Concepts of Experiments at Future Colliders II

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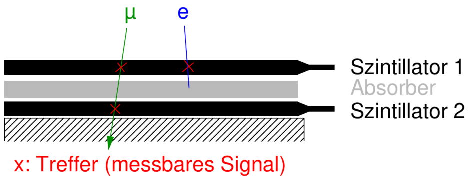
12.07.2024

Trigger systems for experiments at hadron colliders

Example of the coincidence technique

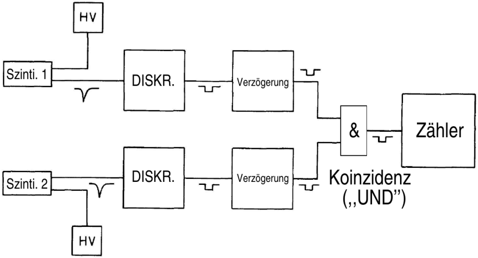
Measurement of the Rates of Muons from Cosmic Rays

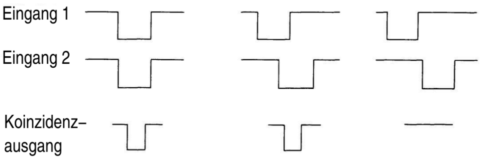
- Simple Setup



- Absorber between two scintillation counters to discard low-energy components from cosmic rays.
- Hits in both scintillators only for high-energy muons ($E_\mu \sim 300$ MeV).

Coincidence Method





Purpose of the trigger (data acquisition trigger)

Selection of those pp collisions that should be recorded for later data analysis.

Operation of the trigger system of the ATLAS

Explanation of the operation of a trigger using the example of the trigger system of the ATLAS experiment at the HL-LHC.

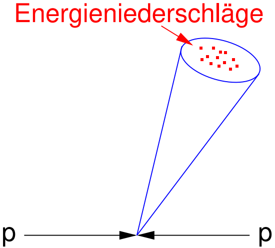
Two-Level System

- Level 1, called L0, for preselection of pp collisions using data from the calorimeters and the muon spectrometer.
  Maximum trigger rate: 1 MHz.
  Available time for the trigger decision, known as latency: <10 μs after a pp collision.
- Level 2, called HLT ("high-level trigger"), for final selection of pp events using data from the entire detector after full event reconstruction.
  Maximum trigger rate: 10 kHz.

Trigger objects in the first trigger level

Using Calorimeter Data

- e/γ: Search for clusters of energy deposits in the electromagnetic calorimeter that do not extend into the hadronic calorimeter.
  $\Rightarrow$ e/γ candidates with η, ϕ, and E_T values.
- Jets: Search for clusters of energy deposits in cone-shaped regions of the calorimeters.



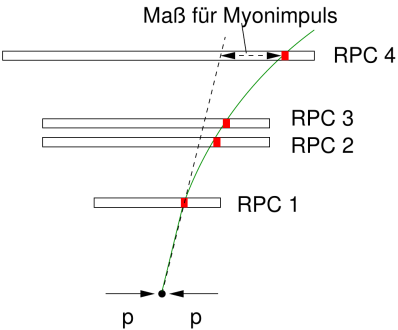
Currently cones with predefined size.
In the future, anti-k_T algorithm.

$\Rightarrow$ Jet candidates with η, ϕ, and E_T values.

- E_T^{miss}: The vector sum of the transverse energies of the energy deposits provides a measure of the missing transverse energy.

Trigger objects in the first trigger level

Using Muon Spectrometer Data ⇒ Muon Candidates



Muon trigger for $|\eta| < 1.05$

Trigger Condition: Coincidence of hits in the 4 RPC layers. Estimates of η, ϕ, and p_T from comparing hit positions.

- RPC trigger chambers are fast. ⇒ Assignment of a detected muon to the pp collision in which the muon was produced is possible.
- Only moderate spatial resolution in the centimeter range. ⇒ Moderate momentum resolution.
- In a second step at L0, the hits in the high-resolution muon drift tube chambers in the vicinity of the RPC hits are used for improved track reconstruction.

⇒ Relative p_T resolution of $\sim 5\%$ is achievable at L0.

