# Whirlwind tour of Monte Carlo simulation for particle physics

Presented by Jackie Brosamer

(most slides by Zach Marshall)
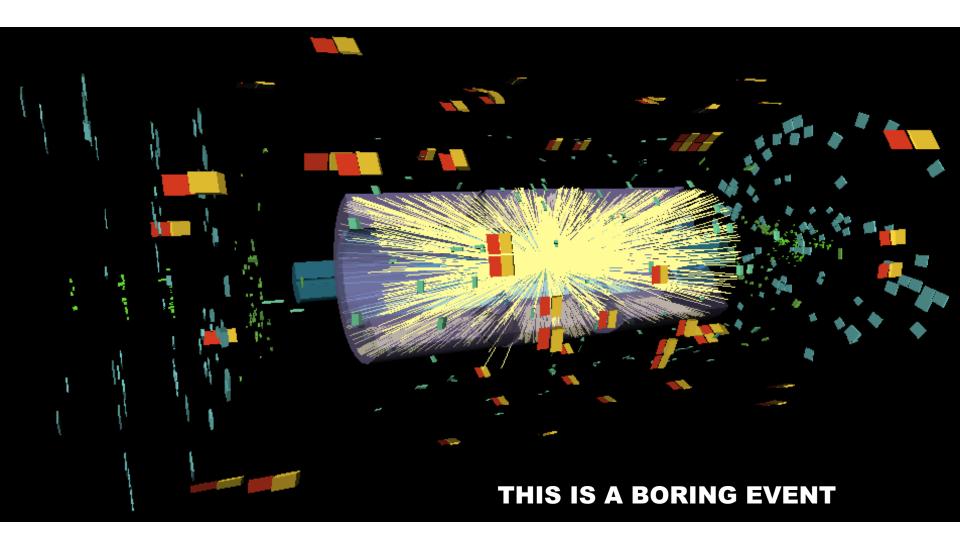
Physics 290E

March 9, 2016

# Outline and Disclaimers

- I'm going to try to tell you how to write a simulation from scratch

  - We'll spend few words about how to use the data you measure to improve your simulation ("tuning") at the end

- I'm about to blitz through about 15 different topics that usually each get their own workshops. **STOP ME** if you have questions, please.

- For obvious reasons, this talk is going to be *super* biased towards the LHC and ATLAS. But I can try to answer questions about other problems as well!

# Why Simulate Anything

- We can (usually) only build one detector
  - What will we miss because of our detector design?
  - How would a slightly different detector affect things?
  - How will the detector stand up to radiation damage?

- Most detectors only measure voltages, currents, and times
  - It's an *interpretation* to say that such-and-such a particle caused such-and-such a signature in the detector
  - We can use simulation to correct our observables and understand our (in)efficiencies

- There is only one right answer in nature
  - What would new physics look like in our detector?
  - Could we find it under realistic conditions?
  - What are the biggest problems, and how do we ease them?

- A good simulation is the way to demonstrate to the world that you understand your detector and the physics you are studying
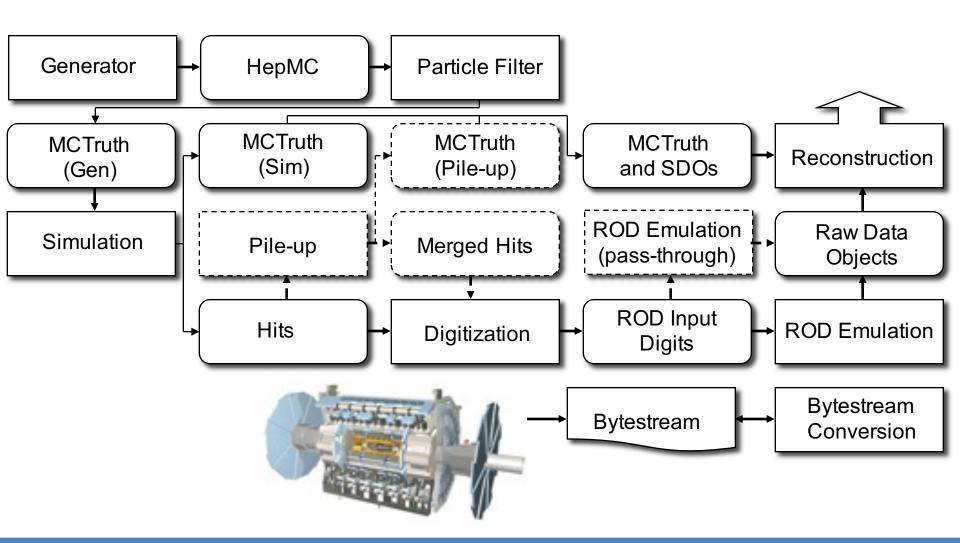
# Write Me a Simulation for This:



**THIS IS A BORING EVENT**

# Simulation Basics

1. Break the problem up as much as possible
   - Do you understand *all the steps* of the system?
2. For each piece of the problem, write some code
   - Did you remember *all the effects* for each step?
3. Spend enough time on each piece that you get the *accuracy that you need* out of them
   - Not a moment longer!!
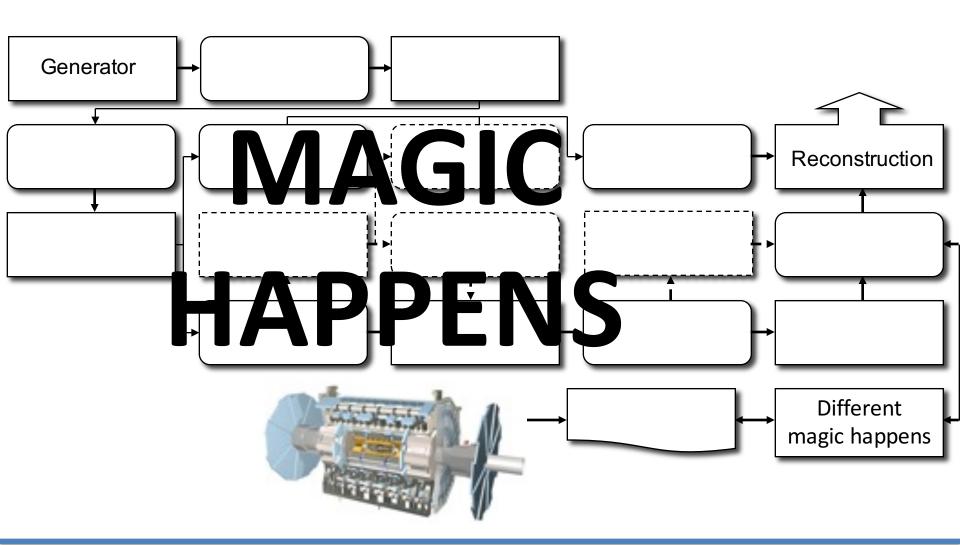4. Cross your fingers and press the button

**How does this look at the LHC?**
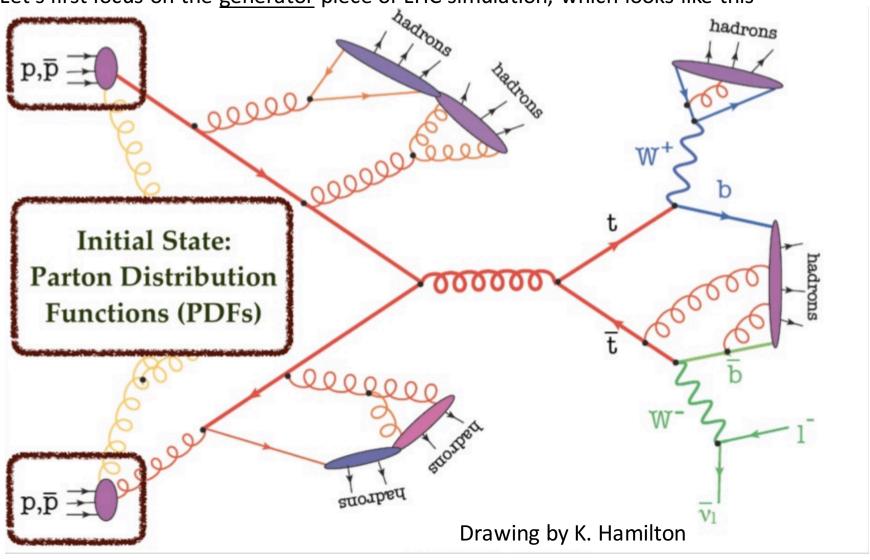
# Our LHC Simulation: The Dream

```
Generator → HepMC → Particle Filter

MCTruth (Gen)   MCTruth (Sim)   MCTruth (Pile-up)   MCTruth and SDOs   Reconstruction

Simulation   Pile-up   Merged Hits   ROD Emulation (pass-through)   Raw Data Objects

Hits → Digitization → ROD Input Digits → ROD Emulation

Bytestream ↔ Bytestream Conversion
```

# Our LHC Simulation: The Reality?

This is most people's view of the situation



Generator

MAGIC HAPPENS

Reconstruction

Different magic happens

# MC event generation

Let's first focus on the <u>generator</u> piece of LHC simulation, which looks like this



Drawing by K. Hamilton

Before we talk about simulating QCD

# PROLOGUE: QCD REVIEW

# QCD=SU(3) [nonabelian] gauge theory

SU(3)

$$\mathcal{L} = \bar{q}_\alpha^{a,j} [ i \gamma_{\alpha\beta}^\mu (\delta_{ab} \partial_\mu + i g_s t_{ab}^r g_\mu^r) - m_j \delta_{ab} \delta_{\alpha\beta}] q_\beta^{b,j} - \frac{1}{4} F_{\mu\nu}^r F^{r,\mu\nu}$$

spin ½ quarks                    spin 1 gluons

$$\alpha, \beta, \ldots = \qquad 1, 2, 3, 4 \qquad \text{Dirac index}$$
$$\mu, \nu, \ldots = \qquad 1, 2, 3, 4 \qquad \text{space time index}$$
$$a, b, \ldots = \quad 1, \ldots, N_C = 3 \quad \text{quark color index} \Bigr\}$$
$$r, s, \ldots = 1, \ldots, N_C^2 - 1 = 8 \quad \text{gluon color index} \Bigr\}\ \text{SU(3)}$$
$$= N_A$$
$$j, k, \ldots = \qquad 1, \ldots, N_F \qquad \text{flavor index}.$$

$$\alpha_s = \frac{g_s^2}{4\pi}$$

coupling constant (only free parameter)

