Dynamics of EW & Strong Interactions

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Lecture 5 - Trieste, 10/01/2023

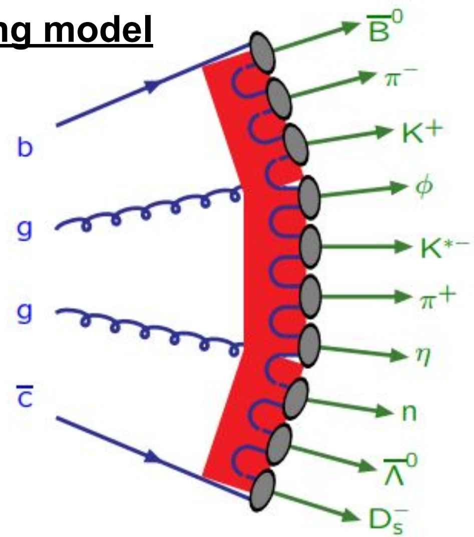
MC simulation (continued)

Hadronization models

- Reminder:
  - Evolution of parton shower to lower and lower energies brings to non-perturbative regime
    - transition between perturbative regime (quark and gluon showers)
      and non-perturbative regime (hadrons) regulated by "hadronization" process

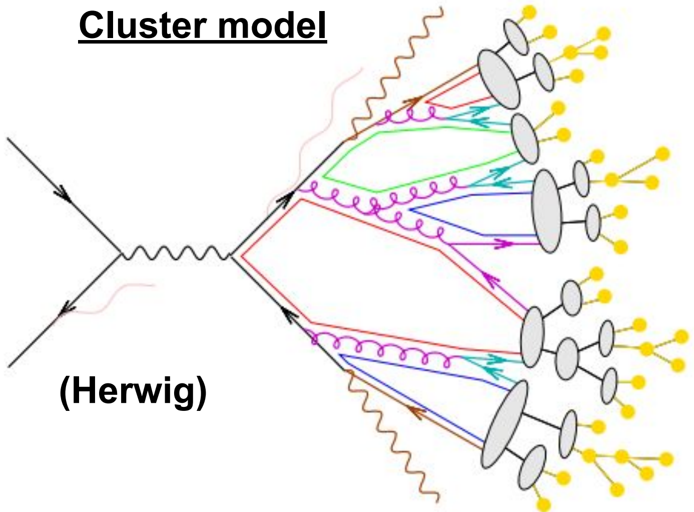
String model

(Pythia)



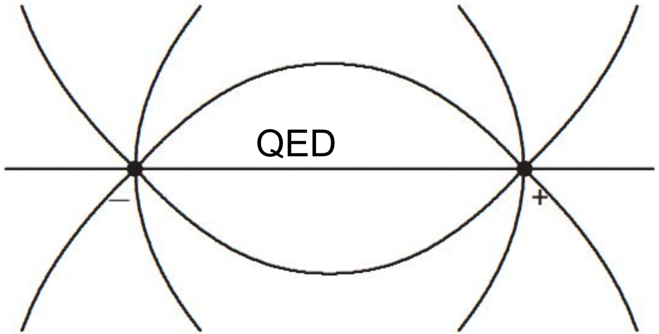
Cluster model

(Herwig)



String Model

- Remind feature of QCD potential:



$$V(\mathbf{x}) \propto \sum_i \frac{1}{|\mathbf{x} - \mathbf{x}_i|}$$

QCD

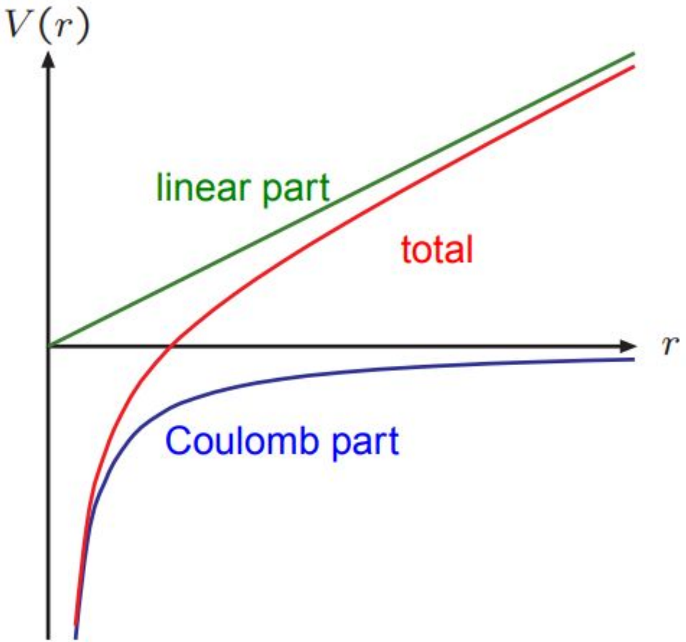
$$V(r) \approx \kappa r$$

(for "large" r)

$\kappa \approx 1\ \mathrm{GeV/fm}$

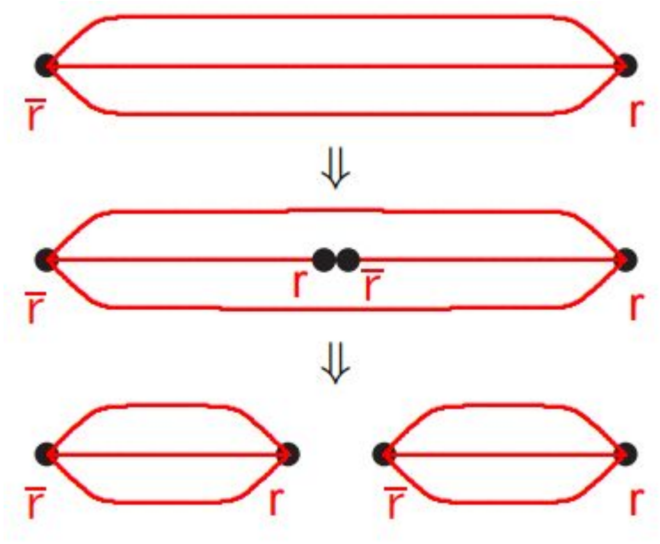
String Model

- Large r ⇒ field lines compressed to tubelike region(s) ⇒ string(s)



