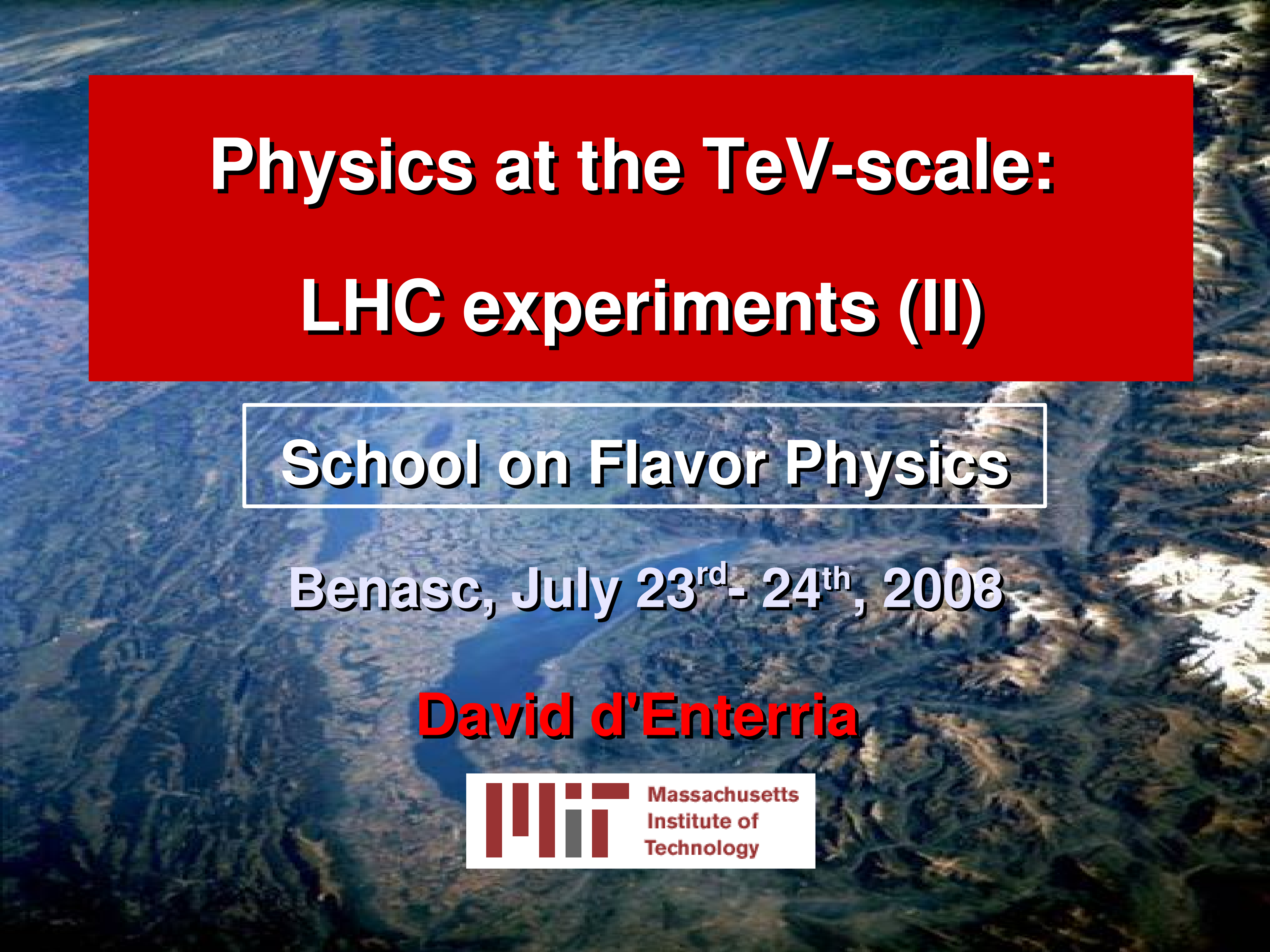


Physics at the TeV-scale:

LHC experiments (II)

School on Flavor Physics

Benasc, July 23rd- 24th, 2008

David d'Enterria

Massachusetts
Institute of
Technology

Plan of lectures

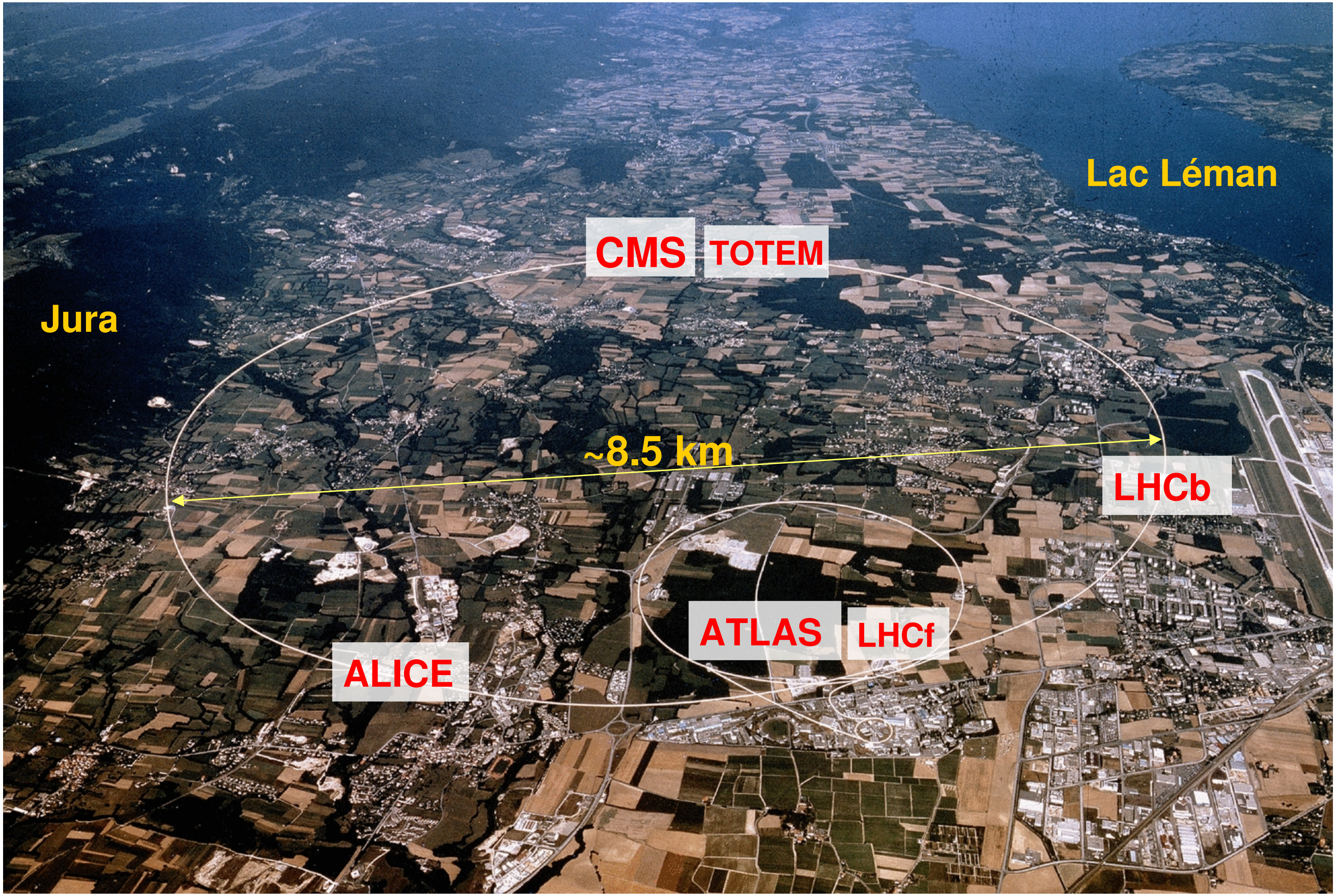
1st

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. Triggering, Computing, Analysis

The LHC experiments



Experiments with answers(?) at the LHC

- “Mass generation” problem:

  (Higgs boson)

  ATLAS CMS

- “Flavour” problem:

  (SUSY, BSM)

  LHCb ATLAS CMS

- “Hierarchy”, “fine tuning”:
- “Dark matter” problem:

  (SUSY, BSM)

  ATLAS CMS LHCb

- “non-perturbative QCD”:

  (QCD, QGP)

  ALICE TOTEM ATLAS CMS

- “Highest-energy cosmic-rays”:

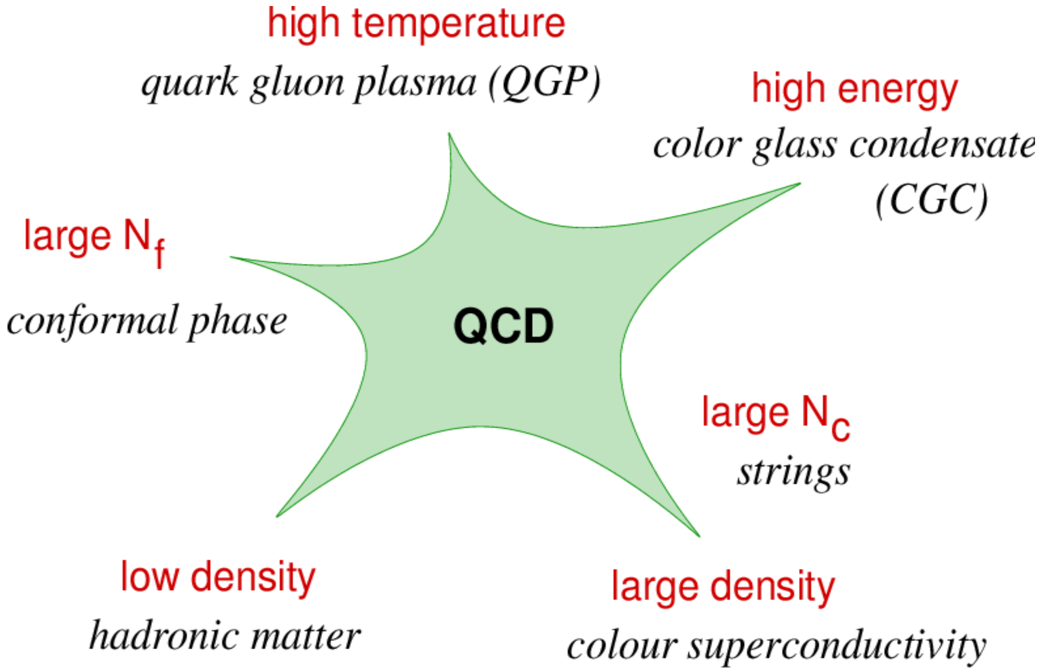
  LHCf ALICE TOTEM ATLAS CMS

ALICE:

Heavy-ion physics at the LHC

The many facets of QCD

- QCD is a QFT with very rich dynamical content: asymptotic freedom, confinement, (approx.) chiral symm., non-trivial vacuum, $U_A(1)$ anomaly...
- The only sector of the SM whose collective behaviour can be studied in the lab: phase transition(s), thermalization of fundamental fields, ...
- QCD has a very diverse many-body phenomenology at various limits:



QCD

high temperature
quark gluon plasma (QGP)

high energy
color glass condensate (CGC)

large N_f
conformal phase

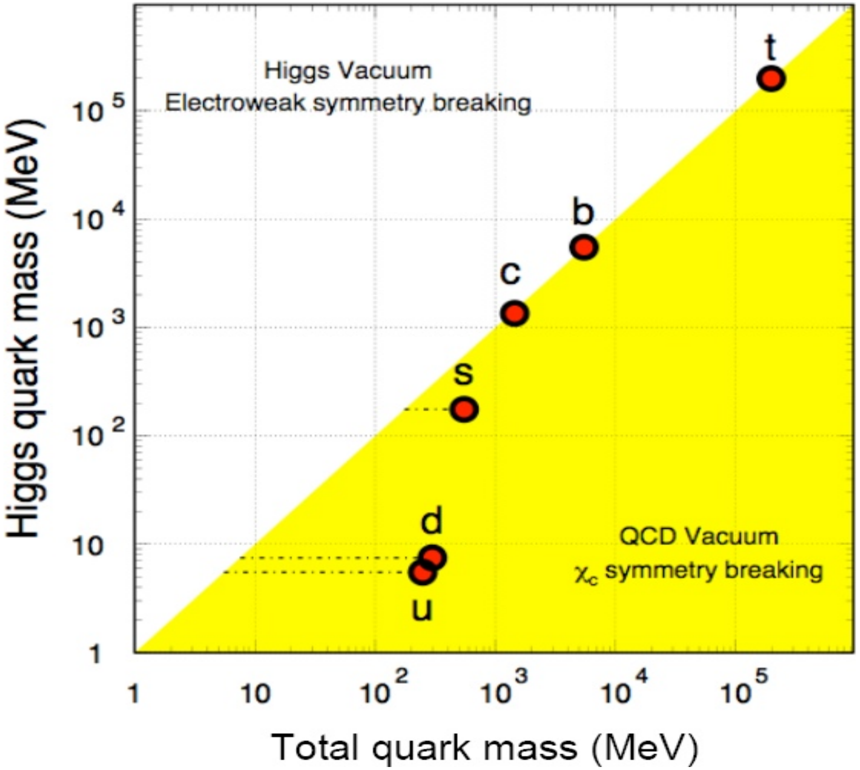
large N_c
strings

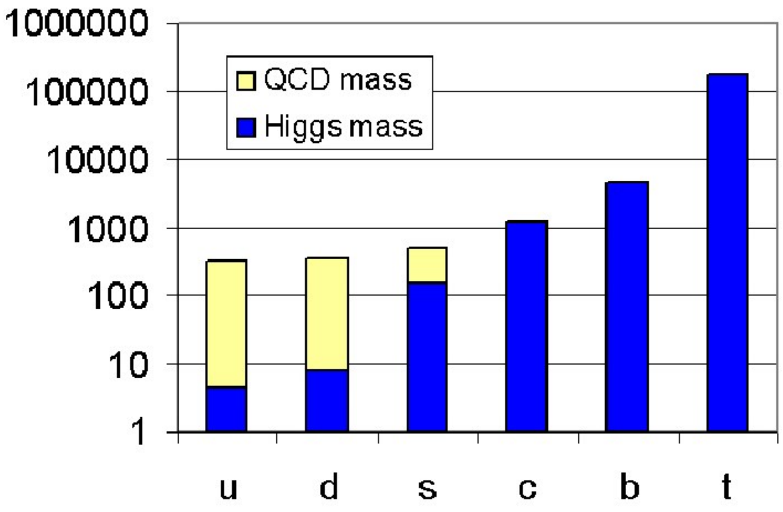
low density
hadronic matter

large density
colour superconductivity

Mass generation (visible universe)

- QCD (χ-symm. breaking) not (!) Higgs (EW-symm. breaking) is truly responsible for the "origin of (baryonic) mass" :





- ~98% of the (light-quarks) mass generated dynamically (gluons) in the QCD confining potential

High-energy heavy-ion physics programme

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

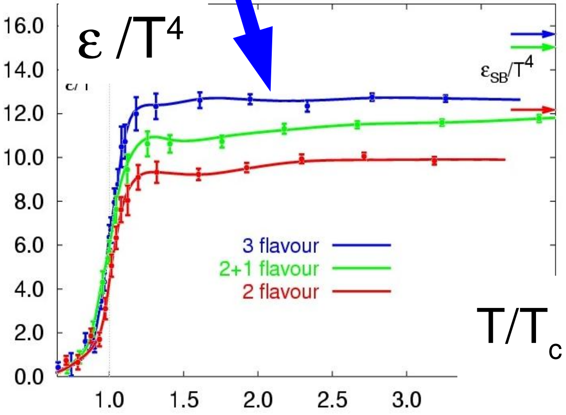
$$\text{where } G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$$

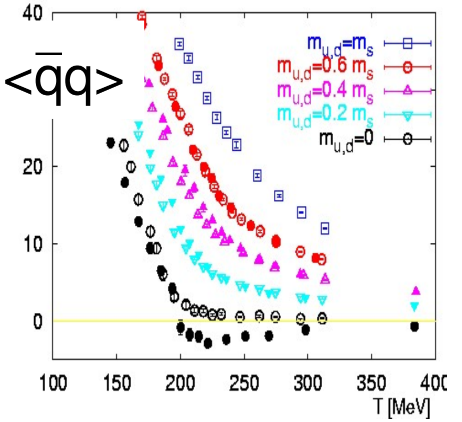
$$\text{and } D_\mu = \partial_\mu + i t^a A^a_\mu \qquad (\alpha_S = g^2/4\pi)$$

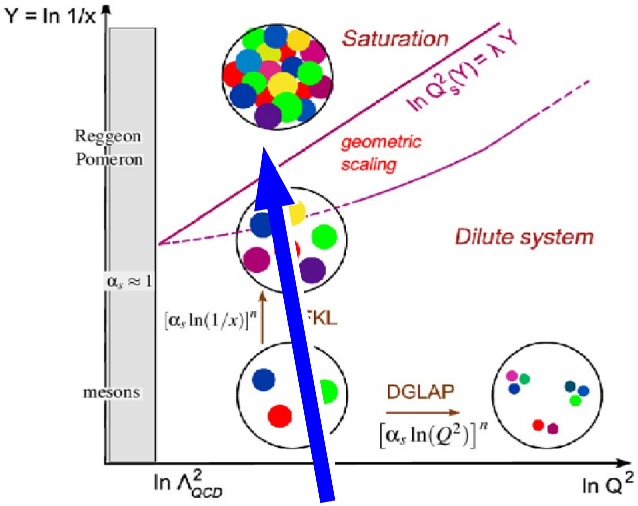
$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

1. Understand (de)confinement, chiral symm. breaking/restoration

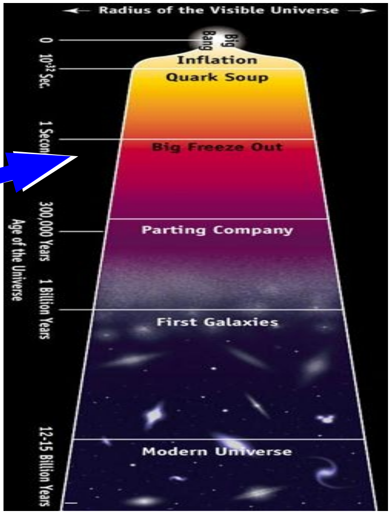
2. Study the phase diagram of QCD matter: produce & study the QGP







3. Probe conditions quark-hadron phase transition in primordial Universe (few μs after Big Bang)



4. Study regime of non-linear (high density) parton dynamics at small-x (CGC)

5. First exp. testbed of **AdS/CFT !?**

AdS/CFT basics

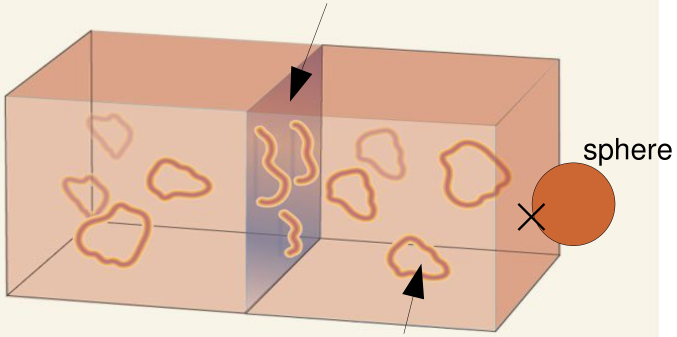
- Anti-de-Sitter/Conformal-Field-Theory correspondence

> Strongly-coupled gauge theories in 4-D brane (CFT in our flat space)
> EQUIVALENT to
> weakly-coupled gravity theories in 5-D neg. curved space-time (AdS)

- Maldacena's holographic conjecture,1998:

> 4-D $\mathcal{N}= 4$ SUSY Yang-Mills SU(N_c) ⇔ IIB string theory (supergravity) in *$AdS_5 \times S^5$*

Gauge: fields (open strings) in 4-D brane



Dual: closed strings in 5-D AdSxS^5 space

Conjecture: Gauge (AdS boundary/horizon) & dual are same theory seen at diff. values of coupling (radial dir. r)

"Technicalities":

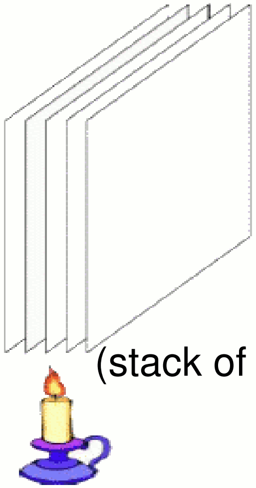
- Gauge sector: 2 params. (g_{YM},N_c), large 't Hooft coupling ($g^2_{YM}N_c >> 1$), conformal (no runn. coupling), supersymm. (gauge field, 4 Weyl fermions, 6 real scalars), $\mathcal{N}$=4 (four copies of D=4 brane)
- Gravity dual: SUGRA (supersymm. to match gauge side), fields (massless: gravitons, ...; massive string excitats.), 5 extra scalars (S^5 sphere), 2 parameters (string tension $1/\ell_s^2$, string coupling g_{st}), small curvature limit ($R/\ell_s >> 1$, classical Einstein GR)

AdS/CFT dictionary

- Strongly-coupled theories (QCD-like) can be studied analytically solving equations-of-motion/thermodynamics in simpler gravity duals.

