NPAC
Particle Physics
Course 6 – Hadron Collisions

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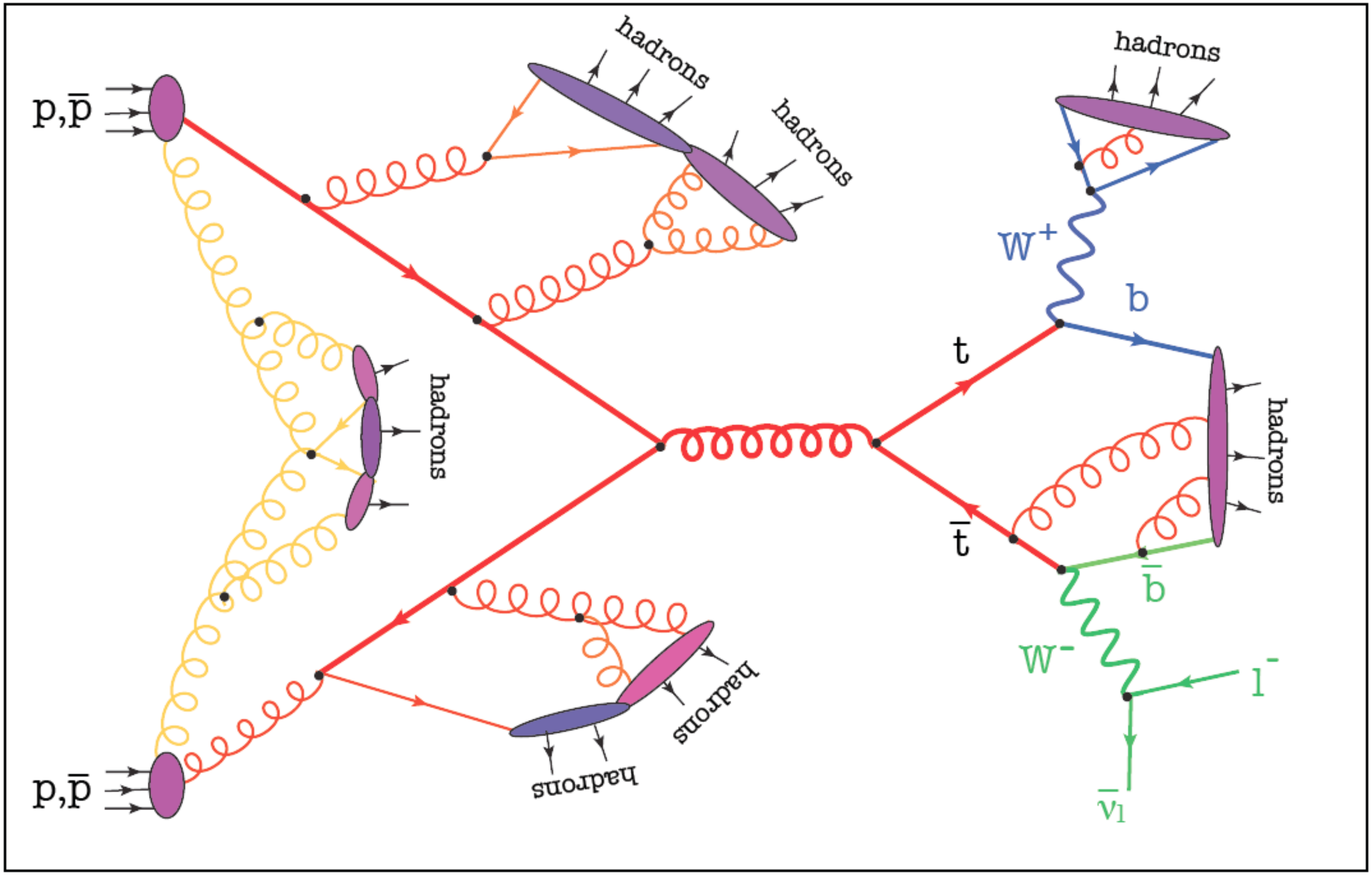
Program

The two sections:
- Soft and collinear divergences
- Jets and infrared safety

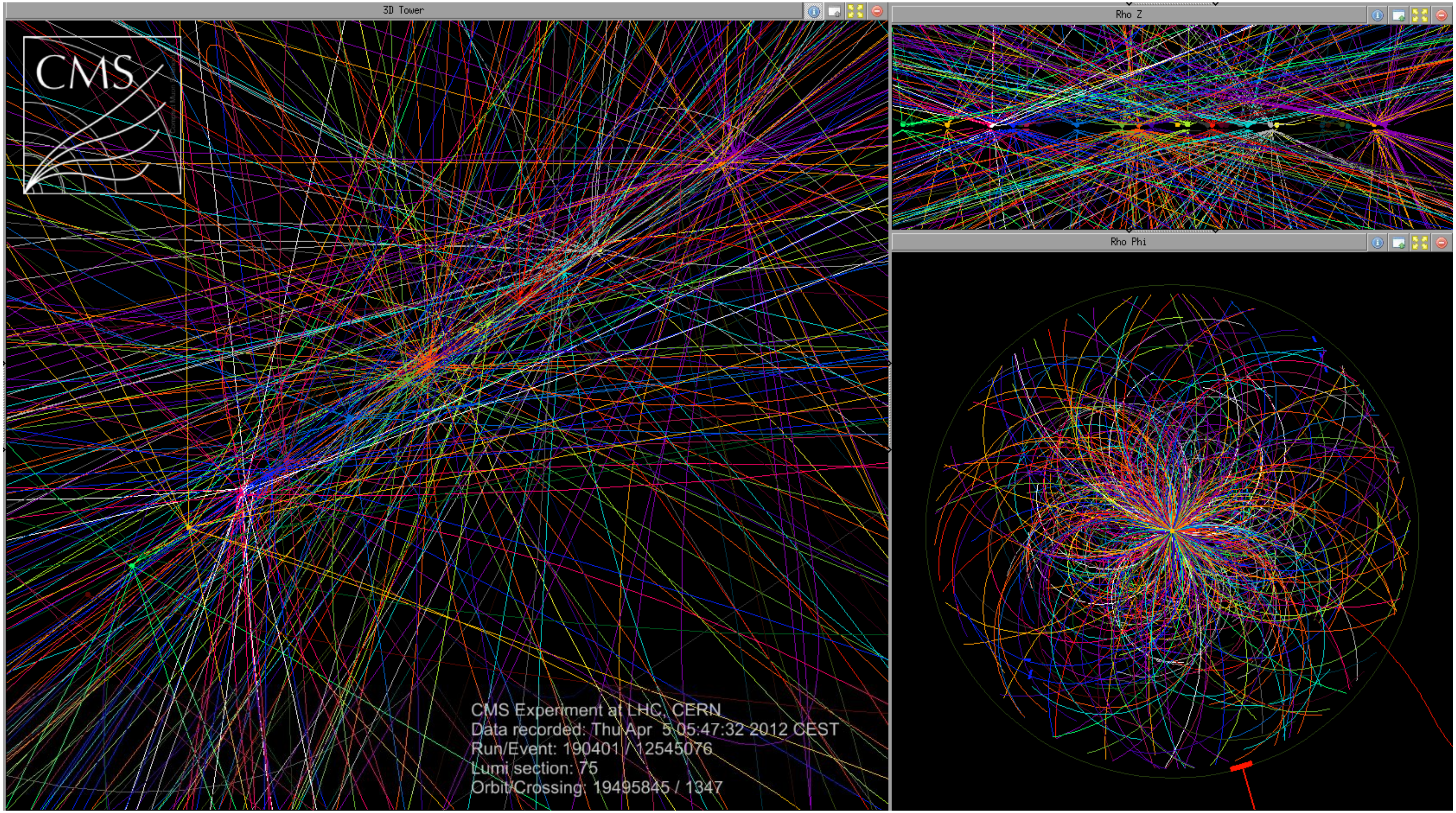
at the end of the Introduction to QCD are very much relevant for this course.
Also PDFs, presented in the course about DIS

