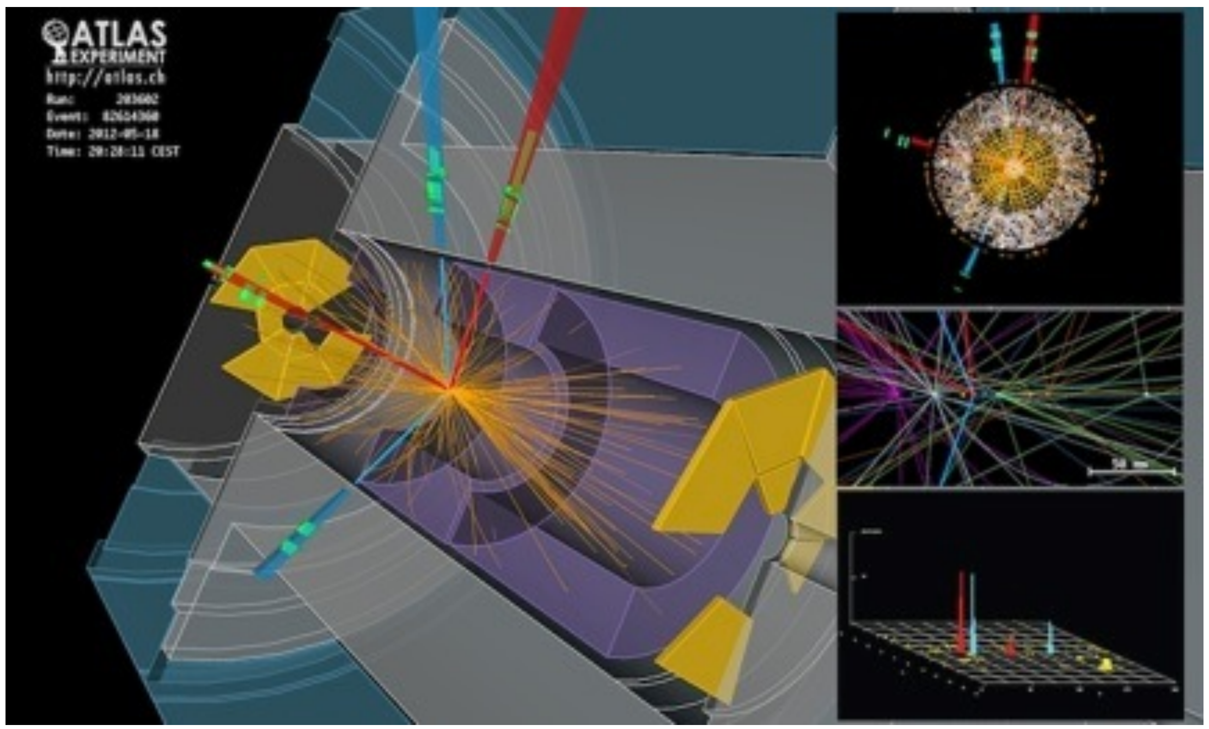
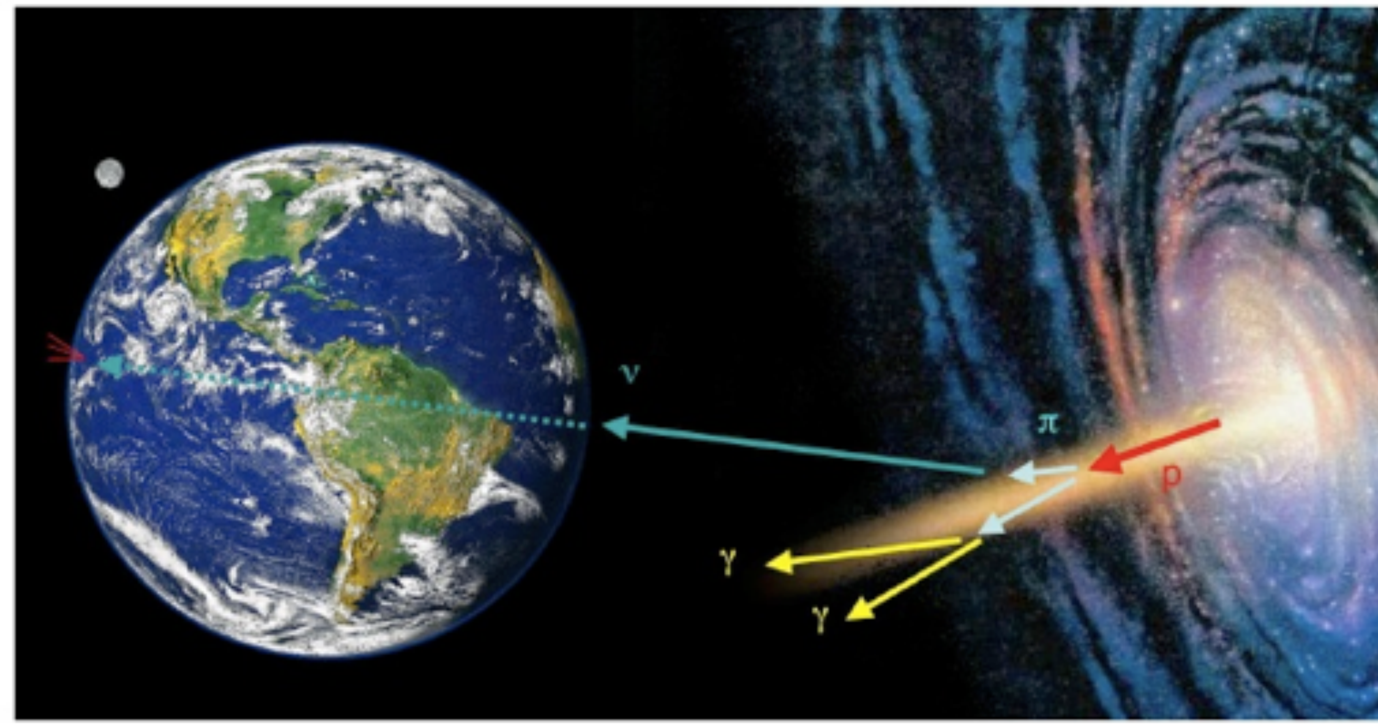
Particle Physics at Colliders and in the High Energy Universe





4. Particle Collisions at High Energy

04.11.2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon
Dr. Bela Majorovits

Overview

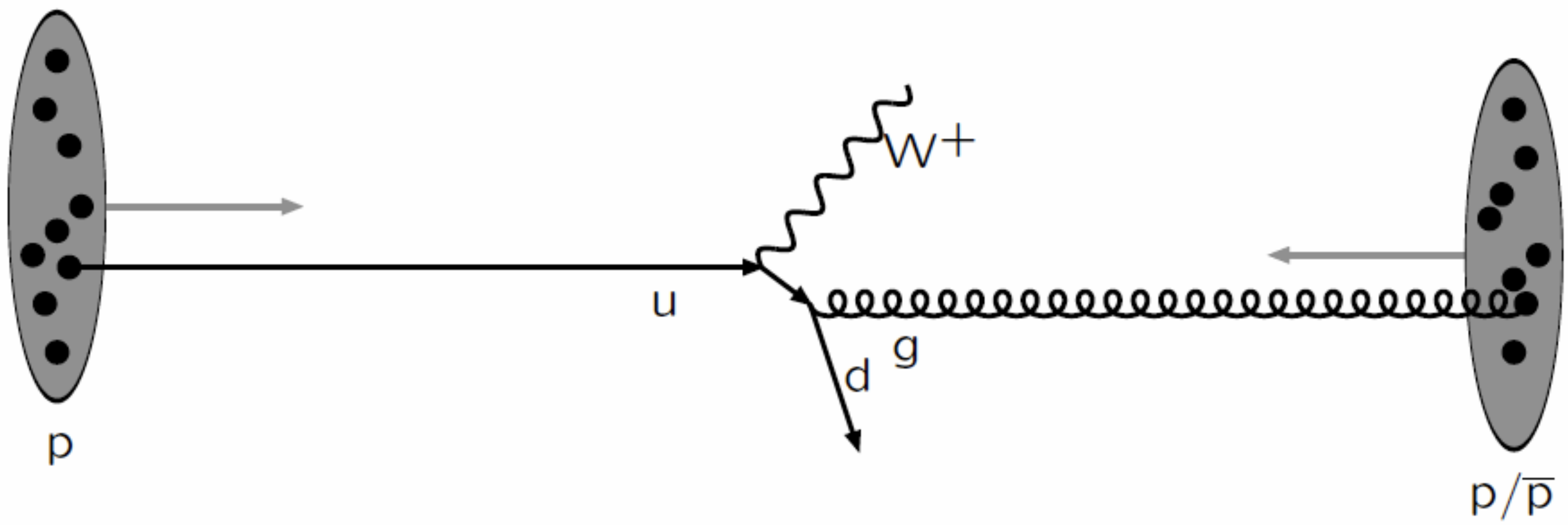
- Schematic overview: The Sequence of a Proton-Proton Collision
- A closer look: Factorization, PDFs, Hadronization and Jets
- Pile-up at LHC

The Schematic Sequence of a p+p Collision

The Schematic Sequence of a p+p Collision

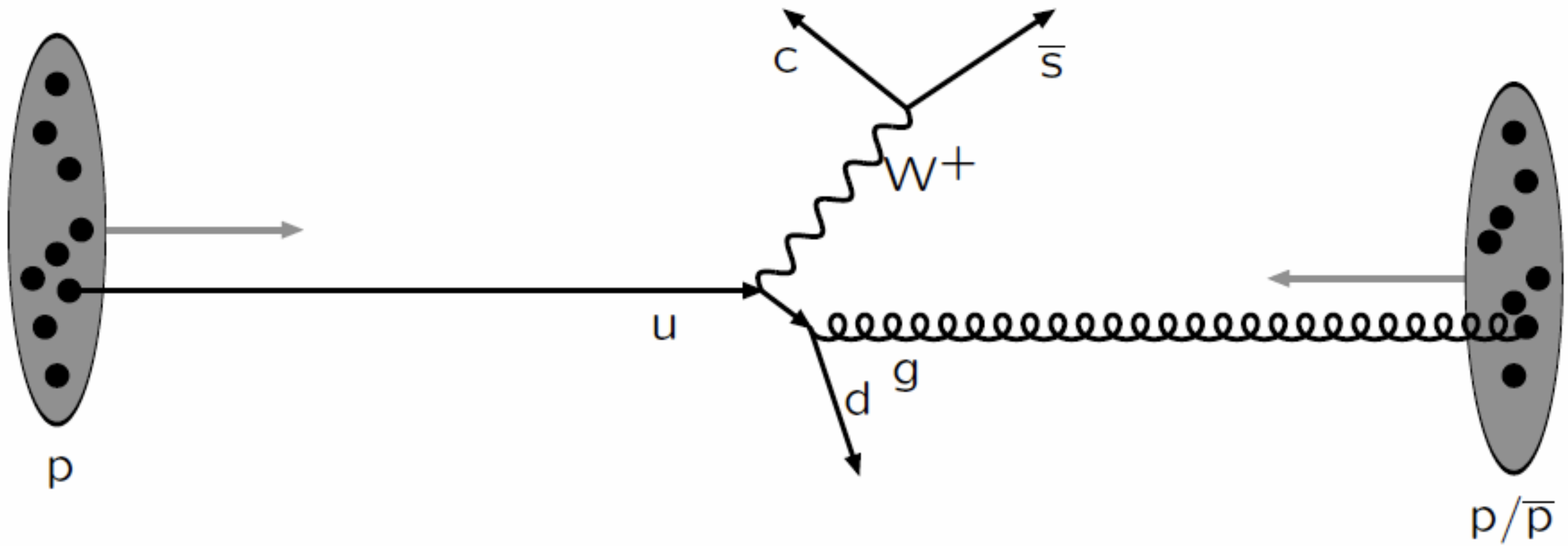
- Beam particles: Substructure described by parton distribution funktions (PDFs)

The Schematic Sequence of a p+p Collision



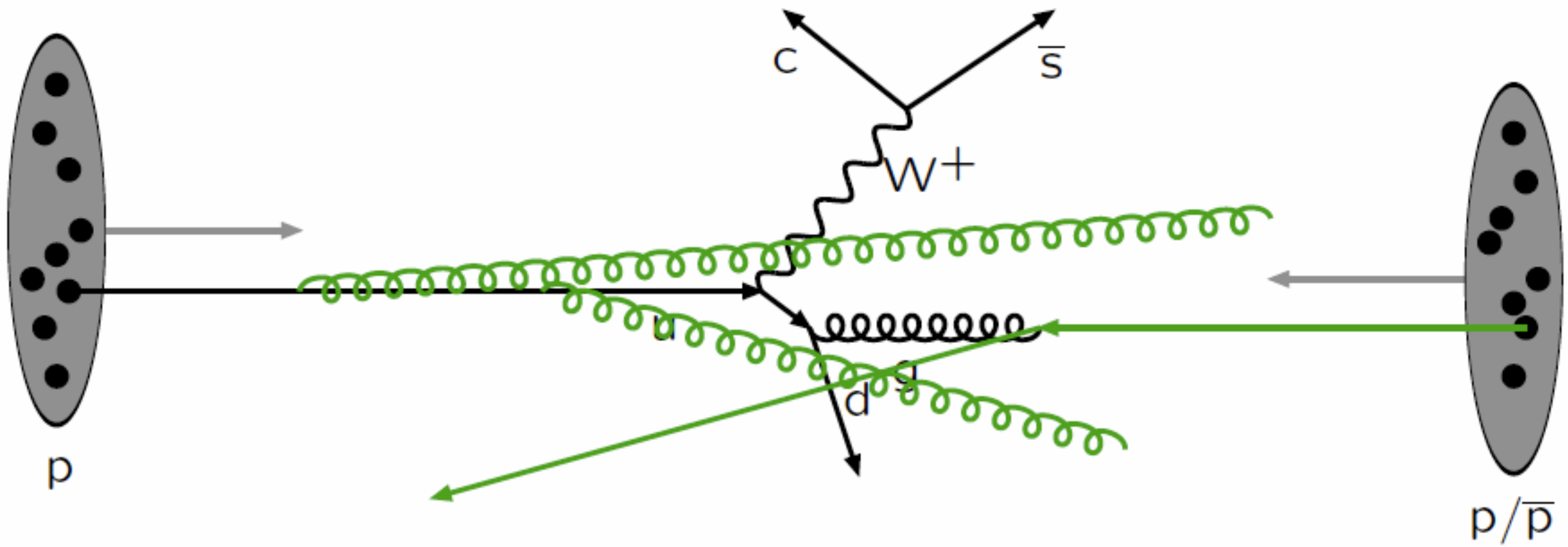
- Hard interaction: Described by the matrix element - This is what we usually draw as Feynman graphs

The Schematic Sequence of a p+p Collision



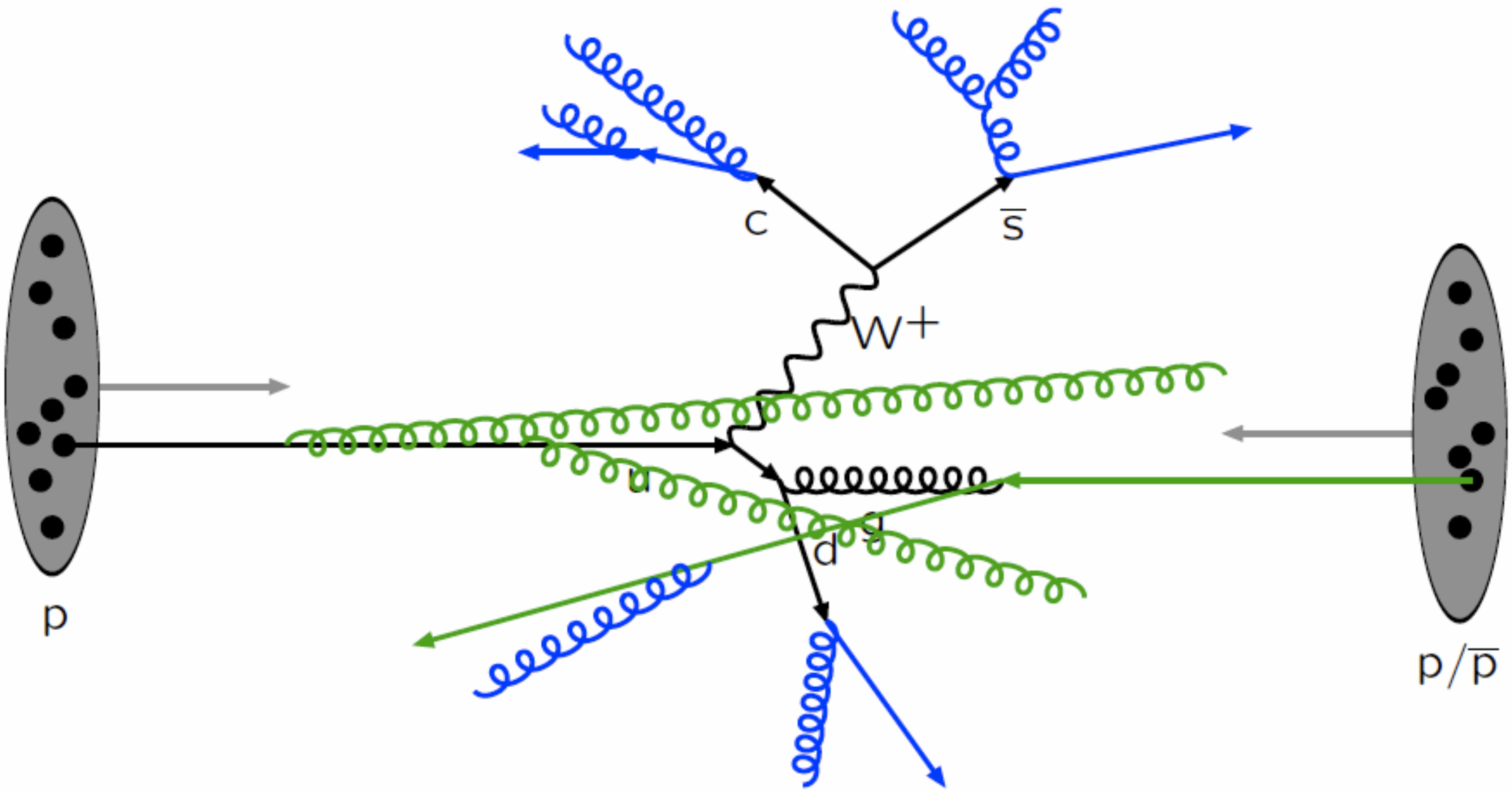
- Decay of short-lived particles connected to the hard interaction

