Teilchenphysik 2 — W/Z/Higgs an Collidern

Sommersemester 2019

Matthias Schröder und Roger Wolf | Vorlesung 7

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)

Kolloquium des Graduiertenkollegs
‘‘Elementarteilchenphysik bei höchster Energie und höchster Präzision’’ und von KSETA

Liebe Doktorandinnen und Doktoranden,

am Donnerstag, dem 6. Juni 2019, spricht

Maria Cepeda Hermida (CIEMAT) über

‘‘Precision Higgs physics at the HL-LHC and beyond’’

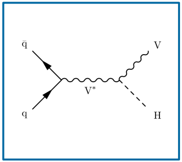
Einführung: Matthias Schröder
Ort: Kleiner Hörsaal A
Zeit: 15.45 - 17.15 Uhr

Programme

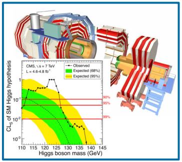
Basics of
electroweak theory

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\Psi}\not{D}\psi \\ &+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ &+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.\end{aligned}$$

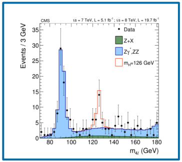
From theory
to observables



Experimental
techniques



Results and
open questions



Cross Section

- Measure of **transition rate** *initial* $\rightarrow$ *final* state for given process
- Follows from Fermi's golden rule:

$$\sigma = \frac{|\text{matrix element}|^2 \cdot \text{phase space}}{\text{flux of colliding particles}}$$

  - matrix element: probability amplitude, encodes process dynamics
  - phase space: number of available final states

- **Link between**
  - **theory**: compute cross section
  - **experiment**: measure cross section

Measuring the Cross Section

Number of events observed in detector
just count . . .

Expected background
from theory prediction
or measured in data

$$\sigma = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\int \mathrm{d}t\mathcal{L} \cdot \epsilon}$$

Luminosity
depending on
accelerator, trigger, . . .

Efficiency
acceptance and efficiency
of detection,
analysis optimisation

Analysis Chain

Nature $\overset{?}{\longleftrightarrow}$ Theory

$\Downarrow$ $\Downarrow$

Detector: data recording
calibrated digitised data
online selection (trigger)

MC simulation
physics process
detector signals

$\Downarrow$

Physics object **reconstruction**
Event **selection**

$\Downarrow$

Statistical analysis: **results**
Comparison with theory

Analysis Chain

Nature $\overset{?}{\longleftrightarrow}$ Theory

$\Downarrow$ $\Downarrow$

Detector: data recording calibrated digitised data online selection (trigger)	**MC simulation** physics process detector signals

$\Downarrow$

Physics object **reconstruction**
Event **selection**

$\Downarrow$

Statistical analysis: **results**
Comparison with theory

3. From Theory to Experiment (and Back)

3.1 From theory to observables

- Cross-section calculation: basic picture
- Fermion propagator and perturbation theory
- Scattering matrix and Feynman rules

3.2 Reconstruction of experimental data

- Reminder: accelerators and particle detectors
- Trigger
- Reconstruction of physics objects

3.3 Measurements in particle physics

- Basic tools (PDFs, Histograms, Likelihood)
- Parameter estimation
- Hypothesis testing
- Determination of physics properties (confidence intervals)
- Search for new physics (exclusion limits)

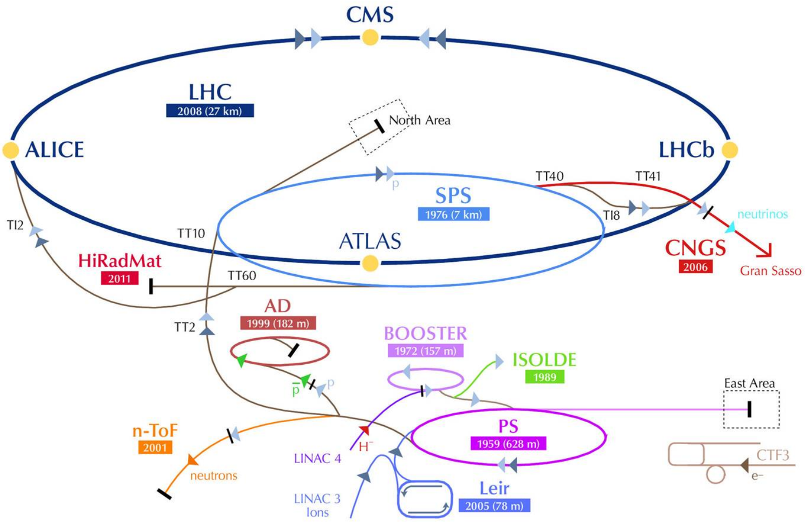
3.4 Experimental techniques

- Efficiency measurements
- Background estimation

3.2 Reconstruction of experimental data

3.2.1. Reminder: accelerators and particle detectors

CERN Accelerator Complex



Reminder: Luminosity

- **Instantaneous luminosity $\mathcal{L}$**: property of experimental setup
  - Relates collision rate and cross section: $\mathrm{d}N/\mathrm{d}t = \mathcal{L} \cdot \sigma$
  - Unit: $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, $10\,\mathrm{Hz}\,\mathrm{nb}^{-1} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  - **At colliders** assuming head-on collisions of two bunched beams with Gaussian beam profiles

$$\mathcal{L} = \boxed{f \cdot n_b} \cdot \frac{\boxed{n_1 \cdot n_2}}{\boxed{4\pi\sigma_x\sigma_y}}$$

