Physics at the TeV-scale: LHC experiments (I)

School on Flavor Physics

Benasc, July 23rd - 24th, 2008

David d'Enterria

Massachusetts Institute of Technology

Plan of lectures

1st

1. Introduction: Key physics issues at the LHC
2. The Large Hadron Collider (LHC)
3. LHC experiments:
   - ATLAS,CMS
   - LHCb
   - ALICE
   - TOTEM, LHCf

2nd

4. Physics programme at the LHC
5. Detectors at the LHC
6. Others: Triggering, Computing, Analysis

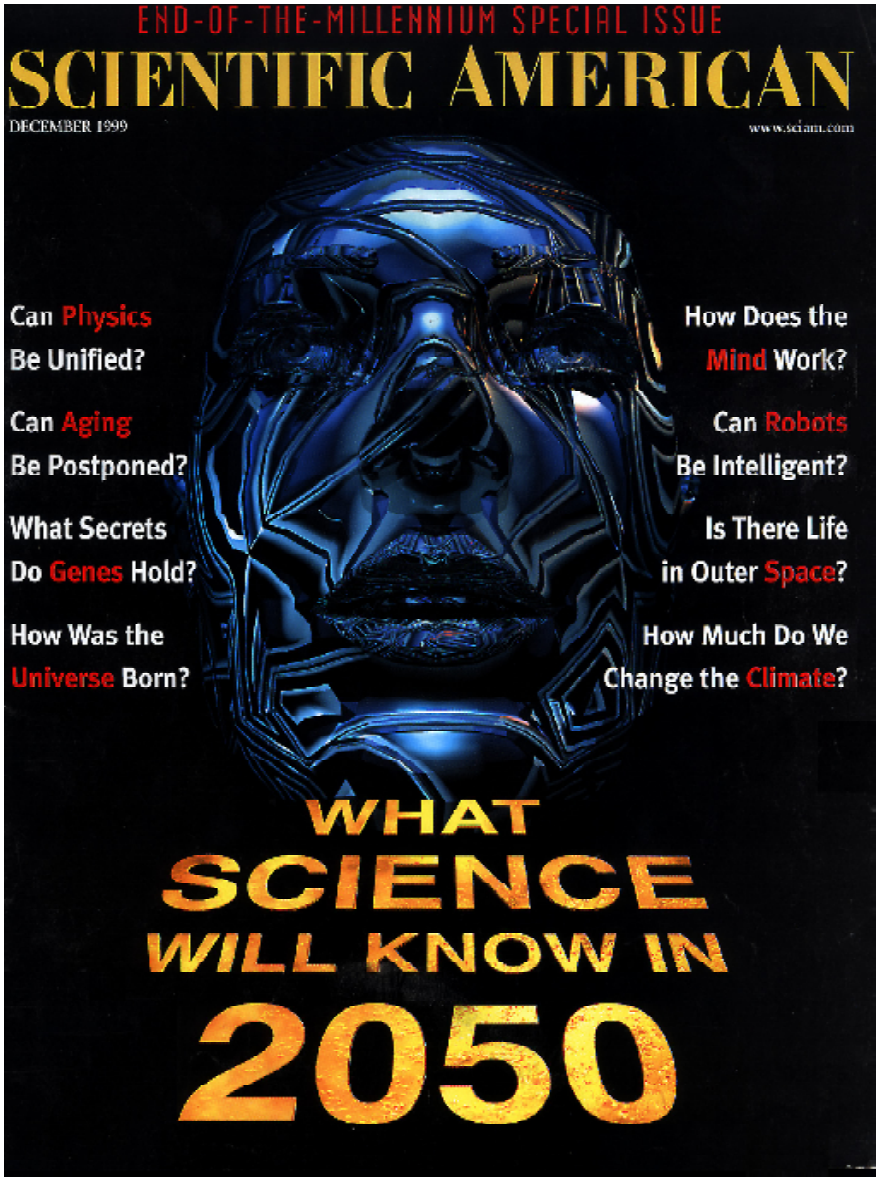
Open questions for the 21th Century

Can Physics
Be Unified ?

Can Aging
Be Postponed ?

What Secrets
Do Genes Hold ?

How Was the
Universe Born ?



How Does the
Mind Work ?

Can Robots
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Is There Life
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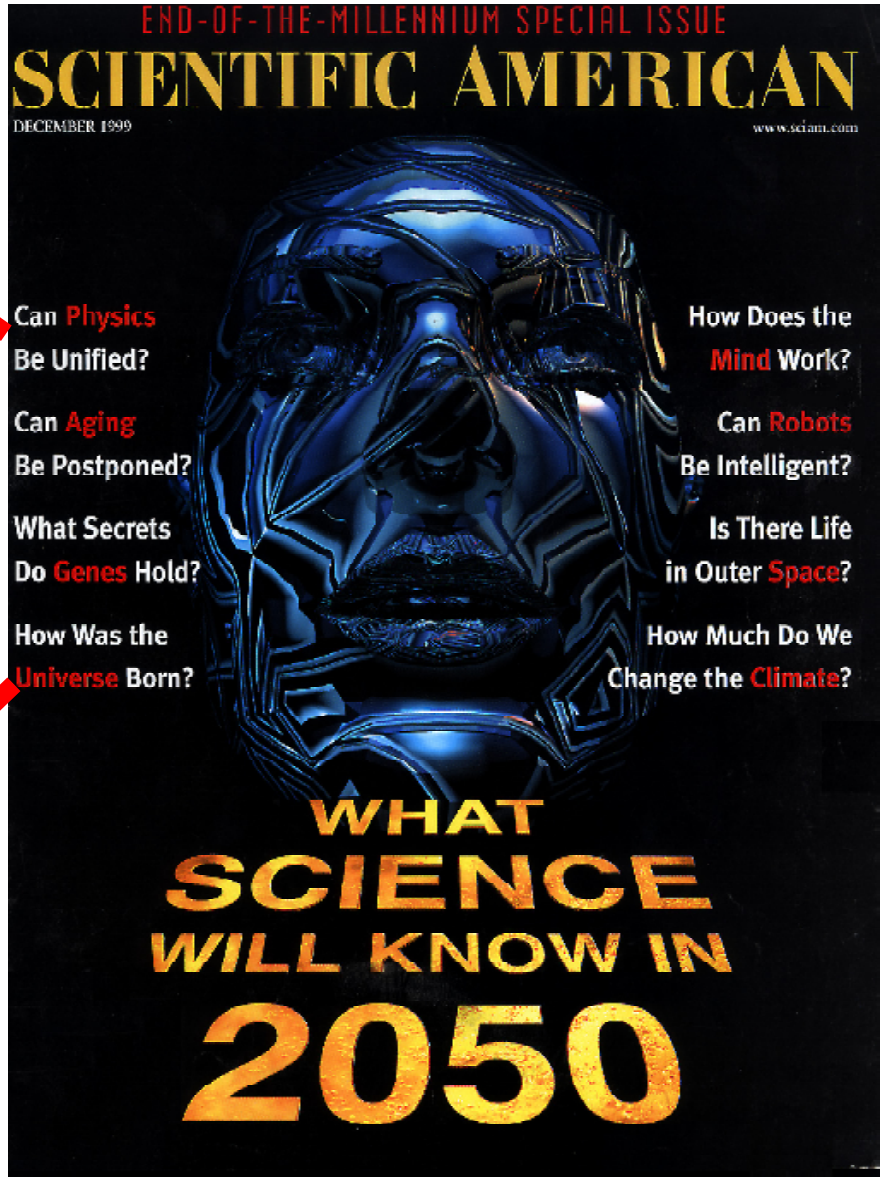

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6 big questions in particle physics

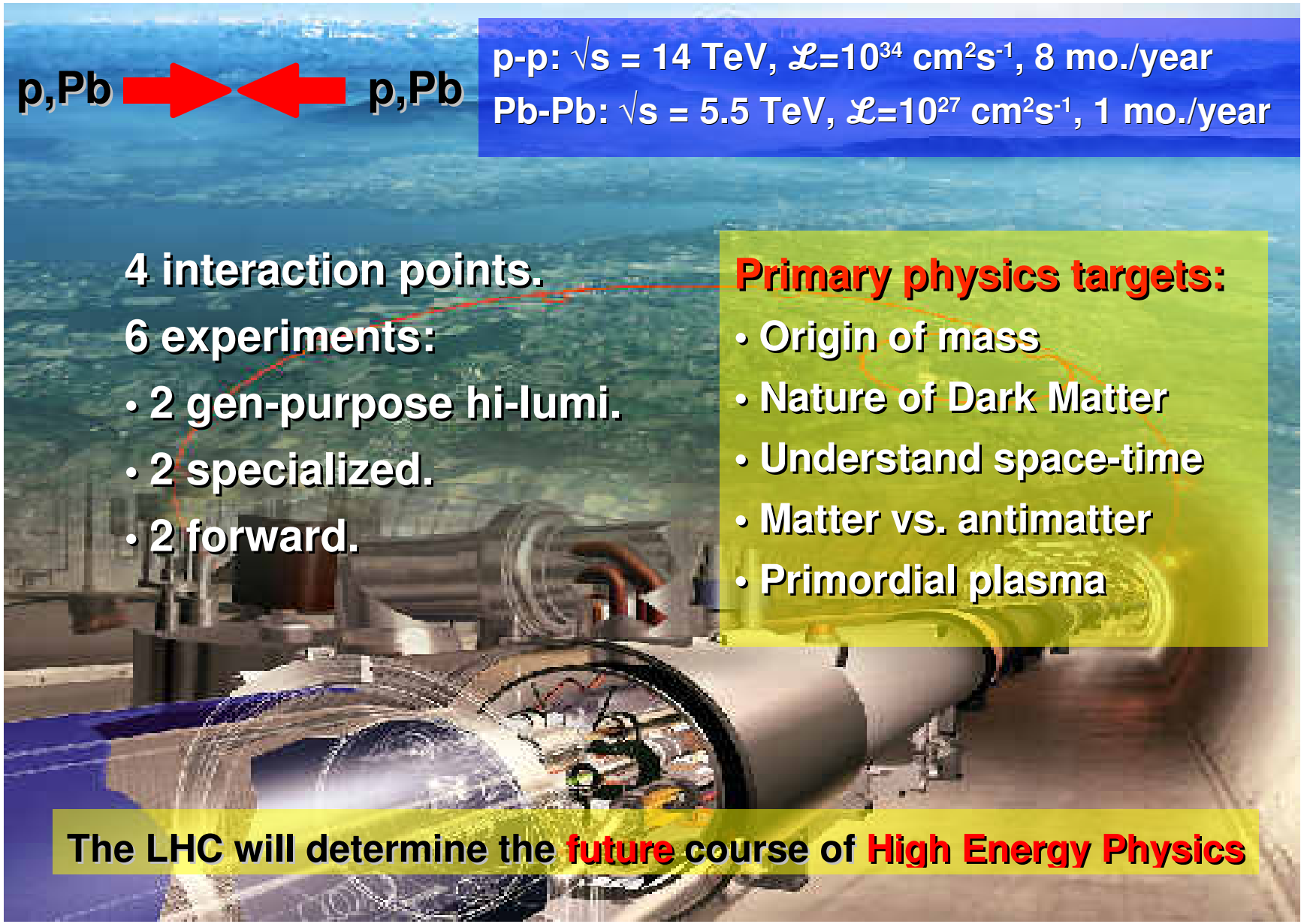
- "Mass generation" problem: What is the origin of elementary particle masses ? Higgs mechanism ? other physics ?
- "Flavour" problem: Why so many types of matter particles ? Origin of baryon asymmetry in the Universe ?
- "Hierarchy", "fine tuning" problem: Why large (10^{16} !) difference between EW & gravity (Planck) scales ? strings ? extra-dims ?
- "Dark matter" problem: ~1/4 matter in universe invisible. SUSY ?
- "QCD in non-perturbative regime" : Why quark confinement ? hadronic cross-sections ? Gauge-String duality (AdS/CFT) ?
- "Highest-energy cosmic-rays" : Sources/nature of CRs at 10^{20} eV?

High-energy (circular) colliders

- HEP tools to probe structure of matter & fundamental interactions:
  Synchrotrons with 2 colliding (stable) beams: $p,\bar{p}$, e^-, e^+, nuclei
- Key parameters: energy ↦heavy particles, luminosity ↦small x-sections
- Maximum energy (limits):
  $e^\pm$: synchrotron radiation: $E_{loss} \propto \gamma^4/R$ (note: $(m_p/m_e)^4 \sim 10^{13}$!)
  p, A: bending power of magnets: $p_{beam}(GeV/c)=0.3\times B(T)\times R(m)$

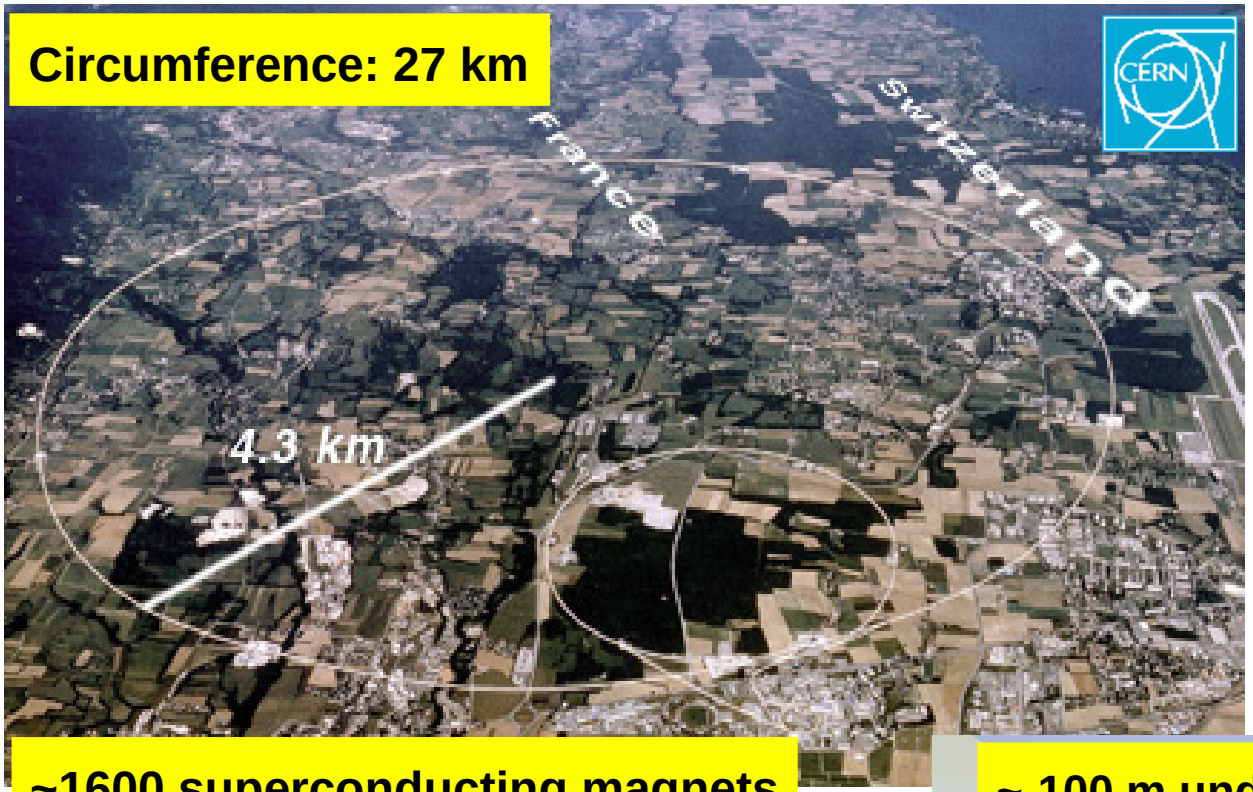
- LHC concept = "Discovery machine"
  - ❤ Highest $\sqrt{s}$ reachable:
    Hadron (not $e^\pm$) collider, largest R (LEP), strongest magnets: B=8.3 T
    $\sqrt{s}$ = 14(5.5) TeV ↦ ×7(×30) larger than Tevatron (RHIC)
  - ❤ Highest luminosity possible:
    Very high beam intensities (10^{11} protons/bunch, 2808 bunches).
    $\mathcal{L}=10^{34}cm^{-2}s^{-1} \Rightarrow 100\ fb^{-1}/year$ ↦ ×100 larger than Tevatron.

