Karlsruhe Institute of Technology

Tools and Techniques for High-p_T Physics

7th ENHEP School on High Energy Physics
Ain Shams University, Cairo, January 26–31, 2019

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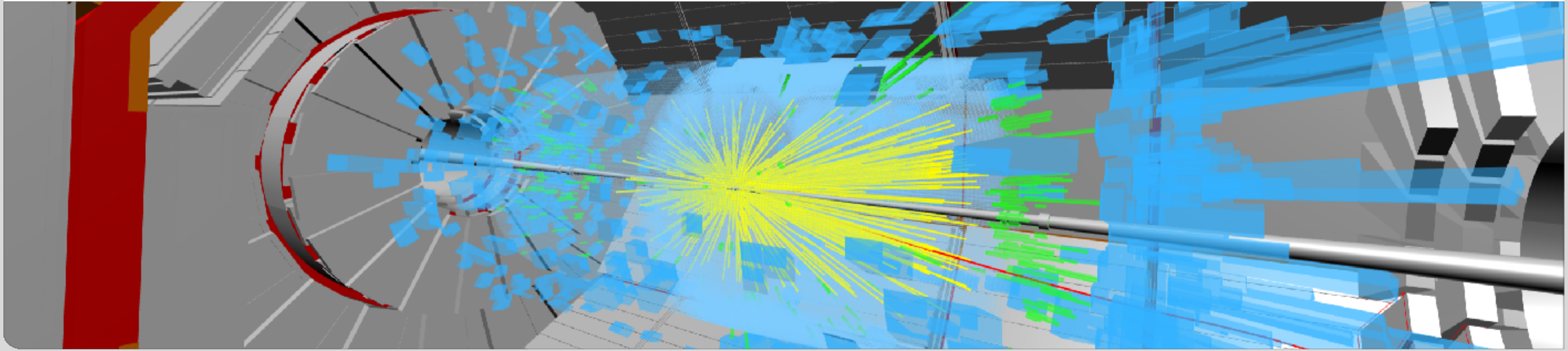


Scope of this Lecture

- Introduction the the most important **tools and techniques** for experimental particle physics at colliders
  - Two one-hour **lectures**: discussion of ideas and concepts
  - One **tutorial** session: deeper understanding by hands-on exercise (at least for one example)
- Please **ask questions** – during and after the lecture and anytime you can grab me otherwise

Outline

From Raw Data to Physics Results

Monte-Carlo Event Generation

Physics Objects

Background Estimation

Advanced Signal Analysis

Overview

FROM RAW DATA TO PHYSICS RESULTS

Cross Section: Master Formula

Number of events observed in detector
just count…

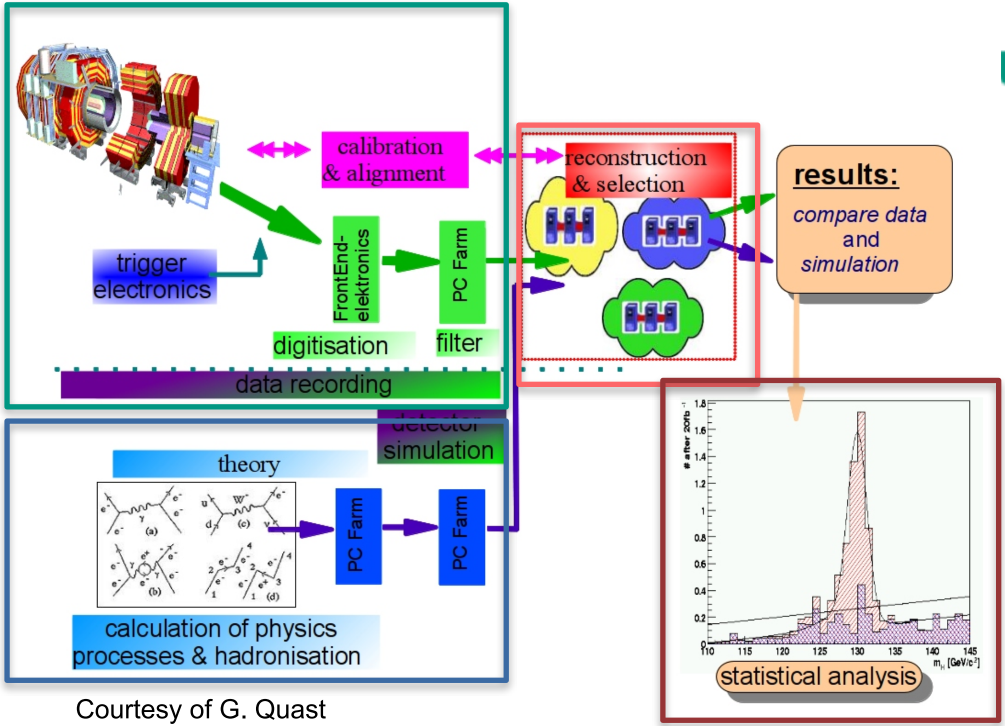
Background
measured in data or from theory prediction

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L}\,\mathrm{d}t \cdot \varepsilon}$$

Luminosity
depending on accelerator, trigger, …

Efficiency
Acceptance and efficiency of detection, analysis-specific optimization

Detector & Analysis Chain



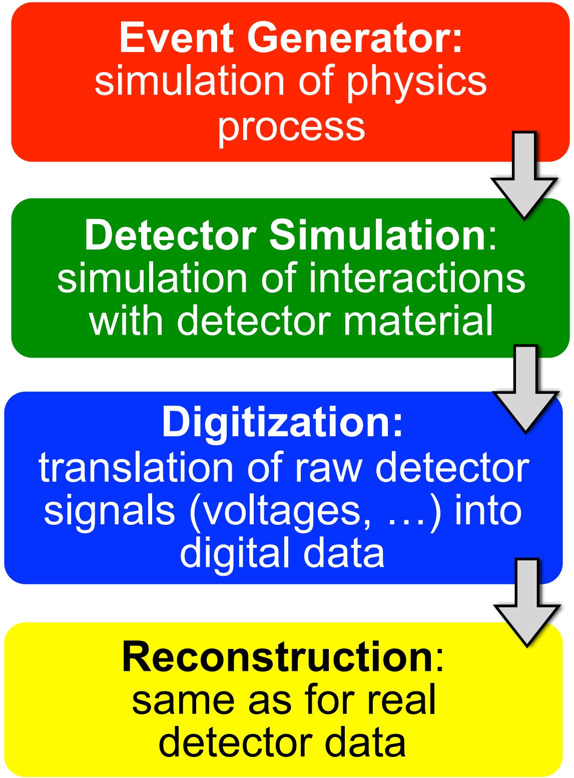
Courtesy of G. Quast

- Collider-based particle physics: complicated analysis chain
  - **Detector** input: calibrated digitized data, online selection ("trigger")
  - **Theory** input: calculations and simulations
  - Physics object **reconstruction** and **selection**
  - **Statistical** analysis & comparison with theory

