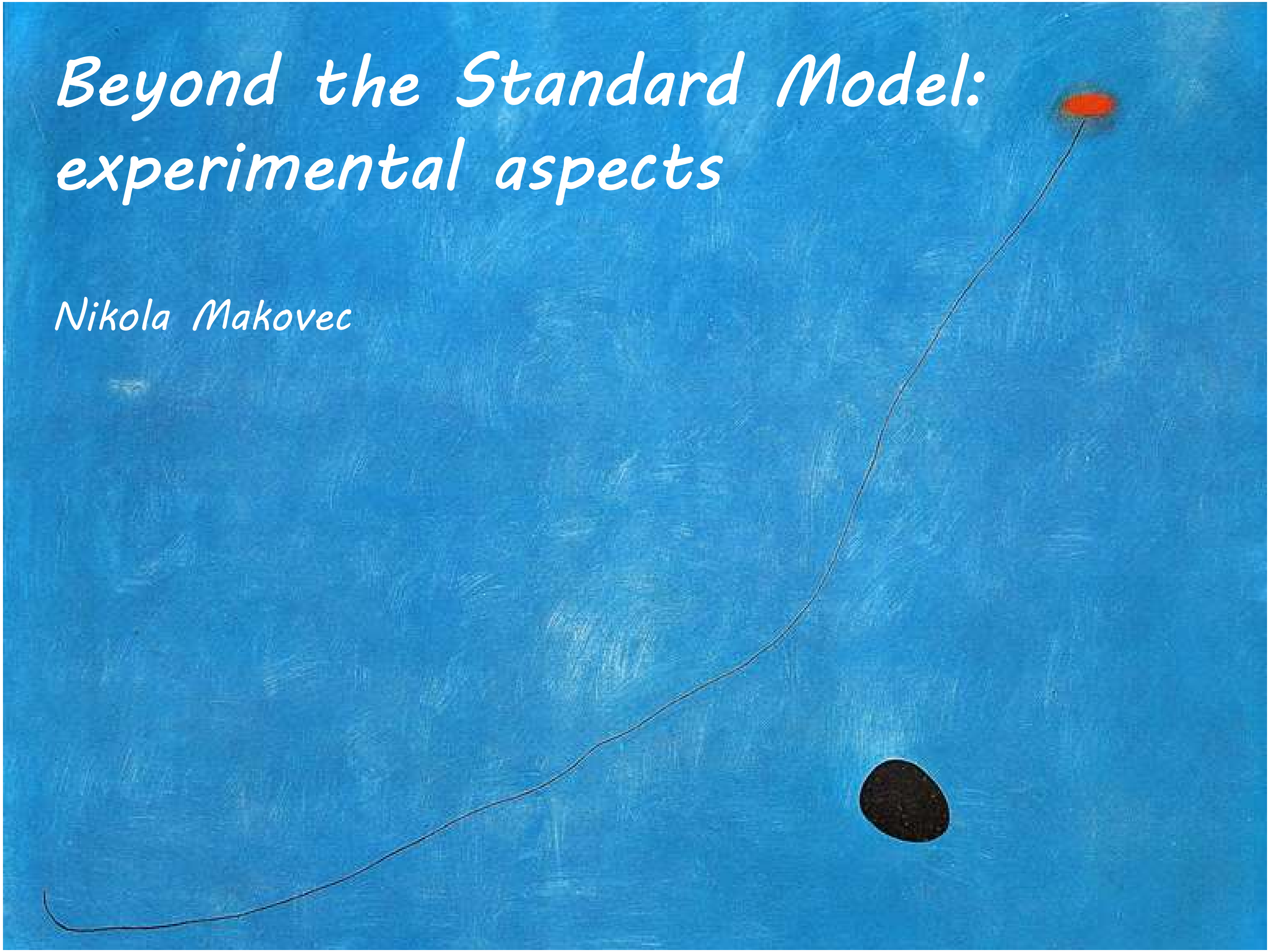
Beyond the Standard Model: experimental aspects

Nikola Makovec



Who am I?

I am a Chargé de Recherche at IJCLab

- 2002-2003: DEA CPM (now Master2 NPAC)
- 2003-2006: D0 Member (Thesis)
- Since 2006: ATLAS Member

Main research interests:

- SUSY searches
- Vector Boson Scattering
- Jet and MET performance
- Design of a High Granularity Timing Detector for HL-HLC

→ explains some biases in these lectures

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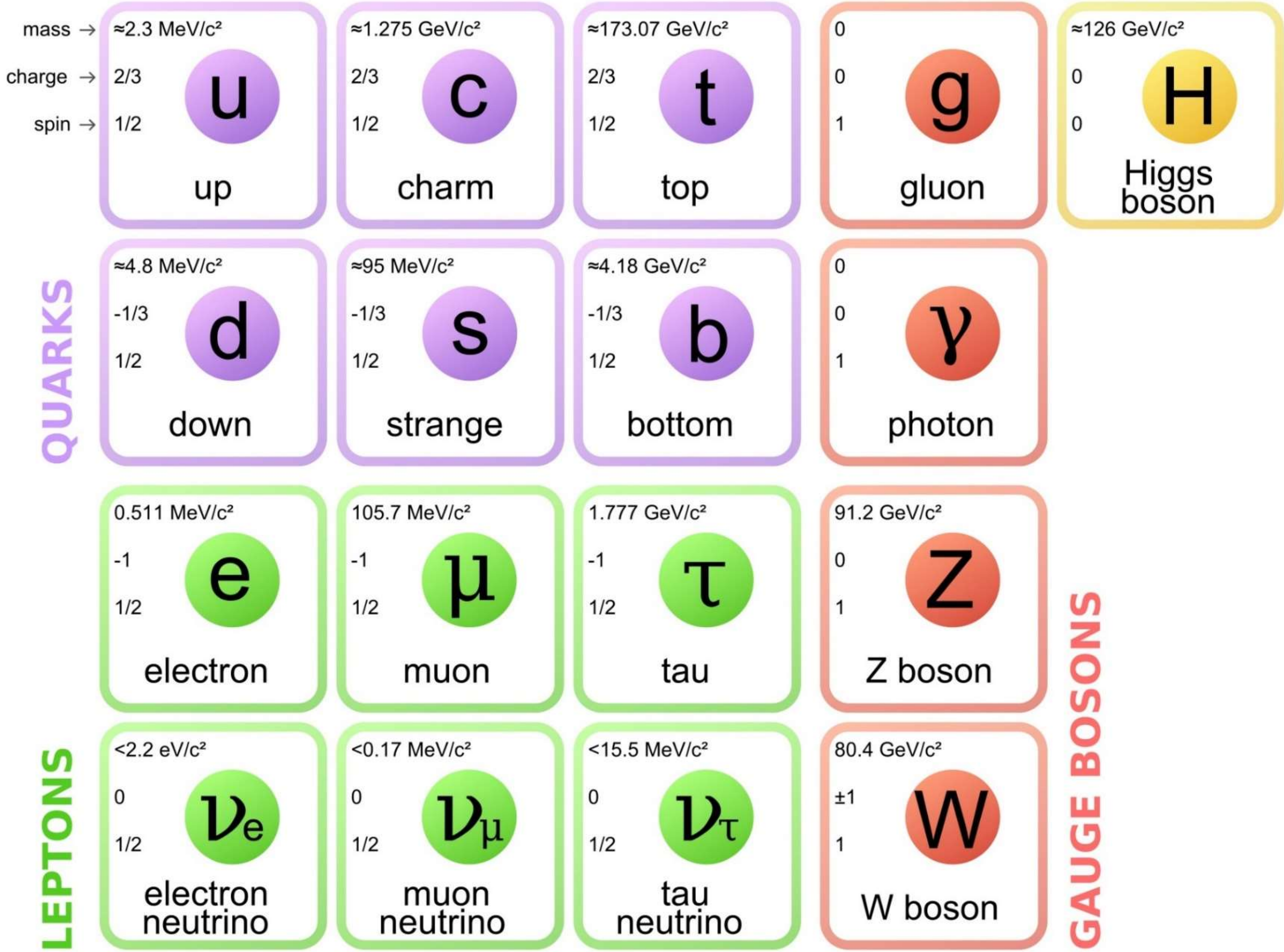
at any time during the lectures

The Standard Model



It looks like the Standard Model is a complete and consistent theory
It describes all observed particle physics in particular at colliders
With m_H = 125 GeV, it can be extrapolated to the Plank scale without the need of New Physics

Physics beyond the SM: why?

What is the physics which reconciles gravity and quantum mechanics?

- New physics expected (at least) at energies ~ 10^{19}GeV !

Why our Universe is made of only 5% of ordinary SM particles?

- Dark matter? Dark energy?

How to produce enough CP-violation to explain the matter-antimatter asymmetry in the universe?

Why do neutrinos have mass yet so light?

- Need right-handed neutrinos (add 7 (+2) parameters to the SM)

Why so many parameters?

- Why four fundamental interactions and not one?
- Why three generations?
- Origin of hierarchical Yukawa couplings?

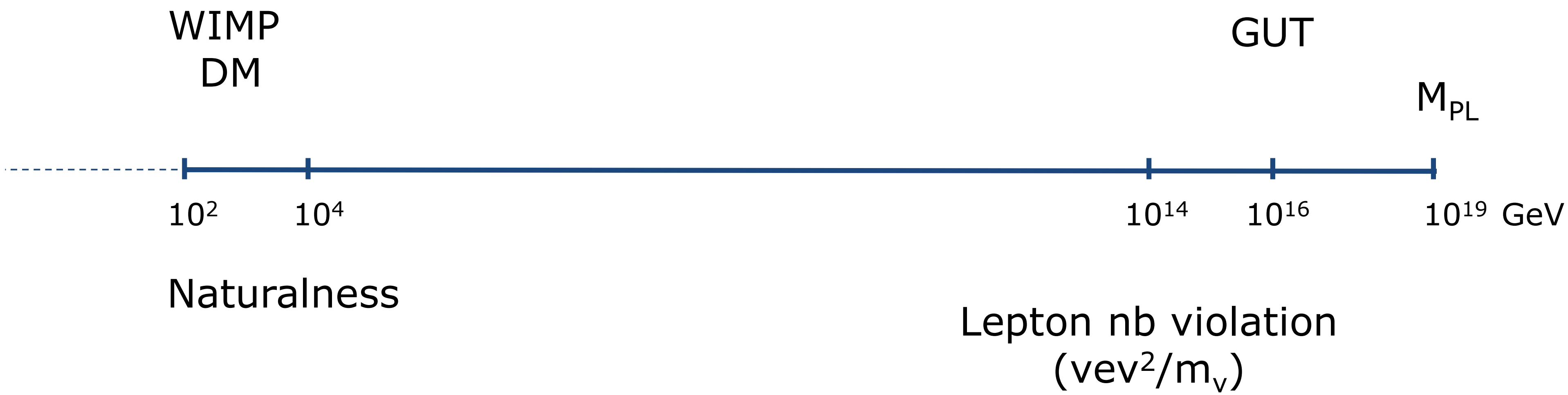
Why the Standard Model is not natural?

- Coupling to a higher energy theory generically leads to the hierarchy problem

$$m_H^2 = m_{bare}^2 + c.\Lambda_{NP}^2$$

New physics at the TeV scale?

Physics beyond the SM: where?



Physics beyond the SM

Many BSM models developed to answer Standard Model limitations.

For instance:

- Supersymmetry: add a new broken symmetry to SM to protect Higgs mass
- Composite Higgs: the Higgs is not elementary, first manifestation of a new strong force

How to look for physics beyond the SM?

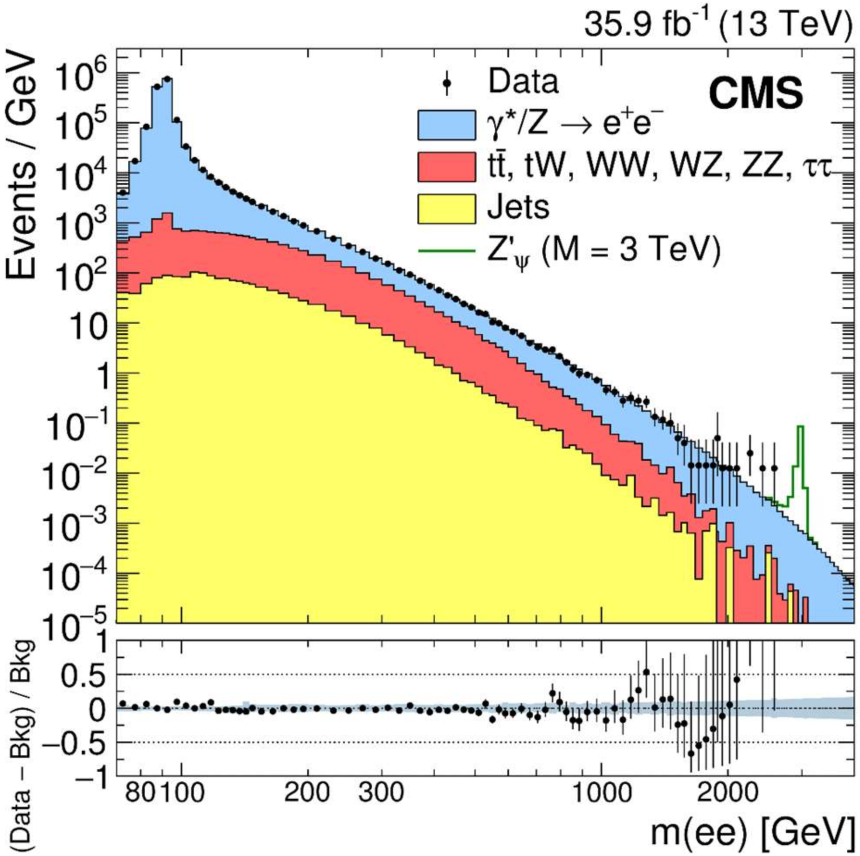
- Energy frontier
  - Direct searches for new heavy particles
  - Need colliders with the largest possible energy

- Intensity frontier
  - SM measurements with unprecedented accuracy requiring large luminosity
  - Searches for rare decays or forbidden processes in SM (ex: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at NA62)
  - Could be sensitive to higher mass scale than direct searches

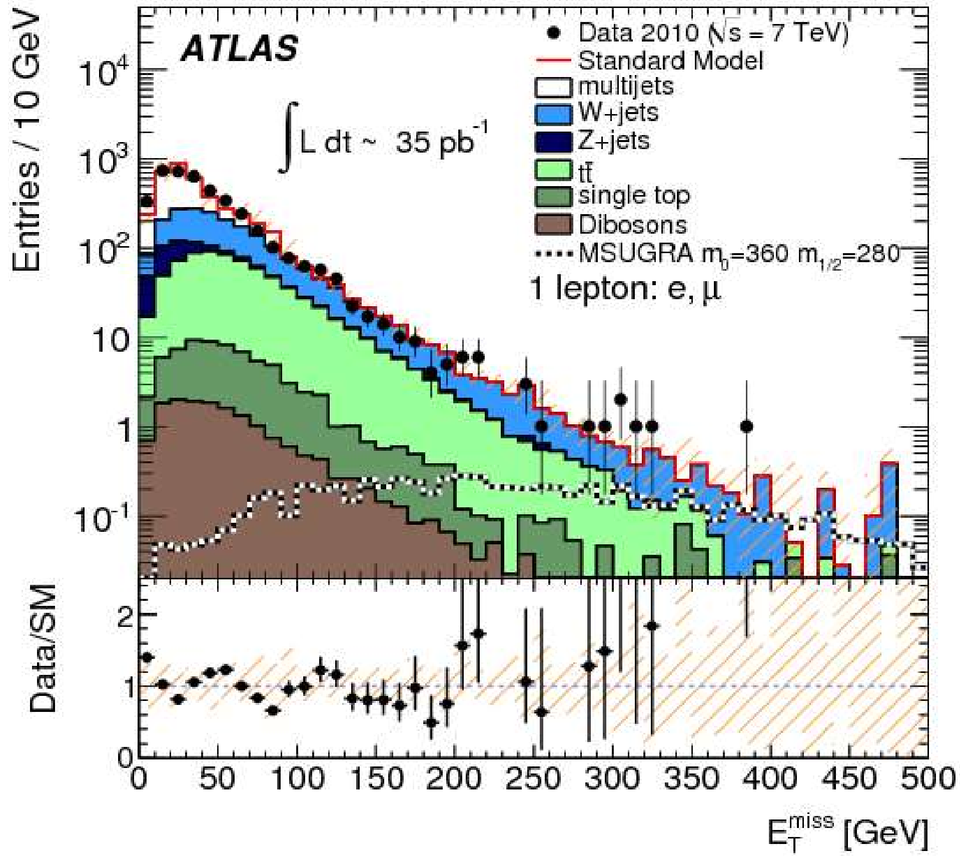
- And also neutrino experiments and cosmological observations
  - Not discussed in these lectures

Direct searches

Bump hunting

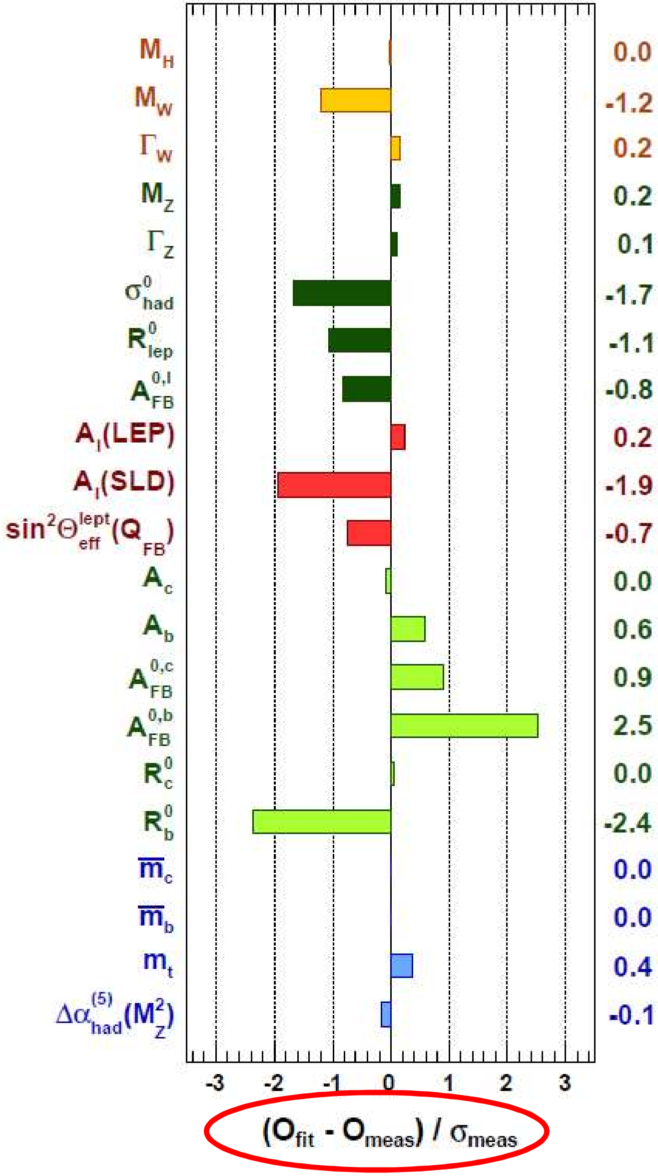


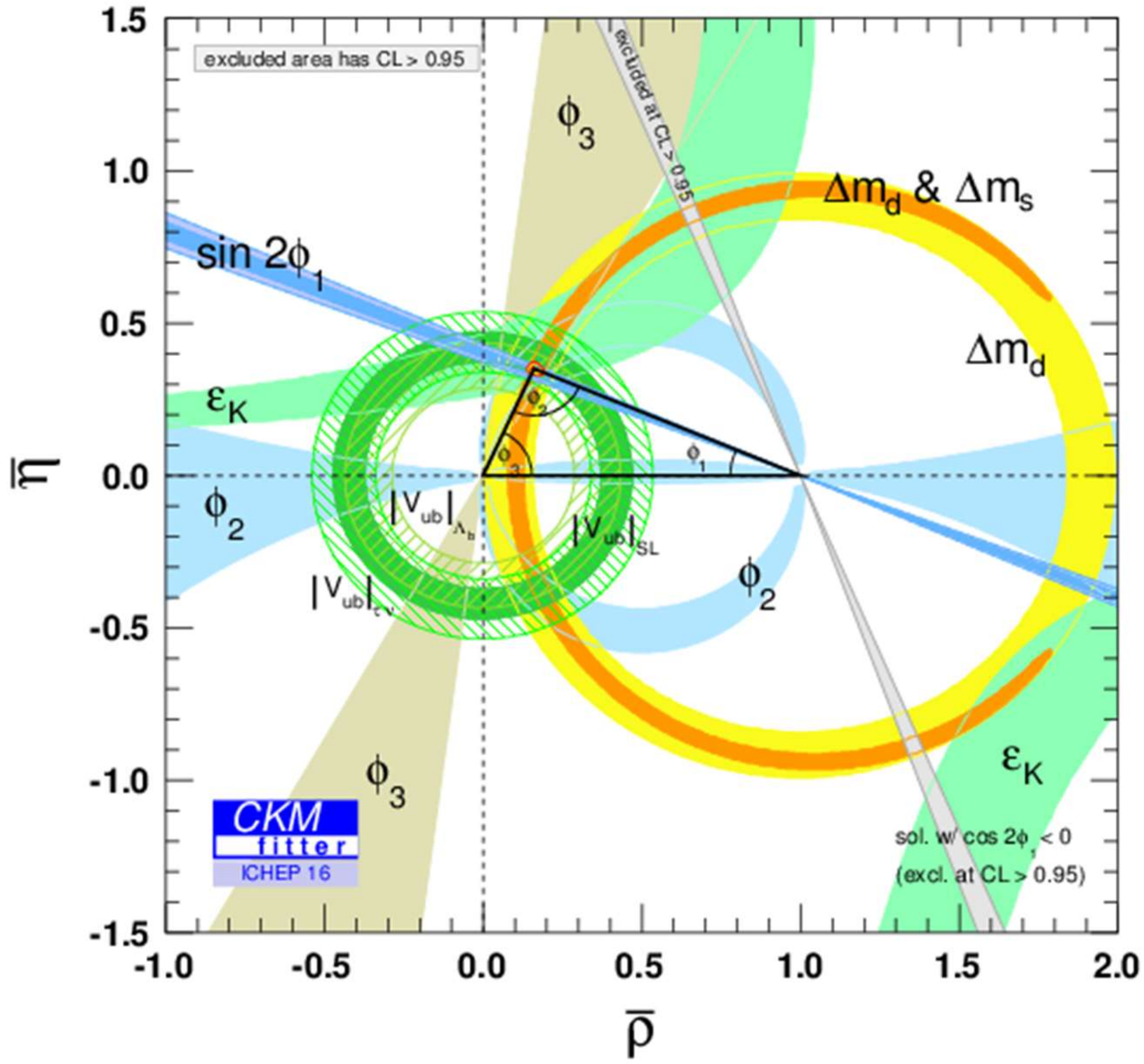
Excess in tails



Can also be a deficit if negative interference

Indirect searches





SM overconstraints → consistency checks
Could be sensitive to higher mass scale than direct searches

Outline

1. **From collisions to physics**
2. **Statistics for BSM searches**
3. **The Higgs boson: a portal to BSM physics**
4. **Search for supersymmetric particles**
5. **Selected topics in BSM physics**
   - Flavour physics
   - Vector like quarks searches
   - Heavy gauge boson searches

Homework:

- Before lecture 4, you should read this paper arXiv:1405.7875

References

CERN Summer Student Lecture Programme Course

- https://indico.cern.ch/category/345/

Results from LHC experiments

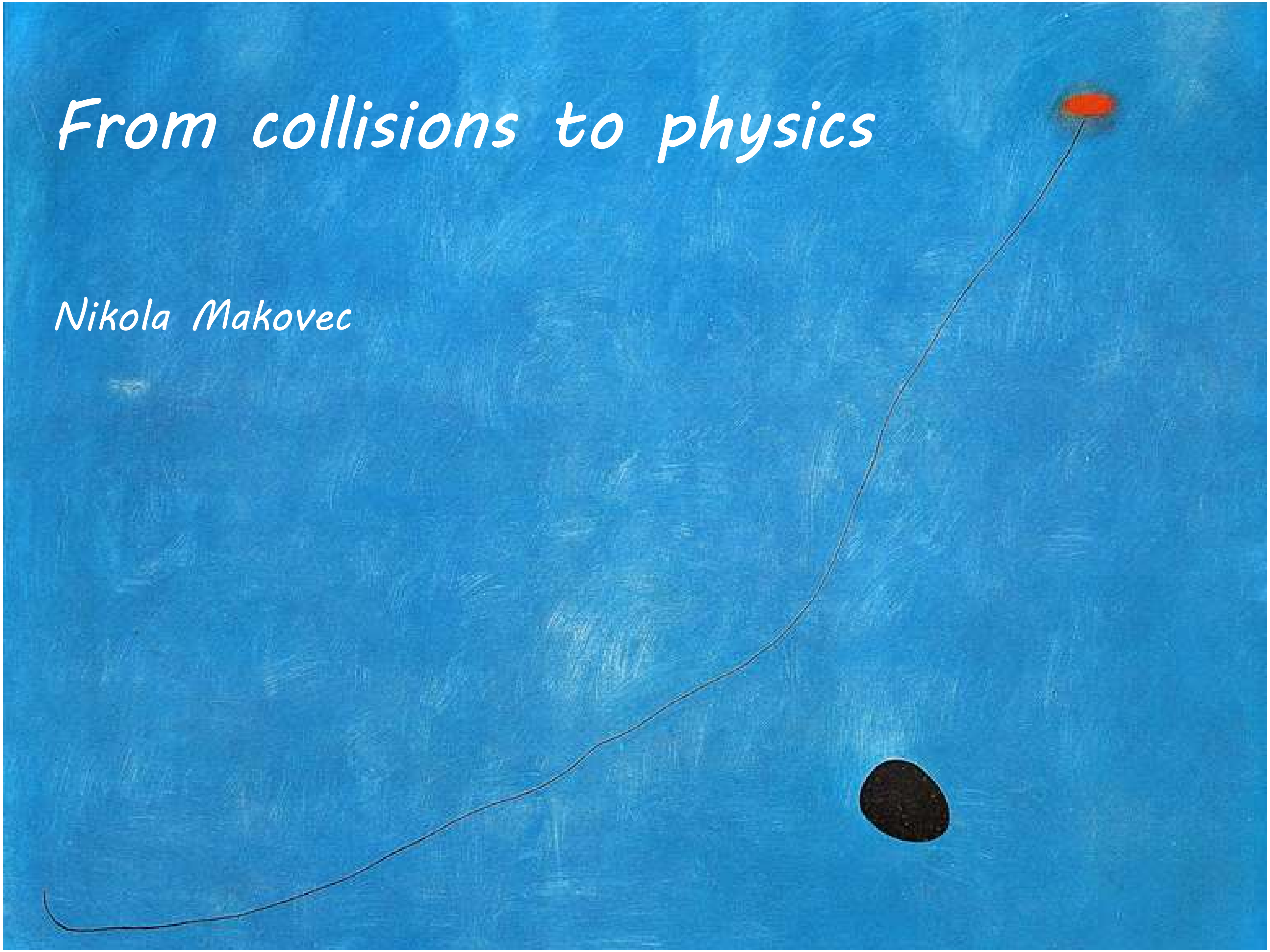
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- http://cms-results.web.cern.ch/cms-results/publicresults/publications/
- http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

Additional references will be given along the lectures

Some ideas and material stolen from many people: H. Bachacou, N. Berger, M. Besancon, C. Botta, J. Boyd, C. Campagnari, C. Clément, J. Conway, G. Cowan, L. di Ciacco, A. Falkowski, P. Francavilla, T. Golling, C. Gütschow, J. Hewett, A. Hoecker, P. Janot, M. Kado, T. Lari, N. Leonardo, F. Meloni, A. Morais, N. Morange, C. Ohm, B. Petersen, G. Piacquadio, W. Pokorski, A. Pomarol, P. Pralavorio, J. Qian, L. Roos, M.-H. Schune, J. Shelton, P. Sphicas, L. Valery, W. Verkerke, M. Williams and many others

From collisions to physics

Nikola Makovec



Outline

- Outline
  1. LHC
  2. Detectors and particle reconstruction
  3. Simulation
  4. Cross-section measurements

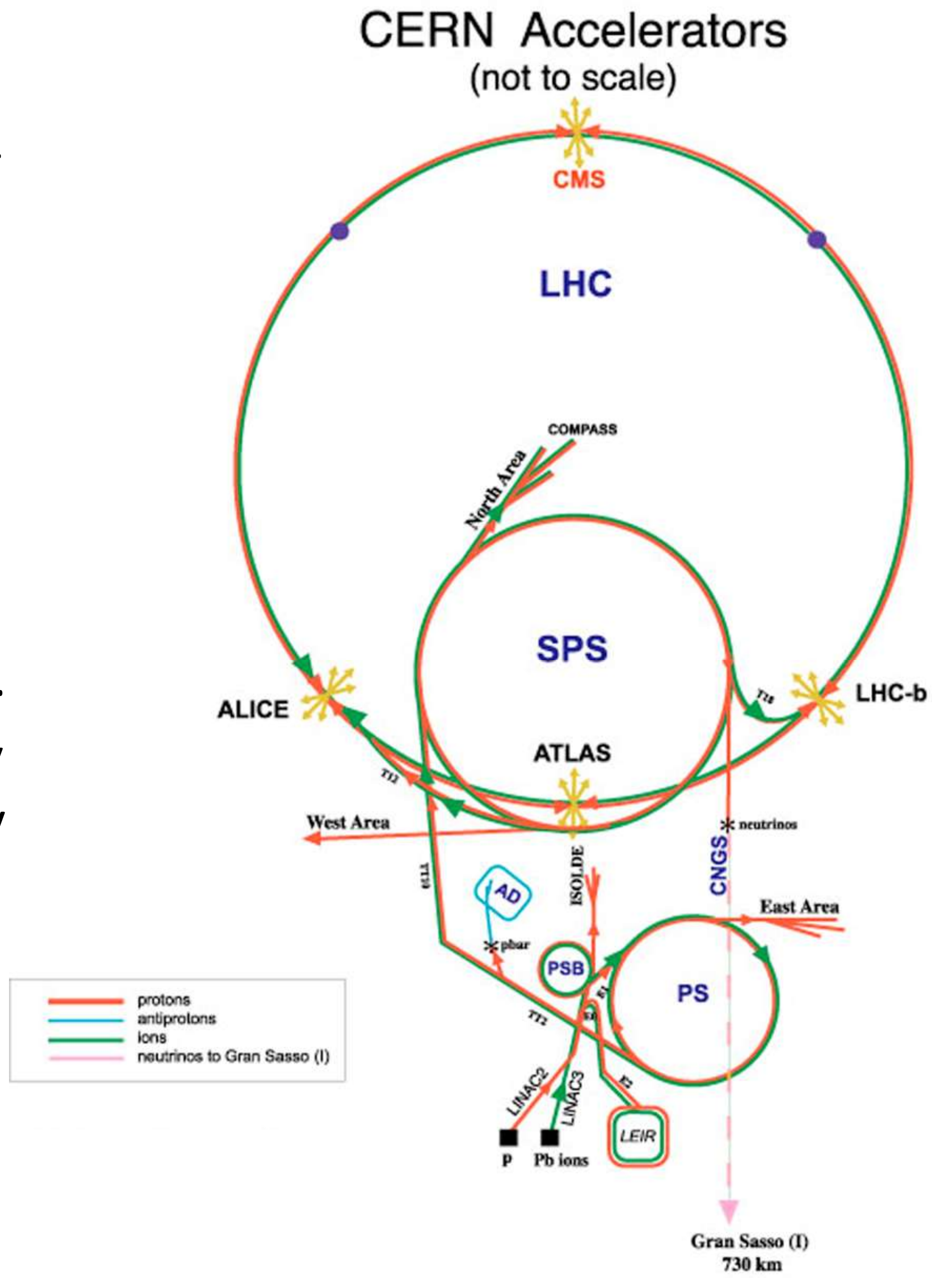
- References
  - Hard Interactions of Quarks and Gluons, J. Campbell et al.
    - arXiv:0611148
  - Lectures on Collider Physics, M. Schwartz
    - arXiv:1709.04533
  - Physics at the LHC Run-2 and Beyond, A. Hoecker
    - arXiv:1611.07864

LHC

LHC

Few interesting facts:

- 9300 Magnets (among which 1232 bending dipoles) reaching 8.3T with current of 11,400 A.
- Beams are made of trains with a total nominal number of bunches of 2808 each containing approximately 100 billion protons.
- Bunches are separated within trains by 25ns (approximately 7m).
- Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.



Instantaneous luminosity

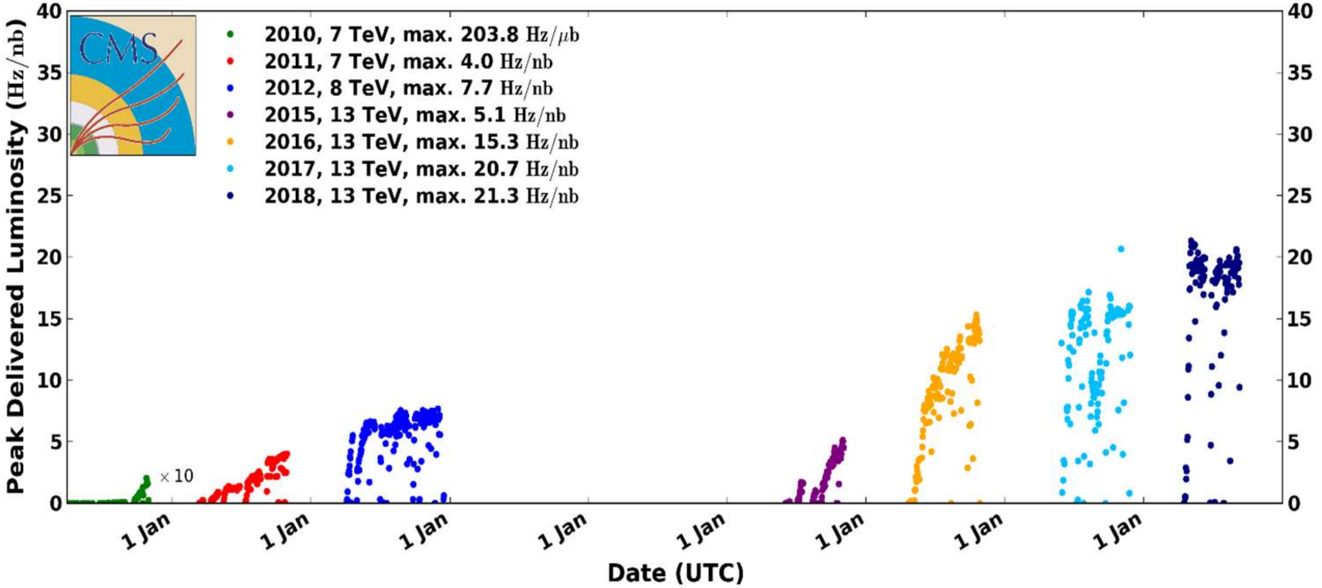
Luminosity is a function of the LHC beam parameters

$$\frac{dN}{dt} = \sigma . L_{inst}$$

$$L \cong \frac{f_{\mathrm{rev}} n_{\mathrm{bunch}} N_p^2}{A} = \frac{f_{\mathrm{rev}} n_{\mathrm{bunch}} N_p^2}{4\pi\sigma_x\sigma_y} \qquad [L] = \frac{1}{\mathrm{s}\cdot\mathrm{cm}^2}$$

$10\ \mathrm{nb}^{-1}\mathrm{s}^{-1} = 10^{34}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$
~ 1 GHz interaction rate

- f_{rev} = 11245.5 Hz is the bunch revolution frequency
- n_{bunch} = 1…2808 is the number of bunches in the machine
- N_{p} = 1.1×10^{11} is the number of protons per bunch ("bunch intensity")
- $\sigma_{x/y}$ = 12…50 μm is the transverse beam width characterising beam optics, $\sigma^2_{x/y} = \varepsilon_{x/y}\,\beta^*_{x/y}$