The Schematic Sequence of a p+p Collision



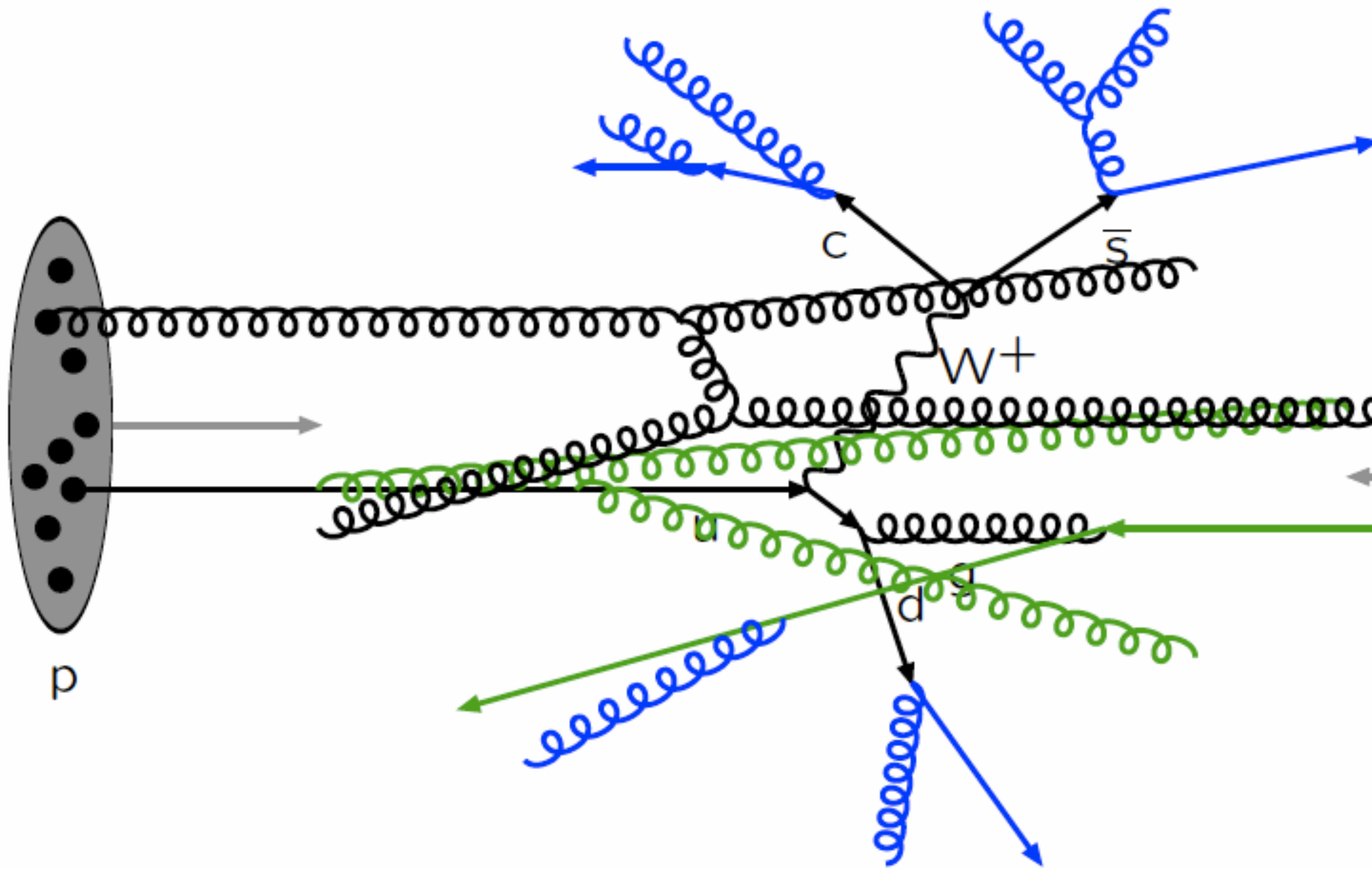
- Initial-State Radiation: Parton showers

The Schematic Sequence of a p+p Collision



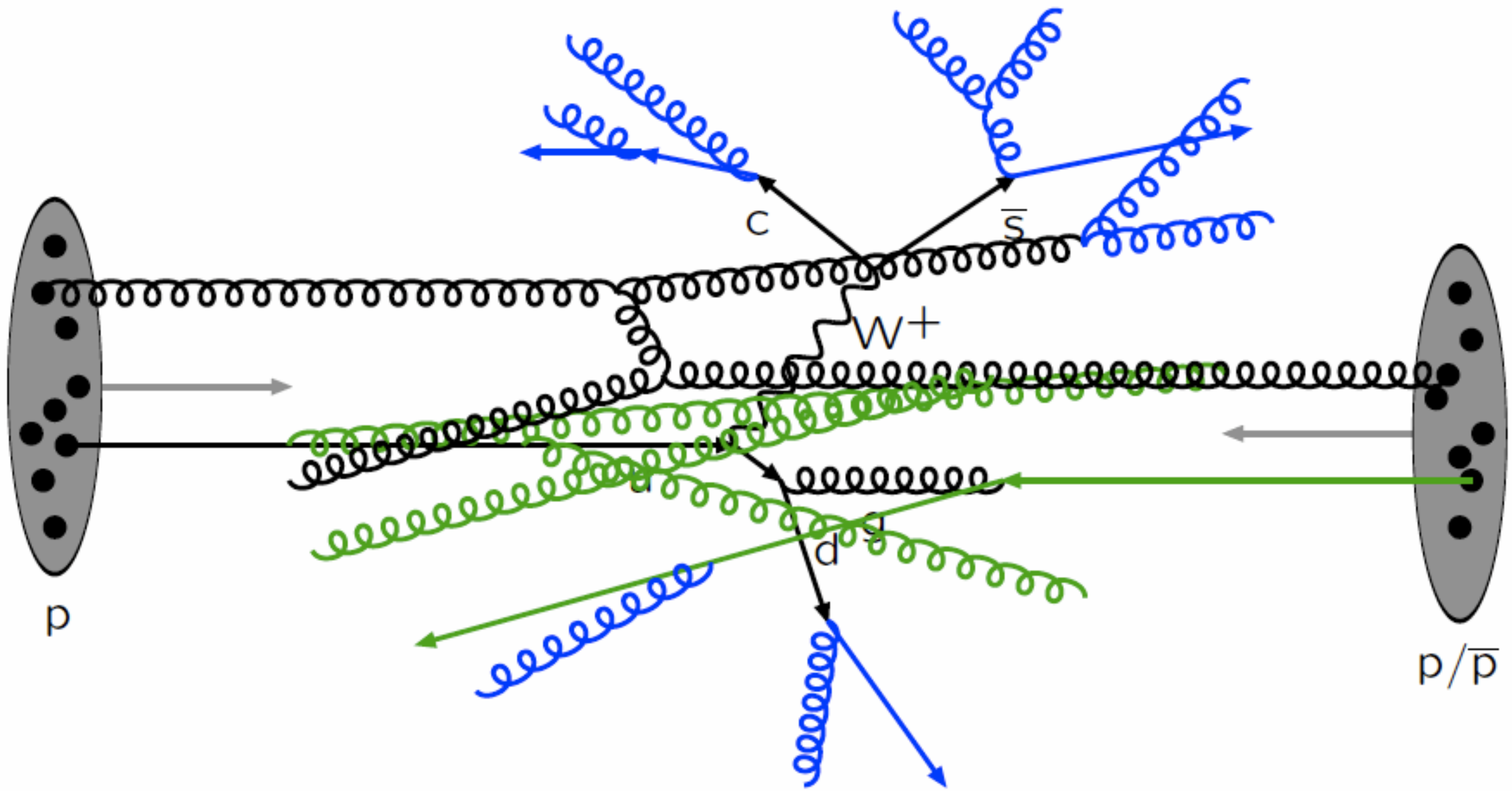
- Final-State Radiation: Parton showers

The Schematic Sequence of a p+p Collision



- “Underlying Event”: Lower-energy processes of the other constituents of the beam particles

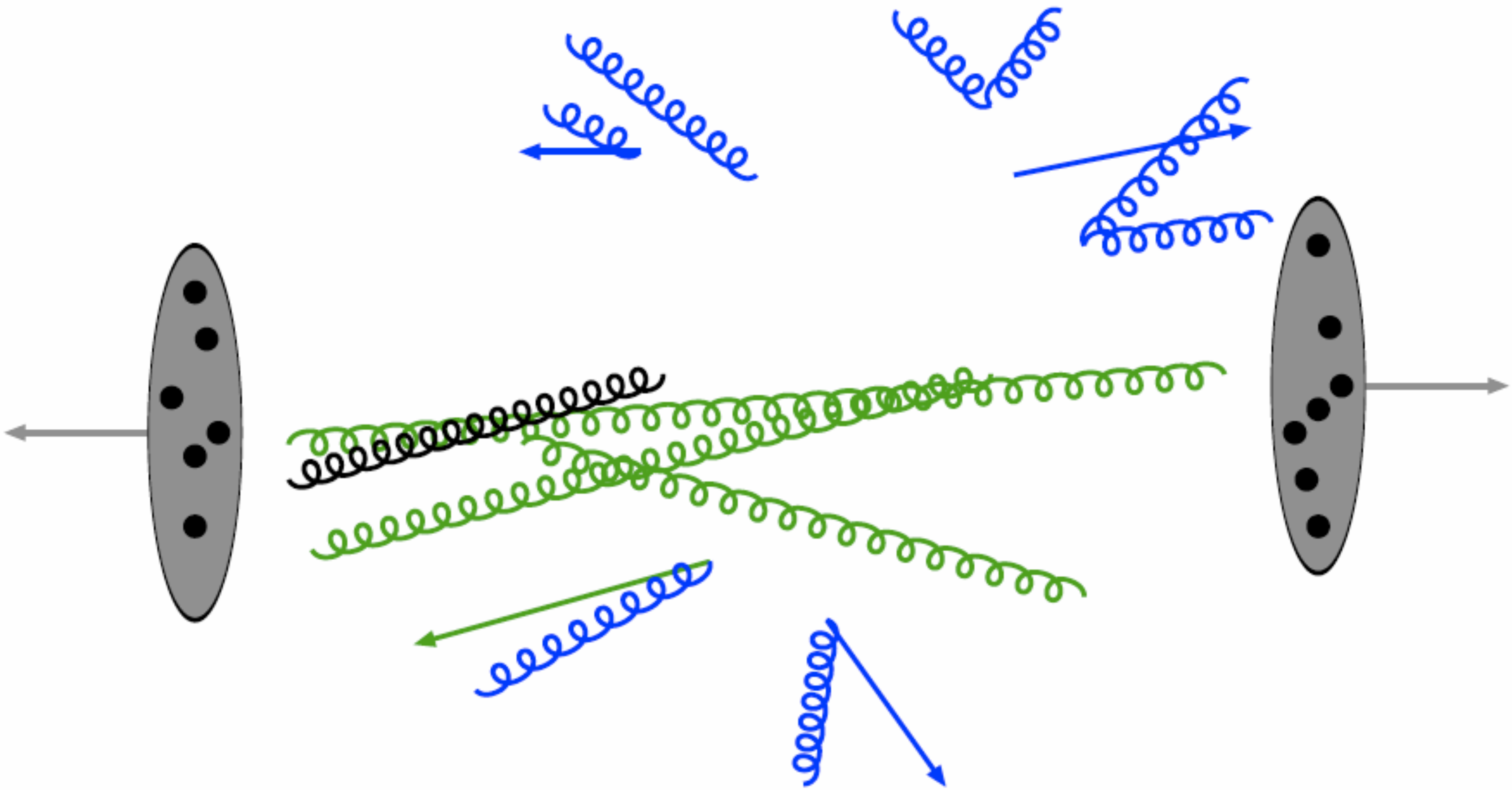
The Schematic Sequence of a p+p Collision



- ... and the corresponding initial and final state radiation

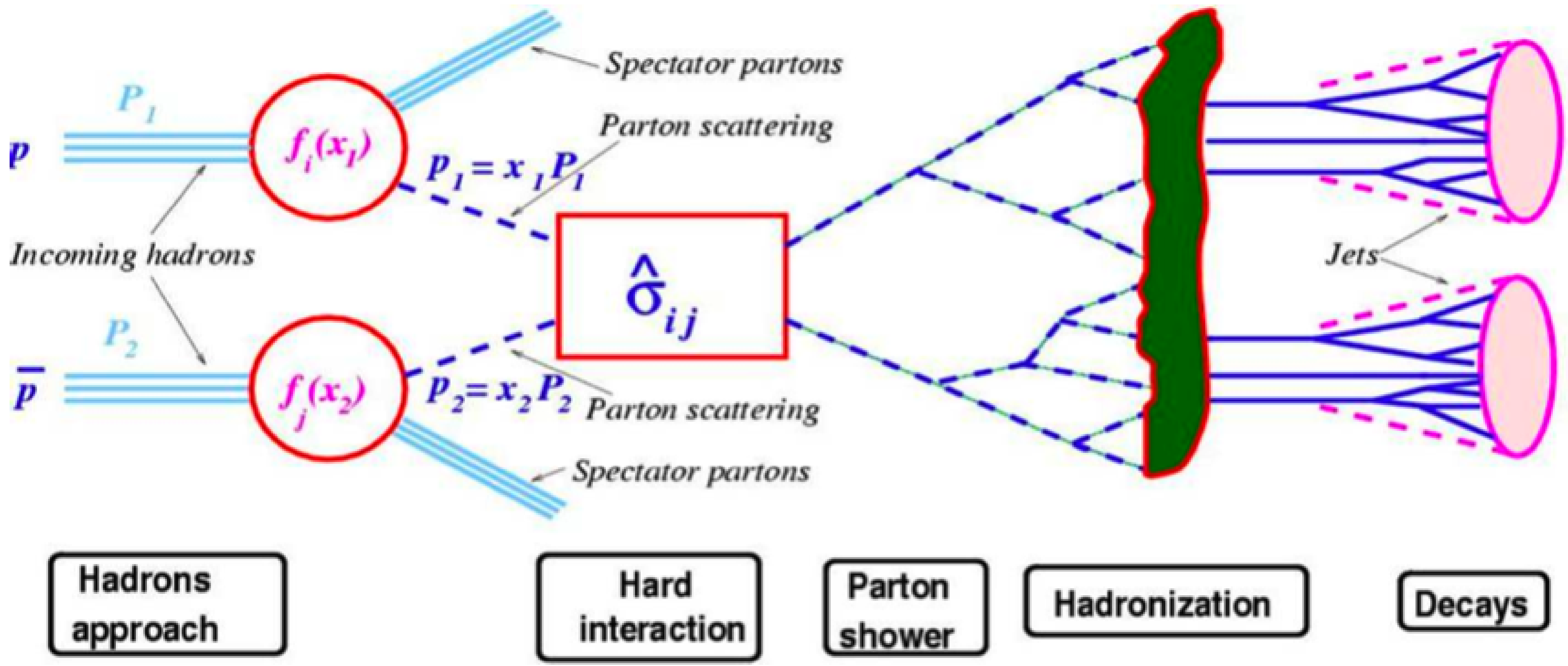
Frank Simon (fsimon@mpp.mpg.de)

The Schematic Sequence of a p+p Collision



- Beam remnants and outgoing partons
- Confinement requires the formation of color-neutral objects: Hadronization
- Short-lived states decay, the other particles reach the detector

The Full Chain



$f(x, Q^2)$: Parton distribution function

matrix element: hard process

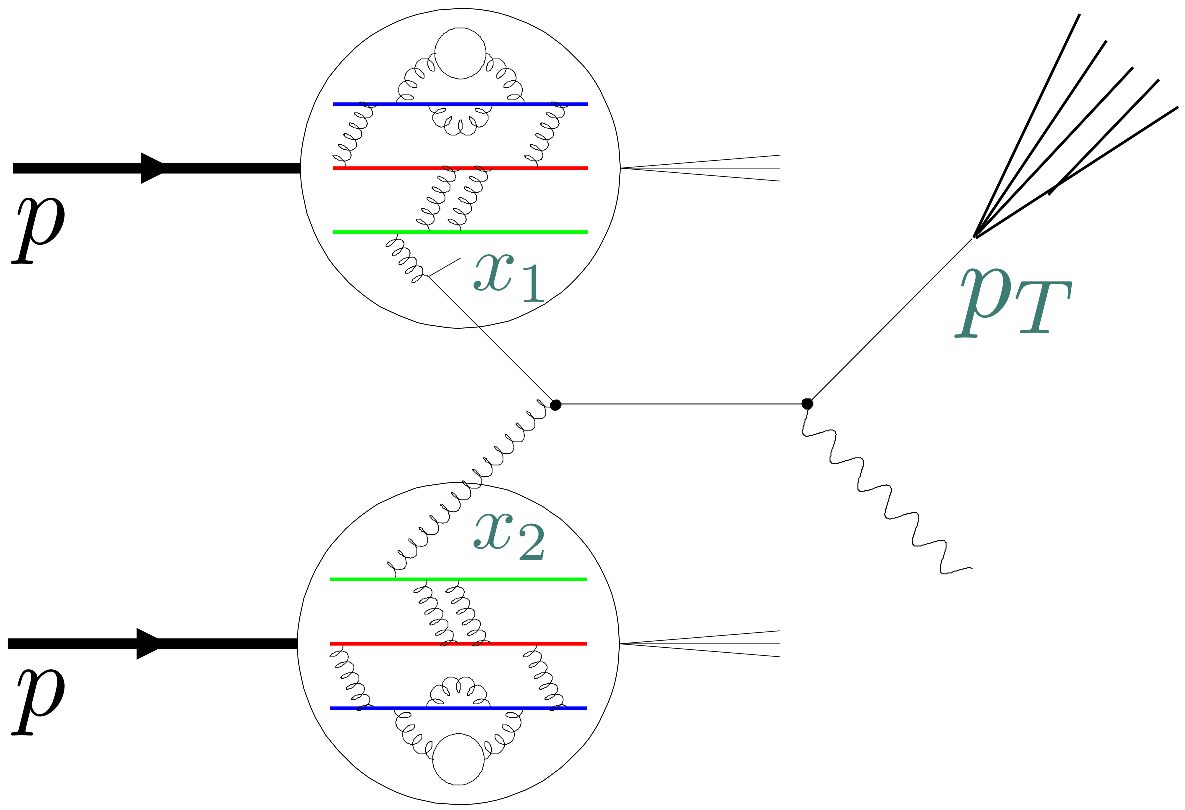
parton shower: QCD radiation / splitting

hadronization: transition from q,g to hadrons: non-perturbative, described by models!