particles per bunch

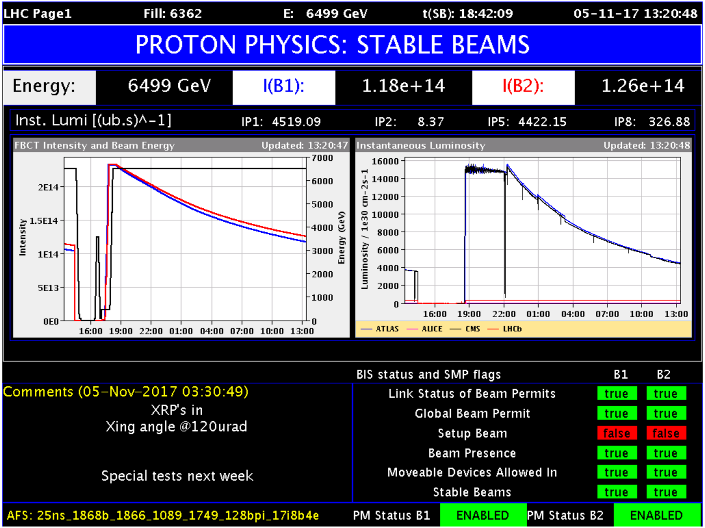
revolution frequency, number of bunches

beam-beam cross-section

beam profiles $\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta^*_{x,y}}$ from
- normalised emittance $\epsilon_{x,y}$
- beta function $\beta^*_{x,y}$

- **Integrated luminosity**: $L \equiv L_{\mathrm{in}} = \int \mathrm{d}t\mathcal{L} \rightarrow N = L \cdot \sigma$
  - Measure of dataset size (unit: cm^{-2}, $1\,\mathrm{fb}^{-1} = 10^{39}\,\mathrm{cm}^{-2}$)
  - Cross-section measurements: **small uncertainty on L_{int}** desirable
    $\rightarrow$ precise luminosity determination mandatory
    (e. g. CMS 2017: 2.3 % CMS-PAS-LUM-17-004)

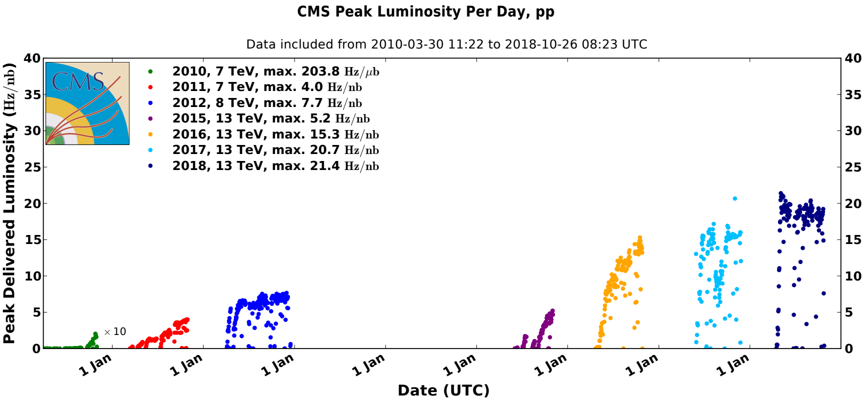
We Want: Many Collisions!



LHC Page 1

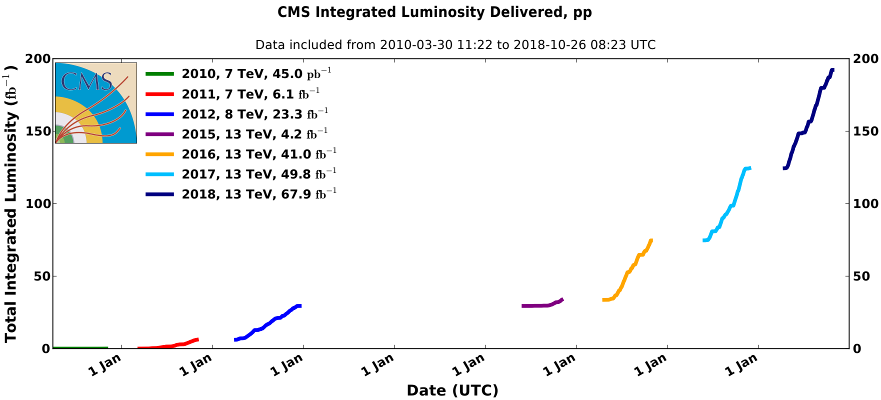
LHC Luminosity

[https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults]

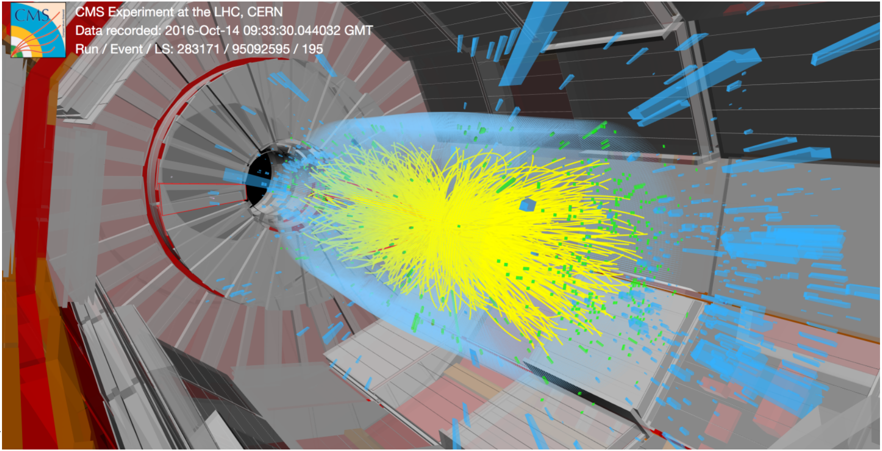


LHC Luminosity

[https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults]

