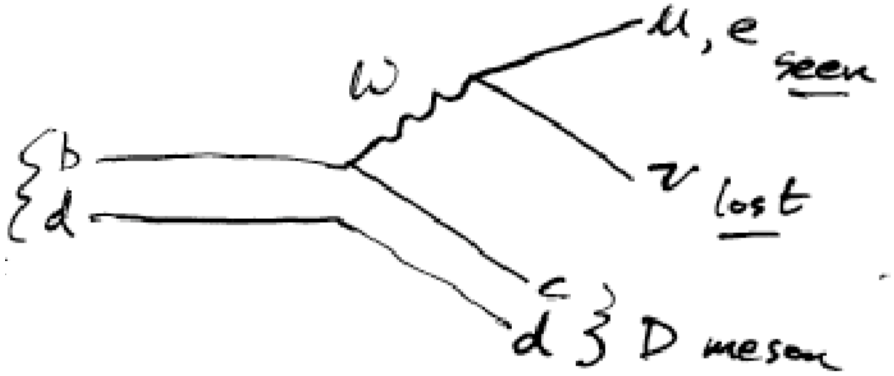
Analysis: Lifetime measurement

Why bother?

Standard model contains 18 parameters, a priori unknown

Particle lifetimes can be written in terms of those

$$\Gamma_Q^{sl} = \Gamma(Q \rightarrow q l v) = \frac{G_F^2}{192\pi^3} m_Q^5 f \left|V_{Qq}\right|^2$$

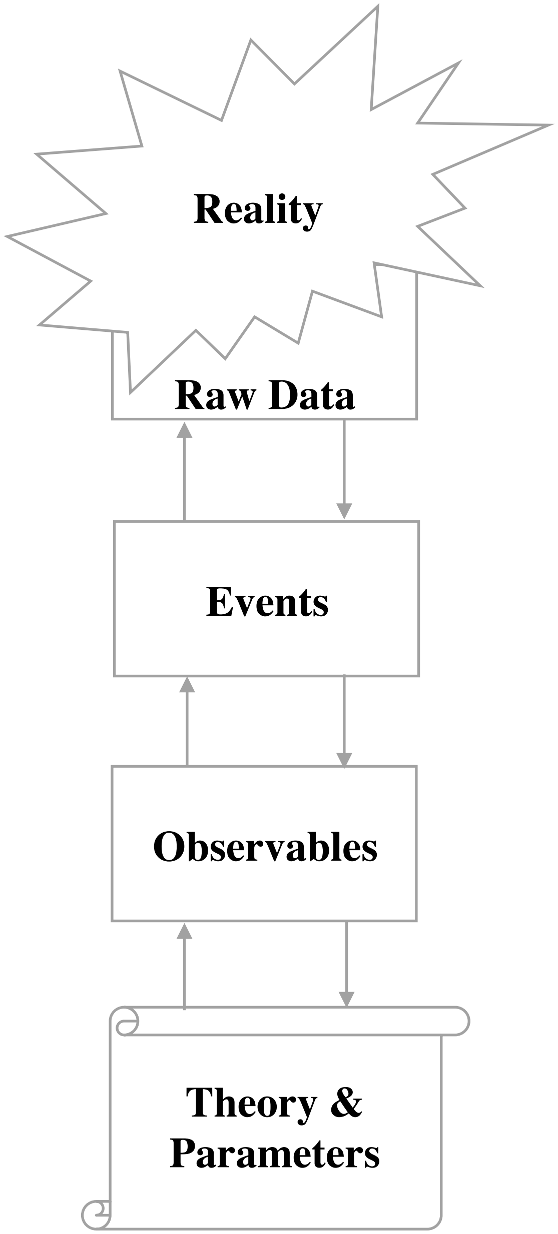


“Measure once to determine a parameter

Measure in another form to check the theory”

Measure lots of processes to check overall consistency

A model of how physics is done.



Reality

Raw Data

Events

Observables

Theory & Parameters

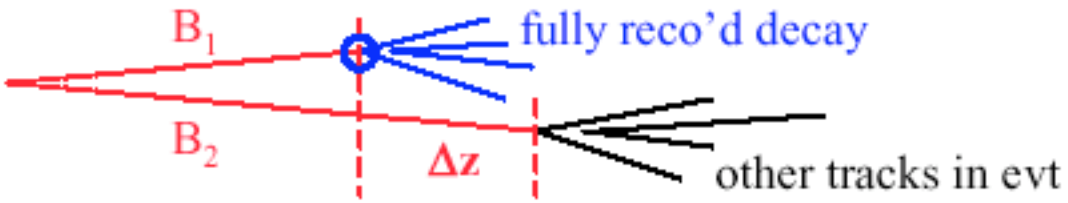
**The imperfect measurement of
a (set of) interactions in the detector**

