Into the woods with particle physics

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Into the woods with the Brothers Grimm

- In the Stephen Sondheim/James Lapine musical "Into the Woods," a baker and his wife will have their wish for a child granted if they can meet a witch's four demands.

- This connects them with Jack (of beanstalks), Cinderella, Little Red Ridinghood, and Repunzel.

- What the witch wants: the cow as white as milk, the cape as red as blood, the hair as yellow as corn, and the slipper as pure as gold.

Into the woods with Feynman and Fermi

- What particle physicists Alice and Bob wish for is to understand everything.

What the witch demands:

- Find the Higgs boson.
- Find dark matter.
- Figure out how the Standard Model could be a low energy approximation to a more complete theory.
- Make sense of the structure of QCD.
- Map the structure of hadrons.

Find the Higgs boson ✓

- In 1995 we discovered the top quark.
- This left the Higgs boson of the Standard Model to be found.
- The theory with an elementary Higgs field has some problems, so maybe the Higgs sector was more complicated.
- But in 2012 we found the Higgs boson.
- A lot of investigation will be needed to test its properties.

Find dark matter

- We have good evidence that most of the mass of the universe consists of "dark matter."
- Presumably the dark matter is one or more particles.
- Maybe dark matter particles don't interact with ordinary particles at all, except through gravity.
- But clues suggest that there is some interaction.
- The search goes on.

Figure out how the Standard Model could be a low energy approximation to a more complete theory.

- There are symmetry reasons why fermion masses can remain small in a low energy sector of a theory with also very heavy particles.
- But the Higgs mass has no symmetry reason to be small. (The large mass would also be passed onto the W and Z bosons.)
- Maybe supersymmetry would help.
- Whatever helps, we need to find some traces of it at the LHC.

- In the woods, problems can arise …
- Little Red Ridinghood overcame the wolf, but didn’t anticipate the problem of the GIANT.
- In physics, we may figure out why the Higgs boson is light, but the problem of the small value of the energy density of the vacuum is bigger.

Make sense of the structure of QCD

- The QCD part of the Standard Model has been very well verified by experiment.
- With all of the experimental success, I am confident that we should not be tempted to fiddle with the QCD lagrangian (beyond adding new, heavy beyond-the-Standard-Model particles that carry color).
- However, we can ask to what extent we really understand QCD.

Lattice gauge theory

- Long ago, pioneer theorists like Ken Wilson and Michael Creutz proposed to simulate QCD on a computer by making space-time discrete and using a lattice approximation to the QCD lagrangian.
- Lattice QCD can't do everything, but it is good for static properties of hadrons.
- This has turned into a very powerful tool.

- It has long been a challenge to calculate the mass difference between the neutron and the proton, given the mass difference between the down quark and the up quark.

- Now there is a new result from Borsanyi *et al*.:

$$m(\mathrm{n}) - m(\mathrm{p}) = (1.51 \pm 0.28)\ \mathrm{MeV}$$

- This agrees with the experimental result,

$$m(\mathrm{n}) - m(\mathrm{p}) = 1.293\ \mathrm{MeV}$$

Perturbative calculations

- We are helped by the fact that $\alpha_s(\mu^2)$ becomes small for large μ^2.

- Calculations beyond the leading order in $\alpha_s(\mu^2)$ are difficult.

- We are helped by the efforts of many very able theorists.

- We have results at next-to-leading order (NLO) and NNLO for a wide variety of important processes.

Summing logarithms

- Often simple perturbation theory isn't sufficient.
- There can be large logarithms, *e.g.* $L = \log(Q^2/Q_0^2)$.
- If

$$\sigma = A_0 + \alpha_{\rm s}[A_{11}L + A_{10}] + \alpha_{\rm s}^2[A_{22}L^2 + A_{21}L + A_{20}] + \cdots$$

or

$$\sigma = A_0 + \alpha_{\rm s}[A_{12}L^2 + A_{11}L + A_{10}]$$
$$+\alpha_{\rm s}^2[A_{24}L^4 + A_{23}L^3 + A_{22}L^2 + A_{21}L + A_{20}] + \cdots$$

and $\alpha_{\rm s}L \sim 1$, then we need to sum the important terms.

Logs of mass scales

- We often get an integration like

$$\int_{Q_0}^{Q} \frac{dk_\perp}{k_\perp}$$

  for each loop in a Feynman diagram.

- This gives one power of L for each α_s.

- Example: $\alpha_s(Q^2)$ as a power series in $\alpha_s(Q_0^2)$

- Example: $f_{a/A}(x, Q^2)$ at a high scale Q^2 from $f_{a/A}(x, Q_0^2)$ at a lower scale Q_0^2.

- We use a *renormalization group* equation.