MONTE-CARLO EVENT GENERATION

MC Simulations in Particle Physics

- Goal: **comprehensive simulation** of collision events based on best knowledge of all physics processes (collision events and interactions in detector)
- Main tools based on **Monte-Carlo (MC) method**:
  - In general: MC = **numerical** techniques to compute **probabilities** using **random numbers**
  - Excellent tool to generate **physics events** (QM = probabilistic theory) and simulate **particle interactions** in detectors



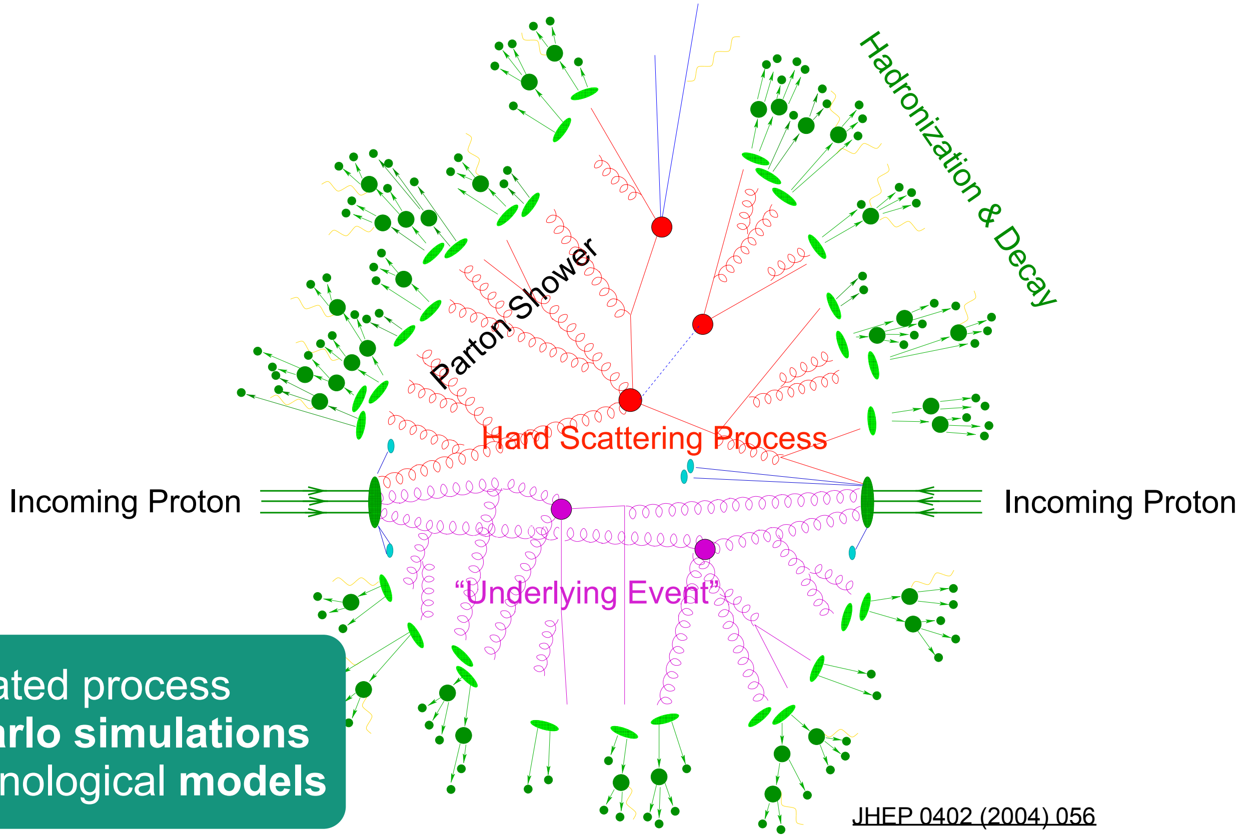
Event Generator: simulation of physics process

Detector Simulation: simulation of interactions with detector material

Digitization: translation of raw detector signals (voltages, …) into digital data

Reconstruction: same as for real detector data

Simulation of a Collision Event



JHEP 0402 (2004) 056

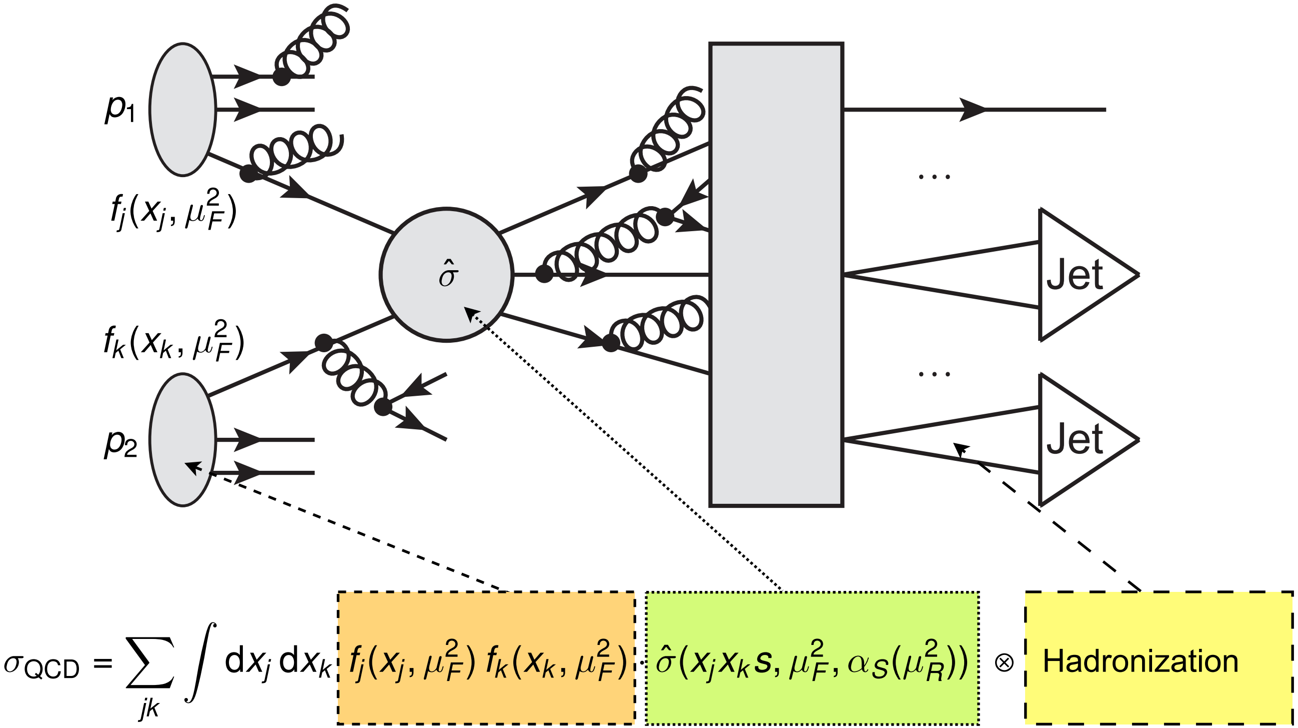
Complicated process
→ **Monte-Carlo simulations**
and phenomenological **models**

MC Event Generators

- Goal: **realistic simulation** of all relevant physics processes in a particle collision
- Problem: **complexity** of hadron-hadron collisions
  - Initial state: hadrons = compound objects, constituents (quarks & gluons) confined in hadron (QCD interactions at low four-momentum transfer Q^2)
  - Final state: many hadrons and leptons
- Way out: **QCD factorization**
  - **Separate treatment** of processes at low and high Q^2
  - High Q^2 (“hard scattering process”, short-distance physics): **perturbation theory** in leading order (LO) or higher orders (NLO, NNLO, …)
  - Low Q^2 (“soft physics”, long-distance physics): phenomenological **models**

QCD Factorization in Pictures

Cross Section = PDFs ⊗ Hard Process ⊗ Hadronization



$$\sigma_{\mathrm{QCD}} = \sum_{jk} \int \mathrm{d}x_j\, \mathrm{d}x_k\, \boxed{f_j(x_j, \mu_F^2)\, f_k(x_k, \mu_F^2)}\, \boxed{\hat{\sigma}(x_j x_k s, \mu_F^2, \alpha_S(\mu_R^2))} \otimes \boxed{\text{Hadronization}}$$

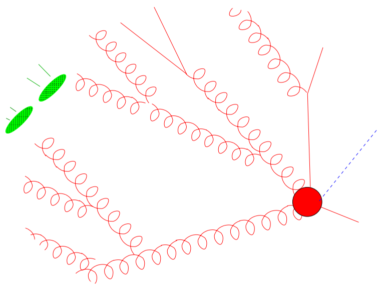
Overview of MC Generators

- Central step in any MC generator: **MC integration** of cross section for hard process in fixed order of perturbation theory (using PDFs as inputs) (Fermi's Golden Rule: cross section = |matrix element|^2 ⊗ phase space)
- **Parton-level** MC generators:
  - Simulation stops at the level of partons (quarks and gluons)
  - No hadronisation, only events weighted with the differential cross section → no full event simulation (still useful for theoretical studies)
- **Particle-level** MC generators:
  - Full event simulation: parton level + unweighting (→ number of MC events corresponds to theoretical expectation) + parton shower + hadronization
  - May be provided as a single comprehensive package or as a combination of ME provider and parton shower MC (SMC) program (examples: later)

Lectures on Event Generators

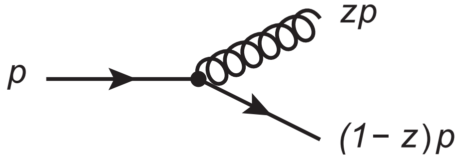
- T. Sjöstrand, Introduction to Event Generators, CTEQ/MCnet School, DESY 2016
  - http://home.thep.lu.se/~torbjorn/talks/desy16a.pdf
  - http://home.thep.lu.se/~torbjorn/talks/desy16b.pdf
  - http://home.thep.lu.se/~torbjorn/talks/desy16c.pdf
  - http://home.thep.lu.se/~torbjorn/talks/desy16d.pdf
- S. Gieseke, Parton Shower Monte Carlos, UA Madrid 2016: https://www.itp.kit.edu/~gieseke/uam/madrid16.pdf
- F. Maltoni, CERN Academic Training Lectures 2012: https://indico.cern.ch/conferenceDisplay.py?confId=181765
- B. Webber, Parton Shower Monte Carlo Event Generators, Scholarpedia, 6(12):10662

Parton Shower



- Parton shower:
  - **Coherent** emission of soft colored particles
    → quantum interference effect
  - Emission process can be modeled by a sequence of **1→2 parton splitting** processes
  - Parton shower = **probabilistic model** of quark fragmentation
- Central object of parton shower: **Sudakov form factor**
  - Probability for a parton i to emit a parton j: **splitting function** P_{ji}
  - Solution of **DGLAP equation** for parton shower: Sudakov form factor

$$\Delta_i(t) = \exp\left[-\sum_j \int_{t_0}^{t} \frac{\mathrm{d}t'}{t'} \int_0^1 \mathrm{d}y\, \frac{\alpha_S}{2\pi} P_{ji}(y)\right]$$

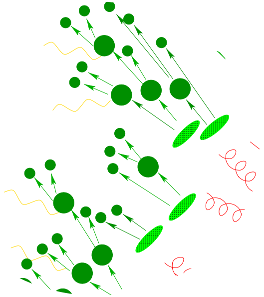


Modern SMC Codes

- General purpose SMC event generators: completely new **C++ developments** based on experience with established FORTRAN codes and new C++ codes
    - **Pythia 8** (http://home.thep.lu.se/~torbjorn/Pythia.html): default: p_T-ordering, other options available
    - **Herwig 7** (http://herwig.hepforge.org): default: angular ordering, optionally: dipole showering
    - **Sherpa** (https://gitlab.com/sherpa-team/sherpa): dipole showering
- LHC Run 2: Pythia 8, Herwig 7, Sherpa as **new standards** for SMC (also in combination with other packages)

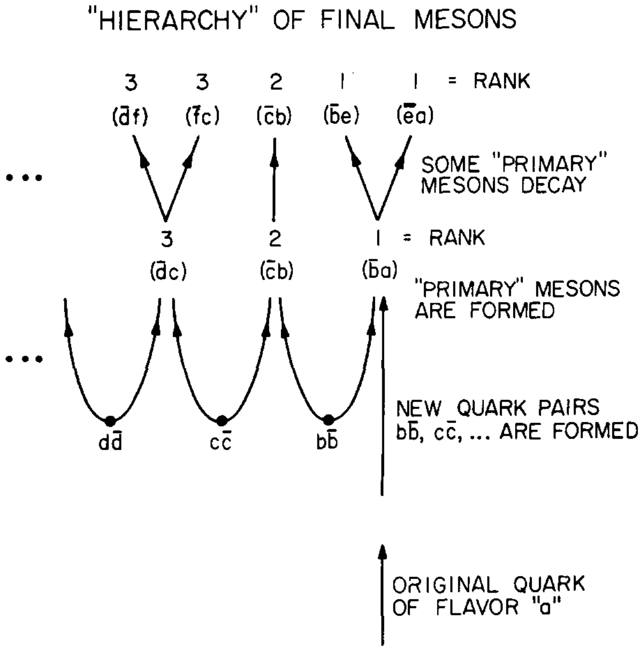
Hadronization Models

- Parton-hadron transition: **non-perturbative** processes
- Phenomenological MC models very successful:
  - Basic assumption: **parton-hadron duality** → very close relation between parton dynamics and properties of final state hadrons
  - Advantage: **full** event simulation → can be used **directly** for experiments
  - Disadvantage: many **ad-hoc** parameters in some models → (rather extensive) **tuning** required
- Most well-known hadronization models:
  - Independent fragmentation (not used any more)
  - Lund **string** model (Pythia)
  - **Cluster** model (Herwig, Sherpa)



Independent Fragmentation

- Fragmentation for each parton **independent** (as the name says…) (R.D. Field, R.P. Feynman, 1978)
- Algorithm (starting from original quark):
  - Quark-antiquark pairs formed out of vacuum → primary mesons with energy fraction *z*
  - New starting point: remaining quark with energy fraction 1–*z*
  - Stop at lower energy threshold
- **Fragmentation function *D*(*z*)**: Probability to find hadron with energy fraction *z* in jet (*D*: non-perturbative object)



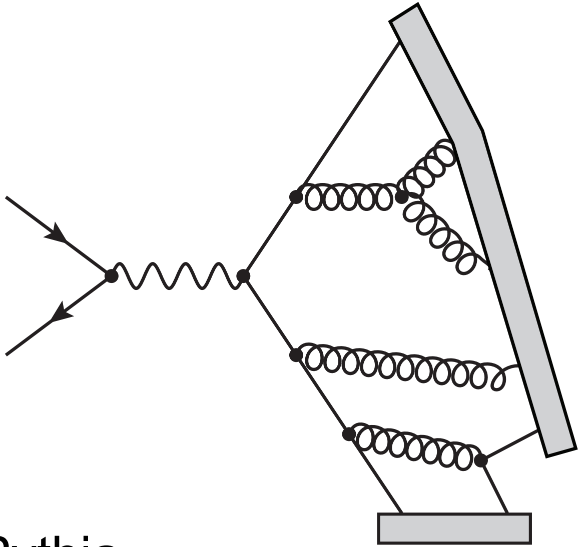
Nucl. Phys. B136 (1978) 1

Lund String Model

- Quark-antiquark pairs form **strings**: (B. Andersson et al., Phys. Rept 97 (1983) 31)
  - Static QCD potential between quark and antiquark: **linear** increase with distance → gluon field collapses to a **string**

$$V(r) = -\frac{4}{3}\frac{\alpha_S(1/r^2)}{r} + kr$$

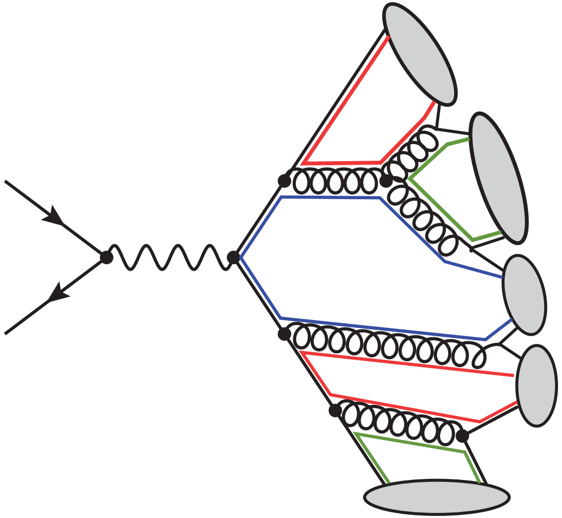
  - Strings **break** once $V(r)$ large enough to form new quark-antiquark pairs
  - Effect of gluons: **"kinks"** in strings
  - Lower energy threshold: formation of hadrons
- Invented at Lunds universitet, Sweden, used in Pythia



after: Ellis et al., QCD and Collider Physics

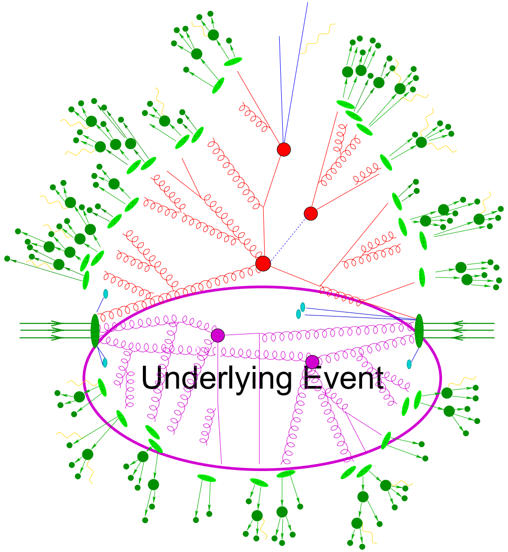
Cluster Model

- Color flow during hadronization governed by **pre-confinement** property of QCD → tendency for partons to form **color-neutral clusters** (B. R. Webber, Nucl. Phys. B238 (1984) 492)
  - Gluons (color-anticolor): splitting into quark-antiquark pairs → **new clusters** with color partners
  - Clusters decay into **hadrons** according to available phase space
  - Advantage: (essentially) no tunable parameters
- Used in **Herwig**



after: Ellis et al., QCD and Collider Physics

Underlying Event

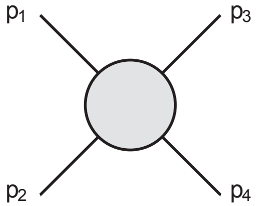


- Total parton-parton cross section ⊗ PDF at the LHC **larger than total proton-proton cross section**
- Reason: **several** parton-parton collisions within the same proton-proton collision
- Definition: **underlying event** = all interactions except hard scattering process (which includes initial state and final state radiation, and beam remnant)
- MC codes include underlying event **models** (tuned to data)

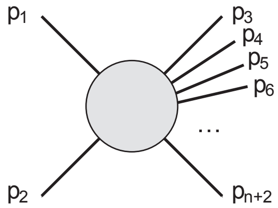
Hard-Scattering Matrix Elements

- First generation of MC codes: **LO** ME for **2→1 and 2→2 processes** → available for all SM and BSM processes
- Improvement I: **LO** matrix elements for important **2→*n* processes**, mostly: **additional real emission** of quarks/ gluons → jets (approximation of higher orders)
- Improvement II: **NLO matrix elements** (= **real** emission + **virtual** corrections = loops) → 2019: available for all SM processes and many BSM processes
- Improvement III: **automation** of ME computations (especially at NLO)

2→2 Process
(e.g. pp → $t\bar{t}$)



2→*n* Process
(e.g. pp → $t\bar{t}$+(n–2) jets)



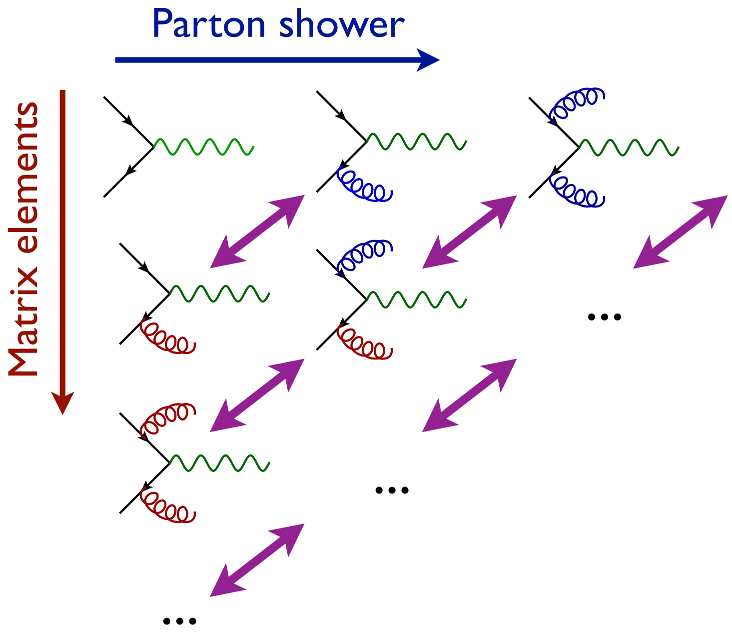
Modern MC Frameworks

- General-purpose SMC codes: **Pythia**, **Herwig**, **Sherpa**
- **LO** for **2→*n*** processes → combination with SMC (non-trivial)
  - **ALPGEN**
  - **MadGraph5_aMC@NLO** (MG5aMC)
  - **Sherpa** (2→*n* processes included in SMC)
- **NLO** (comb. with SMC even less trivial)
  - **POWHEG BOX**
  - **MG5aMC**

Further examples:

- Modern SMC codes also allow using **external ME providers** (e.g.: OpenLoops, GoSam, MG5aMC)
- **Specialized MC code** for important processes (e.g. VBFNLO = parton-level MC for processes with electroweak bosons)

Double Counting and MC Matching



F. Maltoni

- Real emission from both LO 2→n matrix element (ME) and parton shower (PS) → **double counting**
- Solution: **matching** between ME and PS, **removal** of overlap
- Matching algorithms:
  - **MLM** matching (Mangano), e.g. in ALPGEN, MG5aMC
  - **CKKW(-L)** matching (Catani, Krauss, Kuhn, Webber; Lönnblad), e.g. in Sherpa, MG5aMC

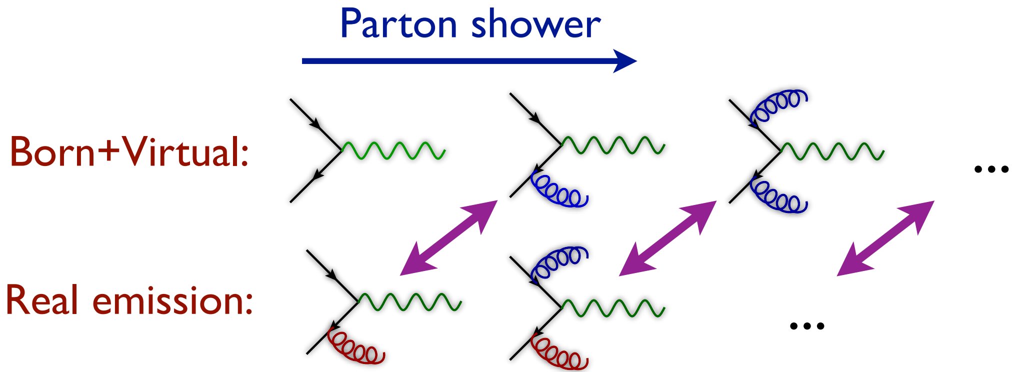
How to Match

- General idea: use ME (PS) only in those areas of phase space where ME (PS) works best

Matrix Element	Parton Shower
fixed order	resummation
numerically expensive	numerically cheap
number of final-state particles limited	arbitralily many final-state particles
works best for hard, well-separated partons	works best for soft/collinear partons

NLO Generators and NLO Merging

- NLO matrix elements: **real** and **virtual** corrections
- Problem: real emission does not only include hard, well separated partons, radiation may also be **soft/collinear**
    - Different separation between NLO ME and PS compared to LO
    - Correct for **two-fold double counting**: real emission & parton shower, virtual corrections and Sudakov form factor
    - Double counting removed by **NLO merging** algorithms (several methods)



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Short Summary

- MC generators may be classified by:
  - Available **physics processes**
  - **Highest order** in perturbation theory for hard scattering matrix elements
  - **Number** of outgoing particles
  - **Partonic** or **hadronic** final state
  - **“Link”** (=matching/merging) between matrix element and parton shower
- Classes of MC generators:
  - Pure parton-level MC generator (LO or NLO)
  - General-purpose parton shower MC generator (SMC)
  - LO matrix element provider combined with parton shower (ME+PS)
  - NLO matrix element provider combined with parton shower (NLO+PS)

PHYSICS OBJECTS

Reminder: Cross Section Formula

Number of events observed in detector

just count…

Background

measured in data or from theory prediction

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L}\,\mathrm{d}t \cdot \varepsilon}$$

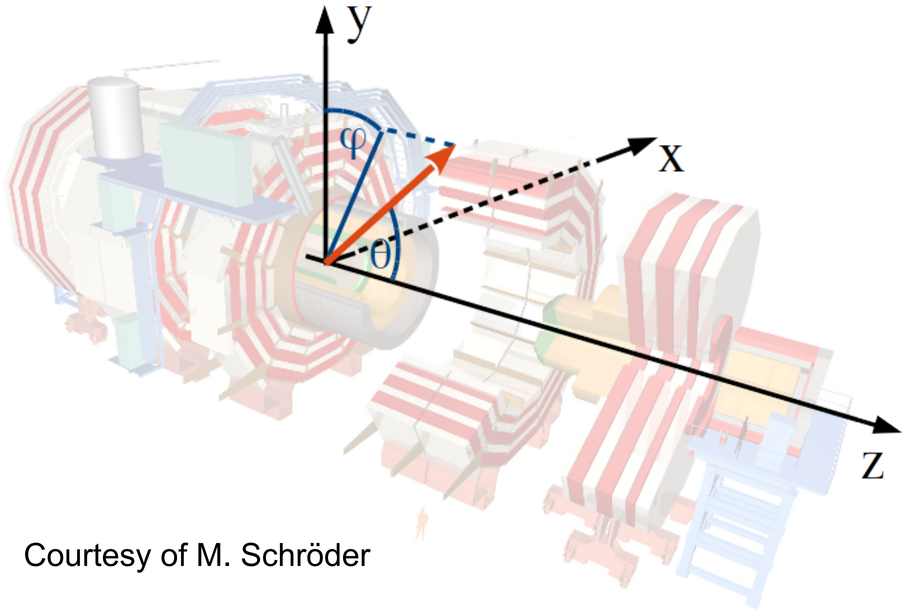
Luminosity

depending on accelerator, trigger, …

Efficiency

Acceptance and efficiency of detection, analysis-specific optimization

Reminder: Collider Kinematics



Courtesy of M. Schröder

- Coordinate system:
  - **Right-handed** system, origin: **center of detector** = nominal collision point
  - **Cartesian** coordinates: *z* axis along counter-clockwise beam direction, *x* axis pointing towards center of the ring, *y* axis pointing upwards
  - **Polar** coordinates: polar angle θ = angle with *z* axis, azimuthal angle ϕ in *xy* plane, measured from *x* axis

Reminder: Collider Kinematics

- Typical **hadron collider observables**:
  - Partonic center-of-mass frame unknown → use **transverse** quantities (invariant under Lorentz boosts along beam axis)
  - Particle-level observables: **transverse momentum** and **pseudorapidity**

$$p_T = \sqrt{p_x^2 + p_y^2} \qquad \eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

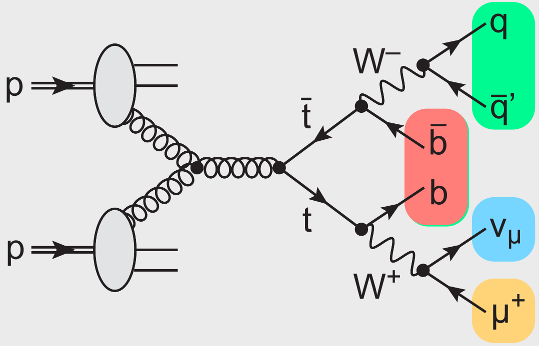
→ four-momenta of particles: particle mass (hypothesis), p_T, η, ϕ

  - **Energy/momentum-sum** observables: **missing transverse momentum**

$$\mathbf{p}_T^{\text{miss}} = -\sum_{\text{rec. particles}} \begin{pmatrix} p_x \\ p_y \end{pmatrix} \quad \rightarrow \quad E_T^{\text{miss}} \equiv p_T^{\text{miss}} \equiv \text{MET} \equiv \left|\mathbf{p}_T^{\text{miss}}\right|$$

Event Selection

Example of cut-based event selection: top lepton+jets selection



Lepton with $p_T > 20$–30 GeV

Neutrino: MET > 30 GeV

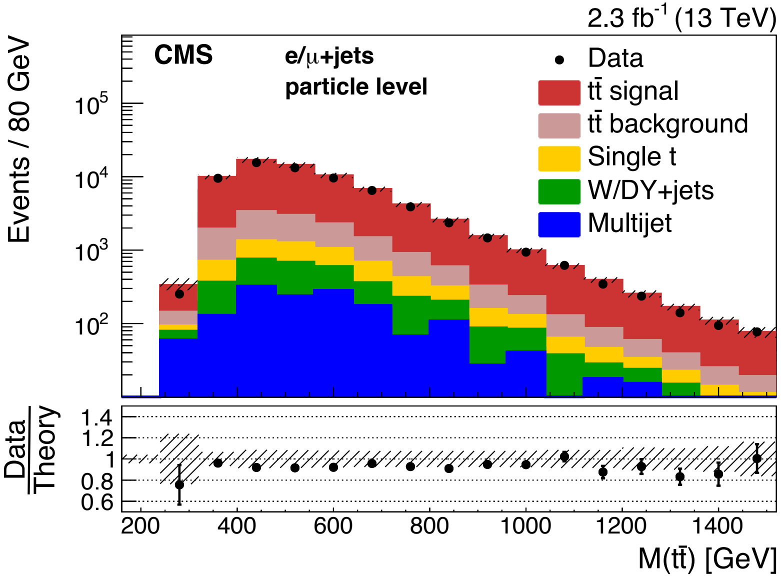
4 jets with $p_T > 40$ GeV

2 of the jets from *B* decays: *b*-tags

- “Art” of data analysis: select events such that signal and background are **optimally separated**
- **Optimization** of selection:
  - Criterion: signal/background ratio $N^{\text{sig}}/N^{\text{bkg}}$
  - Criterion: signal significance $N^{\text{sig}}/\sqrt{N^{\text{sig}} + N^{\text{bkg}}}$
  - Note: use simulated data for optimization, **never optimize the signal on data!**
- **Many methods**, from simple (“cuts”) to sophisticated (multivariate methods)

Background

- **Physics**: which processes **cannot be distinguished** from signal?
- **Instrumental** backgrounds:
  - Detector noise
  - Misidentified objects (“fakes”), e.g. jet misreconstructed as electron
- Example: most important background processes in Higgs and top physics
  - *W* and *Z* boson production in association with jets (“*W/Z*+jets”)
  - QCD multijets



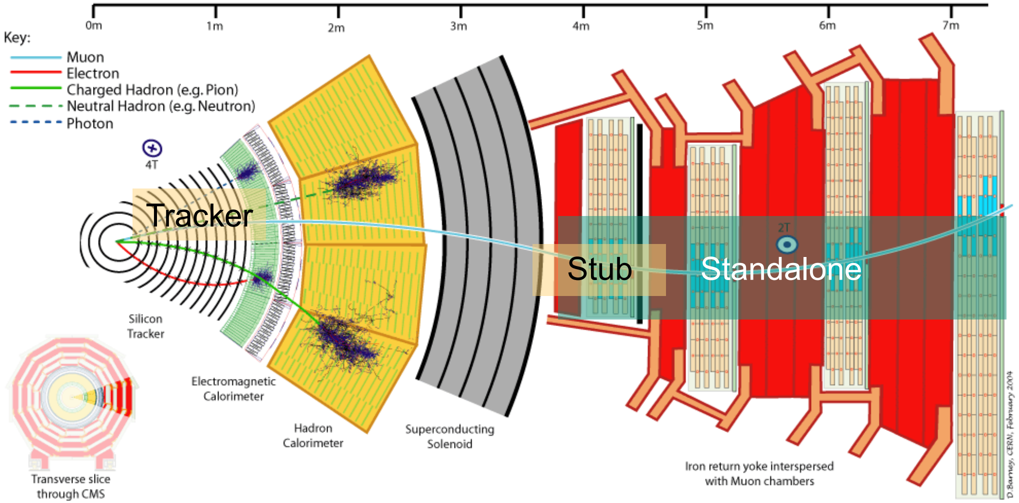
Phys. Rev. D95 (2017) 092001

Hierarchy of Analysis Objects

- Most important physics objects:
  - **Muon**: matching tracks in tracking detector and muon detector
  - **Electron**: ECAL cluster matched to track
  - **Photon**: ECAL cluster without track, conversion into e^+e^-
  - **Charged hadron**: HCAL cluster matched to track
  - **Neutral hadron**: HCAL cluster without track
  - **Jet**: bundles of calorimeter clusters and/or tracks/hadrons
  - **b-Jet**: jet containing B-hadrons
  - **Hadronic tau**: thin jet-like bundle, e.g. one or three charged hadrons
- All physics objects must be **calibrated**:
  - General rule: know where to trust your simulation (and where not)
  - In practice: mixture of **MC-based** and **data-driven** methods

Muon Reconstruction

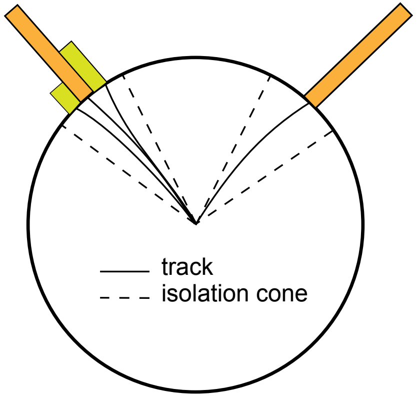
- Typical muon reconstruction strategies (CMS jargon):
  - **Standalone** muons: only reconstructed with muon detector
  - **Tracker** muons: track segment in tracker, “stub” in muon detector
  - **Global** muons: track segments in tracker and muon detector combined