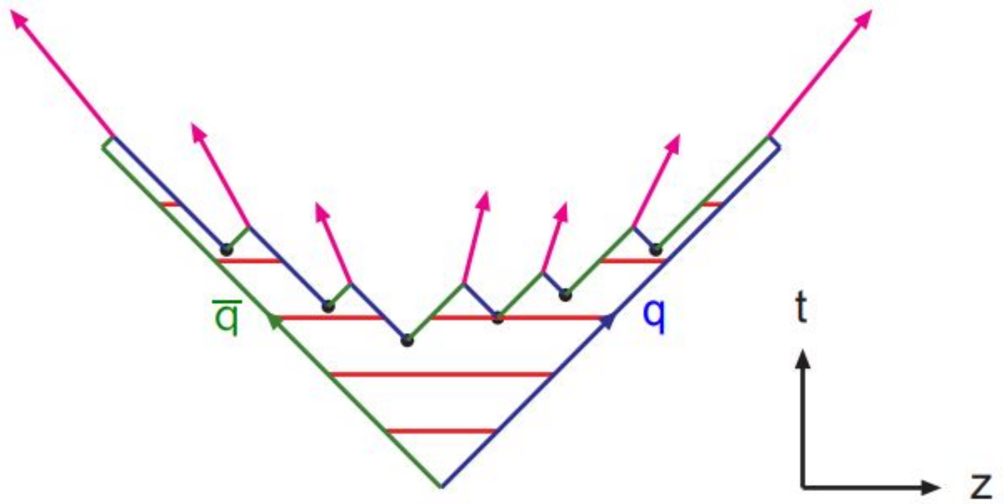
String Model

- What happens when distance becomes larger and larger?
  - string breaks into $q\bar{q}$ pair (more convenient energetically)



Lund String Model

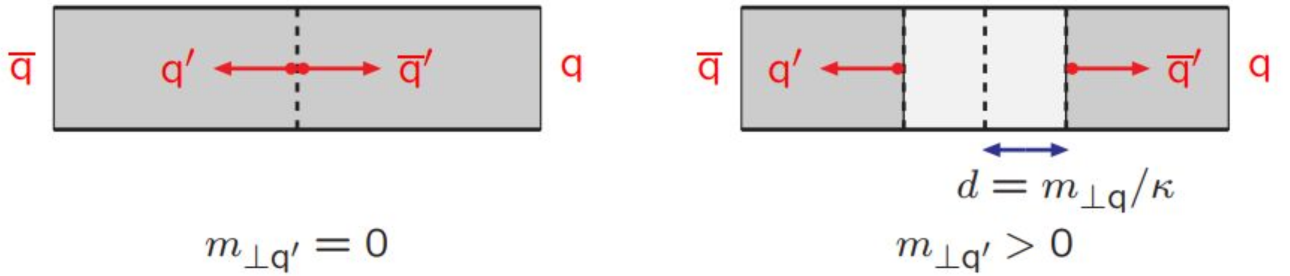
- Repeating for large system → Lund string model (neglects Coulomb part)
- Motion of quarks and antiquarks in a $q\bar{q}$ system:



  - simple but powerful picture of hadron production (with extensions to massive quarks, baryons...)

Lund String Model

- String breaks by tunneling:

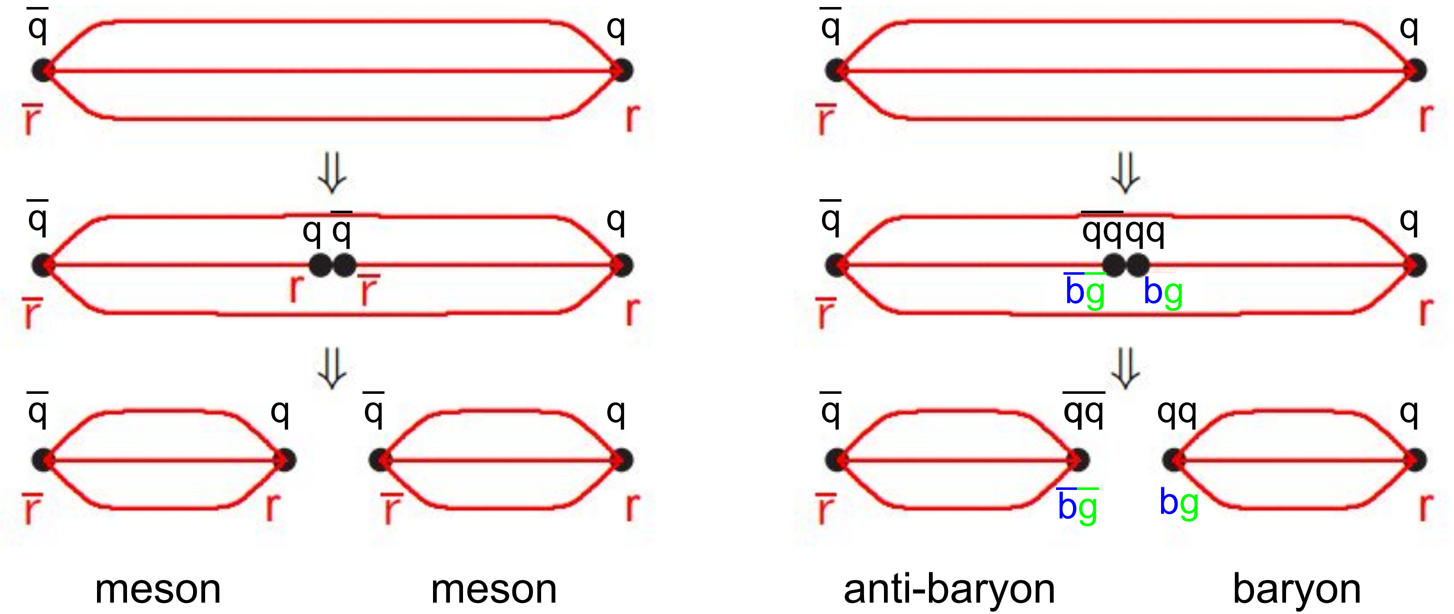


($m_{\perp}$= m+$p_{\perp}$)