Logs of angles

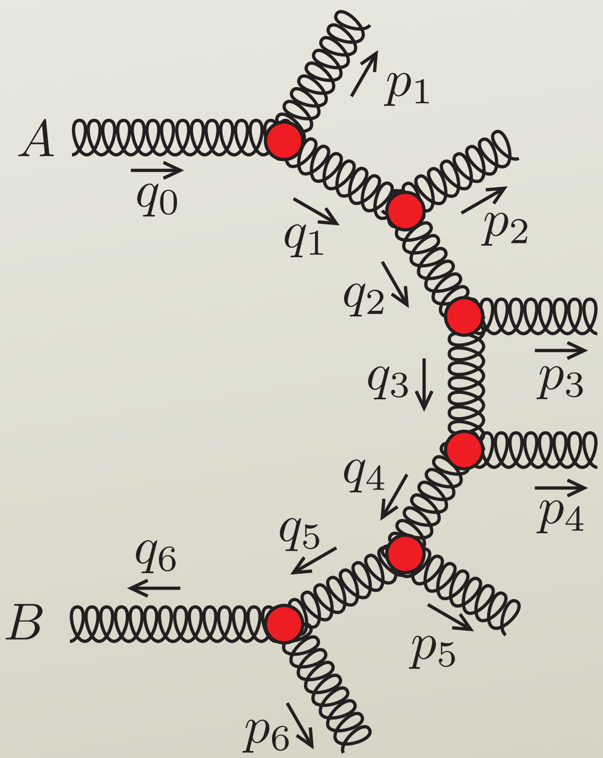
- The amplitude to emit a gluon from a high energy particle is singular when the angle θ between the gluon and the emitting particle goes to zero. This can give us integrals like

$$\int_{\Delta}^{\pi/2} \frac{d\theta}{\theta}$$

- Sometimes the angle integration comes in the form of an integration over the rapidity $y \approx -\log(\tan(\theta/2))$ of an emitted gluon:

$$\int_{y_1}^{y_2} dy$$

- Balitsky-Fadin-Kuraev-Lipatov (BFKL) logs appear, for instance, when there are two high $p_\perp$ jets that have a large separation in rapidity and one examines the probability of creating smaller $p_\perp$ jets between them.



- My impression is that it has been difficult to isolate BFKL effects precisely and to connect them to experimental results.

Double logarithms

- The probability to emit a gluon is singular both when the energy or transverse momentum of the gluon tends to zero and when the angle between the gluon and the emitting parton goes to zero.

