# Data analysis techniques

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# introduction

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- my interpretation of “data analysis techniques” is here “doing a data analysis”
- follow the steps from the beginning (data taking) to the end (the result)
  - the luminosity
  - the trigger, from the point of view of the analysis
  - the reconstruction and detector response
  - the simulation
  - differential cross-section measurement: a di-jet correction
  - searches: the H > WW > lvlv
  - multivariate techniques

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# access to data

RAW data

↓

reconstruction — centralized analysis to identify final state objects (leptons, photons, jets...) ← can be done more than once, to profit of better features derived from previous analyses

↓

skimming — (centralized) copy of sub-set of data, dedicated to analyses (different final states) ← profit of the latest reconstruction

↓

analysis — (personal) selections on the skims, to have a sample which is as small as possible ← well suited to the analysis needs (speed, bkg measurements) do not decouple from the approved definitions

# the cross-section

number of observed events

background contamination in the sample

**cross section:** $$\sigma = \frac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

analysis efficiency

$$\varepsilon = \varepsilon_{tr} \cdot \varepsilon_{reco} \cdot \varepsilon_{ID} \cdot \varepsilon_{sel}$$

luminosity delivered by LHC

$$1 \text{ barn} = 10^{-28} \text{ m}^2 = 10^{-24} \text{ cm}^2$$

# luminosity

# luminosity

$$\sigma = \frac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

number of particles per beam

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

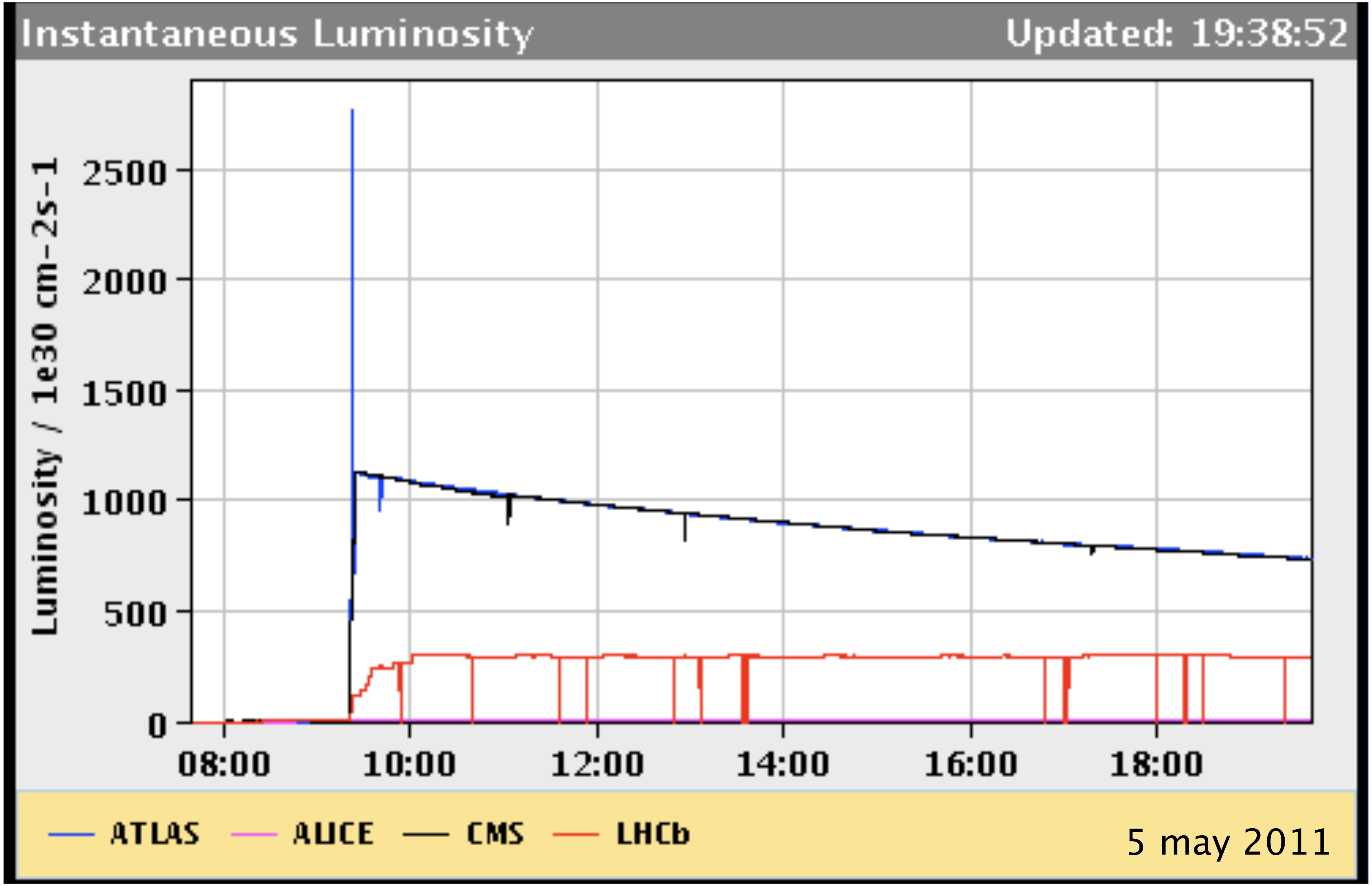
number of colliding bunches

revolution frequency

beam transverse size

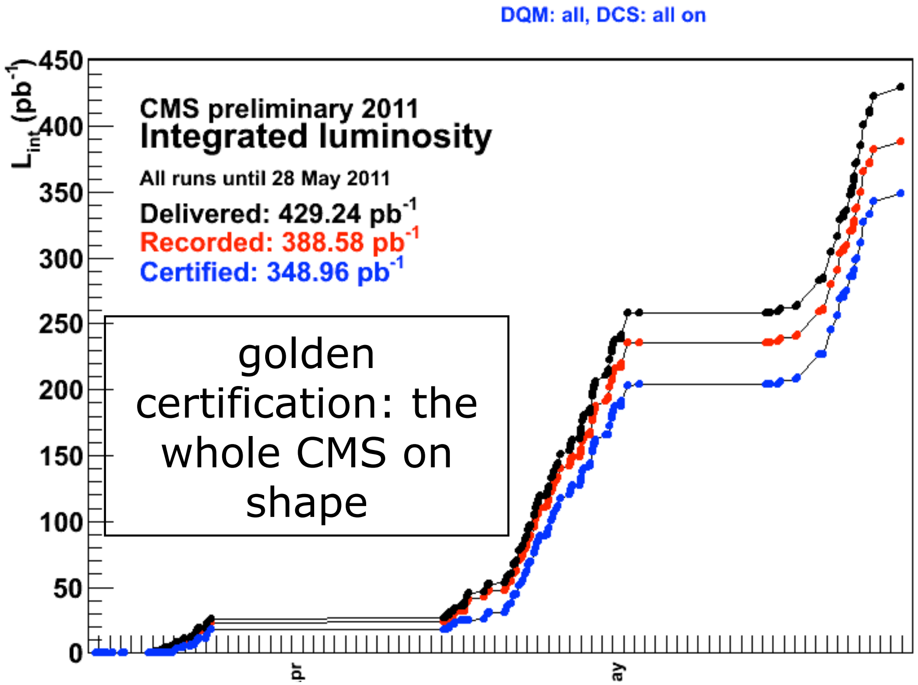
$$1 \text{ barn} = 10^{-28} \text{ m}^2 = 10^{-24} \text{ cm}^2$$

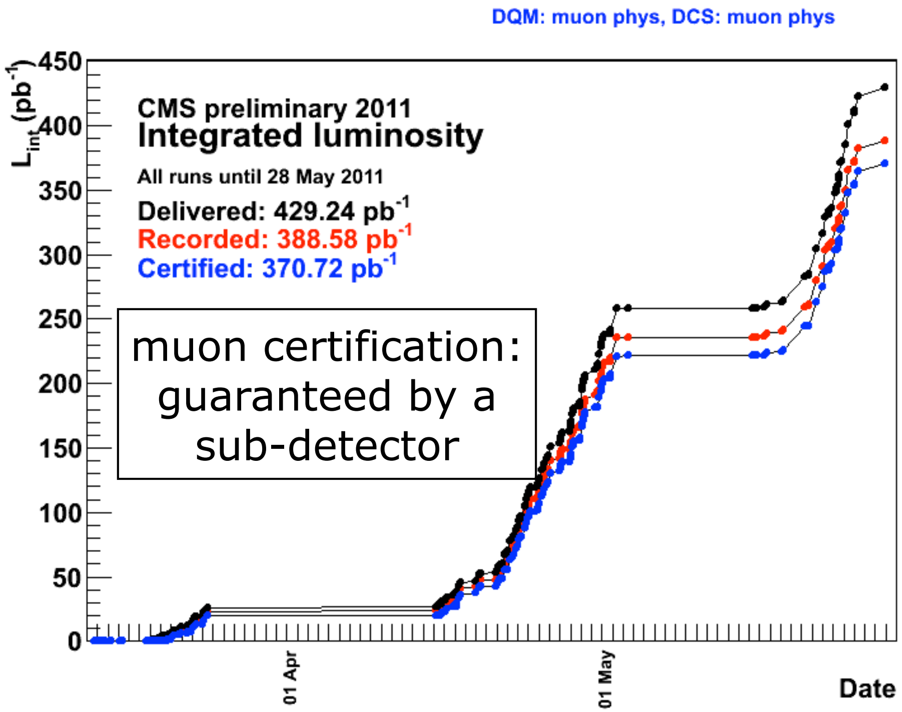
# luminosity



Instantaneous Luminosity
Updated: 19:38:52
Luminosity / 1e30 cm-2s-1
2500
2000
1500
1000
500
0
08:00
10:00
12:00
14:00
16:00
18:00
ATLAS
ALICE
CMS
LHCb
5 may 2011

# delivered luminosity



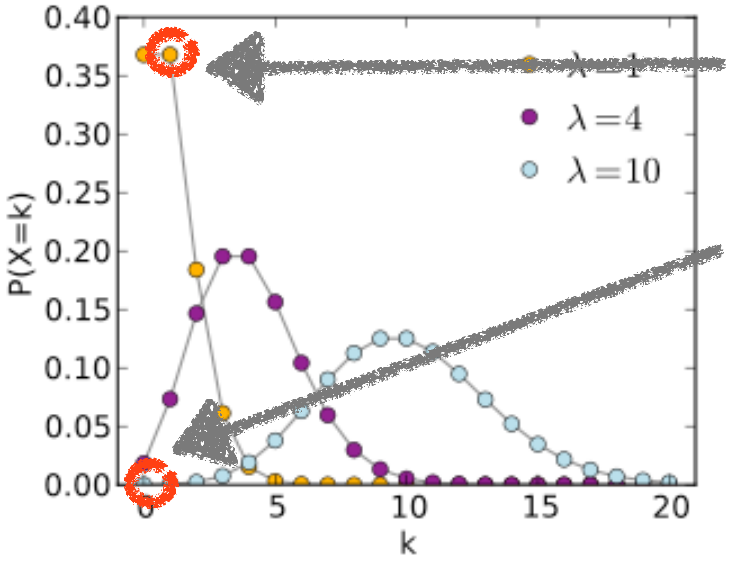

- the **delivered luminosity** is what the LHC gives to an experiment
- the **recorded luminosity** is different from the delivered one, because of data taking inefficiencies
- the **certified luminosity** is different from the recorded one, because of detector problems
- not necessarily all studies need the same level of certification!