1. Initial/final state and factorization
   1.1 PDFs
   1.2 Fragmentation
2. Kinematics at hadron colliders (reminder)
3. Example: di-jet production at the LHC
4. Monte Carlo event generators
5. Jet reconstruction

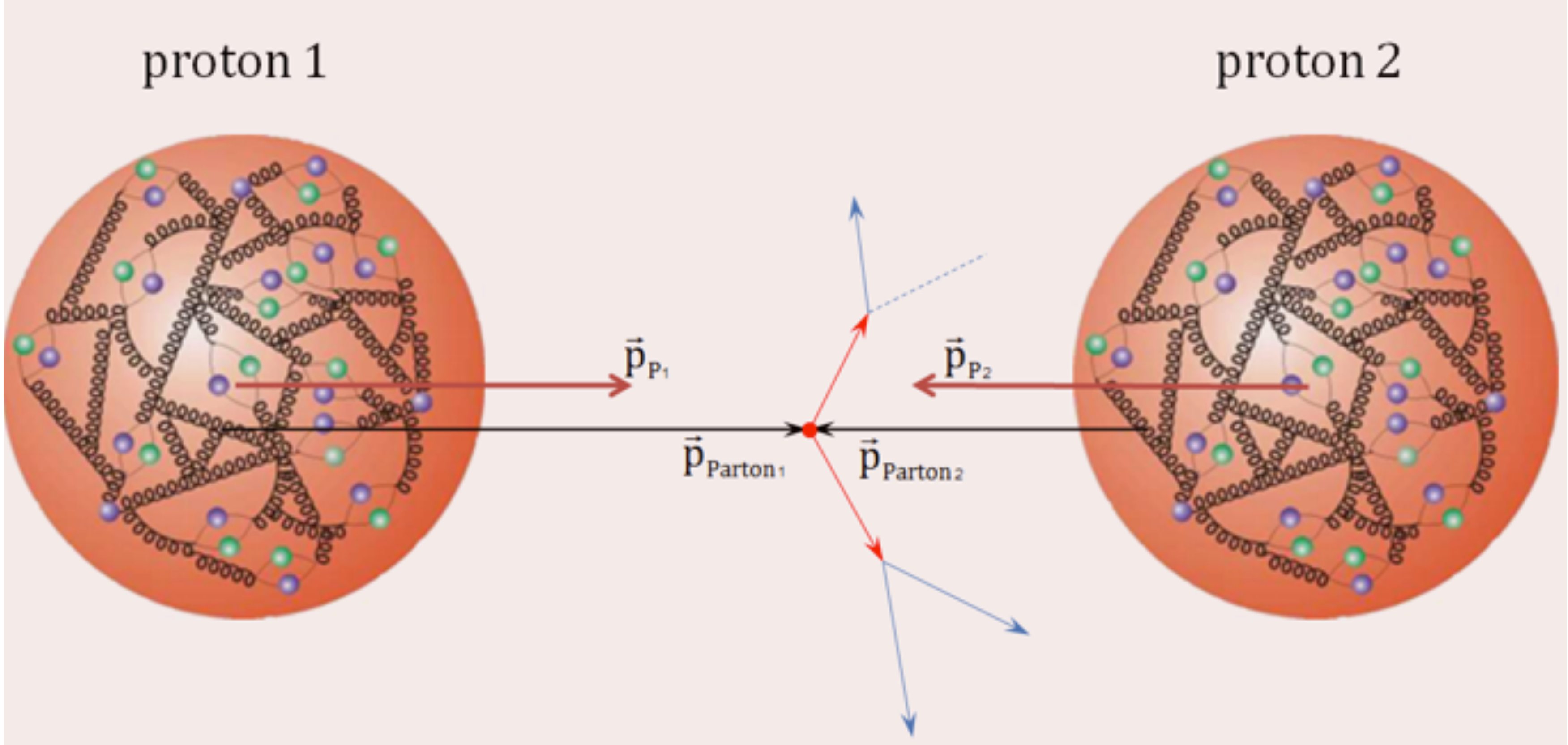
Schematics of a hadron collision



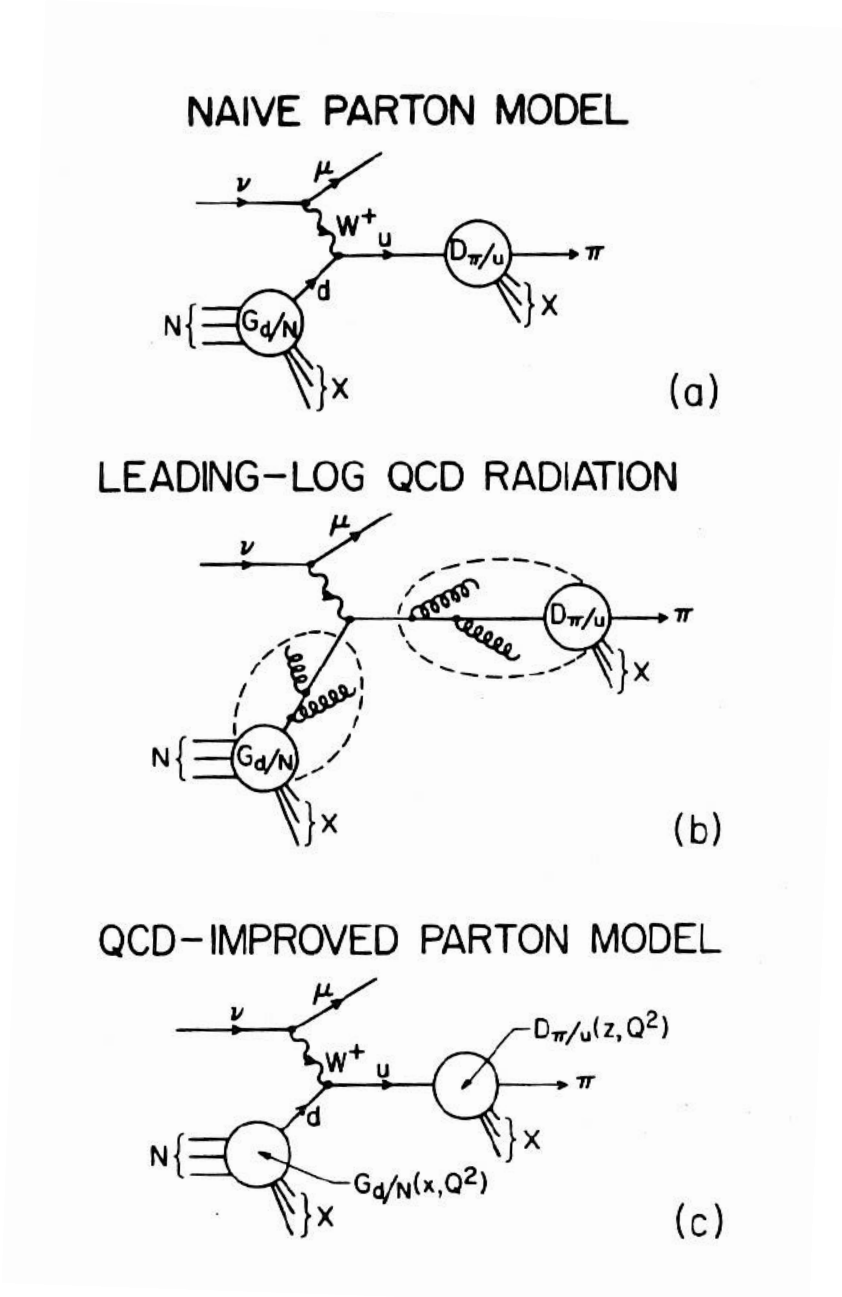
Multiple interactions in a bunch crossing ("pile up")



