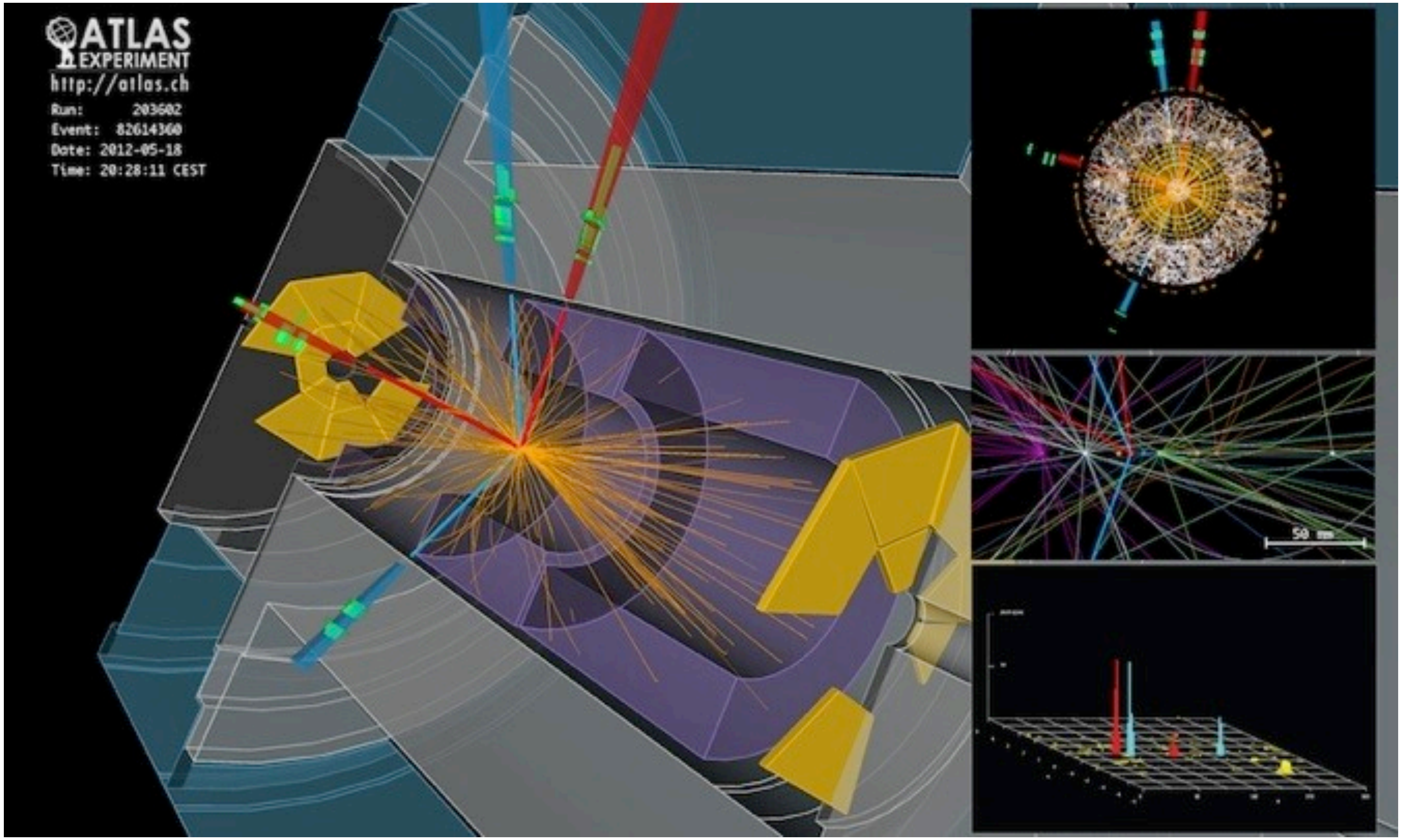
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



7. Event Generators & Detector Simulation

25.11.2013

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

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Overview

- Data analysis at large collider experiments

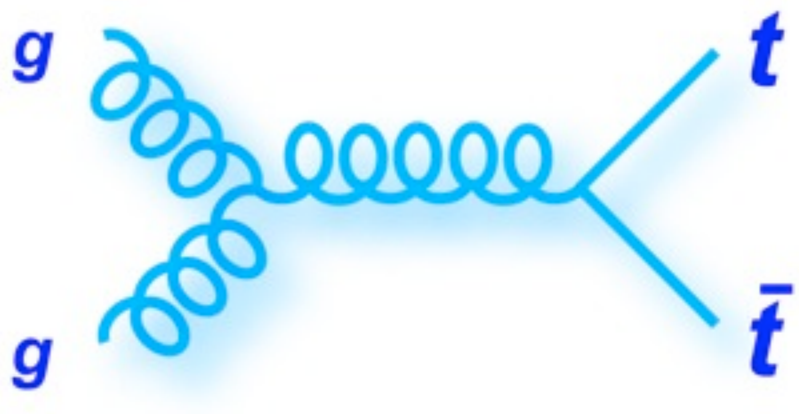
- The anatomy of hadron collisions: Event Generators
  - Overview
  - Parton distributions
  - Hard processes, parton showers
  - Hadronization

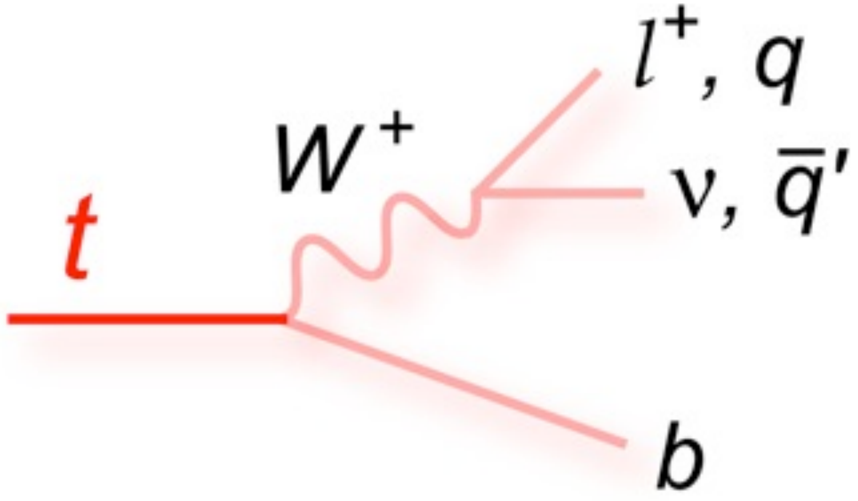
- Simulation of events in the detector
  - Simulation of particles traversing matter
    - The biggest challenge: Calorimeters
  - Detector response

Data Analysis in Big Experiments

The Problem

- Theory:





The Problem

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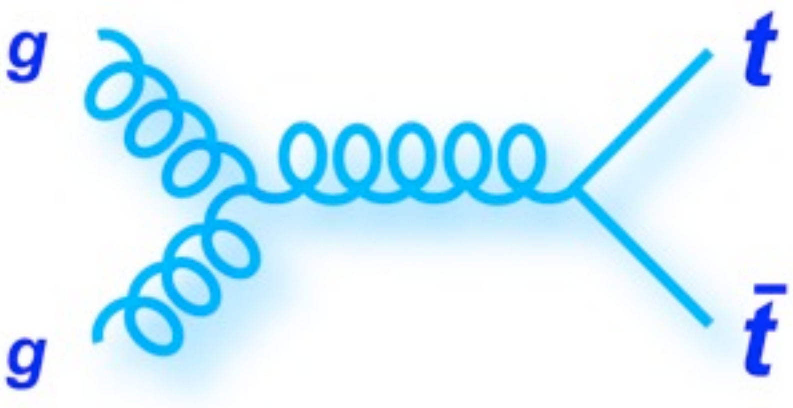
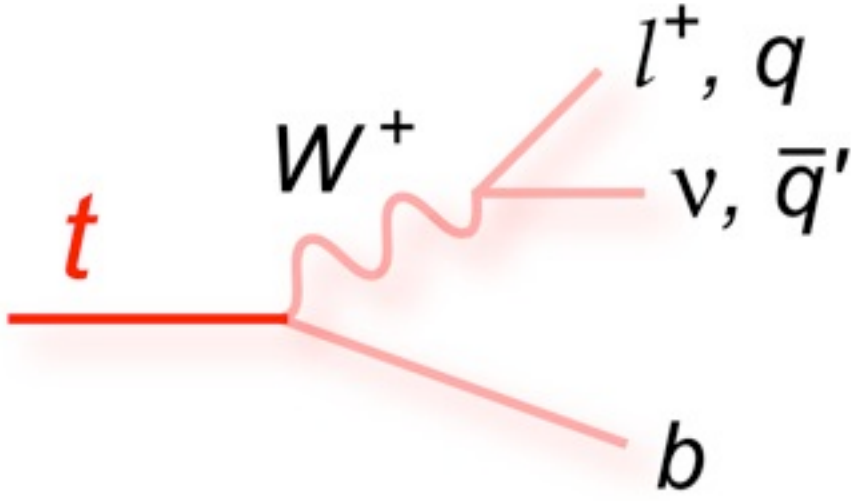
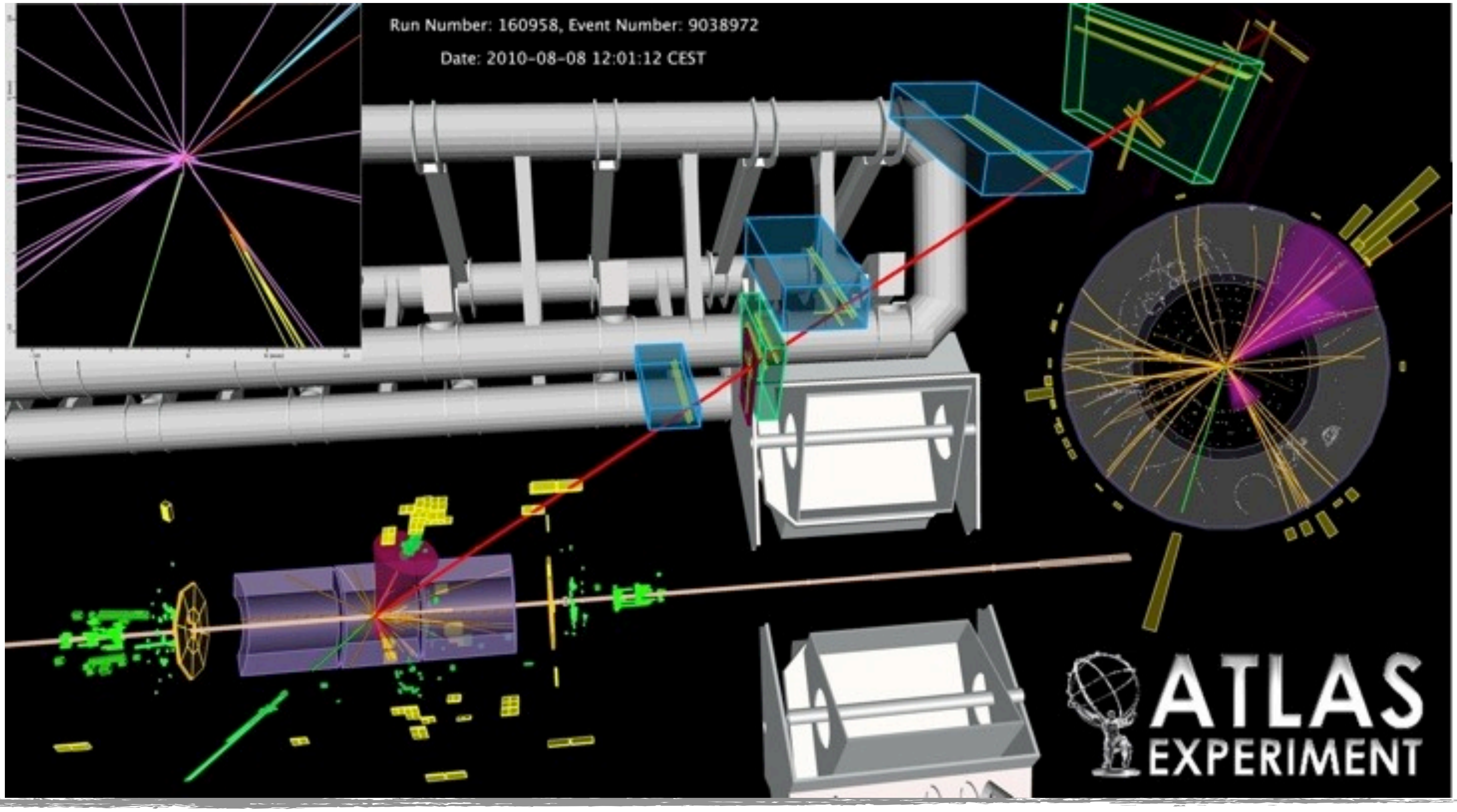
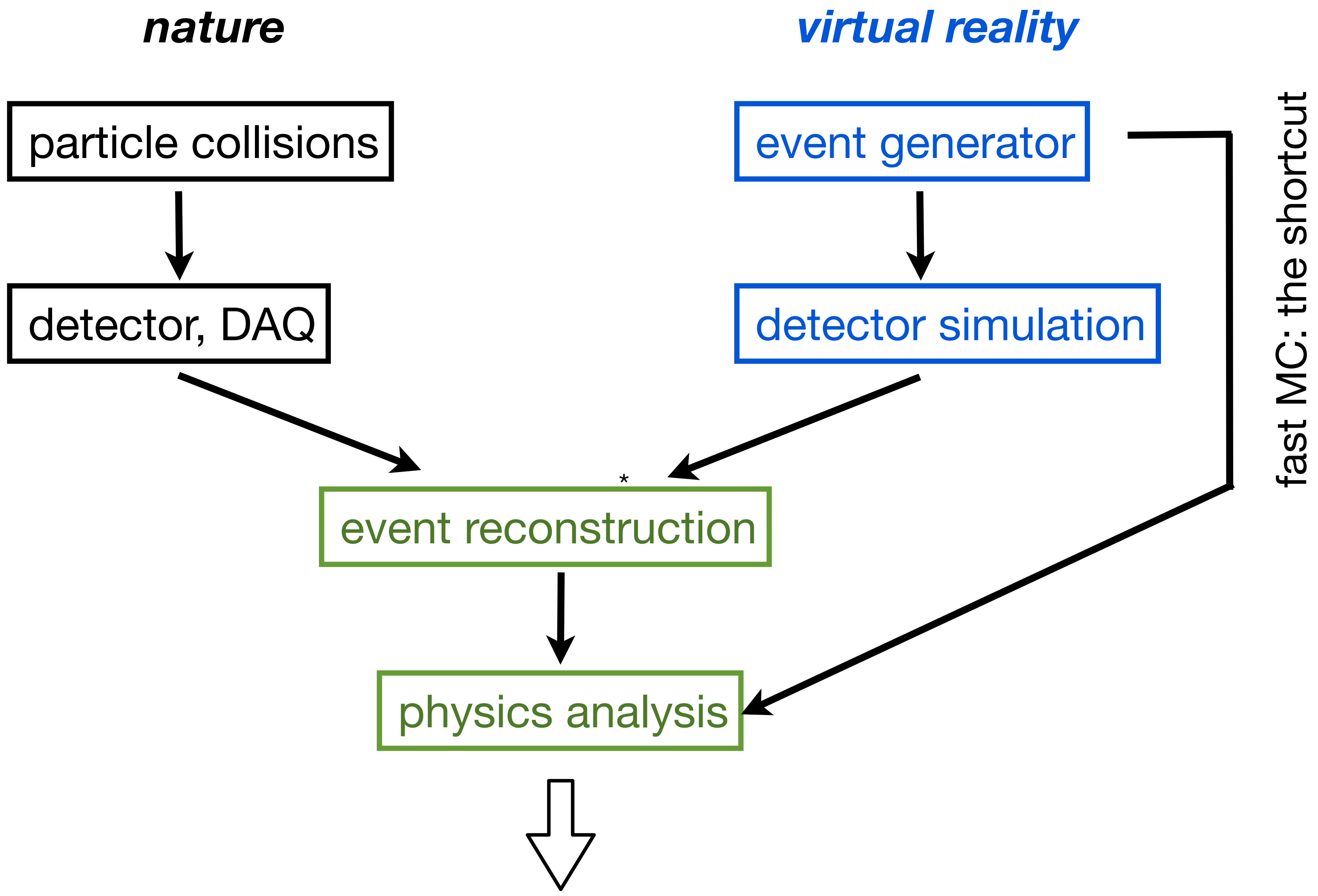




- Experiment:



The “Food Chain”



nature

virtual reality

particle collisions

detector, DAQ

event generator

detector simulation

fast MC: the shortcut

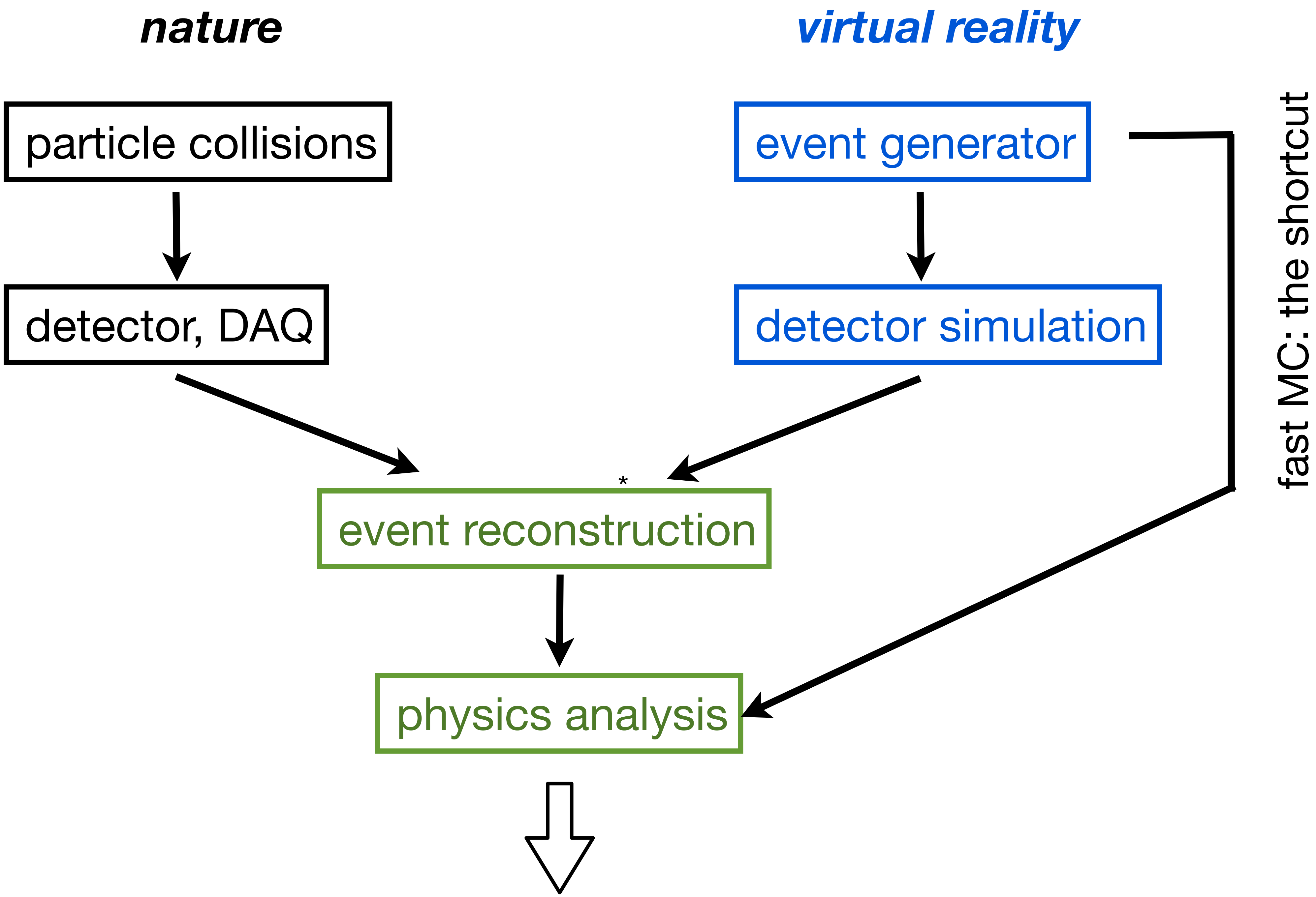
*

event reconstruction

physics analysis

Insight, publications, presentations, Nobel prizes*...