# instantaneous luminosity

the number of interactions per bunch-crossing is poisson-distributed with mean μ

$$\mu = \frac{\sigma \mathcal{L}}{f n_B}$$

$$P(k=0) = \frac{\lambda^0}{0!} e^{-\lambda}$$




- hard to distinguish positive countings => count the zeros and invert the poisson
- already with 10 interactions per bunch-crossing, the poisson is hard to invert (zero starvation)

$$\frac{R_0}{\mathcal{L}_0} = \sigma_{vis}$$

define $\sigma_{vis}$

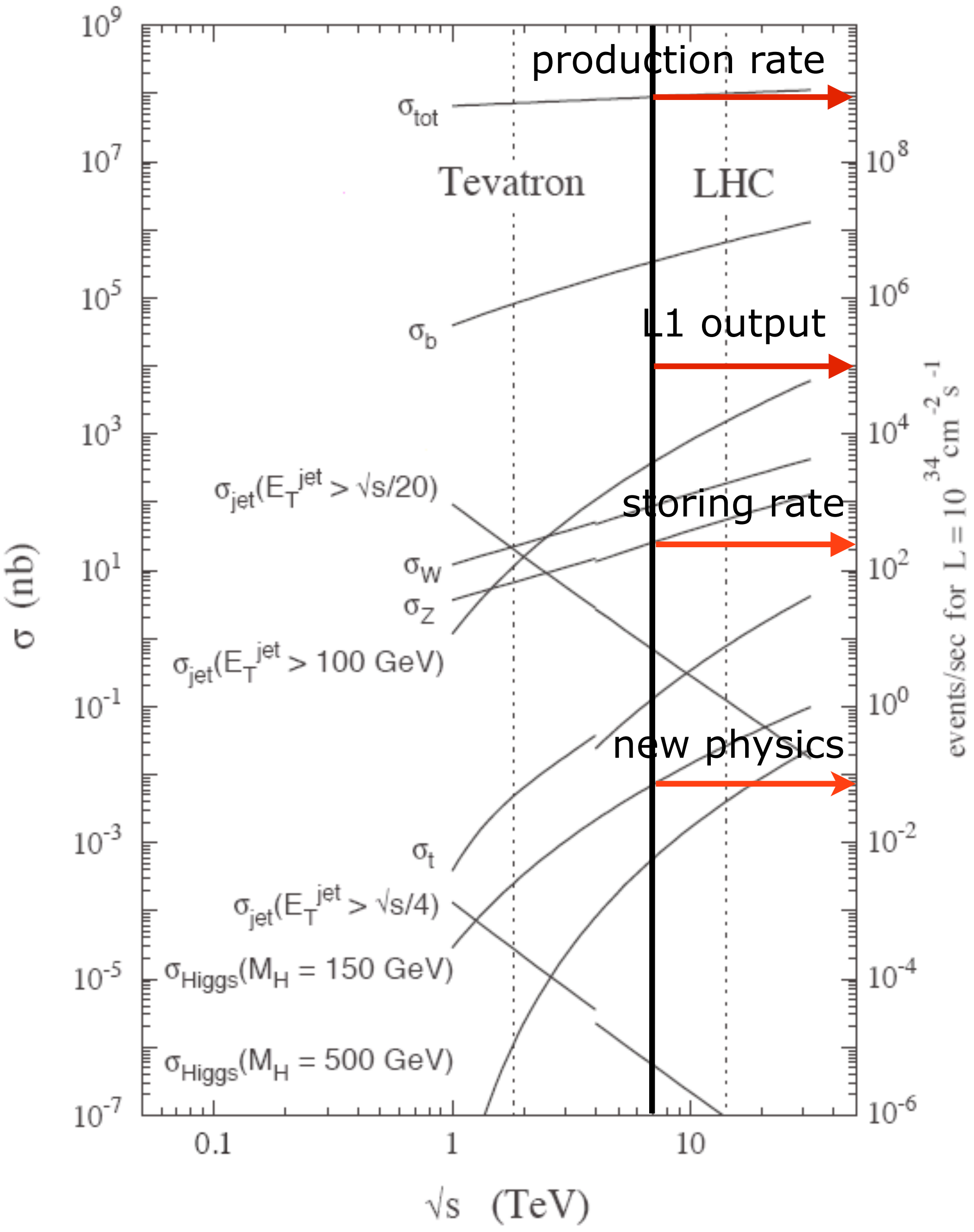
find another process which is linear in the luminosity and calibrate it

$$\mathcal{L}(t) = \frac{R(t)}{\sigma_{vis}}$$

calculate the lumi as a function of a rate

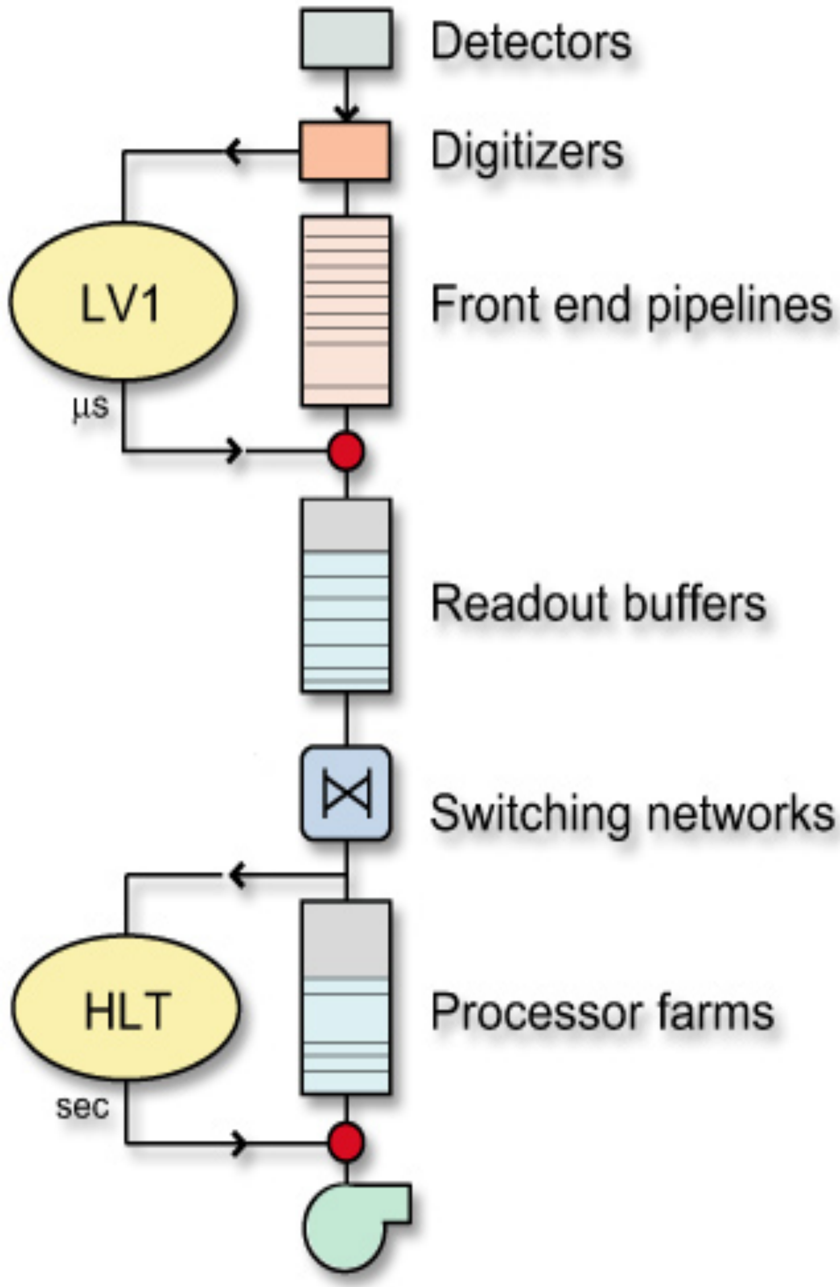
# the trigger

# the trigger




- the vast majority of events are not interesting
- interesting physics happens at low rates (< 10 Hz)
- the final bandwidth is limited: can store up to O(100 Hz) of events (1 event ~ 1 MB)
- the decision has to be taken fast enough (bunch crossing rate = 1/25 ns)

# trigger: the CMS example




- L1 based on regional information, dedicated electronics
- HLT is software-based, runs on commercial computers farm - can be implemented by std::physicist
- performs a first physics reconstruction of the event, with algorithms (very) similar to the ones used in the final analysis
- exploits the expected signatures of the event

# what to trigger

- HLT searches for **interesting physics objects**:
    - high pT leptons
    - leptons with a certain degree of identification (isolation)
    - presence of many leptons
    - large missing energy
    - presence of many jets (+ other requirements)
- HLT is based on the **topology of the analysis it aims for**
- make sure that the events one is interested in are actually triggered. If not, need to **implement a new one** and get it deployed
- low $p_T$, loose ID, few leptons are difficult to trigger

# trigger prescaling

- when the instantaneous luminosity increases, the triggers need to change, since the available bandwidth does not increase
  - increase thresholds
  - build sophisticated triggers
  - prescale the trigger = take only a fraction ($1/p_i$) of the events that would fire a given trigger

$$N_{prod} = \frac{N_{obs}}{\varepsilon_{tr}} \quad \Rightarrow \quad N_{prod} = \frac{p_i \cdot N_{obs}}{\varepsilon_{tr}}$$

# prescaling: example at CMS

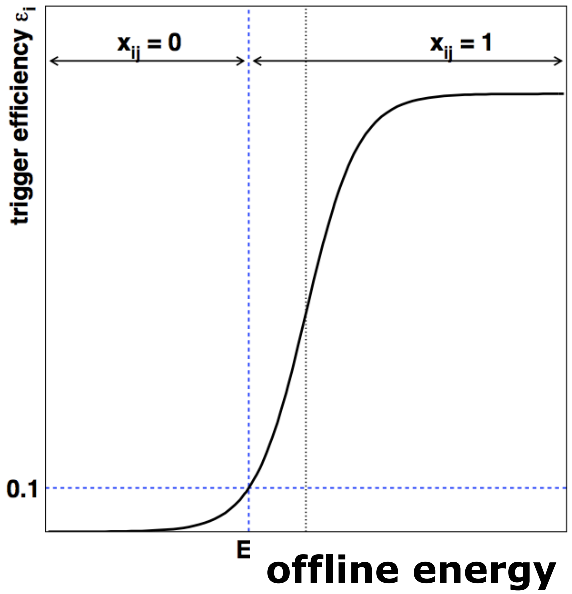
- example of a trigger table

| HLT path | Prescaler inst. lumi ($cm^{-2}s^{-1}$) | | | | | | | | | L1 seed |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2e33 | 1.4e33 | 1e33 | 7e32 | 5e32 | 3e32 | 2e32 | 1.4e32 | 1e32 | |
| ▼ SingleElectron | | | | | | | | | | |
| HLT_Ele25_CaloIdL_CaloIsoVL_TrkIdVL_TrkIsoVL_v1 | 400 | 300 | 200 | 150 | 100 | 70 | 50 | 20 | 10 | L1_SingleEG12 |
| HLT_Ele25_WP80_PFMT40_v1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG12 |
| HLT_Ele27_WP70_PFMT40_PFMHT20_v1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG15 |
| HLT_Ele32_CaloIdVL_CaloIsoVL_TrkIdVL_TrkIsoVL_v2 | 200 | 150 | 100 | 70 | 50 | 30 | 25 | 10 | 5 | L1_SingleEG20 |
| HLT_Ele32_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v4 | 20 | 10 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG20 |
| HLT_Ele42_CaloIdVL_CaloIsoVL_TrkIdVL_TrkIsoVL_v1 | 75 | 50 | 40 | 35 | 30 | 25 | 15 | 10 | 5 | L1_SingleEG20 |
| HLT_Ele42_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG20 |
| HLT_Ele52_CaloIdVT_TrkIdT_v2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG20 |
| HLT_Ele65_CaloIdVT_TrkIdT_v1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG20 |
| ▼ DoubleElectron | | | | | | | | | | |
| HLT_DoubleEle10_CaloIdL_TrkIdVL_Ele10_v6 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_TripleEG5 |
| HLT_DoubleEle45_CaloIdL_v1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG20 |
| HLT_Ele17_CaloIdL_CaloIsoVL_Ele15_HFL_v6 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG12 |
| HLT_Ele17_CaloIdL_CaloIsoVL_Ele15_HFT_v1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG12 |
| HLT_Ele17_CaloIdL_CaloIsoVL_Ele8_CaloIdL_CaloIsoVL | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG12 |
| HLT_Ele17_CaloIdL_CaloIsoVL_v5 | 2000 | 1400 | 1000 | 700 | 500 | 300 | 200 | 140 | 100 | L1_SingleEG12 |
| HLT_Ele17_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL_Ele8_ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG12 |
| HLT_Ele17_CaloIdVT_CaloIsoVT_TrkIdT_TrkIsoVT_Ele8_ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG12 |
| HLT_Ele17_CaloIdVT_CaloIsoVT_TrkIdT_TrkIsoVT_SC8_ | 40 | 30 | 20 | 15 | 10 | 7 | 5 | 3 | 1 | L1_SingleEG12 |
| HLT_Ele32_CaloIdT_CaloIsoT_TrkIdT_TrkIsoT_SC17_v2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_SingleEG20 |
| HLT_Ele8_CaloIdL_CaloIsoVL_Jet40_v5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | L1_SingleEG5 |
| HLT_Ele8_CaloIdL_CaloIsoVL_v5 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | L1_SingleEG5 |
| HLT_Ele8_CaloIdL_TrkIdVL_v5 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | L1_SingleEG5 |
| HLT_Ele8_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL_v4 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | L1_SingleEG5 |
| HLT_Ele8_v5 | 240 | 240 | 240 | 240 | 240 | 240 | 240 | 240 | 240 | L1_SingleEG5 |
| HLT_Photon20_CaloIdVT_IsoT_Ele8_CaloIdL_CaloIsoVL | 20 | 14 | 10 | 7 | 5 | 3 | 2 | 1 | 1 | L1_SingleEG12 |
| HLT_TripleEle10_CaloIdL_TrkIdVL_v6 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | L1_TripleEG5 |

# the trigger and the analysis

- events I am interested in (1) have to be triggered, (2) if not prescaled, it's better
- the trigger is (usually) not 100% efficient on the analysis sample -> **measure the efficiency** (from data) of the trigger for the analysis

$$\sigma = \frac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt} \rightarrow \varepsilon = \varepsilon_{tr} \cdot \varepsilon_{reco} \cdot \varepsilon_{ID} \cdot \varepsilon_{sel}$$




- the **turn-on curve** is the trigger efficiency trend as a function of an offline selection
- the **objects reconstruction** at trigger level is different from the one used in the final analysis
- this produces an **efficiency curve** and a plateau that can be less than 1