The LHC: a proton-proton & ion-ion collider

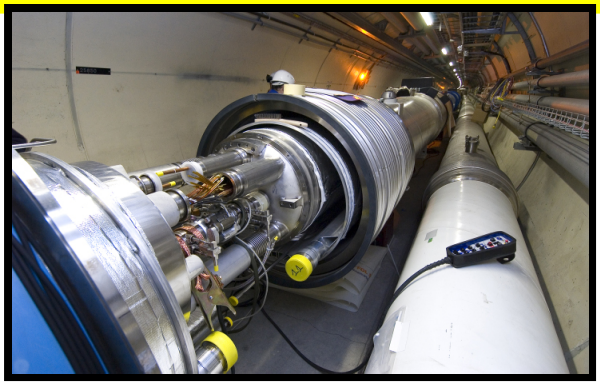


The CERN Large Hadron Collider

Circumference: 27 km



~1600 superconducting magnets



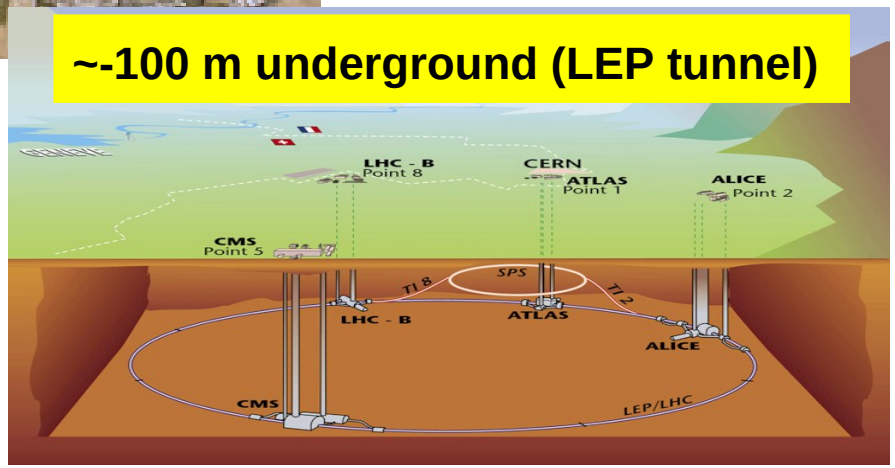
B = 8.4 T

T= 1.9 K

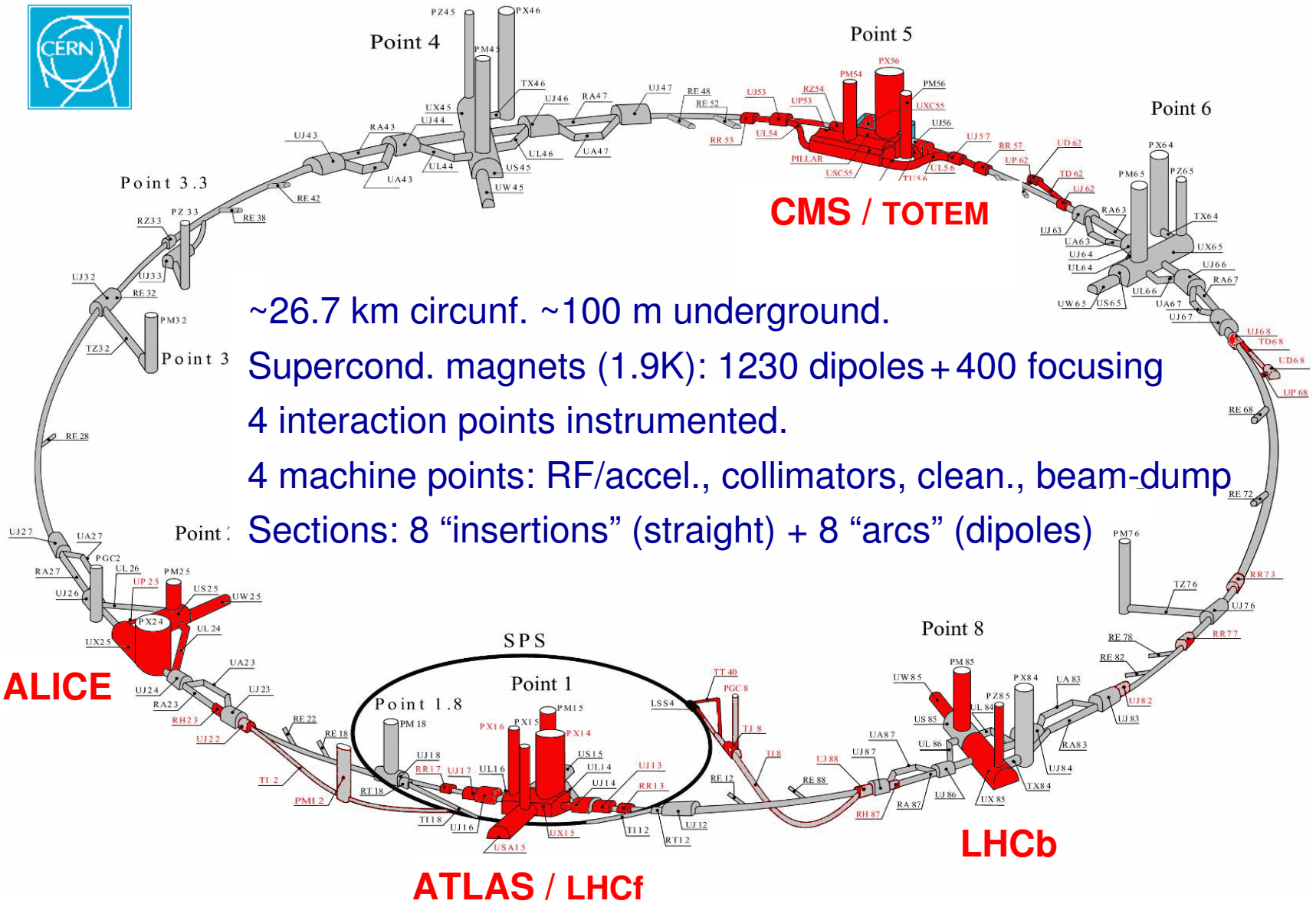
I = 11.7 kA

P=10^{-13} atm

~-100 m underground (LEP tunnel)



The LHC ring



~26.7 km circunf. ~100 m underground.

Supercond. magnets (1.9K): 1230 dipoles + 400 focusing

4 interaction points instrumented.

4 machine points: RF/accel., collimators, clean., beam-dump

Sections: 8 “insertions” (straight) + 8 “arcs” (dipoles)

LHC: center-of-mass energy

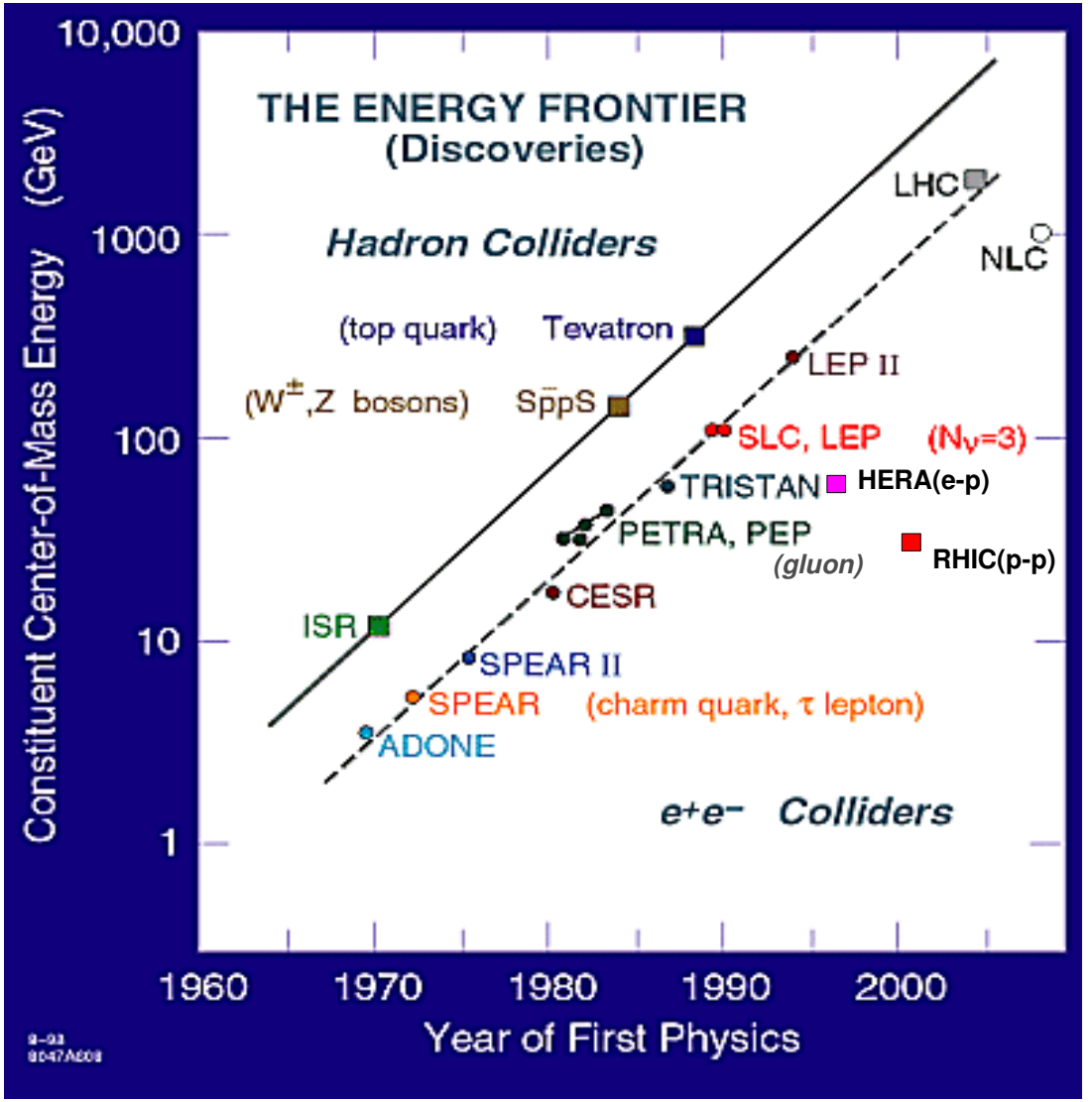
"Livingston plot"

Aim: Search for new physics at energy domain $\sqrt{s}$ >1 TeV

Beam of 7 TeV(*) achieved:

- L = 26.7 km (x4 Tevatron)
- B-field = 8.33 T (x2 Tevatron)

(*) LHC parton beam energy ~1 TeV



LHC: luminosity

- Collider luminosity $\mathcal{L}$ characterizes its "ability" to deliver collisions per unit time & cross-section [$m^{-2}s^{-1}$]:

$$\mathcal{L} = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*} F(\sigma_{x,y})$$

→

k: # of bunches. $k = 2808$

N: # of protons/bunch. $N = 1.15\times10^{11}$

f : revolution frequency. $f = 11.25$ *kHz*

σ_x,σ_y*: beam size at coll. point.* $\sigma_{x,y} = 16\ \mu m$

$F(\sigma_{xy})$*: x-angle at coll. point.* $\sigma_{x,y} = 165\ \mu m$

→ LHC:

$\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$

$\sim 10 nb^{-1}s^{-1}$!

- Events collected in time t for process with cross-section σ: $N = \int \mathcal{L}dt\ \sigma$

LHC: $\int \mathcal{L}dt = 100\ fb^{-1}$ in "1-year" (10^7 s)

- To maximize $\mathcal{L}$:

(1) Many bunches (k)

(2) Many particles per bunch (N^2)

(3) Small beam-size: $\sigma^*_u = (\beta^*\varepsilon)^{1/2}$

(4) Crossing angle: $F(\sigma_{x,y})$

High beam "brilliance" N/ε (particles per phase space vol.) → Injector chain performance !