A Closer Look

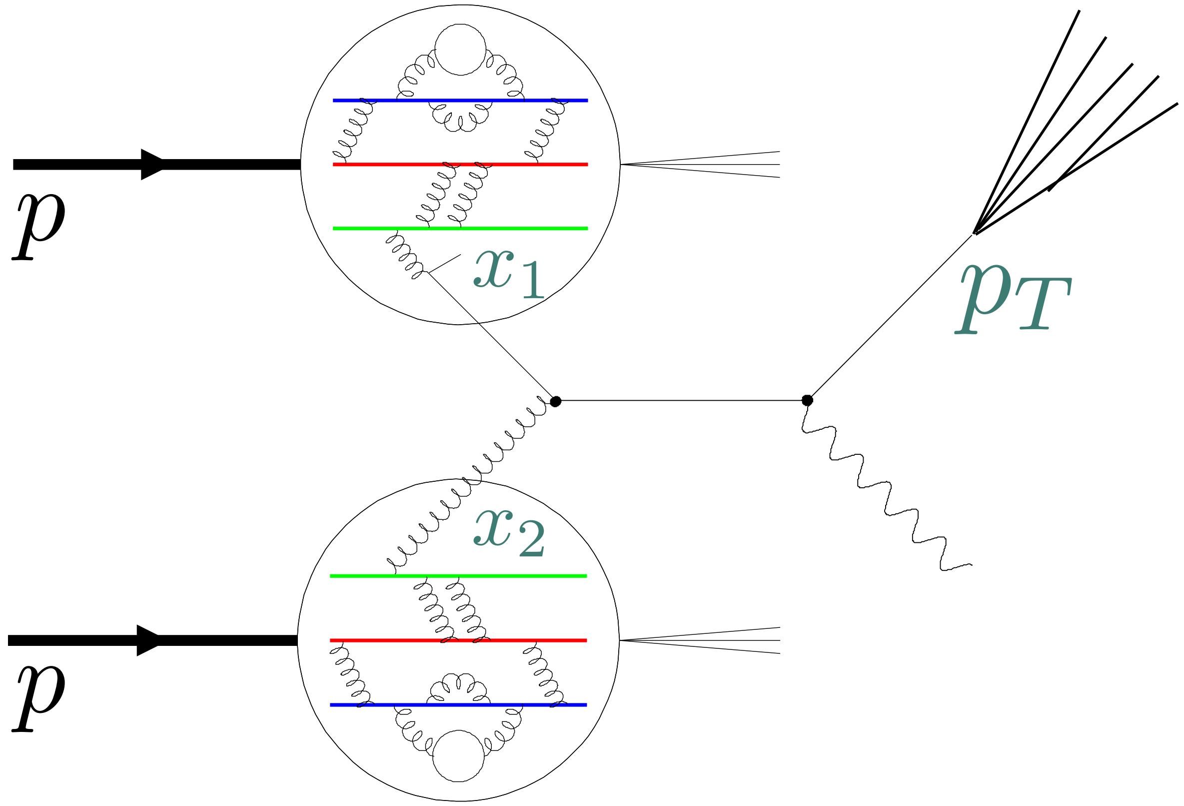
- The theoretical foundation: Factorization
- The proton structure: Parton Distribution Functions
- Hadronisation
- Jets

The Factorization Theorem



Final state X

The Factorization Theorem



Final state X

- The cross section for a high-energy process can be split into universal parton distributions, a partonic matrix element and (if applicable, depending on the final state) a fragmentation function:

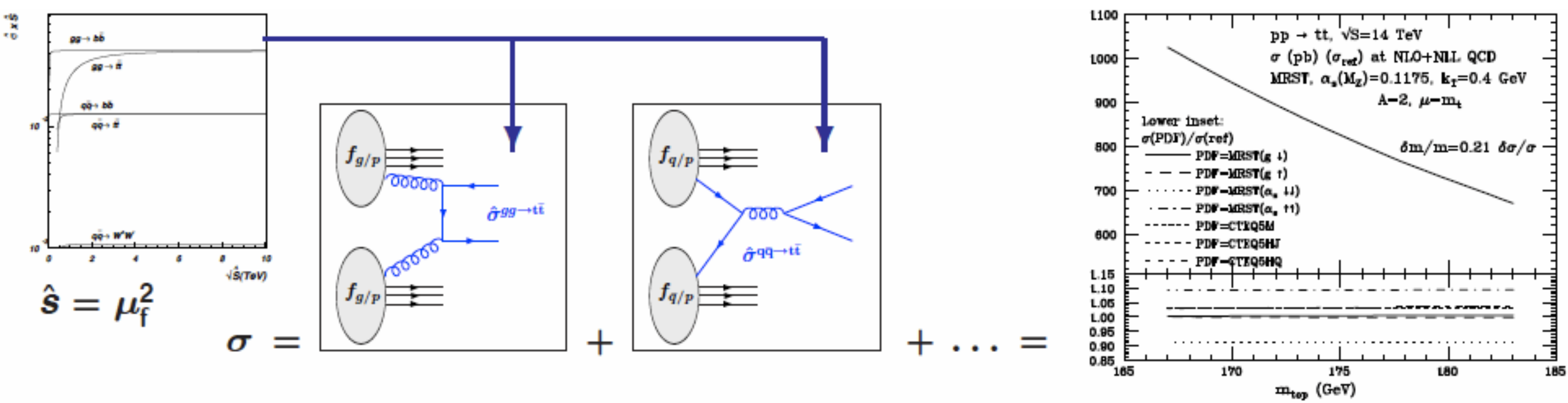
$$\sigma(AB \rightarrow X) = \Sigma_{a,b} \int dx_1 \int dx_2 \, f_{a/A}(x) \, f_{b/B}(x) \, \hat{\sigma}^{ab \rightarrow x} \, D_f^{x \rightarrow X}$$

PDF — matrix element — fragmentation function

Factorization: More complex Processes

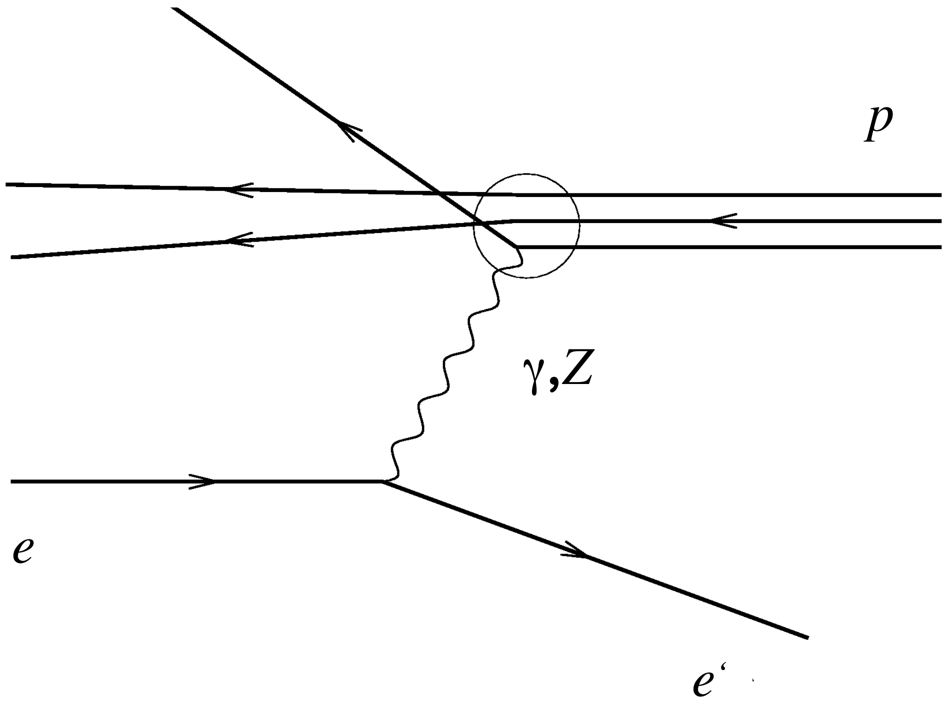
- Often more than one partonic sub-process contribute to a given final state
  - depending on the final state several fragmentation functions can enter
- The parton distribution functions and the fragmentation functions depend on the hard scale (the energy transfer)

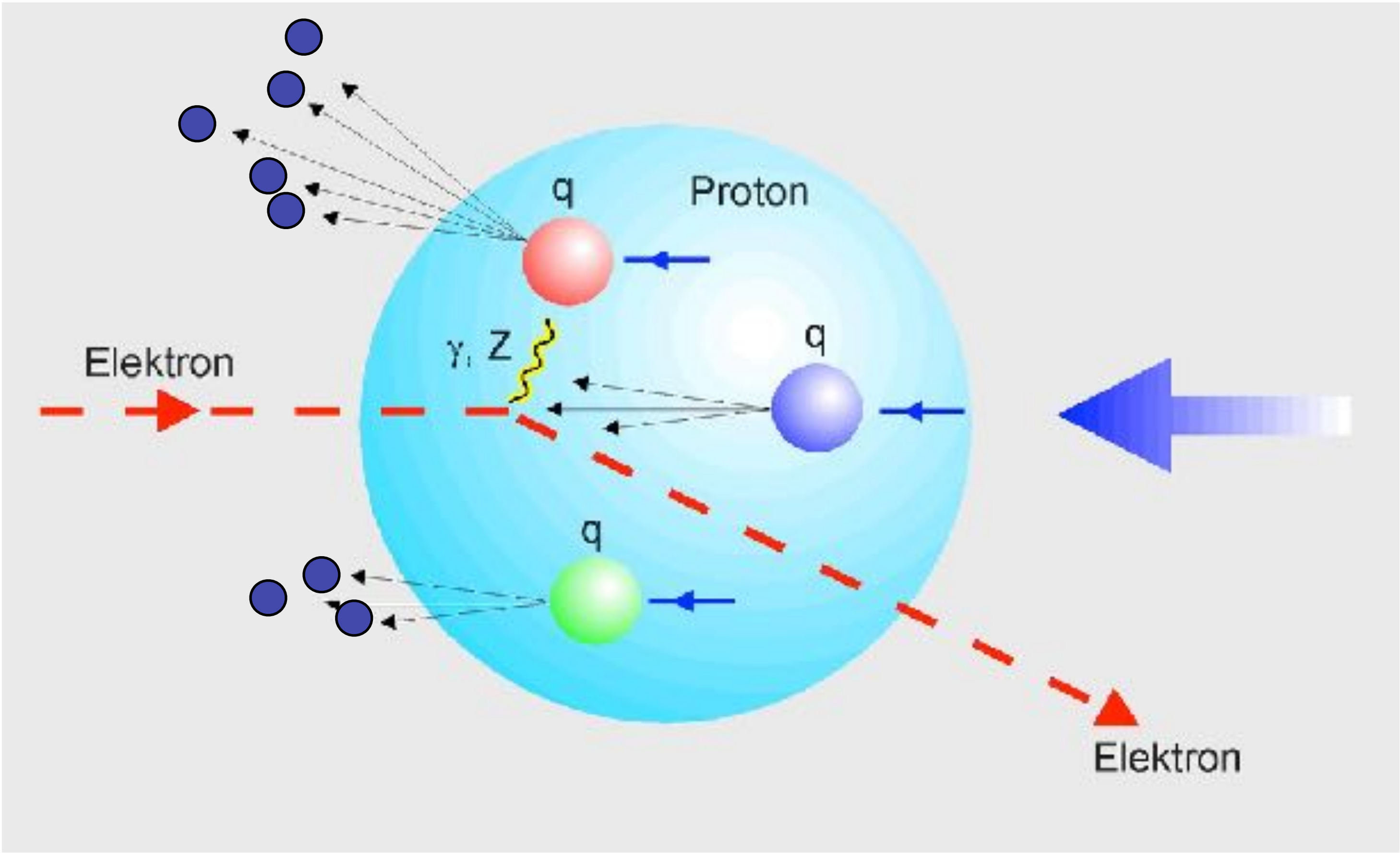
- Example: ttbar - production at LHC



The Structure of the Proton

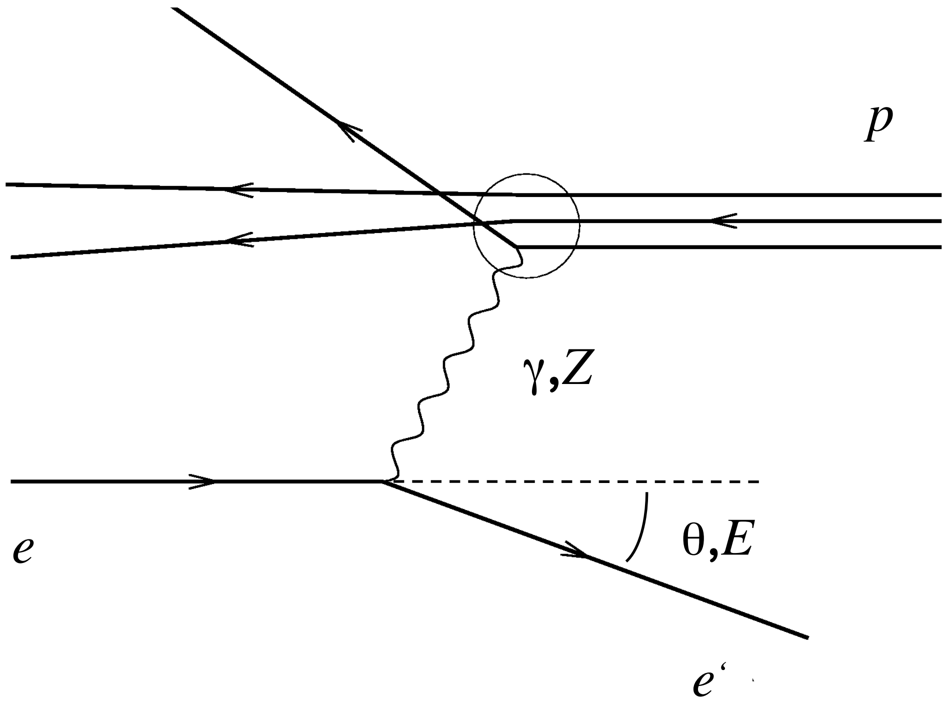
- The main experimental probe: Deep inelastic scattering (DIS)

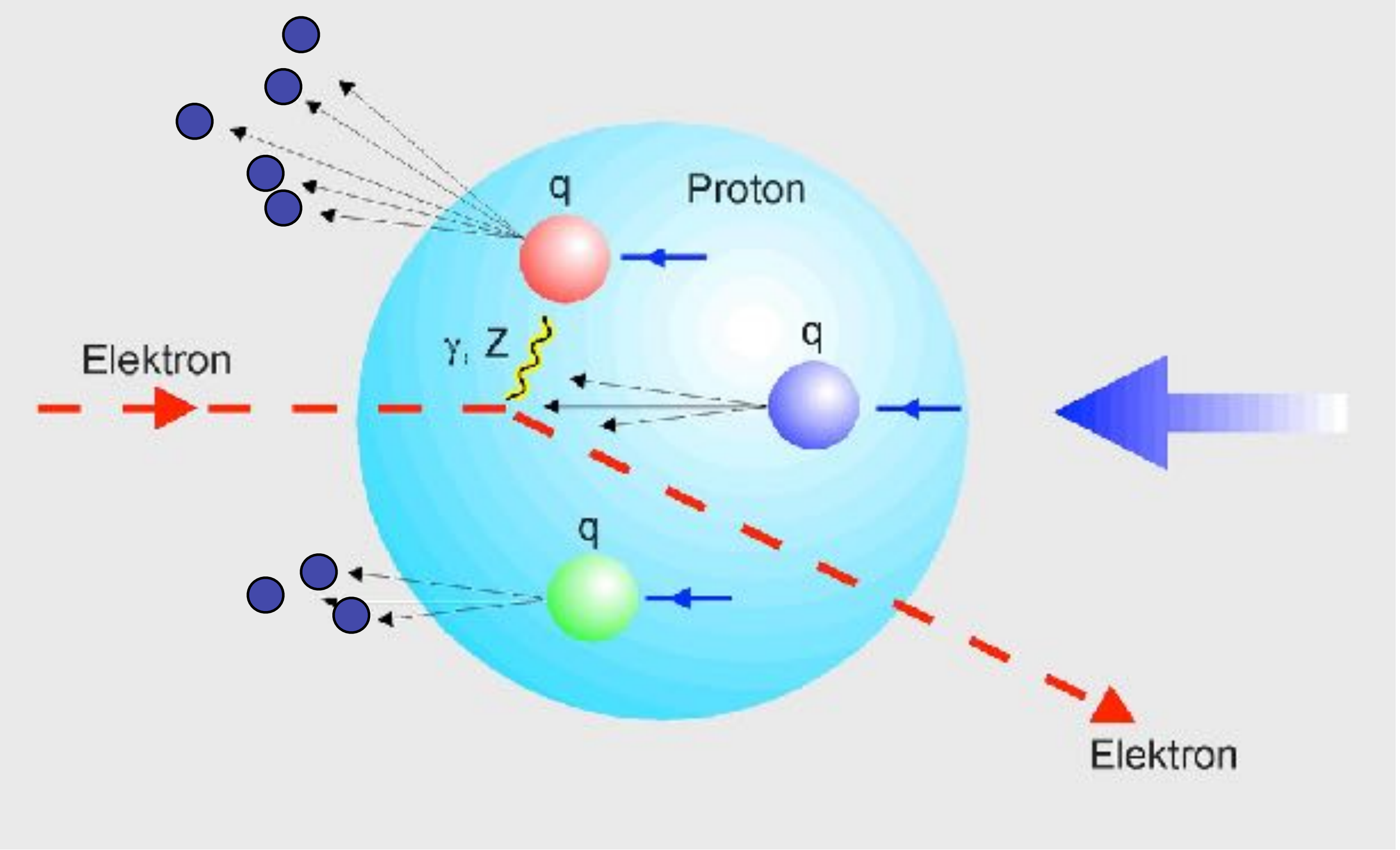




The Structure of the Proton

- The main experimental probe: Deep inelastic scattering (DIS)

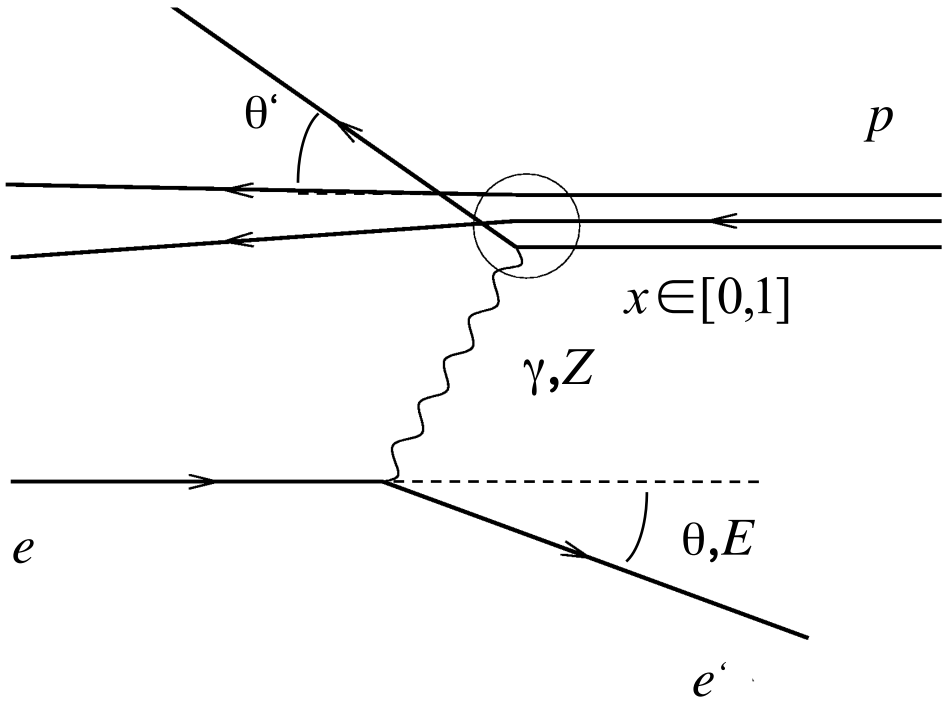


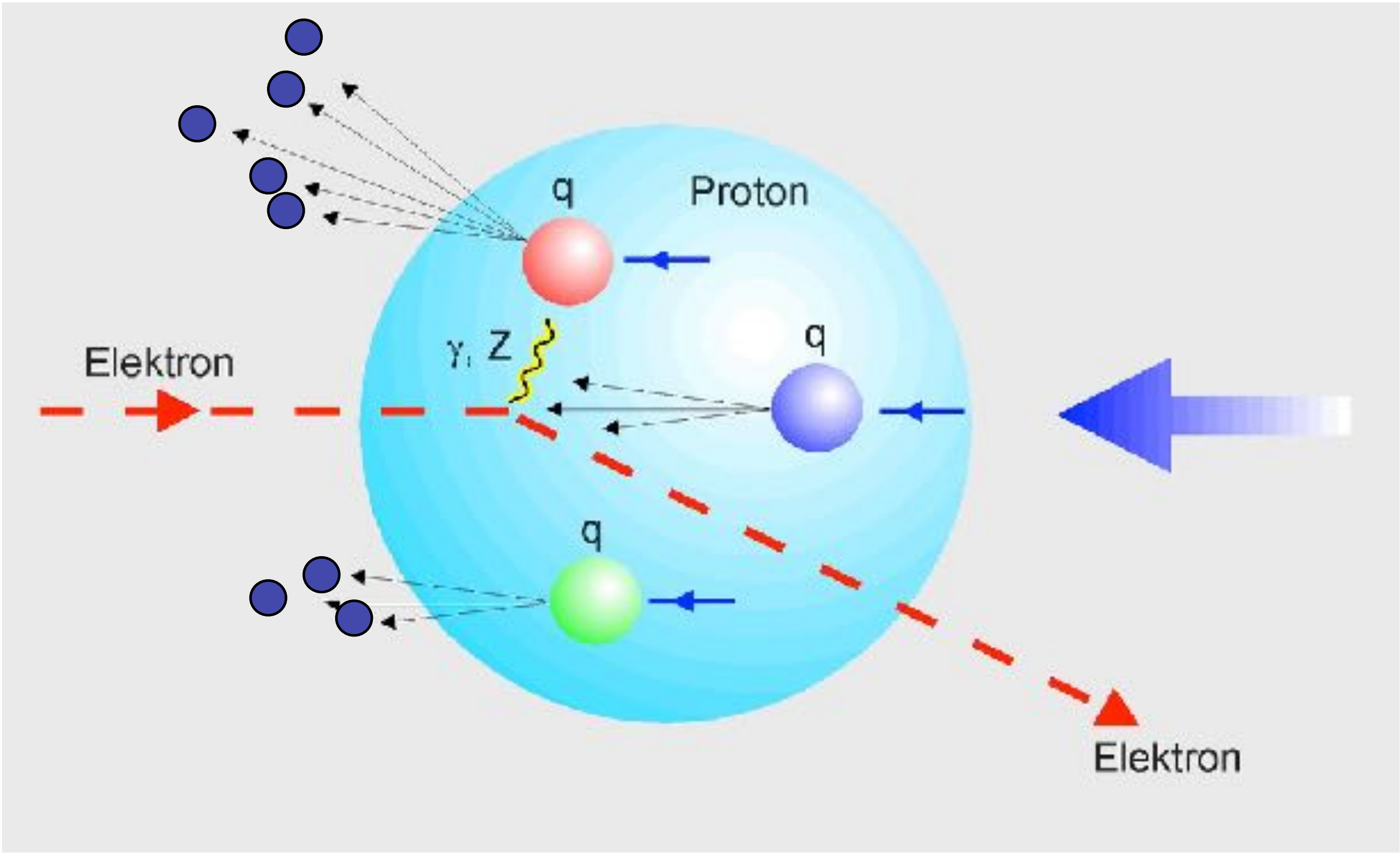


measurement of scattering angle and energy of electrons (2 known variables):

The Structure of the Proton

- The main experimental probe: Deep inelastic scattering (DIS)



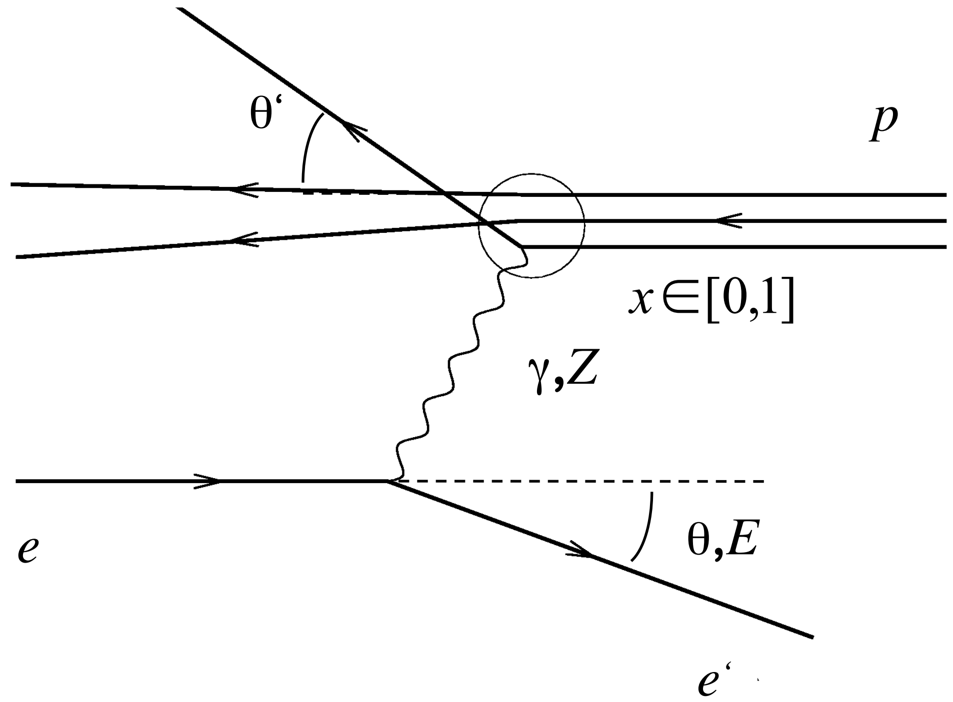


measurement of scattering angle and energy of electrons (2 known variables):

determine angle and momentum fraction *x* of scattering partner of electron (2 unknowns)

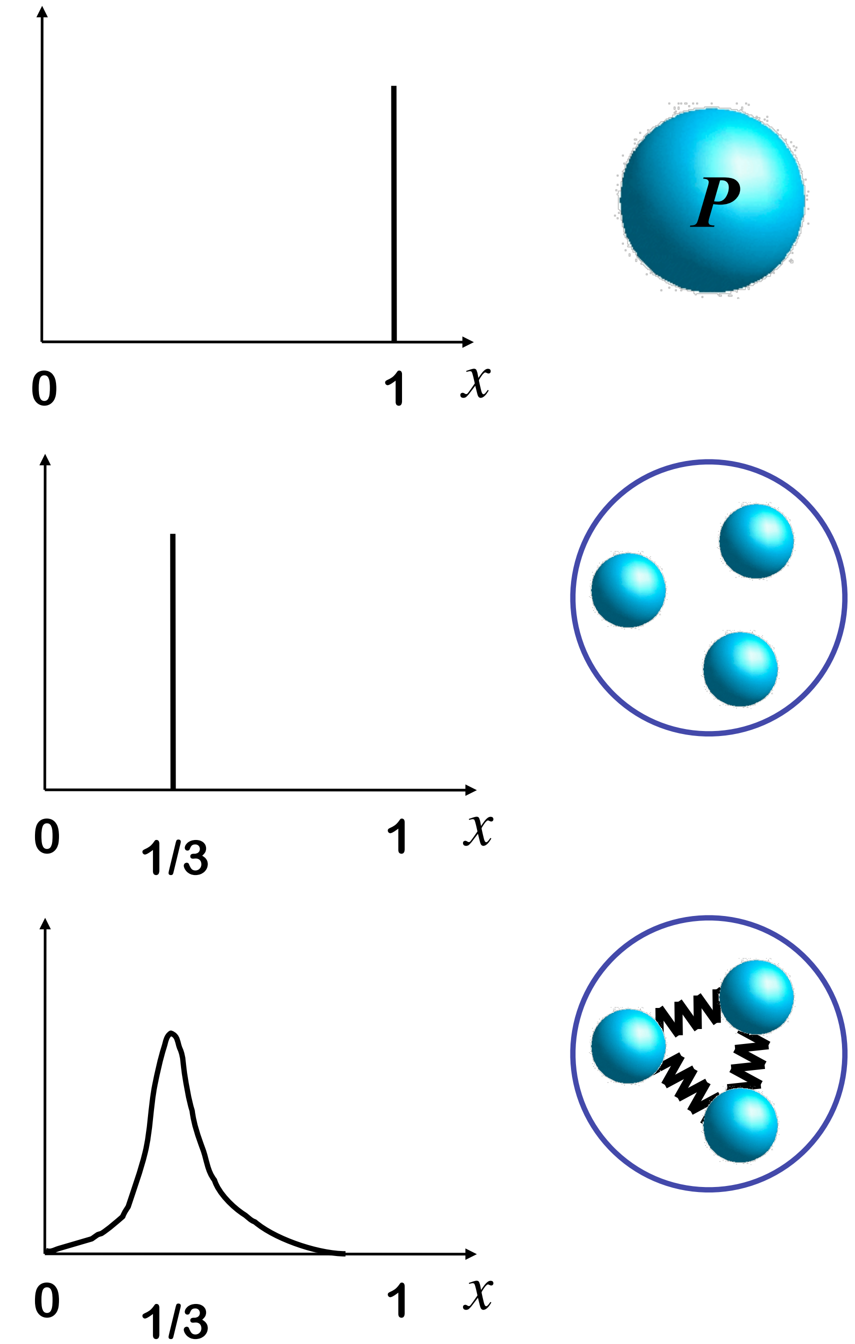
The Structure of the Proton

- The main experimental probe: Deep inelastic scattering (DIS)

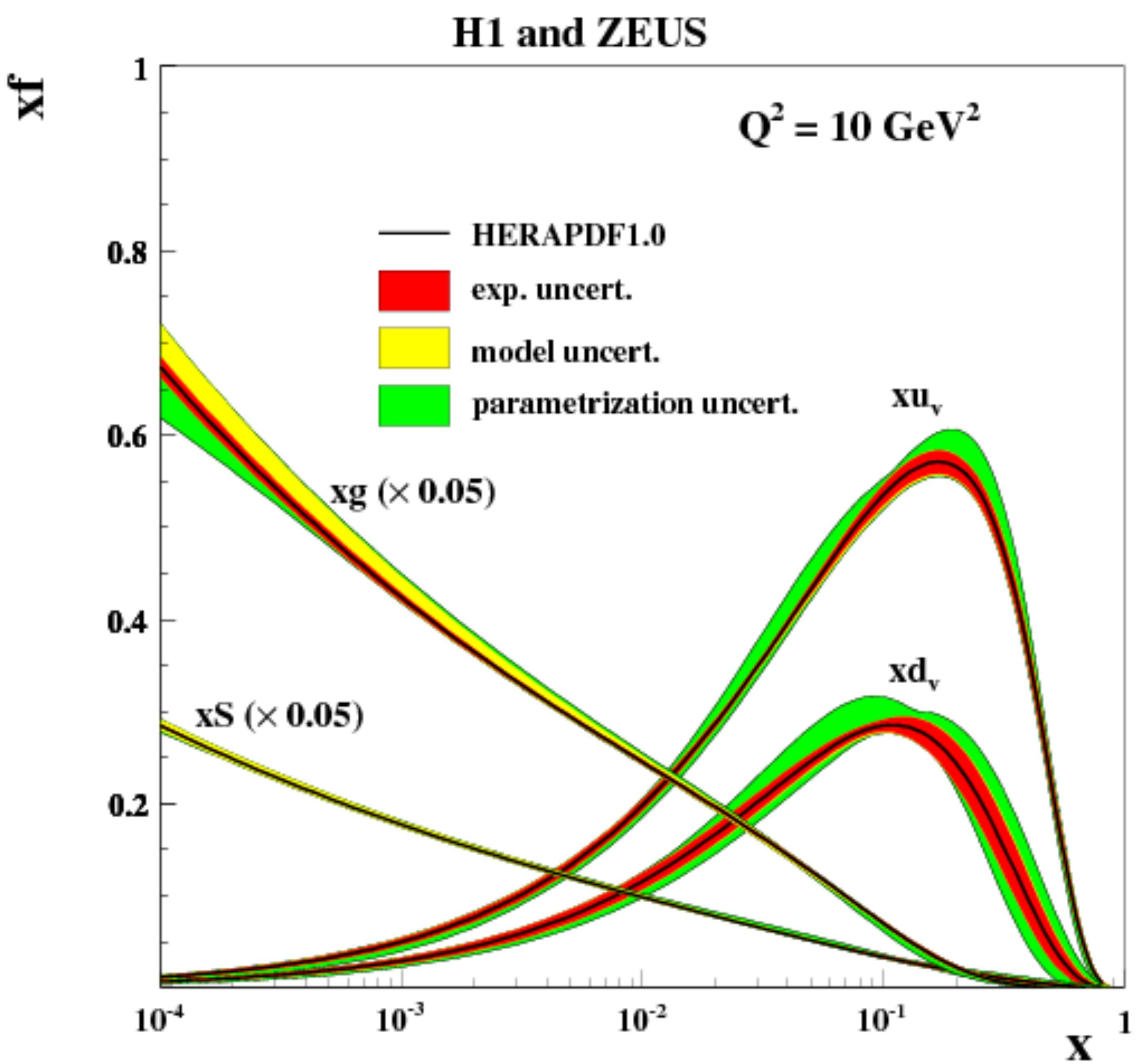


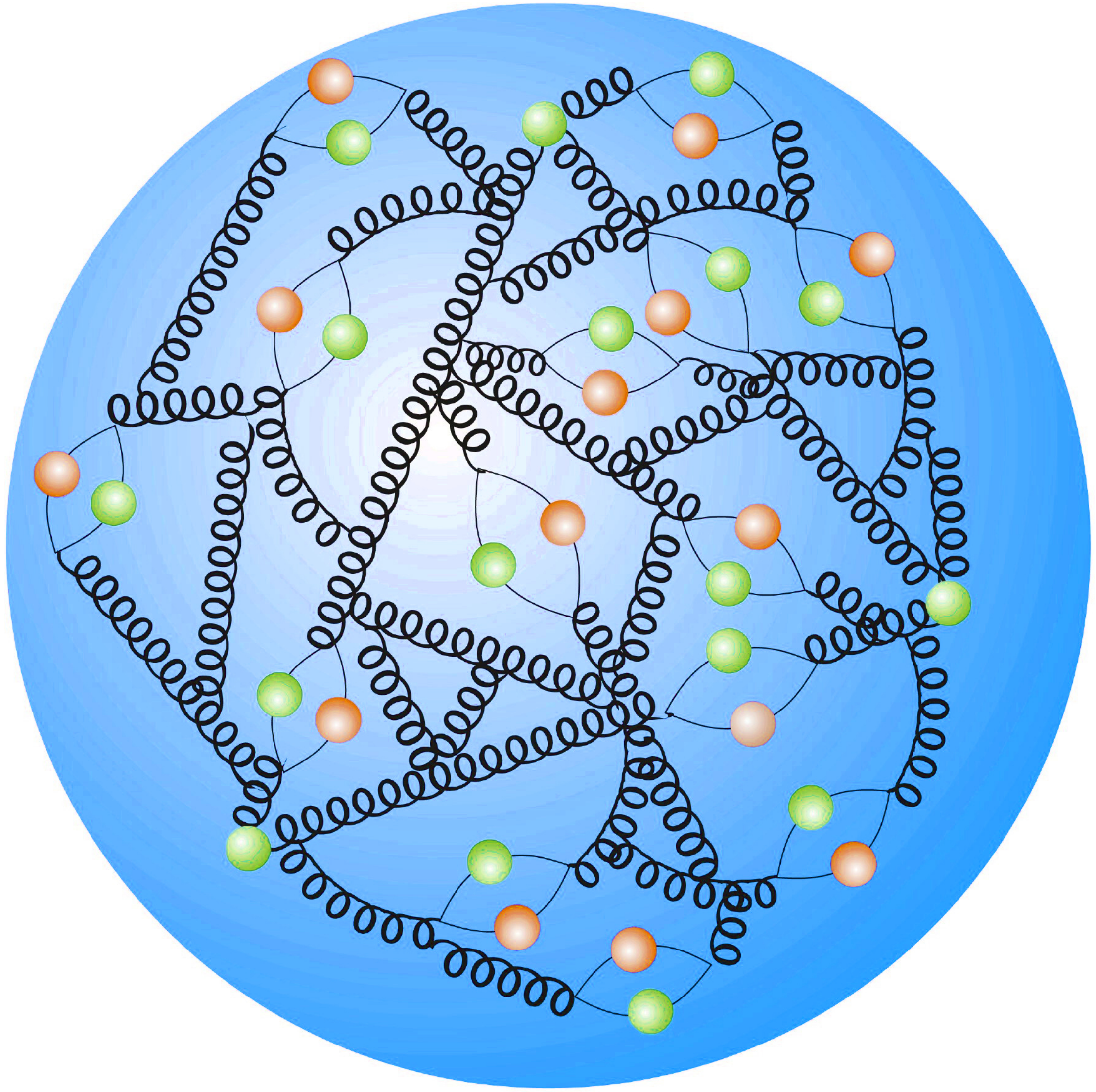
measurement of scattering angle and energy of electrons (2 known variables):

determine angle and momentum fraction *x* of scattering partner of electron (2 unknowns)



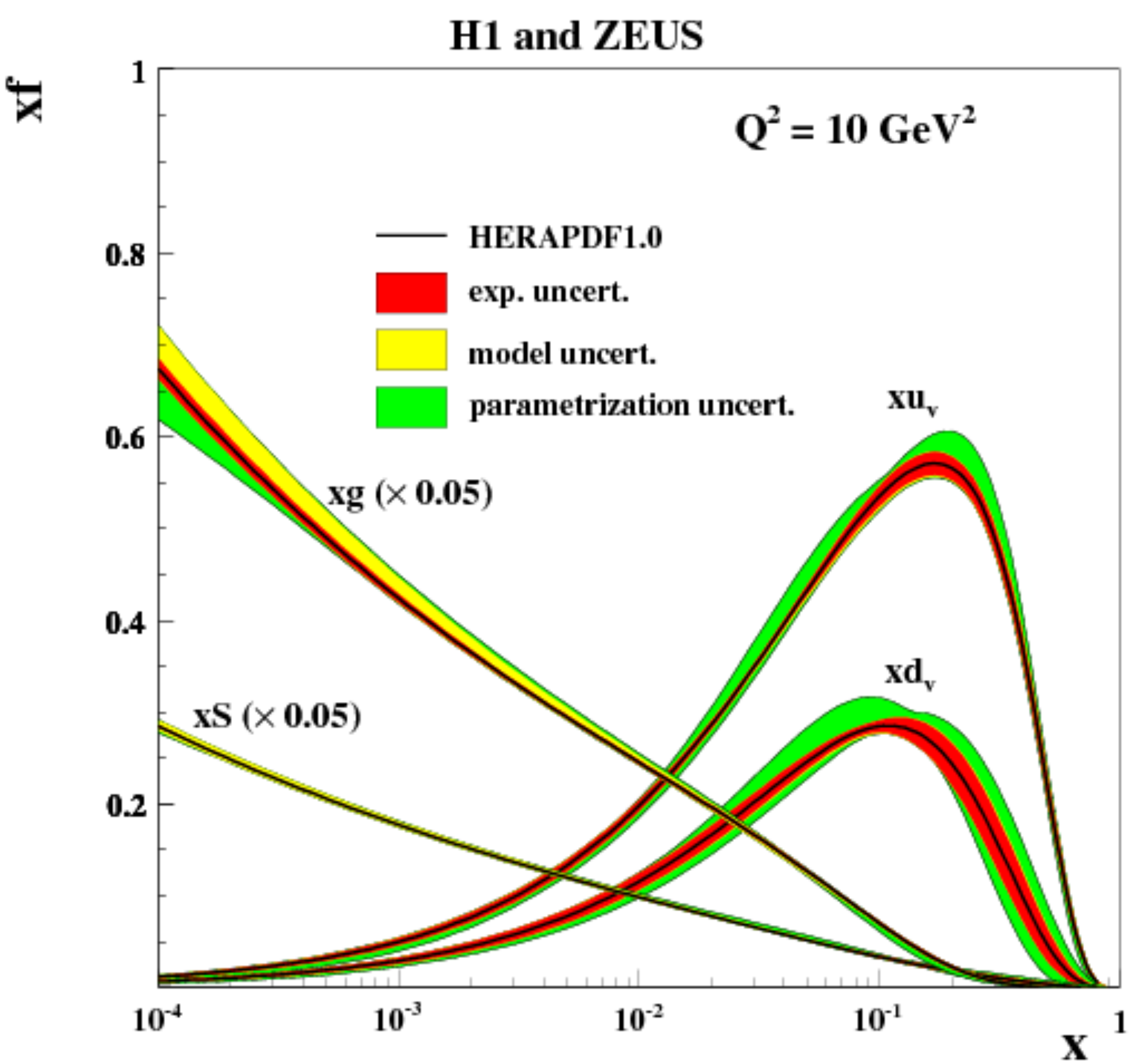
Parton Distribution Functions

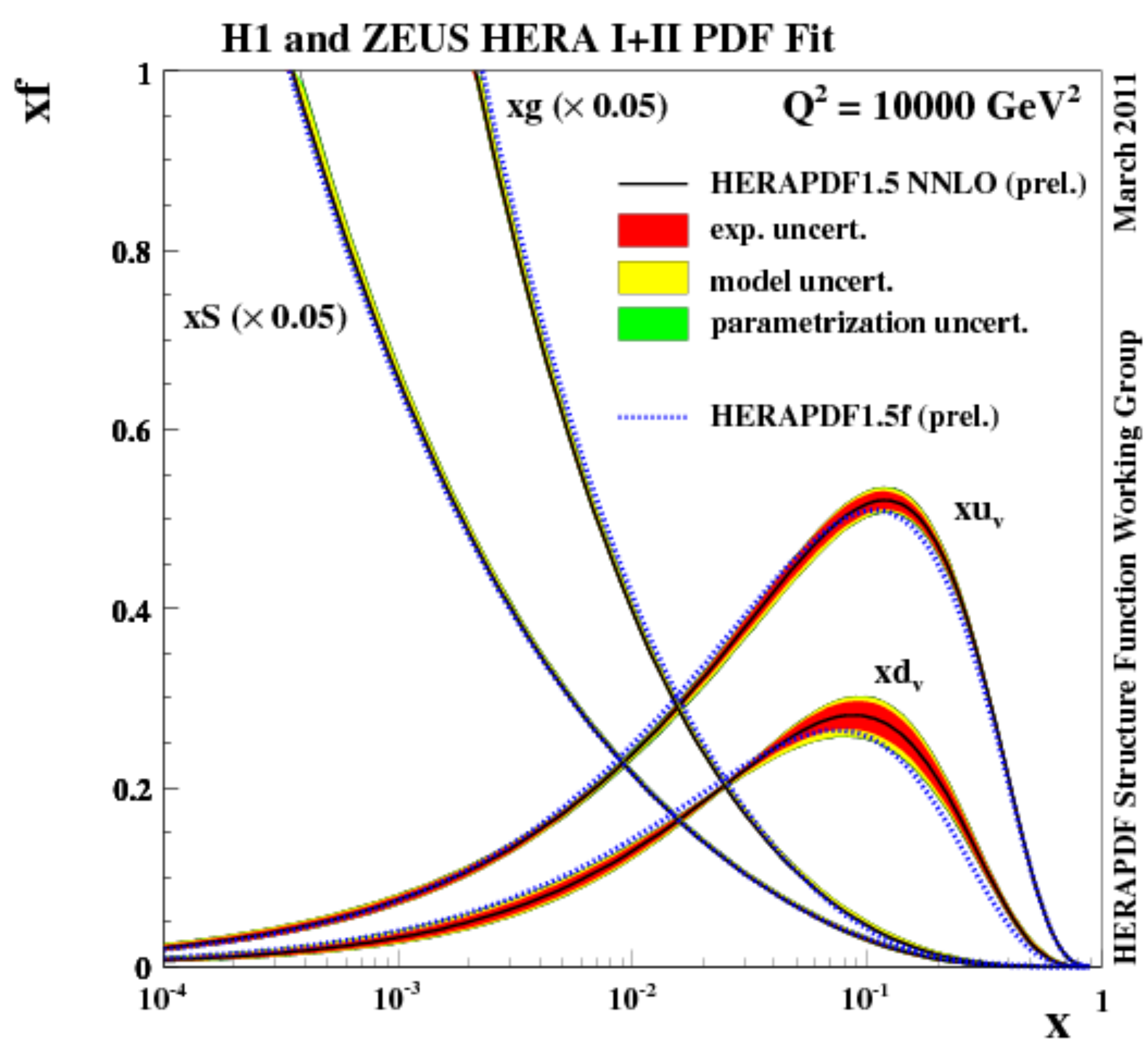




- PDFs describe the distribution of the momentum fraction of different partons in the gluon
  - Depends on momentum transfer!

Parton Distribution Functions



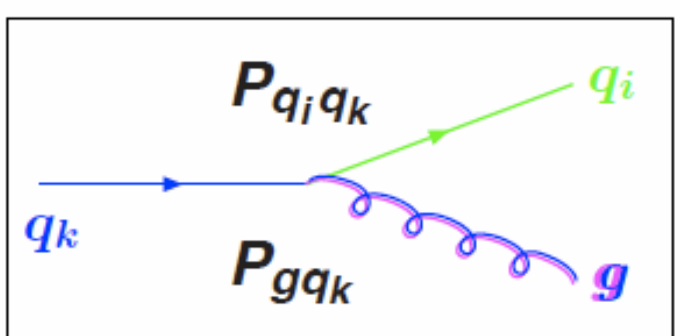


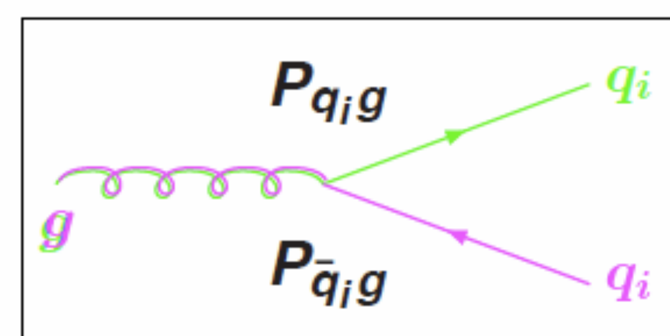
- With higher energy (= higher Q^2): Resolving “finer structures” - predominantly gluons, sea quarks
  - Highly relevant at LHC energies ($Q^2 = 10000$ GeV^2 a typical (lower) value for many LHC processes)

Parton Distribution Functions: Evolution

- The PDFs depend on the scale at which they are evaluated
  - QCD provides a description of the scale evolution of the PDFs: If they are known at one scale, they can be calculated for other scales as well
  - But: Only the evolution can be calculated, not the distributions themselves (e.g., not the structure of the proton) - these need to be measured
  - ▸ Homogeneous evolution equations: DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations
  - Important components: Splitting functions
    - Describe the probability to find a parton *i* with the momentum fraction *z* in parton *k*

Beispiele: $P_{q_i q_k}(z) = \delta_{ik}\left[\frac{4}{3}\frac{1+z^2}{(1-z)_+} + 2\delta(1-z)\right], \quad P_{q_i g}(z) = \frac{1}{2}\left[z^2 + (1-z)^2\right].$





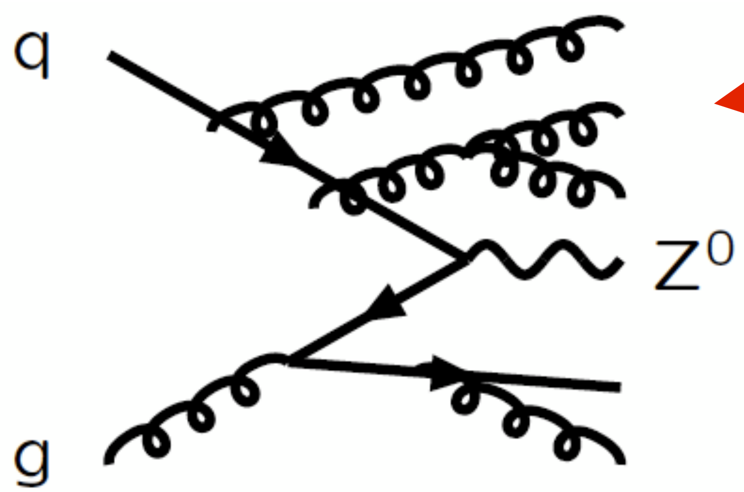
Additional Corrections: Parton Shower

- The cross section of a process is given by the matrix element and the PDFs
- For hard radiation ME at $O(\alpha_s^n)$ is used
  - The precision of the ME is usually given by the order to which it is calculated: LO, NLO, NNLO (already quite rare)...

Additional Corrections: Parton Shower

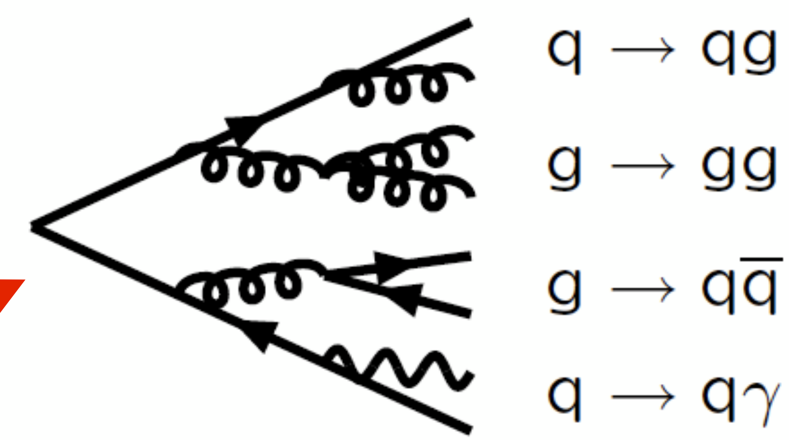
- The cross section of a process is given by the matrix element and the PDFs
- For hard radiation ME at $O(\alpha_s^n)$ is used
  - The precision of the ME is usually given by the order to which it is calculated: LO, NLO, NNLO (already quite rare)...

➩ Soft radiation at higher orders described by parton showers



initial state PS

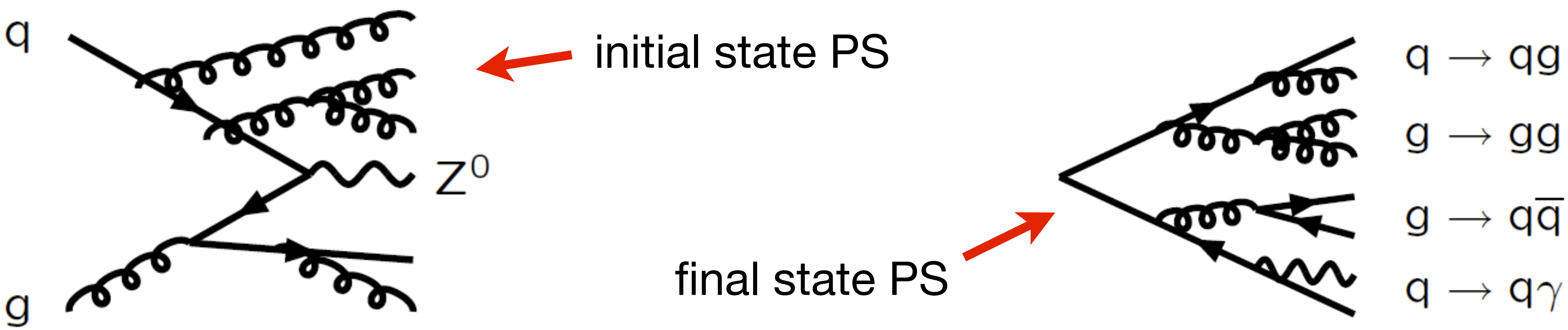
final state PS



Additional Corrections: Parton Shower

- The cross section of a process is given by the matrix element and the PDFs
- For hard radiation ME at $O(\alpha_s^n)$ is used
  - The precision of the ME is usually given by the order to which it is calculated: LO, NLO, NNLO (already quite rare)...

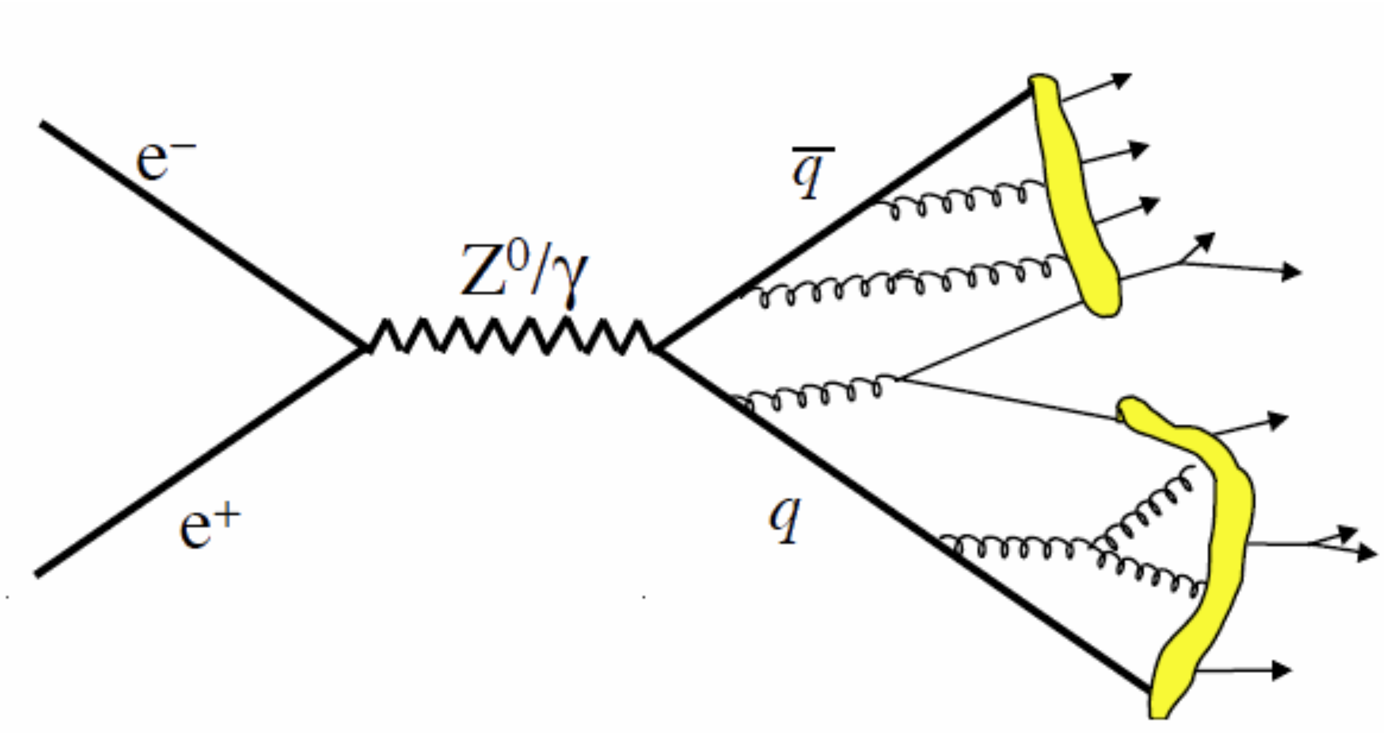
➯ Soft radiation at higher orders described by parton showers



- Parton showers: radiation of gluons, the probability that no radiation takes place is described by “Sudakov factors” (before/after scattering)
- Parton showers do not change the cross section -> radiation harder than the matrix element is forbidden (“matching”)

Final States: Hadronization

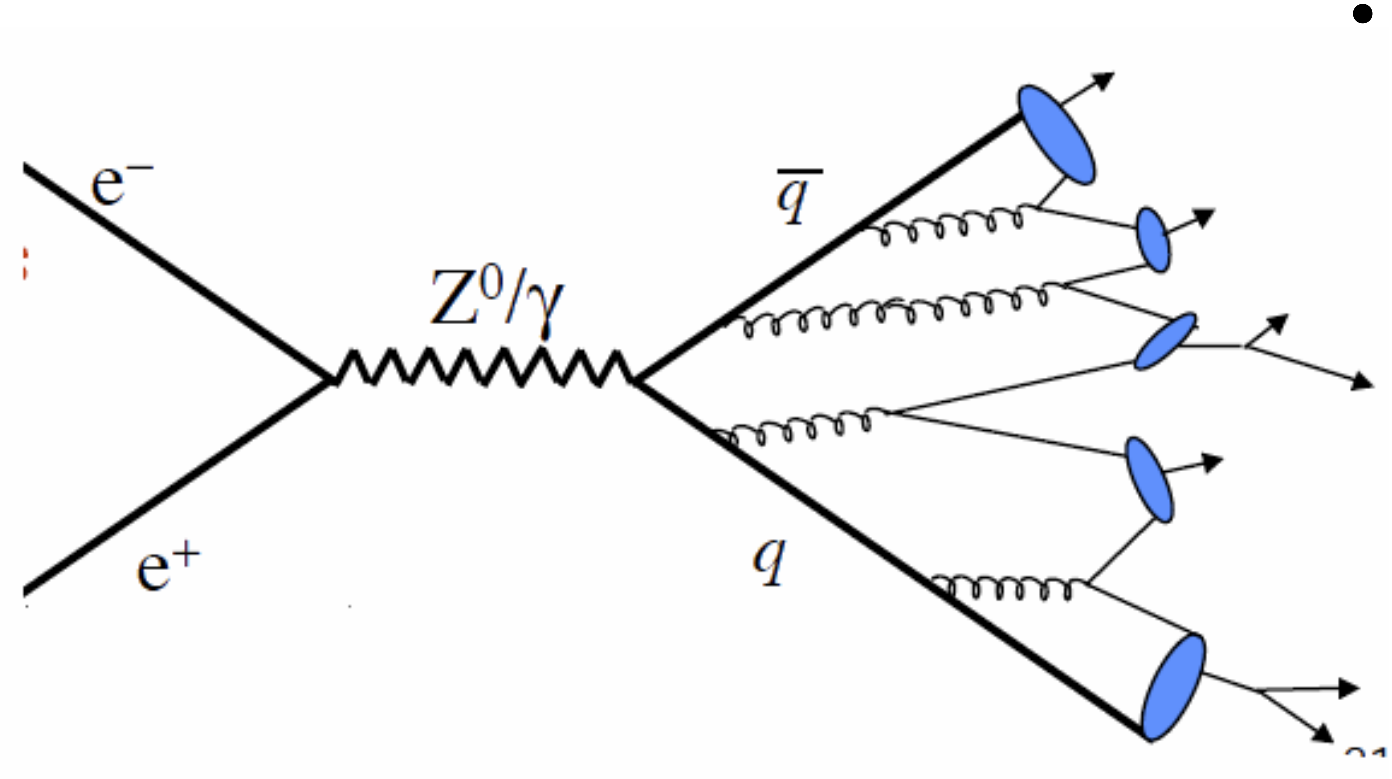
- Describes how hadrons are formed from the final-state partons
  - Experimentally: Measured fragmentation functions
  - For computer simulations: Two commonly used models:



- The Lund string model (Jetset)
  - The colored strings between two partons fragment, given by a string tension of κ = 1 GeV/fm
  - Radiation of hard gluons
  - If the energy in a string is sufficient, a q-Anti-q oder a qqq state is produced
    Probability:

$$P \propto exp\left(\frac{-\pi(m_q^2 + p_{t,q}^2)}{\kappa}\right)$$

Final States: Hadronization

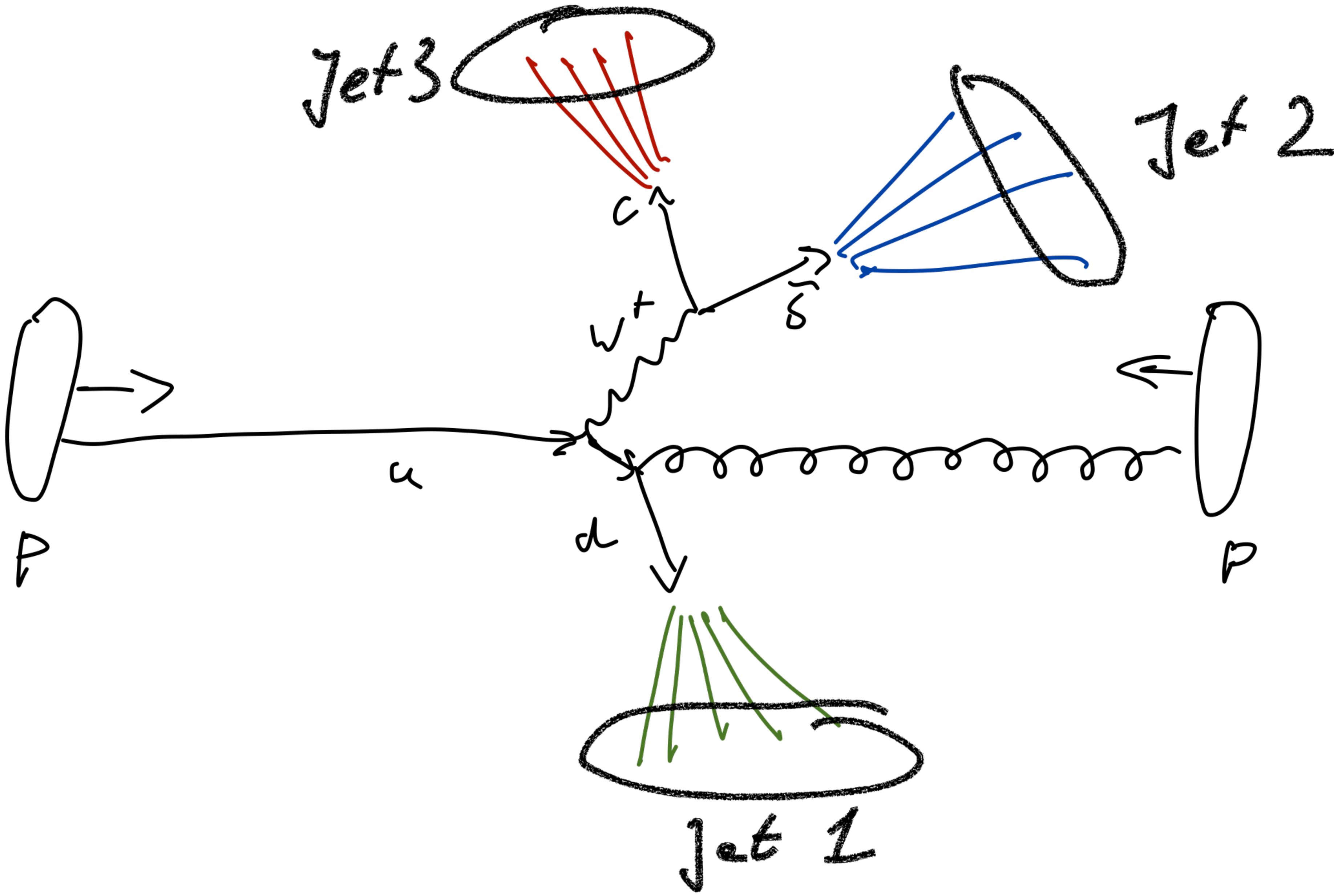


- The Cluster Model (Herwig)
  - Gluons at the end of a shower are non-pertubatively transformed into q-Anti-q pairs
  - Locally color-neutral clusters with a few GeV mass are formed out of quarks
  - Depending on their mass, these clusters are split into two, or are transformed into hadron pairs or single hadrons

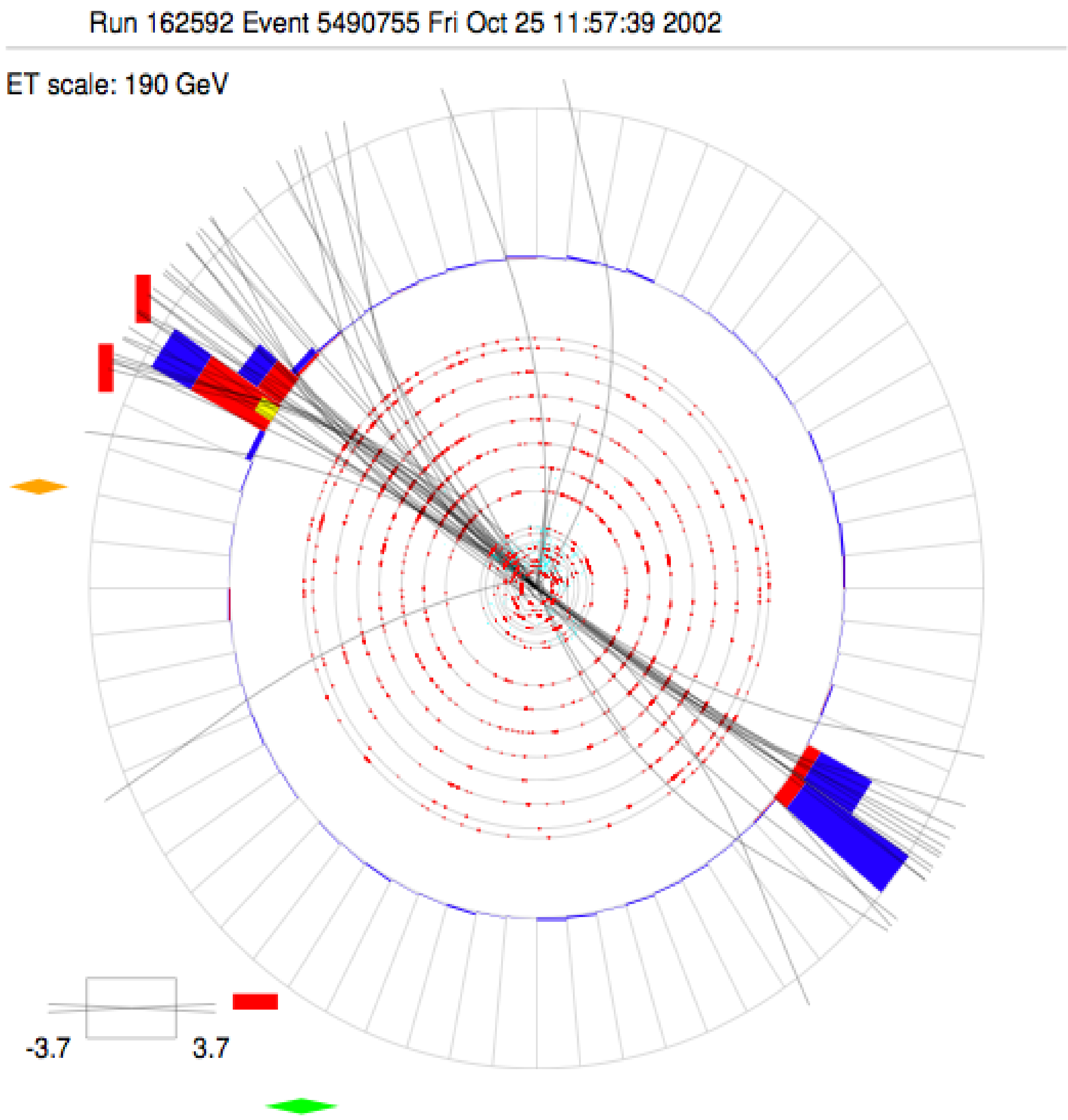
- Both of these hadronization models are often compared to obtain an estimate of systematic uncertainties - which are then given by the differences between the two models

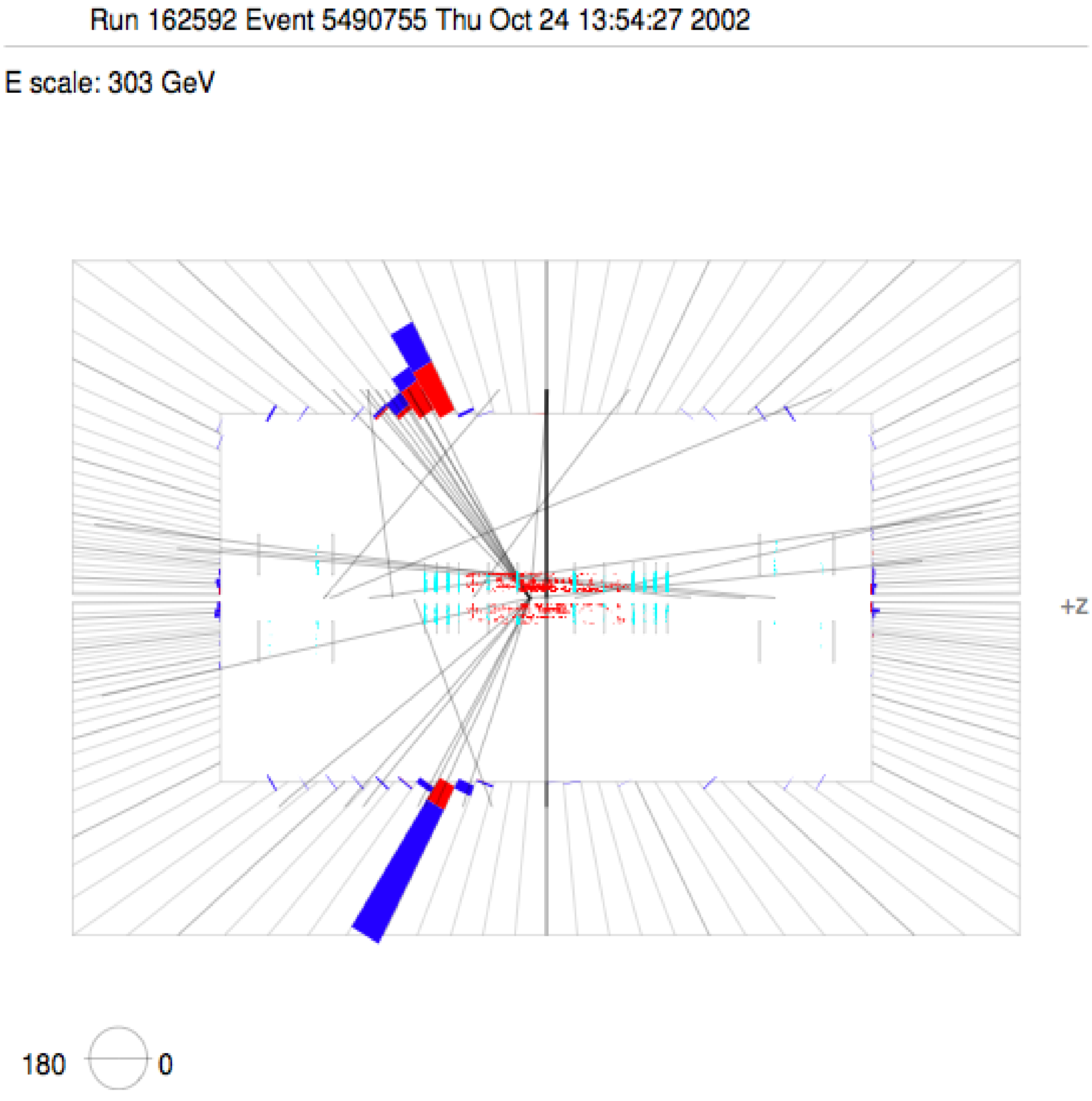
Jets: Connecting Final States to Partons

- In HEP: typically not interested in a particular final-state hadron, but in information about the original final-state parton (quark or gluon)



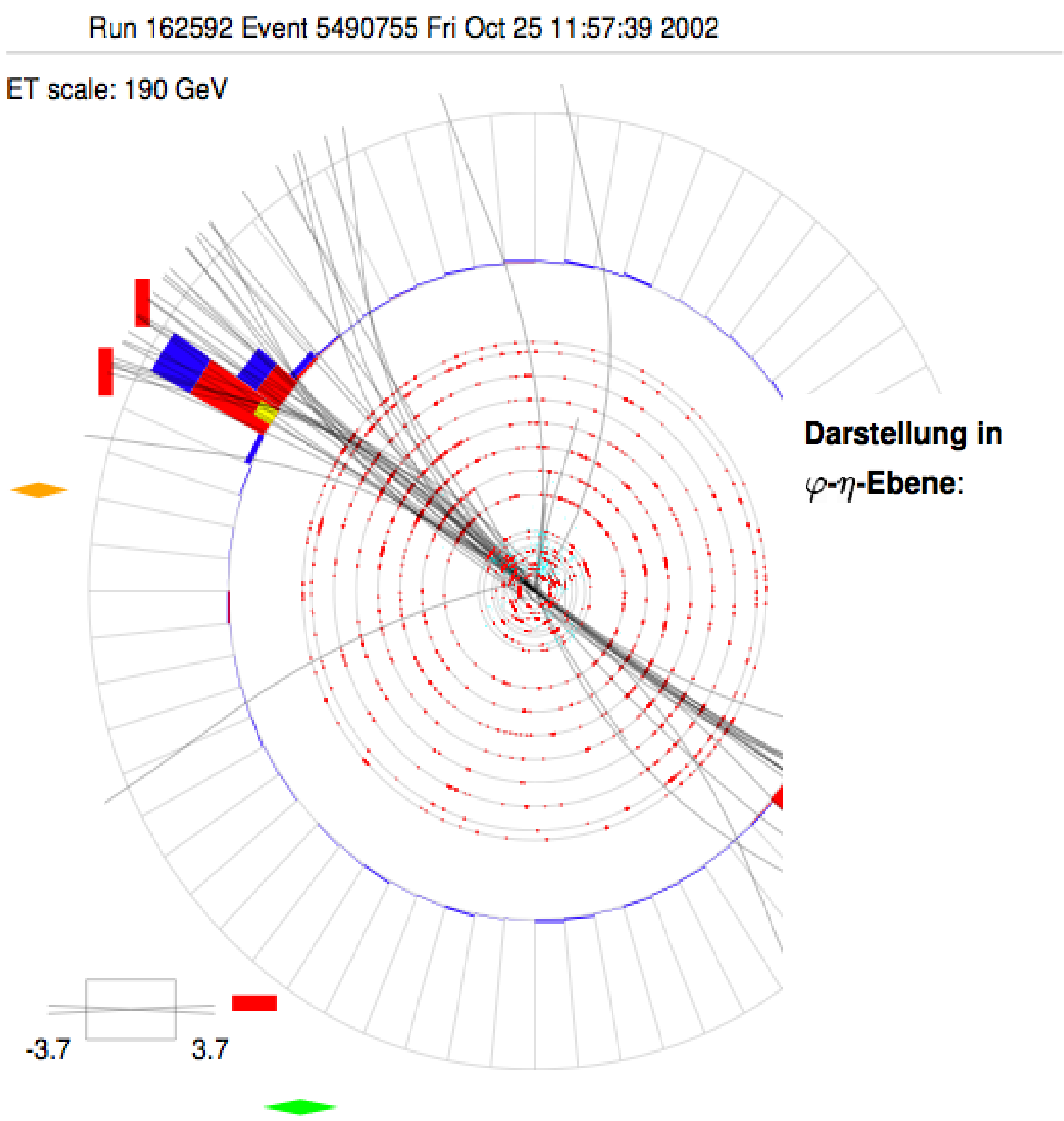
Di-Jet Event at the Tevatron



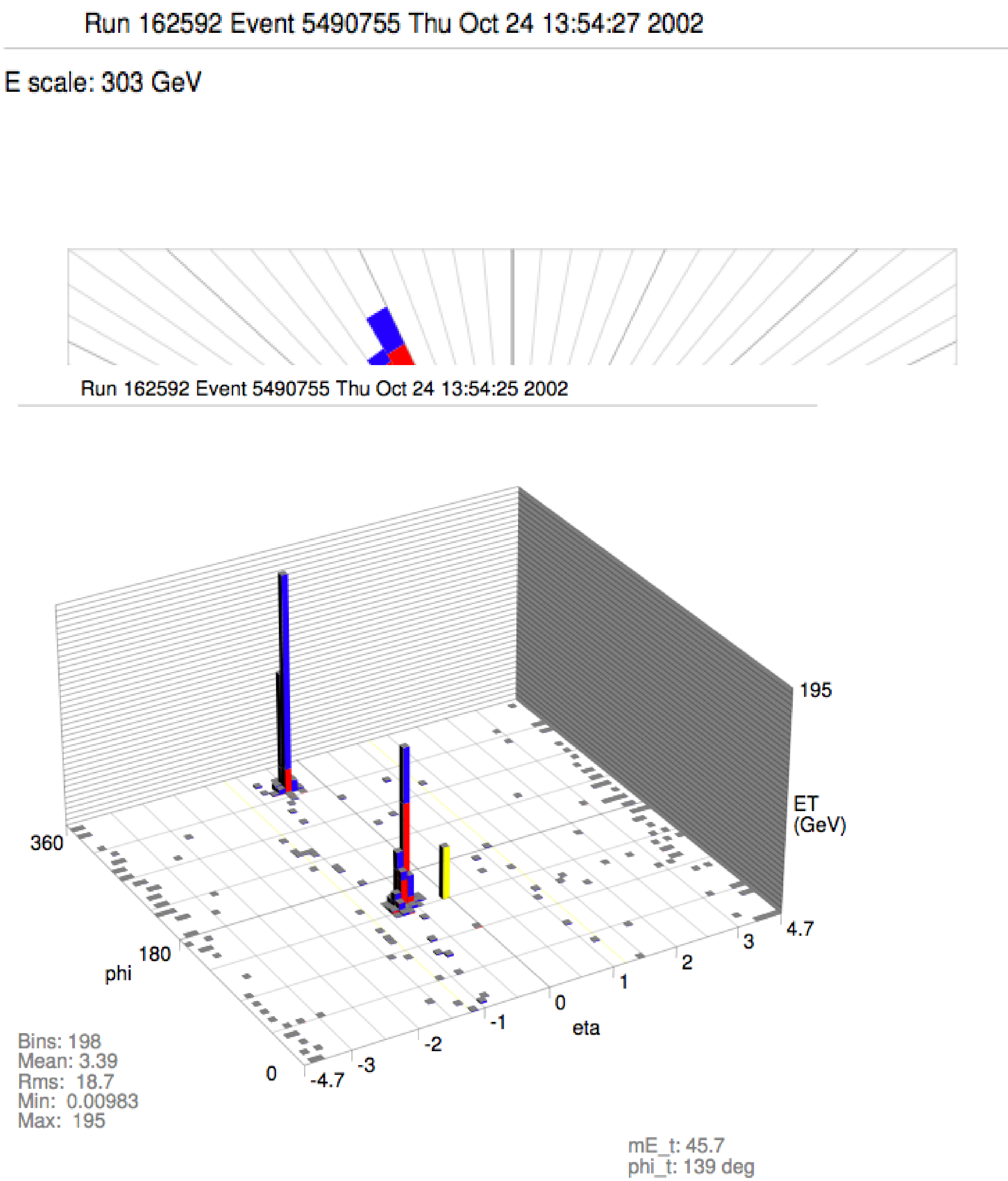


proton - antiproton collision

Di-Jet Event at the Tevatron



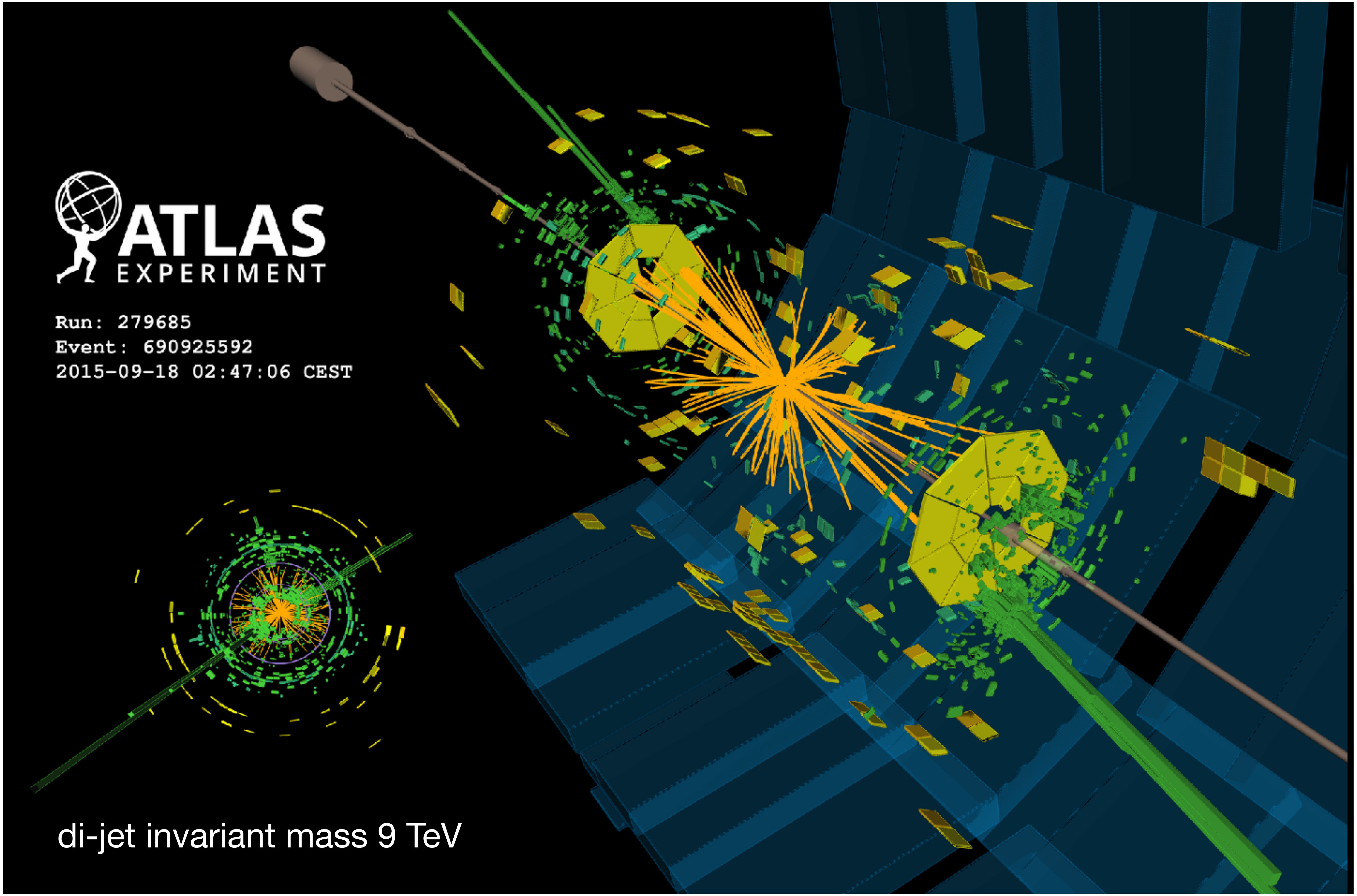
Darstellung in φ-η-Ebene:



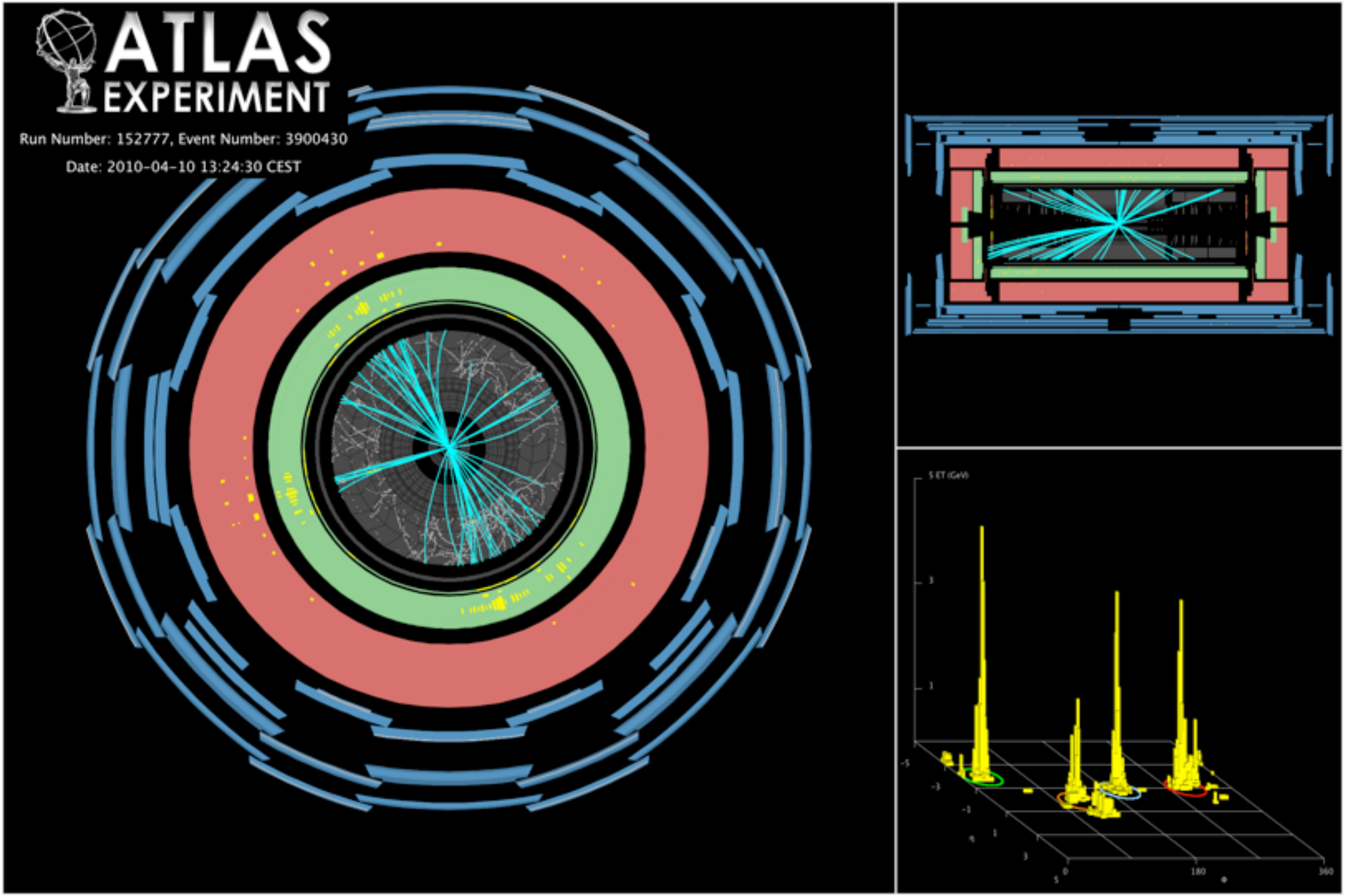
proton - antiproton collision

Azimutwinkel φ, Pseudorapidität $\eta = -\tan(\vartheta/2)$, Polarwinkel ϑ, transversale Energie $E_T = E\sin\vartheta$

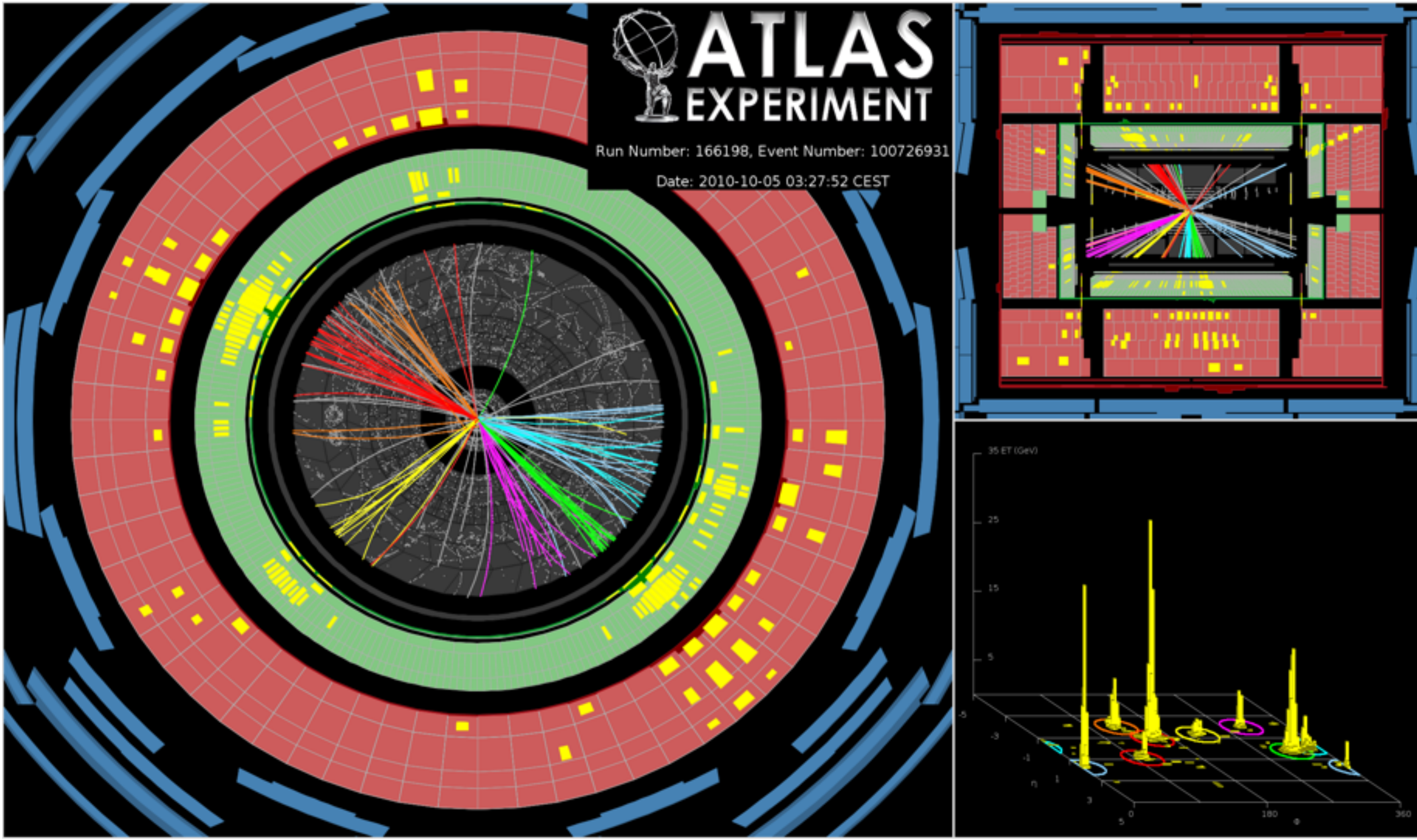
Di-Jets at LHC



LHC 4 - Jet Event

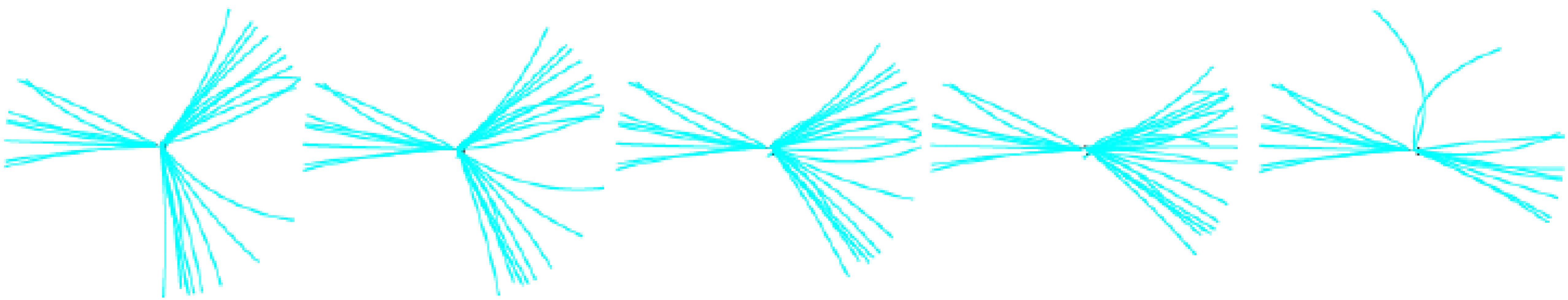


LHC 8 - Jet Event



Defining Jets

- To compare experimental observations to theory, jets have to be defined in a clean and stable way
  - Challenges arise in the assignment of particles to jets - there is no unambiguous assignment



overlapping jets: collinear divergence

low-energy jets: infrared divergence

- A naive (but intuitive) jet definition as cones of energy fails in problematic cases: not “collinear and infrared safe”

Defining Jets

- The solution: Iteratively combine particles to jets based on a distance criterion based on (transverse) momentum and geometrical separation

The k_T algorithm

$$d_{ij} = \min(k_{t,i}^2, k_{t,j}^2)\frac{(\Delta R)_{ij}^2}{R^2};$$

$$d_{iB} = k_{t,i}^2$$

$$(\Delta R)_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

y: rapidity (= 1/2 ln [(E+pz) / (E-pz)])

ϕ: azimuthal angle

calculate for all (pseudo-) particle pairs - combine the two with the smallest d_{ij} to a new pseudo-particle; repeat, if d_{iB} (“beam distance”) is smallest define i as a jet, remove from list; continue until all particles are included in jets

R is a “resolution parameter” up to which objects can be separated, drives behavior of algorithm

Defining Jets

- The solution: Iteratively combine particles to jets based on a distance criterion based on (transverse) momentum and geometrical separation

The anti- k_T algorithm (most common at LHC today)

$$d_{ij} = \min(k_{t,i}^{-2}, k_{t,j}^{-2}) \frac{(\Delta R)_{ij}^2}{R^2}$$

$$d_{iB} = k_{t,i}^{-2}$$

$$(\Delta R)_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

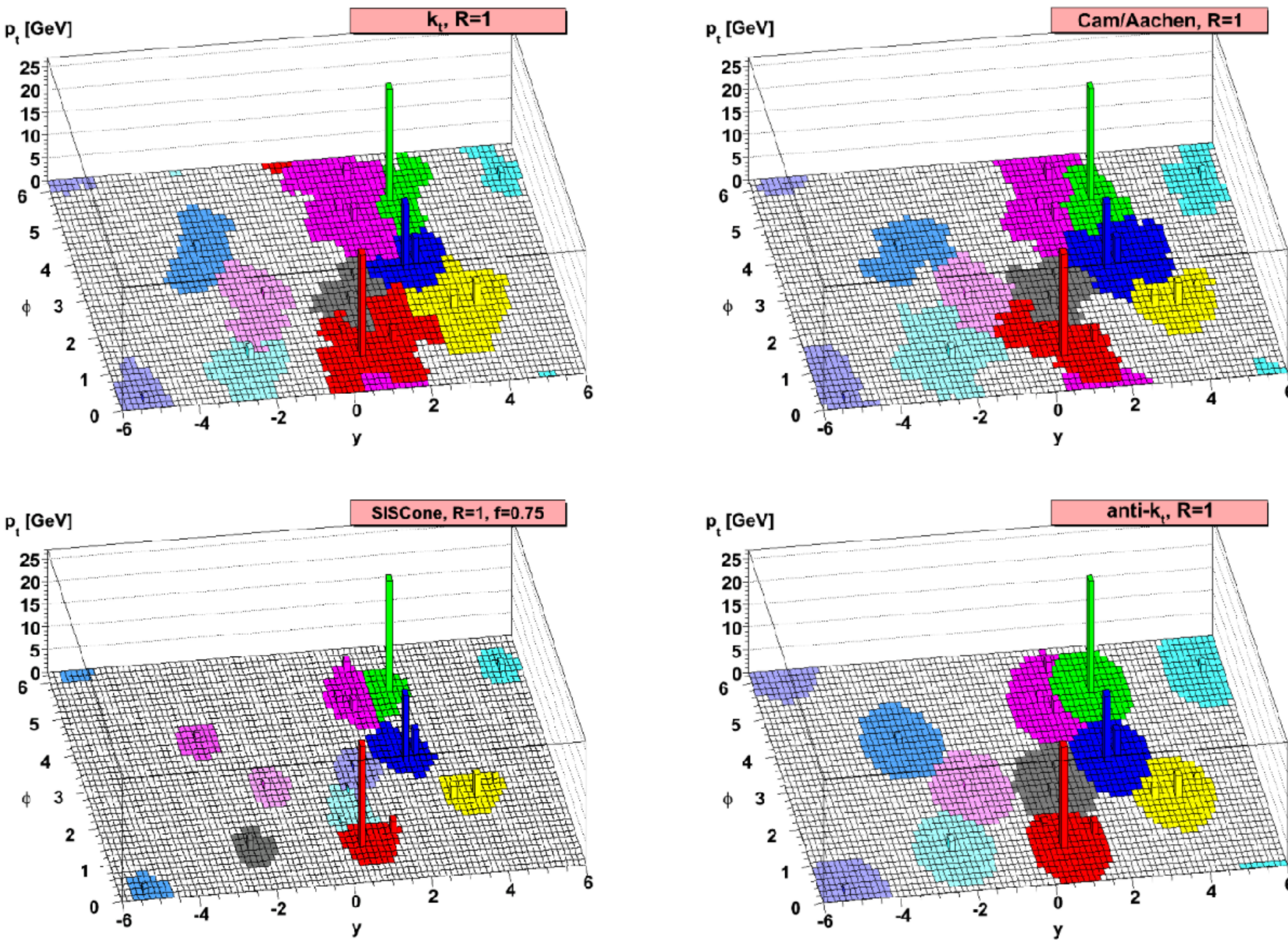
y: rapidity (= 1/2 ln [(E+pz) / (E-pz)])
ϕ: azimuthal angle

Same procedure as k_T algorithm.

The difference: The anti-k_T algorithm starts from the highest-energy particles (large k_T), while k_T starts at low energy: Impact on the shape of jets - both are collinear and infrared safe, and thus good for theory

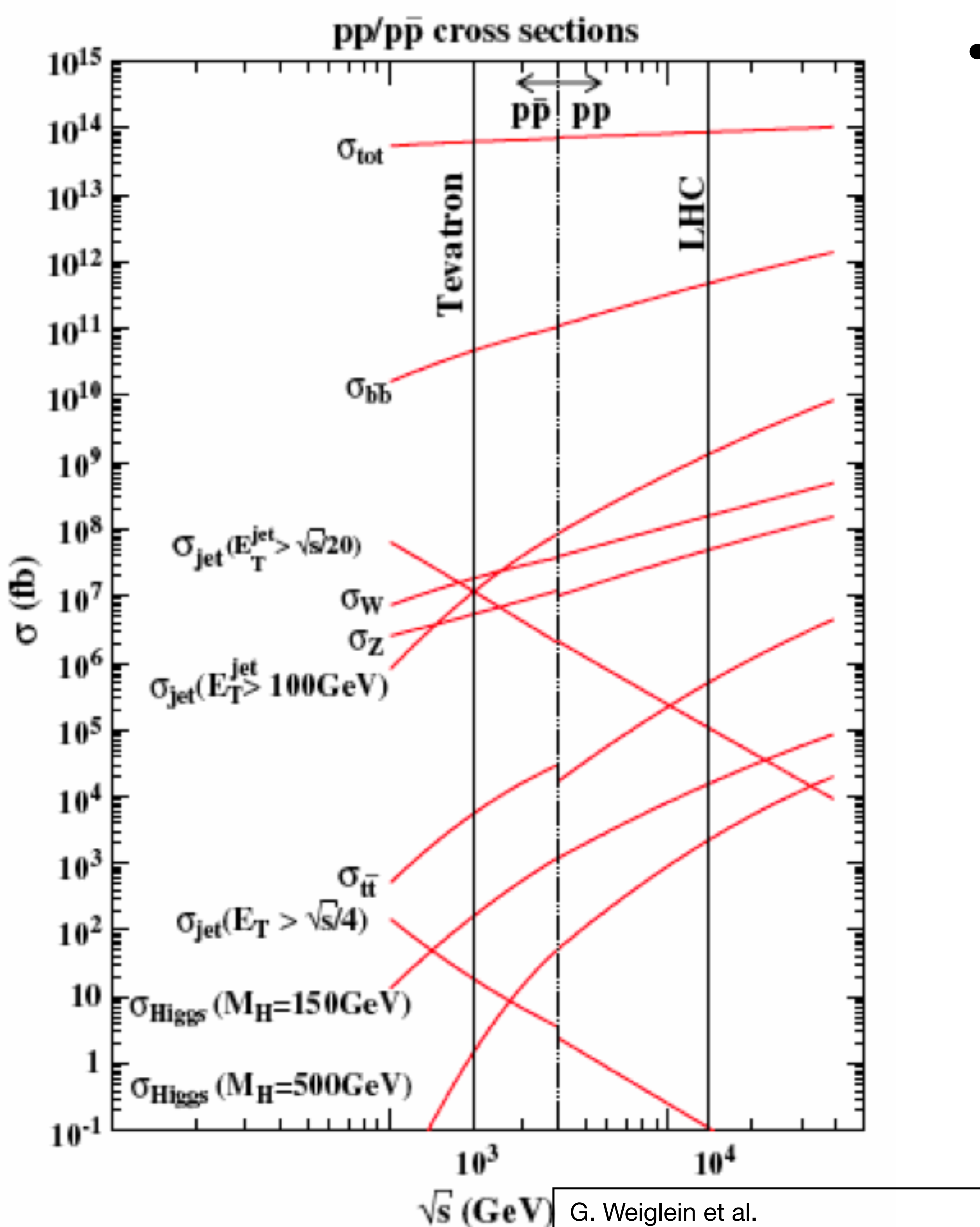
Typical R values at LHC: 0.4 - 0.7

Jet Algorithms and Clustering Behavior



using only energy and angle between particles

Additional Complications: Pileup



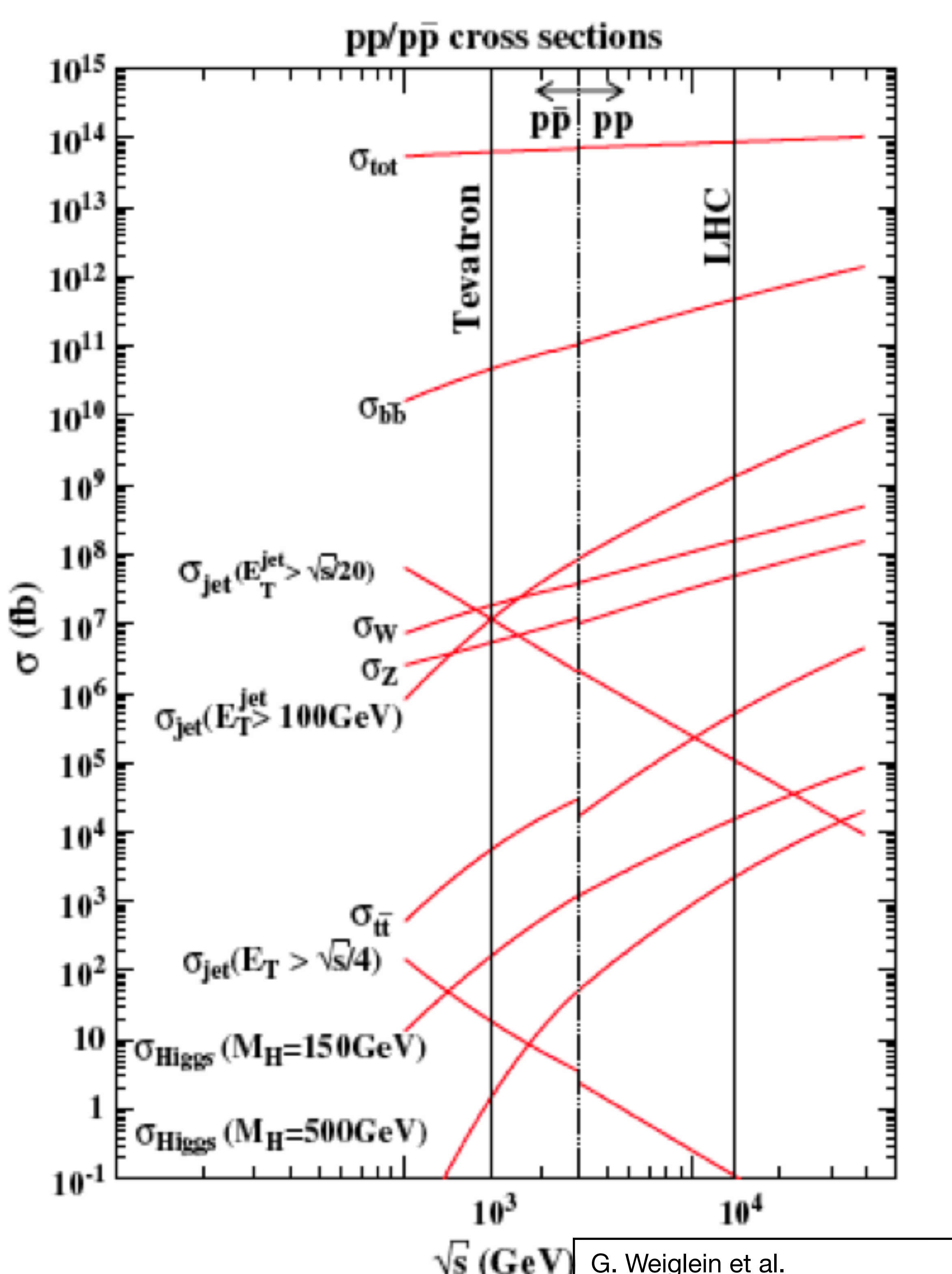
G. Weiglein et al.
Physics Reports 426 (2006) 47–358

- The total p+p cross section is relatively large: High probability for interaction
- Interesting processes are rare compared to the overall cross section:

$$\sigma(t\bar{t})/\sigma_{tot} \sim 10^{-8}$$

$$\sigma(H, M_H = 150\,\mathrm{GeV})/\sigma_{tot} \sim 10^{-10}$$

Additional Complications: Pileup



G. Weiglein et al.
Physics Reports 426 (2006) 47–358

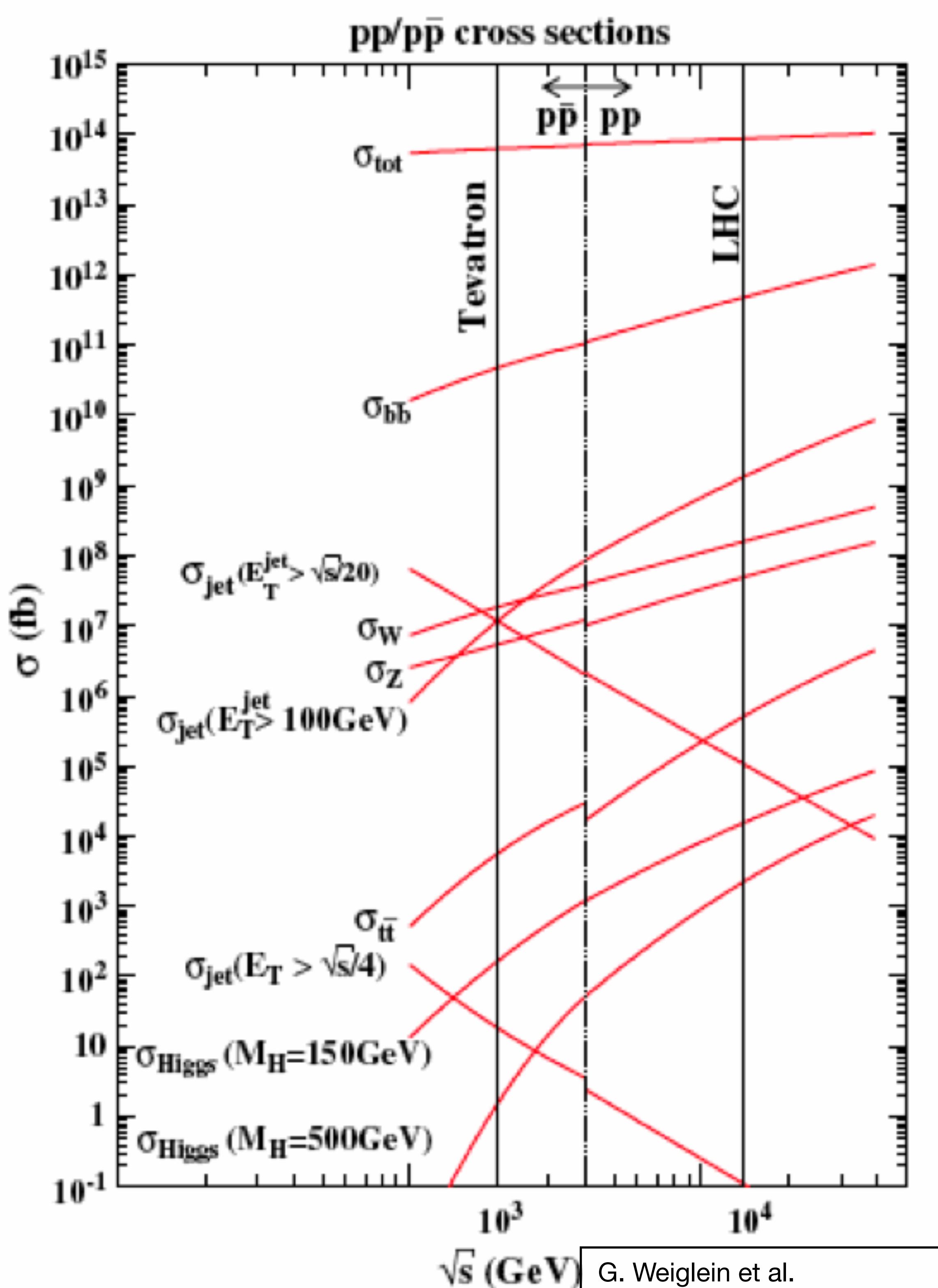
- The total p+p cross section is relatively large: High probability for interaction
- Interesting processes are rare compared to the overall cross section:

$$\sigma(t\bar{t})/\sigma_{tot} \sim 10^{-8}$$

$$\sigma(H, M_H = 150\,\text{GeV})/\sigma_{tot} \sim 10^{-10}$$

▸ Very high event rates required!

Additional Complications: Pileup



G. Weiglein et al.
Physics Reports 426 (2006) 47–358

- The total p+p cross section is relatively large: High probability for interaction
- Interesting processes are rare compared to the overall cross section:

$$\sigma(t\bar{t})/\sigma_{tot} \sim 10^{-8}$$

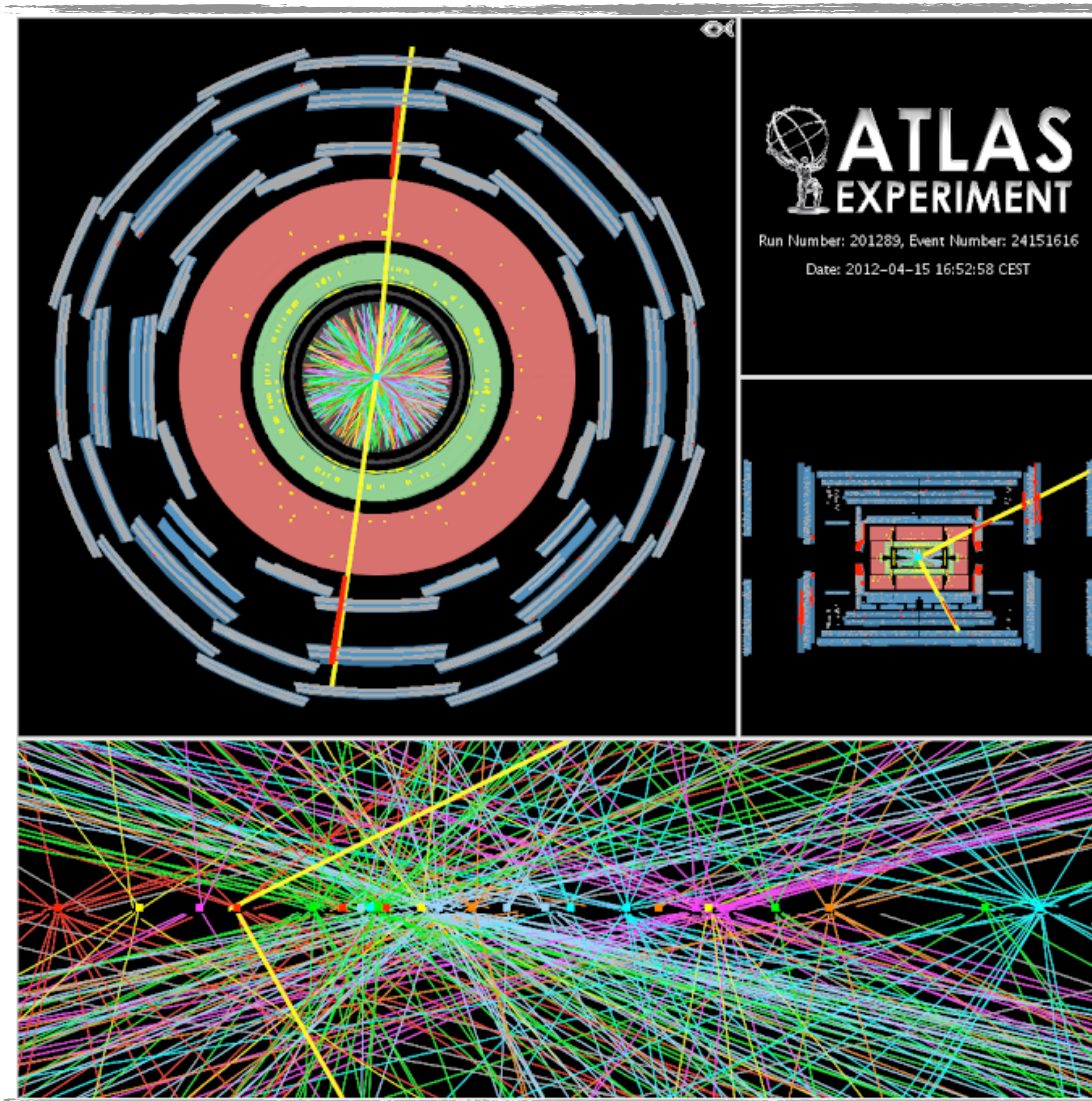
$$\sigma(H, M_H = 150\,\mathrm{GeV})/\sigma_{tot} \sim 10^{-10}$$

▸ Very high event rates required!

LHC luminosity: ~ 2 x 10^{34} $cm^{-2}s^{-1}$
total cross section: ~ 100 mb = 10^{-25} cm^2

Interaction rate: ~ 2 GHz, with collisions every 25 ns: ~ 50 reactions per bunch crossing => “pile up”

Pile-up at LHC



Z -> μμ

... and 25 other collisions

(from 2012 at 8 TeV, today ~ x 2 !)

An interesting problem for jet finding, data analysis and detectors…

Summary

- Proton-proton collisions are described by a sequence of processes at different scales:
  - The proton structure described by PDFs
  - The hard process given by the matrix element
  - The hadronization described by fragmentation functions / by models
  - + additional particles and corrections from the strong interaction
- The factorization theorem of QCD allows a splitting of the description of these processes into clearly defined parts, which can be considered more or less independently
- Jets are the typical final states at LHC: theoretically associated with final-state quarks and gluons - definition of jets requires care to be theoretically "safe"

Summary

- Proton-proton collisions are described by a sequence of processes at different scales:
  - The proton structure described by PDFs
  - The hard process given by the matrix element
  - The hadronization described by fragmentation functions / by models
  - + additional particles and corrections from the strong interaction
- The factorization theorem of QCD allows a splitting of the description of these processes into clearly defined parts, which can be considered more or less independently
- Jets are the typical final states at LHC: theoretically associated with final-state quarks and gluons - definition of jets requires care to be theoretically "safe"

Next Lecture: The Higgs Boson, F. Simon 11.11.2019

Lecture Overview

14.10.	Introduction, Particle Physics Refresher	*F. Simon*
21.10.	Introduction to Cosmology I	*B. Majorovits*
28.10.	Introduction to Cosmology II	*B. Majorovits*
04.11.	Particle Collisions at High Energy	*F. Simon*
11.11.	The Higgs Boson	*F. Simon*
18.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
25.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
02.12.	Particle Colliders	*F. Simon*
09.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
16.12.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
	Christmas Break	
13.01.	Detectors for Particle Colliders	*F. Simon*
20.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
27.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
03.02.	Physics beyond the Standard Model in the Early Universe	*B. Majorovits*