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_q^2}{\kappa}\right)$$

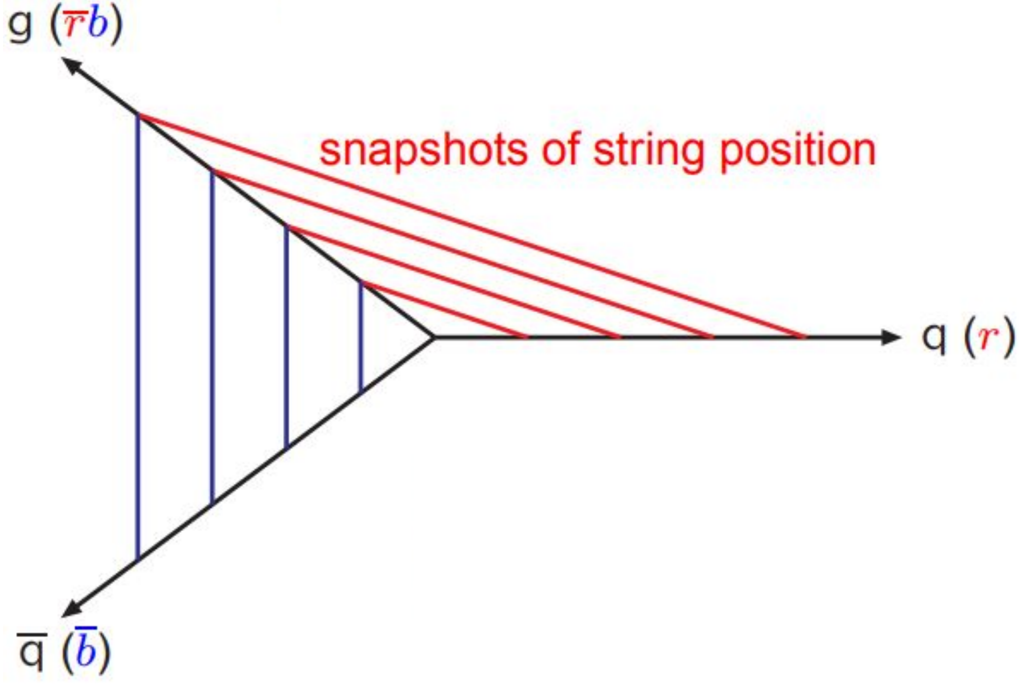
Lund String Model

- What about baryons?
  - can replace $\bar{q}$ by qq' pair!



Lund String Model

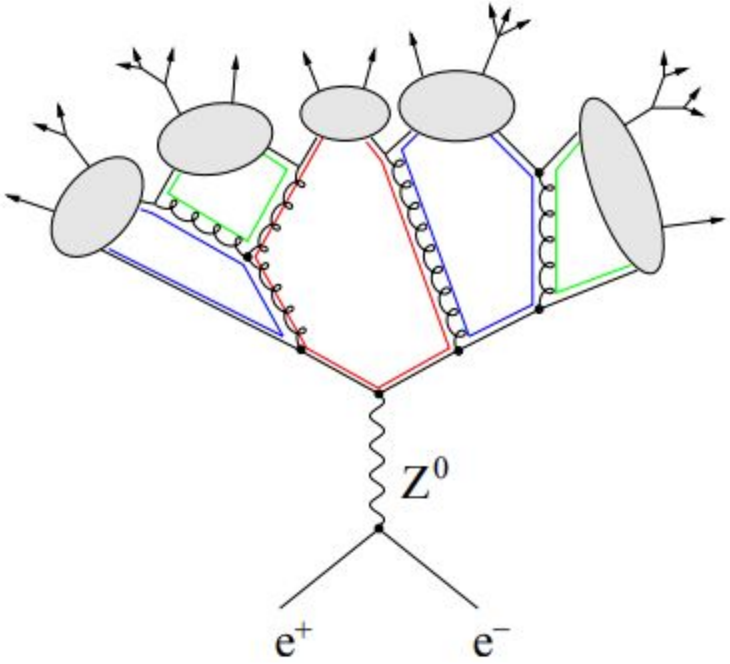
- What about gluons?



Cluster Model

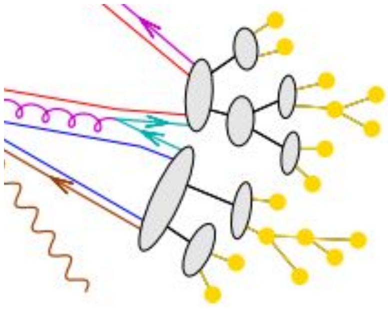
- Based on production of clusters, i.e. colour-neutral pseudo-particles that decay to ordinary hadrons
  - made possible by pre-confinement
    (i.e. colour flow local in coherent shower evolution)

- Basic steps:
  - force $g \rightarrow q\bar{q}$ splitting
  - form colour singlet clusters
  - decay clusters isotropically to 2 hadrons

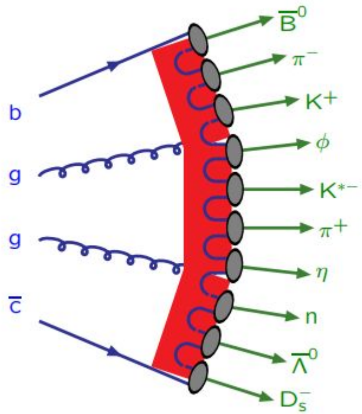


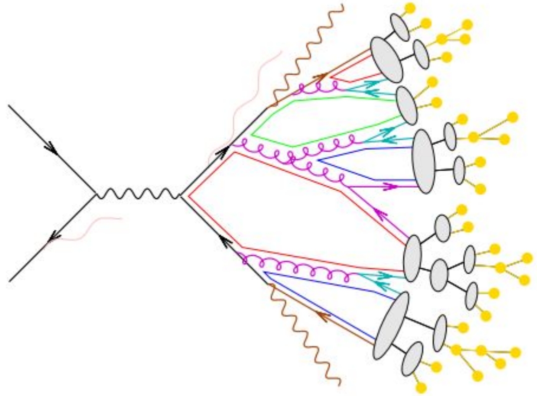
Cluster Model

- Problems & corrections:
  - very large-mass clusters tend to be produced (e.g. no emission in shower...)
    - split big clusters into 2 along "string" direction, iterate if required
      ⇒ ~ 15% of primary clusters split, giving raise to ~ 50% of total hadrons
  - baryons: clusters from $q\bar{q}$ always B=0?
    - splitting $g \rightarrow qq+\overline{qq}$ introduced
  - too soft charm/bottom spectra
    - anisotropic leading-cluster decay
  - ...