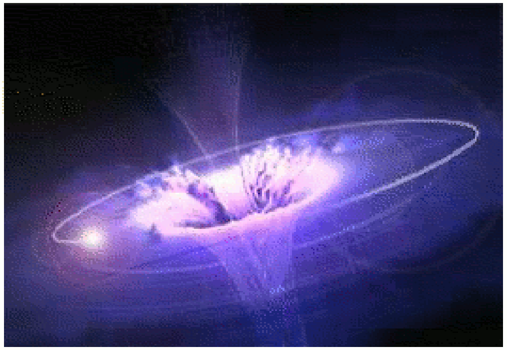
$$\mathcal{L} = \frac{1}{2g_{\rm YM}^2}{\rm Tr}(F_{\mu\nu}F^{\mu\nu}) + i{\rm Tr}(\bar{\psi}\gamma^\mu D_\mu\psi) \longleftrightarrow ds^2 = \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + \frac{R^2}{r^2}d\Omega_5^2$$

$\mathcal{N}$= 4 SU(N_c)



(stack of 4 branes)

=



BH in AdS$_5$ x S^5

Duality relation between couplings: $g^2_{SYM} = 4\pi g_{\rm st}$ $\quad g^2_{SYM}N_c = \left(\frac{R}{l_{\rm st}}\right)^4$

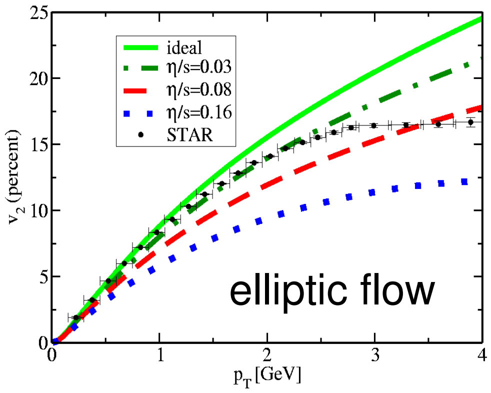
- Key point: find the “dictionary” that relates both sides of duality for a given observable e.g.: Hawking T <==> QGP T: $T_H = r_0/4\pi R^2$

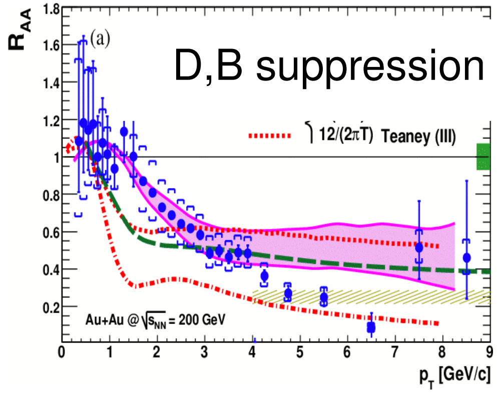
AdS/CFT: QGP applications

- The Quark-Gluon-Plasma @ RHIC is "strongly coupled":

Strong parton flows consistent w/ ideal hydro (viscosity η~0)

Large heavy-Q (& light-q) E_{loss} (very opaque medium)


elliptic flow


D,B suppression

- AdS/CFT gives access to real-time (transport) QCD quantities.
- Large differences between QCD & SYM "wash out" at finite-T:

- Universal shear viscosity η bound (~ σ_{abs} of soft gravitons in BH): $\eta/s > 1/4\pi$

  [Kovtun&Son&Starinets, PRL94:111601,2005]

- Quenching parameter qhat (Wilson loop from strings): $\hat{q}_{\rm SYM} \approx 26.69\sqrt{\alpha_{\rm SYM} N_c}\, T^3$

  [Liu&Rajagopal&Wiedemann, PRL97, 182301, 2006]

- Heavy-Q diffusion coefficient D (Wilson loop from strings): $D \underset{SYM}{\simeq} \frac{1.0}{2\pi T}\left(\frac{1.5}{\alpha_{SYM} N}\right)^{1/2}$

  [Herzog, Gubser, Casalderrey-Solana, ...]

- virtual/real γ emission rates (thermal spectral functions), ...

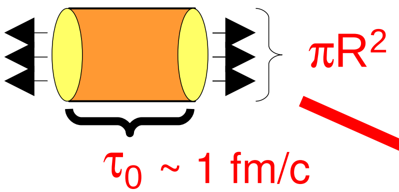
  [Kovtun, Teaney, ...]

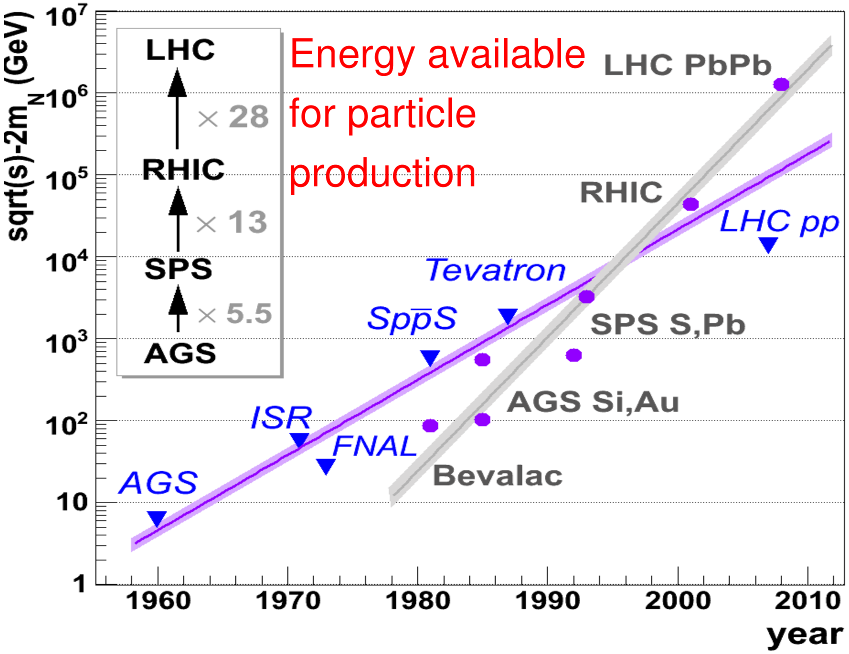
Energy densities in central A-A collisions

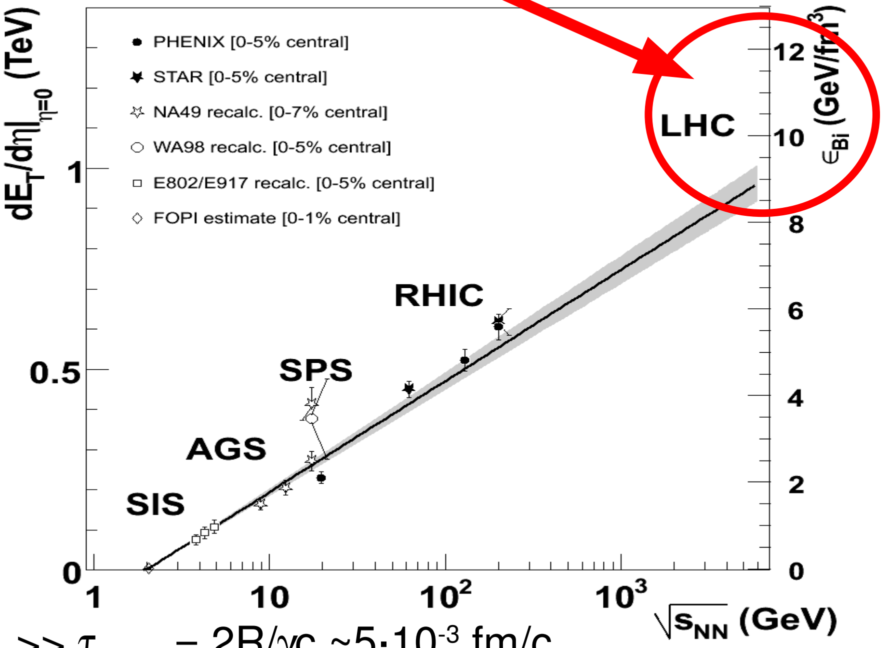
- T.D. Lee [Rev. Mod. Phys. 47 (75) 267]: *"In HEP we've concentrated on experiments in which we distribute a higher & higher amount of energy into a region with smaller & smaller dimensions. In order to study the question of 'vacuum' (...) we should investigate 'bulk' phenomena by distributing high energy over a relatively large volume."*

- Energy density: "Bjorken estimate" (for a longitudinally expanding plasma):

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$







>> $\tau_{cross}^{LHC} = 2R/\gamma c \sim 5\cdot 10^{-3}$ fm/c

TOTEM: Elastic & Diffractive physics at the LHC

Total p-p cross-section

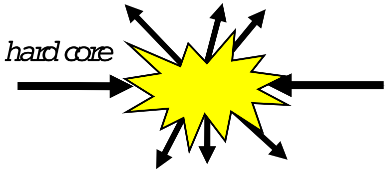
- Total proton-proton cross-sections at the LHC:

$\sigma_{tot} = \sigma_{el} + \sigma_{in}$

$\sigma_{in} = \sigma_{parton} + \sigma_{SD} + \sigma_{DD} + \sigma_{DPE}$

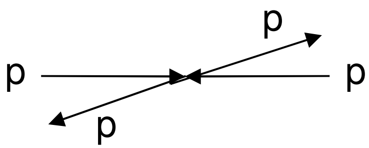
σ_{tot}~100 mb

~60% of the time a **"hard"** collision occurs



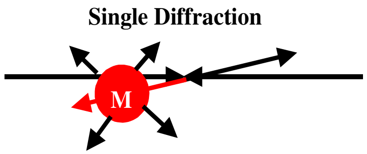
σ_{hc}~60 mb

~25% of the time the protons **scatter elastically**

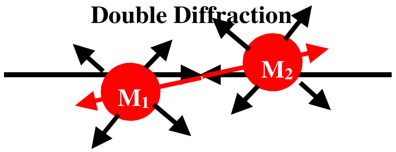


σ_{el}~25 mb

~10% of the time **single diffraction** occurs

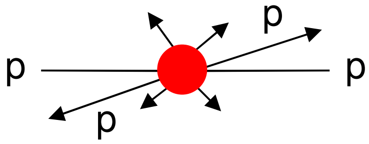


~1% of the time **double diffraction** occurs



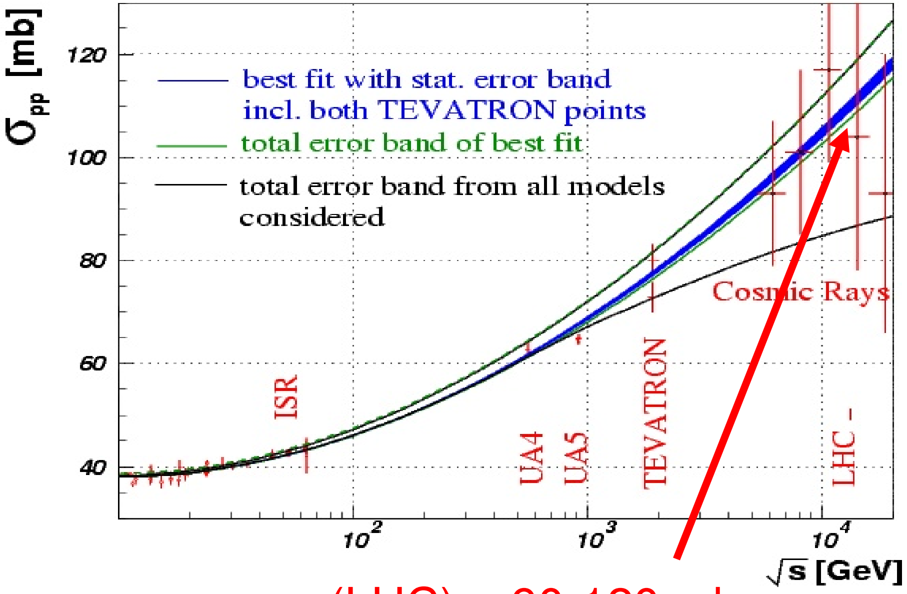
σ_{diff}~15 mb

~1% of the time **central (exclusive) diffraction** occurs



Total p-p cross section, elastic scattering

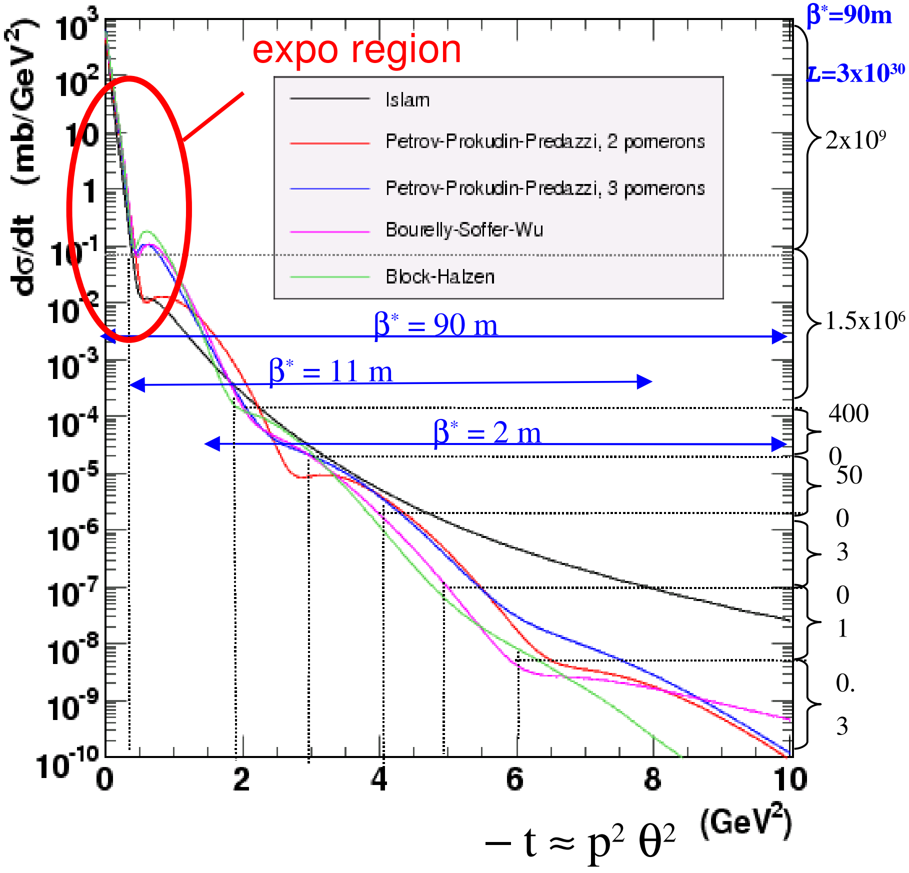
- Non-computable from 1^{st}-principles QCD, but ...
- Constrained by fundamental QM relations: Froisart bound, optical th., dispersion relations.
- Extrapolations vary by $^{+10}_{-20}$ %.



σ_{tot}(LHC) = 90-120 mb

- TOTEM goal: ~1% precision

special run/optics: various β*, low lumi.



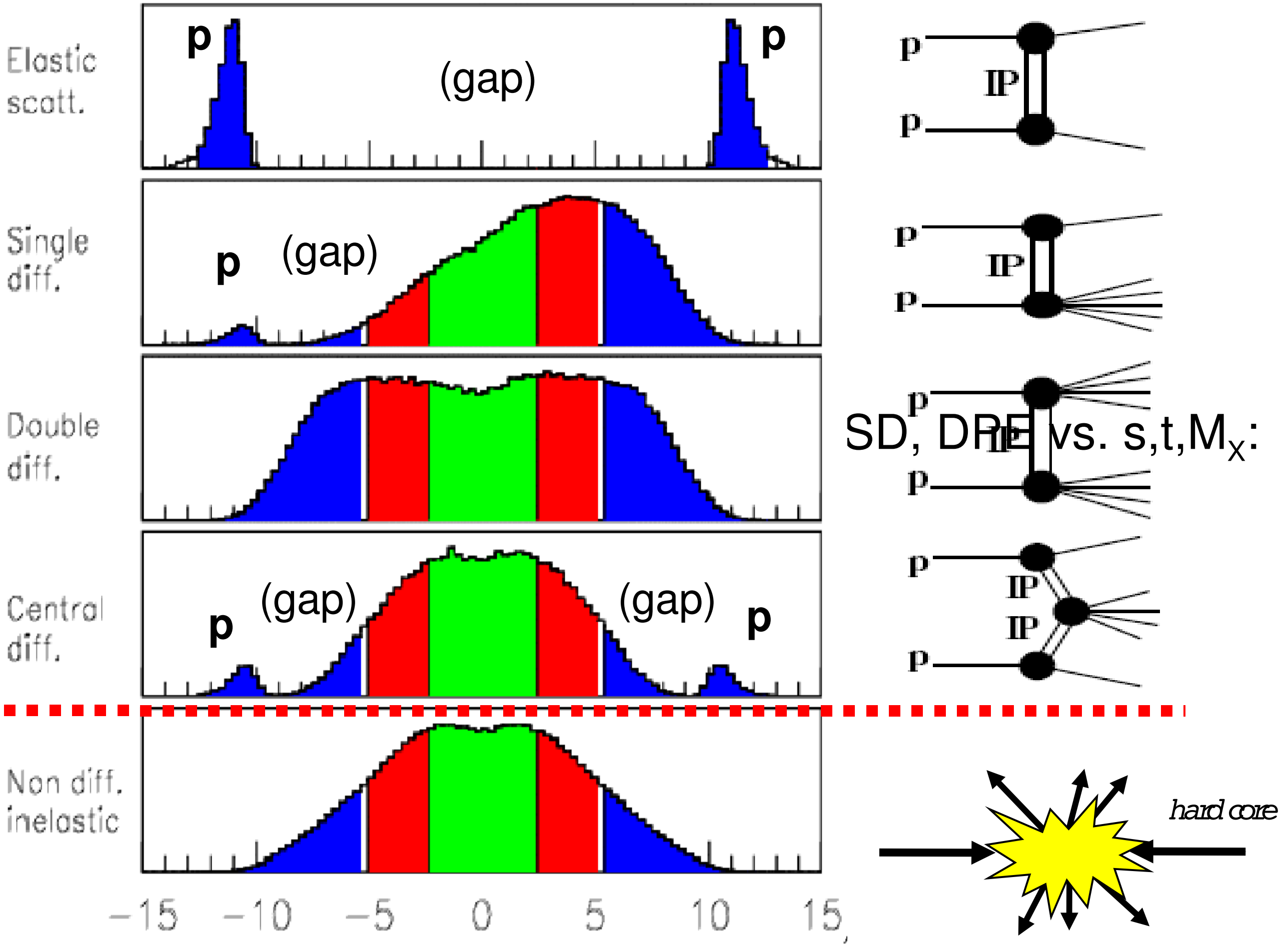
t: 4-mom. transfer squared

Pomeron-induced processes

- Diffractive/Elastic scattering is ~40% p-p σ_{tot} at the LHC !
- Proton(s) intact (scattered at low angles→TOTEM), rapidity-gap(s):

- No colour flux !
- Colourless exchange with vacuum quantum-numbers: |Pomeron = 2-gluons in colour singlet state

(“standard” collisions)

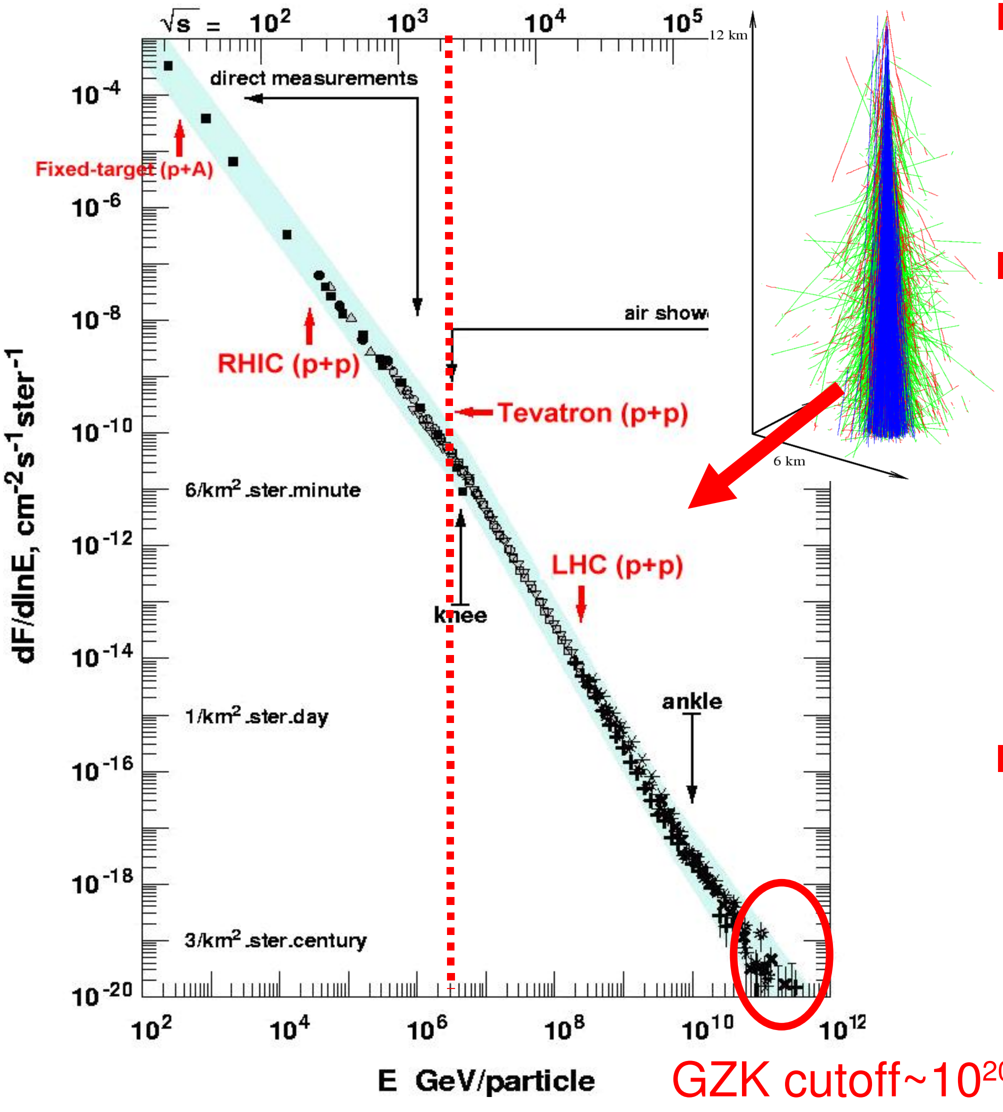


SD, DPE vs. s,t,M_X:

LHCf: Cosmic-rays physics

UHE cosmic-rays via extended air-showers (I)

- Cosmic-ray energy spectrum:



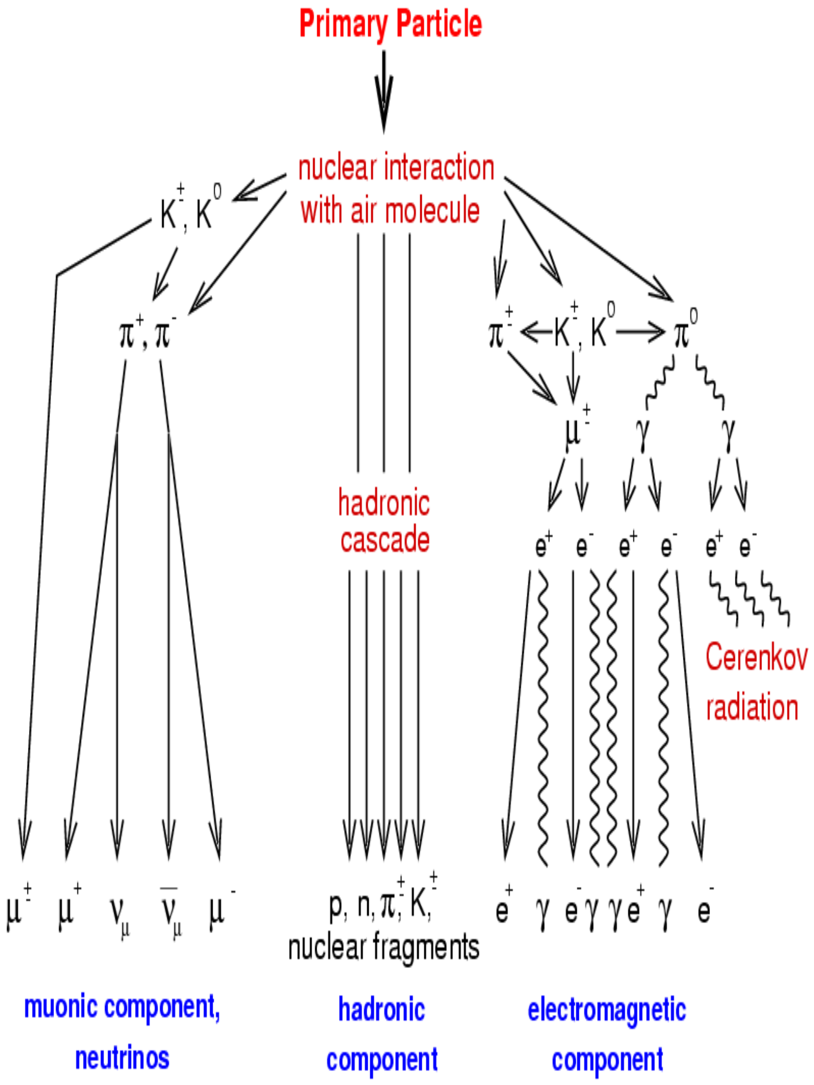
GZK cutoff~10^{20}eV

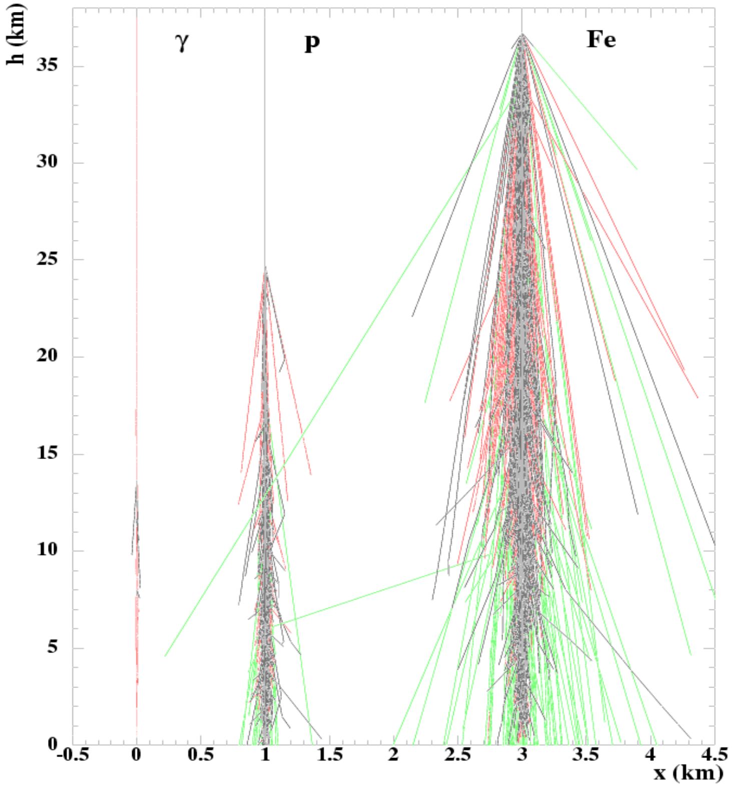
- Only "indirect" measurements (EAS) above E_{lab} ~100 TeV
- CR energy & mass determined comparing shower properties to hadronic MCs:

  Shower development dominated by fwd., soft QCD interactions.
- Uncertain x10^6 extrapolations SppS,Tevatron to GZK limit.

LHC: $\sqrt{s}$ = 14 TeV ⇔ E_{lab} = 10^{17} eV

UHE cosmic-rays via extended air-showers (II)

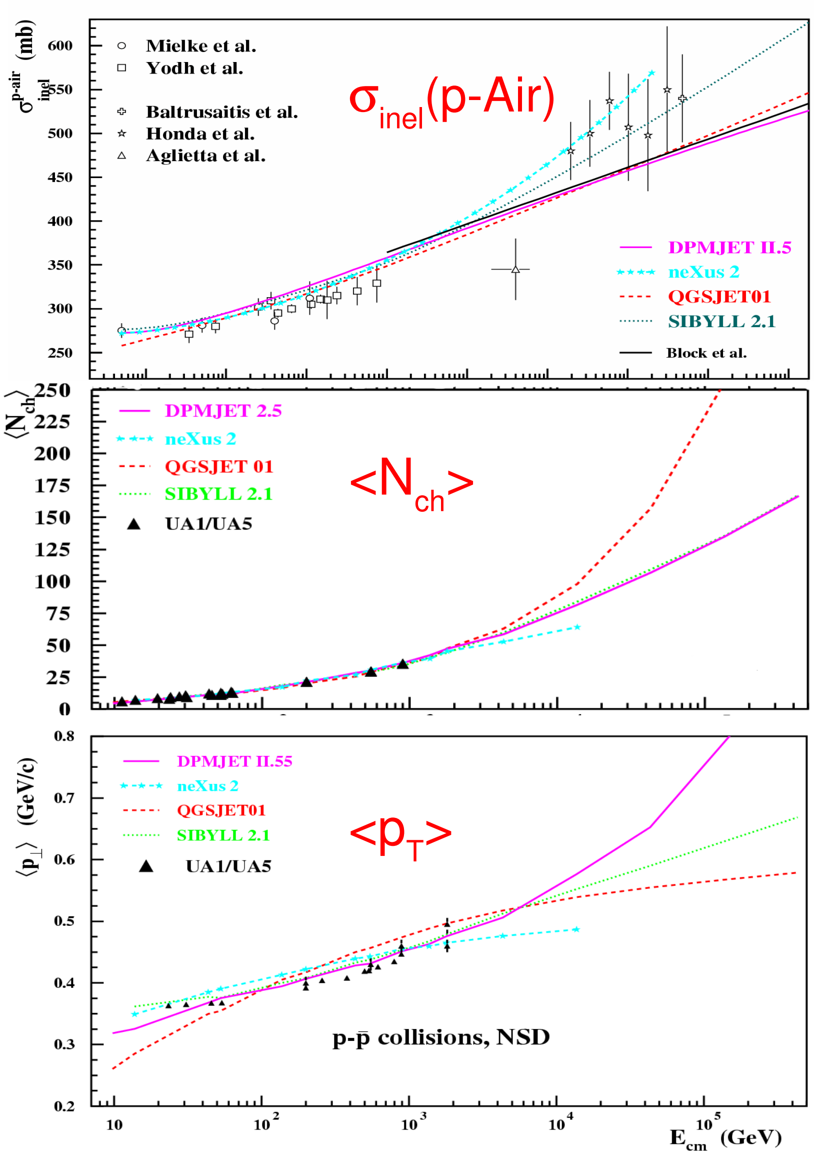


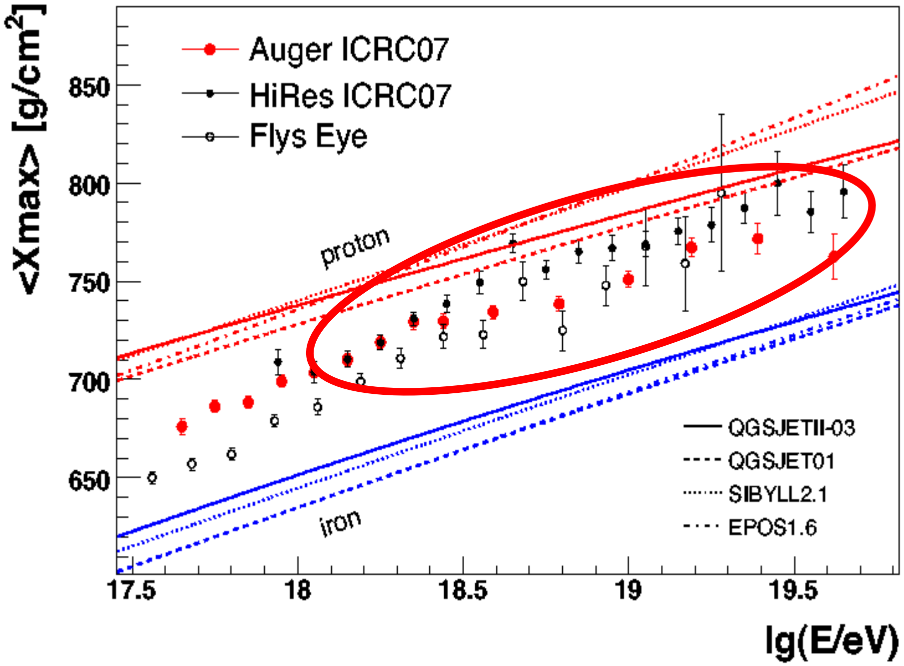


- Determination of E,mass of cosmic rays depends on description of primary UHE QCD interactions.
- Hadronic MCs need to be tuned with existing accelerator data.

Cosmic-ray MCs: uncertainties

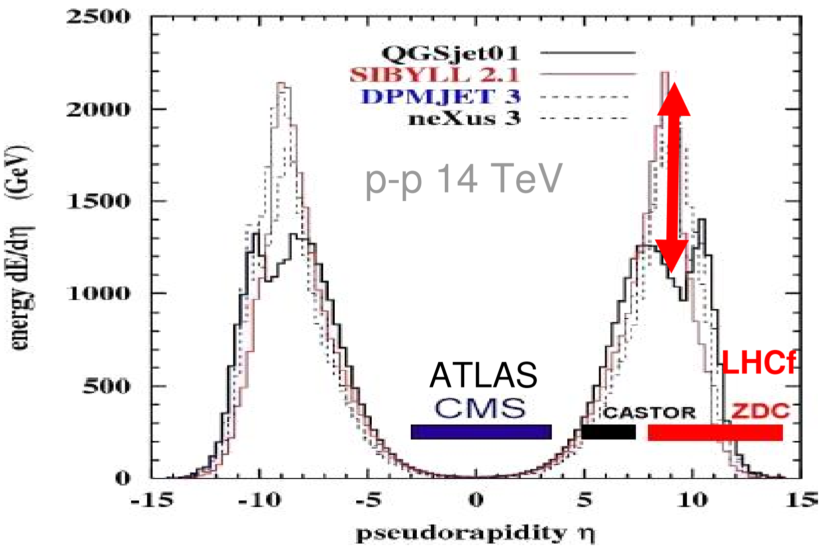
- Beyond 10^{17} eV large uncertainties in MCs ⇨ CR identity & energy.



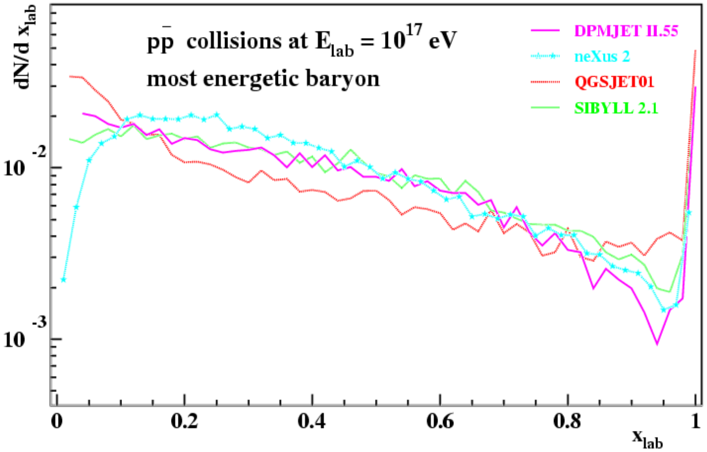


- Wide range of predictions !
- Yet, air-showers less sensitive (x-section & multiplicity partially compensate).
- ~20% energy & composition uncertainties esp. at high-end of spectrum (E $>10^{18}$ eV)

Cosmic-ray MCs: LHC comes to help



- MC predictions for forward multiplicity & energy flow differ by large factors:



- Leading baryon (inelasticity) ?

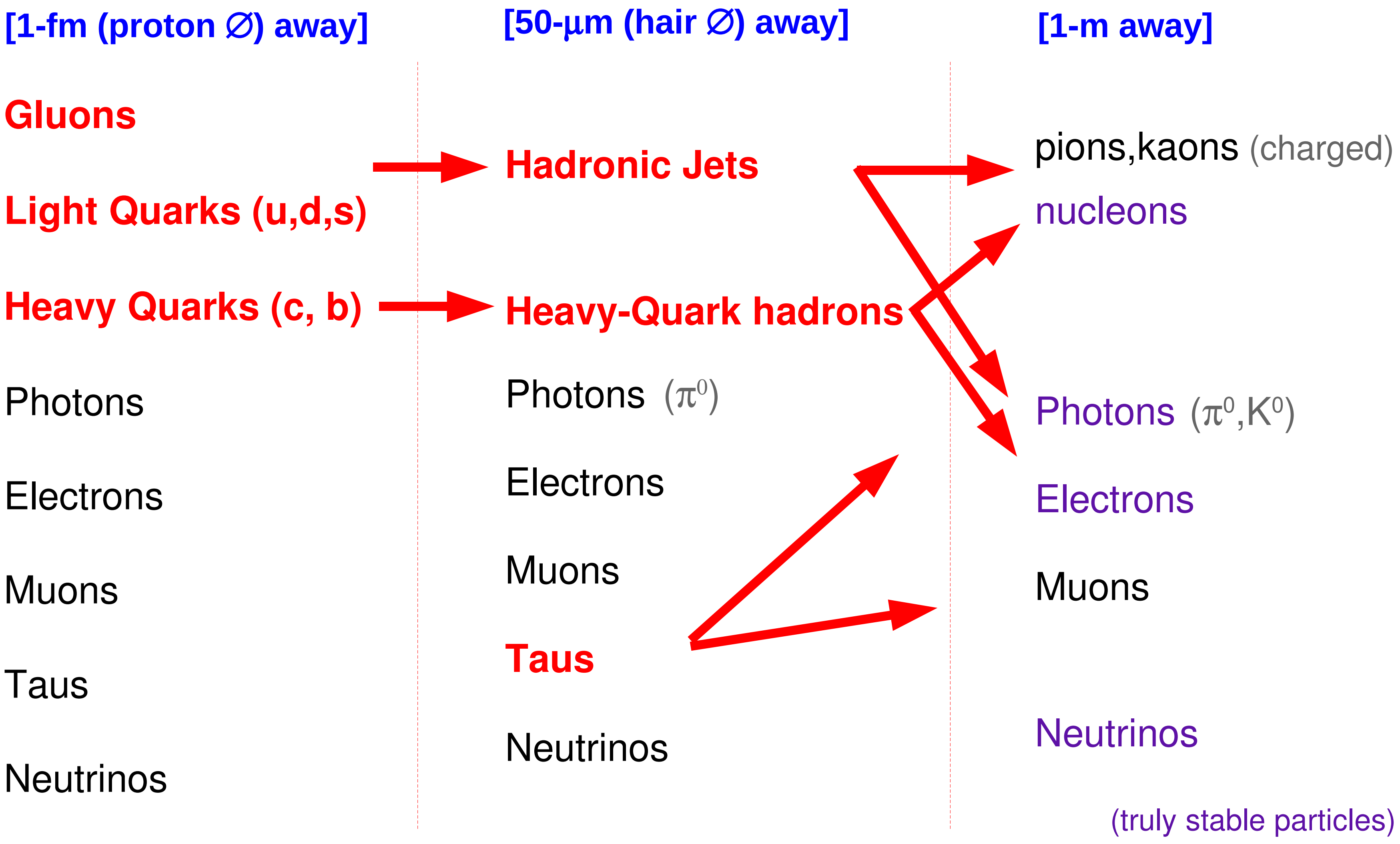
  Neutrals in ZDCs / LHCf:
  neutrons, mesons (π^0, $K^0_s \rightarrow \gamma$)

- Measurements of forward particle in pp, pA, AA [CRs: p-Air, α-Air, Fe-Air] @ LHC (E_{lab}~100 PeV) will strongly constrain EAS Monte Carlos.

Detectors at the LHC

What comes out of a collision?

Distance from the interaction point



[1-fm (proton ∅) away]

Gluons

Light Quarks (u,d,s)

Heavy Quarks (c, b)

Photons

Electrons

Muons

Taus

Neutrinos

[50-µm (hair ∅) away]

Hadronic Jets

Heavy-Quark hadrons

Photons (π^0)

Electrons

Muons

Taus

Neutrinos

[1-m away]

pions,kaons (charged)

nucleons

Photons (π^0, K^0)

Electrons

Muons

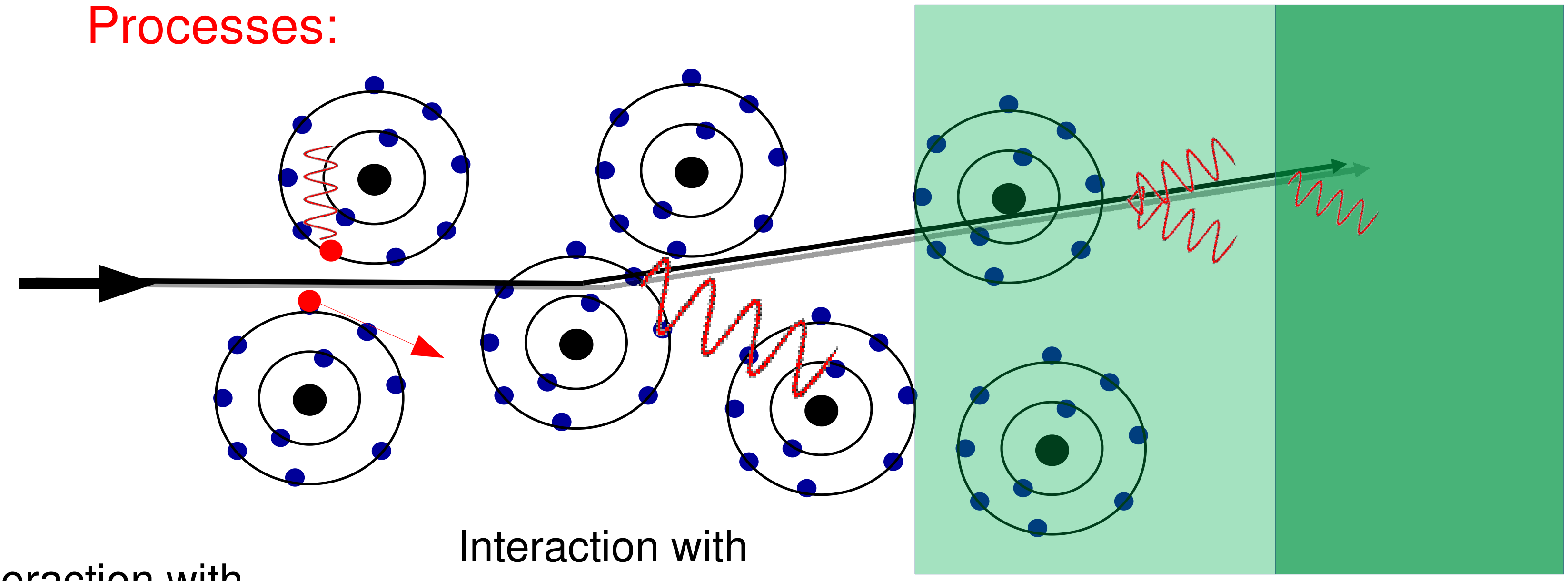
Neutrinos

(truly stable particles)

Particle detection

- To detect particles energy must be transferred to the detecting medium.

Processes:



Interaction with atomic electrons:

The incoming particle loses energy via excitation or ionization of the detector material

Trackers

Interaction with atomic nucleus: The particle suffers multiple scatt. in the material. Bremsstrahlung photon can be emitted.

Calorimeters

If particle velocity > light-velocity in medium →EM shock-wave emitted: Cerenkov Radiation (UV photons).

If particle crosses boundary between 2 media, there is a ~1% probability of emitting transition radiation (X-rays)

Particle detectors

- Detectable particles:

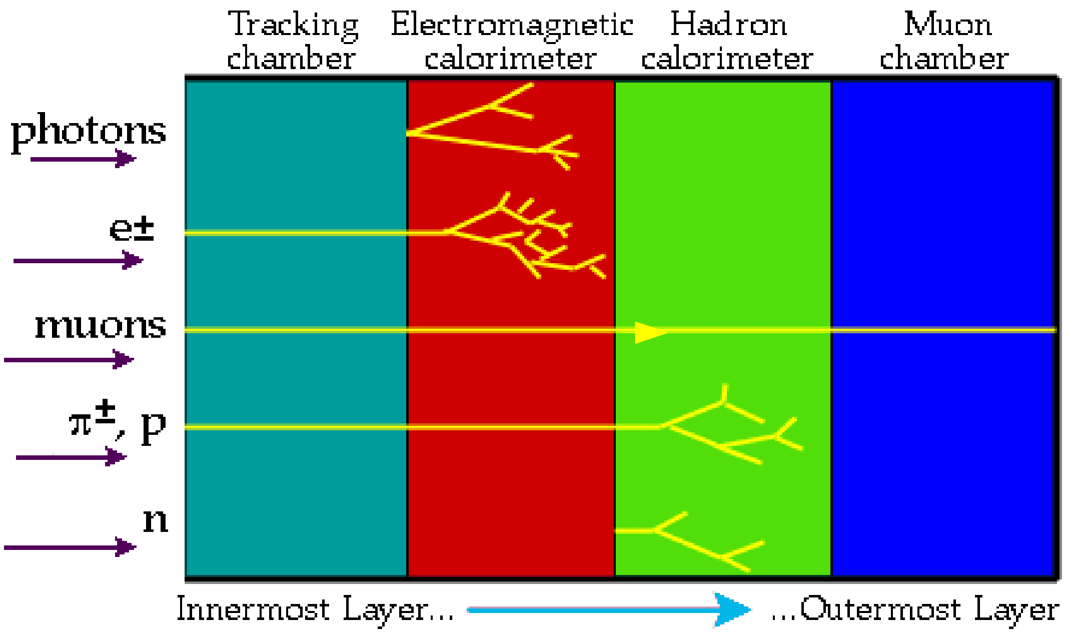
  Photons,

  Electrons

  Muons

  pions, kaons, nucleons

  Neutrinos (MET)



- 3 key measurements:

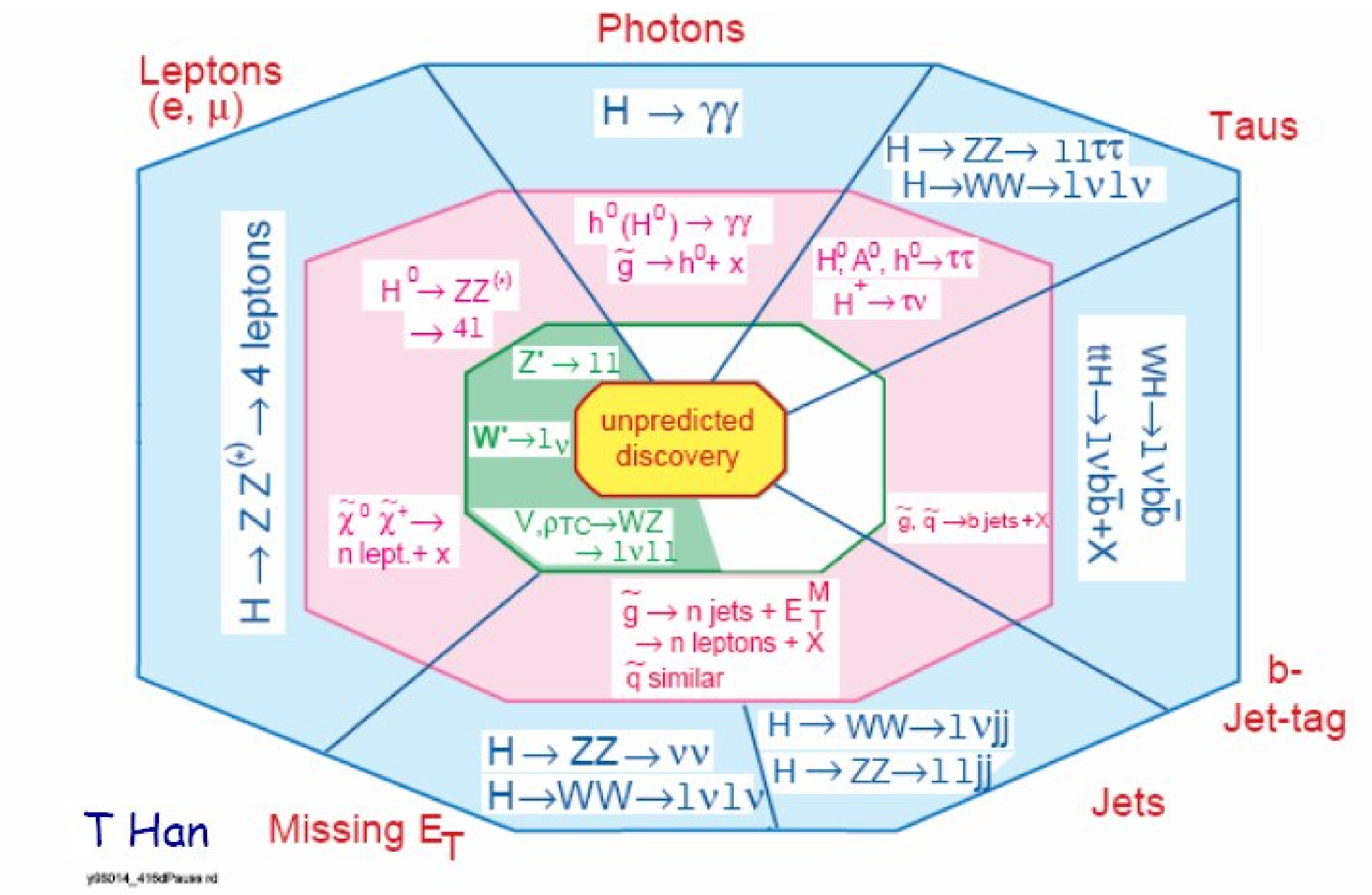
  (1) Four-momentum:
  - Trackers (charged particles): $\Delta p/p \propto p$
  - Calorimeters (neutrals, jets, MET): $\Delta E/E \propto 1/\sqrt{E}$

  (2) Vertex: → Inner trackers: 50 μm precision for τ & B,D meson decay

  (3) Particle identification (PID): → ToF, Cerenkov, RICH, TRD, ...

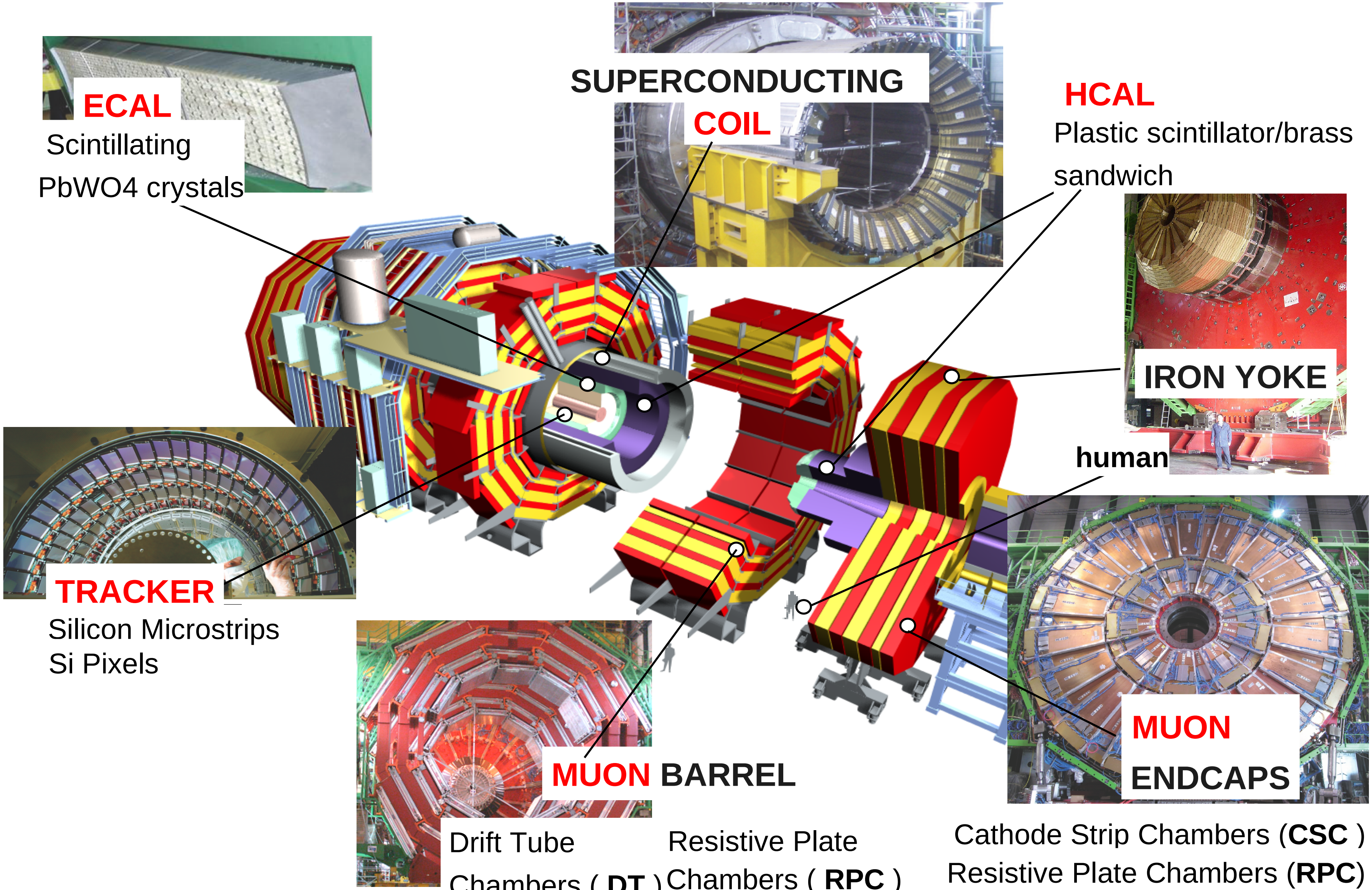
- In addition ... composite objects jets, heavy-Q jets & taus

Finding new particles (from known ones) ...



- Many SM analysis require invariant mass reco. of pairs of particles .
- Many BSM analysis involve MET measurements.

CMS detectors



ECAL
Scintillating
PbWO4 crystals

SUPERCONDUCTING
COIL

HCAL
Plastic scintillator/brass
sandwich

IRON YOKE

human

TRACKER
Silicon Microstrips
Si Pixels

MUON BARREL

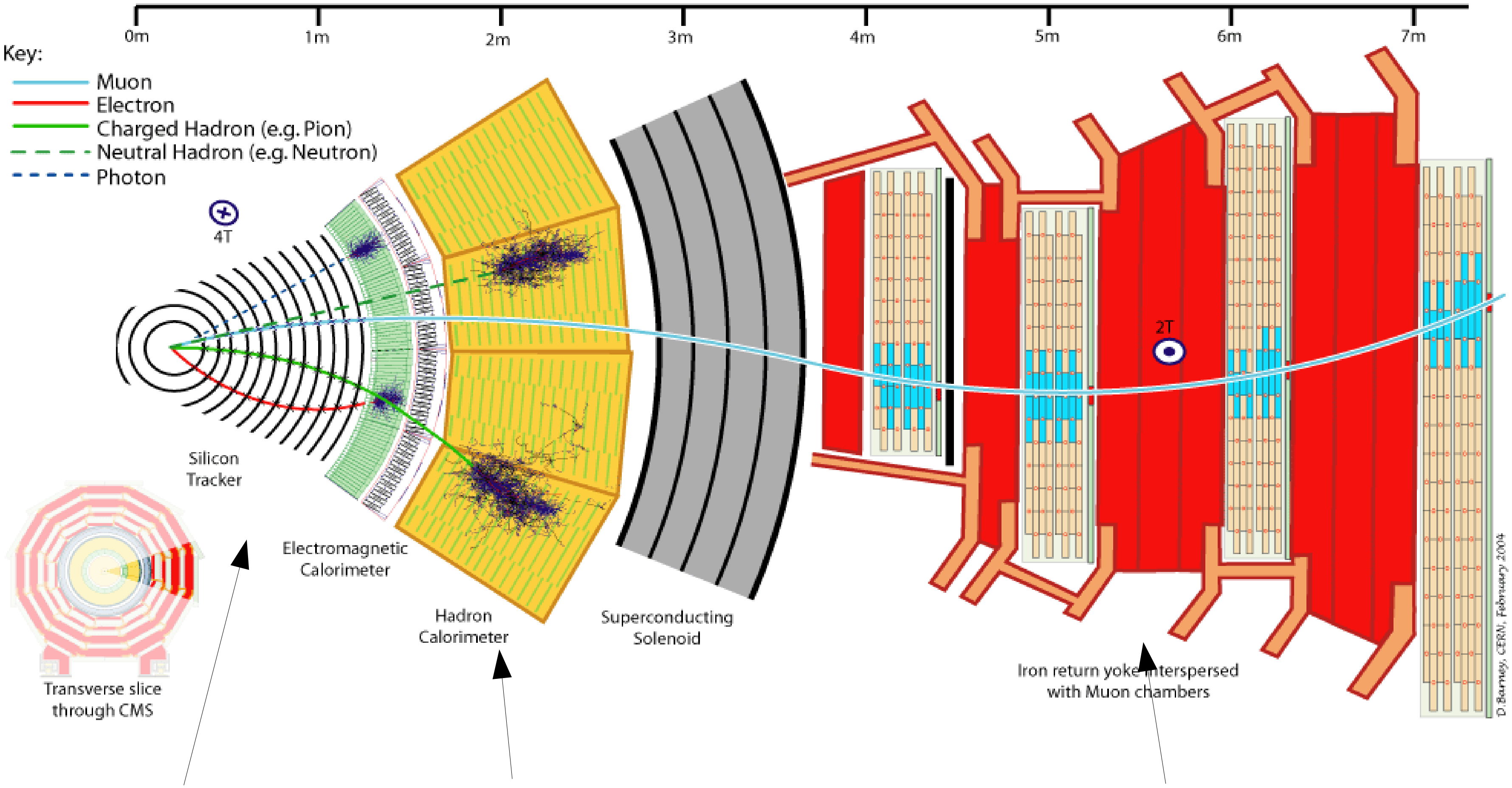
Drift Tube
Chambers (**DT**)

Resistive Plate
Chambers (**RPC**)

MUON
ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

CMS: $h^\pm$, $e^\pm$, γ, $\mu^\pm$ measurement



Si TRACKER

Silicon Microstrips
and Pixels

CALORIMETERS

ECAL
$PbWO_4$

HCAL
Plastic Sci/Steel sandwich

MUON BARREL

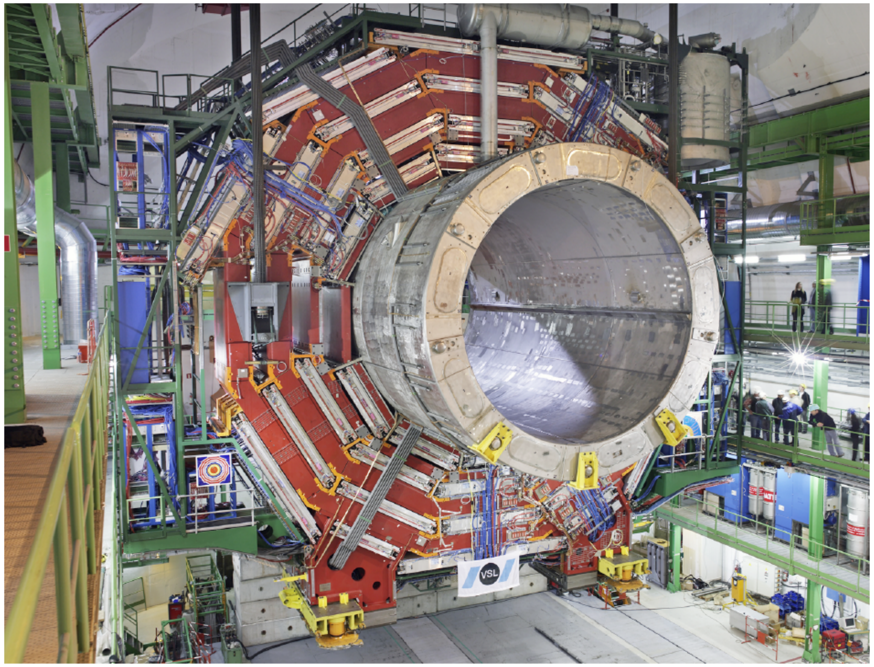
Drift Tube
Chambers (**DT**)

Resistive Plate
Chambers (**RPC**)

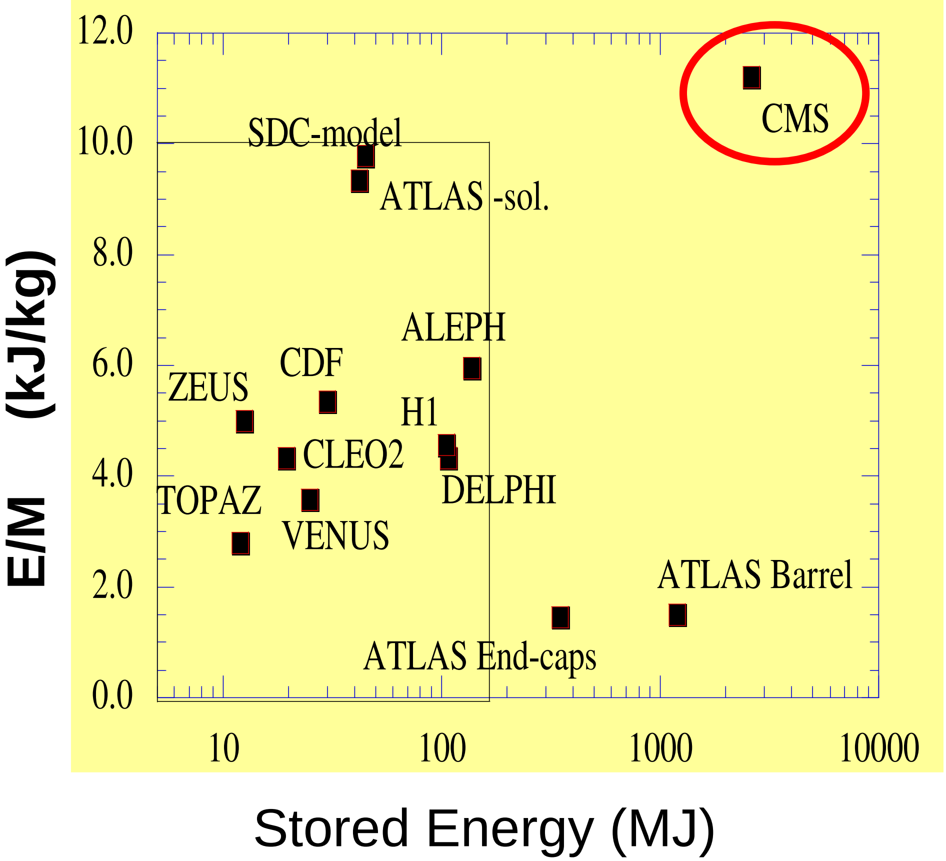
CMS: Strongest solenoid at the LHC

- Design Goal: B=4T to measure $p_T=1$ TeV/c μ's with <10% resolution
- Since bending power: $p(\mathrm{GeV}/c)=0.3\times B(\mathrm{T})\times R(\mathrm{m})$

  2 ways to reach that ... increase: R (ATLAS), B (CMS)

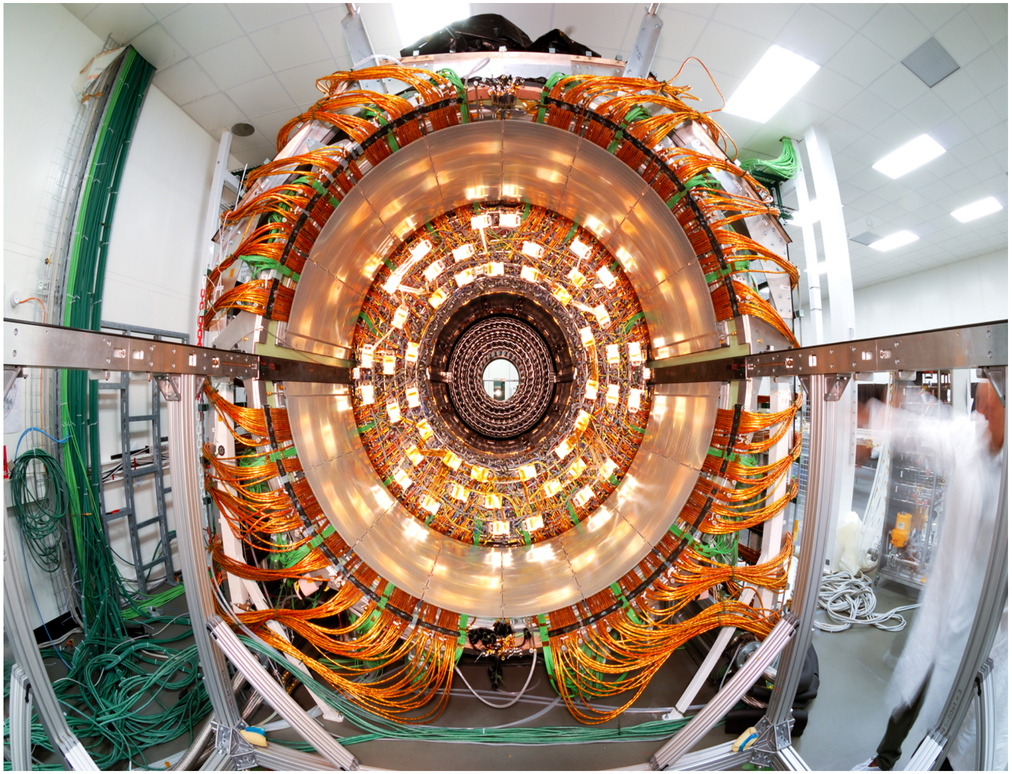


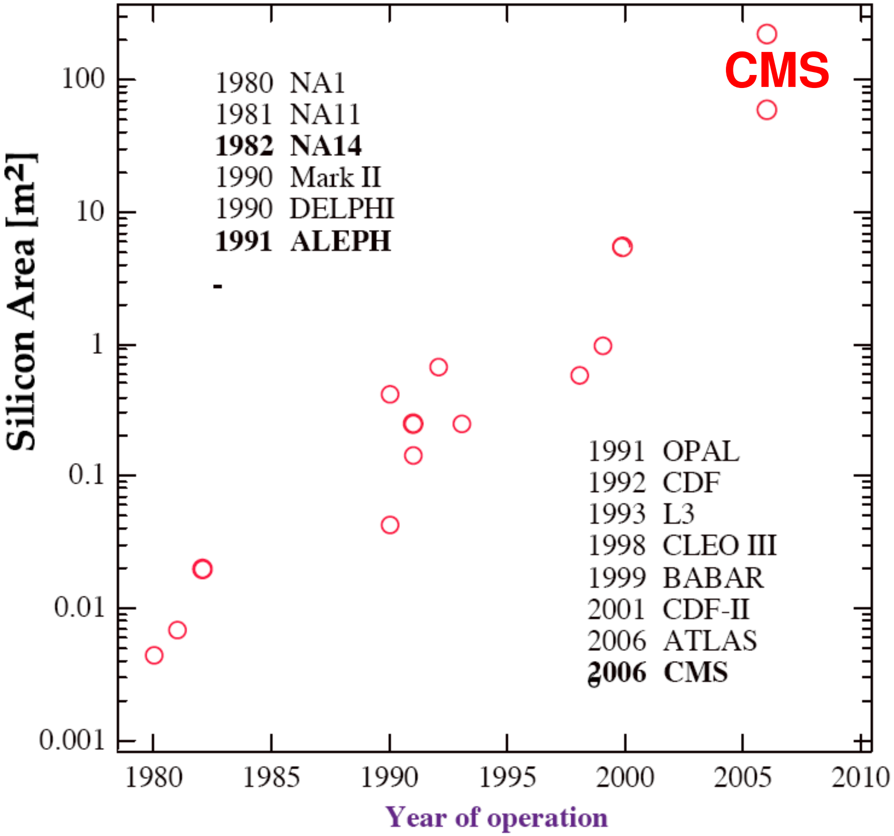
YB0 landing in the CMS experiment hall



CMS: Largest silicon tracker ever ...

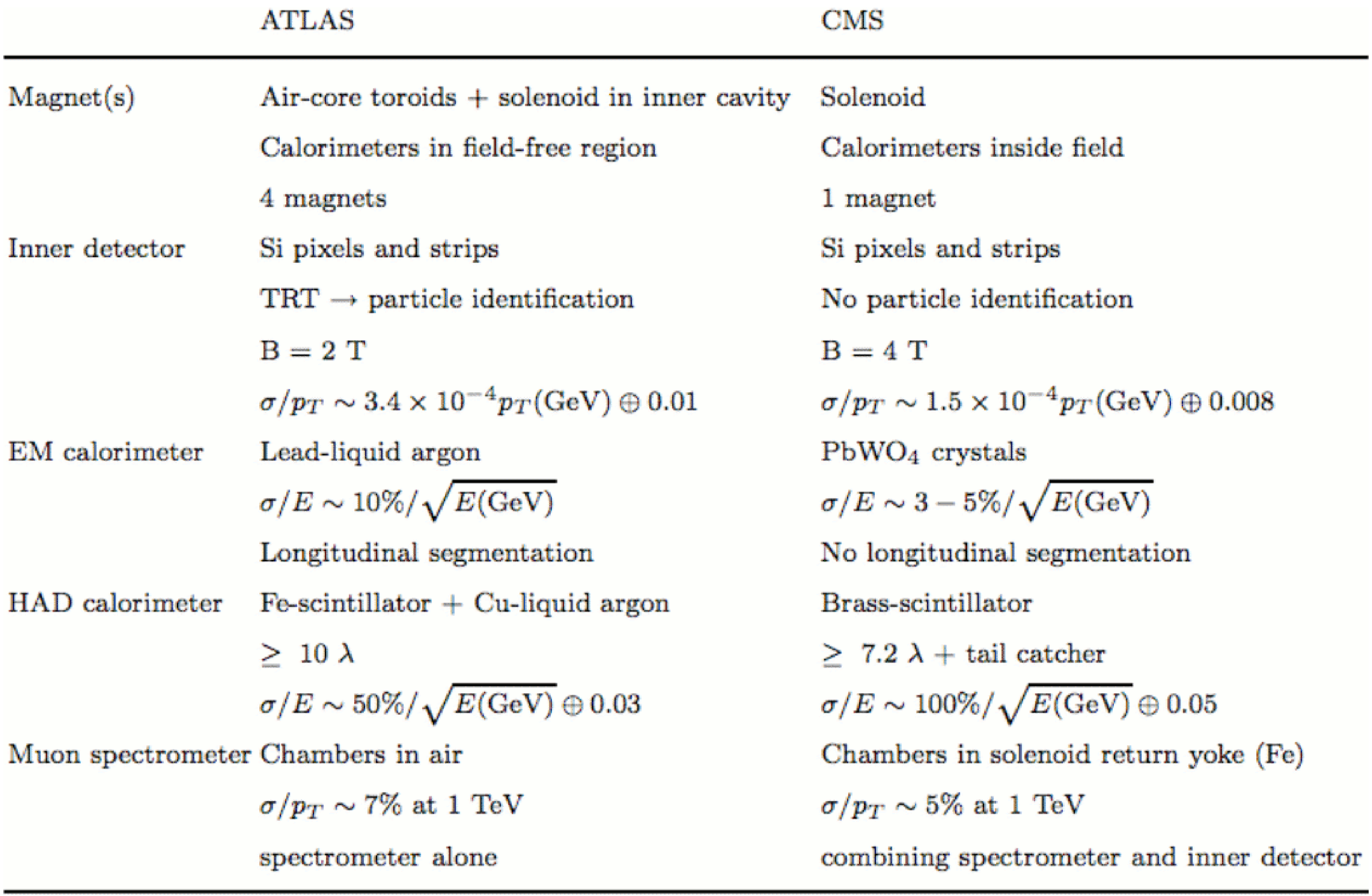
- Design Goals: x10 better mom. resolution than at LEP: 16 Si layers, low occupancies: 1000 particles emerging every crossing (25 ns)
  ~200 m^3, 100M Silicon channels !





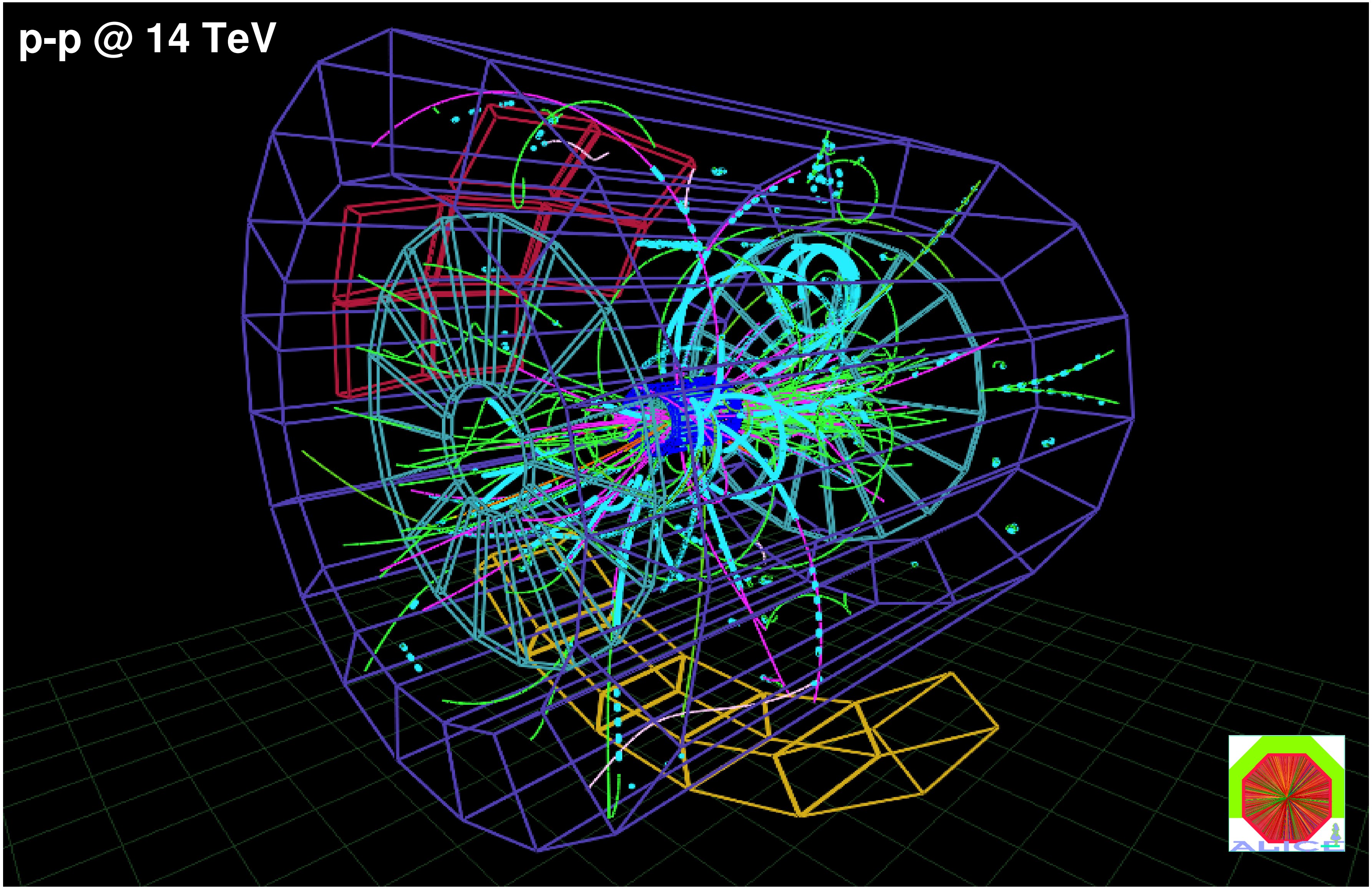
[ATLAS vs. CMS]

- Dissimilar details. Similar detection/physics performances.

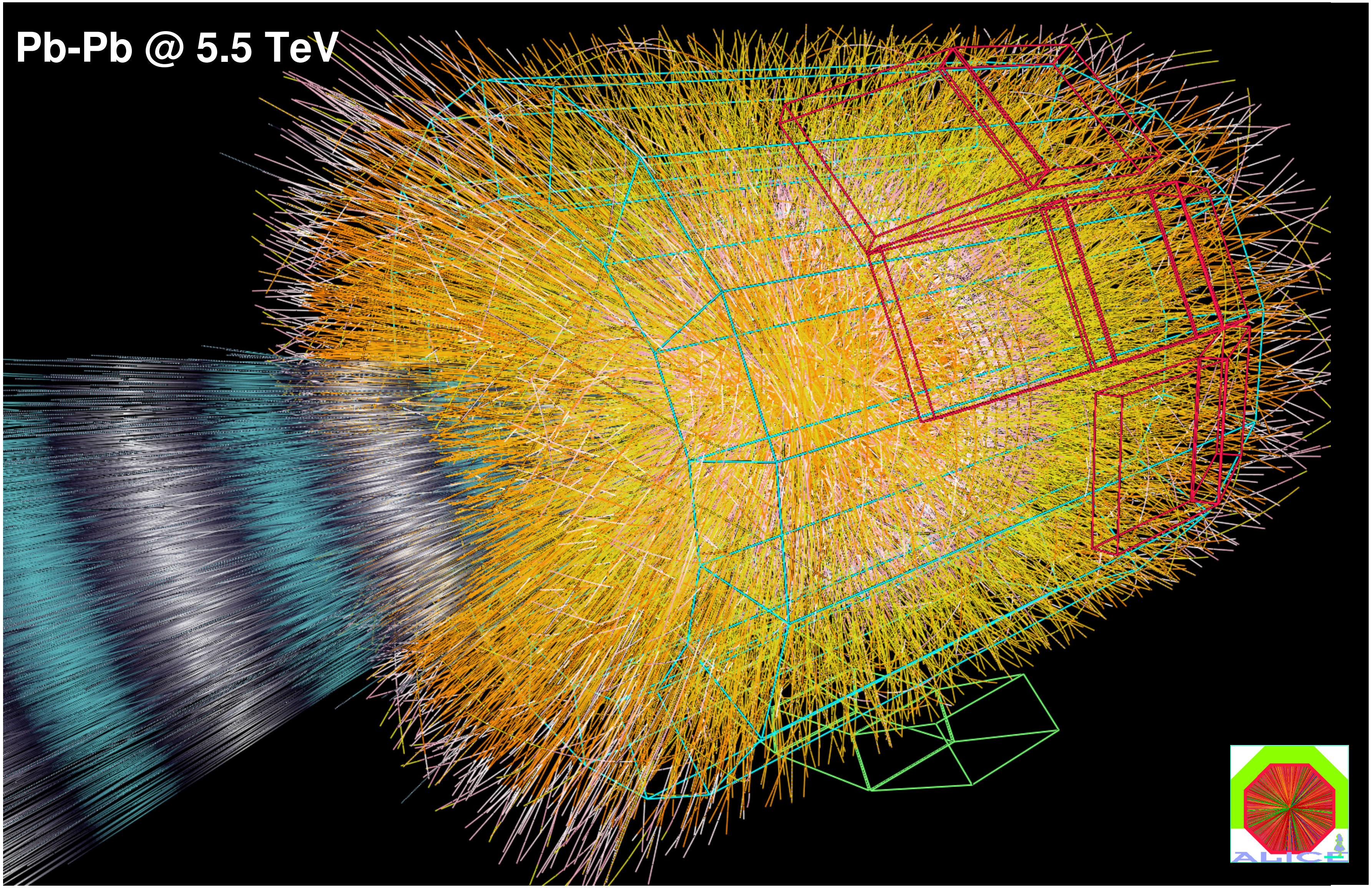


	ATLAS	CMS
Magnet(s)	Air-core toroids + solenoid in inner cavity	Solenoid
	Calorimeters in field-free region	Calorimeters inside field
	4 magnets	1 magnet
Inner detector	Si pixels and strips	Si pixels and strips
	TRT → particle identification	No particle identification
	$B = 2$ T	$B = 4$ T
	$\sigma/p_T \sim 3.4 \times 10^{-4} p_T(\mathrm{GeV}) \oplus 0.01$	$\sigma/p_T \sim 1.5 \times 10^{-4} p_T(\mathrm{GeV}) \oplus 0.008$
EM calorimeter	Lead-liquid argon	$PbWO_4$ crystals
	$\sigma/E \sim 10\%/\sqrt{E(\mathrm{GeV})}$	$\sigma/E \sim 3-5\%/\sqrt{E(\mathrm{GeV})}$
	Longitudinal segmentation	No longitudinal segmentation
HAD calorimeter	Fe-scintillator + Cu-liquid argon	Brass-scintillator
	$\geq 10\ \lambda$	$\geq 7.2\ \lambda$ + tail catcher
	$\sigma/E \sim 50\%/\sqrt{E(\mathrm{GeV})} \oplus 0.03$	$\sigma/E \sim 100\%/\sqrt{E(\mathrm{GeV})} \oplus 0.05$
Muon spectrometer	Chambers in air	Chambers in solenoid return yoke (Fe)
	$\sigma/p_T \sim 7\%$ at 1 TeV	$\sigma/p_T \sim 5\%$ at 1 TeV
	spectrometer alone	combining spectrometer and inner detector

High-multiplicity tracking: ALICE TPC

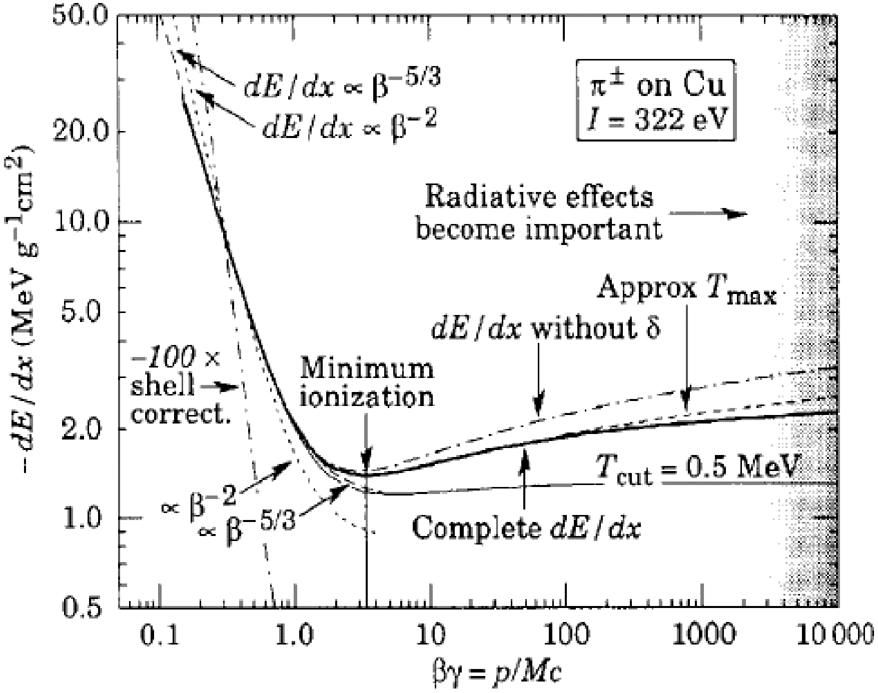


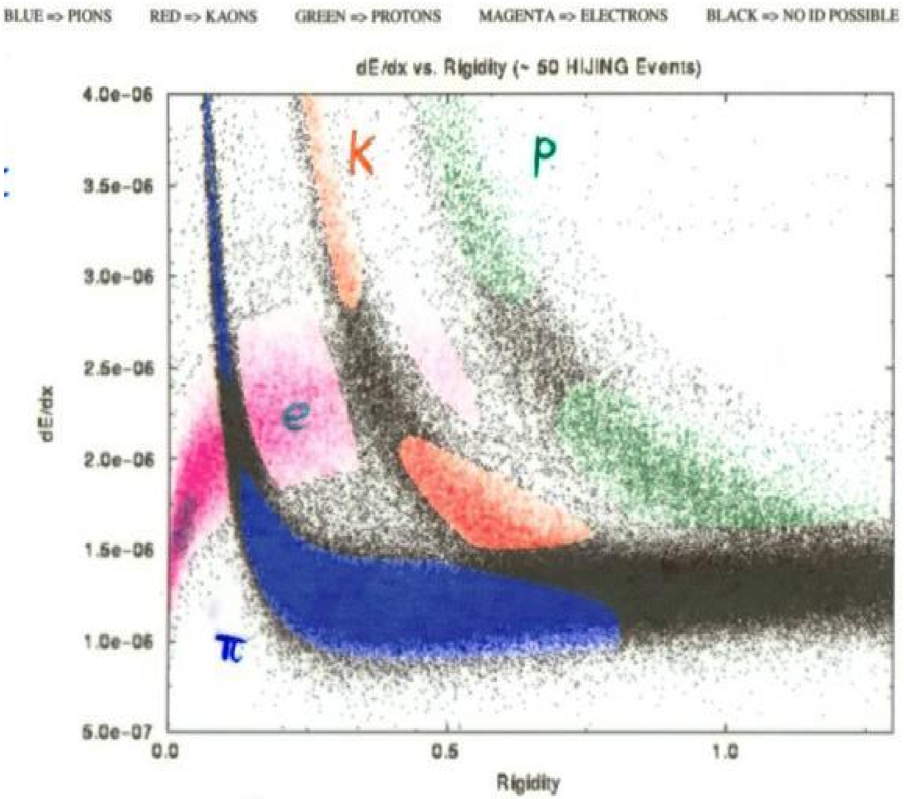
High-multiplicity tracking: ALICE TPC



ALICE TPC: PID at low-p_T

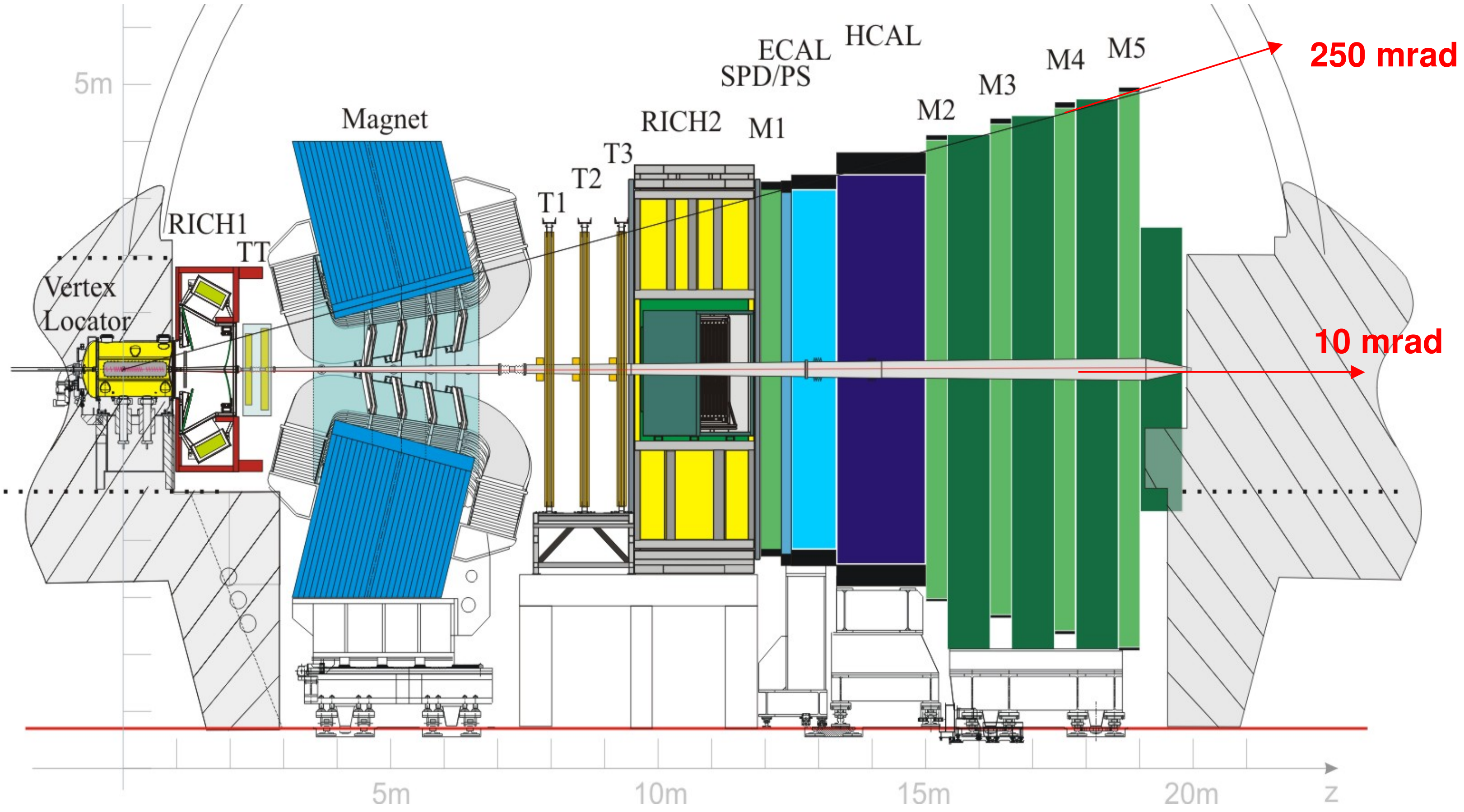
- Ionization energy loss (dE/dx) versus momentum (Bethe-Bloch formula)





- Different particles: different dE/dx (in TPC gas) vs momentum (bending)
- Limited to p_T~<4 GeV/c (bands merge above).

LHCb detector: Particle ID & Vertexing



Vertex reconstruction:
VELO

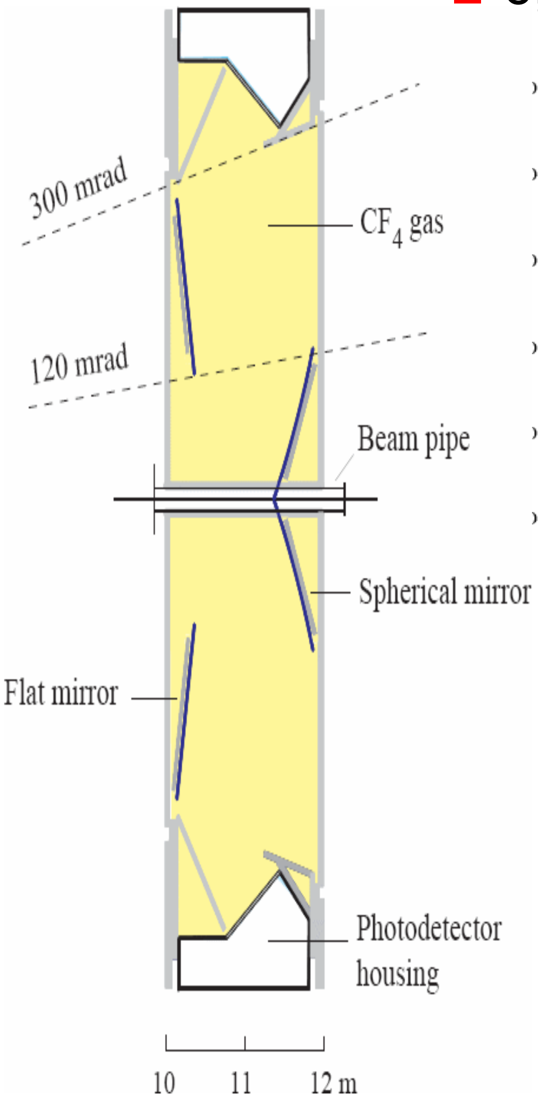
Trigger:
Muon Chambers
Calorimeters
Tracker

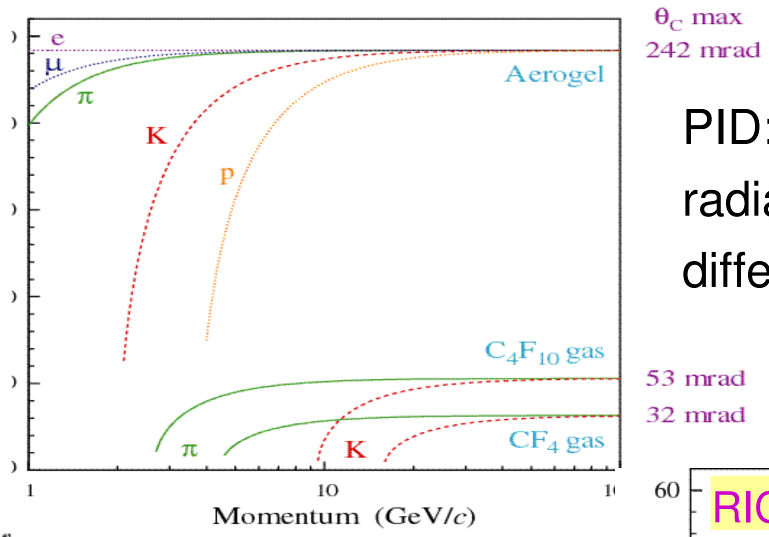
PID:
RICHs
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

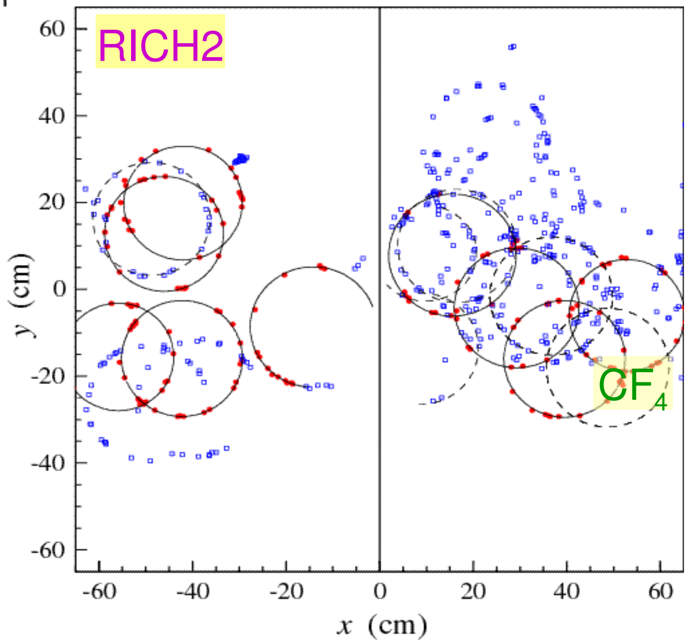
PID with RICH detector (LHCb)

- e,μ,π,k,p identification over momentum 1-100 GeV/c





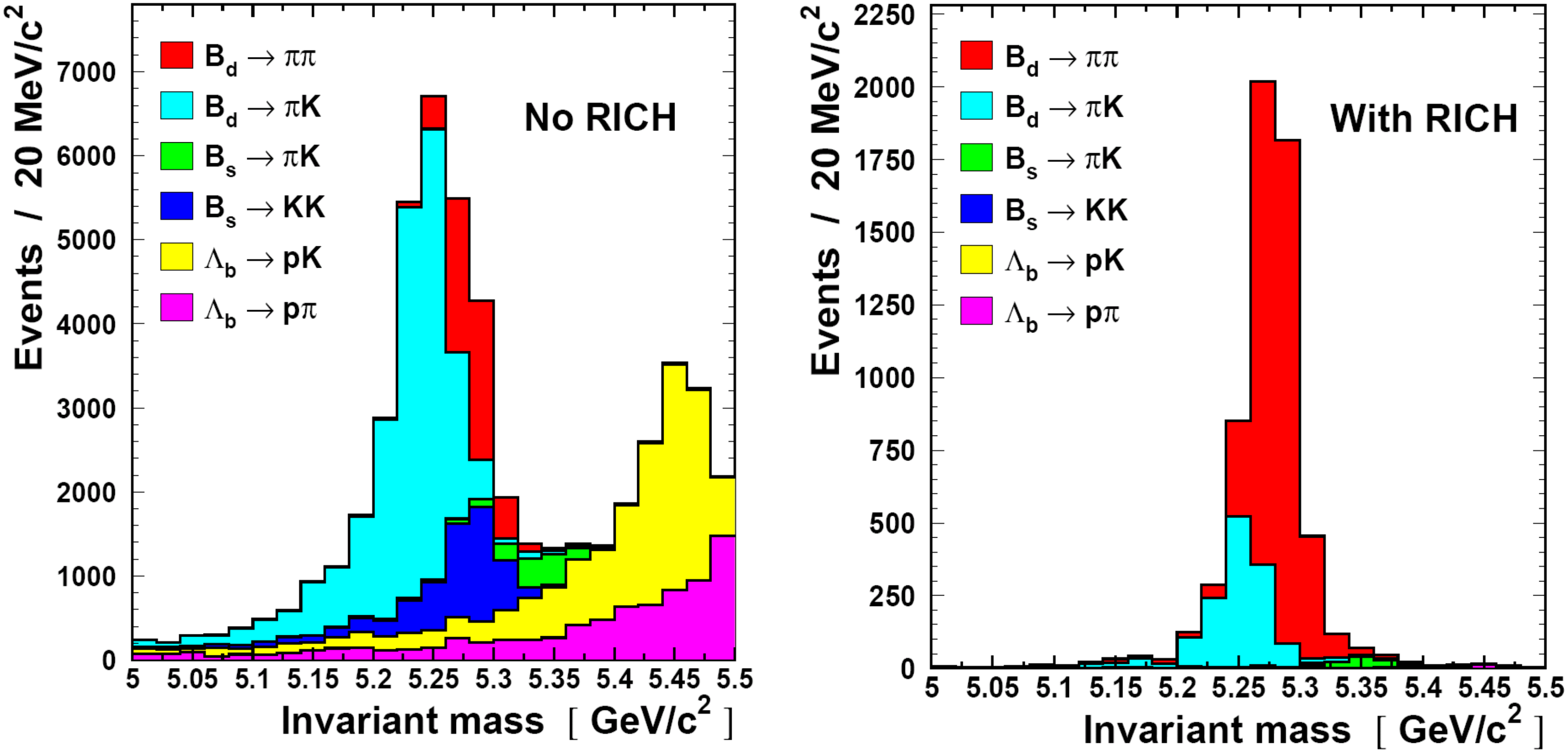
PID: particles with diff. β=p/m, radiate Cerenkov-light at different β thresholds.



- Electron identification (& momentum measure) via Cerenkov rings: θ=acos(1/nβ)

Material (index n) tuned: CF_4, C_4F_{10}, ...

PID with RICH detector (LHCb)



- Able to distinguish $B_d \to \pi\pi$ from other similar topology 2-body decays.
- Able to distinguish B from anti-B using K-tagging.

Trigger & readout

at the LHC

Triggering: selection of events

ATLAS/CMS, total about

~100M electronic channels

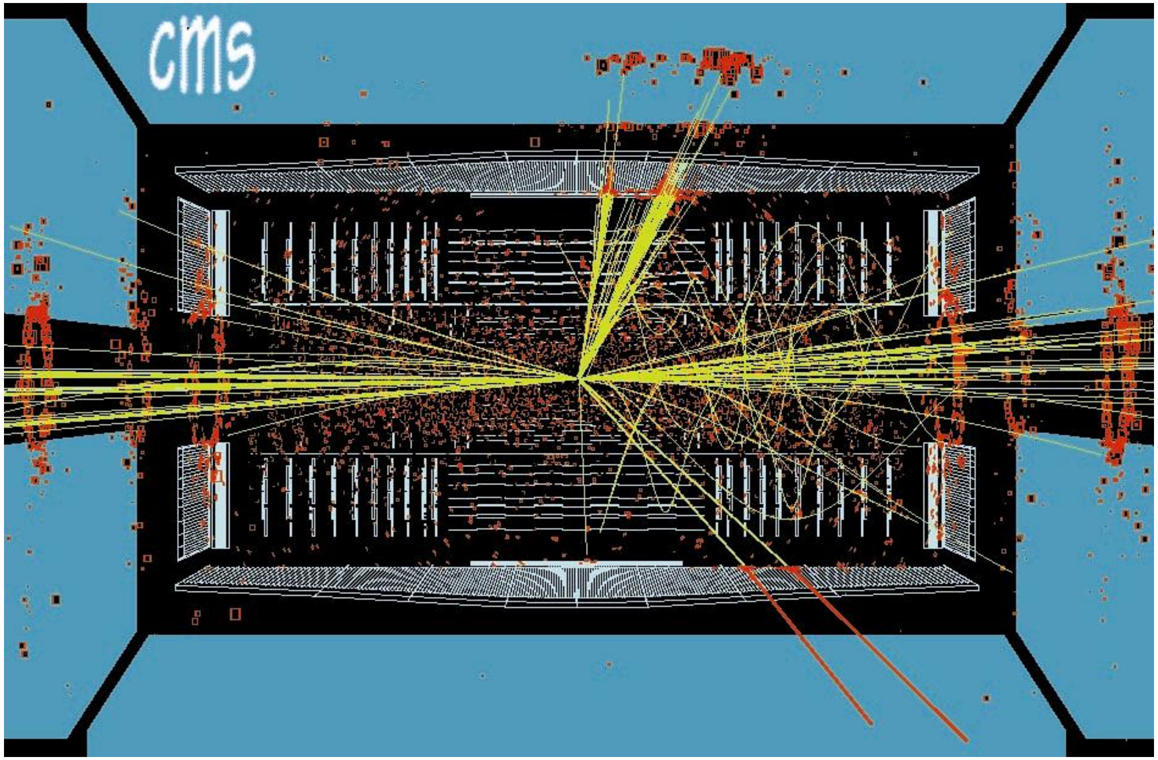
Each channel checked

40M times/second

(collision rate is 40 Mhz)

Amount of data (1 collision)

>1.5 Mbytes



Trigger (online event selection):

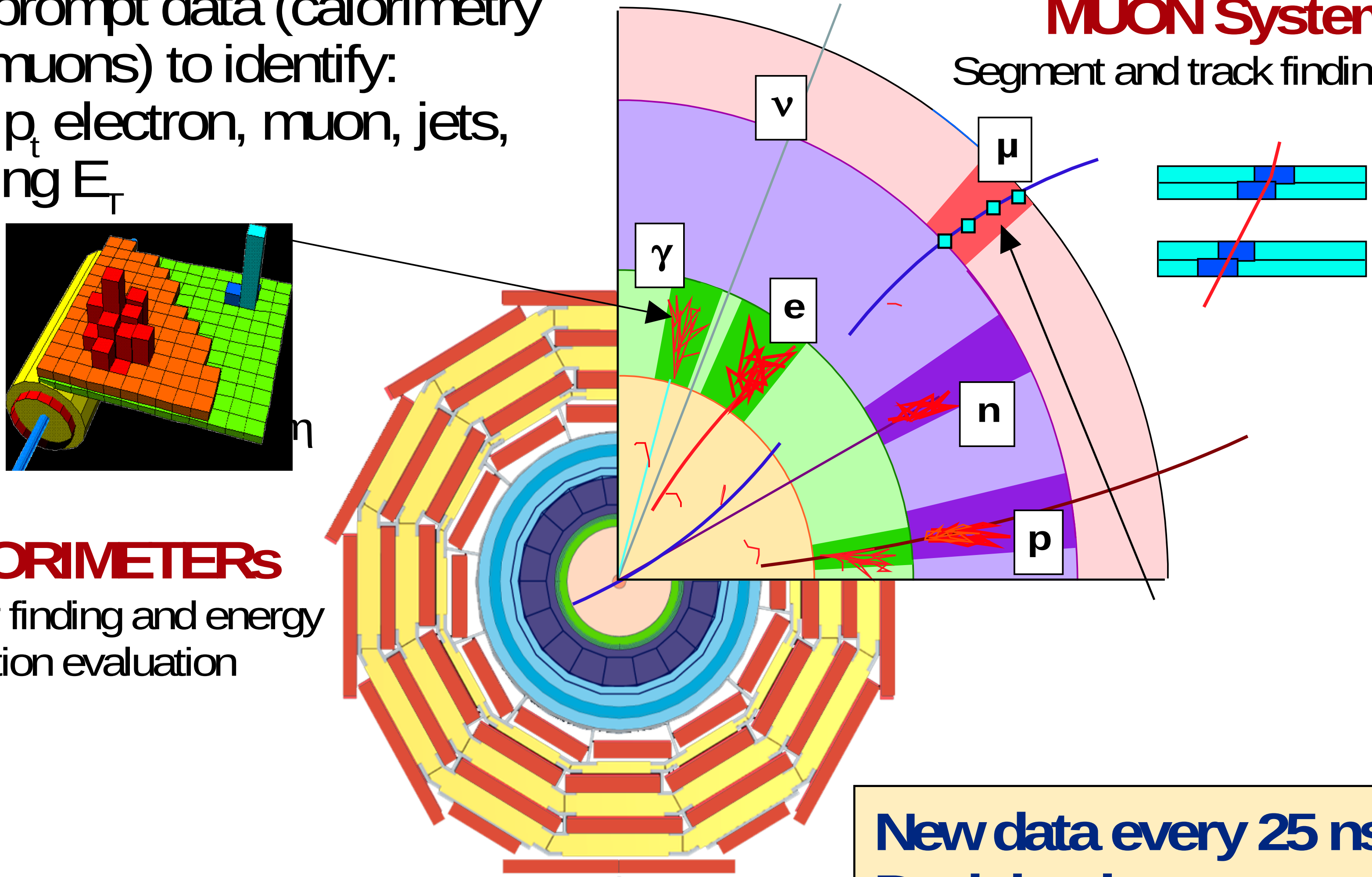
Reduce 40 MHz collision rate to ~100 Hz data recording rate

Readout to disk:

100 collisions/sec ~petaBytes of data/year

Level-1 trigger

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



MUON System

Segment and track finding

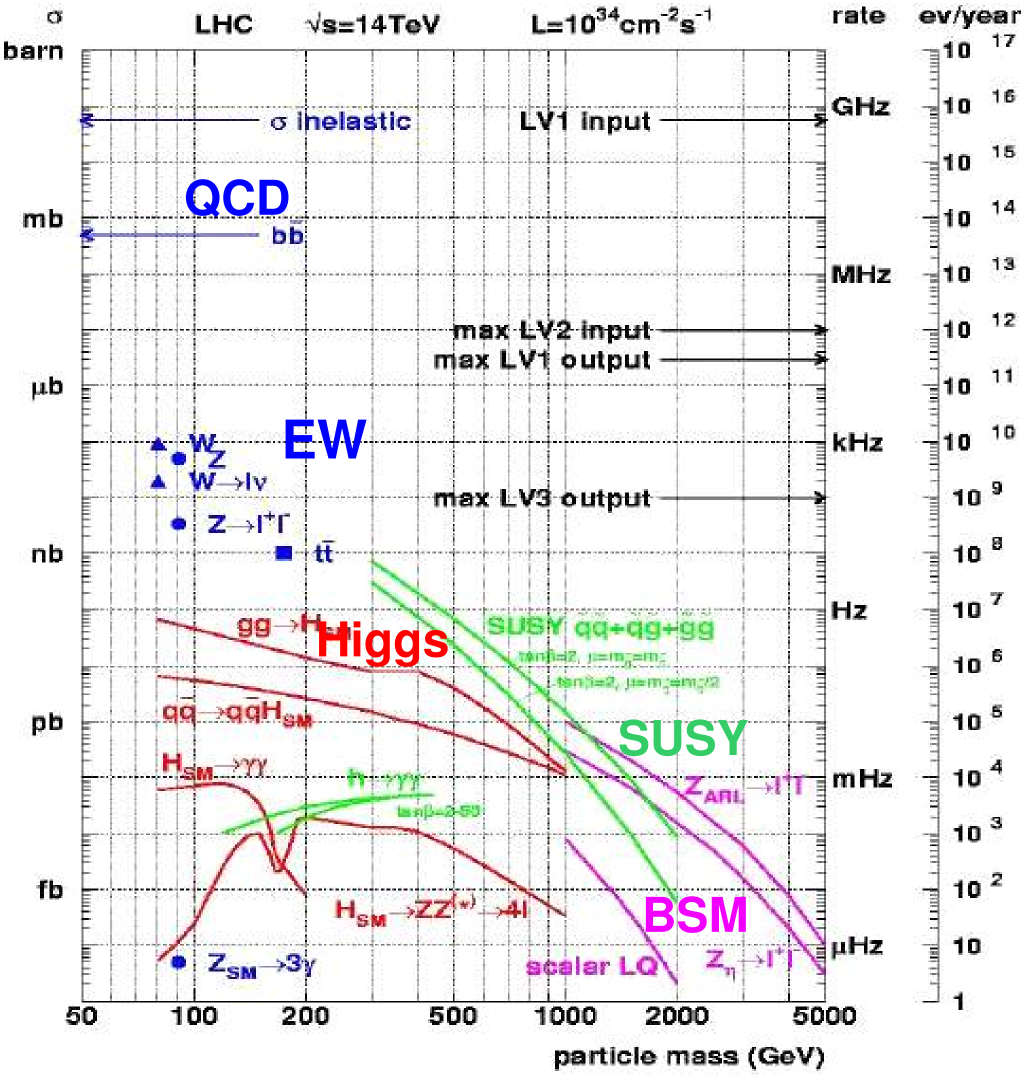
CALORIMETERs

Cluster finding and energy deposition evaluation

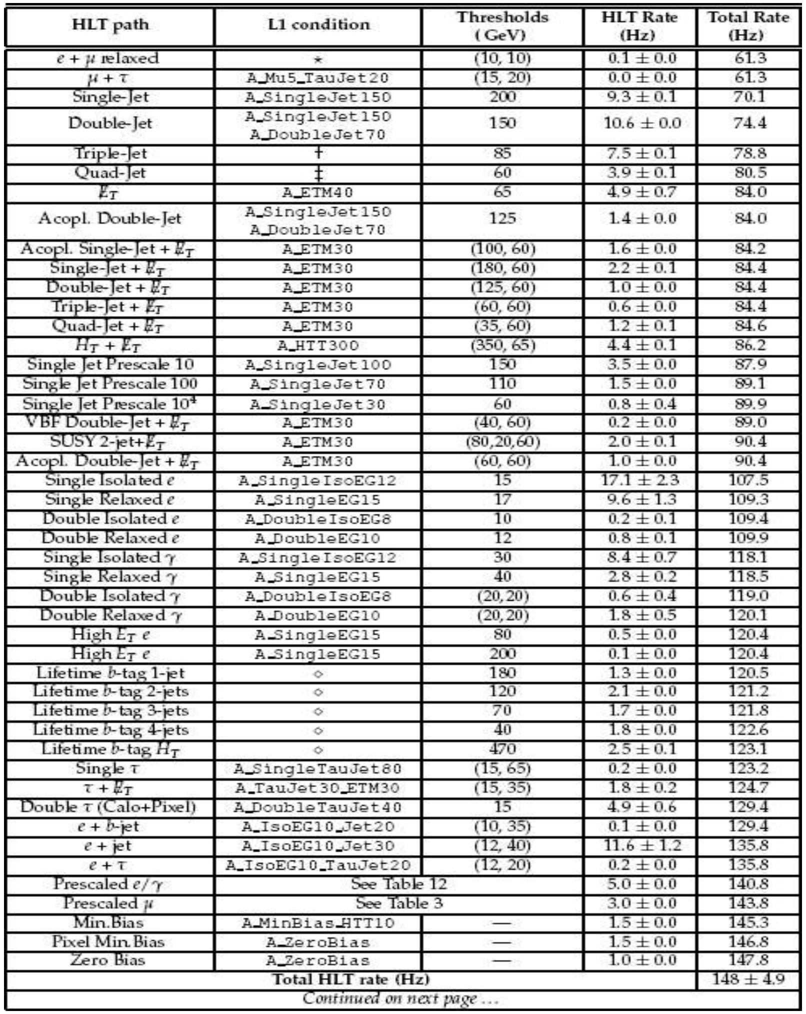
L1 ~10^3 data reduction: 40MHz →20kHz

New data every 25 ns
Decision latency ~ µs

High-Level-Trigger: extra selection



Trigger tables: QCD,EWK,Higgs, BSM ...

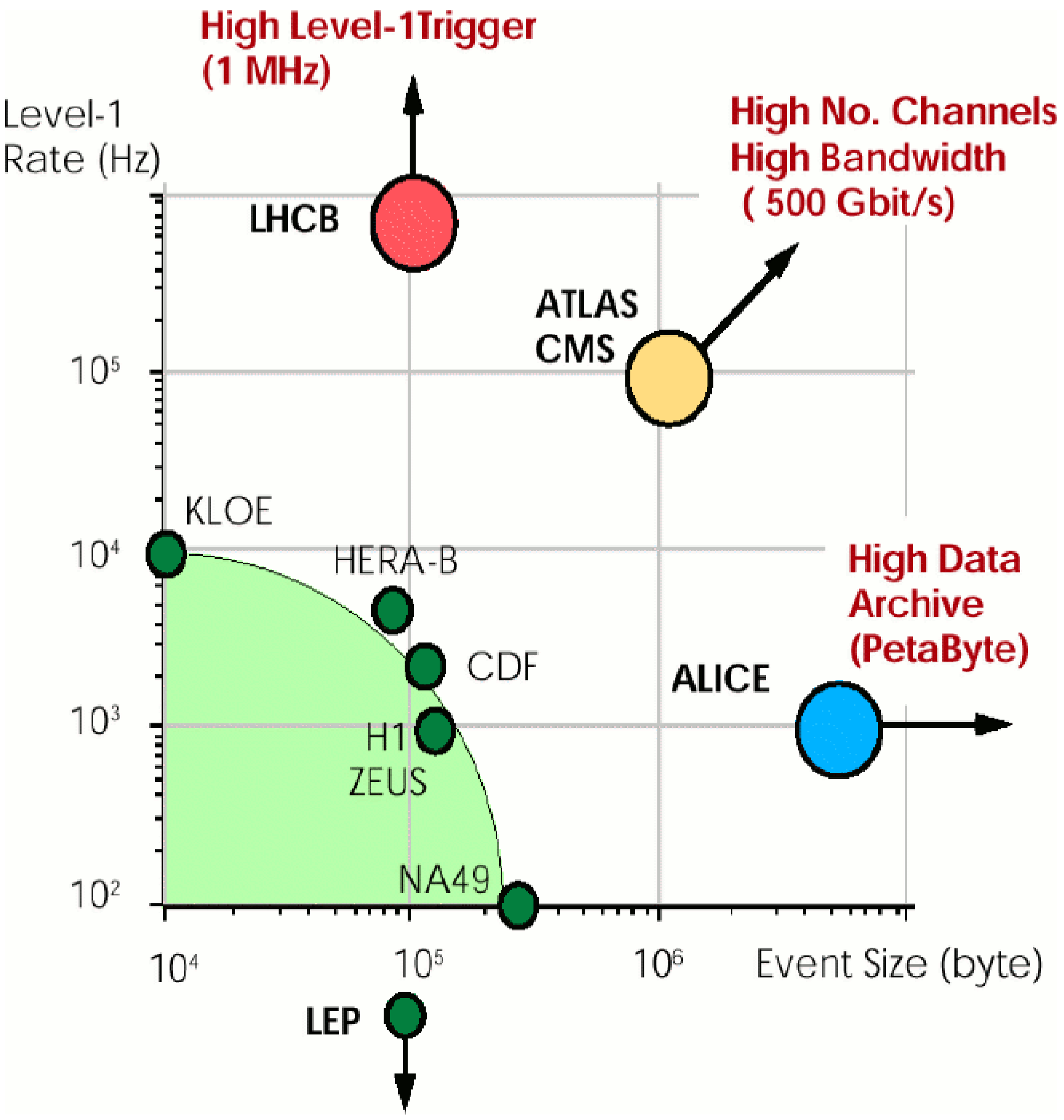


HLT path	L1 condition	Thresholds (GeV)	HLT Rate (Hz)	Total Rate (Hz)
$e+\mu$ relaxed	$\star$	(10, 10)	0.1 ± 0.0	61.3
$\mu+\tau$	`A_Mu5_TauJet20`	(15, 20)	0.0 ± 0.0	61.3
Single-Jet	`A_SingleJet150`	200	9.3 ± 0.1	70.1
Double-Jet	`A_SingleJet150` `A_DoubleJet70`	150	10.6 ± 0.0	74.4
Triple-Jet	†	85	7.5 ± 0.1	78.8
Quad-Jet	‡	60	3.9 ± 0.1	80.5
$\not\!\!E_T$	`A_ETM40`	65	4.9 ± 0.7	84.0
Acopl. Double-Jet	`A_SingleJet150` `A_DoubleJet70`	125	1.4 ± 0.0	84.0
Acopl. Single-Jet + $\not\!\!E_T$	`A_ETM30`	(100, 60)	1.6 ± 0.0	84.2
Single-Jet + $\not\!\!E_T$	`A_ETM30`	(180, 60)	2.2 ± 0.1	84.4
Double-Jet + $\not\!\!E_T$	`A_ETM30`	(125, 60)	1.0 ± 0.0	84.4
Triple-Jet + $\not\!\!E_T$	`A_ETM30`	(60, 60)	0.6 ± 0.0	84.4
Quad-Jet + $\not\!\!E_T$	`A_ETM30`	(35, 60)	1.2 ± 0.1	84.6
$H_T + \not\!\!E_T$	`A_HTT300`	(350, 65)	4.4 ± 0.1	86.2
Single Jet Prescale 10	`A_SingleJet100`	150	3.5 ± 0.0	87.9
Single Jet Prescale 100	`A_SingleJet70`	110	1.5 ± 0.0	89.1
Single Jet Prescale 10^4	`A_SingleJet30`	60	0.8 ± 0.4	89.9
VBF Double-Jet + $\not\!\!E_T$	`A_ETM30`	(40, 60)	0.2 ± 0.0	89.0
SUSY 2-jet+$\not\!\!E_T$	`A_ETM30`	(80,20,60)	2.0 ± 0.1	90.4
Acopl. Double-Jet + $\not\!\!E_T$	`A_ETM30`	(60, 60)	1.0 ± 0.0	90.4
Single Isolated e	`A_SingleIsoEG12`	15	17.1 ± 2.3	107.5
Single Relaxed e	`A_SingleEG15`	17	9.6 ± 1.3	109.3
Double Isolated e	`A_DoubleIsoEG8`	10	0.2 ± 0.1	109.4
Double Relaxed e	`A_DoubleEG10`	12	0.8 ± 0.1	109.9
Single Isolated γ	`A_SingleIsoEG12`	30	8.4 ± 0.7	118.1
Single Relaxed γ	`A_SingleEG15`	40	2.8 ± 0.2	118.5
Double Isolated γ	`A_DoubleIsoEG8`	(20,20)	0.6 ± 0.4	119.0
Double Relaxed γ	`A_DoubleEG10`	(20,20)	1.8 ± 0.5	120.1
High E_T e	`A_SingleEG15`	80	0.5 ± 0.0	120.4
High E_T e	`A_SingleEG15`	200	0.1 ± 0.0	120.4
Lifetime b-tag 1-jet	$\diamond$	180	1.3 ± 0.0	120.5
Lifetime b-tag 2-jets	$\diamond$	120	2.1 ± 0.0	121.2
Lifetime b-tag 3-jets	$\diamond$	70	1.7 ± 0.0	121.8
Lifetime b-tag 4-jets	$\diamond$	40	1.8 ± 0.0	122.6
Lifetime b-tag H_T	$\diamond$	470	2.5 ± 0.1	123.1
Single τ	`A_SingleTauJet80`	(15, 65)	0.2 ± 0.0	123.2
$\tau + \not\!\!E_T$	`A_TauJet30_ETM30`	(15, 35)	1.8 ± 0.2	124.7
Double τ (Calo+Pixel)	`A_DoubleTauJet40`	15	4.9 ± 0.6	129.4
$e + b$-jet	`A_IsoEG10_Jet20`	(10, 35)	0.1 ± 0.0	129.4
e + jet	`A_IsoEG10_Jet30`	(12, 40)	11.6 ± 1.2	135.8
$e + \tau$	`A_IsoEG10_TauJet20`	(12, 20)	0.2 ± 0.0	135.8
Prescaled e/γ	See Table 12		5.0 ± 0.0	140.8
Prescaled μ	See Table 3		3.0 ± 0.0	143.8
Min.Bias	`A_MinBias_HTT10`	—	1.5 ± 0.0	145.3
Pixel Min.Bias	`A_ZeroBias`	—	1.5 ± 0.0	146.8
Zero Bias	`A_ZeroBias`	—	1.0 ± 0.0	147.8
Total HLT rate (Hz)				148 ± 4.9

Continued on next page ...

HLT ~100 data reduction: 20kHz →150Hz

Trigger rate / Data size



Huge computing effort !

~1 PB of raw data/year

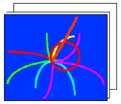
3000 CPU's at CERN

>5000 in regional centers

Data GRID project

⇒ Crucial for LHC data analysis

Detectors → Trigger → DAQ → Storage



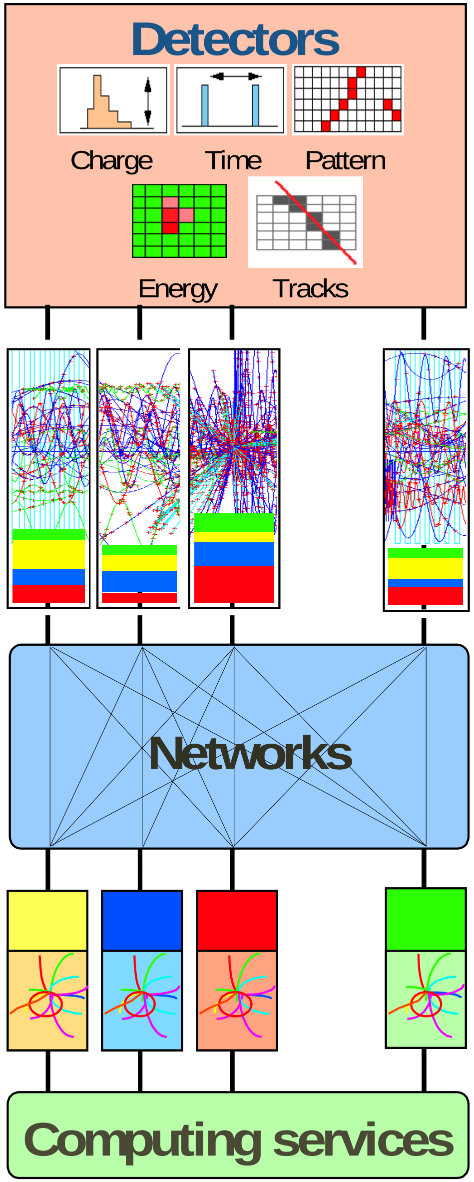
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

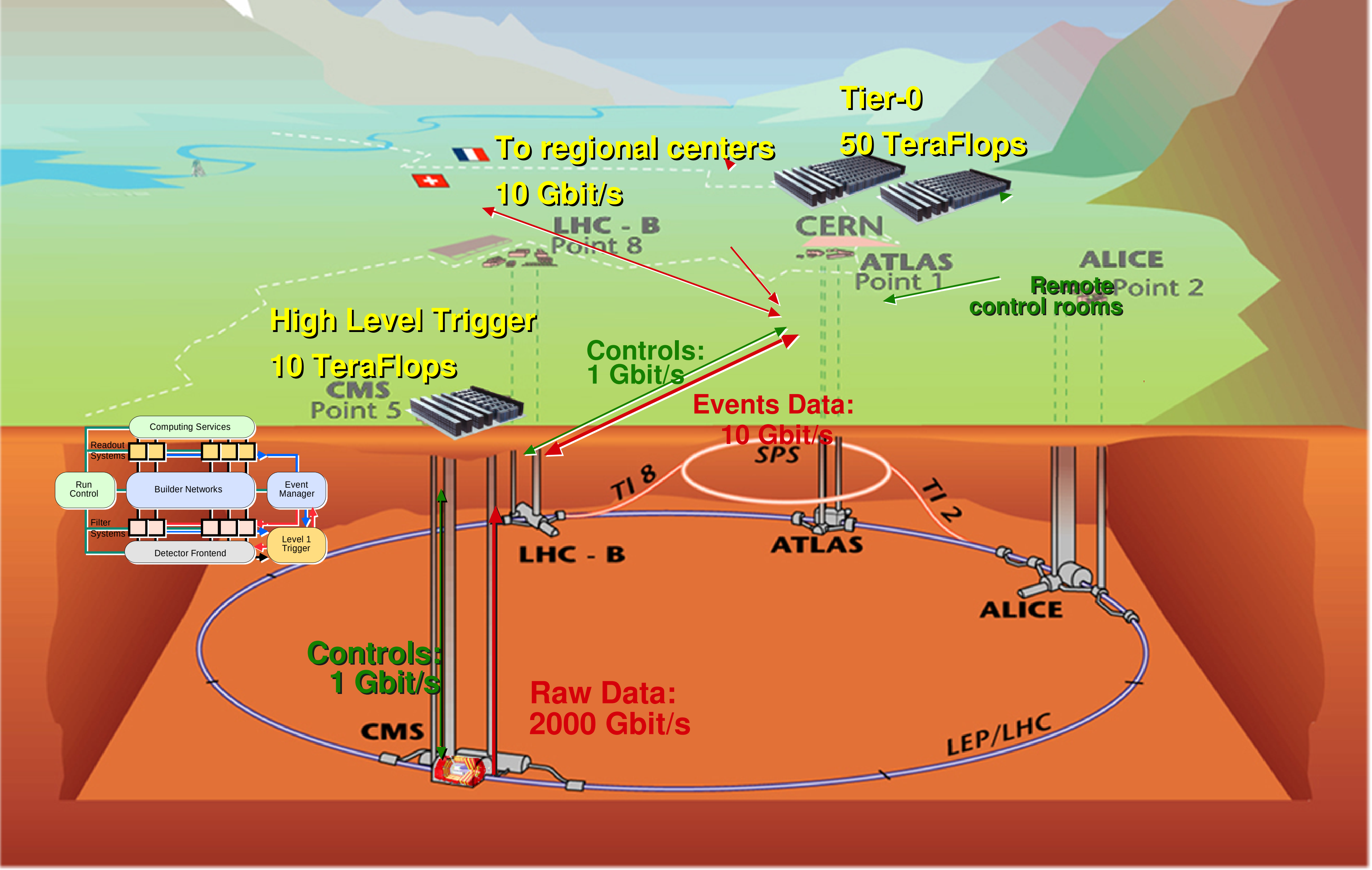
EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

Data flow & on/off line computing



Tier-0

50 TeraFlops

To regional centers

10 Gbit/s

Remote control rooms

High Level Trigger

10 TeraFlops

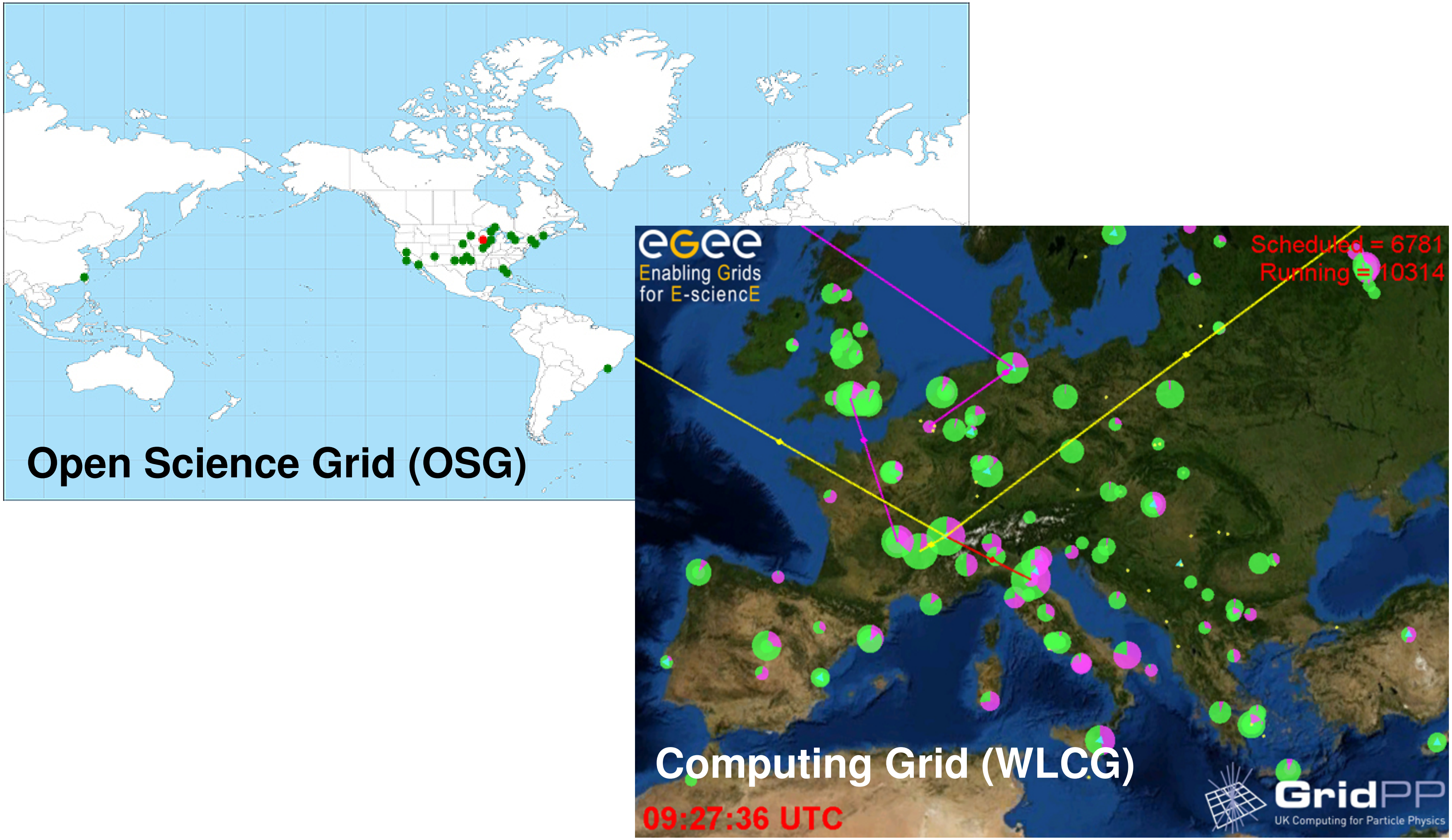
Controls:
1 Gbit/s

Events Data:
10 Gbit/s

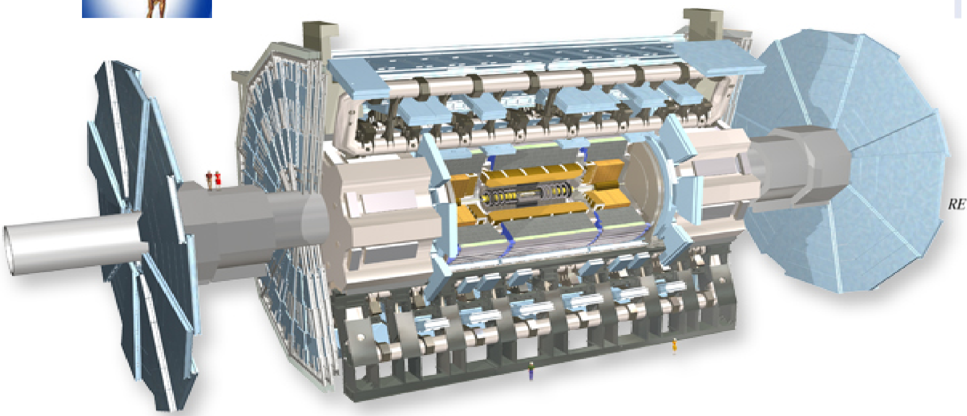
Controls:
1 Gbit/s

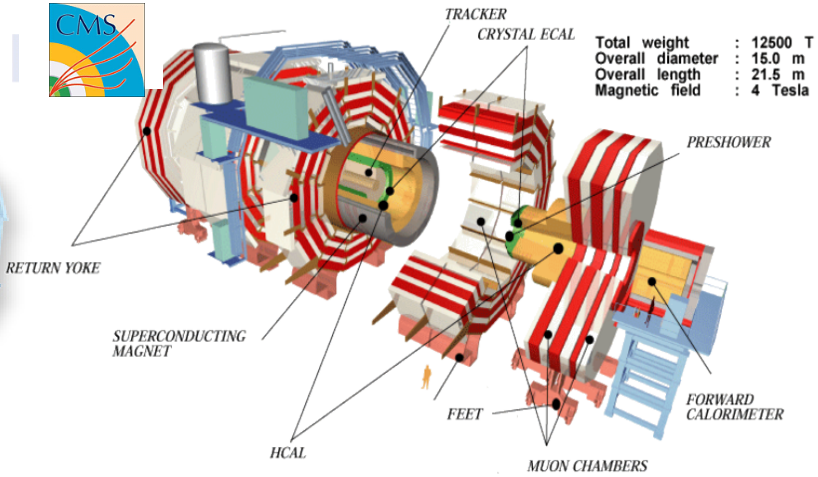
Raw Data:
2000 Gbit/s

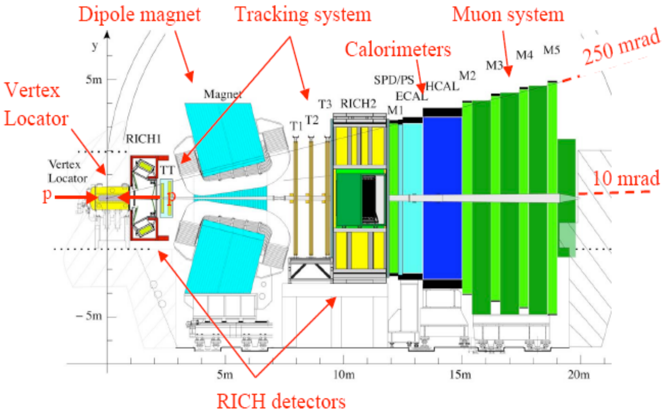
The Grid: worldwide LHC

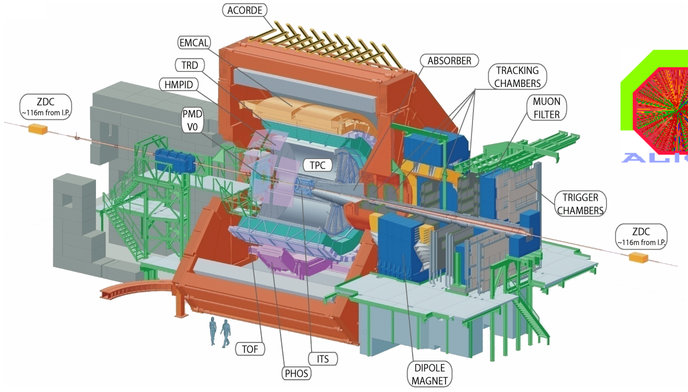


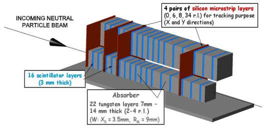
Summary: Experiments at the LHC

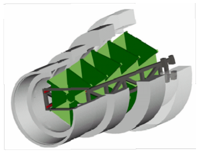


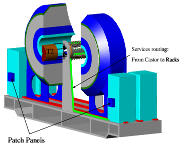


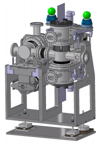






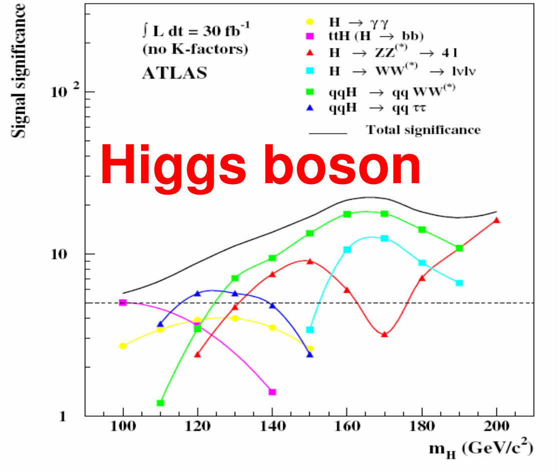




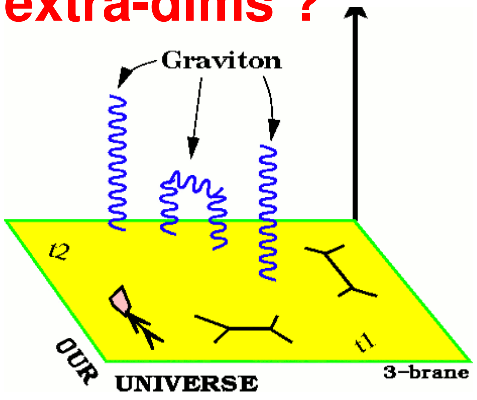


Summary: Physics at the LHC

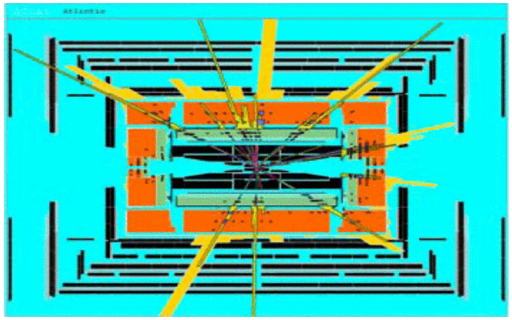
Higgs boson



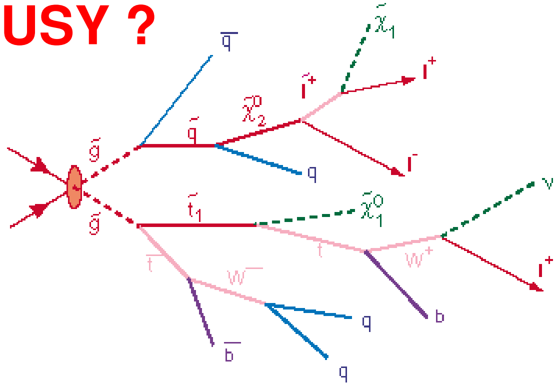
extra-dims ?



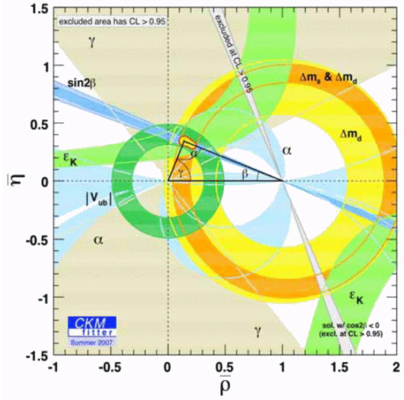
mini black-holes ??



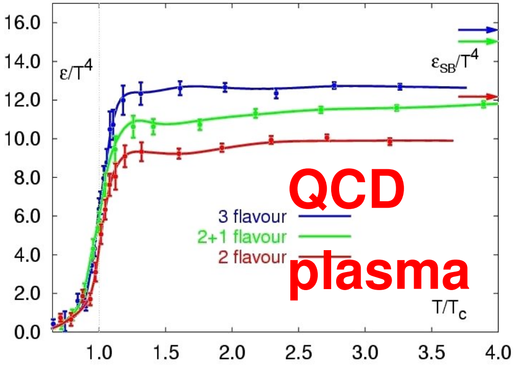
SUSY ?



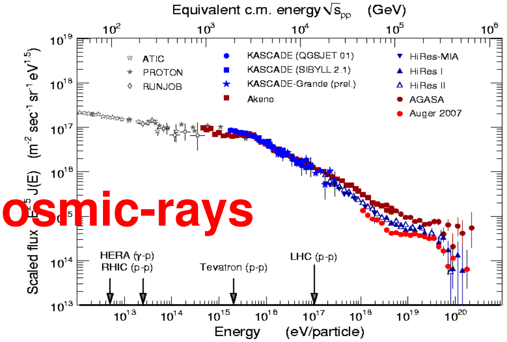
CP-violation



QCD plasma



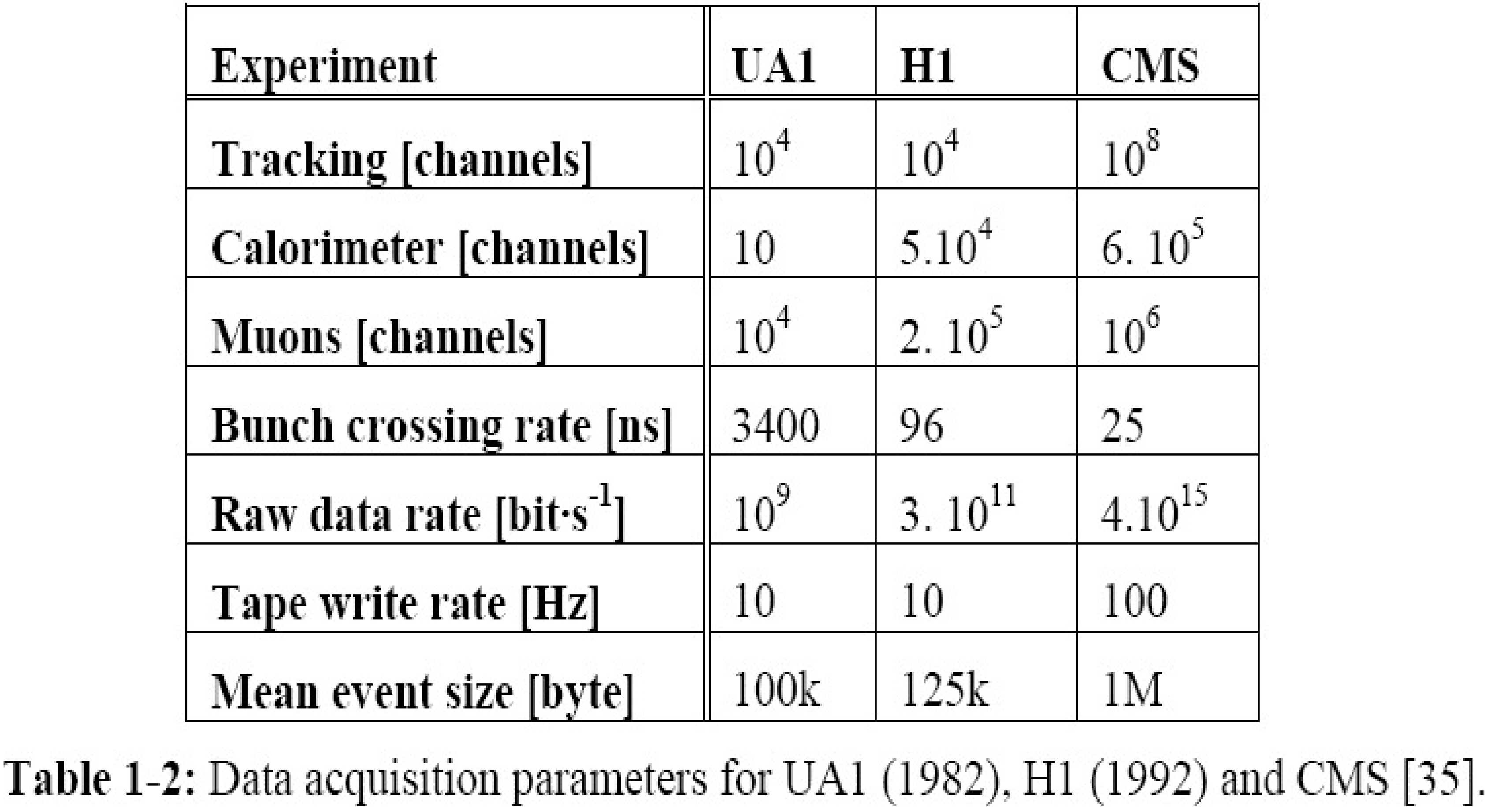
GZK cosmic-rays



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

Backup slides

Dectector/Data size: 1982-2008

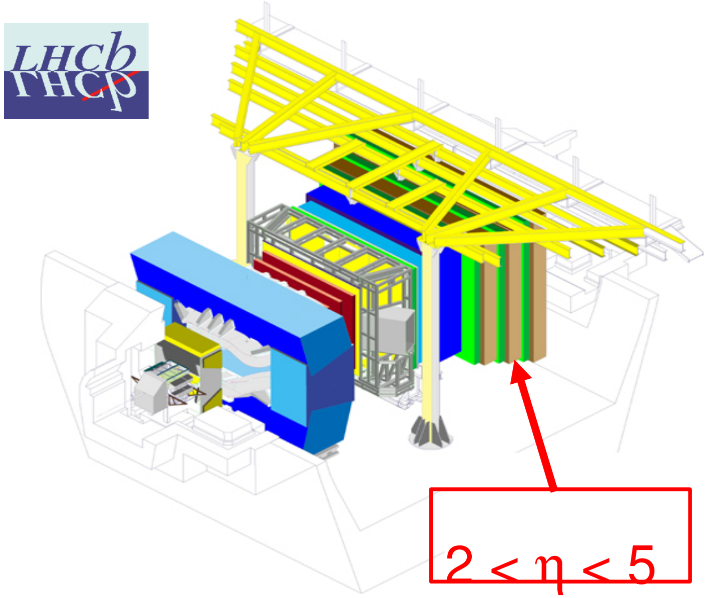


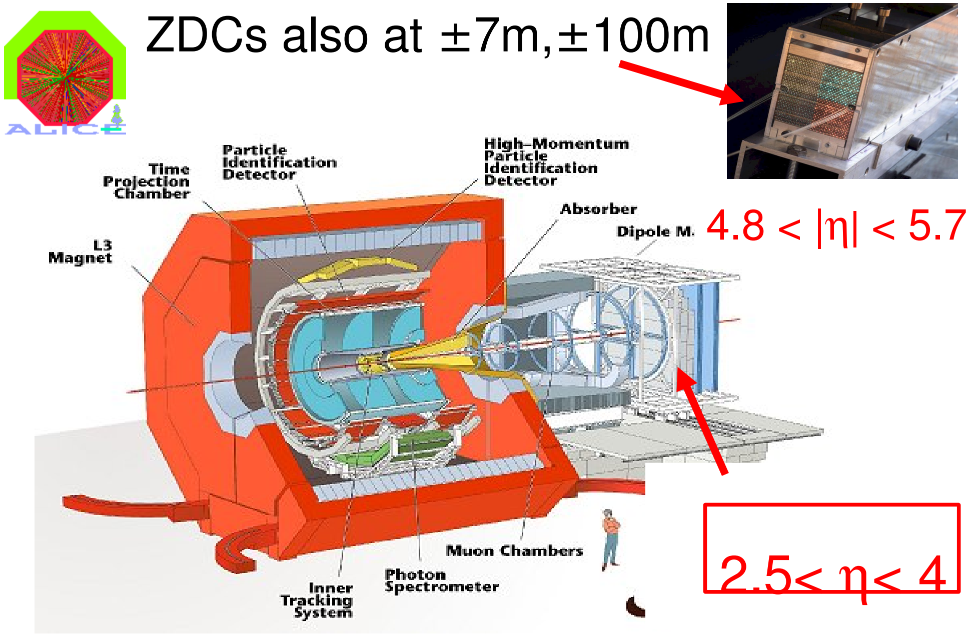
Experiment	UA1	H1	CMS
Tracking [channels]	10^4	10^4	10^8
Calorimeter [channels]	10	5.10^4	$6.\ 10^5$
Muons [channels]	10^4	$2.\ 10^5$	10^6
Bunch crossing rate [ns]	3400	96	25
Raw data rate [bit·s^{-1}]	10^9	$3.\ 10^{11}$	4.10^{15}
Tape write rate [Hz]	10	10	100
Mean event size [byte]	100k	125k	1M

Table 1-2: Data acquisition parameters for UA1 (1982), H1 (1992) and CMS [35].

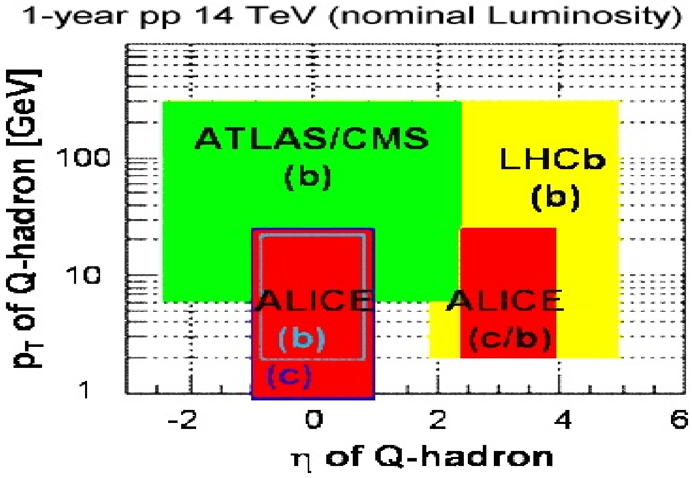
ALICE & LHCb forward detectors

- Forward muon spectrometers:

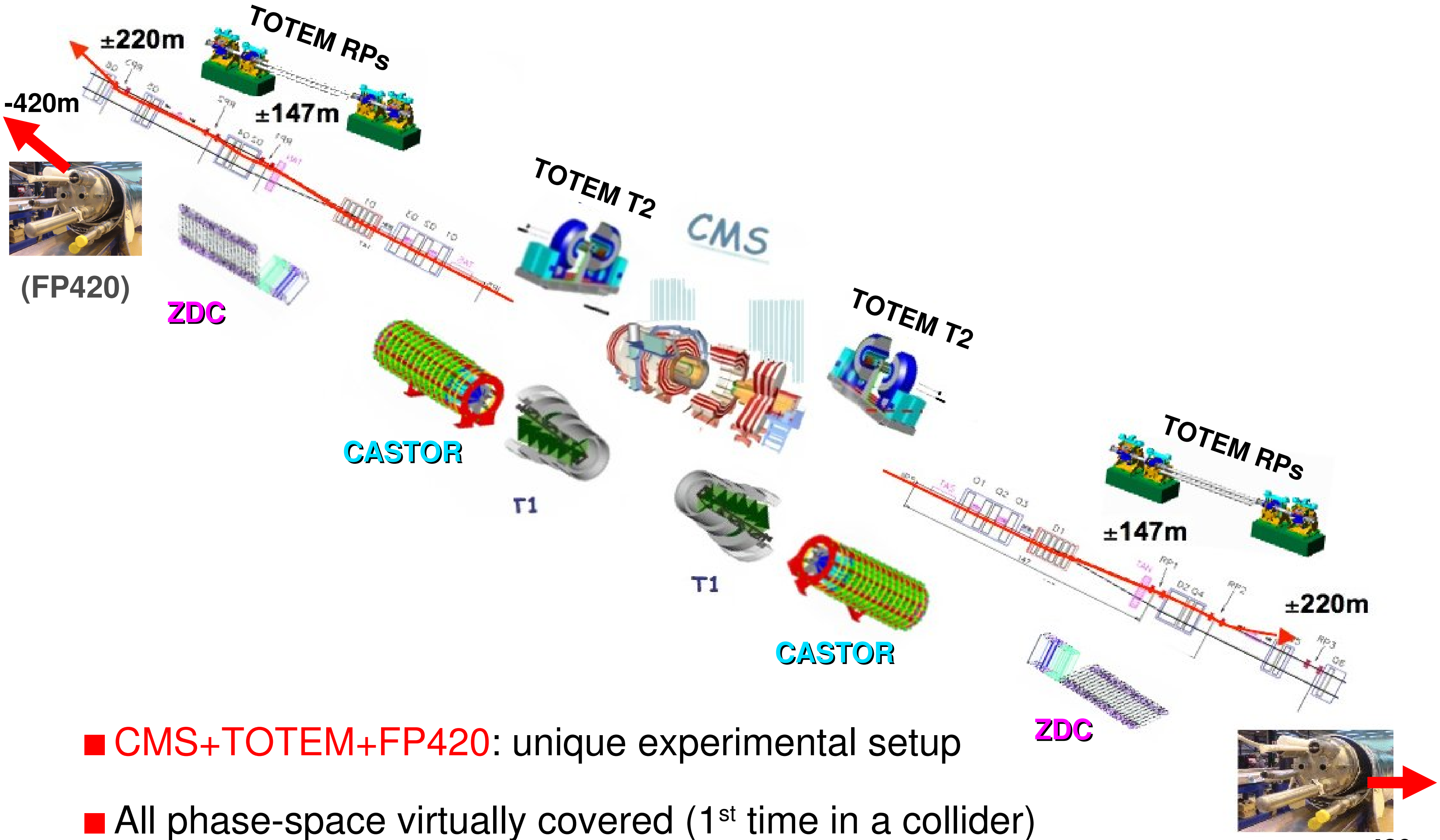




- Good capabilities for fwd. heavy-Q, $Q\bar{Q}$, gauge bosons measurements: (low-x PDFs)



TOTEM & LHCf: forward detectors



- CMS+TOTEM+FP420: unique experimental setup
- All phase-space virtually covered (1st time in a collider)