**A unique happening:
Run 21007, event 3916 which
contains a J/psi -> ee decay**

**Specific lifetimes, probabilities, masses,
branching ratios, interactions, etc**

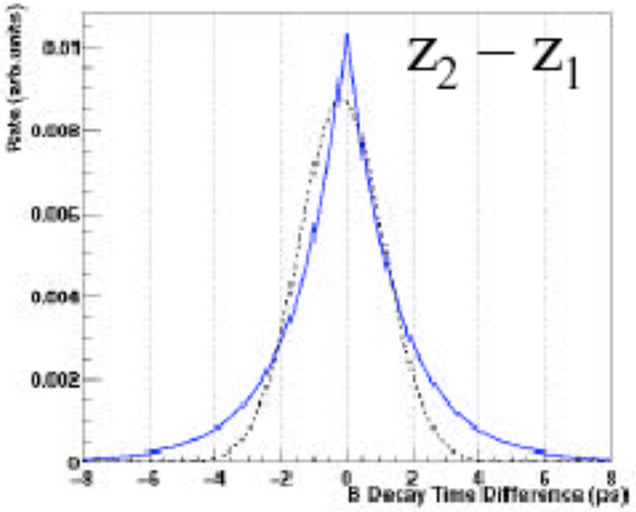
**A small number of general equations, with specific
input parameters (perhaps poorly known)**

B lifetime: What we measure at BaBar:



$$\boxed{dN \propto \exp(-|\Delta z| / \beta_z \gamma c\, \tau_B)}$$

Unfortunately, we can't measure Δz perfectly:



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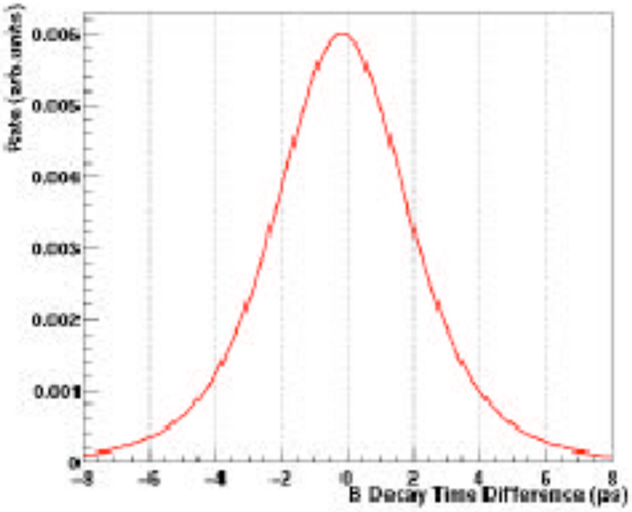


First, you have to find the B vertex

To reconstruct a B, you need to look for a specific decay mode

(Un)fortunately, there are lots!

B0-> D*+ pi-
D*+ rho-
D*+ a1-
D+ pi-
D+ rho-
D+ a1-
J/Psi K*0bar

Each involves additional long-lived particles, which have to be searched for:

D*+ -> D0 pi+
D*0 -> D0 pi0

D0 -> K- pi+, K- pi+ pi0,
K- pi+ pi- pi+, K0S pi+ pi-

D+ -> K- pi+ pi+, K0S pi+

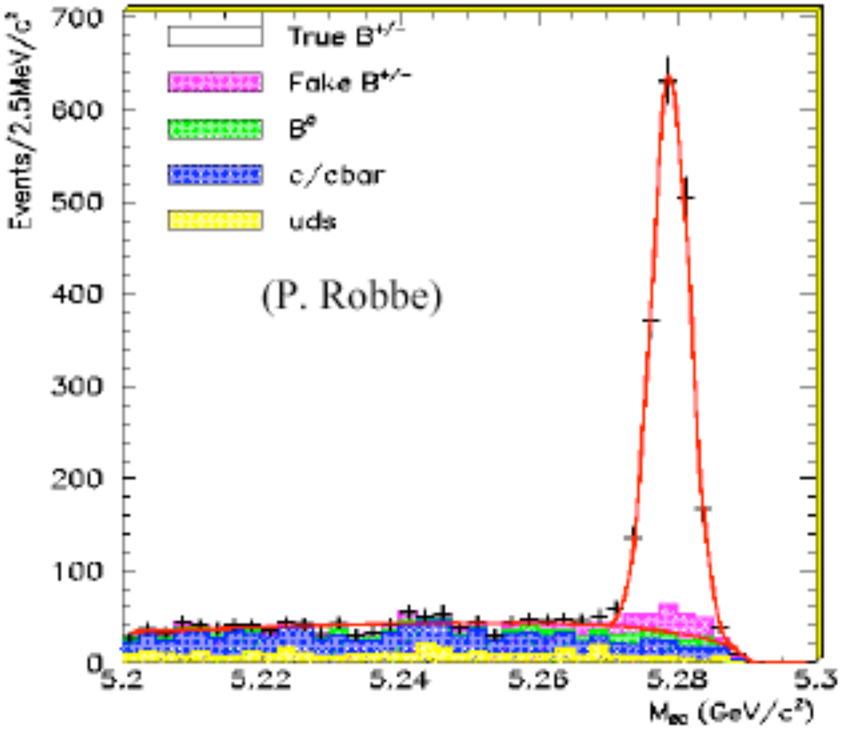
K0S -> pi+ pi-

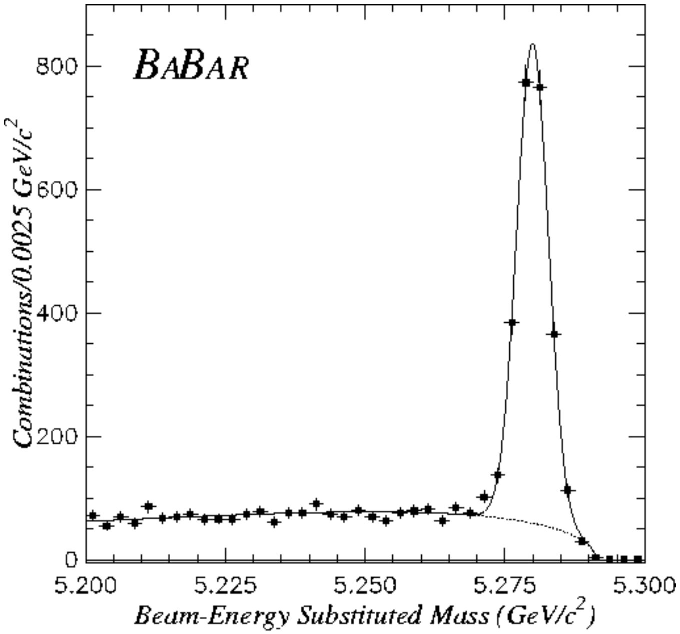
a1- -> rho0(-> pi+ pi-) pi-
rho- -> pi- pi0
pi0 -> gamma gamma

Psi(2S) -> J/Psi pi+ pi-, mu+ mu-, e+ e-
J/Psi -> mu+ mu-, e+ e-

K*0bar -> K- pi+,

And some will be wrong:



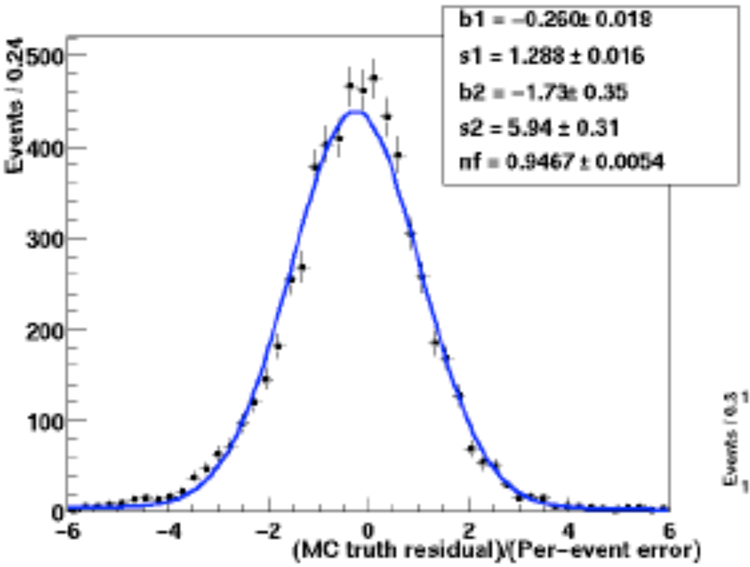


Have to correct for effects of these when calculating the result

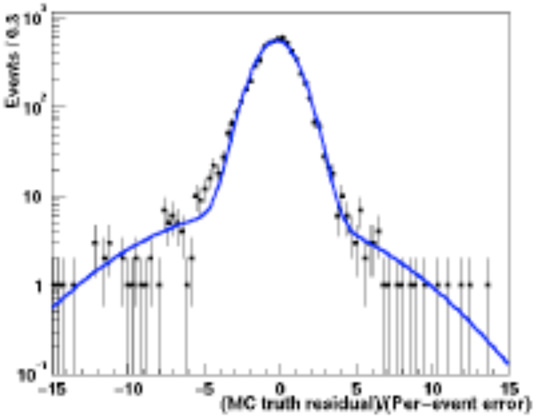
Including a term in systematic error for limited understanding

Next, have to understand the resolution:

Studies of resolution seen in Monte Carlo simulation:



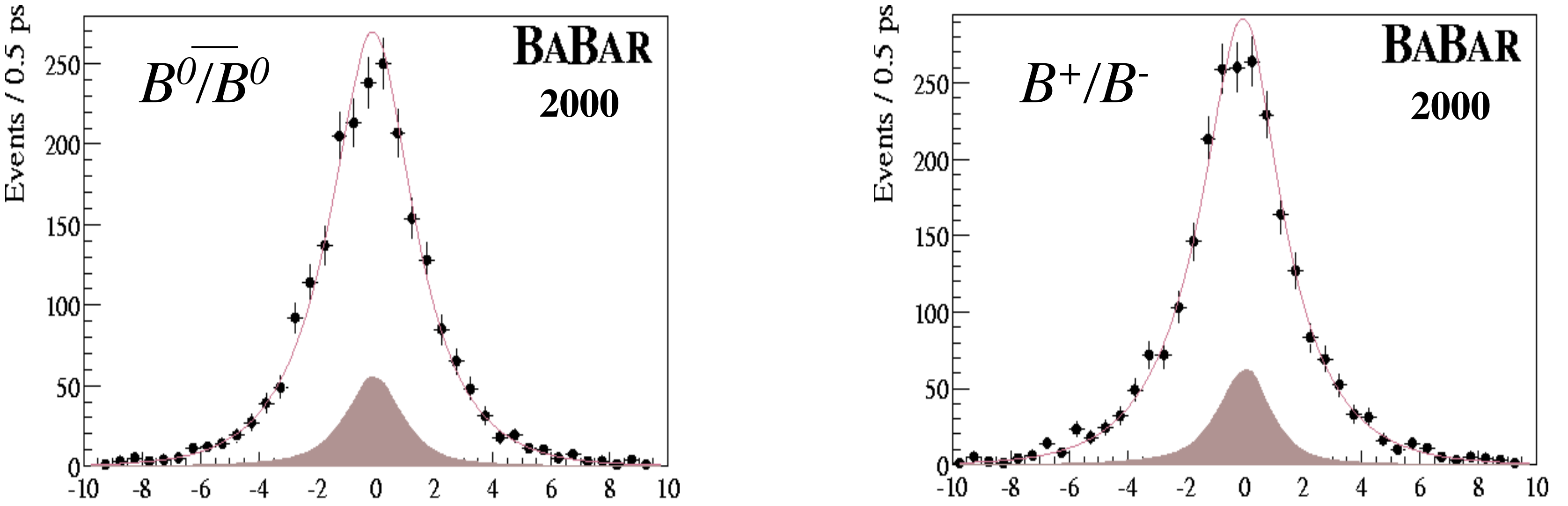
G+G fit to Δt "pulls"
in D*lν signal MC



But how do you know the simulation is right?

- Find ways to compare data and Monte-Carlo predictions
- Watch for bias in your results!

Combined fit to the data gives the lifetime:



$\tau_{B0} = 1.506 \pm 0.052 \text{ (stat)} \pm 0.029 \text{ (syst) ps}$ [PDG= 1.548 ± 0.032]

$\tau_{B+} = 1.602 \pm 0.049 \text{ (stat)} \pm 0.035 \text{ (syst) ps}$ [PDG= 1.653 ± 0.028]

$\tau_{B+}/\ \tau_{B0} = 1.065 \pm 0.044 \text{ (stat)} \pm 0.021 \text{ (syst)}$ [PDG= 1.062 ± 0.029]

Note that systematic errors are not so much smaller than statistical ones:
2001 data reduces the statistical error; only improved understanding reduces systematic

What about the computing behind this?

BaBar records about 30k B events per day

- Hidden in 3 million events recorded/day
- Take data about 340 days per year

'Prompt processing'

- Want data available in several days
- Reconstruction takes about 3 CPU seconds/evt
- Processed multiple times