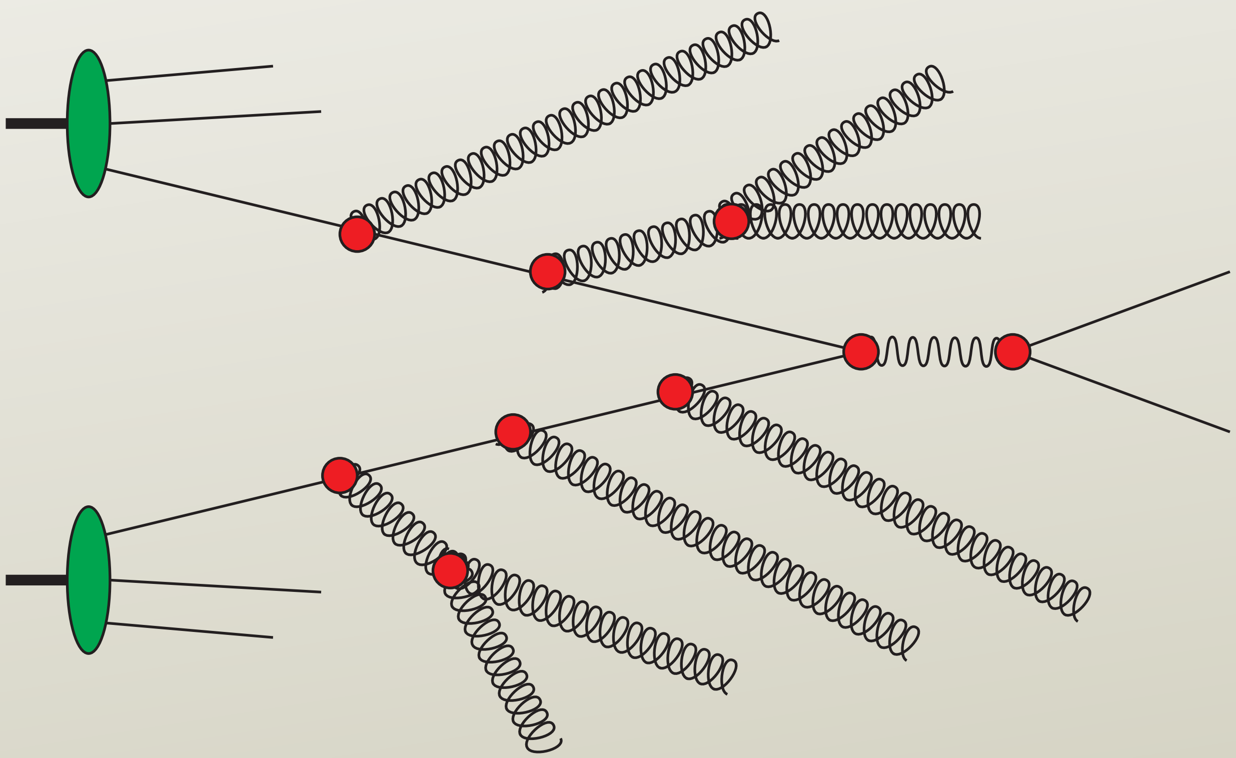
- Thus we get integrals like

$$\int_{Q_0}^{Q} \frac{dk_\perp}{k_\perp} \int_{\Delta}^{\pi/2} \frac{d\theta}{\theta}$$

- Now there are two logarithms per power of $\alpha_{\rm s}$.

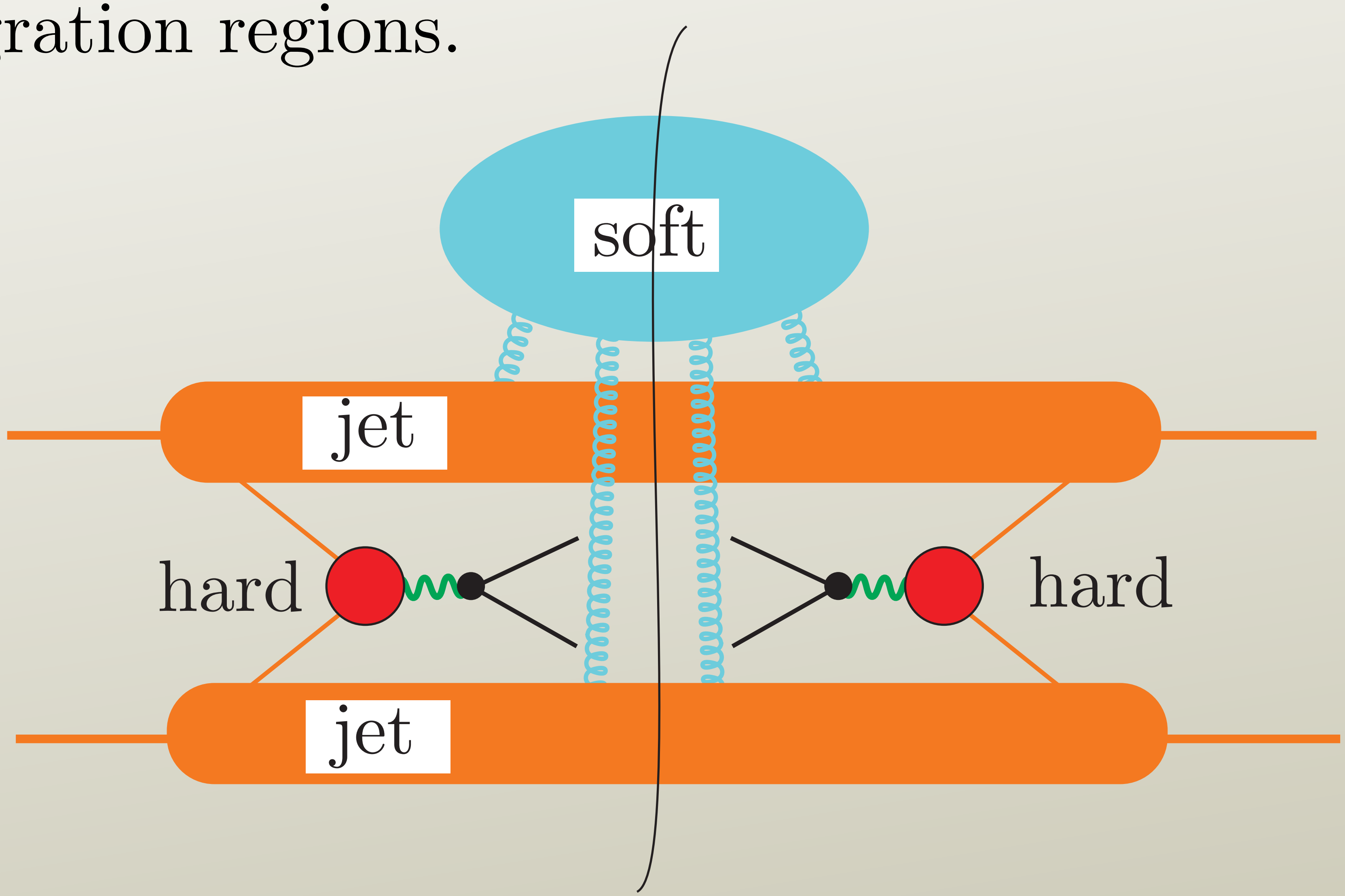
- A classic example $\mathrm{p} + \mathrm{p} \to \gamma^* + X \to e^+ + e^- + X$.