String vs. Cluster



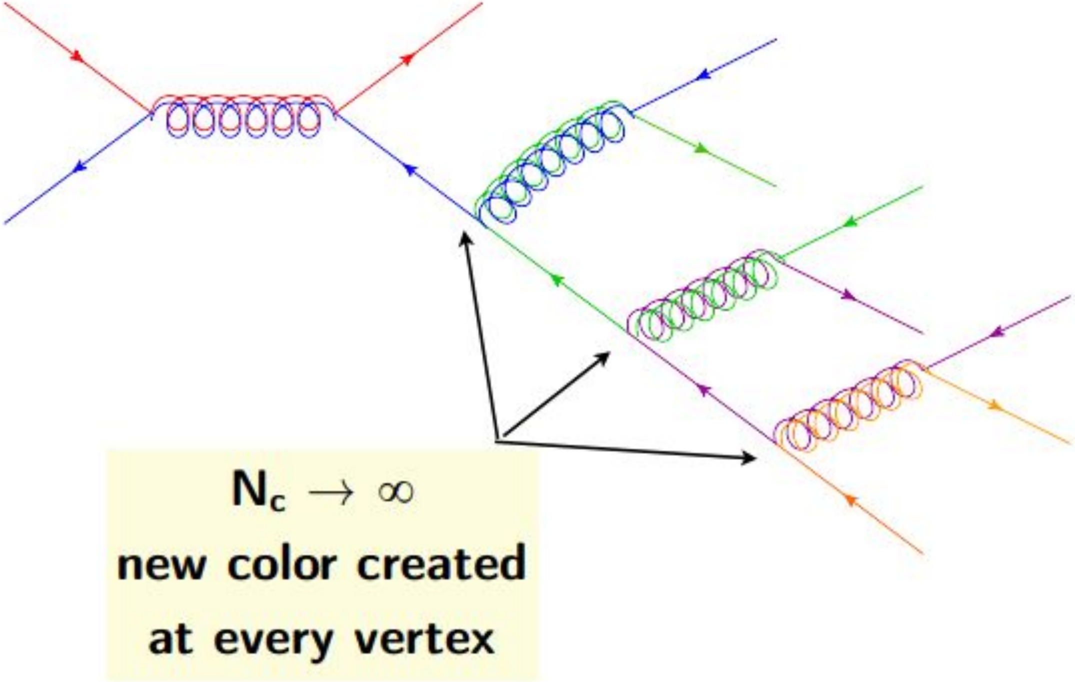


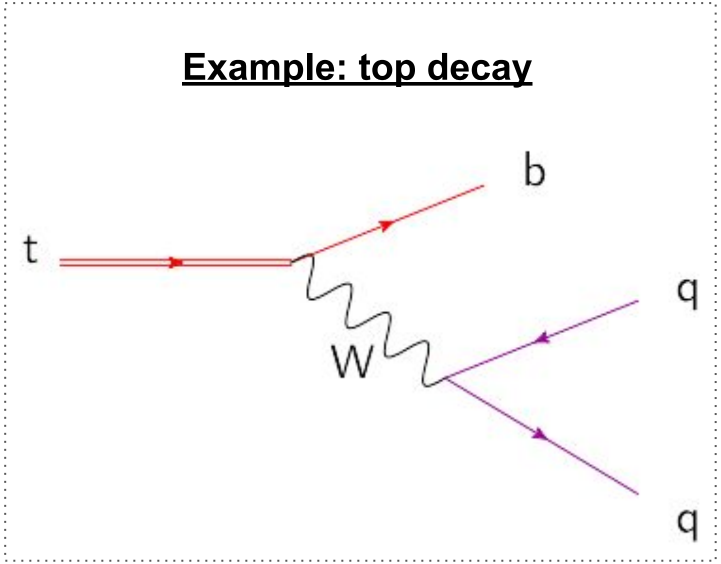
program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful predictive	simple unpredictive
parameters	few	many
flavour composition	messy unpredictive	simple in-between
parameters	many	few

"There ain't no such thing as a parameter-free *good* description"

Colour reconnection

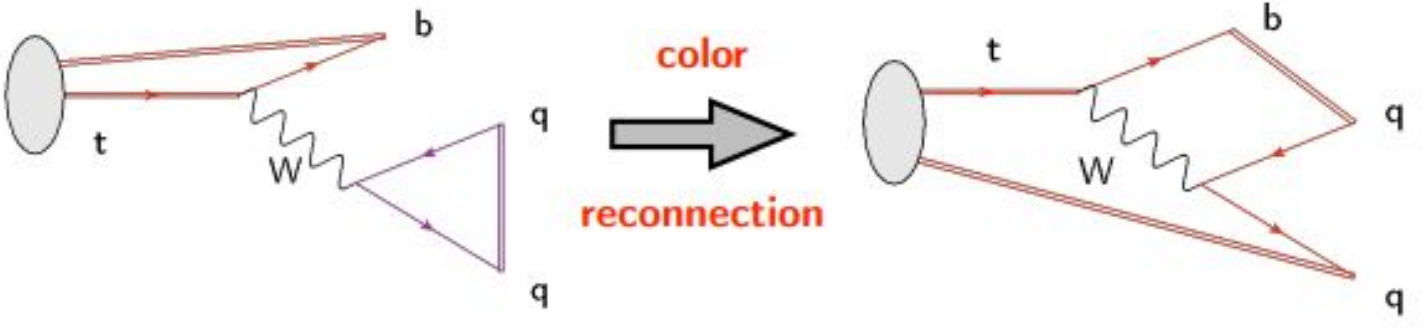
- Usually parton showers work in $N_c \to \infty$ approximation:





Colour reconnection

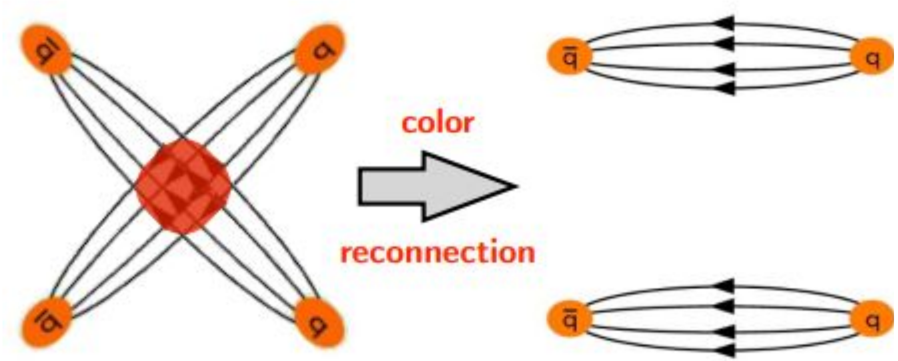
- Moving away from $N_c \to \infty$ approximation, colour flow can connect partons from different vertices



- Colour reconnection = ad-hoc mechanism to describe:
  - sub-leading color effects in the perturbative part of the calculation
  - interactions between color fields during the hadronization transition