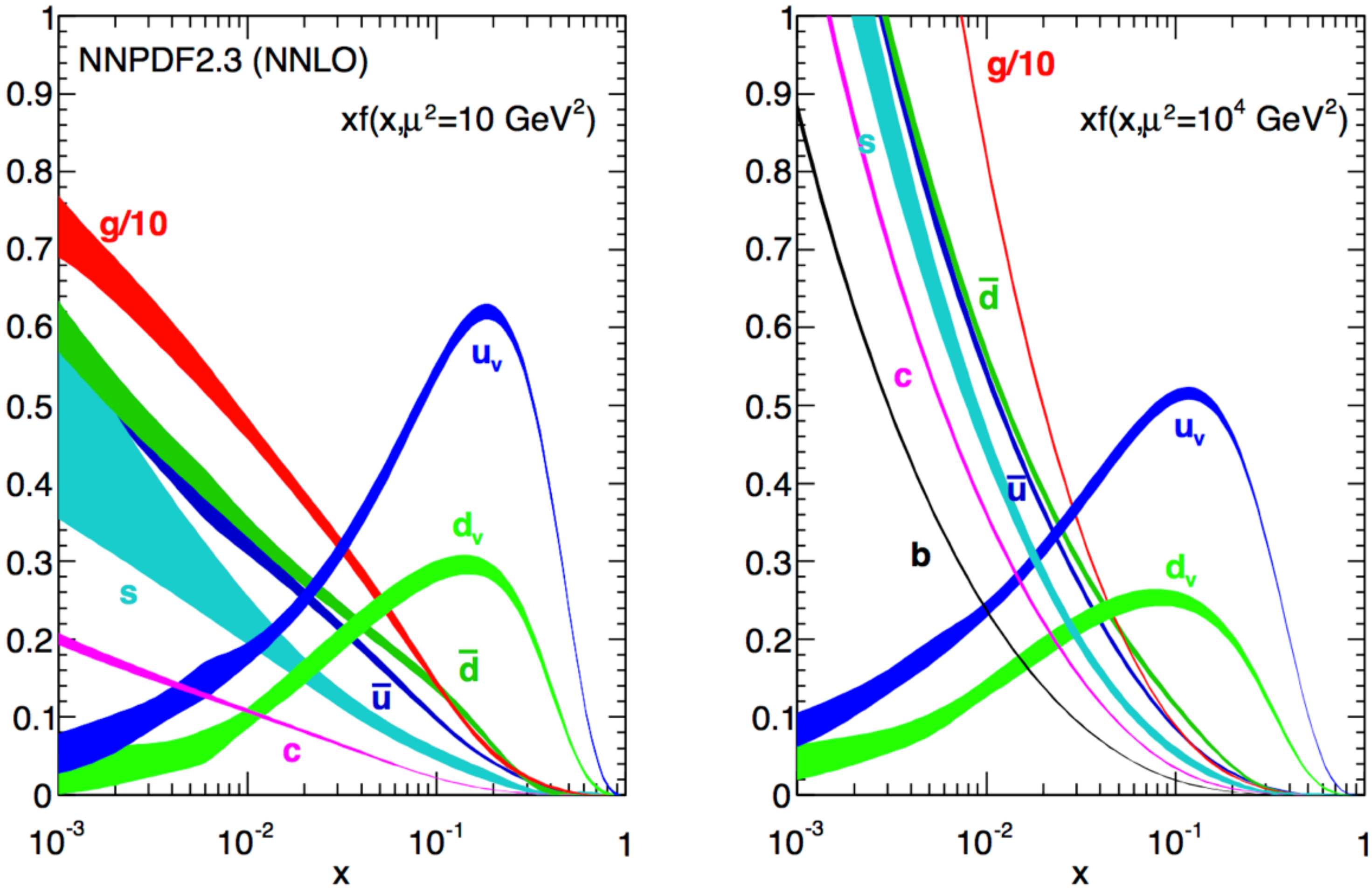
Proton content



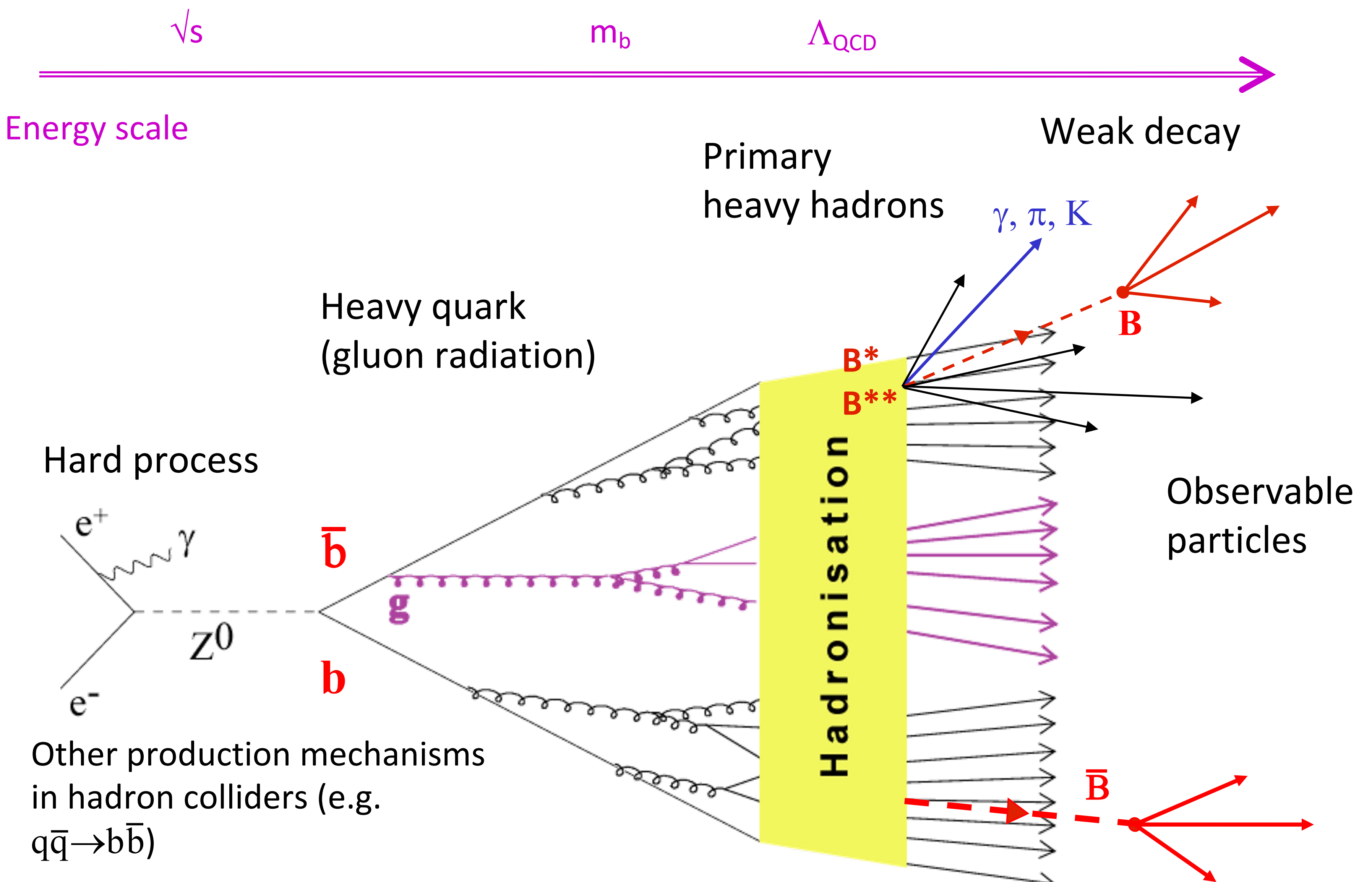
Factorization



PDF evolution



Fragmentation I

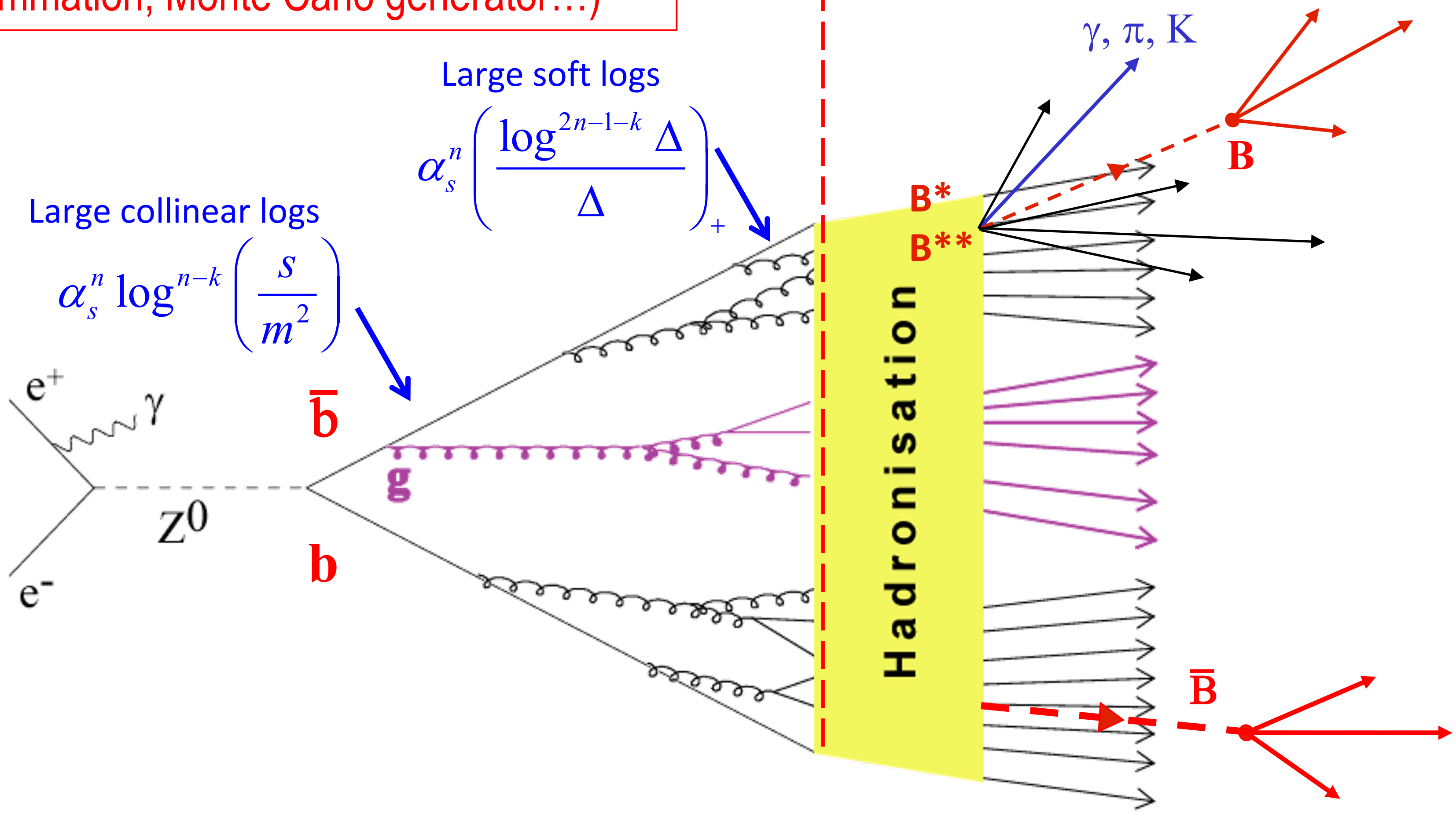


Fragmentation II

Perturbative (calculable in QCD)

Non-perturbative (non-calculable, usually described by a hadronisation model)

The boundary depends on the perturbative QCD computation (order and technique of resummation, Monte Carlo generator…)



Fragmentation III

Fragmentation function: probability density function of a variable relating quark - hadron kinematics ($x_B^{weak}, x_p^{weak}, z$)

