Electroweak Physics at the LHC
– Introductory Lecture –

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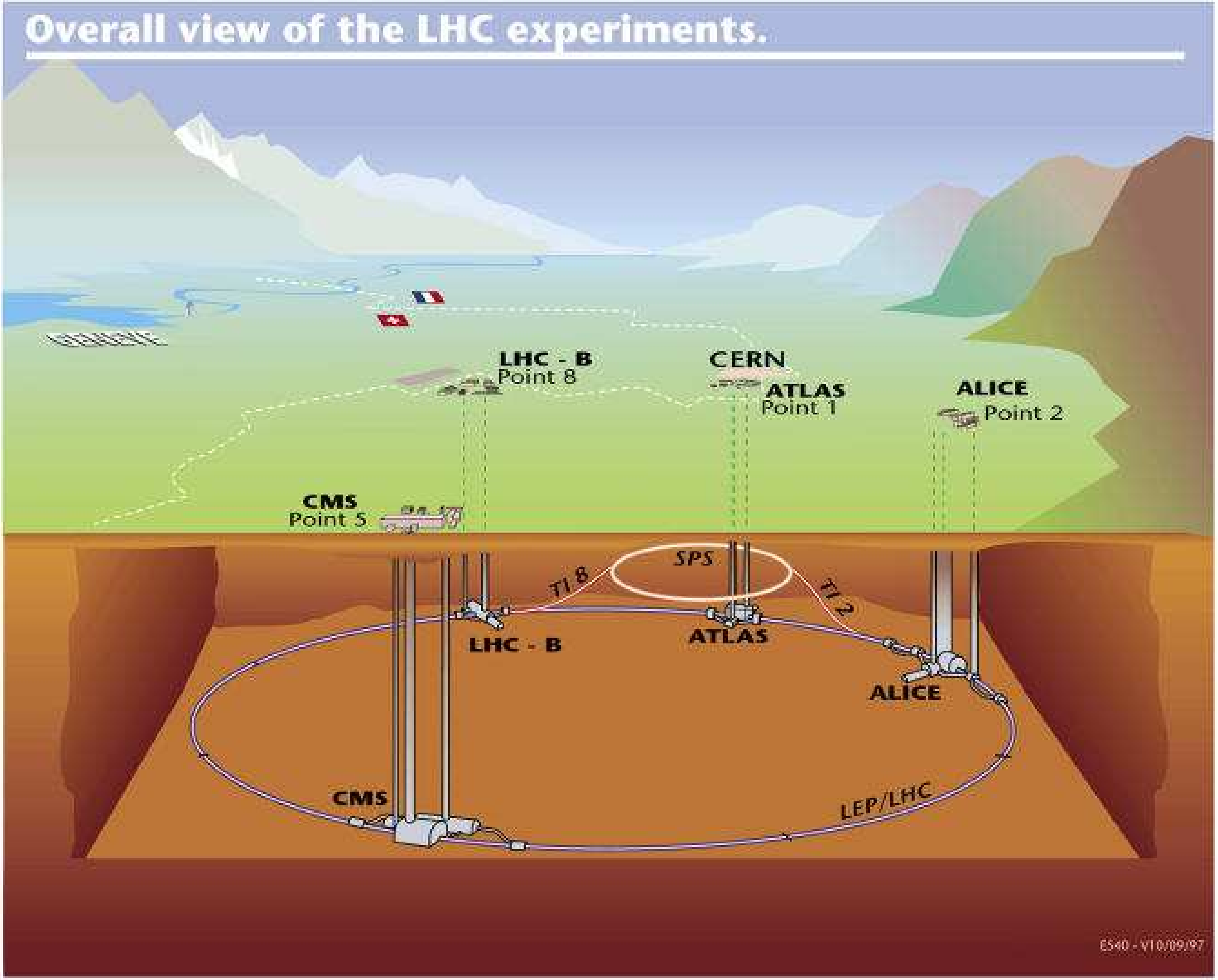
1 The Large Hadron Collider (LHC) – the world largest particle accelerator


Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

Some facts about the LHC:

- Planned startup: May 2008 (CERN Council, June '07)

  After accumulated delay in LHC installation, the originally planned low-energy run is dropped.

- Accelerator: circumference $= 27\,\mathrm{km}$
  2 beam pipes in "2 in 1 magnet design"

- Magnets: 1232 superconducting dipole magnets
  (length $14\,\mathrm{m}$, operating at $B = 8\,\mathrm{T}$, $T = 1.9\,\mathrm{K}$)

- Beams: two proton beams with energy $E_{\mathrm{beam}} = 7\,\mathrm{TeV} = 7000\,\mathrm{GeV}$,
  energy per beam up to $360\,\mathrm{MJ}$

  for comparison:

  $1\,\mathrm{TeV} \approx 1000 \times m_{\mathrm{p}}$ $\sim$ energy of motion of a flying mosquito

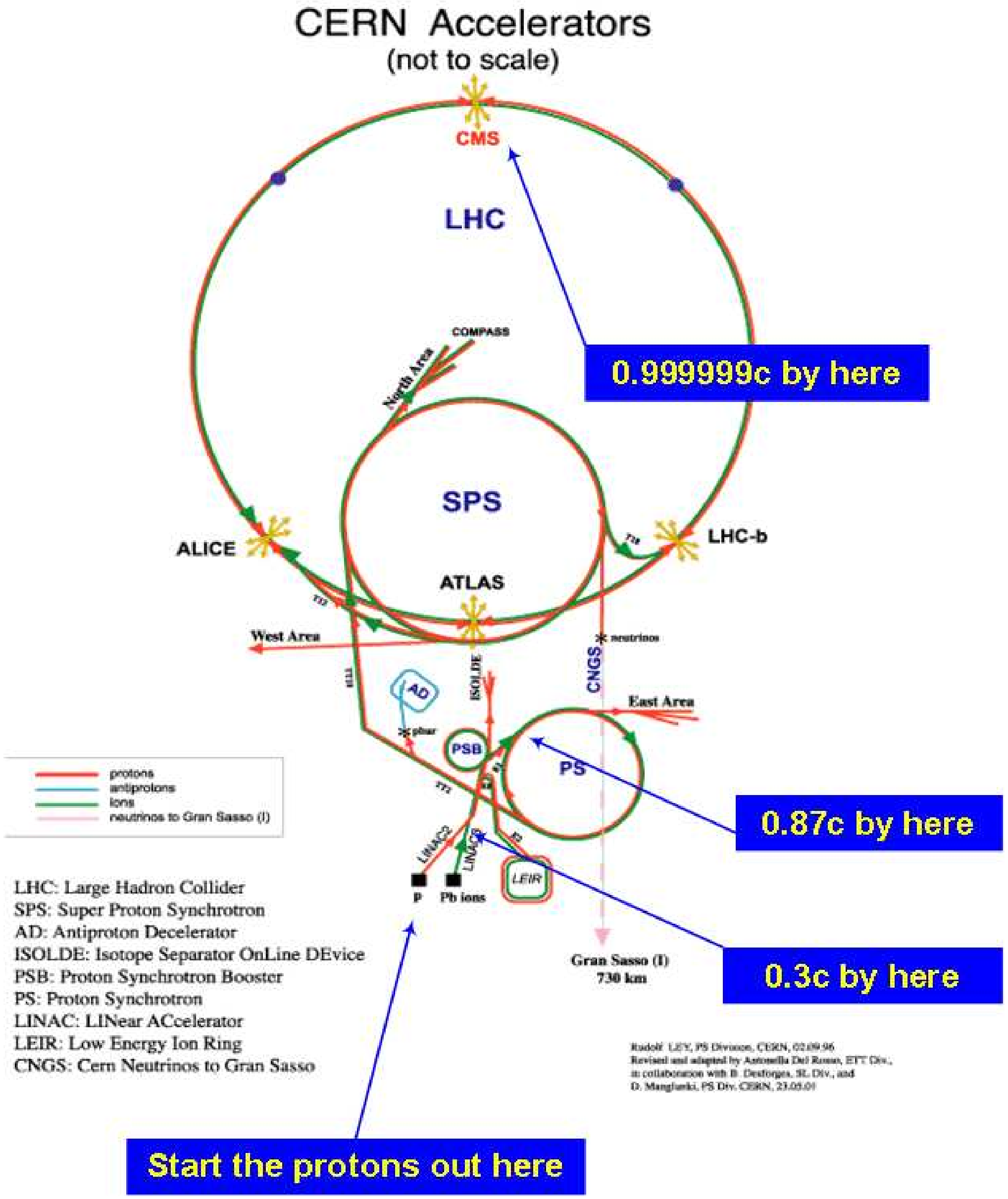
  $360\,\mathrm{MJ}$ $\sim$ energy of motion of an aircraft carrier at $12\,\mathrm{knots}$

- Bunches: 2808 bunches per beam, 10^{11} protons per bunch,
  beam size of $16\,\mu\mathrm{m}$ at IP

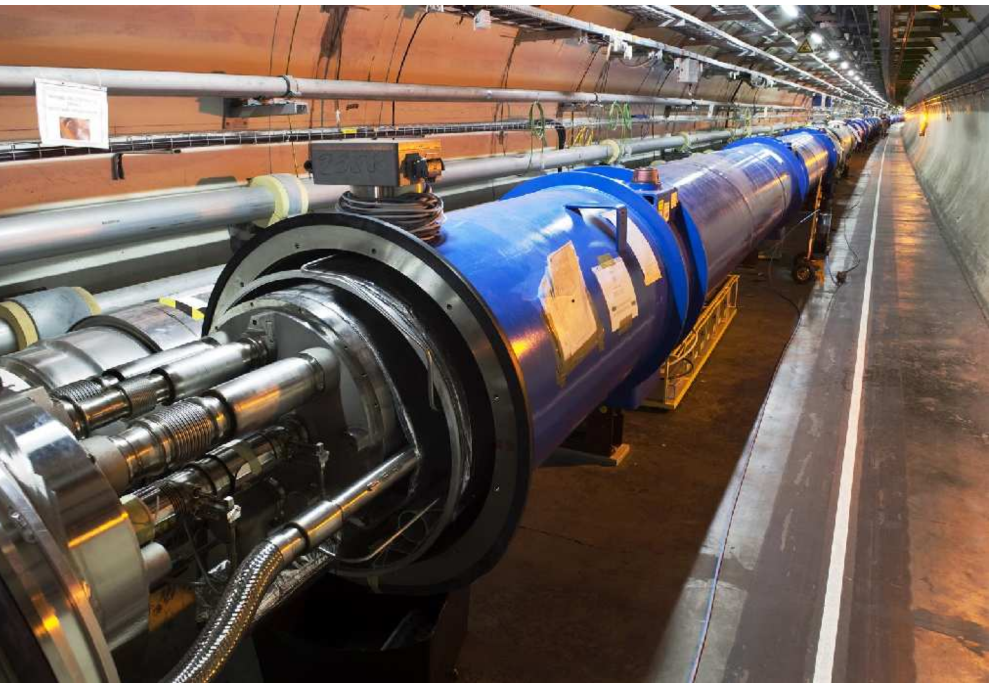
- Luminosity: $L \sim 100\,\mathrm{fb}^{-1}$ / exp. / year

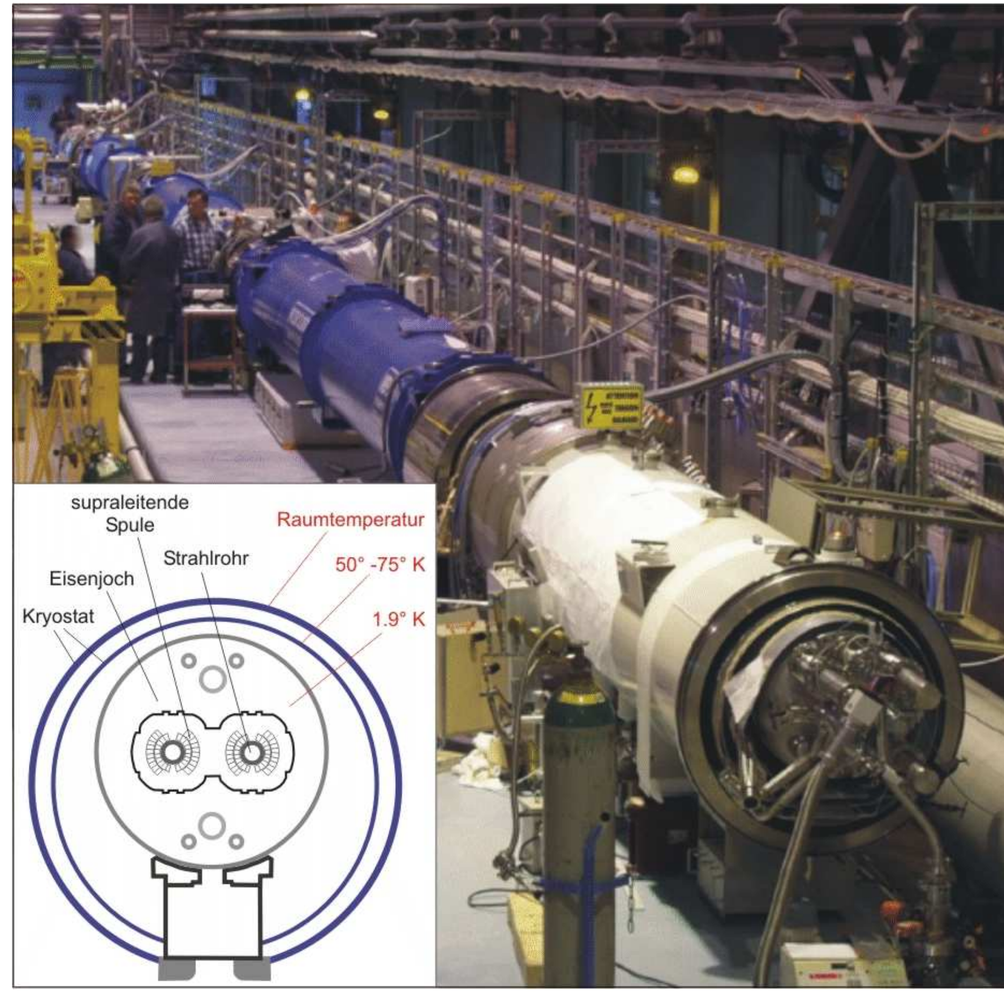
- Trigger: $\sim 10^9$ collisions$/s$ $\underset{\text{online}}{\longrightarrow}$ $\sim 10^2$ interesting collisions$/s$
  $\hookrightarrow$ offline reconstruction $\rightarrow$ millions of Gbytes / exp. / year