Colour reconnection

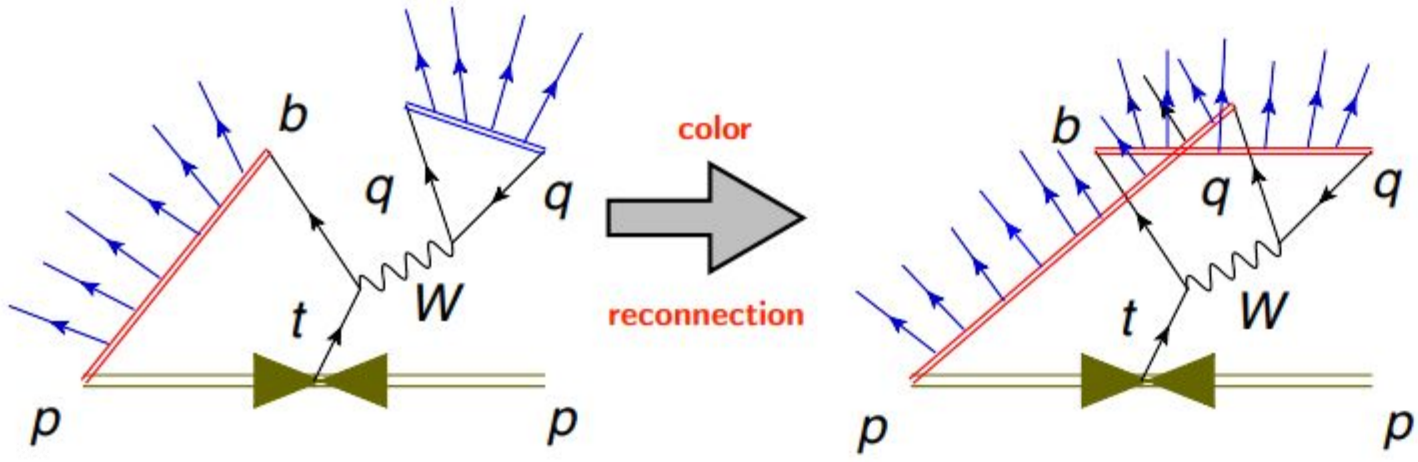
- Another way to see colour reconnection - at the string level:



Colour reconnection

- Implementation in MC:
  - certain probability assigned for recombination
  - following different possible models

- Effect on final-state particles:



Uncertainties in MC simulation

- Typical systematic uncertainties affecting a NLO+PS MC prediction:
  - ME:
    - scale variations (see later)
    - PDF uncertainties
  - ME+PS:
    - matching scheme / matching scale
  - PS:
    - choice of algorithm ordering, recoil...
    - scale variations / effective α_S
  - Hadronization:
    - choice of hadronization model
    - uncertainties on hadronization parameters (e.g. in fragmentation functions)
  - All:
    - colour reconnection model
    - theory parameters: masses and couplings (such as α_S)

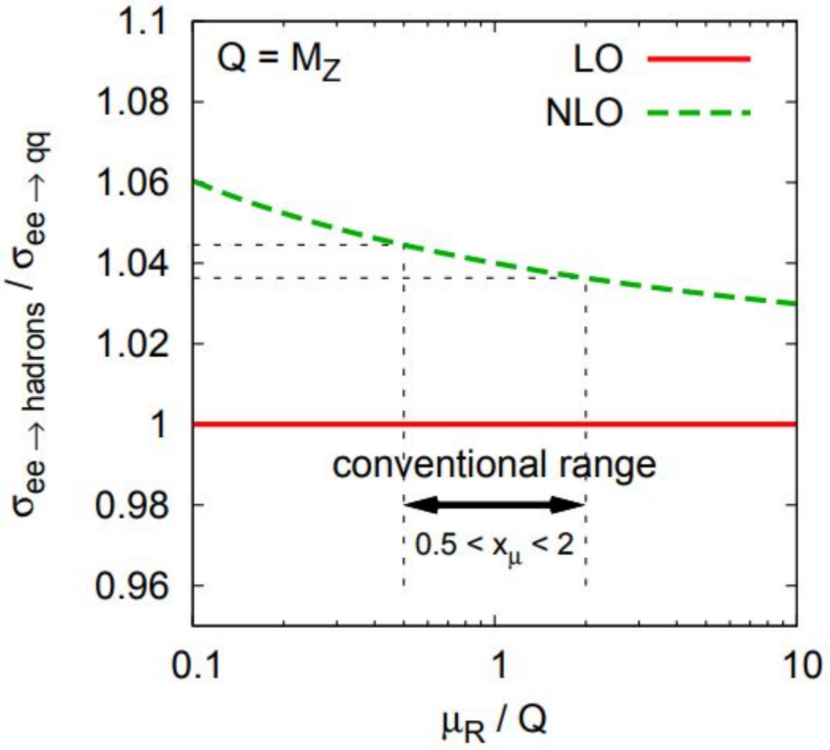
Scale dependence

- Consider $e^+e^- \to$ hadrons
  - start with first order that contains QCD (NLO)
  - coupling α_S needs to be evaluated for a certain renormalization scale, μ_R

$$\sigma^{\rm NLO} = \sigma_{q\bar{q}}\,(1 + c_1\alpha_s(\mu_R))$$

  - the result (at fixed order, NLO) depends on choice of μ_R ⇒ "scale" uncertainty

- Typically:
  - μ_R chosen as = Q (m_Z in this case)
  - "renorm. scale uncertainty" accessed by varying μ_R between Q/2 and 2Q



Scale dependence

- Scale variations interpreted as "missing higher orders" uncertainty - why?
- Let's express results for arbitrary μ_R in terms of $\alpha_s(Q)$:

$$\sigma^{\mathrm{NLO}}(\mu_R) = \sigma_{q\bar{q}}\left(1 + c_1\,\alpha_s(\mu_R)\right)$$

$$\alpha_S(\mu_R) = \frac{1}{1 + 2\beta_0\alpha_S(Q)\log\frac{\mu_R}{Q}}$$

$$= \alpha_s(Q) - 2\beta_0\alpha_s^2(Q)\log\frac{\mu_R}{Q} + \mathcal{O}(\alpha_s^3)$$

$$= \sigma_{q\bar{q}}\left(1 + c_1\,\alpha_s(Q) - 2c_1 b_0 \ln\frac{\mu_R}{Q}\,\alpha_s^2(Q) + \mathcal{O}\left(\alpha_s^3\right)\right)$$

  - if $\mu_R \neq Q \Rightarrow \alpha_s^2$ terms introduced
  - i.e. some set of NNLO terms (!!)

