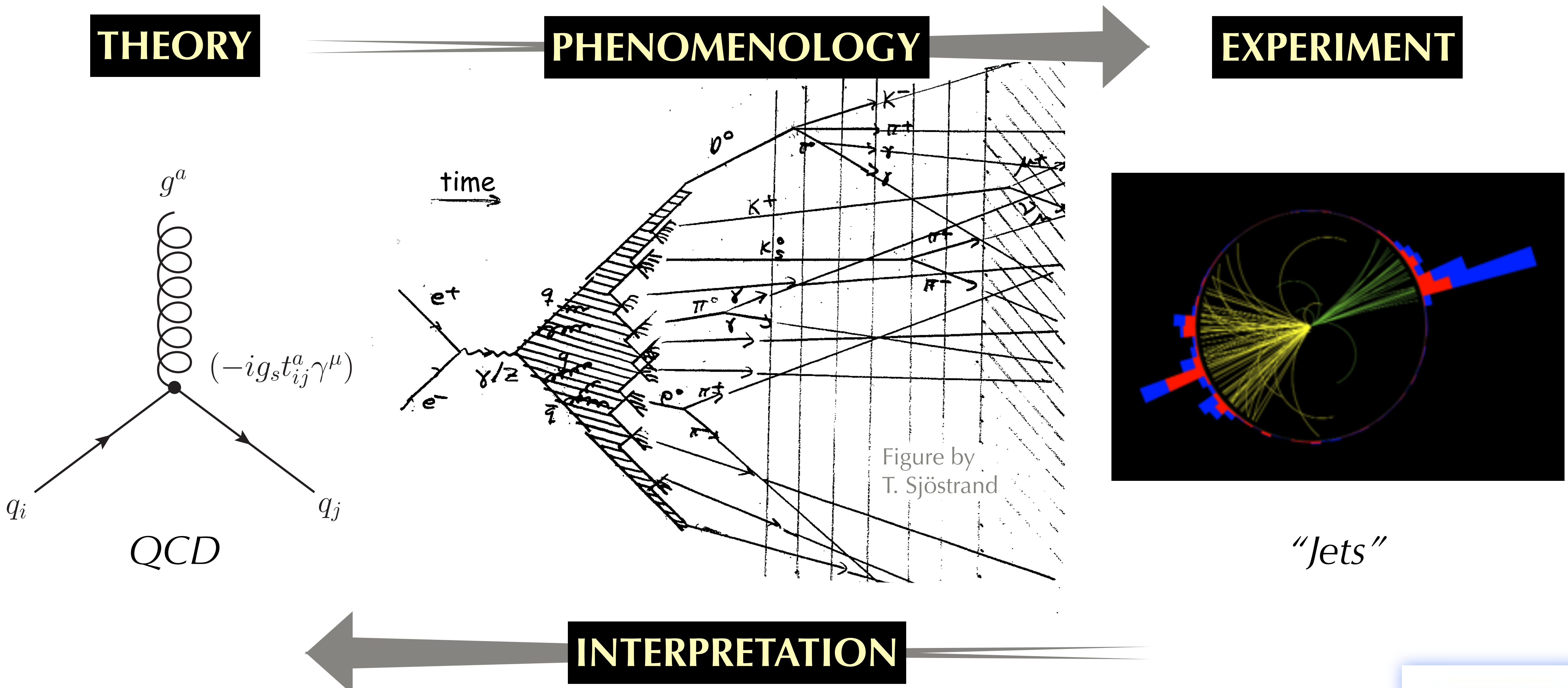
Particle Physics Phenomenology

Peter Skands, Monash University



October 1-2, 2015, Sydney

Spring School on Particle Physics & Cosmology

The Phenomenology Pipeline

Come up with theory **idea** (e.g., SM, SUSY, QGP, ~~CP~~, …)

… should be testable in experiments

Formulate phenomenological **model** (based on theoretical ideas)

… working-hypothesis physics model capturing essence of idea

Propose new sensitive **observables** (based on models)

… which can be measured in experiments

Make (detailed and precise) **calculations**

… which can be compared (statistically) against experiments

Provide theoretical **interpretations**

… of the experimental results

Masses (& units)

The main particle-physics units of energy is MeV, GeV, TeV

1 electron-Volt = kinetic energy obtained by an electron accelerated by potential difference of 1 Volt

$$1\,\mathrm{eV} \;=\; Q_e \cdot 1\,\mathrm{V} \;=\; 1.602176565(35) \times 10^{-19}\,\mathrm{C} \cdot 1\,\mathrm{J/C} \;=\; 1.6 \times 10^{-19}\,\mathrm{J}$$

(So for accelerators, the beam energy in eV is a measure of the equivalent electrostatic potential difference, for unit charge)

Planned **linear** accelerators (ILC, CLIC) could reach E_{CM} ~ 1000 GeV.

The highest-energy (**circular**) accelerator LHC ~ 6500 GeV/beam.

Using E=mc^2 we typically express mass in units of eV/c^2

$$\begin{aligned} m_e &= 9.11 \times 10^{-31}\mathrm{kg} = 0.511 \;\; \mathrm{MeV}/c^2 \\ m_\mu &= 106 \;\; \mathrm{MeV}/c^2 \\ m_\tau &= 1780 \;\; \mathrm{MeV}/c^2 \end{aligned}$$

$$m_{\mathrm{proton}} = 938\ \mathrm{MeV}/c^2 \sim 1\ \mathrm{GeV}/c^2$$

(sometimes we don't even say the 1/c^2; it is implied by the quantity being mass)

Natural Units

In fact, we use MeV and GeV for ***everything***!

Define a set of units in which $\hbar = c = 1$

Action [Energy*Time] : dimensionless ($\hbar = 1$)

All actions are measured in units of $\hbar$

Velocity [Length/Time] : dimensionless ($c = 1$)

All velocities are measured in units of c (i.e., $\beta = v/c$)

Energy : dimension 1

Mass : dimension 1 (E=m)

E.g., $m_p = 0.94$ GeV; masses ~ measured in units of m_p

Time : dimension -1 ($\Delta E \Delta t \geq 1$; $E = 2\pi\nu$)

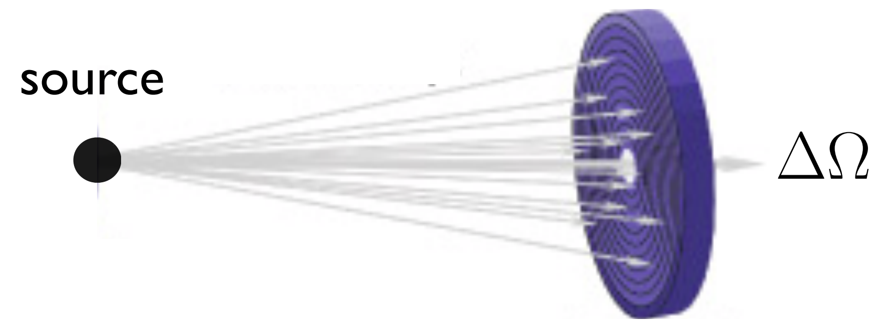
Length : dimension -1 (velocity is dimensionless)

Momentum : dimension 1 ($\Delta p \Delta x \geq 1$)

Example:
lengths → energies

	λ	➡ E
HEP	< 1 fm	> 1 GeV
gamma	1 pm	1 MeV
X-rays	0.1 nm	10 keV
UV	100 nm	10 eV

Scattering Experiments



LHC detector
Cosmic-Ray detector
Neutrino detector
X-ray telescope
…

→ Integrate differential **cross sections** over specific **phase-space** regions

Predicted number of counts
= integral over solid angle

$$N_{\mathrm{count}}(\Delta\Omega) \propto \int_{\Delta\Omega} \mathrm{d}\Omega \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$$

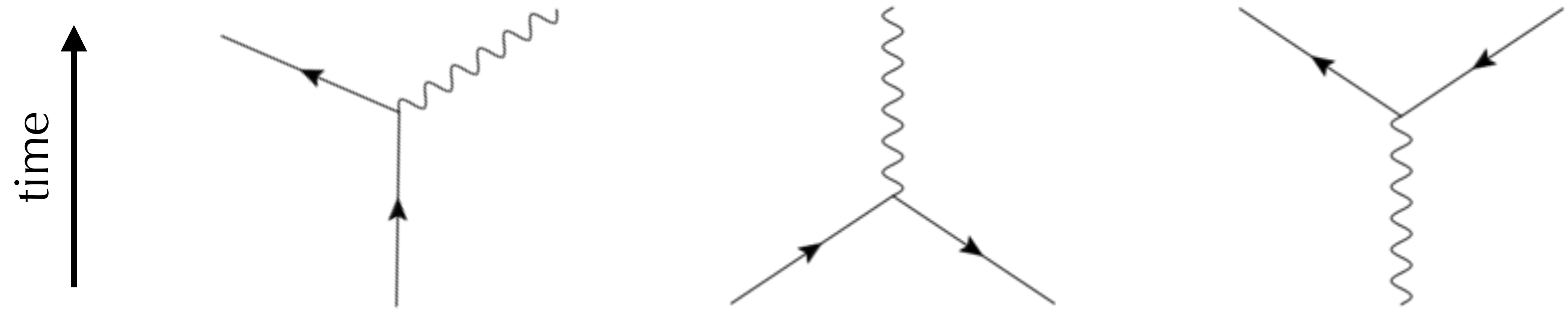
$$\mathrm{d}\Omega = \mathrm{d}\cos\theta\,\mathrm{d}\phi$$

In particle physics:
Integrate over all quantum histories
(+ interferences)

Preview of Interacting Quantum Field Theory

Consider Electromagnetism = electron-photon interactions

All based on the same vertex



1) $e \to e + \gamma$ 2) $e^- + e^+ \to \gamma$ 3) $\gamma \to e^- + e^-$

What about 4-momentum conservation?

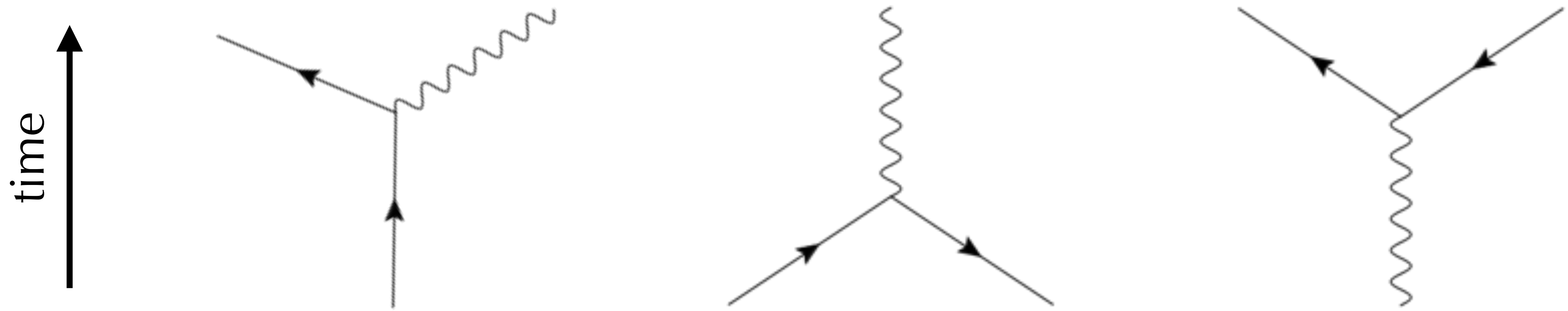
1) Electron at rest decaying to a recoiling electron + a photon?
2) Two massive particles reacting to produce a massless photon?
3) Massless photon decaying to two massive electrons?

This all sounds very strange (even for relativity)

Virtual Particles

Let us consider first the pure electromagnetic interactions

All based on the same vertex



1) $e \to e + \gamma$ 2) $e^- + e^+ \to \gamma$ 3) $\gamma \to e^- + e^-$

What about 4-momentum conservation?

At least one of the involved particles must have $E^2 - p^2 \neq m^2$

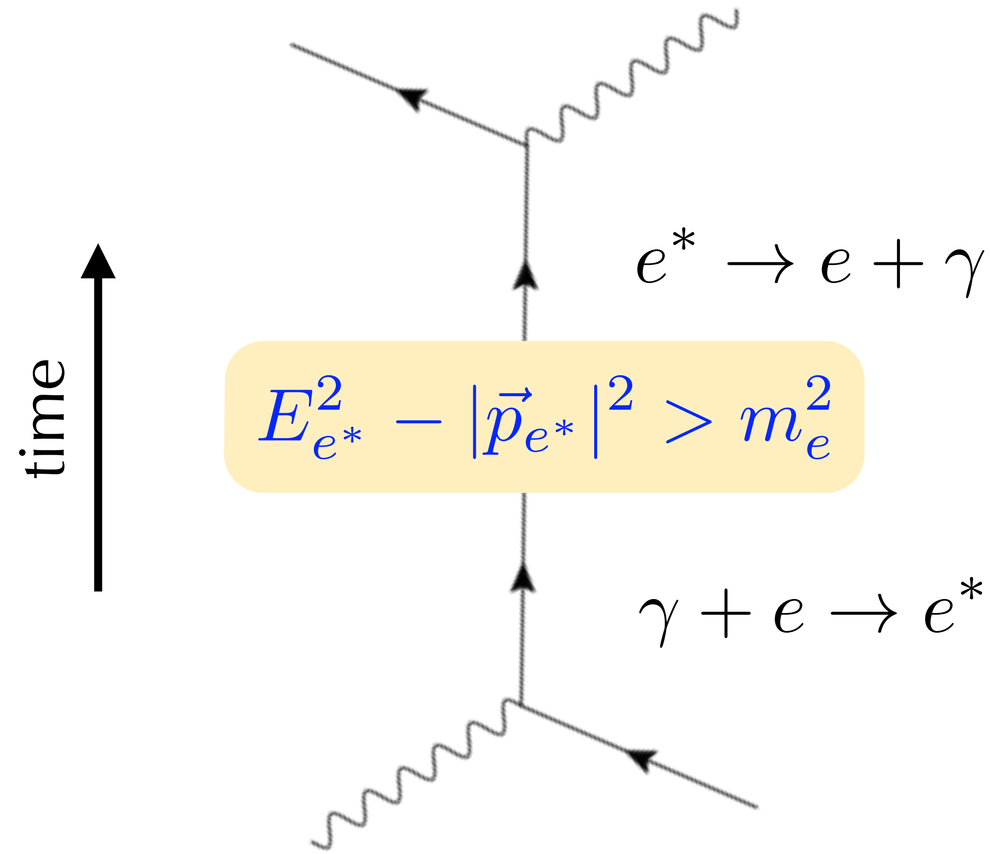
(Can exist for a brief time due to Heisenberg)