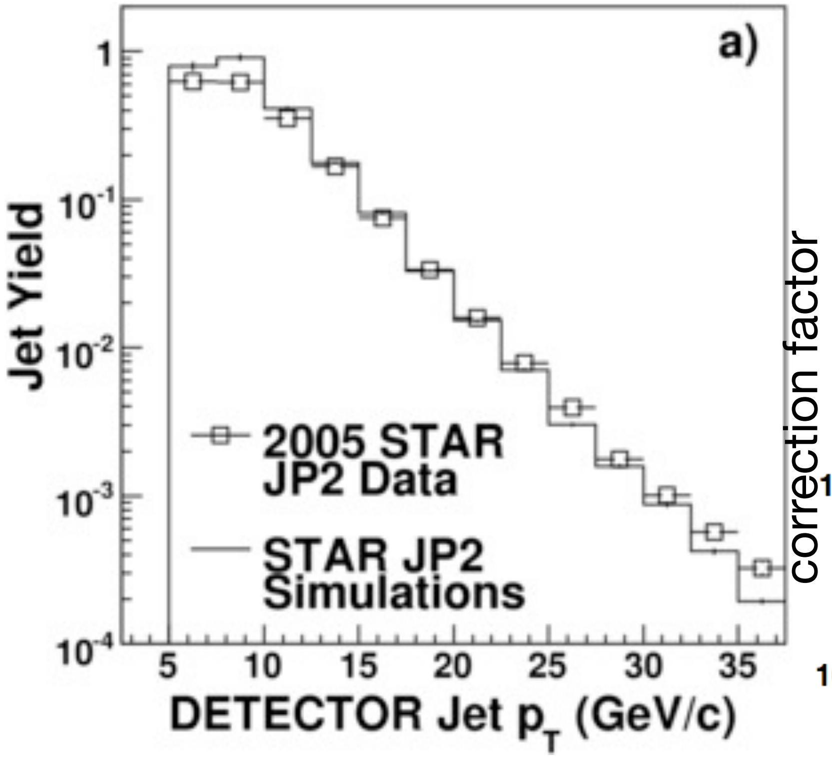
The "Food Chain"



Insight, publications, presentations, Nobel prizes*...

[*] only steps 1 - 3 are guaranteed

The Importance of Simulations & Generators I



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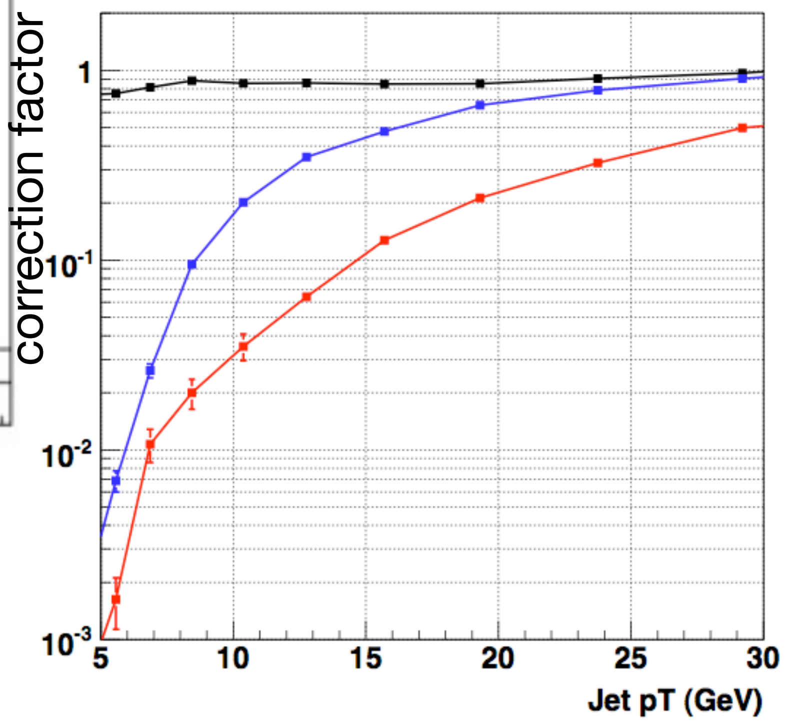

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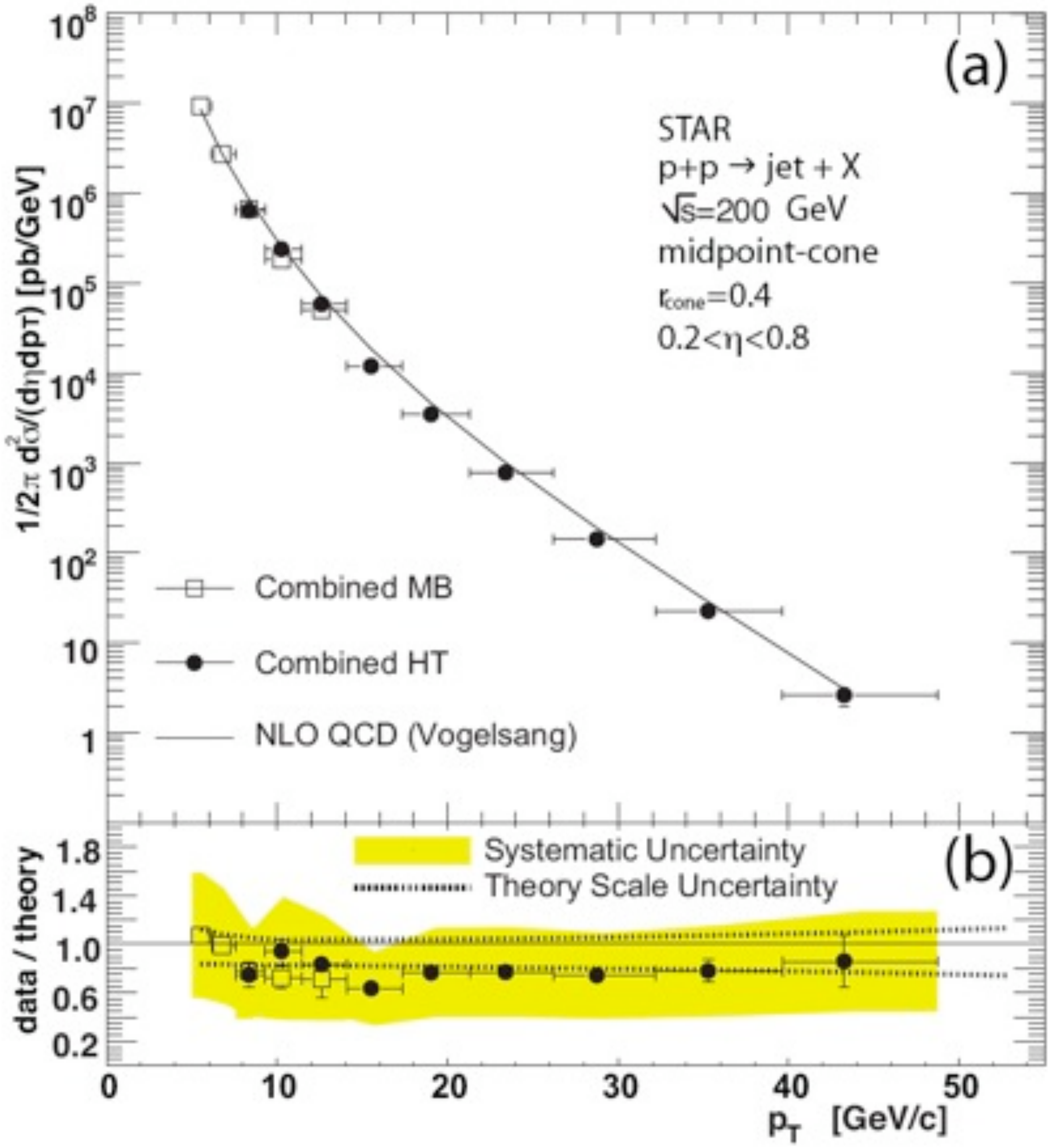
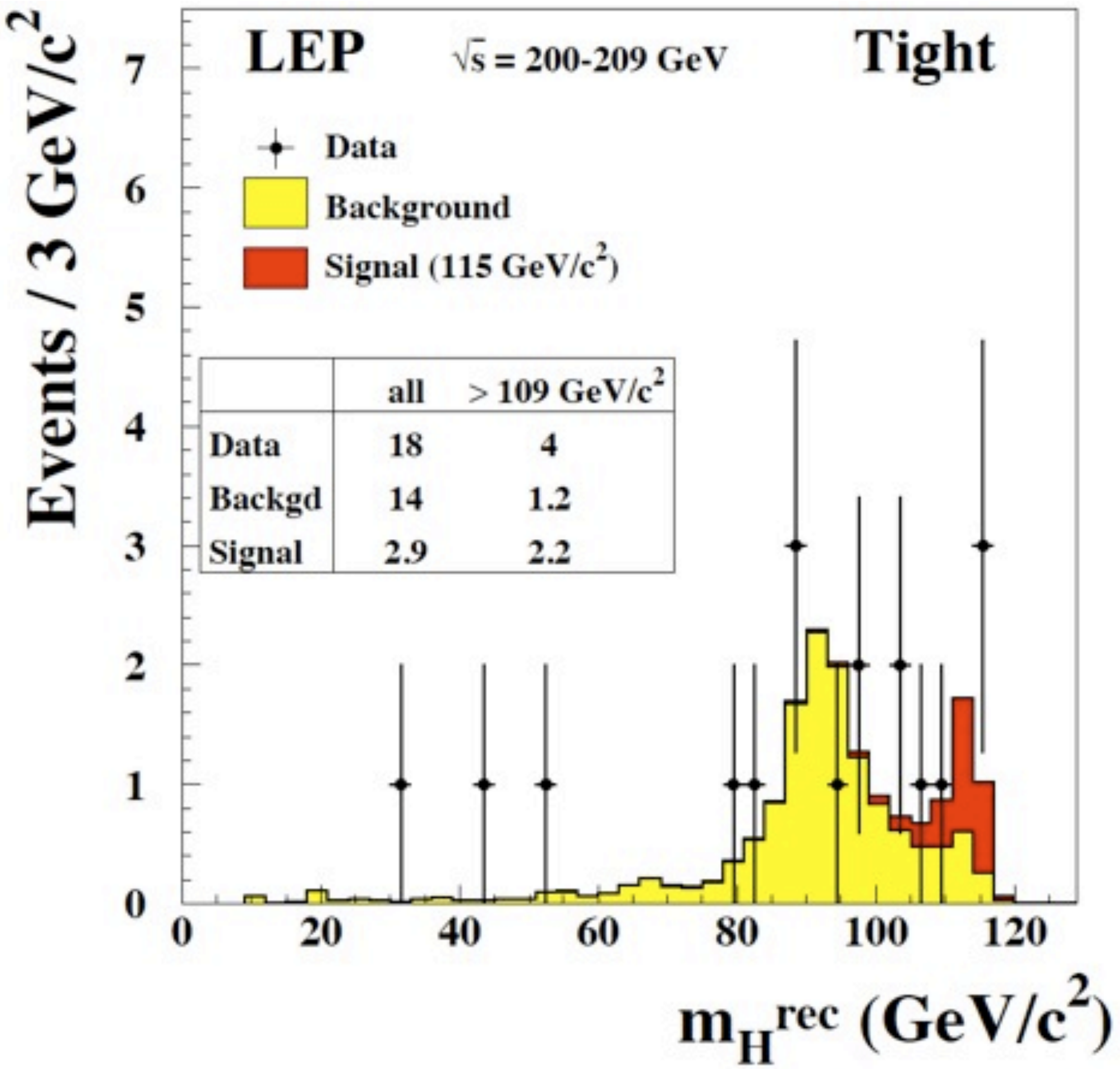


- Determination of correction factors: Requires excellent understanding of detector response
    - A realistic modelling is usually impossible without simulations!

The Importance of Simulations & Generators II

- Precise description of known processes mandatory to enable the discovery of new phenomena (or not...):
  - Example: Higgs searches at LEP



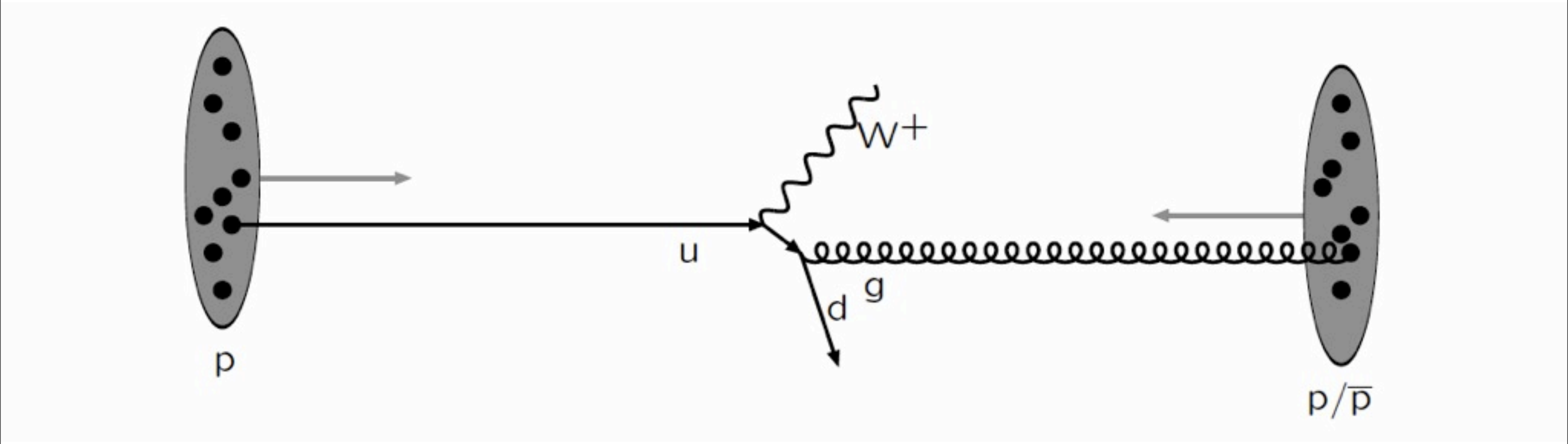
	all	> 109 GeV/c^2
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

The Anatomy of Hadron Collisions
-
Event-Generators

The Schematic Sequence of a p+p Collision

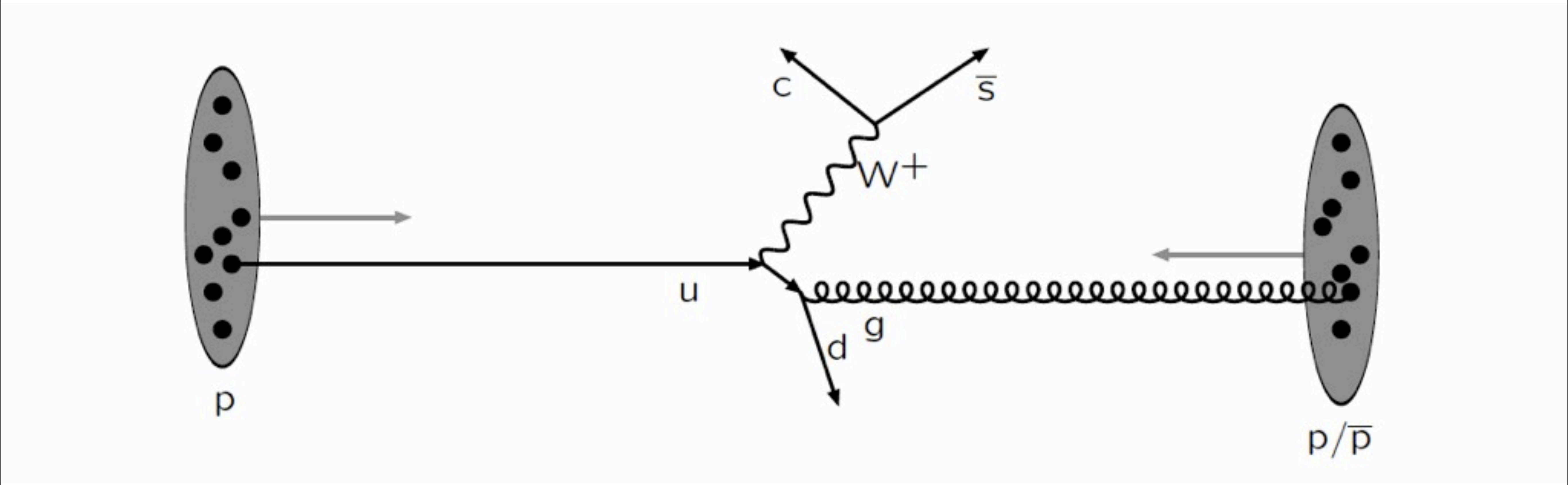
- Beam particles: Substructure described by parton distribution funktions (PDFs)