LHC accelerator, beam delivery, and experiments



LHC equipment in real life





Experiments at the LHC:

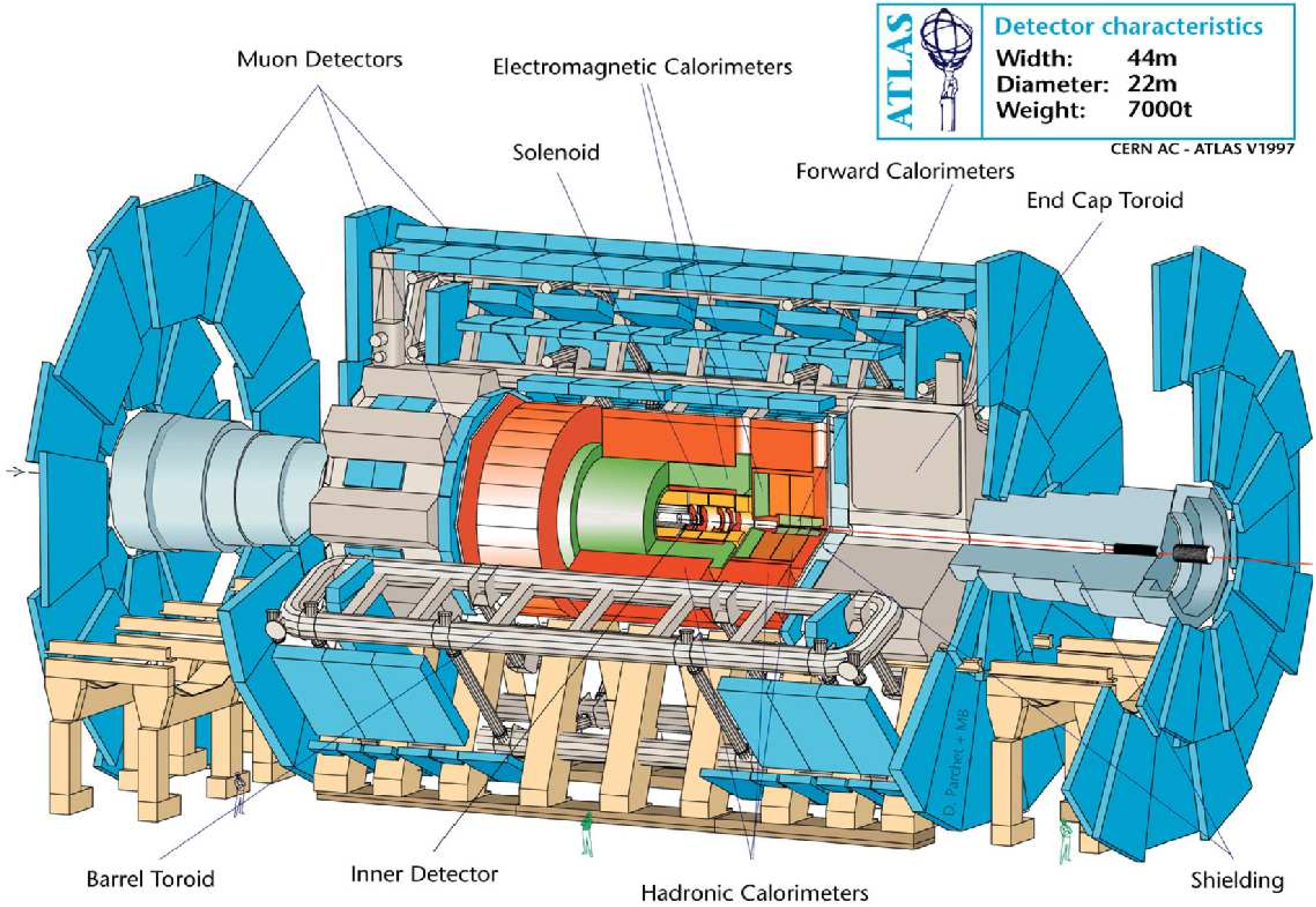
ATLAS	–	A Toroidal LHC ApparatuS
CMS	–	Compact Muon Solenoid
LHCb	–	LHC-beauty
ALICE	–	A Large Ion Collider Experiment
TOTEM	–	Total Cross Section, Elastic Scattering and Diffraction Dissociation
LHCf	–	LHC-forward

ATLAS & CMS (~ 1800 scientists from ~ 150 institutes each)

$\hookrightarrow$ general-purpose experiment for recording proton-proton collisions

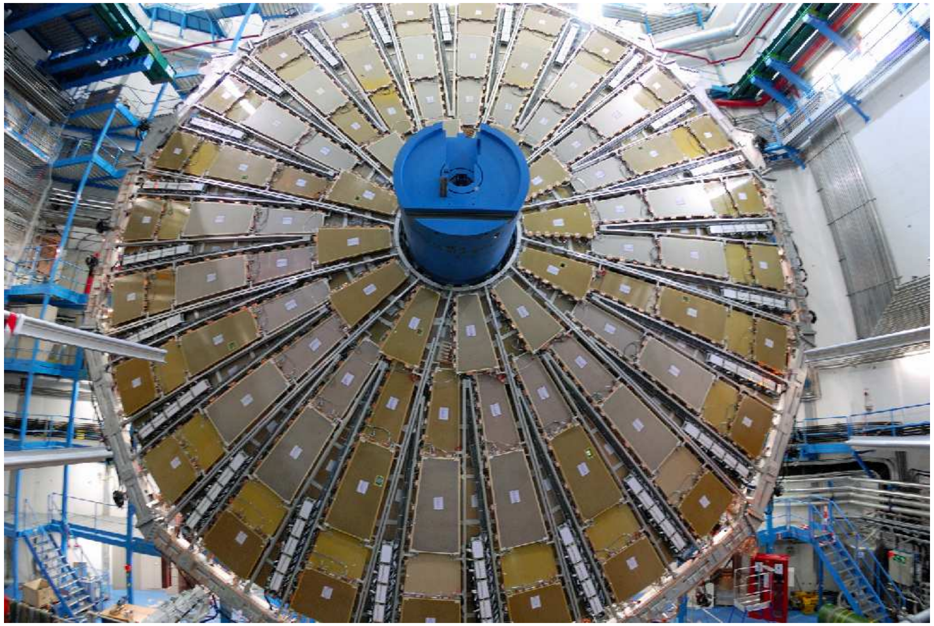
- searches for Higgs bosons and alternative schemes for the spontaneous symmetry-breaking mechanism
- searches for new particles
  (supersymmetric particles, new gauge bosons, leptoquarks, etc.)
- study possible quark and lepton compositeness
- physics of the top quark
- study physics of B mesons (CP violation, rare decays, spectroscopy, mixing)