From T. Hebbeker

$$F_{\mu\nu}^r = \partial_\mu g_\nu^r - \partial_\nu g_\mu^r - g_s f^{rst} g_\mu^s g_\nu^t.$$
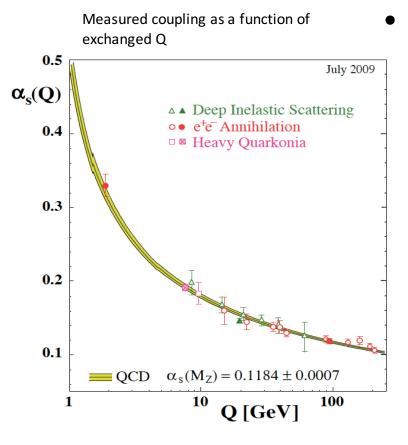
SU(3)

# QCD Feynman diagrams

$$\mathcal{L} = \bar{q}_\alpha^{a,j} [\, i\, \gamma_{\alpha\beta}^\mu \left(\delta_{ab}\, \partial_\mu + i\, g_{\mathrm{s}} t_{ab}^r g_\mu^r\right) - m_j\, \delta_{ab}\, \delta_{\alpha\beta}]\, q_\beta^{b,j} - \frac{1}{4} F_{\mu\nu}^r\, F^{r,\mu\nu}$$

q

q

g

$$|...|^2 \sim \alpha_s\, C_F$$

$$|...|^2 \sim \alpha_s\, C_A$$

$$|...|^2 \sim \alpha_s^2\, C_A^2$$

$$C_A = N_C = 3 \qquad C_F = \frac{1}{2} \cdot \frac{N_A}{N_C} = \frac{4}{3}$$

From T. Hebbeker

$$F_{\mu\nu}^r = \partial_\mu g_\nu^r - \partial_\nu g_\mu^r - g_{\mathrm{s}}\, f^{rst}\, g_\mu^s\, g_\nu^t.$$

# Running of QCD coupling constant

Measured coupling as a function of exchanged Q



$$\alpha_S(Q) = \frac{12\pi}{(33 - 2N_f)\ln\left(\frac{Q^2}{\Lambda^2}\right)}$$

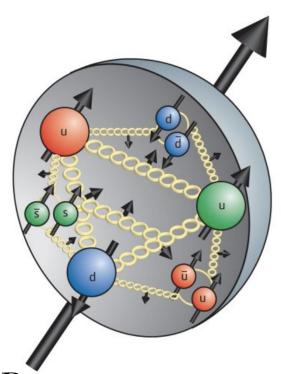- The QCD coupling ($\boldsymbol{\alpha}$s) depends on the energy and distance of interaction: it "runs"
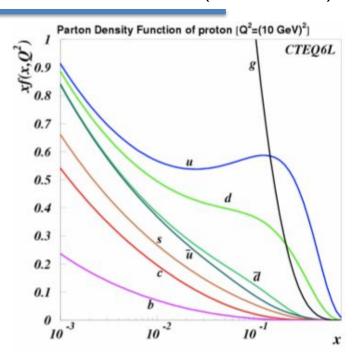
Partons (quarks and gluons) have "asymptotic freedom"

  – At small R (<<1fm, $\boldsymbol{\alpha}$s<1), partons can be described as individual <u>free particles</u> using <u>perturbative</u> QCD

  – At small R (>~1fm, $\boldsymbol{\alpha}$s~1), partons exist only in <u>bound</u>, <u>colorless</u> states called <u>hadrons</u>

# Parton density functions (PDFs)



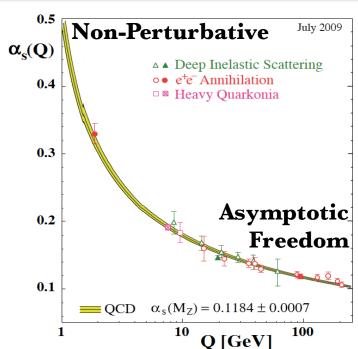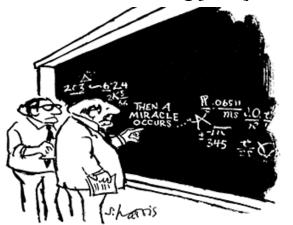Parton Density Function of proton $[Q^2=(10\ GeV)^2]$

CTEQ6L

- Protons are composite particles composed of a collection of quarks and gluons

- PDFs are experimentally measurements of what fraction of the proton's momentum the different partons have

So you want to write a simulation?  Start with a…
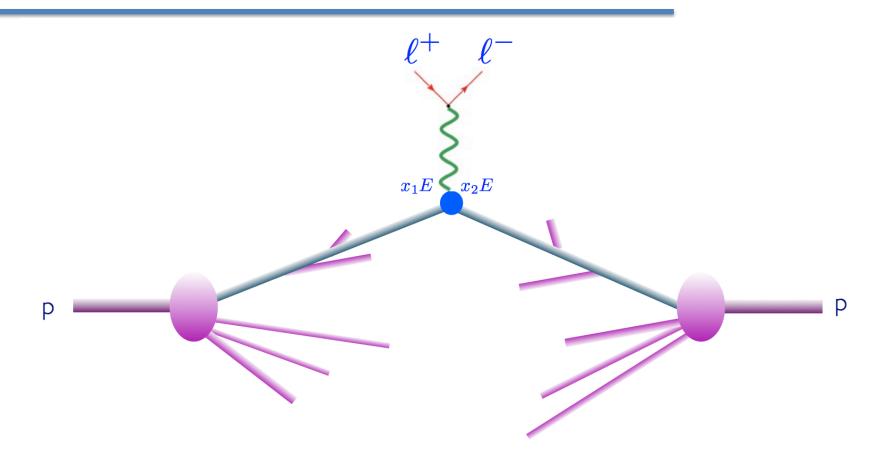
# MONTE CARLO GENERATOR

J Brosamer - MC Simulation

# Start from the Strong Force



Non-Perturbative

July 2009

- △ ▲ Deep Inelastic Scattering
- ○ ● $e^+e^-$ Annihilation
- □ ⊠ Heavy Quarkonia

Asymptotic Freedom

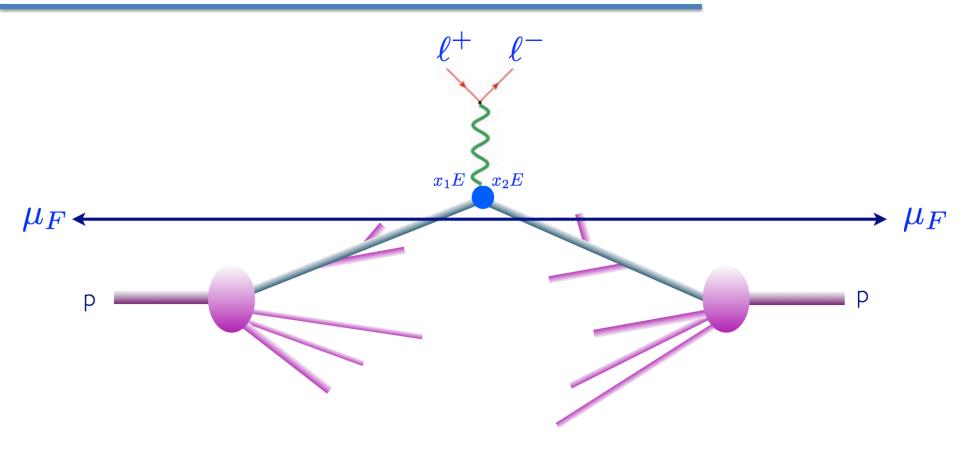QCD   $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
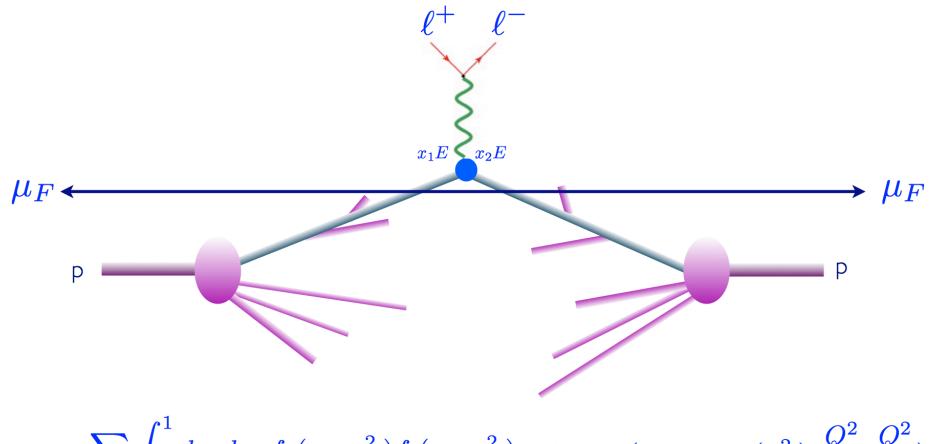
$\alpha_s(Q)$

$Q$ [GeV]



"I think you should be more explicit here in step two."