The Schematic Sequence of a p+p Collision



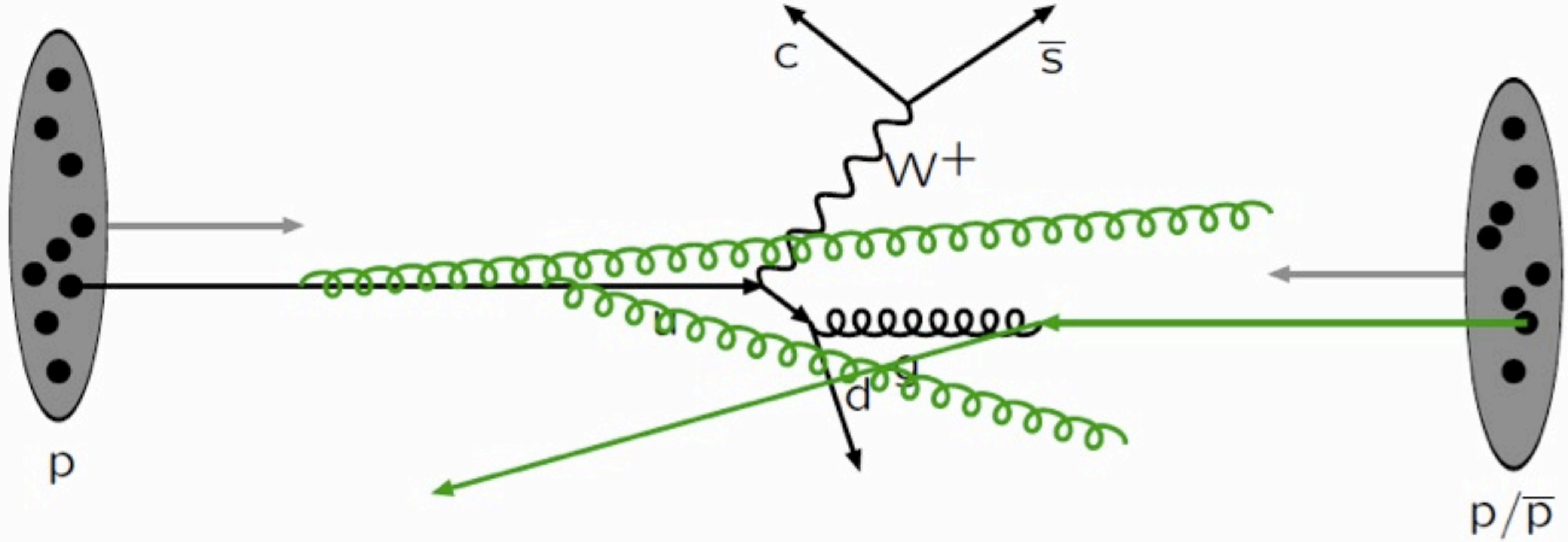
- Hard interaction: Described by the matrix element - This is what we usually draw as Feynman graphs

The Schematic Sequence of a p+p Collision



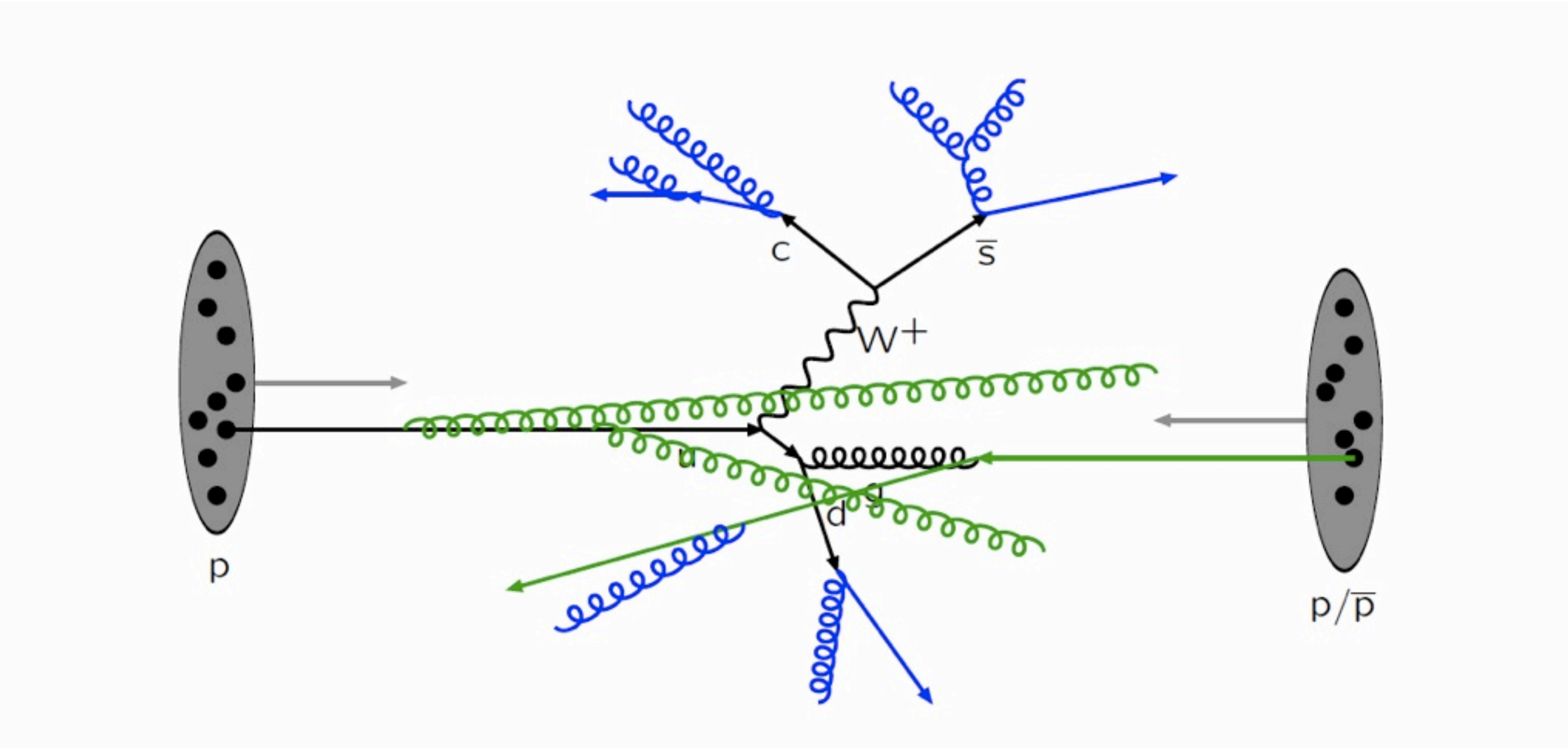
- Decay of short-lived particles connected to the hard interaction

The Schematic Sequence of a p+p Collision



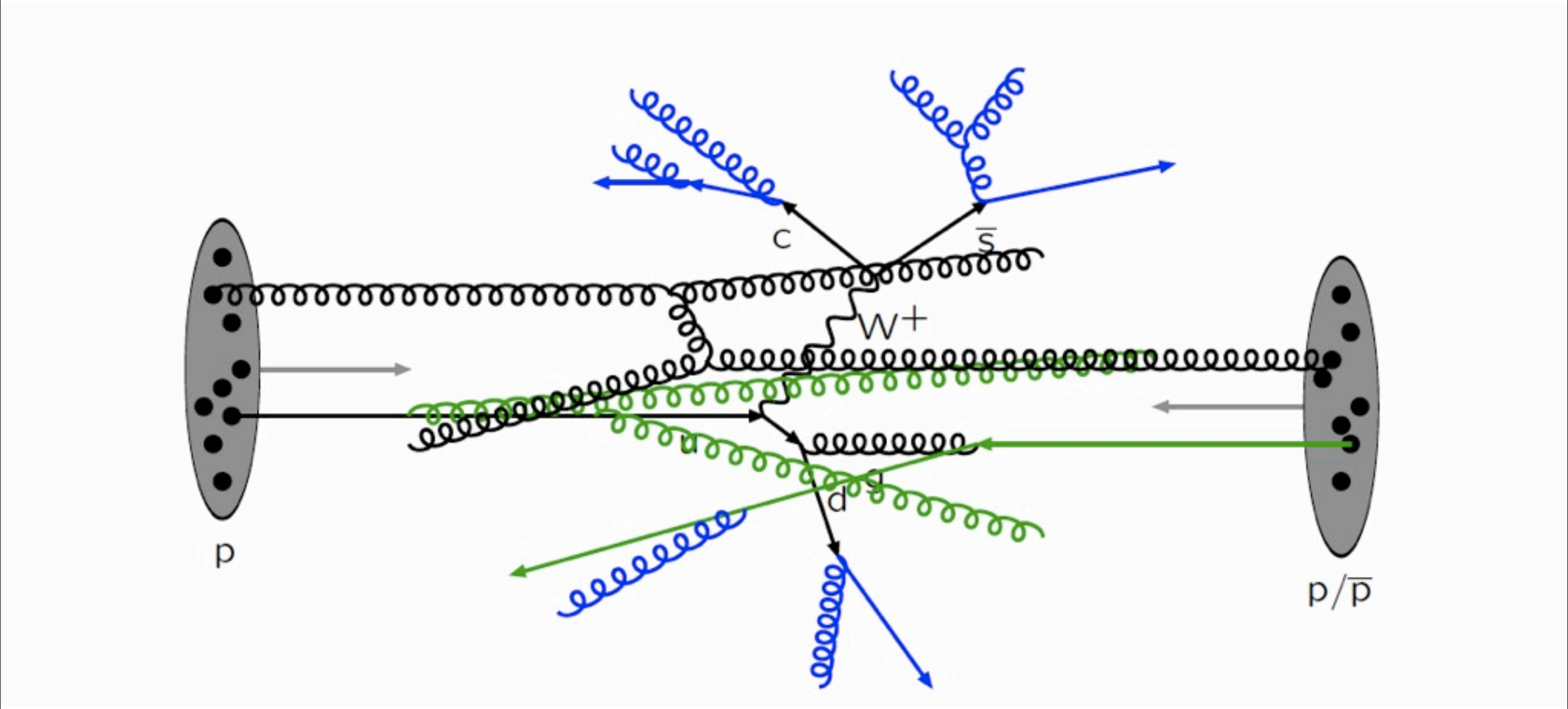
- Initial-State Radiation: Parton showers

The Schematic Sequence of a p+p Collision



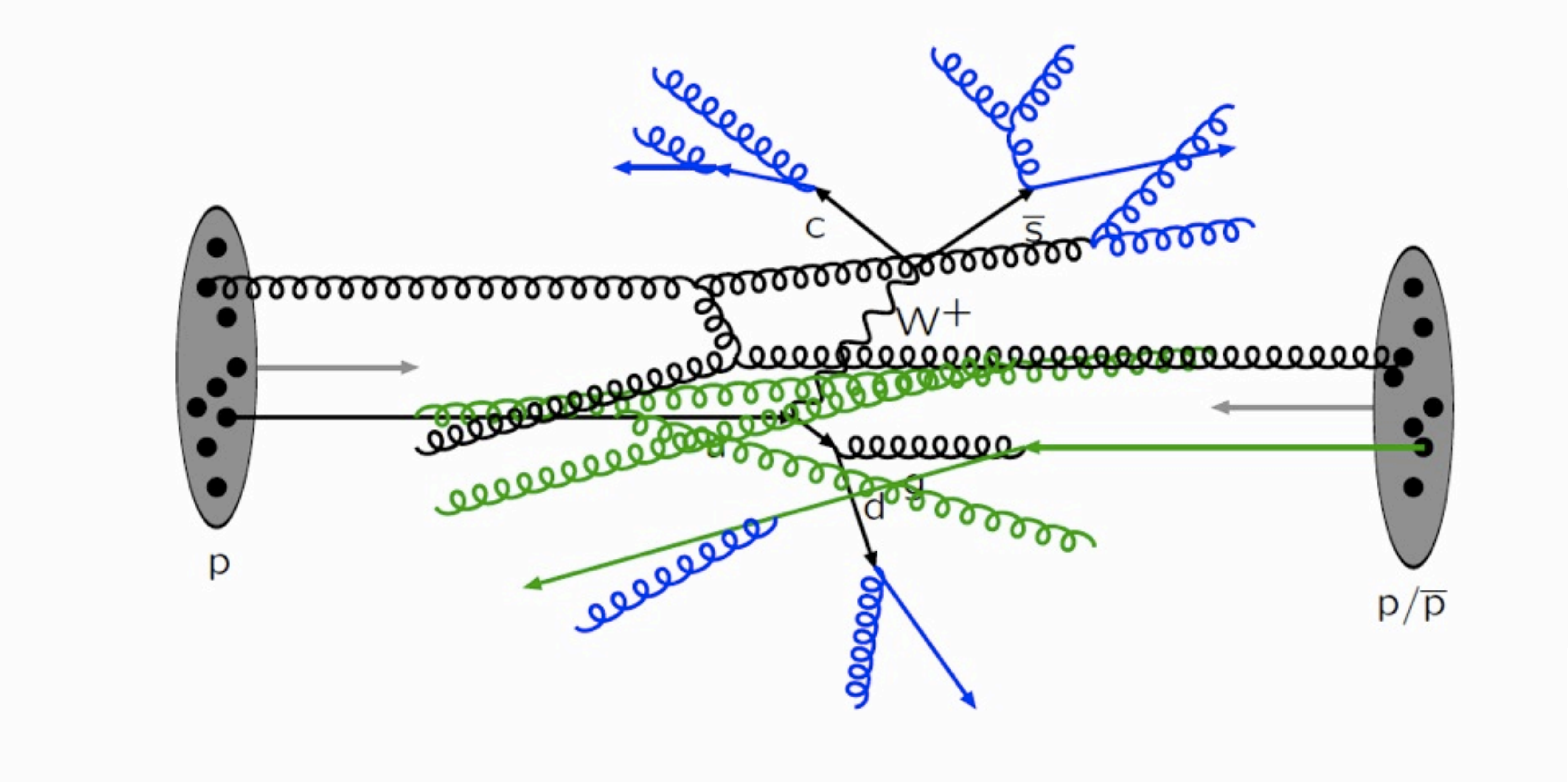
- Final-State Radiation: Parton showers

The Schematic Sequence of a p+p Collision



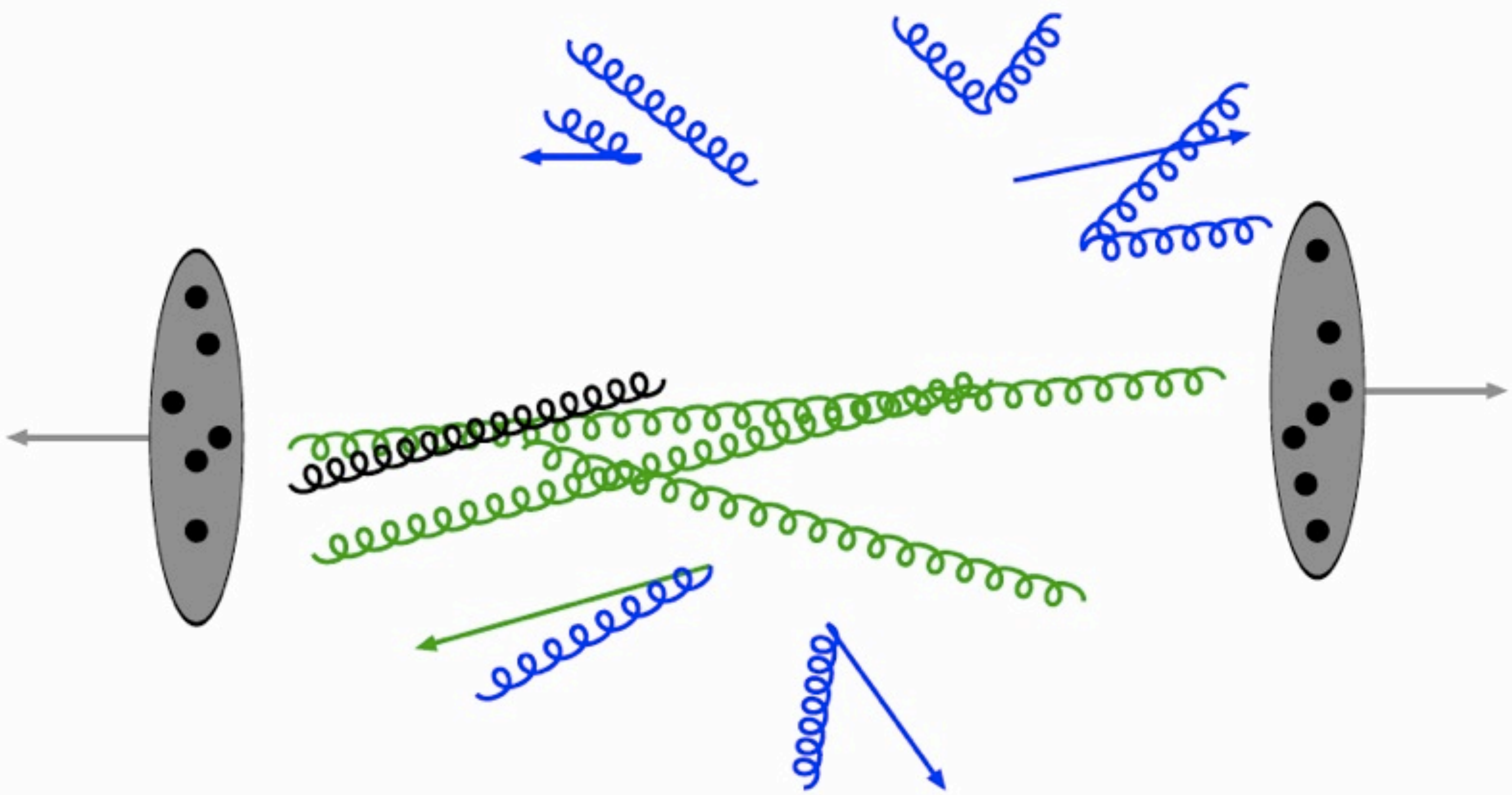
- “Underlying Event”: Lower-energy processes of the other constituents of the beam particles

