

Python for Data Science 2

Lecture 4- Models at the Large Hadron Collider

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What is a “Model”?

- The context of science, data science, machine learning, etc, the word model is often used...
 - e.g disease transmission model, plate model, Standard Model of particle physics, neural network model, ...
- In science, models often try to capture some phenomena in a mathematical or heuristic way.
 - There are likely assumptions in a model, which often are simplifications
- Why? to understand, define, quantify, visualize, simulate, predict, ...
- Often the general knowledge of a discipline (e.g. particle physics), is captured in a model.
 - It therefore represents what is known.
- Scientific research then becomes the iterative process of
 - comparing the model predictions with experimental results
 - improve the model
- Key is to understand what experiments to best reveal the weaknesses of these models.

- To understand the most fundamental phenomena in nature, the Physicists application of the scientific method:

1. Build Models

- The **Standard Model of HEP** describes the building blocks of matter and their interactions.
 - SM requires the existence of a set of fundamental particles with very specific properties.
 - Tested and validated through experiments, including some of the most precise measurements ever.
 - Yet, has **failures**, e.g. no Dark Matter. Not compatible with Gravity.
 - And, has **inconsistencies**: e.g. both SM predicts the Higgs mass to be big and requires it to be small.
 - Models are **expressed mathematically**
 - Ideally build on a minimal set of rules (principles/laws)
 - SM Mathematical Framework: Quantum Field Theory- Way beyond this class.
 - Renormalization: encapsulating unknown (effects at high energy) in measurable parameters.
 - SM is a Model with **19 parameters**. Masses of particles. Strengths of forces. etc...
 - None are fundamental like speed of light or Planck's constant.

2. Build new model that tackle inconsistencies.

3. Create experiments (target weaknesses in the model)

Physics Models

Classical:
Calculus (Infinitesimal)
Object (a particle) described by $x, y, z, \alpha, \beta, \gamma$ and their derivatives (ie momentum).

Relativity explains Electromagnetic Unification. EM fields inherently relativistic.

Classical Field Theory:
eg Electrodynamics
Interaction of particles with a dynamic field $A(x, y, z)$.

Atomic scales

General Relativity:
Tensor Calculus
Gravity = Curvature of Space Time.
Gravity weak, so curvature ignorable on small scales.

Relativistic Particles

Quantum Mechanics:
Probabilistic
A particle described by a complex wavefunction $P(x, y, z, \alpha, \beta, \gamma + \text{derv})$.

Relativistic QM
Requires Creation of Particles... leads to Fields

Quantum Field Theory:
eg: QED, Standard Model
Particles = Fields.
Gauge Symmetries = the classical dynamic Fields = Particles = Electroweak
Calculate Probability of interaction.

Building the SM

Field Theory + Quantum Mechanics + Relativity = Quantum Field Theory

Ingredients

1. Leptons + Quarks

FERMIONS

matter constituents spin = 1/2, 3/2, 5/2, ...		
Leptons spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

2. Three Local Gauge Symmetries

- Each Symmetry implies existence of a new set of boson (spin 1) fields
- These bosons “carry” the Forces

Unified Electroweak spin = 1

Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

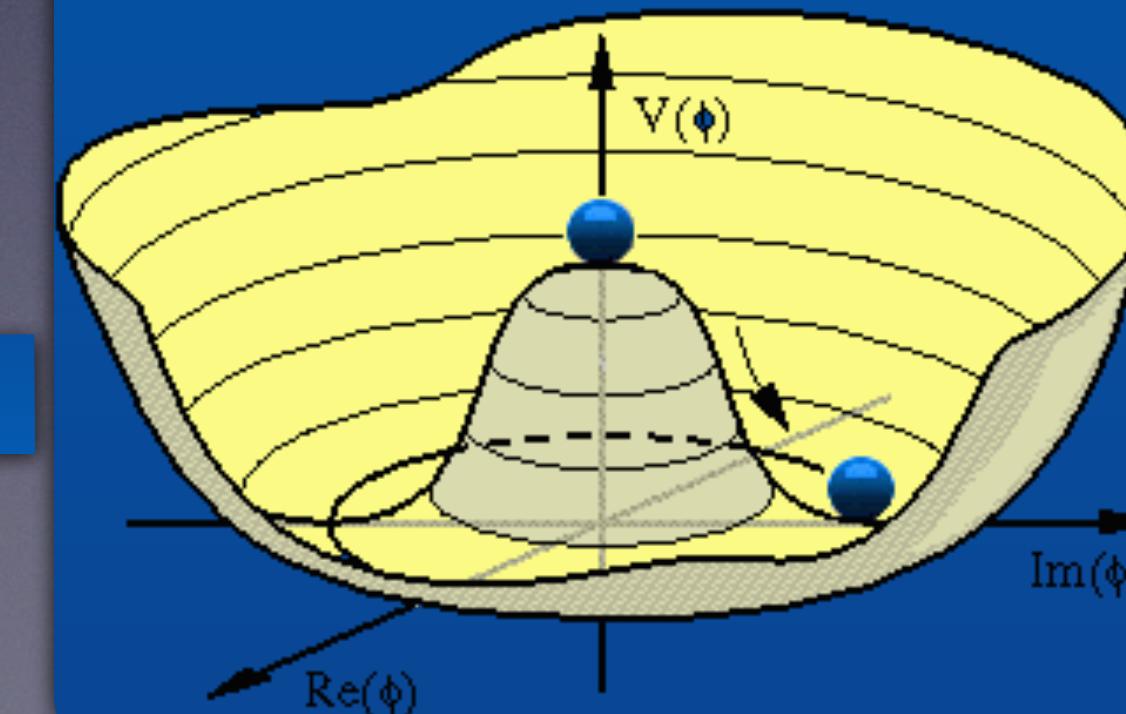
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