- Look at the transverse momentum $Q_\perp$ of the e^+e^- when $\log(Q^2/Q_\perp^2)$ is large.



- It is sometimes convenient to think of the cross section for this process as being the convolution of two transverse momentum dependent parton distributions, one for each of the incoming protons.

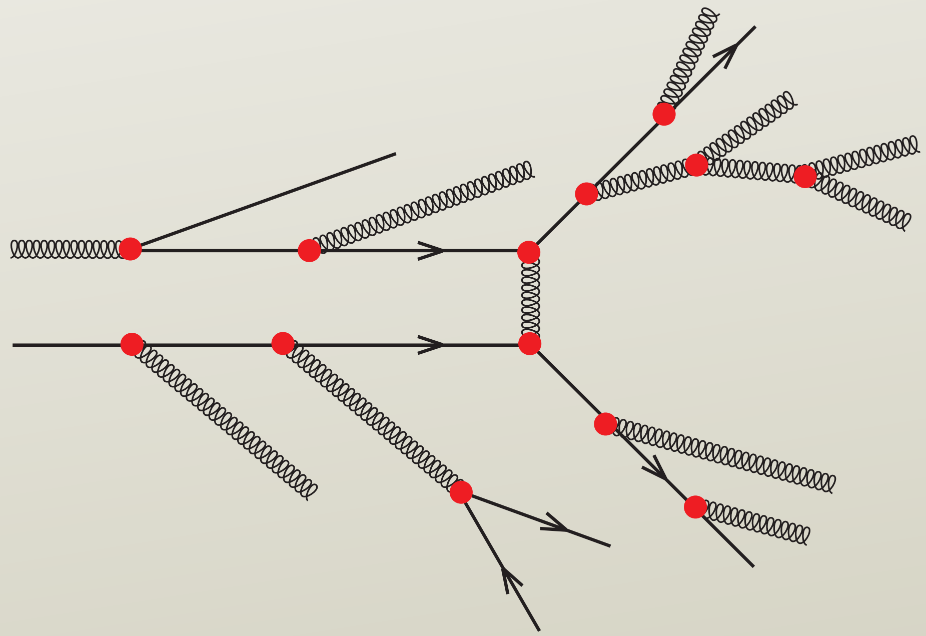
- There are analytic QCD formulas available for this.
- The starting point is the picture of leading integration regions.



- One can directly analyze Feynman diagrams or one can use soft collinear effective theory (SCET).

Parton shower generators

- Much of the physics that we have discussed can be simulated by a parton shower event generator.