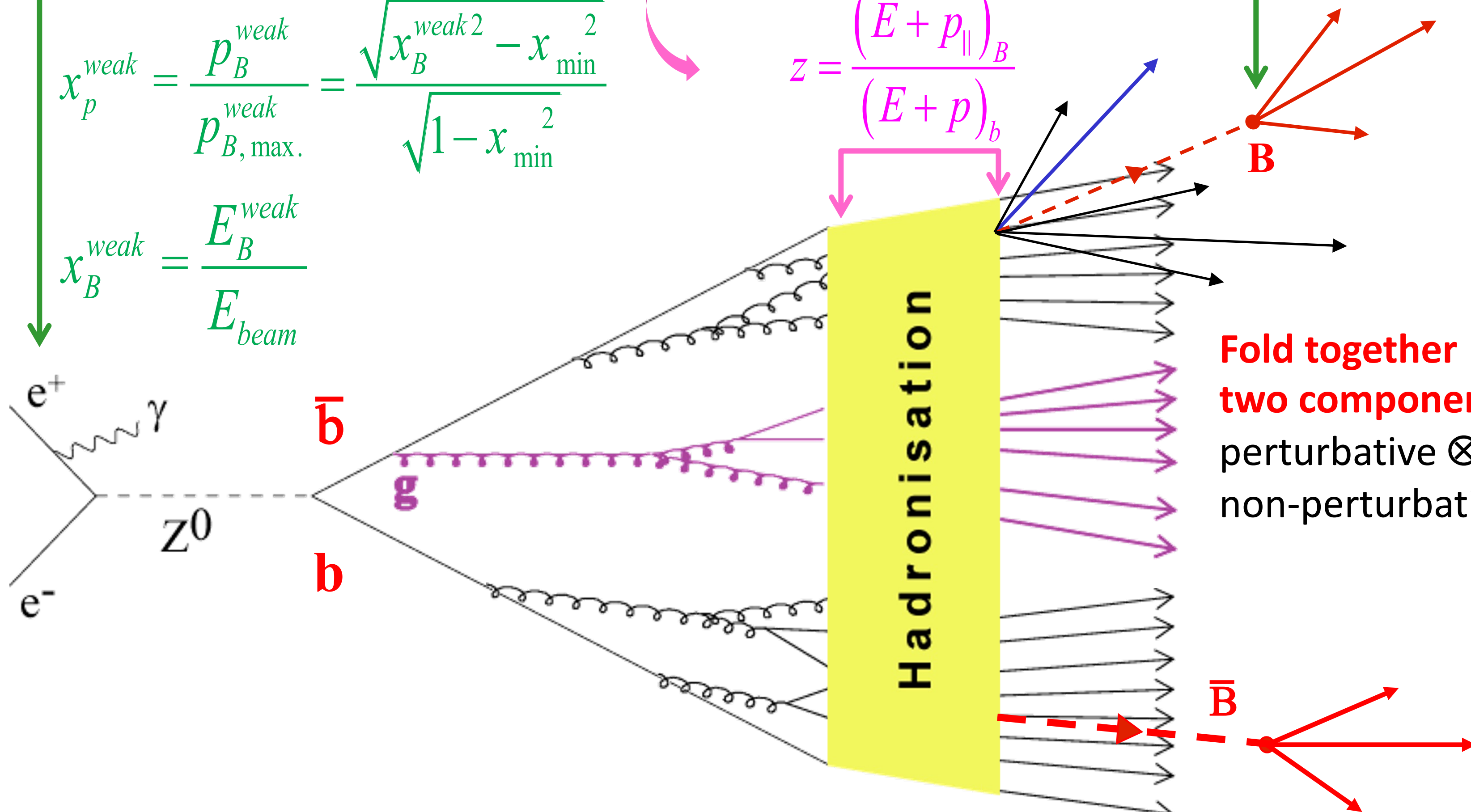
Directly measurable by experiments

$$x_p^{weak} = \frac{p_B^{weak}}{p_{B,\max.}^{weak}} = \frac{\sqrt{x_B^{weak\,2} - x_{\min}^2}}{\sqrt{1 - x_{\min}^2}}$$

$$x_B^{weak} = \frac{E_B^{weak}}{E_{beam}}$$

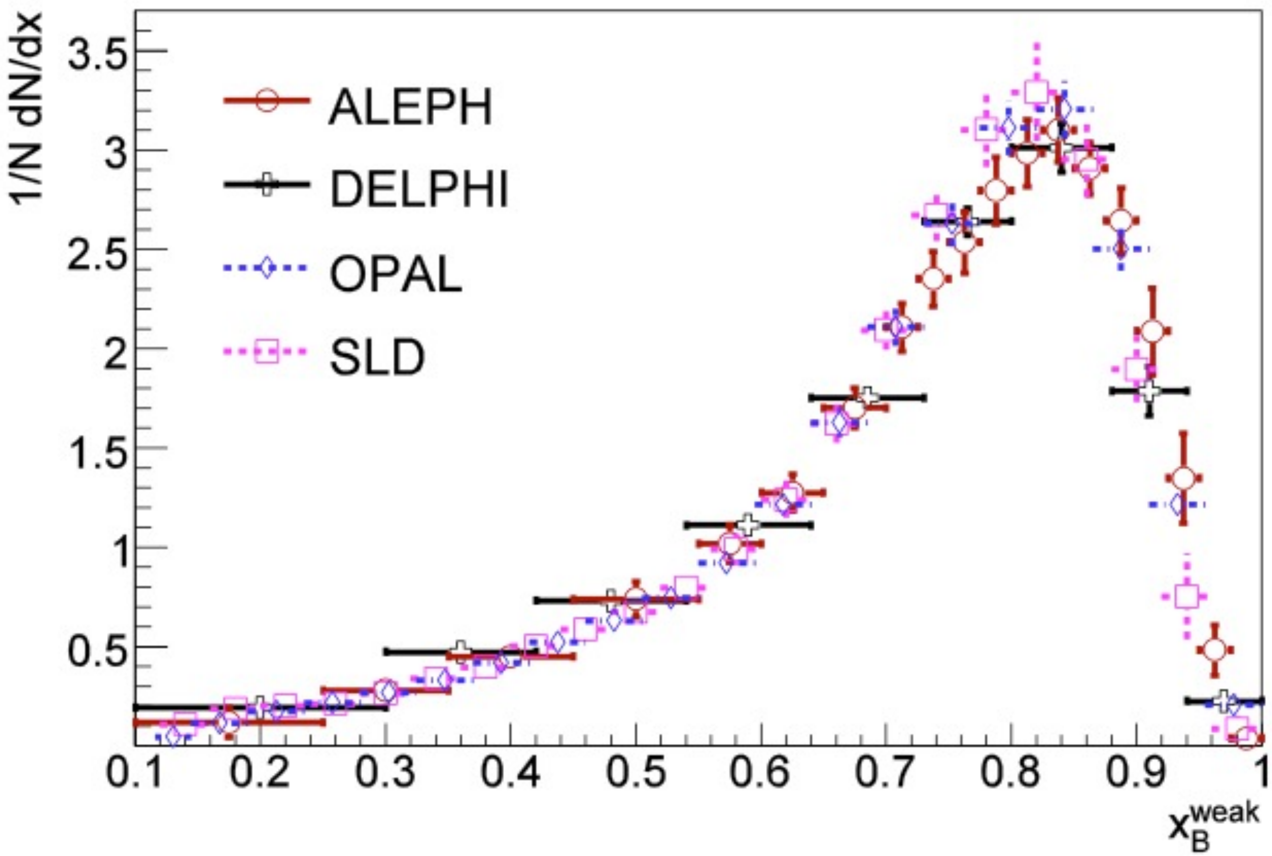
Defined within event generators

$$z = \frac{(E + p_{\parallel})_B}{(E + p)_b}$$



Fold together two components:
perturbative ⊗ non-perturbative

b-quark Fragmentation measurements from LEP



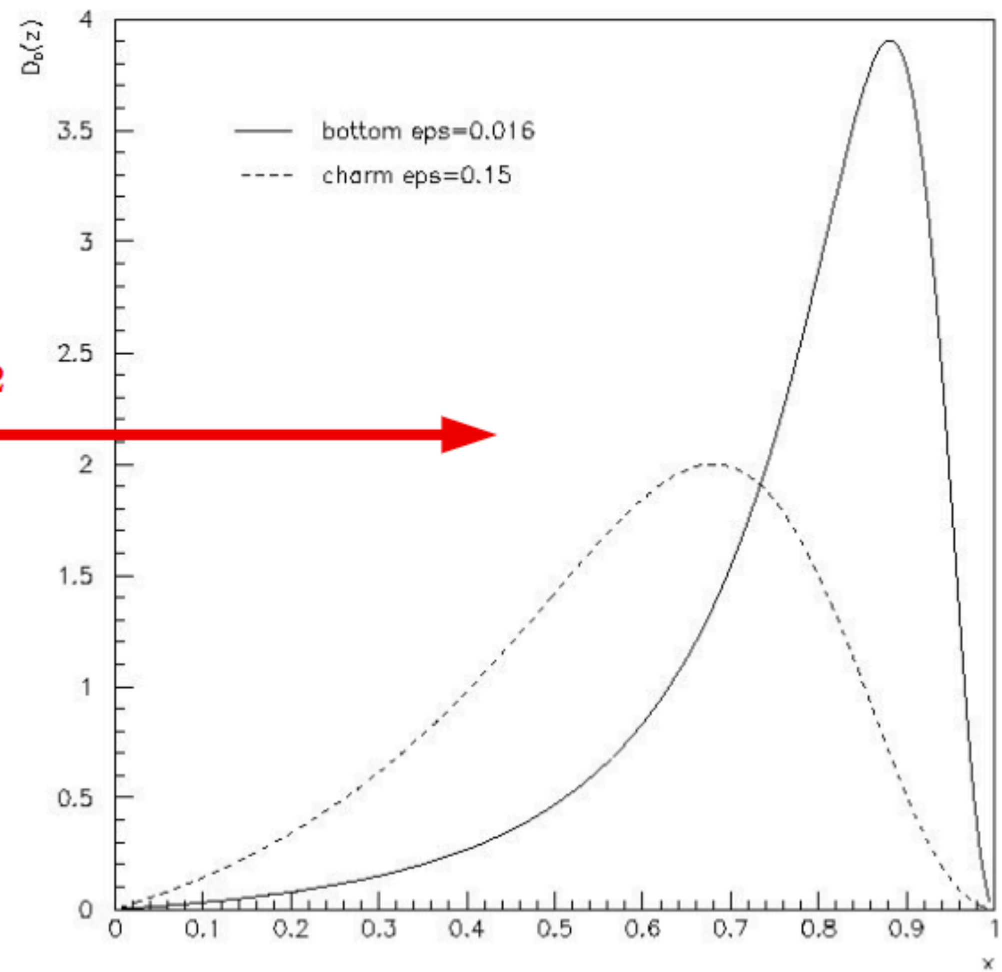
$x_B^{weak} = 0.7092 \pm 0.0025$

(The *b*-hadron takes ~70% of the *b*-quark energy)

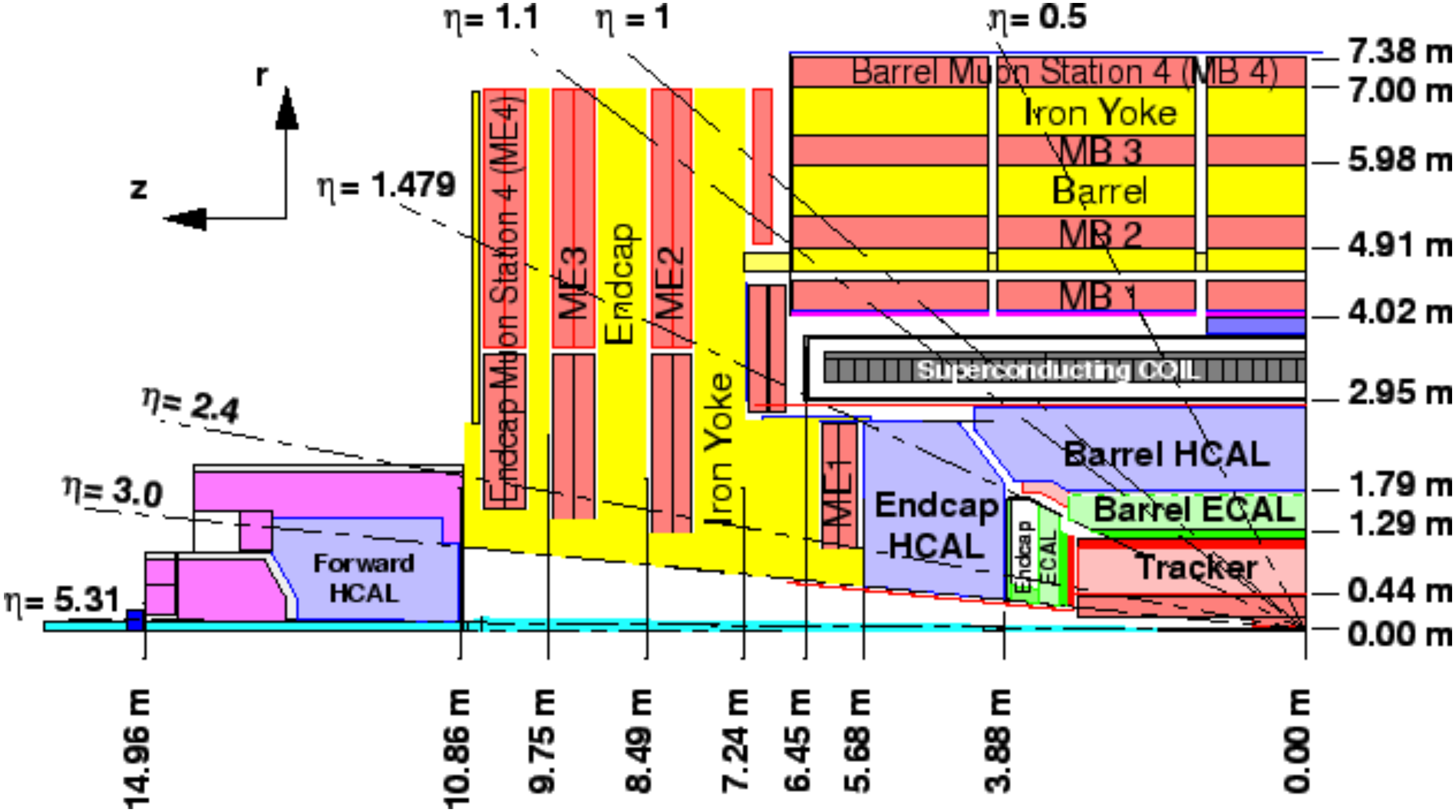
Fragmentation: Peterson model for b and c quarks (non-perturbative component)

Peterson FF: (C. Peterson, D.Schlatter,I.Schmitt,P.Zerwas, PRD27 (1983) 105)

$$D_Q(z) = \frac{N}{z}\left[1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z}\right]^{-2}$$



CMS acceptance

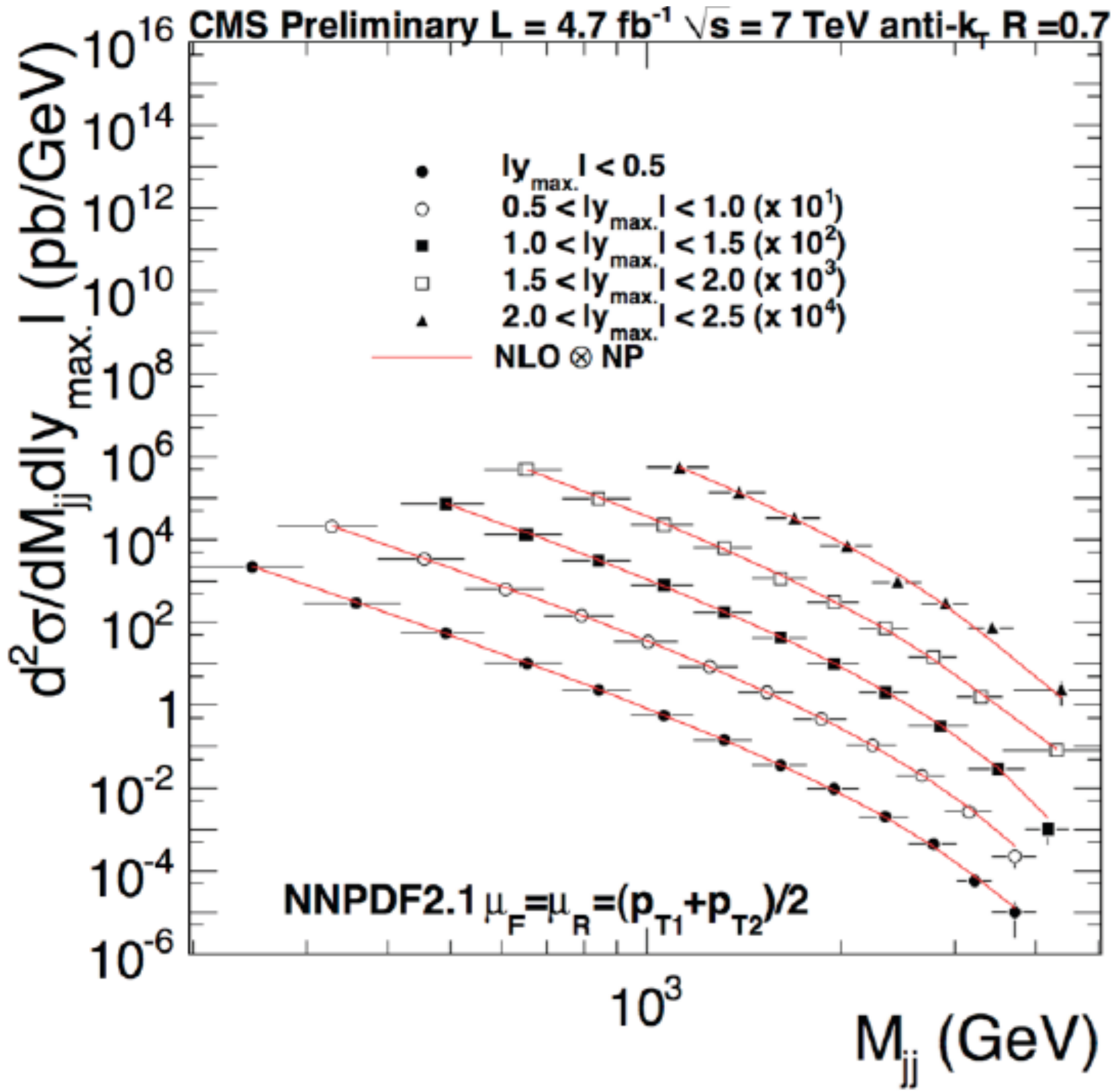


$2 \to 2$ processes at the LHC

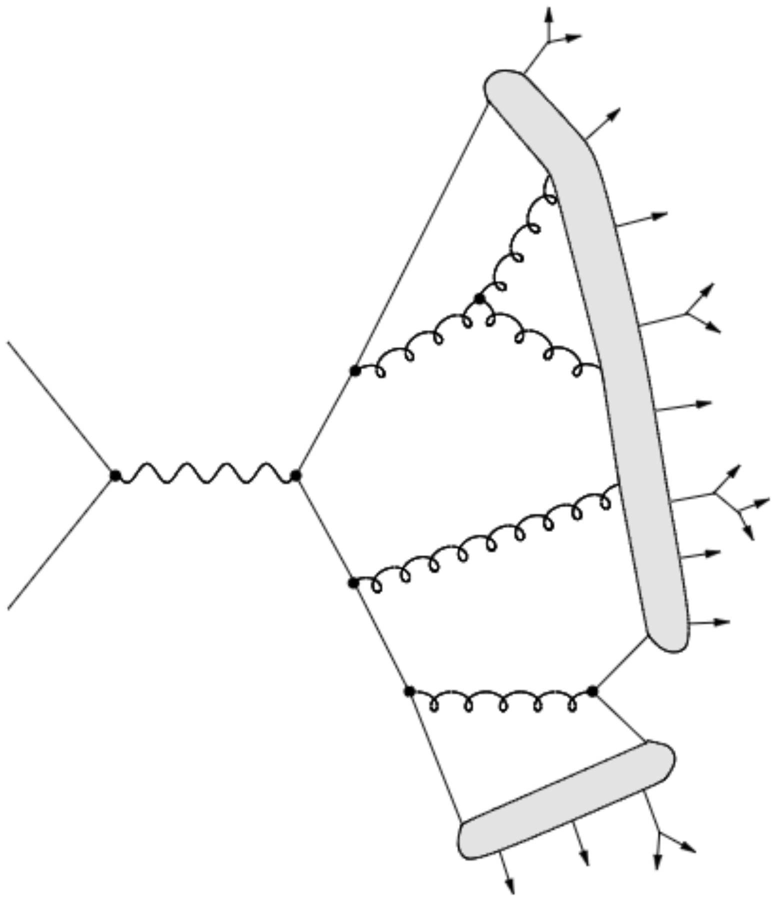
For illustration… as a part of the example of the dijet cross-section calculation

Process	$\frac{d\hat{\sigma}}{d\Phi_2}$
$qq' \to qq'$	$\frac{1}{2\hat{s}} \frac{4}{9} \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$qq \to qq$	$\frac{1}{2} \frac{1}{2\hat{s}} \left[\frac{4}{9} \left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2} \right) - \frac{8}{27} \frac{\hat{s}^2}{\hat{u}\hat{t}} \right]$
$q\bar{q} \to q'\bar{q}'$	$\frac{1}{2\hat{s}} \frac{4}{9} \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \to q\bar{q}$	$\frac{1}{2\hat{s}} \left[\frac{4}{9} \left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2} \right) - \frac{8}{27} \frac{\hat{u}^2}{\hat{s}\hat{t}} \right]$
$q\bar{q} \to gg$	$\frac{1}{2} \frac{1}{2\hat{s}} \left[\frac{32}{27} \frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{8}{3} \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2} \right]$
$gg \to q\bar{q}$	$\frac{1}{2\hat{s}} \left[\frac{1}{6} \frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{3}{8} \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2} \right]$
$gq \to gq$	$\frac{1}{2\hat{s}} \left[-\frac{4}{9} \frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}} + \frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2} \right]$
$gg \to gg$	$\frac{1}{2} \frac{1}{2\hat{s}} \frac{9}{2} \left(3 - \frac{\hat{t}\hat{u}}{\hat{s}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2} \right)$

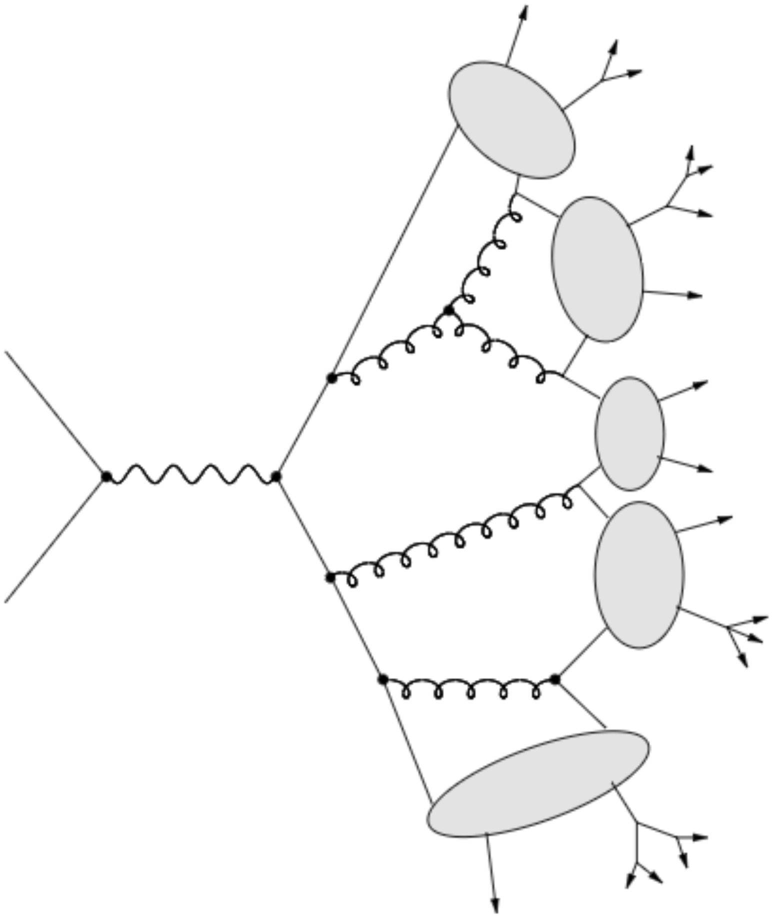
CMS dijet cross-section



Parton showers and clustering

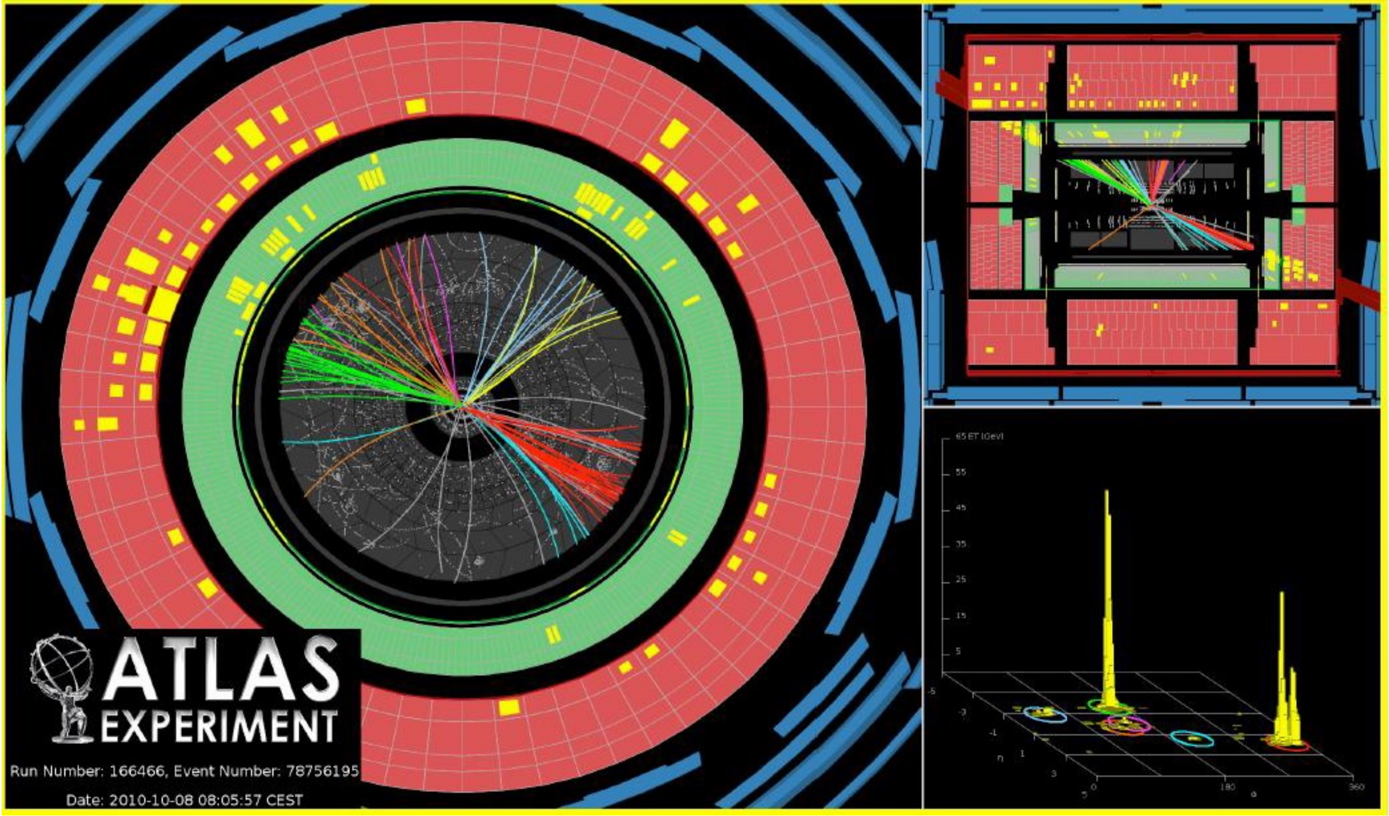


String fragmentation (Pythia)



Cluster fragmentation (Herwig)

Event display with jets



Jet algorithms I

- **Two main families of jet algorithms**:
  - Top-down → cone algorithms
  - Bottom-up → sequential recombination

- Example of a top-down algorithm: cone algorithm with seed

  Definition: jet radius $R^2 = \Delta y^2 + \Delta\phi^2$
  Here, a fixed R is the main parameter

1. Order objects (particles) by decreasing p_T
2. Choose 1st object (maximum p_T) as the seed
3. Collect all objects in a cone within R around the seed
4. Recalculate jet axis
5. Stable axis?

   No → take new jet axis as seed (from step 4), go to step 3
   Yes → the ensemble of objects is a **jet**. Remove from list and go to step 2
   (until the list is empty)

   It is clear that this algorithm gives round jets

Jet algorithms II

- Example of a bottom-up algorithm: Inclusive k_T algorithm (iterative pairwise clustering)

Definitions: d_{ij} (distance between two objects i, j)
d_{iB} (between object i and beam)

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2} \quad \text{with} \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$
$$d_{iB} = p_{Ti}^2$$

1. For each particle/object *i* compute the distances d_{ij} and d_{iB}
2. Find the minimum distance of all
3. Is it d_{ij} or d_{iB}?
   d_{ij} → combine *i* + *j* into a single object and go to step 1
   d_{iB} → object i is a **jet**. Remove it from the list and go to step 1
   (until the list is empty)
   Use only jets with $p_T > p_{Tmin}$

Features:
+ collinear and IR safe
+ each hadron uniquely assigned to a jet
− sensitive to noise (underlying event, pile-up…)
– It is clear that this algorithm gives jets with complicated shapes

Computing time (for *N* objects) $\propto N \log N$

Jet algorithms III

- Anti- k_T algorithm

  same as k_T, with : $d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\frac{\Delta R_{ij}^2}{R^2}$

  This gives more regular jets and is easier to calibrate experimentally

  → it is often used in LHC experiments

- In general, the jet radius R has to be optimized to reject background and keep signal
  - Less pollution from underlying event and pile up ➔ small R
  - Include QCD radiation;
    englobe particles that participate in hadronization ➔ large R

Jet algorithms IV