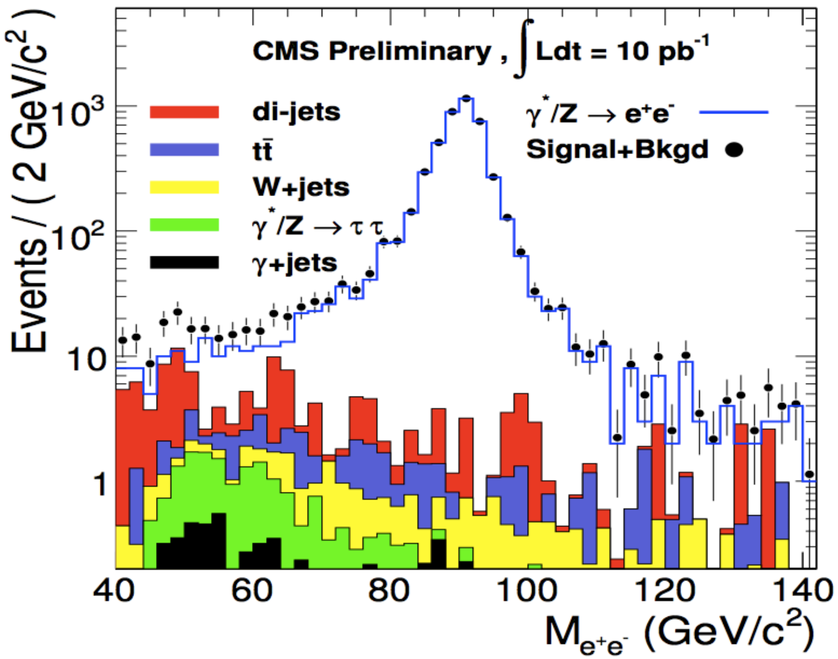
# trigger efficiency measurements

- **different methods** available
  - (by means of a software trigger emulator)
  - with **tag & probe** methods
  - compare to the efficiency of **looser triggers** (bootstrapping)
  - from a sample defined by an **orthogonal trigger**
- it changes **with respect to the kinematics**
  - perform measurements as a function of $p_T$, $\eta$

# an example: the tag & probe

- select the **object that would fire the trigger** in a way independent of the trigger itself

- count **how many times it fires** the trigger




- **under the Z peak** basically only the Z production is expected

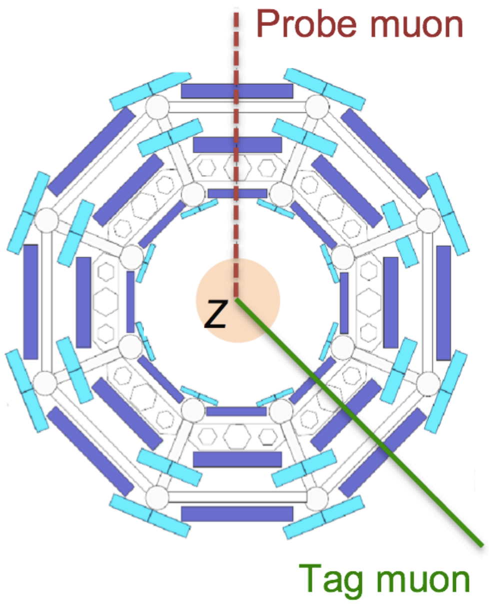
- given one good lepton, use the **$M_{ll}$ constraint to identify it**

- the result has to be corrected for combinatorial background under the Z peak (or the counting done by fitting the shapes)

- With sufficient statistics the efficiency can be evaluated in bins of $p_T$, $\eta$ ,$\varphi$

# an example: the tag & probe

- basic object of the muon reconstruction (track)
- minimum $p_T$ threshold applied
- $M(tag,probe) \sim M_Z$




- triggered by single muon trigger
- minimum $p_T$ threshold applied

$$\varepsilon_{\text{muon tr}} = \frac{\text{nb. of probes that fire the trigger}}{\text{nb. of probes}}$$

- both muons might fire the trigger

$$\varepsilon_{\text{muon tr}} = \frac{2TT + TP}{2TT + TP + TF}$$

T = **T**ag
P = **P**robe that fires a trigger
F = probe that **F**ails a trigger

# bootstrapping

- ask a utility trigger with **loose requirements**, to check a tight one
- **prescale** it (it will be needed, as requirements are loose)
- within the events triggered, search the ones that **survive the offline analysis selections** and match to the trigger object
- check whether these events **would pass also the tight trigger** and get an efficiency
- if the utility trigger is loose enough (es. a calorimetric deposit for electrons), it can be considered of efficiency 1 and the efficiency obtained is the one of the tight trigger

**keep an eye on the statistics**: a utility trigger is given lower rate + prescaling => not many events will survive the offline selections

build many utility triggers for different variables, rather that a single one with everything loose

# other techniques

- use a trigger defined on **information independent of the trigger** with unknown efficiency (orthogonal)
  - muon triggers to test calorimetry triggers, or vice-versa

- when implementing a trigger for an analysis, need to be sure that also **utility triggers** are present, to measure the efficiency of the main one
  - they will probably be prescaled

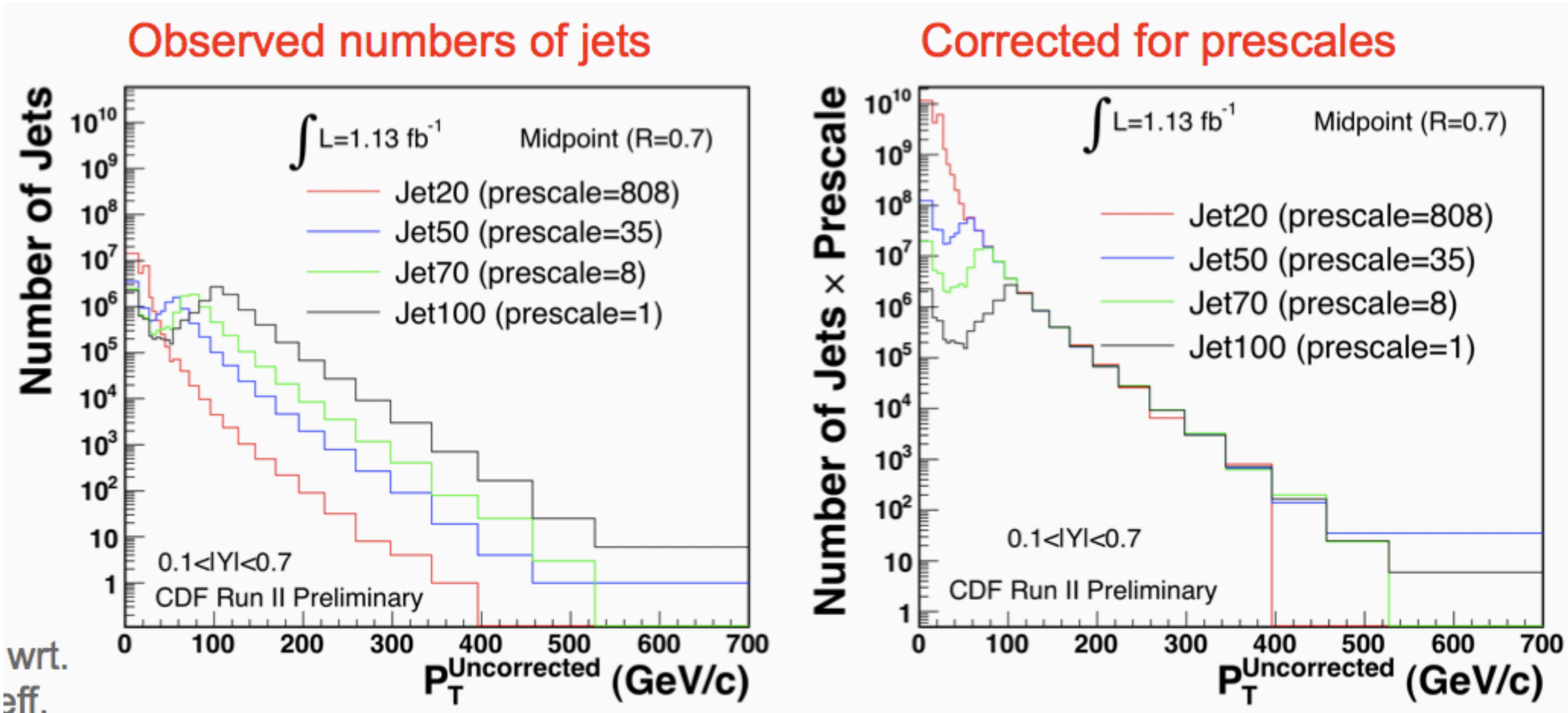
# combining triggers

- to increase the number of signal events, or increase the phase space covered:
  - different energies (with different prescales!)
  - different sub-detectors (2 muons in different regions)
  - different signals (electrons OR muons)
- different ways to do it
  - **division**: one trigger per phase space region
    *the simplest, measure the efficiencies separately*
  - **exclusion**: one analysis per trigger, according to the one that has the lowest prescale
    *better performing*
  - **inclusion**: the “OR” of all the triggers is considered
    *the best one, can become complicated*

**Combining Triggers in HEP Data Analysis**, arXiv:0901.4118

# different energies

- choose the trigger as a function of jet energy (division method)
- choose the trigger with lowest prescale (exclusion method)
- select events if they fire any triggers (inclusion method)



# the inclusion method

- the "OR" of all the triggers is considered:

$$P_{tot}(\text{evt}) = 1 - \prod_{i=1}^{triggers} (1 - P_i(\text{evt}))$$

no triggers fired

- for two triggers:

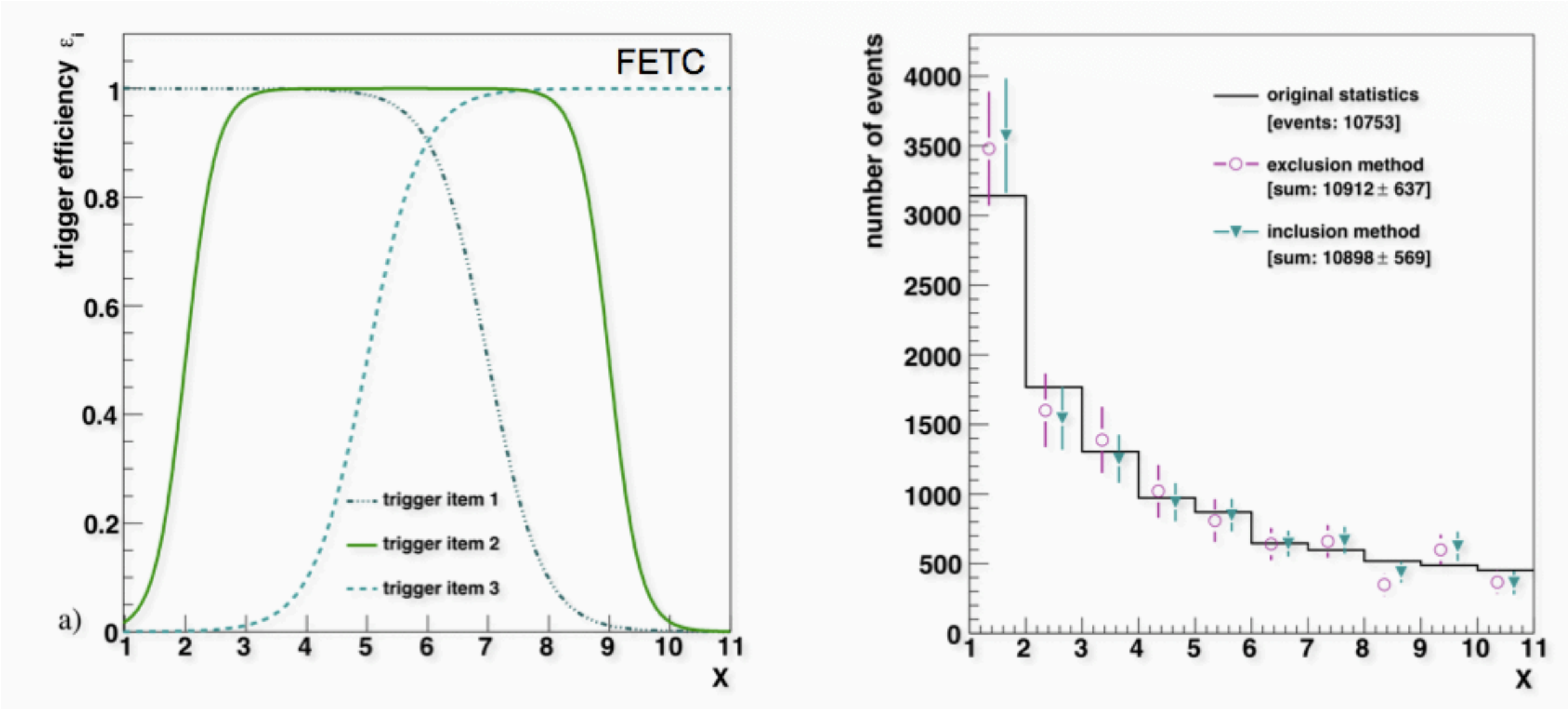
$$P_{tot}(\text{evt}) = P_1(\text{evt}) + P_1(\text{evt}) - P_{1|2}(\text{evt})P_2(\text{evt})$$

- for the uncorrelated case:

$$P_{tot}(\text{evt}) = P_1(\text{evt}) + P_1(\text{evt}) - P_1(\text{evt})P_2(\text{evt})$$

- in general, correlations need to be considered
  - instrumental (common inefficient elements, common electronics, same level 1 trigger)
  - physical (jets and track triggers might be correlated)