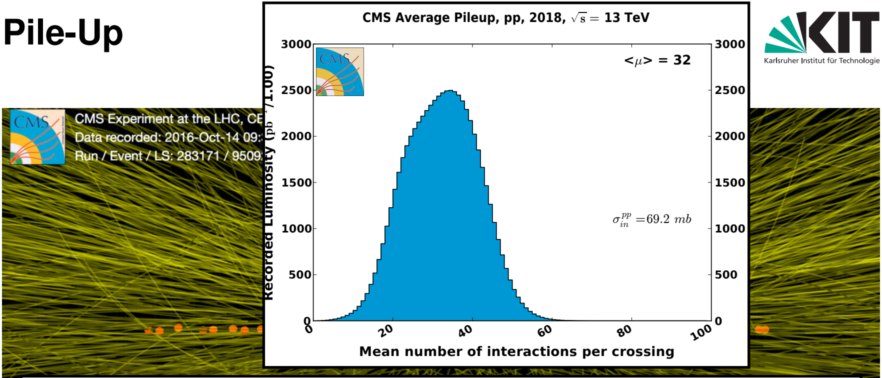


Pile-Up



https://cds.cern.ch/record/2231915

Pile-Up



https://cds.cern.ch/record/2231915

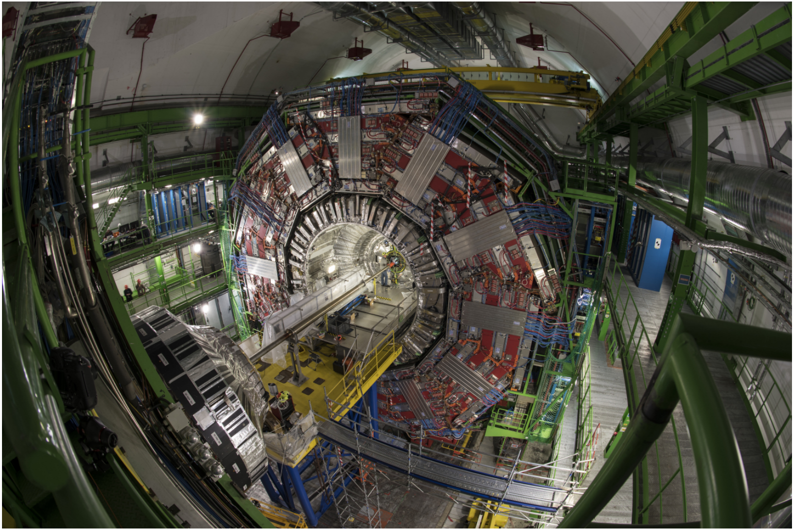
Pile-up: **simultaneous pp collisions in same bunch crossing**

- Rough rate estimate:
  $15\,\mathrm{Hz\,nb}^{-1} \times 100\,\mathrm{mb} = 1.5\,\mathrm{GHz} = 37.5 \times 40\,\mathrm{MHz}$
  $\rightarrow$ almost **40 simultaneous pp collisions** on average
- **Callenge: additional particles** $\rightarrow$ higher detector occupancy, tracking ambiguities, worse resolution

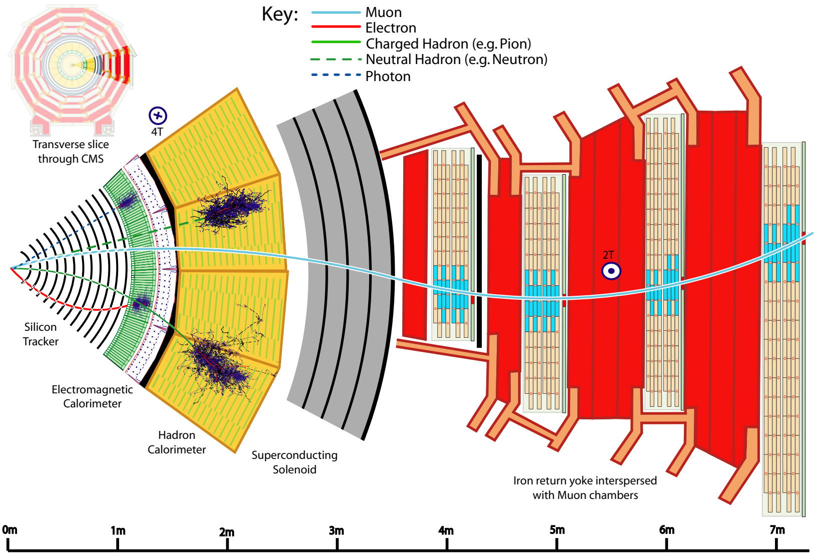
In-time and Out-of-Time Pile-Up

- **In-time** pile-up: effects of simultaneous collisions in the **same** bunch crossing
  - What we have discussed so far
- In addition, **out-of-time** pile-up: effects of collisions in **previous** and **following** bunch crossings
  - Depends on filling scheme of accelerator (gaps between batches)
  - Relevant if pulse shape in readout electronics much longer than bunch spacing
- Detailed in-time and out-of-time **pile-up simulation** in MC datasets

Particle Detector (Example: CMS)