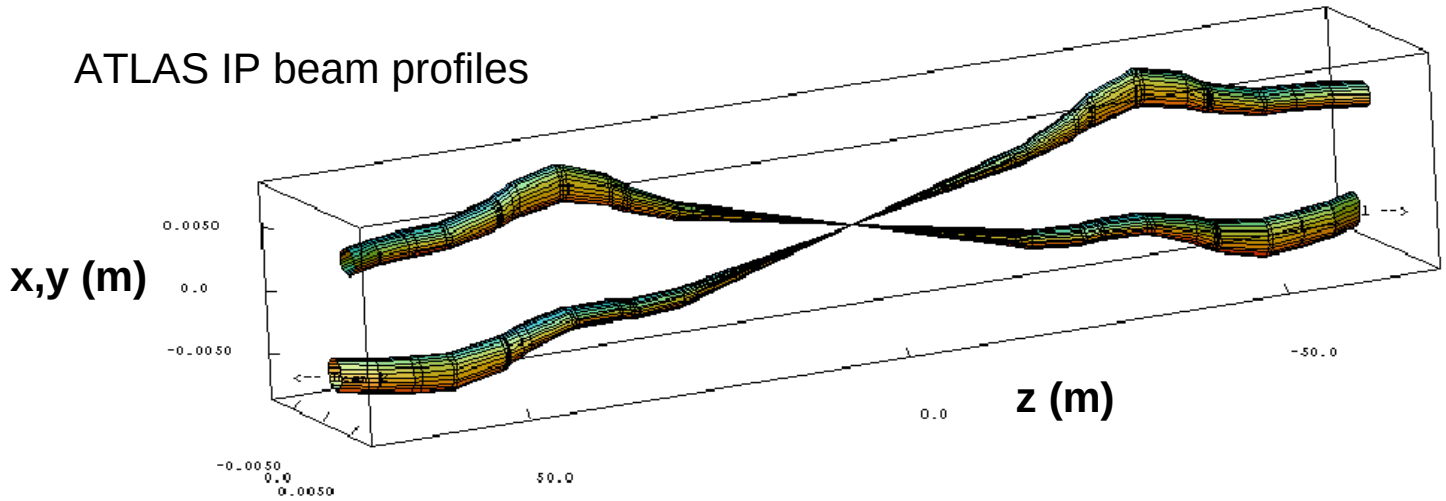
Small envelope → Strong focusing !

Beam overlap at IP → Beam-lines

(LHC: $10^{34}\ cm^{-2}s^{-1} \gg$ Tevatron: $2\cdot10^{32}\ cm^{-2}s^{-1} \gg$ SppS: $6\cdot10^{30}\ cm^{-2}s^{-1}$)

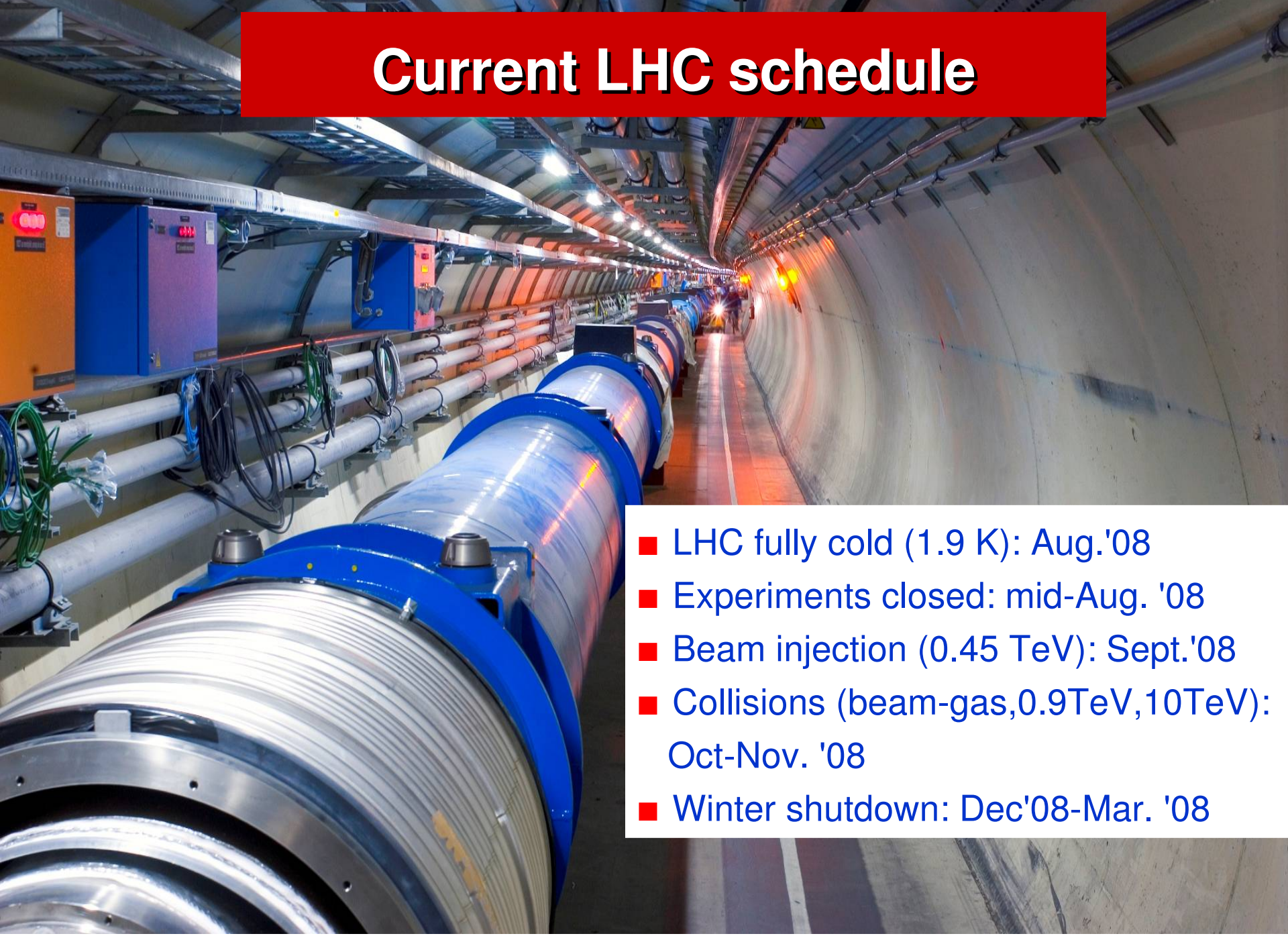
LHC beams

- Protons accelerated in 2808 bunches spaced by 25 ns (~7. m)
- Each bunch: ~10^{11} protons (1 cc of hydrogen = ~10^{19} protons)
- Each bunch is z = 7.5 cm long, squeezed down to x,y=15μmx15μm (1/3 human-hair) at interaction point:



- Each proton occupies a volume of 15x15x75000/10^{11} ~ 10^{-4} μm^3 (much bigger than an atom!) so collisions are still rare.
- Yet, with 10^{11} p/bunch: ~25 interactions every crossing.

Current LHC schedule

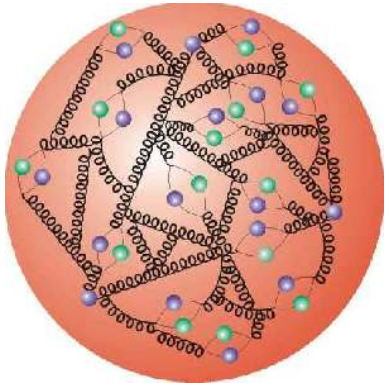


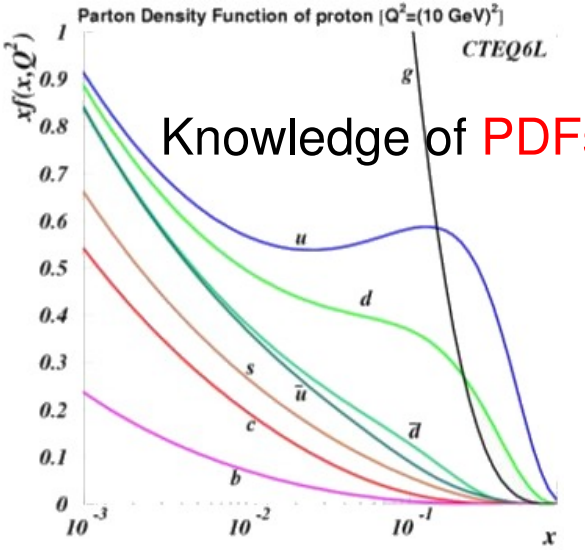
- LHC fully cold (1.9 K): Aug.'08
- Experiments closed: mid-Aug. '08
- Beam injection (0.45 TeV): Sept.'08
- Collisions (beam-gas,0.9TeV,10TeV): Oct-Nov. '08
- Winter shutdown: Dec'08-Mar. '08

Hadron collisions: challenges

- Protons have structure:

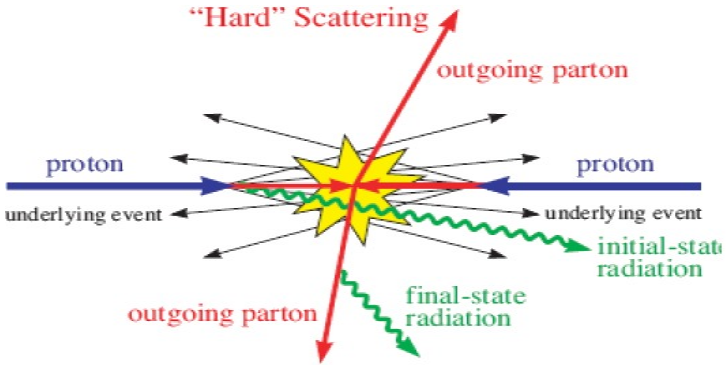
  Hard scatters: glue-glue, q-g, q-q.





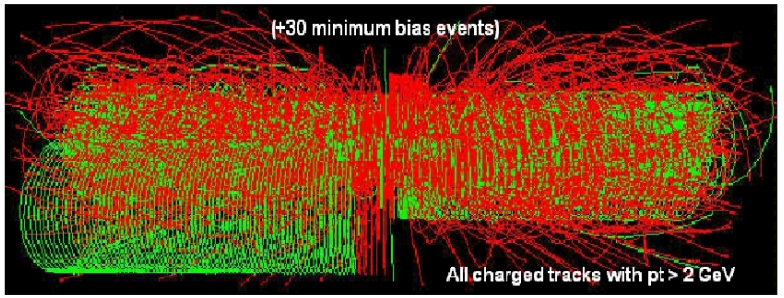
Knowledge of PDFs essential !

- Underlying event: multi-parton interactions, beam-remnants, ISR, FSR

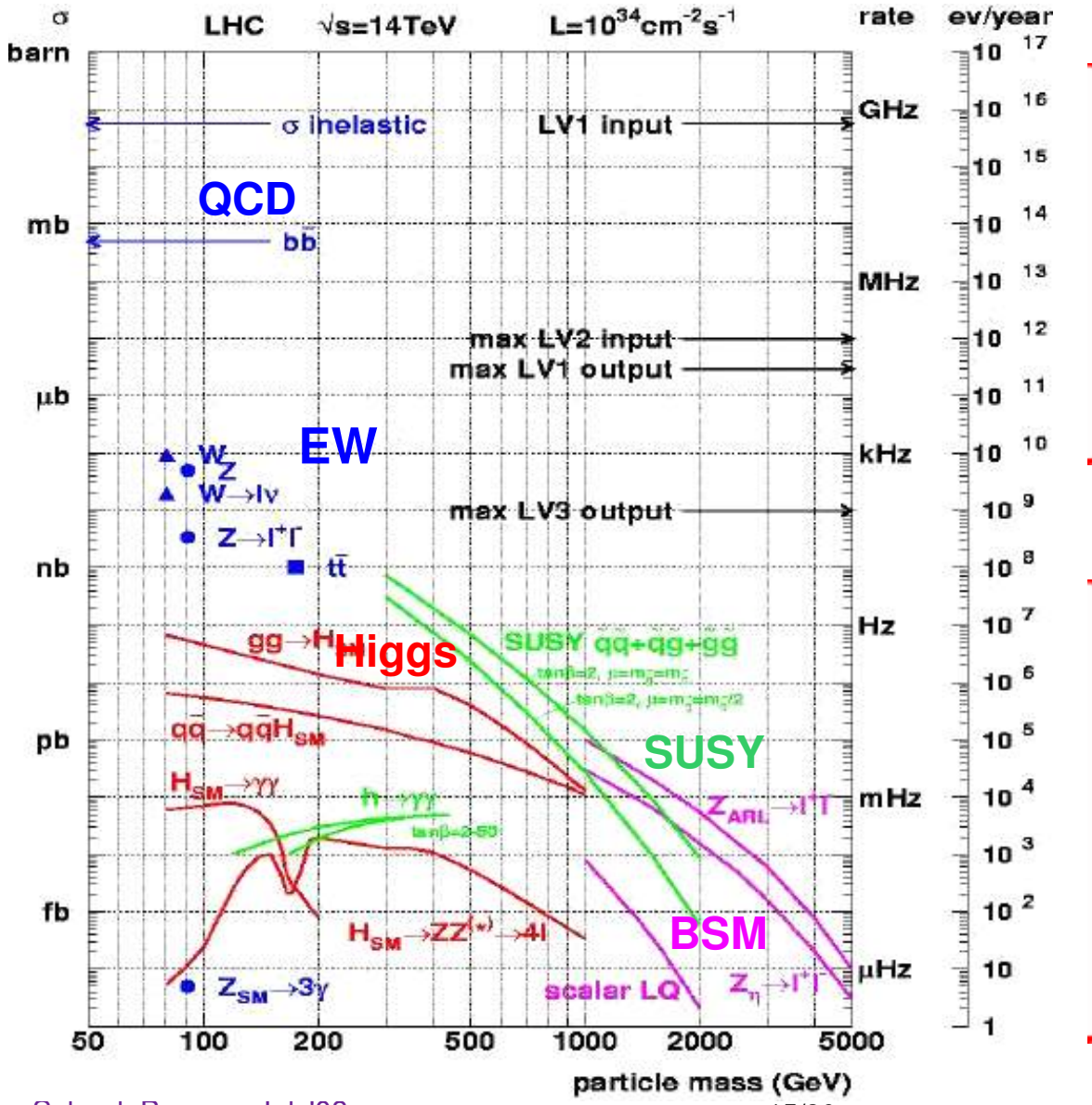


- Pile-up:

  ~25 p-p collisions/crossing



Hadron collisions: challenges (cont'd)



- Cross-sections ...
- Known processes:
  ("backgrounds")

  $\sigma \sim 1/(100\ \text{MeV})^2$

10^{-8} !