# a toy comparison



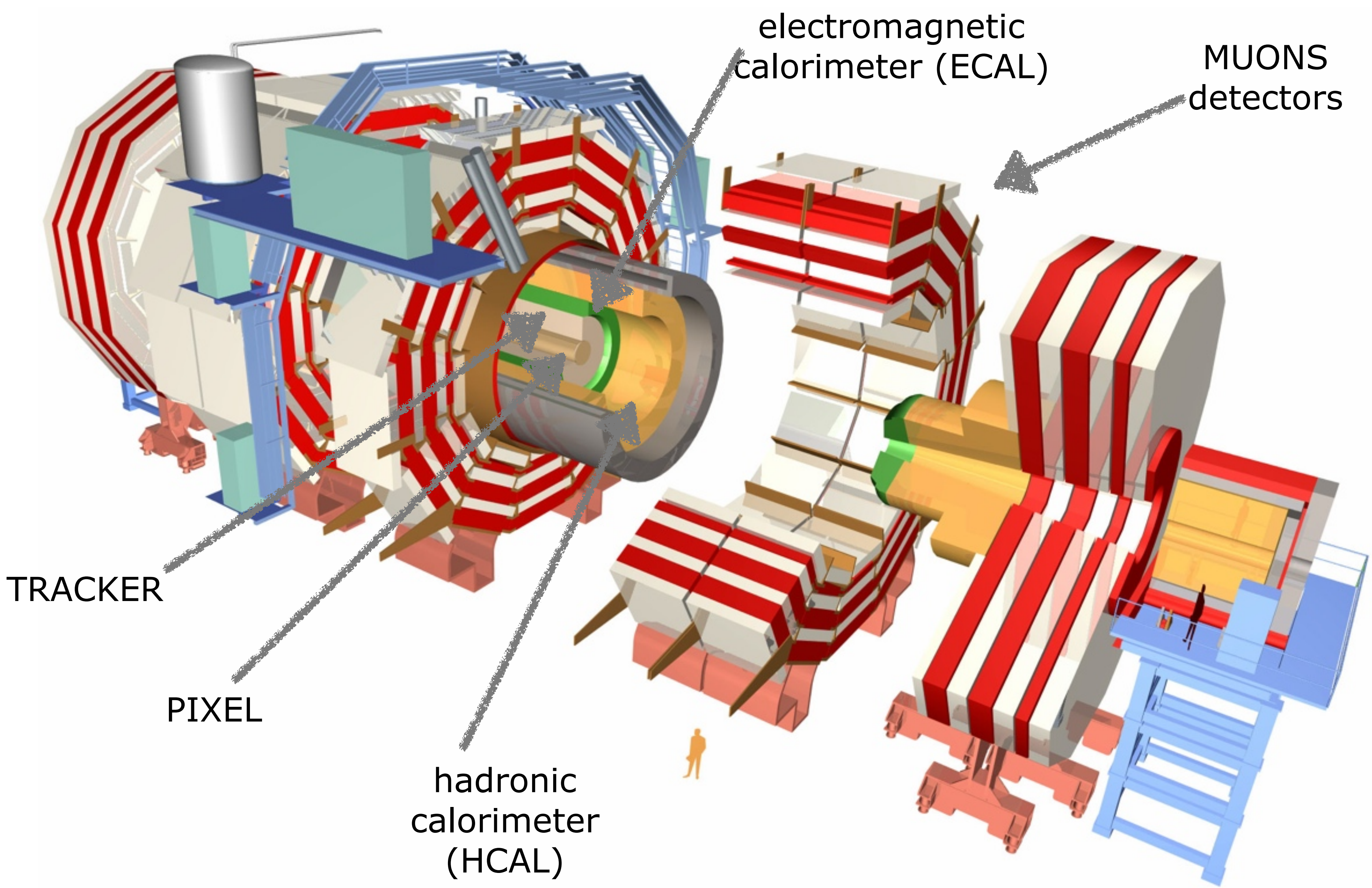

- keep the trigger simple
- the price payed in systematics might not be worth the effort of combining in the most sophisticated way, or sitting on the turn-on part of the efficiency curve

# physics objects reconstruction

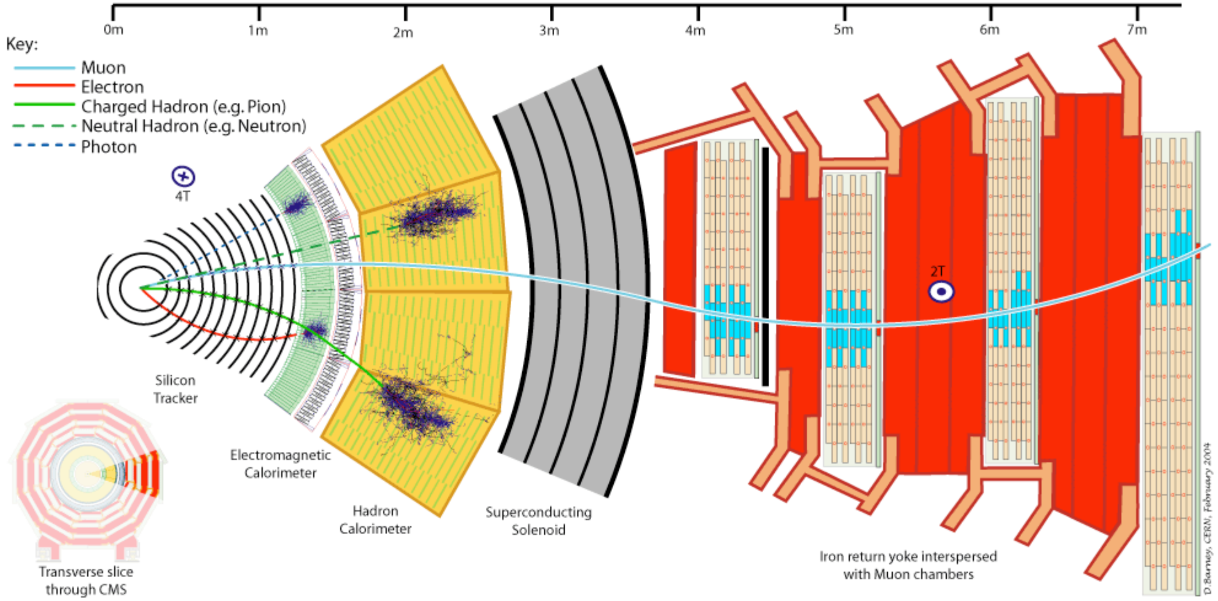
# physics objects reconstruction

- obtain **physics objects from the detector response**
  - hits in the tracker and muon detectors
  - energy deposits in the calorimeters
- two ways are available in CMS
  - **single objects** reconstruction: build final objects (e.g. muons, electrons, jets) from the detector response
  - **particle-flow** reconstruction: build a coherent list of stable particles and produce the analysis objects on top of them

# the cms detector



# the particle flow




hits in the tracker → **tracker tracks**

cells in the calorimeter → **calorimetric clusters**

hits in muon detectors → **muon tracks**

link the single objects with geometrical requirements on the extrapolated trajectories and create **blocks**

# the particle flow

**blocks**

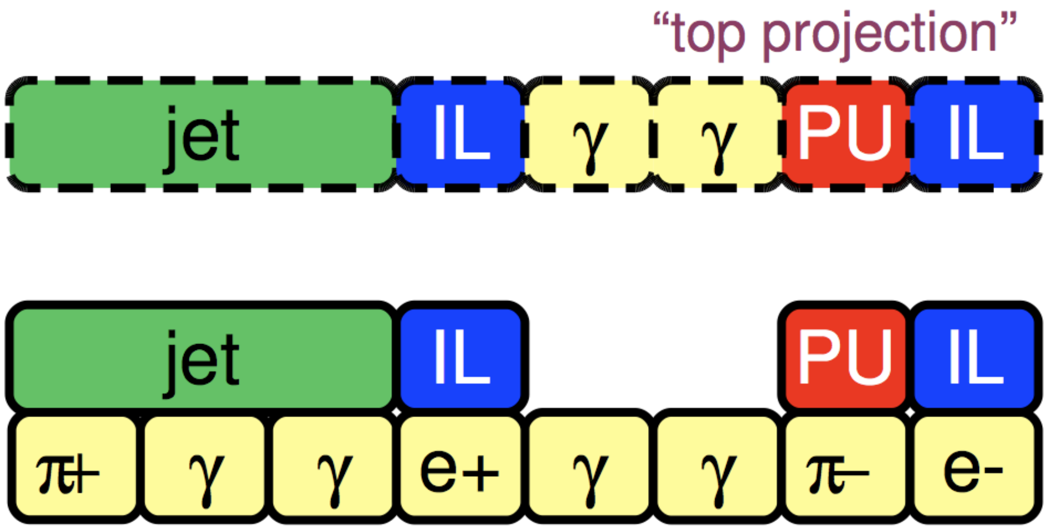
identify muons, promote the block

identify electrons, promote the block

match the remaining tracks to clusters, define charged hadrons and neutrals from calorimetric excess

the charged energy contribution is measured well from the tracker

the remaining calorimetric deposits define neutrals

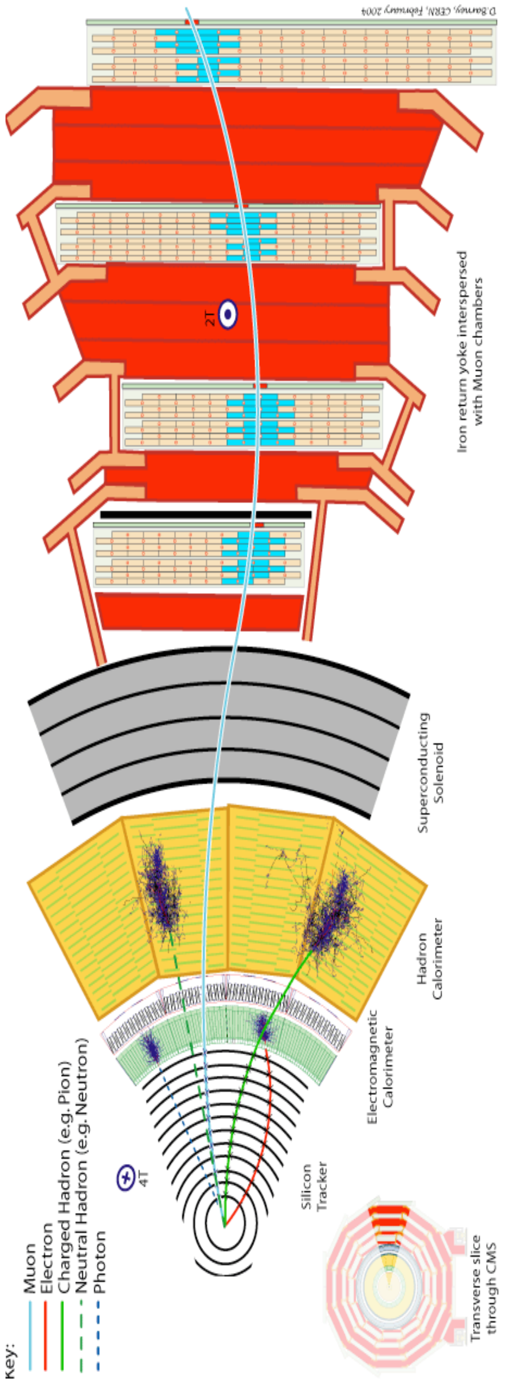



The list of PFCandidates

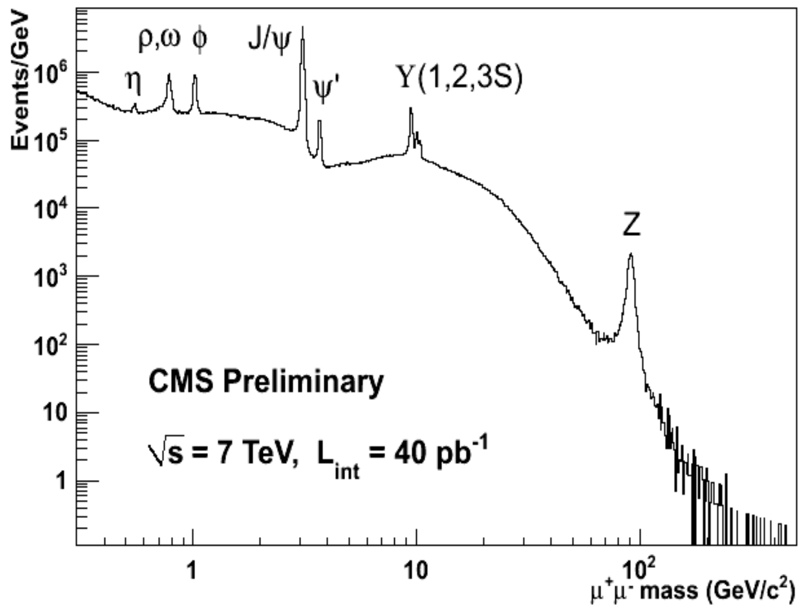
$$+ \ \overrightarrow{MET} = -\sum_{i=0}^{N_{particles}} \vec{E}_T^i$$

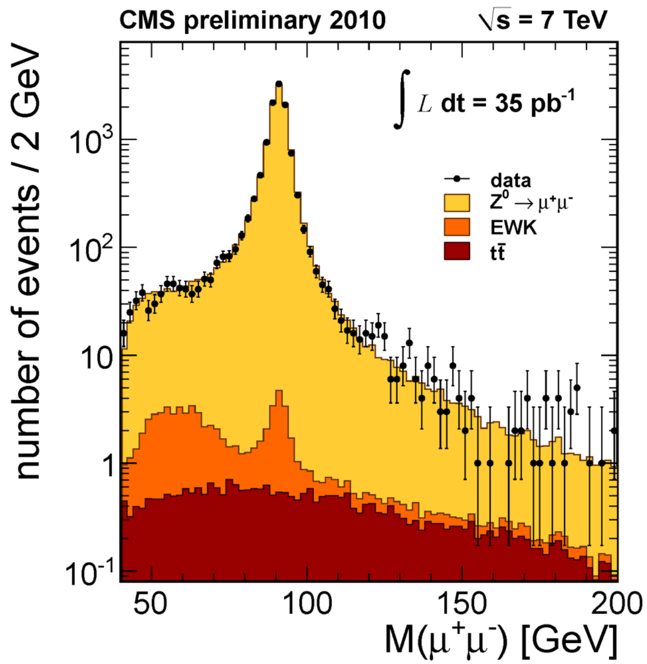
the list of particles obtained (candidates) is used for high level objects classification and reconstruction, to be used in the analysis