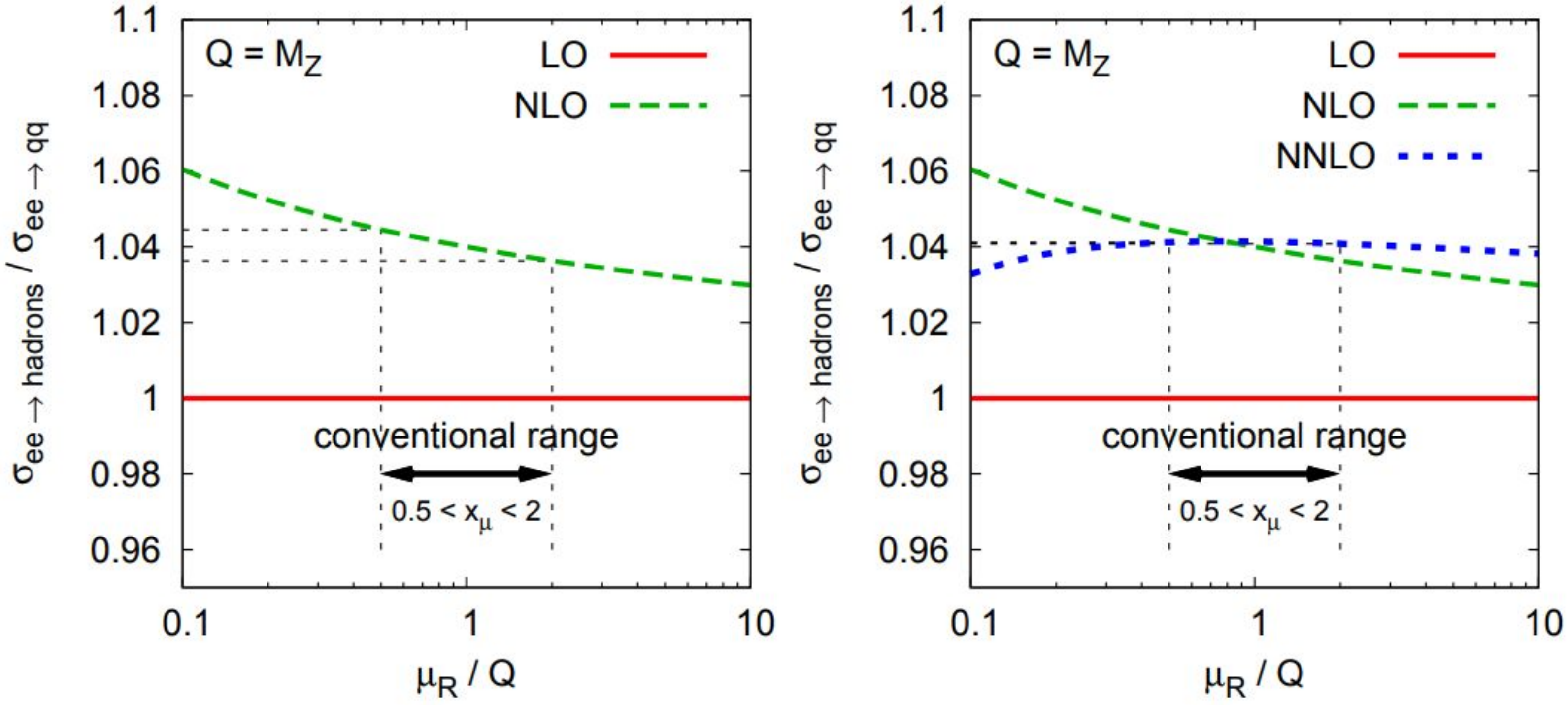
Scale dependence

- If we then calculate full NNLO correction
  ⇒ will cancel the $\mathcal{O}(\alpha_s^2)$ scale variation:

$$\sigma^{\mathrm{NNLO}}(\mu_R) = \sigma_{q\bar{q}} \left[1 + c_1\,\alpha_s(\mu_R) + \left(c_2 + 2c_1 b_0 \ln\frac{\mu_R}{Q}\right)\alpha_s^2(\mu_R)\right]$$

  - and remaining scale uncertainty will be $\mathcal{O}(\alpha_s^3)$

Scale dependence

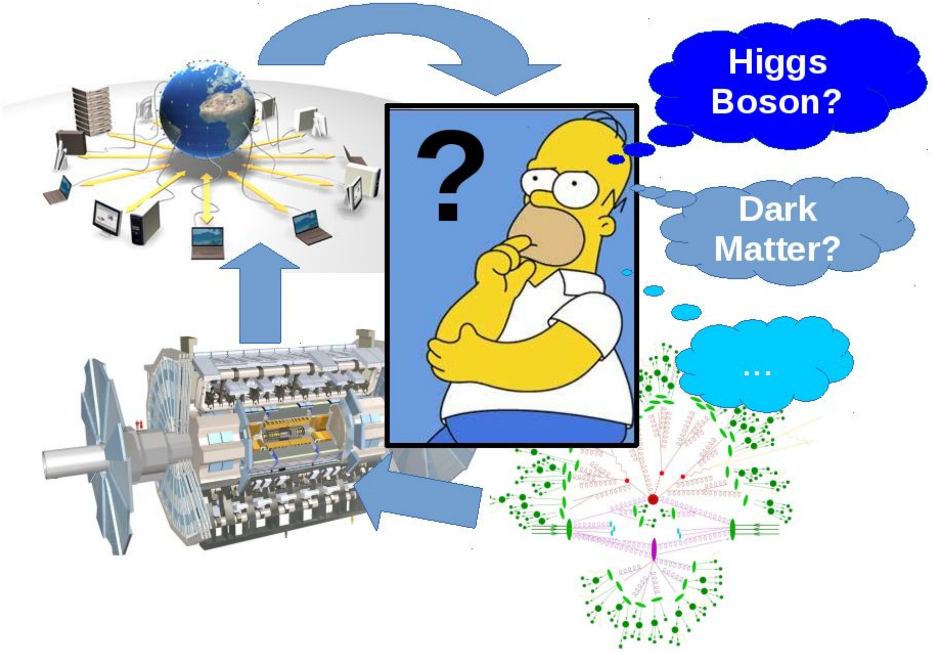


NB: if we had a large number of orders of perturbation theory, scale dependence would just disappear

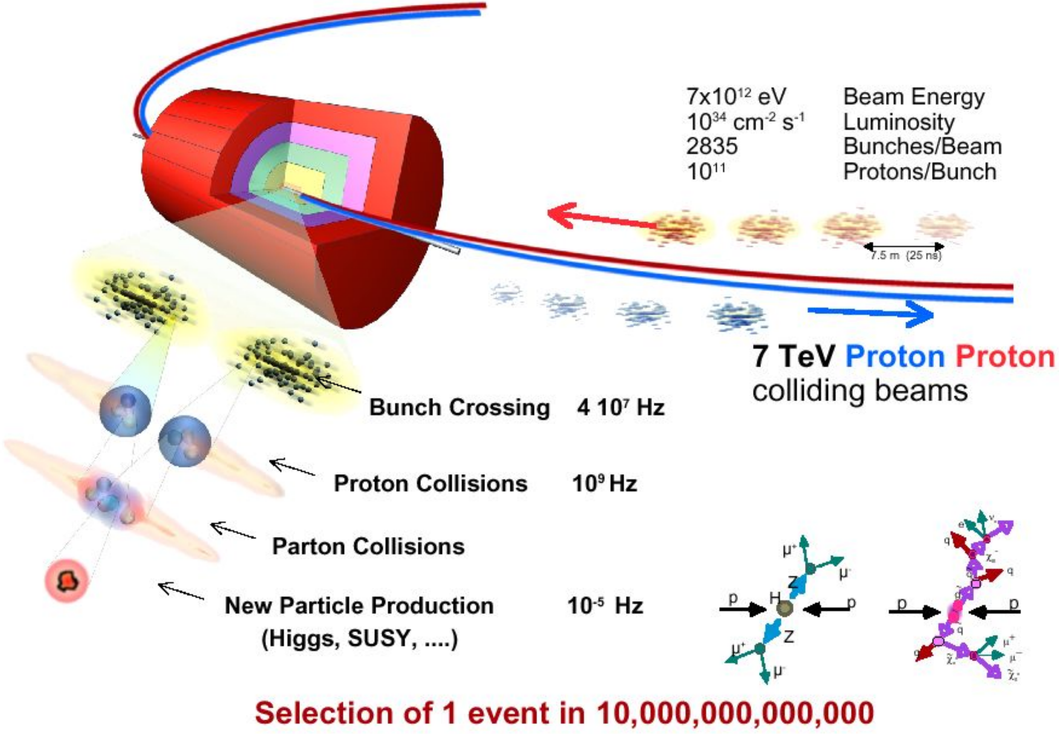
HEP data analysis

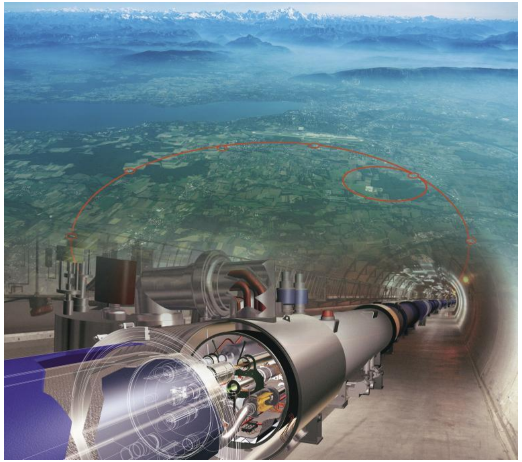
LHC data analysis

- What does it mean “analyse ATLAS/CMS data”?



The Large Hadron Collider



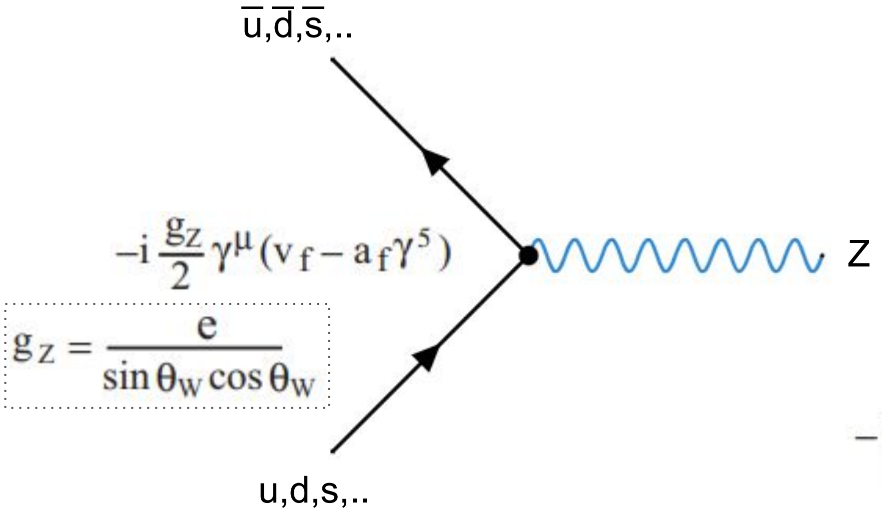


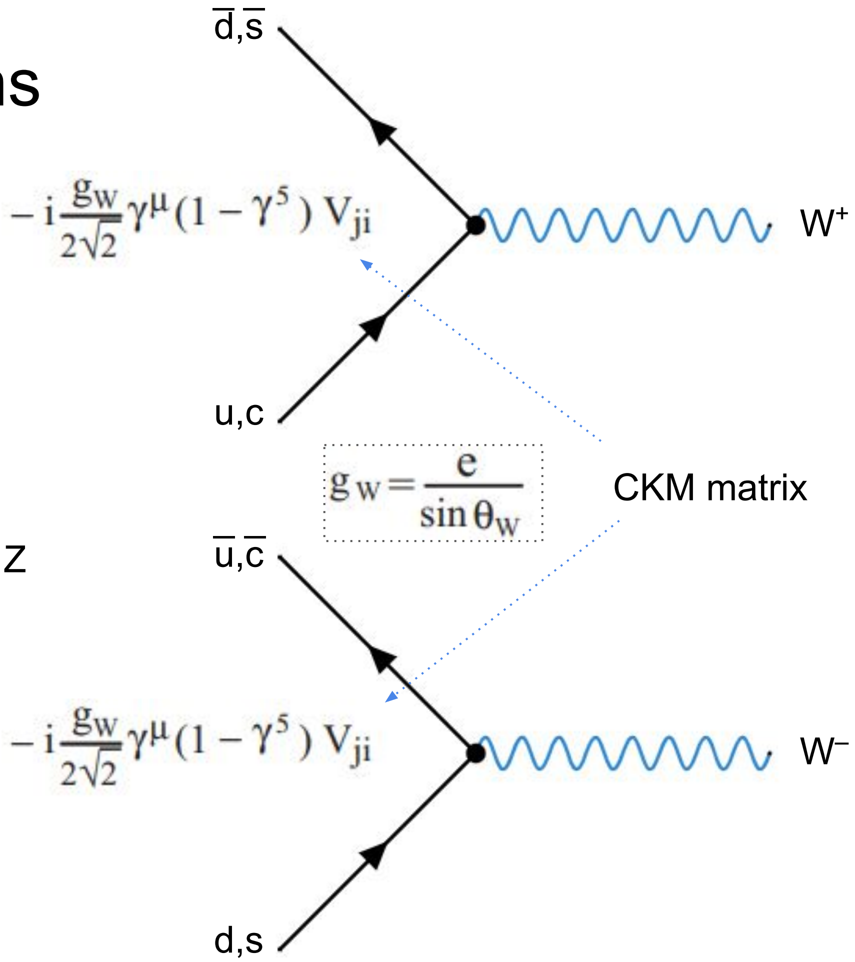
What is interesting out of what LHC produces?

- Hadron colliders produce mostly quarks and gluons
  - and mostly "soft" (small transverse momentum)

- Typically considered as "interesting":
  - heavy gauge boson production (W, Z)
  - Higgs boson production
  - heavy quarks (especially top: $t \rightarrow Wb$)
  - jets with (very) large transverse momentum
  - invisible particles (e.g. dark matter candidates)

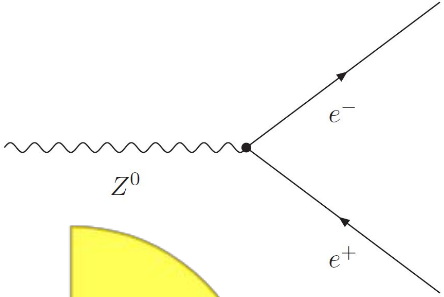
Producing W and Z bosons

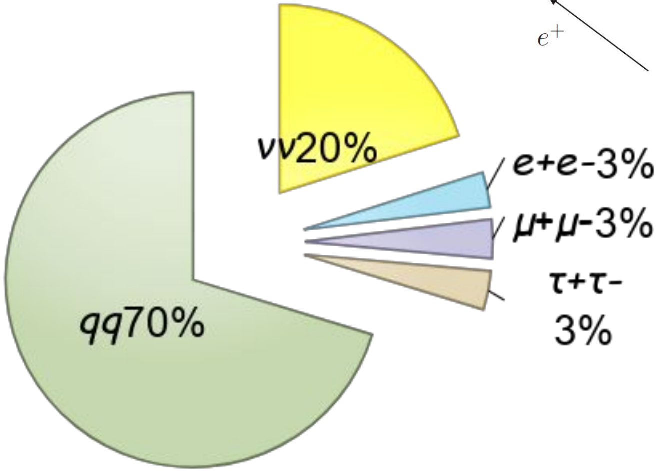


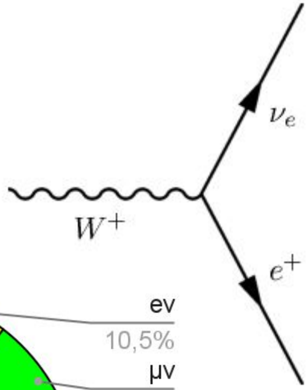


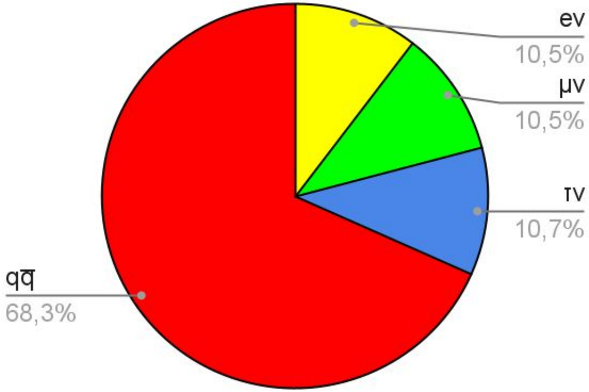
Seeing the interesting particles

- The Higgs/W/Z bosons can only be seen via decay products



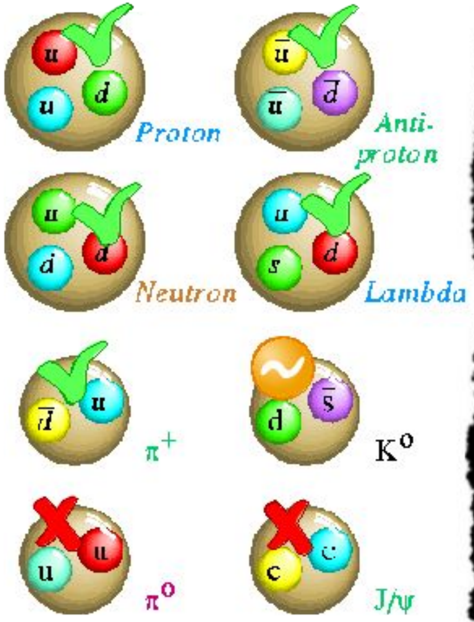


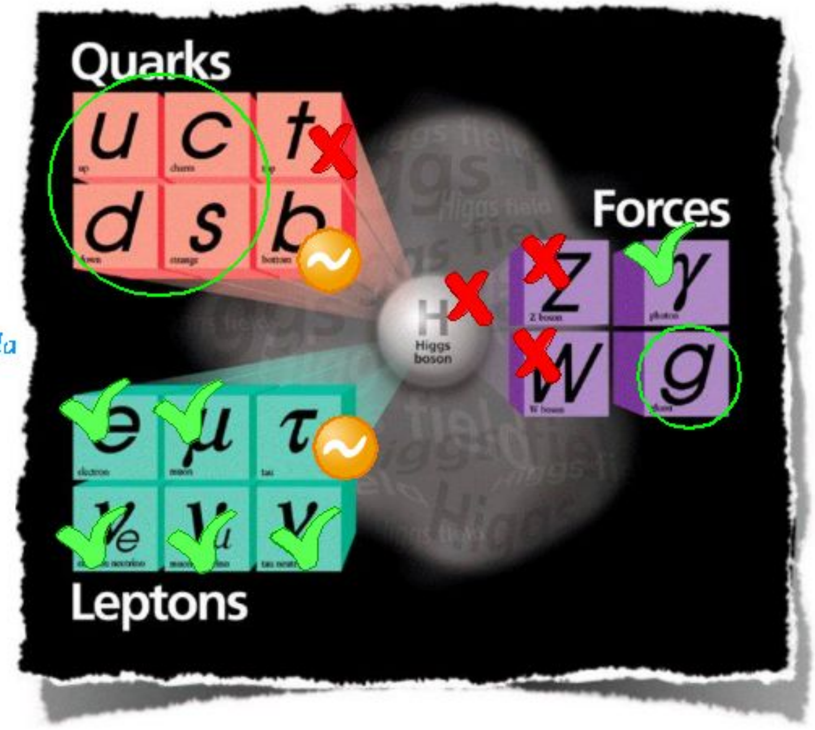




Seeing the interesting particles

- The Higgs/W/Z bosons can only be seen via decay products
  - "Stable" and "unstable" particles:





References

- Gavin Salam:
  - https://gsalam.web.cern.ch/gsalam/repository/talks/2009-Bautzen-lecture4.pdf
  - https://gsalam.web.cern.ch/gsalam/repository/talks/2009-Bautzen-lecture3.pdf
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