  E.g. new algorithms, constants, etc

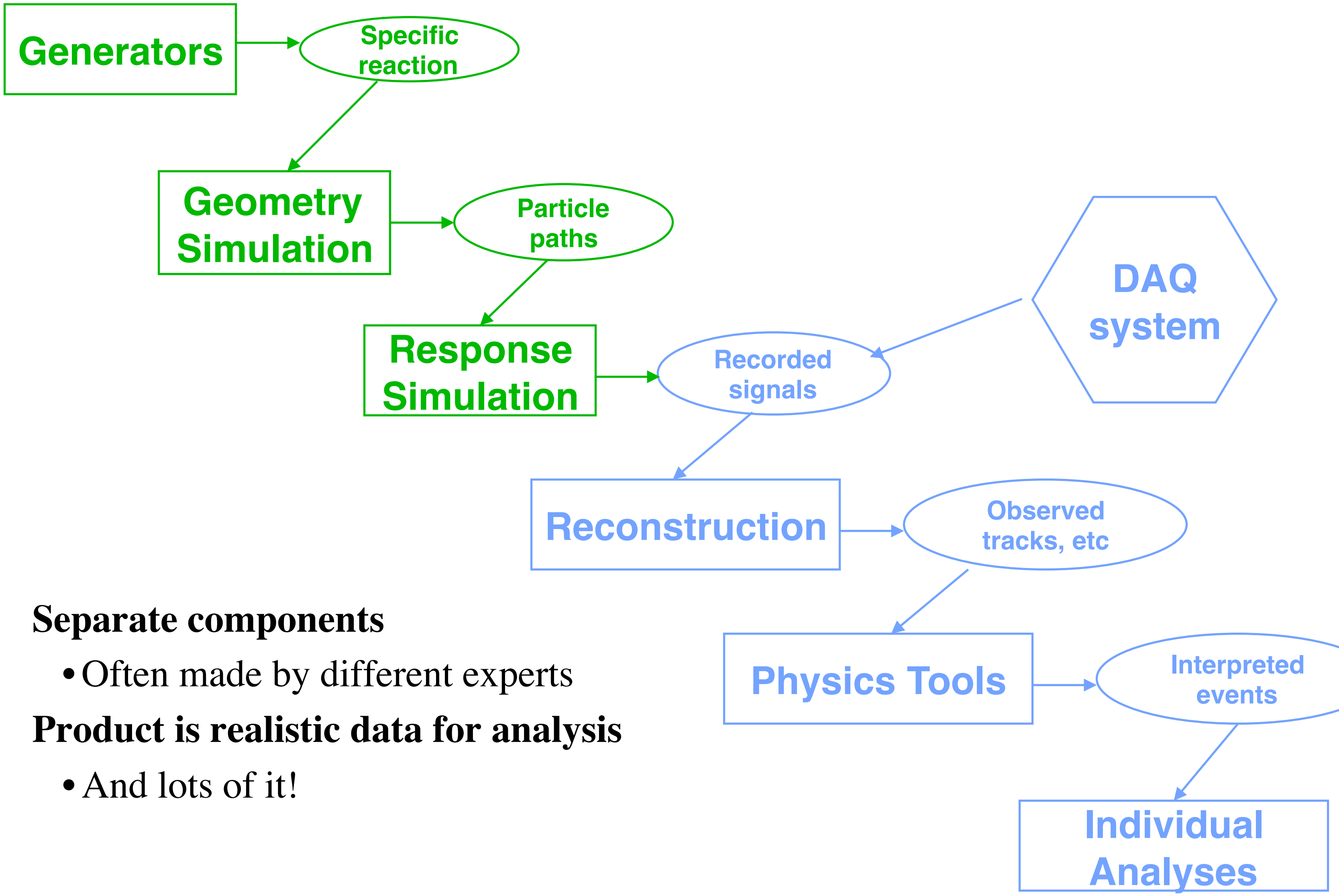
We have about 100 million simulated events to study