# muons reconstruction

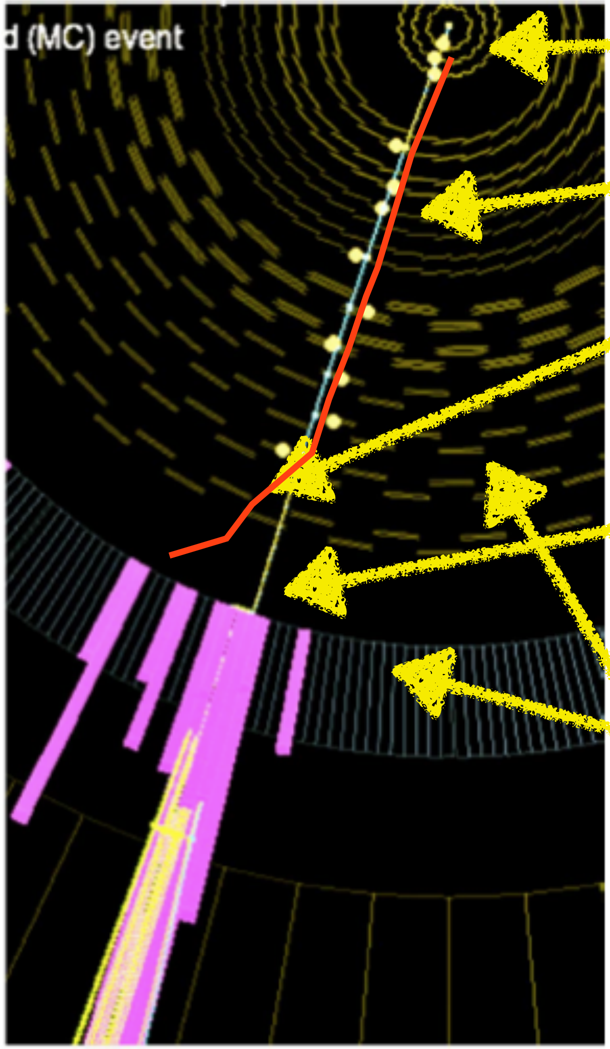



- high **purity** = fit with hits in both tracker and muon
- high **efficiency** = fit in the tracker + confirmation in the muon detector
- **momentum determination** from both tracker and muons information: best resolution from the tracker for $p_T$ < 200 GeV, from the muons above (effect of multiple scattering)
- above 1 TeV, the **bremsstrahlung** is significant



# electron reconstruction




Seeding

electron tracking: GSF

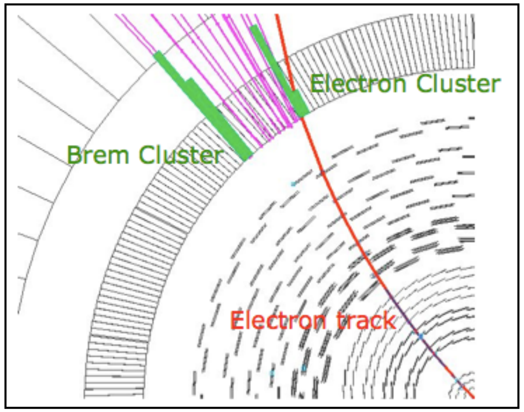
cleaning of GSF track duplicates

Identification of all the electron energy deposits in the ECAL

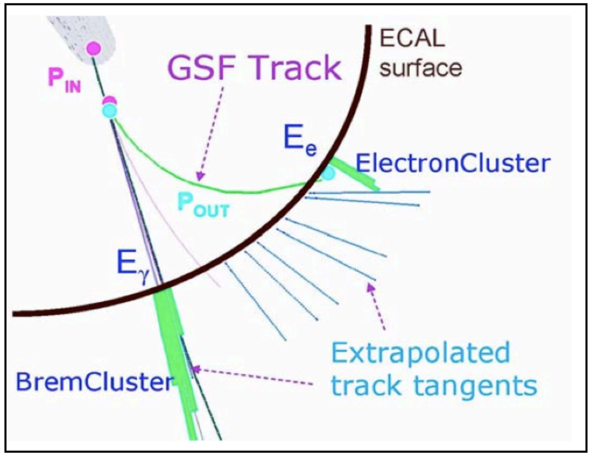
electron 4-mom determination.

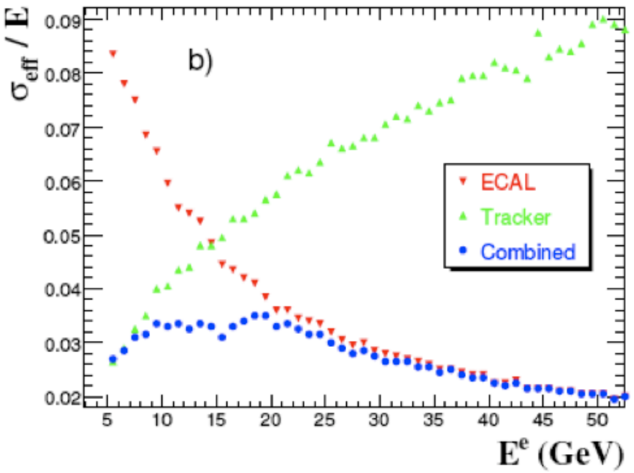
Identification against charged-particles interacting in the ECAL

from ECAL clusters or tracks:



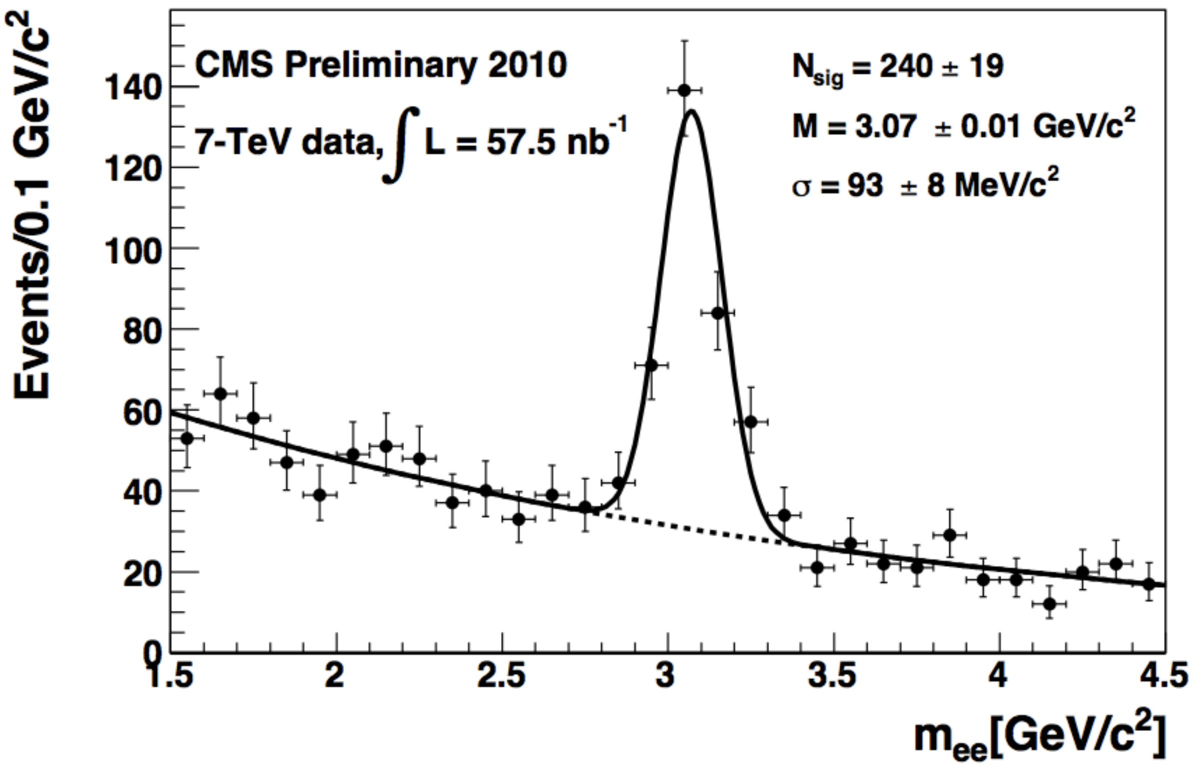

from ECAL footprint or tracks extrapolation:




use ECAL at high $p_T$, tracker at low $p_T$

# electron reconstruction




search for the decay:

$$J/\Psi \rightarrow e^+e^-$$

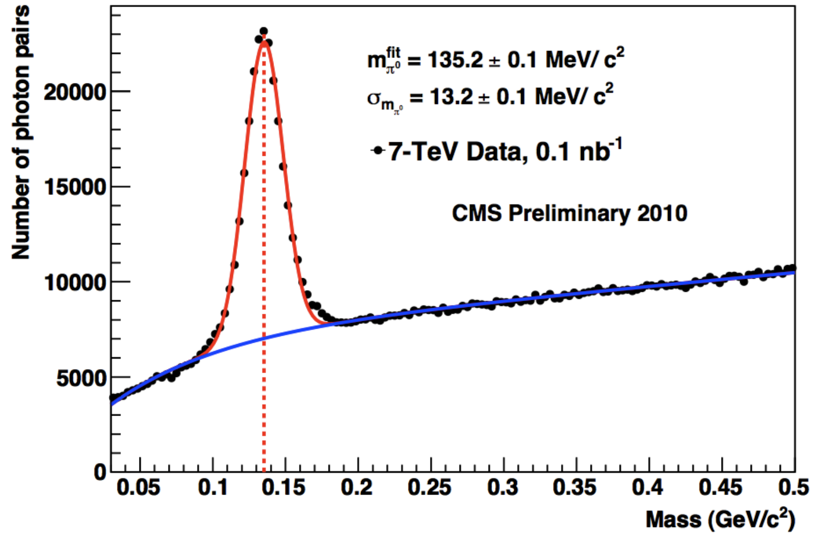
contamination sources:

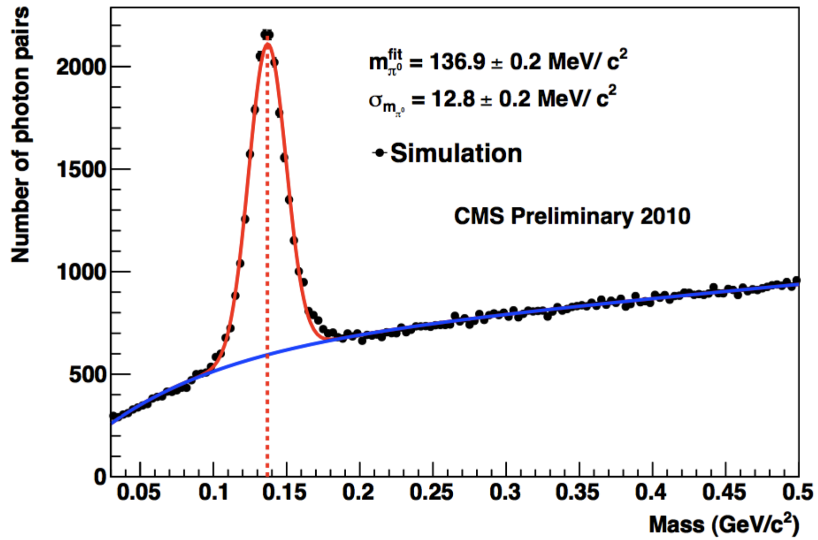
- real electrons, either from photon conversions or from semi-leptonic b-hadron decays,
- mis-identified charged hadrons.