- The LHC collides protons – that means we're dealing with QCD
- That means that *one size does not fit all*
- There are parts of the process where QCD will be a perturbative theory
  - This will be the easy part, and the popular part to work on
- There are part of the process where QCD will be non-perturbative
  - Here be dragons
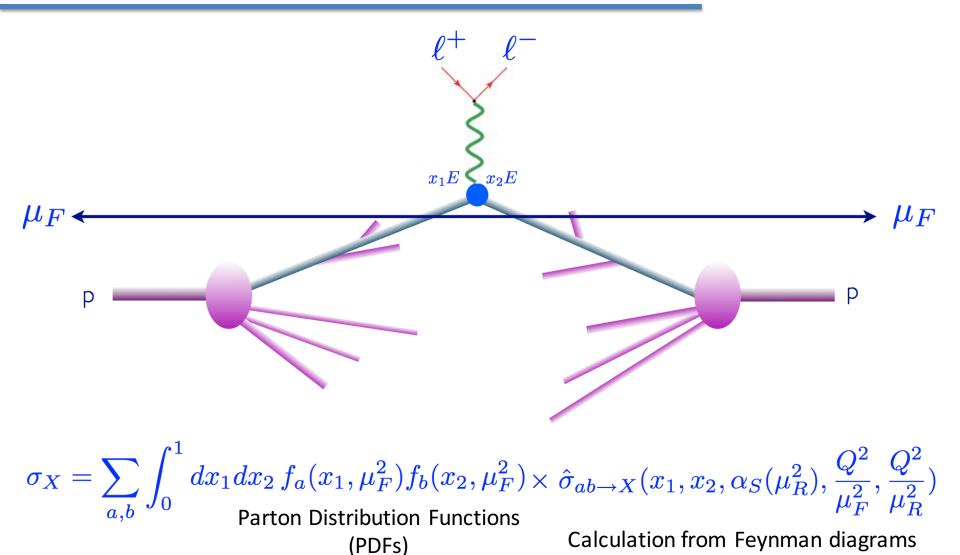  - Lots of lore, little knowledge

# The Master Formula*



*from Fabio Maltoni

# The Master Formula*



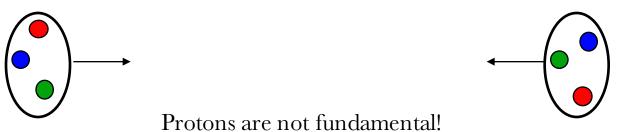*from Fabio Maltoni

# The Master Formula*



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}\left(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$
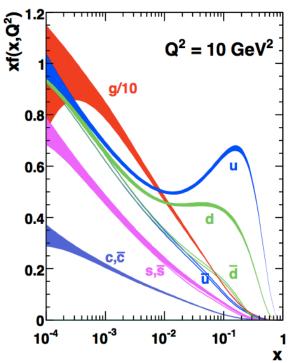
*from Fabio Maltoni

# The Master Formula[*]



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}\left(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Parton Distribution Functions
(PDFs)

Calculation from Feynman diagrams
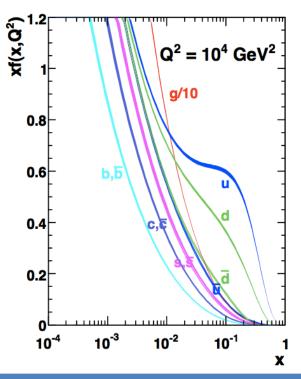
*from Fabio Maltoni

# Parton Distribution Functions

Protons are not fundamental!
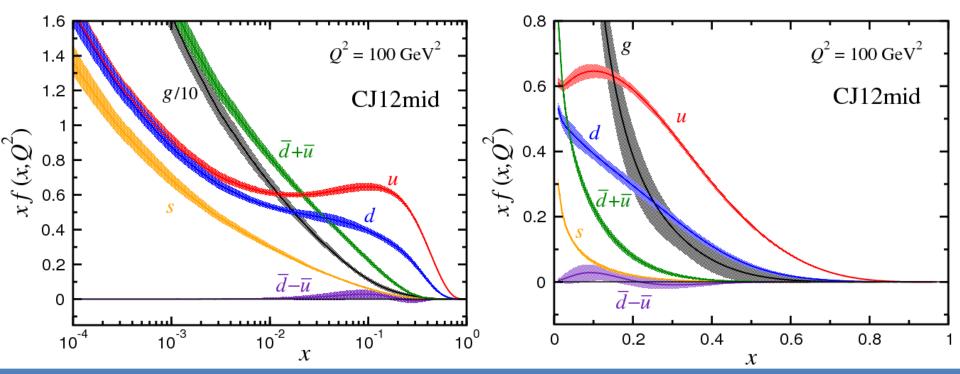We need to know what exactly we are colliding…

- Distributions of the partons within them have been well studied

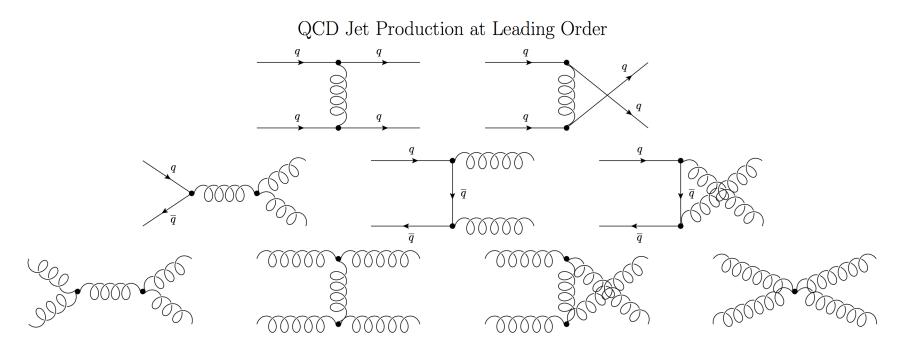- Described by the fraction of proton momentum carried by the parton (x) and the momentum transfer of the interaction ($Q^2$)

**MSTW 2008 NNLO PDFs (68% C.L.)**



$Q^2 = 10$ GeV$^2$

g/10

u

d

c,$\bar{c}$

s,$\bar{s}$

$\bar{u}$

$\bar{d}$

$Q^2 = 10^4$ GeV$^2$

g/10

b,$\bar{b}$

u

d

c,$\bar{c}$

s,$\bar{s}$

$\bar{d}$

$\bar{u}$

# Other Options

- Proton structure is very much *not* an understood thing
  - There are *aspects* that we have a pretty good handle on
- CTEQ and MSTW/MRST are the two biggest players, and they have fundamental disagreements about some issues
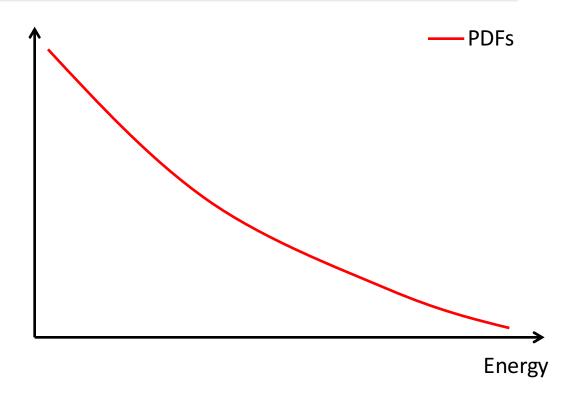  - This is only going to get more complicated... where is the top?

# Cross Section History

- IN THE BEGINNING… there was 2→2
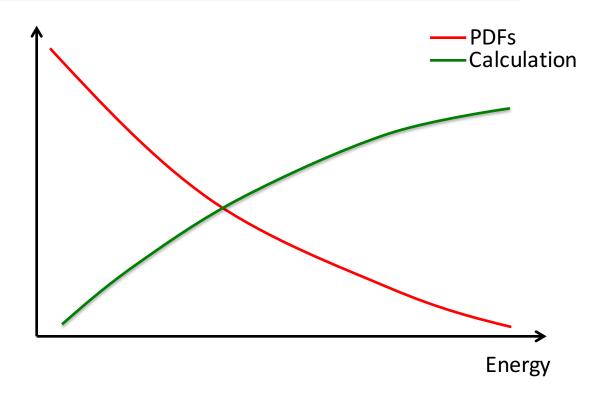
QCD Jet Production at Leading Order



- But of course, we don't observe any of these things!
  - Let's start here, and we'll come back to more accurate models in a few minutes

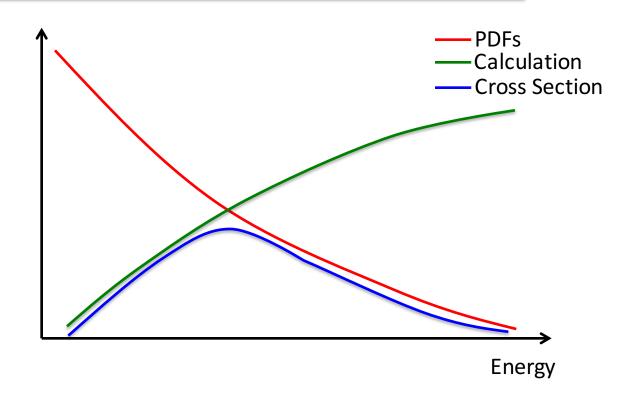# Making an Event



PDFs

Energy

# Making an Event



Legend: PDFs (red), Calculation (green). Horizontal axis: Energy.
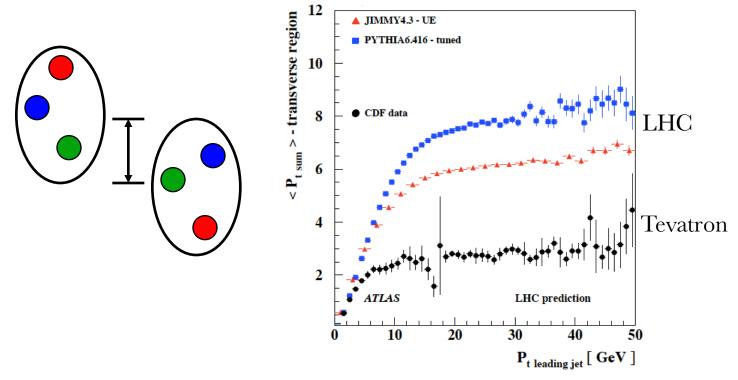
# Making an Event



Now all we do is sample from that distribution, and we have an event!