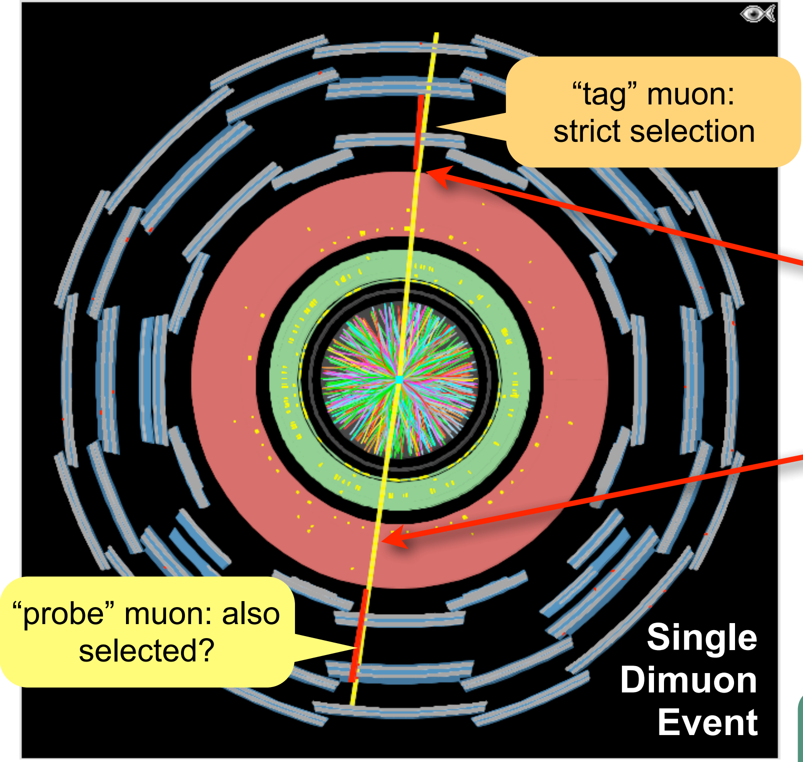
D. Barney, CMS Detector Slice, CC-

Muon Identification

- Muon identification (ID) algorithms:
  - Criteria: quality of track fit, number of tracker layers with hits, impact parameters w.r.t. primary vertex, low energy deposit in calorimeters (MIP)
  - Muons from electroweak decays (e.g. *W*, *Z*): improved ID using track or calorimeter **isolation** (low transverse momentum sum of tracks/energy deposits around muon)
  - Today: combined in **multivariate muon ID** variable
- Muon selection: pre-defined **working points,**
  - Typically: “loose” for high efficiency, “tight” for high purity
  - Advantage: muon ID efficiency determined **centrally**, e.g. by **tag&probe** method (→ next slide)



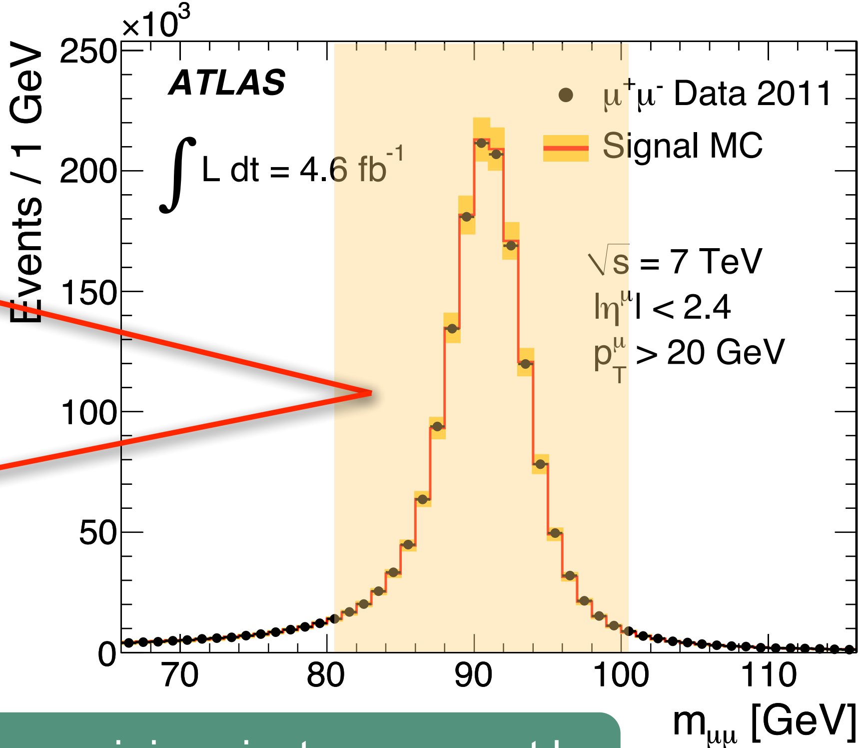
Muon Efficiency: Tag&Probe



“tag” muon: strict selection

“probe” muon: also selected?

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayStandAlone



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-06/

Muon pair invariant mass: must be in window around *Z*-boson mass

Tag&Probe Method

- Kinematic **constraint**: muon pair invariant mass in **window around *Z*-boson mass** (width ≥ natural width ⊕ detector resolution)
- **Tag&probe** algorithm:
  - “**Tag**” muon: **strict** selection, e.g. muon trigger and clean reconstruction
  - “**Probe**” muon: opposite charge, **looser** selection criteria (e.g. no trigger)
  - **Tag&probe efficiency** (often as a function of kinematics, e.g. p_T and η):

$$\epsilon_{\text{tag\&probe}} = \frac{N_{\text{tag\&probe}}}{N_{\text{tag}}}$$

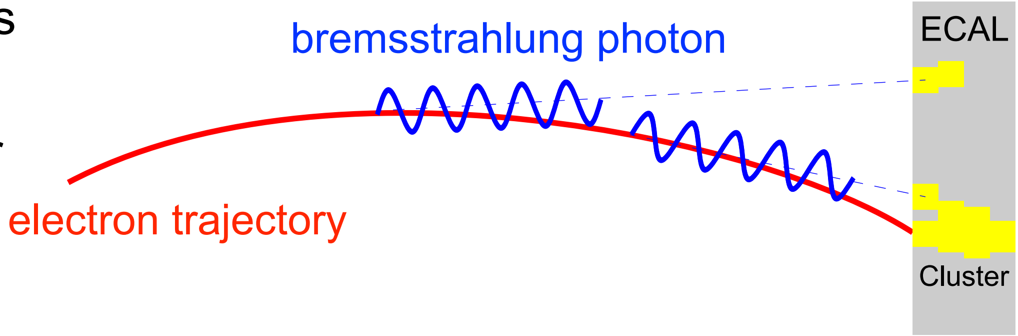
(proper determination of uncertainties → tutorial)

  - Compute tag&probe efficiency in data and simulation: determine **correction factor** (“scale factor”) for simulation (again: as a function of kinematics)

$$\text{SF} = \frac{\epsilon^{\text{data}}_{\text{tag\&probe}}}{\epsilon^{\text{MC}}_{\text{tag\&probe}}}$$

Electron Reconstruction and ID

- Typical electron reconstruction strategy:
  - **Clustering** of energy deposits in calorimeter cells
  - **Matching** of track and cluster
  - **Bremsstrahlung** recovery



- Electron identification:
  - Criteria: number of tracker layers with hits, impact parameter w.r.t. primary vertex, shape of electromagnetic shower, leakage into HCAL, …
  - **Isolation**: similar to muons
  - Today: combined in **multivariate electron ID** variable (loose, tight, …)

Summary

- Hierarchy of analysis objects:
  - Hits/clusters → tracking and calorimeter objects → **physics objects** (charged leptons, jets, b-jets, boosted objects …)
  - Lepton ID: **multivariate** discriminant, isolation
- All objects must be properly calibrated:
  - Tracks: **alignment** of tracking detectors
  - Leptons: **scale factors**, e.g. via tag&probe method