We call such particles **virtual**; and say they are **off mass shell**

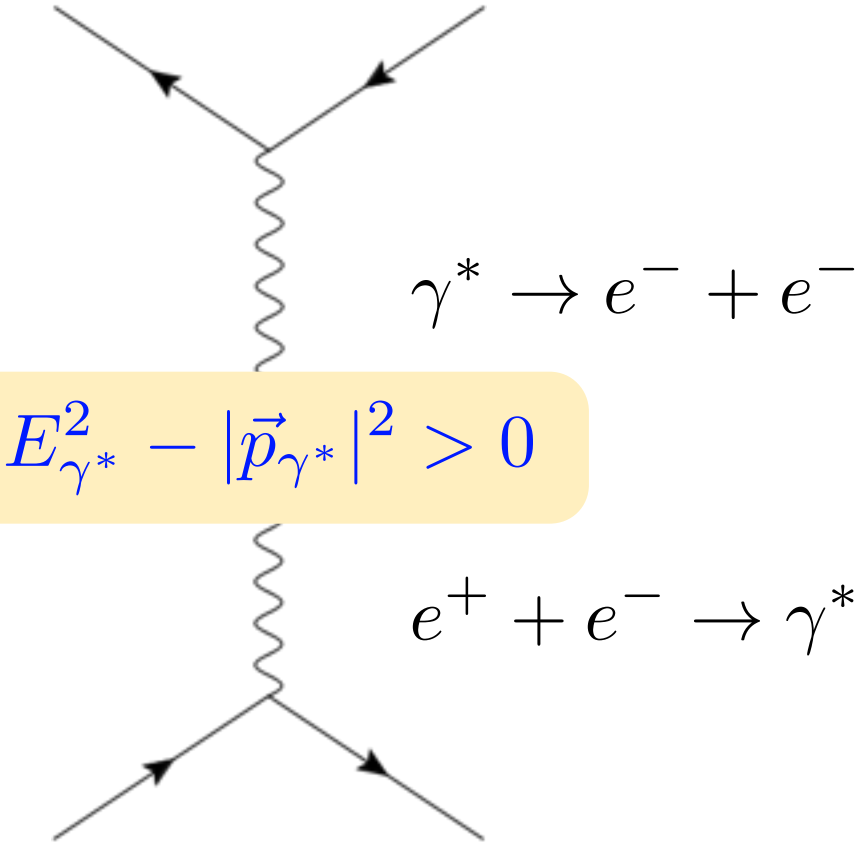
Virtual Particles: Examples

Stitch vertices together to form **Feynman diagrams**

EXTERNAL PARTICLES: "ON SHELL"; **INTERNAL** ONES CAN BE "OFF SHELL"



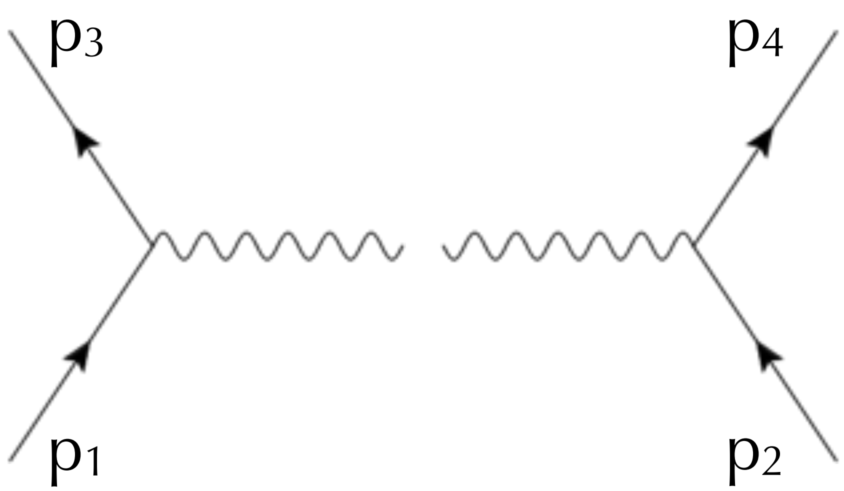
$$E_{e^*}^2 - |\vec{p}_{e^*}|^2 > m_e^2$$



$$E_{\gamma^*}^2 - |\vec{p}_{\gamma^*}|^2 > 0$$

A) $E_{\gamma^*}^2 - |\vec{p}_{\gamma^*}|^2 > 0$?

B) $E_{\gamma^*}^2 - |\vec{p}_{\gamma^*}|^2 < 0$?



(for $m_e = 0$)

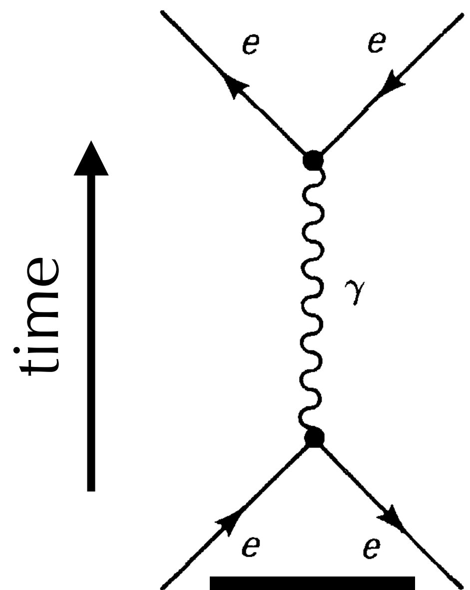
$$p_\gamma^2 = (p_1 - p_3)^2$$

Feynman Diagrams

Quantum Field Theory (QFT)

We use **Feynman diagrams** to draw the possible histories

These are symbolic (correspond to state changes in the underlying QFT)



BHABHA

Diagram representing QM amplitude for:
"an electron and a positron annihilated to produce a (virtual) photon, which then split back up into an e^+ e^- pair again."

$$e^-(p_1) + e^+(p_2) \to e^-(p_3) + e^+(p_4)$$

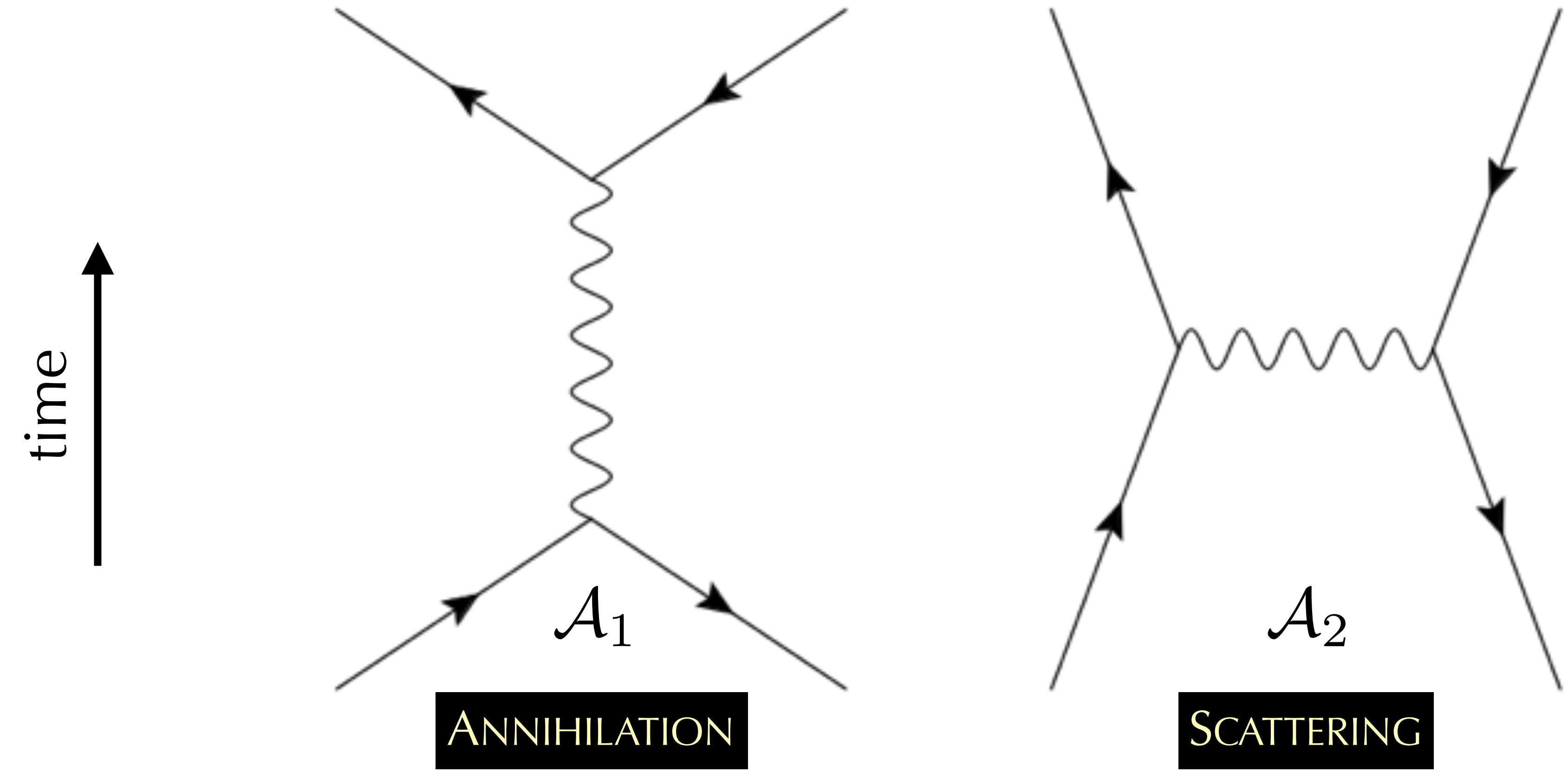
E.g., in Bhabha scattering, the force is attractive (an electron and a positron attract) but we still draw them as heading away from each other)

EXAMPLE (UNITS IN GEV):

$$p_1 = (5, 0, 0, 5)$$
$$p_2 = (5, 0, 0, -5)$$
$$p_3 = (5, 0, 3, 4)$$
$$p_4 = (5, 0, -3, -4)$$

(Interferences)

Actually, two Quantum "histories" contribute to Bhabha



Must sum both amplitudes; then square to get probability

(two "paths"; analogously to double-slit experiment)

$$|\mathcal{A}|^2 = |\mathcal{A}_1 + \mathcal{A}_2|^2 = |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + 2\mathrm{Re}\left[\mathcal{A}_1\mathcal{A}_2^*\right]$$

Q.M. interference

Physical Observables = Event Rates

Scattering : cross sections

Want to express scattering probability independently of the intensity (flux) of incident particles (beams)

N_{events} = Probability-per-particle * Number-of-particles

➜ N_{events} = Probability [area/particle] * Nparticles/area

➜ N_{events}/time = Probability [area/particle] * Nparticles/area/time

Event Rate = Cross Section * Luminosity

"σ"

Measure in Experiment
Compare with Prediction

Calculate from
fundamental theory

Determined by
accelerator parameters.
In principle measurable
(eg Van der Meer scans)

Physical Observables = Event Rates

Disintegration : decay rates

Murphy's law for particles: anything that **can** decay, **will** decay

What we actually measure is typically a cross section times a branching fraction

E.g., the event rate for $h^0 \to \gamma\gamma$ observed at LHC is compared to a theoretical calculation of

$N(h^0 \to \gamma\gamma)_{LHC} = \mathrm{sigma}(pp \to h^0) * BR(h^0 \to \gamma\gamma) * L_{pp} \quad * <\mathrm{efficiency}>$

How does a particle decay?

It sits in its rest frame and gets time evolved, by e^{iHt}

Unstable ➜ H contains operators that want to kill it …

They compete about which one goes first (can only decay once)

Decay Rates

Particles are **elementary**, indistinguishable.

Any "history" information is encoded in their quantum numbers

An "old" particle doesn't have a higher probability of decaying in the next second than a "young" one

What matters is the instantaneous decay rate per unit time

$$\mathrm{d}N = -\Gamma N \mathrm{d}t \quad \rightarrow \quad N(t) = N(0)e^{-\Gamma t} \quad \rightarrow \quad \tau = \frac{1}{\Gamma}$$

Generalise to multiple different decay modes

$$\Gamma = \sum_i \Gamma_i$$

Γ_i : *"Partial Width"*

$$\text{Branching Ratio} : \mathrm{BR}(i) = \frac{\Gamma_i}{\sum_j \Gamma_j}$$

or *"branching fraction"*

π^+ DECAY MODES K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+ \nu_\mu$	[a]	(99.98770 ± 0.00004) %	
Γ_2	$\mu^+ \nu_\mu \gamma$	[b]	$(2.00 \pm 0.25) \times 10^{-4}$	
Γ_3	$e^+ \nu_e$	[a]	$(1.230 \pm 0.004) \times 10^{-4}$	
Γ_4	$e^+ \nu_e \gamma$	[b]	$(7.39 \pm 0.05) \times 10^{-7}$	
Γ_5	$e^+ \nu_e \pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$	
Γ_6	$e^+ \nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$	
Γ_7	$e^+ \nu_e \nu \overline{\nu}$		$< 5 \times 10^{-6}$	90%

example from the "PDG book" *pdg.lbl.gov*

Thresholds

An object cannot be produced unless the colliding particles have enough CM energy to create its rest mass

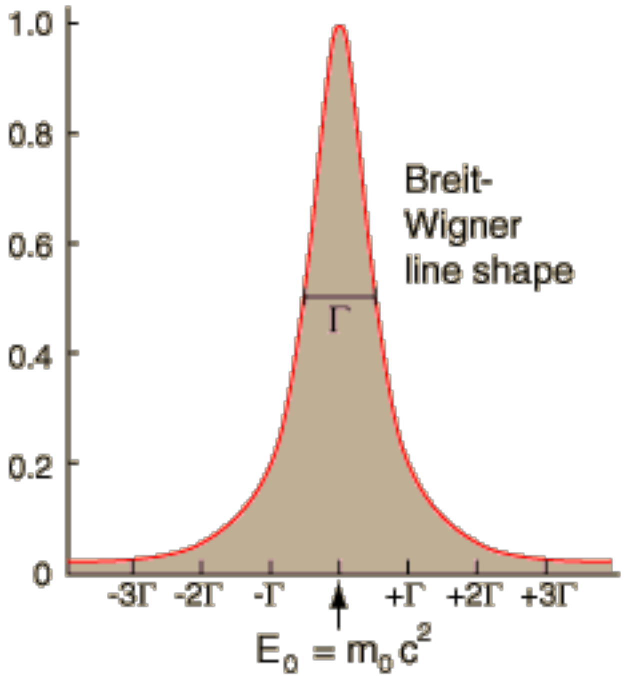
An object cannot decay to any (combination of) particles heavier than itself

Unless …

Heisenberg: the energy is uncertain…

If a particle is unstable (has a non-zero decay rate), then we at most have the duration of its life to measure its energy.