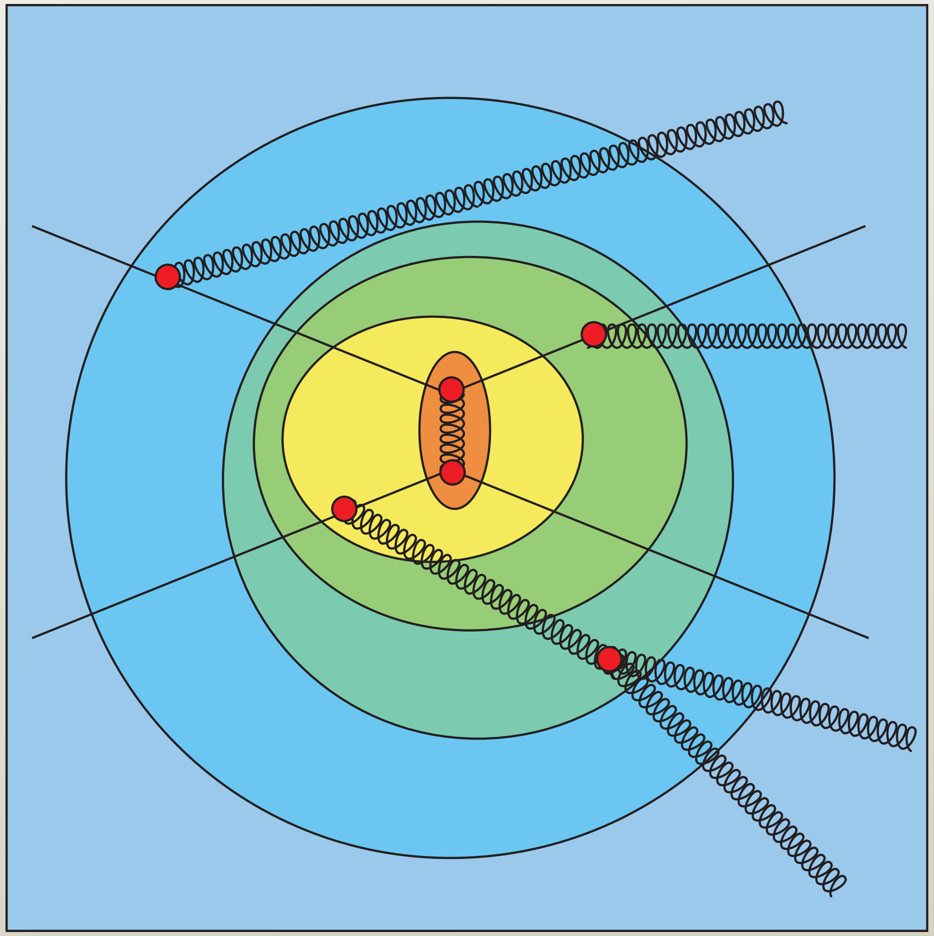


- Examples include PYTHIA, HERWIG, SHERPA, and a new one by Zoltan Nagy and me, DEDUCTOR.

- HERWIG is organized differently (angle ordered) so I concentrate on the others.

Factor hard from soft

- Parton shower evolves with "shower time" t.
- Small $t \Rightarrow$ hard.
- Large $t \Rightarrow$ soft.
- For initial state interactions, evolution is backwards in physical time.



- At each stage, softer reactions are not resolved.
- That is, we sum over all of the ways that a jet can turn into subjets.

Parton showers sum logarithms

- If you are going into the woods, you have to be careful: do they sum logarithms correctly?

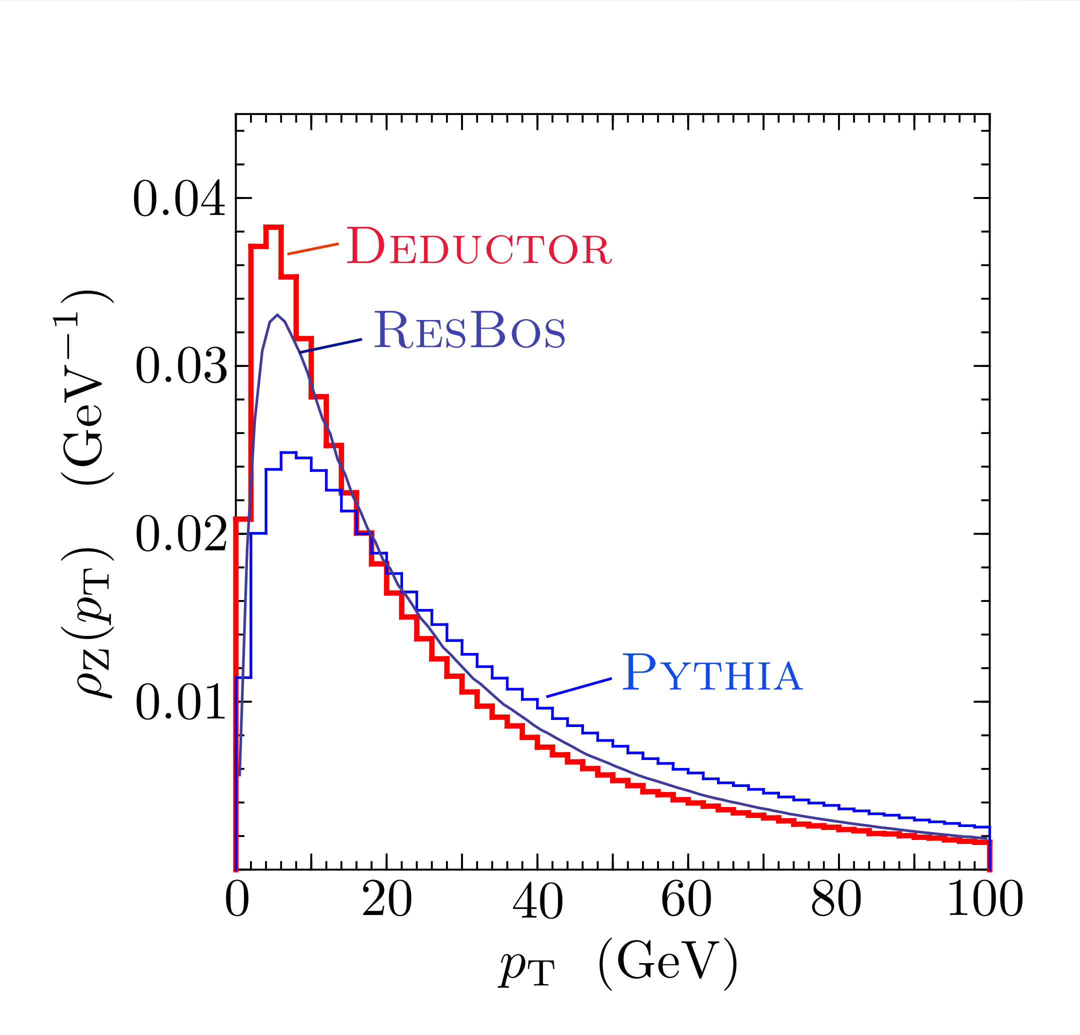
- That depends on what logarithms.