Particle Detector (Example: CMS)



cms.cern

Data Rates at the LHC

- Rough estimate: analogue signals from 100 million detector channels, 8-bit digitisation, 40 MHz readout $\rightarrow$ **4000 TB s^{-1} of raw data**
- LHC data rate **impossible to store** with current technology

$\rightarrow$ **parallelisation** and multi-step **data reduction**

- **Massively parallelised** processing: first processing **at detector front-end**
- Early **zero suppression**: read out channels with **non-zero signals** only
- **Fast online selection** of interesting events: **trigger system**

Data Rates at the LHC

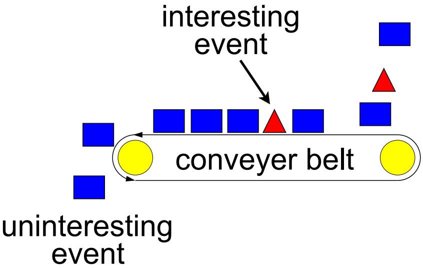
- Rough estimate: analogue signals from 100 million detector channels, 8-bit digitisation, 40 MHz readout $\rightarrow$ **4000 TB s^{-1} of raw data**
- LHC data rate **impossible to store** with current technology

$\rightarrow$ **parallelisation** and multi-step **data reduction**

  - **Massively parallelised** processing: first processing **at detector front-end**
  - Early **zero suppression**: read out channels with **non-zero signals** only
  - **Fast online selection** of interesting events: **trigger system**

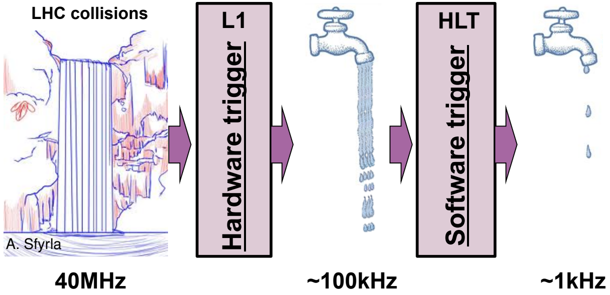
3.2.2. Trigger

Trigger



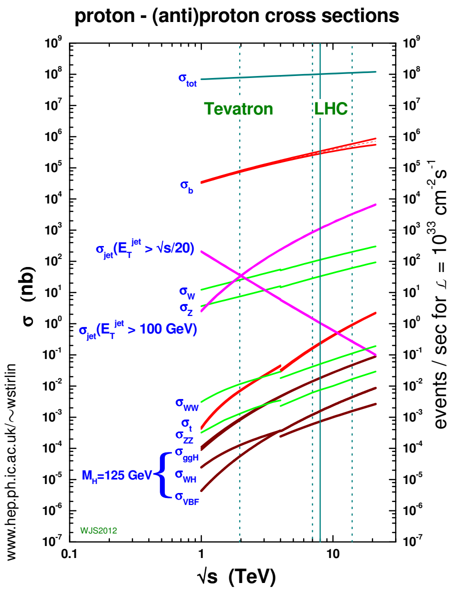
- Trigger: **multi-level online data filter**
  - Data stored in **buffers** at detector front-end
  - Data read out if accepted by trigger, discarded otherwise
- Trigger is **crucial part of experiment**
  - Events that are lost by the trigger can never be recovered
  - Mistakes in the trigger cannot be fixed a posteriori

Trigger Rates



- Trigger systems at the LHC: rate **suppression by factor 10^6**
  - **Level-1 trigger** (L1): fast (few µs) pre-selection of simple signals using **custom electronics**
    $\rightarrow$ L1 accept rate: 100 kHz (100 GB s^{-1})
  - **High-level trigger** (HLT): slower (several 100 ms) processing of pre-selected events on **large farm** of commodity computers
    $\rightarrow$ HLT accept rate (to storage): 1 kHz (1 GB s^{-1})

Interesting Physics: Event Rates



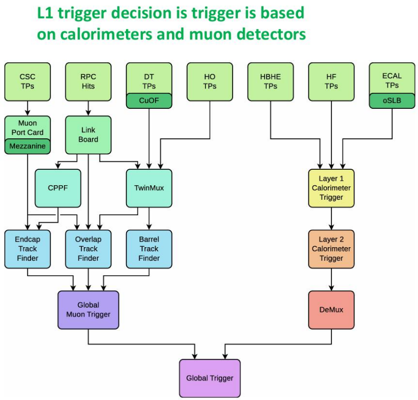
← input rate: 1 GHz (10^{34} cm^{-2} s^{-1})

← storage rate: 1 kHz (10^{34} cm^{-2} s^{-1})

Much of "interesting physics" at low rates

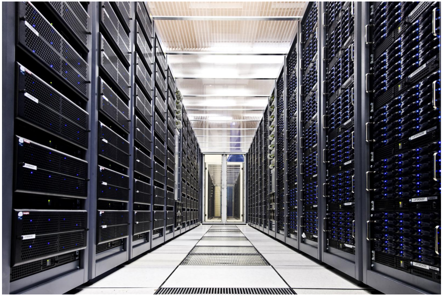
L1 Trigger: from 1 GHz to 100 kHz

- Events kept in readout buffers until **very fast L1 decision** (3.2 μs)
  - L1 rate limited by hardware: exceeding it results in dead time
- L1 input: data from **muon detectors** and **calorimeters**
  - Coarse: readout with **reduced granularity**
- L1 trigger menu ($\approx$ 400 seeds)
  - **Single object**: muons, electrons, photons, taus, jets
  - **Global**: energy sums, $\not{E}_{\mathrm{T}}$
  - Different **thresholds**, e. g. on p_{T}
  - **Logical OR** of individual seeds: topolocial cuts, e. g. dijets
- If L1 accepts event: event fully readout and sent to HLT

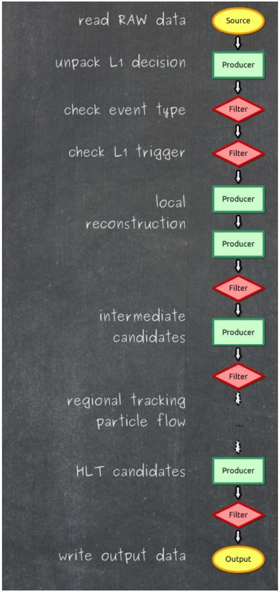


HLT: from 100 kHz to 1 kHz

- HLT selection **purely software based**: more flexibility
  - Dedicated farm: 26 000 processor cores
- Time budget per event 260 ms (with some flexibility)
- Input: data from **all sub-detectors at full granularity**
- Data processing with **“offline-like” algorithms**
  - Most time-consuming: track reconstruction

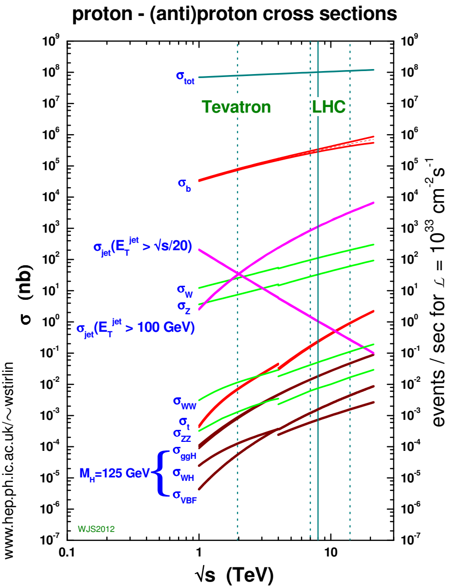


HLT Path



- Selection that targets specific events
  - L1 decisions combined and refined
- Each path consists of **several modules** that perform **reconstruction or filtering**
  - Filters can stop execution along a path (other paths not affected: parallel execution)
  - Goal: **stop each path as early as possible**
- For HLT, **order of modules matters**
  - Try to reject uninteresting events as fast as possible: run fast reconstruction (calorimeter, muons) first and slower ones (tracking) later
  - Instead offline reconstruction: must run all algorithms for every event

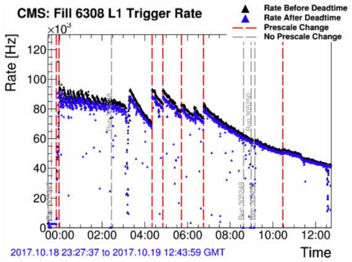
Trigger Prescales



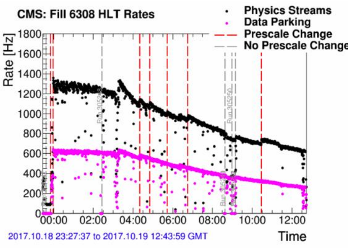
- For some processes of interest, **event rates still too high** to keep every event
  - e. g. jet with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$
- But still need at least some of the events for physics analysis or background studies
- **Prescale factors ("prescales")** applied at L1 and HLT
  - Prescale n = every n-th event that trigger accepts is recorded

Trigger Prescales

- Instantaneous **luminosity decreases** during fill
  - Losses from collisions, increasing emittance, . . .
- **Adapt prescale factors** as a function of luminosity ("prescale columns")
  - L1 and HLT prescales usually changed at the same time
  - Further L1 seeds can also be enabled



L1 trigger rate:
~100 kHz
HLT output rate:
~1kHz on average



HLT Menu

Karlsruher Institut für Technologie

- Approximately 500 HLT paths
  - Many of them differ only in thresholds and are a subset of others

HLT path (for 1.5E34)	1.6E+34	1.5E+34	1.4E+34
HLT_IsoMu_24	27	**24**	24
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8	17,8	**17,8**	17,8
HLT_Ele32_WPTight_Gsf	32	**32**	27
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ	23,12	**23,12**	23,12
HLT_DoubleEle25_CaloIdL_MW	25	**25**	25
HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass95	30,22	**30,22**	30,22
HLT_DoubleMediumChargedIsoPFTau35_Trk1_eta2p1	40	**35**	35
HLT_PFHT1050	1050	**1050**	1050
HLT_PFMETNoMu120_PFMHTNoMu120_IDTight	140	**120**	120
HLT_PFMETNoMu120_PFMHTNoMu120_IDTight_PFHT60	120	**120**	120

Example: part of HLT menu from 2018

Streams and Datasets

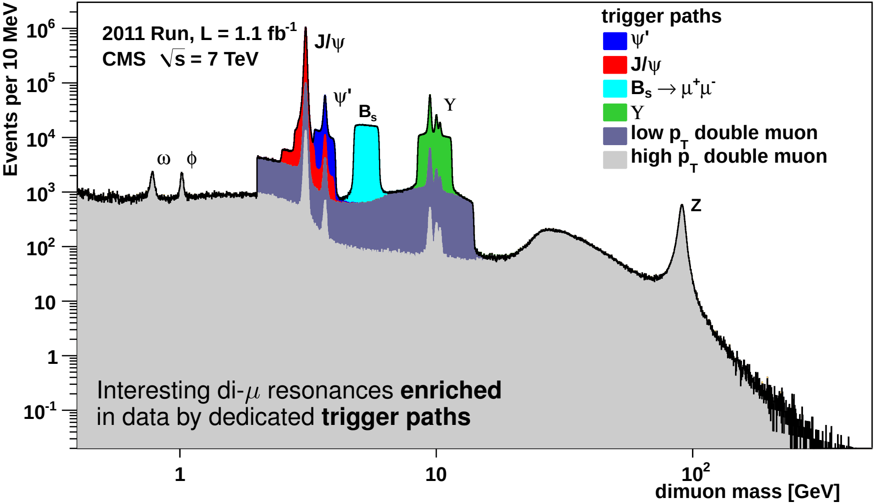
Karlsruher Institut für Technologie

- Data split into different **non-exclusive streams depending on passed HLT paths**

Physics streams	$\approx 1\,\mathrm{kHz}$	(MB/event)
Trigger studies	$\approx 10\,\mathrm{kHz}$	(kB/event)
DQM/monitoring	$\approx 1\,\mathrm{kHz}$	(kB/event)
Alignment & calibration	$\approx 10\,\mathrm{kHz}$	(varying)

- Streams sub-divided into “primary datasets” (PD)
  - Subsets of the full data with similar topologies, e. g. two muons, MET
  - PDs are reconstructed and sent to computing centres for analysis

Example: Dimuon Resonances



twiki.cern.ch

Analysis Chain

Nature $\overset{?}{\longleftrightarrow}$ Theory

$\Downarrow$ $\Downarrow$

Detector: data recording
calibrated digitised data
online selection (trigger)

MC simulation
physics process
detector signals

$\Downarrow$

Physics object **reconstruction**
Event **selection**

$\Downarrow$

Statistical analysis: **results**
Comparison with theory

3.2.3. Reconstruction of physics objects

Hierarchy of Analysis Objects

Karlsruher Institut für Technologie

- Basic **detector** objects
  - **Hits** in single detector cells (e. g. digitised signal of charge deposited in single silicon pixel)
  - **Clusters** of hits in adjacent cells (e. g. energy deposits of electromagnetic showers in ECAL, charge sharing between silicon pixels)
- **Tracking** objects
  - **Tracks**: patterns of hits/clusters in several detector layers
  - **Vertices**: common origin of $\geq$ 2 tracks
- **Calorimeter** objects: groups of energy deposits

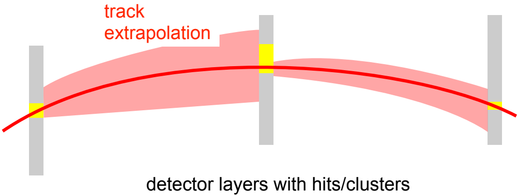
Hierarchy of Analysis Objects

- Most important physics objects
  - **Muon**: matching tracks in inner 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**: bundle of calorimeter clusters and tracks or of reconstructed particles
  - **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**
  - Mixture of **MC-based** and **data-driven** methods

Tracking at the LHC

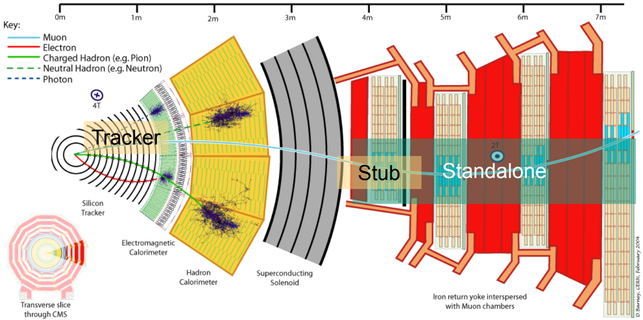
- Tracking **strategies**
  - **Standalone** tracking: separate reconstruction in each subdetector
  - **Inside-out** tracking: track seed in innermost detector layers (pixel detector), extrapolated to outer layers
    $\rightarrow$ more than 90 % of all tracks
  - **Outside-in** tracking: track seed in outer detector layers
    $\rightarrow$ additional secondary particles from decays and photon conversion

- Tracking **algorithms**: **iterative**, often variants of **Kalman filter**
  - Equivalent to global χ^2 fit but avoids inversion of large covariance matrix
  - Easy to incorporate multiple scattering



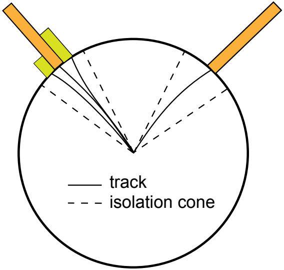
Muon Reconstruction

- 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



Muon Identification

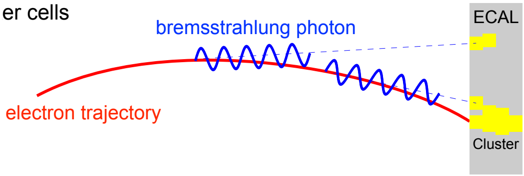
- Muon identification (ID) algorithms
  - Criteria: quality of track fit, number of tracker layers with hits, impact parameter w. r. t. primary vertex, low energy deposit in calorimeters (MIP)
  - Muons from electroweak decays (e. g. W, Z): improved ID using track or calorimeter **isolation** (low p_T sum of tracks/energy deposits around muon)
  - Nowadays: 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**

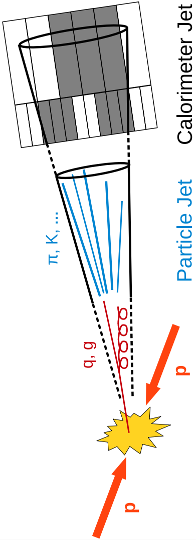
Electron Reconstruction and ID

- 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, . . . (depending on calorimeter)
  - **Isolation**: similar to muons
  - Nowadays: combined in **multivariate electron ID** variable (several working points: loose, tight, . . .)

Reminder: Jets



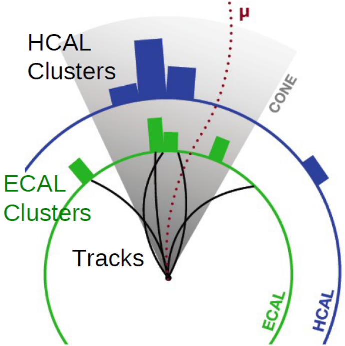
- Jet **definitions**
  - **Parton level** ("theory jets")
  - **Particle level** (stable hadrons)
  - **Detector level** (calorimeter/tracker/reconstructed particles "particle-flow candidates")
- Jet **algorithms**
  - Requirements: independent of definition level, Lorentz invariant, **infrared and collinear safe** (same jet if soft or collinear particle is added)
  - Two main classes: **sequential recombination** and **cone** algorihtms
  - LHC standard: **anti-k_t algorithm** $\rightarrow$ sequential recombination with distance measure

$$d_{ij} = \min\left(\frac{1}{k_{t,i}^2, k_{t,j}^2}\right) \frac{\Delta R_{ij}}{R}$$

(typical choice of radius parameter at LHC Run 2: $R = 0.4$)

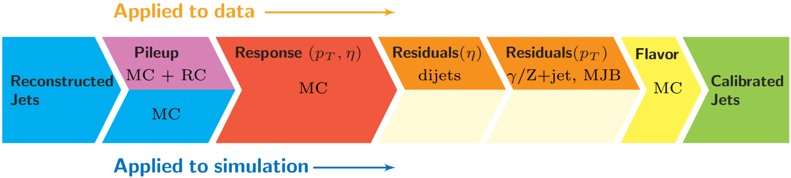
Jet Reconstruction Strategies

- Pure **calorimeter jets** or **track jets**
- **Combination** of calorimeter and tracker information
- **Particle flow**: optimal combination of subdetectors for reconstruction of each particle type (e. g. HCAL energy only for neutral hadrons)



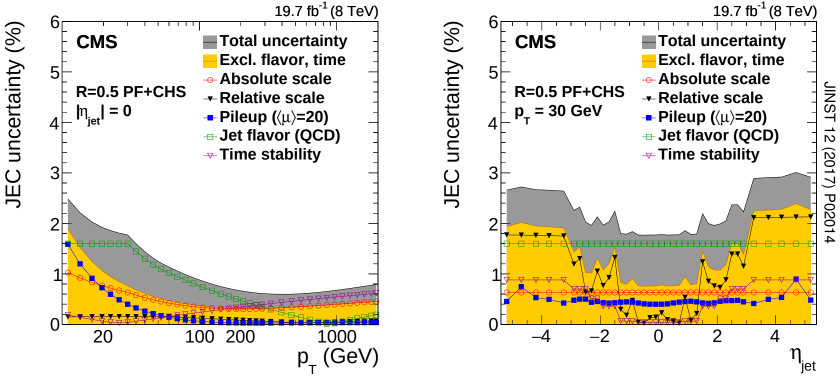
Jet Calibration: CMS Method

- Multi-stage **jet energy corrections** in CMS:



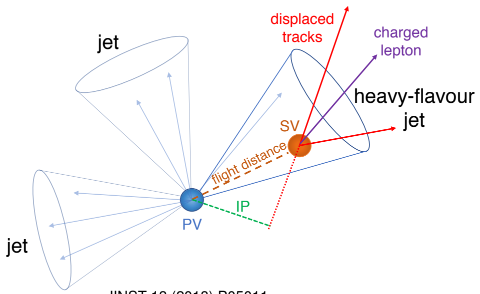
  - **Pile-up** and electronic **noise** (MC based, may be different in data $\rightarrow$ additional "residual" correction)
  - **Response** correction: uniform response as a function of p_{T} and η (MC)
  - **Residual** corrections for data in η (dijet events with one well-calibrated jet in the barrel region)
  - **Residual** corrections for data in p_{T} (balance of Z or γ recoiling against jet)
  - (Optional) **jet flavour** correction: different response from light quarks, gluons, heavy quarks (MC)

Jet Calibration: Results



- Typical **uncertainties** of jet energy corrections: **1–2 %**
- Uncertainties propagated into more complex observables, e. g. $\not{E}_T$
- Jet energy **resolution** in data worse than in MC → “smear” MC

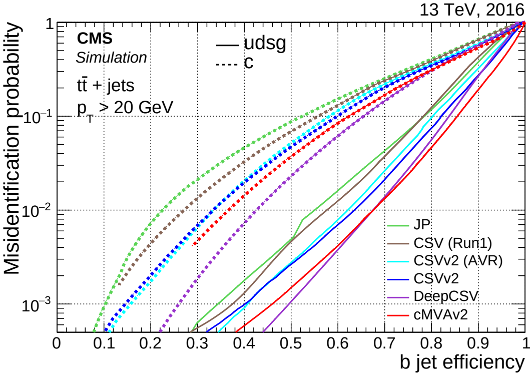
Reminder: B-Tagging



JINST 13 (2018) P05011

- B-tagging algorithms at hadron colliders
  - **Secondary vertex** and **large impact parameter** algorithms: long B hadron lifetime (picoseconds)
  - **Soft lepton** algorithms: semileptonic B hadron decays B $\rightarrow l\nu$X
  - **Large b-quark mass**: wider jets, large relative p_{T} of lepton in B $\rightarrow l\nu$X
  - **Hard b-quark fragmentation**: B-hadron carries most of b-quark energy
- LHC Run 2: algorithms combined in **multivariate** discriminant (DNNs)