The ATLAS detector

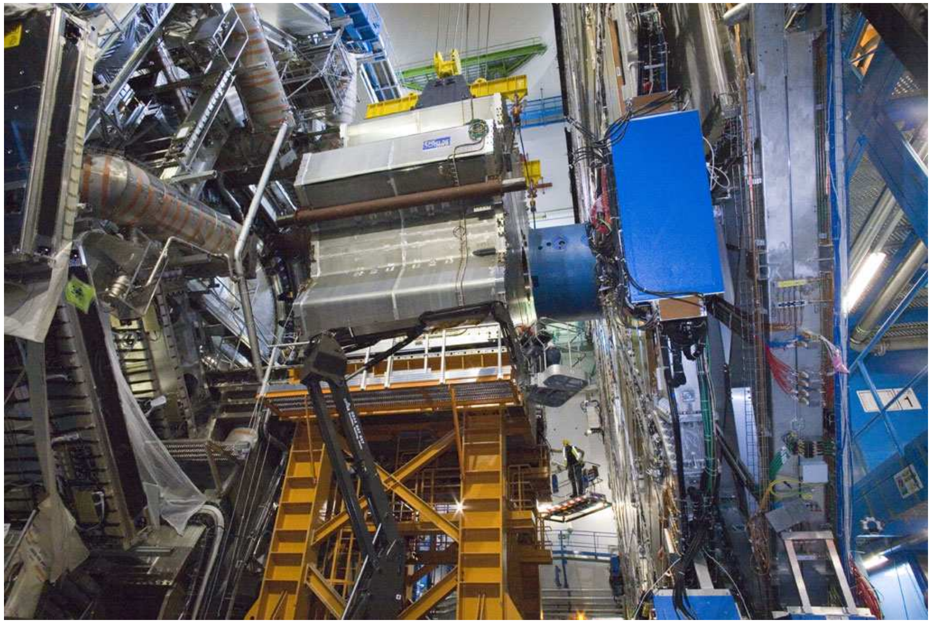


ATLAS in real life

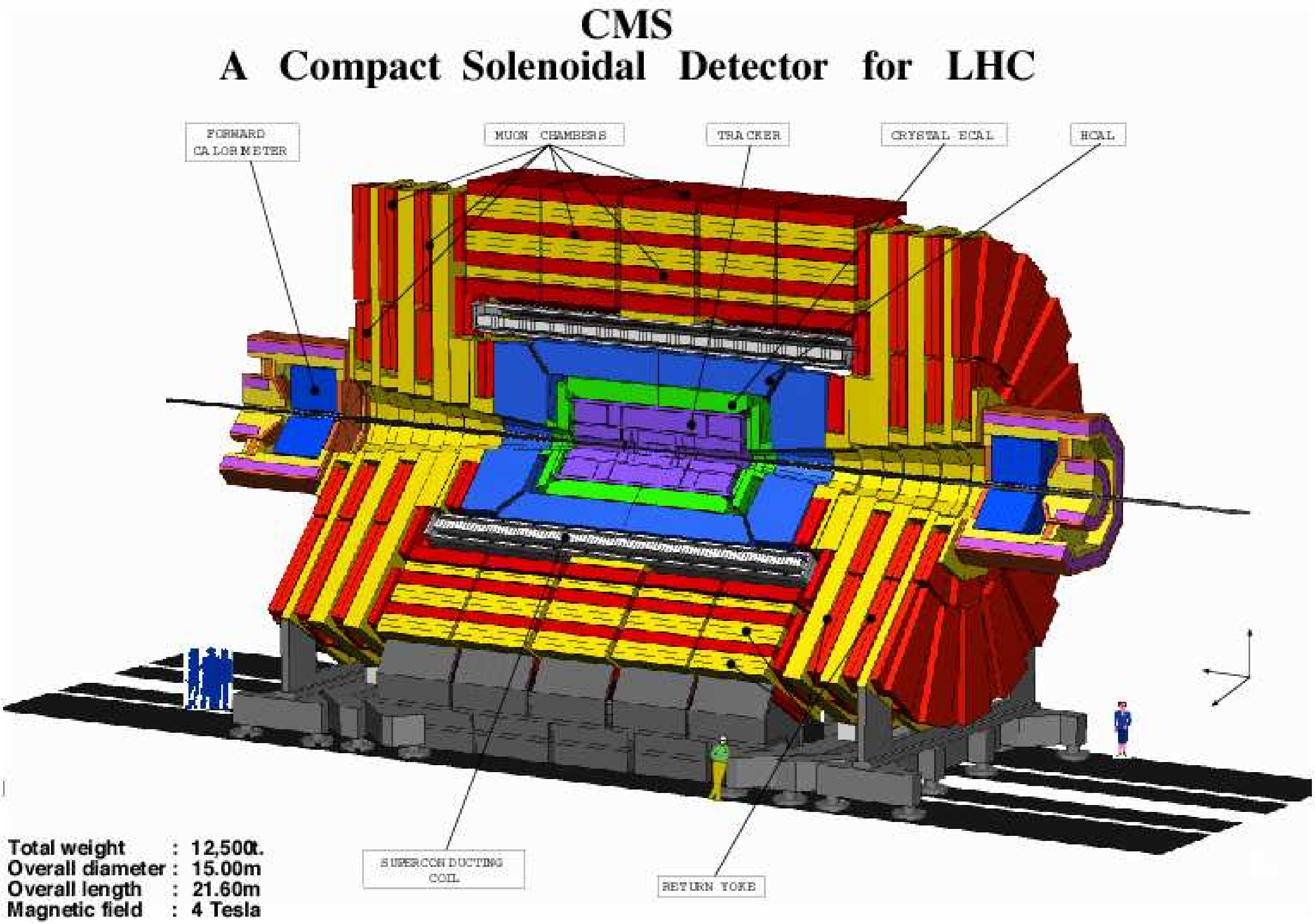
“Wheel” of the muon system



Mounting of the endcap

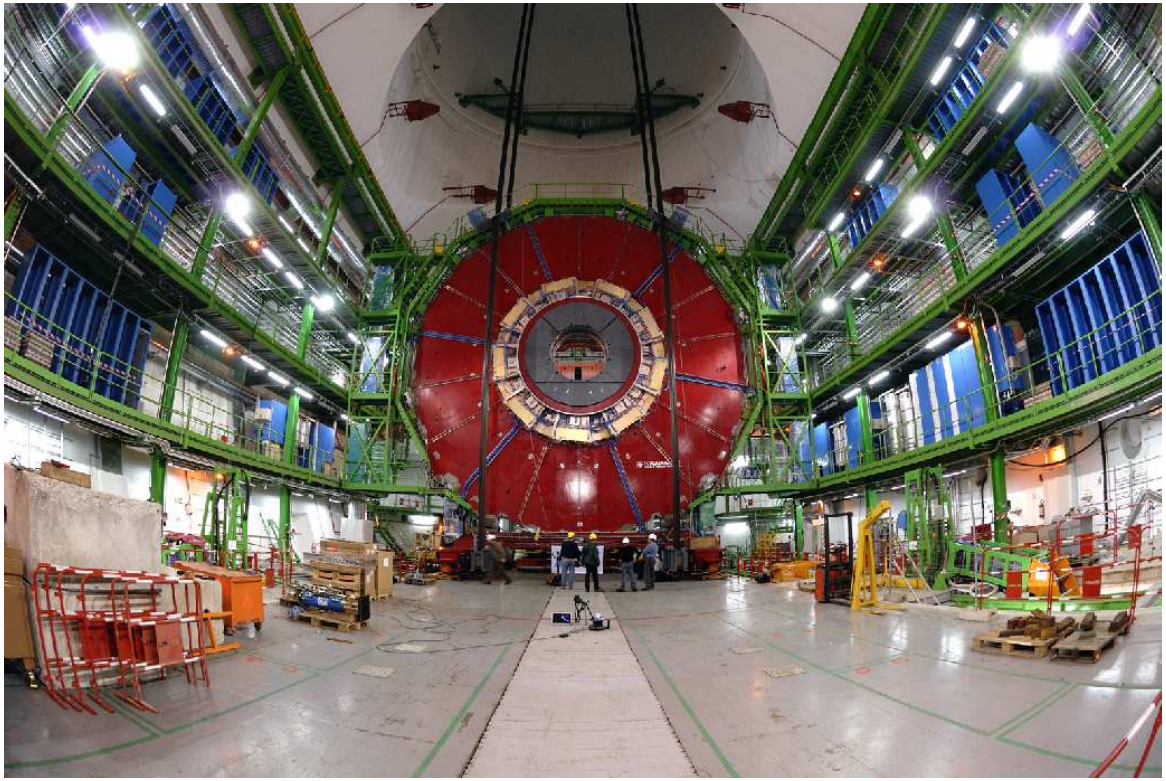


The CMS detector

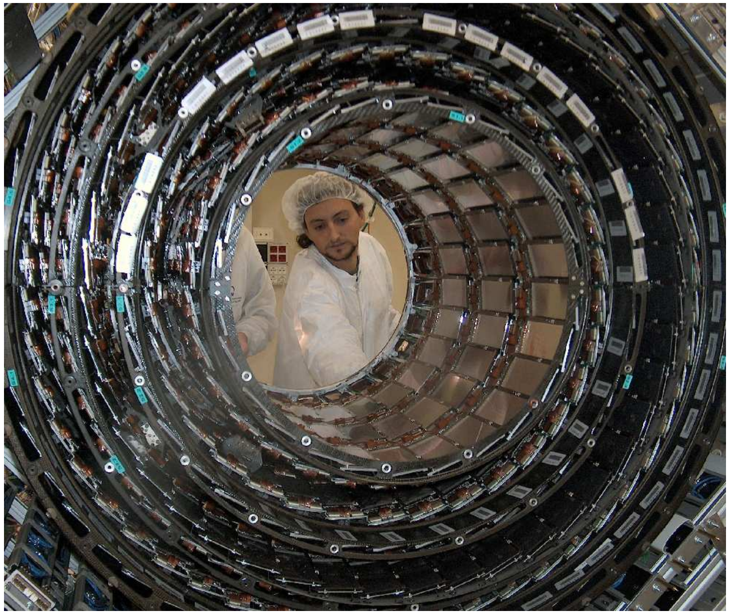


CMS in real life

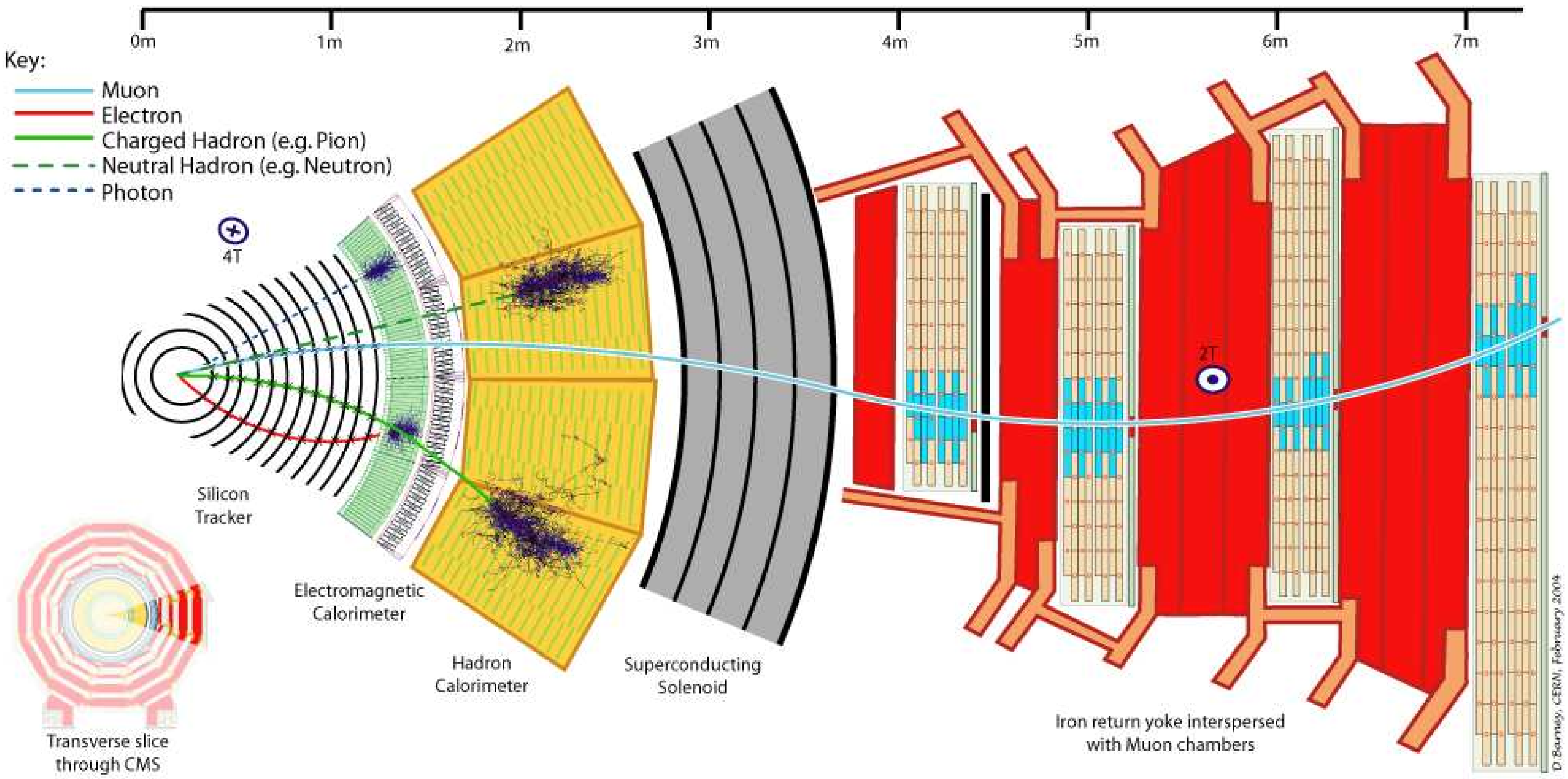
Hadronic calorimeter endcap



Tracking system



Particle detection at CMS



How Higgs production might look at the LHC...

$\mathrm{H} \to \mathrm{ZZ} \to \mu^+\mu^-\mu^+\mu^-$ at CMS (=a “clean” event)

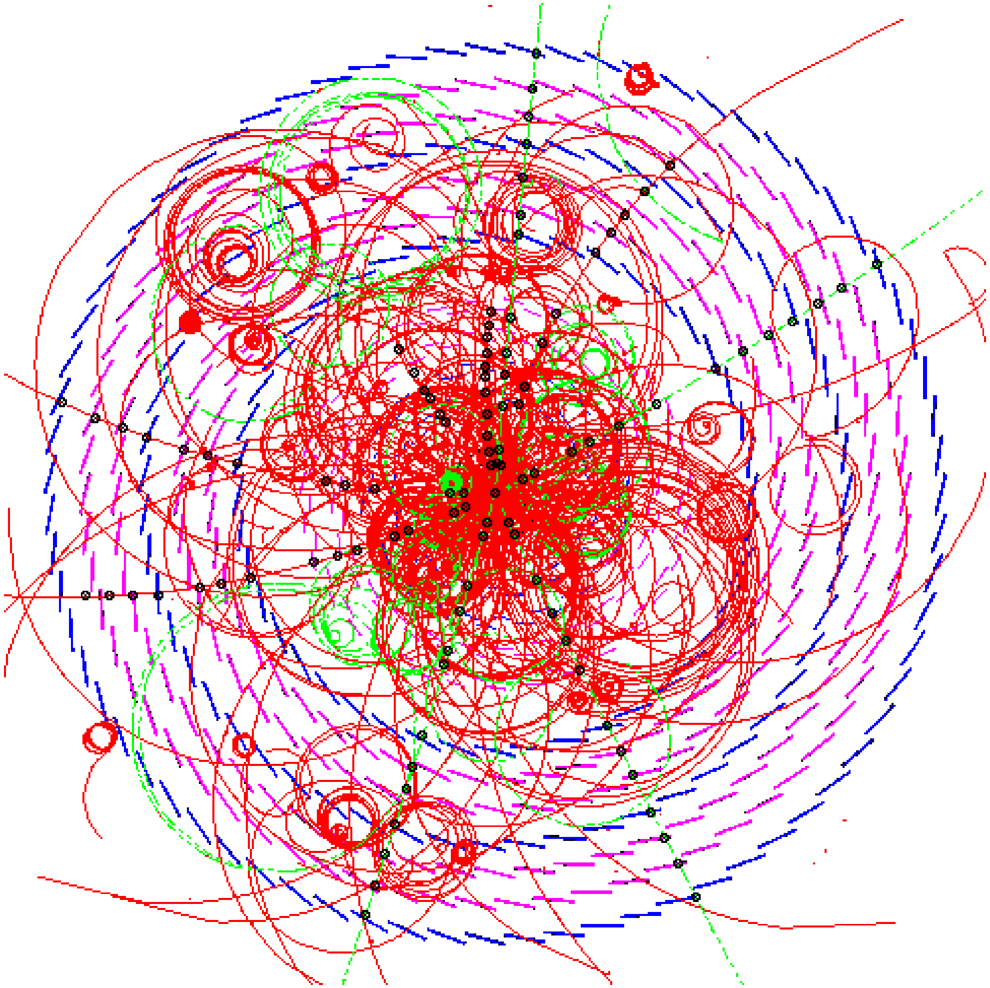
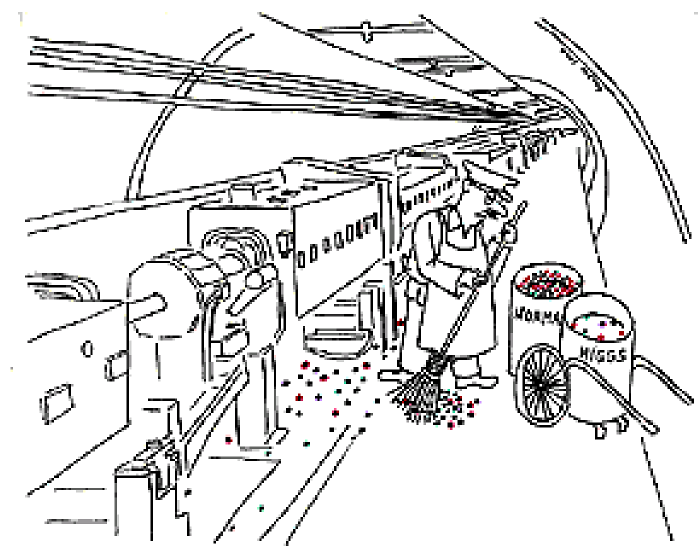
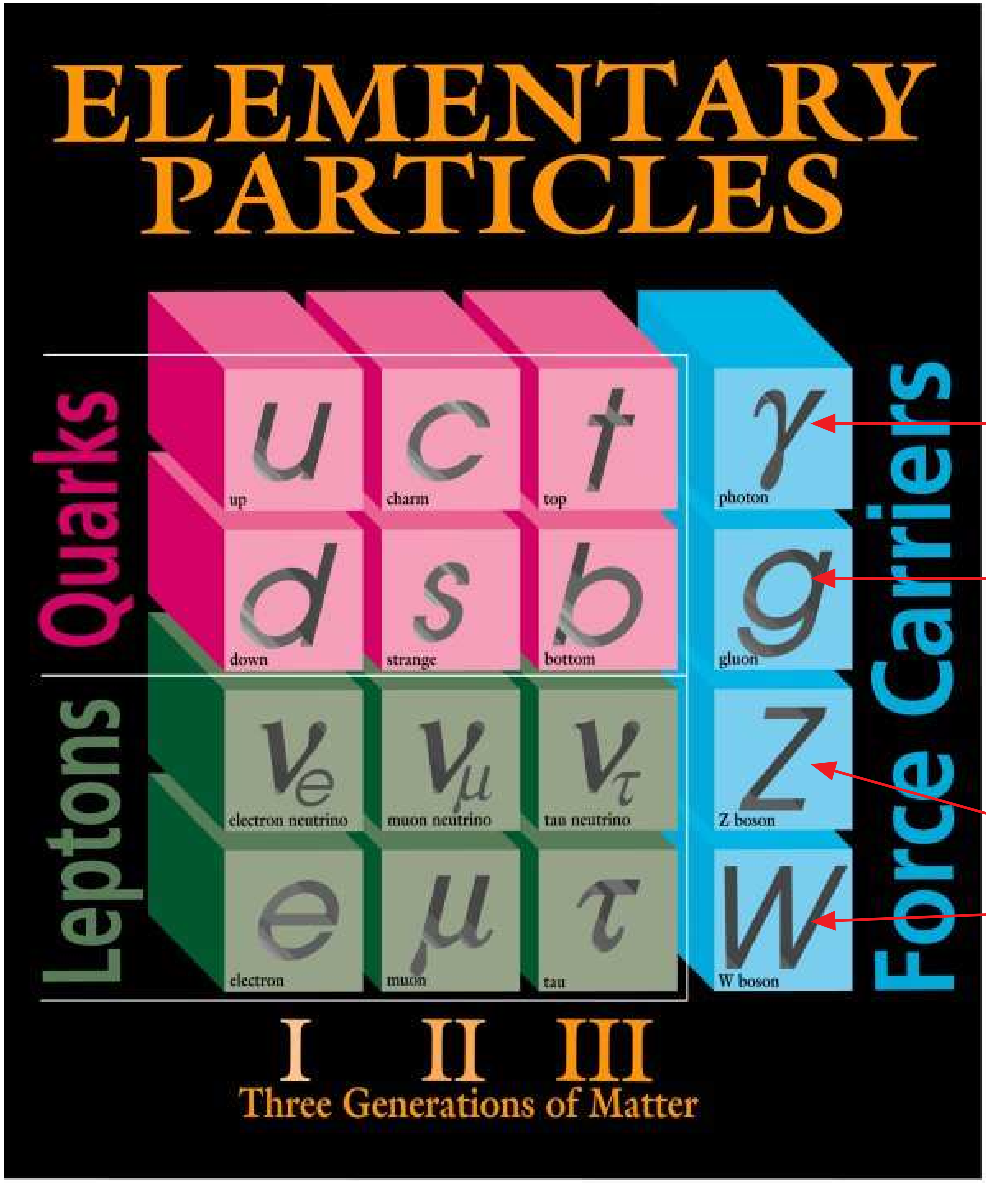