- at most one hit missing in the pixel detector (reduce conversions)
- electrons originate from the same vertex (reduce the b-decay background)
- quality cuts to reject charged hadrons contamination
- opposite charge

# photons reconstruction

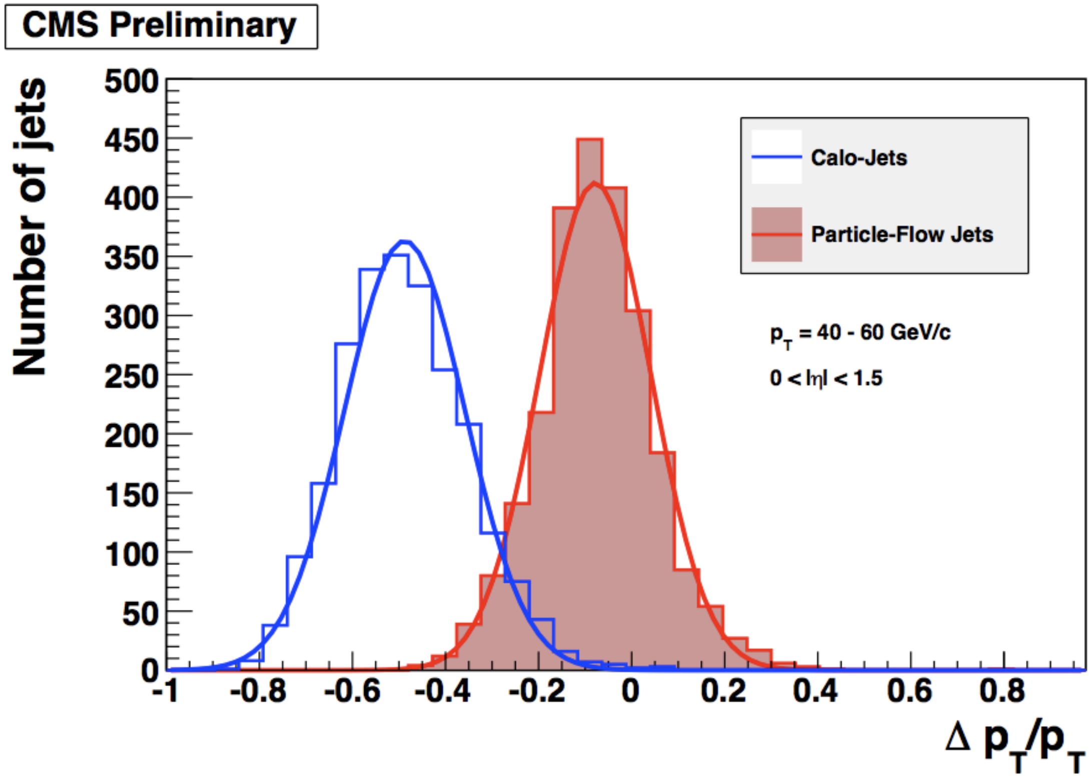
- **ECAL clusters** not associated to a track, nor a deposit in the hadronic calorimeter
- ECAL detector response is **calibrated**, to account for the effect of the noise cut on the single crystals readout
- **check the photons energy scale** calibration with 2010 data, by looking at the $\pi^0$ peak position
- pair all photons with at least 400 MeV energy
- determine the peak position with a combined fit of signal + background

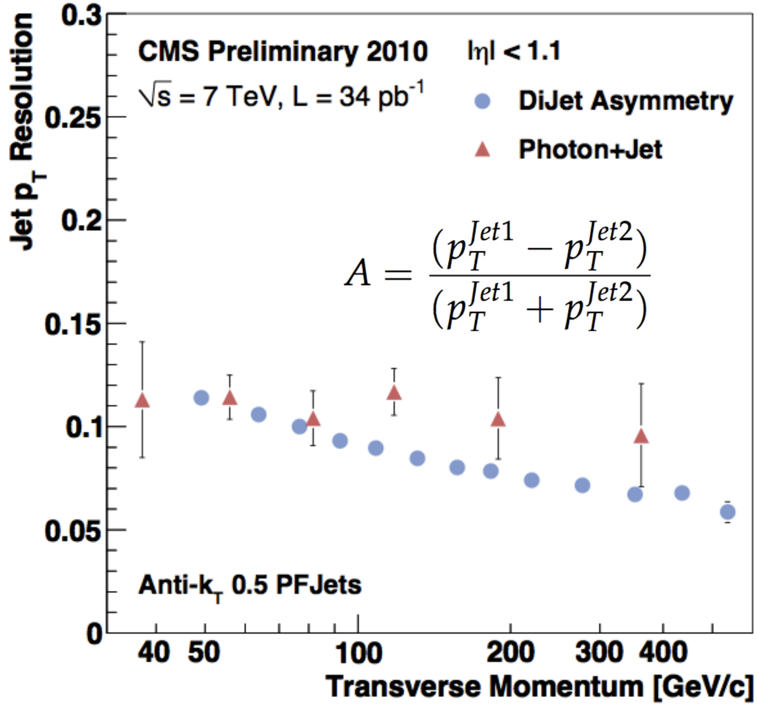


# jet reconstruction

- jets are reconstructed with the AKT5 algorithm
- for the single object reconstruction: with calorimetric deposits
- for the particle-flow: with particle flow candidates

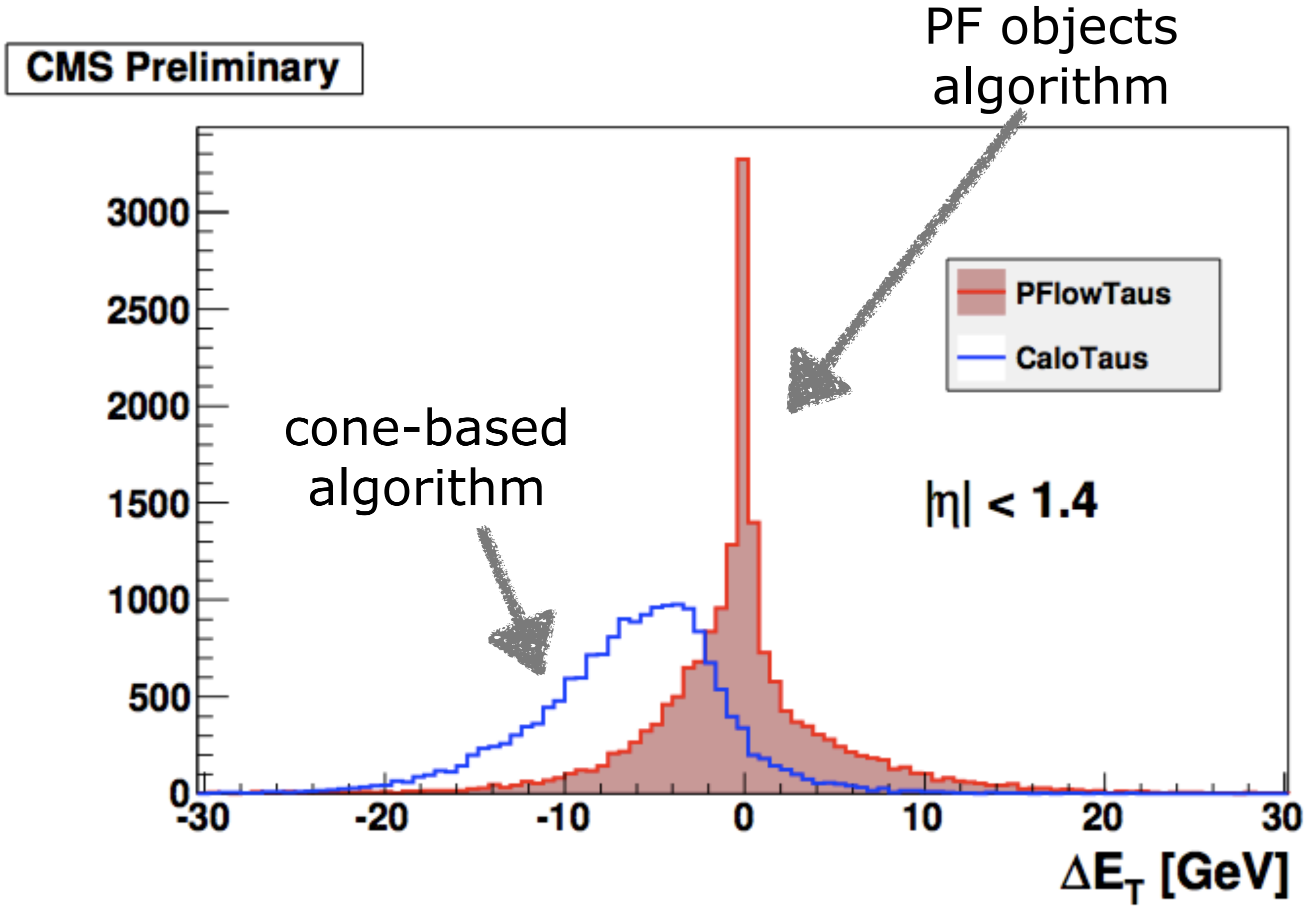



the jet energy resolution measured from 2010 data

# tau reconstruction

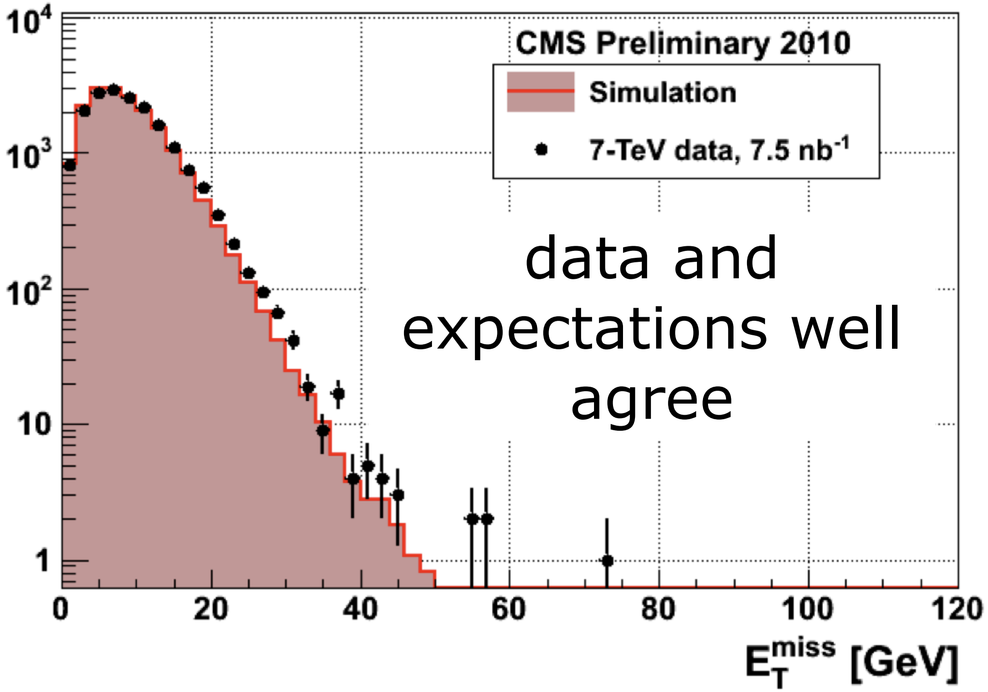
- reconstructed as narrow jets in the standard case, as the sum of the particles compatible with the tau decay in a narrow cone in the particle flow case

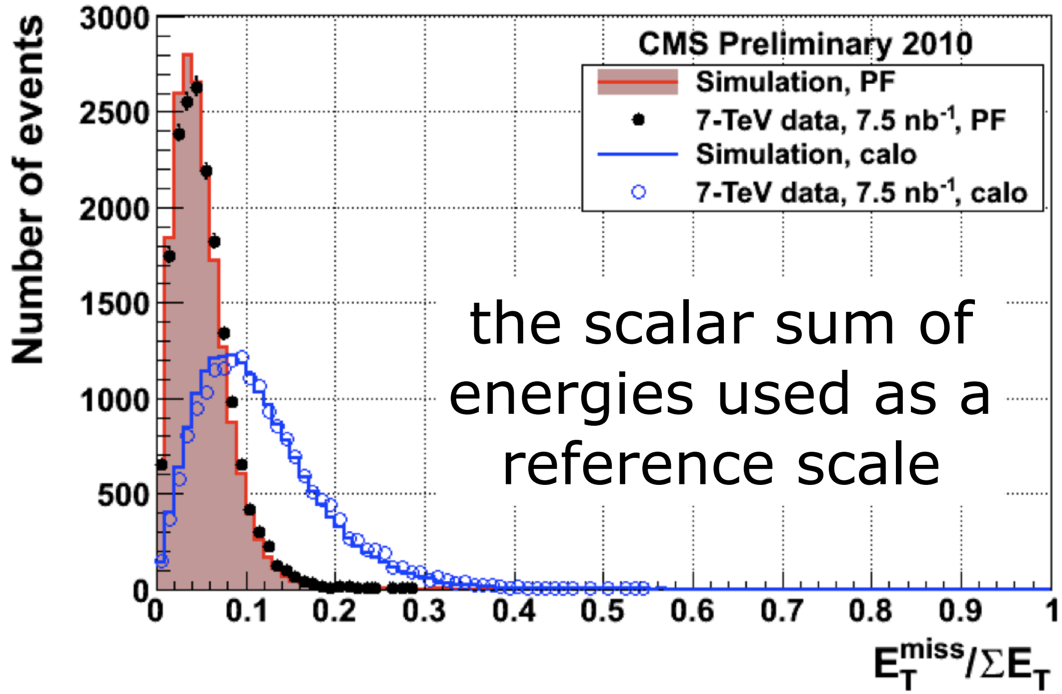



reconstructed taus $E_T$ compared to the expected one, test performed on a simulated Z > ττ sample

# missing energy reconstruction

- derived from (minus) the sum of "all the rest"
- sensitive to uncertainties in all the other physics objects
- noise effects, mis-calibrations, etc. generate fake missing energy in events without missing energy
- perform a test on a di-jet sample