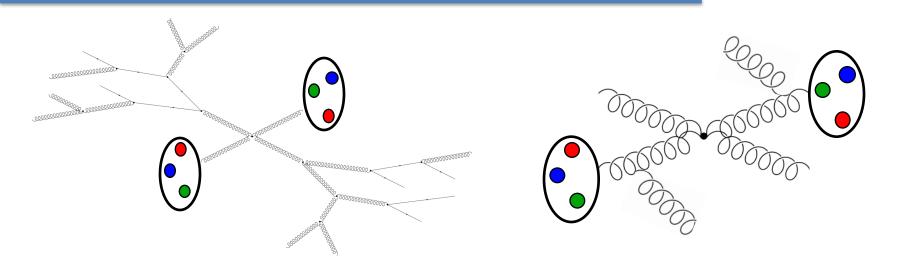Have to include (weighted appropriately) all the desired initial states and all the desired final states

# The "Underlying Event"



- Additional parton-parton interactions are added
  - Probability rises with the 'overlap' between the protons
- These are particularly important at the LHC
  - Parton-parton cross section rises faster with center-of-mass energy than proton-proton cross section
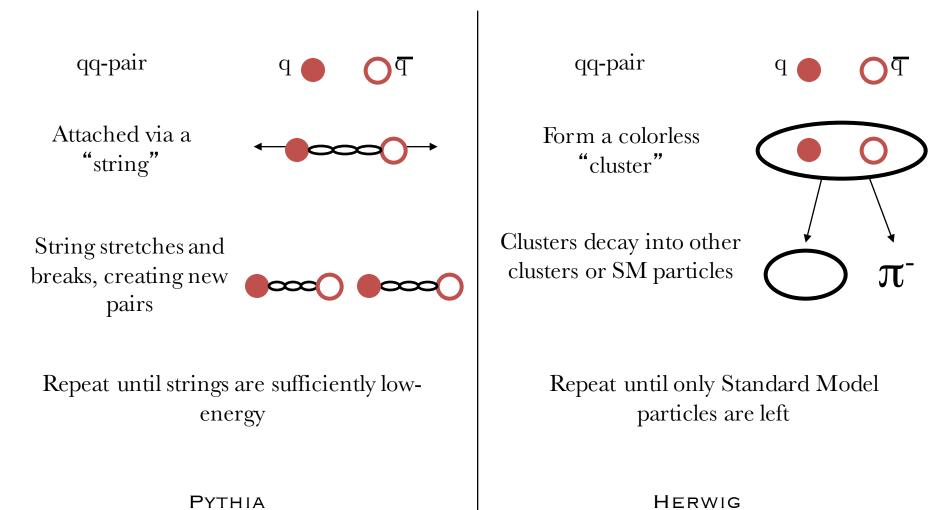
# Parton Showers



- Partons are "evolved" down to ~1 GeV (the non-perturbative regime) using the DGLAP equations
  - Describe probability for one particle to branch into two
  - Accurate to **leading *logarithm***
- Avoid double counting in two ways:
  - Showers must be strictly ordered in some variable
    - Common choices are $Q^2$, $p_T$, or opening angle
  - Ensure that a shower does not move an event from one matrix element's phase-space into another
    - Create gg→gqq in the matrix element *or* in the parton shower

# Hadronization
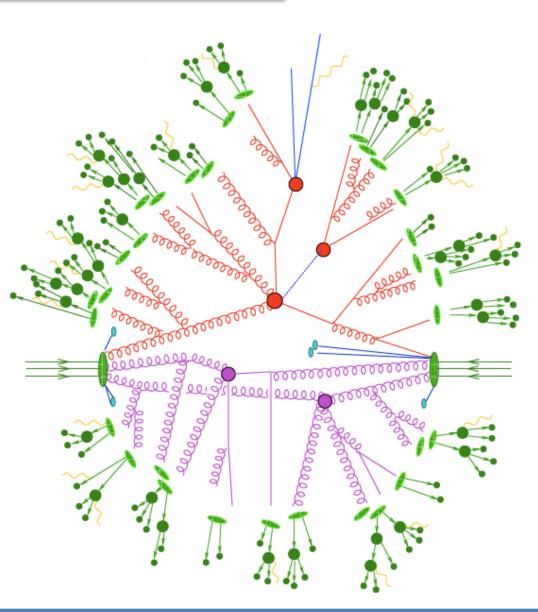
- Two approaches: string and cluster fragmentation

| | | | |
|---|---|---|---|
| qq-pair | q ● ○ q̄ | qq-pair | q ● ○ q̄ |
| Attached via a "string" | | Form a colorless "cluster" | |
| String stretches and breaks, creating new pairs | | Clusters decay into other clusters or SM particles | π⁻ |

Repeat until strings are sufficiently low-energy

Repeat until only Standard Model particles are left

PYTHIA

HERWIG

# The Full Picture

- A generator is *meant* to go from a Lagrangian to that mess on the right

- The reality is WAY nastier than this

- Also, this picture is a bit misleading – what QM process looks like that??

Really good generator paper:
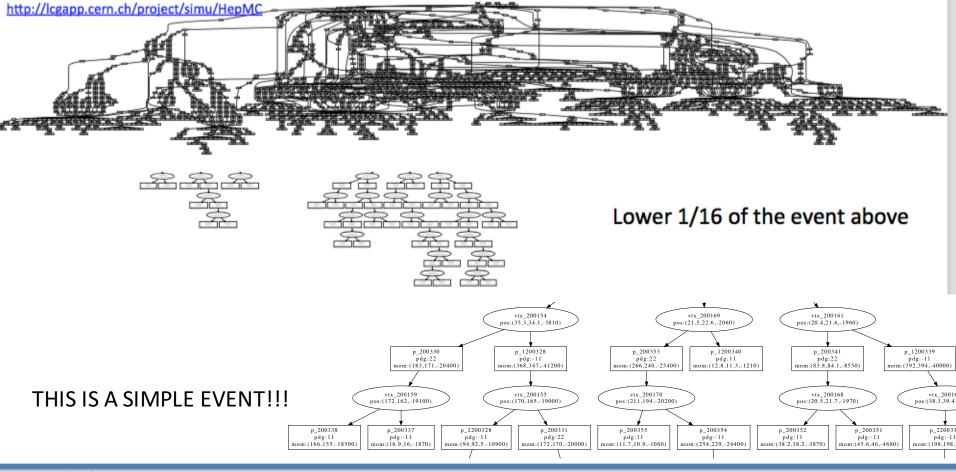
http://arxiv.org/abs/0911.5286

# Four Types of Generators

- Some generators are used for cross-sections ONLY
  - These make matrix elements at most (most don't even do that)
  - MCFM is a very common one
- Most generators are used for matrix elements
  - These just give you parton (usually) four-vectors from the hard scatter
  - They (usually) give output in "public" HepMC format (almost human-readable, but it is a text file – you can get this from a theorist)
  - Alpgen, MadGraph, MC@NLO, PowHeg are all pretty common
- Some can generate the rest of the event (or the whole event)
  - These give final state *particles*!!  And we write EVNT (ATLAS) format.
  - Pythia/Herwig (fortran) and Pythia8/Herwig++/Sherpa (not fortran)
  - They include the parton shower, addition of multiple parton-parton interactions, initial state radiation, hadronization, and some decays
- Afterburners that improve the modeling of some observable
  - Tauola and Photos are super popular.  Also EVTGEN and some HI stuff.
  - Jimmy should really be *here* – it is an MPI afterburner for fHerwig

https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/McGeneratorsForAtlas

# Generator Myths and Evil

- The generator event record is NOT a connected tree of branchings
  - There may be loops, breaks, particles disappear or appearing…
  - Some generators in particular (Sherpa) omit some particles (Zs and Ws)
  - This is why you ALWAYS want to look at observables if they are available!!

http://lcgapp.cern.ch/project/simu/HepMC

Lower 1/16 of the event above

THIS IS A SIMPLE EVENT!!!

# Generator Myths and Evil

**Pretty advanced...**

- The "hard process" in a generator is NOT just pQCD
  - Pythia in particular has many "tricks" to make the output agree with the data
  - Sherpa has tricks to make it "better than LO" (so we use an NLO PDF)

- Generally, matrix element generators run in two(+1) steps:
  - "Phase space integration" – figure out what to generate
  - Matrix element generation, sometimes with weights according to where in phase space the event landed
  - [Optional: event unweighting, to try to remove the weights. Alpgen does this.]
  - Weights are >0, except in MC@NLO (virtual diagrams get negative weights)
    - This is why we like PowHeg

- Phase space integration is slow for high-multiplicity (days)

- Event generation (can be) relatively quick – as long as you don't put some strange filter on the back end
  - ATLAS's lowest acceptable generation speed is ~5-10 events per DAY

# Tuning

- All your generators are heavily *tuned* to reproduce data
  - Most of the hadronization data come from LEP
  - Most of the UE data come from the Tevatron and LHC
- There are NOT enough knobs to reproduce all data perfectly
  - fHerwig/Jimmy in particular has no knobs left
    - Big fight in the generator community: do we include more knobs or try to include models that fundamentally should reproduce the data and say they fail if they don't? We had to introduce *energy scaling* by hand in Herwig already!
  - The data are re-weighted to blow up low-$p_T$ error bars and shrink high-$p_T$ error bars and to emphasize different measurements in the tuning
  - The first step of tuning is actually selecting which knobs you will tune!
- ATLAS has quite a bit of tuning machinery in place
  - If you do a Standard Model measurement that is more than a cross-section, please write a Rivet routine to help the MC match your result!
- ATLAS has also dropped the ball on tuning quite a few times
  - MC11b was a TUNING problem, not a fundamental Pythia8 problem
  - Our constant struggle with Z samples started with a Z-$p_T$ *tuning* problem, not from any fundamental difficulty modeling Z-bosons

# Generators to Watch

- ## MadGraph
  - I really like the developers, and they are quite good
  - They have big support for UFOs, which is probably the best theorist-experimentalist interface I've seen

- ## Sherpa
  - ATLAS have basically never produced a bug-free Sherpa sample that I'm aware of – but at least the developers are responsive! (We seem to be close-ish now…)
  - They have big support for BlackHat, which is Lance Dixon's 4-vector generator that supports a *lot* of processes at NLO / NNLO

- ## PowHeg
  - Up side: some nice NLO modeling of various processes
  - Down side: implemented process-by-process, so there is no good version control!