Fig. 6.3: Decay of the Standard Model Higgs into 4 muons.
All tracks with p_t>2 GeV are reconstructed.



2 Our present understanding of elementary particle physics



Fermilab 95-759

Gauge bosons (spin 1) for

elmg. interaction

strong interaction

weak interaction

Comparison of the Standard Model (SM) and QED:

	QED	SM
matter fields (spin $\frac{1}{2}$)	$\mathrm{e}^{\pm}$	leptons + quarks
gauge symmetry	$\mathrm{U}(1)_{\mathrm{em}}$	$\mathrm{SU}(2) \times \mathrm{U}(1)$
$\to$ gauge bosons (spin 1)	γ	γ, Z^0, $\mathrm{W}^{\pm}$

Differences to QED:

- non-abelian gauge group
  $\to$ gauge-boson self-interactions
- spontaneous symmetry breaking $\quad \mathrm{SU}(2) \times \mathrm{U}(1) \to \mathrm{U}(1)_{\mathrm{em}}$
  $\to$ massive gauge bosons Z^0, $\mathrm{W}^{\pm}$
  Higgs boson H (spin 0)

$\Rightarrow$ Common description of electromagnetic and weak interactions

Comparison of the Standard Model (SM) and QED:

	QED	SM
matter fields (spin $\frac{1}{2}$)	$\mathrm{e}^{\pm}$	leptons + quarks
gauge symmetry	$\mathrm{U}(1)_{\mathrm{em}}$	$\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$
$\rightarrow$ gauge bosons (spin 1)	γ	γ, Z^0, $\mathrm{W}^{\pm}$, g

Differences to QED:

- non-abelian gauge group
  $\rightarrow$ gauge-boson self-interactions
- spontaneous symmetry breaking $\mathrm{SU}(2) \times \mathrm{U}(1) \rightarrow \mathrm{U}(1)_{\mathrm{em}}$
  $\rightarrow$ massive gauge bosons Z^0, $\mathrm{W}^{\pm}$
  Higgs boson H (spin 0)

$\Rightarrow$ Common description of electromagnetic and weak interactions as well as strong interactions

Higgs mechanism and electroweak symmetry breaking

SM: all particles receive their mass via interaction
with the vacuum expectation value of the Higgs field

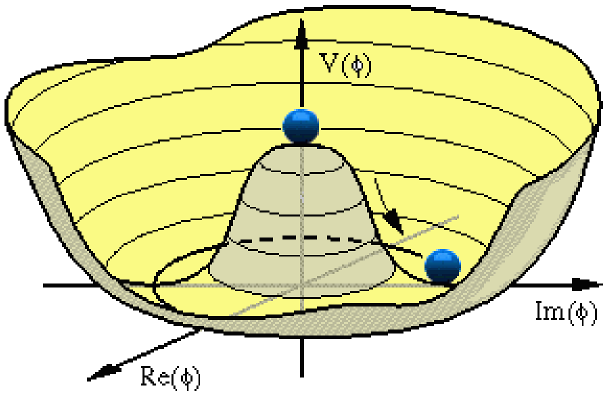
$\hookrightarrow$ “a quantum-field theoretical ether theory”

but: “medium Higgs field” has its own particle excitation = Higgs boson

Important ingredient: “spontaneous symmetry breaking”

$\hookrightarrow$ non-vanishing vacuum expectation value of a scalar field

SM: “ad hoc” introduced Higgs potential drives symmetry breaking



Investigation of Higgs self-interaction
$\hookrightarrow$ window to mechanism of symmetry breaking

CERN's down-to-earth explanation:

The Higgs field is like a room full of physicists chattering quietly:

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A particle is a well-known scientist walking in, attracting a cluster of admirers, thereby receiving resistance to movement ("mass").

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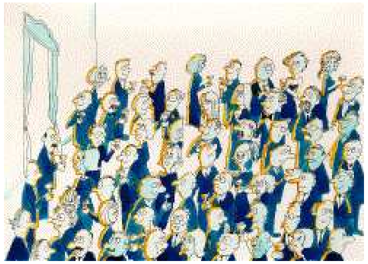
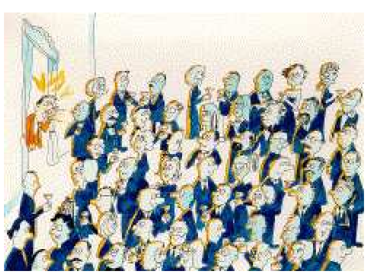
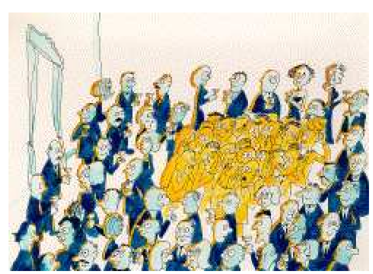


A particle is a well-known scientist walking in, attracting a cluster of admirers, thereby receiving resistance to movement (“mass”).

The Higgs boson is like a rumor crossing the room, creating the same kind of clustering, but this time among the scientists themselves.





Theoretical and experimental facts about the Higgs field / boson:

- Higgs boson not yet found,

  $e^+e^- \not\to \mathrm{ZH}$ at LEP2 $\quad\Rightarrow\quad M_\mathrm{H} > 114.4\,\mathrm{GeV}$ (95% C.L.)

  LEPHIGGS '02

- SM fit to precision measurements (μ decay, LEP1, LEP2, SLC, Tevatron)

  M_H enters perturbative predictions $\quad\Rightarrow\quad M_\mathrm{H} < 144\,\mathrm{GeV}$ (95% C.L.)

  LEPEWWG Winter '07

- theoretical bound from "triviality" and unitarity arguments: $M_\mathrm{H} \lesssim 1\,\mathrm{TeV}$

- Higgs field rescues renormalizability and unitarity of the gauge theory with massive gauge bosons

  $\hookrightarrow$ SM is closed theory down to arbitrarily small scales ("UV closure")
  (though this requires some "fine-tuning" in the renormalization of the Higgs sector)

Theoretical description of particle interactions and processes

Starting point: quantum field theory defines model

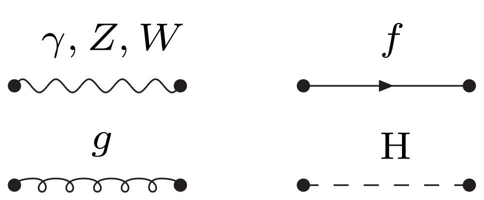
- each particle corresponds to a field ϕ_i
- Lagrangian $\mathcal{L}(\phi_i)$ for free motion & interactions

Perturbative evaluation of quantum field theories

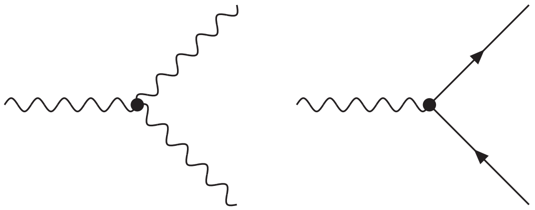
Transition amplitude $\langle f|S|i\rangle = \sum$ Feynman graphs for $|i\rangle \to |f\rangle$

Form graphs following Feynman rules:

free propagators:



vertices = elementary interactions:



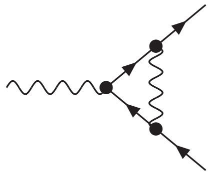
etc.

propagators & vertices $\longleftrightarrow$ terms in $\mathcal{L}(\phi_i)$

Perturbative series for $g \to 0$

= power series in g^n
= power series in $\hbar^m$
= expansion in # loops in diagrams

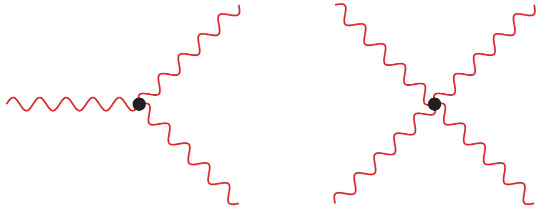
$\Rightarrow$ loop diagrams
= quantum corrections



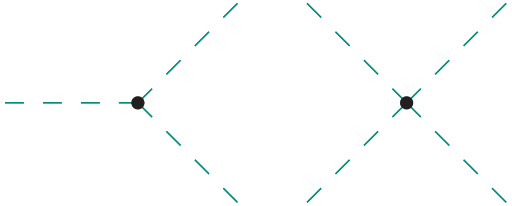
etc.

Elementary couplings of electroweak interaction:

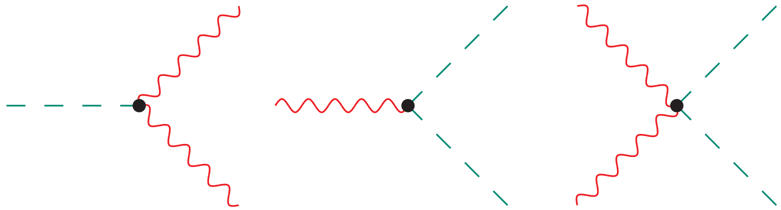
gauge-boson self-interaction:



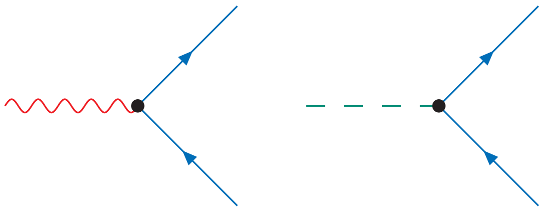
Higgs self-interaction:



gauge-boson–Higgs interation:

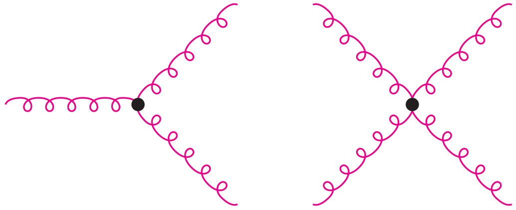


fermionic interaction:

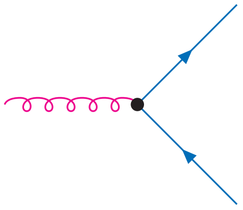


Elementary couplings of the strong interaction:

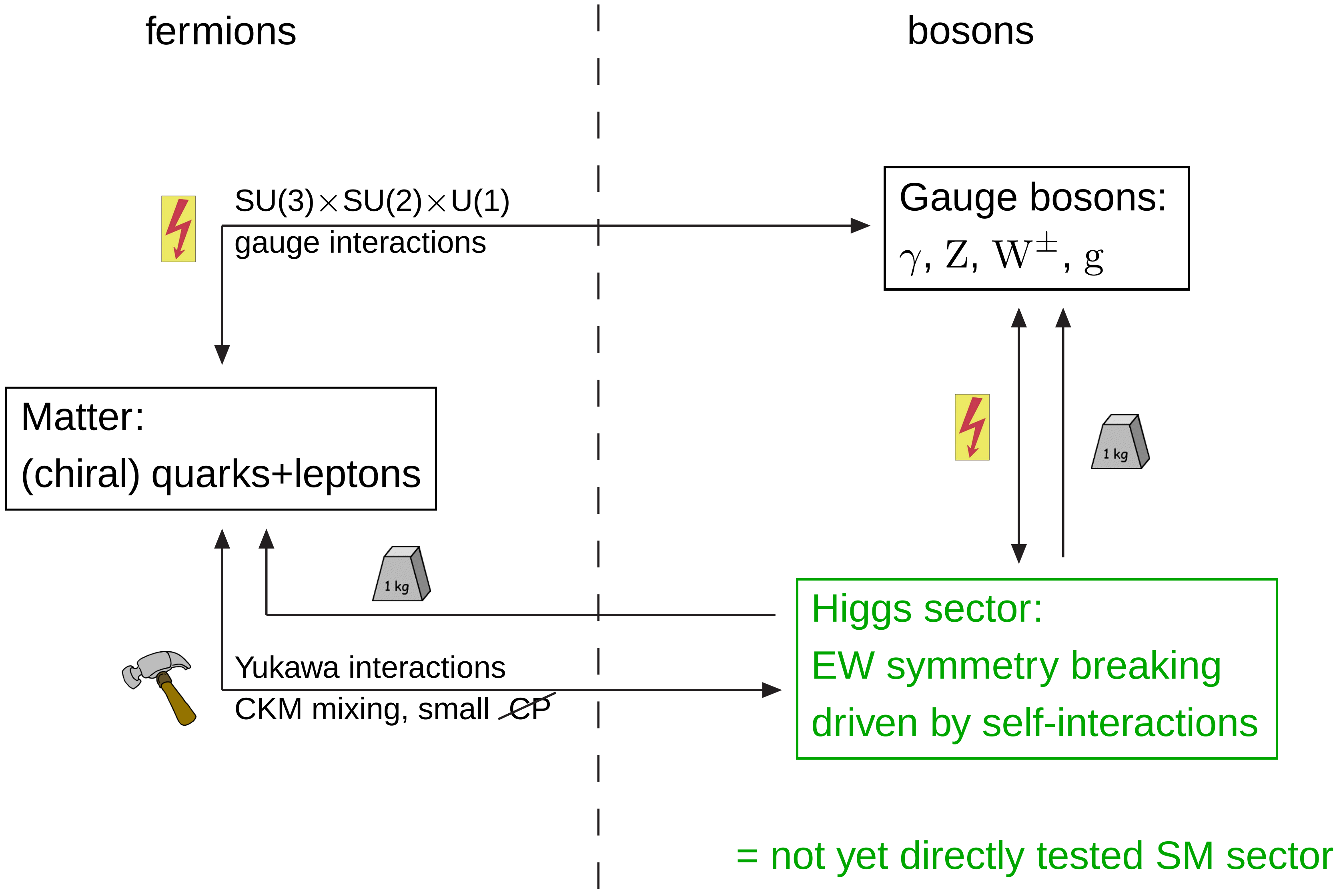
gluon self-interation:



quark–gluon interaction:



The Standard Model and ideas beyond



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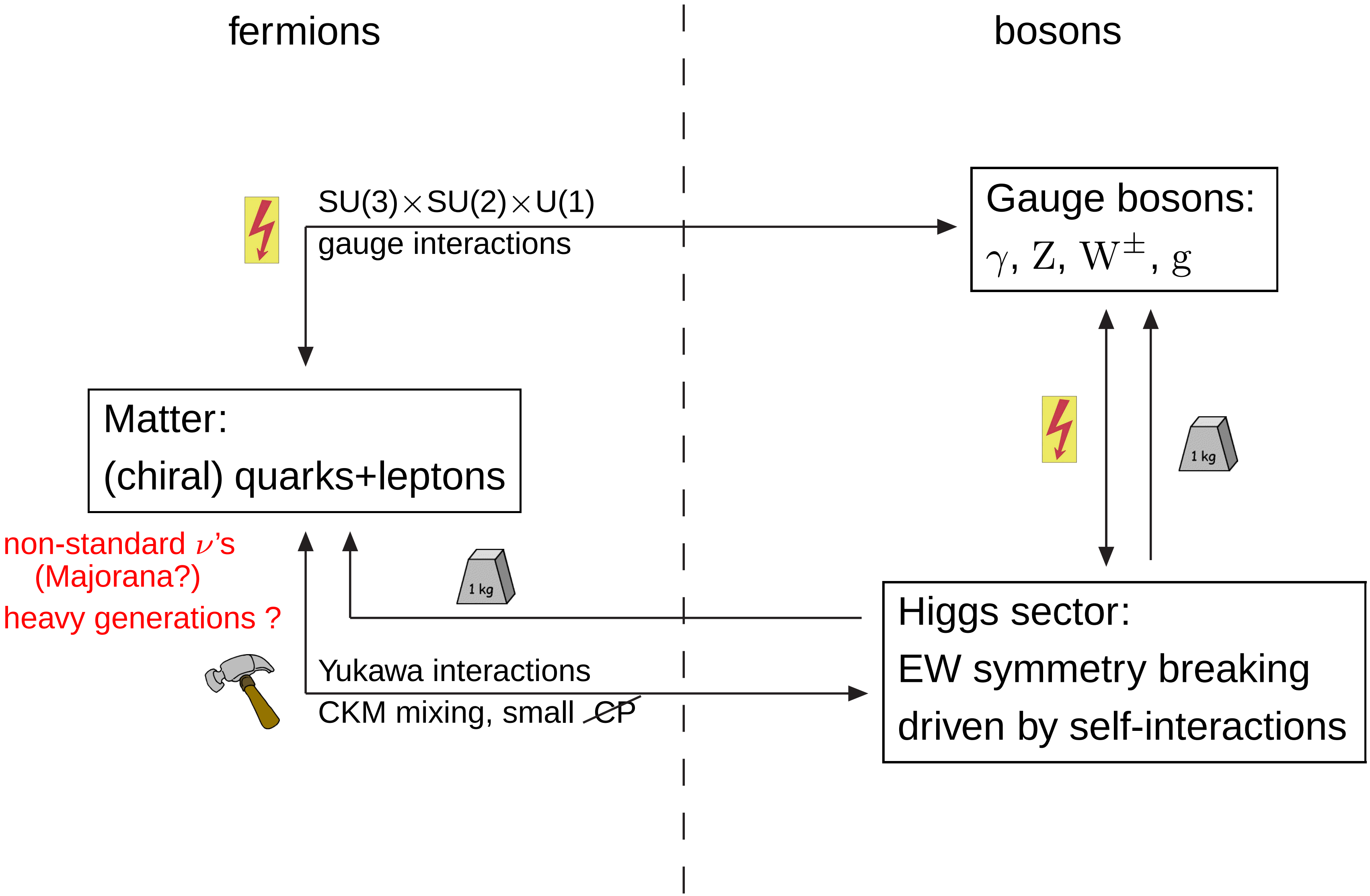

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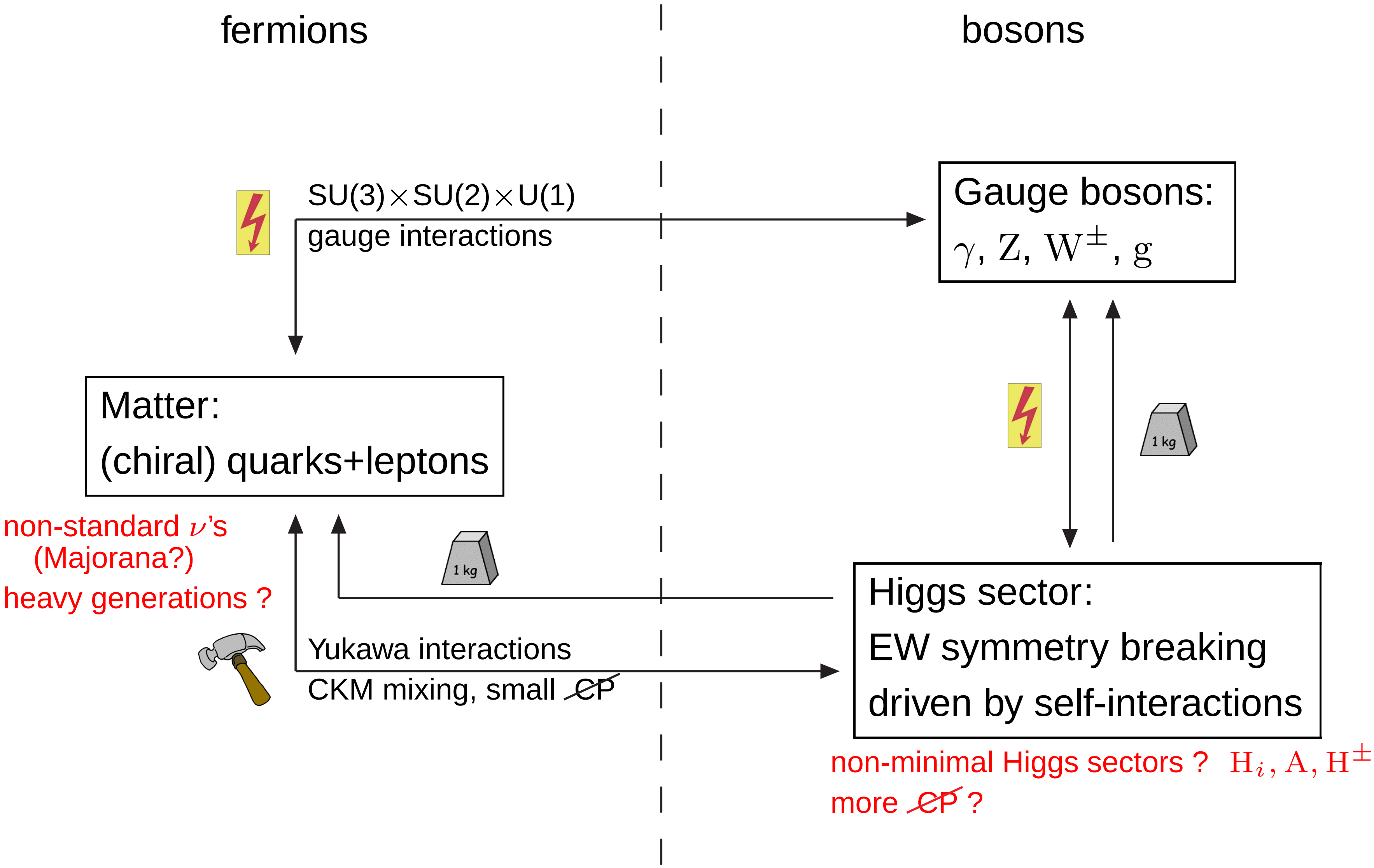

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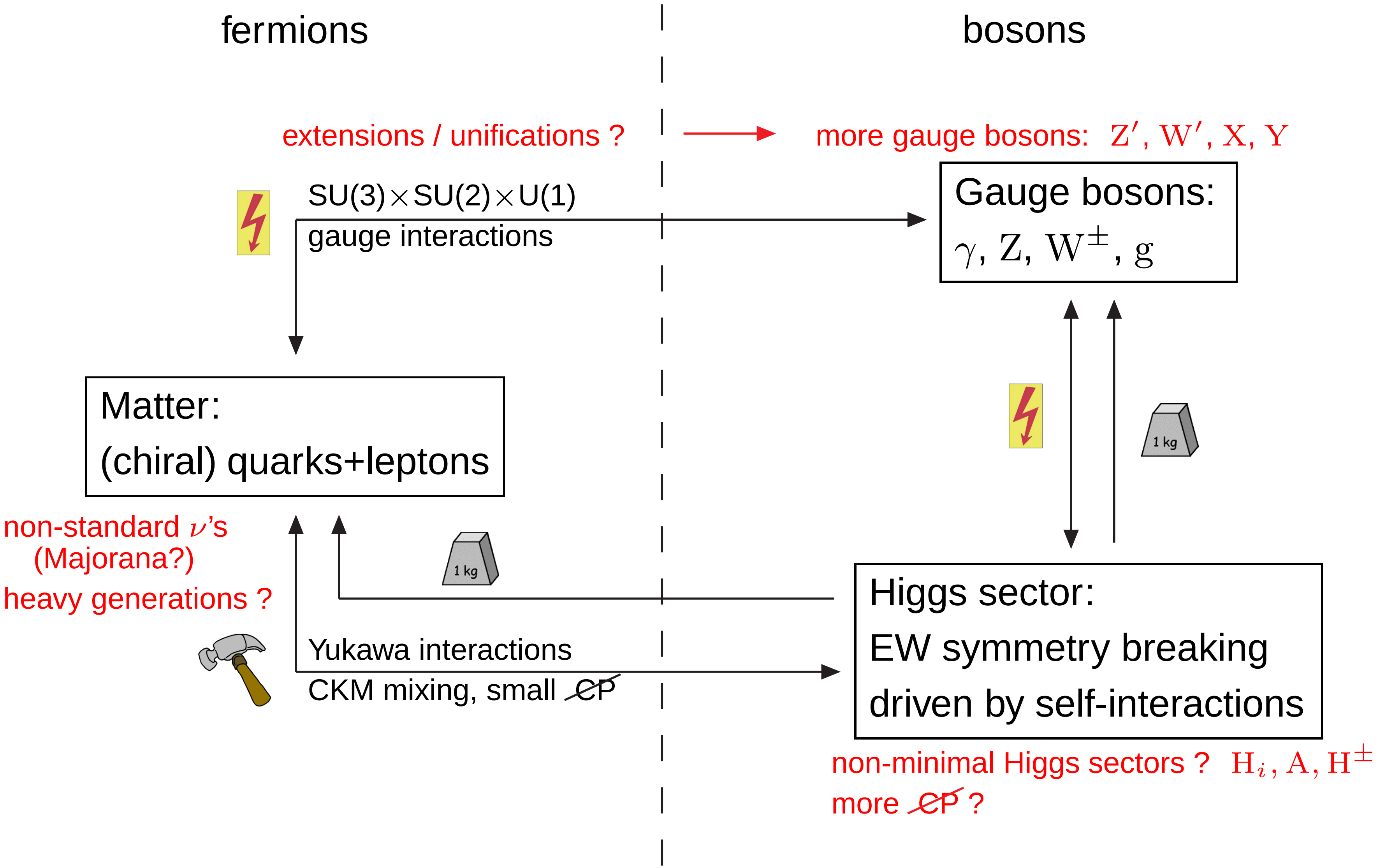