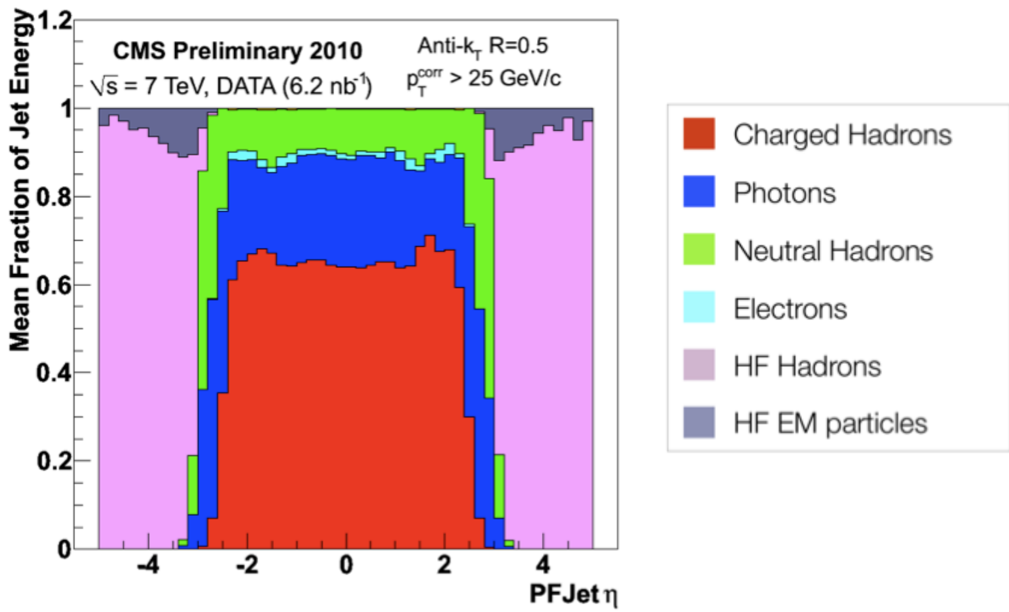


# reconstruction: in summary

- the reconstruction obtains from the detector measurements the physics objects in the final state
- in a coherent way, to close the kinematics (as much as possible)
- making use of the most precise sub-detector
- reconstruction and identification are not (always) disentangled, for example electrons need to be separated from jets
- data-driven techniques necessary to assess the performances

jet composition: only for neutral hadrons one cannot profit of tracker measurements



# detector response

- the detector response is not perfect
- the output of the reconstruction needs to be **calibrated for the detector response**
- use **known physics processes** to get the calibrations and the relative uncertainty
- for example
  - **resonances** for leptons (energy scale, tag&probe)
  - **cosmic** rays (alignments)
  - transverse momentum **balances**
  - ....

# ECAL calibration

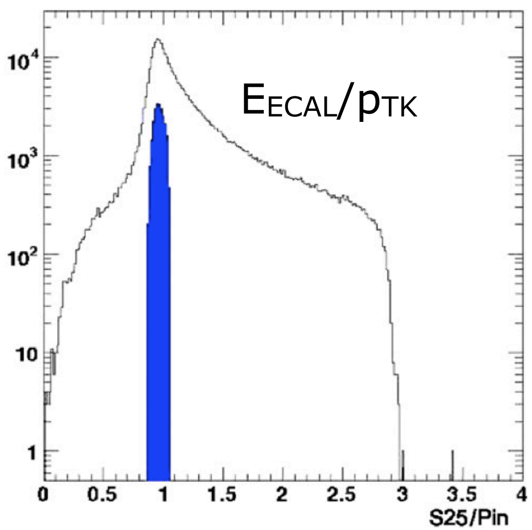
- each ECAL channel needs a calibration factor to equalize the response of all detector elements
- for electrons, the energy is measured in the tracker and in the ECAL
- find the calibration coefficients by minimizing a $X^2$ of:

$$|\mathcal{E} \times \bar{c} - \mathcal{P}|$$

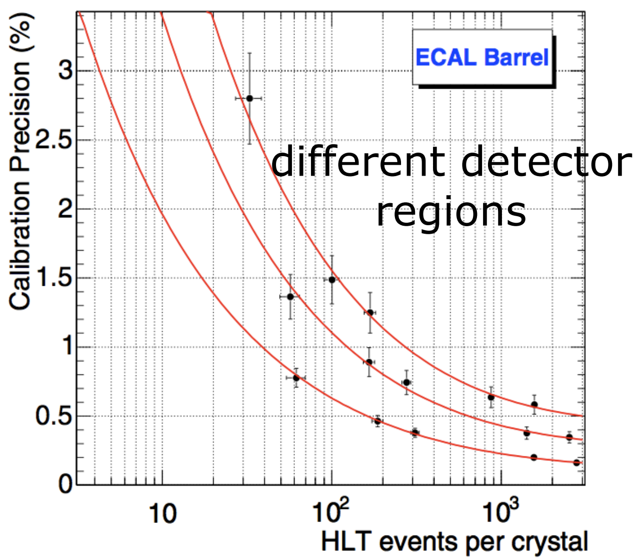
energy in single elements → $\mathcal{E}$

electrons momenta → $\mathcal{P}$

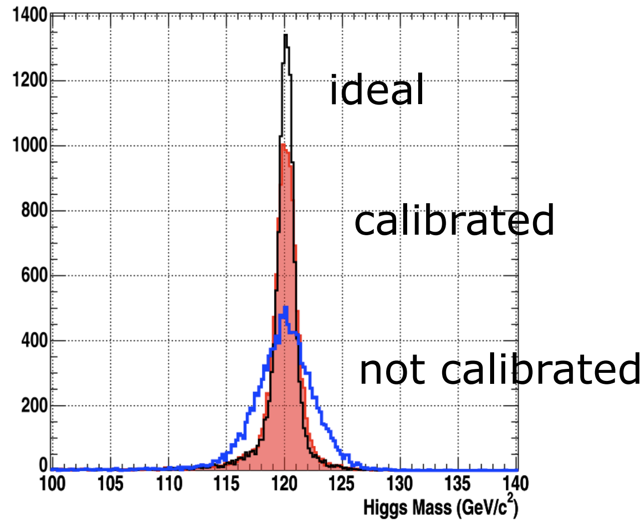
unknown coefficients → $\bar{c}$




select good isolated electrons




statistical trend with luminosity




effect on $H \rightarrow \gamma\gamma$ invariant mass

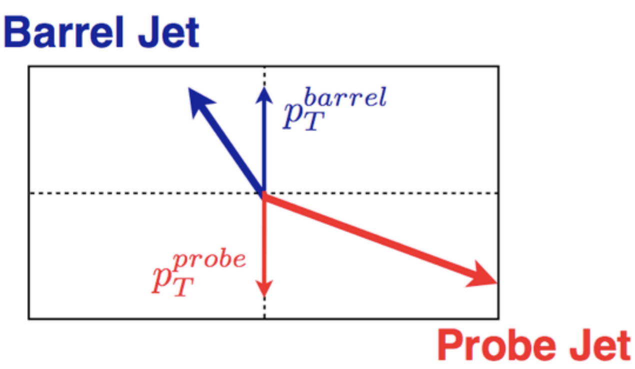
# jet energy corrections

- the jet energy scale needs to be calibrated, as a function of various variables


detector noise effects, pile-up

tag&probe like: di-jets events assumed to be balanced, get a relative correction

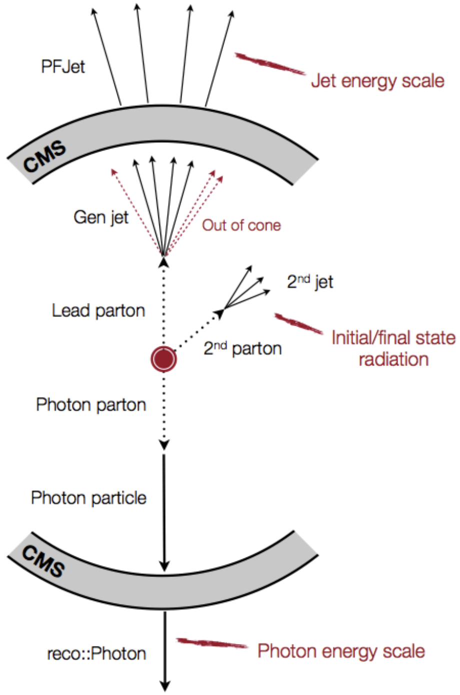
Υ+jet balance in the transverse plane




$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2+ <B>}{2- <B>}$$



# the simulation

# the simulation

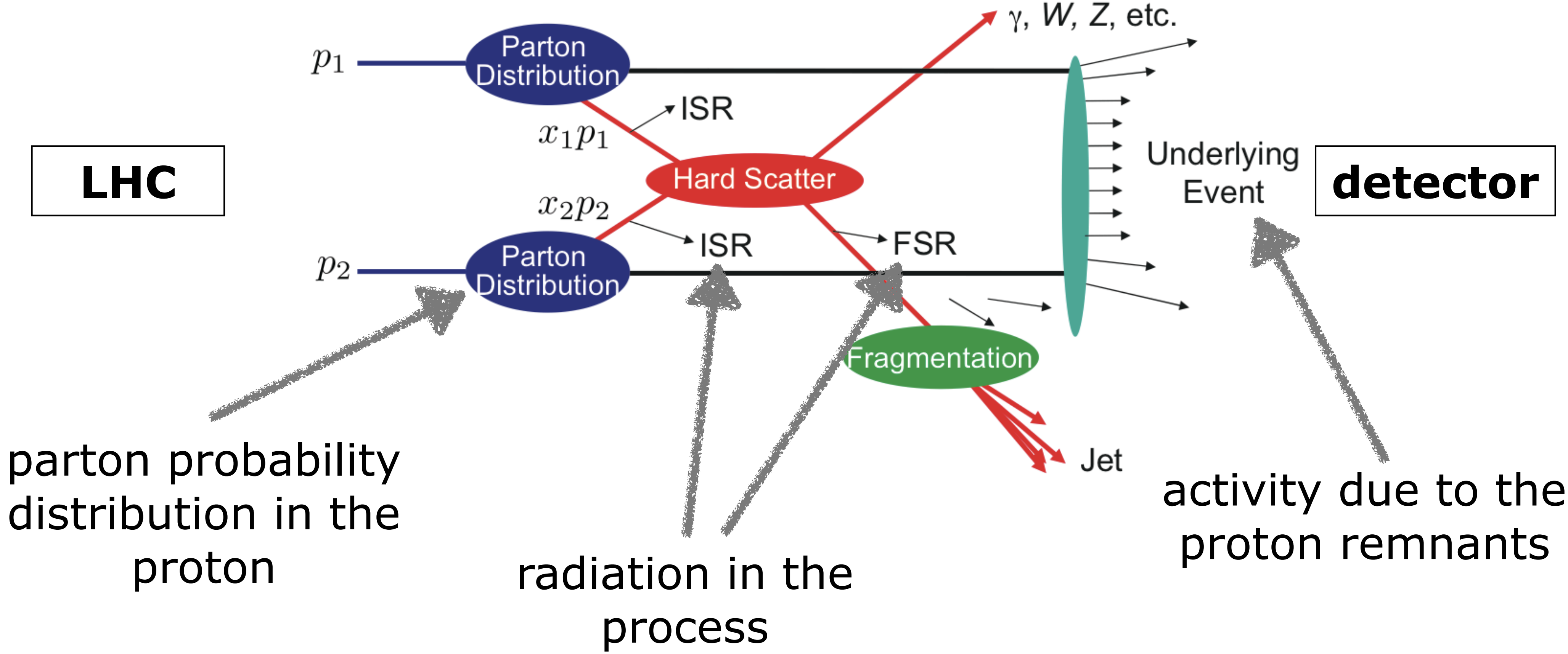
$$\sigma = \frac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

$$\varepsilon = \varepsilon_{tr} \cdot \varepsilon_{reco} \cdot \varepsilon_{ID} \cdot \varepsilon_{sel}$$

- calculate what fraction of events from a given decay **falls within the detector acceptance and the selections** of the analysis
- need a **forecast of how the event develops** in space, after the interaction
- the **simulations** are necessary both for known physics objects (Z, W production) and, of course, to build searches for new physics
- the **uncertainty** in the input parameters is source of systematics

# the simulation

- calculate **inclusive cross-sections**
- calculate **differential cross sections** as a function of variables of interest in the analysis
- provide **simulated events**, that mimic Physics, and have on average the behaviour foreseen by the theoretical model