Analogous to line-broadening of lines in spectra of excited atoms



➜ *Shapes like this:* "Breit-Wigner" "resonances"

The Cross Section

Quantity of interest:

Effective cross-sectional area presented by a "target particle" to a stream of "incident particles"

- Relativity ➜ must get the same if we swap the roles of incident and target particles, or in any other frame
- So more precisely it's really the cross-sectional area two streams of particles present to each other

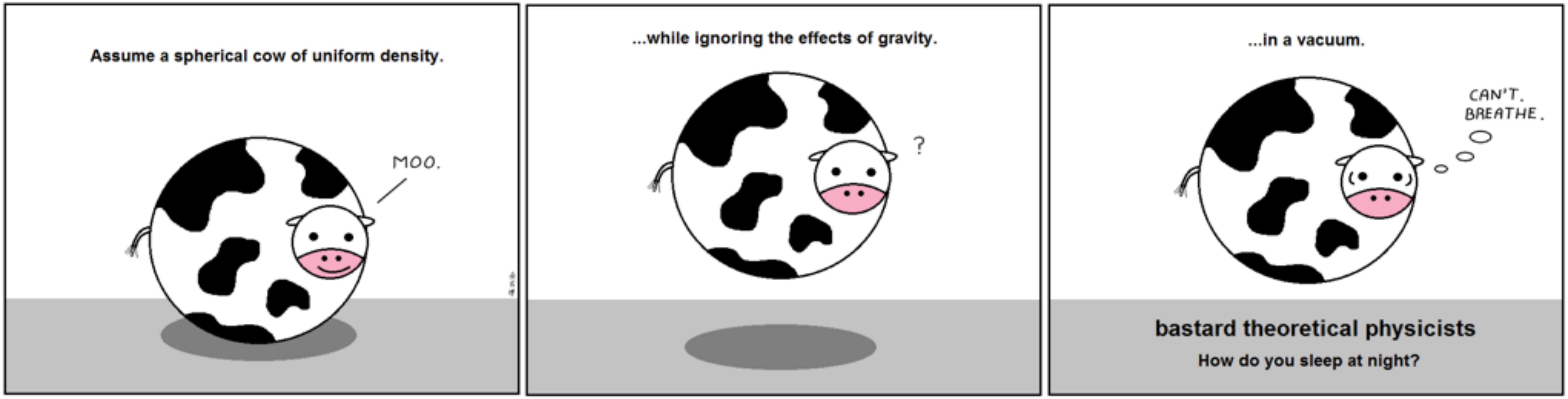
Complications

This isn't classical physics: each particle has a probability to go through the target unaffected, + all possible scatterings

- A plane wave comes in
- An interaction Hamiltonian (of which the incoming plane wave is not an eigenstate) evolves it for a while
- ➜ the evolved state is a superposition of **all possible outgoing states**

+ not only ***elastic*** scattering. Creation + annihilation : ***inelastic***.

Scattering off a Hard Spherical Cow



What's the total cross section?

(Scattering off a hard sphere)

Generalise to quantum scattering of relativistic particles: ***Quantum Field Theory***

Fermi's Golden Rule

Two basic ingredients to **calculate** decay rates and cross sections

1) The **amplitude** for the process: $\mathcal{M}$

Contains all the *dynamical* information; couplings, propagators, …

Calculated by evaluating the relevant Feynman Diagrams, using the **"Feynman Rules"** for the interaction(s) in question

2) The **phase space** available for the process

Contains only *kinematical* information;

Depends only on external masses, momenta, energies;

"Counts" the number/density of available final states

The Golden Rule is*: $$\text{transition rate} = \frac{2\pi}{\hbar}|\mathcal{M}|^2 \times (\text{phase space})$$

**For a derivation, see QM (nonrelativistic) or QFT (relativistic)*

Many from One (well … from Two, really)

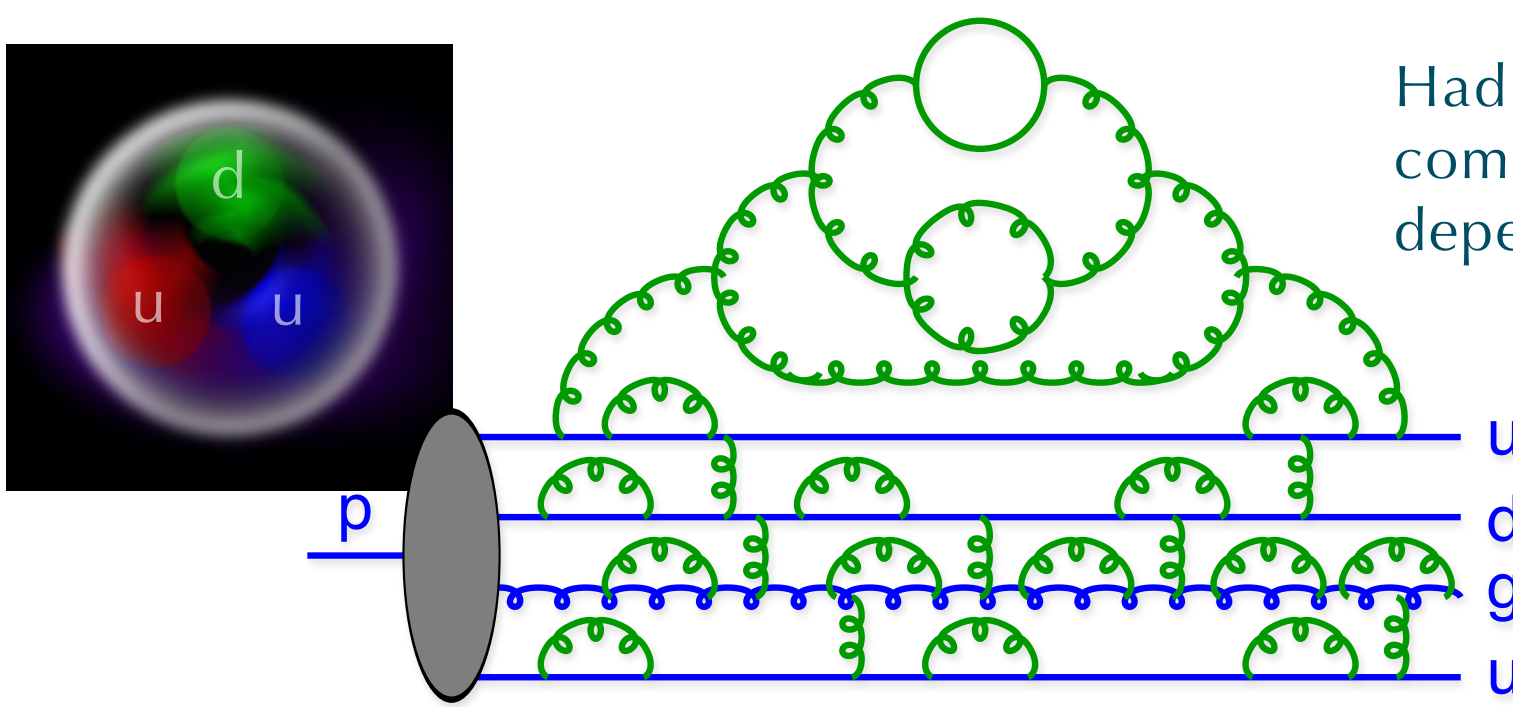
Quantum processes convert the kinetic energy of the beam particles into rest energy (mass) + momentum of outgoing particles

$$E = mc^2\sqrt{1 + p^2/(m^2c^2)}$$

E = *energy*
m = *mass*
p = *momentum*
c = *speed of light*

What are we really colliding?

Take a look at the quantum level



Hadrons are composite, with time-dependent structure

Pheno at the LHC

Many from One (well … from Two, really)

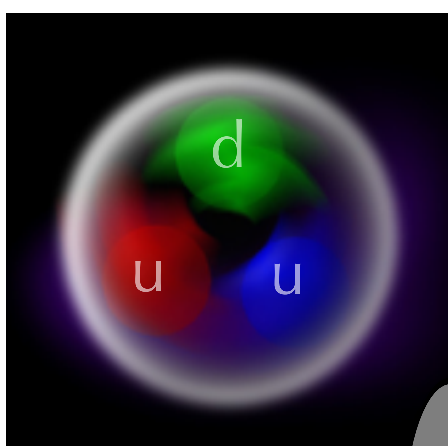
Quantum processes convert the kinetic energy of the beam particles into rest energy (mass) + momentum of outgoing particles

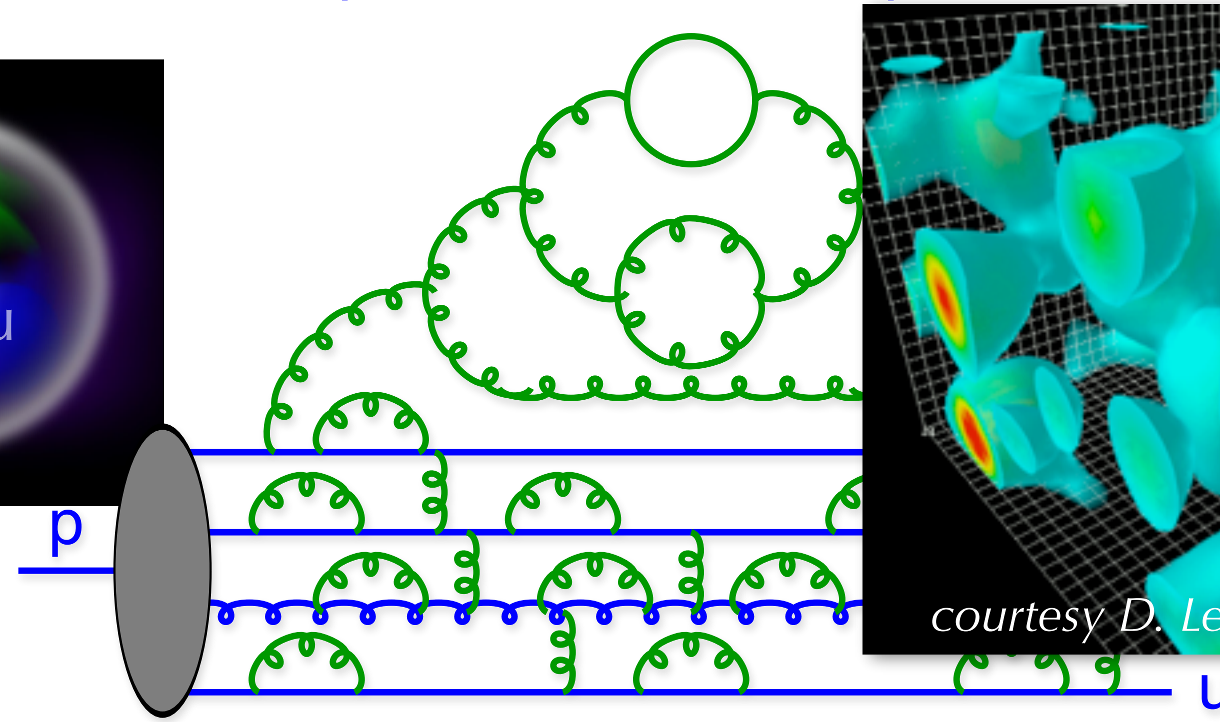
$$E = mc^2\sqrt{1 + p^2/(m^2c^2)}$$

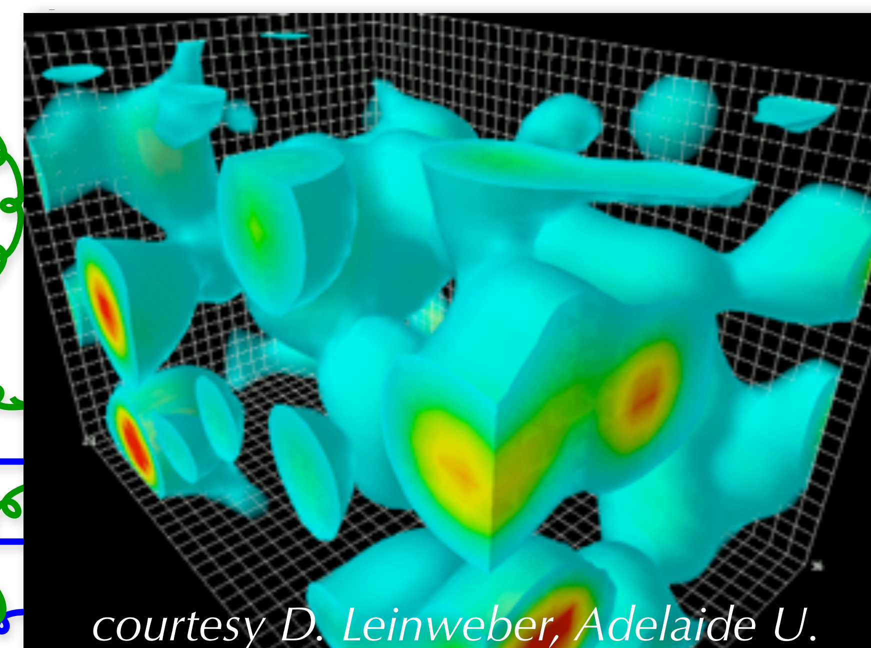
E = energy
m = mass
p = momentum
c = speed of light

What are we really colliding?