- About half in specific decay modes
- Half 'generic' decays to all modes

About 4 million lines of code in simulation and reconstruction programs

- Plus the individual analyses

Traditional flow of data - real and simulated



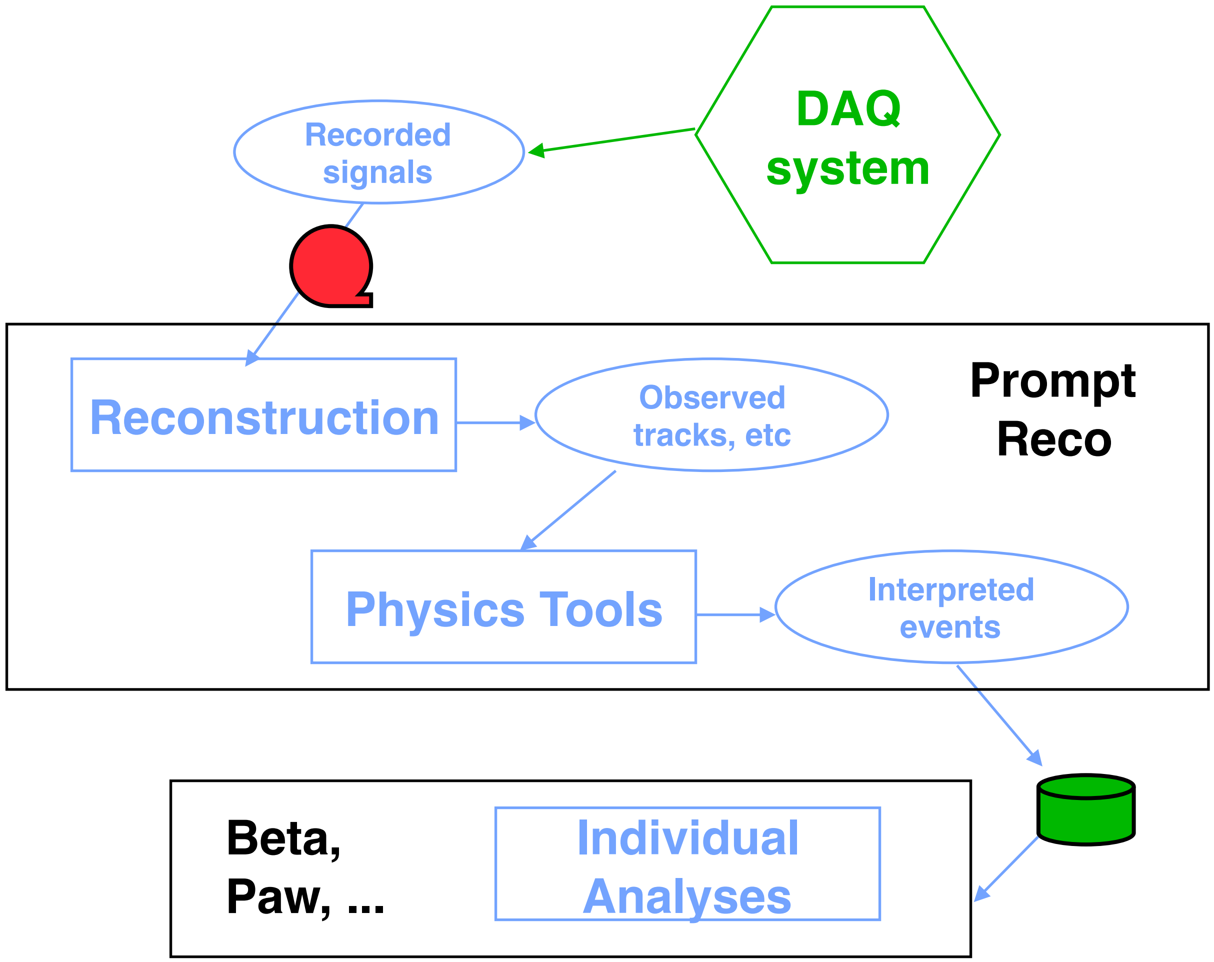
Separate components

- Often made by different experts

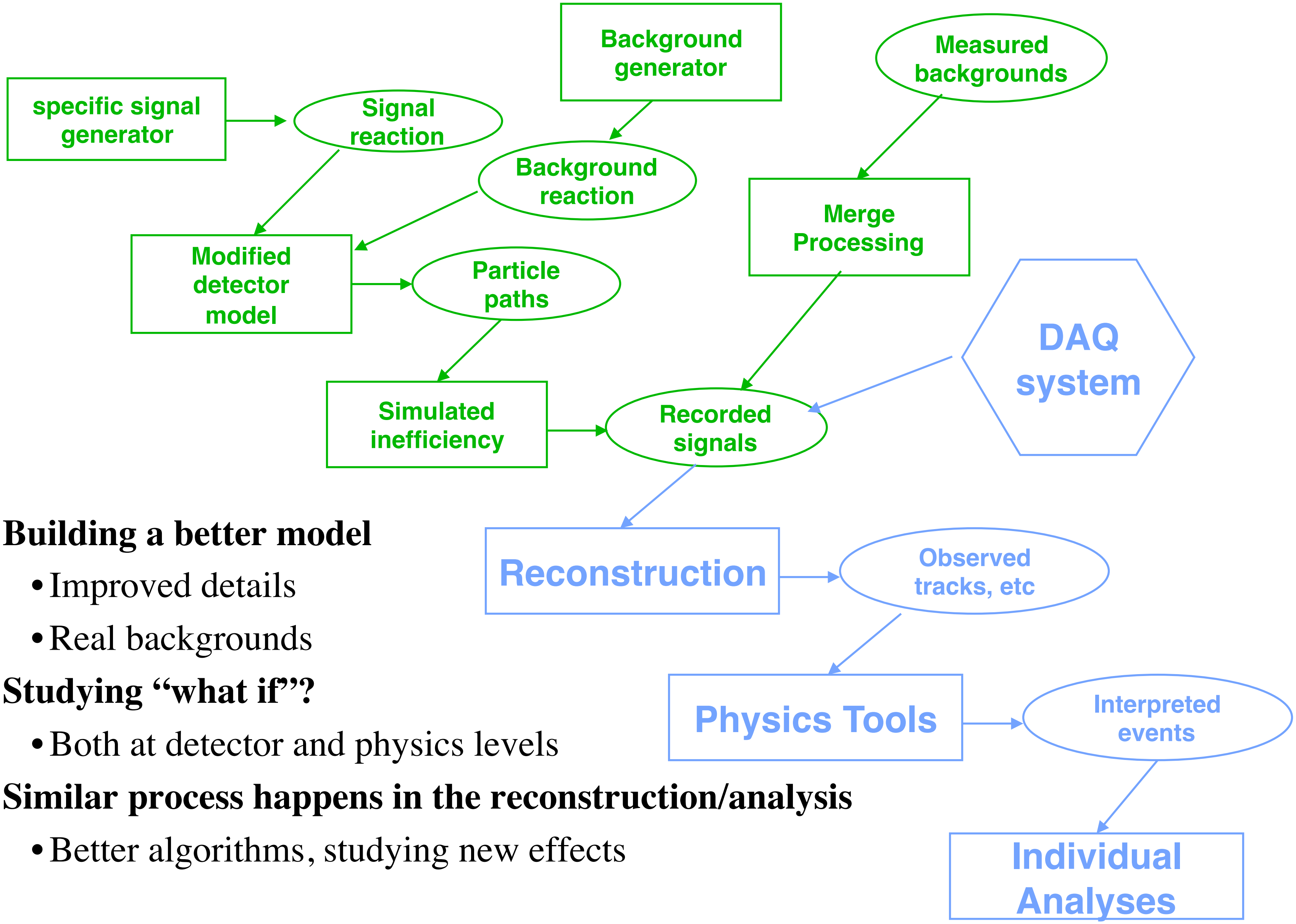
Product is realistic data for analysis

- And lots of it!

Processing real data



More detailed studies via more detailed simulation



specific signal generator

Signal reaction

Background generator

Background reaction

Measured backgrounds

Modified detector model

Particle paths

Merge Processing

Simulated inefficiency

Recorded signals

DAQ system

Reconstruction

Observed tracks, etc

Physics Tools

Interpreted events

Individual Analyses

Building a better model

- Improved details
- Real backgrounds

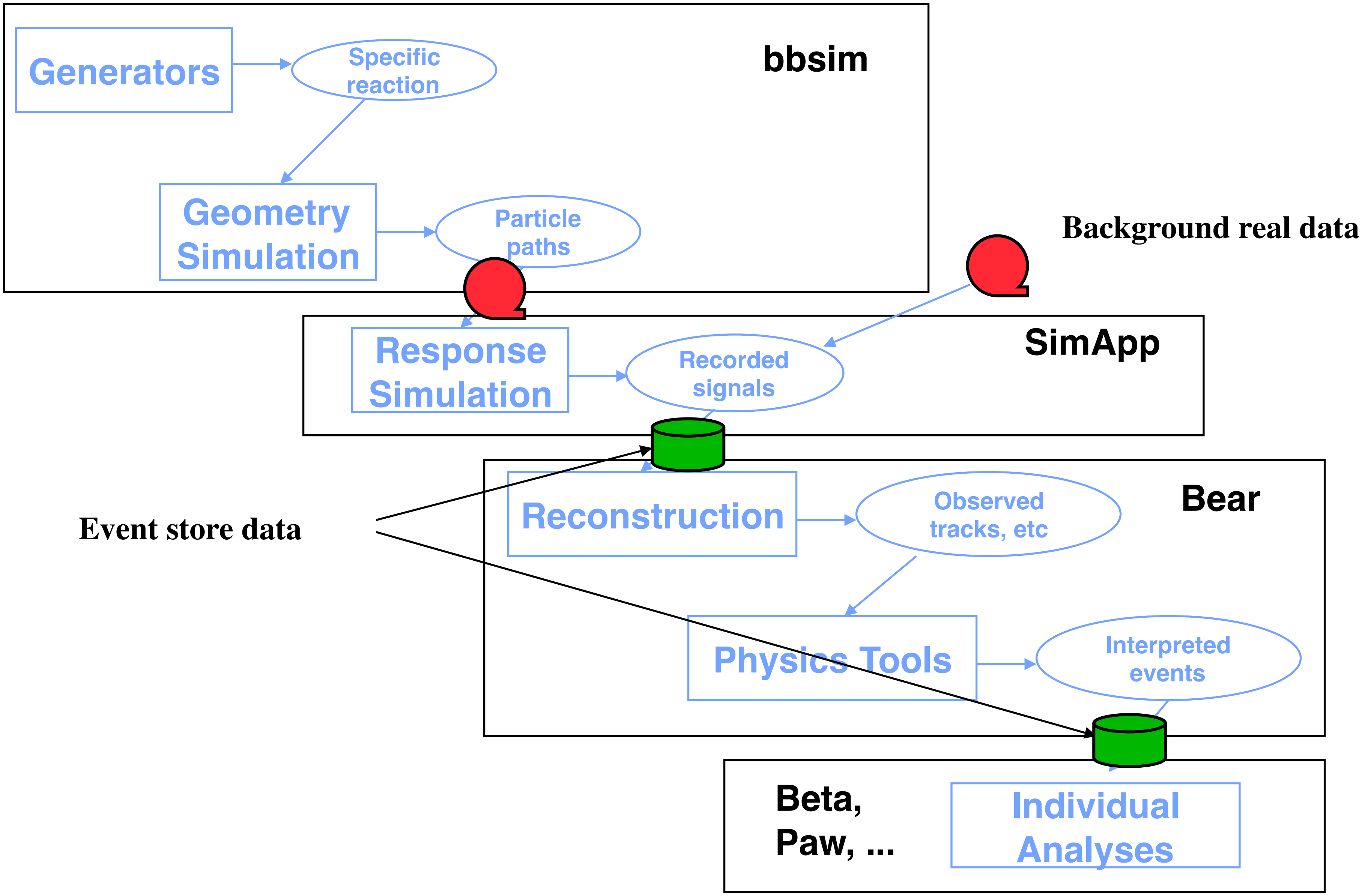
Studying “what if”?

- Both at detector and physics levels

Similar process happens in the reconstruction/analysis

- Better algorithms, studying new effects

Partitioning production system into programs



bbsim

Generators

Specific reaction

Geometry Simulation

Particle paths

Background real data

SimApp

Response Simulation

Recorded signals

Event store data

Bear

Reconstruction

Observed tracks, etc

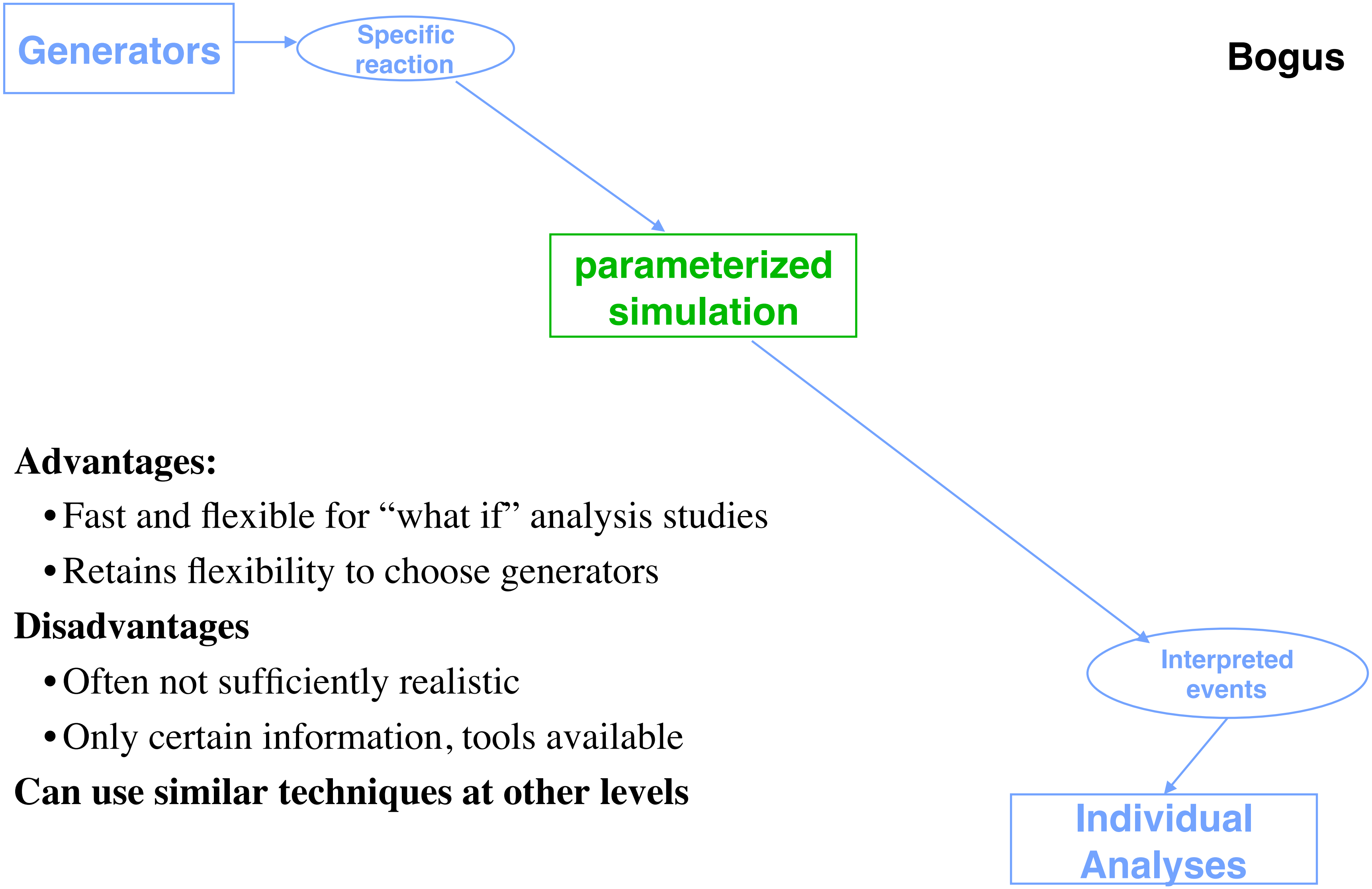
Physics Tools

Interpreted events

Beta, Paw, ...

Individual Analyses

Speed, simplify simulation by crossing levels



Generators

Specific reaction

Bogus

parameterized simulation

Interpreted events

Individual Analyses

Advantages:

- Fast and flexible for “what if” analysis studies
- Retains flexibility to choose generators

Disadvantages

- Often not sufficiently realistic
- Only certain information, tools available

Can use similar techniques at other levels

Why do we do this?

Detailed simulations are part of HEP physics

- Simulations are present from the beginning of an experiment
  - Simple estimates needed for making detector design choices
- We build them up over time
  - Adding/removing details as we go along
- We use them in many different ways
  - Detector performance studies
  - Providing efficiency, purity values for analysis
  - Looking for unexpected effects, backgrounds

Why do we use such a structure?

- Flexibility - we have different versions of the pieces
  - Comparison forms an important cross check
- Efficiency
  - We build up collections of data at each step for repeated study
  - "I found this background effect in the Spring dataset…"
- Manageability
  - Large programs are hard to build, understand, use

Day 2 summary:

Track fitting as a sample reconstruction problem

- How to make "oh, just draw a line" more quantitative
- How realities of detector, computation effect solution

B lifetime as a sample analysis

- What it tells you
- What you need to know to make the measurement
- The roles of real and simulated data

Offline computing

- Why it's not trivial
- A typical system organization

Tomorrow:

- How we try to tell particles apart
- What to do when theory isn't precise
- Summary