Standard Model

Agreement with all experimental results so far

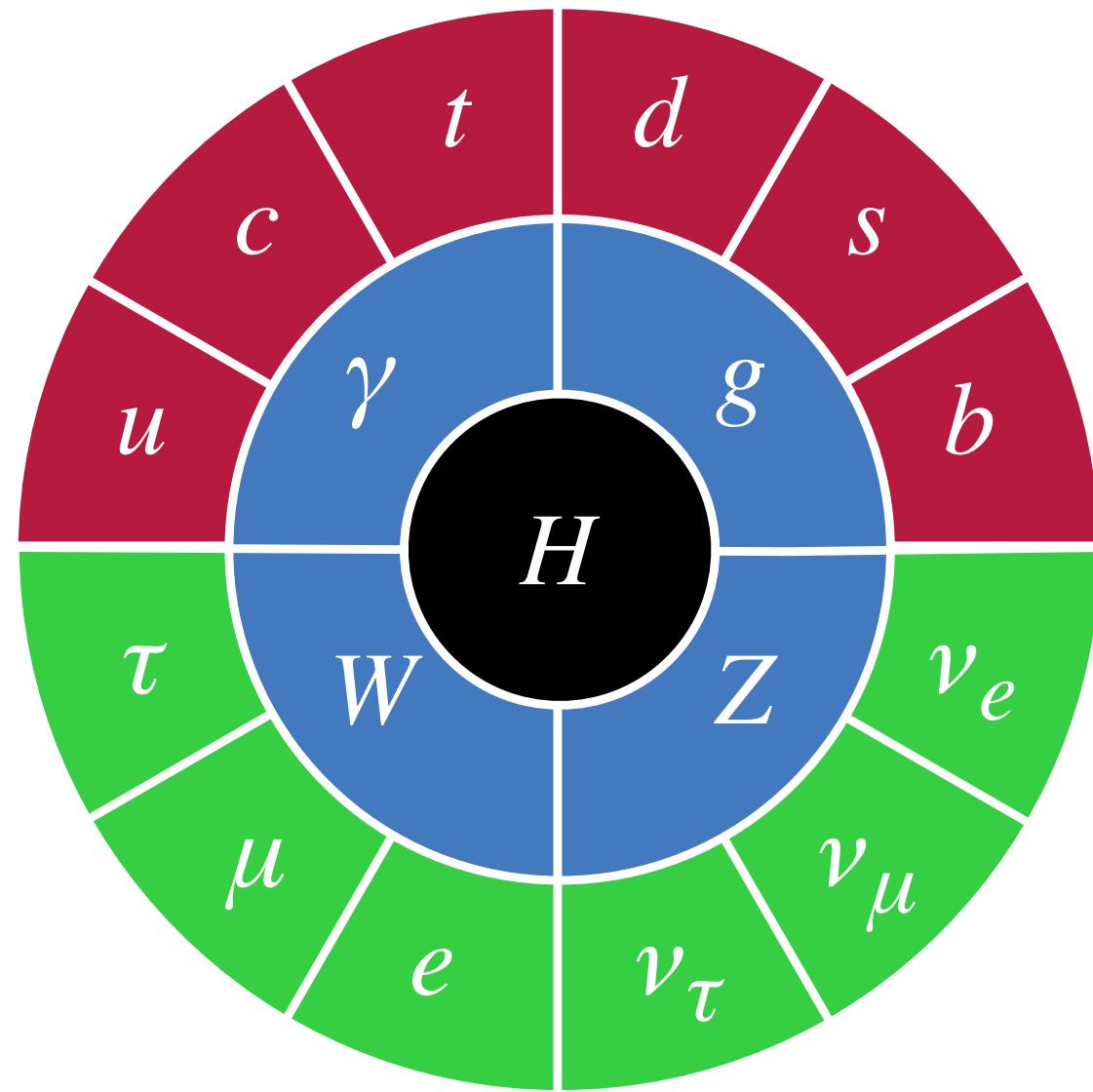
3. Higgs Mechanism

- Every particle interacts with a scalar (spin 0) field
- This field has non-zero Vacuum Expectation Value
 - Breaks symmetry between E&M and Weak Forces
 - Gives masses to all particles w/o breaking Gauge Symmetries



PARTICLE PHYSICS: 19 PARAMETERS

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}}_{\text{kinetic energies and self-interactions of the gauge bosons}} + \underbrace{\bar{L}\gamma^\mu(i\partial_\mu - \frac{1}{2}g\tau \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)L + \bar{R}\gamma^\mu(i\partial_\mu - \frac{1}{2}g'YB_\mu)R}_{\text{kinetic energies and electroweak interactions of fermions}} + \underbrace{\frac{1}{2}|(i\partial_\mu - \frac{1}{2}g\tau \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)\phi|^2 - V(\phi)}_{W^\pm, Z, \gamma, \text{and Higgs masses and couplings}} + \underbrace{g''(\bar{q}\gamma^\mu T_a q)G_\mu^a}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$



Symbol	Description	Value
m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_τ	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV
m_d	Down quark mass	4.4 MeV
m_s	Strange quark mass	87 MeV
m_c	Charm quark mass	1.32 GeV
m_b	Bottom quark mass	4.24 GeV
m_t	Top quark mass	172.7 GeV
θ_{12}	CKM 12-mixing angle	13.1°
θ_{23}	CKM 23-mixing angle	2.4°
θ_{13}	CKM 13-mixing angle	0.2°
δ	CKM CP-violating Phase	0.995
g_1	U(1) gauge coupling	0.357
g_2	SU(2) gauge coupling	0.652
g_3	SU(3) gauge coupling	1.221
θ_{QCD}	QCD vacuum angle	~0
v	Higgs vacuum expectation value	246 GeV
m_H	Higgs mass	125 GeV

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Flavor	Mass GeV/c ²	Electric charge	Approx. Mass GeV/c ²	Electric charge
ν_e electron neutrino	<0.08	0	0.000511	-1
e electron	0.000511	-1	d down	0.006
ν_μ muon neutrino	<0.0002	0	c charm	1.3
μ muon	0.106	2/3	s strange	1.75
ν_τ tau neutrino	<0.02	0	t top	175