# the physics event generation

add the underlying event

↑

let hadronic decay

↑

hadronize partons

↑

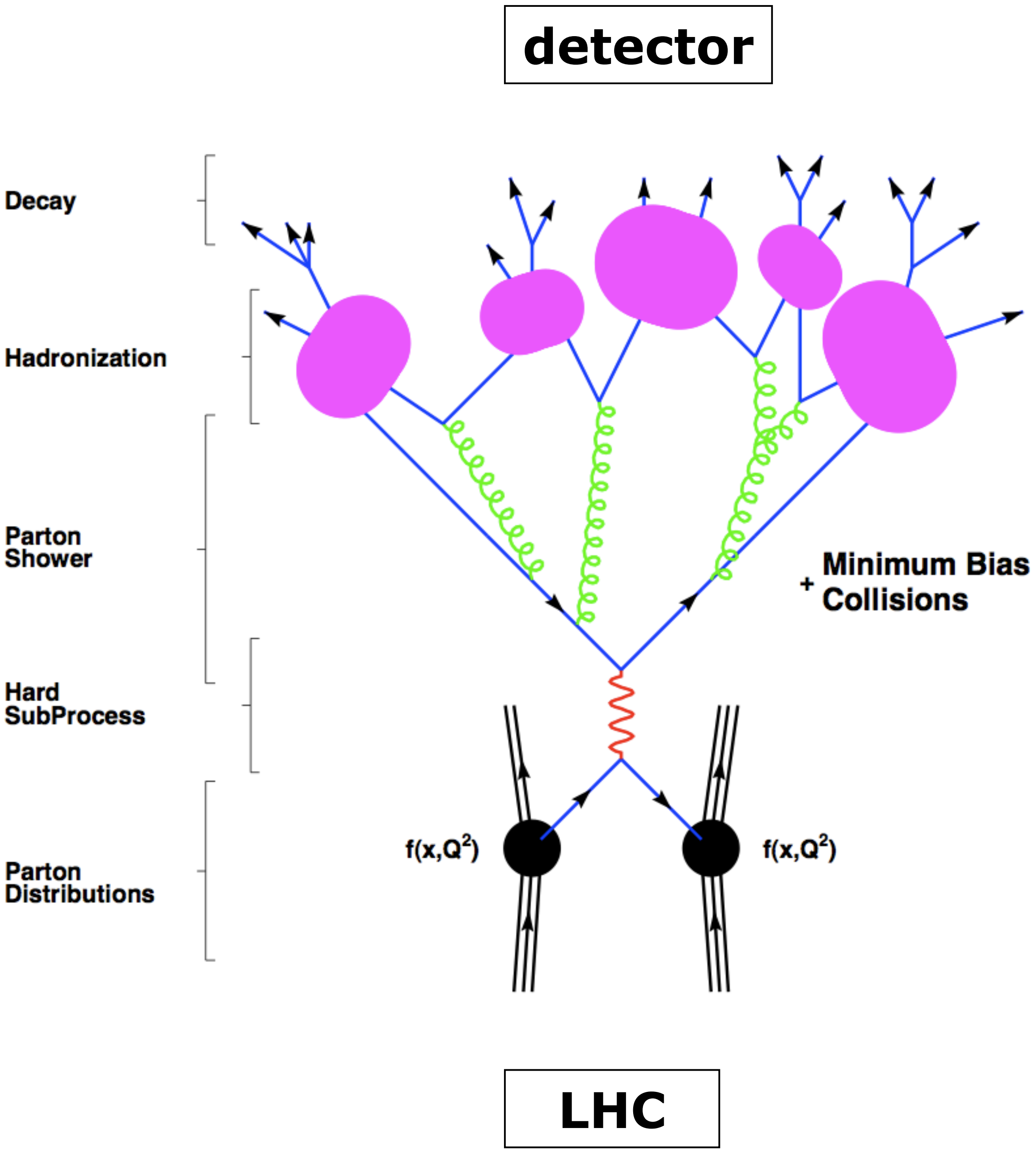
add the parton showers

↑

add initial and final state radiations

↑

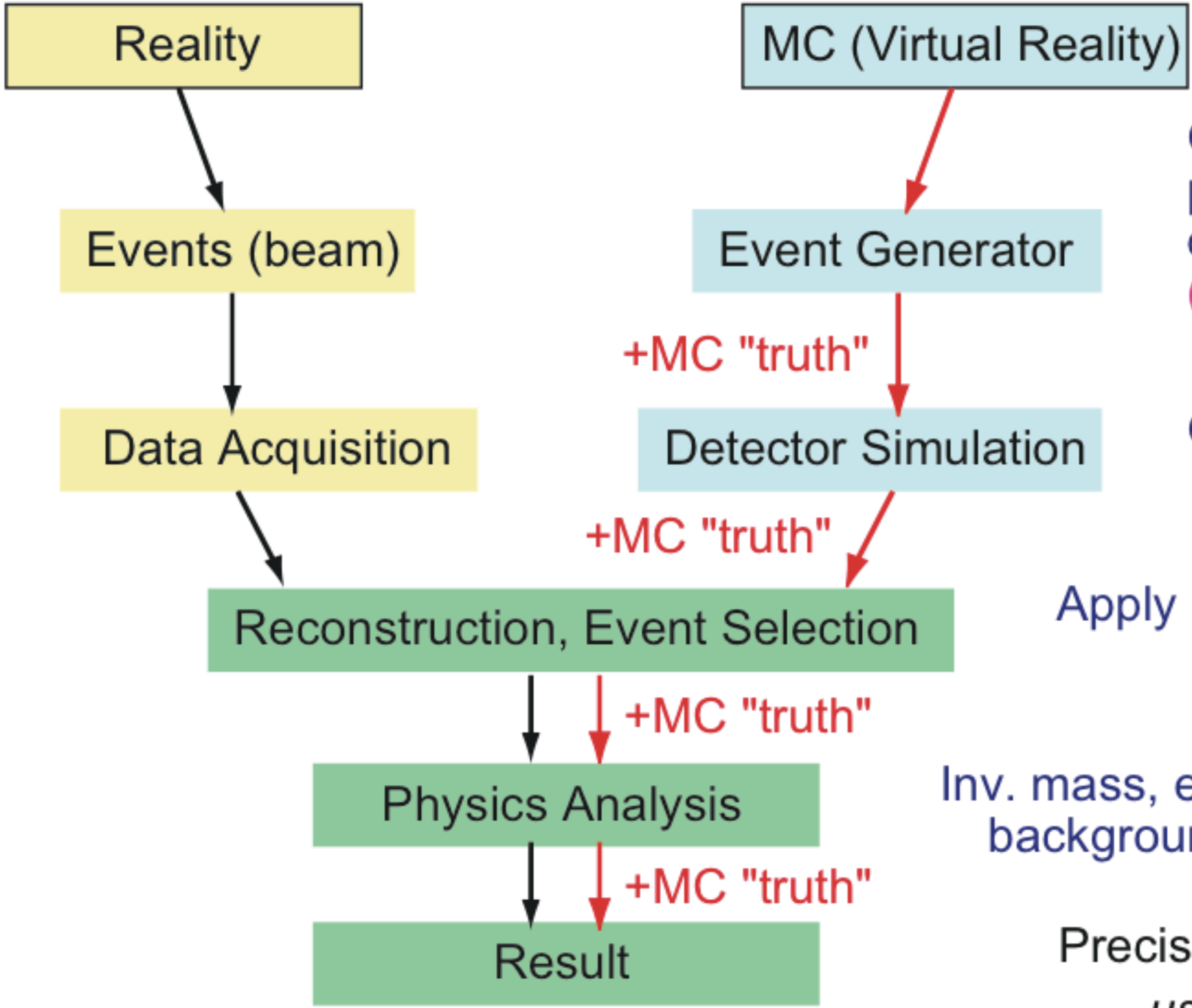
generate hard process



# the simulation of the detector

- each experiment creates a **simulation of the detector**
- the GEANT program uses generator output (4-vectors) and simulates the **interaction of particles within the detector volume** (need a good description of the geometry):
    - particle ionization in trackers
    - energy deposition in calorimeters
    - intermediate particle decays/radiation
- the GEANT code is merged with (experiment specific) **detector simulation**
- final output: the response of the electronics readout
- MC events are in the **same format as real raw data**

# the samples processing




Generates 4-vectors for the particles, resonances, ang. dist., decays, etc. (PYTHIA, HERWIG, ALPGEN, Sherpa...)

Generates detector relevant quantities (GEANT 4)

Apply boundary conditions Acceptance

Inv. mass, efficiency, purity backgrounds, *any* dist.

Precision $\approx 1/\sqrt{N}$

*usually:*

$$N^{\rm MC}_{\rm signal} \gg N^{\rm Data}_{\rm signal}$$

$$N^{\rm MC}_{\rm backg} \ll N^{\rm Data}_{\rm backg}$$ (QCD!)

# levels of simulation

Three typical levels of MC simulation:

- Full

  Particle → Energy Deposit → Detector Response → Electronics → Analog Signal → Digitization

  Time consuming, smaller samples

- "Fast" or parameterized

  Intelligently smeared 4-vectors, effiiciencies, noise (from data and full MC)

  And/or calorimeter shower libraries

  Larger samples

- Toy

  Only throw from the handful of prob. dist. functions that you care about (with correlations)

  "Roll your own", usually write (easy in root!) and run yourself

  Crazy-large samples, quickly

  To determine probability of fluctuations, checks for systematic effects, etc..

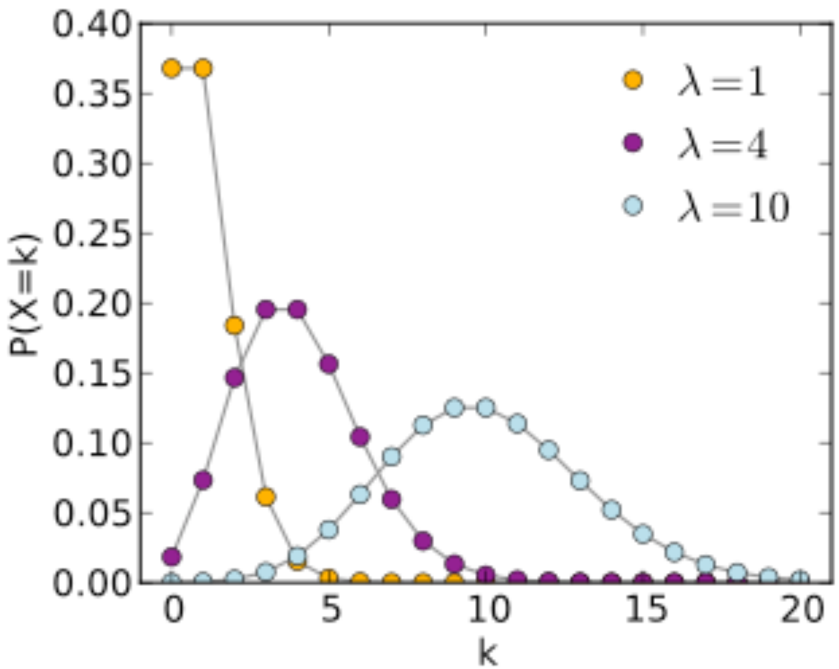
# comparison with data

- the simulation is a multi-dimensional **parametrization** of the knowledge of the detector and standard model predictions
  - is the theoretical simulation correct for the analysis?
    - additional jets production is crucial for analyses that apply a jet veto
    - spin correlations in the Higgs decay need to be treated correctly
  - is the behaviour of the simulation in **agreement** with data, in the phase space of interest for the analysis?

# the pile-up

# the pile-up

- At LHC, the interaction rate is higher than the bunch crossing rate
- Within a bunch crossing in LHC, more interactions happen
- An event of interesting physics will be **recorded together with other events overlapped**, that are proton-proton interactions with low physics interest
- they are equivalent to a non-interesting event (**minimum bias**)




- given an average number of interactions, the number of PU events per bunch-crossing is expected to have roughly a poissonian distribution

# measure the pile-up

- multiply the luminosity (per bunch) by the minimum bias cross-section (71.3 mb) gets the expected rate per bunch:

$$\text{Rate}_{\text{pileup}_{\text{xing,ls}}} = \mathscr{L}_{\text{xing,ls}} \cdot \sigma_{\text{minimum bias}}$$

- divide by the revolution frequency of a bunch to get the number of PU events:

$$\mathscr{N}_{\text{pileup}_{\text{xing,ls}}} = \frac{\mathscr{L}_{\text{xing,ls}} \cdot \sigma_{\text{minimum bias}}}{\text{cirulation rate}}$$

- calculate average distributions over longer periods, weighting by the luminosities

# effects of pile-up

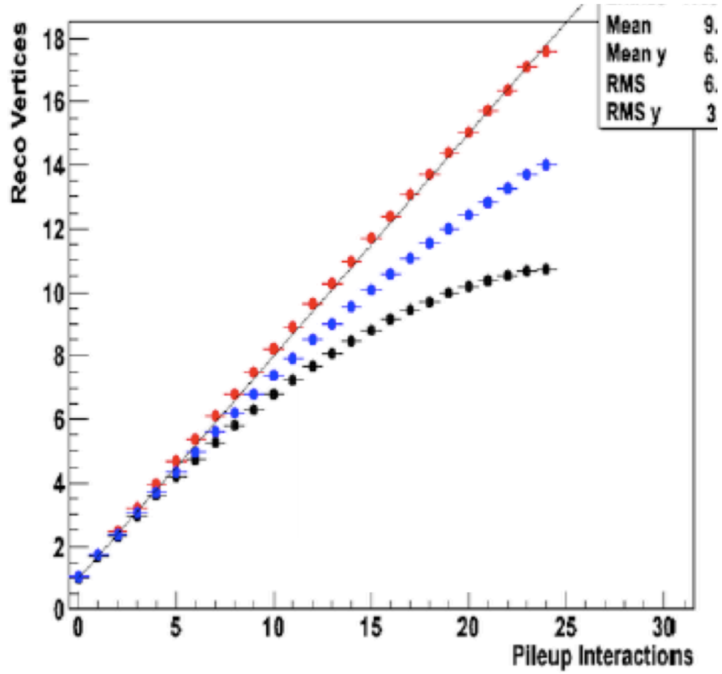
- fill in the detector with deposits:
  - **jet reconstruction** algorithms incorporate pile-up deposits
  - **lepton isolation** cones are filled in with pile-up deposits
  - **new jets** might appear in the event
  - more hits in the **tracker** appear
  - the **trigger** is affected
  - **MET** resolution worsens
  - ....

# how to deal with it

- apply strict r**equirements on the vertexing of tracks** - need a precise vertex reconstruction algorithm

- measure the **pile-up density** event by event, and use it to subtract from the jets energy a pile-up term (FastJet)

- do the same with isolation cones




- subtract in the isolation cone the contribution of tracks that do not aim at the same vertex of the lepton

- reconstruct the MET only with particles that aim at a given vertex

M. Cacciari, G. Salam and G. Soyez, **FastJet** http://www.lpthe.jussieu.fr/~salam/fastjet/