Compare:

needle (10^{-8} m^3)

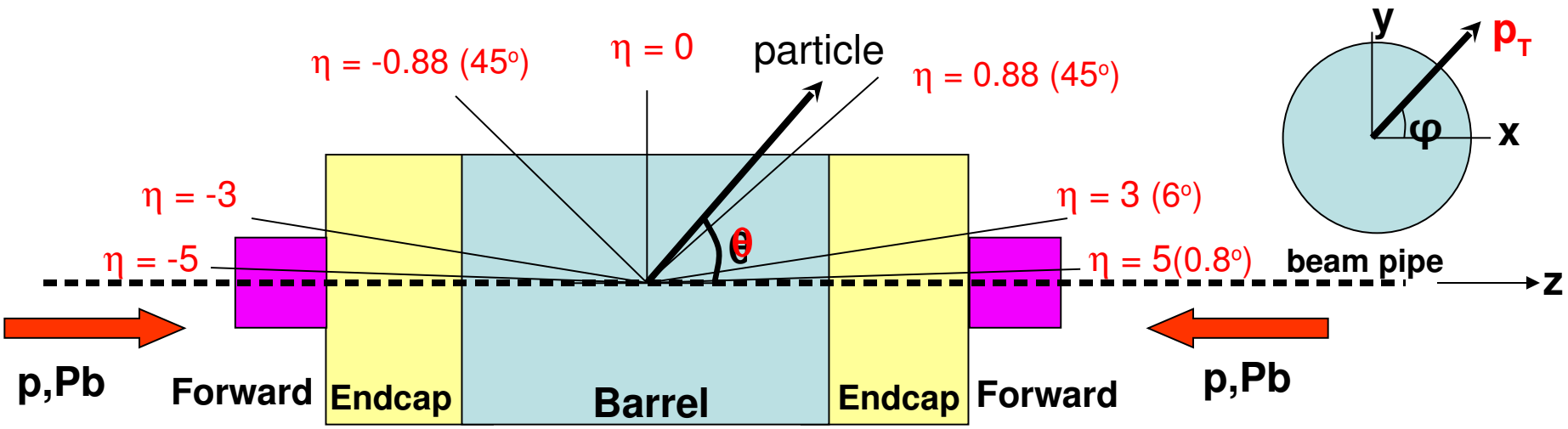
in haystack (100 m^3)

- New Physics:

  $\sigma \sim 1/(1\ \text{TeV})^2$

Hadron collisions: kinematics

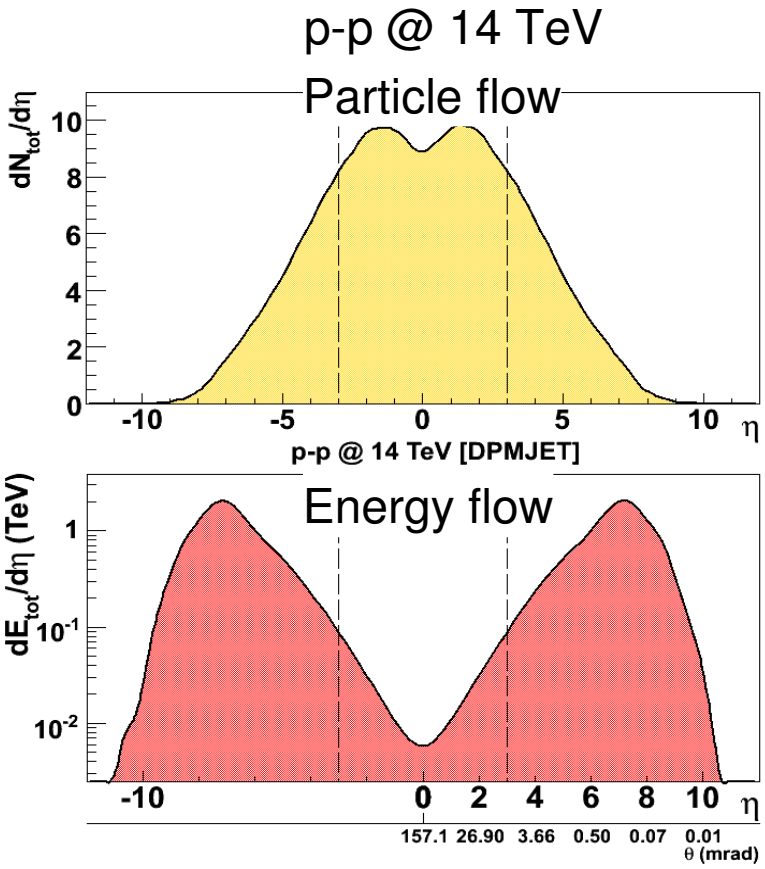
- Hadron = "beam" of partons with initial p_T~0 but unknown p_L fractions

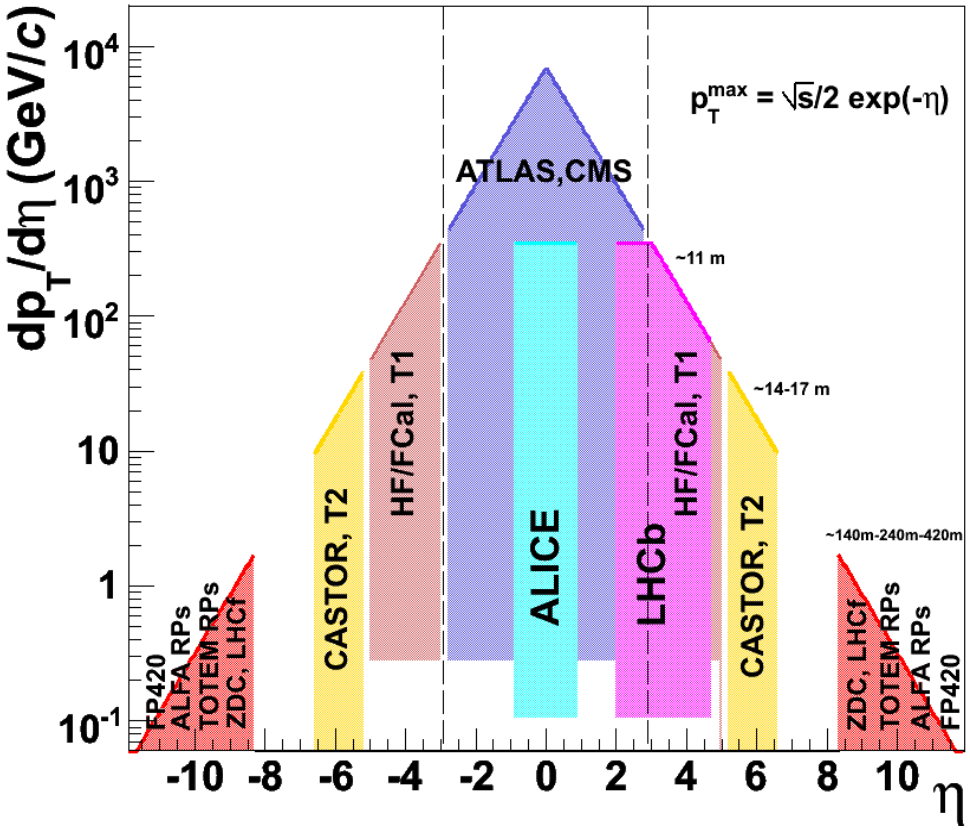


- Transverse momentum: $\mathbf{p}_T = (p_x, p_y)$ $|\mathbf{p}_T| = p \sin(\theta)$
- Rapidity: $y = \frac{1}{2}\log\frac{E + p_z}{E - p_z}$ (Differences in rapidity are conserved under Lorentz boosts in the z-direction)

Pseudorapidity: $\eta = -\ln[\tan(\theta/2)]$ η ~y if E≫m, and θ not too small)

Hadron collisions: (p_T,η) acceptance





- Particle production at the LHC over $\Delta y \sim 2 \cdot y_{beam} = 2 \cdot \ln(\sqrt{s})/m_p \sim 20$
- Most of phase-space covered (1st time in a collider !)

Experiments with answers(?) at the LHC

- "Mass generation" problem:
  (Higgs boson)

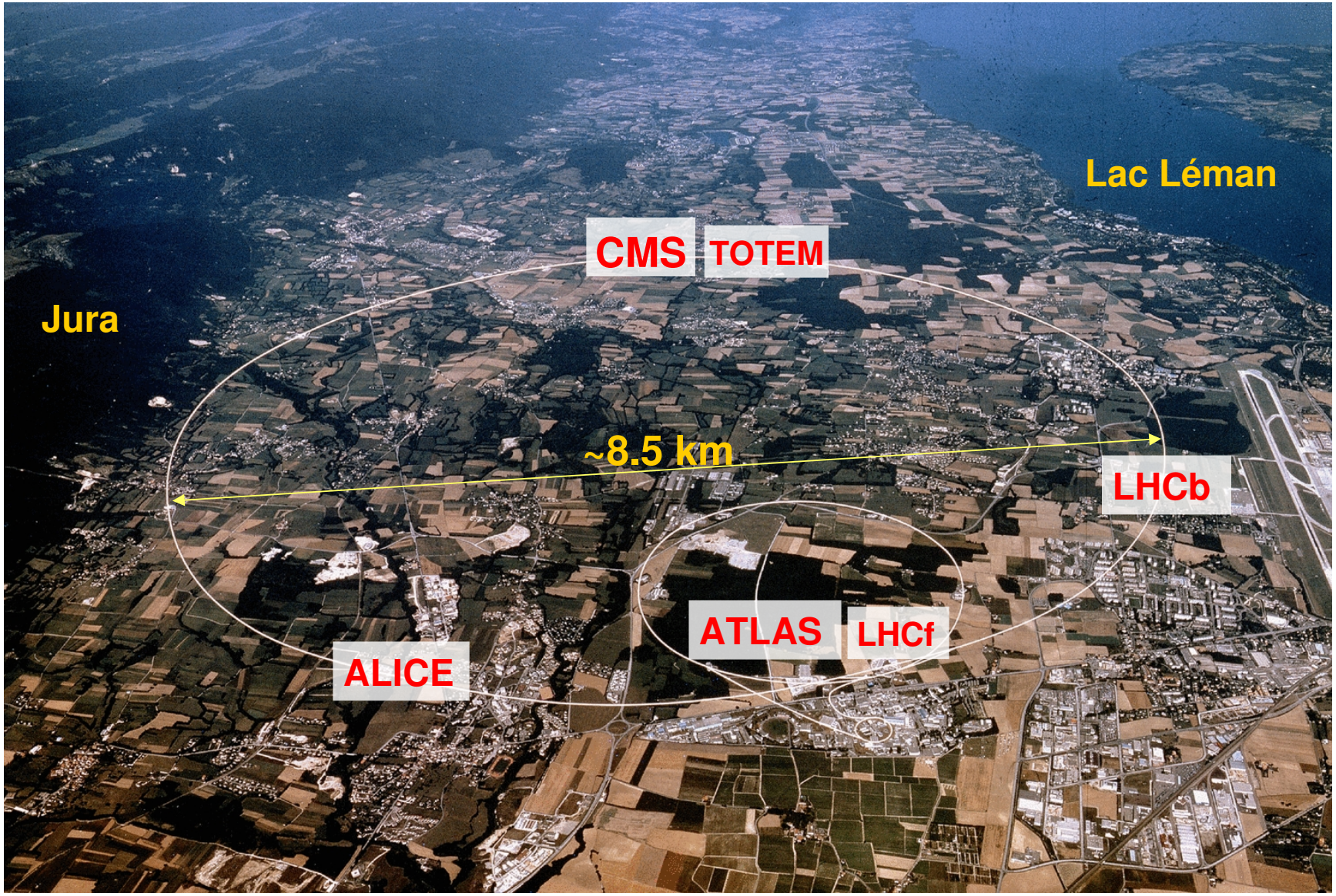
- "Flavour" problem:
  (SUSY, BSM)

- "Hierarchy", "fine tuning":
- "Dark matter" problem:
  (SUSY, BSM)

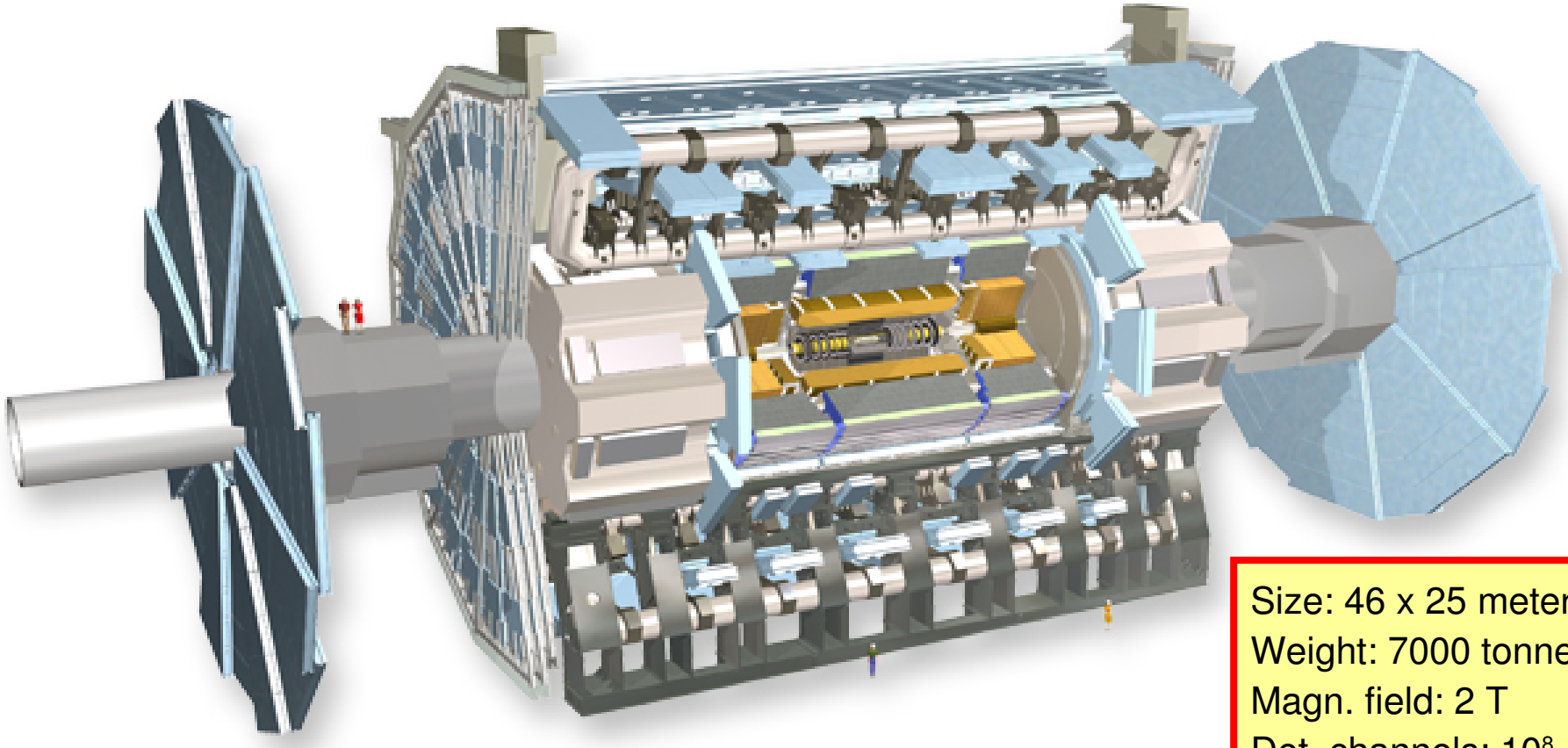
- "non-perturbative QCD":
  (QCD, QGP)

- "Highest-energy cosmic-rays":

The LHC experiments



ATLAS: general purpose detector

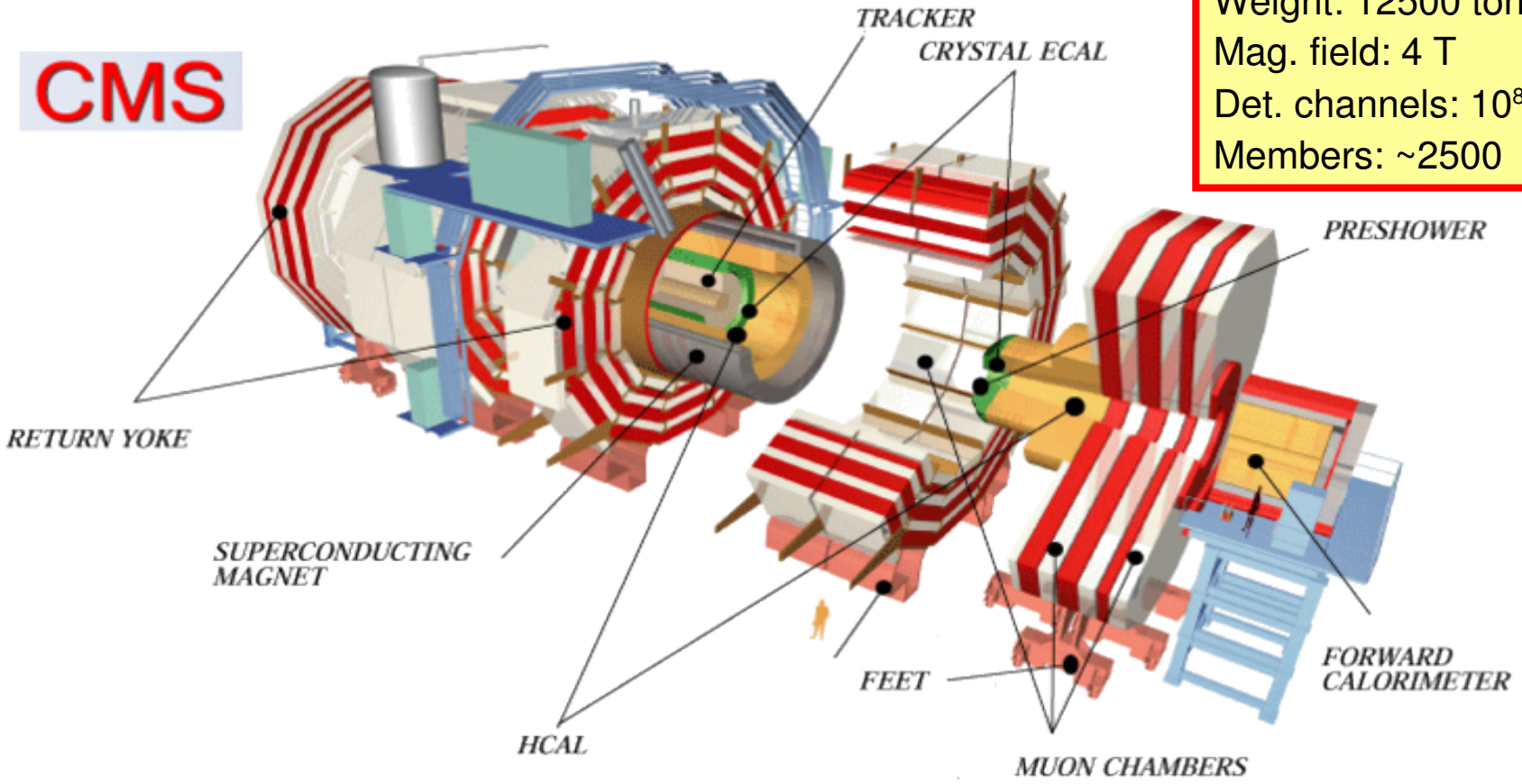


Size: 46 x 25 meters
Weight: 7000 tonnes
Magn. field: 2 T
Det. channels: 10^8
Members: ~2000

- Multi-purpose detector: SM, new physics, heavy-ions, ...
- Key aspects: Largest detector ever (highest-p_T), toroidal muon magnet

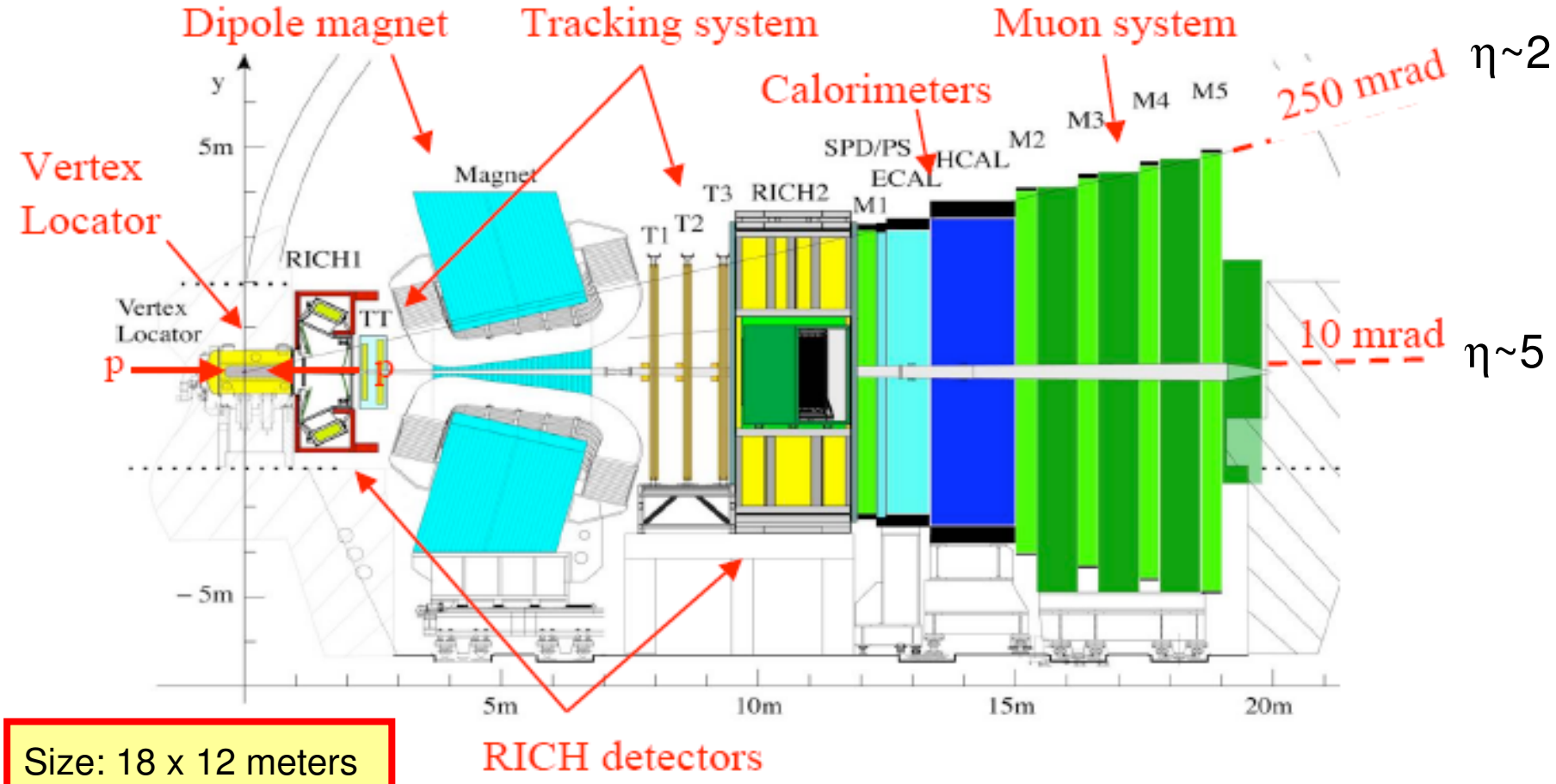
CMS: general purpose detector

Size: 22 x 15 meters
Weight: 12500 tonnes
Mag. field: 4 T
Det. channels: 10^8
Members: ~2500



- Multi-purpose detector: SM, new physics, heavy-ions, ...
- Key aspects: largest magn. field (highest-p_T), fwd. acceptance, heaviest

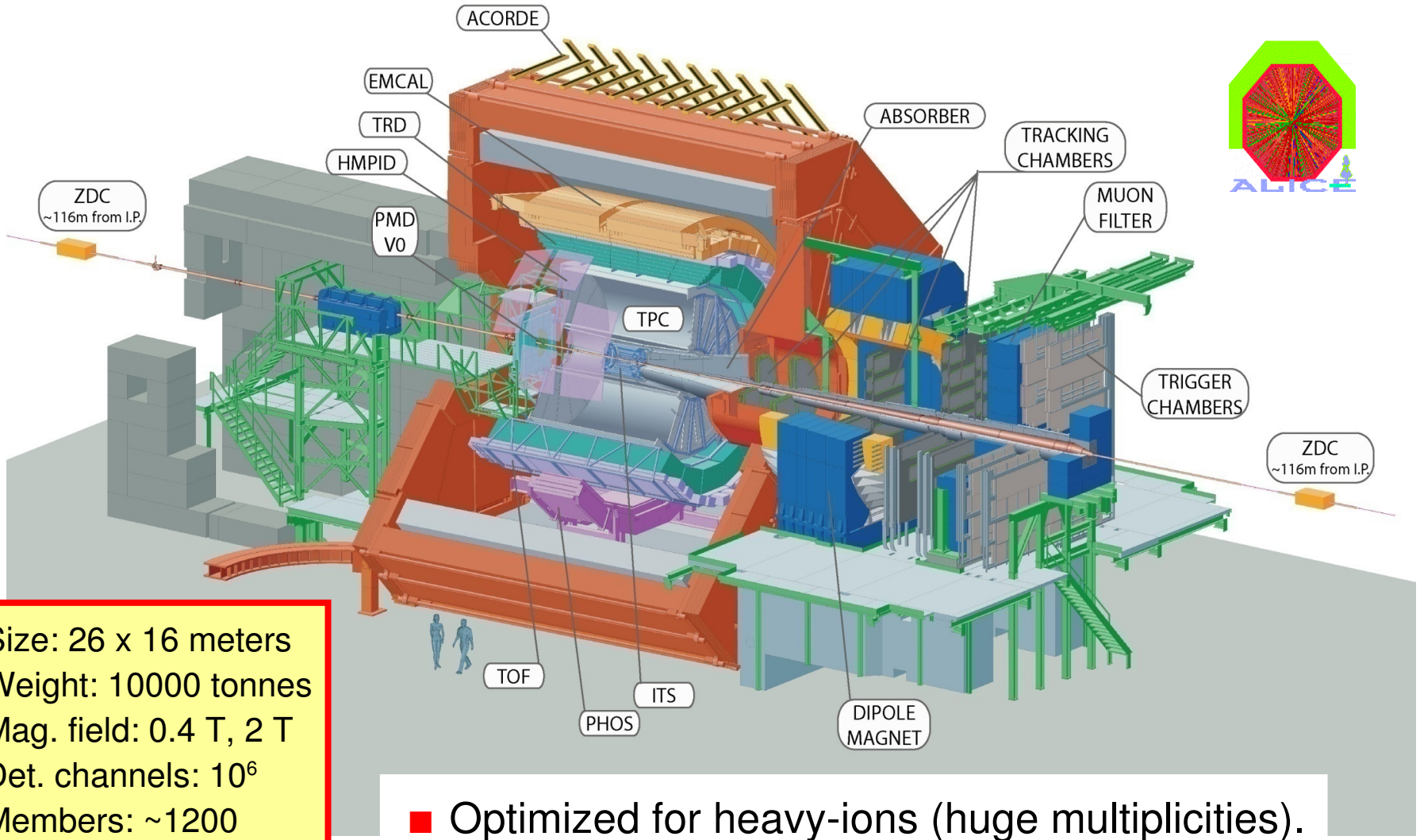
LHCb: B-physics dedicated detector



Size: 18 x 12 meters
Weight: 4300 tonnes
Mag. field: 2 T
Det. channels: 10^6
Members: ~600

- Single-arm detector optimized for B-meson reco.
- Key issues: Particle ID, secondary vertexing

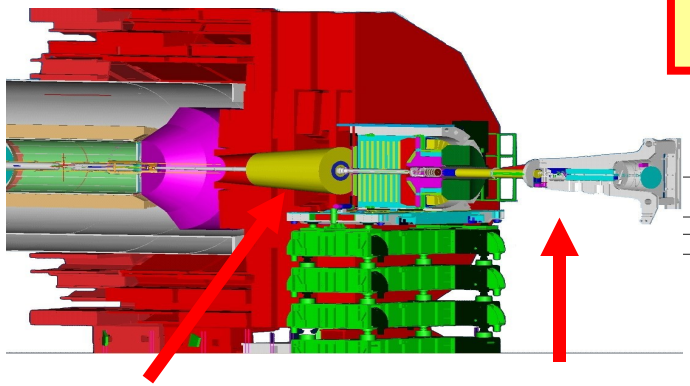
ALICE: heavy-ions dedicated detector



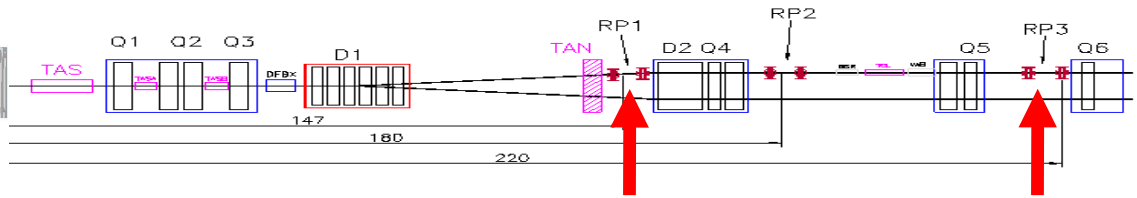
Size: 26 x 16 meters
Weight: 10000 tonnes
Mag. field: 0.4 T, 2 T
Det. channels: 10^6
Members: ~1200