τ tau	1.7771	2/3	b bottom	4.3

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/e = 6.58 \times 10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of e. The charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember $E = mc^2$), where 1 GeV = 10^9 eV = 10^{33} joule. The mass of the photon is 0.938 GeV/c² = 1.67×10^{-27} kg.

- Why Look Beyond the Standard Model?

- Takes 19 parameters (eg Masses)... Why these values?

- Still looking for the Higgs particle.

- Gravity not included! Why gravity is so much weaker than everything else?

- Misses a lot of the Universe: No Dark matter candidate. Can't explain Dark Energy.

- Doesn't have enough asymmetry between matter/anti-matter to explain why we exist!

- At ~ 1 TeV of energy, some of the SM predictions don't make sense. So something **new** has to happen at 1 TeV.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interaction between their color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons $q\bar{q}$ and baryons qqq .

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interaction between their color-charged constituents. It is similar to the residual electromagnetic interaction between two electrically neutral molecules. It can also be

PROPERTIES OF THE INTERACTIONS

Baryons qqq and Antibaryons q-q-q					
Baryons are fermionic hadrons.					
There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.94	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Matter and Antimatter
For every particle type there is a corresponding anti-particle type, denoted by a bar over the particle symbol. Particle and anti-particle have identical masses and charges. Some electrically neutral bosons (e.g., Z^0 , γ , and ν_e = $\bar{\nu}_e$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W^- boson. This is neutron β decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and \bar{B}^0 mesons via a virtual Z boson or a virtual photon.