Electronics used in the trigger

- Triggerless readout of the calorimeters and muon chambers: Hit data is continuously sent from the detectors over gigabit links to the (remotely located) trigger logic.
- Trigger algorithms for the first level are implemented on FPGAs or FPGAs with embedded microprocessors.
- In the HLT, the inner detector data is quickly reconstructed using specialized pattern recognition chips before the data is processed on a computer farm with full event reconstruction.

⇒ Complex trigger conditions in the HLT are possible, e.g., the requirement for the presence of b-quark and τ-jets.

Physics processes accessible with the trigger

CERN-LHCC-2017-020 ; ATLAS-TDR-029

Physics Drivers @ HL-LHC		Processes	Trigger Signatures	TDR Sect.
Precision measurements of the properties of the Higgs Boson	Couplings to fermions	$H \to \tau\tau$, $H \to \mu\mu$, $t\bar{t}H$, $H \to bb$	single/di-e or μ / di-τ	2.2, 2.4
	Couplings to W/Z, diff. cross-sections	$H \to \gamma\gamma$, $H \to W^+W^- \to \ell^+\nu\ell^-\nu$, $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$	e/μ, di-γ	2.3
	Self-coupling	$HH \to bb\tau\tau$ / $bb\gamma\gamma$ / $4b$	di-τ/γ, multi-jets	2.5
	Scalar Higgs boson vs. BSM composite	$H \to \ell\ell'$, $ZH \to \ell\ell + (\text{inv})$	e/μ	
Precision Standard Model Measurements	Forward/backward asymmetry	$Z \to e^+e^-, \mu^+\mu^-$	single e/μ	
	Vector-boson scattering	$WWjj$, $WZjj$	single e/μ	
	Precision top mass and cross-sections	$t\bar{t}$ production	e/μ, large R-jets/multi-jets	2.1
Searches for BSM Signatures	Searches for new vector bosons	Vector Boson Fusion (VBF) $Z' \to \ell\ell$	high-p_T single e/μ	
	Searches for electroweak SUSY	$\chi_1^+\chi_2^0 \to WH\chi_1^0\chi_1^0$	E_T^{miss}, single/di-e, μ, τ	2.2, 2.6
	SUSY top partners	$\tilde{t}_1 \to t\chi_1^0$	large R-jets/multi-jets+E_T^{miss}	
	Dark matter	ISR+$\chi_1^0\chi_1^0$	jets+E_T^{miss}	
	New resonances, SUSY	$Z', \chi_1^0 \to jjj$	jets, large R-jets, e/μ, γ, E_T^{miss}	2.3, 2.5
	Long-lived particles	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \to \pi^\pm\tilde{\chi}_1^0$	high impact parameter, E_T^{miss}	
Flavour Physics	Lepton Flavour Violation	$\tau \to \mu\mu\mu$	low p_T di-μ	
	Searches for FCNC in top decays	$t \to u/c + H/Z$	single e/μ	
	Rare B-meson decays	$B \to \mu\mu$, $B_s \to J/\Psi + \Phi$	low p_T di-μ	2.10
Heavy-Ion Physics	Light-by-light scattering	$\gamma\gamma \to \gamma\gamma$	low p_T di-photons	
	Electroweak production	W/Z/t	single e/μ	
	In-medium parton energy loss (jets in PbPb)	mono-jets	jet, minbias	
	Quarkonia production	$J/\Psi, \Upsilon$	low-mass di-e/μ	2.11

Summary of the summer semester material

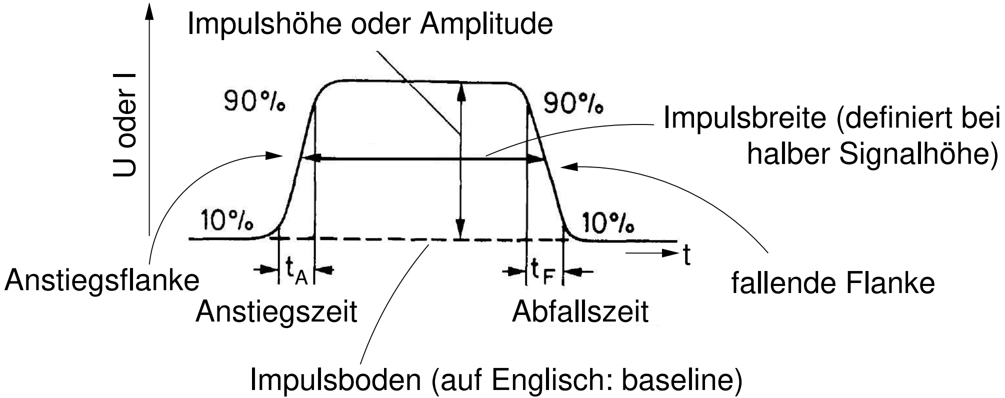
Electronics for detector read-out: signal types

Analog Signal: Contains information in the continuous variation of electrical signal properties, such as pulse height, pulse duration, or pulse shape.