- Optimized for heavy-ions (huge multiplicities).
- Key issues: TPC tracking, particle-ID, low p_T

TOTEM & LHCf: forward detectors

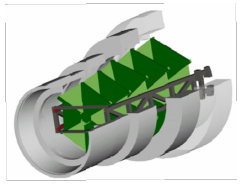


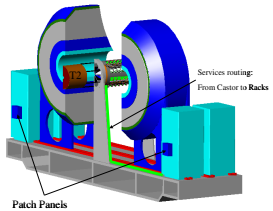
Det. channels: 10^4. Members: ~80

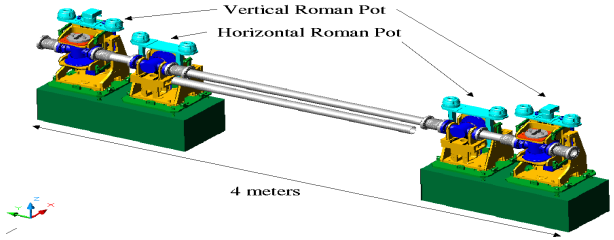


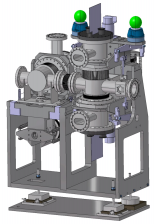
■ **Roman Pots:** RPs@147m RPs@220m

■ **T1,T2** (±10m,±13m CMS):

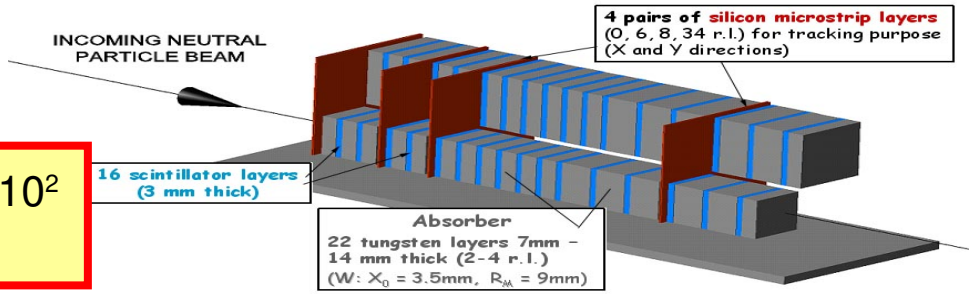


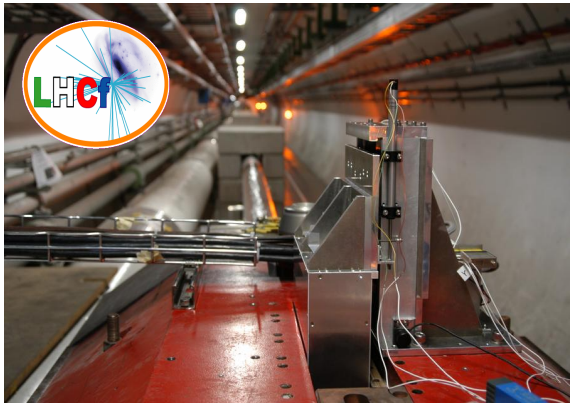






■ **LHCf** (±140m in ATLAS tunnel):





Det. channels: 10^2
Members: ~30

ATLAS/CMS:
Higgs & BSM
physics at the LHC

SM Higgs: production

- Higgs couplings ∝ **mass**

  - Gluon fusion:

    gg → H, dominant,

    large QCD backgrounds

  - Vector-Boson-Fusion:

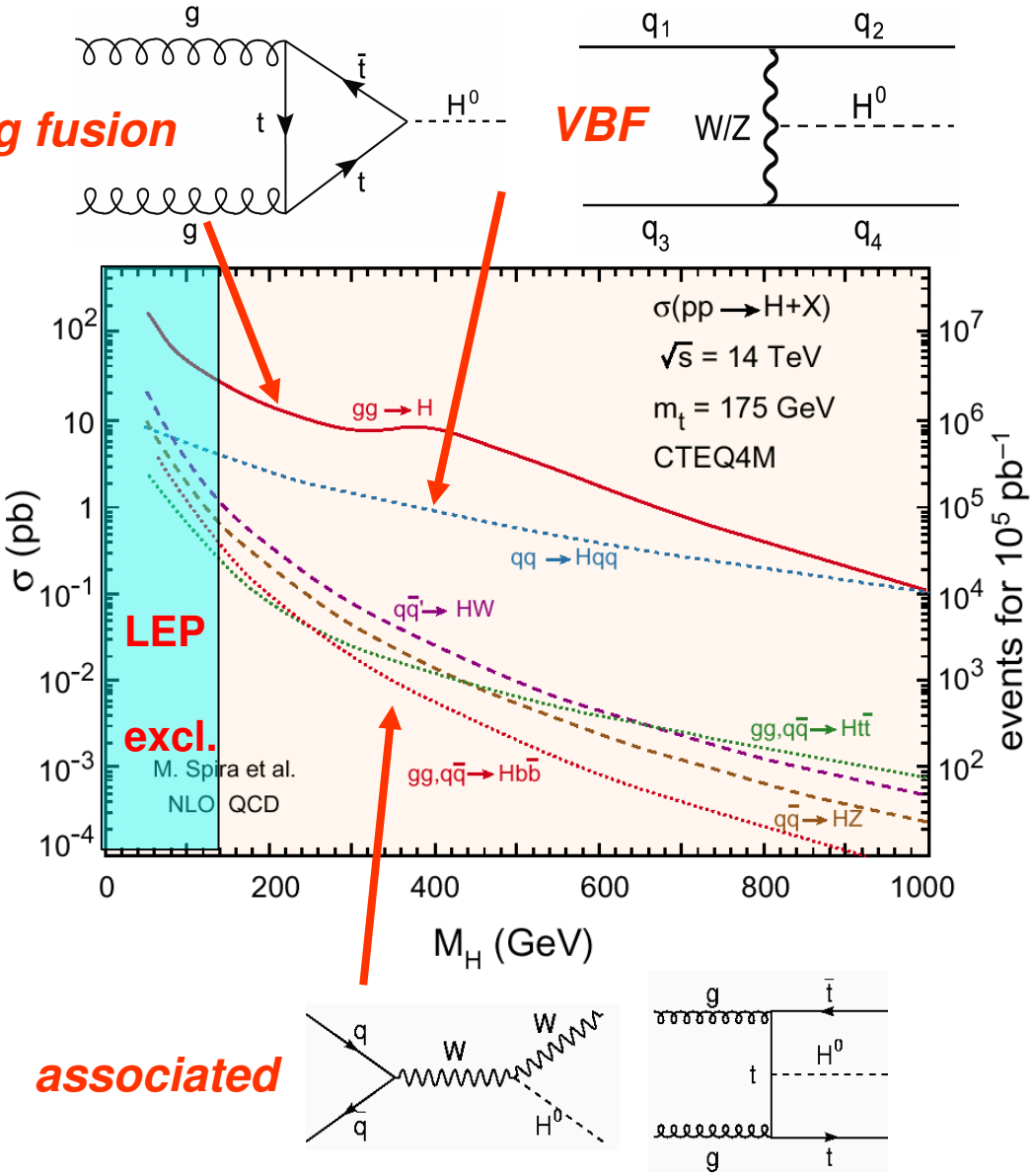
    qq → qq H, ~20% of σ_H

    distinct final state (fwd. jets)

  - Associated:

    ttH, WH, ZH

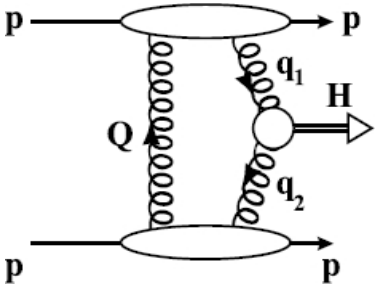
    small cross-sections



[SM Higgs: alternative production]

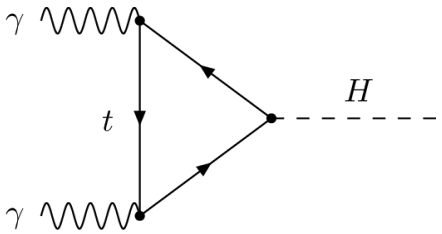
- 2 additional channels actually ...

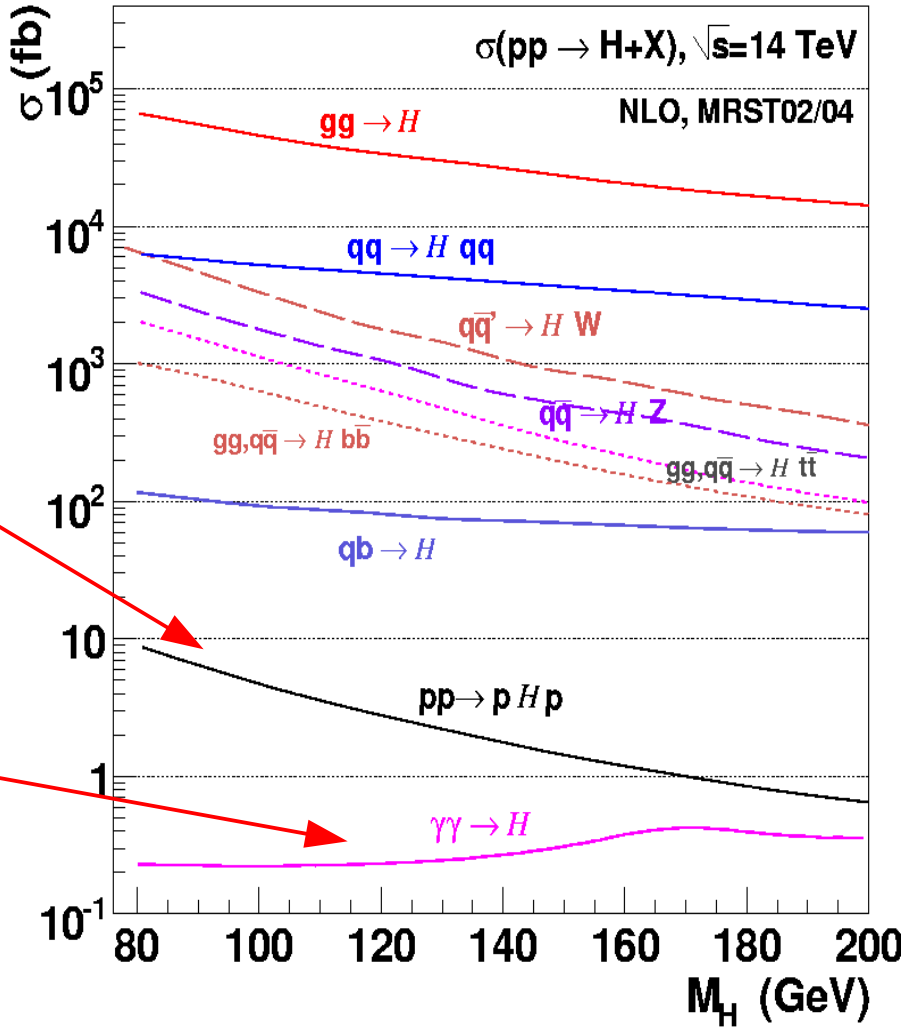
Central Exclusive production:



Two-photon fusion production:

pp→**γ**→H





- Low cross-sections but "zero" background. Require forward proton tagging (FP420 project: arXiv:0806.0302)

SM Higgs: decay

- M_H<135 GeV:

Dominant BR: b-bar

Huge QCD bckgd !

Very difficult at the LHC(*)

Discovery channels: $\gamma\ \gamma$, $\tau^+\tau^-$

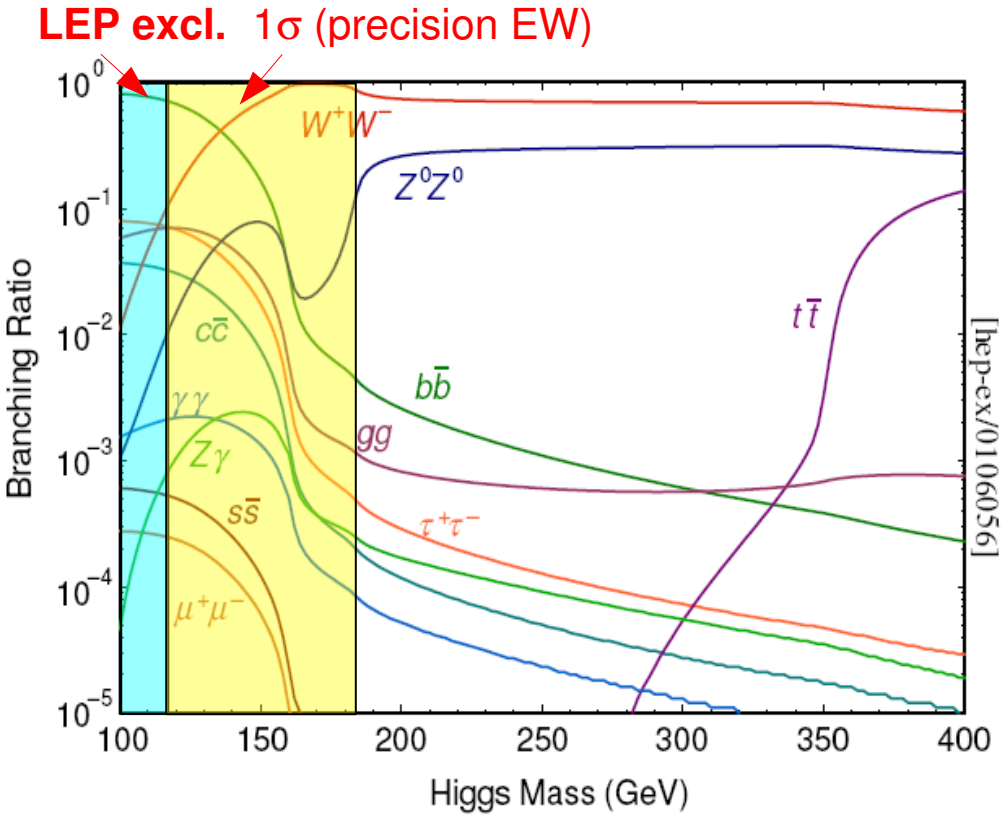
(*) except maybe in central-exclusive

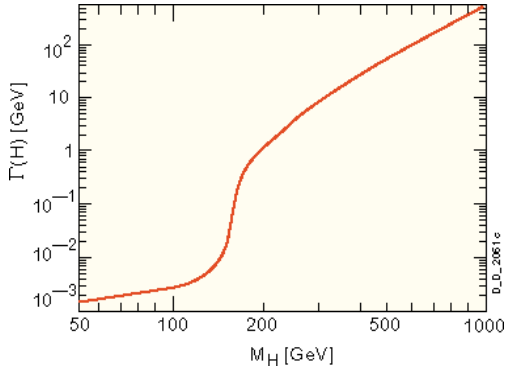
- M_H>135 GeV:

Dominant BR: $WW^{(*)}$,$ZZ^{(*)}$

Relatively easy discovery via

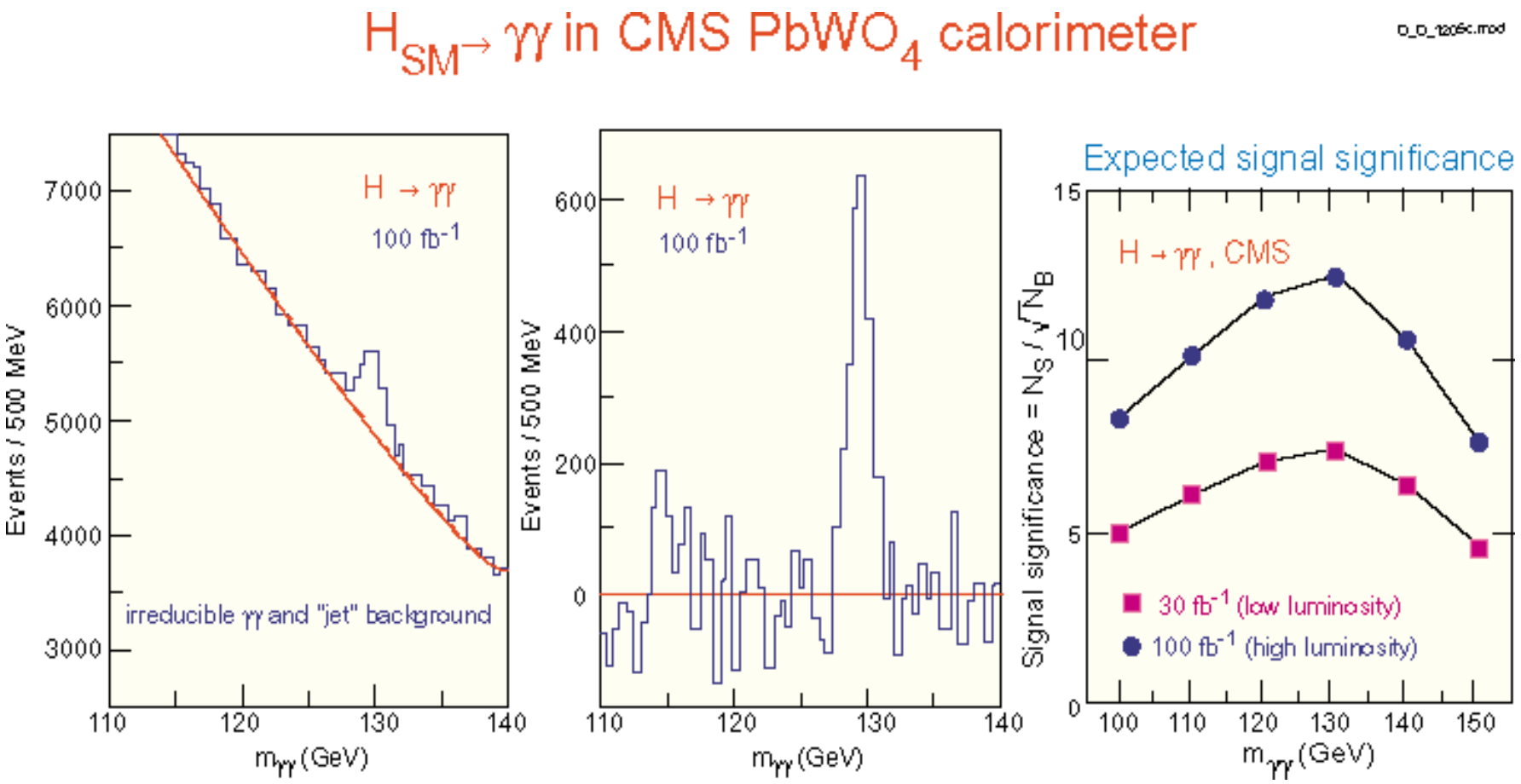
leptonic W,Z→e,τμ decays



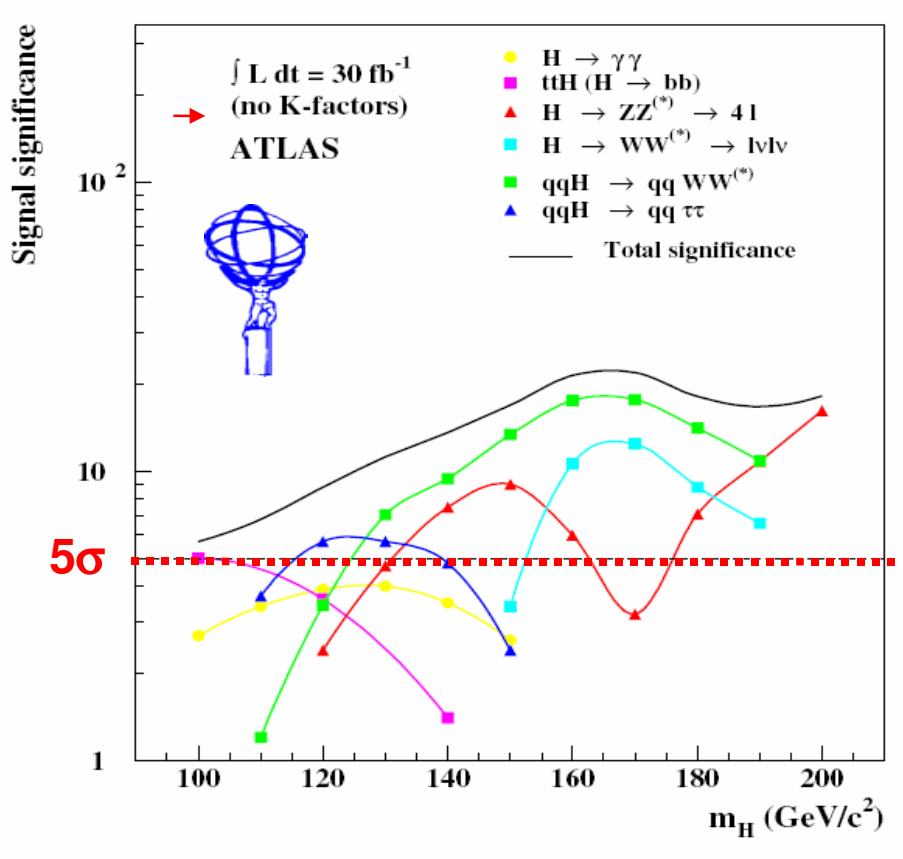


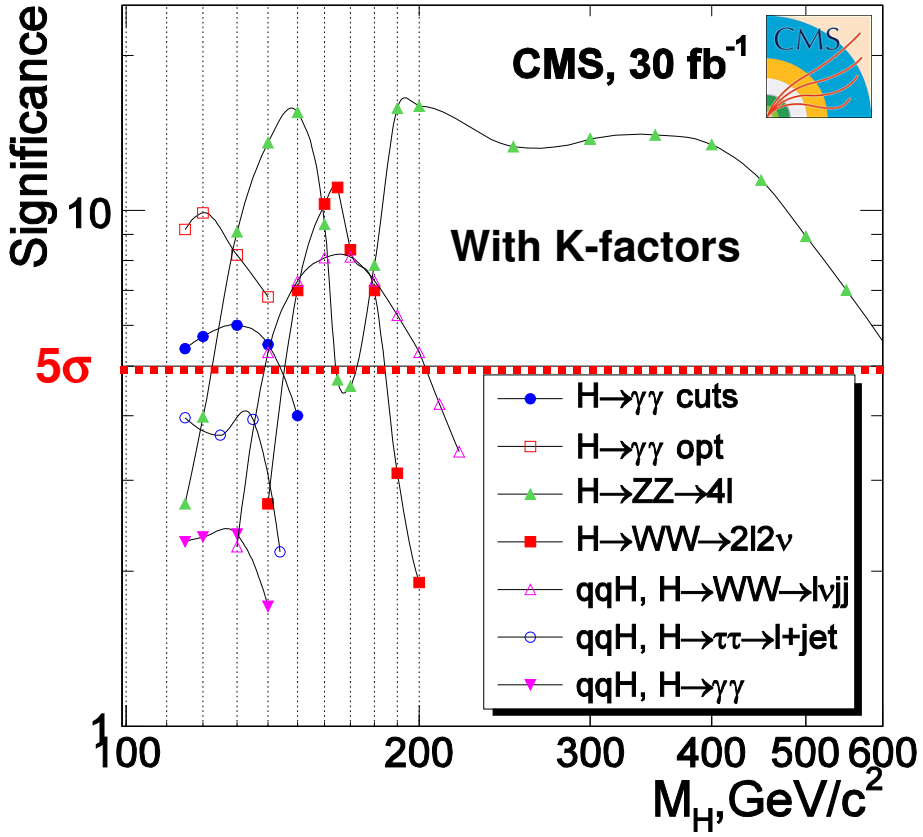
Width becomes large as WW mode opens.

SM Higgs: H→γγ example



SM Higgs: signal significance (30 fb^{-1})



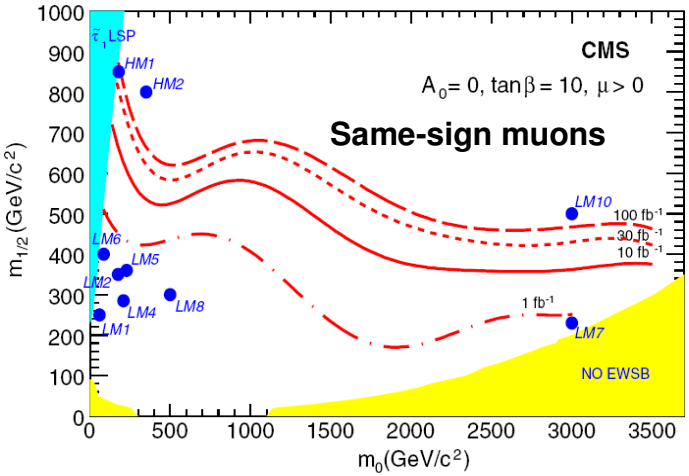


- If it exists, Higgs discovered ($S/\sqrt{B}=5\sigma$) with a few tens fb^{-1}
- LHC: ~1 fb^{-1} in 2009(?), increasing to 100 fb^{-1}/year at design luminosity.

"Hierarchy" problem: BSM searches ...

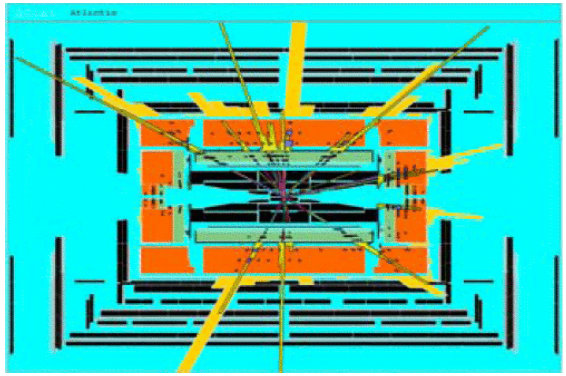
- Popular candidate beyond-SM theories ...

SUSY (MSSM, mSUGRA)



Extra-dimensions:

(RS, ADD: KK-towers, mini-BH)



spherical evt.,
"thermal"
particle prod.

also: technicolour, Little Higgs, unparticles, ...

high-p_T, large-mass reco capabilities required !

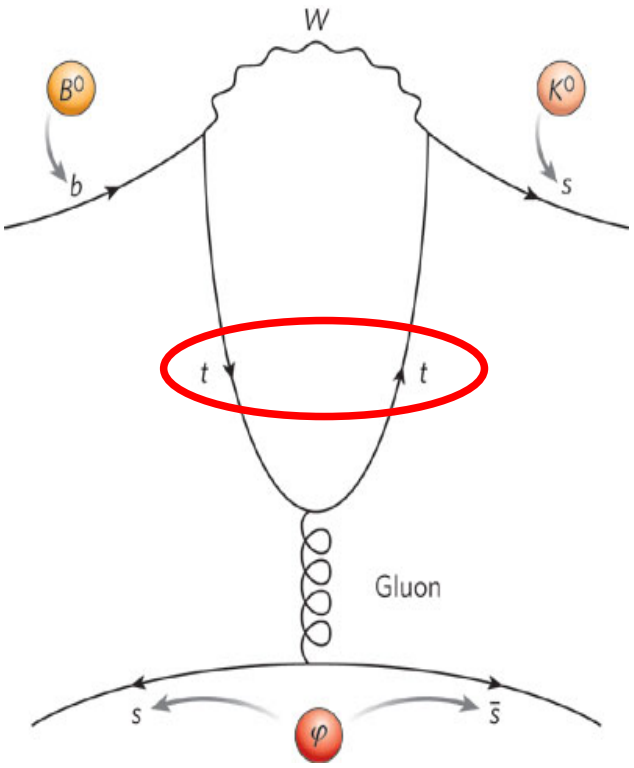
- Other general final-state searches: Z',W', lepto-quarks, heavy-ν compositeness, anomalous gauge couplings, contact interactions, ...

LHCb:

B-physics at the LHC

New physics via virtual particles

- Major goal of quark flavour physics at the LHC: look for flavour-changing beyond the SM appearing in loop processes.