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

Mesons qq					
Mesons are bosonic hadrons.					
There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
K ⁻	kaon	s \bar{u}	+1	0.140	0
ρ^+	rho	u \bar{d}	+1	0.770	1
B ⁰	B-zero	d \bar{b}	0	5.279	0
η_c	eta-c	c \bar{c}	0	3.980	0

Visit the award-winning web feature The Particle Adventure at <http://ParticleAdventure.org>

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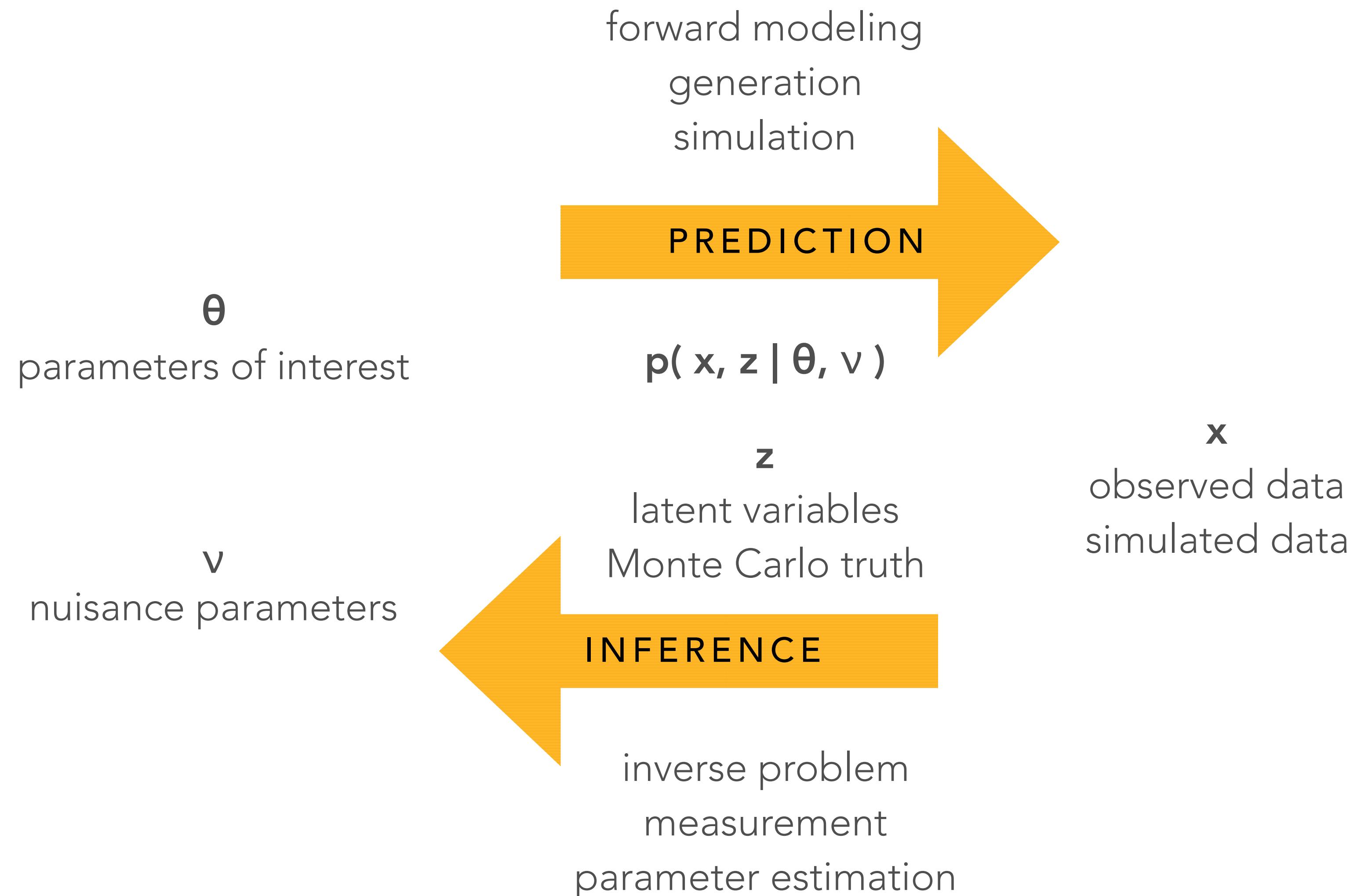
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Data Model