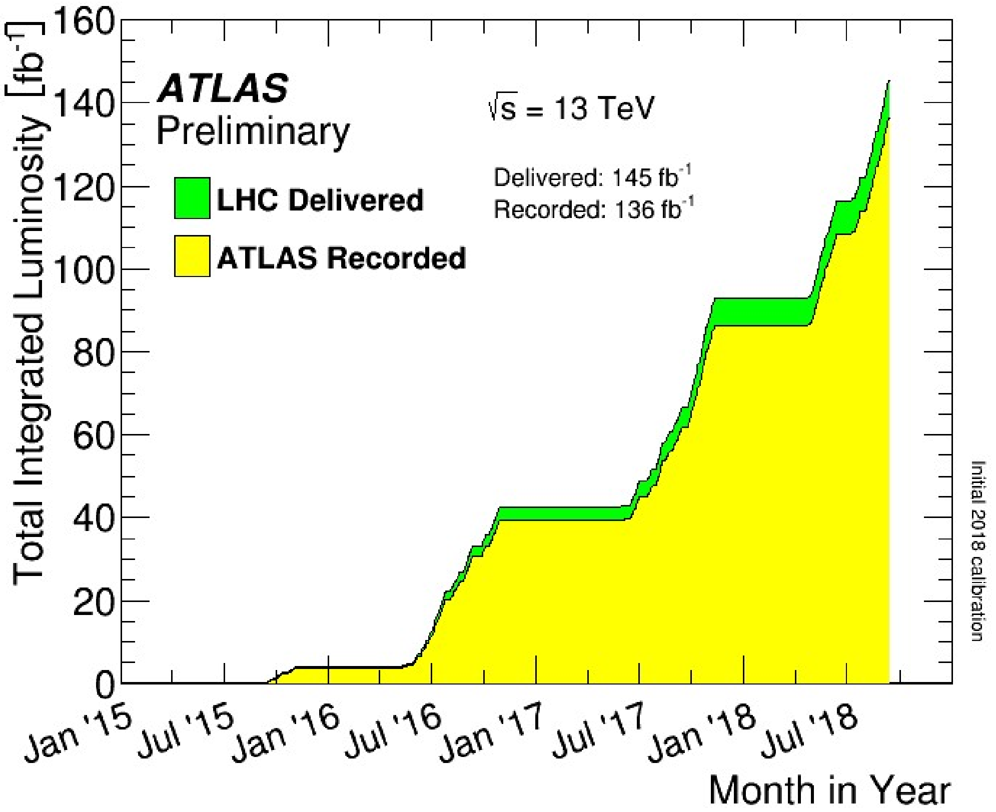


Integrated luminosity

The highest possible instantaneous luminosity is not a goal per se. The challenge is to have the highest possible integrated luminosity in the best possible conditions for experiments

$$L_{int} = \int L dt$$

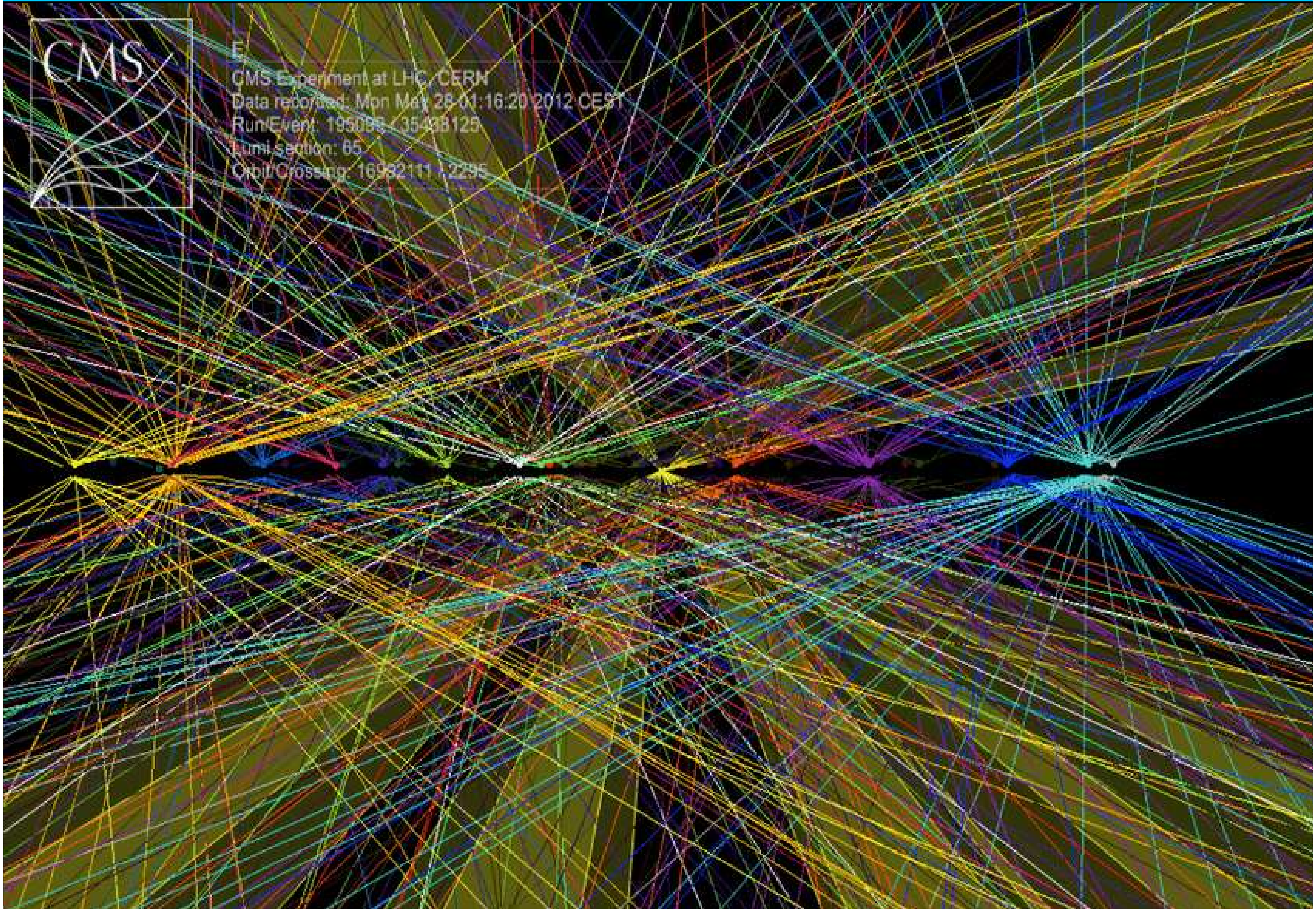
$$N = \sigma . L_{int}$$



Example: σ_{Higgs}=50.6pb

→ ~7 millions Higgs produced at the LHC run2

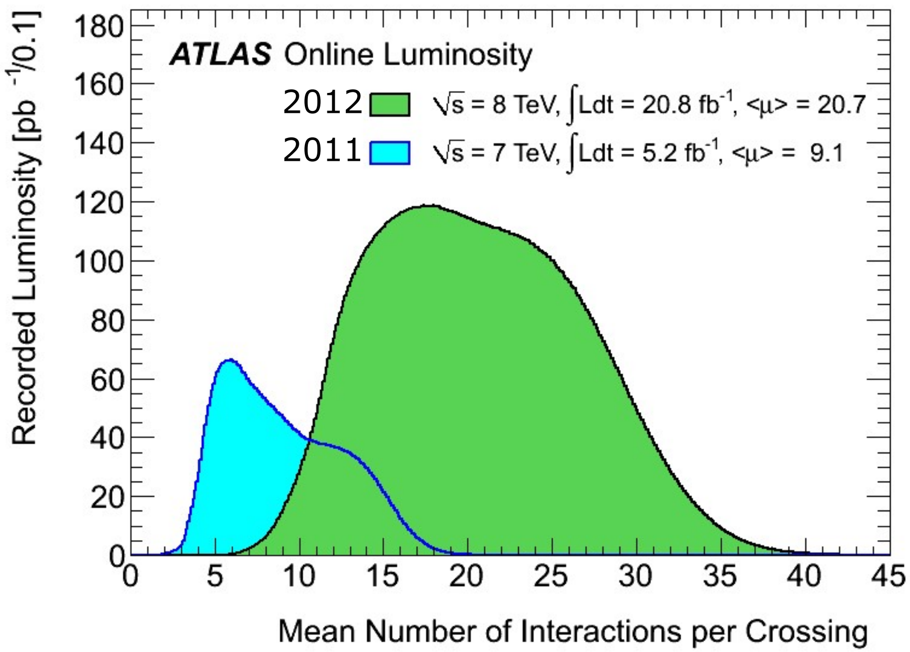
Luminosity comes at a cost: pile-up

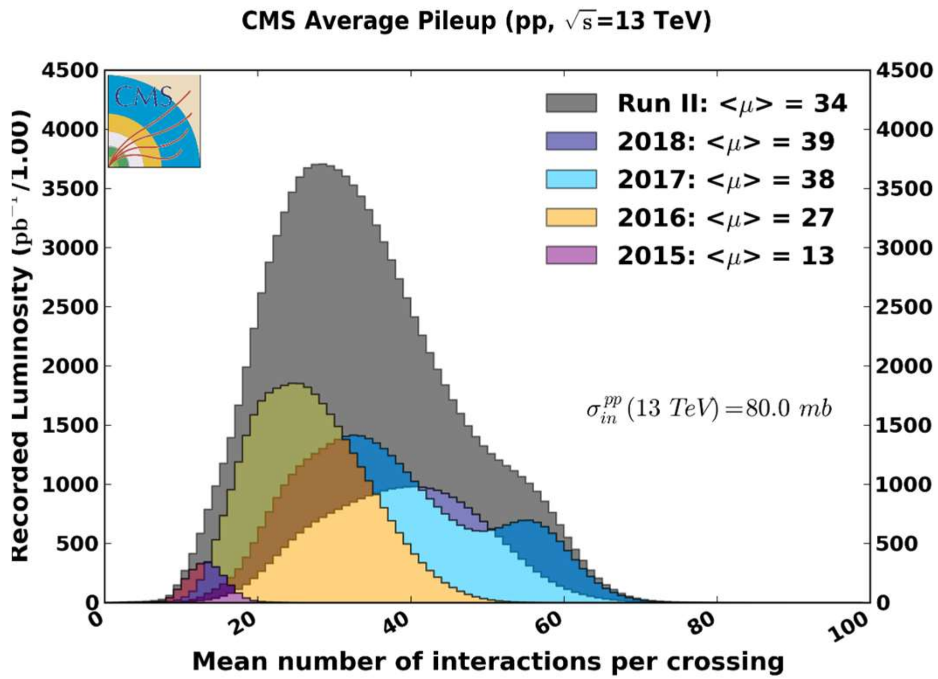


Pile-up

Pile-Up: additional inelastic interactions per bunch crossings

It pollutes the reconstruction of the final state of the collisions (ex: deterioration of jet resolution, additional pileup jets,...) → need methods to mitigate its impact



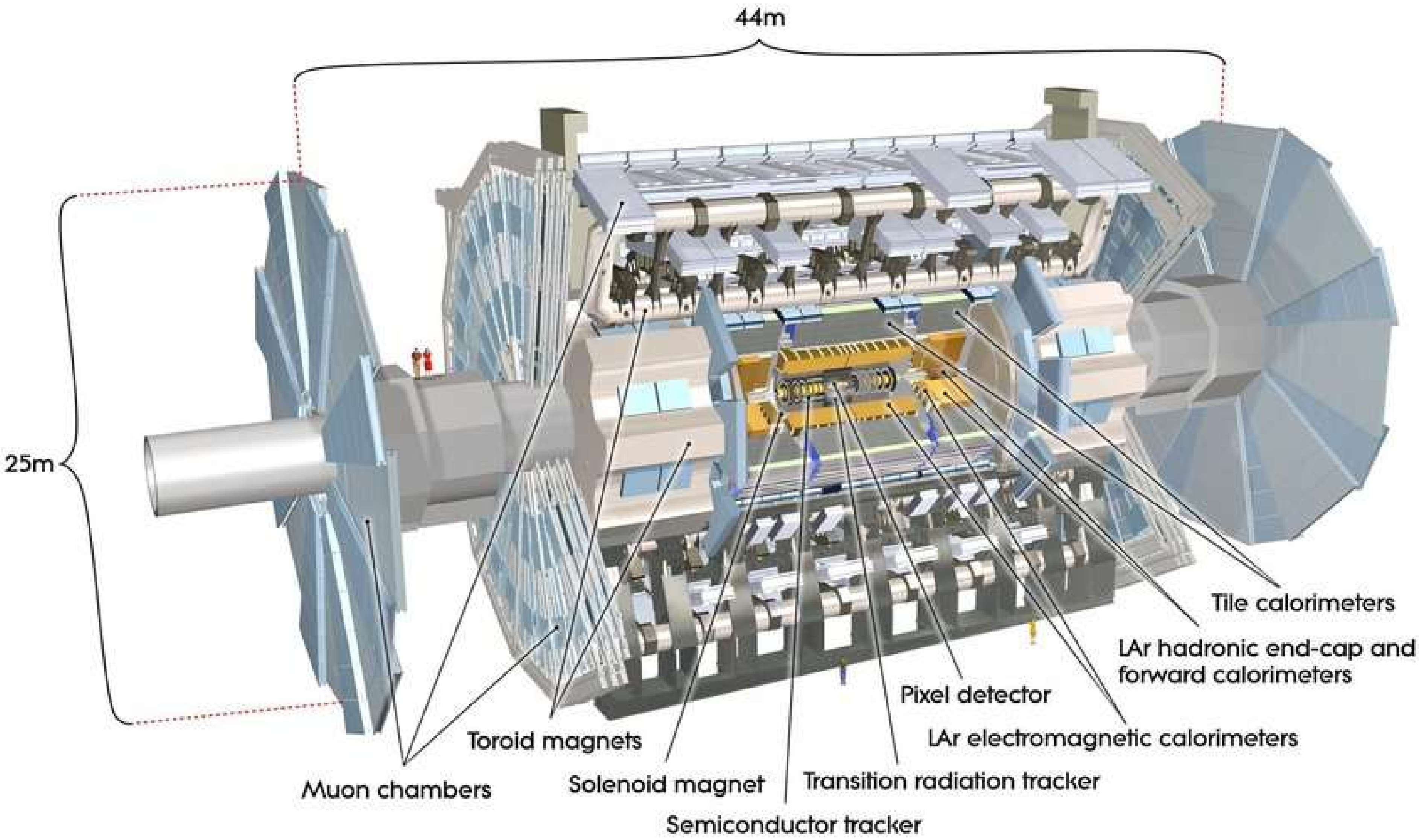


In time pile-up = pp collisions from the same bunch crossing

Out of time pile-up = pp collisions from another bunch crossing

Detectors and particle reconstruction

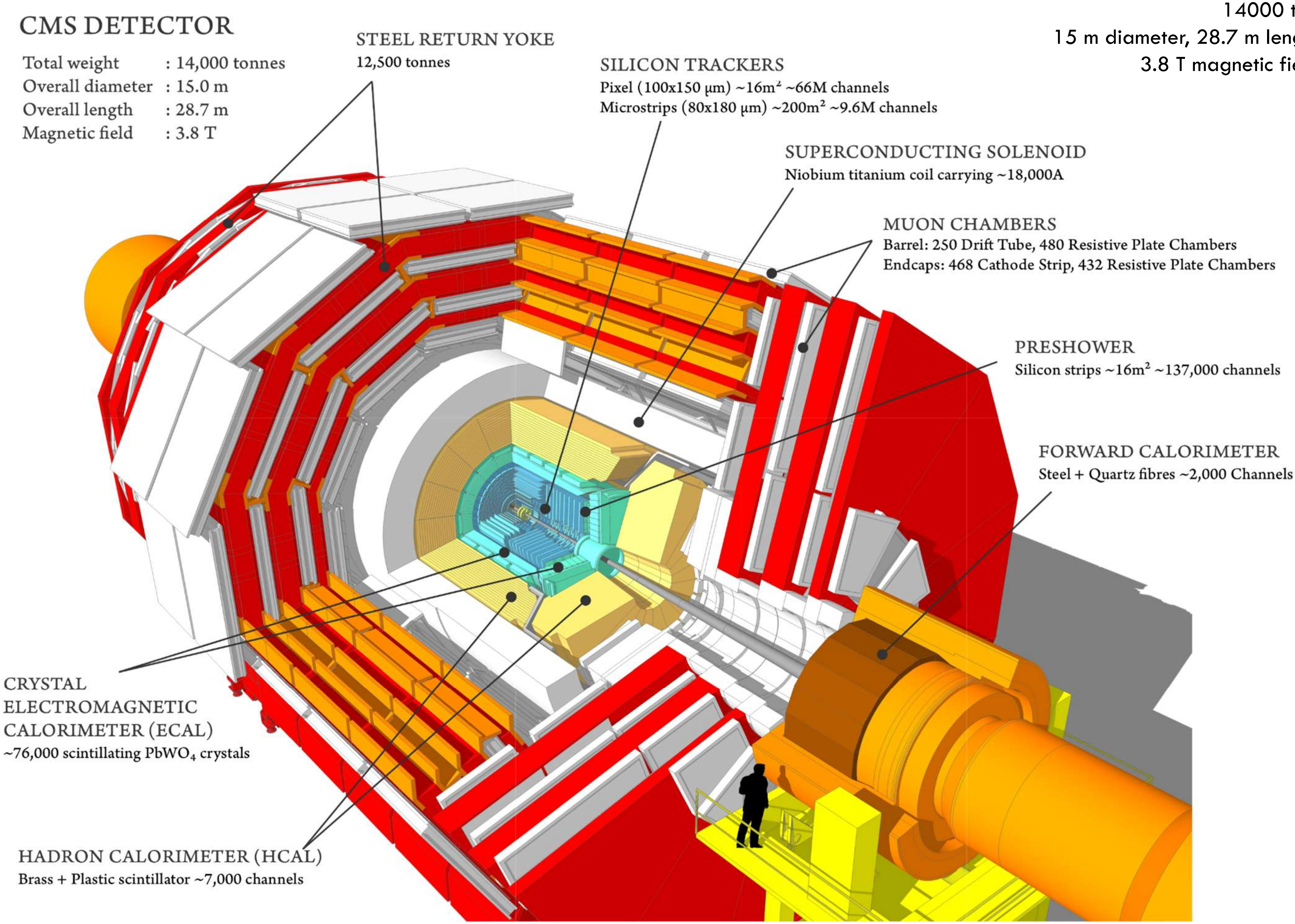
ATLAS



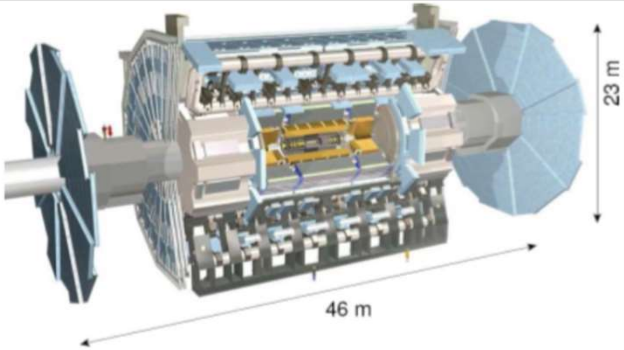
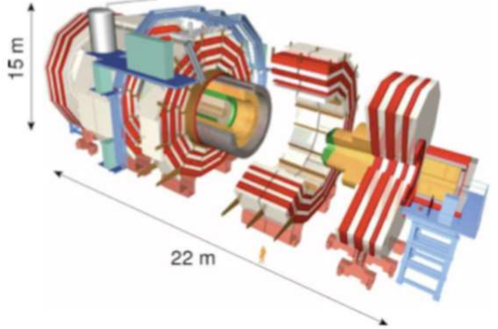
7000 tonnes
2T magnetic field

CMS

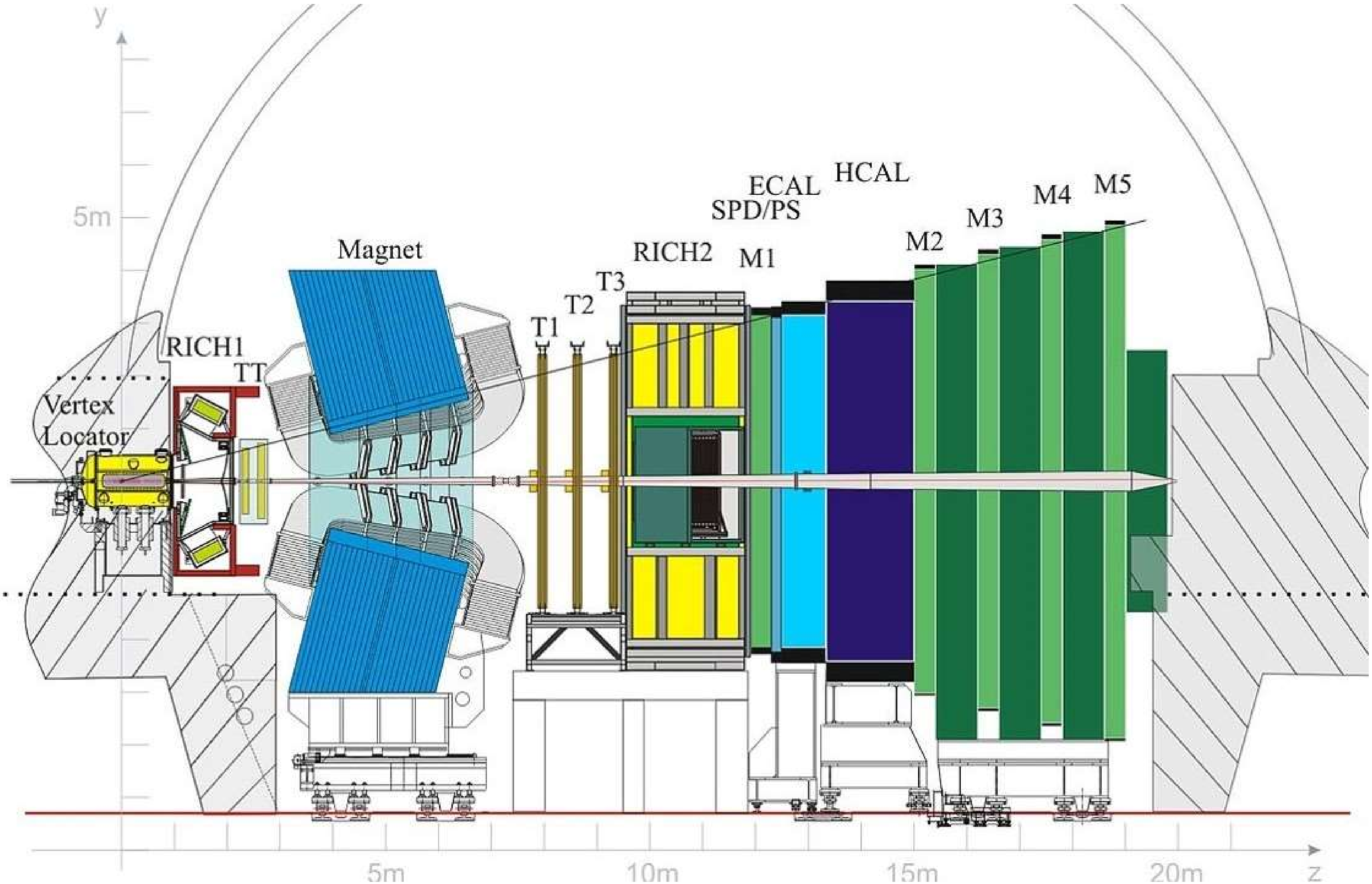
14000 tons
15 m diameter, 28.7 m length.
3.8 T magnetic field.



ATLAS vs CMS

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

LHCb

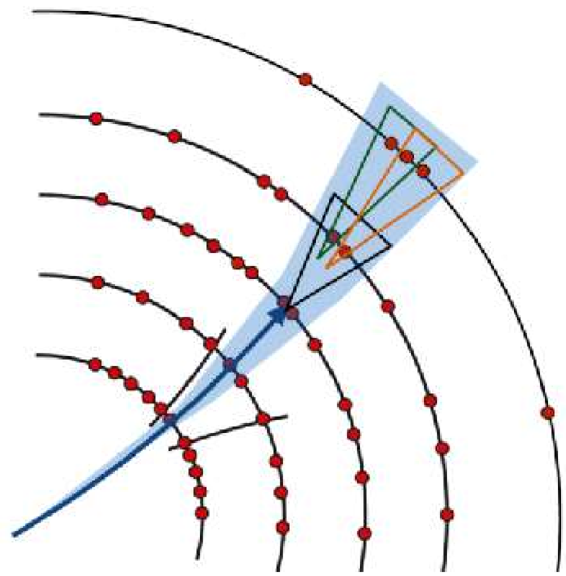


Forward-arm detector

Reconstruction

Reconstruction: algorithms to select and combine detector signals (ex: electrical current) into representative physics observables for experimental analysis

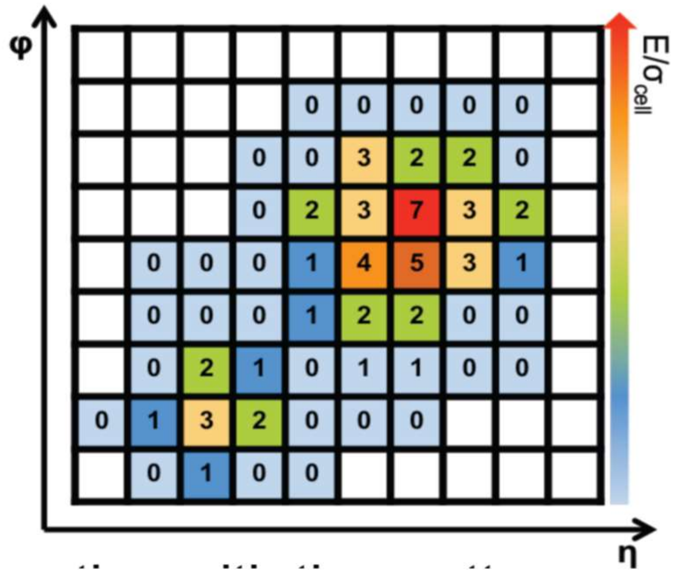
- First step: electric signal to energy conversion for each channels/pixels
- Second step: track finding and calorimeter cell clustering
- Third step: reconstruct physics objects (vertex, electron, jets, …) and measure the kinematical properties



Best performance as possible: high efficiency, low fake rate, good resolution and linearity, pile-up stability,….

Very complex software (ATLAS: 2 millions c++ lines, 20s/event)

Worldwide LHC Computing Grid: store, distribute and analyse the ~50-70 Petabytes of data expected every year



Kinematics

In pp collisions the longitudinal momentum of the system is not known a priori, however the total transverse momentum is known to nearly vanish

The momentum of particle is not invariant under a longitudinal boost along z → **transverse momentum**

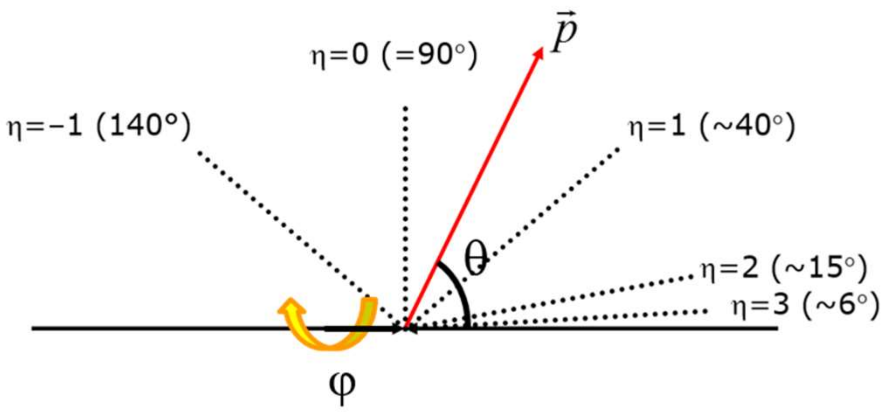
$$p_T = p\sin\theta = \sqrt{p_x^2 + p_y^2}$$

Rapidity differences Δy are invariant Invariant under z-boost because:

$$y' \underset{\text{z-boost}}{\longrightarrow} y - \ln\sqrt{\frac{1+\beta}{1-\beta}}$$

The polar angle is not invariant under a longitudinal boost along z → **rapidity**

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$



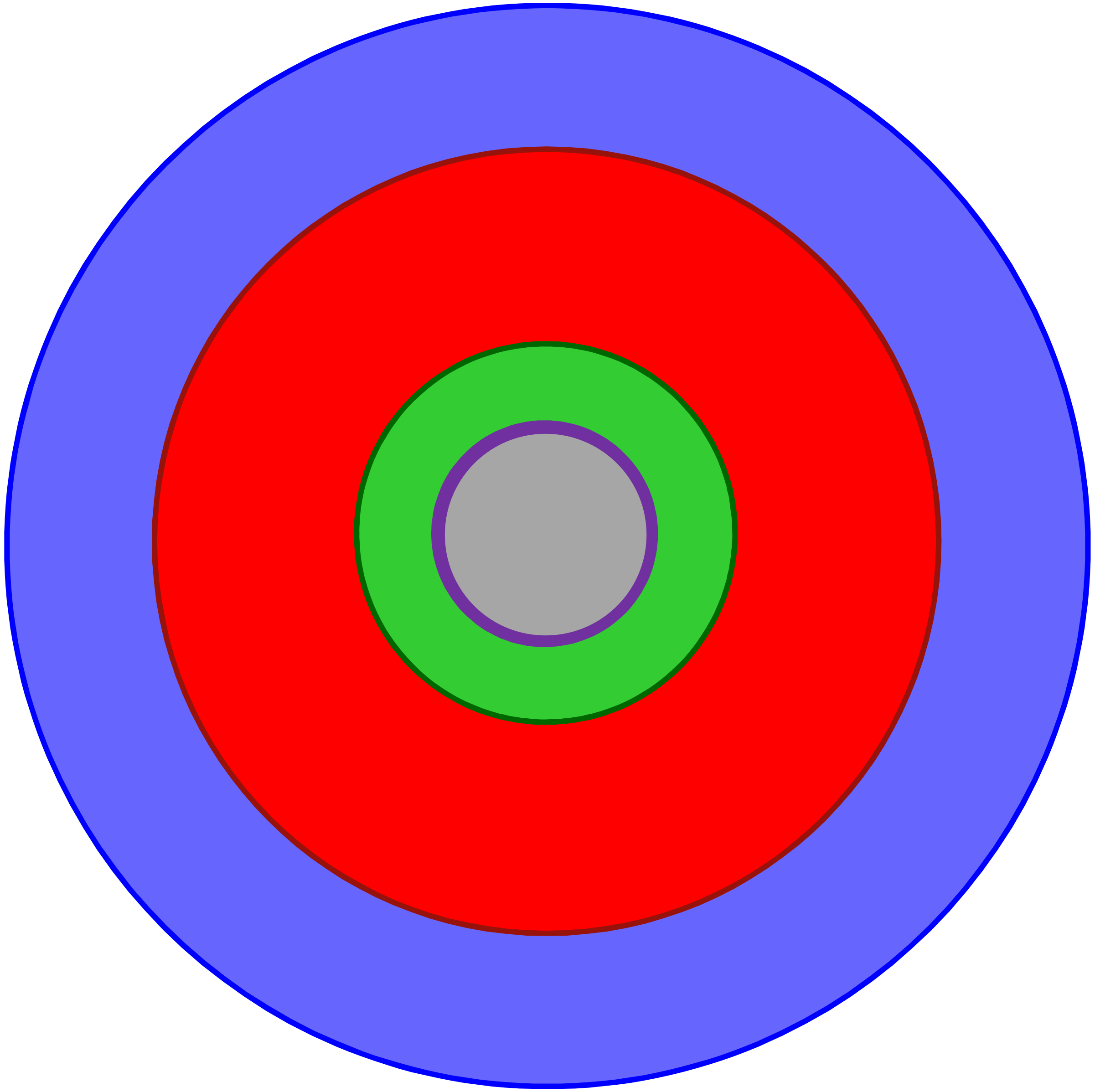
Ultra relativistic limit (or massless systems):

$$y \rightarrow \eta = -\ln(\tan\frac{\theta}{2})$$

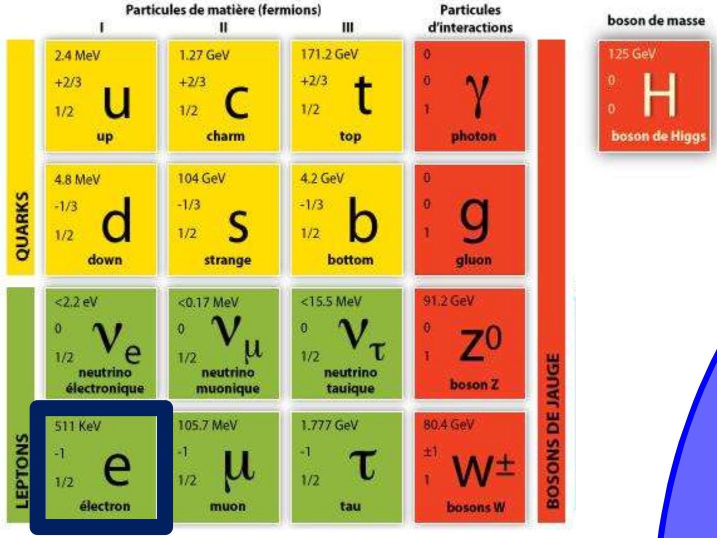
Particles at the LHC are then described by 3 variables: pT, η (or y) and φ

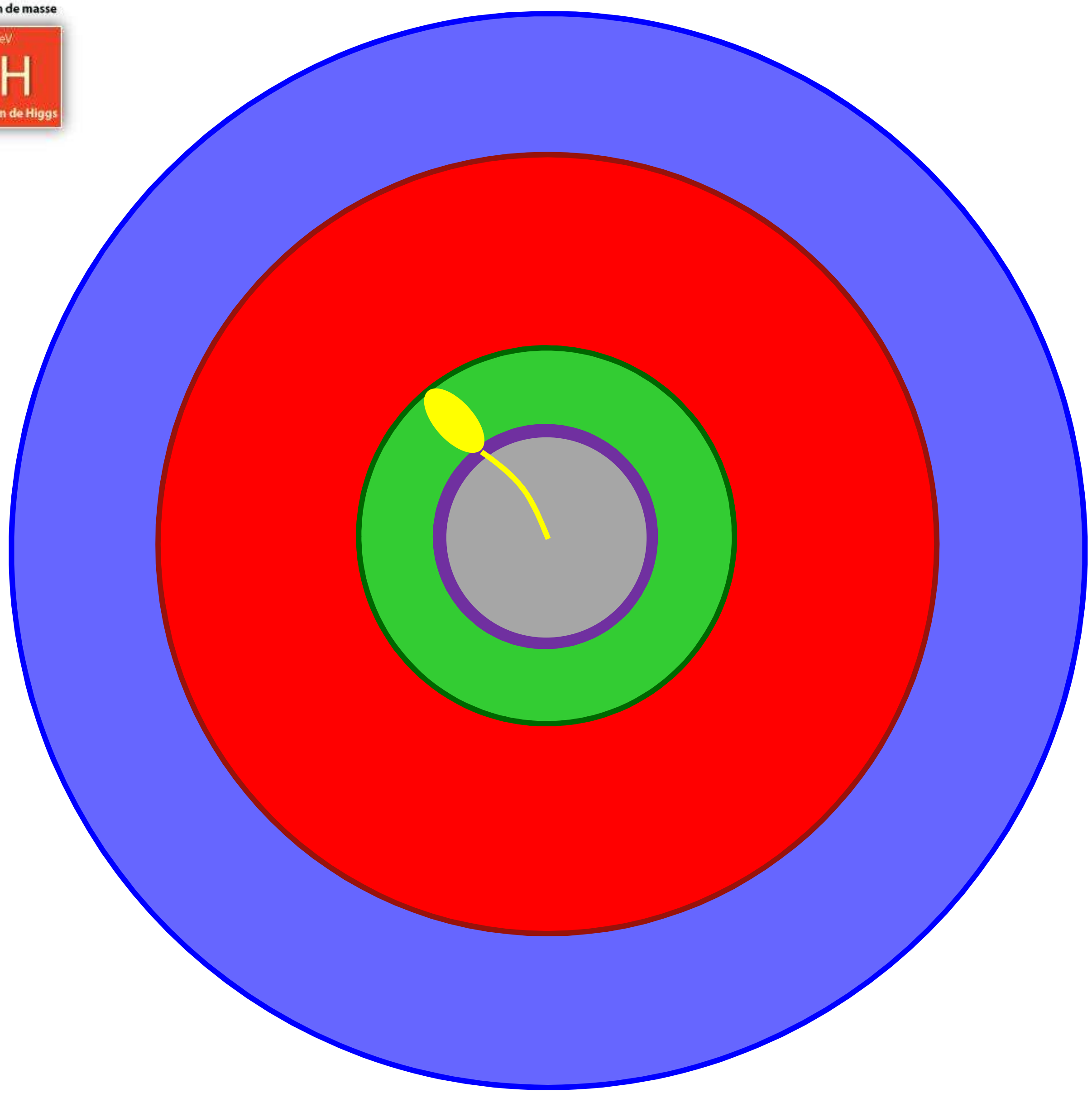
Transverse view of a simplified detector

Tracker
Solenoid
EM calorimeter
Hadronic calorimeter
Muon spectrometer



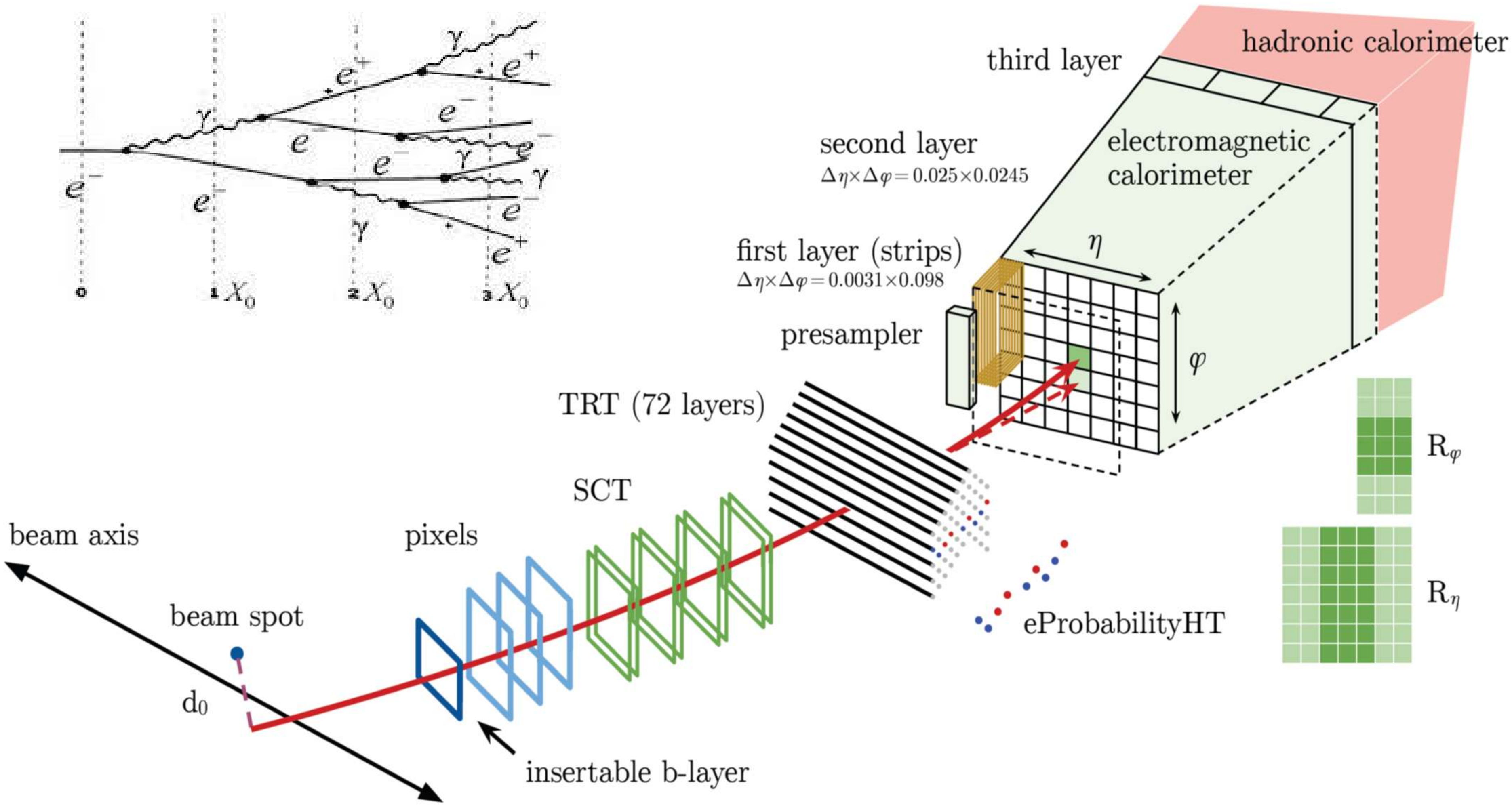
Electron





Tracker
Solenoid
EM calorimeter
Hadronic calorimeter
Muon spectrometer

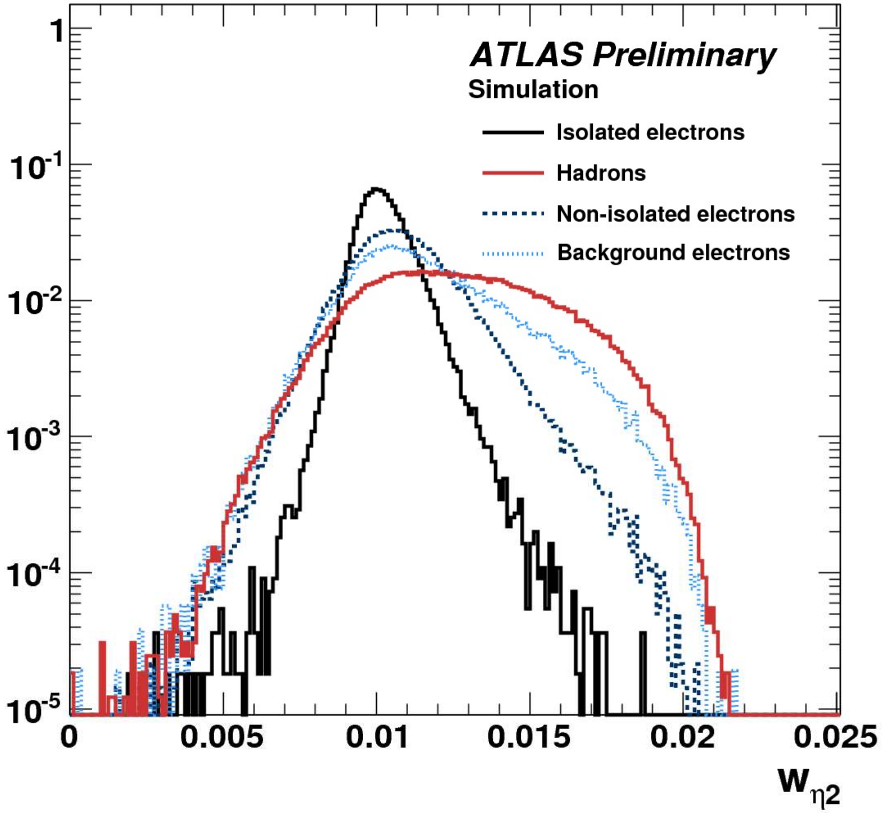
Electron: reconstruction



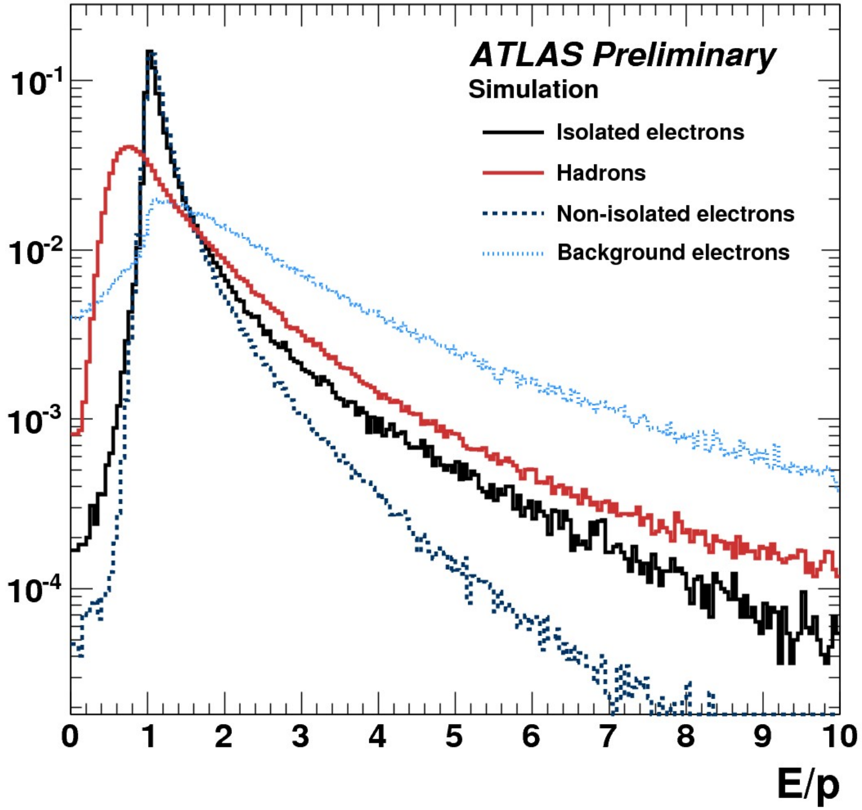
Along with continuous tracking, the TRT provides electron identification capability through the detection of transition radiation X-ray photons which arises when ultra-relativistic charged particles cross a boundary between media with different dielectric constants