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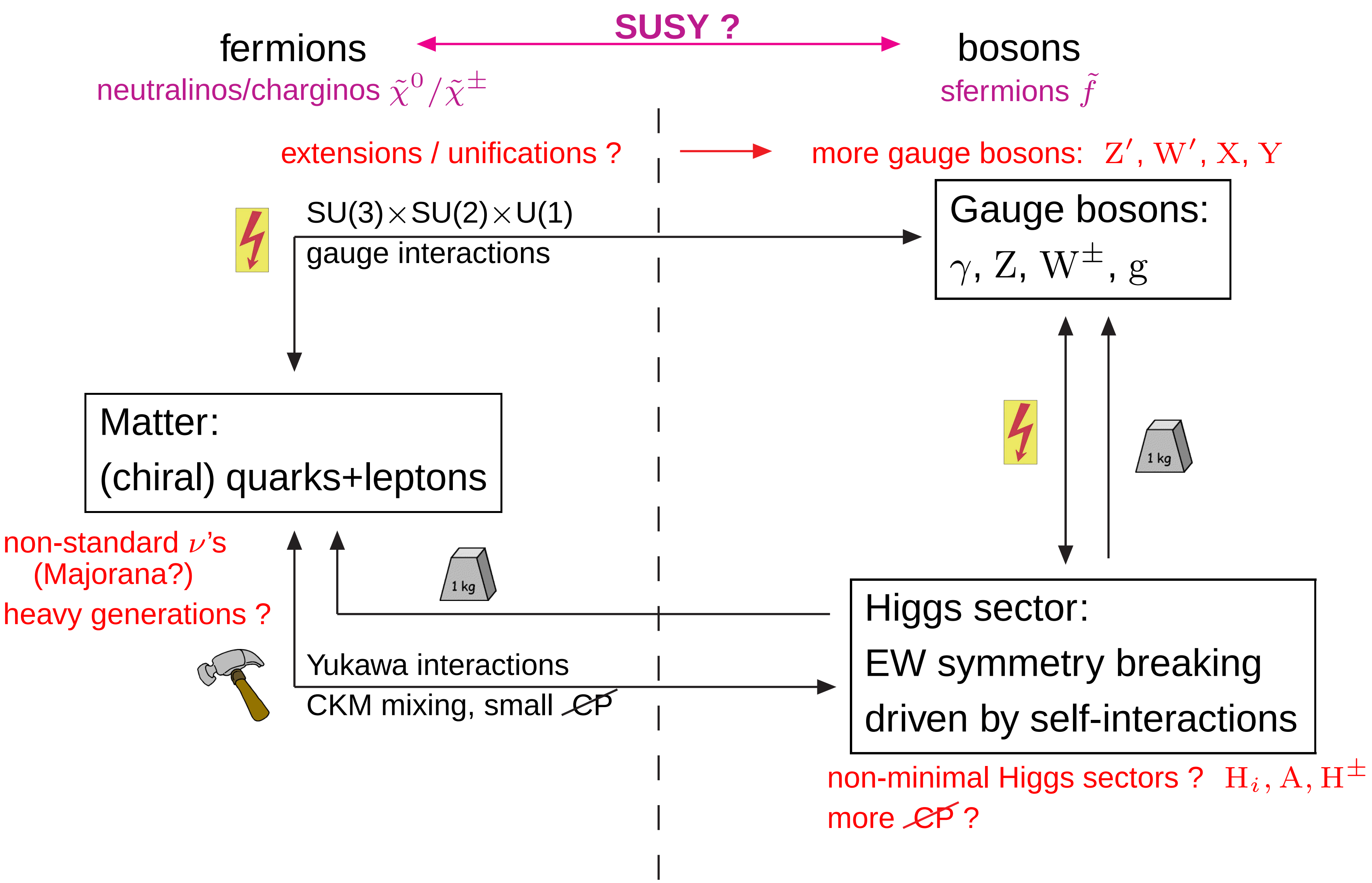

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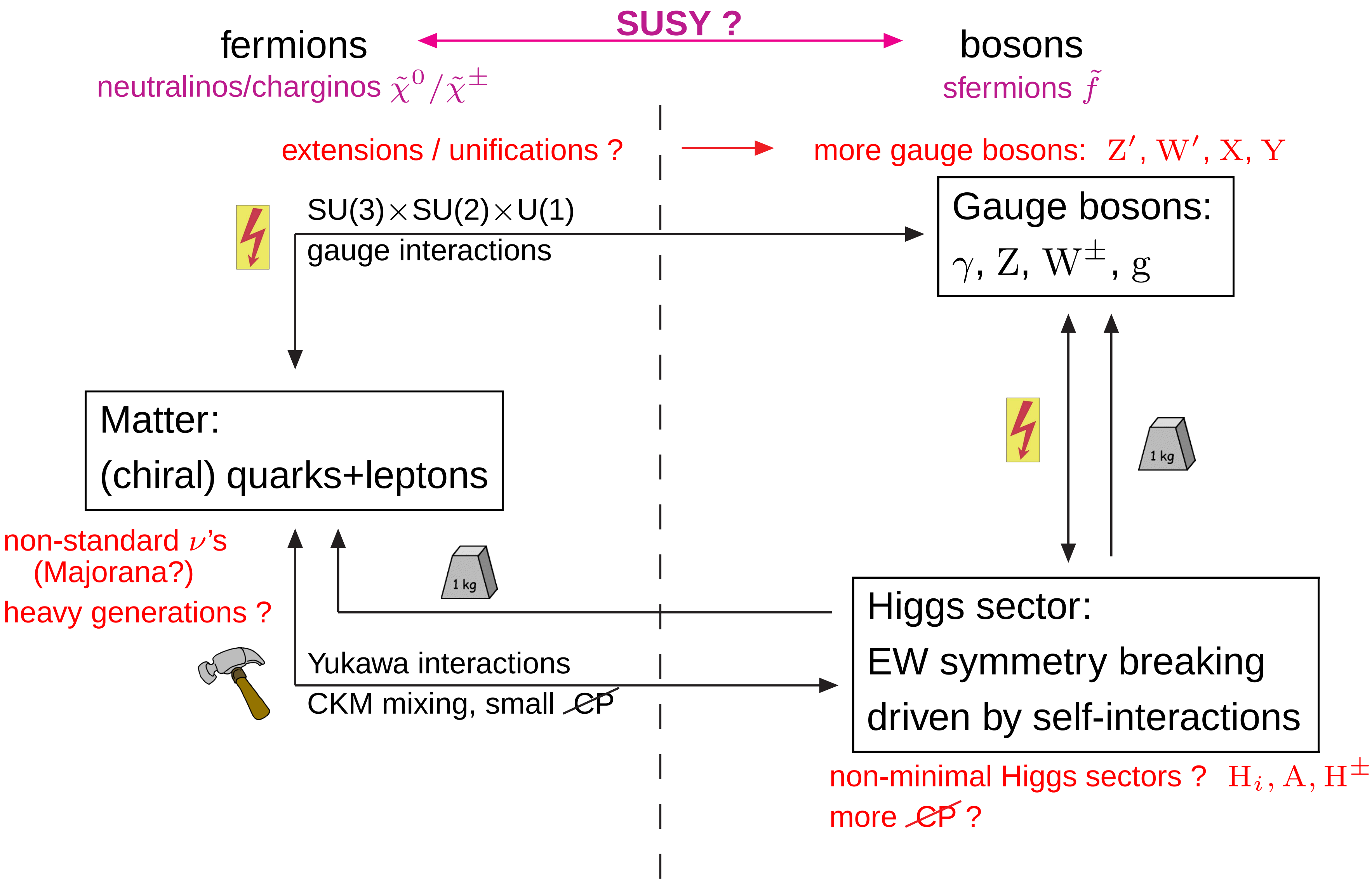


+ more exotic ideas (extra dimensions, little Higgs, . . .)

Electroweak (EW) issues at the LHC $\rightarrow$ covered in this lecture series

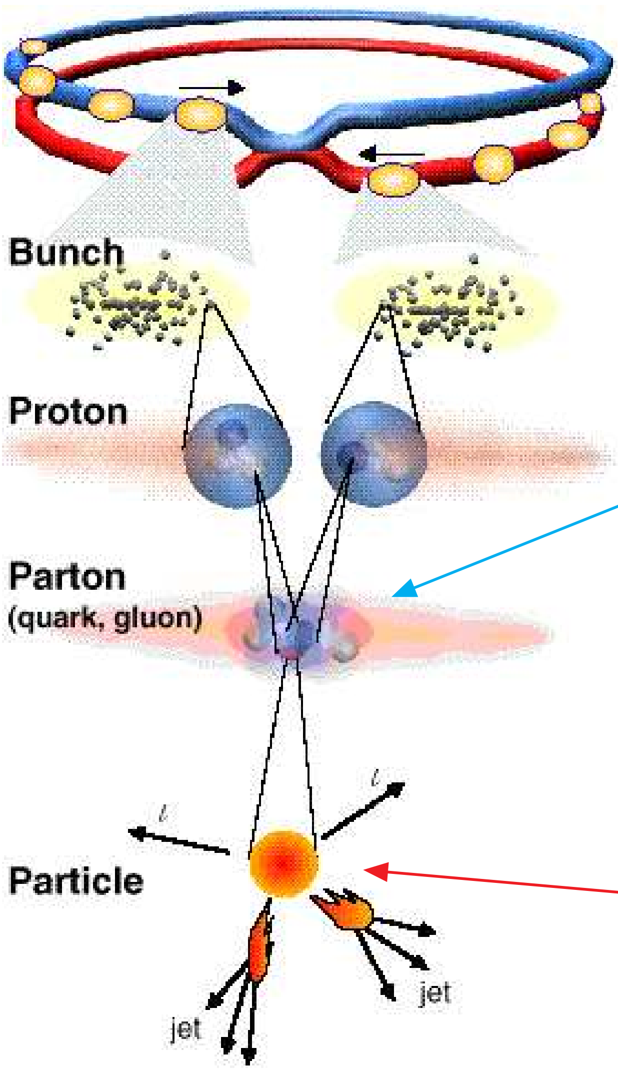
- Higgs physics:
  Higgs discovery, analysis of its quantum numbers, decay channels, first studies of couplings, extended Higgs sectors
- production of single EW gauge bosons:
  EW precision physics (calibration, M_{W}, $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$), strengthen SM consistentcy check and indirect bounds on M_{H}, search for new gauge bosons W', Z'
- EW gauge-boson pair production:
  find or constrain non-standard couplings among EW gauge bosons
- triple gauge-boson production and $\mathrm{W_L W_L} \rightarrow \mathrm{W_L W_L}$:
  behaviour of longitudinal weak gauge bosons
  weakly (as in Higgs models) or strongly coupled $\mathrm{W_L}$

Theoretical requirements: $\rightarrow$ partially developed in this lecture

- electroweak theory
  $\hookrightarrow$ SM, Higgs mechanism, basics of EW precision physics, unstable particles
- understand hadronic environment
  $\hookrightarrow$ QCD-improved parton model, radiative corrections *"No QCD, no party!"*

3 Physics at the LHC

Inelastic hadronic collisions:



Parton content of the proton:

valence quarks uud,

sea quarks $\mathrm{u}, \mathrm{d}, \mathrm{c}, \mathrm{s}, (+\mathrm{b},)$

gluons g (+photons γ)

"Parton distribution functions" (PDF) $f_{i/\mathrm{p}}(x, Q)$

determine fraction x of the p momentum

carried by parton i at "factorization scale" Q

= non-perturbative input (from exp.),

but process independent

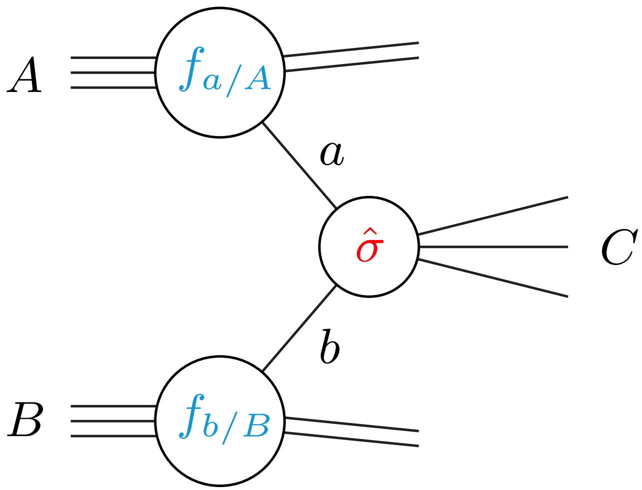
Hard interaction of partons

$\hookrightarrow$ perturbative QCD applicable,

model for hard interactions

(apart from QCD) enters only here

Parton model description of hadronic collisions



hadronic momenta: p_A, p_B

hadronic CM energy: $\sqrt{s} = E_A + E_B$

partonic momenta: $p_a = x_A p_A, \; p_b = x_B p_B$

partonic CM energy: $\sqrt{\hat{s}} = \sqrt{x_A x_B s}$

Hadronic cross section for $AB \to C + X$: ($X =$ any hadronic remnant/activity)