- Lets formalize what we mean by a **dataset** with a Probabilistic Model:
 - Assumption: Observed **Data is a mixture of M different processes**
 - Data set of N **data points**, $\{\{x_d\}_i\}$
 - each $\{x_d\}_i$ consisting of
 - d **observations** $\{x_d\}$
 - probability f_j of uniquely coming from one of M **classes**
 - each class has label c_j is indexed by j
 - dependent on parameters $\{a_k\}_j$ (some **parameters of interest**, some **nuisance parameters**)
 - Dependent on other parameters $\{\beta\}$
 - $\Rightarrow P(\{x\}|\theta) = P(\{x\}|\{f_j, c_j, \{\{a_k\}_j\}, \{\beta_l\}\}) = \sum_j f_j P(\{x\}|c_j, \{a_k\}_j, \{\beta_l\})$

What is it good for?

- If we know $P(X|\theta)$, what is it good for? (Statistical Inference)
 - ***Prediction***: Assume $\theta \implies$ distribution of $\{x_d\}$.
 - ***Classification***: Observation $\{x_d\} \implies$ most likely class c
 - ***Regression***: Dataset $\{\{x_d\}_i\} \implies$ parameters of interest $\{a_j^k\}$ or $\{\beta_l\}$
 - ***Hypothesis test***: Dataset $\{\{x_d\}_i\} \implies$ is H_1 true (or H_0 null hypothesis)



Data Analysis

- Objectives:
 - **Searches** (hypothesis testing): Likelihood Ratio Test (Neyman-Pearson lemma)
 - **Limits** (confidence intervals): Also based on Likelihood
 - **Measurements**: Maximum Likelihood Estimate

$$\frac{P(x|H_1)}{P(x|H_0)} > k_\alpha$$

- **Likelihood**

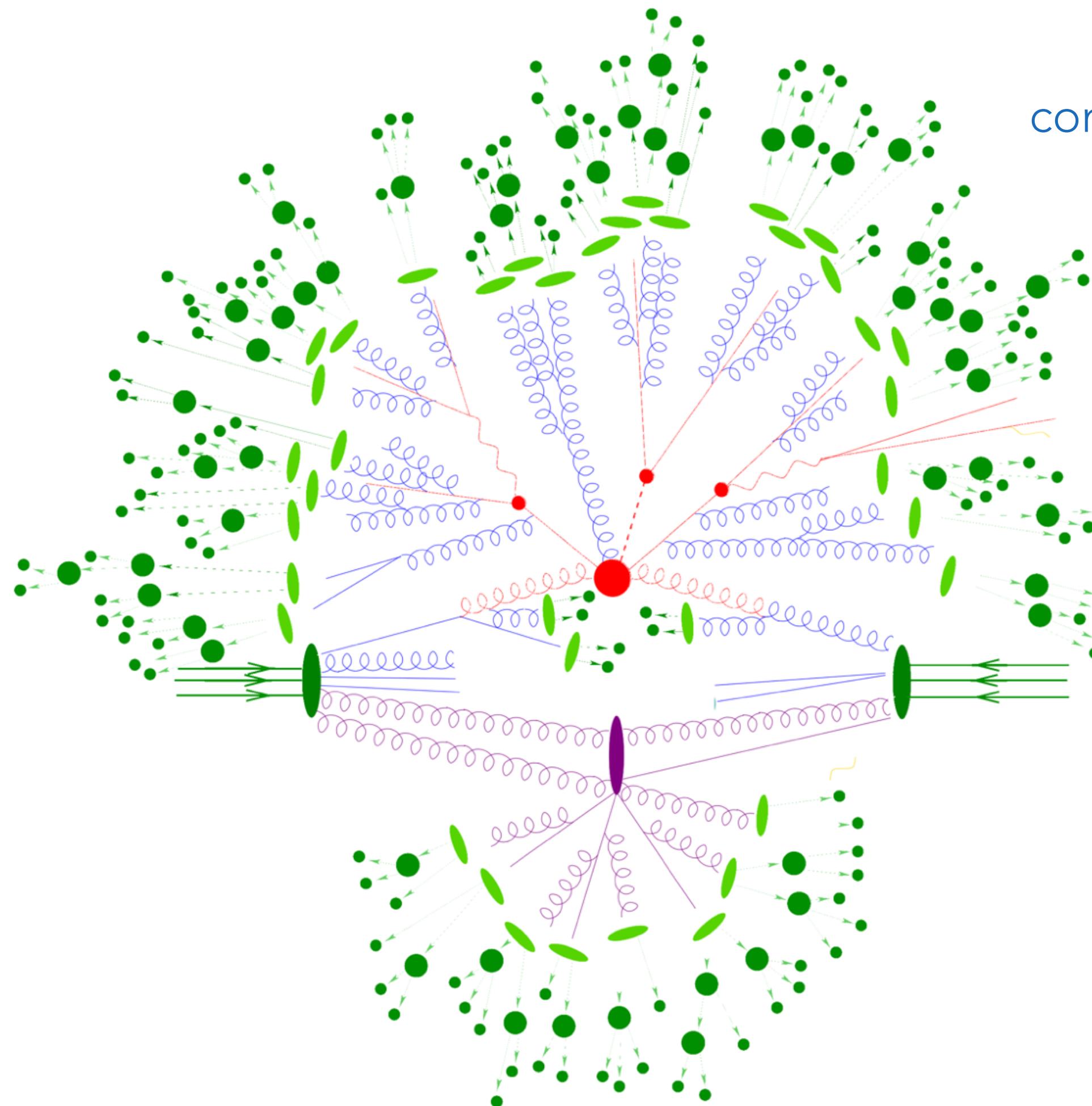
$$p(\{x\}|\theta) = \text{Pois}(n|\nu(\theta)) \prod_{e=1}^n p(x_e|\theta)$$

- n Independent Events (e) with Identically Distributed Observables ($\{x\}$)
- Significant part of Data Analysis is **approximating the likelihood** as best as we can.

Obtaining the Likelihood

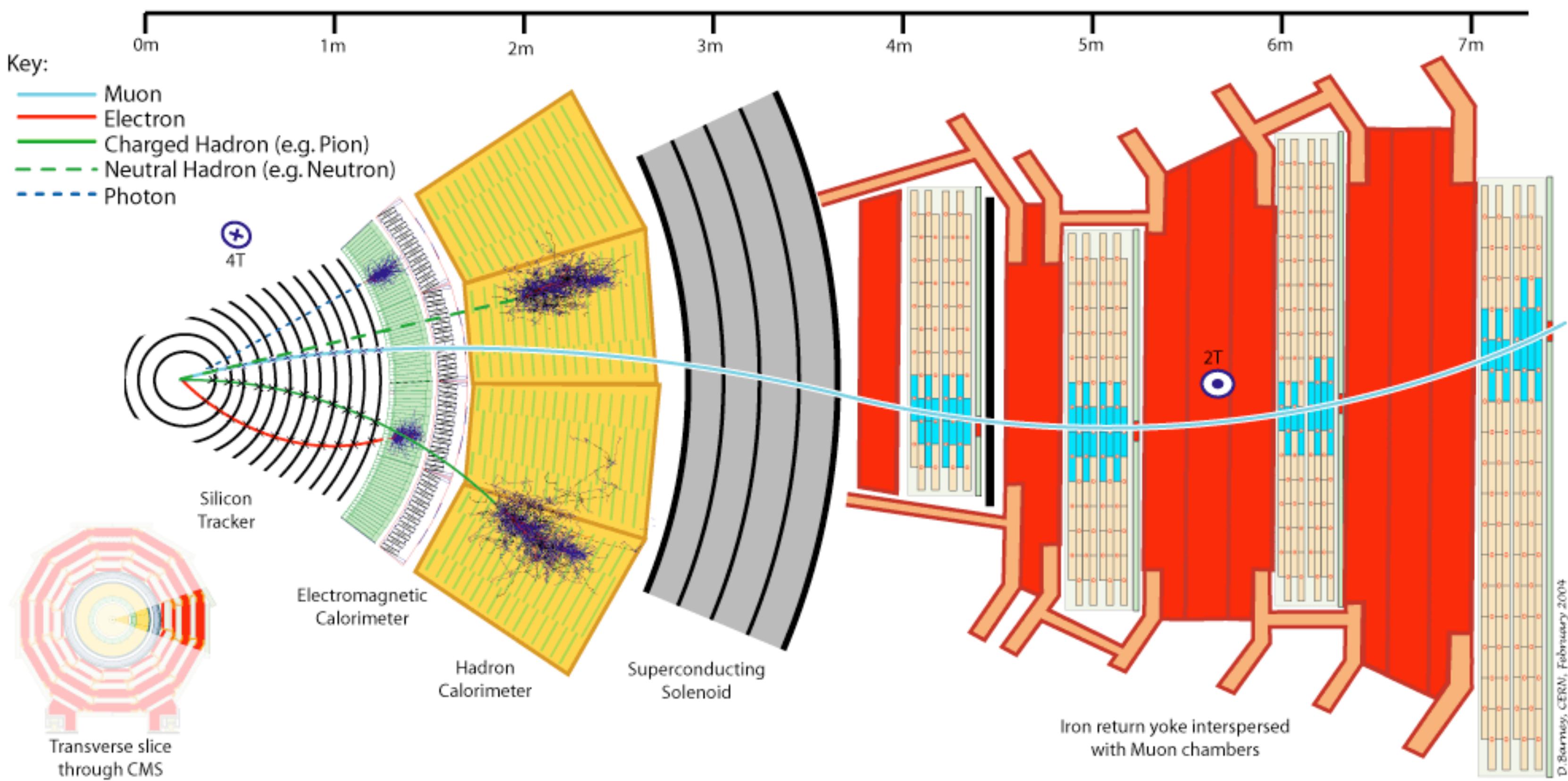
- How do we obtain $P(X|\theta)$?
 - In HEP, we have precise ***algorithmic simulations*** that generate $\{x_d\}$ given θ .
 - We estimate P by comparing observed x_d with simulated $\{x_d\}$.
 - We can build ***analytical first principle models***. *Matrix Element Method* is such a technique.
 - But it's technically difficult, computationally expensive, and only tractable with physics and detector simplifications.
 - We can build a statistical model P based on previous data.
 - We can use ML to learn P from simulation or data.

pencil & paper calculable from first principles
 $p(z_1 | \theta)$



controlled approximation of first principles
 $p(z_2 | z_1, v_1)$

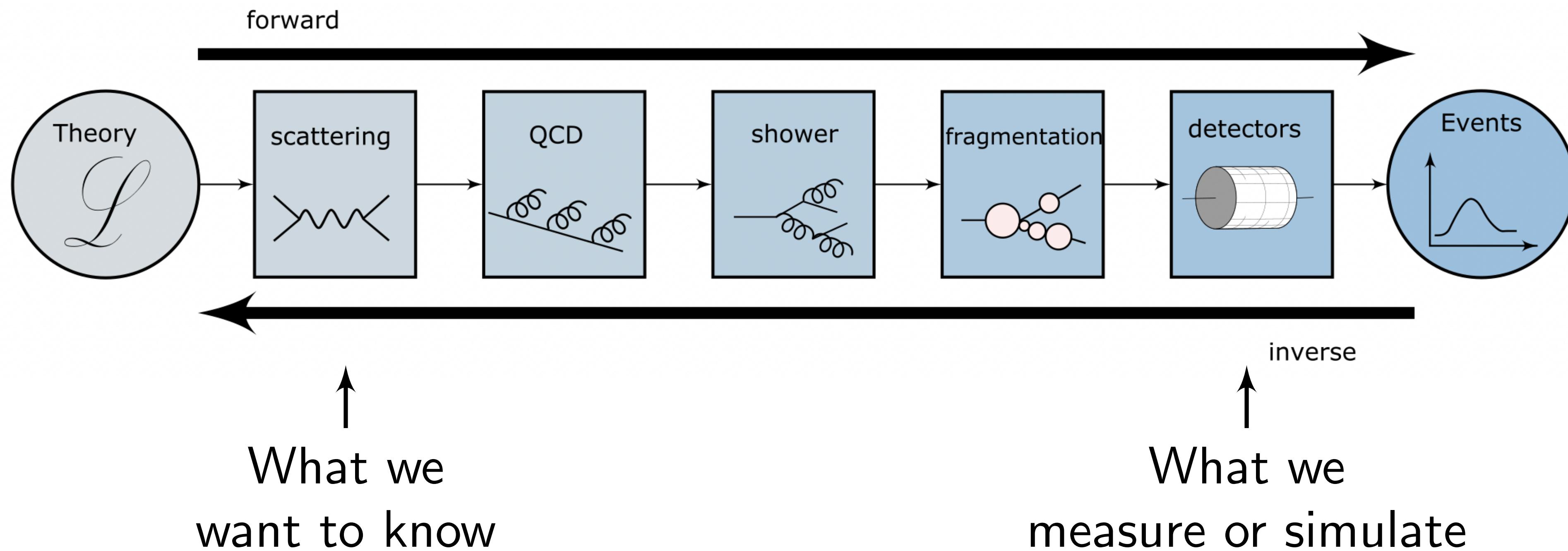
phenomenological model
 $p(z_3 | z_2, v_2)$



Detector Simulation $p(x | z_3, v_3)$:

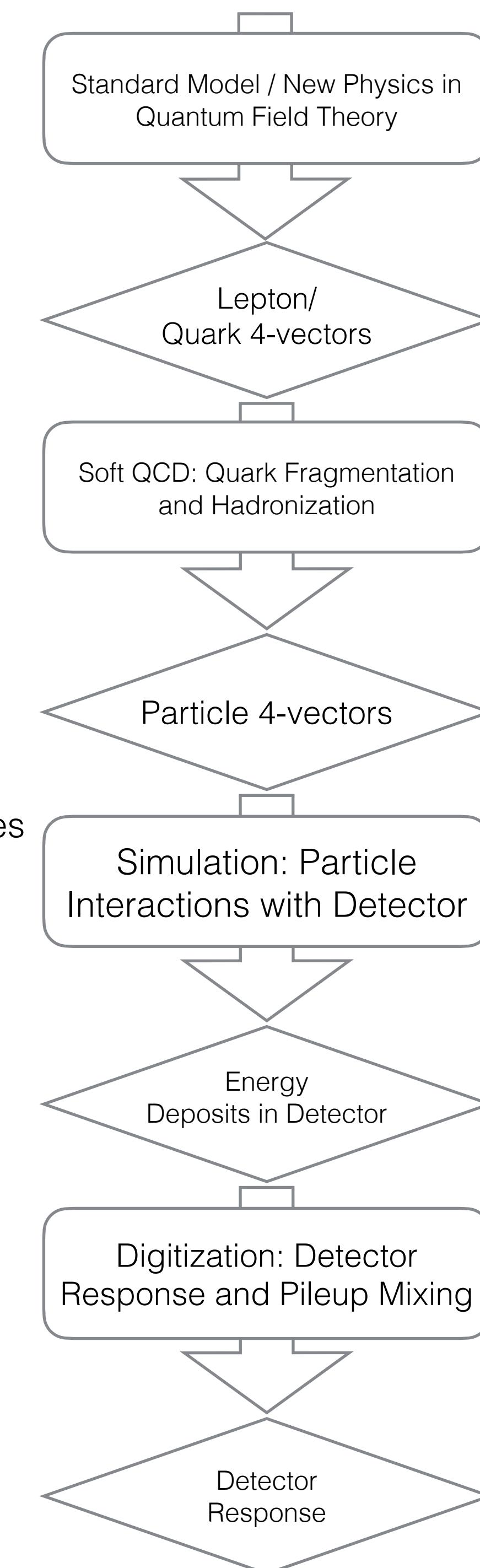
- detailed engineering (eg. CAD)
- in situ measurements of temperature, magnetic field, alignment, calibration constants
- first-principles description of interaction of particles with matter
- measured interaction of particles with matter

Simulation for LHC



Algorithmic Simulation

- Physics is all about establishing a very precise “model” of the underlying phenomena... so in general ***we can model our data very well.***
- For example for LHC we do ***multi-step ab-initio simulations:***
 1. ***Generation:*** Standard Model and New Physics are expressed in language of Quantum Field Theory.
 - Feynman Diagrams simplify perturbative prediction of HEP interactions among the most fundamental particles (leptons, quarks)
 2. ***Hadronization:*** Quarks turn to jets of particles via Quantum Chromodynamics (QCD) at energies where theory is too strong to compute perturbatively.
 - Use semi-empirical models tuned to Data.
 3. ***Simulation:*** Particles interact with the Detector via stochastic processes
 - Use detailed Monte Carlo integration over the “micro-physics”
 4. ***Digitization:*** Ultimately the energy deposits lead to electronic signals in the O(100 Million) channels of the detector.
 - Model using test beam data and calibrations.
- Output is fed through ***same reconstruction as real data.***



Likelihood Approximations

- Need $P(\{x_d\} | \theta)$ of an observed event (i). The better we do, the more sensitive our measurements.
- Steps 2 (Hadronization) and 3 (Simulation) can only be done in the ***forward mode***...
 - ***cannot evaluate the likelihood***.
- So we simulate a lot of events and generally use histograms (a crude *Probability Density Estimator (PDE) technique*)
 - $\{x_d\} = \{100M$ Detector Channels} or even { particle 4-vectors } are too high dimensional.
 - Curse of dimensionality... more on this later
 - Instead we derive $\{x_d\} = \{ \text{small set of physics motivated observables} \}$ → ***Lose information***.
 - ***Isolate signal*** dominating regions of $\{x_d\}$ → ***Lose efficiency***.
 - Sometimes use ***ML-based classifiers*** to further reduce dimensionality and improve significance
 - ***Profile the likelihood*** in 1 or 2 (ideally uncorrelated) observables.