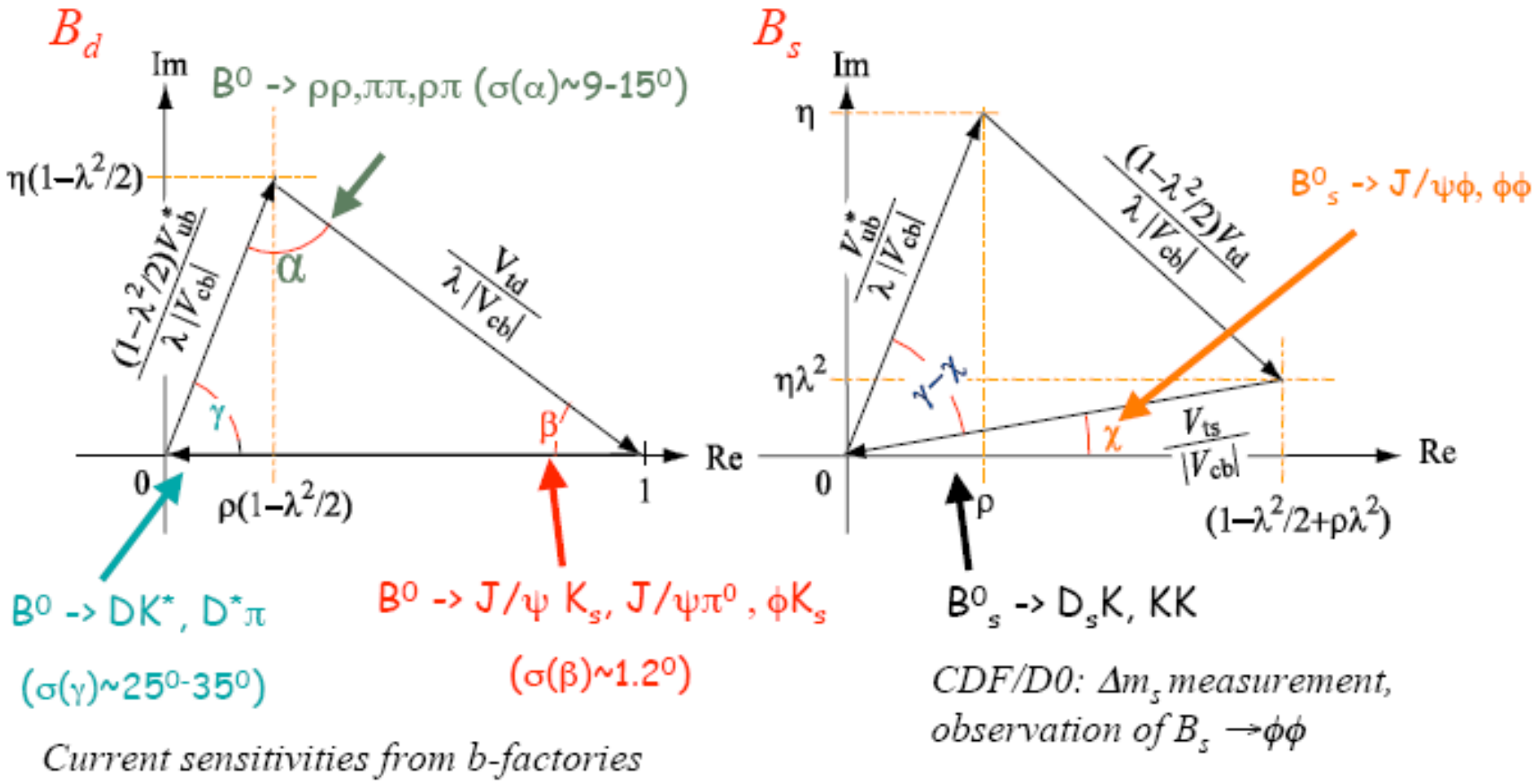


- Examples ...

- increased penguin and/or box contributions appearing in branching ratios, oscillation frequencies and/or CP violation, with/without additional mixing parameters
- deviation from the V-A structures

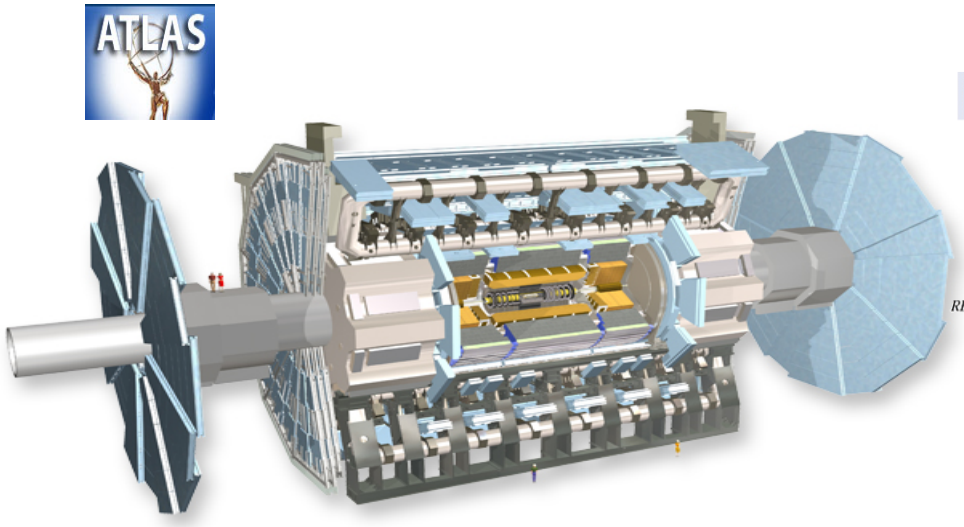
T.Nakada (LHCb) [13-15 July]

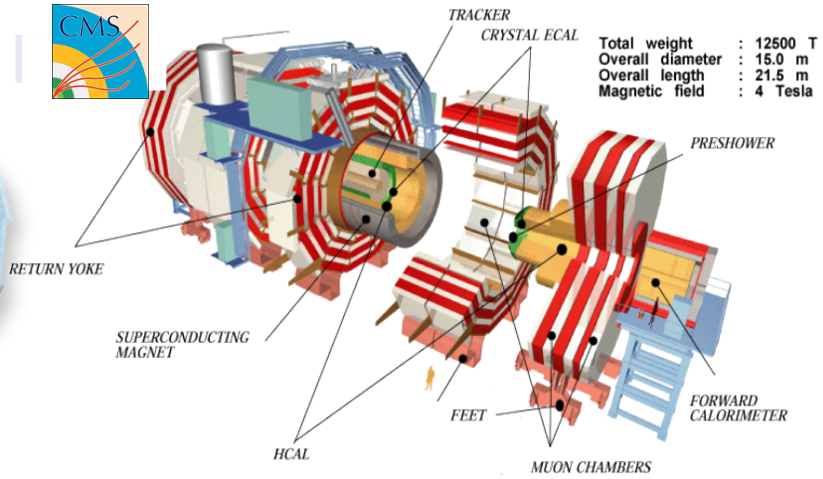
New physics via virtual particles

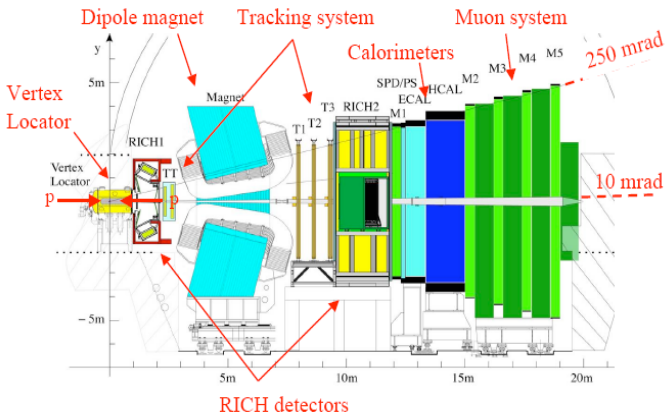


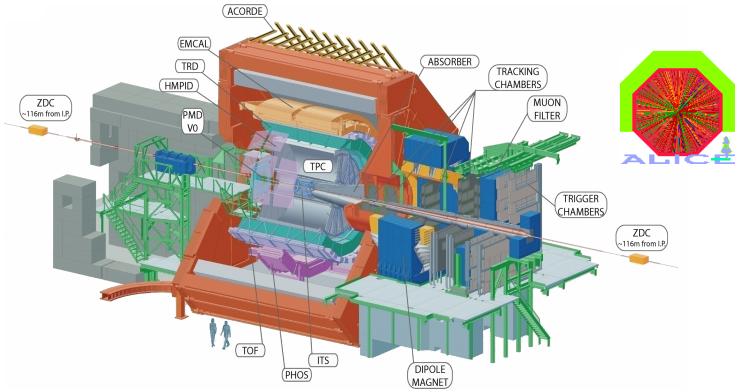
- Measurements of decay rates & kinematics tell us about squark mixings
- Over-constraining triangles: sensitivity to new physics through loop effects.

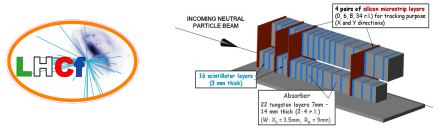
Summary Lecture-I: Experiments at the LHC

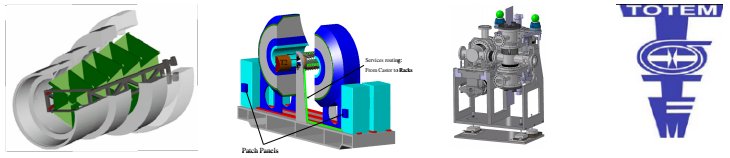






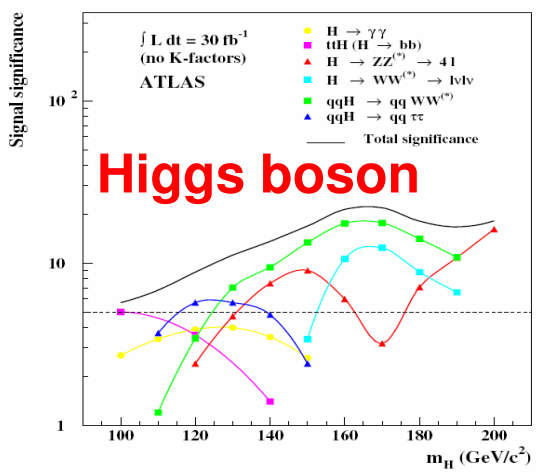






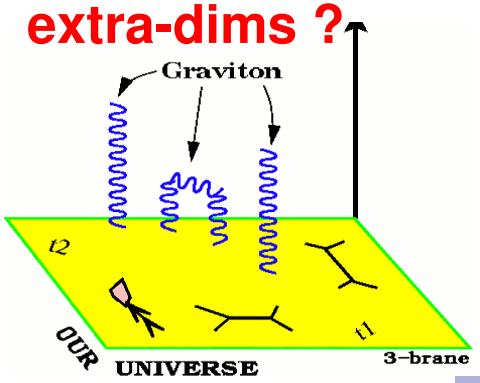
Flavor School, Benasc, July'08 35/36 David d'Enterria (MIT)

Summary Lecture-I: Physics at the LHC

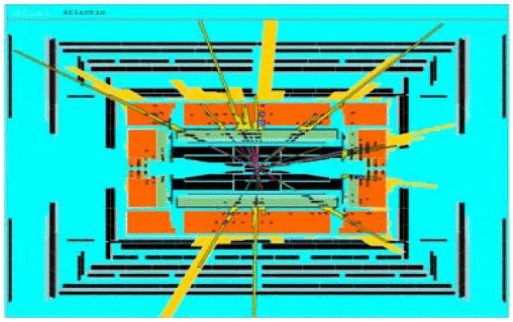


Higgs boson

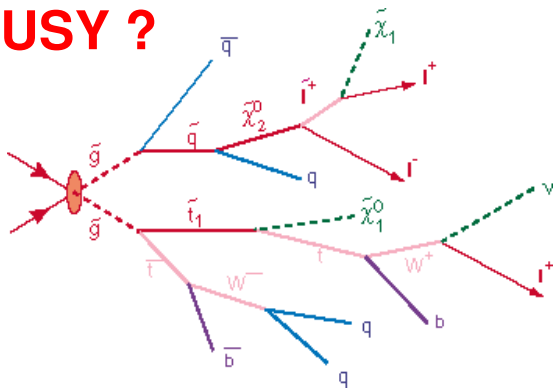
extra-dims ?



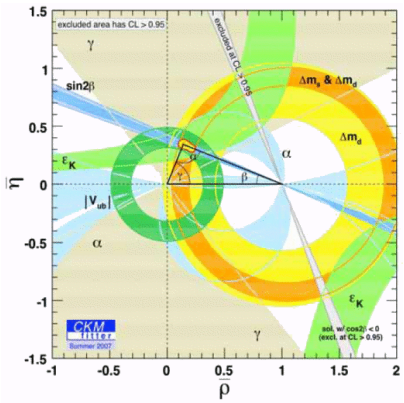
mini black-holes ??



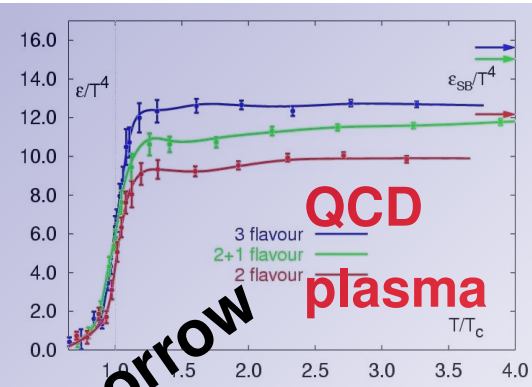
SUSY ?



CP-violation

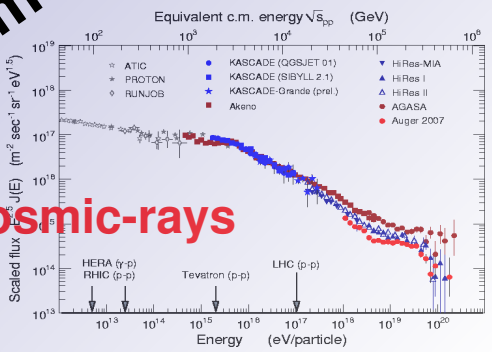


QCD plasma



tomorrow

GZK cosmic-rays



+ precision SM (QCD, EW, top, ...)