Digital Signal: Information stored in discrete form.

Example. TTL (Transistor-Transistor Logic):
Logical 0: Signal between 0 and 0.8 V.
Logical 1: Signal between 2 V and 5 V.

Advantage of a digital signal: No information loss during small signal disturbances.



Slow Signal: $t_A \gtrsim 100$ ns.

Fast Signal: $t_A \lesssim 1$ ns.

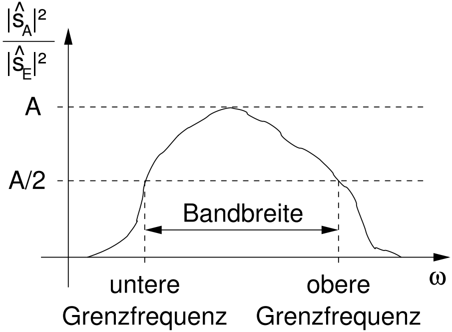
Attenuation and bandwidth

Attenuation

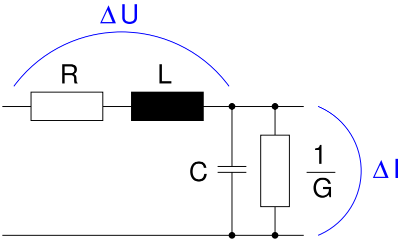
Attenuation [dB] $:= 10 \cdot \log_{10} \left(\frac{|\hat{s_A}|^2}{|\hat{s_E}|^2} \right)$.

$$-3 \text{ dB} = 10 \cdot \log_{10} \left(\frac{|\hat{s_A}|^2}{|\hat{s_E}|^2} \right) \Leftrightarrow \frac{|\hat{s_A}|^2}{|\hat{s_E}|^2} = 10^{-\frac{3}{10}} = \frac{1}{2}.$$

Bandwidth



Equivalent Circuit for a Δz length of a coaxial cable



R, L, C, $\frac{1}{G}$ represent resistance, inductance, capacitance, and conductance per unit length.

In an ideal cable, R and G are both zero.

General wave equation for a coaxial cable

$$\frac{\partial^2 U}{\partial z^2} = LC\frac{\partial^2 U}{\partial t^2} + (LG + RC)\frac{\partial U}{\partial t} + RGU.$$

Ideal cable: R=0, G=0.
$$\frac{\partial^2 U}{\partial z^2} = LC\frac{\partial^2 U}{\partial t^2}$$

(Wave equation with $v = \frac{1}{\sqrt{LC}}$).

Processing analog detector signals

- Analog signals coming directly from particle detectors are generally very small.

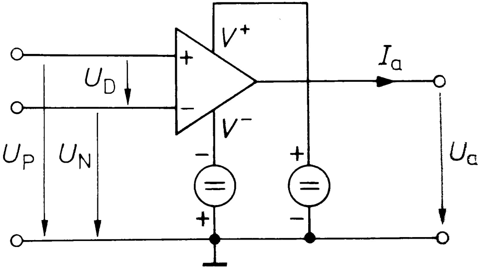
  Example: MDT drift tube with Ar/CO_2 (93:7) at 3 bar.
  $\frac{dE}{dx} = 7.5$ keV/cm$\hat{\approx} 7.5/0.03 = 250$ electron-ion pairs/cm.
  With a gas amplification of 20000, this corresponds to a total charge of only ~ 1 pC.

$\Rightarrow$ Protection of the small signals using a Faraday cage.

$\Rightarrow$ Amplification of the signals.

$\Rightarrow$ Routing of the unamplified signals over the shortest possible distances.

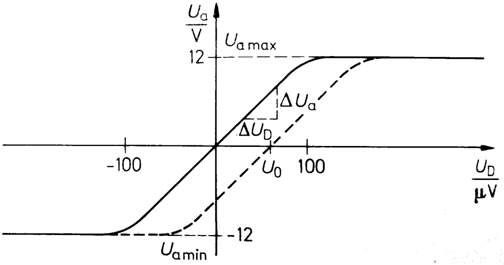
- Operational amplifiers (op-amps) are wideband differential amplifiers with high gain and high input impedance.
- Operational amplifiers are available as integrated circuits using bipolar and field-effect transistors.



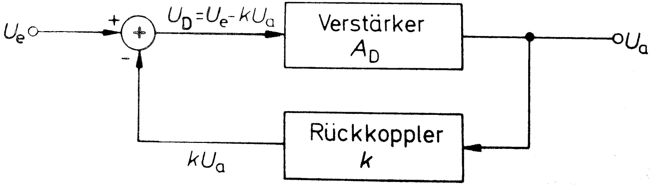
- Input stage configured as a differential amplifier, hence two inputs (+ and -).
- Positive and negative supply voltage required to drive the inputs and outputs positively and negatively.

- Open-loop gain:

$$A_D := \frac{dU_a}{dU_D}.$$



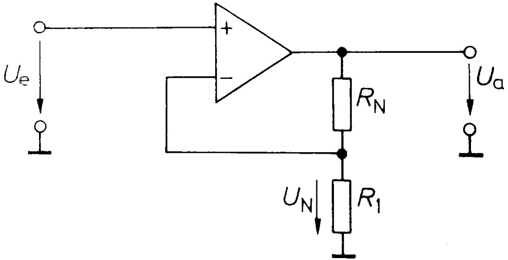
- Offset voltage U_0 can be adjusted in most operational amplifiers.
- Linear dependence of U_a on U_D in a small range around U_0.
- Constant output voltage outside of this range (amplifier saturation).



- $U_a = A_D(U_e - kU_a) \Leftrightarrow U_a = \frac{A_D}{1+kA_D} U_e \underset{A_D \to \infty}{\approx} \frac{1}{k} U_e$.
- $U_P = U_e$, $U_N = kU_a$, $|U_a|$<const. Thus,

$$|U_P - U_N| = \frac{U_a}{A_D} \underset{A_D \to \infty}{\rightarrow} 0,$$

i.e., $\boxed{U_P = U_N}$.



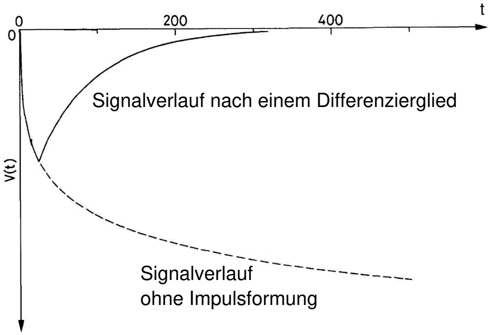
$$U_e = {\color{blue} U_P = U_N} = \frac{R_1}{R_1 + R_N} U_a$$

$$\Leftrightarrow \quad U_a = \left(1 + \frac{R_N}{R_1}\right) U_e.$$

- Positive gain.
- Gain value determined entirely by the choice of R_N and R_1.

Pulse shaping

Introductory example: Signal pulse of a cylindrical drift tube

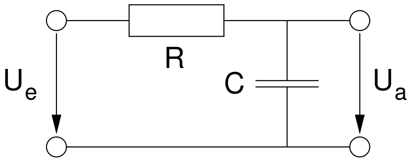


Pulse shaping with a differentiator

- Preserves the information of the signal onset time.
- Significantly reduces the dead time of the tube compared to the case without pulse shaping.

Low-pass and high-pass Filters

Low-pass

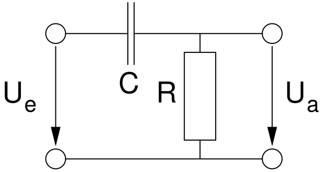


$$U_a = \frac{\frac{1}{i\omega C}}{R + \frac{1}{i\omega C}} U_e = \frac{1}{1 + i\omega RC} U_e.$$

$\omega \to 0$: $U_a \to U_e$.

$\omega \to \infty$: $U_a \to 0$.

High-pass

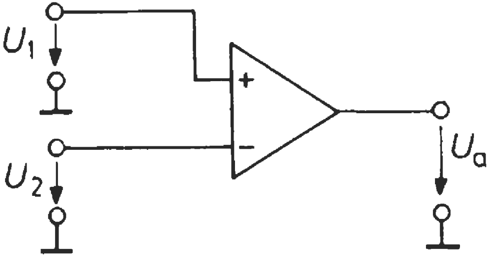


$$U_a = \frac{R}{R + \frac{1}{i\omega C}} U_e = \frac{1}{1 + \frac{1}{i\omega RC}} U_e.$$

$\omega \to 0$: $U_a \to 0$.

$\omega \to \infty$: $U_a \to U_e$.

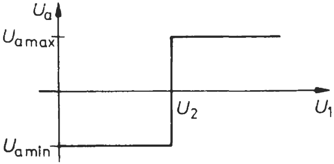
- An operational amplifier saturates when $|U_P - U_N|$ exceeds a small threshold.
- Comparators are operational amplifiers where this threshold is set very small.



Ideally:

$$U_a = \begin{cases} U_{a,\mathrm{max}} & \text{for } U_1 > U_2, \\ U_{a,\mathrm{min}} & \text{for } U_1 < U_2. \end{cases}$$

Characteristic Curve:



Logical basic functions, disjunctive normal form

Two states: logical 0 and logical 1.

Logical basic functions

- Conjunction: $y = x_1 \wedge x_2 = x_1 \cdot x_2 = x_1 x_2$.
- Disjunction: $y = x_1 \vee x_2 = x_1 + x_2$.
- Negation: $y = \bar{x}$.

To create more complex logical functions, one can use the disjunctive normal form.

n input variables $x_1, \ldots, x_n$. 1 output variable y.

1. Create a table where the desired output value is listed for all possible input values. This table is also known as the truth table.
2. Identify all rows in the truth table where $y = 1$.
3. From each of these rows, form the conjunction of all input variables; set x_k if it is 1, otherwise $\bar{x}_k$.
4. The desired function is obtained by taking the disjunction of all these product terms.

Probability distributions

- A physical measurement is a random process.
- A quantity x, which indicates the outcome of a random process, is referred to as a random variable or random quantity.
- Any function of x is also a random variable.
- If the random variable can only take discrete values, there is a probability associated with the occurrence of each of these values, which is the probability function.
- For random variables with a continuous range of values, the probability density $p(x)$ replaces the probability function. Let Ω be a measurable set of possible values of x with a measure greater than zero. Then,

$$\int_{\Omega} p(x)\, dx$$

is the probability of observing a value $x \in \Omega$.

Point estimation

Let α be a parameter of a probability distribution. The goal of point estimation is to find the best estimate (the best measurement in physicist's parlance) of α.

x: Random variable representing experimental measurement values.
$p(x;\alpha)$: Probability density for the measurement of x depending on the parameter α.

x and α can be multidimensional.

Definition. A point estimator $\mathcal{E}_\alpha$ is a function of x used to estimate the value of the parameter α. Let $\hat{\alpha}$ denote this estimate, so $\hat{\alpha} = \mathcal{E}_\alpha(x)$.

Objective is to find a function $\mathcal{E}_\alpha$ such that $\hat{\alpha}$ is as close as possible to the true value of α.

Since $\hat{\alpha}$ is a function of random variables, $\hat{\alpha}$ itself is a random variable.

$$p(\hat{\alpha}) = \int_D \mathcal{E}_\alpha(x) p(x;\alpha)\, dx,$$

where α denotes the true value of the parameter.

Consistency

n: Number of measurements used for the point estimation.
$\hat{\alpha}_n$: Corresponding estimate.
α_0: True value of α.
$\mathcal{E}_\alpha$ is called a consistent point estimator if $\hat{\alpha}_n$ converges stochastically to α_0. That is, the probability of estimating a value different from α_0 tends to 0 as $n \to \infty$.

Unbiasedness

The bias of an estimator $\hat{\alpha}$ is defined as

$$b_n(\hat{\alpha}) := E(\hat{\alpha}_n - \alpha_0) = E(\hat{\alpha}_n) - \alpha_0.$$

The point estimator is unbiased if

$$b_n(\hat{\alpha}) = 0, \quad \text{that is,} \quad E(\hat{\alpha}_n) = \alpha_0$$

for all n.