Take a look at the quantum level







courtesy D. Leinweber, Adelaide U.

Such Stuff as Beams are Made Of

Lifetime of typical fluctuation ~ r_p/c (=time it takes light to cross a proton)

~ 10^{-23} s; Corresponds to a frequency of ~ 500 billion THz

To the LHC, that's slow! (reaches "shutter speeds" thousands of times faster)

Planck-Einstein: $E=h\nu$ ➜ ν_{LHC} = 13 TeV/h = 3.14 million billion THz

➜ Protons look "frozen" at moment of collision

But they have a lot more than just two "u" quarks and a "d" inside

Hard to calculate, so use statistics to parametrise the structure: **parton distribution functions** (PDFs)

Every so often I will pick a gluon, every so often a quark (antiquark)

Measured at previous colliders, as function of energy fraction

Then compute the probability for all possible quark and gluon reactions and compare with experiments …

Rates and Triggers

We get ~ 40 million collisions / sec.

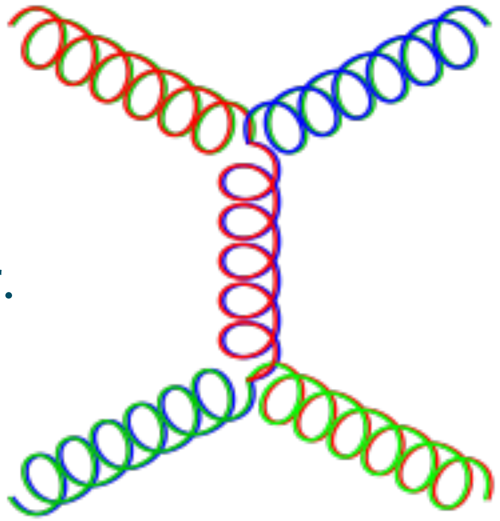
We can save ~ 100 / sec to disk.

WHICH ONES?

Automated "trigger" systems decide which collisions may be interesting

Not all reactions are created equally

- The most likely collision type is gg → gg
- The top quark is the heaviest elementary particle
  - Discovered in 1995 by Fermilab's "Tevatron" accelerator.
  - The LHC can make ~ 1 top quark / second.
- The reaction gg → Higgs will happen ~ 1 / minute
  - We don't want to loose too many of them …



Easy to collect millions of events of "high-cross-section-physics"

➜ Test models of "known physics" to high precision

Triggers target the ***needles in the haystack***

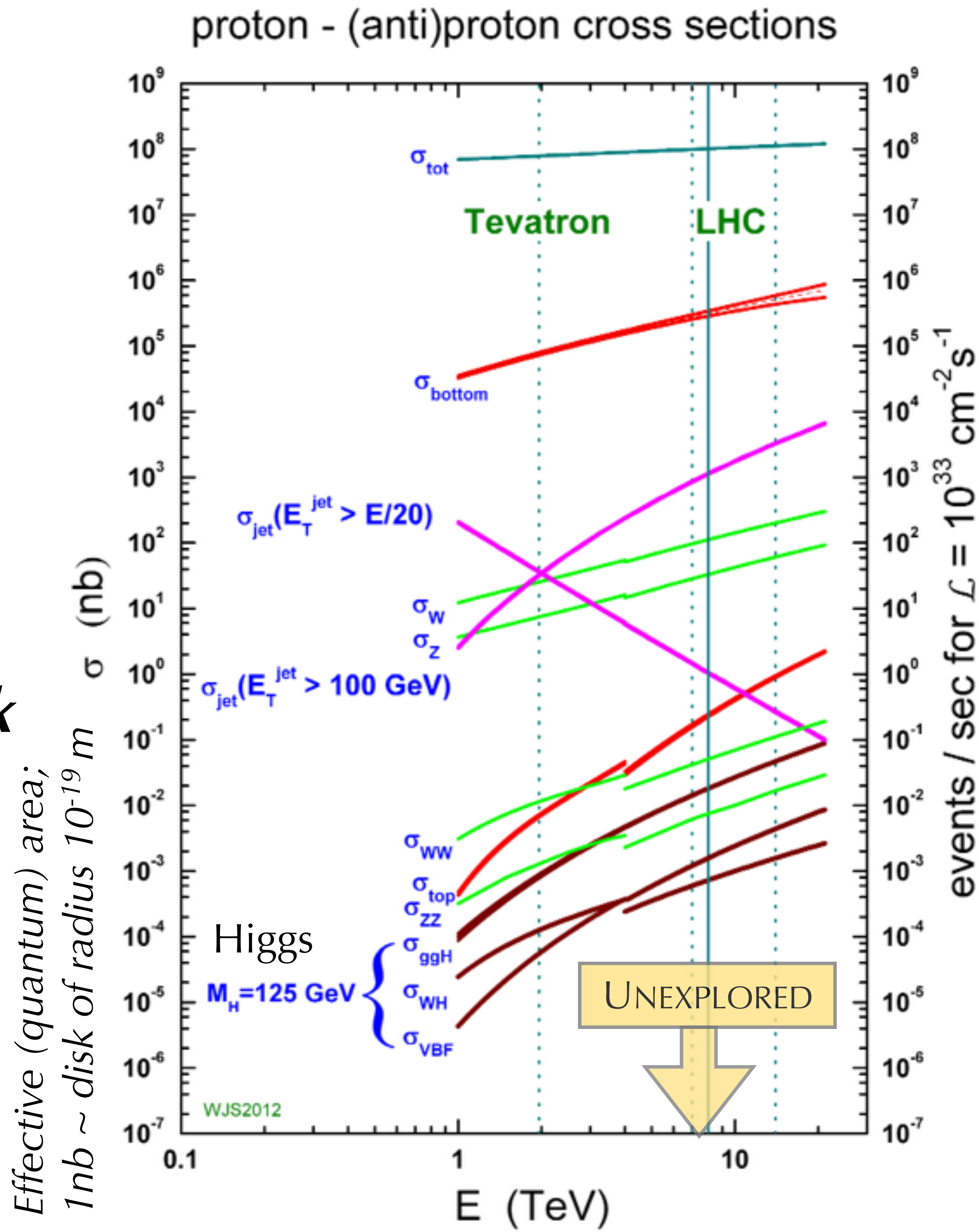
Trigger on signatures of decays of heavy particles, violent reactions

"Photons"

"Leptons"

"Missing Energy"

"Jets"



Precision

Precision & **Discovery** go hand in hand

quantum structure

E.g., after the Higgs disovery, now comes ***precision study***

Recognise the unknown: understand the known

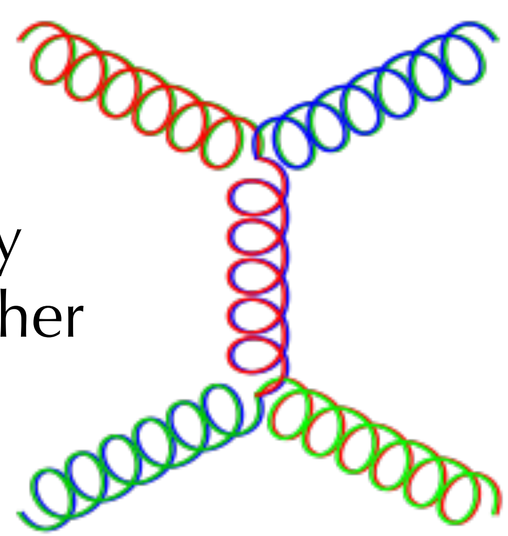
Calibrate your methods, test your strategies, …

& occasionally discover that you didn't understand "the known" …

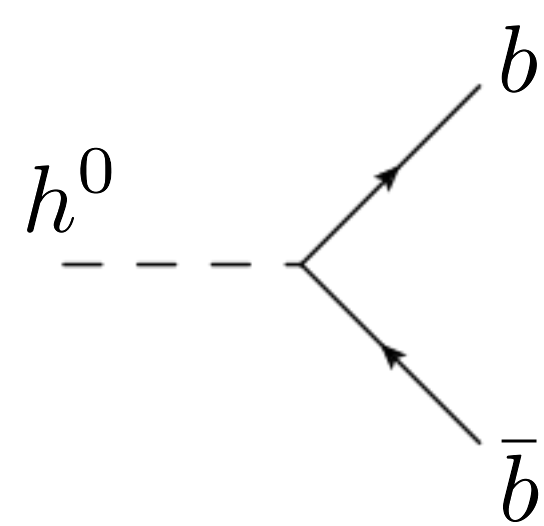
My own work focuses on the modelling of "jets"

Sprays of nuclear matter, produced by energetic quarks and gluons

Such as when they scatter off each other



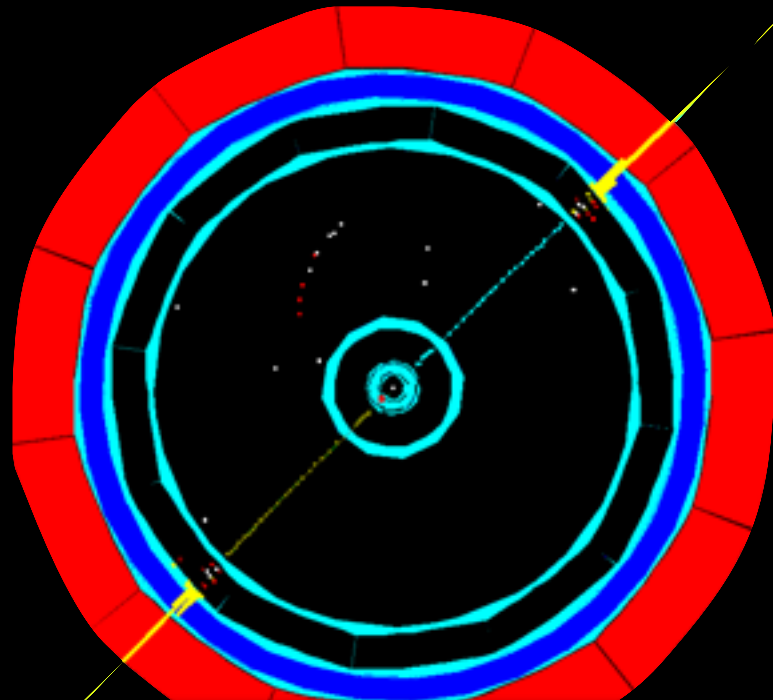
Or when a heavy particle decays to quarks / gluons

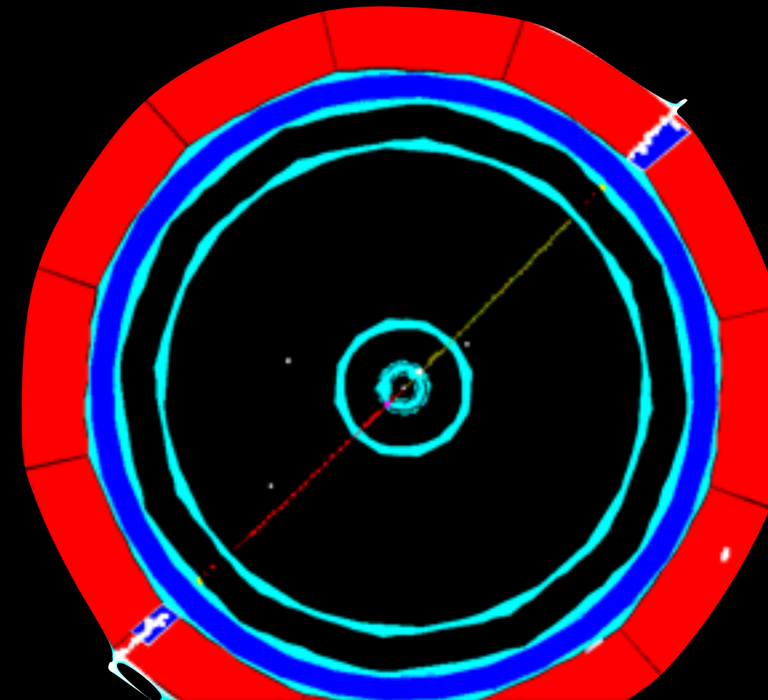


Example: Decays of the Z boson

Leptons

electron-
positron
pair creation



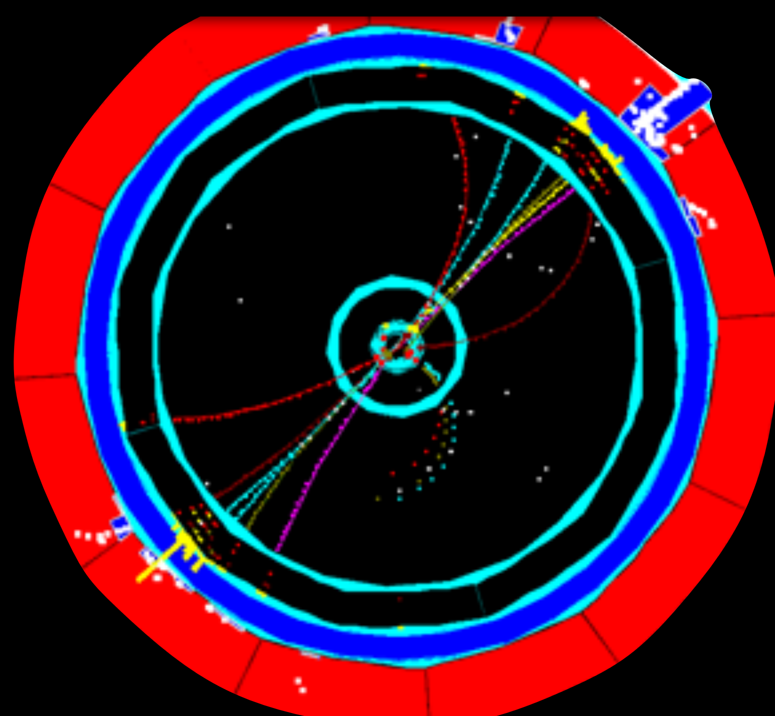


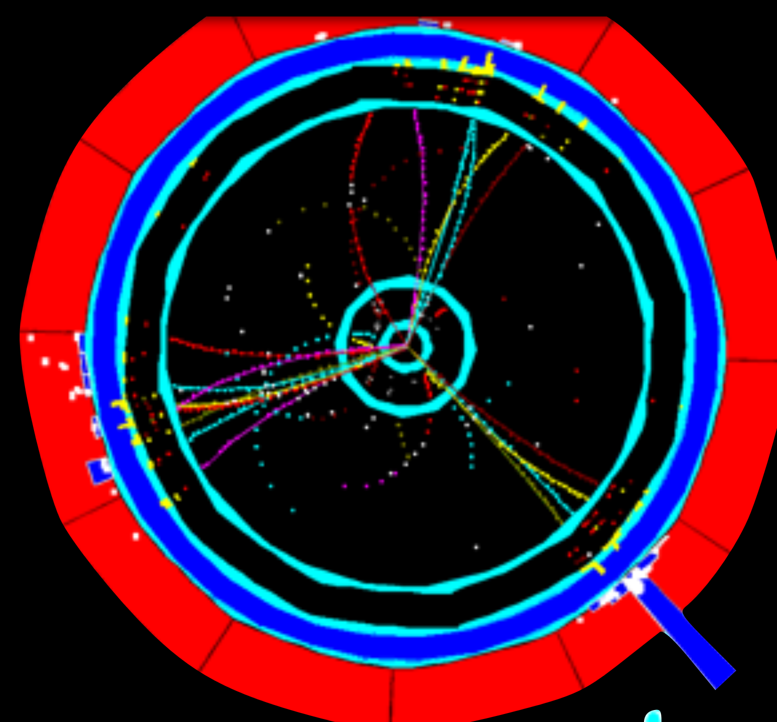
muon-
antimuon
pair creation

(from the ALEPH experiment at the Large Electron Positron Collider)

Jets

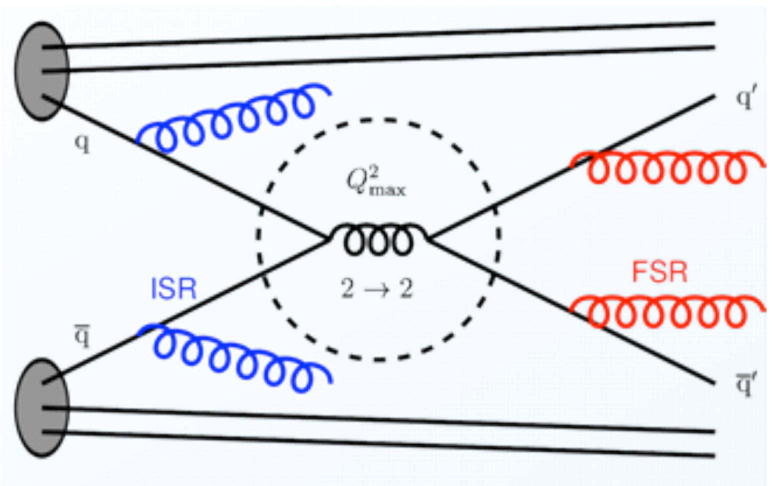
quark-
antiquark
pair creation
➜ 2 Jets

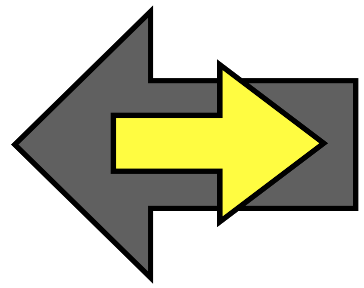




quark-
antiquark
+ gluon
➜ 3 Jets

Collider Calculations





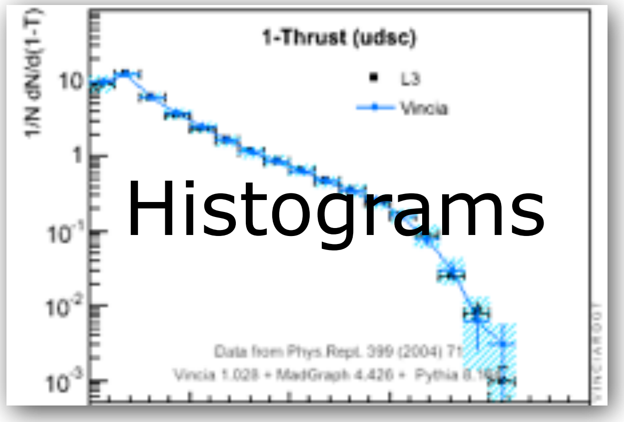
Calculate Everything ≈ solve QFT* → requires compromise!

Start from lowest-order perturbation theory,
Include the 'most significant' corrections
→ **Monte Carlo event generators**

connect with the observable world

↔

of hadrons, photons, and leptons



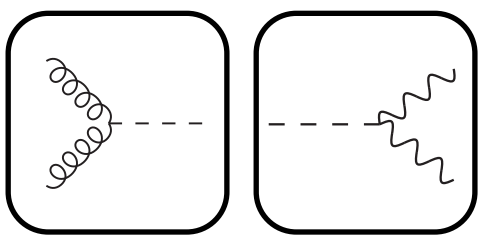
*QFT = Quantum Field Theory

Organising the Calculation

Divide and Conquer → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers

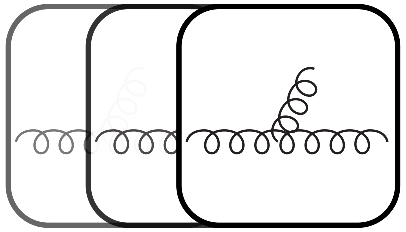
$$\mathcal{P}_{\mathrm{event}} = \mathcal{P}_{\mathrm{hard}} \otimes \mathcal{P}_{\mathrm{dec}} \otimes \mathcal{P}_{\mathrm{ISR}} \otimes \mathcal{P}_{\mathrm{FSR}} \otimes \mathcal{P}_{\mathrm{MPI}} \otimes \mathcal{P}_{\mathrm{Had}} \otimes \ldots$$



Hard Process & Decays:

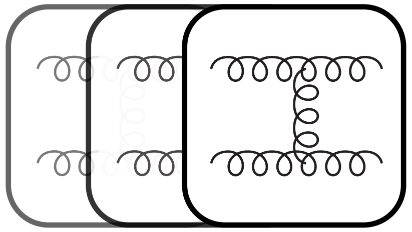
The basic hard process. E.g., $gg \to H^0 \to \gamma\gamma$

→ Sets highest resolvable scale: Q_{MAX}



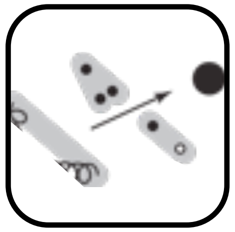
Initial- & Final-State Radiation (ISR & FSR):

Bremsstrahlung, driven by differential evolution equations, dP/dQ^2, as function of resolution scale; run from Q_{MAX} to ~ 1 GeV



MPI (Multi-Parton Interactions)

Protons contain lots of partons → can have additional (soft) parton-parton interactions → Additional (soft) "Underlying-Event" activity



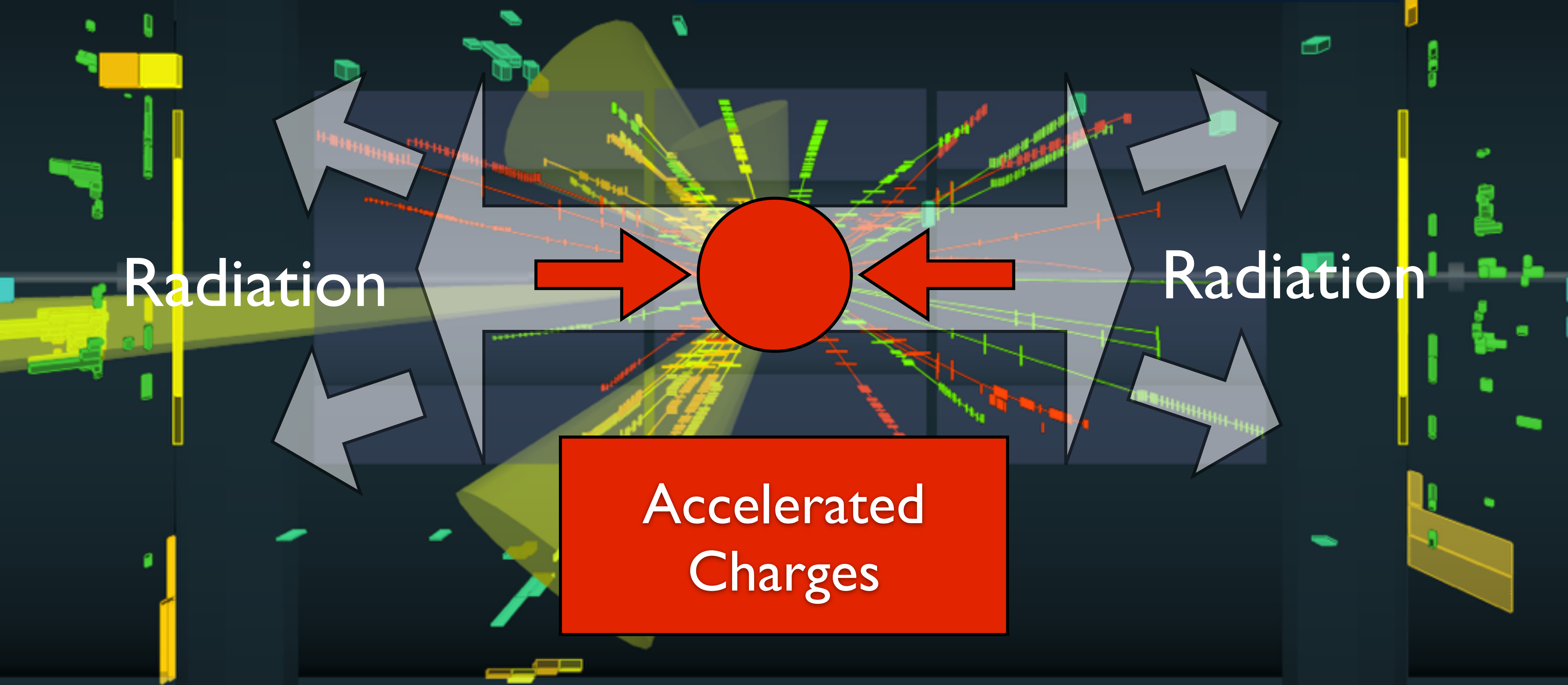
Hadronization

Non-perturbative modeling of parton → hadron transition

Bremsstrahlung

cf. equivalent-photon approximation
Weiszäcker, Williams ~ 1934

a.k.a. Initial- and Final-state radiation

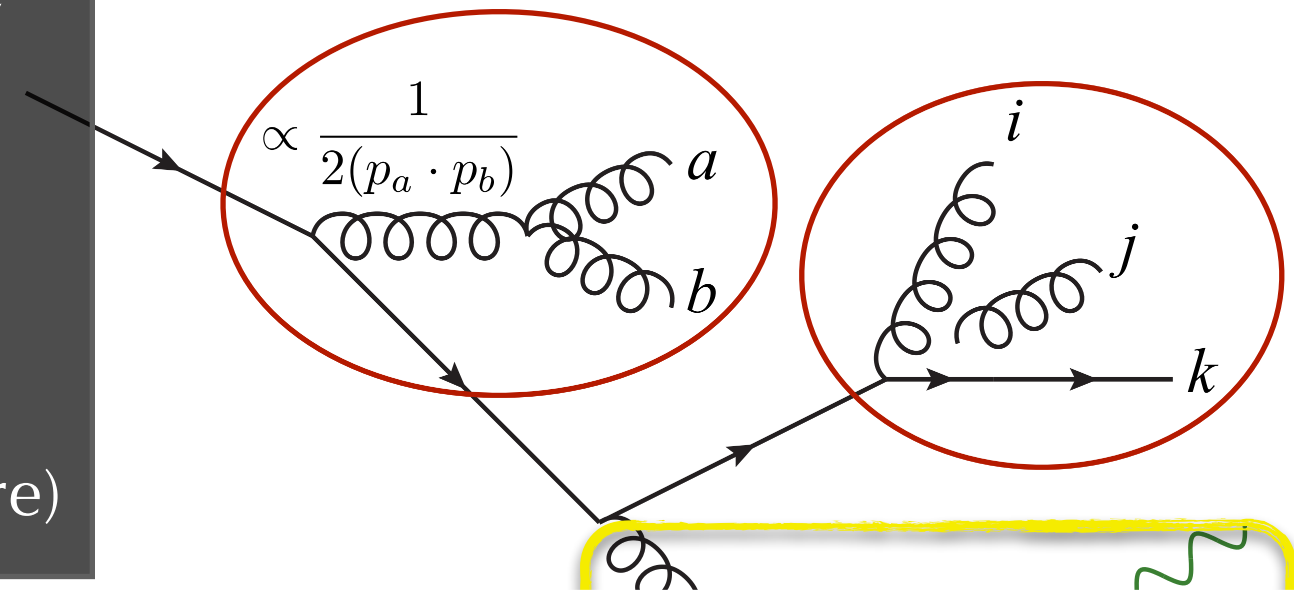


The harder they get kicked, the harder the fluctations that continue to become strahlung

The Structure of Jets

Most bremsstrahlung is driven by divergent propagators → simple structure

Amplitudes *factorize* in singular limits (→ universal "scale-invariant" or "conformal" structure)



Partons ab → "collinear":

P(z) = DGLAP splitting kernels, with z = energy fraction = $E_a/(E_a+E_b)$

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \overset{a||b}{\to} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

Gluon j → "soft":

Coherence → Parton j really emitted by (i,k) "colour antenna"

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \overset{j_g\to 0}{\to} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

+ scaling ***violation***: $g_s^2 \to 4\pi\alpha_s(Q^2)$

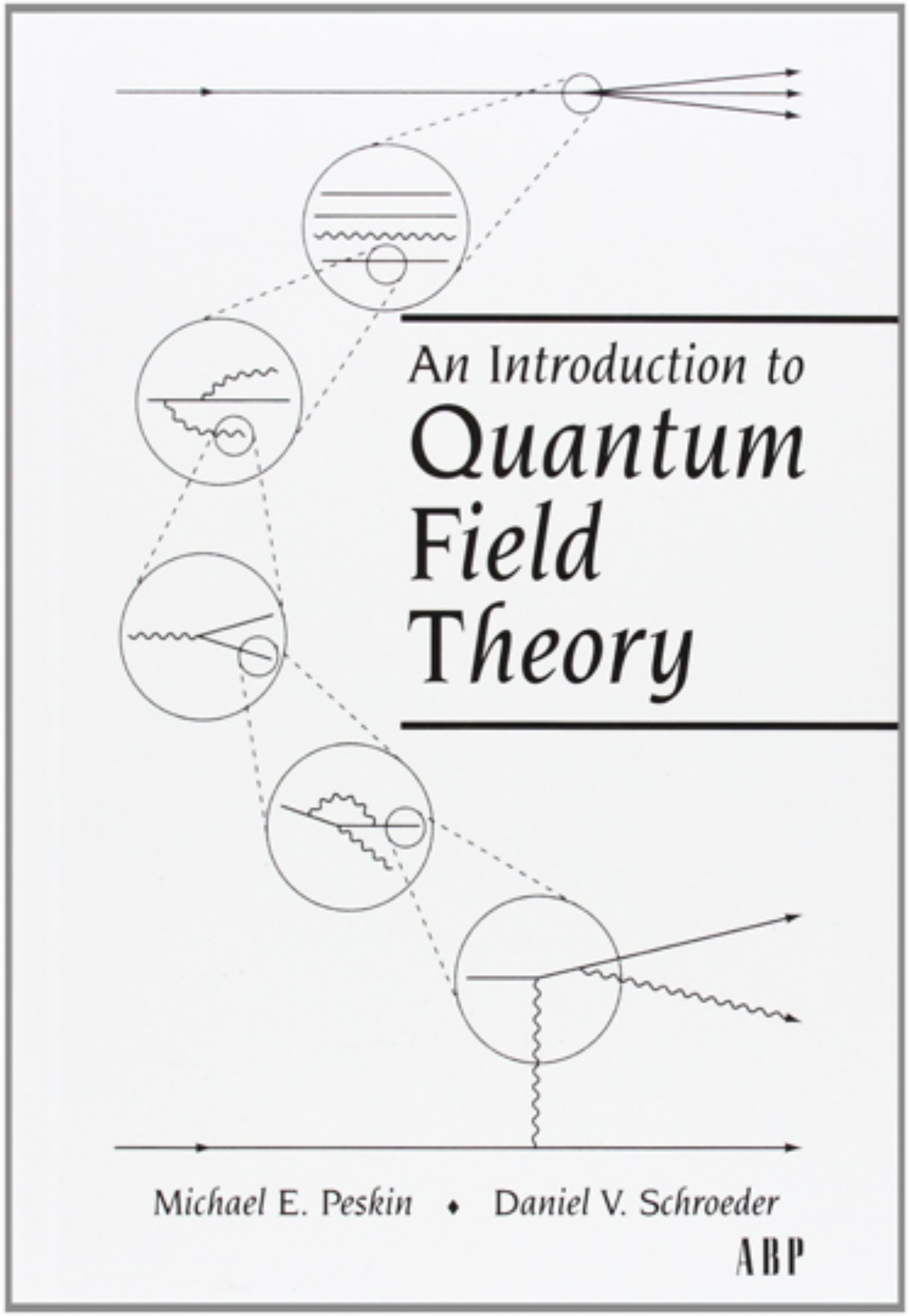
See: PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Can apply this many times
→ nested factorizations

The Structure of Quantum Fields

What we actually see when we look at a "jet", or inside a proton

- An ever-repeating self-similar pattern of quantum fluctuations
- At increasingly smaller energies or distances : ***scaling*** (modulo $\alpha(Q)$ scaling violation)
- To our best knowledge, this is what a fundamental ('elementary') particle really looks like



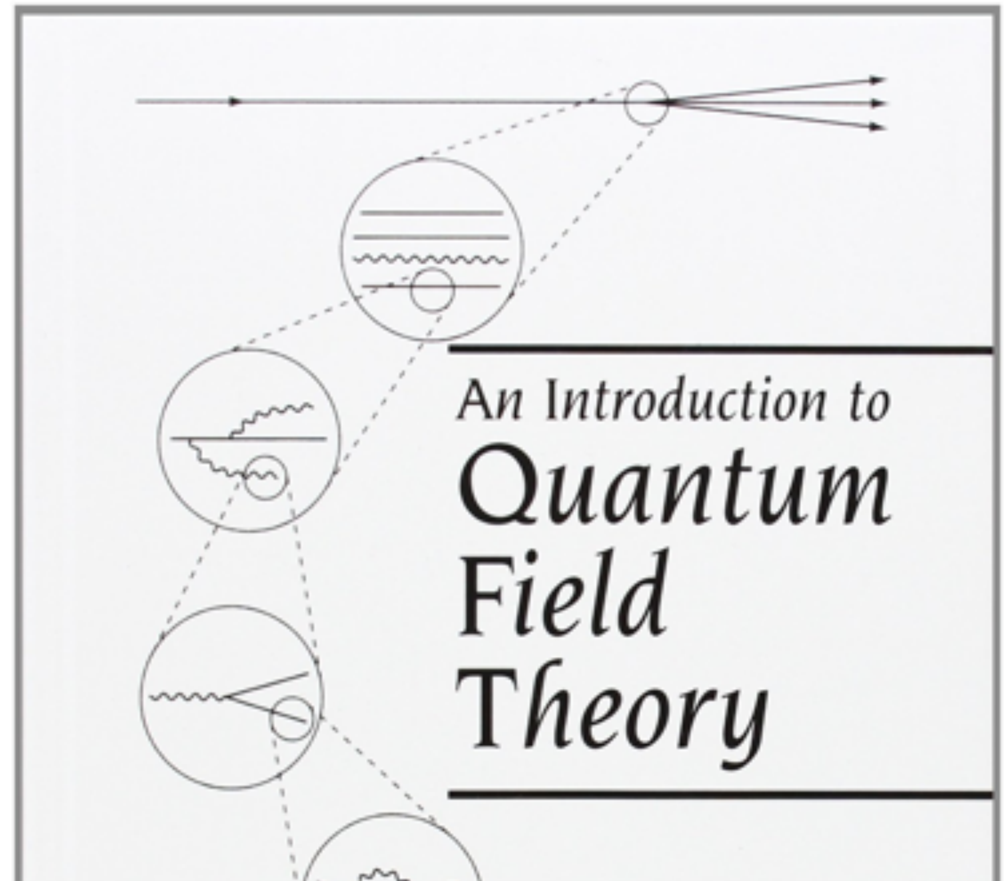
The Structure of Quantum Fields

What we actually see when we look at a “jet”, or inside a proton

An ever-repeating self-similar pattern of quantum fluctuations

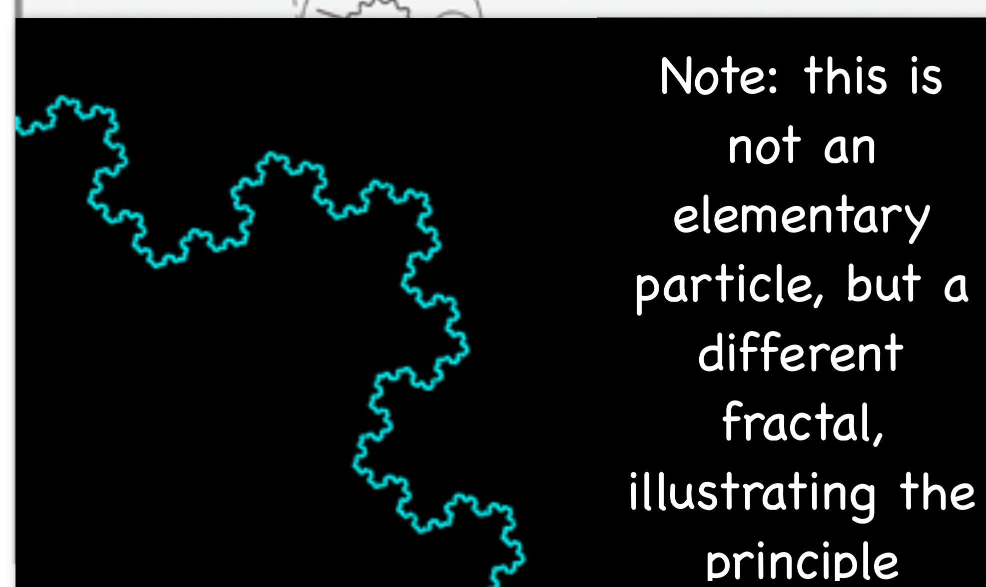
At increasingly smaller energies or distances : ***scaling*** (modulo $\alpha(Q)$ scaling violation)

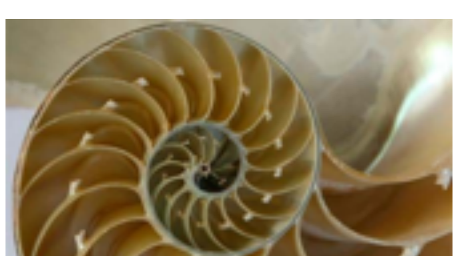
To our best knowledge, this is what a fundamental (‘elementary’) particle really looks like



Nature makes copious use of such structures

Called **Fractals**



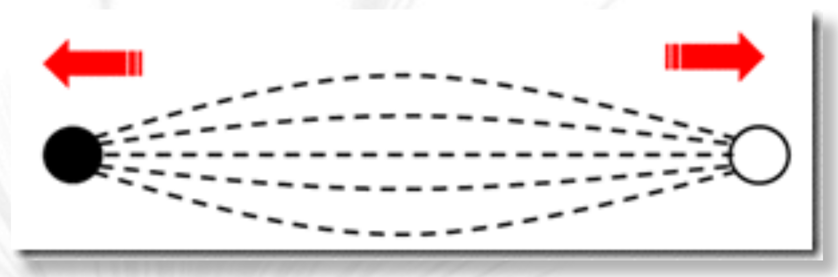


Confinement

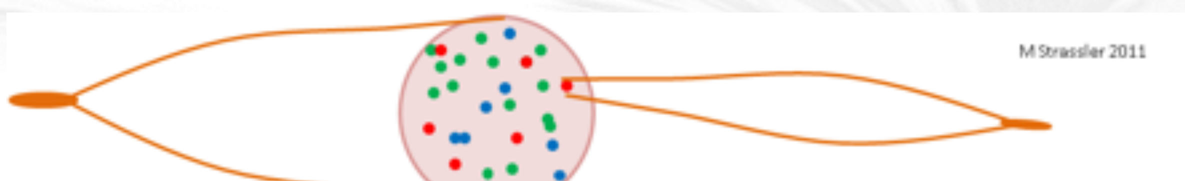
When highly energetic quarks fly apart, a very strong potential builds up between them

Increase in potential energy
~ 1 GeV / femtometer

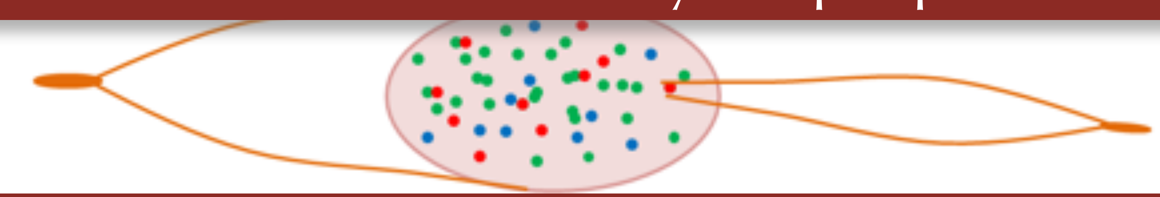
(~ energy density of pure nuclear matter)



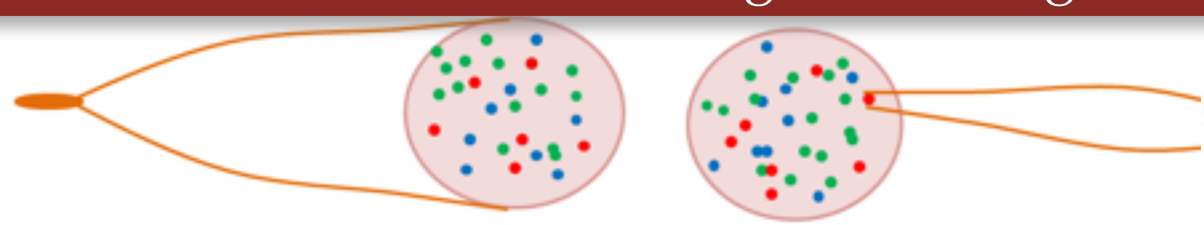
16-TON TRUCK



This is the force that normally keeps quarks locked inside hadrons



But when the kick is hard enough, $E=mc^2$ gets a second chance to act



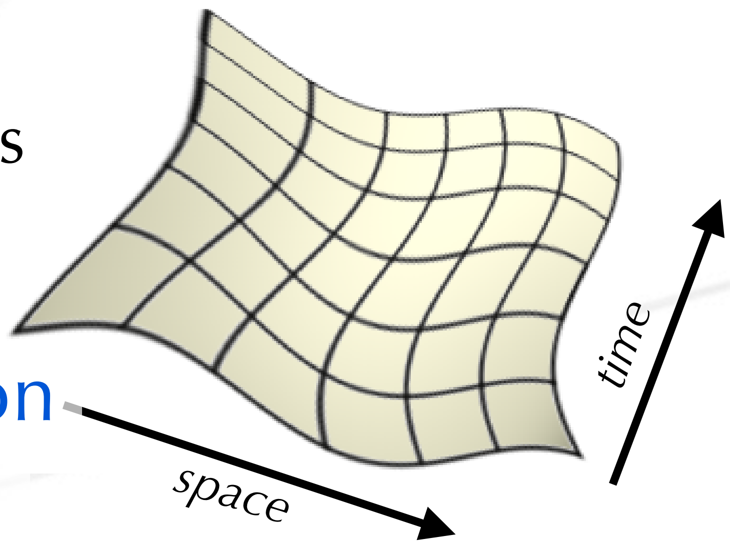
As the quarks separate, this happens multiple times → **Jets**

Vortices Through the Vacuum

The force is approximately **constant** with distance

Suggestive of **strings** (aka vortex lines)

Similar to those in superfluids and superconductors



Inspired the **"string model"** of jet fragmentation

Breakup process modelled by **quantum tunnelling**

Used for 30 years

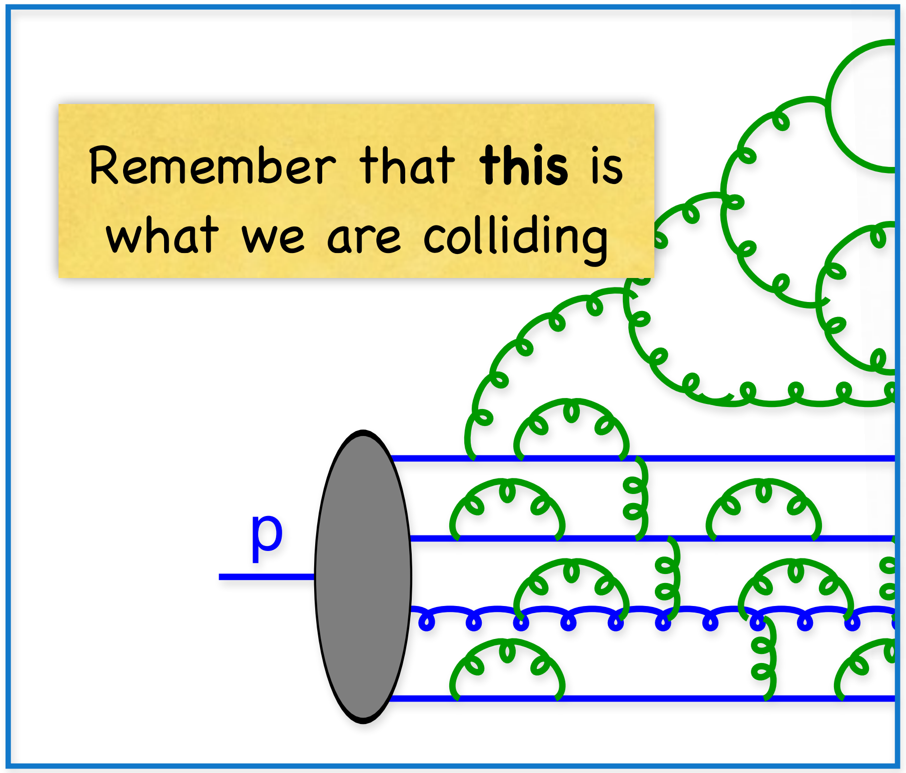
Generally good agreement with collider experiments

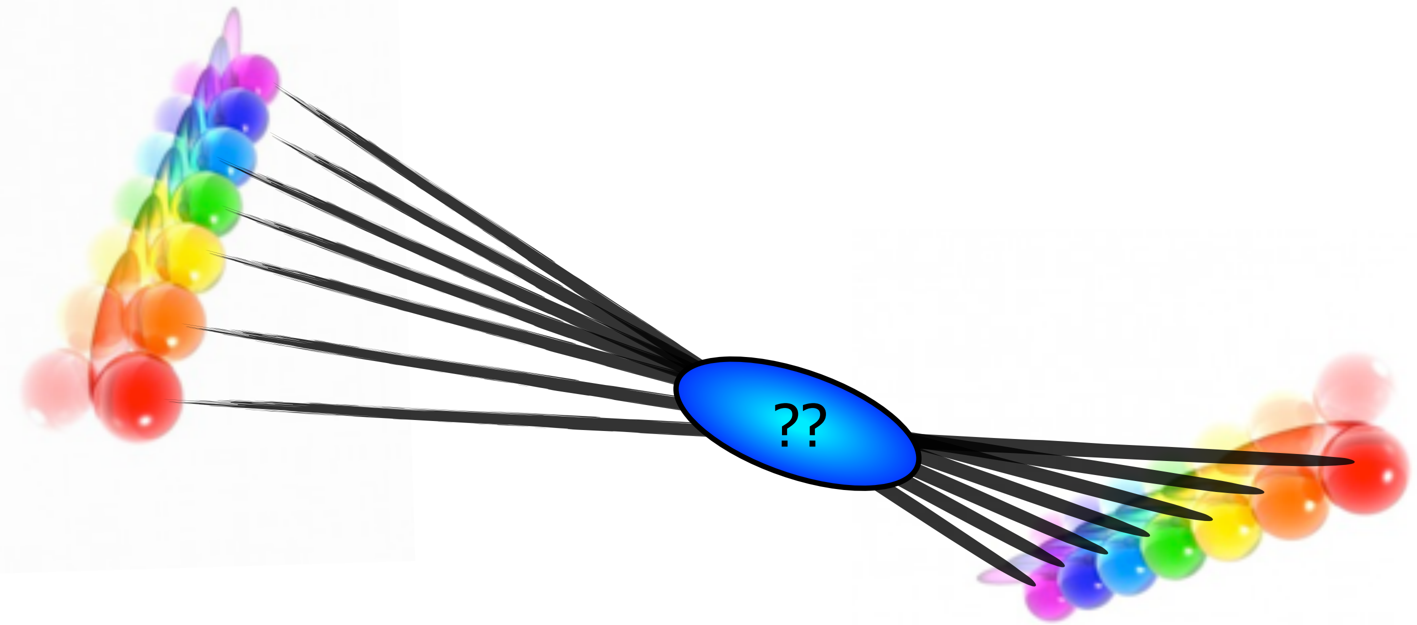
Until we started looking closely at the LHC Run-1 data …

More high-mass hadrons appear to be produced (than predicted)

And they appear to be moving faster (than predicted)

What's Going On?





This is one of the main problems that are currently causing me to scratch my head

Heat? Hydrodynamics?

String-String Forces?

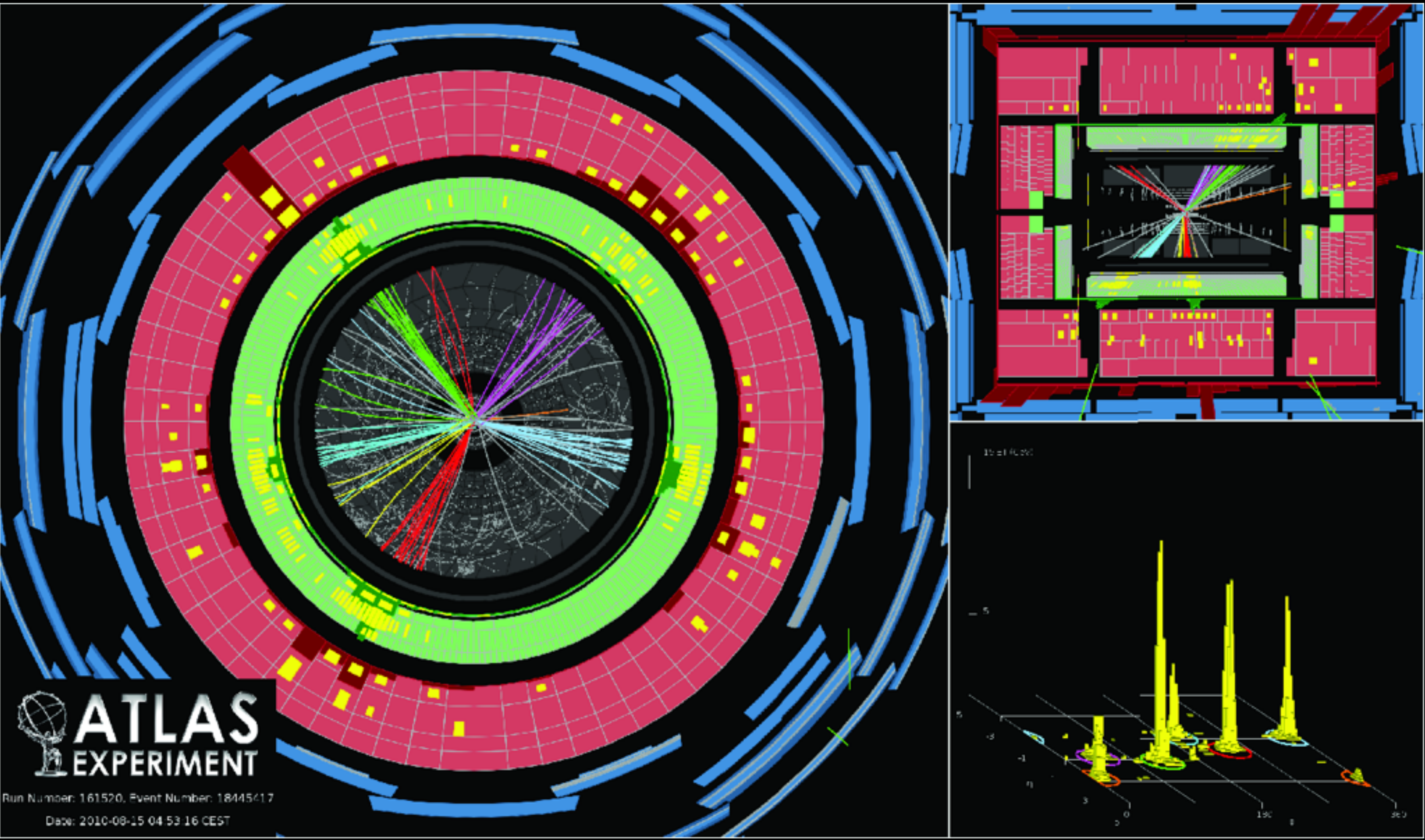
String Reconnections?

Fat Strings?

Black Strings?

Hadron-Gas Rescattering?

Thank You


ATLAS
EXPERIMENT
Run Number: 161520, Event Number: 18445417
Date: 2010-08-15 04:53:16 CEST

What *is* a Fundamental Particle?

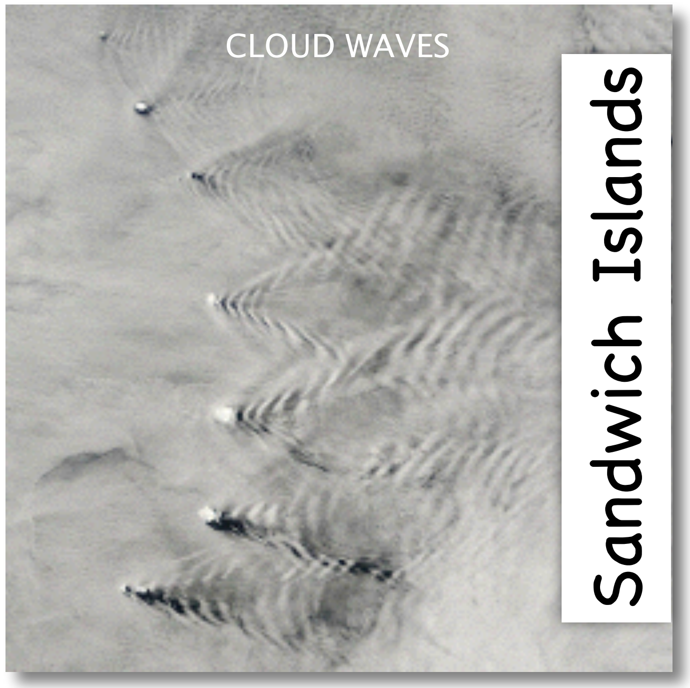
Abstractly, we think of an idealised "pointlike" particle

But could we ever really see "a point"?

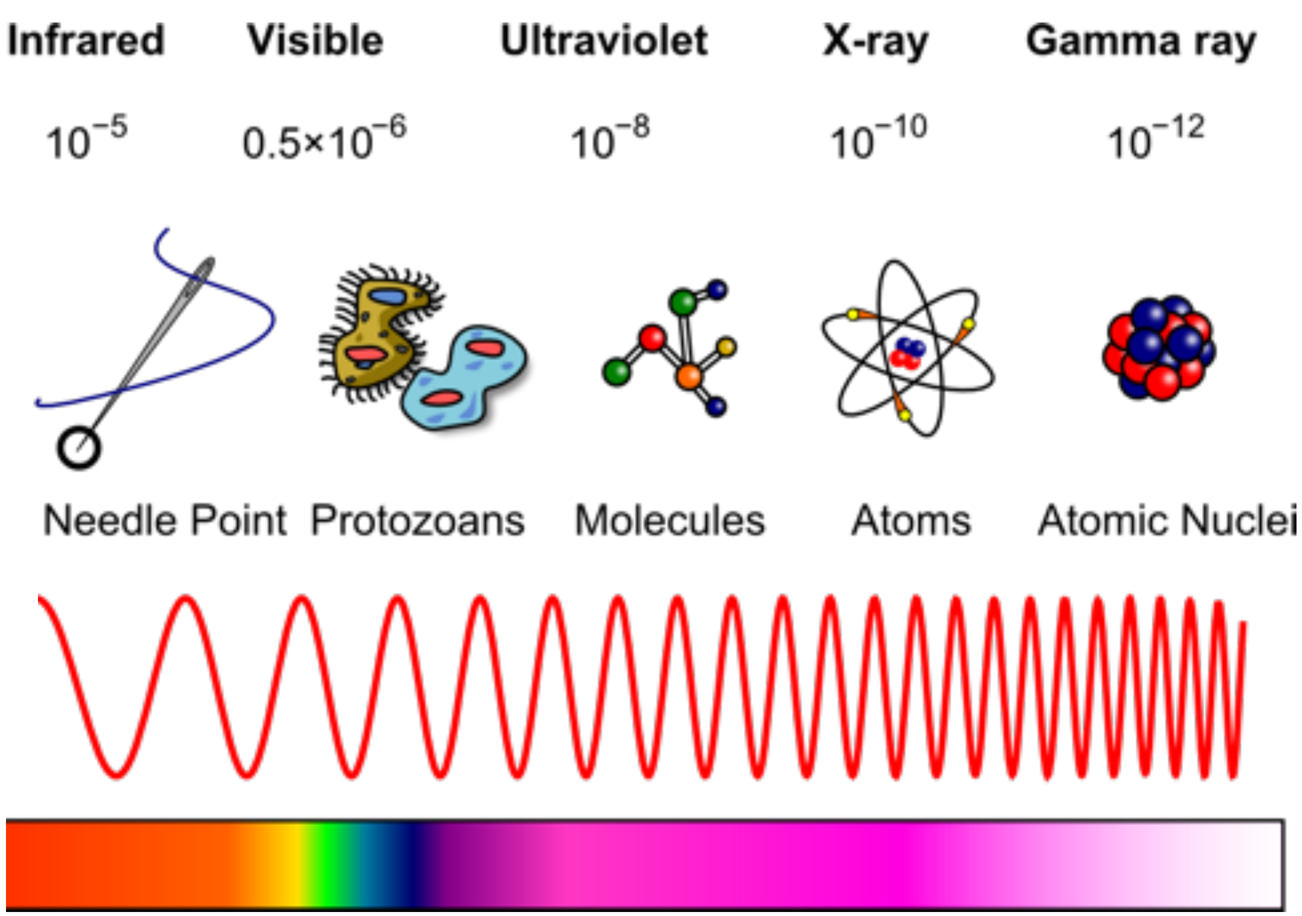
How do we see, in the quantum world?

To see something small, we scatter waves off it

➜ Heisenberg's uncertainty principle.



NASA – MODIS



To resolve "a point", we would need infinitely short wavelengths

Heisenberg would then give it an infinitely hard kick

Hard-Sphere Scattering

(Classical) particle bouncing off a (classical) hard sphere

What is the relation between *b* and θ?

$$\theta = 2\cos^{-1}(b/R)$$

If the particle comes in with an **impact parameter** between *b* and *b+db* it will emerge with a **scattering angle** between θ and θ+dθ.

If the particle passes through an infinitesimal **area dσ**, it will scatter into a corresponding **solid angle dΩ**

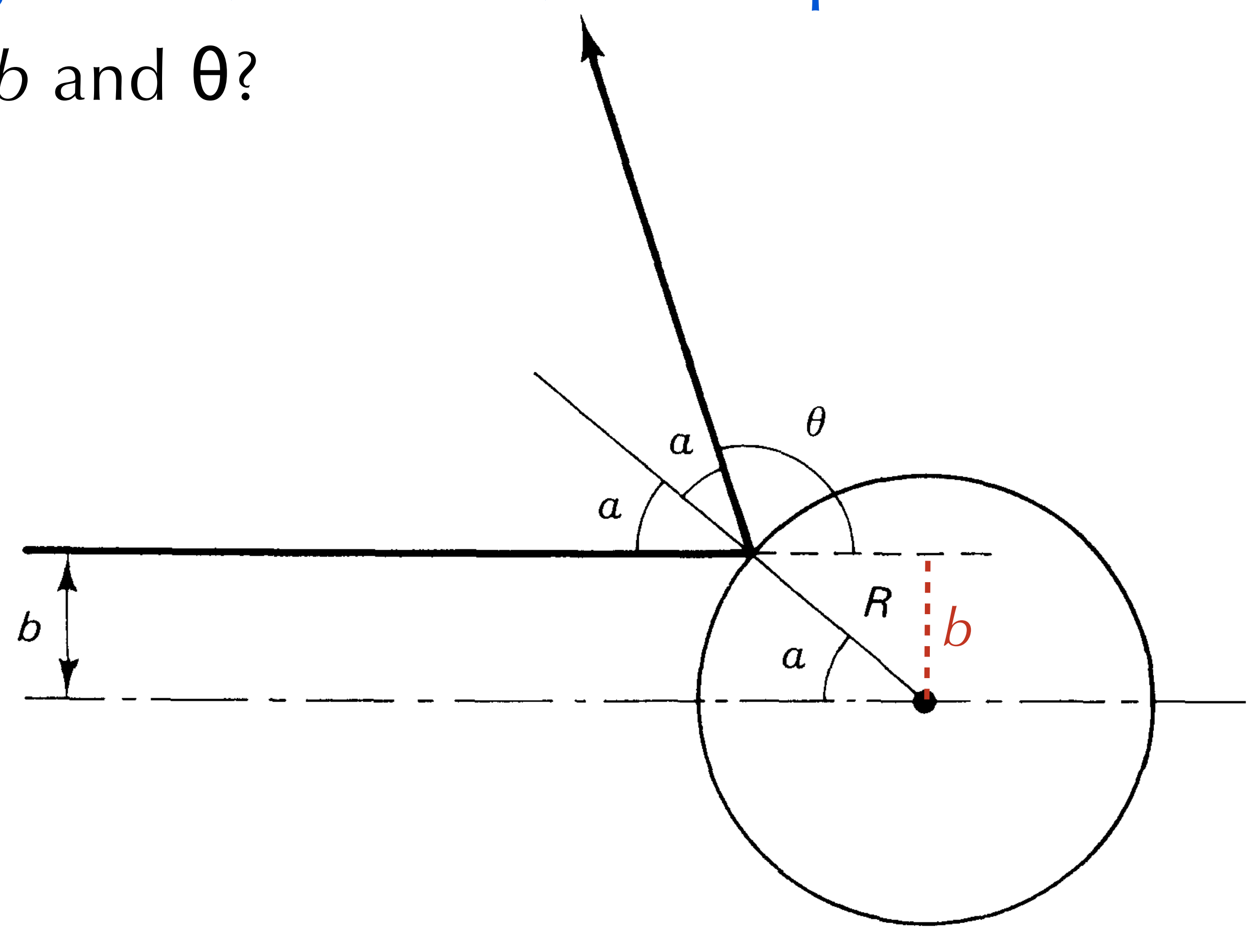


Figure 6.2 Hard-sphere scattering.

$$b = R \sin\alpha, \qquad 2\alpha + \theta = \pi$$

Thus $\sin\alpha = \sin(\pi/2 - \theta/2) = \cos(\theta/2)$

and hence $b = R\cos(\theta/2) \quad \text{or} \quad \theta = 2\cos^{-1}(b/R)$

dΩ Solid Angle

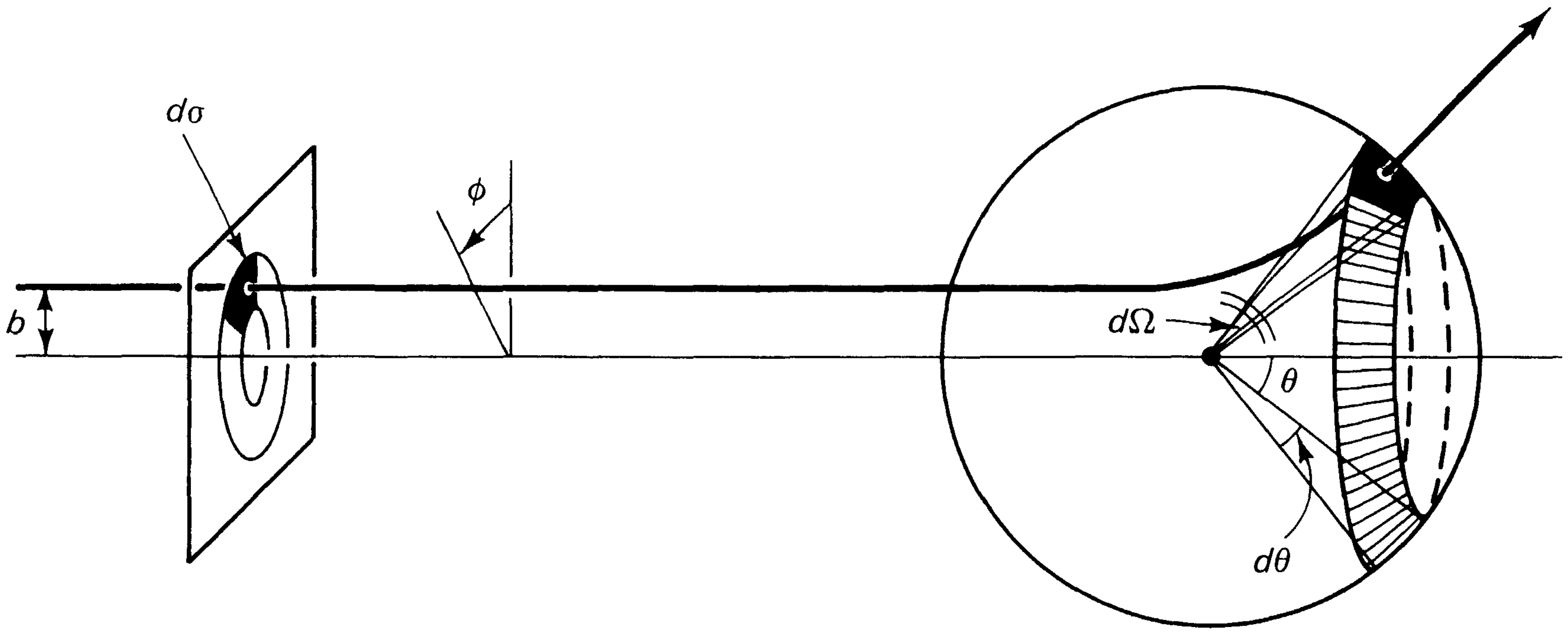


Figure 6.3 Particle incident in area $d\sigma$ scatters into solid angle $d\Omega$.

A differential quantity of interest for 2→2 is thus

The differential scattering cross section per unit solid angle

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$$

Back to the Hard Sphere

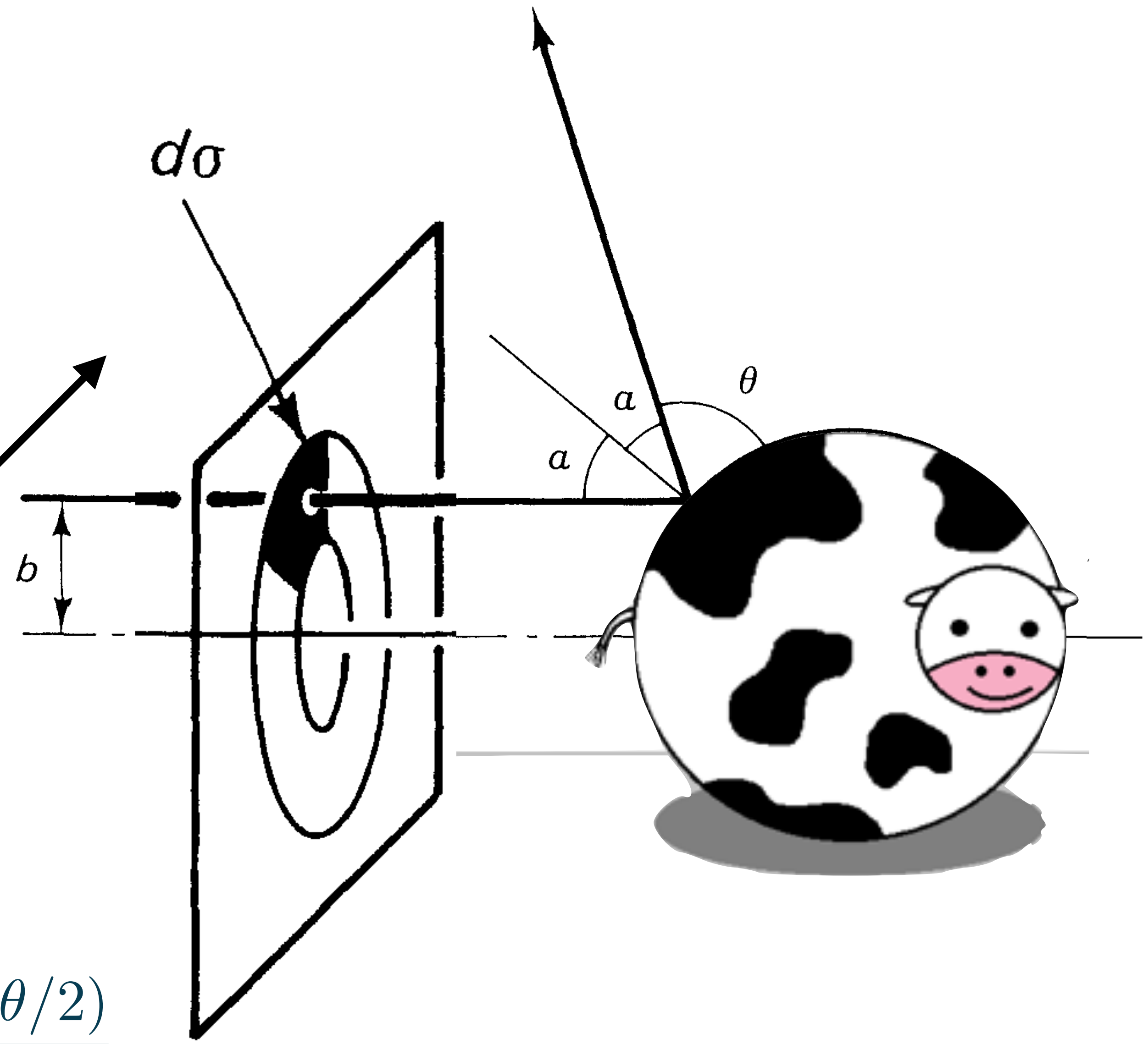
We found the relation

$$b = R\cos(\theta/2)$$

Hence:

$$\frac{\mathrm{d}b}{\mathrm{d}\theta} = -\frac{R}{2}\sin(\theta/2)$$

Note:
$$d\sigma = |b\ \mathrm{d}\phi\ \mathrm{d}b|$$
$$d\Omega = |\mathrm{d}\phi\ \mathrm{d}\cos\theta|$$



So the differential cross section is:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{|b\ \mathrm{d}\phi\ \mathrm{d}b|}{|\sin\theta\ \mathrm{d}\phi\ \mathrm{d}\theta|} = \frac{R\ b\ \sin(\theta/2)}{2\sin\theta}$$

$$= \frac{R^2\ \cos(\theta/2)\sin(\theta/2)}{2\sin\theta} = \frac{R^2}{4}$$

Integration yields:

$$\sigma = \int \frac{R^2}{4}\, d\Omega = \pi R^2$$