Discriminating variables

Lateral shower width



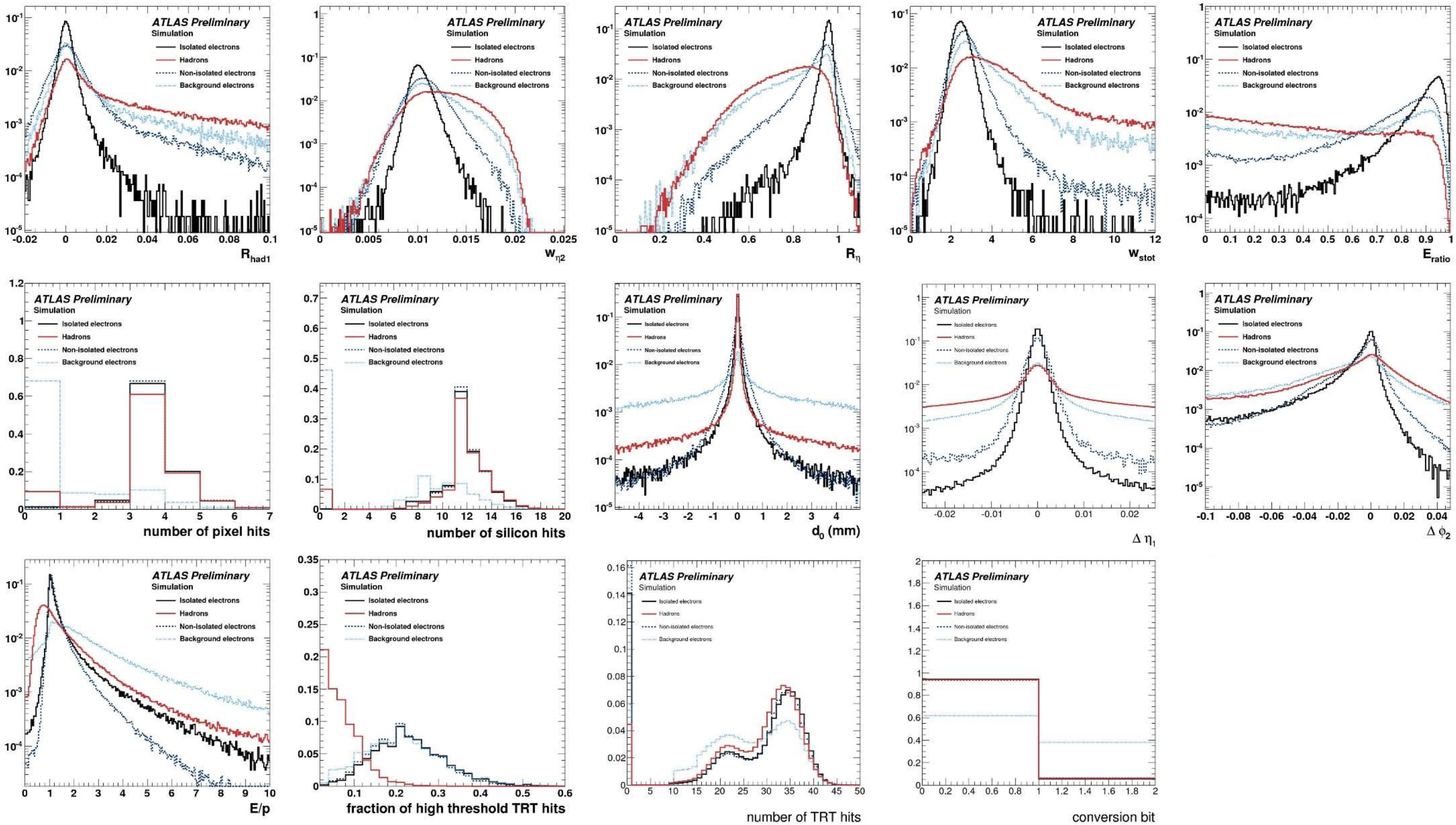
E/p



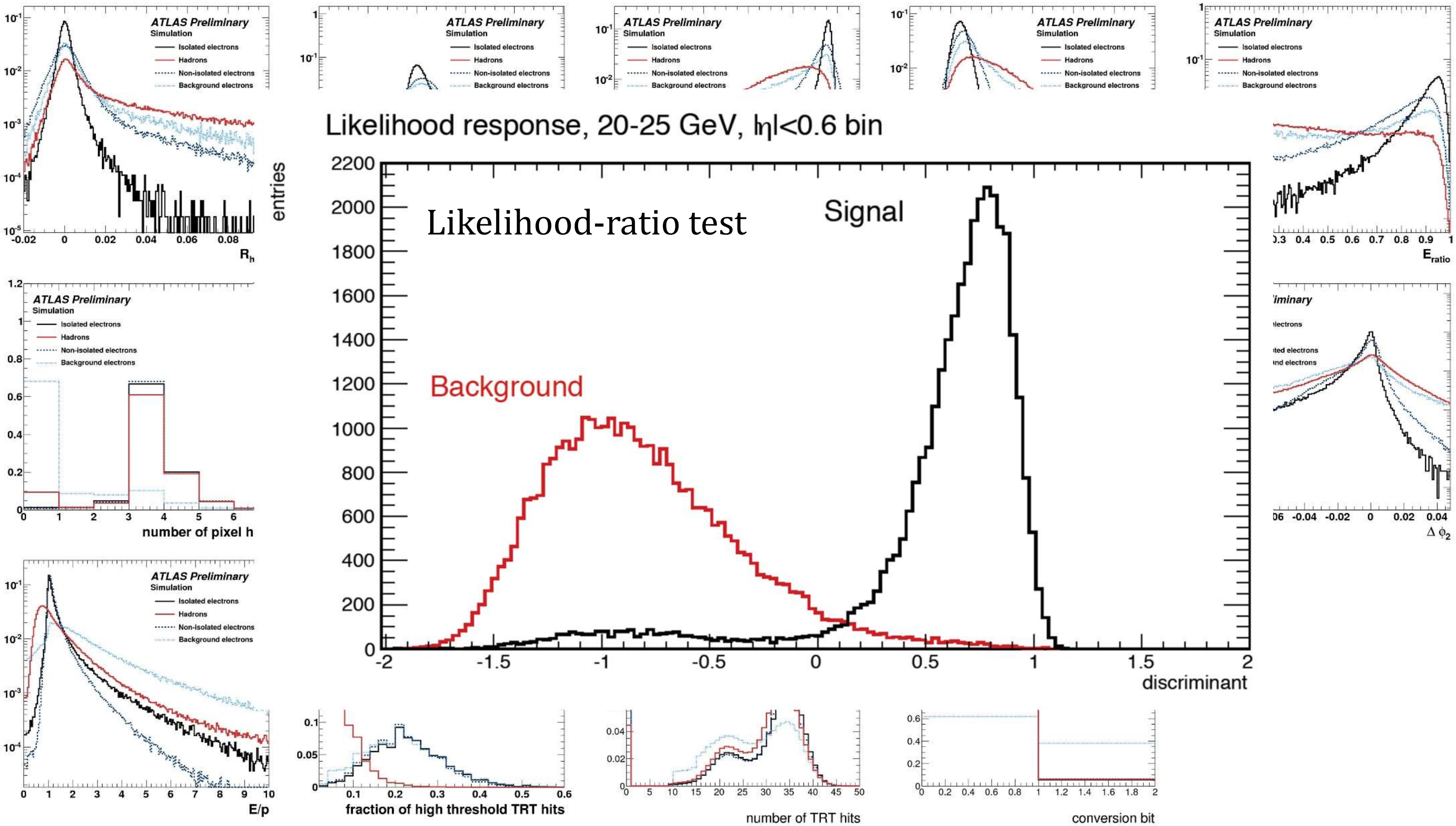
$$w_{\eta 2} = \sqrt{\frac{\sum_i E_i \eta_i^2}{\sum_i E_i} - \left(\frac{\sum_i E_i \eta_i}{\sum_i E_i}\right)^2},$$

Background electron originating from photon conversions

More discriminating variables

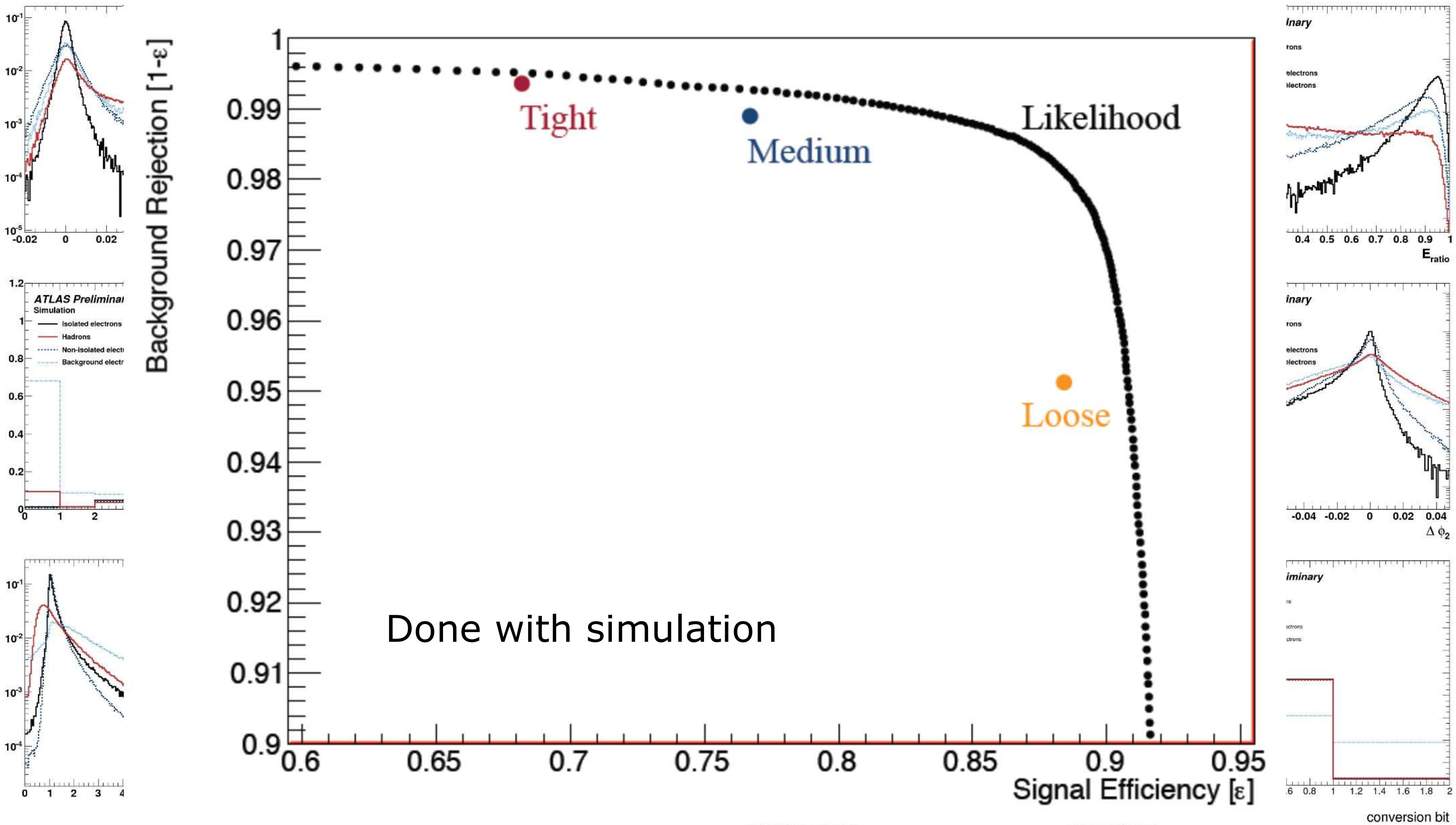


More discriminating variables

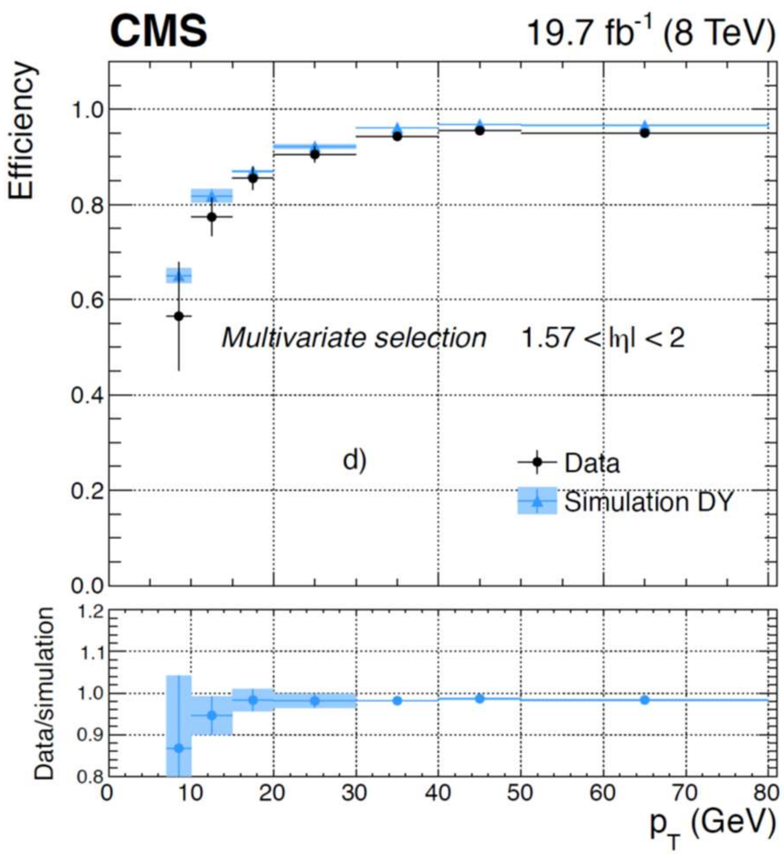


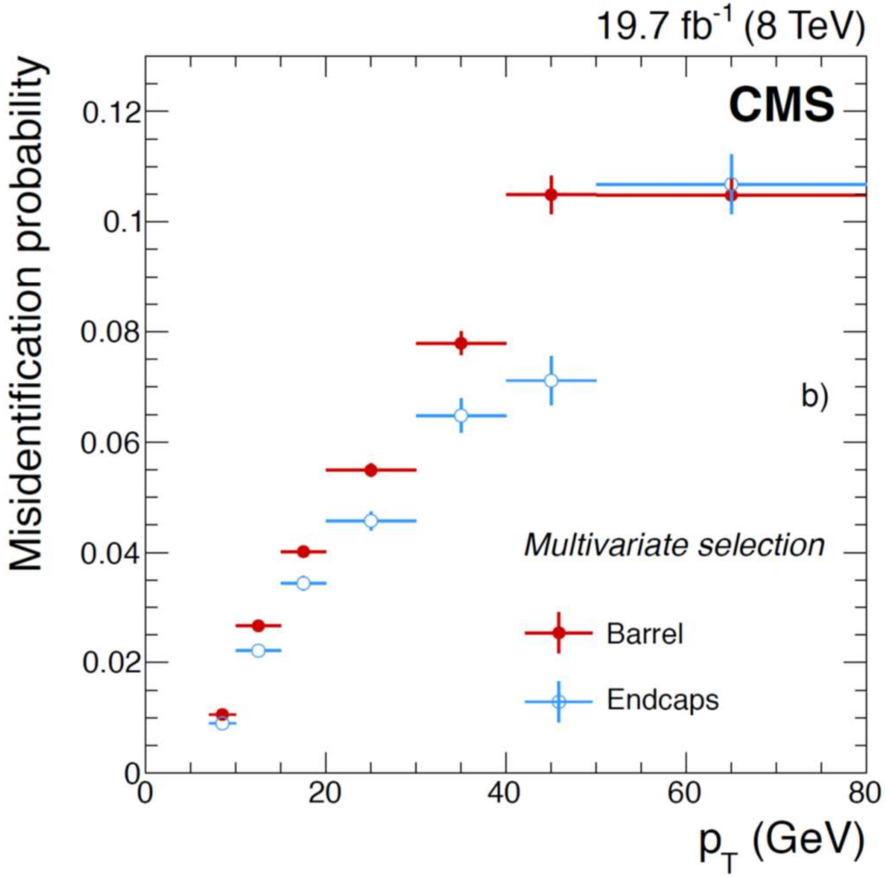
https://root.cern.ch/tmva
https://scikit-learn.org/

Rejection vs efficiency



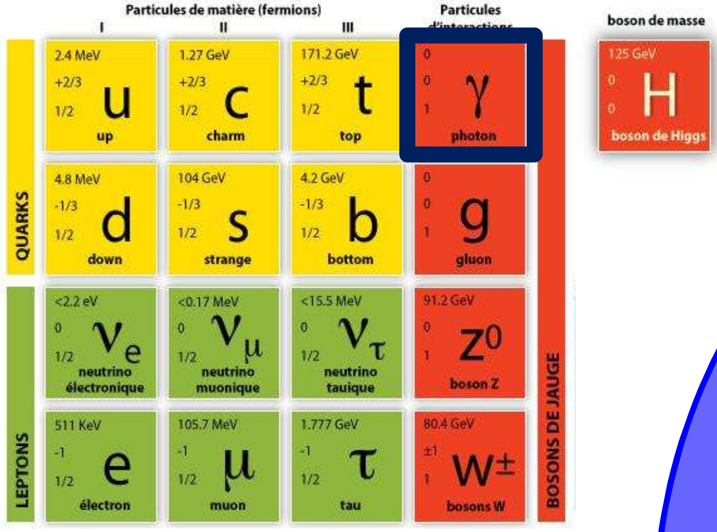
Electron performance

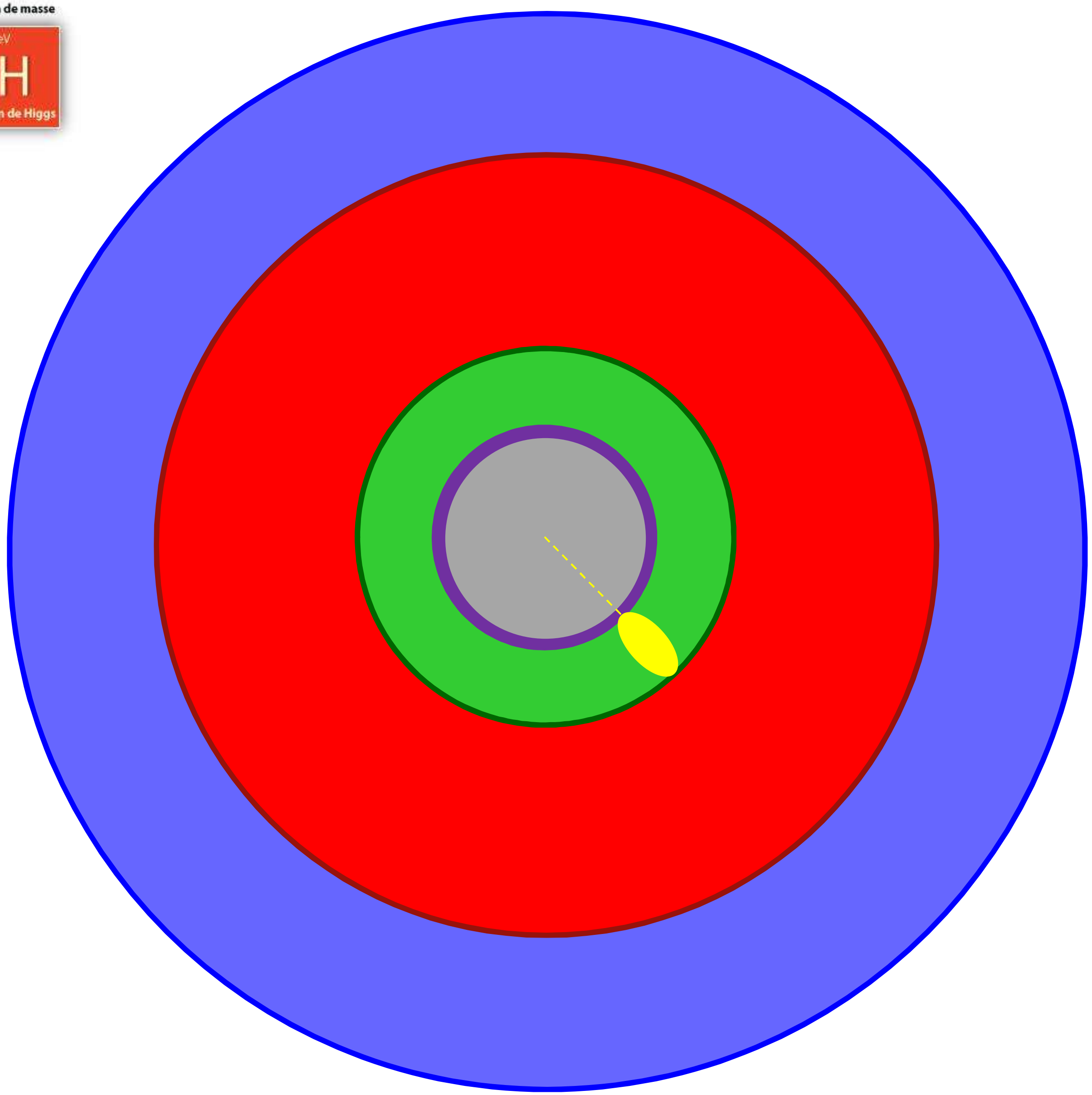




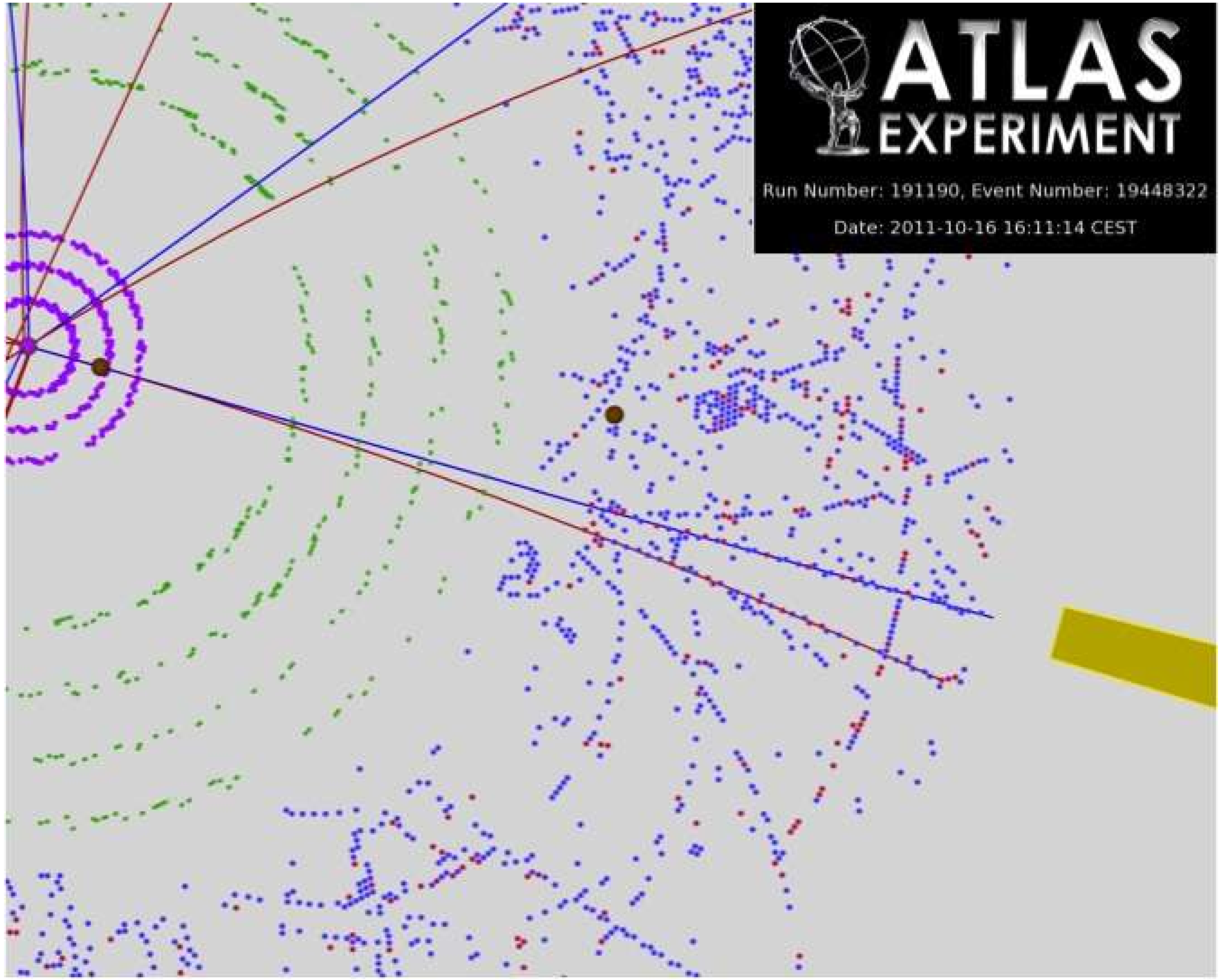
Quite often the performance studies/training are made with simulation
- How well do we know the performance in data?
- Need to correct for detector and modelling effects

(Unconverted) photon

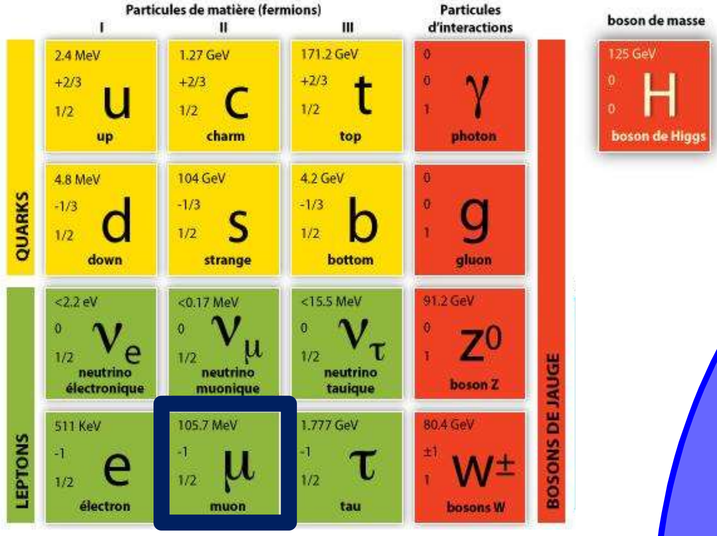


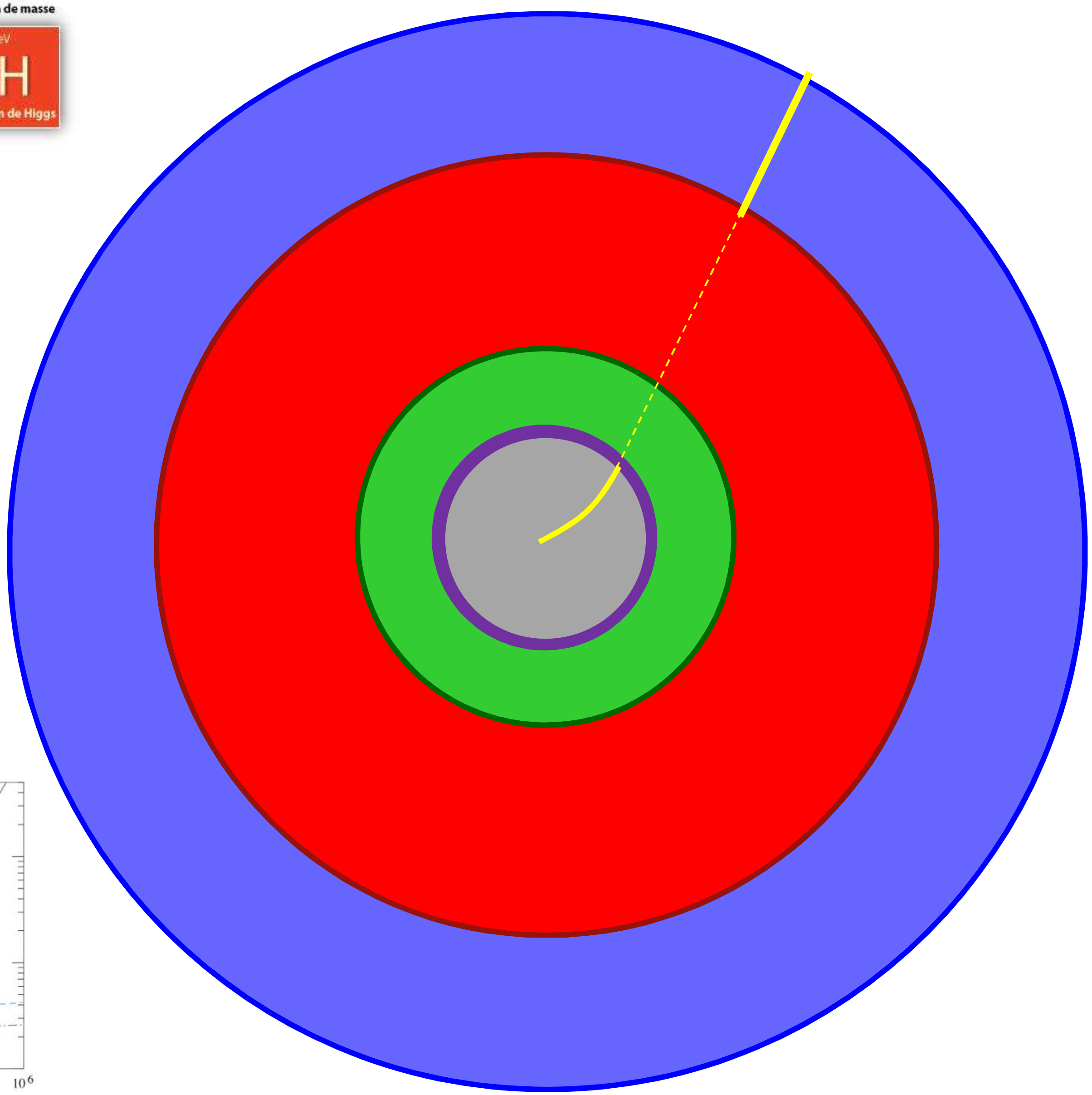


Converted photon



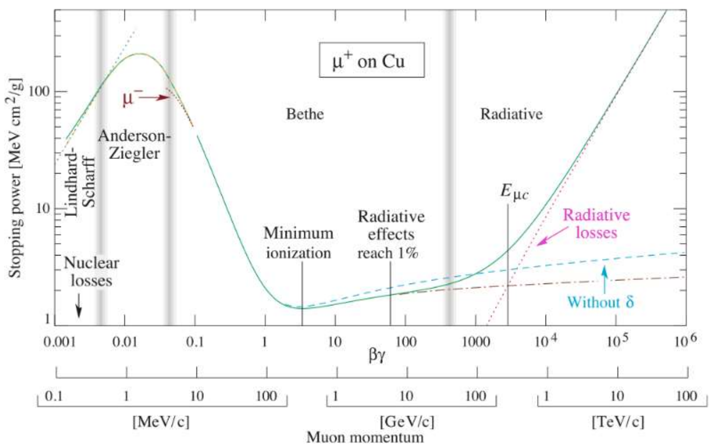
Muon



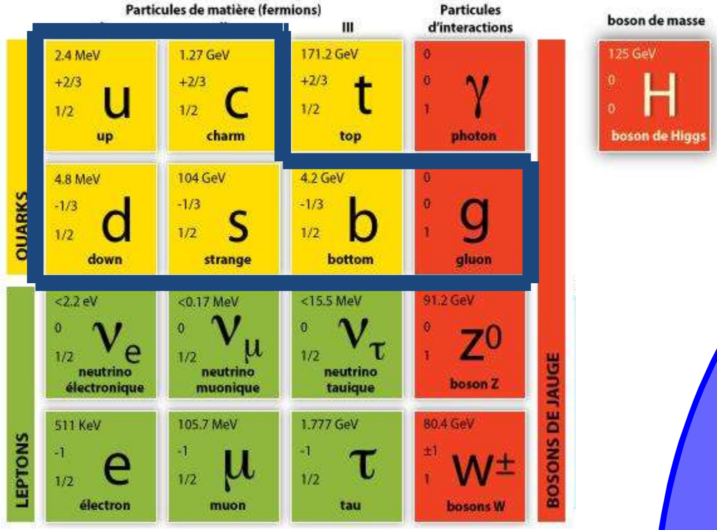


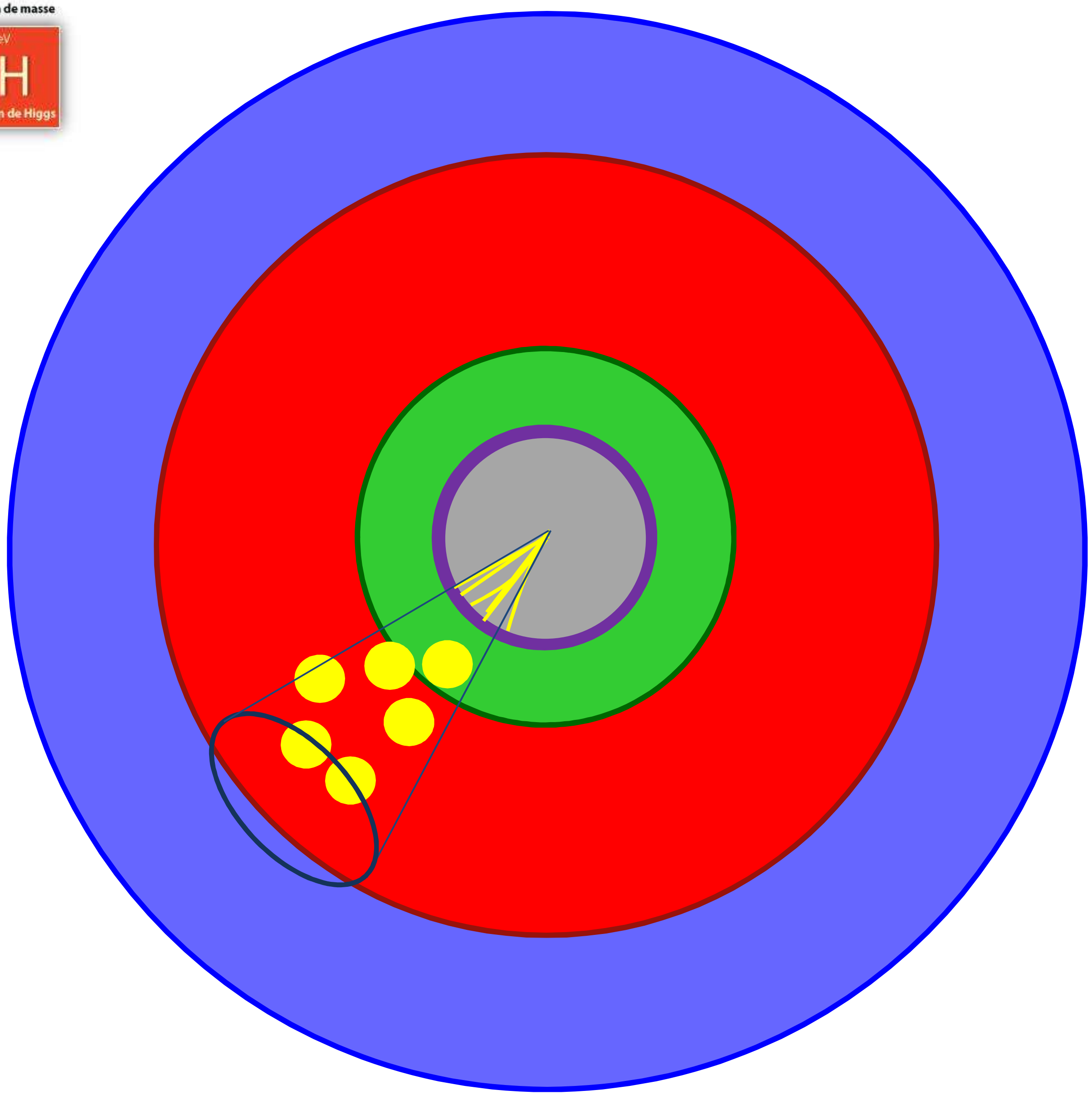
$\tau_\mu \sim 2\mu s$

$\rightarrow c\tau_\mu \sim 600m$

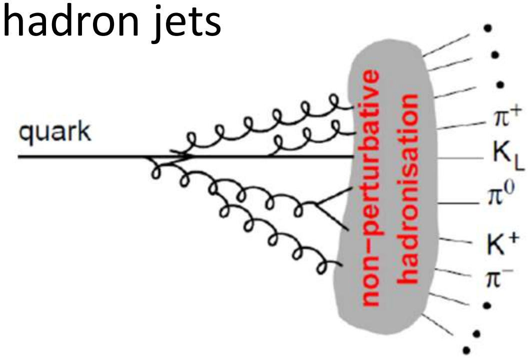


Jets





Quarks/gluons can't be observed as free particles (confinement)
→ hadron jets



Need an algorithm to merge hadrons in a jet

Jets

arXiv:0906.1833

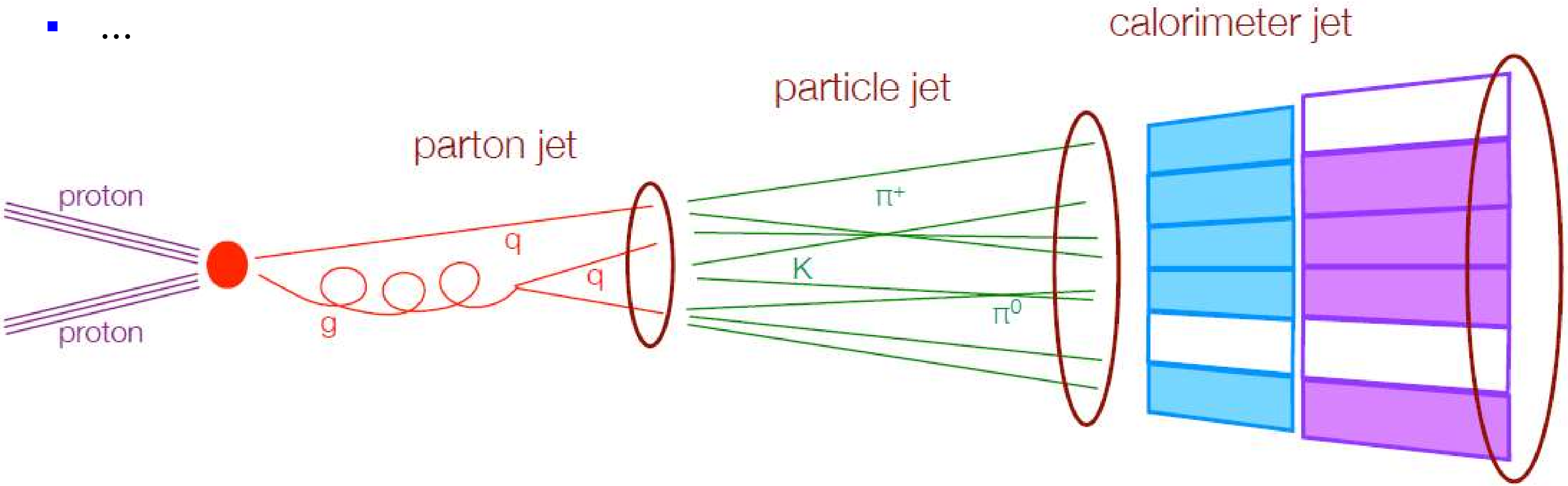
Collimated sprays of energetic hadrons produced via the fragmentation of partons

Window on parton but there is no unique way to define a jet

Need a jet algorithm to group neighbouring objects into a single object

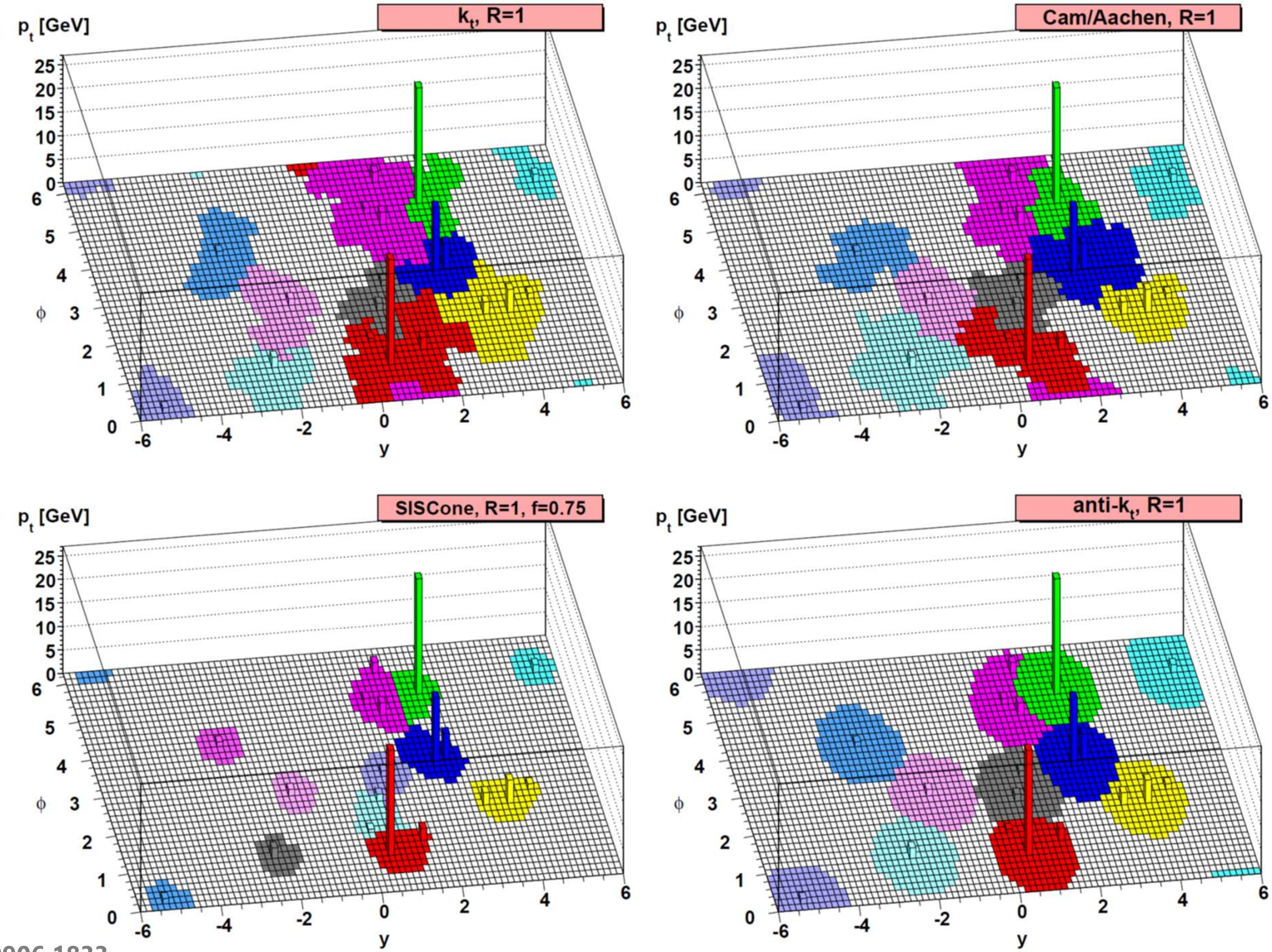
Jet inputs:

- Groups of calorimeter cells -> calorimeter jets or simply jets
  - First merge cells into clusters or towers
- Tracks
- PFlow objects
- Truth particles
- Truth partons
- …



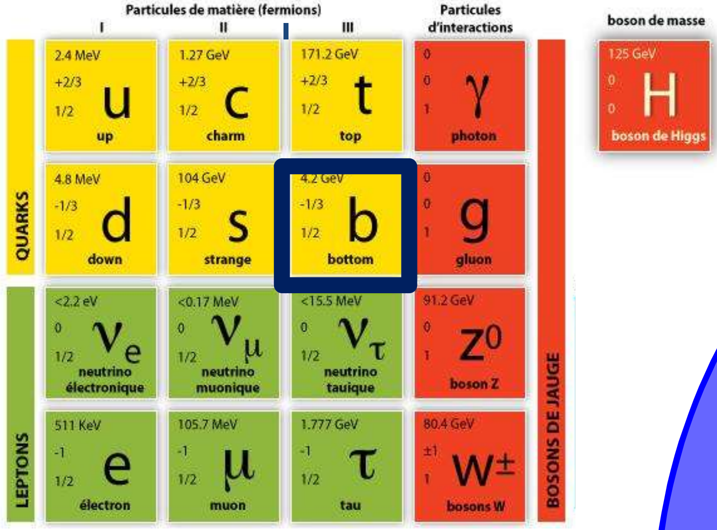
Jets

Each reconstructed jet has a different color

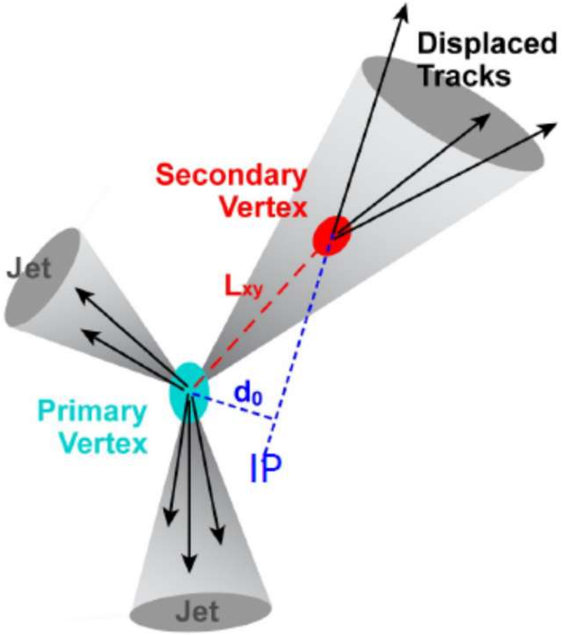


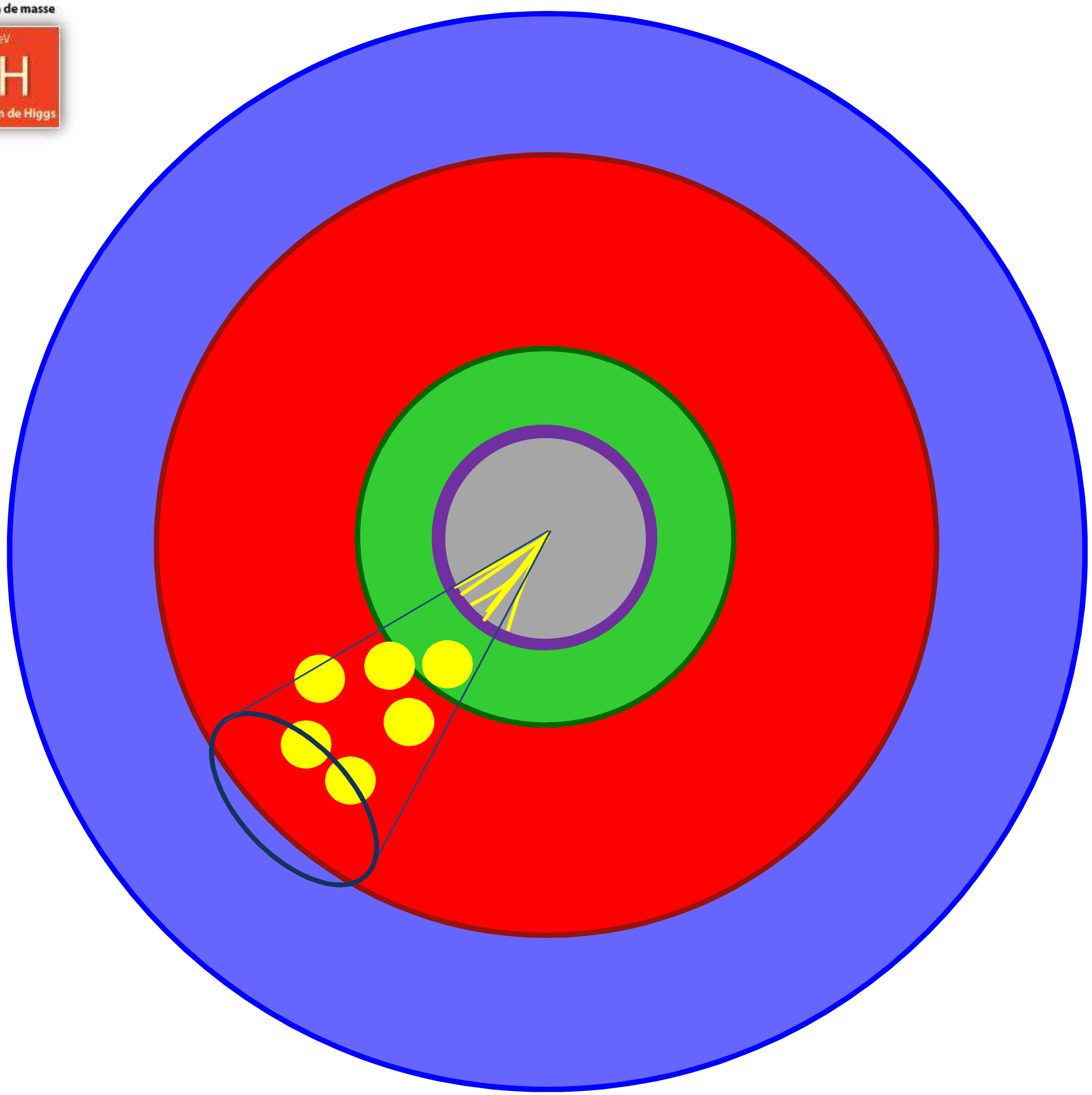
arXiv:0906.1833

B-jets

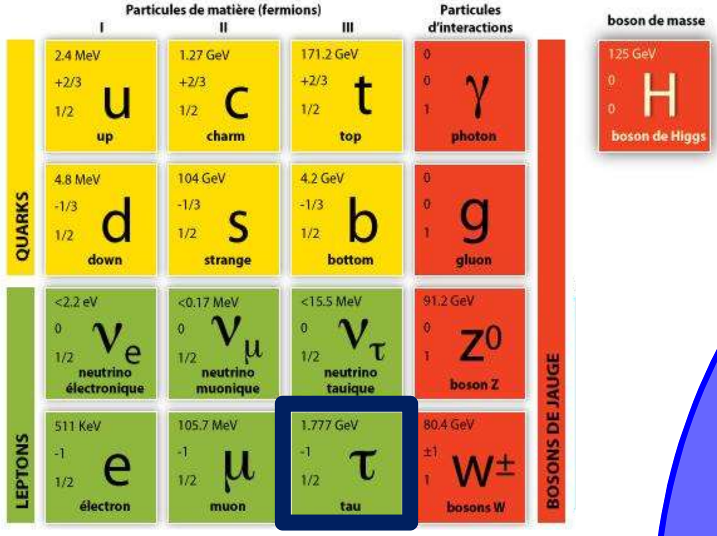


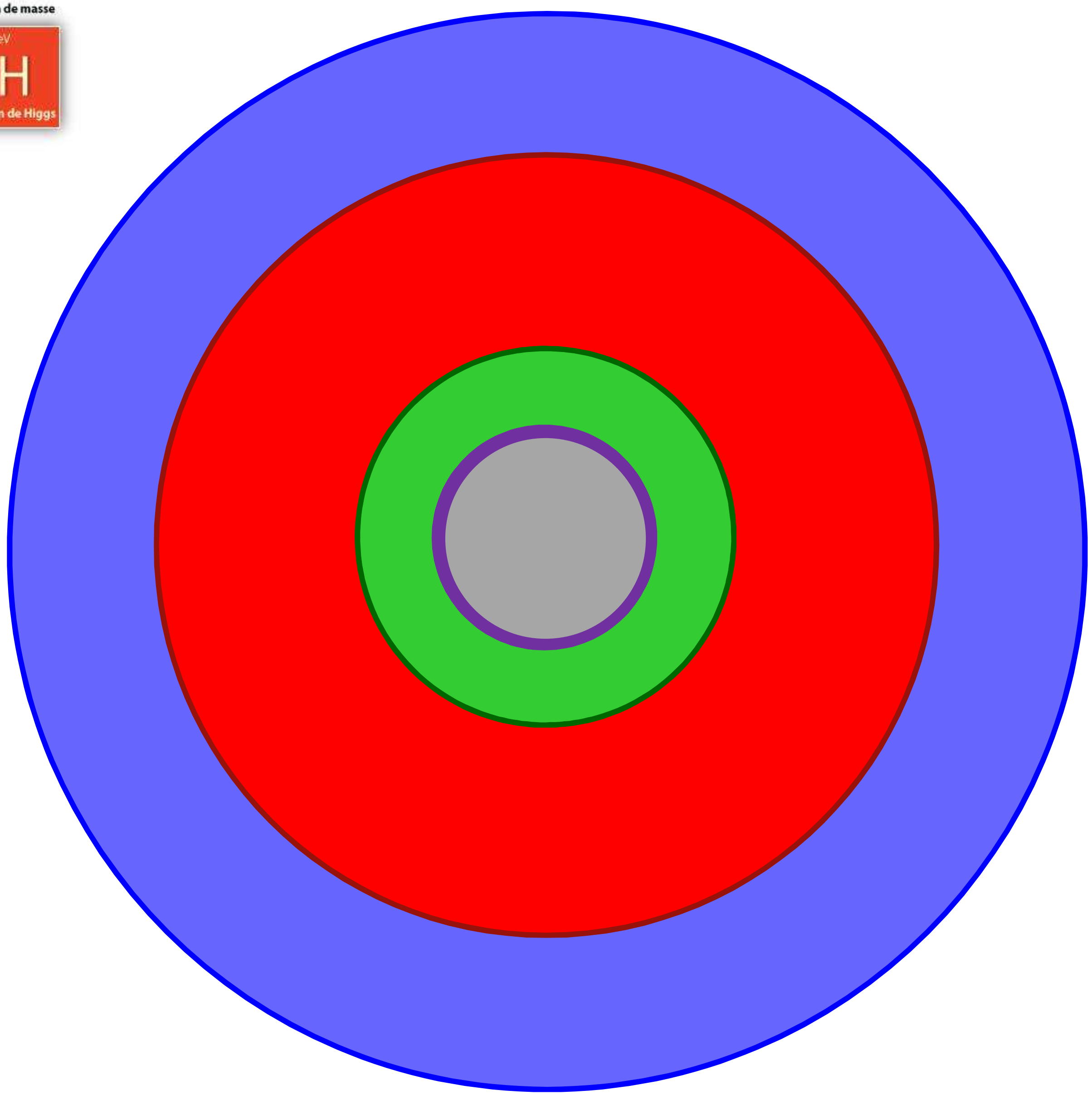
B-hadrons: $c\tau_b$~500μm



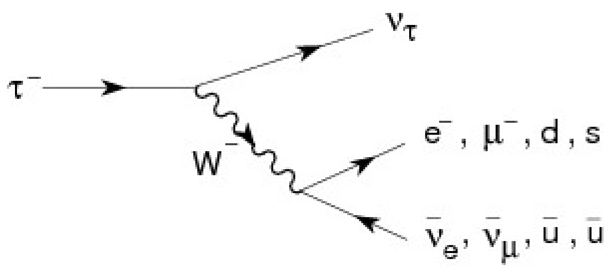


τ lepton

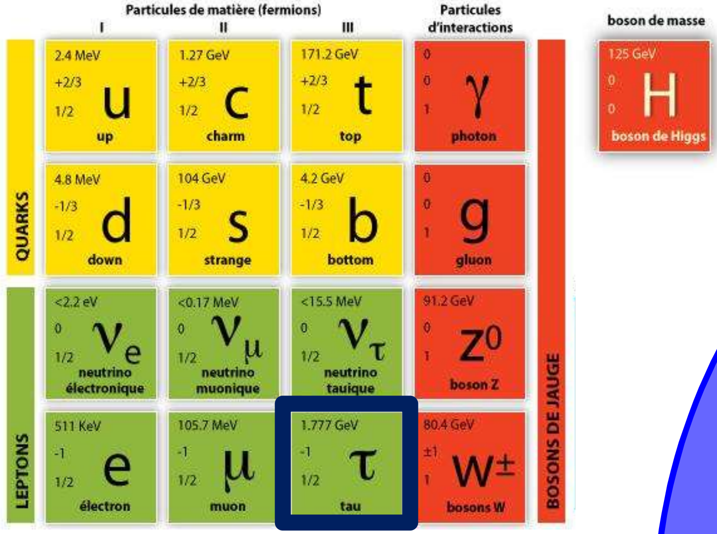


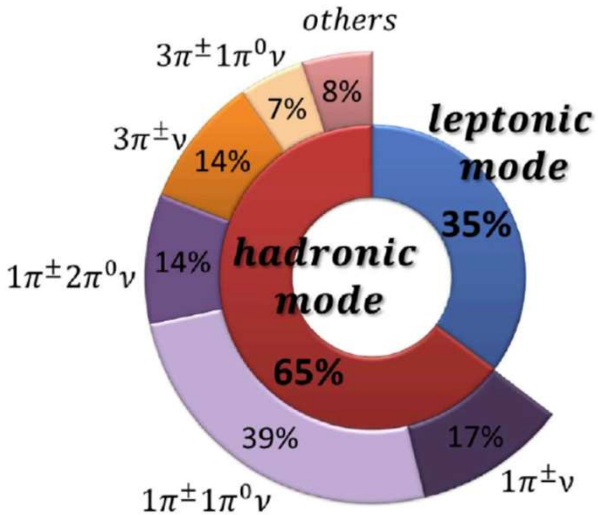


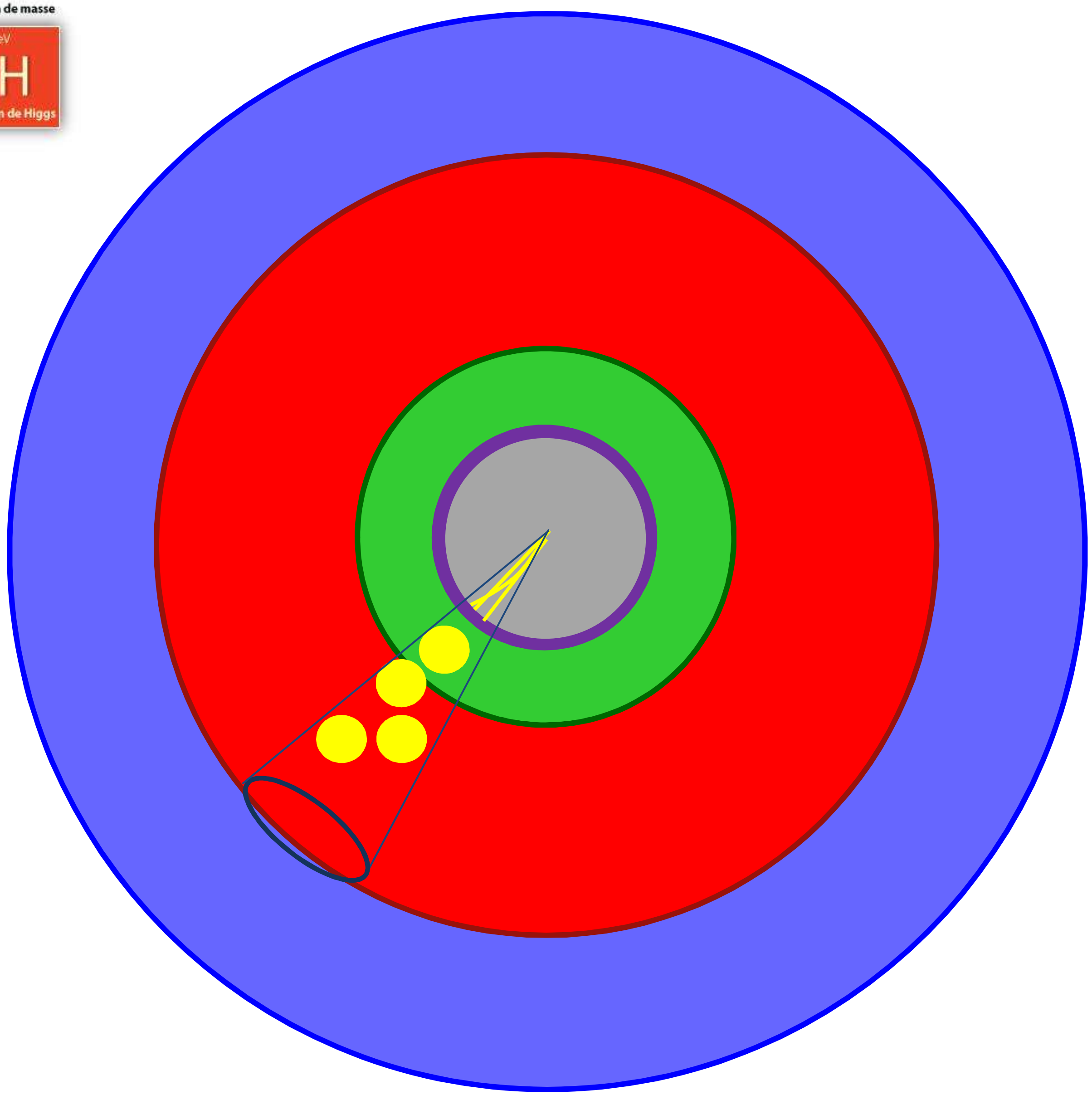
$c\tau_\tau = 87\mu m$



τ lepton (hadronic)

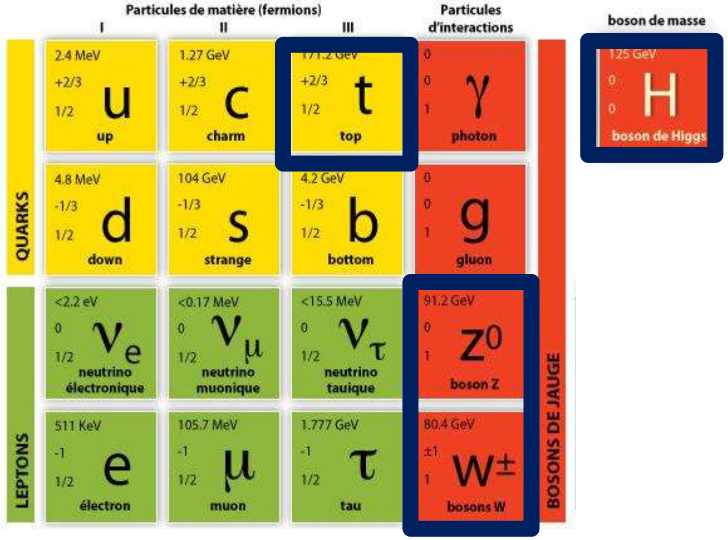


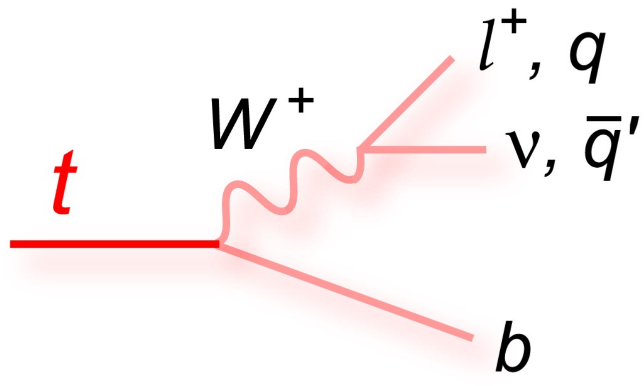


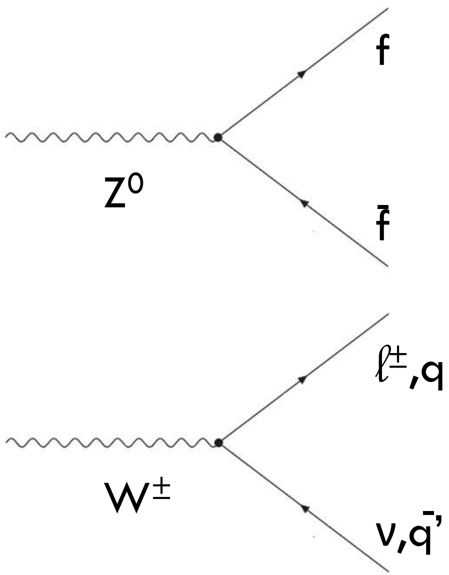


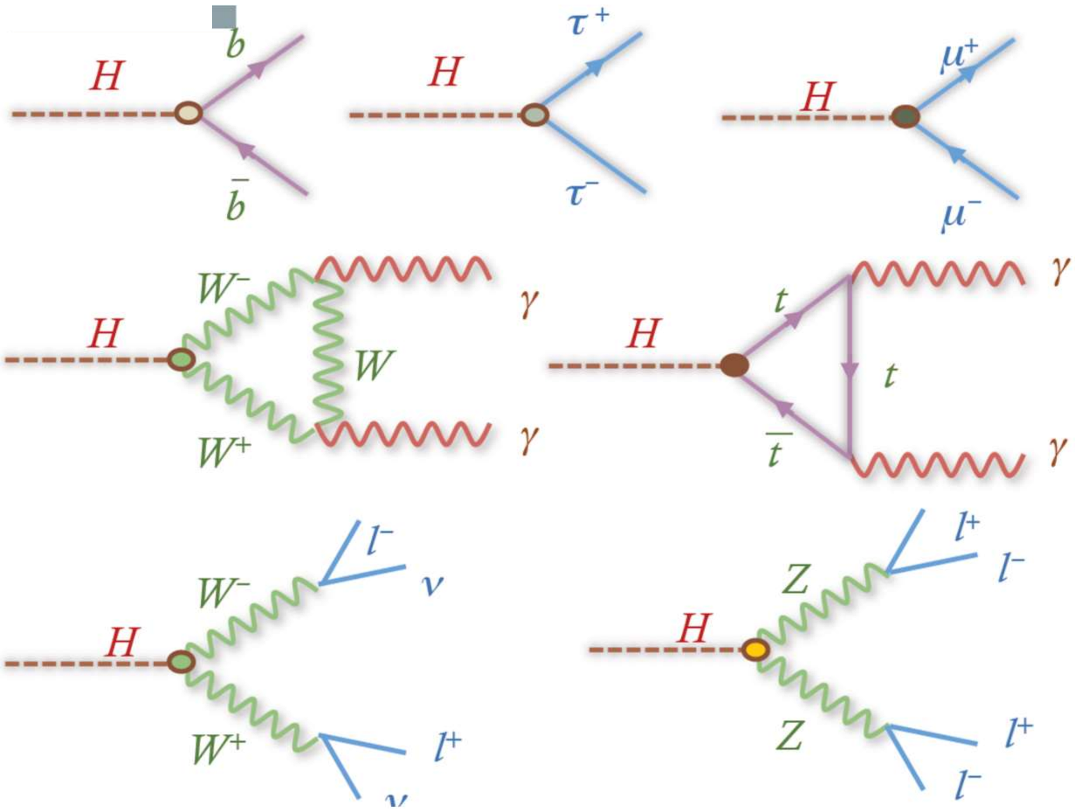
Hadronic τ: narrow jet with one or three tracks

Other instable particles

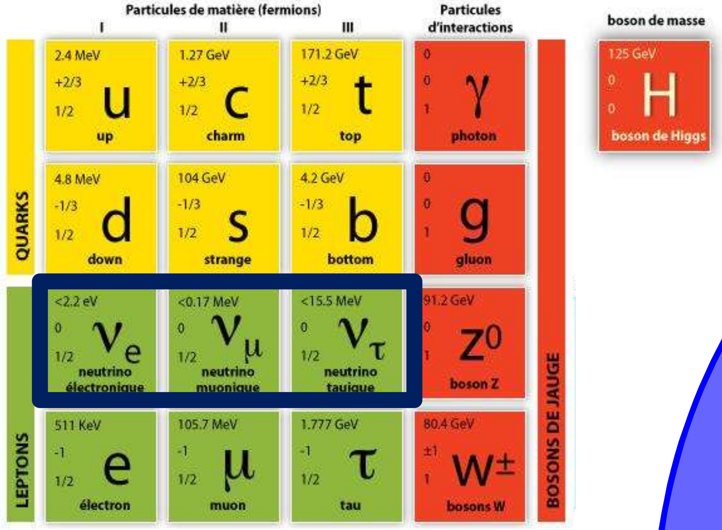


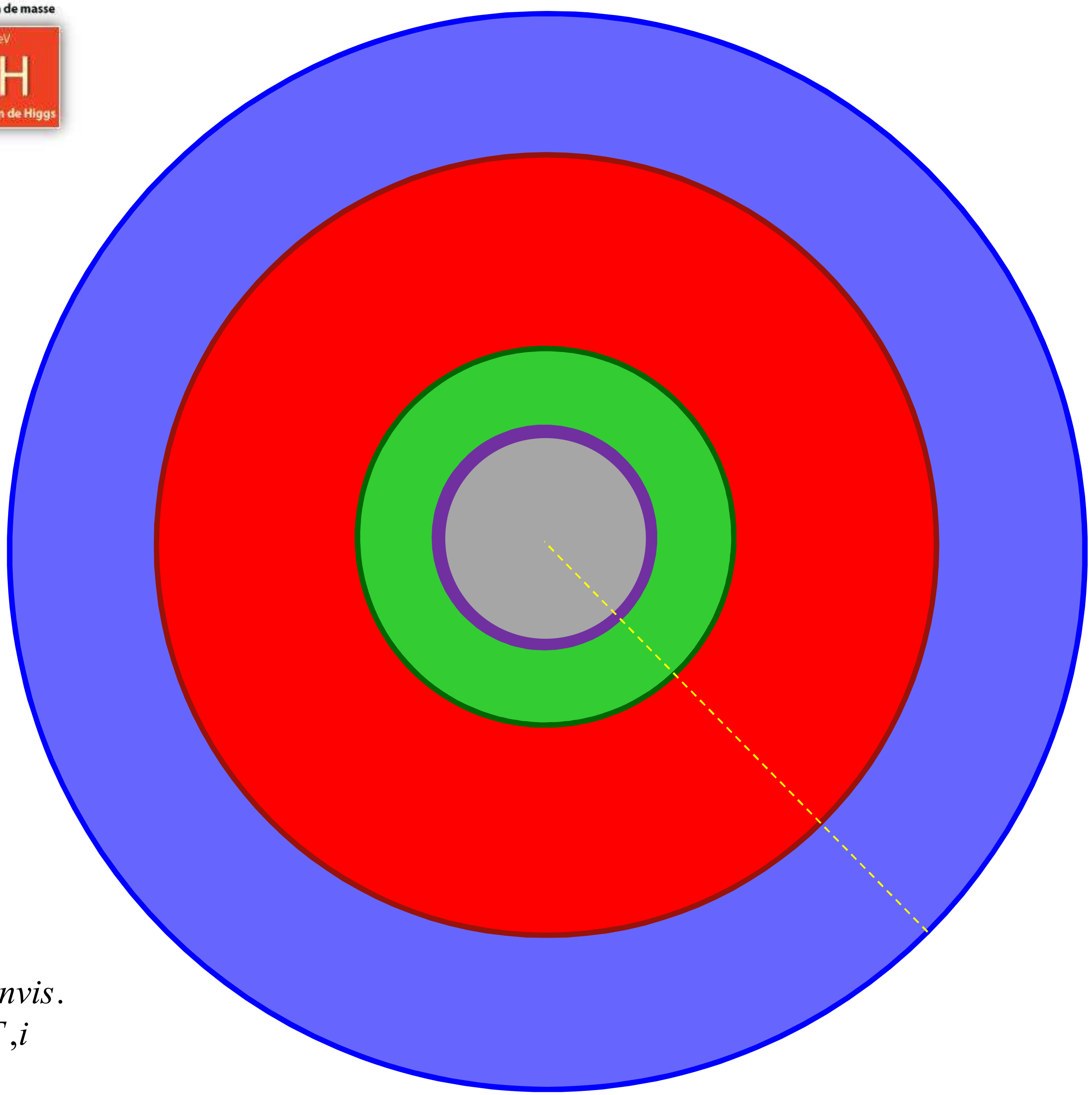






Missing transverse energy



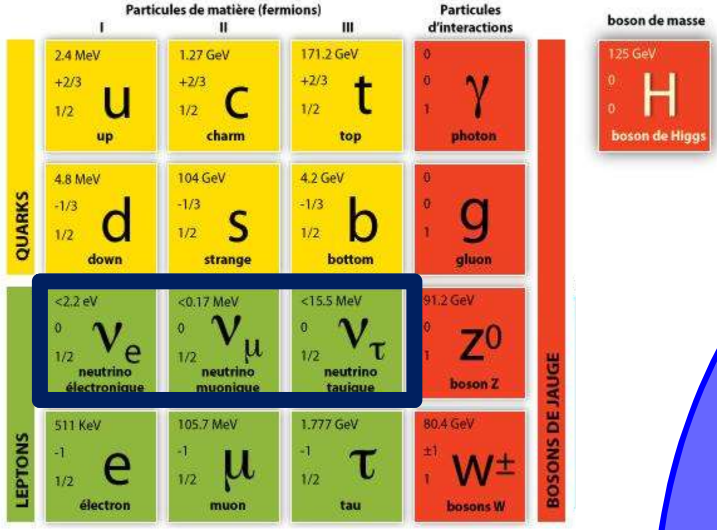


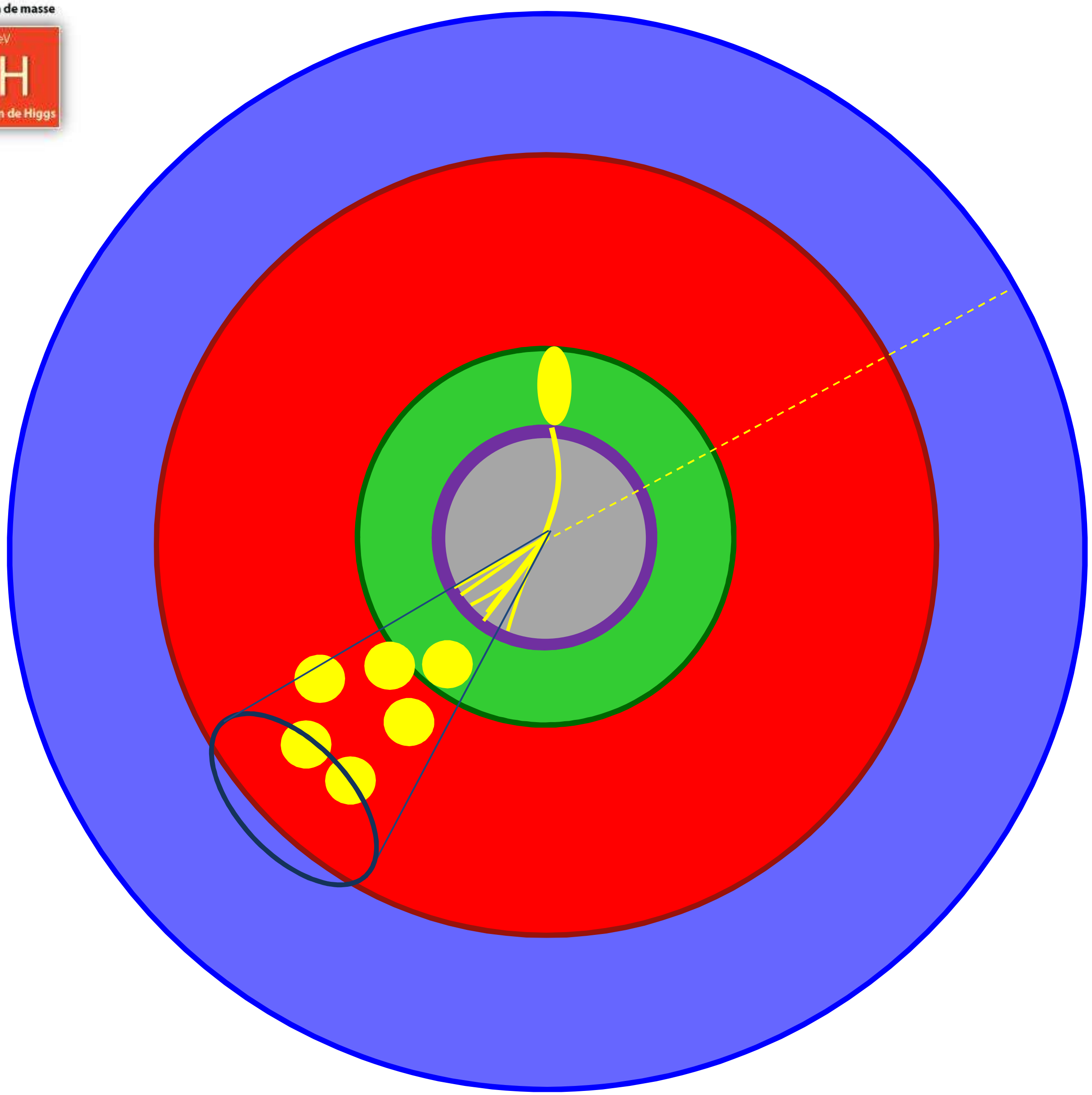
$$\sum_i \vec{p}_{T,i} \approx \vec{0}$$

$$\sum_i \vec{p}^{\,vis.}_{T,i} + \sum_i \vec{p}^{\,inv.}_{T,i} \approx \vec{0}$$

$$M\vec{E}T = -\sum_i \vec{p}^{\,vis.}_{T,i} \approx \sum_i \vec{p}^{\,invis.}_{T,i}$$

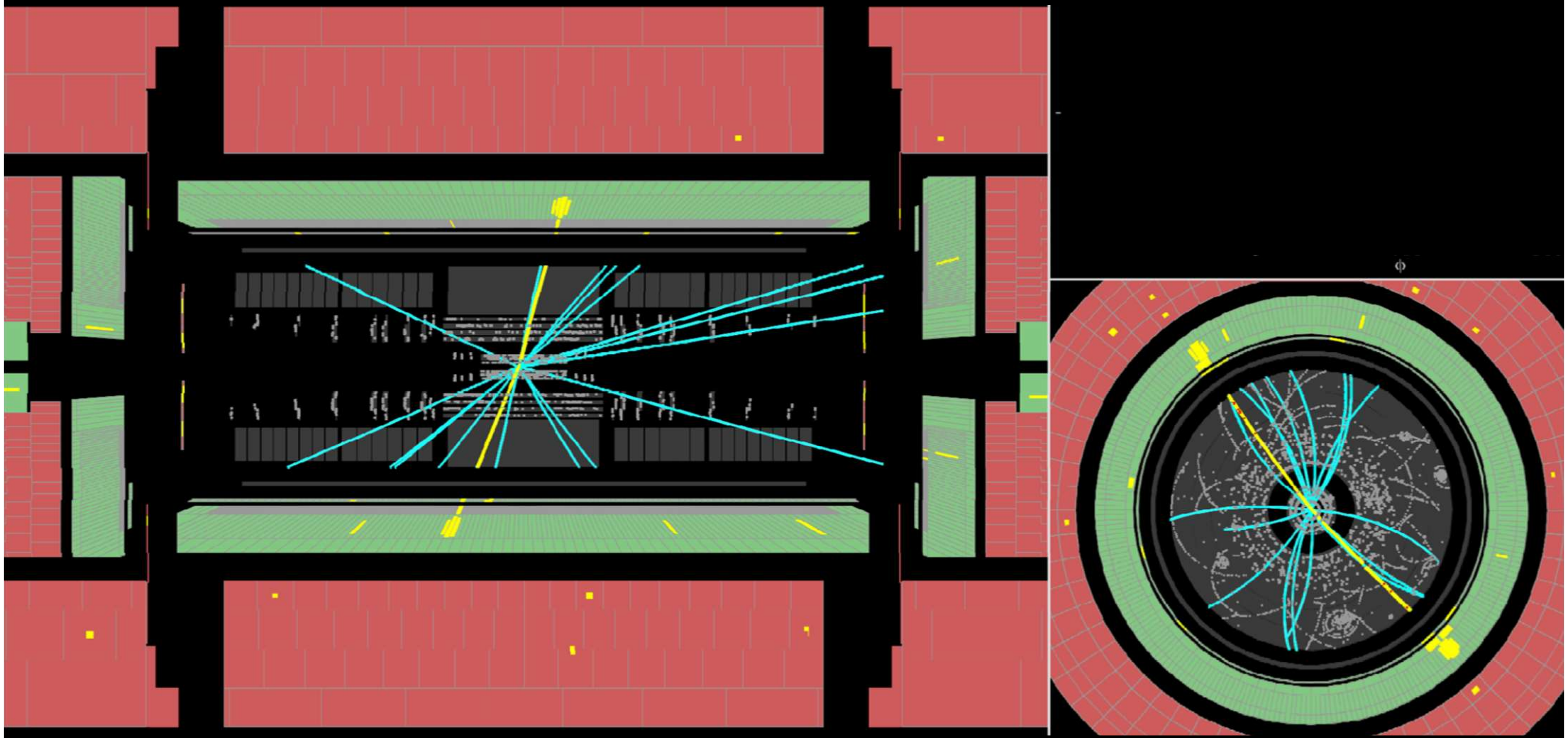
Missing transverse energy

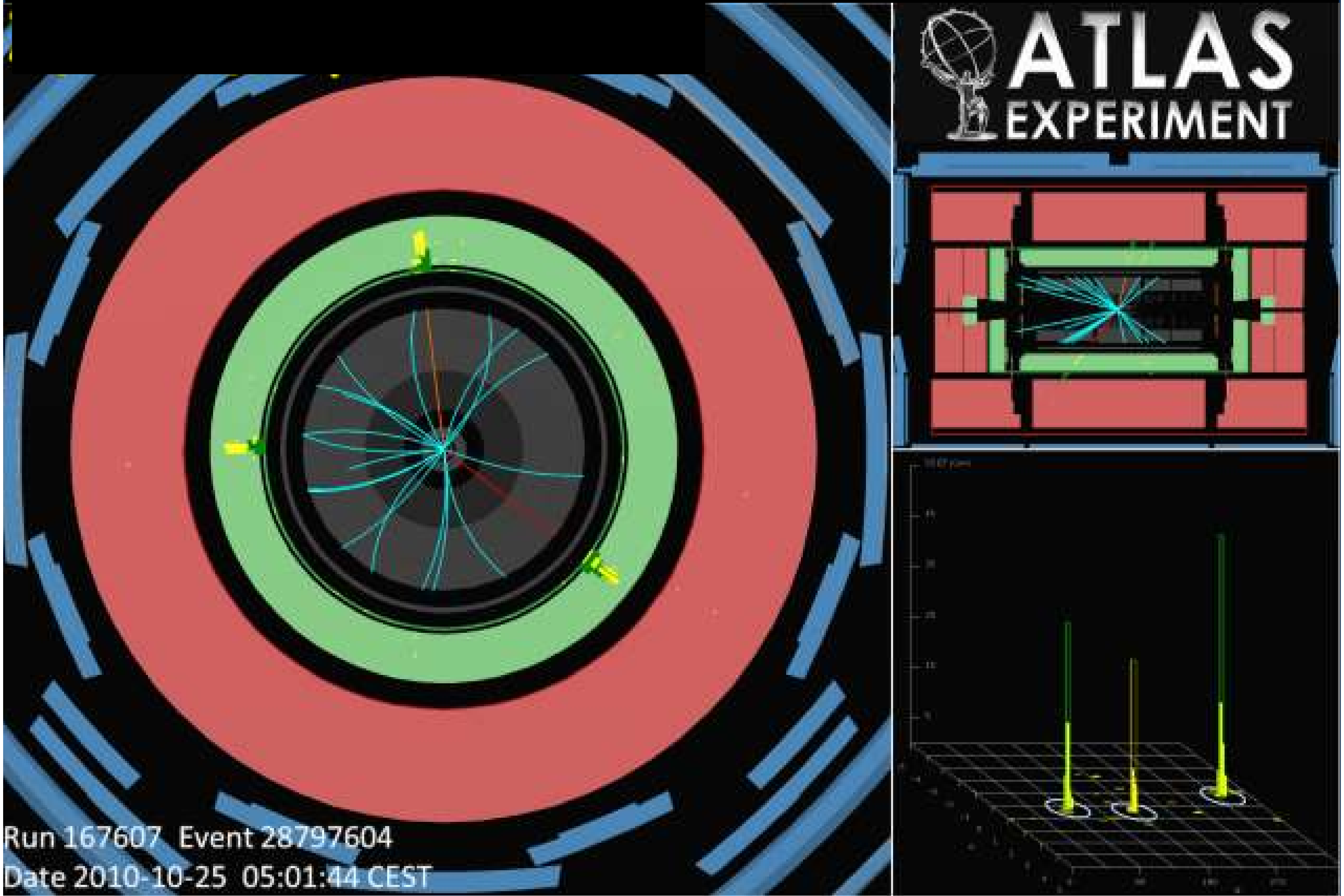


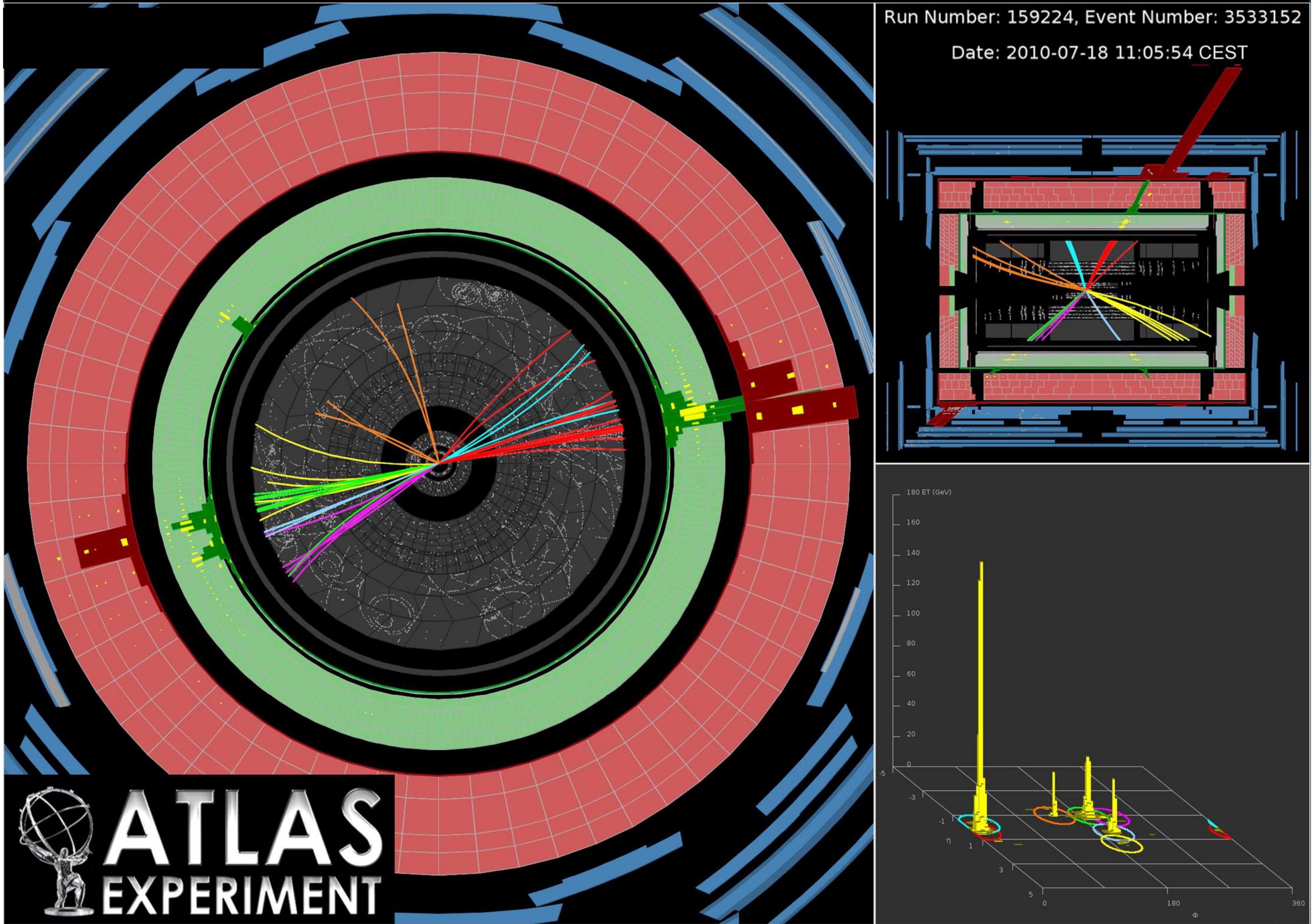


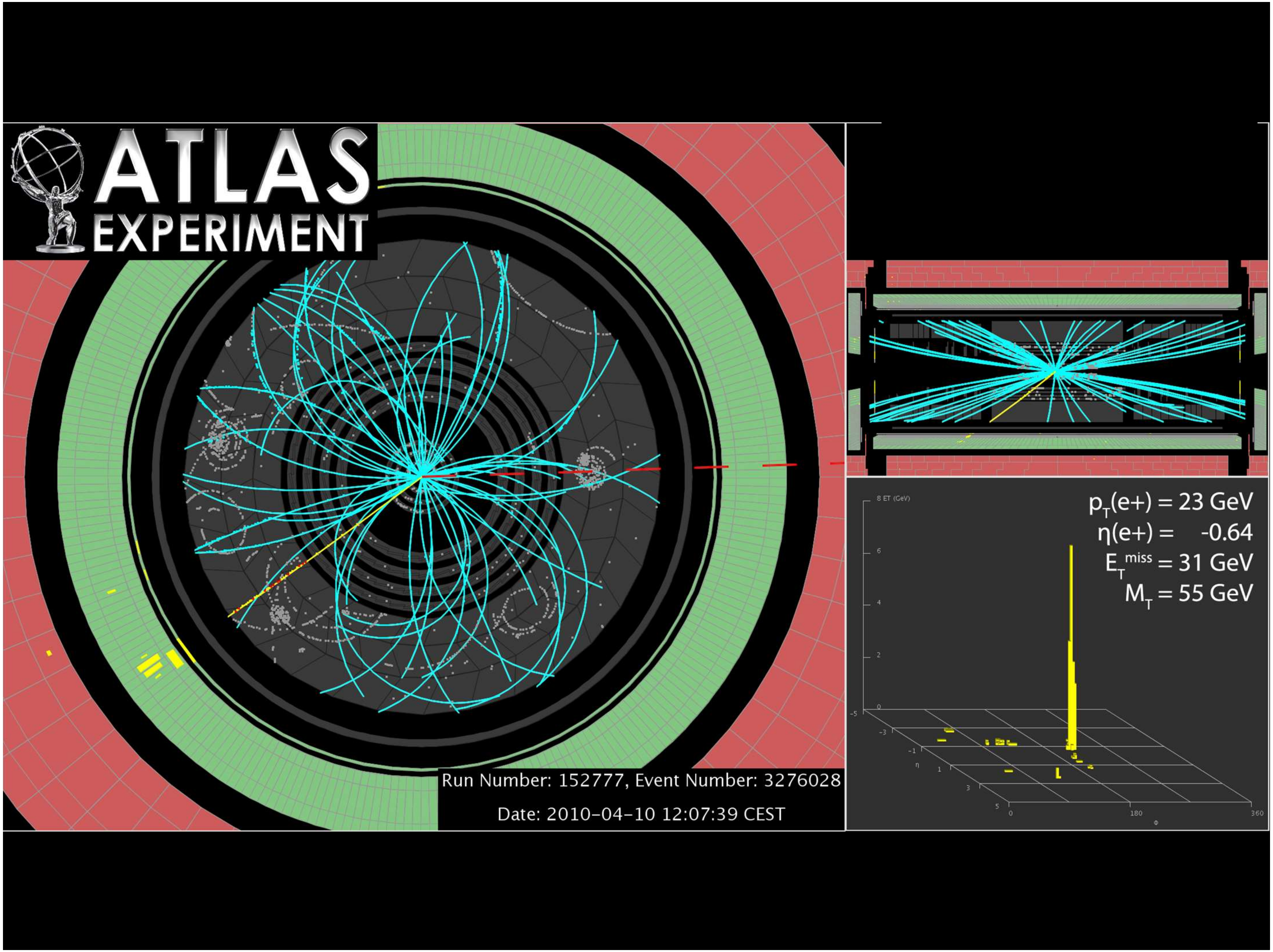
Example:

$$\vec{MET} = -\vec{p}_T^{\,electron} - \vec{p}_T^{\,jet}$$




ATLAS
EXPERIMENT
Run 167607 Event 28797604
Date 2010-10-25 05:01:44 CEST

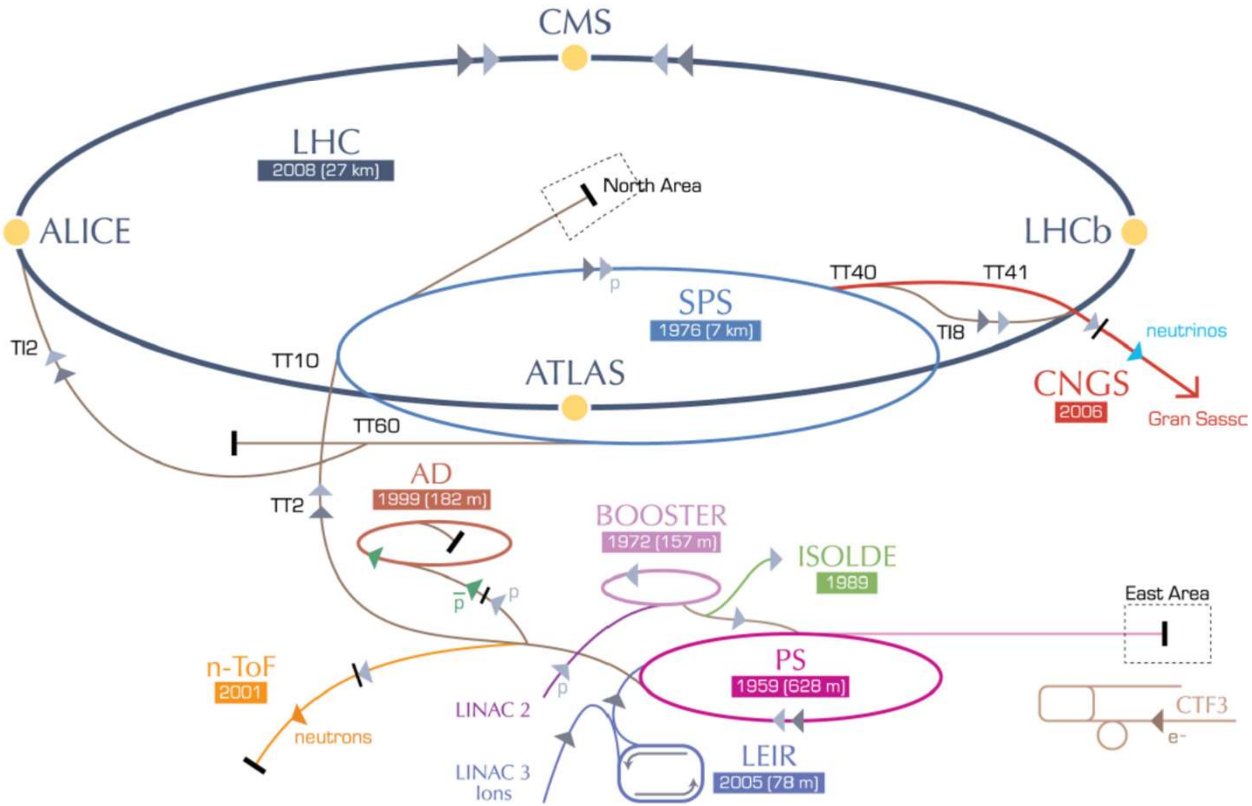

Run Number: 159224, Event Number: 3533152
Date: 2010-07-18 11:05:54 CEST
180 ET (GeV)
160
140
120
100
80
60
40
20
0
η
0
180
360
Φ
ATLAS
EXPERIMENT


ATLAS
EXPERIMENT
$p_T(e+) = 23$ GeV
$\eta(e+) = -0.64$
$E_T^{miss} = 31$ GeV
$M_T = 55$ GeV
Run Number: 152777, Event Number: 3276028
Date: 2010-04-10 12:07:39 CEST

Trigger

- **First question:** Why don't we just record **every single event** produced in ATLAS?

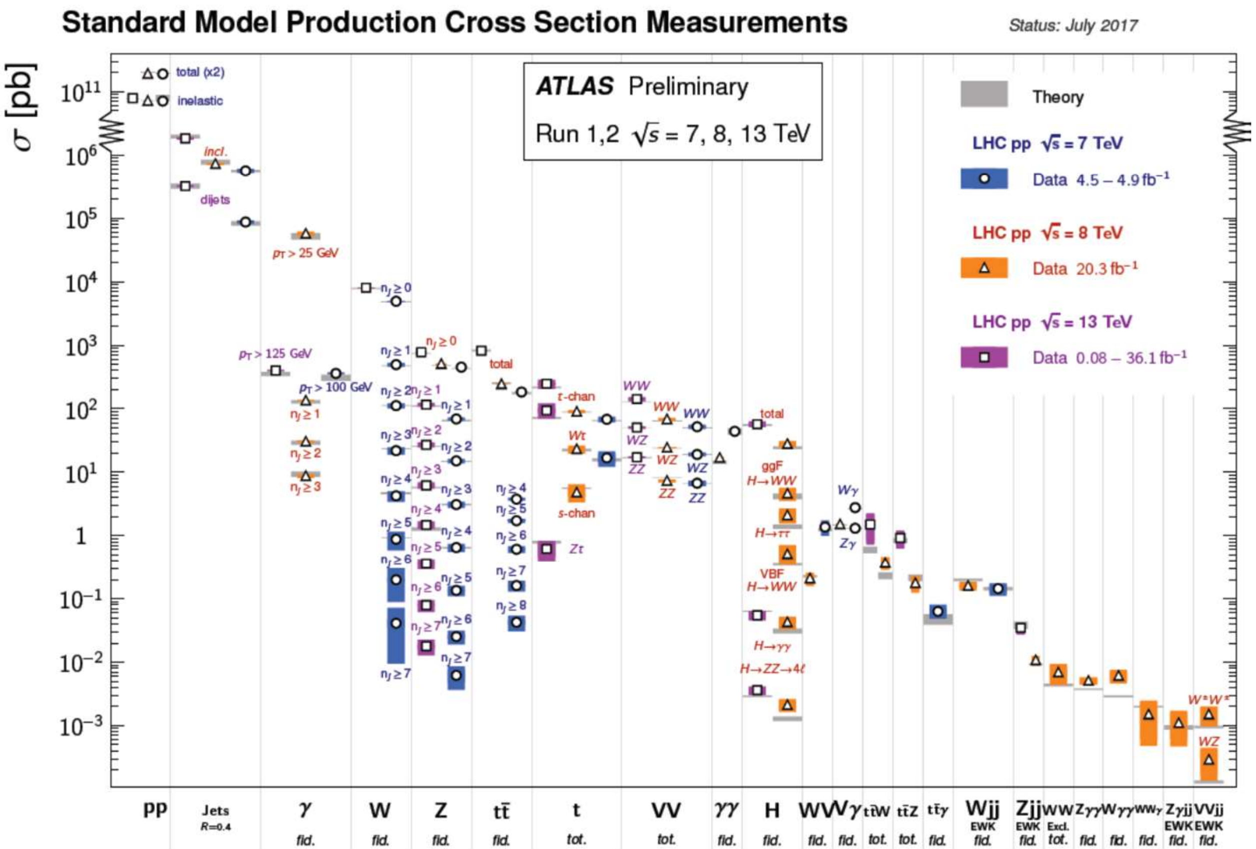
- **Reason #1:** The data rates are **too damn high!**
- Nominal LHC bunch crossing rate is **40MHz**
- A **raw** ATLAS event is $\mathcal{O}(2MB)$
- Back of the envelope, $\mathcal{O}(80\ TB/s)$, $\mathcal{O}(288\ PB/hr)$, $\mathcal{O}(6.9\ EB/day)$



Trigger

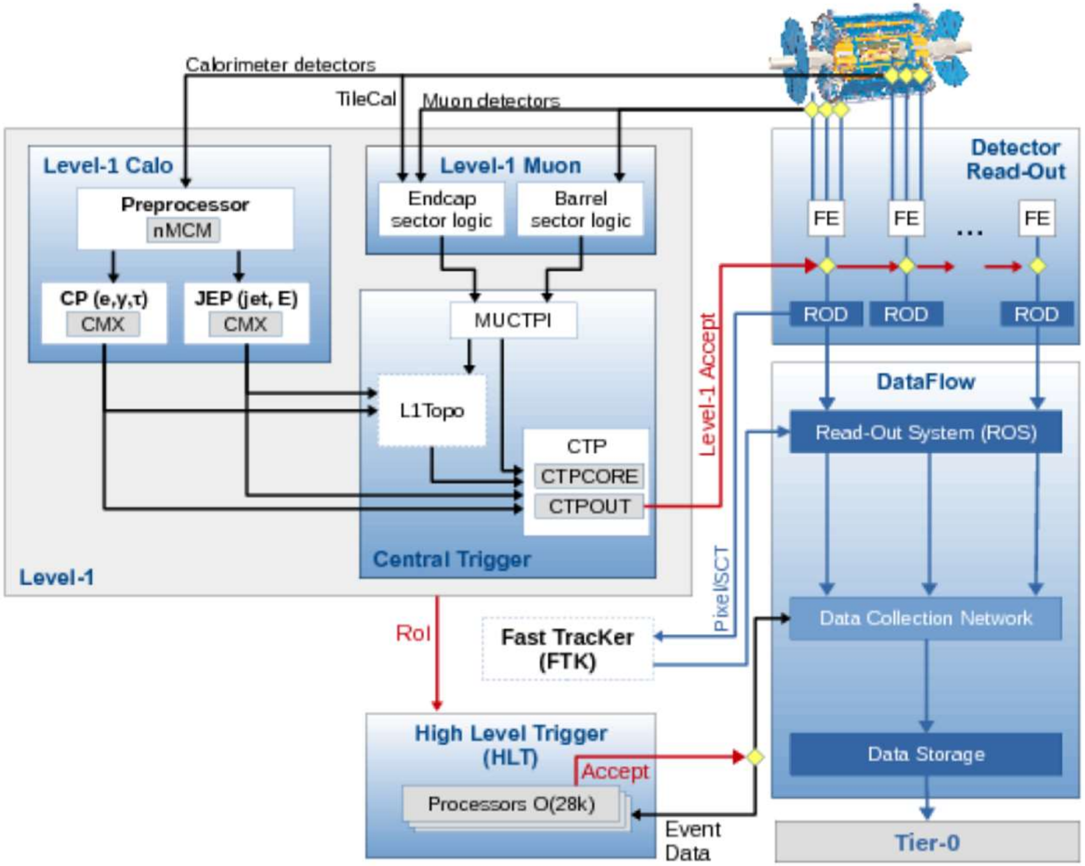
- **Second question:** Do we even **want** to record **all** events?

- **Reason #2:** Most events are really quite boring (subjectively)
- Of the **total cross-section** $\mathcal{O}(10^{11}pb)$
- Most collisions are **inelastic**
- Or **jet** production (it is a hadron collider)
- "**Interesting**" stuff (subjective) doesn't start for **many orders** of magnitude
- The more you **record**, the more you need to **throw away** later



Trigger

- ATLAS deploys a **multi-level** trigger system alongside its detector readout
- **Level-1**:
  - **Hardware** based trigger
  - **Fast**, $2.2\mu s$ latency
  - Uses **coarse data** from calorimeters and muon system
  - **Reduces** input rate to $75 - 100kHz$
- **High-level trigger (HLT)**:
  - **Software** based trigger
  - **Slower**, $\mathcal{O}(1s)$ latency
  - Uses event data from **all detectors**
  - **Reduces** input rate to $\mathcal{O}(1kHz)$
  - $\mathcal{O}(2GB/s)$ recorded to tape



Simulation

Simulation

Simulation: ‘virtual’ experiment

Simulated data samples needed for

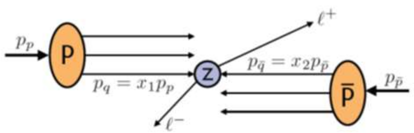
- Designing experiments
- Tuning analysis selections
- Background estimation

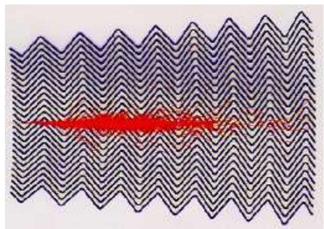
To get best physics outputs from the experiment it is essential to have an accurate simulation of the physics and the detector

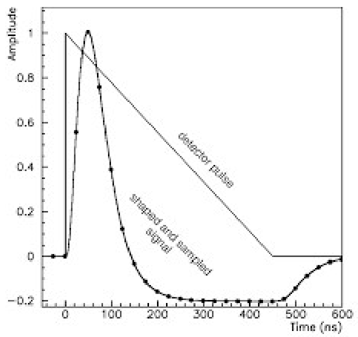
4-vectors → energy → electric signal

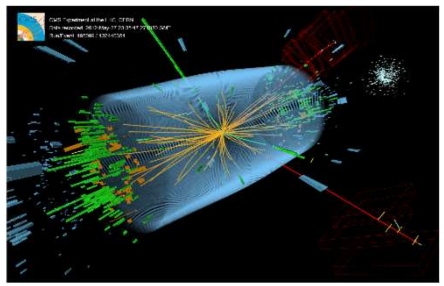
Event generation → **Detector simulation** → **Digitisation** → **Reconstruction**

Event generation	Detector simulation	Digitisation	Reconstruction
Hard scattering event	Geat4 or parameterised	Mimics detector readout “Mix-in” pileup events	Same as for real data









Monte-Carlo generators at LHC

- The calculation of a collision is typically split up into the following steps:
  - Parton Density Function (PDF)
    - Proton collisions are really *parton* collisions. PDFs give the probability of a particular proton constituent having a particular fraction of the proton momentum.
  - Hard-scatter
    - Exact theoretical calculation up to stated accuracy (e.g. LO or NLO) of the ME
    - Limit on the number of final state particles
    - Valid for hard and well-separated partons
  - Parton Shower (PS):
    - QCD radiation matched to the matrix element (ISR/FSR)
      - Valid for soft and/or collinear partons
    - Hadronisation/beam-remnants/MPI
    - Phenomenological models describing non-perturbative physics
  - Higher-order calculations blur these distinctions
    - Complicated interplay between ME and PS
    - Solutions: merging and matching (eg. CKKW, MLM)

- Many generators available on the market with different levels of accuracy, PS models,…
  - Sherpa, MadGraph, Herwig, Powheg Box, Pythia,…
  - Systematics uncertainties: renormalization and factorization scales, PDF, shower model, …
  - Need to find the one that best represents the data your are interested in

- More information in https://arxiv.org/abs/1101.2599

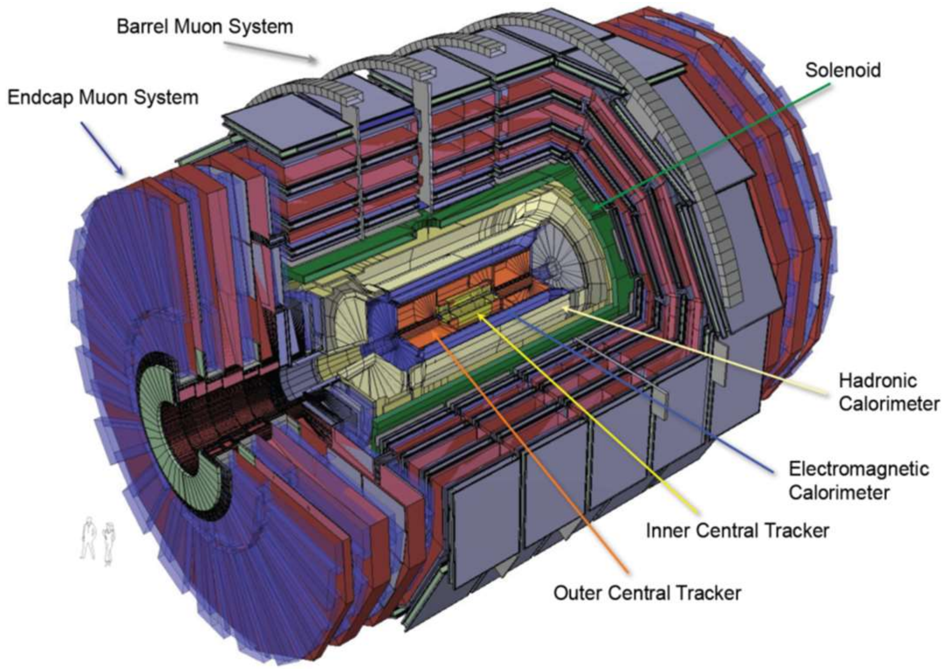
Detector simulation (aka transportation)

Simulation of the passage of the produced particles through the experimental apparatus using transportation code like **Geant4**.

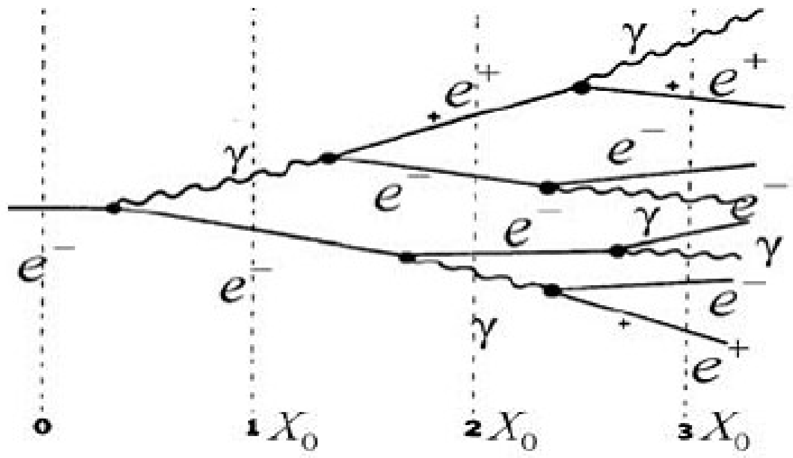
- Propagates particles through geometrical structures of materials, including B field
- Simulates processes the particles undergo
- Calculates the deposited energy along the trajectories

Two ingredients:

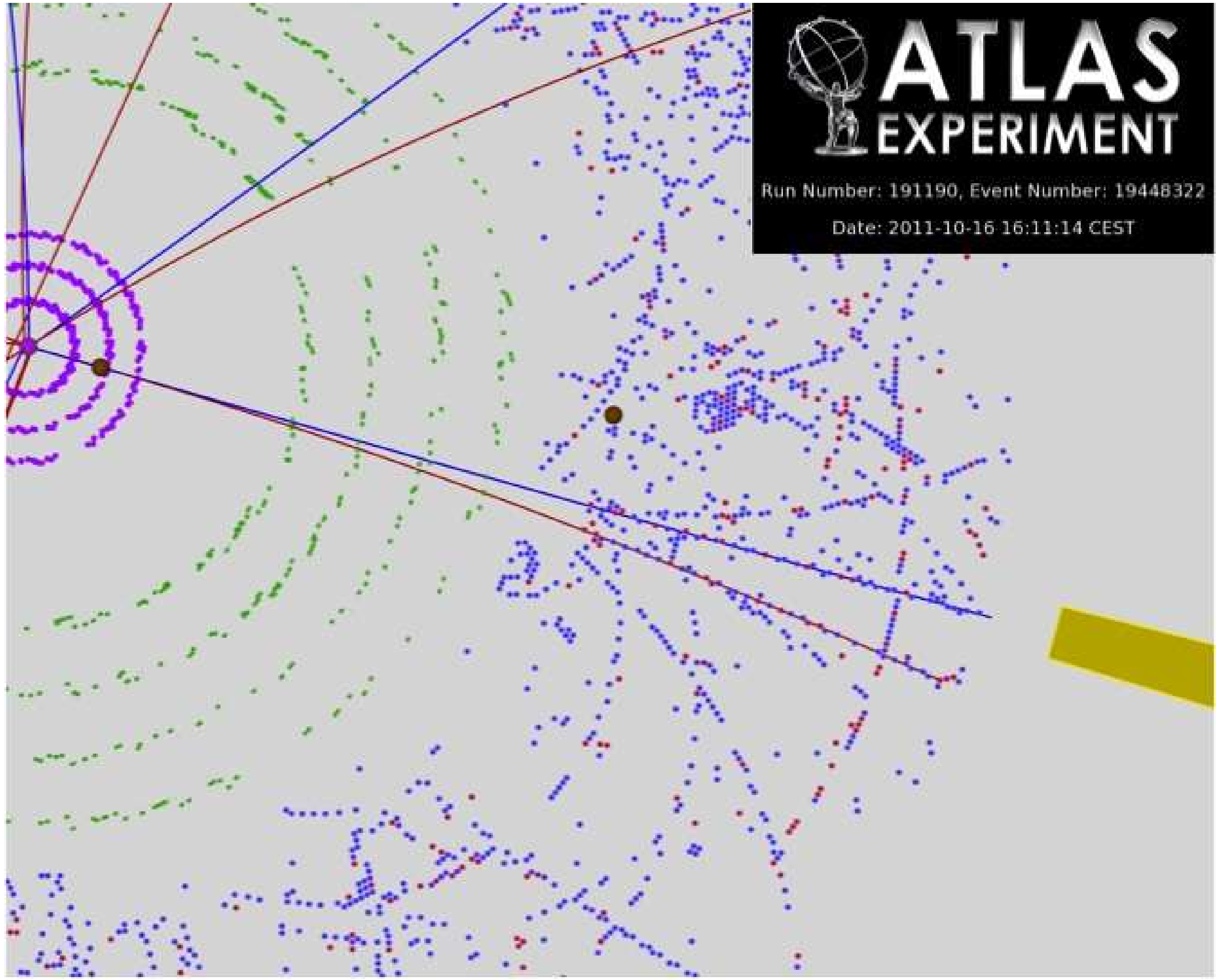
Detector geometry

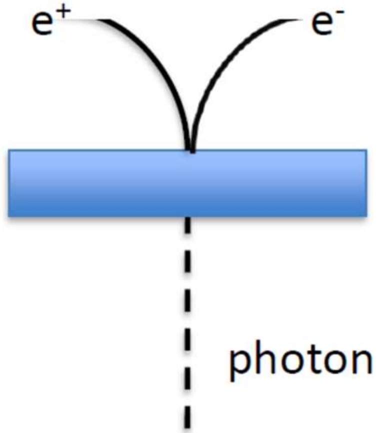


Physics lists

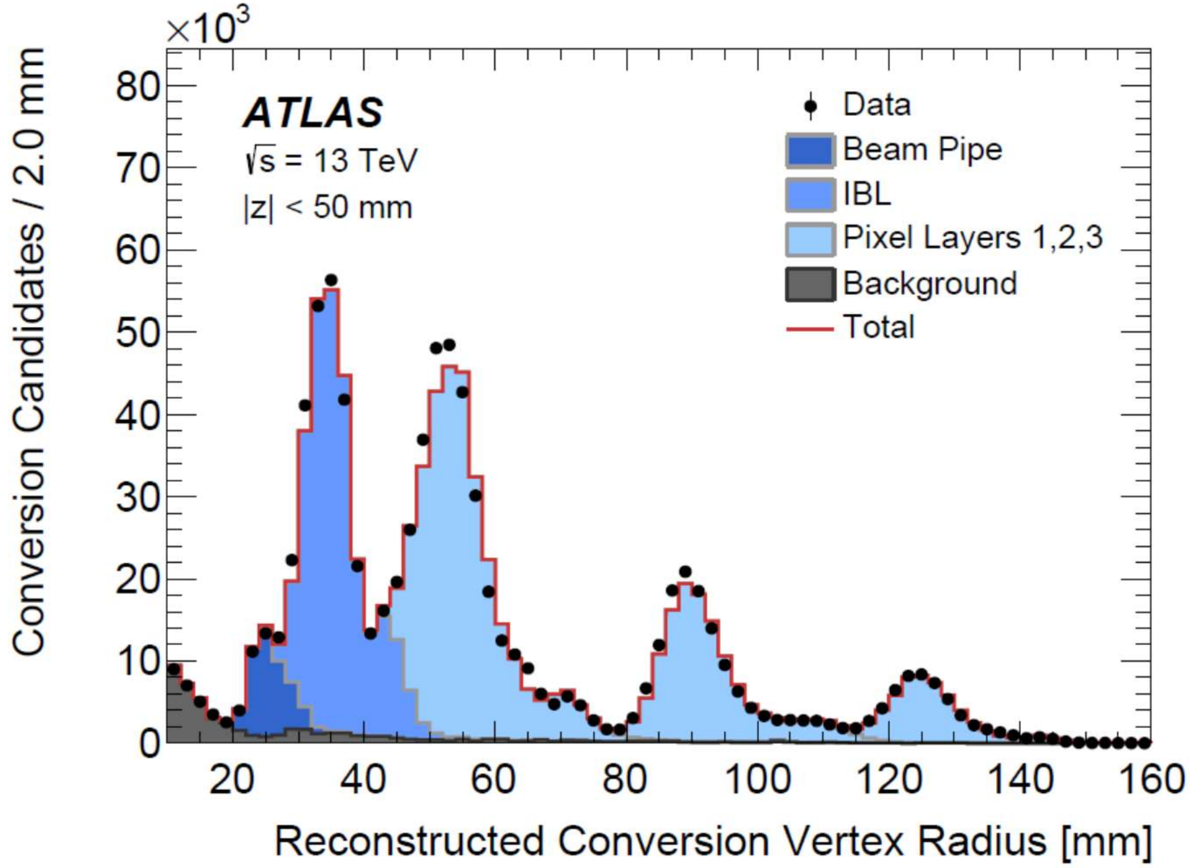


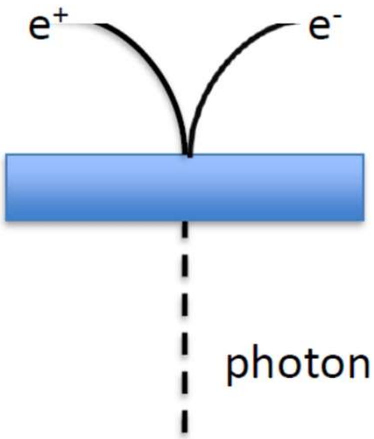
Validation of the tracker geometry



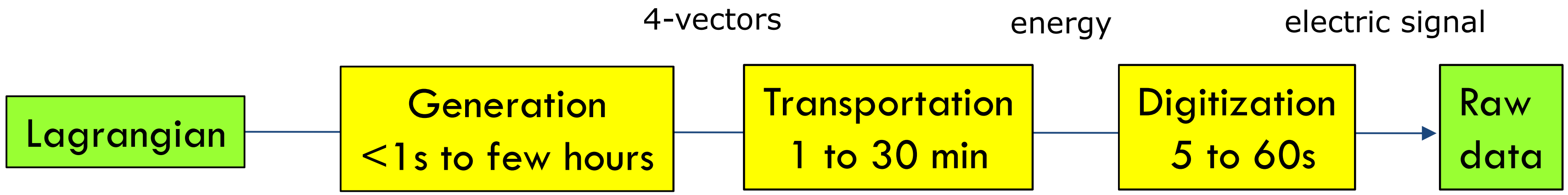


Validation of the tracker geometry

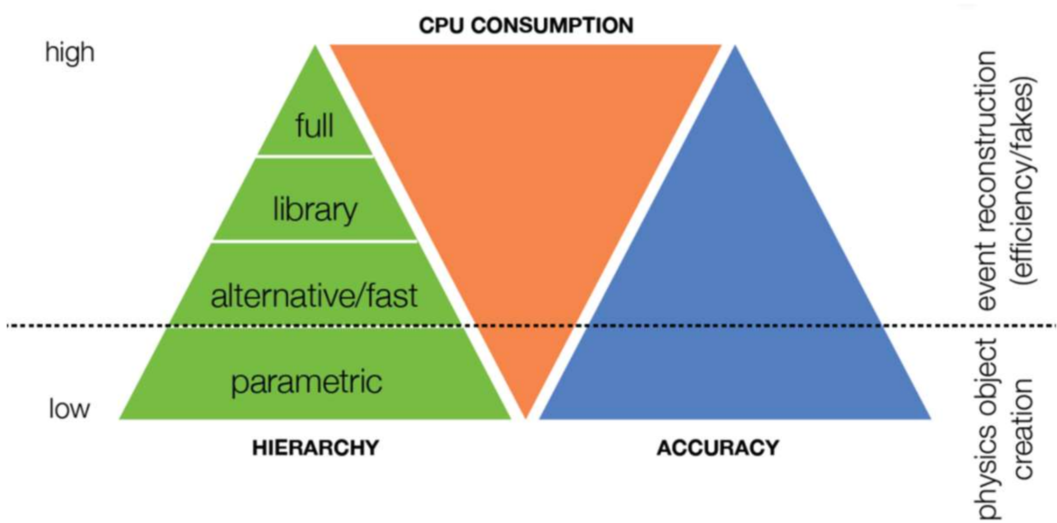




Simulation: conclusion



Accuracy vs CPU



In new physics searches:

- bkg: full simulation
- Signal: fast simulation

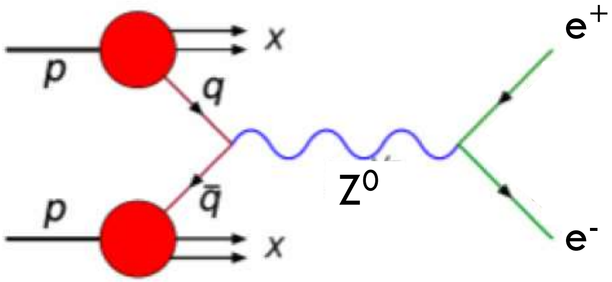
Validation and tuning of the simulation is mandatory to give best description of the data (testbeams and in-situ collisions)

Cross-section measurements

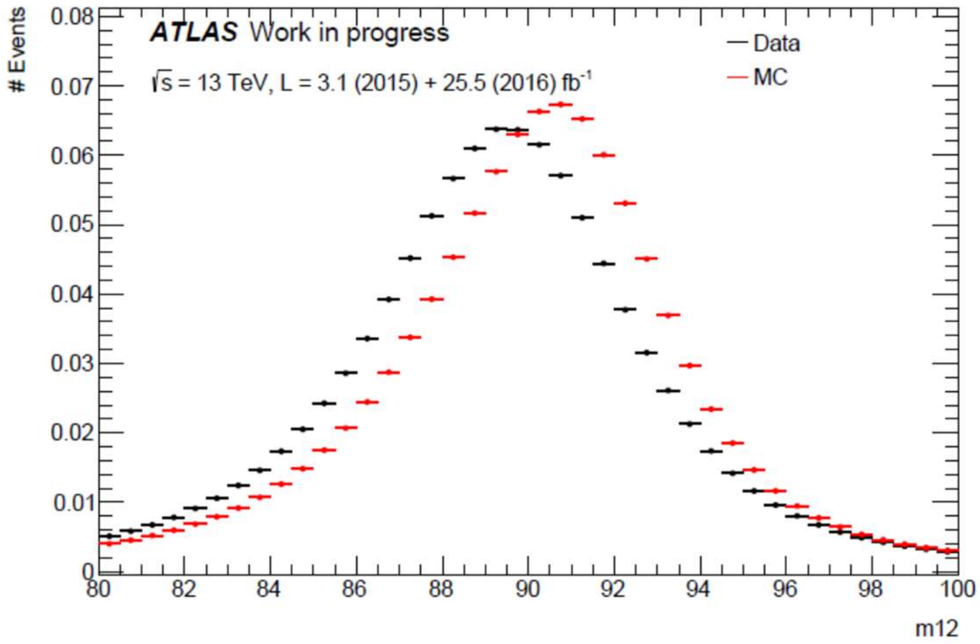
Standard Model processes

Any new physics channel will have some SM physics backgrounds, so it is essential to check that the SM works in the new region of phase space opened up by the LHC

Moreover SM physics processes (particularly W and Z decays to leptons) provide 'standard candles' to understand and calibrate the detector performance



$$M_{12} = \sqrt{2E_1E_2(1 - cos\theta_{12})}$$



Cross-section measurements

Total cross-section:

$$\sigma_{tot} = \frac{N}{L}$$

Cross-section measurements

Total cross-section:

$$\sigma_{tot} = \frac{N - N_{bkg}}{A \times \varepsilon \times L}$$

Fiducial cross-section:

$$\sigma_{fid} = \frac{N - N_{bkg}}{\varepsilon \times L}$$

Less model-dependant

σ_{tot} is the total cross section for a given process (which includes the decay branching fractions)

N is the number of events observed after the selection cuts

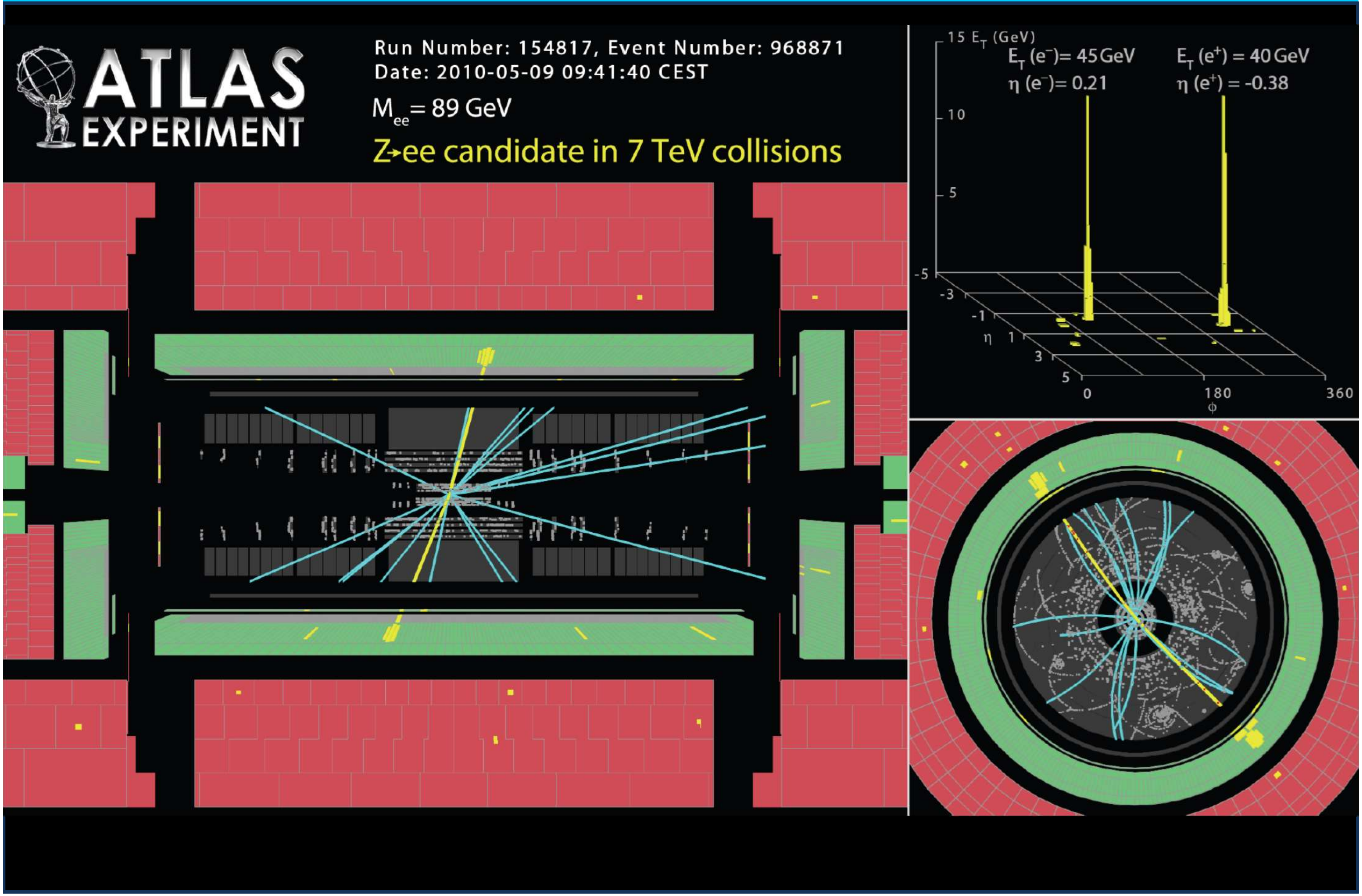
N_{bkg} is the expected number of backgrounds events (reducible or irreducible)

L is the integrated luminosity

ε is experimental efficiency (online and offline)

A is the the acceptance defined by the ratio of number of events produced in the fiducial volume to the total number of events. It is an extrapolation factor estimated by theory (typically with Monte Carlo)

$Z/\gamma^* \to \ell^+\ell^-$ production cross-section

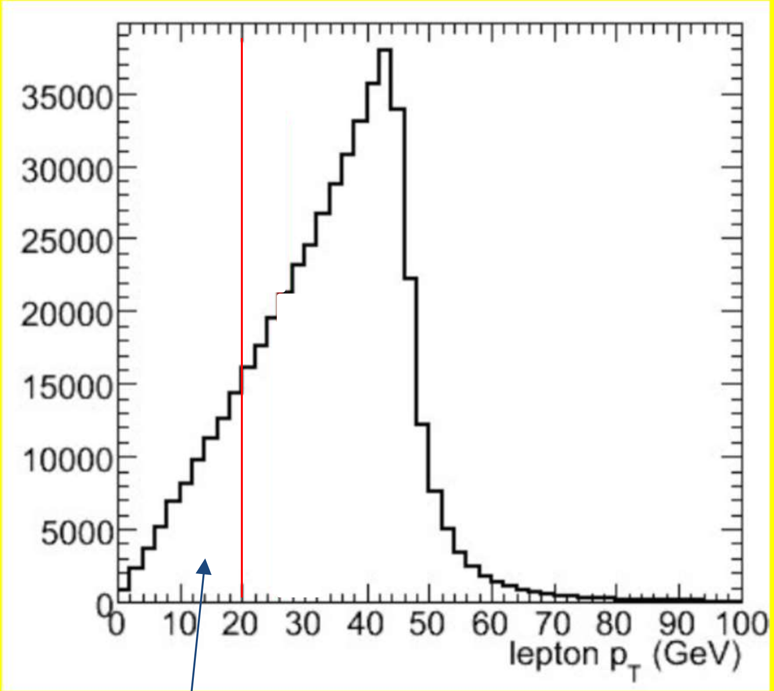


$Z/\gamma^* \rightarrow \ell^+\ell^-$ production cross-section

Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST

$E_T(e^-) = 45$ GeV $\quad E_T(e^+) = 40$ GeV
$\eta(e^-) = 0.21 \quad \eta(e^+) = -0.38$

- Two leptons (muon ou electron) with $p_T > 20$GeV
- Opposite charges
- Invariante mass~M_Z



Acceptance loss

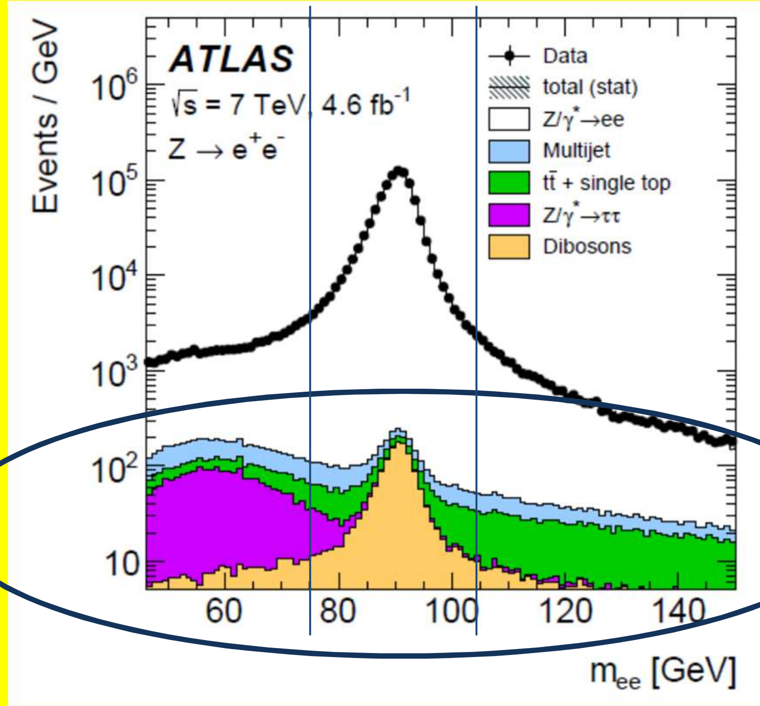
$Z/\gamma^* \to \ell^+\ell^-$ production cross-section

Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST

$E_T(e^-) = 45$ GeV $E_T(e^+) = 40$ GeV
$\eta(e^-) = 0.21$ $\eta(e^+) = -0.38$

- Two leptons (muon ou electron) with $p_T > 20$GeV
- Opposite charges
- Invariante mass~M_Z

Bkg



$Z/\gamma^* \to \ell^+\ell^-$ production cross-section @ 7TeV

	$\sigma^{\text{fid}}_{Z/\gamma^* \to \ell\ell}$ [pb]
$Z/\gamma^* \to e^+e^-$	$502.7 \pm 0.5\,(\text{stat}) \pm 2.0\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \mu^+\mu^-$	$501.4 \pm 0.4\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \ell\ell$	$502.2 \pm 0.3\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 9.0\,(\text{lumi})$

Good agreement between channels

Improvement of the statistical uncertainty by combining the channels

Systematic uncertainties cover our lack of knowledge

- Need to be determined on every aspect of measurement by varying assumptions within sensible reasoning
- There is no "correct way"
- Need to develop a "feeling" and discuss with colleagues / theorists!

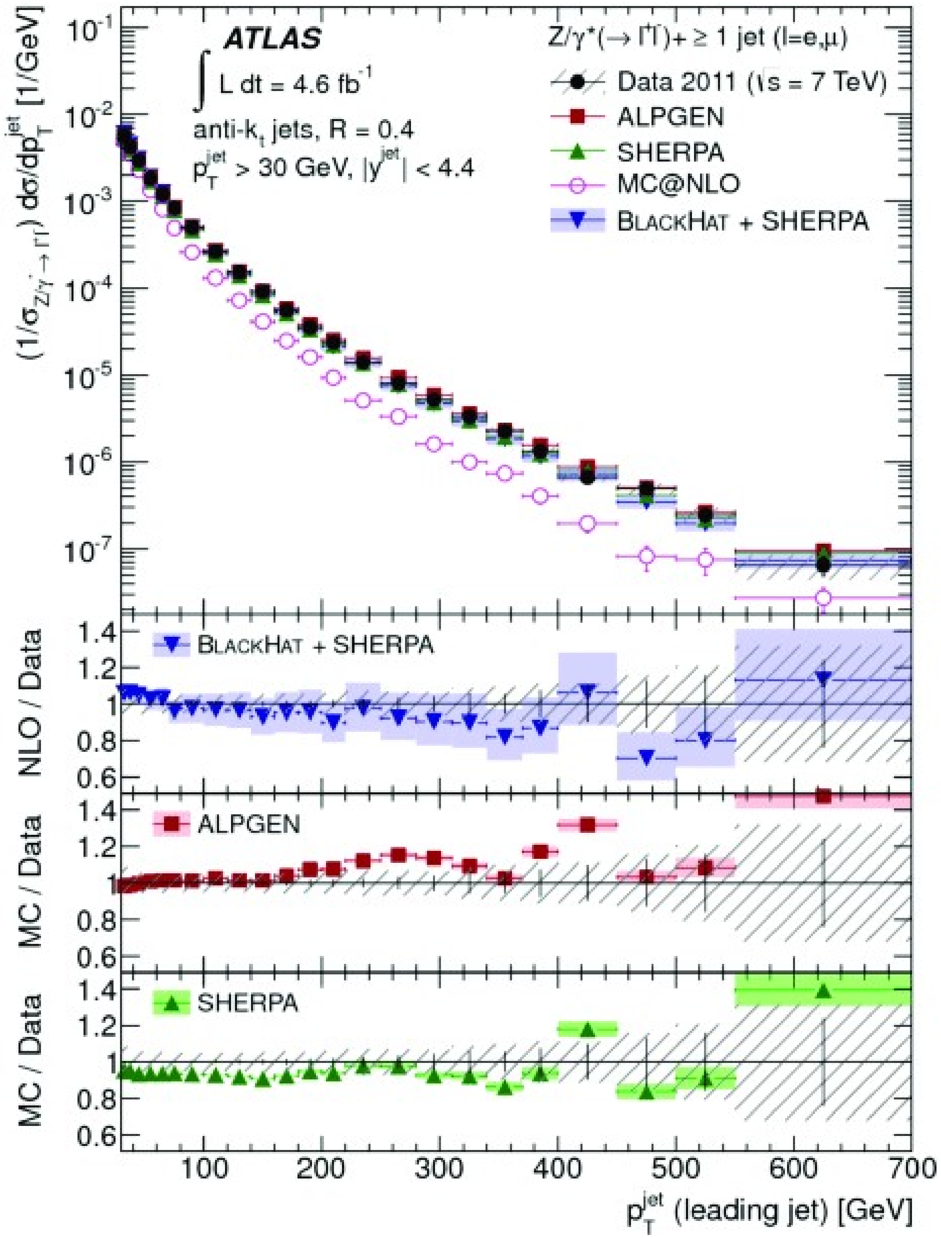
Source	Electron	Muon
Trigger efficiency	0.03	0.05
Reconstruction efficiency	**0.20**	**0.30**
Identification efficiency	**0.16**	**0.15**
Lepton pT reso	0.01	<0.01
Lepton pT scale	0.08	0.03
Signal modeling (ME)	0.03	0.04
Signal modeling (PS)	**0.18**	**0.22**
PDF	0.09	0.07
Boson pT	0.01	0.04
Multijet bkg	0.03	0.07
Ewk+Top background	0.02	0.02
Bkg MC stat.	<0.01	0.01
Unfolding	0.04	0.02
Total	**0.35**	**0.43**

arXiv:1612.03016v2

$Z/\gamma^* \to \ell^+\ell^-$ production cross-section: theory comparison

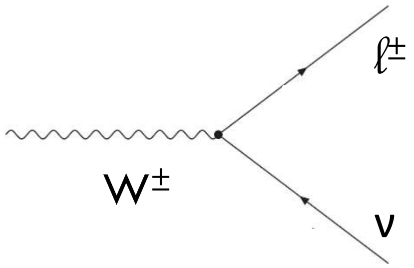
Current best knowledge:
NNLO QCD and NLO EW

PDF set	$\sigma^{\text{fid}}_{Z/\gamma^*\to\ell\ell}$ [pb]
ABM12	490.8 ± 5.7
CT14	481^{+11}_{-14}
HERAPDF2.0	497^{+16}_{-9}
JR14	484.4 ± 2.2
MMHT2014	$485^{+7.4}_{-6.9}$
NNPDF3.0	472.2 ± 7.2
Data	502.2 ± 9.2

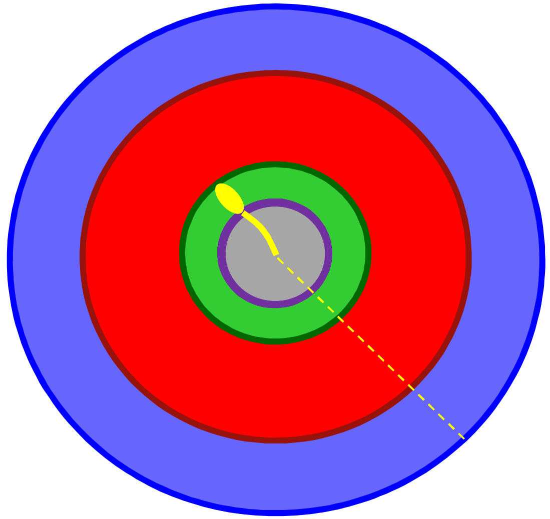


Differential cross-section

$W\to\ell\nu$ production cross-section



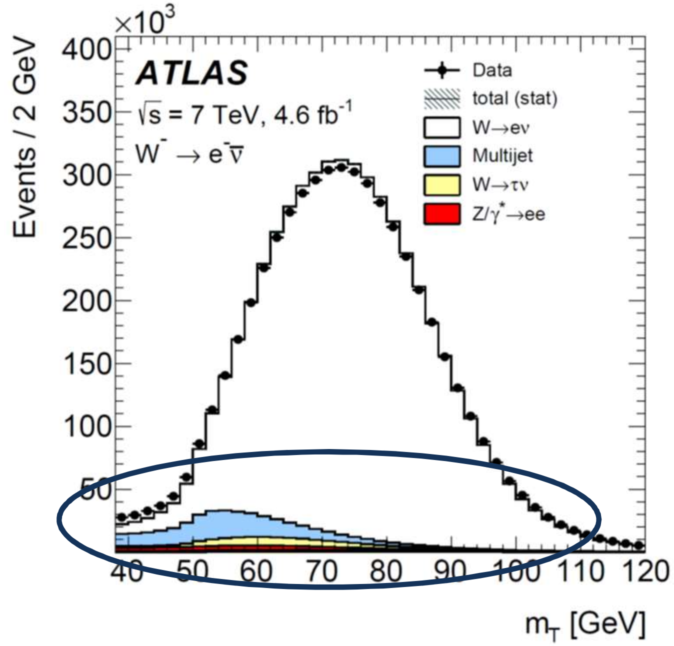
$$M\vec{E}T = \vec{p}_T^{\,neutrino} = -\vec{p}_T^{\,electron}$$



- Transverse mass

$$M_T = \sqrt{2E_{T1}E_{T2}(1 - cos\theta_{12})}$$

- Selection:
  - 1 lepton with pT>25GeV (muon ou electron)
  - MET>25GeV
  - M_T>40GeV

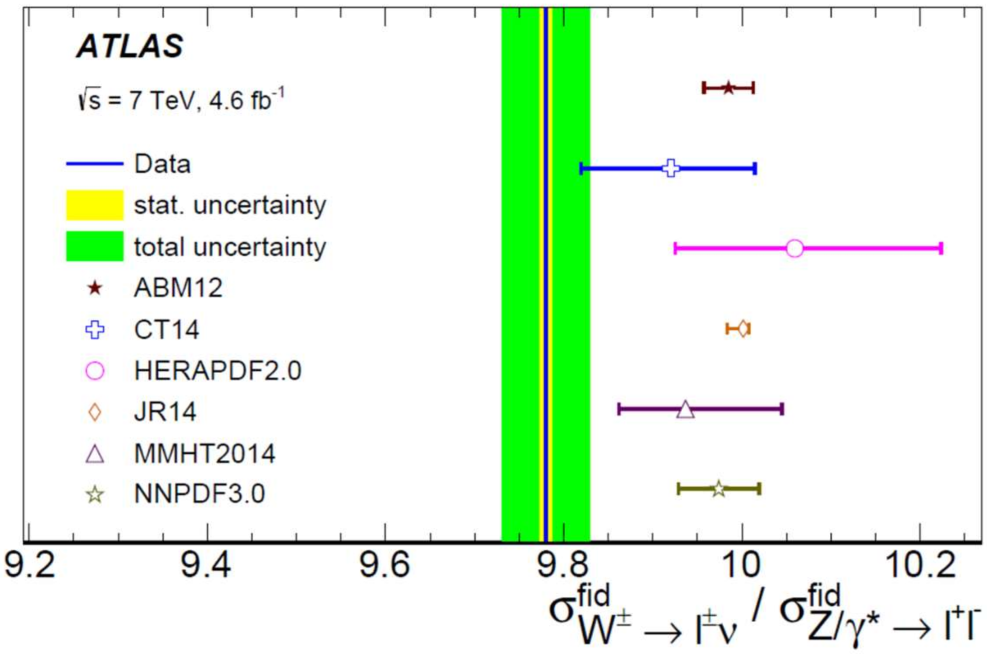


$W\rightarrow\ell\nu$ production cross-section

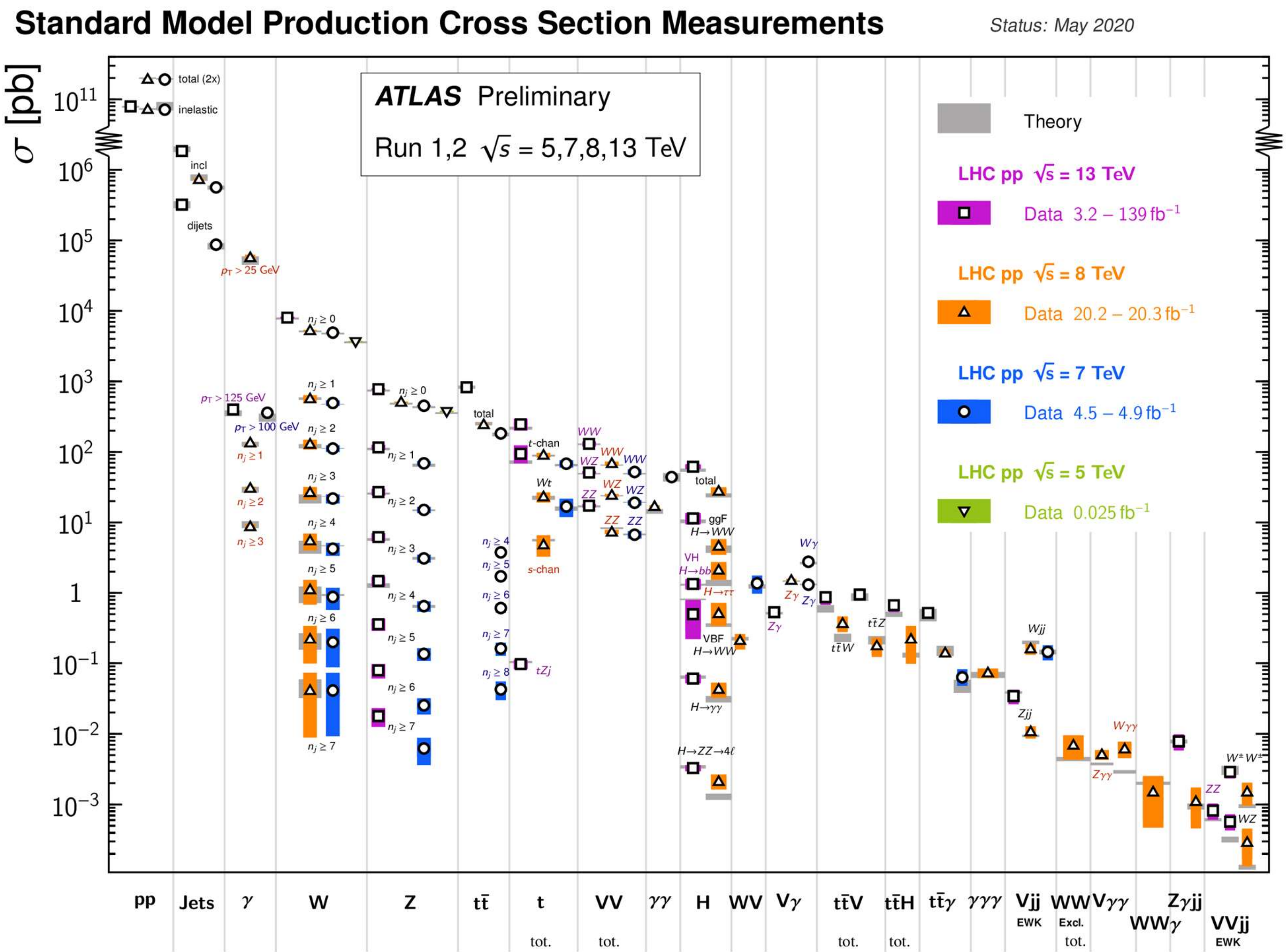
	$\sigma^{\text{fid}}_{W\rightarrow\ell\nu}$ [pb]
$W\rightarrow e\nu$	$4896 \pm 2\,(\text{stat}) \pm 49\,(\text{syst}) \pm 88\,(\text{lumi})$
$W\rightarrow \mu\nu$	$4912 \pm 1\,(\text{stat}) \pm 32\,(\text{syst}) \pm 88\,(\text{lumi})$
$W\rightarrow \ell\nu$	$4911 \pm 1\,(\text{stat}) \pm 26\,(\text{syst}) \pm 88\,(\text{lumi})$

Cross-section ratio → cancellation of correlated systematic uncertainty (ex: lumi)

$R^{\text{fid}}_{W^+/W^-}$	$1.5006 \pm 0.0008\,(\text{stat}) \pm 0.0037\,(\text{syst})$
$R^{\text{fid}}_{W/Z}$	$9.780 \pm 0.006\,(\text{stat}) \pm 0.049\,(\text{syst})$
$R^{\text{fid}}_{W^+/Z}$	$5.869 \pm 0.004\,(\text{stat}) \pm 0.029\,(\text{syst})$
$R^{\text{fid}}_{W^-/Z}$	$3.911 \pm 0.003\,(\text{stat}) \pm 0.021\,(\text{syst})$



Much more measurements



Conclusion: what is important for BSM searches?

Accumulate the largest sample of collisions data

- The statistical uncertainties decreases as the square root of luminosity
- The significance of a search increase with the square root of the luminosity

High trigger efficiency

- Events rejected by the trigger are lost forever

Understand the performance of the detector

- The reconstruction of physics objects must be well mastered as well as the efficiency of the reconstruction and the calibration of the objects together with the uncertainties

Validation and tuning the simulation

- Physics generators
- Simulation of the detectors

Understand the physics background

- Need to measure SM processes and use data to be confident in “extreme” phase space regions


That's all Folks!

Info exam:

- Motivation for BSM physics
- What is supersymmetry? What is Higgs compositness? What is a vector-like quarks?
- Complementarity between direct and indirect searches
- Analysis techniques:
  - Experimental signatures of SM particles
  - Background estimation (simulation, CR, VR,…)
  - Statistics: p-value, exclusion at 95% CL

The Standard Model of particle physics

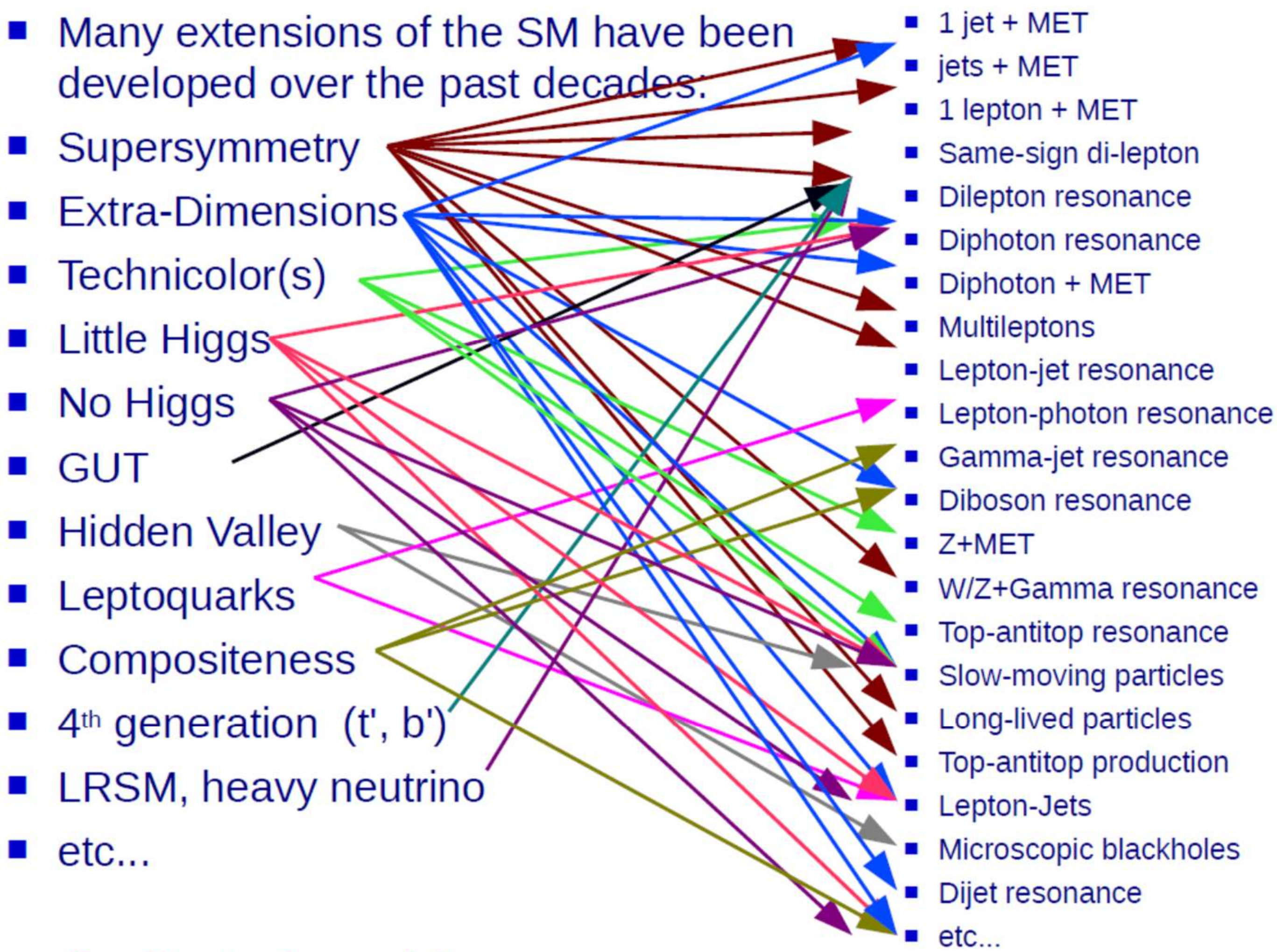
Most general renormalizable lagrangian including all SM fields with $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge groups:

$$
\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{2g^2} \mathrm{Tr}(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2g_s^2} \mathrm{Tr}(G_{\mu\nu} G^{\mu\nu}) \\
& + \bar{Q}_i i \not{D} Q_i + \bar{L}_i i \not{D} L_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{e}_i i \not{D} e_i \\
& + (Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i e_j H + \mathrm{h.c.}) \\
& + (D_\mu H)^\dagger (D^\mu H) - \lambda (H^\dagger H)^2 - \mu^2 H^\dagger H \\
& + \frac{\theta}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr}(G_{\mu\nu} G_{\rho\sigma})
\end{aligned}
$$

19 parameters:

- 3 gauge coupling constants
- 9 fermion Yukawa couplings
- 3 CKM mixing angles + 1 phase
- μ, λ or m_Z, m_H
- θ_{strong}

A very long list of models and signatures



(for illustration only)

A very long list of models and signatures

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

A complex 2D problem

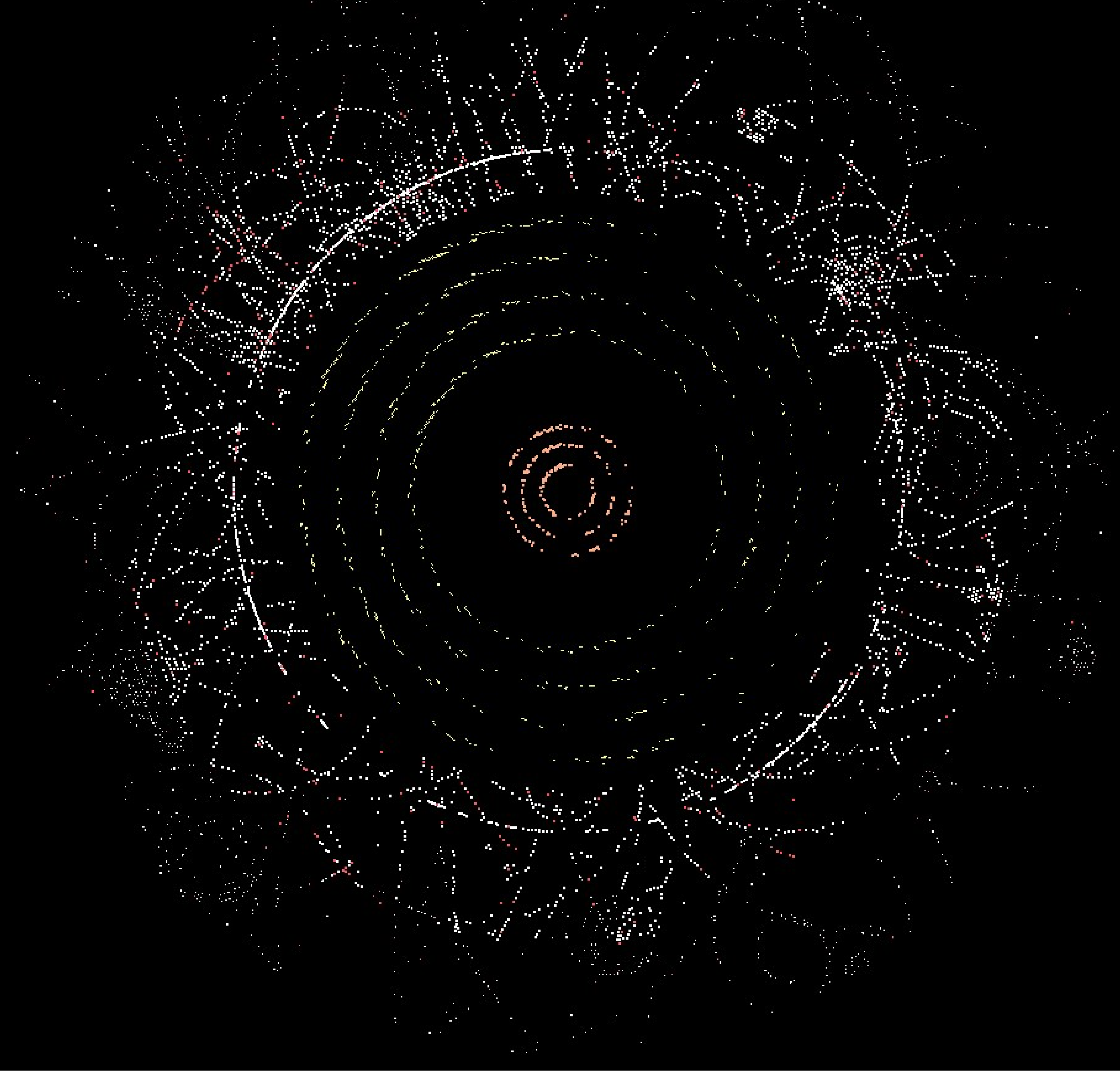
Experimentally, a signature standpoint makes a lot of sense:

→ Practical

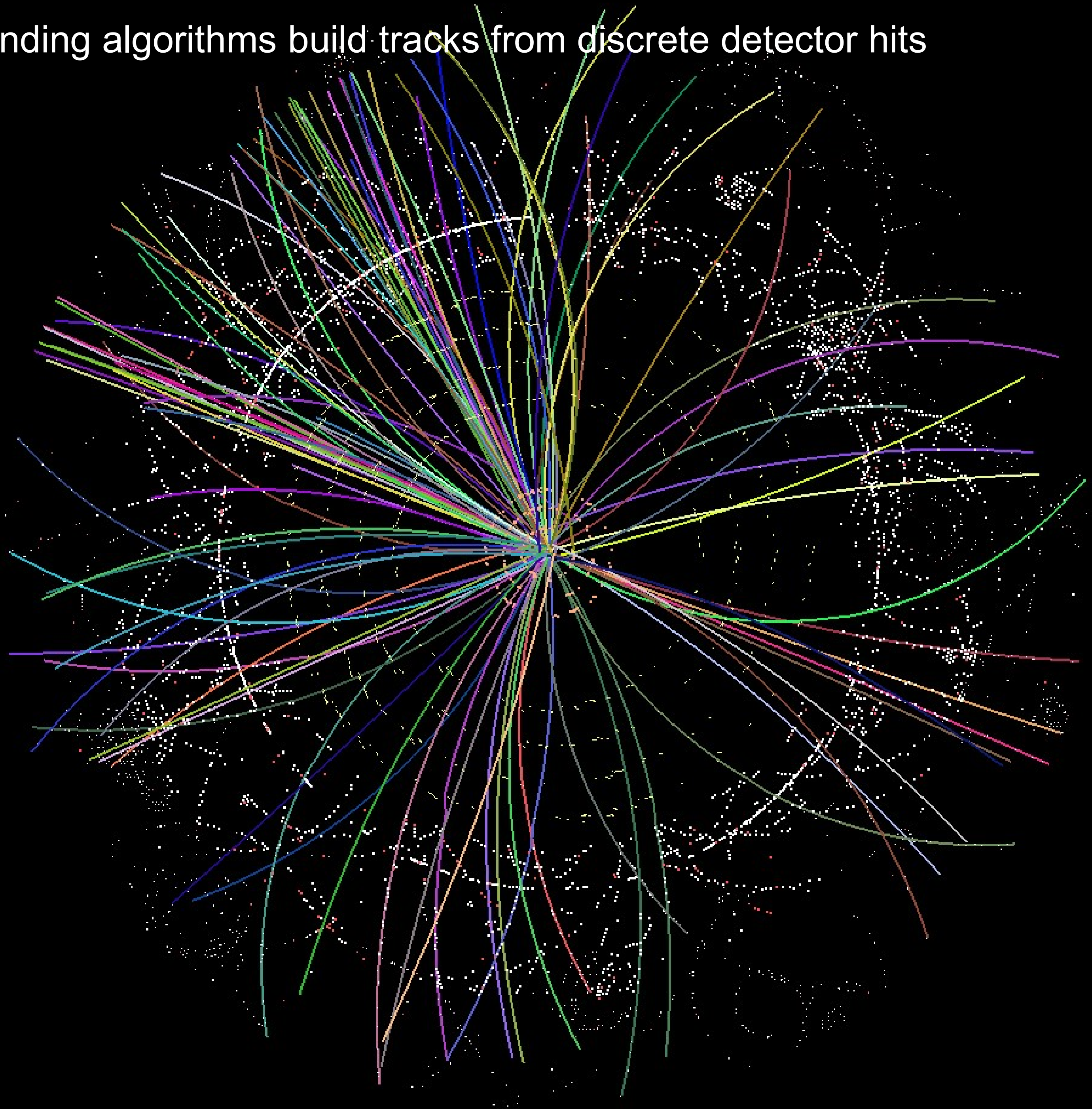
→ Less model-dependent

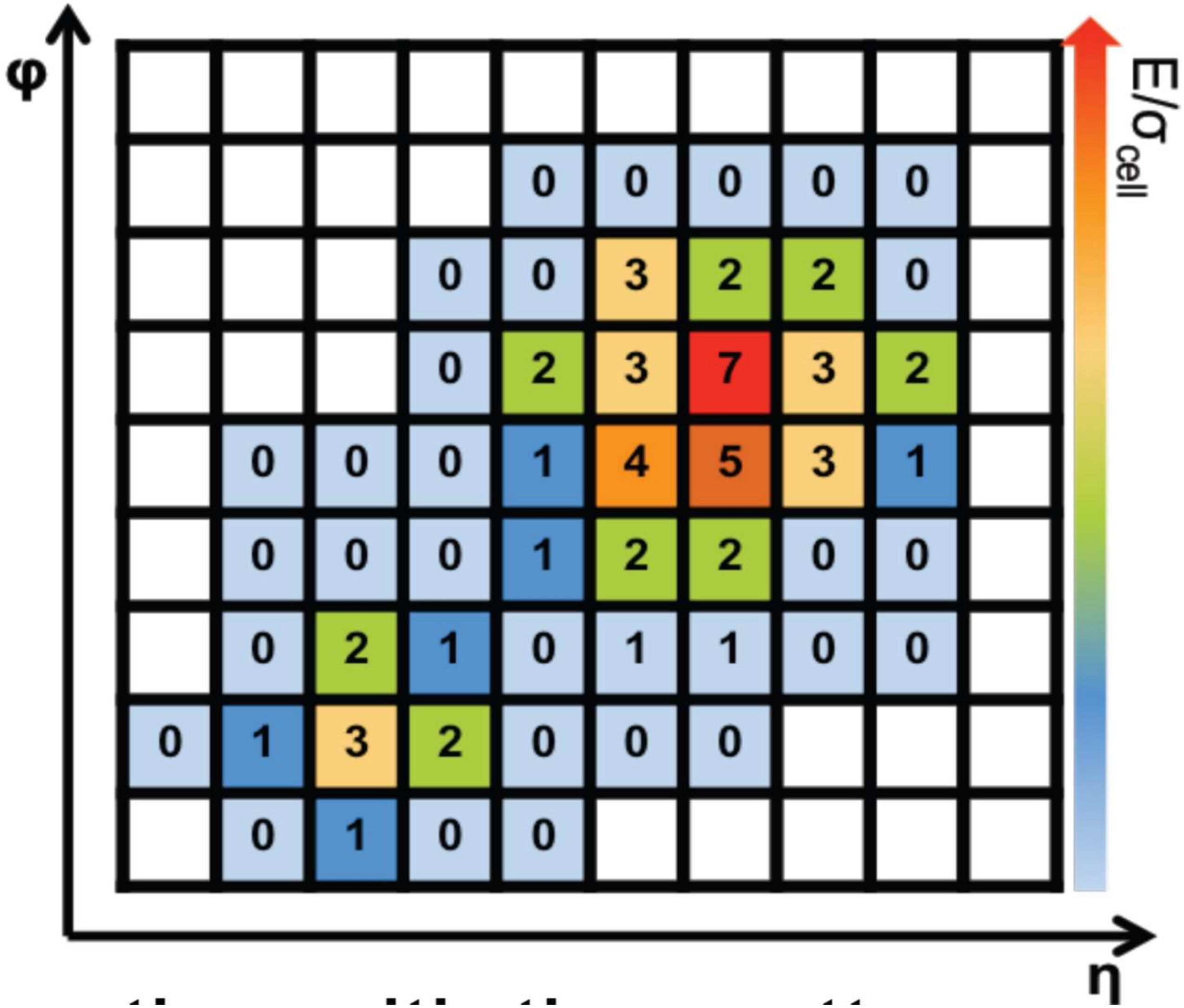
→ Important to cover every possible signature

Pattern finding algorithms build tracks from discrete detector hits



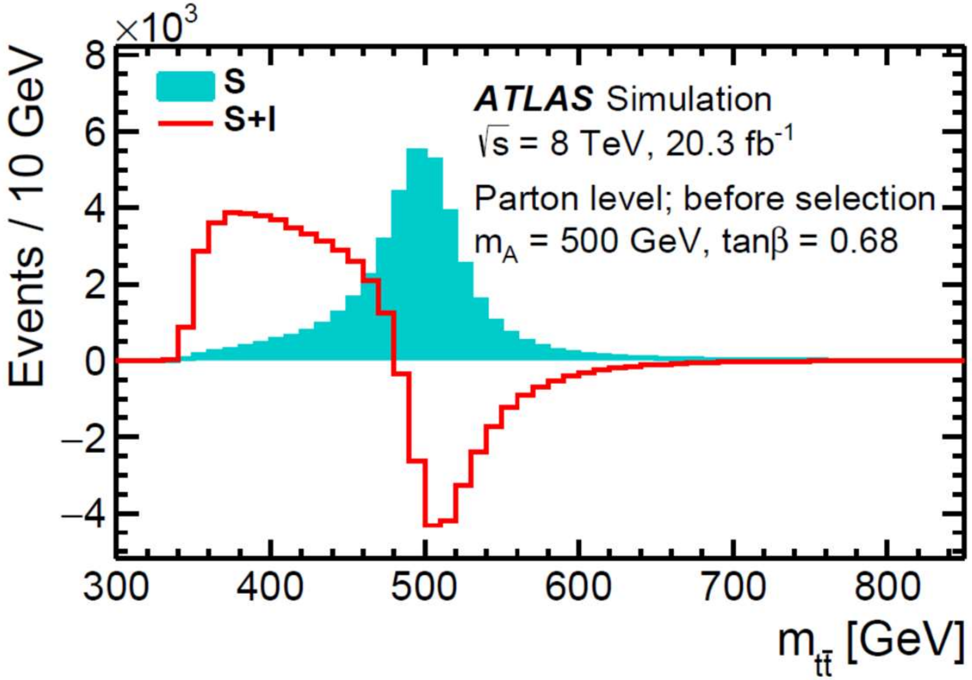
Pattern finding algorithms build tracks from discrete detector hits

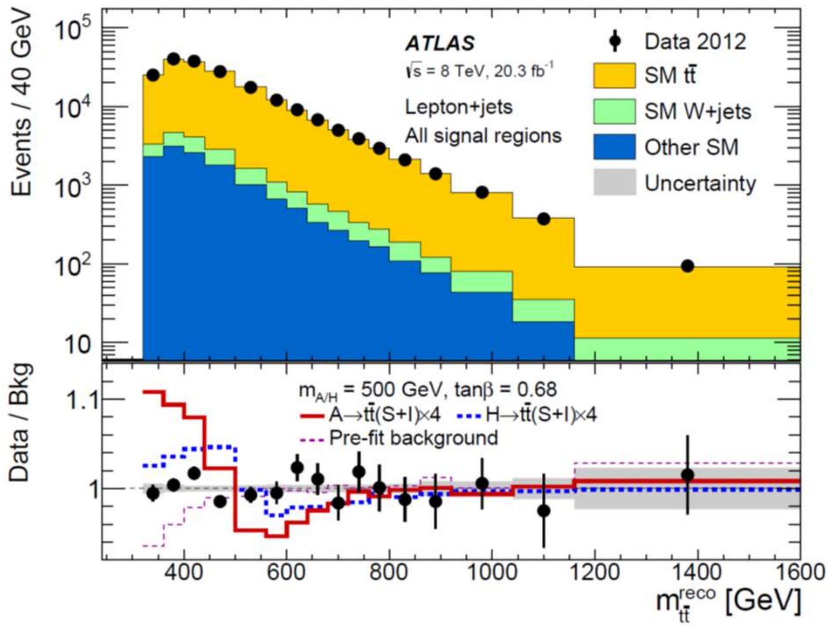


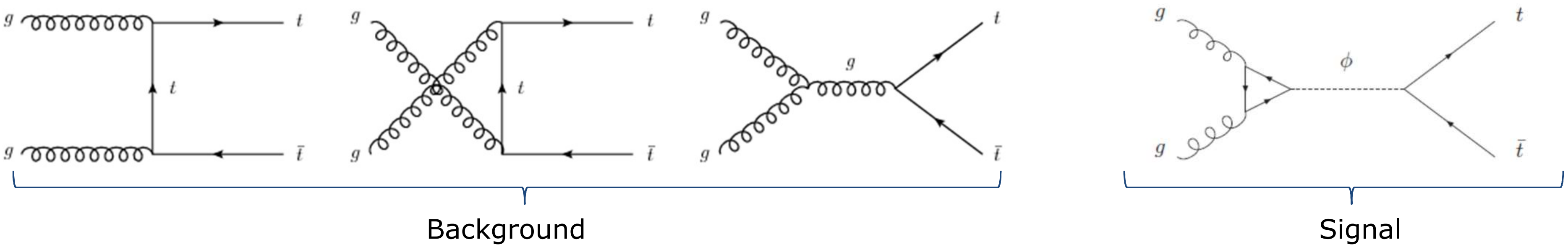

φ
η
E/σcell

Direct searches

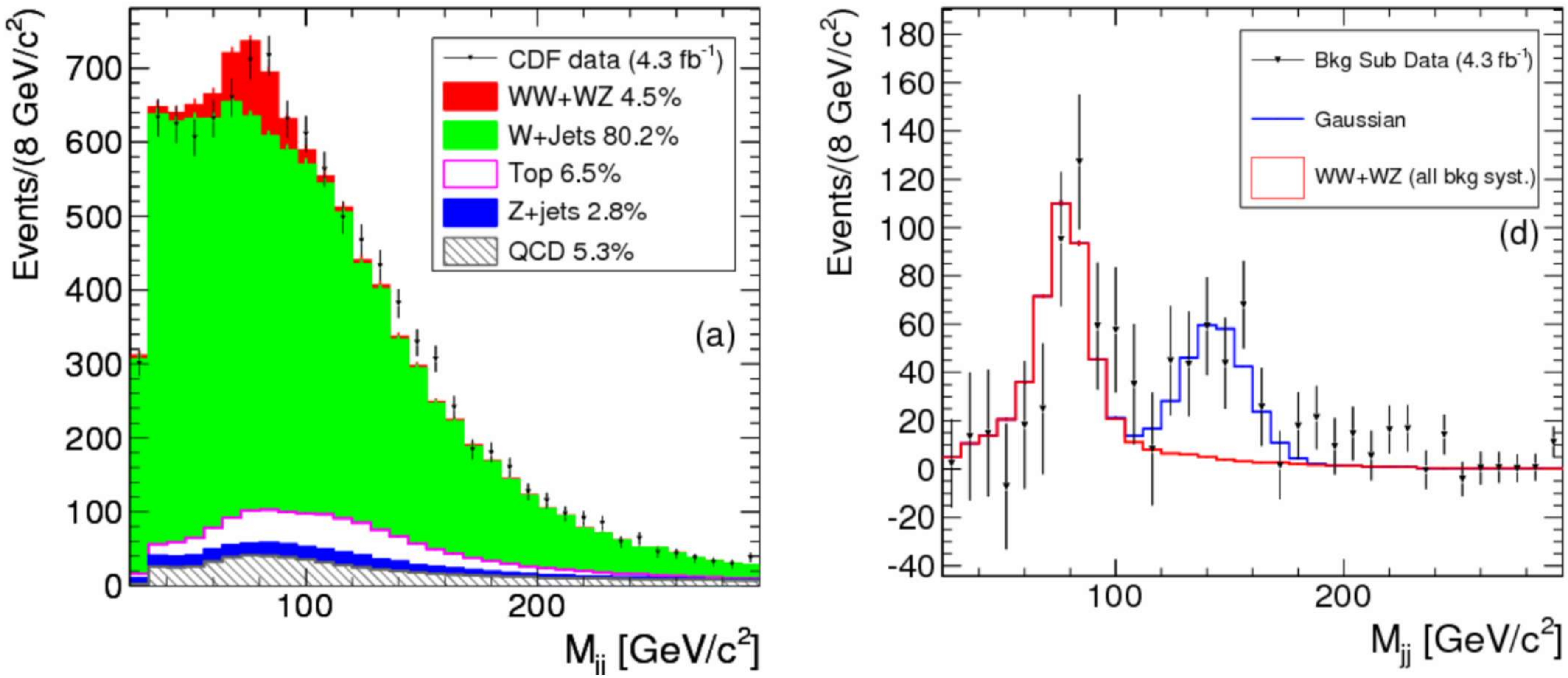
In few cases, a direct search of new physics can be observed as a deficit of events due to interference between the signal and the background







Need to understand the detector and its performance



3σ excess observed by CDF but further investigations
showed that it is an artefact of jet energy (mis)calibration

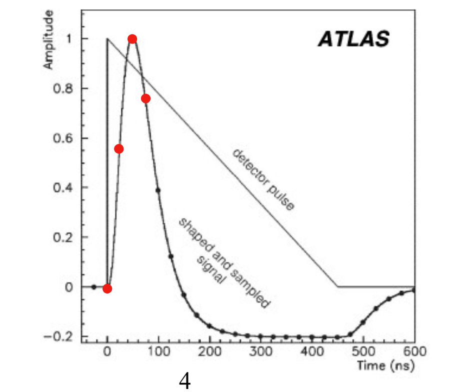
arXiv:1104.0699
arXiv:1402.7044

Electron calibration

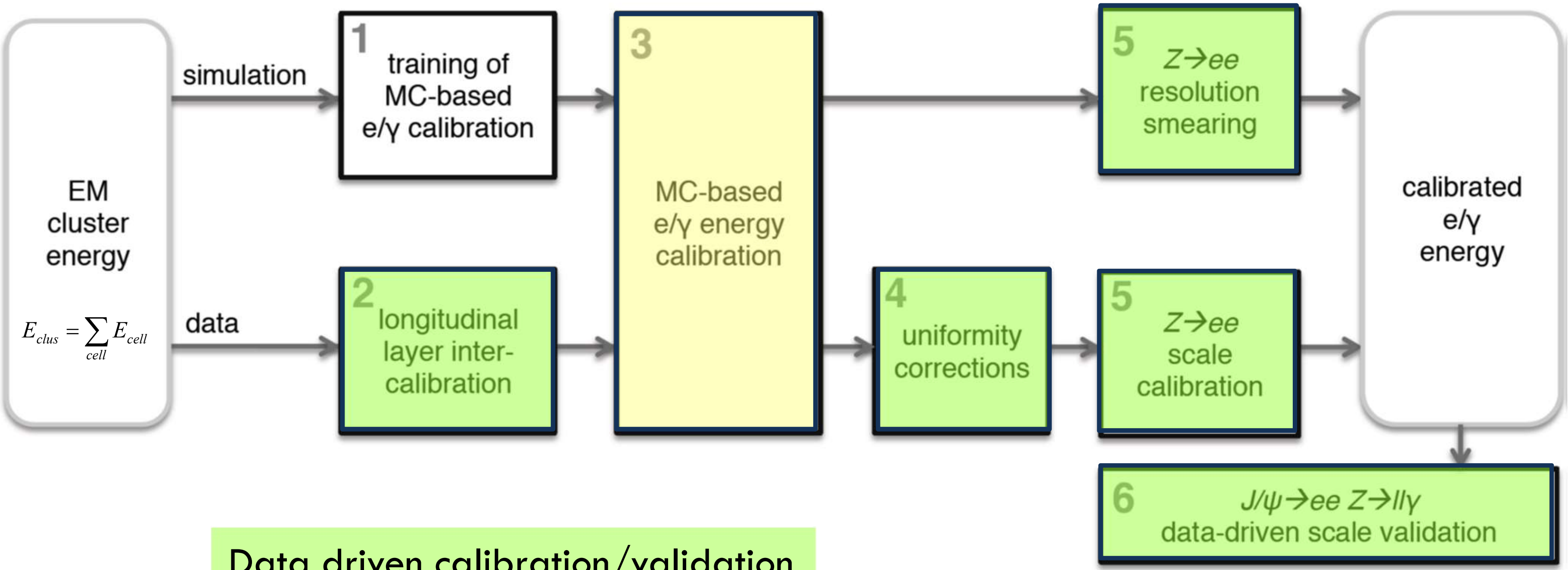
MC based calibration for:

- Loss in dead material
- Lateral leakage
- inhomogeneities in φ an η

Size: 5 et 15%

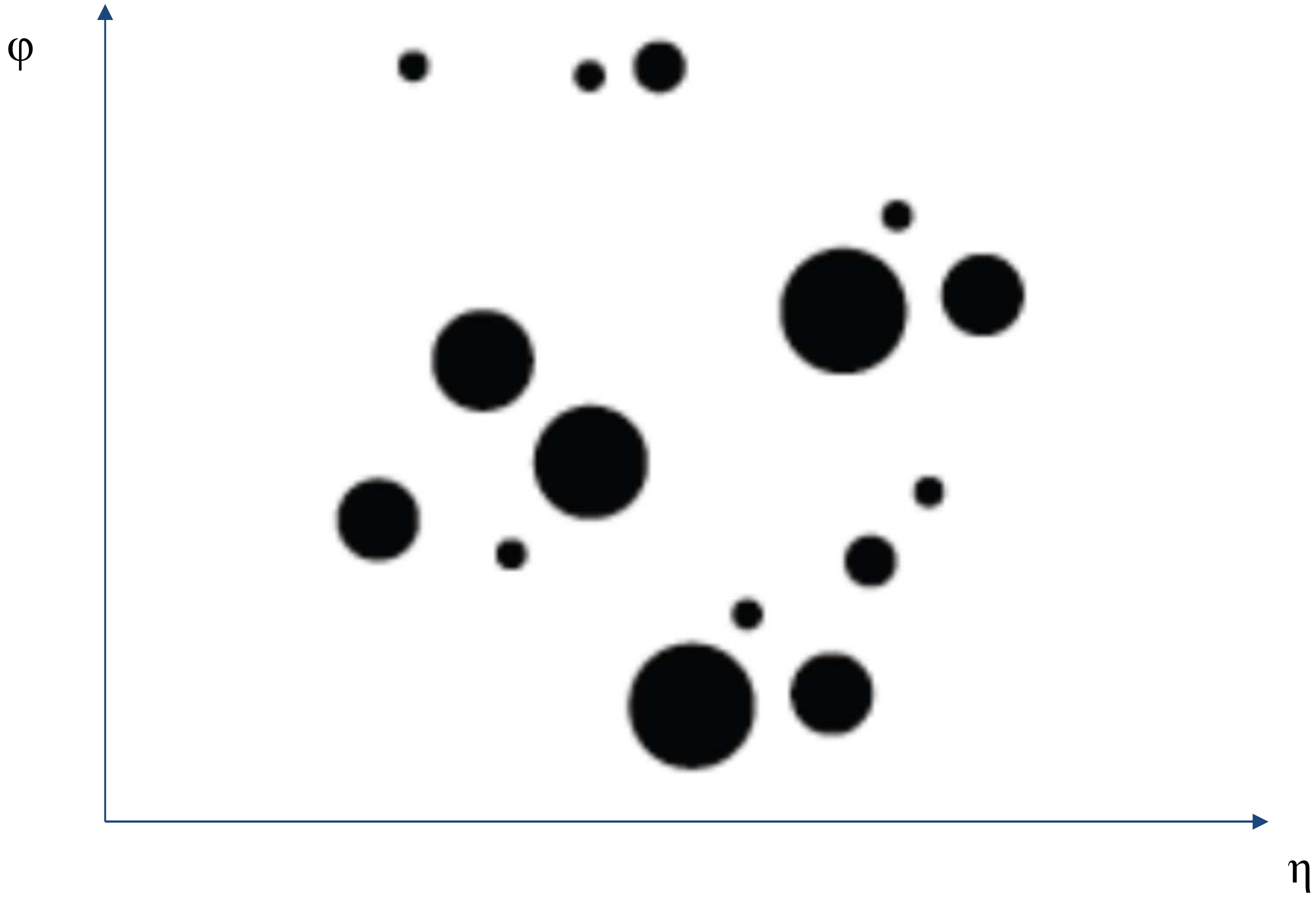


$$E_{cell} \propto \sum_{i=1}^{4} a_i (ADC_i - P)$$



Data driven calibration/validation

Jets



Sequential recombination algorithm:

- Find min of all d_{ij} and d_{iB},
- If min is a d_{ij}, merge and iterate
- If min is a d_{iB}, classify as a final jet
- Continue until list is exhausted

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\, \Delta R_{ij}^2 / R^2$$

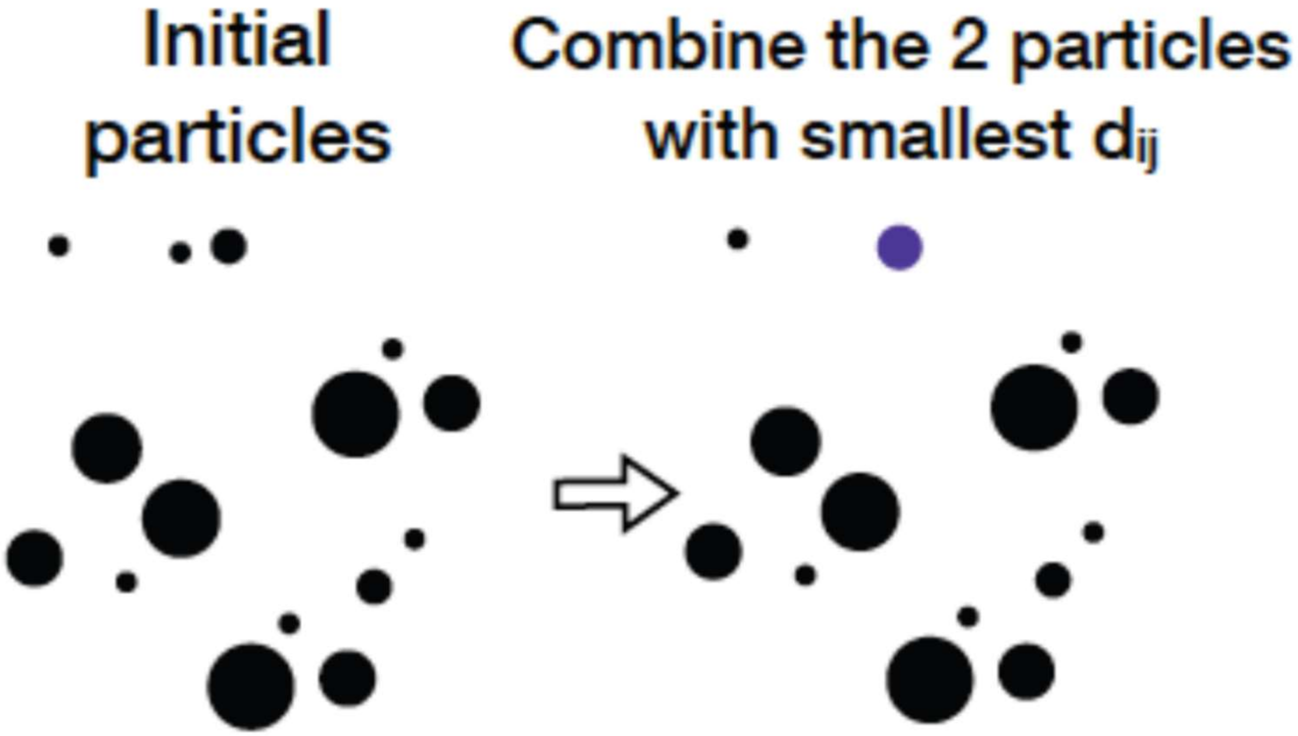
$$d_{iB} = p_{ti}^{2p}$$

$p = 1$ → kt algorithm (KT)

$p = 0$ → Cambridge Aachen algorithm (CA)

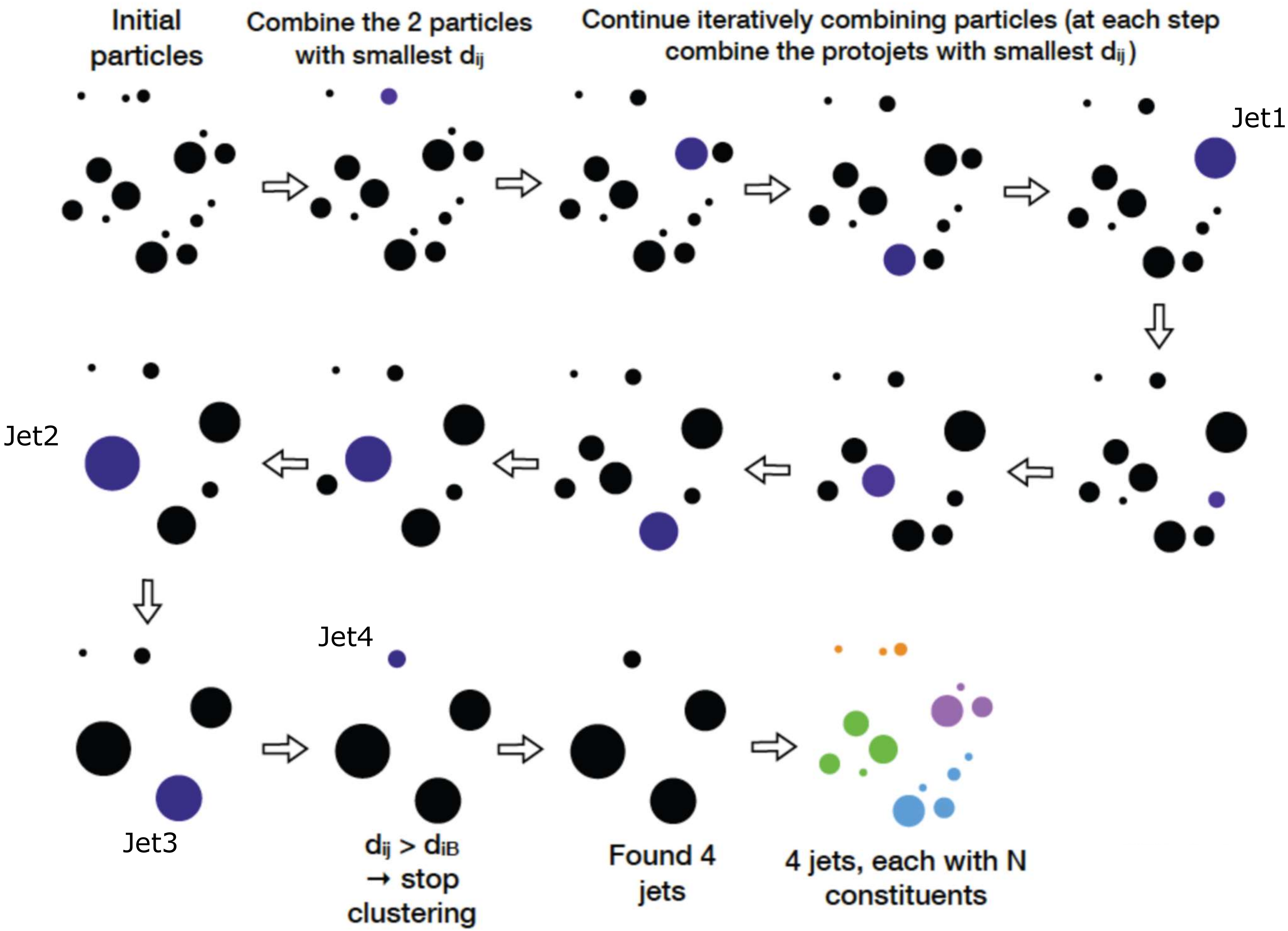
$p = -1$ → anti-kt algorithm (AK)

Jets



Initial particles
Combine the 2 particles with smallest d_{ij}

Jets


Initial particles
Combine the 2 particles with smallest d_ij
Continue iteratively combining particles (at each step combine the protojets with smallest d_ij)
Jet1
Jet2
Jet4
Jet3
d_ij > d_iB → stop clustering
Found 4 jets
4 jets, each with N constituents

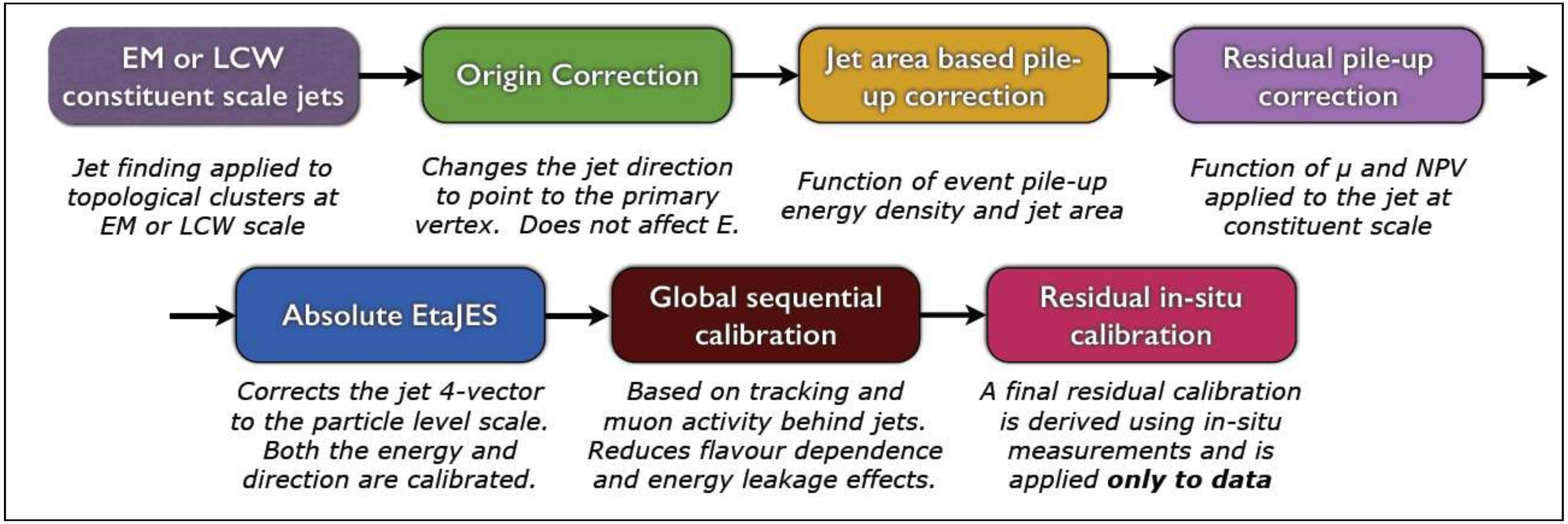
Jets

Why do we calibrate jets?

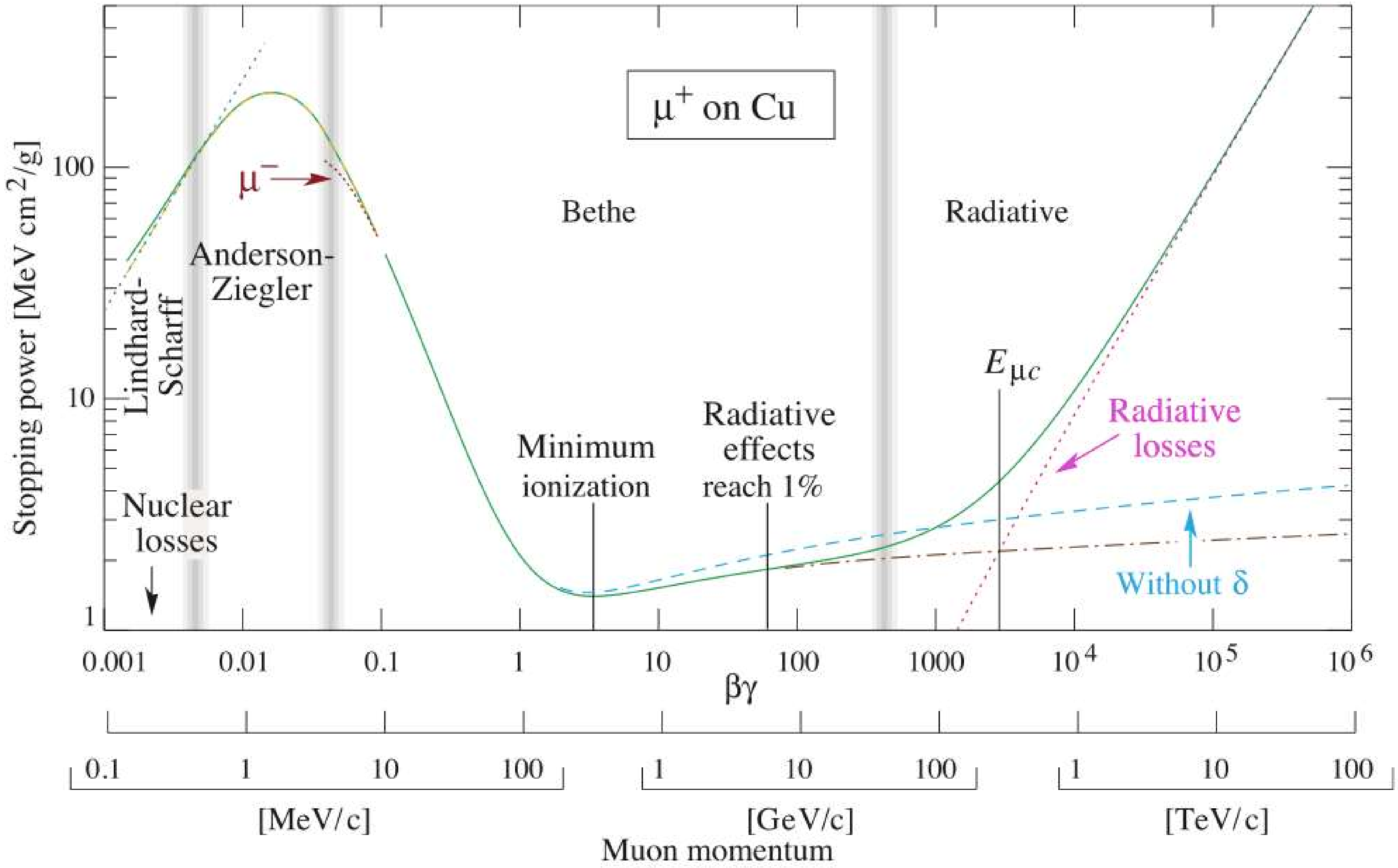
- Calorimeter non-compensation (e/h > 1)
- Dead material: energy deposited in non-instrumented region
- Energy deposits below noise thresholds
- Pile-up
- Lateral leakage: particle shower outside the jet cone
- Longitudinal Leakage: energy deposited beyond the calorimeter region (punch-through)

How do we calibrate jets?

- Want to calibrate the jet energy at the particle level
- A combination of MC and in-situ data techniques employed to calibrate detector signals to physics-level objects



Bethe-Bloch

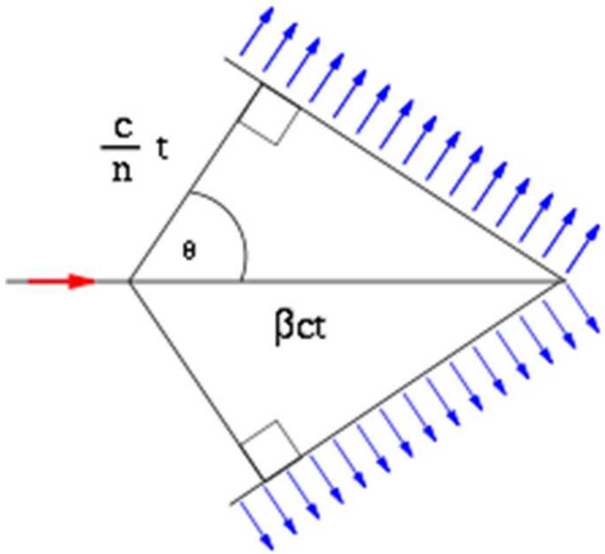


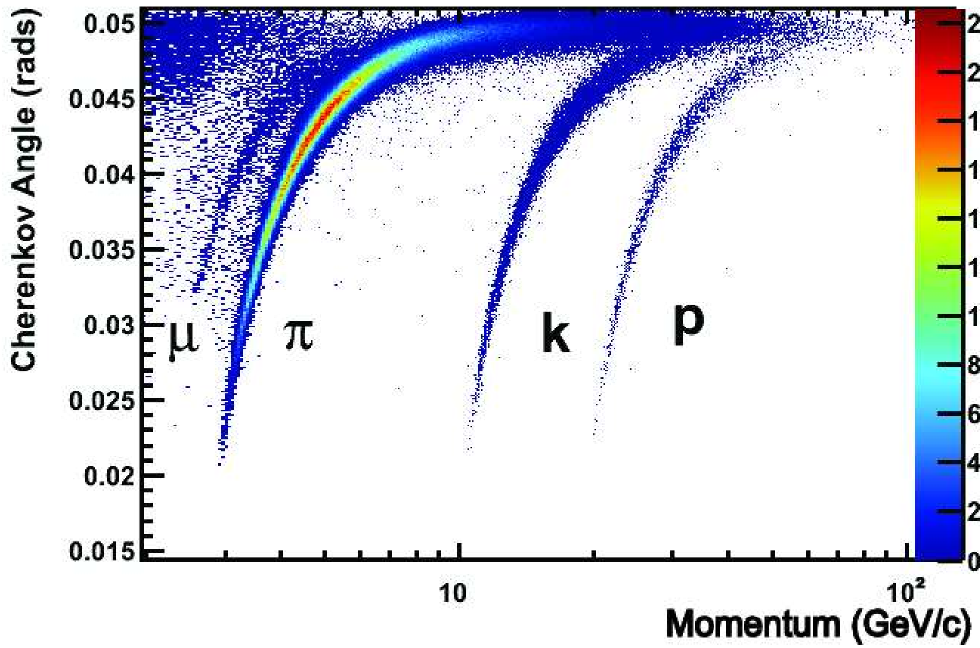
μ⁺ on Cu
Stopping power [MeV cm²/g]
100
10
1
μ⁻
Anderson-Ziegler
Lindhard-Scharff
Nuclear losses
Bethe
Radiative
Minimum ionization
Radiative effects reach 1%
E_μc
Radiative losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10⁴
10⁵
10⁶
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

LHCb: Ring-Imaging CHerenkov detectors

Charged particles faster than light produce cone of Cherenkov photons

$$\cos\theta = \frac{1}{n\beta}$$

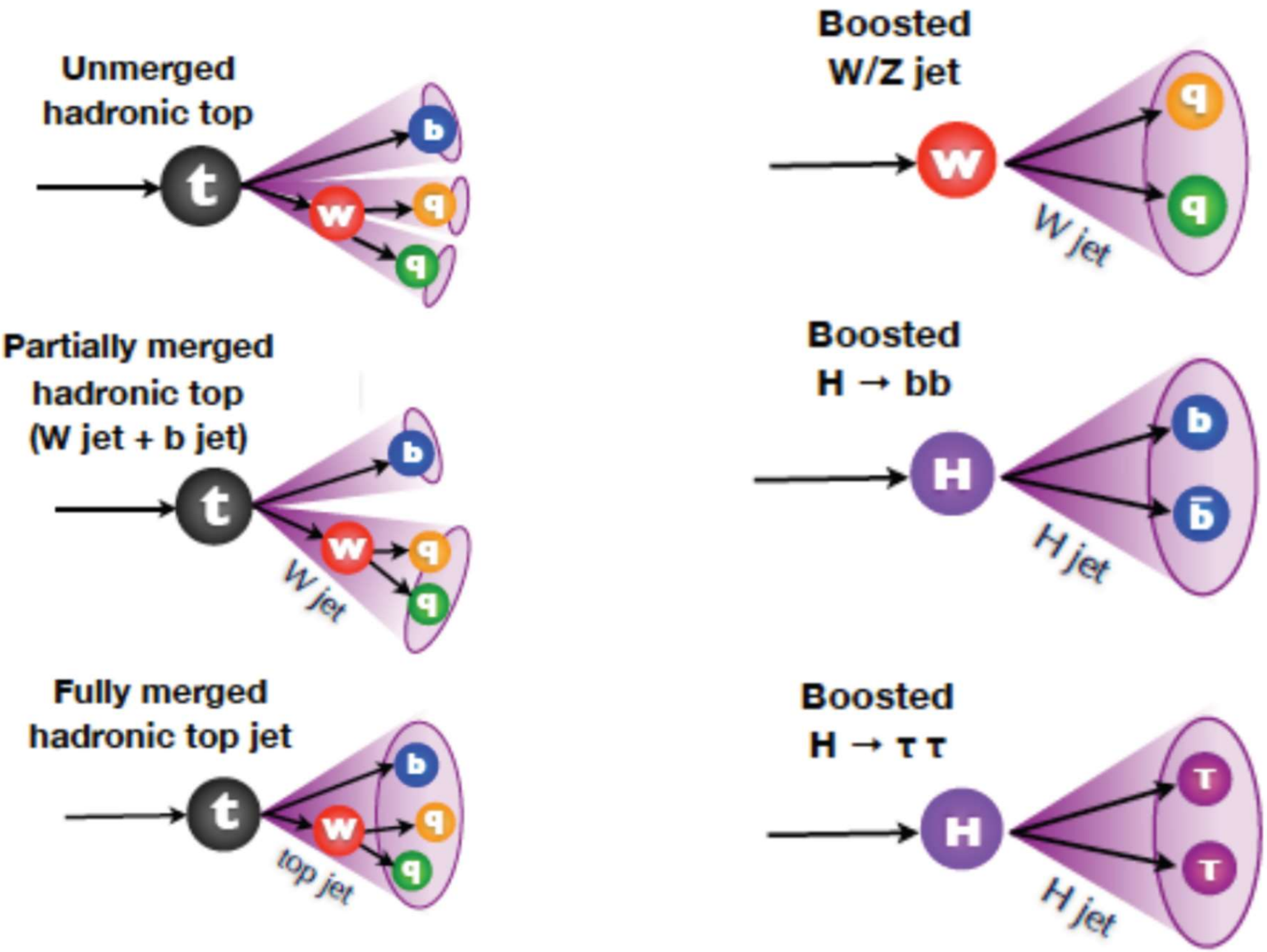




By measuring the track momentum and θ, one can identify the particle type

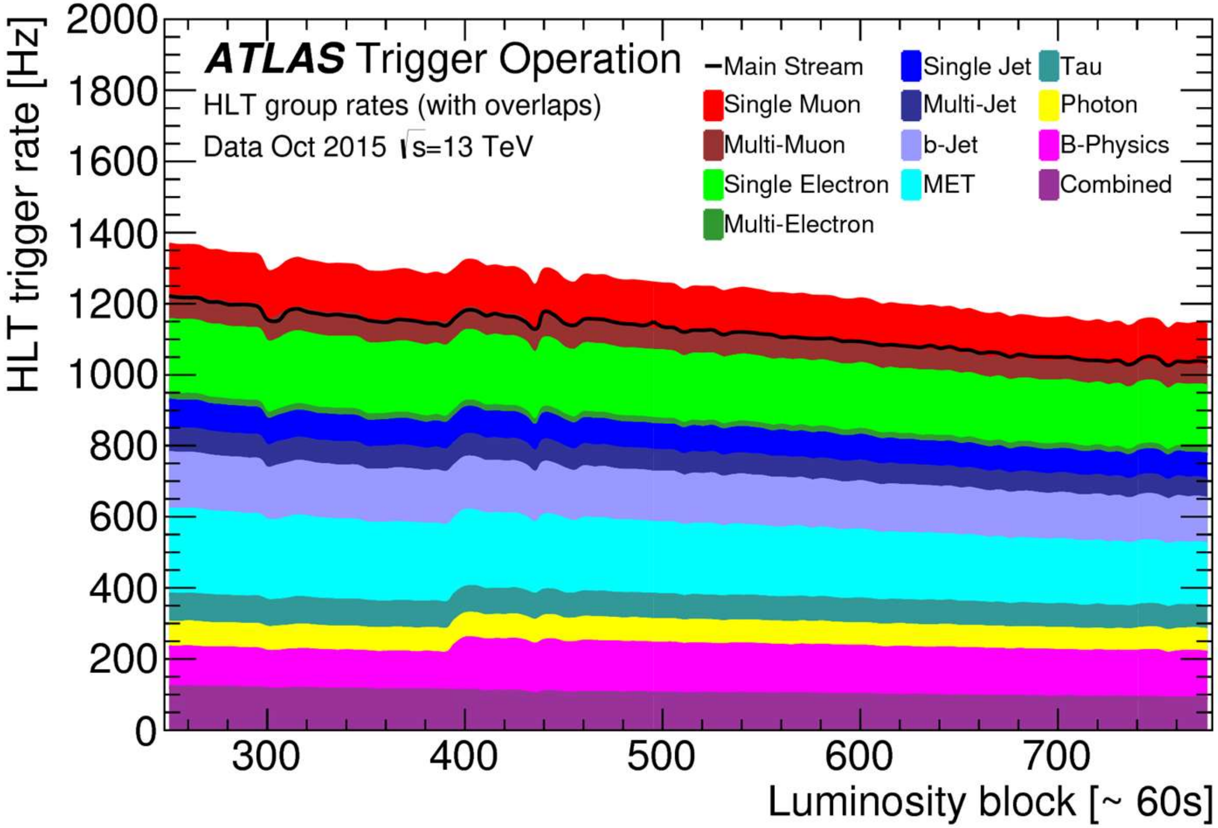
$$p = \gamma m v = mc\frac{\beta}{\sqrt{1-\beta^2}}$$

Boosted unstable particles



Trigger menu

Final state	Thres.
Single electron	26GeV(i)
Di-electron	17GeV
Photon	140GeV
Single muon	26GeV(i)
Di-muon	14GeV
Single tau	160GeV
Single jet	420GeV
Tri-jet	200GeV
MET	110GeV



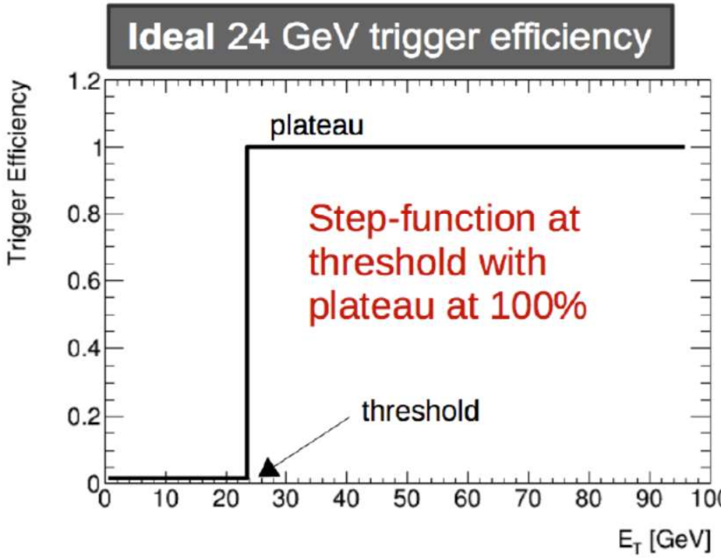
Events rejected by the trigger are lost forever

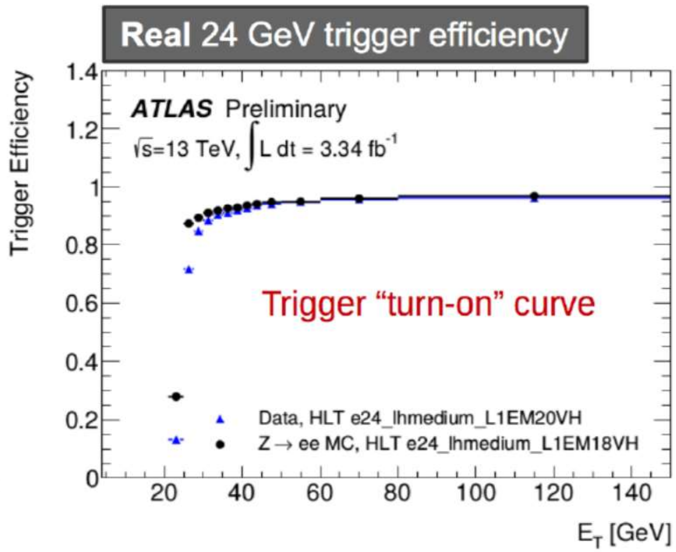
Trigger: analyser point of view

Three Main Things

- Where is the trigger **turn-on**?
  - Where does the trigger reach **maximal** efficiency w.r.t. offline objects?
- What is the **peak** efficiency?
  - Is it 100%? Or do you need a **scale factor**?
- Is it **prescaled**?
  - Am I getting **all** the events? Or do I have to **correct** for a prescale?

- **Turn on** and **peak** efficiency are a function of:
  - **Resolutions**
  - **Inefficiencies**
  - **Online/Offline** differences

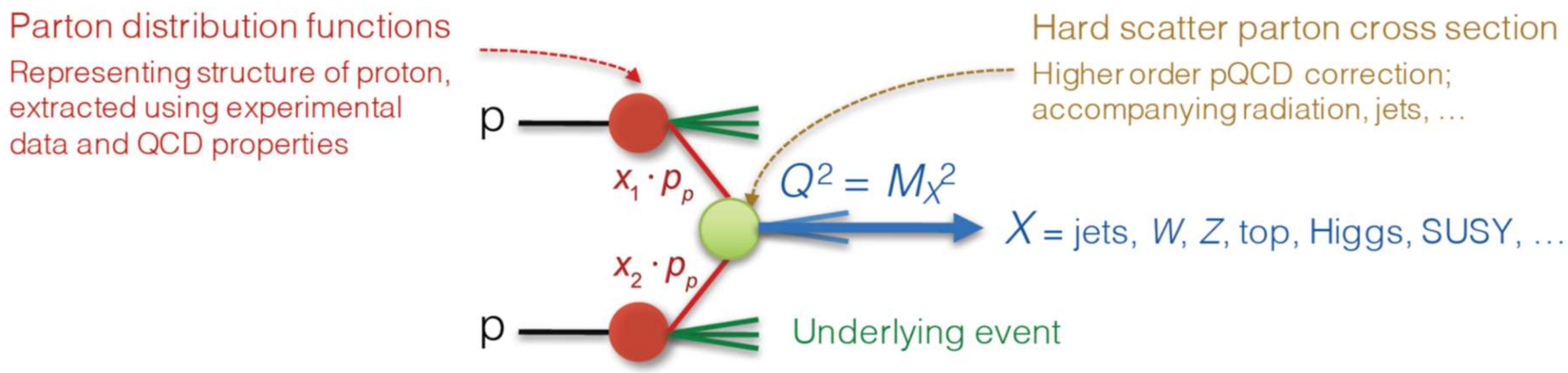




Proton-proton collisions

For proton–proton collisions, phenomena at different energy scales factorize

A hard scattering collision, can be viewed at first order as the interaction between two partons of each proton each carrying a fraction x_1 and x_2 of the incoming protons



Cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element

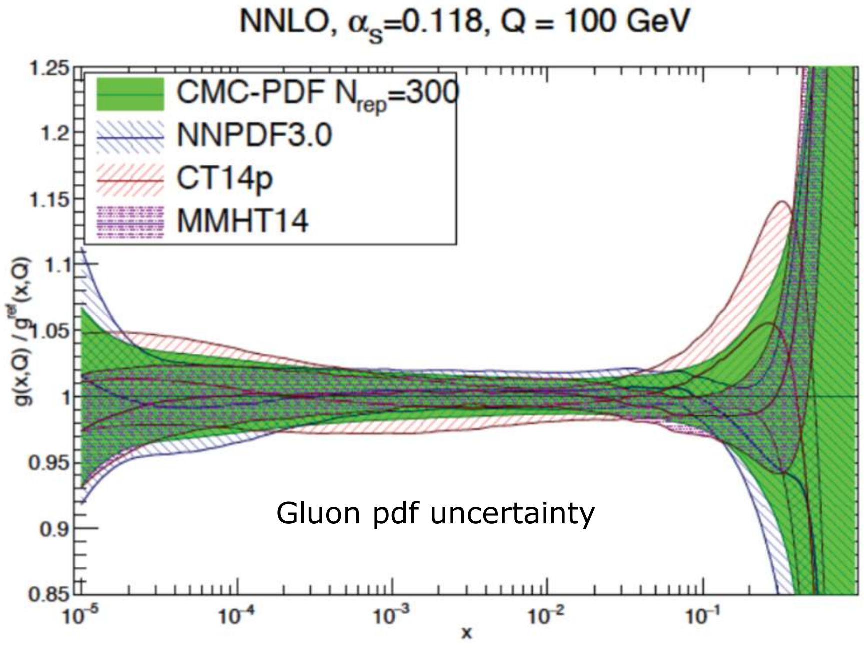
$$\sigma(pp \to X) = \sum_{i,j} \int_0^1 dx_i dx_j f_i(x_i, Q^2) f_j(x_j, Q^2) d\hat{\sigma}(q_i q_j \to X, \hat{s}, Q^2)$$

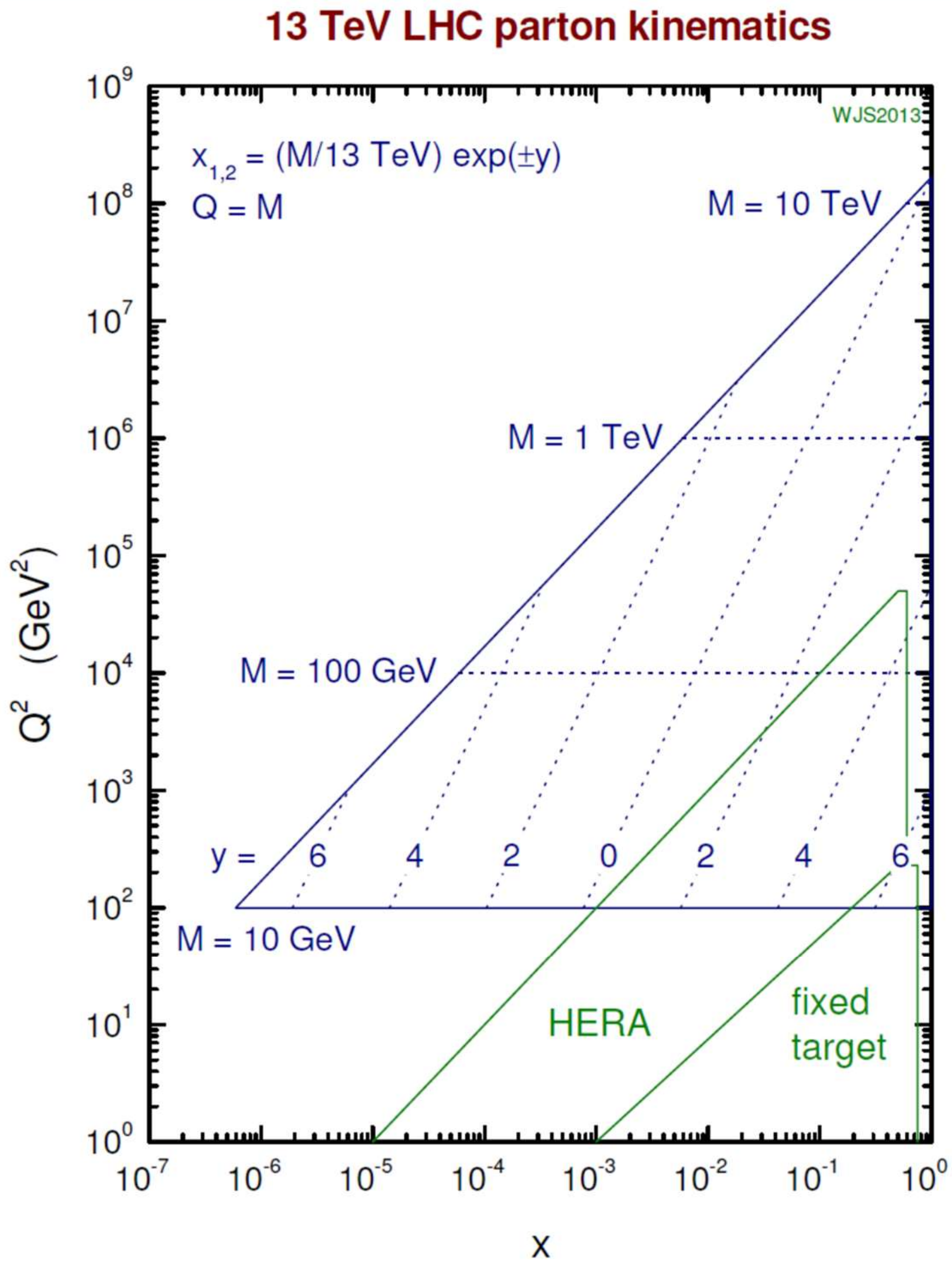
The centre-of-mass energy of the interaction is not known a priori: $\hat{s} = x_1 x_2 s < s$

LHC kinematic regime

$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

At Q~O(TeV) New Physics cross-section predictions dominated by PDF uncertainties high x





Detector simulation

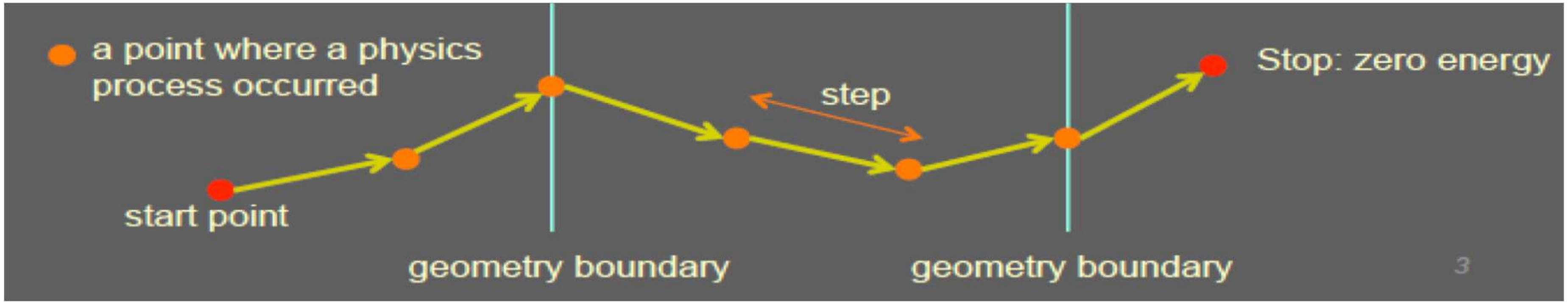
Treat a particle in steps

For each step

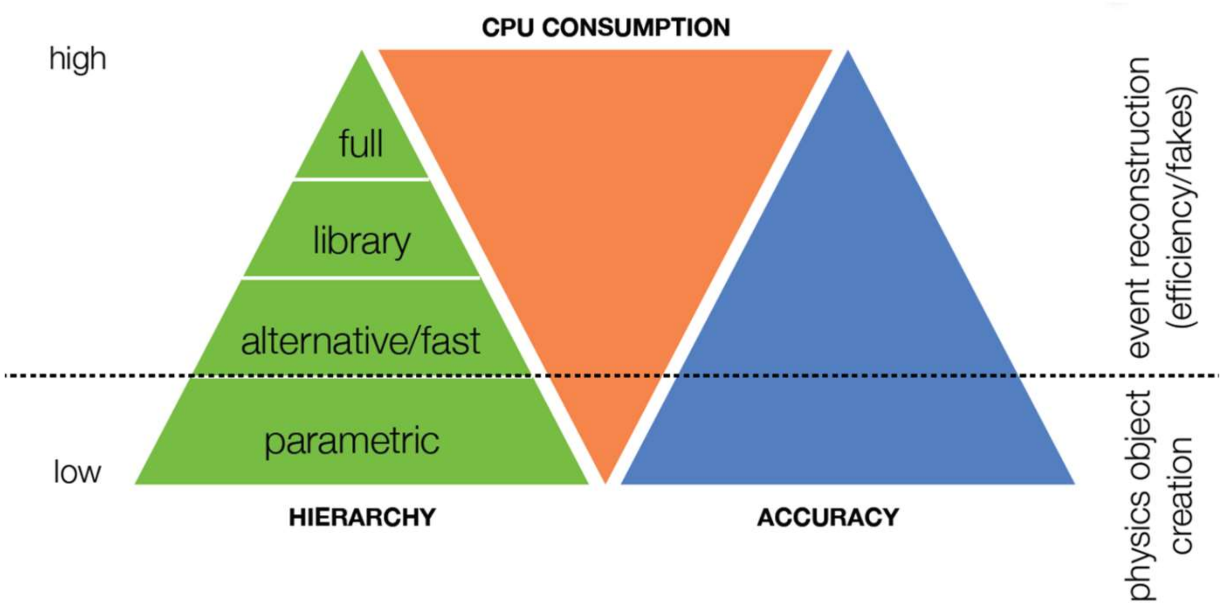
- the step length is determined by the cross sections of the physics processes and the geometrical boundaries; if new particles are created, add them to the list of particles to be transported;
- local energy deposit; effect of magnetic and electric fields;
- if the particle is destroyed by the interaction, or it reaches the end of the apparatus, or its energy is below a (tracking) threshold, then the simulation of this particle is over; else continue with anotherstep.

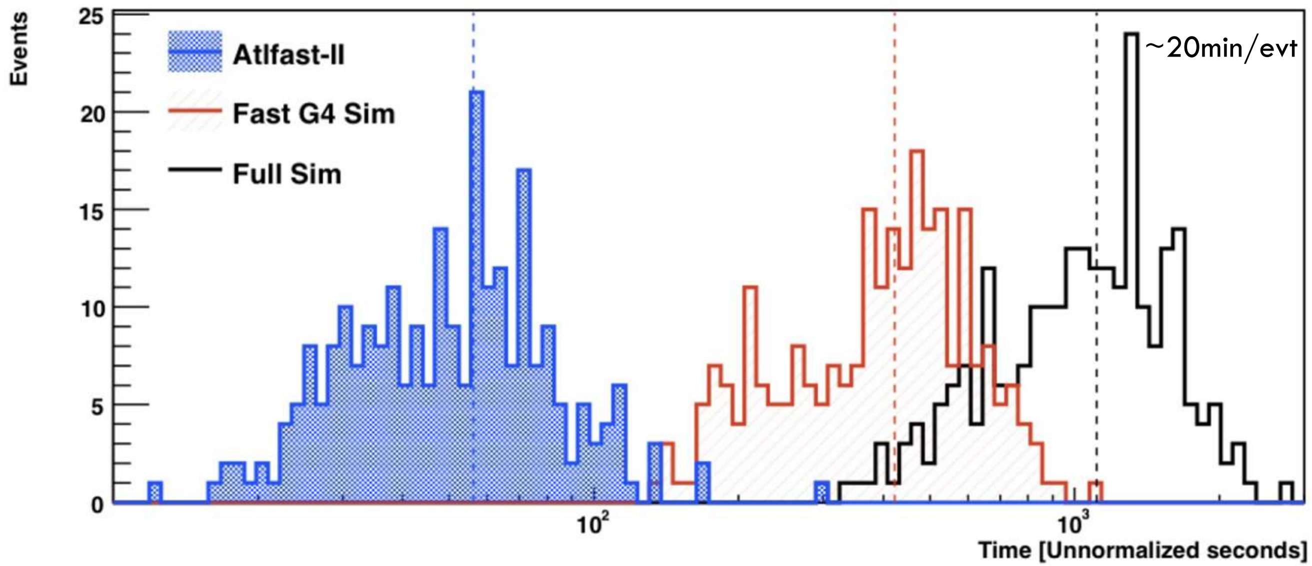
Output

- new particles created (indirect)
- local energy deposits throughout the detector (direct)



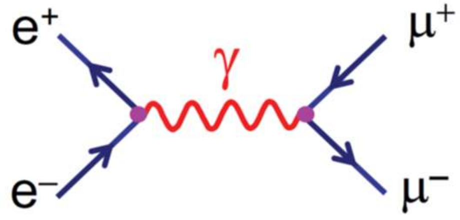
Fast simulation





Generation: a very simple example

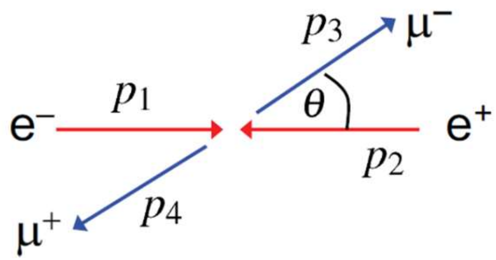
QED process: $e^+e^- \to \mu^+\mu^-$



2 independents variables: θ et φ

Differential cross-section

$$\frac{d\sigma}{d\cos\theta\, d\varphi} = \frac{\alpha_{em}^2}{4s}(1+\cos^2\theta)$$



Total cross-section

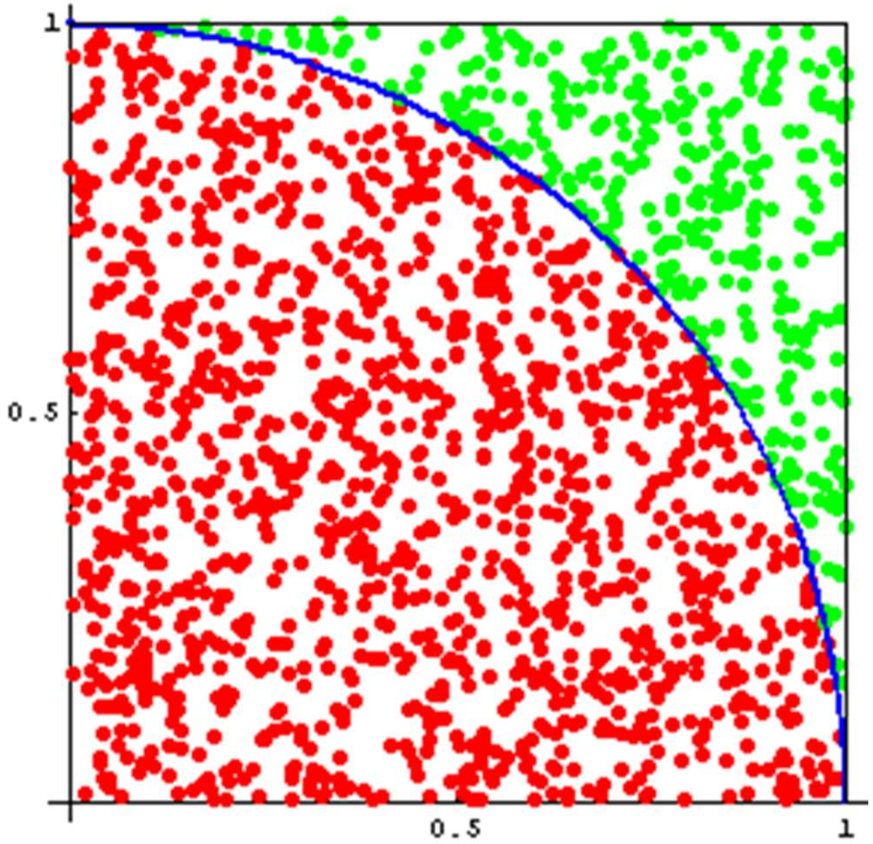
$$\sigma = \frac{\alpha_{em}^2}{4s}\int_{\Omega}(1+\cos^2\theta)d\theta\, d\varphi = \frac{4\pi\alpha_{em}^2}{3s}$$

In most cases, analytical computation are not possible → compute integrals numerically with the Monte Carlo method using pseudorandom numbers and the acceptance–rejection method ('hit or miss')

- Fast convergence in many dimensions

The Monte-Carlo method

How to compute π with random numbers?



$$\hat{\pi} = 4 \frac{N_{red}}{N_{red+green}}$$

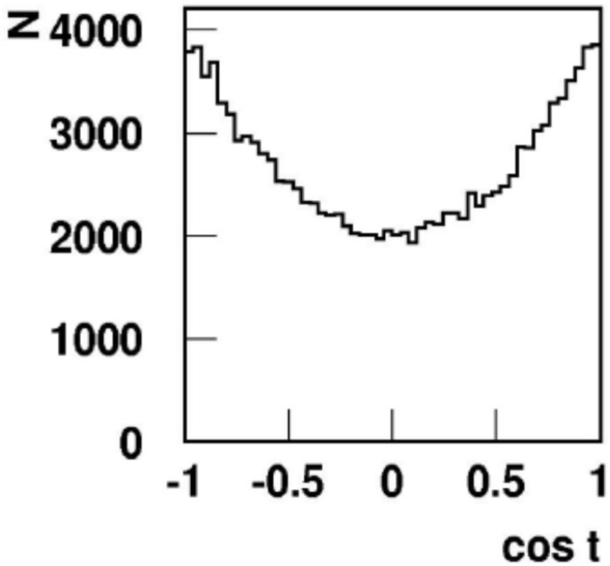
Uncertainty decreases as $1/\sqrt{N}$

Generation: a very simple example

For θ:

$$f(\theta) = 1 + \cos^2\theta$$

Draw 2 random numbers uniformly:
θ between [-1,1]
y_θ between [0,2]
If $y_\theta > f(\theta)$ reject θ otherwise accept θ



For φ:

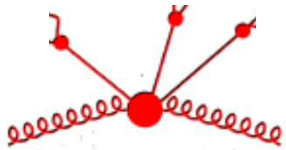
$$f(\varphi) = \text{cte}$$

Draw 1 random number φ uniformly between $[0,2\pi]$

The list of accepted (θ, φ) values allows to build the list of simulated events with average and fluctuations right

Anatomy of proton-proton collisions

At parton level



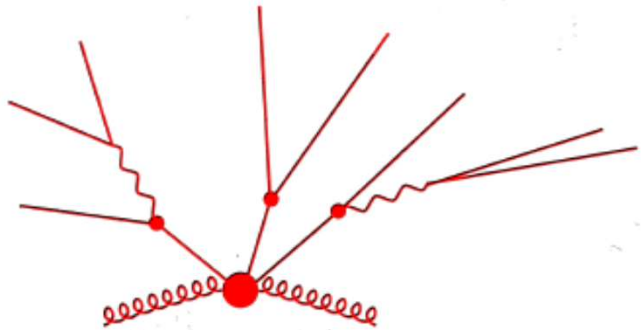
➜ **hard scatter** – matrix elements from first principles

$$\hat{\sigma} = \alpha_S^k \left(\hat{\sigma}^{(0)} + \frac{\alpha_S}{\pi} \hat{\sigma}^{(1)} + \left(\frac{\alpha_S}{\pi} \right)^2 \hat{\sigma}^{(2)} + \ldots \right)$$

By truncating the perturbative series at a fixed order we have introduced a dependence of the cross section on an unphysical renormalisation scale, μ_R

Anatomy of proton-proton collisions

At parton level



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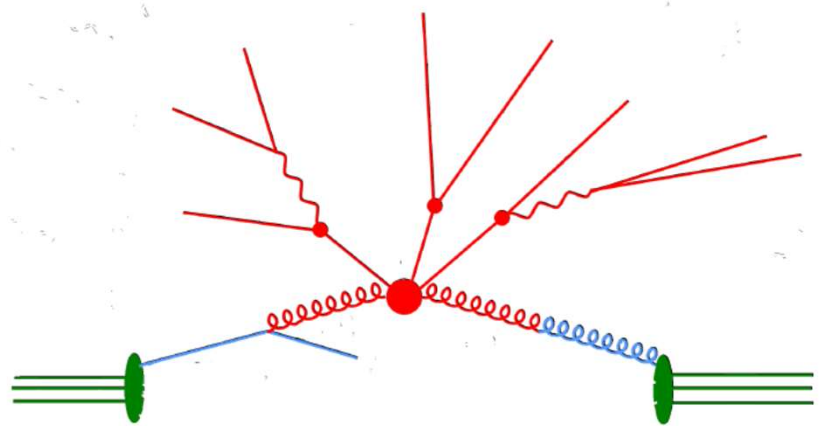
k=2 for dijet production
k=0 for boson production

By truncating the perturbative series at a fixed order we have introduced a dependence of the cross section on an unphysical renormalisation scale, μ_R

Anatomy of proton-proton collisions



- **hard scatter** – matrix elements from first principles
  - incoming partons from parton-distribution functions (PDFs)

Factorization theorem:

$$\sigma(pp \to X) = \sum_{i,j} \int_0^1 dx_i dx_j f_i(x_i, Q^2) f_j(x_j, Q^2) d\hat{\sigma}(q_i q_j \to X, \hat{s}, Q^2)$$

Computed cross-section depends also on an unphysical factorization scale, $Q=\mu_F$

Parton density functions $f(x,Q^2)$

PDFs give the probability to find a parton with a momentum fraction x when probed with energy Q

PDFs are not calculable, but measured in DIS experiments (e.g. HERA) but also at the LHC

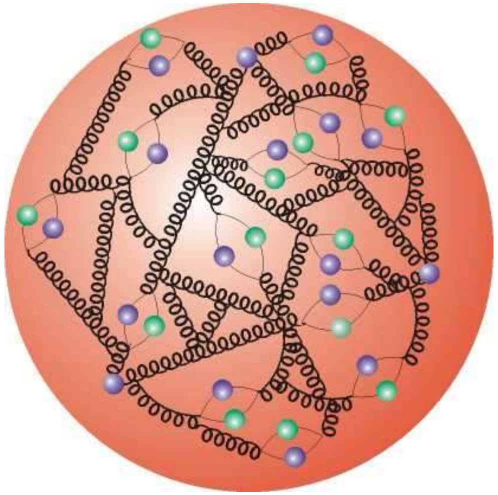
PDFs evolution in Q^2 given are calculable (with DGLAP equations)

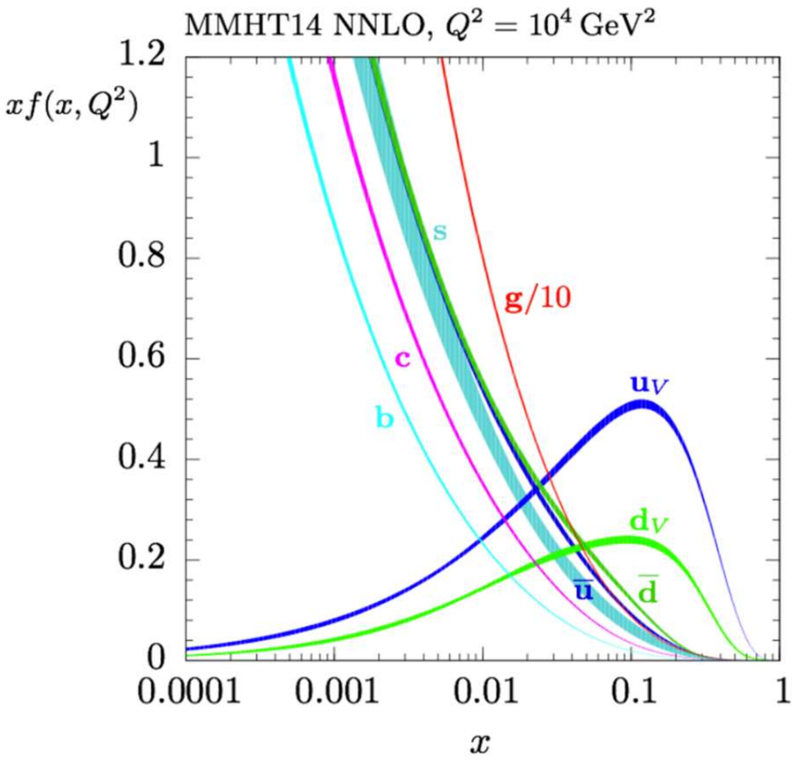
Flavour conservation sum rules:

$$\int_0^1 (f_u(x,Q^2) - f_{\overline{u}}(x,Q^2))dx = 2$$

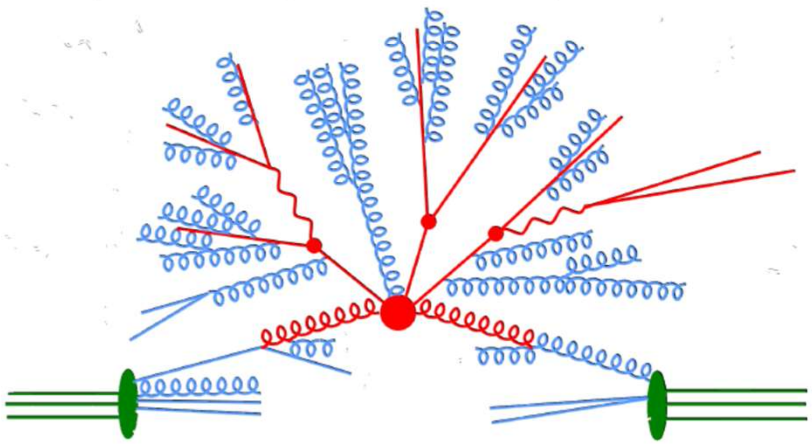
$$\int_0^1 (f_d(x,Q^2) - f_{\overline{d}}(x,Q^2))dx = 1$$

$$\int_0^1 (f_s(x,Q^2) - f_{\overline{s}}(x,Q^2))dx = 0$$



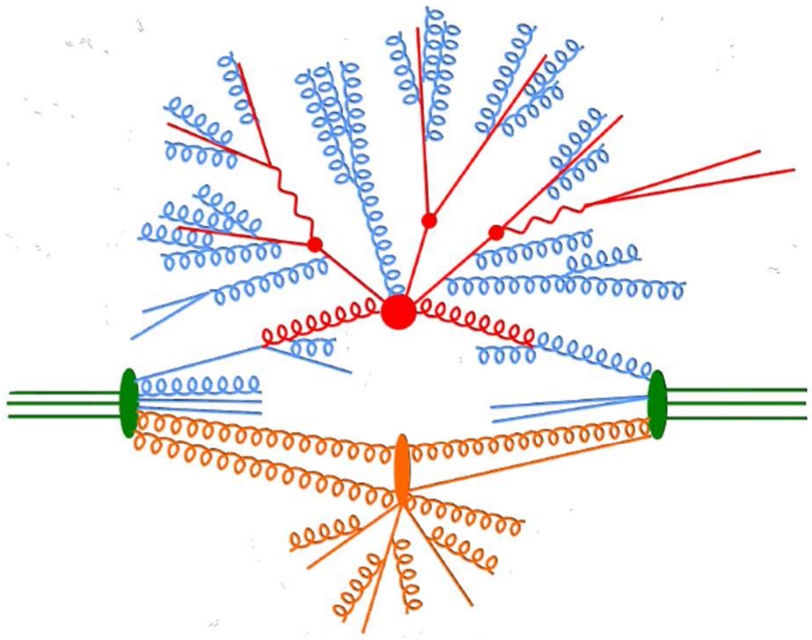


Anatomy of proton-proton collisions



- **hard scatter** – matrix elements from first principles
  - incoming partons from parton-distribution functions (PDFs)
- **radiative corrections** – resumming logarithms to all orders (parton showers)

Anatomy of proton-proton collisions



- **hard scatter** – matrix elements from first principles
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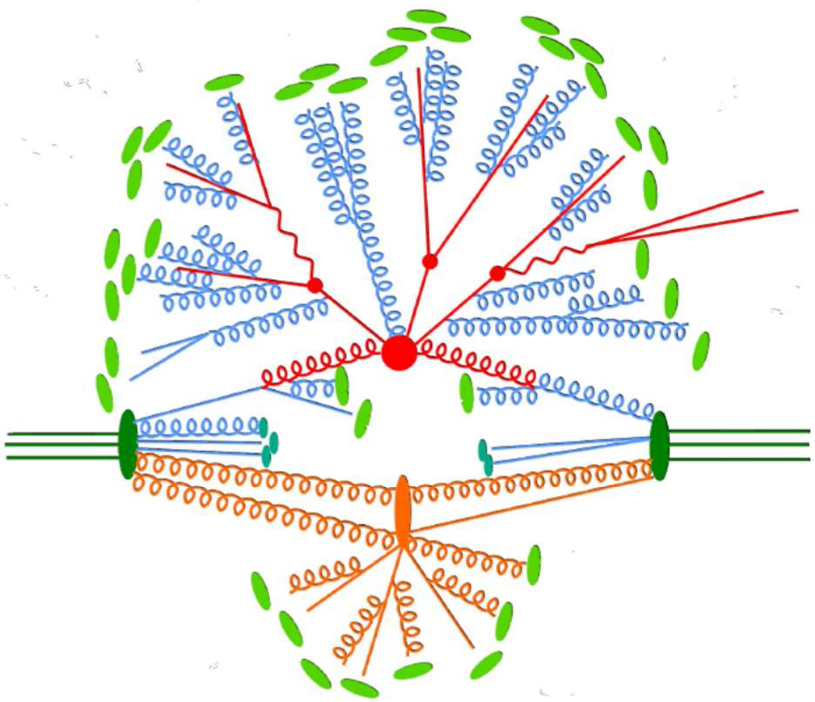
- **multiple parton interactions** – additional interactions between proton remnants

Anatomy of proton-proton collisions



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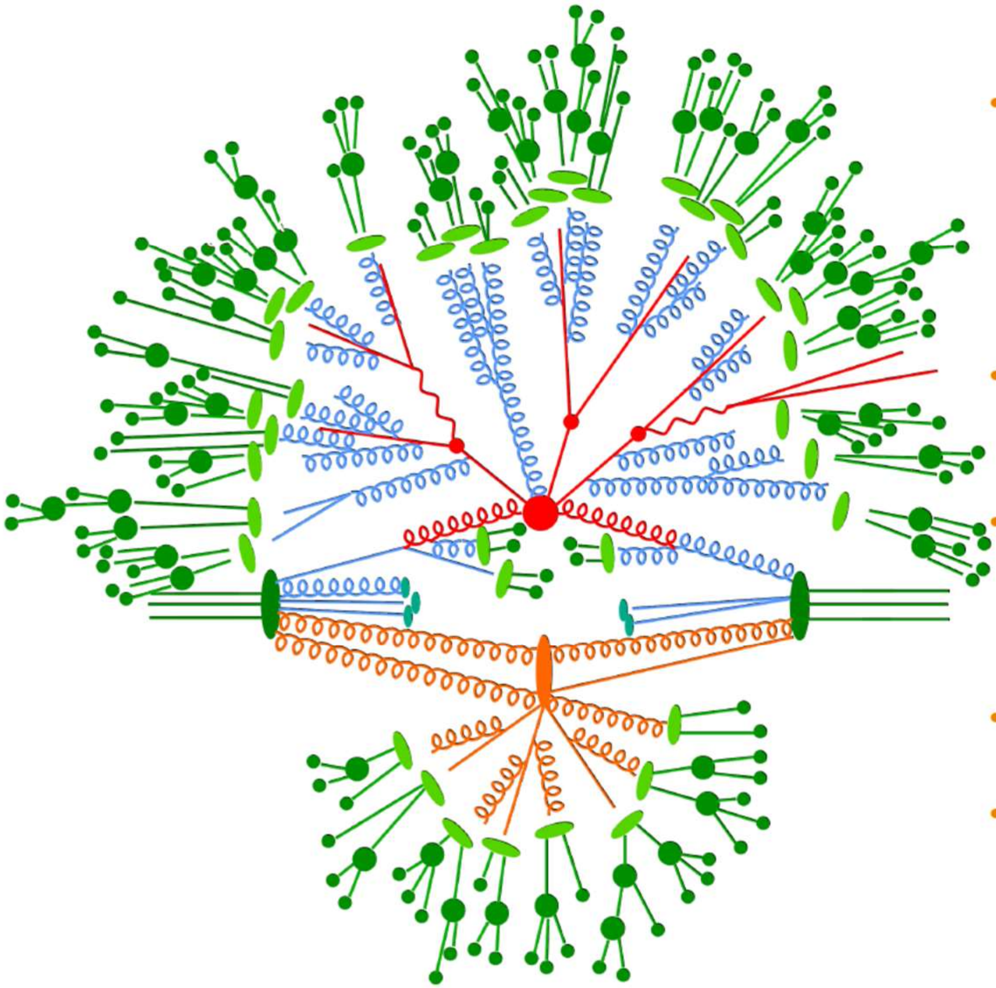
- **hadronisation** – going colourless

Anatomy of proton-proton collisions



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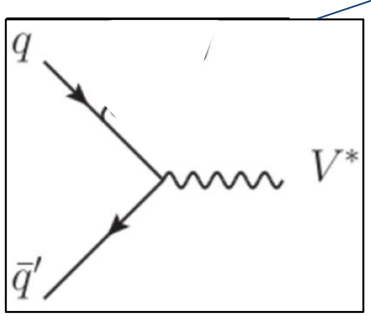
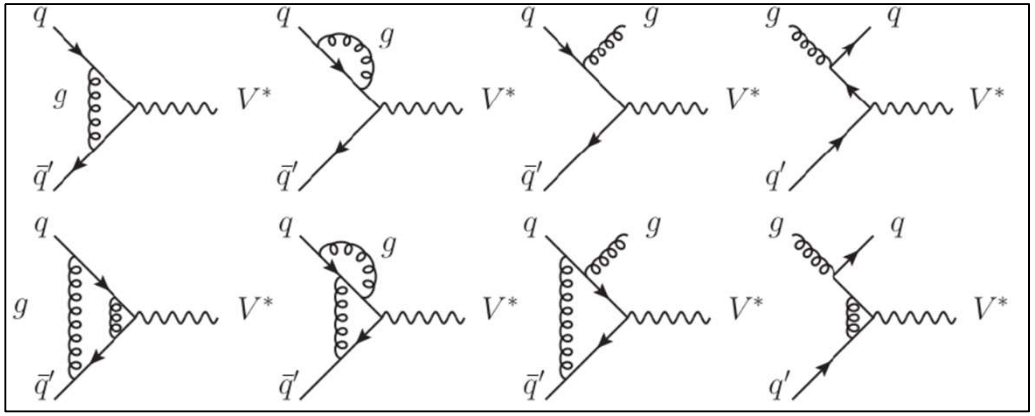
  - incoming partons from parton-distribution functions (PDFs)
- **radiative corrections** – resumming logarithms to all orders
- **multiple parton interactions** – additional interactions between proton remnants
- **hadronisation** – going colourless
- **hadron decays** – from excited states to final-state particles

$Z/\gamma^* \rightarrow \ell^+\ell^-$ production cross-section: theory comparison

$$\sigma_{AB} = \int dx_a dx_b\, f_{a/A}(x_a, \mu_F^2)\, f_{b/B}(x_b, \mu_F^2) \;\times\; [\, \hat{\sigma}_0 + \alpha_S(\mu_R^2)\, \hat{\sigma}_1 + \ldots]_{ab \to X}$$



LO



QCD NLO

Current best knowledge: NNLO QCD and NLO EW