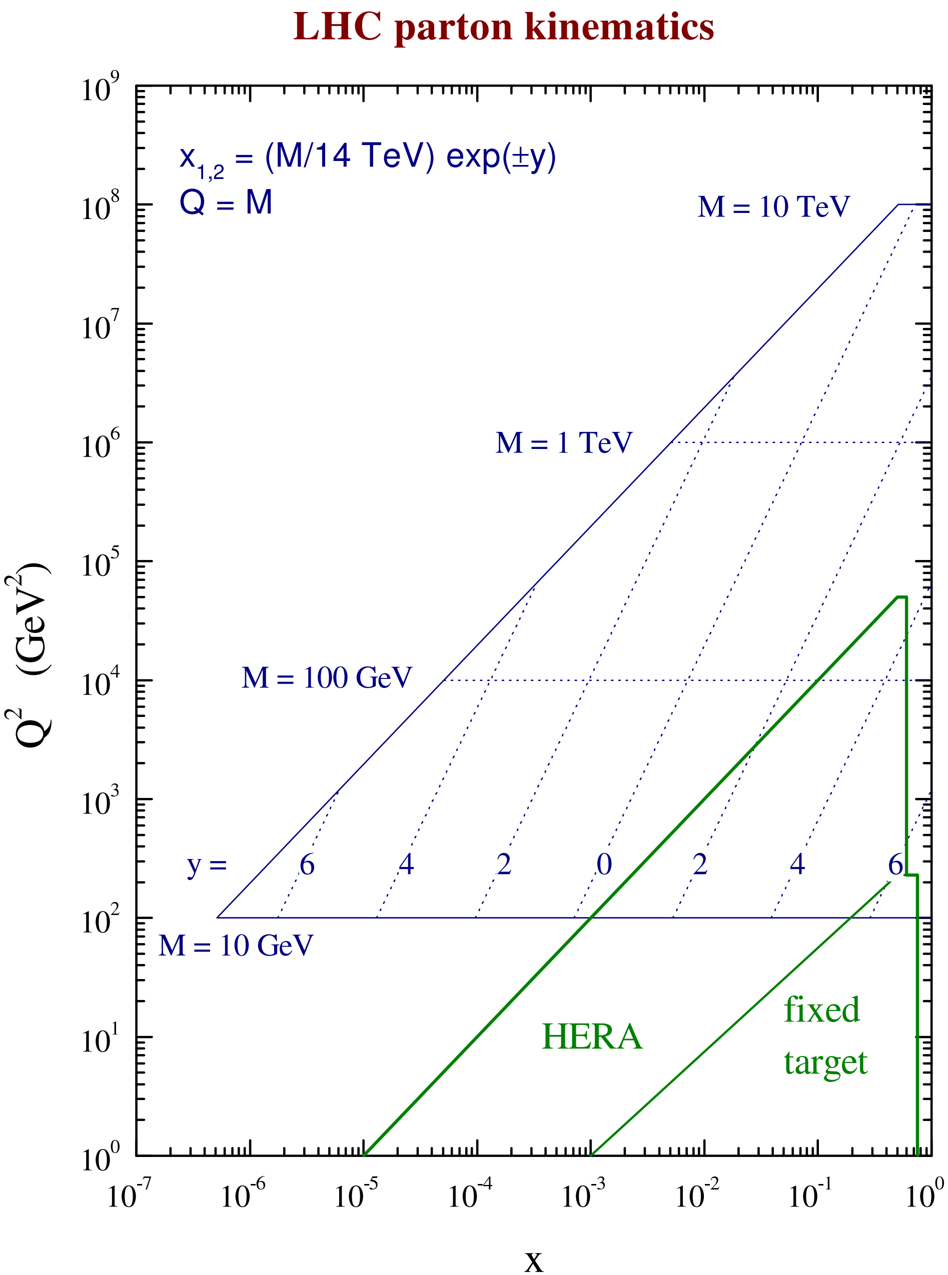
$$\sigma_{AB\to C+X}(s) = \int_0^1 \mathrm{d}x_A \int_0^1 \mathrm{d}x_B \sum_{a,b} f_{a/A}(x_A, Q)\, f_{b/B}(x_B, Q)\, \hat{\sigma}_{ab\to C}(\hat{s}, Q)$$

Factorization scale Q separates soft from hard contributions.

- Q dependence of PDFs $f_{a/A}(x_A, Q)$ ruled by DGLAP evolution equations
- Q dependence of hard scattering cross section $\hat{\sigma}_{ab\to C}(\hat{s}, Q)$ universal
- Q drops out in “all-order” calculations for $\sigma_{AB\to C+X}(s)$

$\hookrightarrow$ residual Q dependence in finite-order predictions reflects theoretical uncertainty

Kinematical range in terms of PDF variables



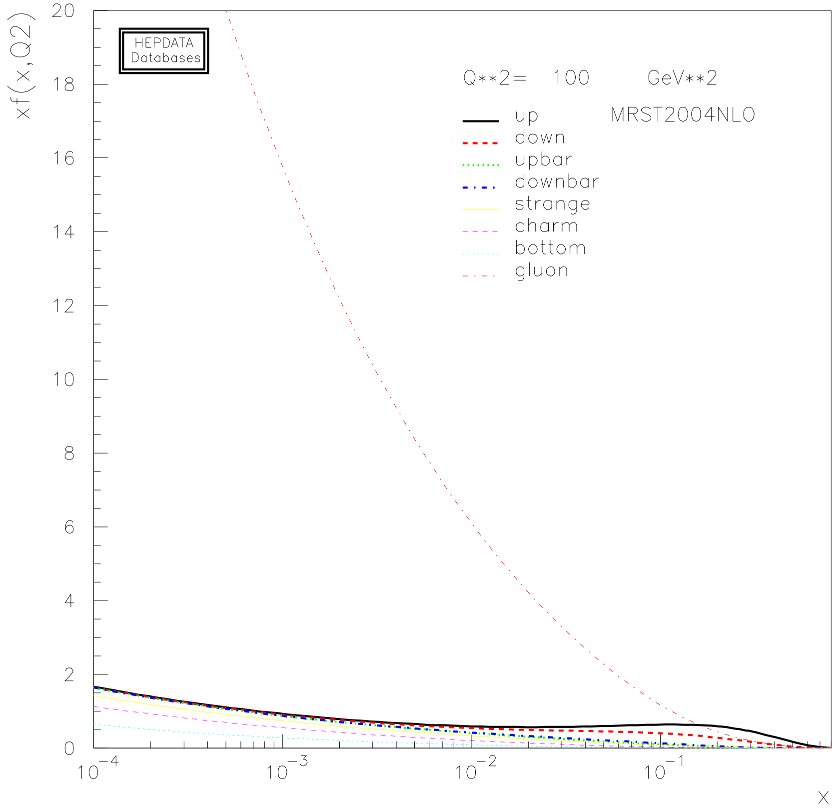
$M =$ parton–parton invariant mass

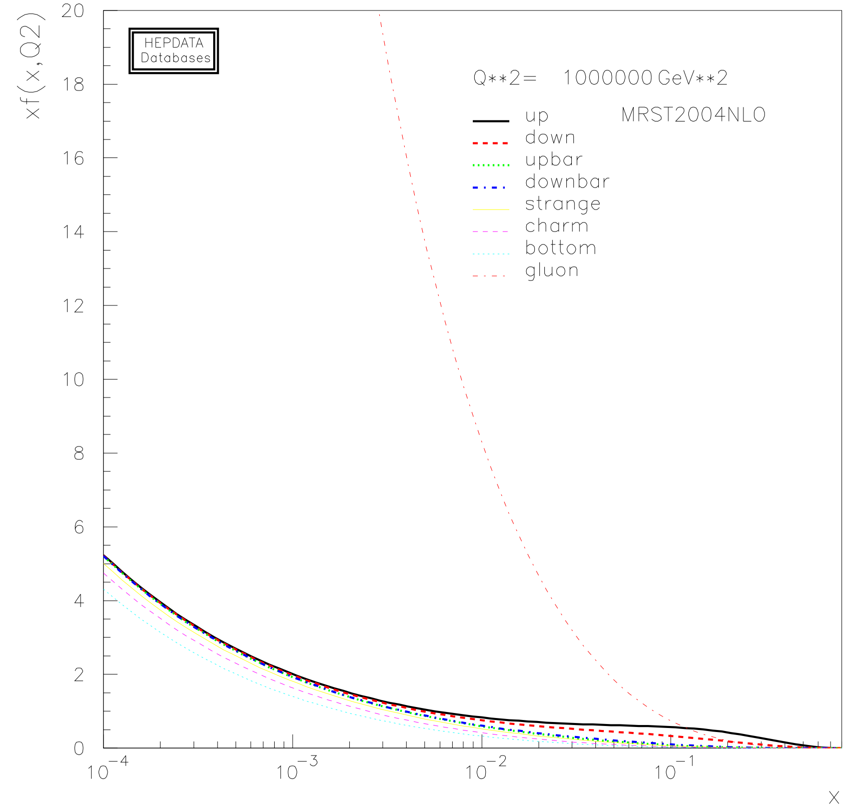
$y =$ rapidity of partonic CM frame
($y=0$ partonic CM frame not boosted)

LHC explores new territory in (x, Q)

$\hookrightarrow$ PDF extrapolation from existing data not sufficient, LHC data have to be included in new PDF fits

Parton distribution functions





- DGLAP evolution to larger Q shifts PDFs to lower x

  $\hookrightarrow$ enhancement of sea-quark and gluon PDFs

- Processes with both gg and $q\bar{q}$ channels (e.g. $\mathrm{t\bar{t}}$ production)

  Tevatron: $q\bar{q}$ often dominates by $\sim 90\%$

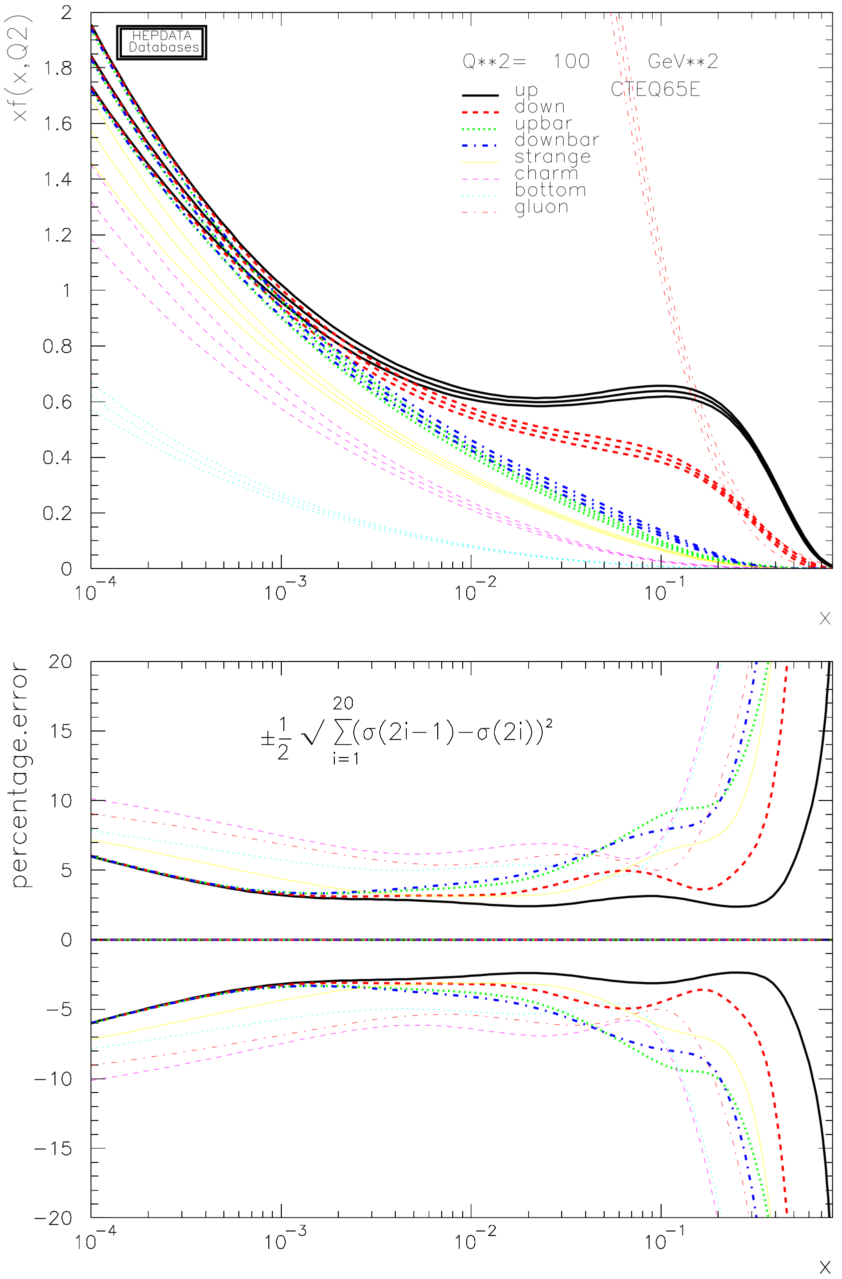
  LHC: gg often much more important than $q\bar{q}$

An idea about PDF uncertainties:

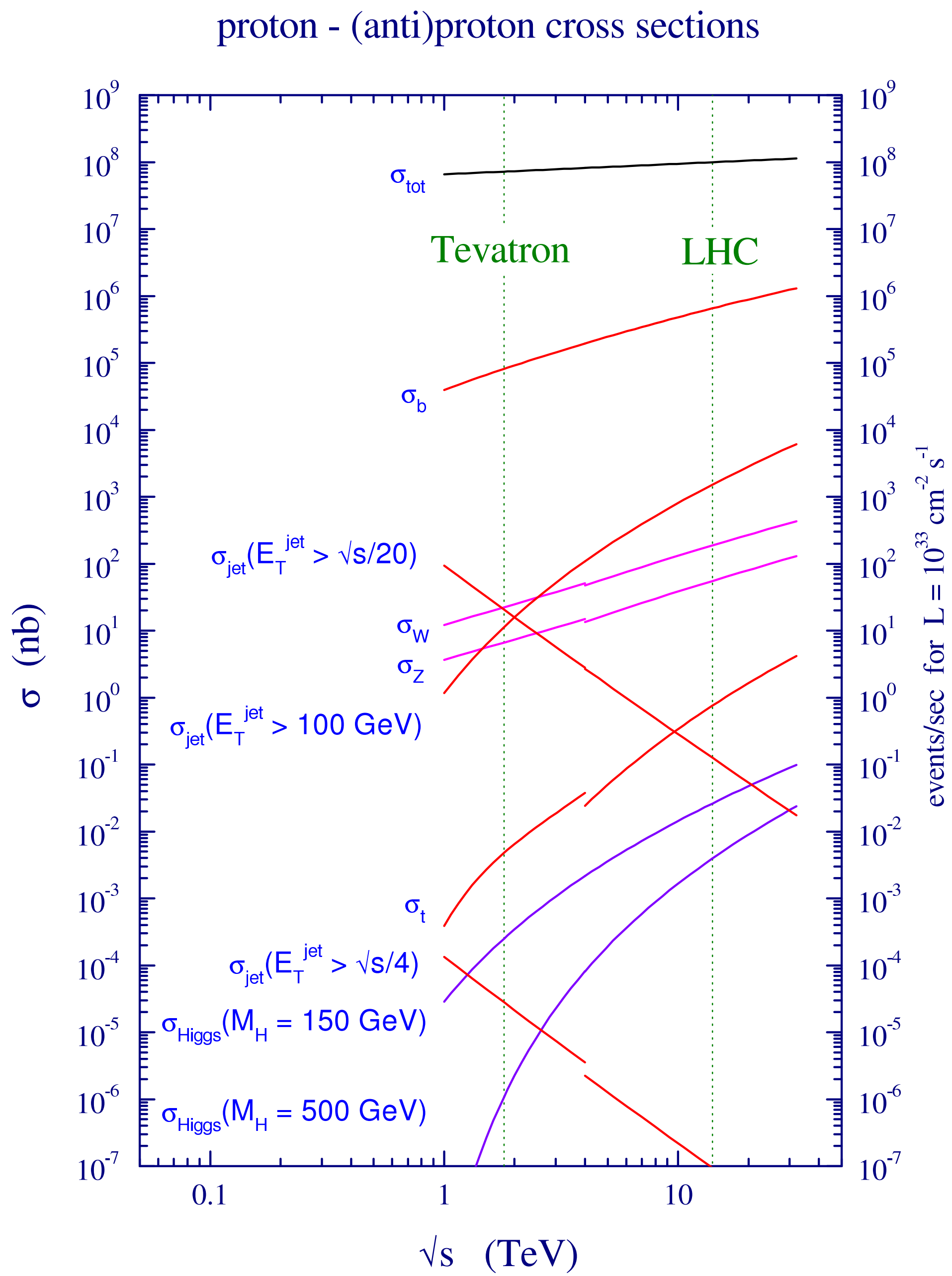
Uncertainties estimated
from eigenvector analysis of χ^2 fit

uncertainties $\sim\ 5–10\%$

for $x\ \sim\ 10^{-4}–10^{-1}$



Some Standard Model cross sections at the Tevatron ($p\bar{p}$) and the LHC (pp)



events $= \sigma \times$ luminosity

design luminosity: $100\,\mathrm{fb}^{-1}\mathrm{a}^{-1}$/exp.

2 experiments in 5 years:

$\sigma \sim 1\,\mathrm{pb} \quad \rightarrow \quad \sim 10^6$ events

$\hookrightarrow$ precision physics
(systematics dominates uncertainty)

$\sigma \sim 1\,\mathrm{fb} \quad \rightarrow \quad \sim 10^3$ events

$\hookrightarrow$ good prospects for searches
(statistics dominates uncertainty)

BUT:
inclusive cross sections reduced
by branching ratios, event selection,
experimental efficiencies, etc.

Production probability versus experimental reconstruction

Realistic event numbers do not follow from total cross sections for various reasons

- hadronically decaying particles (W, Z, t, H) cannot be reconstructed without additional signature

  e.g. $\mathrm{BR}(\mathrm{W} \to \mathrm{leptons}) \approx 1/3, \quad \mathrm{BR}(\mathrm{W} \to \mathrm{hadrons}) \approx 2/3,$

  similar for $\mathrm{t} \to \mathrm{bW}$ with subsequent W decay

- no full coverage of detectors

  e.g. ATLAS: $|y| < 2.5(\text{inner tracker}),\ 2.7(\text{muons}),\ 3.2(\text{em.cal.}),\ 4.9(\text{had.cal.})$

- event selection cuts might be necessary to reduce background

  e.g. in Higgs production via “vector-boson fusion”:

  $\sigma_{\mathrm{H+2jets}}$ reduced by factor $2{-}3$ (2 antipodal hard jets with rapidity gap)

- tagging efficiencies are not 100%

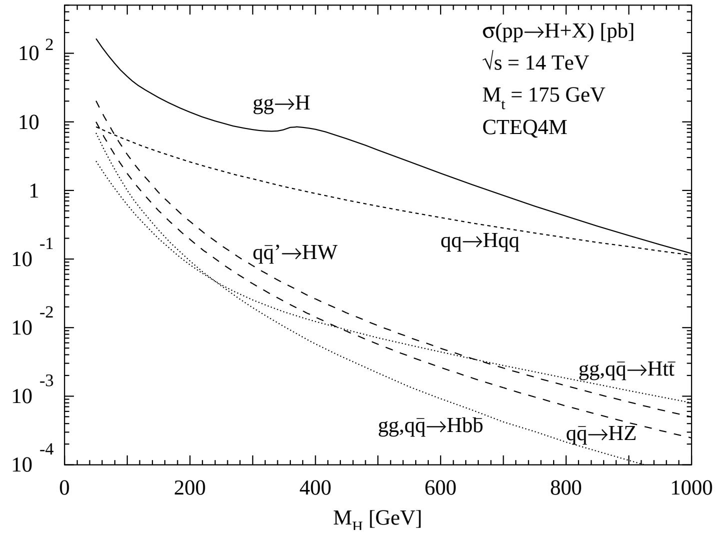
  e.g. b tagging in vertex detectors $\sim 30{-}60\%$

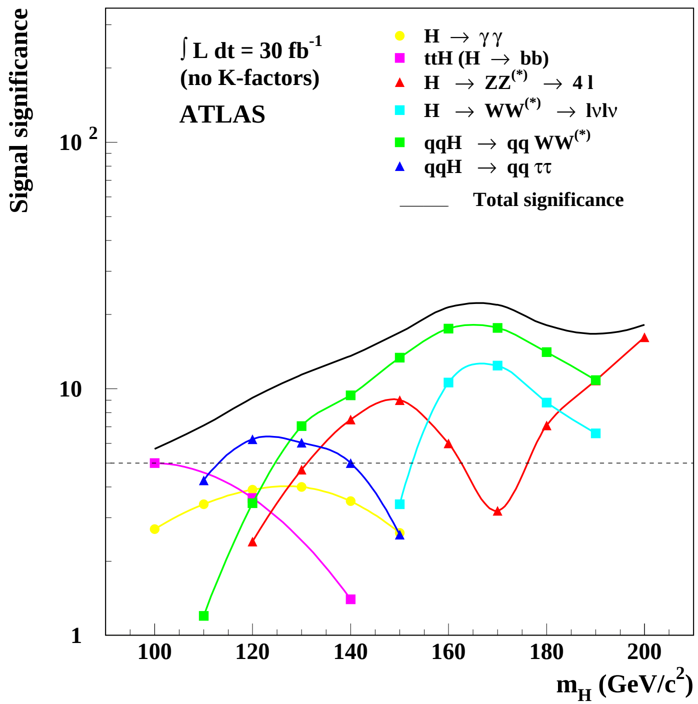
An example: Higgs discovery potential of ATLAS and CMS

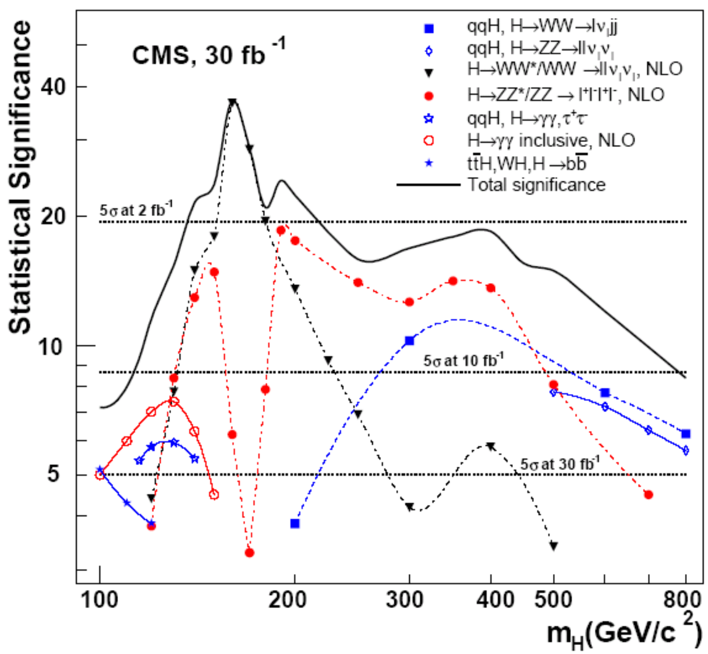
Signal significance

- does not follow total hierarchy of cross sections for different channels

- differs between ATLAS and CMS







Parton model and "reality"

Theoretical separation of "hard" and "soft" interaction not possible in events !

$\hookrightarrow$ "Soft" physics has to be understood:

- "Underlying events" (UE): everything except for the hard process of interest

  (more than one definition for UE on the market)

  - ◇ UE are not independent from hard scattering (colour and momentum correlated)
  - ◇ UE comprise:
    – ISR/FSR (coherent emission belongs to the hard process)
    – multiple parton interactions
    – beam remnants and interaction with beam remnants
  - ◇ UE increase with collider energy, large effects expected for jets at the LHC

- "Minimum bias events" (MBE): elastic, soft inelastic and diffractive events

  Tevatron: 1% of all MBE events have a jet with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$

- "pile-up events":

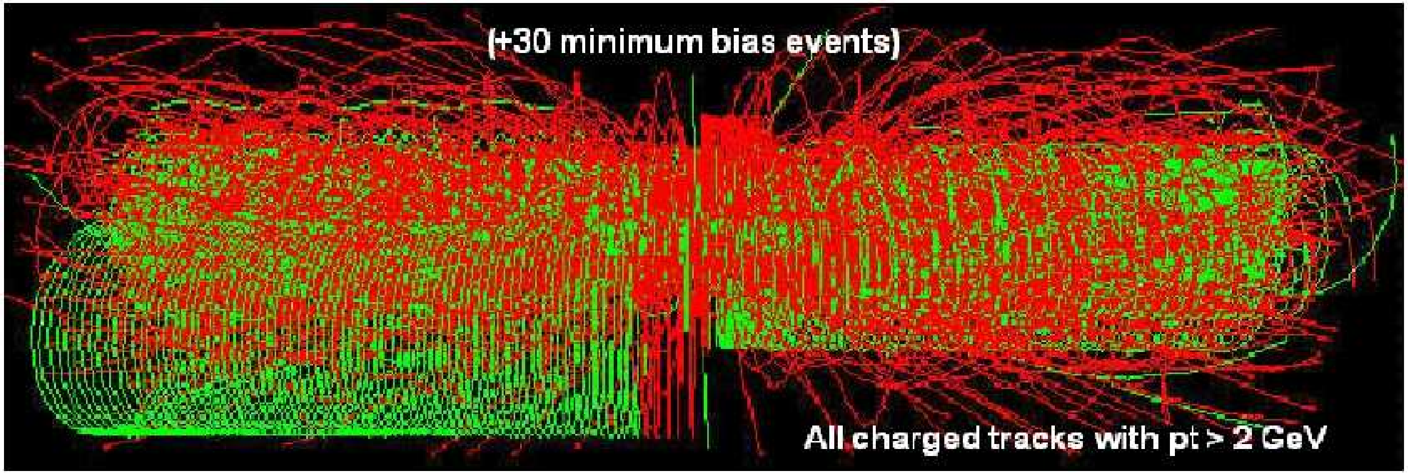
  accumulating activity from multiple proton scattering per bunch crossing

Little theoretical understanding, extrapolation from Tevatron to LHC very uncertain

$\hookrightarrow$ Measurements and modelling necessary at the LHC !

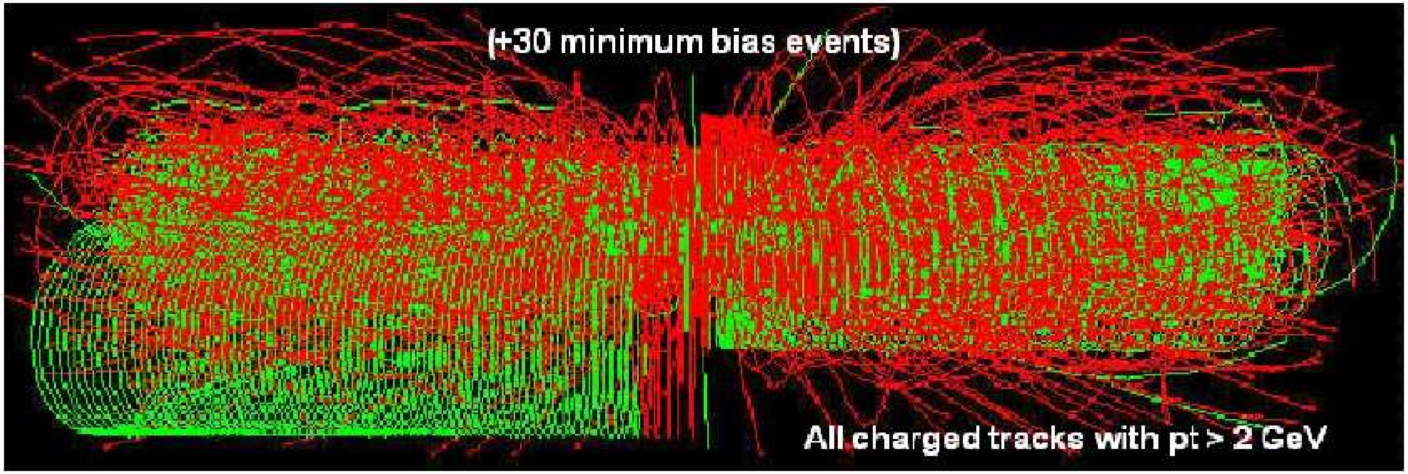
A simulated event at the LHC

... before event reconstruction:



A simulated event at the LHC

... before event reconstruction:



... after event reconstruction: