Making Predictions for Hadron Colliders

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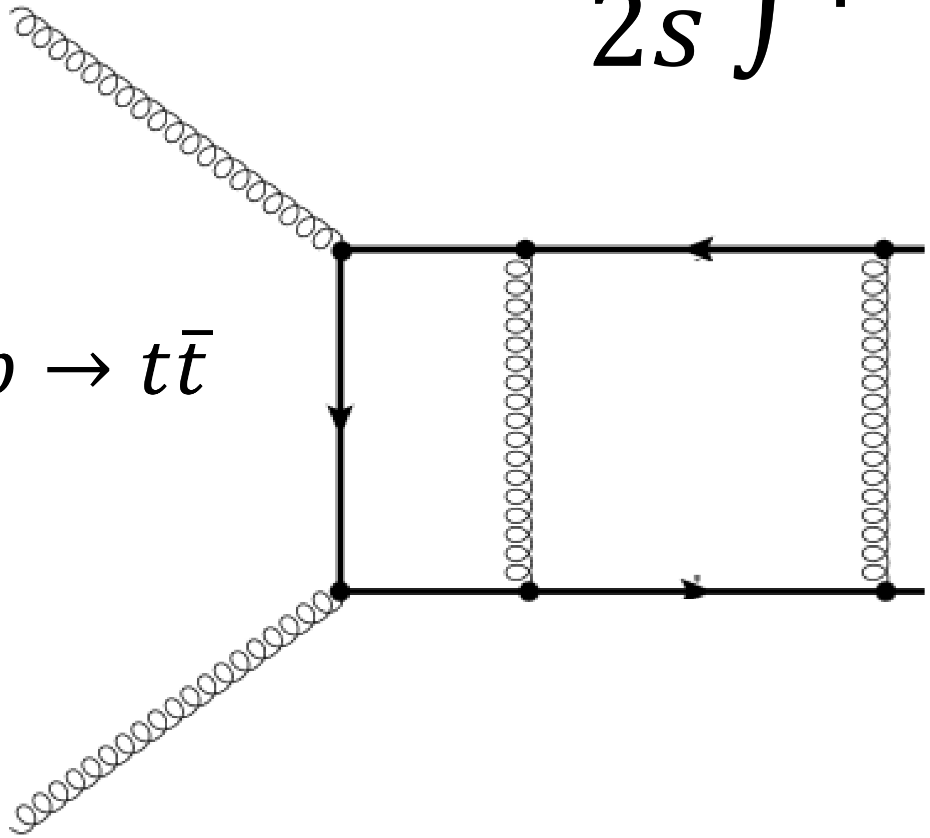
Making Predictions for Hadron Colliders

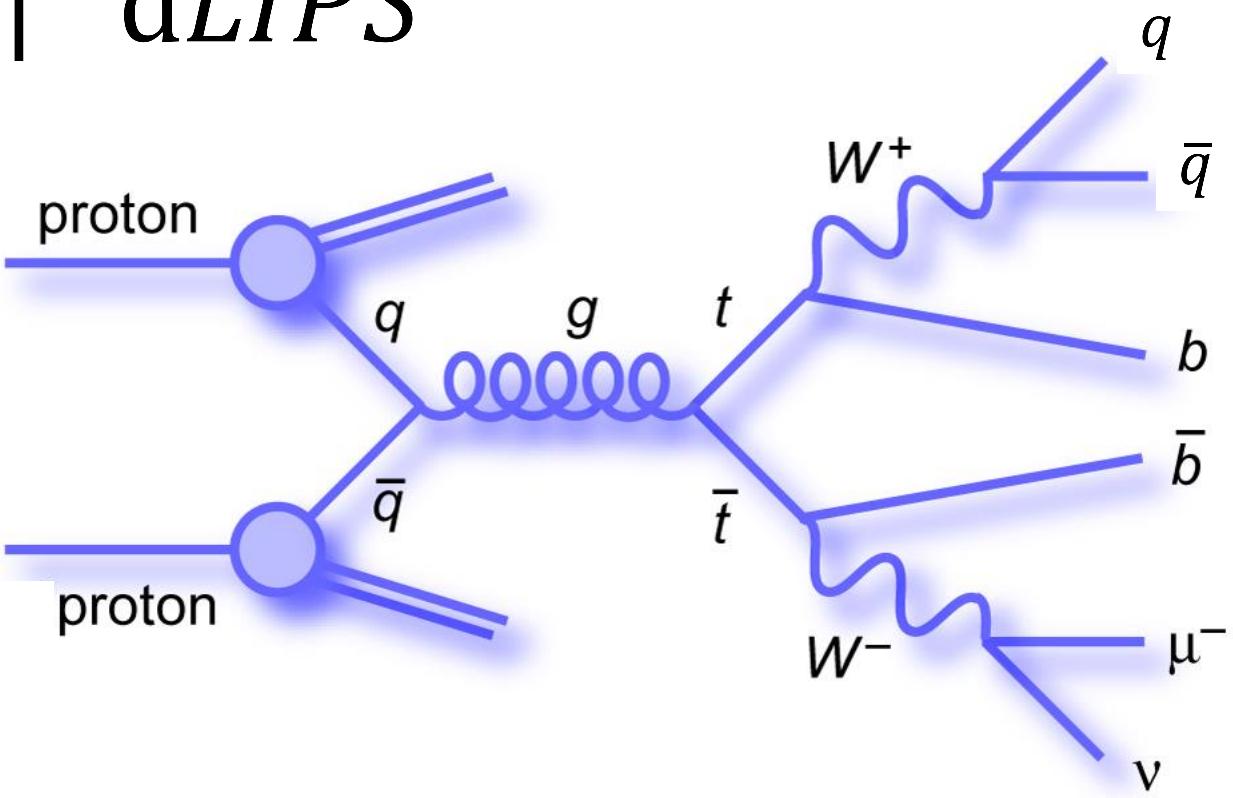
2. From Cross Sections to Events

Cross Sections

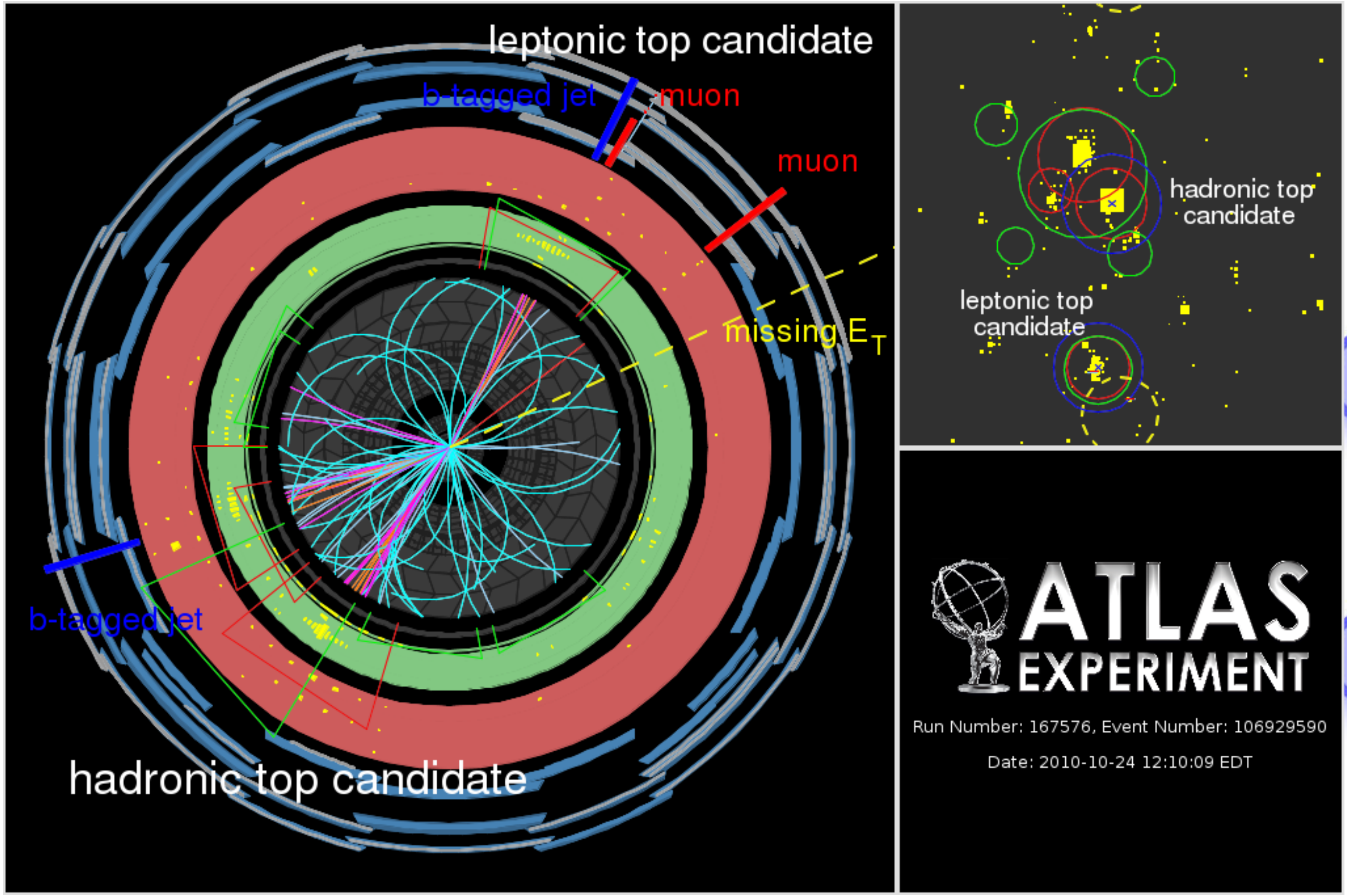
$$\sigma = \frac{1}{2s} \int |\mathcal{M}|^2 \, \mathrm{d}LIPS$$

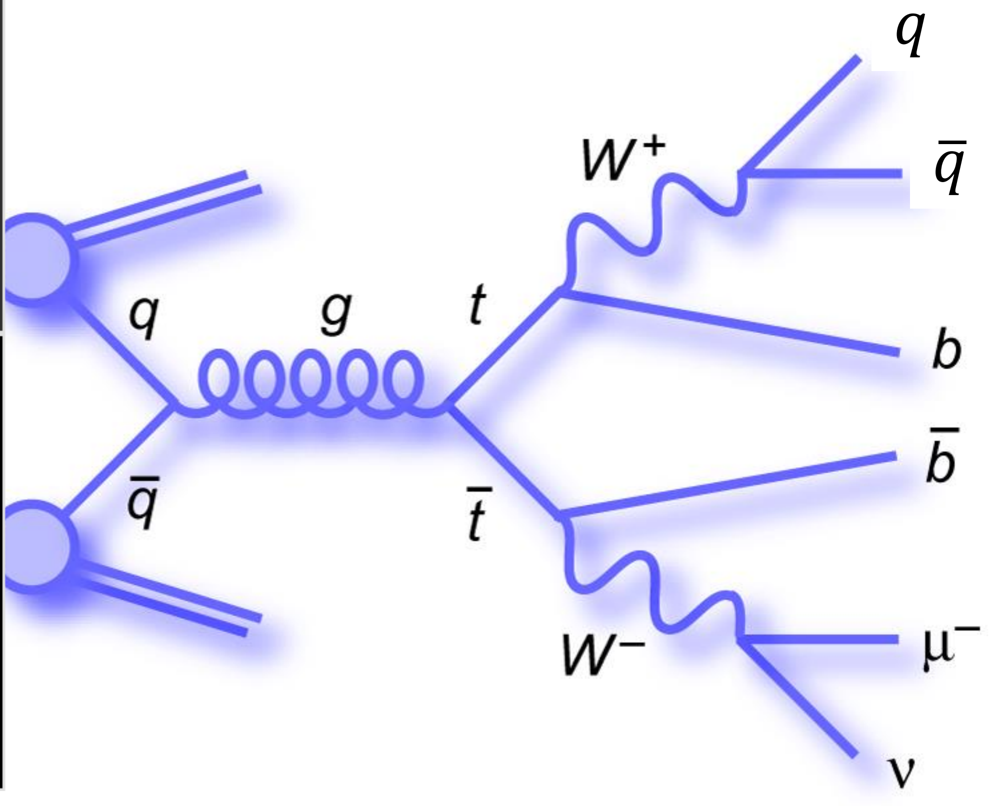
e.g. $pp \to t\bar{t}$
NNLO





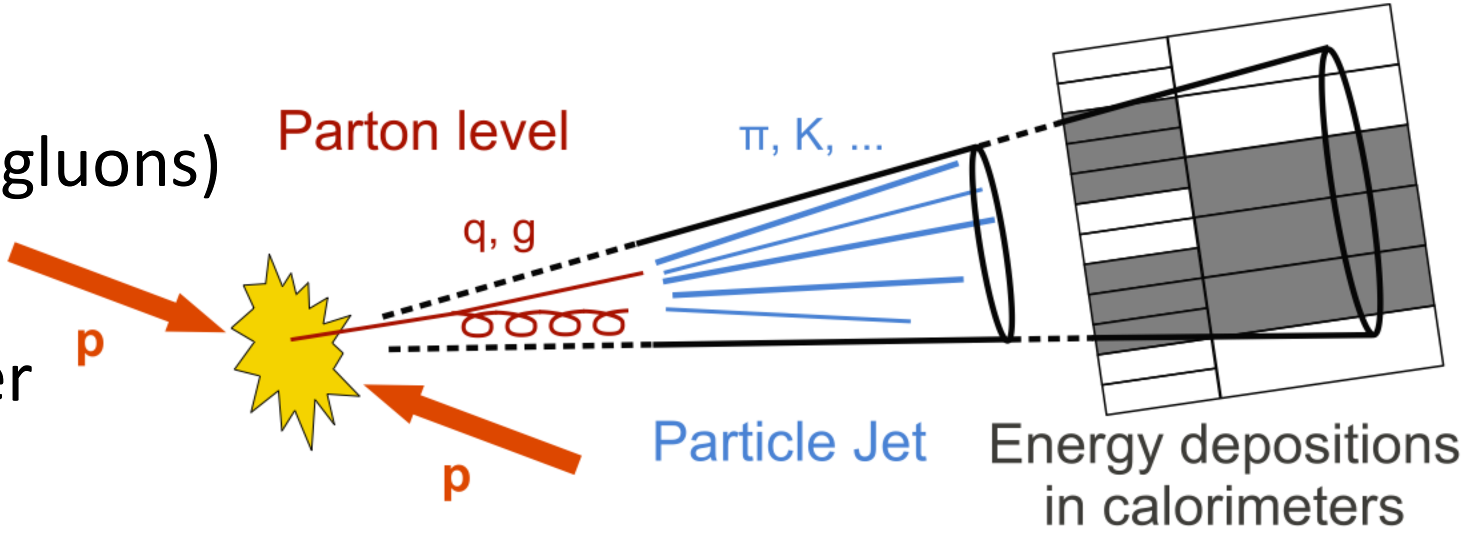
Cross Sections are not enough





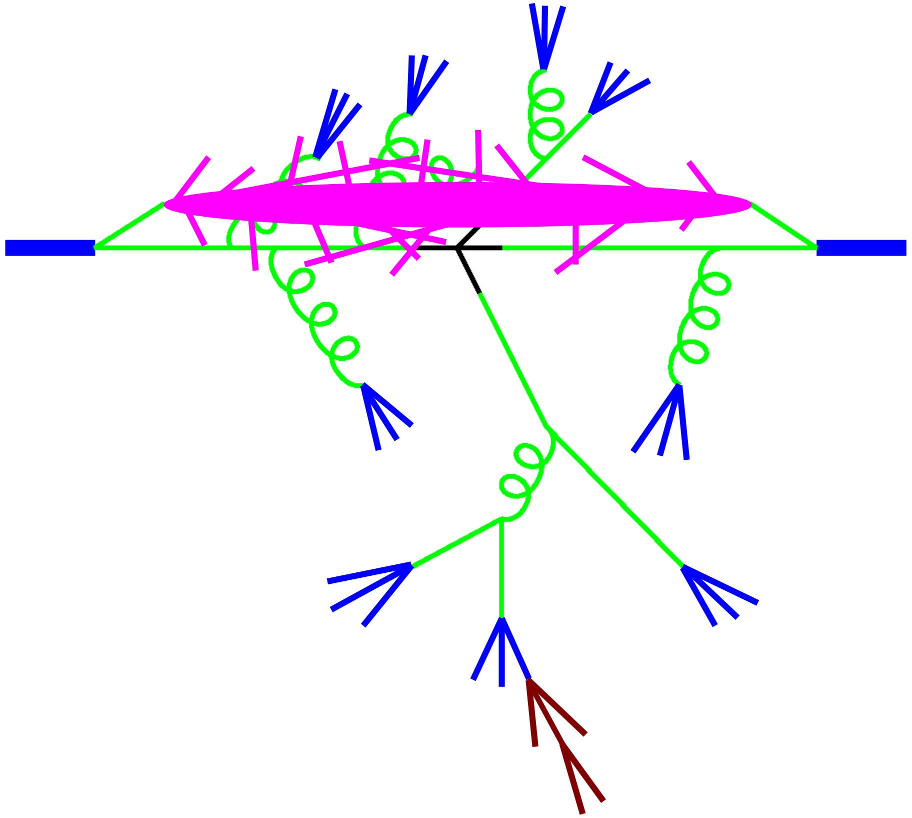
Need to describe *event structure*

- Hadrons (not quarks and gluons)
- Jets of hadrons
- Remnants of protons after parton extracted
- Unstable particle decays



Need Event Generators

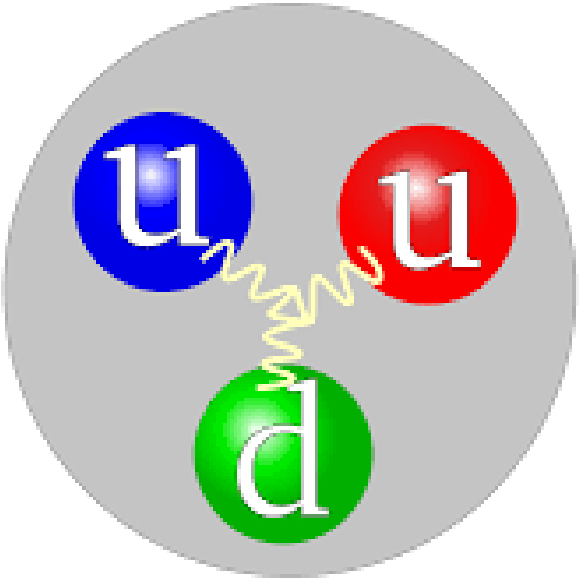
1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Parton showers and colour

- Quantum field theory of strong nuclear force = Quantum ChromoDynamics, QCD
- Quarks carry *colour*
- Gluons couple to colour
- Gluons carry colour

→ Gluons couple to gluons



Parton showers and colour

- Quantum field theory of strong nuclear force = Quantum ChromoDynamics, QCD
- Quarks carry *colour*
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- Gluons carry colour

→ Gluons couple to gluons

QED: accelerated charges radiate.

QCD identical: accelerated colours radiate.

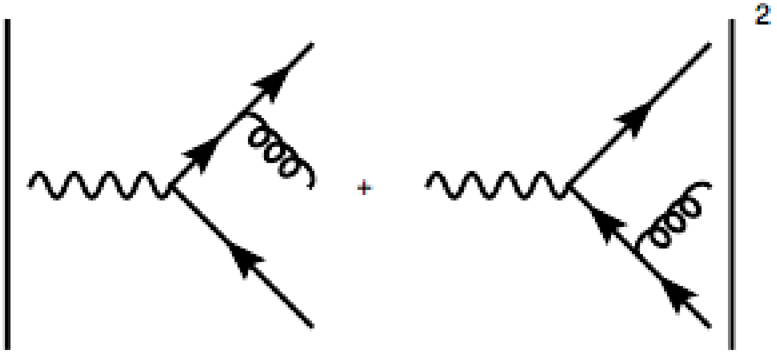
gluons also charged.

→ cascade of partons.

= parton shower.

Gluon emission is universal

e.g. $e^+e^- \to 3$ partons:



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}z_g} \sim \sigma_0\, C_F\, \frac{\alpha_s}{2\pi}\, \frac{2}{\sin^2\theta}\, \frac{1+(1-z_g)^2}{z_g}$$

- z_g: $E_g/E_{g,max}$
- σ_0: $e^+e^- \to 2$ partons
- C_F: "quark charge squared"
- α_s: QCD running coupling ~ 0.1

Divergent in collinear limit $\theta \to 0,\pi$ (for massless quarks)

and soft limit $z_g \to 0$

$$d\sigma = \sigma_0 \sum_{\text{jets}} C_F \frac{\alpha_s}{2\pi}\frac{d\theta^2}{\theta^2}\, dz \frac{1+(1-z)^2}{z}$$

Parton branching is universal

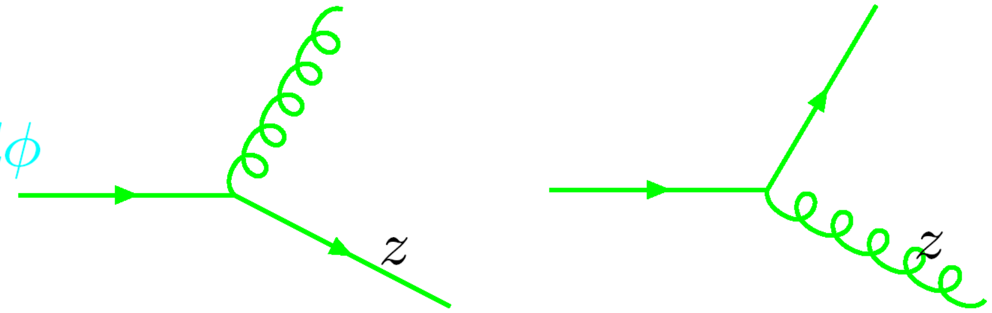
$$d\sigma = \sigma_0 \, \frac{\alpha_s}{2\pi} \, \frac{d\theta^2}{\theta^2} \, dz \, P(z, \phi) d\phi$$

$$P(z, \phi) =$$

"Splitting function":
dependent on flavour and spin but not on how parton was produced

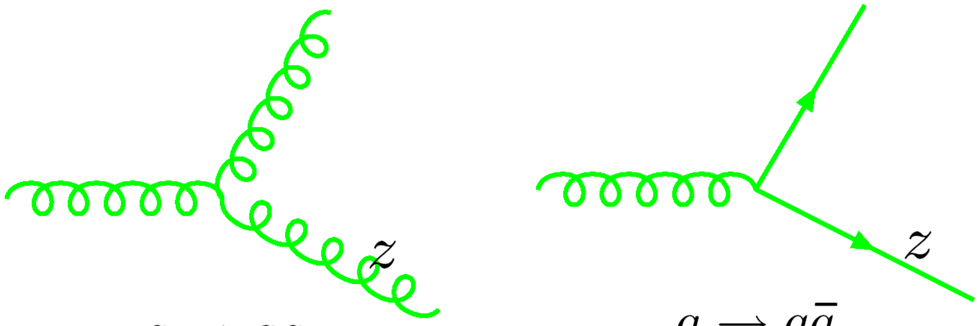
→Probability distribution for parton branching

→Simulation



$q \to qg$: $C_F \frac{1+z^2}{1-z}$

$q \to gq$: $C_F \frac{1+(1-z)^2}{z}$



$g \to gg$: $C_A \frac{z^4+1+(1-z)^4}{z(1-z)}$

$g \to q\bar{q}$: $T_R \left(z^2 + (1-z)^2\right)$

Parton branching is universal

$$d\sigma = \sigma_0 \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2} dz\, P(z, \phi) d\phi$$

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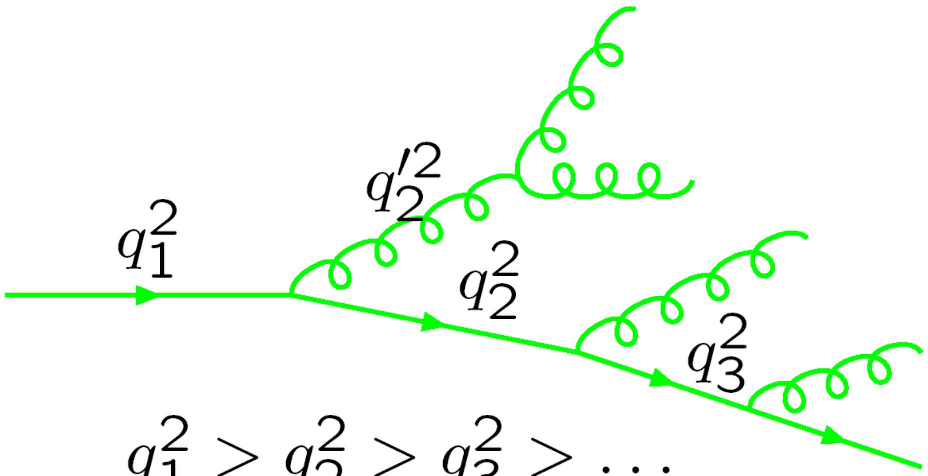
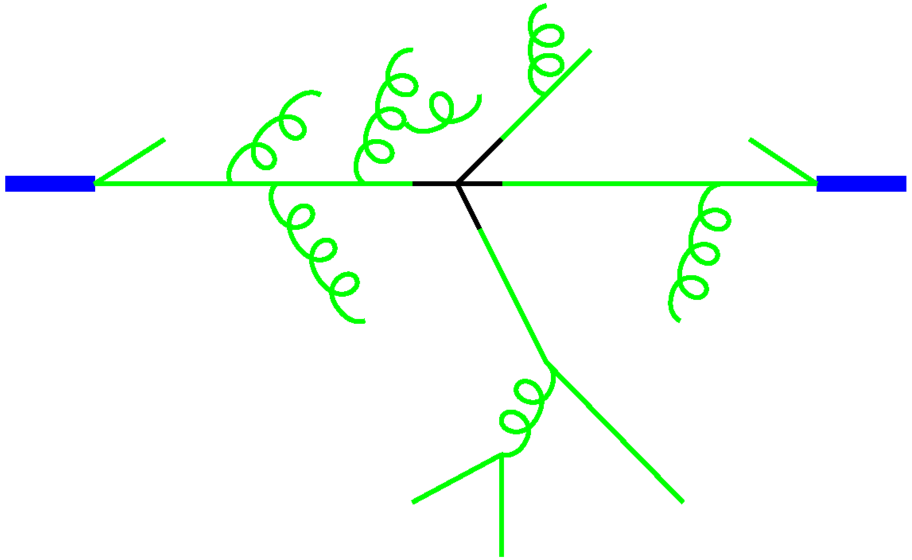


$$q_1^2 > q_2^2 > q_3^2 > \ldots$$
$$q_1^2 > q_2'^2 \ldots$$

→Iterative evolution

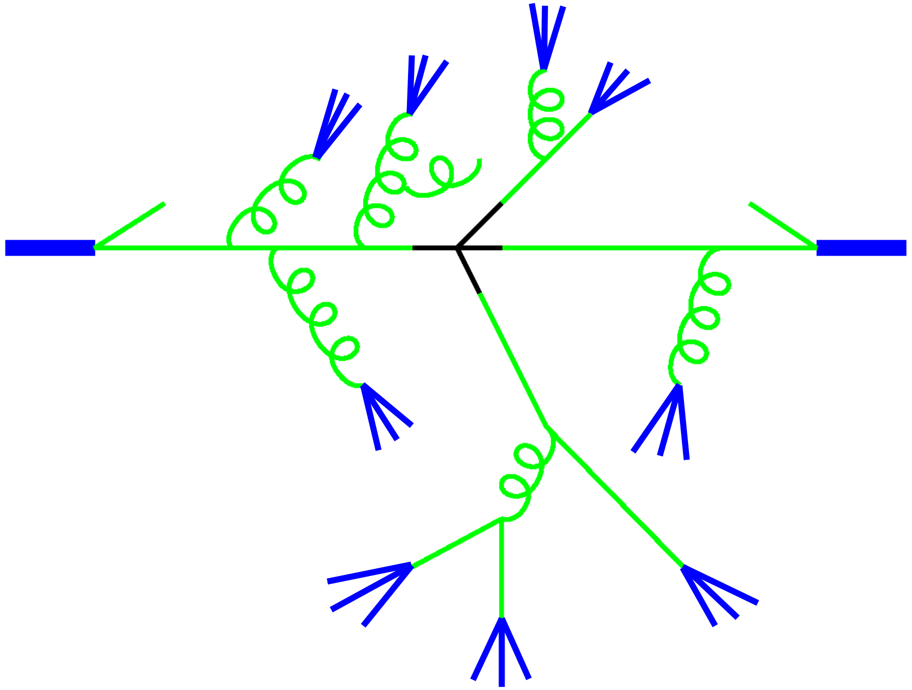
Need Event Generators

1. Hard process
2. Parton shower
    - Start from hard process and work outwards
    - Evolve *downwards* in momentum scale
    - Strong coupling gets *stronger*



Need Event Generators

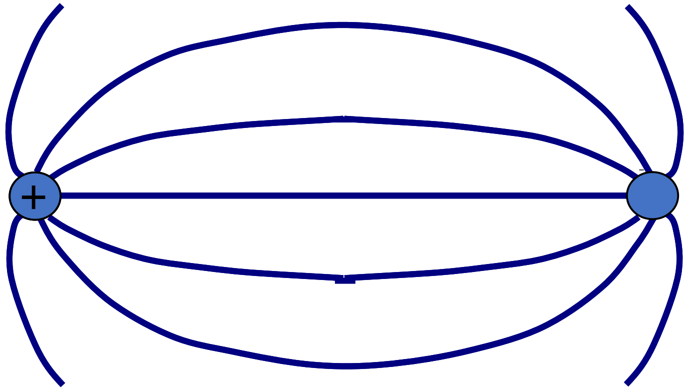
1. Hard process
2. Parton shower
3. Hadronization



Confinement

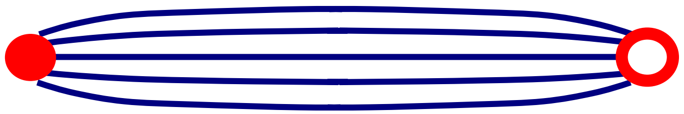
Asymptotic freedom: $Q\bar{Q}$ becomes increasingly QED-like at short distances.

QED:



but at long distances, gluon self-interaction makes field lines attract each other:

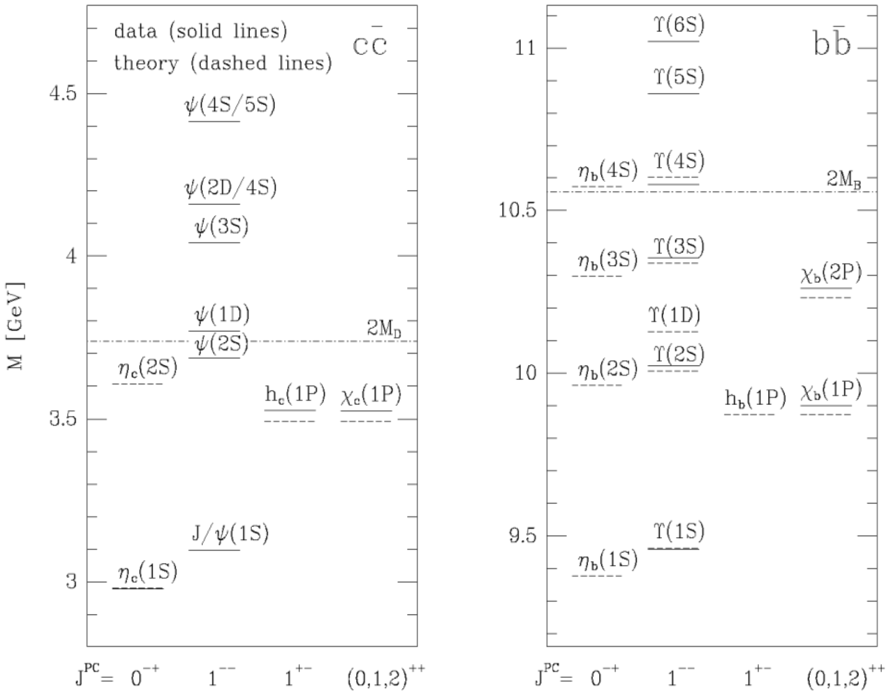
QCD:



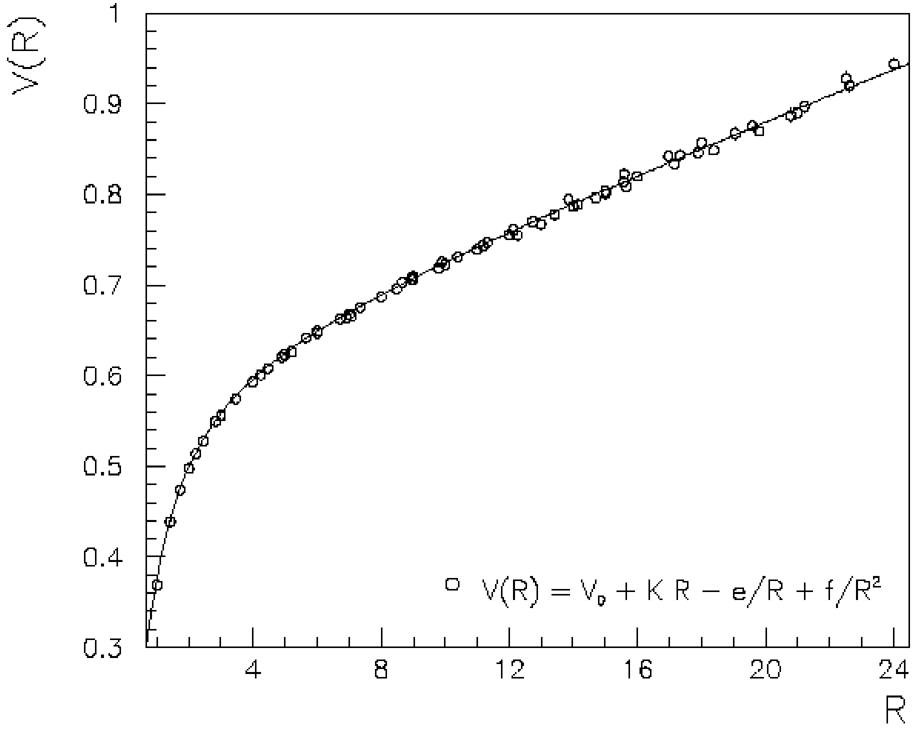
→linear potential → confinement

Interquark potential

Can measure from quarkonia spectra:



or from lattice QCD:

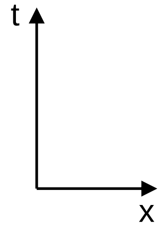


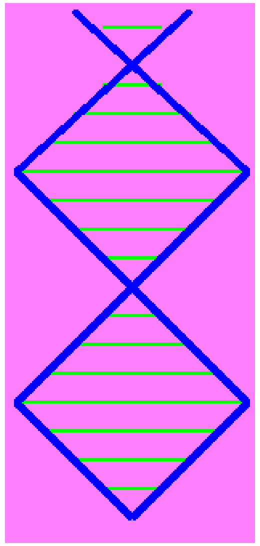
→ String tension $\kappa \approx 1\ \text{GeV/fm}$.

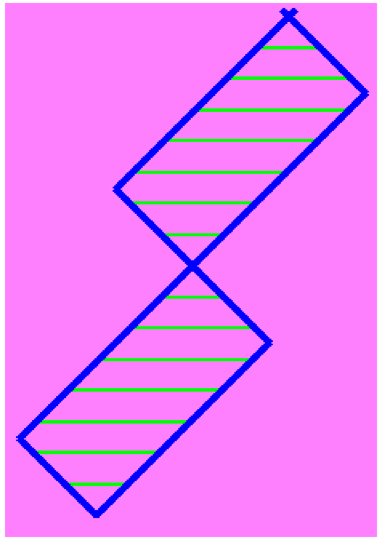
String Model of Mesons

Light quarks connected by string.

L=0 mesons only have 'yo-yo' modes:







The Lund String Model

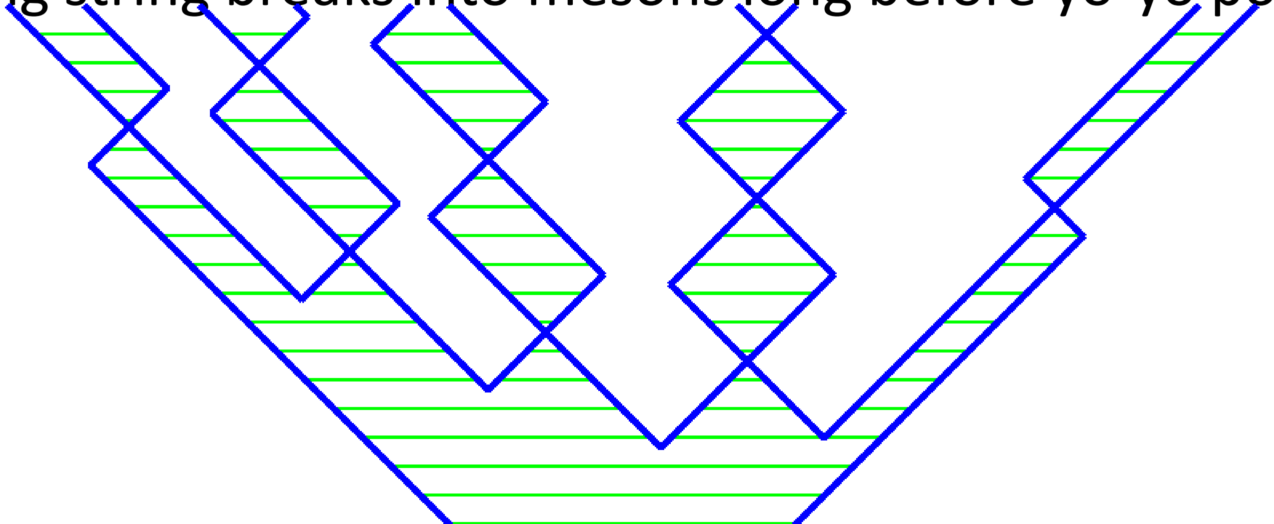
Start by ignoring gluon radiation:

e^+e^- annihilation = pointlike source of $q\bar{q}$ pairs

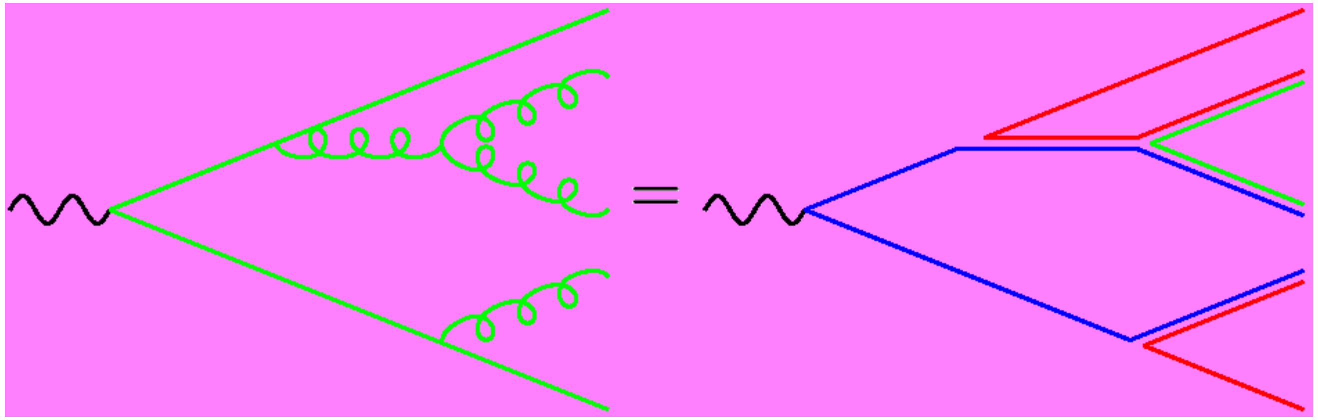
Intense chromomagnetic field within string → $q\bar{q}$ pairs created by tunnelling. Analogy with QED:

$$\frac{d(\text{Probability})}{dx\ dt} \propto \exp(-\pi m_q^2/\kappa)$$

Expanding string breaks into mesons long before yo-yo point.



Colour and confinement



- Hadronization happens in the space between partons

Need Event Generators

1. Hard process
2. Parton shower
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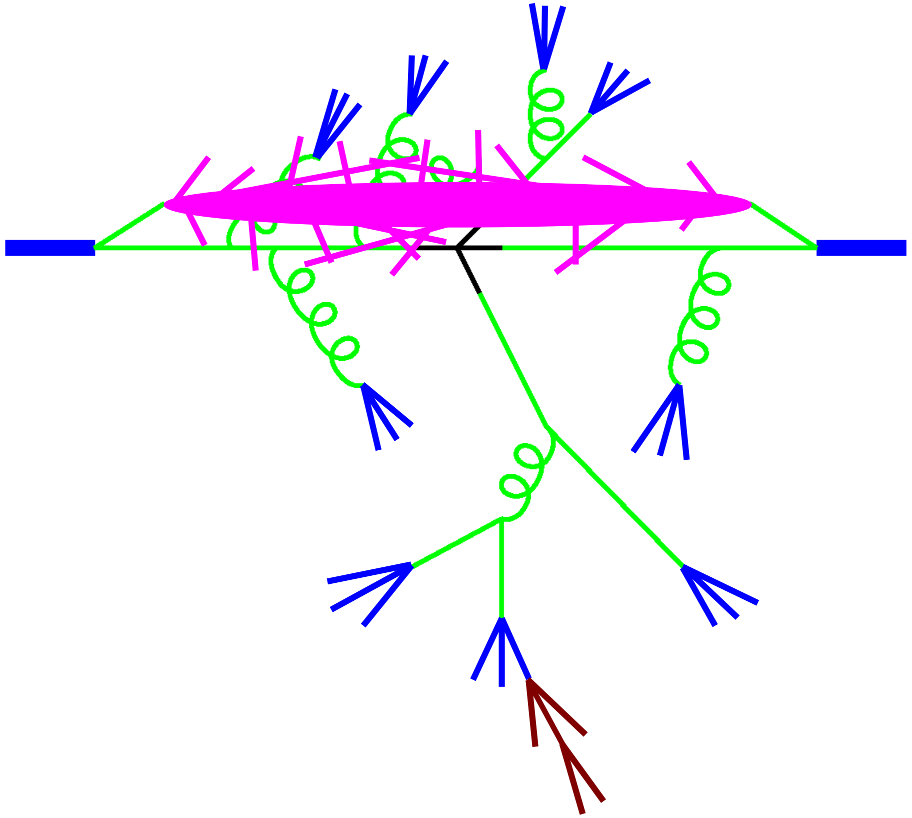
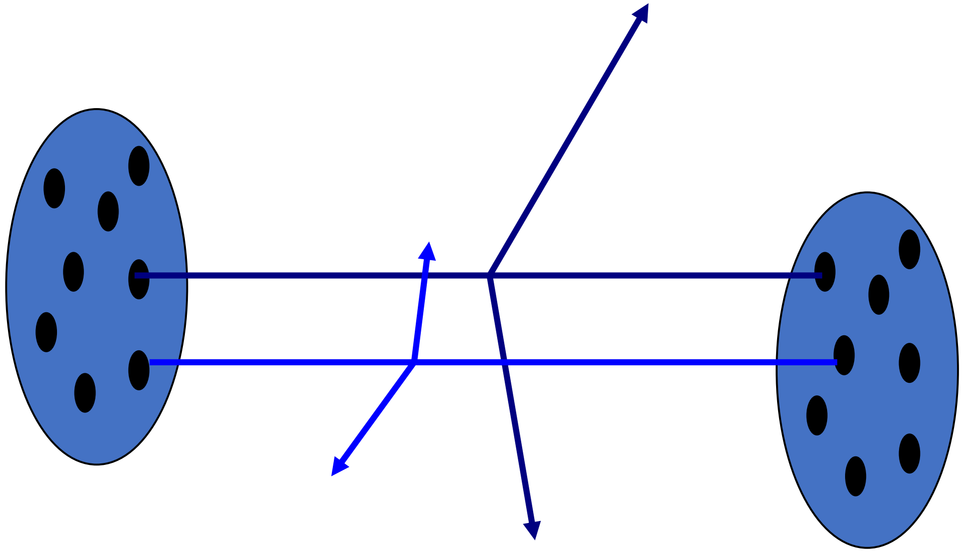
4. Underlying event
5. Unstable particle decays



The Underlying Event

- Protons are extended objects
- After a parton has been scattered out of each, what happens to the remnants?



Multi-parton interactions:
need model of parton distributions in proton
scattering can then be calculated

Need Event Generators

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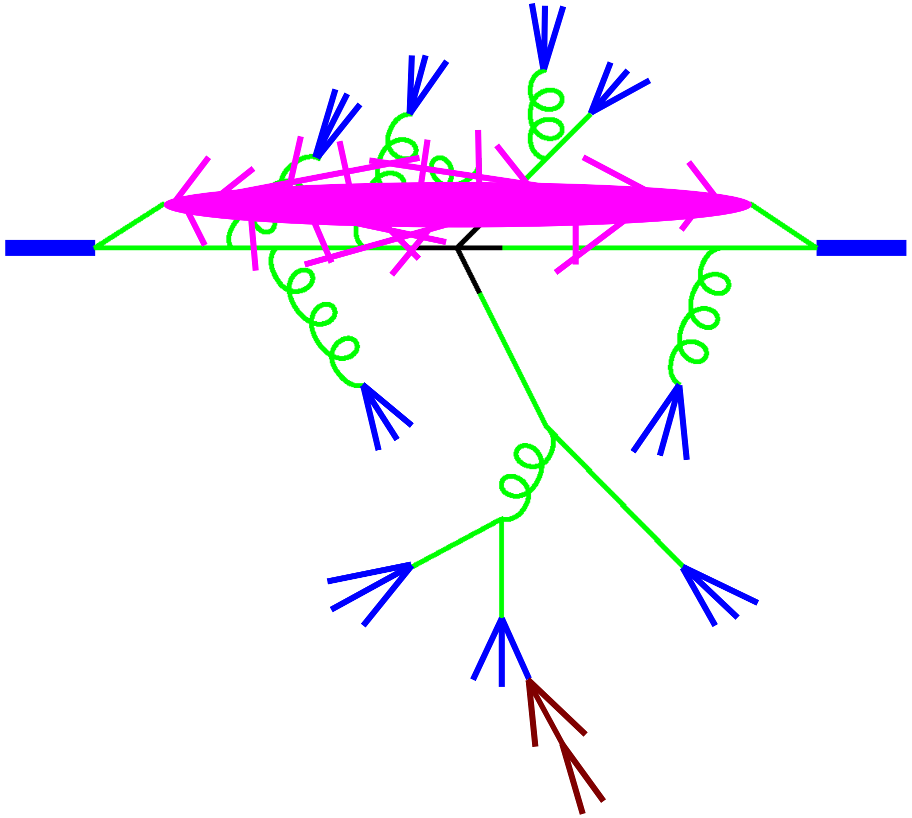
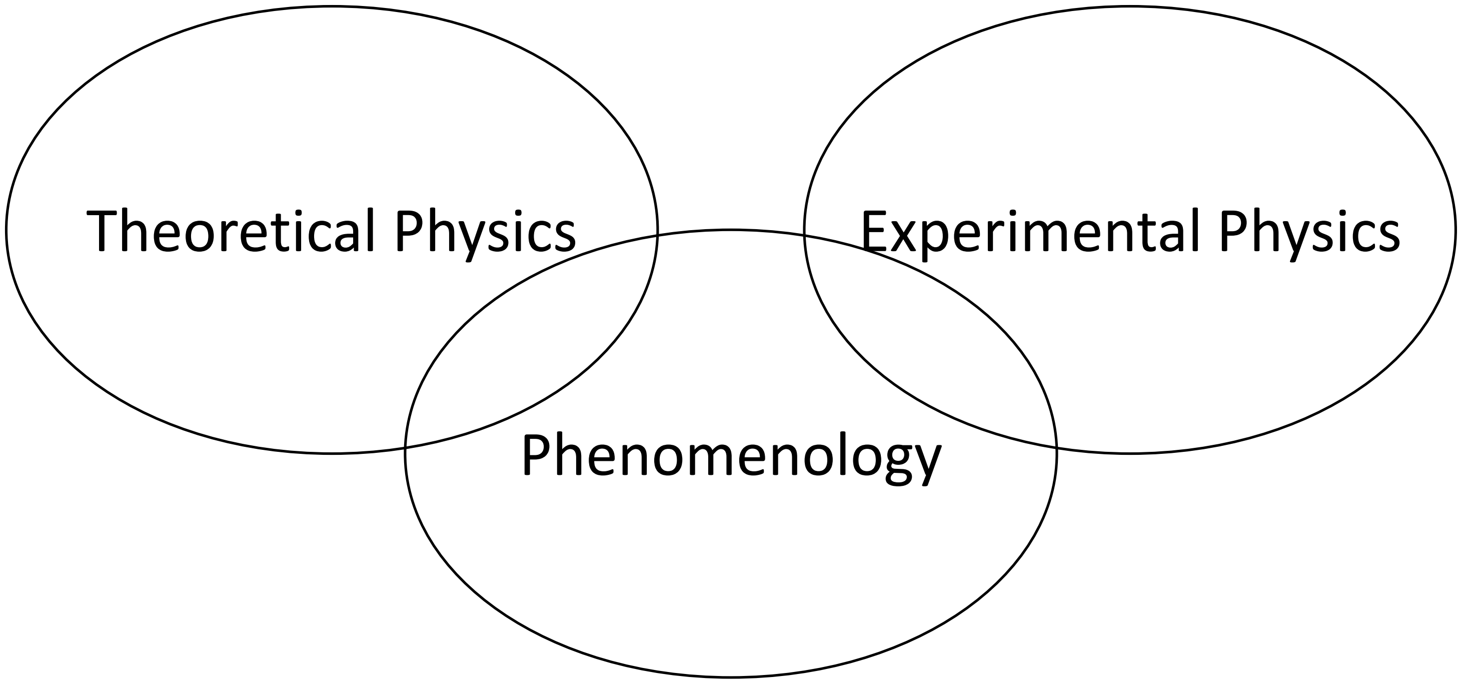
Herwig, Pythia, Sherpa



Phenomenology



Making your measurements futureproof – Rivet

- Flexible and powerful framework to implement generator- and experiment-independent analyses
- Check in your analysis and it is preserved forever
- Check in your (published) data and it can be compared with theory forever – even theories that haven't been dreamt up yet!