- For $\mathrm{p} + \mathrm{p} \to \gamma^*/Z^* + X \to e^+ + e^- + X$, analytic investigation (by Z. Nagy and me) shows that for a suitable parton shower algorithm, logs of $Q_\perp^2/Q^2$ are correctly summed.

This works numerically too

- Look at the distribution of $p_{\rm T}$ of e^+e^- pairs with mass $>$ 400 GeV.

- $\int_0^{100\ \rm GeV} dp_{\rm T}\, \rho(p_{\rm T}) = 1.$



- I compare DEDUCTOR (no hadronization), PYTHIA (hadronization turned off), and the analytic summation (with fit nonperturbative contributions) in RESBOS.

Map the structure of hadrons

- The woods used to seem simple, before we looked closely.
- The proton and neutron were each made of three quarks.
- Their masses were around 300 MeV.
- Spins and magnetic moments worked pretty well.

- But this constituent quark model wasn't quite right.
- We now understand that the nucleons are made of lots of quarks, antiquarks, and gluons.
- For a description in the nucleon rest frame, we really need the full power of a strongly interacting quantum field theory. (*Cf.* lattice QCD.)
- The rest frame description doesn't help much for high energy collisions.

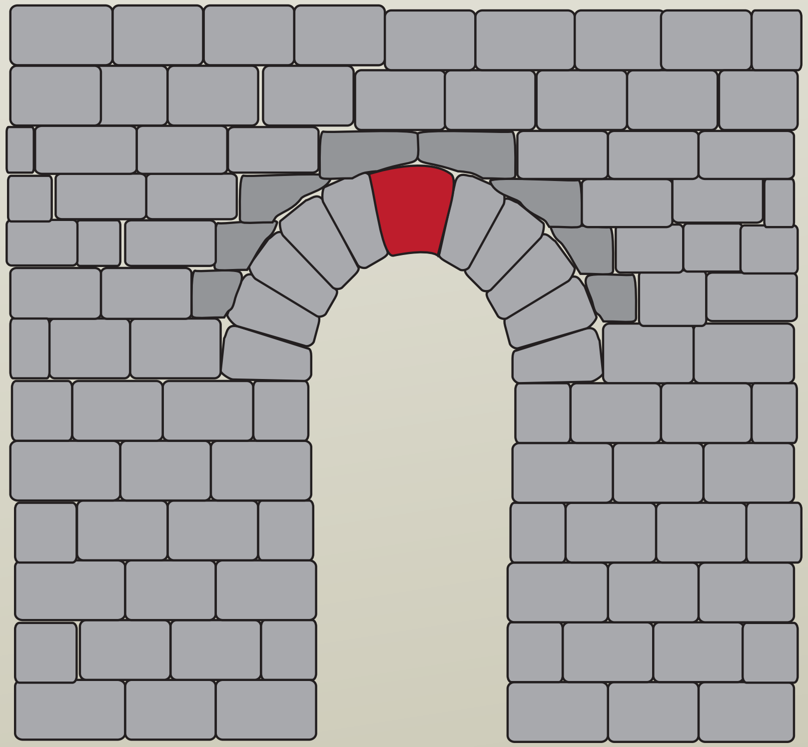
Parton distribution functions

- There is simple picture that applies to nucleons that have very high energy: the parton picture as realized in full QCD.

- This picture is useful for collisions at the LHC, for DESY deeply inelastic scattering experiments, and for experiments at RHIC and Jefferson Lab.

- We need a large scale Q^2 and we must neglect contributions to cross sections that are suppressed by a factor $(1\ \mathrm{GeV}^2)/Q^2$.

- There are lots of quarks, antiquarks, and gluons in a proton.
- Their distribution, when measured at scale μ^2, is given by functions $f_{a/A}(x, \mu^2)$.
- Without knowing parton distribution functions, we would be at a loss to understand anything that we see at the LHC.
- Thus the DIS experiments on which the parton distribution functions are largely based are like a keystone in the arch that supports the edifice of particle physics.



Beyond parton distribution functions

- There is more to know about the structure of hadrons than is contained in the ordinary parton distribution functions.

Spin of the proton

- For a proton of helicity $+1/2$ we can ask what is the probability $f_{a/\mathrm{p}}(x, \lambda; \mu^2)$ to find in the proton a parton of flavor a having helicity λ.
- One often defines

$$\Delta f_{q/\mathrm{p}}(x; \mu^2) = f_{q/\mathrm{p}}(x, +1/2; \mu^2) - f_{q/\mathrm{p}}(x, -1/2; \mu^2)$$
$$\Delta f_{\mathrm{g}/\mathrm{p}}(x; \mu^2) = f_{\mathrm{g}/\mathrm{p}}(x, +1; \mu^2) - f_{\mathrm{g}/\mathrm{p}}(x, -1; \mu^2)$$

- For the total quark distribution, the DSSV fit gives

$$\sum_q \int_{0.001}^{1} \Delta f_{q/\mathrm{p}}(x; \mu^2) = 0.366, \qquad \mu^2 = 10\ \mathrm{GeV}^2$$

- If there were no gluons in the protons and the partons had no orbital angular momentum, this would be 1.

- For the gluon, including results from the RHIC 2009 run, DSSV find

$$\int_{0.001}^{1} \Delta f_{\mathrm{g/p}}(x;\mu^2) \approx 0.4, \qquad \mu^2 = 10\ \mathrm{GeV}^2$$

with a rather large uncertainty.

- This is a large number, considering that $\lambda = \pm 1$ for gluons.
- We can also expect that a good fraction of the proton spin comes from the orbital angular momentum of the quarks and gluons.
- In the woods, the division of the angular momentum into pieces is not without ambiguity.

Transversity distribution

- If we polarize the proton so that it has a transverse spin $\boldsymbol{S}_\perp$, then there is a preferred transverse direction.
- Then the probability $f_{q/\mathrm{p}}(x, \boldsymbol{s}_\perp; \mu^2)$ to find in the proton a quark of flavor q having transverse spin $\mathbf{s}_\perp$ can be nonzero:

$$f_{q/\mathrm{p}}(x, \boldsymbol{s}_\perp; \mu^2) \propto \boldsymbol{s}_\perp \cdot \boldsymbol{S}_\perp$$

Transverse momentum

- The partons in a proton carry momentum components transverse to the beam direction.

- Thus there are transverse momentum dependent (TMD) parton distributions

$$f_{a/A}(x, \boldsymbol{k}_\perp, Q^2)$$

- If you are going into the woods, you have to be careful: there are some subtle issues in the definitions of these.

- On an intuitive level

$$f_{a/A}(x, Q^2) \sim \int d\boldsymbol{k}_\perp \; f_{a/A}(x, \boldsymbol{k}_\perp, Q^2)$$

Transverse momentum and spin

- As soon as we bring measured parton transverse momentum into the picture, there is a rich dependence on the spin of partons that is possible.
- For example, in an unpolarized proton, the transverse spin of a quark can be correlated with the transverse momentum of the quark:

$$f_{q/\mathrm{p}}(x, \boldsymbol{k}_\perp, \boldsymbol{s}_\perp) \propto \epsilon^{ij} k_\perp^i s_\perp^j$$

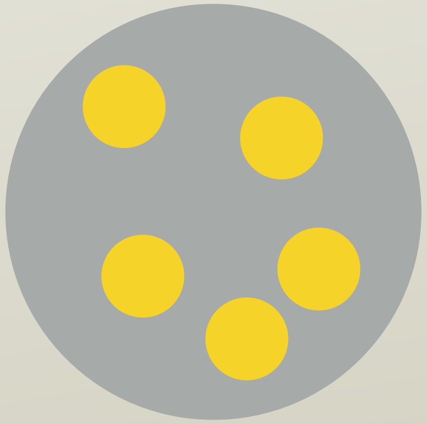
- There is quite a variety of spin and $\boldsymbol{k}_\perp$ dependent parton distribution that we can try to determine from experiment.

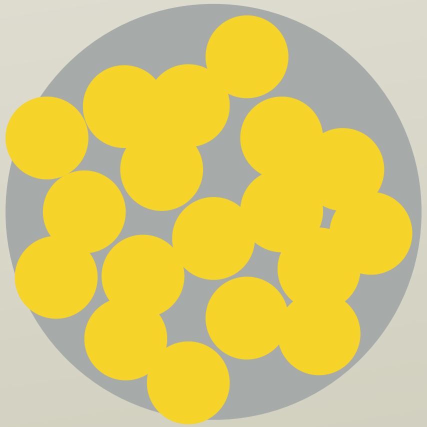
Where are the partons?

- Where are the partons located in transverse position $\boldsymbol{b}$?
- For that we need distributions $f_{a/A}(x, \boldsymbol{b}^2)$ derived from generalized parton distributions (GPDs).
- These are something like x dependent form factors.
- They are studied using *exclusive* final states obtained with a highly virtual probe.

Hadron structure at small x

- In $f_{a/A}(x, \mu^2)$, we see parton structure down to a resolution $\Delta \boldsymbol{b} \sim 1/\mu$.
- Think of a gluon having a size $\Delta \boldsymbol{b} \sim 1/\mu$.
- At small x, there are lots of gluons per unit $\log x$.
- Then if $1/\mu$ is not too small, the gluons can fill the hadron.