The Schematic Sequence of a p+p Collision



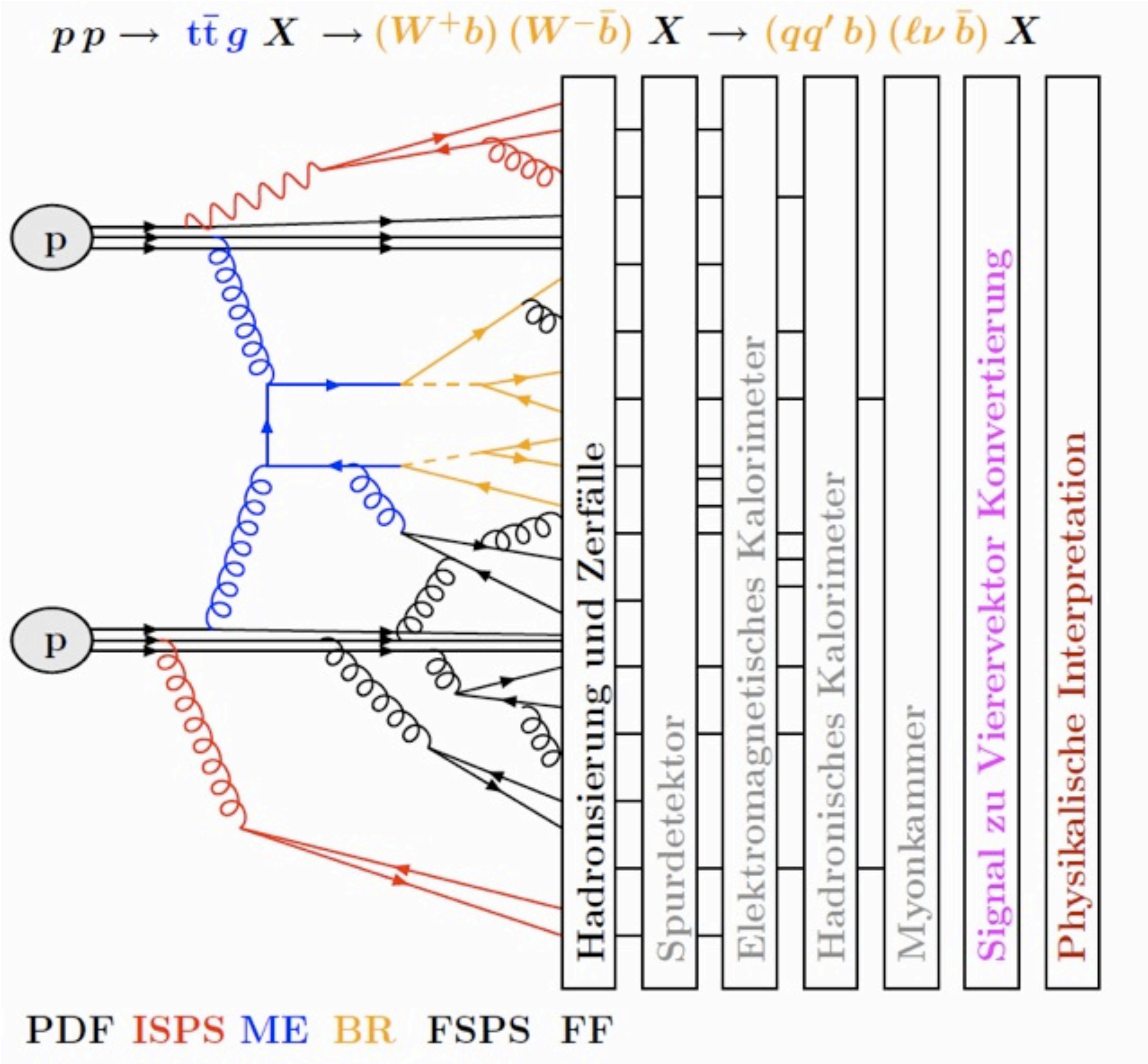
- ... and the corresponding initial and final state radiation

The Schematic Sequence of a p+p Collision



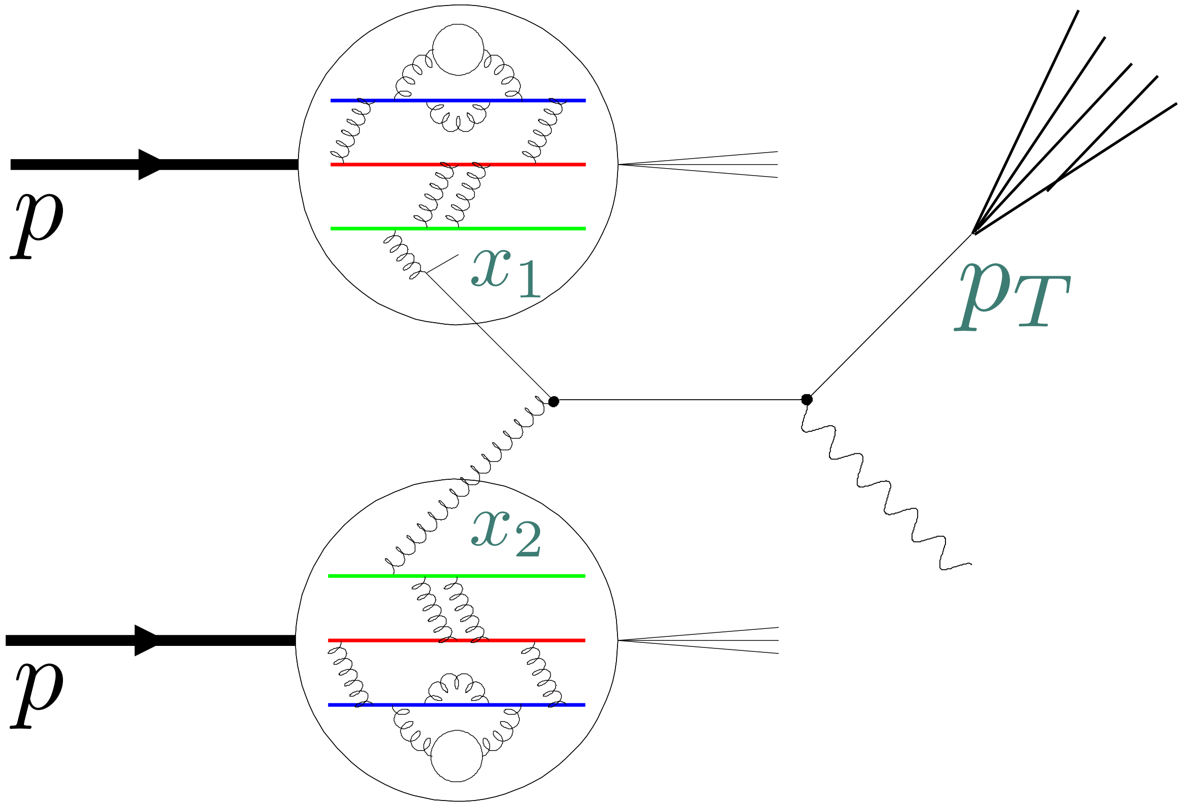
- Beam remnants and outgoing partons
- Confinement requires the formation of color-neutral objects: Hadronization
- Short-lived states decay, the other particles reach the detector

The Full Chain



- Parton distribution-functions
- Initial state parton showers, splitting functions, ...
- Matrix elements, higher order corrections
- Decay rates, quark mixing
- final state parton showers
- Hadronization, fragmentation functions
- Detector geometry and properties, interaction with matter,...

The Basics: The Factorization Theorem



Final state X

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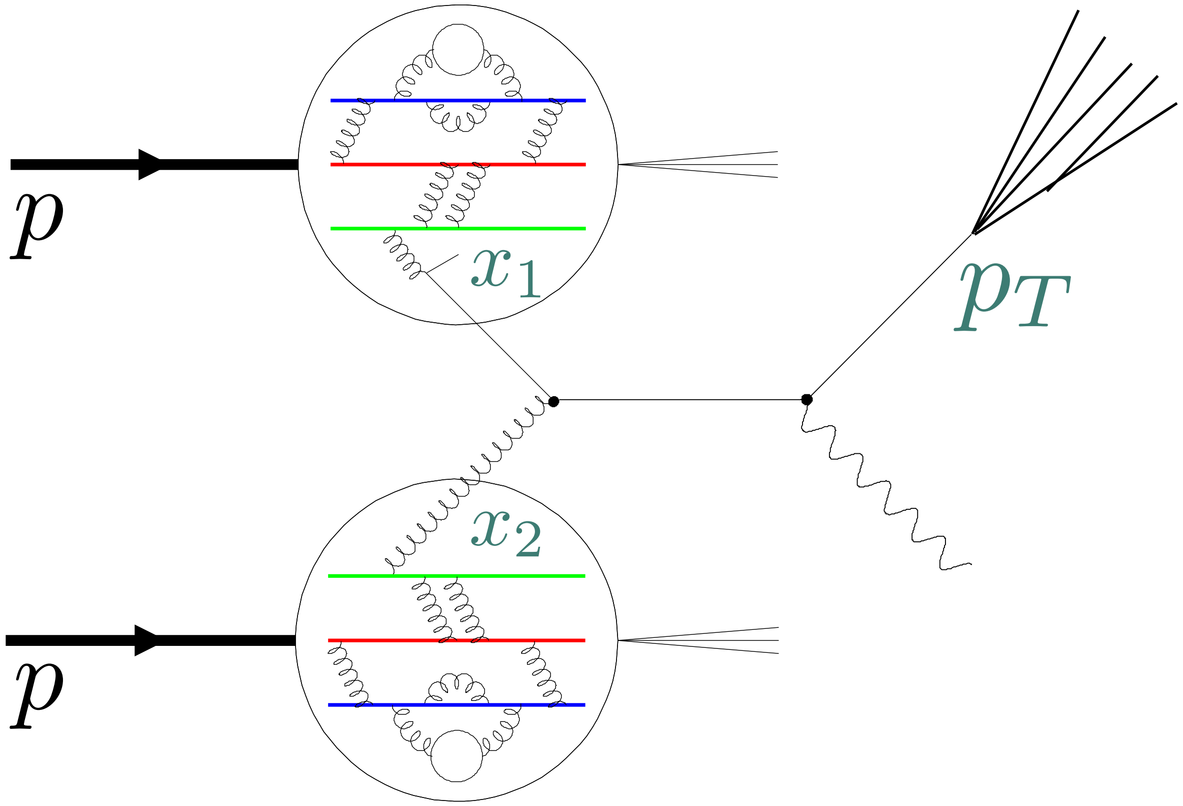


Final state X

- 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:

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

PDF

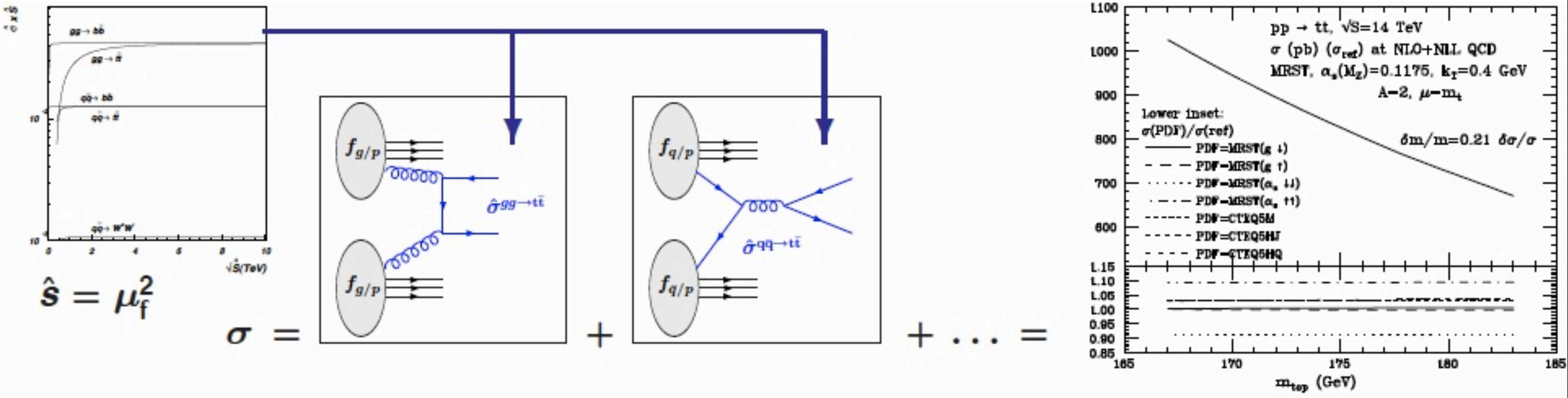
matrix element

fragmentation function

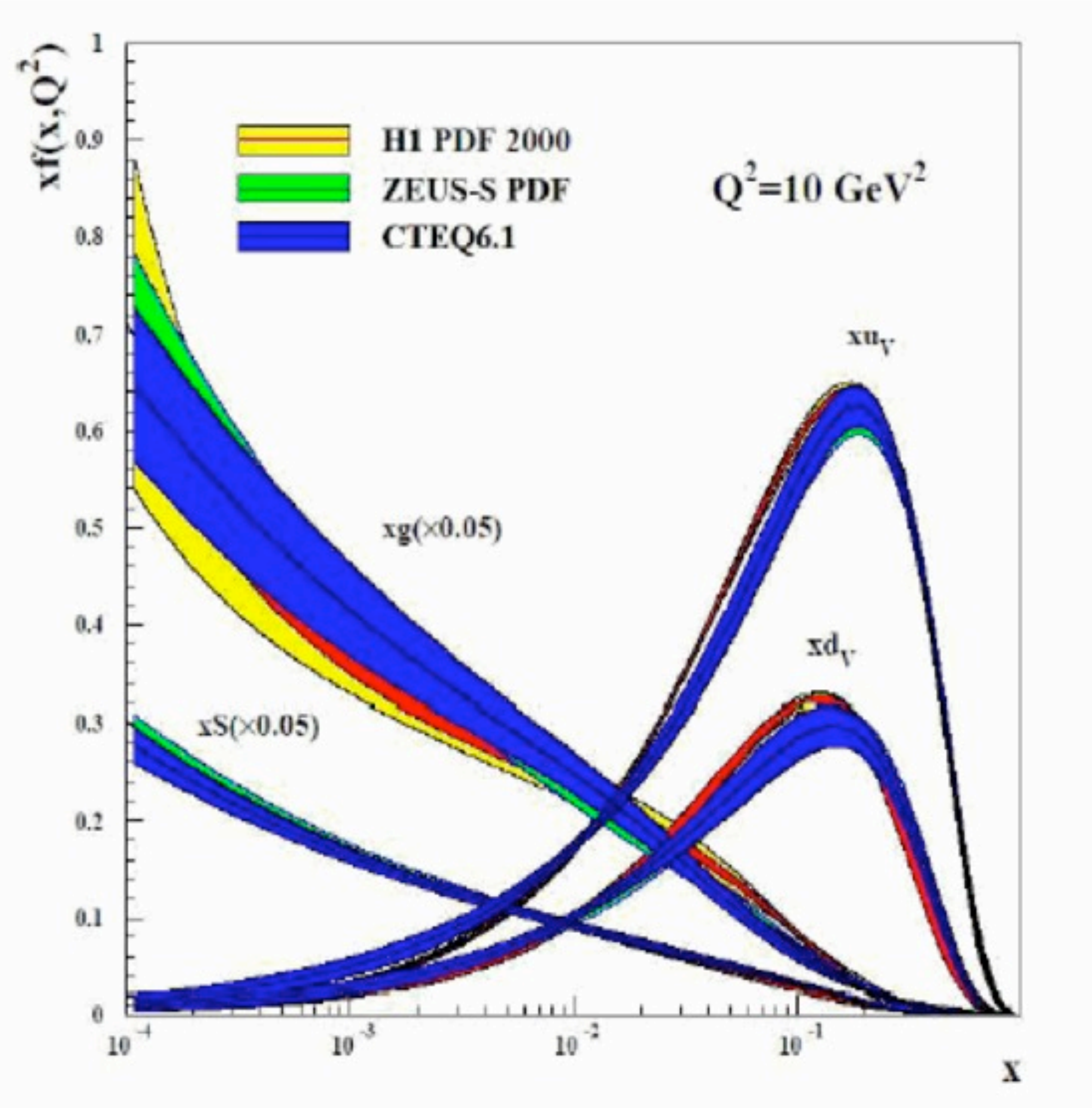
Factorization II

- 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



Parton Distribution Functions I

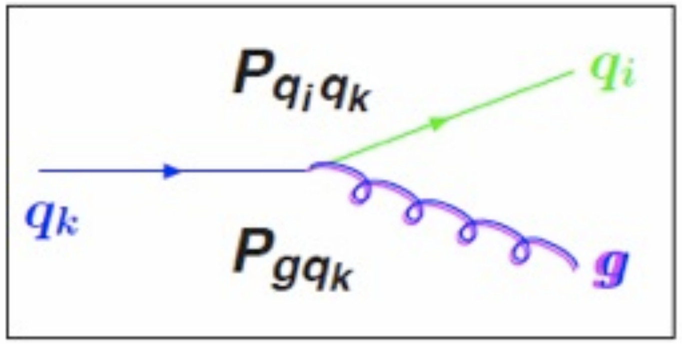


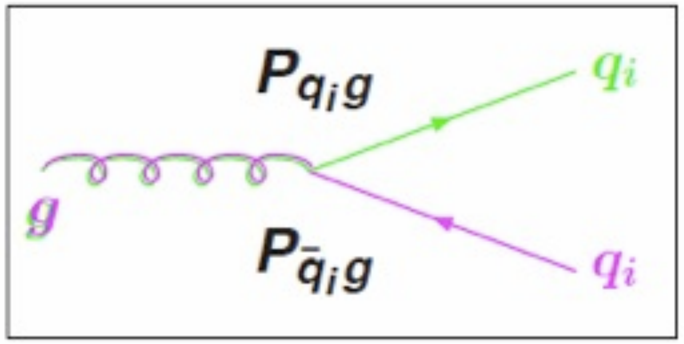
- Distribution of partons (here: valence quarks, sea quarks, gluons) in the proton as a function of x
  - x is the fraction of the total momentum of the proton carried by the parton
- Meausred in e+p collisions at HERA
- Parton distributions are universal: The distributions measured via e+p scattering are also applicable to p+p collisions

Parton Distribution Functions II

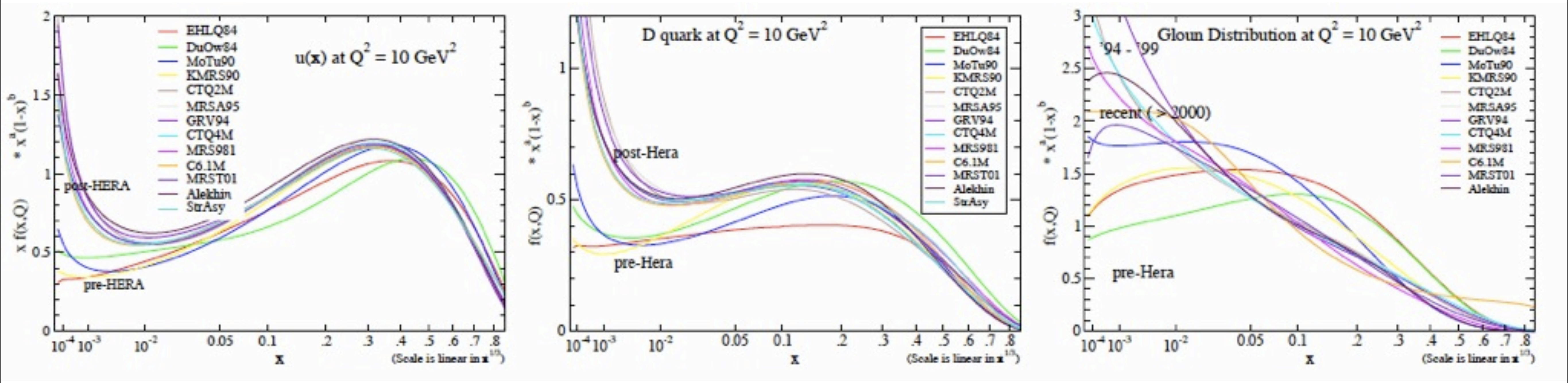
- The PDFs depend on the scale at which they are evaluated
  - QCD provides a description of the scale evolution of the PDFs: If they are known at one scale, they can be calculated for other scales as well
  - But: Only the evolution can be calculated, not the distributions themselves (e.g., not the 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*

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





Problems: PDFs at Extreme Kinematics



- Extrapolation to small x is guesswork: Up to now the estimates have always turned out to be wrong!
    - PDFs at small x are important for many process at LHC

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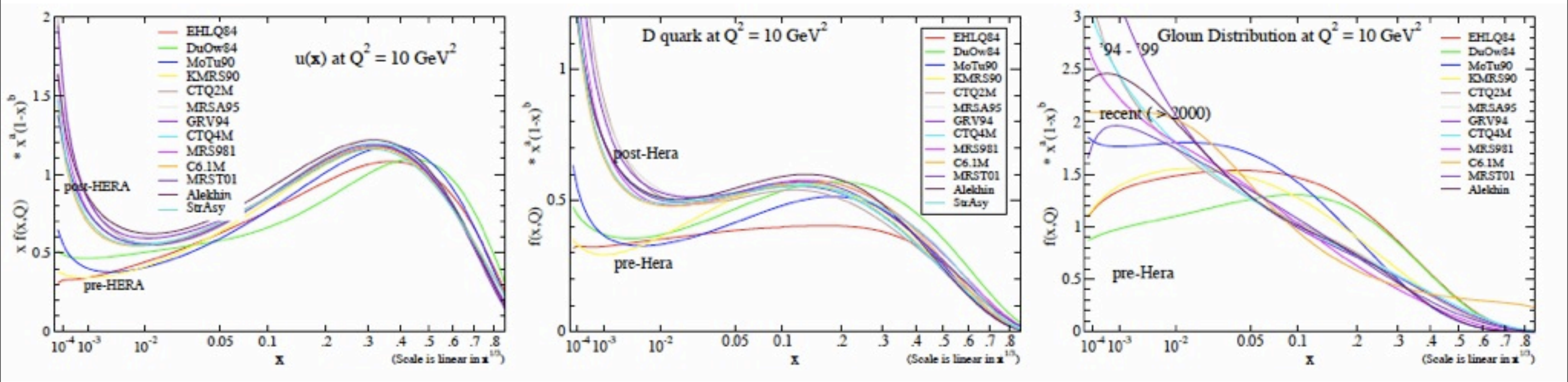

- Extrapolation to small x is guesswork: Up to now the estimates have always turned out to be wrong!
  - PDFs at small x are important for many process at LHC
- For the production of heavy particles the knowledge of the PDFs is quite good:
  - Example: Top-Quark - In the center-of-mass frame of the parton-parton collision 2 m_t have to be available

$$E_{cm} = \sqrt{s} = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2} = \sqrt{m_1^2 + m_2^2 + 2E_1 E_2 (1 - \beta_1 \beta_2 \, cos\theta)}$$

$$\Rightarrow \; 2\, m_t \; \approx \; \sqrt{4\, x_1\, x_2 E_{LHC}^2} \; \Rightarrow \; x_1\, x_2 \; = \; \frac{m_t^2}{E_{LHC}^2} \; \approx \; 6 \times 10^{-4}$$

[x ~ 2.5 x 10^{-2}]

Parton Showers

- The cross section of a process is given by the matrix element and the PDFs
- For hard radiation ME at O(α_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)...

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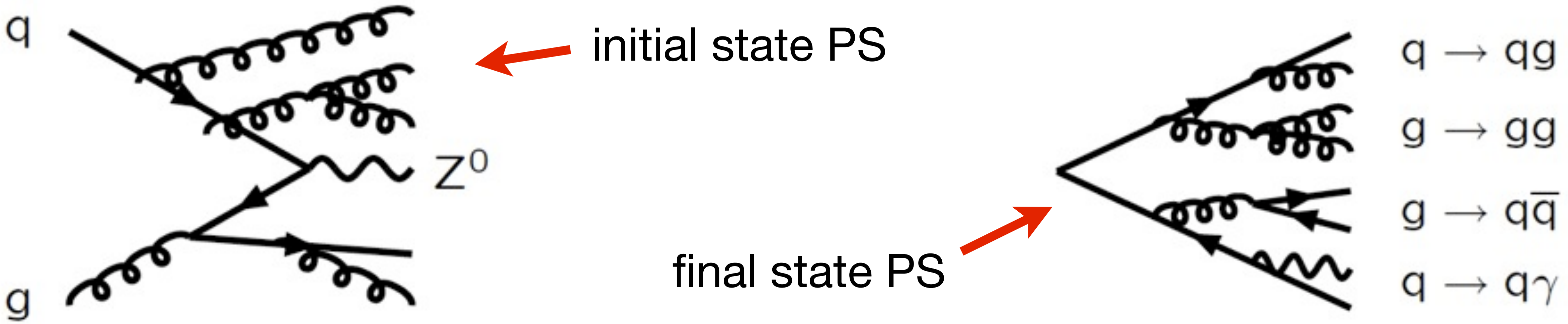
➩ Soft radiation at higher orders described by parton showers



initial state PS

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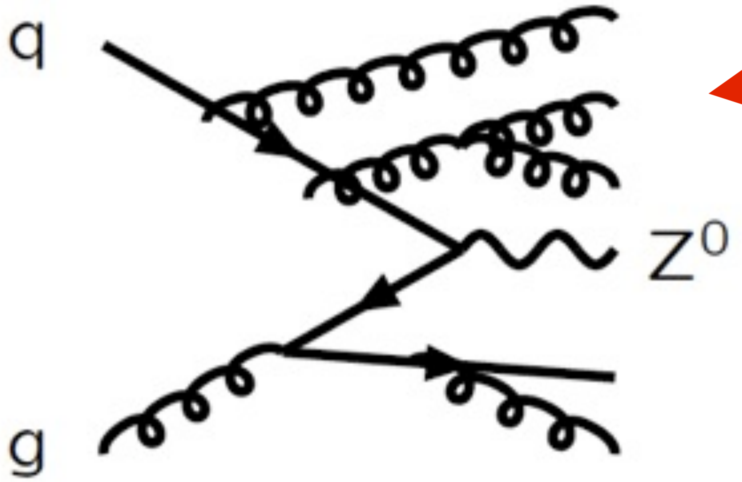

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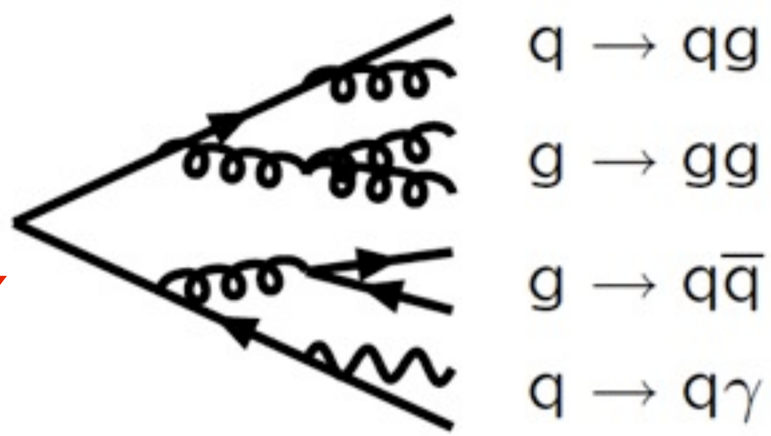
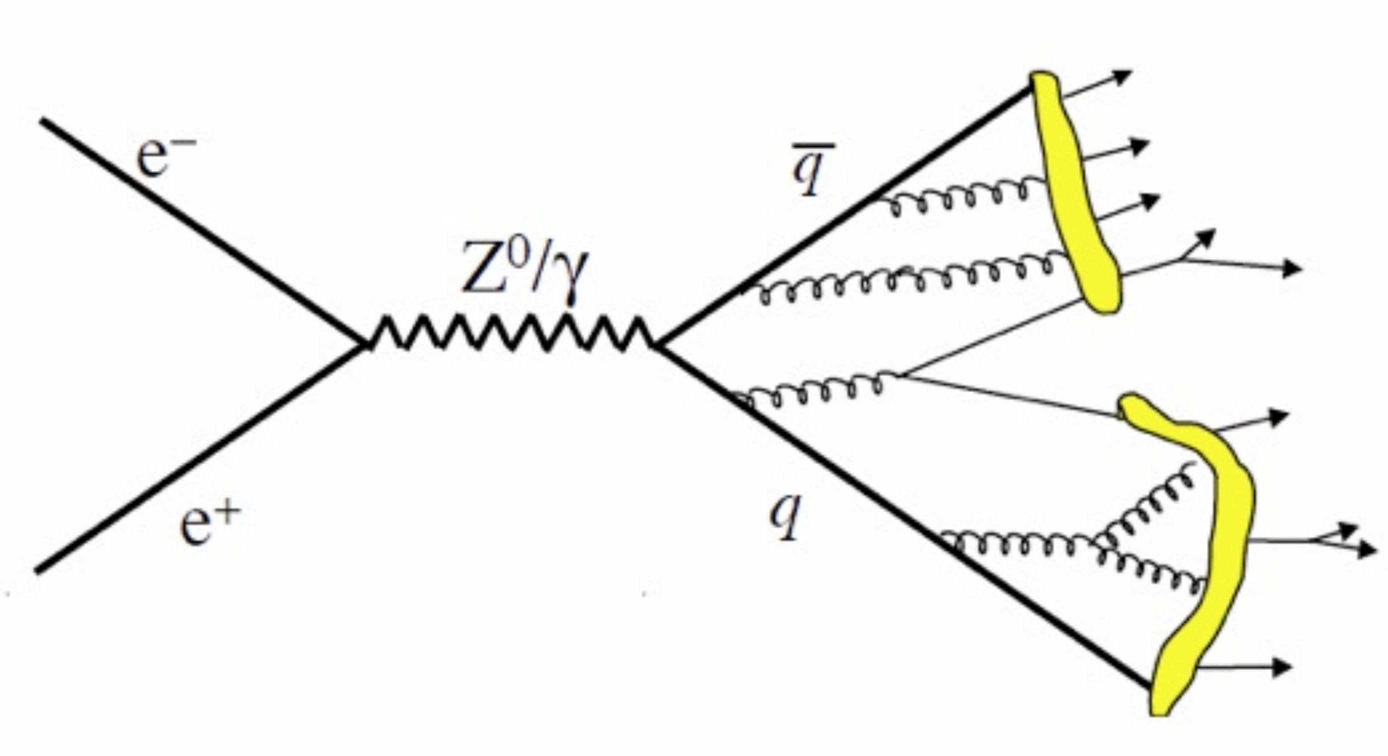


- Parton showers: radiation of gluons, the probability that no radiation takes place is described by “Sudakov factors” (before/after scattering)
- Parton showers do not change the cross section -> radiation harder than the matrix element is vorbidden (“matching”)

Hadronization I

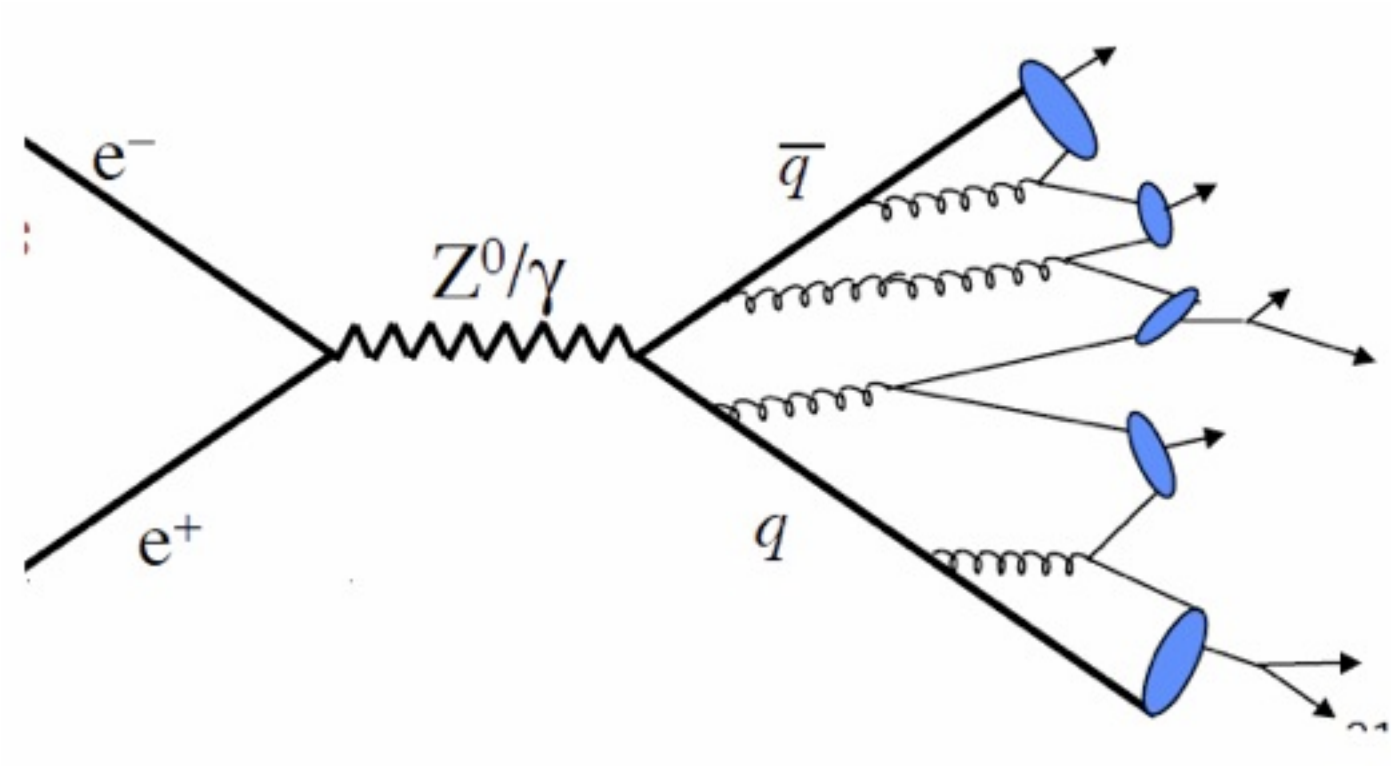
- Describes how hadrons are formed from the final-state partons
  - Experimentally: Measured fragmentation functions
  - For computer simulations: Two commonly used models:



- 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:

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

Hadronization II



- 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

The Code Armada

- ***PDFs***
  - MRSxx, CTEQyy, HERAPDFzz, different α_s and renormalization schemes
- ***Matrix element generators LO/NLO***
  - MC@NLO, Alpgen, . . .
- ***Matrix element - parton shower matching***
  - LO: CKKW, MLM
  - NLO: MC@NLO, PHOWEG
- ***Event generators***
  - HERWIG, PYTHIA, SHERPA, . . .
- ***Hadronization models***
  - String model, cluster model
- ***Detector simulations***
  - GEANT4, EGS showers, Fluka showers

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A large number of possible combinations!

Detector Simulations

The Task

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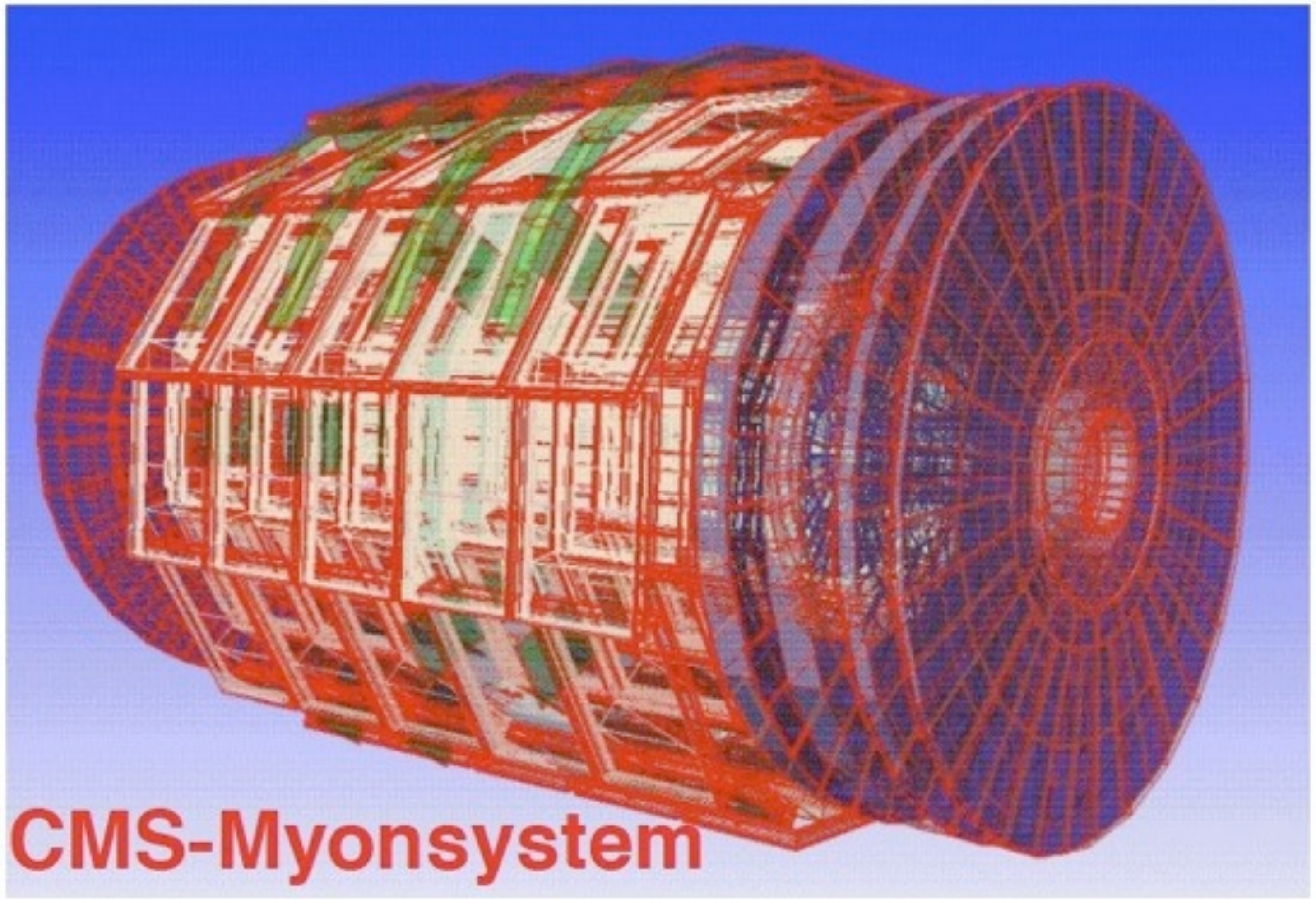
▸ Very complex, but indispensable for detector design and data analysis!

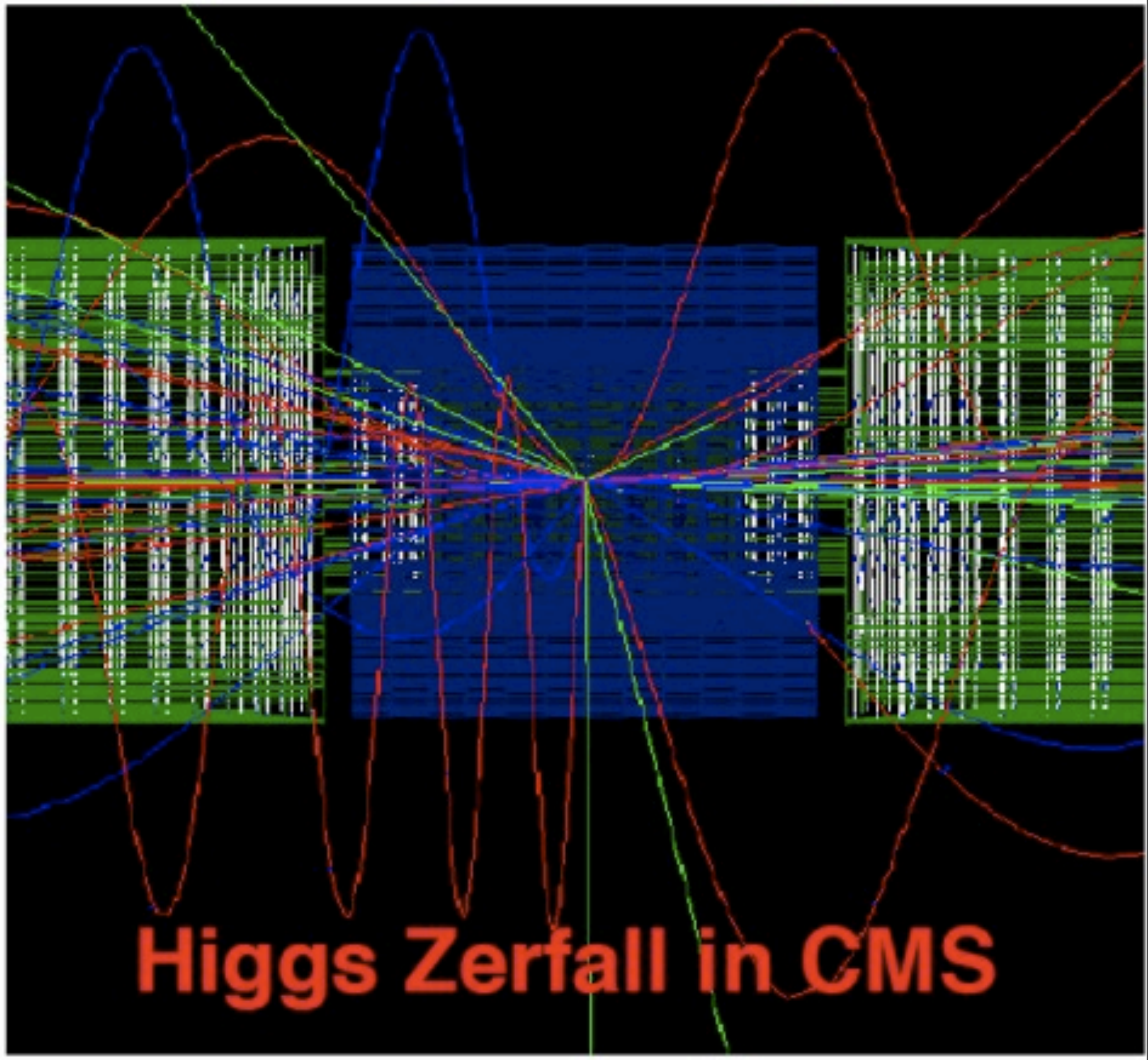
The Standard Tool Today: GEANT4

- A software package (“tool kit”) to simulate the passage of particles through matter
  - Many possibilities to describe geometry and materials
  - Large libraries for particle-matter interactions (“physics lists”), custom combinations can be created



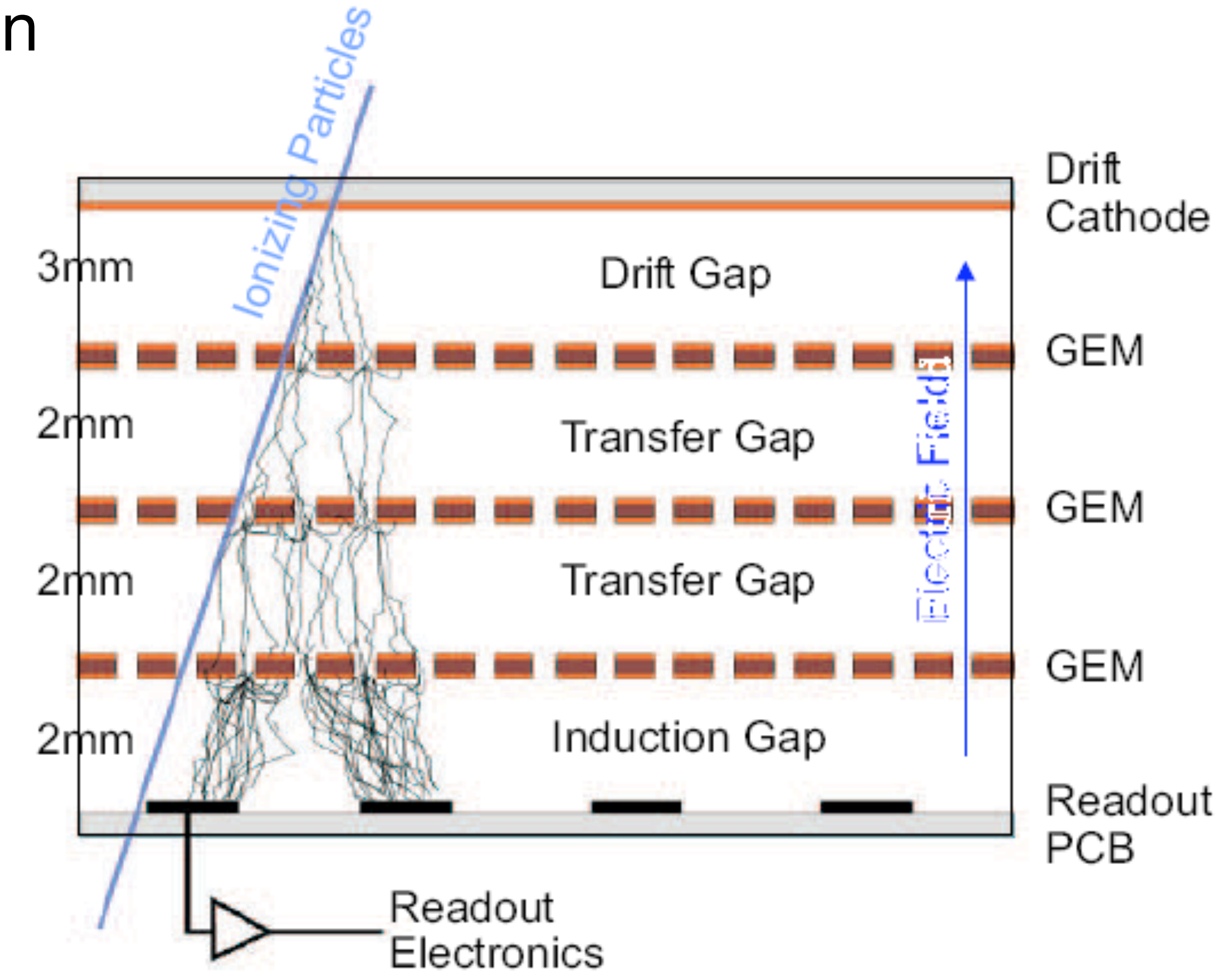
GEANT

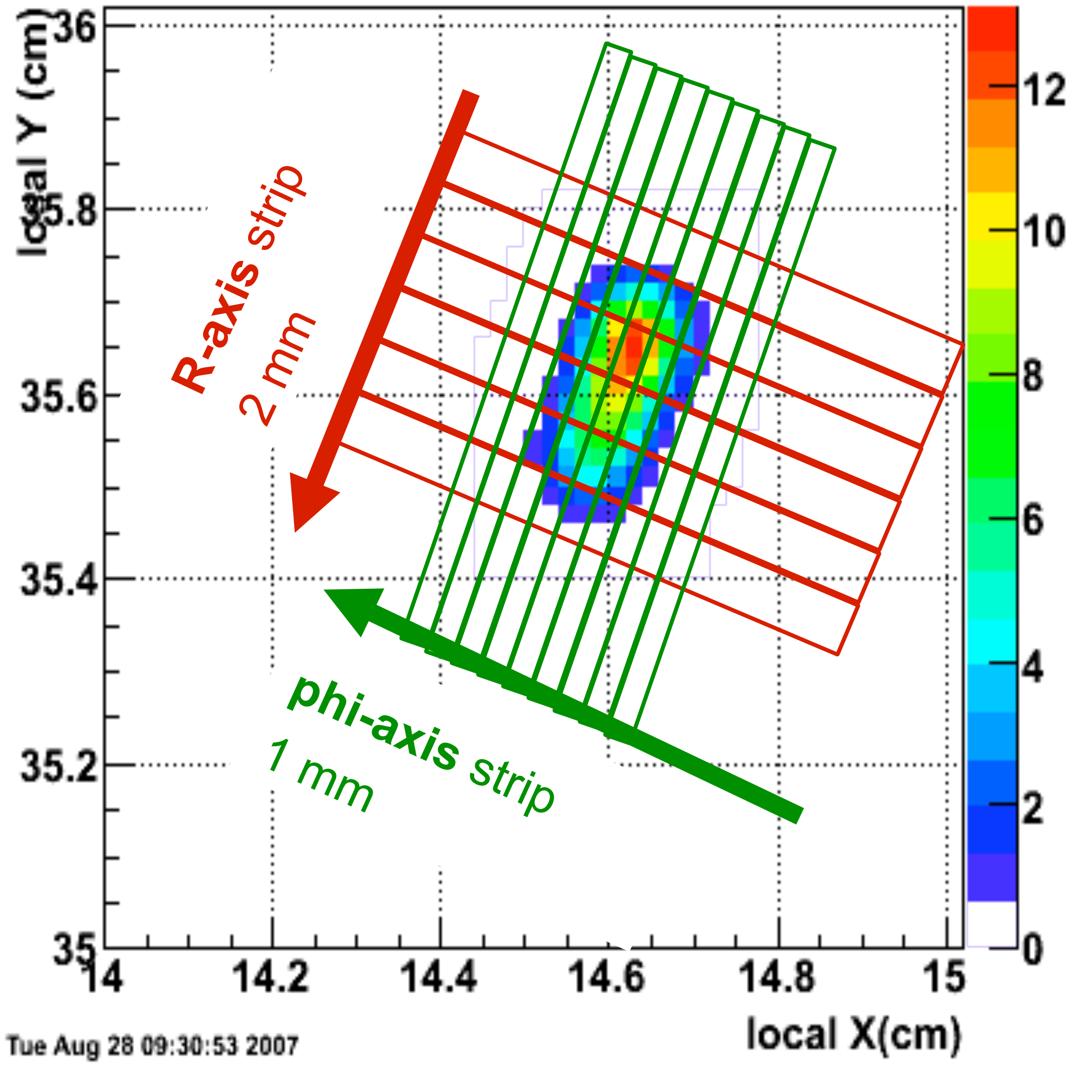
- The working principle
  - Step-wise tracking of particles through the detector material ("Steps")
    - For each step:: Position, momentum and energy changes, energy deposition, probabilistic selection of interactions based on the cross sections given by the physics list
    - The step length is automatically adjusted based on the material (density, interaction probability, ...), at least one step per material layer
  - Analogous: Tracking of all secondary particles ...



Detector Simulation: Example STAR FGT

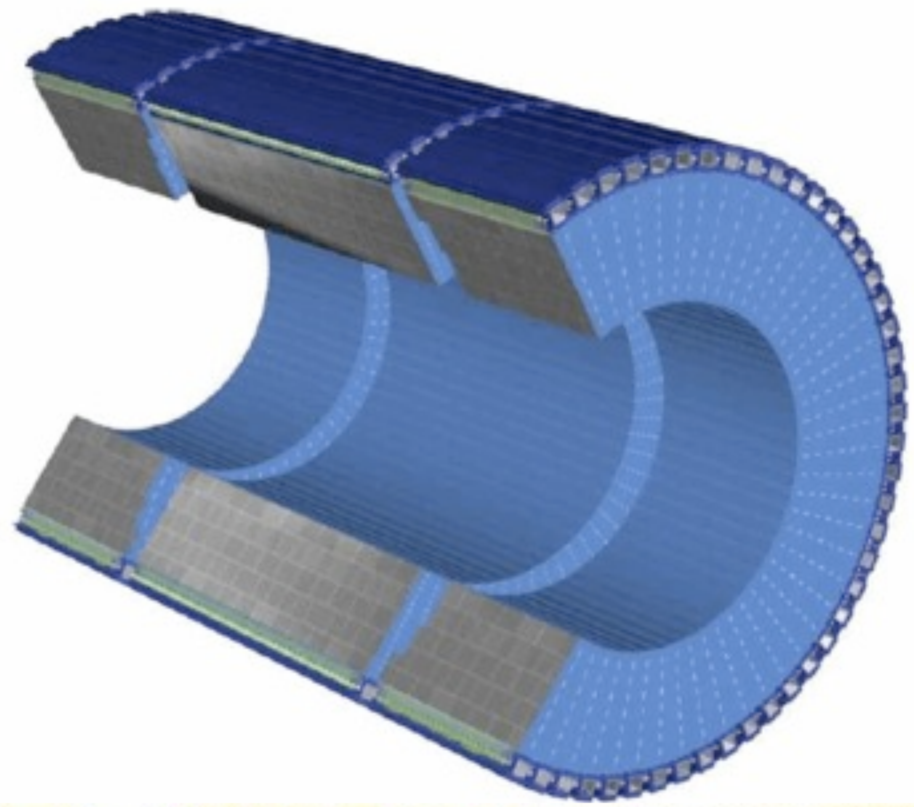
- Energy deposition of particles by ionization in sensitive volume of the detector
    - Transformation of the individual energy depositions into created free electrons

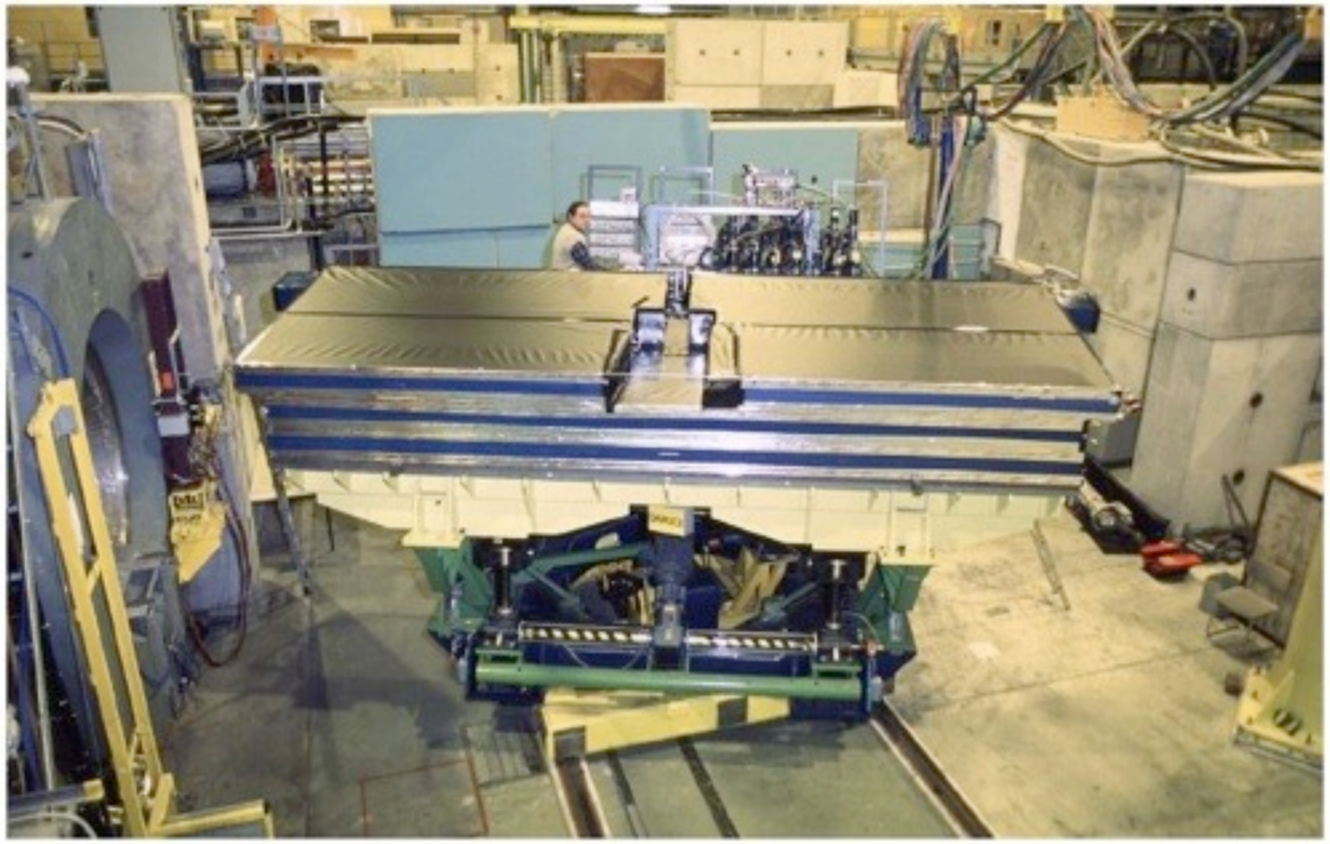




- Simulation of the drift of the electrons in electric field (including diffusion), amplification processes
- Projection on readout strips, charge sharing
- Simulation of the response of the electronics

Application of Detector Simulations: ATLAS HCAL

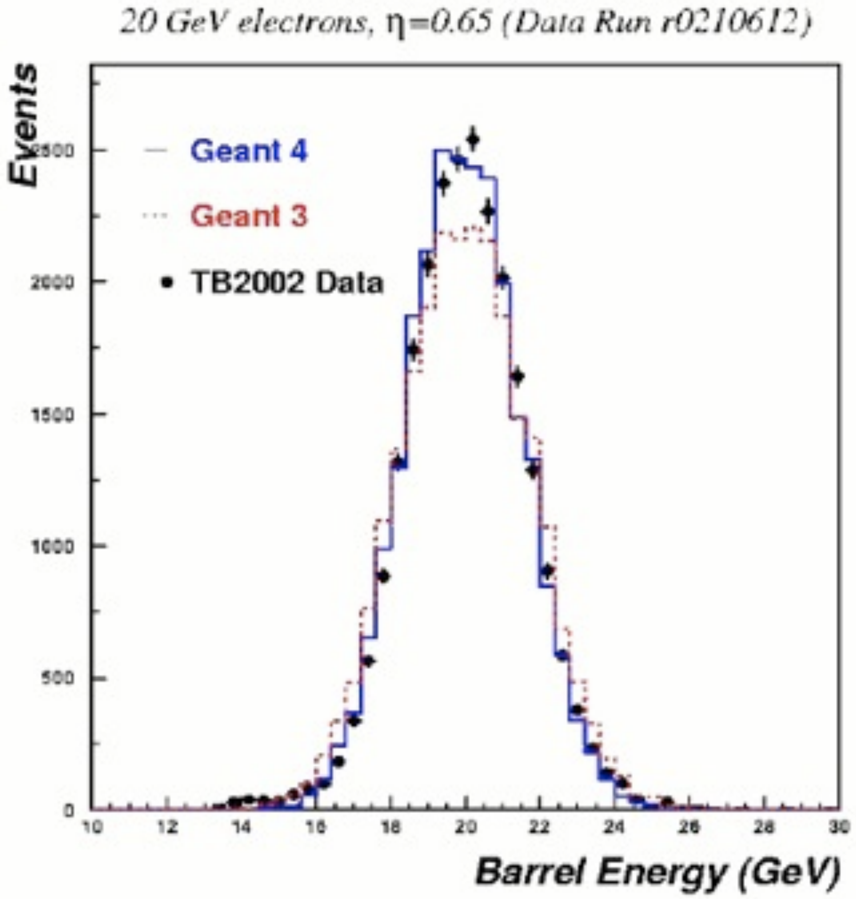




- Steel (82%) / Scintillaotr (18%), 7.2 λ
- Comparison of simulations with test beam data:

  Electrons

  Hadrons



- Energy resolution for hadrons:

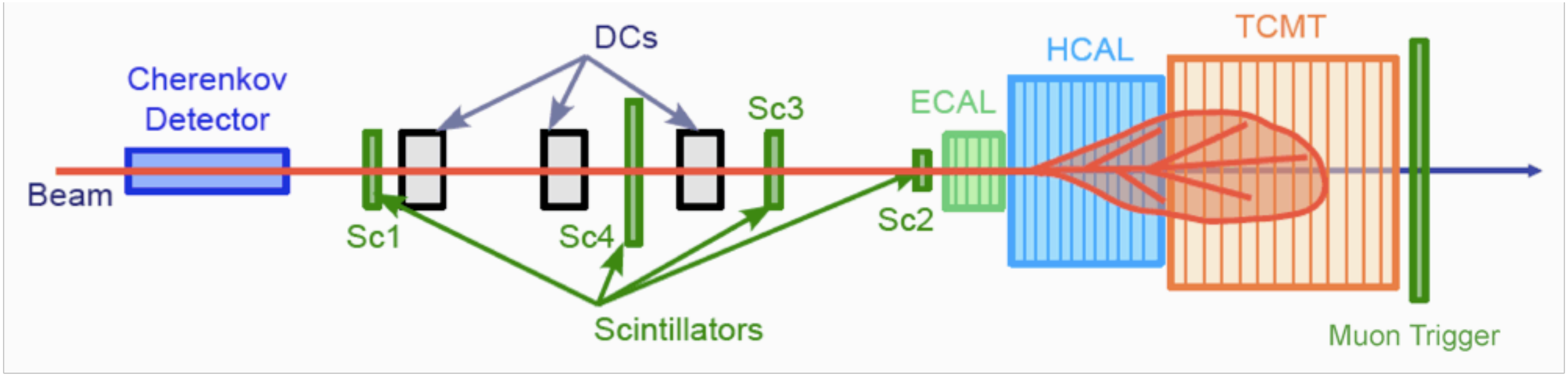
  Data: 53±2%/√E ⊕ 2.0±0.2%

  MC-QGSP: 58±3%/√E ⊕ 2.6±0.5%

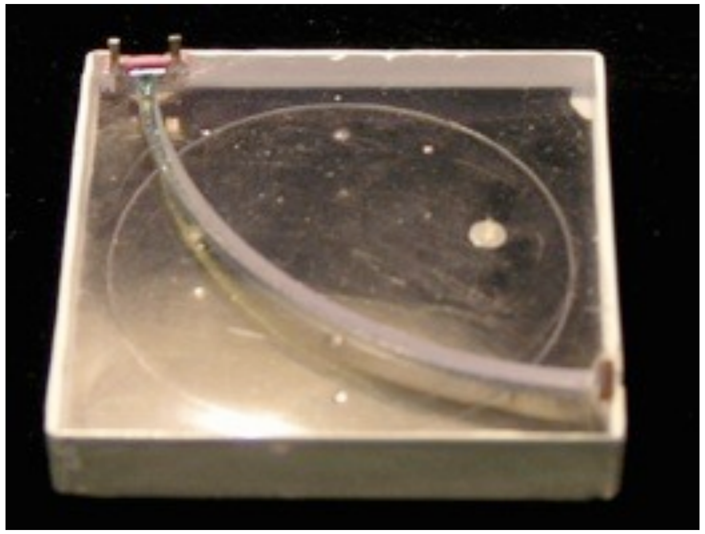
  MC-LHEP: 59±3%/√E ⊕ 2.4±0.5%

▸ Not perfect, but already quite close...

Detector Simulations - CALICE

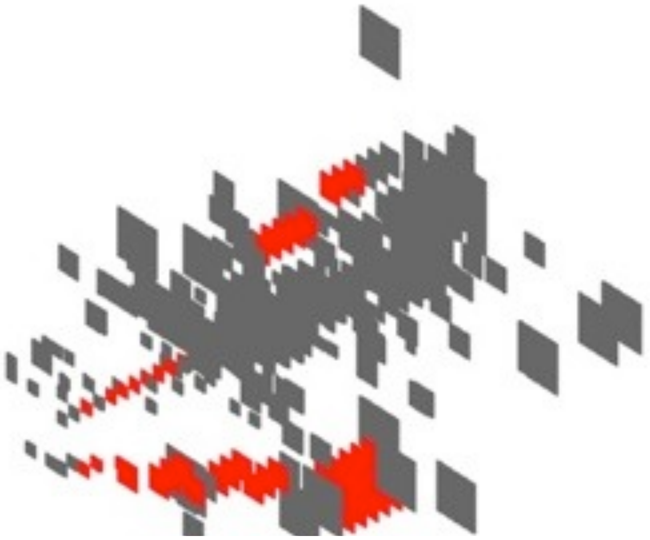


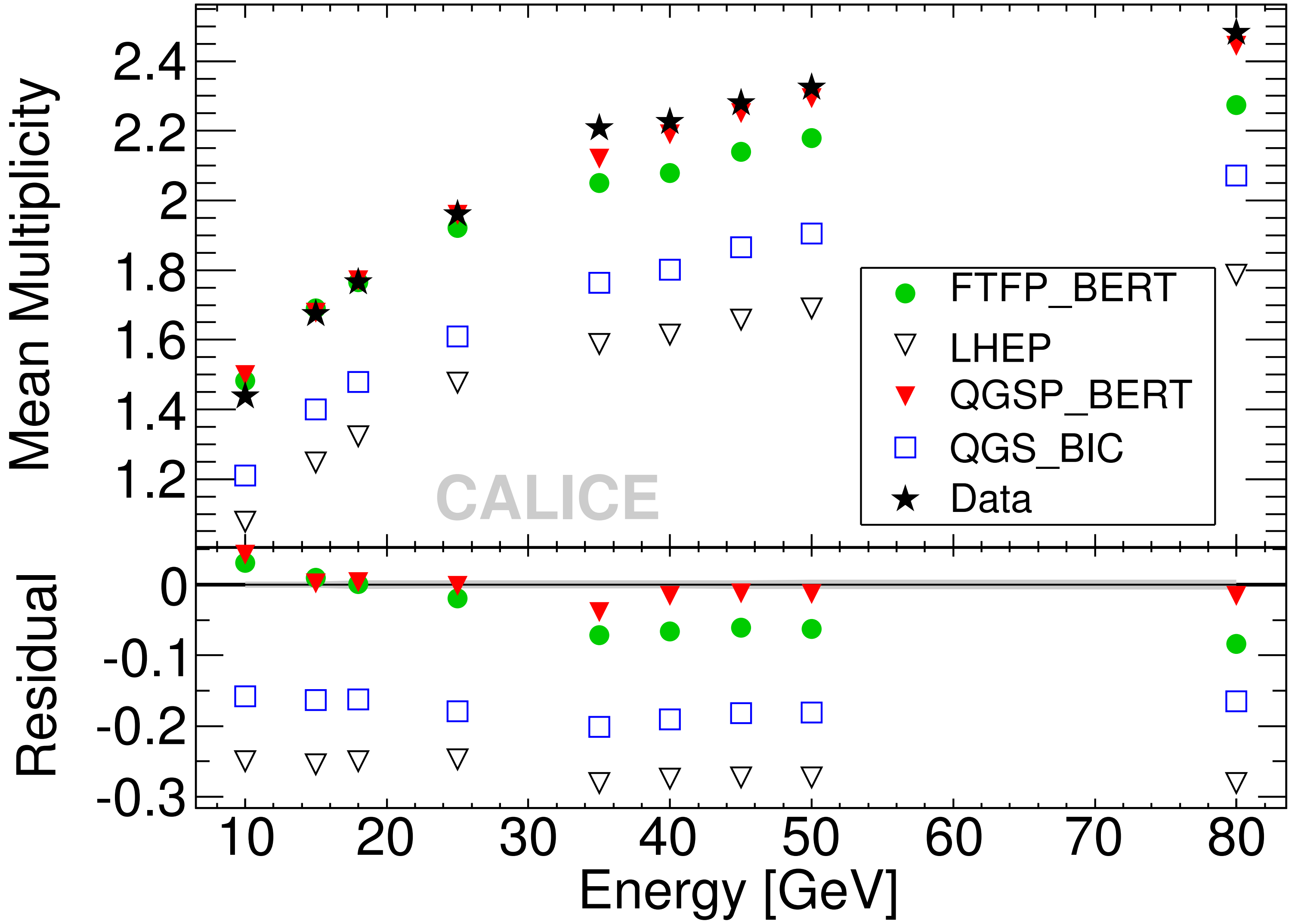
- Development of highly granular calorimeters for future experiments



- The “physics program”: Study of the physics of hadronic showers, improvement of simulations with data with unprecedented spatial resolution

Simulating & Understanding Showers





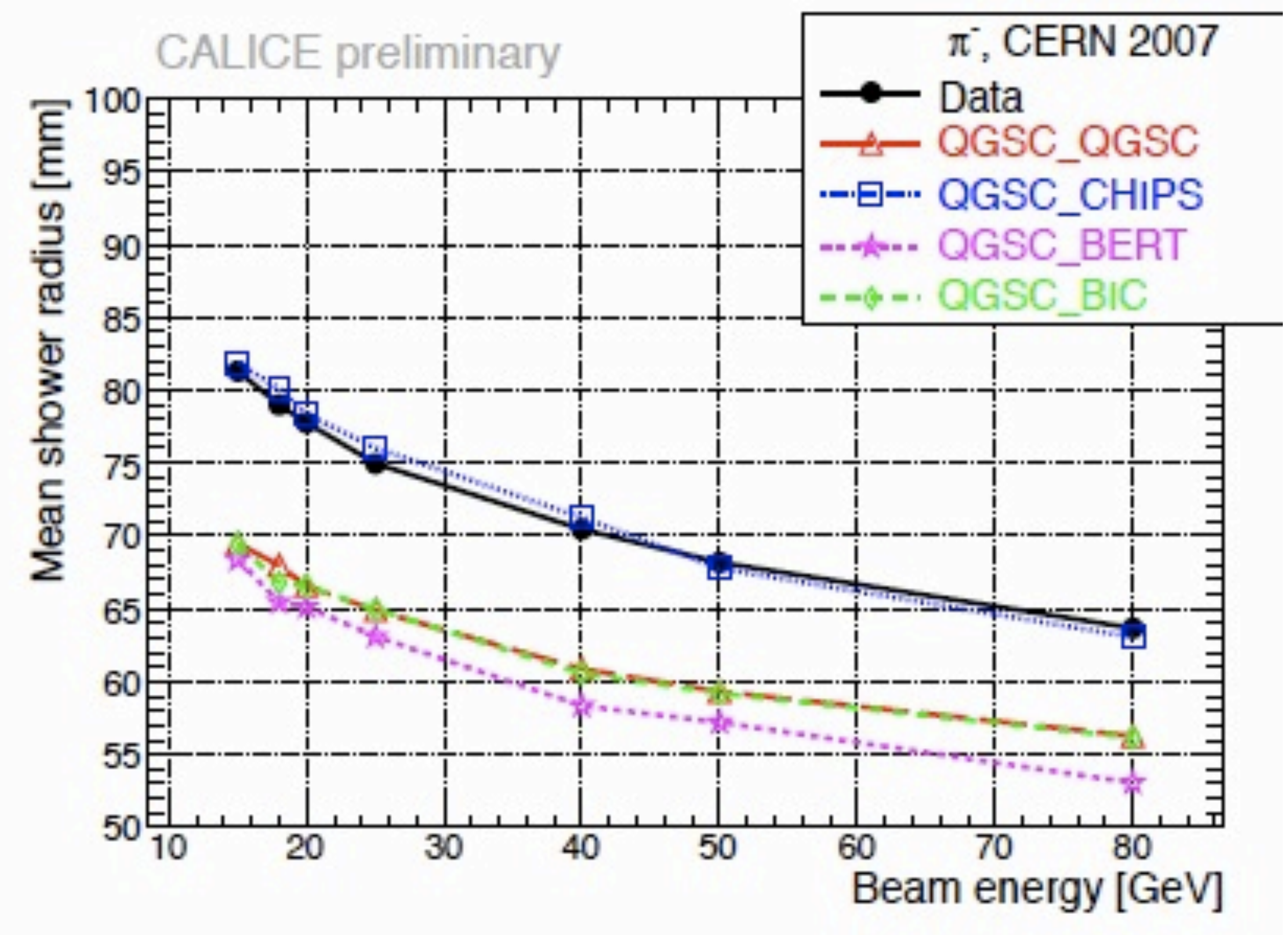
Identification of MIP-like track segments in the AHCAL:

Hadronic showers are **not** amorphous blobs of energy in the detector, but tree-like structures with MIP-like hadrons connecting regions of denser activity

... and modern simulation models in GEANT4 predict / reproduce this structure already with good accuracy! - Much improved compared to LHC development phase!

JINST 8 P09001 (2013)

Detailed Tests of Shower Models - Pitfalls



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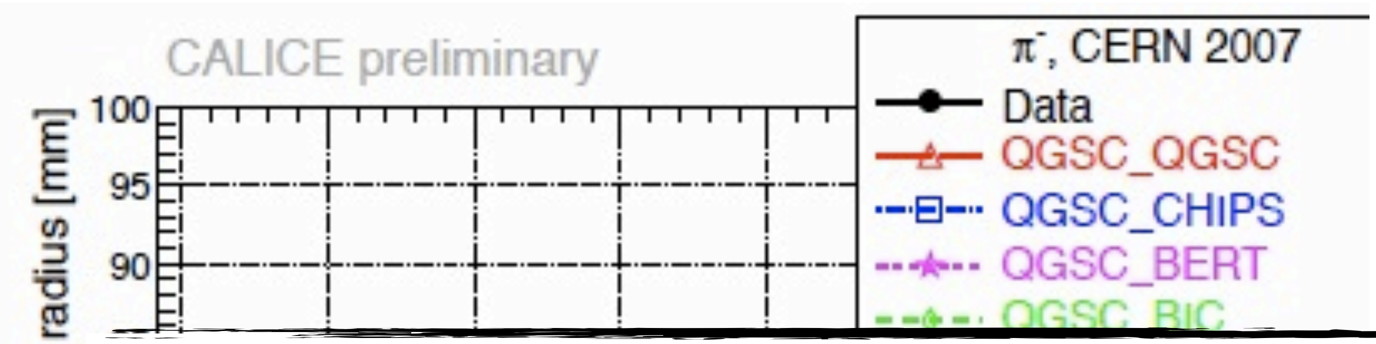
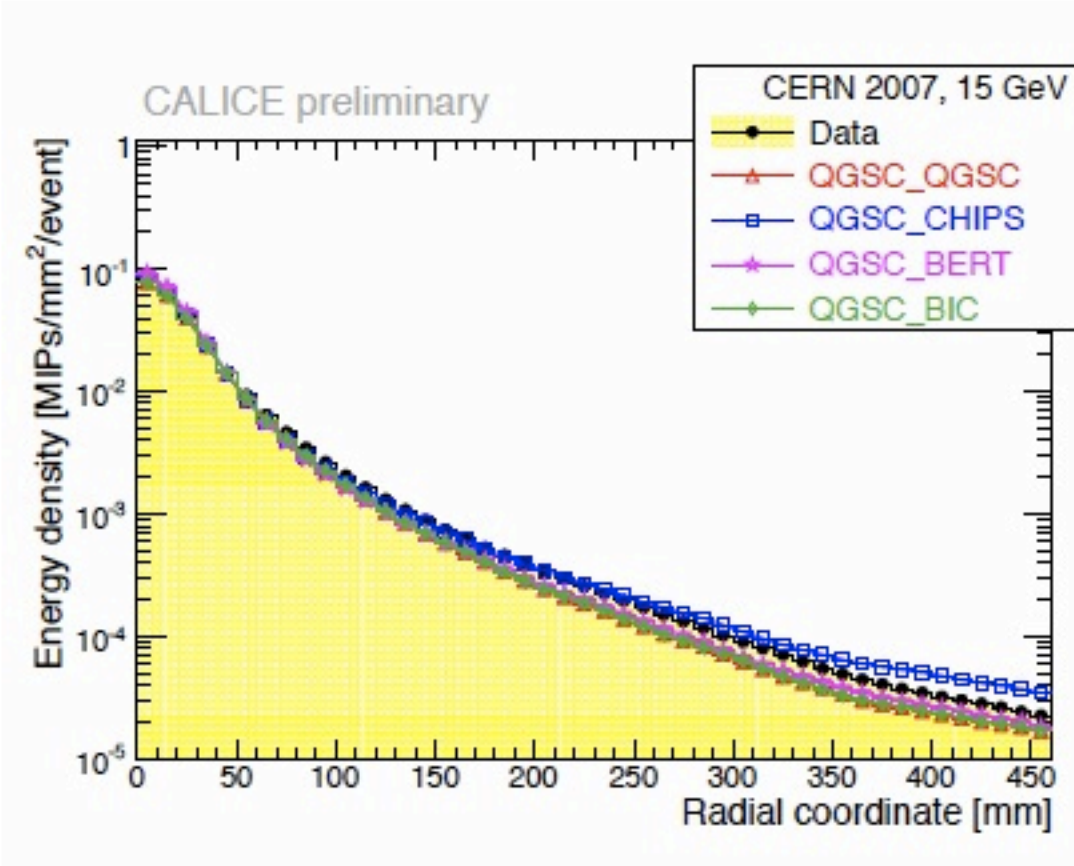
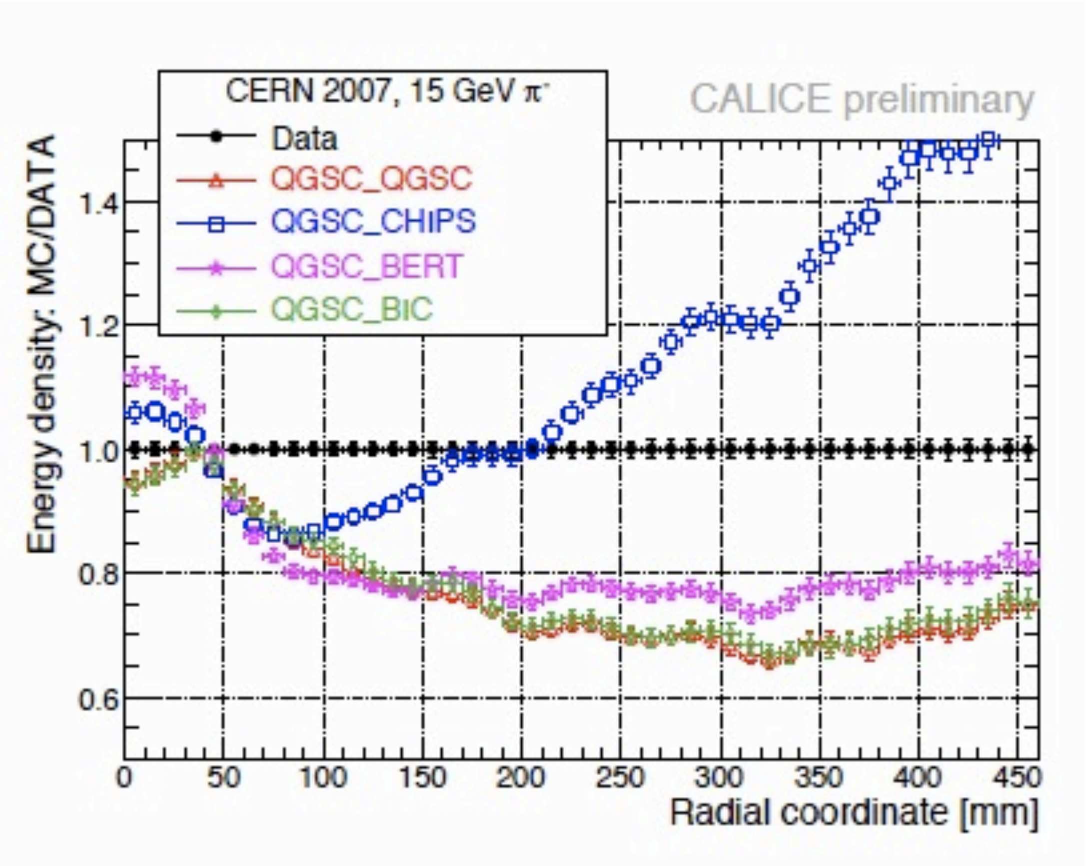


But beware: Agreement in one variable does not necessarily mean a model works well for the full shower description!





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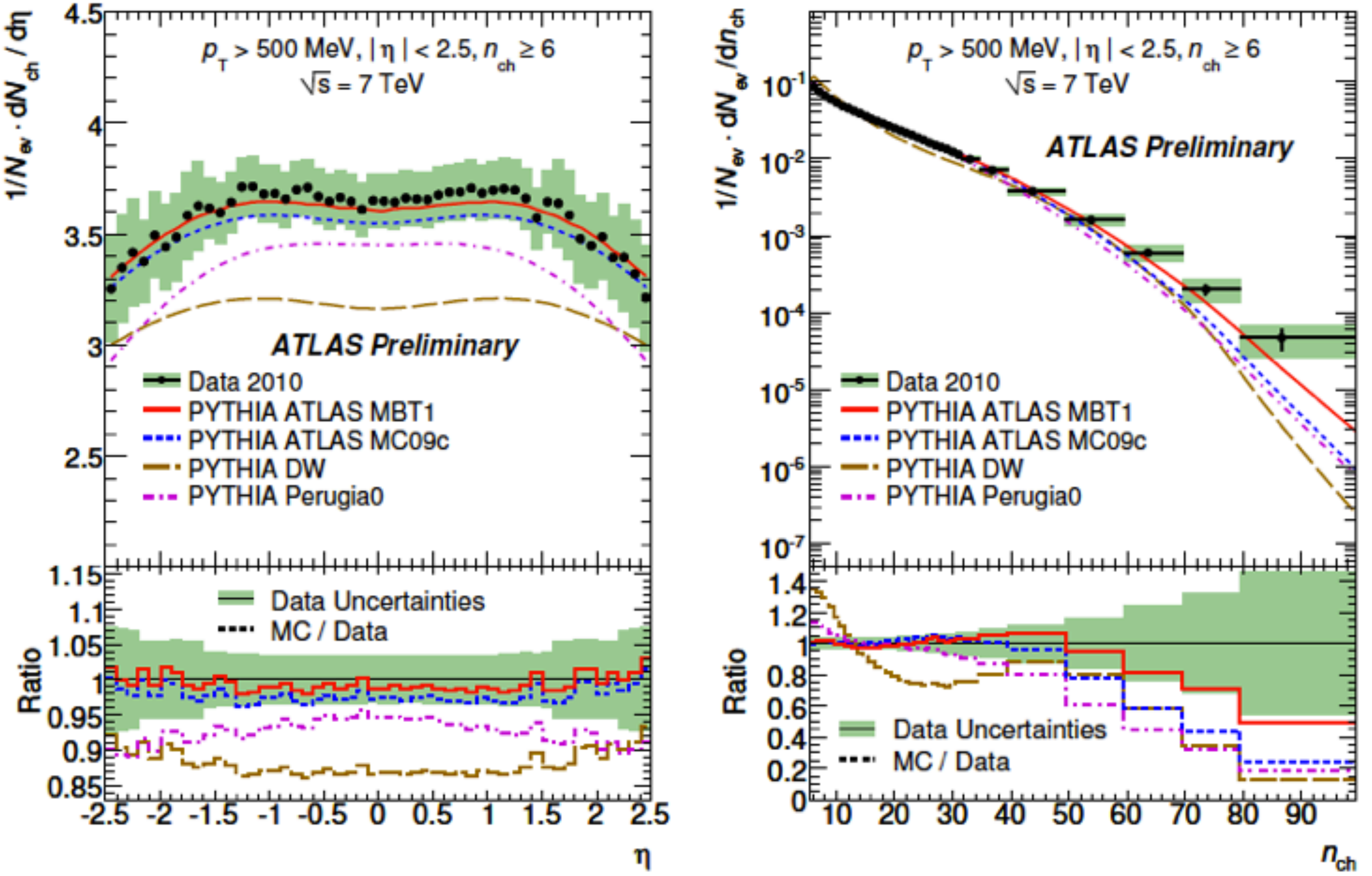
    - ▸ Still: Modifications are usually necessary once the first data comes in...

Frank Simon (fsimon@mpp.mpg.de)

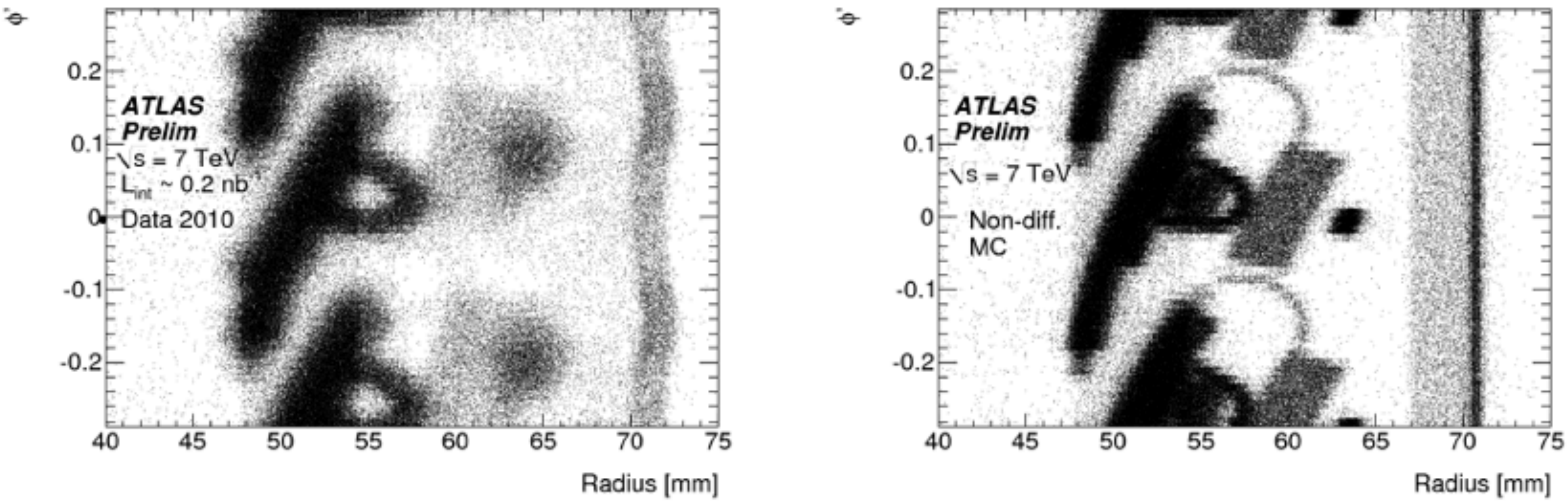
Tuning - An Example

- Tuning of PYTHIA based on data - adjusting selected model parameters
    - Crucial to be able to describe background distributions for physics processes, used for many analyses - Extrapolation from lower energy not always reliable



ATLAS: Simulation & Reality

- Detailed study of material and geometry with photon conversions



first layer of
pixel detector

A Buckley, IEEE-NSS 2010

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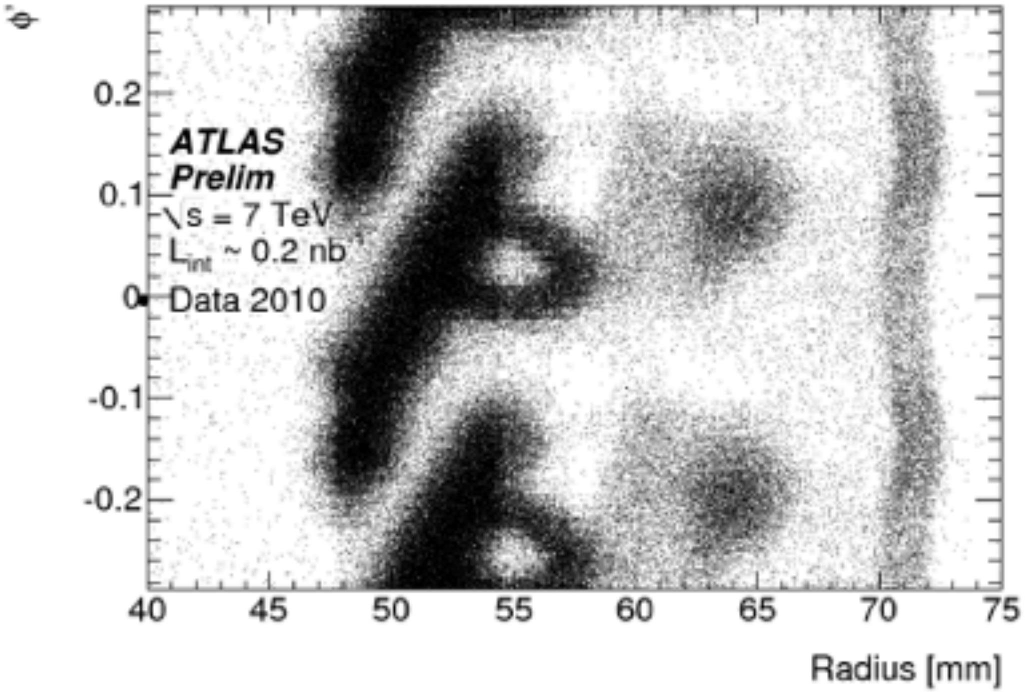

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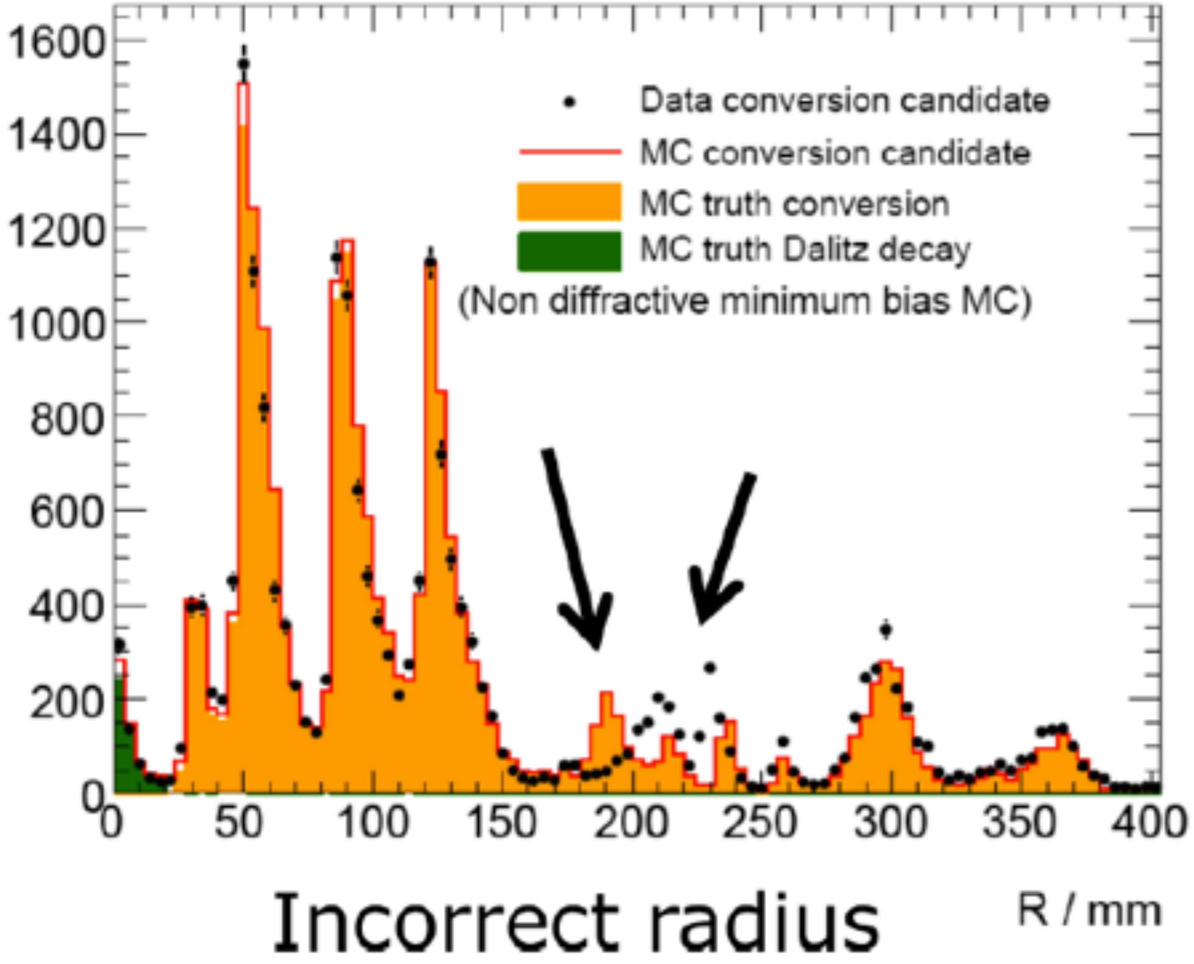

Incorrect radius

Comparison of real data and simulations is crucial to find problems in the detector description (and mistakes do happen!)

A Buckley, IEEE-NSS 2010

Summary

- Event generators and detector simulations are indispensable tools for the optimization of detectors and for the analysis of particle collisions

- The factorization theorem of QCD allows a splitting of the description of processes into clearly defined parts, which can be considered more or less independently
- PDFs have a special role in hadron collisions, precise knowledge is important for analysis, also for the discovery of New Physics
- The non-perturbative hadronization is described by two complementary models

- A detailed modelling of the detector response to particles, including the simulation of the propagation and interaction of particles in the detector material is very important, and used in all modern experiments
    - Large steps have been made, but further improvement is still necessary, in particular in the area of hadronic showers

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Nächste Lecture: QCD, Jets, Structure Functions, S. Bethke 02.12.2013

Zeitplan

1.	Einführung; Stand der Teilchenphysik	14.10.
2.	Hadronenbeschleuniger: Tevatron und LHC	21.10.
3.	Standard-Modell Tests	28.10.
4.	Teilchendetektoren an Tevatron und LHC (I)	04.11.
5.	Trigger, Datennahme und Computing	11.11.
6.	Teilchendetektoren an Tevatron und LHC (II)	18.11.
7.	Monte Carlo Generatoren und Detektor Simulation	25.11.
8.	QCD, Jets, Strukturfunktionen	02.12.
9.	Top Quark	09.12.
10.	Higgs-Physik (I)	16.12.
	----------- fällt vermutlich aus -------------	23.12.
	-----------Weihnachten ---------------------	
11.	Higgs-Physik (II)	13.01.
	----------- fällt vermutlich aus -------------	20.01.
12.	SUSY, Physik jenseits des Standard-Modells	27.01.
13.	Andere Modelle jenseits des SM, Ausblick	03.02