Additional quality criteria for point estimators

Efficiency

Let V_{min} be the minimum possible variance among all estimators for a real-valued parameter. The efficiency of a specific point estimator is given by the ratio $\frac{V_{min}}{Var(\hat{\alpha})}$, where $Var(\hat{\alpha})$ is the variance of $\hat{\alpha}$ for this estimator.

Sufficiency

Any function of data x is called a statistic. A sufficient statistic for α is a function of the data that contains all the information about α.

Method of maximum likelihood

$p(x;\alpha)$: Probability of obtaining measurements x given a parameter α.

- Substituting the measured values x into the function $p(x;\alpha)$ yields a statistic of x called the likelihood or likelihood function $L(x;\alpha)$.
- The term likelihood is used to indicate its relationship with the probability density $p(x;\alpha)$ while emphasizing that L is not a probability function.

Let $f(x_k;\alpha)$ denote the probability density for the outcome of a single measurement x_k. For n independent measurements $x = (x_1, \ldots, x_n)$, the likelihood function is

$$L(x_1, \ldots, x_n; \alpha) = \prod_{k=1}^{n} f(x_k;\alpha).$$

In the method of maximum likelihood, the estimator for α is chosen to be the value of α that maximizes $L(x;\alpha)$.

Goal: Determination of an interval that with a specified probability contains the true value of a parameter.

Limit case of the normal distribution

Let's assume the variable $x \in \mathbb{R}$ follows a normal distribution, i.e.,

$$p(x) = N(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}}.$$

If μ and σ are known, then

$$p(a < x < b) = \int_a^b N(x;\mu,\sigma)\,dx =: \beta.$$

If μ is unknown, we can compute $p(\mu + c < x < \mu + d)$:

$$\begin{aligned}\beta = p(\mu + c < x < \mu + d) &= \int_{\mu+c}^{\mu+d} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}}\,dx = \int_c^d \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\frac{y^2}{\sigma^2}}\,dy \\ &= p(c - x < -\mu < d - x) = p(x - d < \mu < x - c).\end{aligned}$$

Hypothesis testing

Goal: To determine which hypothesis (regarding a probability distribution) describes the observed data distributions (data).

Nomenclature: H_0: Null hypothesis.
H_1: alternative hypothesis.

Simple and composite hypotheses

- If hypotheses H_0 and H_1 are completely specified without free parameters, they are called simple hypotheses.
- If a hypothesis contains at least one free parameter, it is referred to as a composite hypothesis.

Procedure

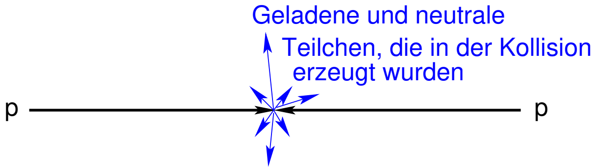
For hypothesis testing, one must choose W such that

$$p(\text{data} \in W \mid H_0) = \alpha$$

with a small chosen α, and simultaneously

$$p(\text{data} \in D \backslash W \mid H_1) = \beta$$

with β as small as possible.



Particles producible in a collision in the final state

Leptons

- Neutrinos: stable, weakly charged. ⇒ No interaction leading to a measurable electrical signal in the detector components.
- Electrons: stable, electrically charged. ⇒ Electrical signals in the detector components.
- Muons: unstable, but due to being ultra-relativistic in the laboratory frame, they are long-lived and do not decay within the detector; electrically charged. ⇒ Electrical signals in the detector components.
- τ-Leptons: unstable. ⇒ Detectable only through their decay products.

Other particles producible in a collision in the final state

Hadrons

- Initially, quarks and gluons are produced in the elementary collision. Due to confinement, these are not directly observable; instead, jets of hadrons arising from quarks and gluons are observed.
- Special role of two quarks:
  b-quarks form long-lived b-hadrons, enabling the identification of b-quark jets.
  t-quarks are so short-lived that they cannot form hadrons. They are detectable via their decay $t \to Wb$.

Photons

Photons are stable. Although electrically neutral, they can produce electromagnetic showers in matter, which can be detected in the detector.

Thank you very much for your interest and participation in the lecture!
Best of luck with your master's thesis!