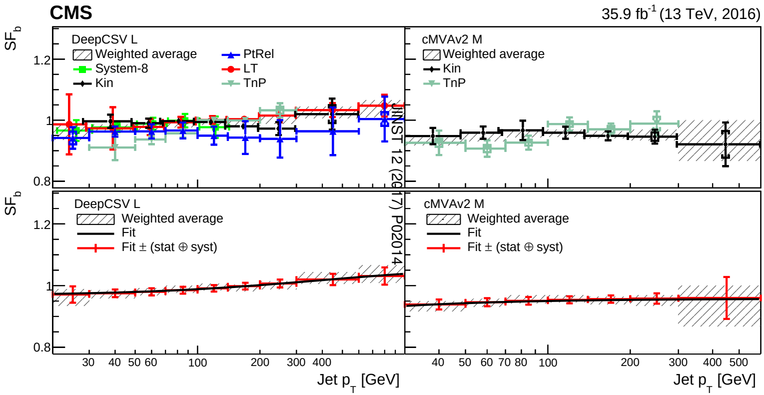
B-Tagging Performance



JINST 12 (2017) P02014

- **b-jet tagging efficiency**: fraction of true b jets tagged as b jets
- **Misidentification probability** (“mistag rate”): fraction of true light-flavour (uds), charm (c), or gluon (g) jets wrongly tagged as b jets
- Representation: **receiver operating characteristic** (ROC)

B-Tagging Calibration



- **Measure** b-tag efficiency and mis-tag rate for benchmark processes (e. g. QCD dijets, $t\bar{t}$) with **different methods** in **data and MC**
- **Correct MC** with scale factors depending on jet kinematics

Summary

- Hierarchy of analysis objects
  - Hits/clusters $\rightarrow$ tracking and calorimeter objects $\rightarrow$ **physics objects** (charged leptons, jets, b jets, . . .)
  - Lepton ID: **multivariate** discriminant, isolation
- All objects must be properly **calibrated**
  - e. g. jets: multi-stage calibration of **energy scale**
  - e. g. b jets: **scale factors** for difference in efficiency/mis-tag rate in data and MC

Programme

Date	Room	Type	Topic
Wed Apr 24.	Kl. HS B	LE 01	1. Organisation and introduction: particle physics at colliders + W/Z/H history
Tue Apr 30.	30.23 11/12	—	*no class*
Wed May 01.	Kl. HS B	—	*no class*
Tue May 07.	30.23 11/12	LE 02	2.1 Gauge theory & 2.2 The electroweak sector of the SM I
Wed May 08.	Kl. HS B	LE 03, EX 01	2.3 Discovery of the W and Z bosons & EX gauge theories
Tue May 14.	30.23 11/12	LE 04	2.4 The Higgs mechanism
Wed May 15.	Kl. HS B	EX 02	Exercise “SM Higgs mechanism”
Tue May 21.	30.23 11/12	—	*no class*
Wed May 22.	Kl. HS B	LE 05	2.5 The electroweak sector of the SM II (Higgs mechanism + Yukawa couplings)
Tue May 28.	30.23 11/12	SP 01	Specialisation of 2.4 and 2.5
Wed May 29.	Kl. HS B	LE 06	3.1 From theory to observables & 3.2 Reconstruction + analysis of exp. data
Tue Jun 04.	30.23 11/12	EX 03	Exercise “Trigger efficiency measurement”
Wed Jun 05.	Kl. HS B	LE 07	3.3 Measurements in particle physics (part 1)
→ Tue Jun 11.	30.23 11/12	EX 04	Exercise on statistical methods
Wed Jun 12.	Kl. HS B	LE 08	3.3 Measurements in particle physics (part 2)
Tue Jun 18.	30.23 11/12	SP 02	Specialisation “Limit setting”
Wed Jun 19.	Kl. HS B	SP 03	Specialisation “Unfolding”
Tue Jun 25.	30.23 11/12	LE 09	4.1 Determination of SM parameters
Wed Jun 26.	Kl. HS B	LE 10	4.2 Measurement and role of W/Z bosons at the LHC
Tue Jul 02.	30.23 11/12	EX 05	Paper seminar “Z pole measurements”
Wed Jul 03.	Kl. HS B	LE 11	4.3 Processes with several W/Z bosons
Tue Jul 09.	30.23 11/12	EX 06	Paper seminar Higgs
Wed Jul 10.	Kl. HS B	LE 12	5.1 Discovery and first measurements of the Higgs boson
Tue Jul 16.	30.23 11/12	EX 07	Exercise “Machine learning in physics analysis”
Wed Jul 17.	Kl. HS B	LE 13	5.2 Measurement of couplings and kinematic properties
Tue Jul 23.	30.23 11/12	EX 08	Presentations: results of ML challenge
Wed Jul 24.	Kl. HS B	LE 14	5.3 Search for Higgs physics beyond the SM & 5.4 Future Higgs physics