# Stat Shot: ATLAS Generators

- ~30 MC Generators (how many can you name?)
  - Actually, it's been over 50 in run 1, from my count!
  - >>50 Combinations (Powheg+Pythia vs Powheg+Jimmy)
  - Remember: pick the model that is *as accurate as you need* to describe the physics that is important to you!
- 34 000 samples in the last MC campaign
- MC for 2011: ~5B events
- MC for 2012: ~6.6B events
  - Fastest is a few minutes / 5k events. Slowest is 5 events per ***DAY***
  - We record data at ~400Hz, for reference ☺
- We are still getting better at event generation
  - That is one place where we really need help and better interactions with theorists and with each other

One down…

# NOW WE HAVE A MODEL FOR PRODUCING HADRONS

# On to the Simulation!

- The simulation is agnostic about what happened in the matrix element

- It *only* cares about "final state particles" (stable particles)

- What is "final state" *depends on the experiment!!*

  - ATLAS uses c$\tau$<10 mm.

- Remember that your generator does not know *anything* about your detector geometry or magnetic field. So you don't want it to handle anything that would move through a detector element or bend significantly in a field
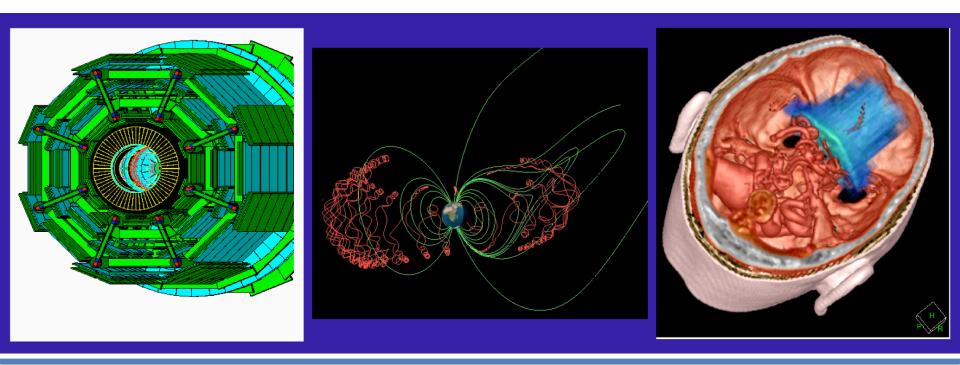
# Simulation: Where do we begin?

- There are two options for a detector simulation
- We can go straight for the final state
  - "A pion will look like such-and-such"
  - Smear things directly
  - These are *always* home-brewed
- We can simulate every little detail along the way
  - Usually we use either Geant4 (GEometry ANd Tracking) or FLUKA (public software)
- In ATLAS we try to do both
  - Actually we have half a dozen "kinds" of simulation that are combinations of these two approaches…

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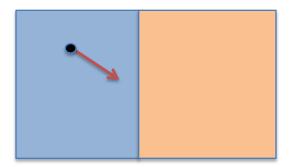
# Geometry and Tracking

- People do all kinds of crazy stuff with Geant4
  - Space physics, medical physics, collider physics, nuclear physics, protein folding, radiation surveys…

# Simulation Primer

- To Geant4, *every* problem looks like this:

- It has the concepts of:
  - Particle (if it isn't standard model, G4 has no idea about it!)
  - Material (you define everything except the elements)
  - Magnetic field (you define it at every point)
  - Physics process (you get to pick from their list!)
- It is *only a toolbox* – it's up to you to put the pieces together
  - Don't expect it to be any smarter than you are.

# Simulation Step 1

π⁻

Question 1: What am I looking at, and what can it do?

Grab a particle from the 'stack' and see what type of particle it is
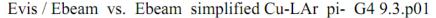
If necessary, figure out where it is
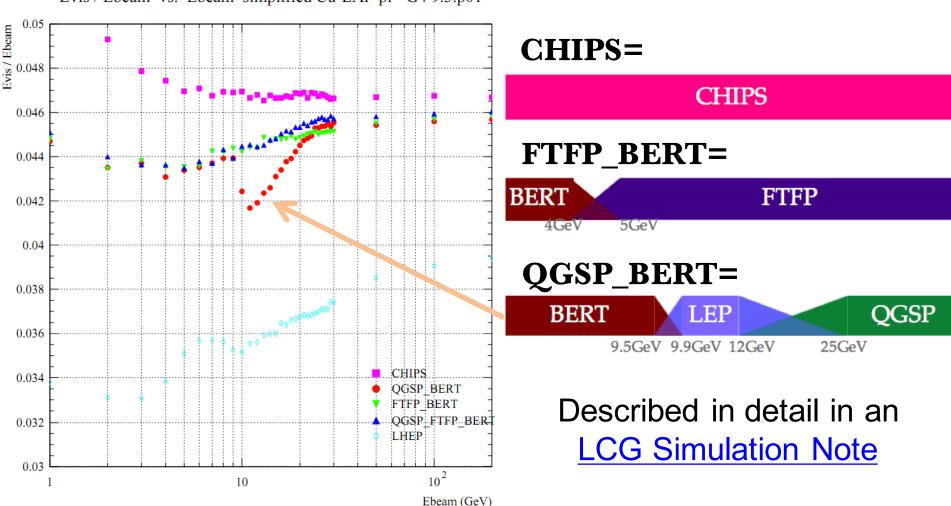
# Nature is continous

- But numerical models are not!
  - All processes become *discrete*, including "transportation"
- Use phenomenological models tuned to experimental data
  - Never solve a Lagrangian!!
- Some interactions are easy
  - Photon conversion
- Some are hard to model
  - The nucleus gets its own simulation!
- Some have a variety of models
  - ATLAS covers keV to TeV physics:
    - **>9** orders of magnitude!!
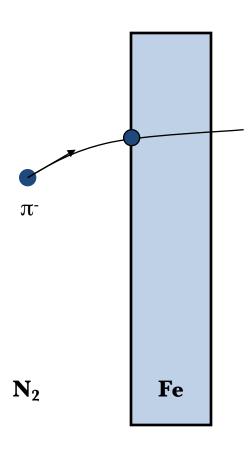  - Good in an energy range
  - Transitions can be problematic!!



It's Just a THEORY!

Argument, Instant Effect

All scientific theories and the phenomena they describe are instantly invalidated.

Gravity ceases, evolution ends and your monitor turns off as the electromagnetic theory reverts to superstition and myth.

# Different Models

## Hadronic physics is really nasty stuff



Evis / Ebeam  vs.  Ebeam  simplified Cu-LAr  pi-  G4 9.3.p01

**CHIPS=**

CHIPS

**FTFP_BERT=**

BERT · FTFP · 4GeV · 5GeV

**QGSP_BERT=**

BERT · LEP · QGSP · 9.5GeV · 9.9GeV · 12GeV · 25GeV

Described in detail in an
[LCG Simulation Note](#)

# Simulation Step 2
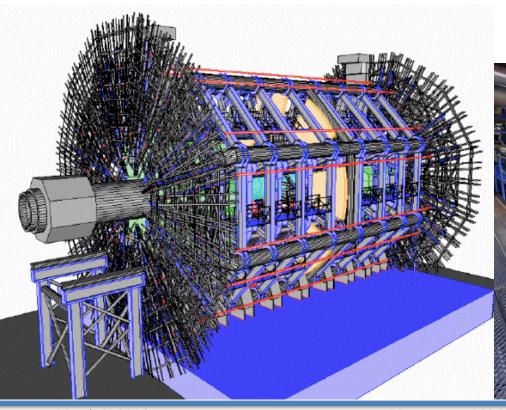
Question 2: How far may I go?

Never move farther than a volume boundary - the physics could change!!
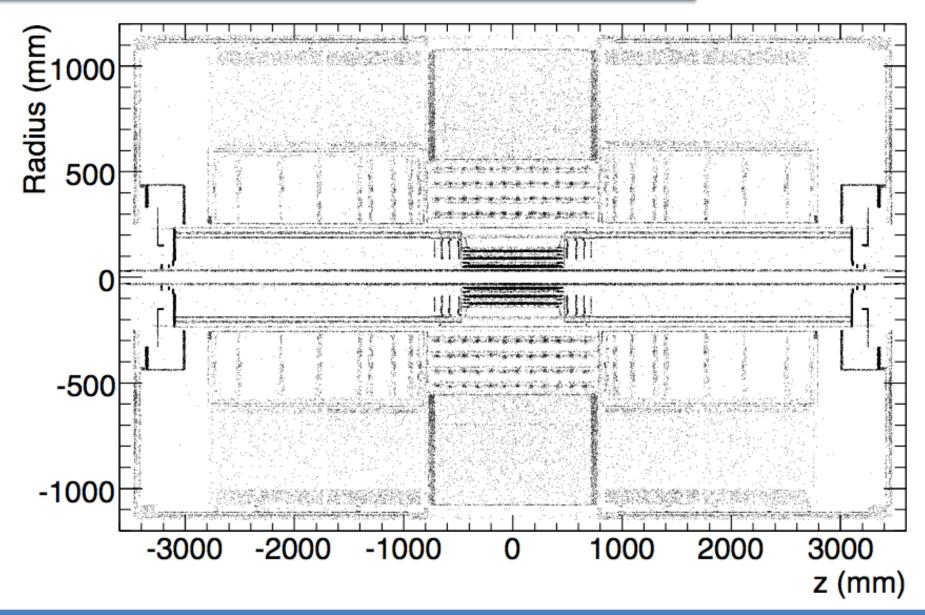
$\pi^-$

$N_2$

Fe

# Detector Descriptions

- Need a consistent detector description
  - We are still making things more 'realistic'
    - But some things aren't worth worrying about
  - Once you are done: *just weigh the detector!*
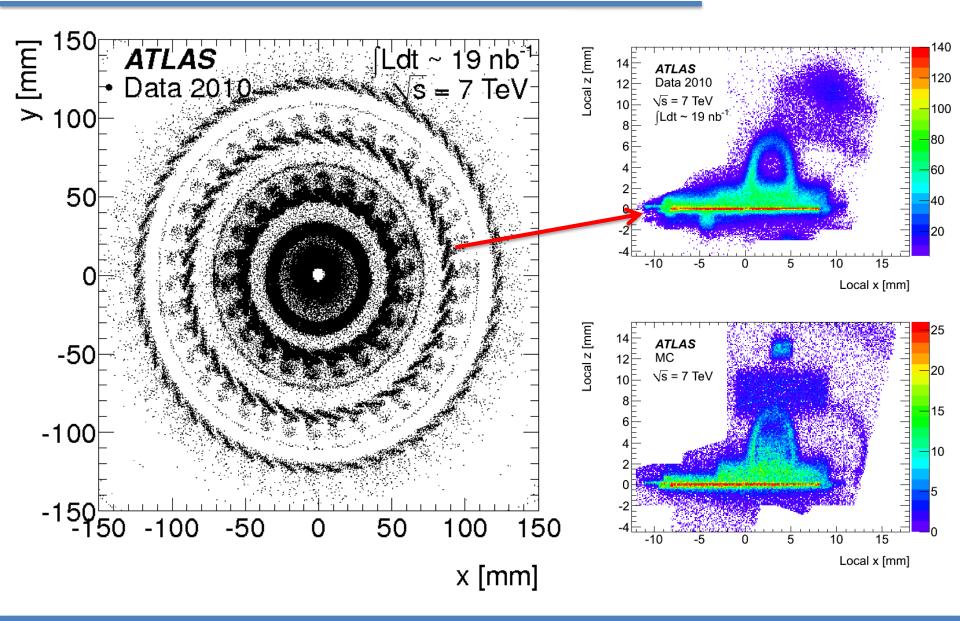  - Of course, with collisions, we can get fancier…
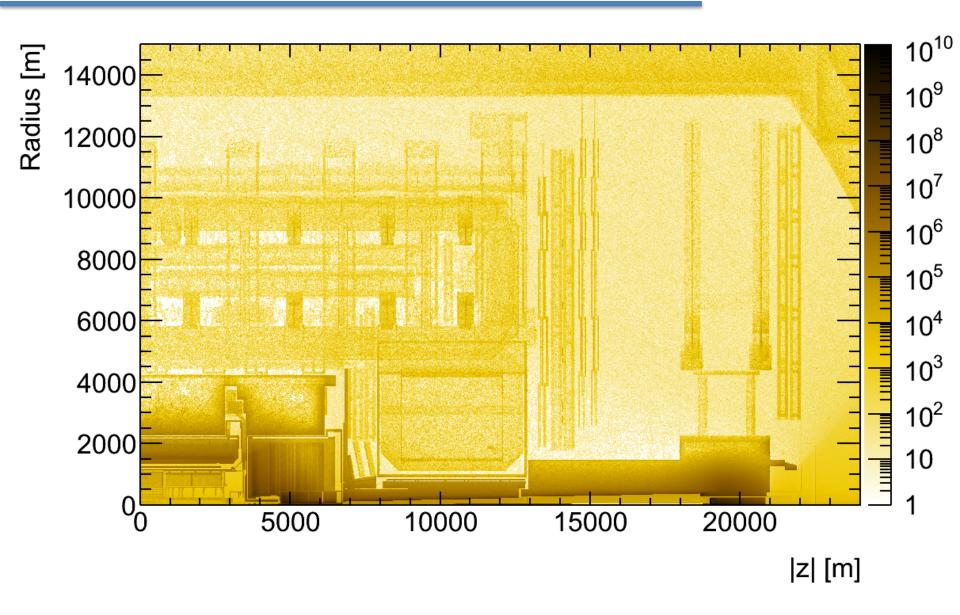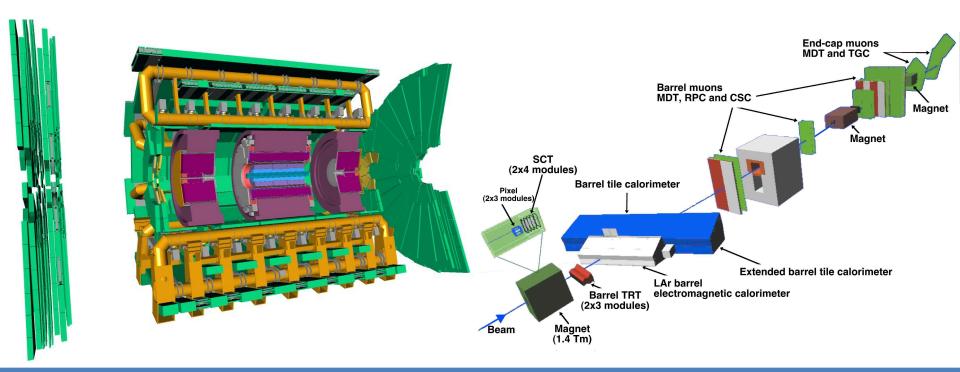
# Photon Conversions

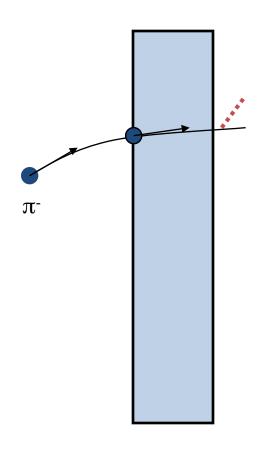# Hadronic Interactions

# The Full Detector

# Strange Geometries

- We have commissioning layouts for cosmic ray data taking
  - See the calorimeter and muon wheel positions on the left there?
- We have layouts for test beams, IBL, NSW, Lucid, ZDC, ALFA
- If you want to simulate it, you had better write a geometry!



End-cap muons
MDT and TGC

Barrel muons
MDT, RPC and CSC

Magnet

Magnet

SCT
(2x4 modules)

Pixel
(2x3 modules)

Barrel tile calorimeter

Extended barrel tile calorimeter

Barrel TRT
(2x3 modules)

LAr barrel
electromagnetic calorimeter

Beam

Magnet
(1.4 Tm)

# Simulation Step 3

Question 3: What will happen next?

Check on all physics models. For a pion, this means multiple scattering, bremsstrahlung, nuclear interactions, decay, ionization…
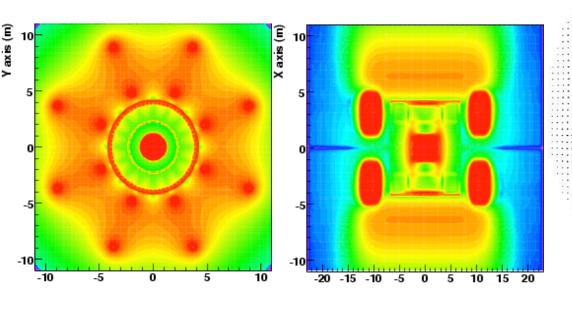
Add any new particles to the stack

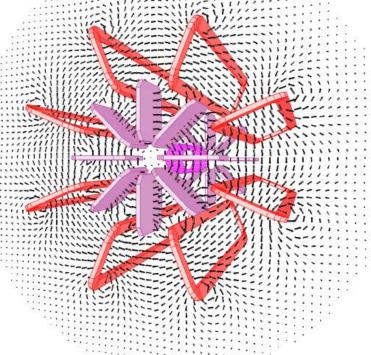Adjust energy and momentum accordingly

π⁻

# The Magnetic Field

- No hope for simulating on the fly - must have a *map*
  - Do they match *reality*?
  - Do they match the *geometry*? (I always love finding a magnetic field map that has the wrong solenoid position…

- ATLAS keeps a handful of hall cubes on the detector to measure the field
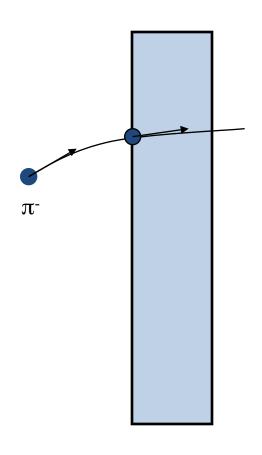  - Parameterizes elsewhere

# Where Do Those Steps Go?

- Each iteration is called a "step"
- The number of steps dictates the speed of the simulation
  - The best code changes get us ~3-10% speed ups; the best physics changes get us 20-50% speed ups
- Most time just moving stuff around in the calorimeter
  - Here is the table for 50 ttbar events
- 50% of your simulation time is spent moving $e^\pm$ and $\gamma$ below 10 MeV

| Process | Inner Detector | calorimeter | Muon System |
|---|---|---|---|
| Transportation | $1.76 \times 10^6$ | $1.46 \times 10^7$ | $2.31 \times 10^5$ |
| MSC | $2.31 \times 10^5$ | $1.48 \times 10^7$ | 5,200 |
| Photoelectric Effect | 6,760 | $1.37 \times 10^6$ | $2.32 \times 10^5$ |
| Compton Scattering | 14,800 | $1.66 \times 10^6$ | $5.03 \times 10^5$ |
| Ionization | $1.03 \times 10^5$ | $4.81 \times 10^6$ | $9.71 \times 10^5$ |
| bremsstrahlung | 6,060 | $1.22 \times 10^6$ | $1.92 \times 10^5$ |
| Conversion | 416 | 86,800 | 18,100 |
| Annihilation | 271 | 87,000 | 18,500 |
| Decay | 212 | 1,670 | 402 |
| Other Hadronic Interaction | 2,190 | $6.66 \times 10^5$ | $1.23 \times 10^5$ |
| Other Process | 426 | 25,400 | 5,720 |
| **Total** | $2.13 \times 10^6$ | $3.93 \times 10^7$ | $2.69 \times 10^6$ |

# Simulation Step 4

$\pi^-$
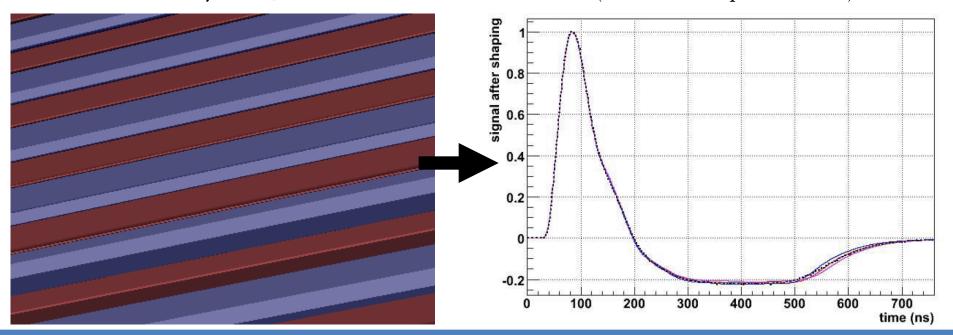
## Question 4: Anything else to do?

The user is allowed a hook at the end of this "step" to perform any necessary action, for example to **make a record of energy deposition**

All particles are tracked to zero energy or their exit of your world (this is different from the old days of simulation…)
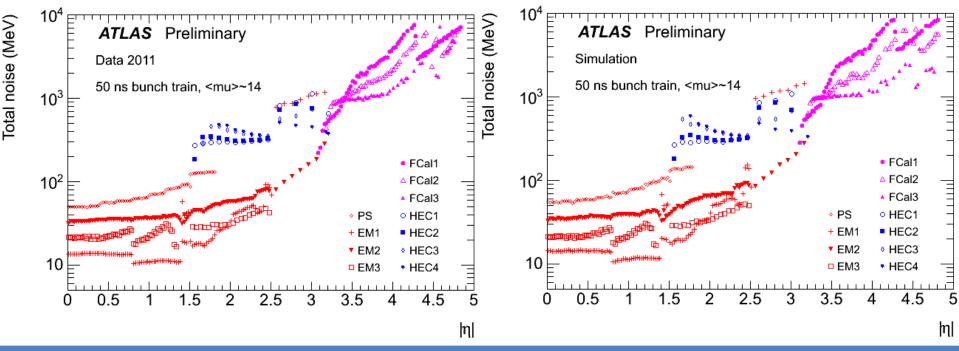
# Detector Modeling: Digitization

- Geant4 has no idea how our detector *reacts* to particles
  - It only deposits *energy* with a position and time
- First we have to do some *energy collection*, then we have to do a *conversion* into something we can read out
  - How that's done depends completely on the detector
  - Have to take into account detector timing, pulse shapes, charge collection effects (sometimes conditions dependent)
- This is very hard, and all custom ATLAS code (with lots of parameters)

# Modeling Noise

- One critical thing to get right is electronics noise
- You can imagine these models can get *very* complicated
  - Especially if you have to try to model channel cross-talk
- We are generally pretty good at this stuff, but there are still effects that we don't get right
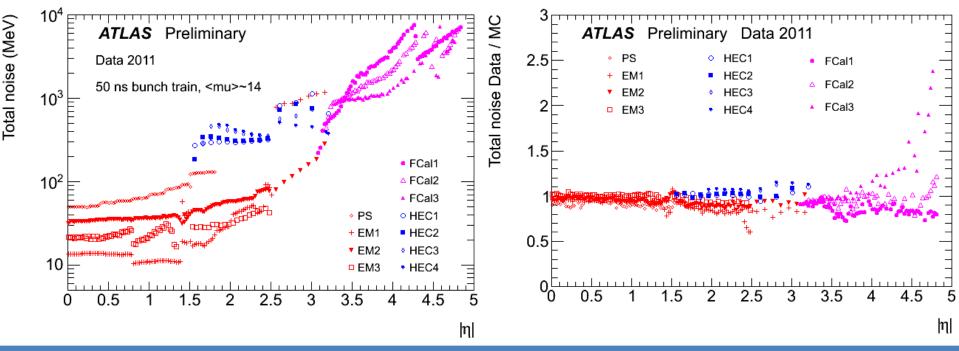
# Modeling Noise

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# Things Change

- ATLAS has to deal with many types of "conditions"
  - Beam spot, misalignments, which parts are masked or disabled…
- To save time and energy, conditions are always applied as late as possible
  - Channels can be masked long after simulation finishes!
  - But moving the interaction region is a whole other story…
- Some misalignments have to be applied in the simulation
  - We have to be VERY careful that things don't overlap! Geant4 could get lost… and then the result is the bad kind of random



Exaggerated (10x) sagging in the EM barrel calorimeter
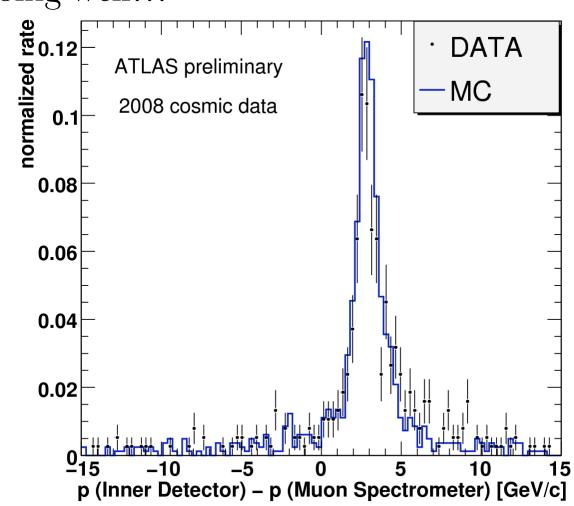
So you have finished your Monte Carlo!

# NOW PRESS THE BUTTON…

# How Do You Know It Worked?

- When the simulation can recreate something it *was not designed for*, you're doing well…

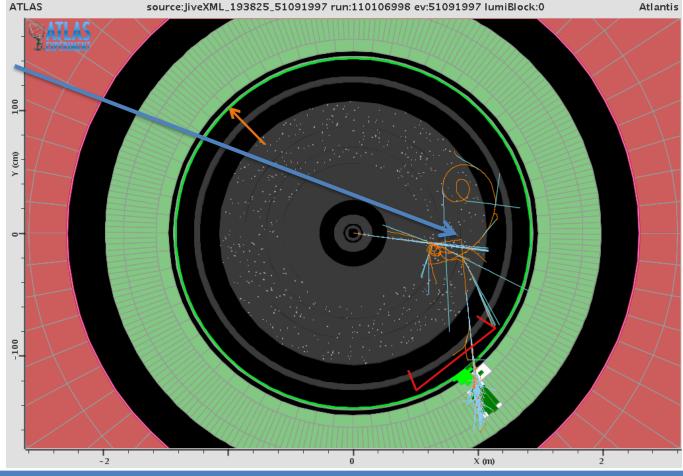Cosmic rays are one interesting test. Use the simulation to propagate muons from the Earth's surface to the detector!

Here: energy loss in the calorimeter by a muon
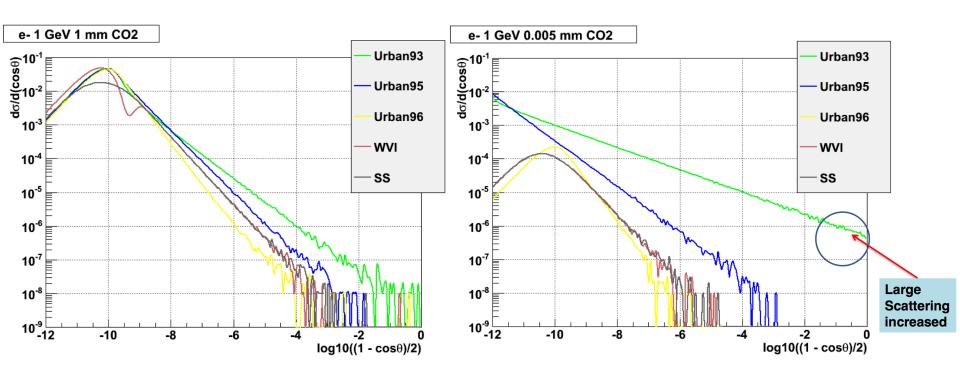
# What Happens When It Didn't?

- A visualization of an ATLAS simulation bug

# Extrapolating

- Turned out to be a "feature" in extrapolation of the multiple scattering parameterization
- Always know your model's region of validity!

# What Could Possibly Go Wrong??

- What is the production threshold for very low energy stuff?

- How long may a particle fly before you need to treat it with the detector simulation?

- Did the approximations you made apply?

- Have you checked for CRAZY things?

- Are the models all accurate enough for you?

# What Could Possibly Go Wrong??
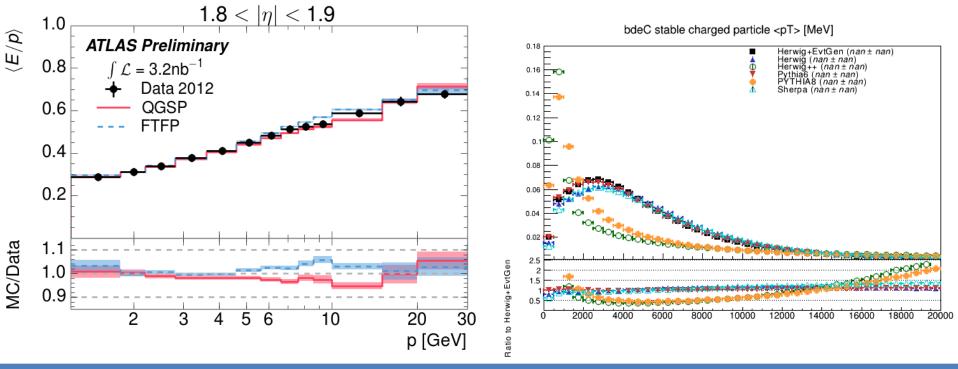
- What is the production threshold for very low energy stuff?
  - **Cost: ~6 months of simulation**

- How long may a particle fly before you need to treat it with the detector simulation?
  - **Cost: ~1 month of simulation**

- Did the approximations you made apply?
  - **Cost: ~1/2 month of simulation**

- Have you checked for CRAZY things?

- Are the models all accurate enough for you?
  - **Costs: Lots of sleepless nights and quite a few painful emails**

Yup, been there, done that, got the T-shirt...

# Feeding Back

- If your model isn't good enough, then find a measurement that can tell you something about *the specific reason* it isn't

- It's a rare treat when this works, and it takes some very creative thinking to come up with something that does the job

# The Real Fun

- The best part of working on an MC is getting to learn *everything*
- Problems with the detector…
  - Did we install muon chambers upside down?
  - Do we know how big the gaps and shielding blocks are in our detector?
  - Did they accidentally build the ends of the detector differently?
  - Is there a leak, so that we might have to change detector gas?
- Problems with computing…
  - Random numbers ☺
  - From float v double to trampolining in virtual classes
- Problems with the physics…
  - What happens when a highly charged particle passes through the detector?  ~100e kind of charged, like a monopole?  Did we model those effects?
  - What is a quirk?
  - What's the rate of beam halo from the two sides of the detector?

# Let's Stop Here…

- I've tried to run through all of the main issues with writing your own simulation

- There are a LOT of things that we could talk more about
  - The devil is in the details
  - ESPECIALLY in the details of how to make the data and the MC simulation that you've written line up

**What are *you* most curious about?**

# BONUS

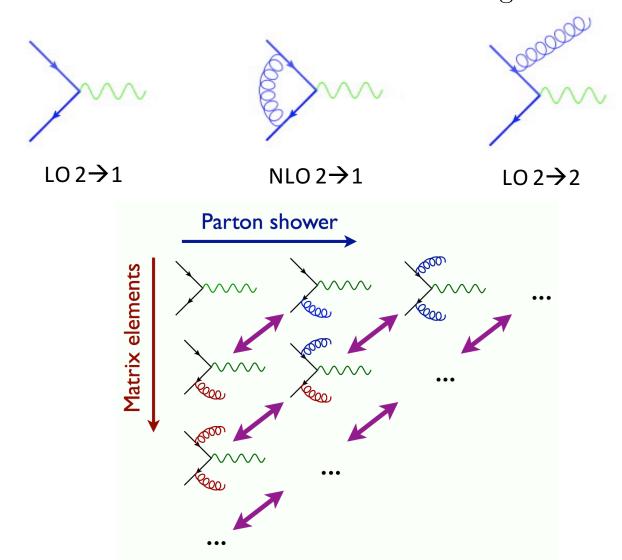Is always tilted slightly to the left for some reason
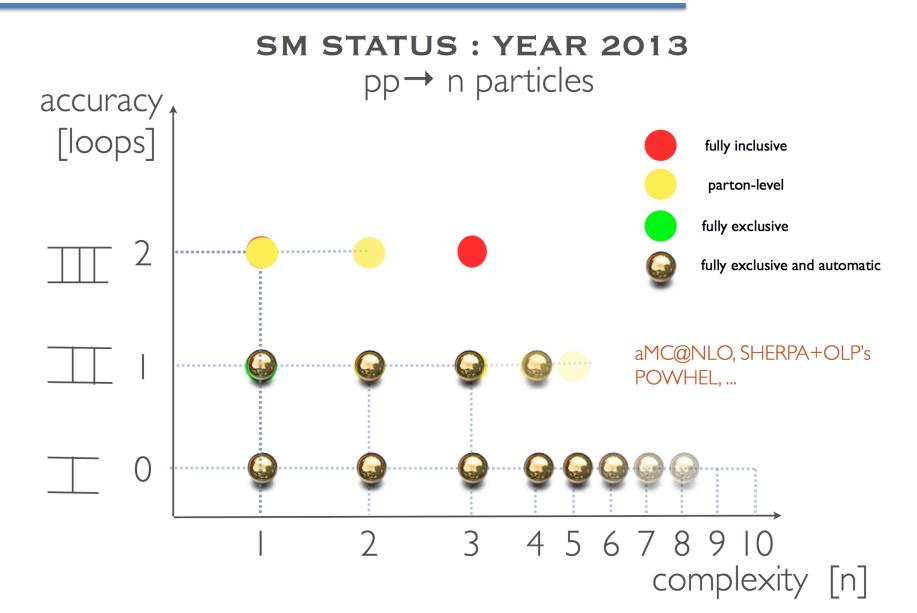
# The Cross Section

- Here we want to use the most accurate thing we can



LO 2→1          NLO 2→1          LO 2→2

# Generator Status



**SM STATUS : YEAR 2013**
pp → n particles

accuracy [loops]

- 🔴 fully inclusive
- 🟡 parton-level
- 🟢 fully exclusive
- 🟤 fully exclusive and automatic

aMC@NLO, SHERPA+OLP's
POWHEL, ...

complexity [n]

# Aside: Random Numbers

*Yury mentioned these!*

## Random Numbers

- At the core of MC method is ability to generate (pseudo)random numbers

  □ Issue is generating truly random numbers

    ☞ Computers are (so far) deterministic

    ☞ If each computer had an ADC, could use Josephson's noise

    ☞ But in practice resort to pseudo-random sequences

$$x_{j+1} = f(x_j, x_{j-1}, ..., x_2, x_1)$$

  □ Requirements

    ☞ Longest period possible

    ☞ Smallest correlation between sequential steps $corr[x_{j+1}, x_j]$

# Aside: Random Numbers

32

## Random Numbers

- At the core of MC method is ability to generate (pseudo)random numbers
  - ❑ Issue is generating truly random numbers
    - ☞ Computers are (so far) deterministic
    - ☞ If each computer had an ADC, could use Josephson's noise

**We had serious discussions about this at the LHC (using thermal noise to generate random numbers) Why *wouldn't* you want to do it?**

# Aside: Random Numbers

## Random Numbers

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**We had serious discussions about this at the LHC (using thermal noise to generate random numbers) Why *wouldn't* you want to do it?**

**Reproducibility!**
**We want things to be *random* but *reproducible!!***

# Aside: Random Numbers

## Random Numbers

- Ex: linear congruent generators
  - ☞ Generate integers in range [0..m-1]
  - ☞ $n_{j+1} = (a\, n_j + c)\, \% \, m$
  - ☞ Sequence is periodic, depends on increment $c$ and modulus $m$
  - ☞ Sequence depends on initial seed $n_0$
  - ☞ Ex: $m = 2147483399$, $a = 40692 \rightarrow T = m-1 \approx 2 \times 10^9$

- Generate floats
  - ☞ $r = n_{j+1}/m \in [0..1]$
  - ☞ $x = a + r(b-a) \in [a..b]$

# Aside: Random Numbers

- These are multiplicative congruent generators

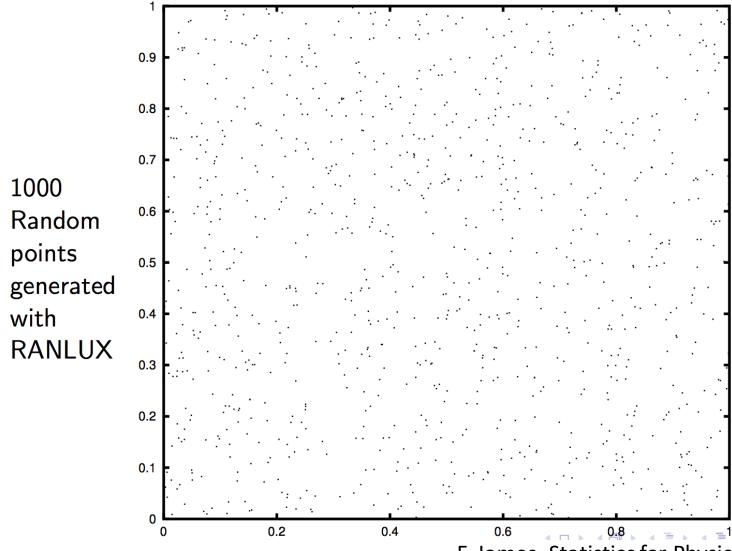$$u_{i+1} = [u_i \times m] \mod 2^b$$

*During the software development for the LEP experiments, two different physicists were surprised to see a simulated event exactly the same as one they had seen before. With a period of $10^9$, the probability of this happening is $10^{-4.5}$ per event.*

- So they invented an upgrade with a period $2^{18}$ longer:

$$u_{i+1} = [(u_i + u_{i-1}) \mod 2^b \times m] \mod 2^b$$

F. James, Statistics for Physicists Ch. 10

# What is Random? (I)

## Looking at Random Point Sets

1000
Random
points
generated
with
RANLUX



F. James, Statistics for Physicists Ch. 10

# What is Random? (II)

## Looking at Quasirandom Point Sets

1000 Quasi-Random points generated with Corput (1,2)



F. James, Statistics for Physicists Ch. 10