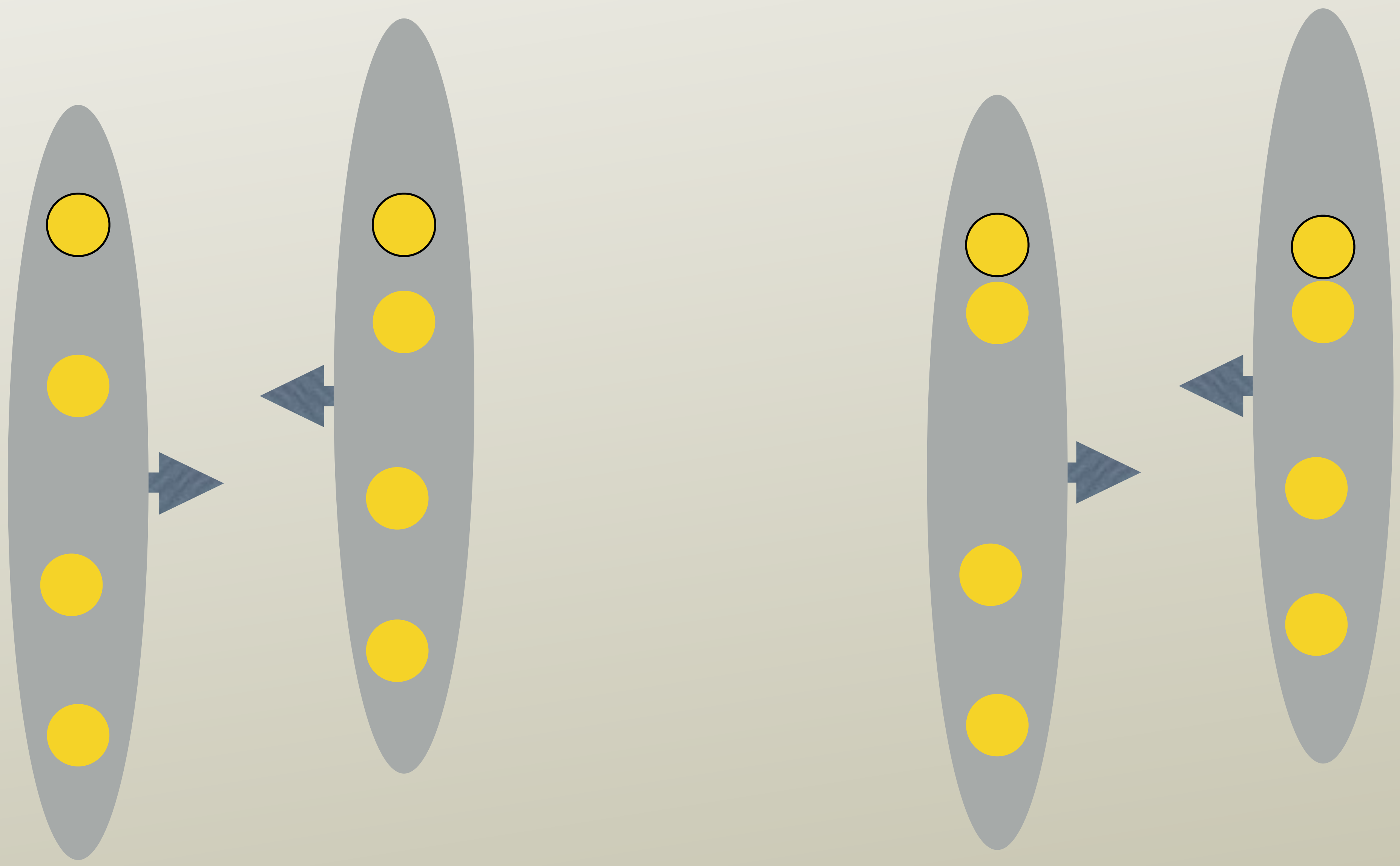
- This *saturation* regime can be analyzed using ideas of the *color glass condensate.*

Parton correlations

- Knowing one particle inclusive distributions like $f_{a/A}(x, k_\perp, Q^2)$ leaves a lot of questions unanswered.
- Does a quark comes with its own little cloud of gluons?
- Is it attracted to another quark to form a di-quark system?
- How do any effects like this depend on the colors and spins of the other partons?

- In part, one can investigate these sort of questions by looking for double parton scattering in hadron-hadron collisions.

- If the transverse separation between high x partons in the same proton is typically small, then the probability to have a second hard collisions when you have had one is large.



Experimental tools

- We would like to understand everything, but we can't do that without suitable experimental apparatuses.
- Fortunately, we heard this week that the U.S. Nuclear Science Advisory Committee has given an electron-ion collider a high enough priority that it seems likely that such a machine will be built.
- This will make possible a wide variety of investigations along many of the lines that I have outlined above.

Conclusion

- Life for Alice and Bob is not going to be just living happily ever after.
- There are lots of challenges, lots of physics answers to find through hard work and careful analysis.
- What we find may not be what we are expecting.
- But if we know in advance what we will find, there is no sense in doing experiments.