LHC Physics and Detectors

ETH Institute for Particle Physics

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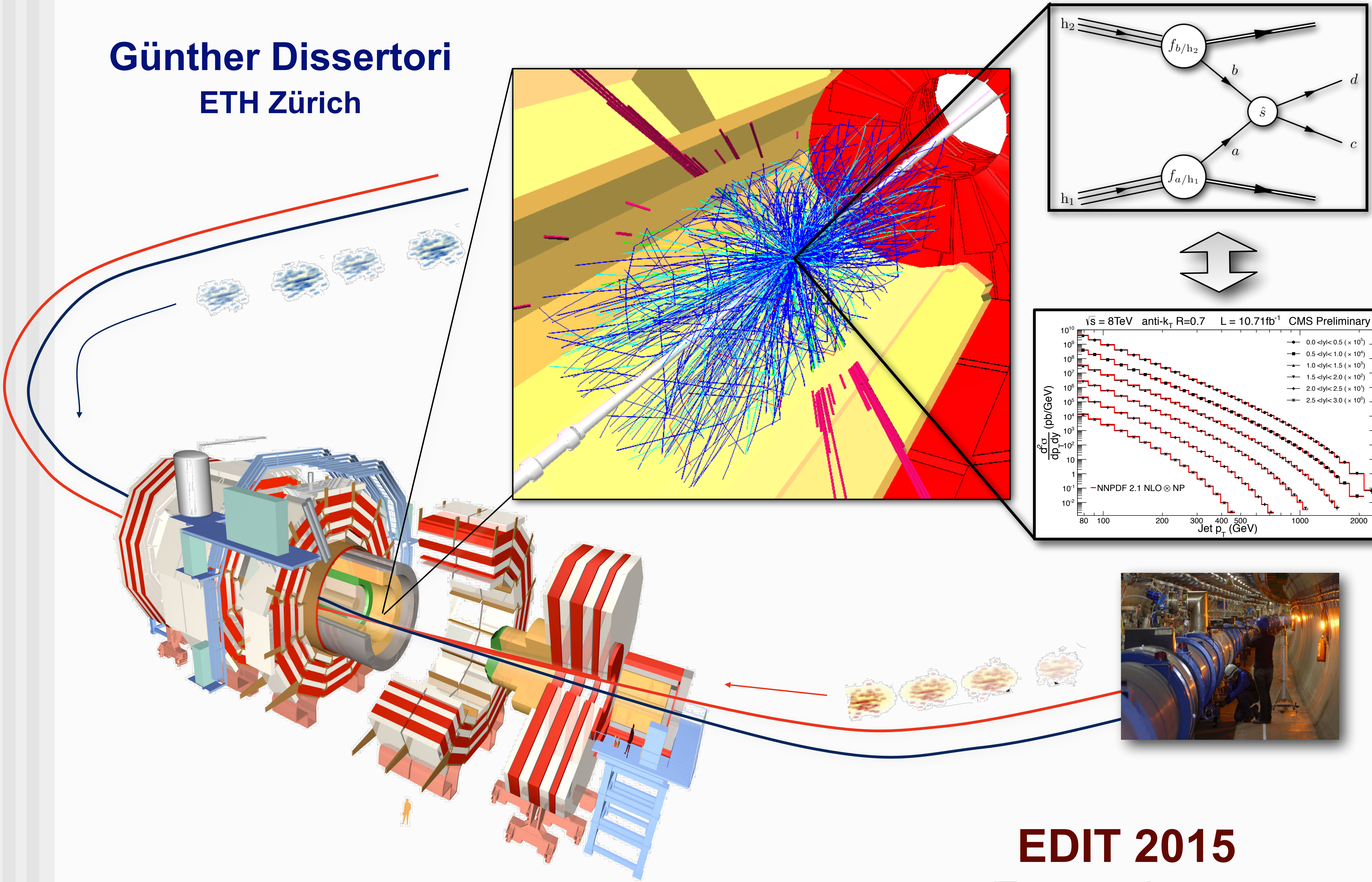

EDIT 2015
Frascati, Italy

Outline:

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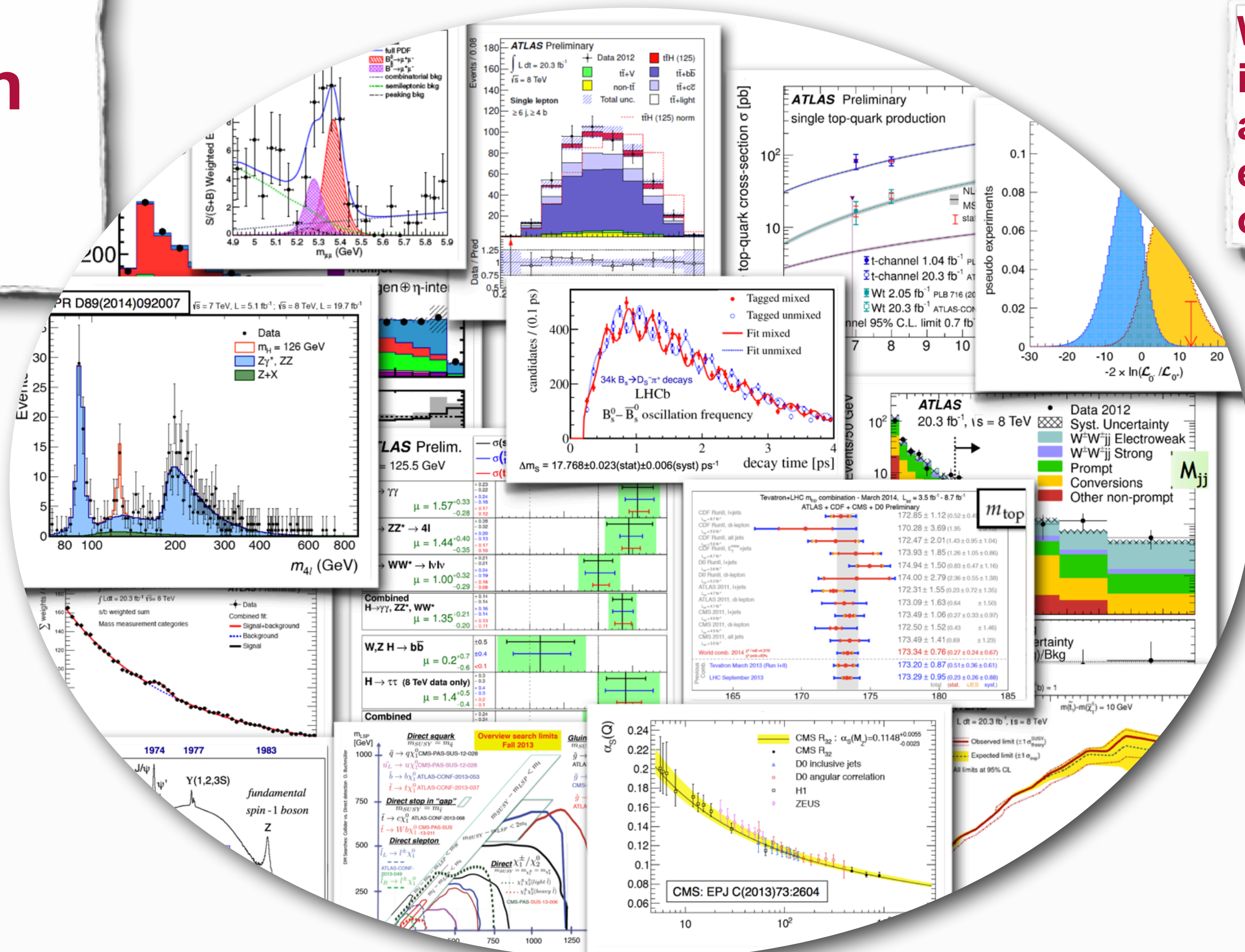
How to design an LHC detector



We will see all the issues to be taken into account,including the expected physics, of course

what achieved? Highlights….

see also other lectures, of course!

- this will not be a review talk of LHC results
- for sure, it will not be comprehensive, balanced, or anything similar; also, some of the plots might not be the latest/greatest
- in particular, both because of lack of time, I will mostly focus on ATLAS and CMS, and only shortly mention LHCb (ALICE will be covered in lecture by Harris)

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Our milestones:

1. Why do ATLAS and CMS look like they look like today?
2. Some highlights, achievements

Our milestones:

1. Why do ATLAS and CMS look like they look like today? A bit of "history"...
2. Some highlights, achievements

Variables used in pp collisions

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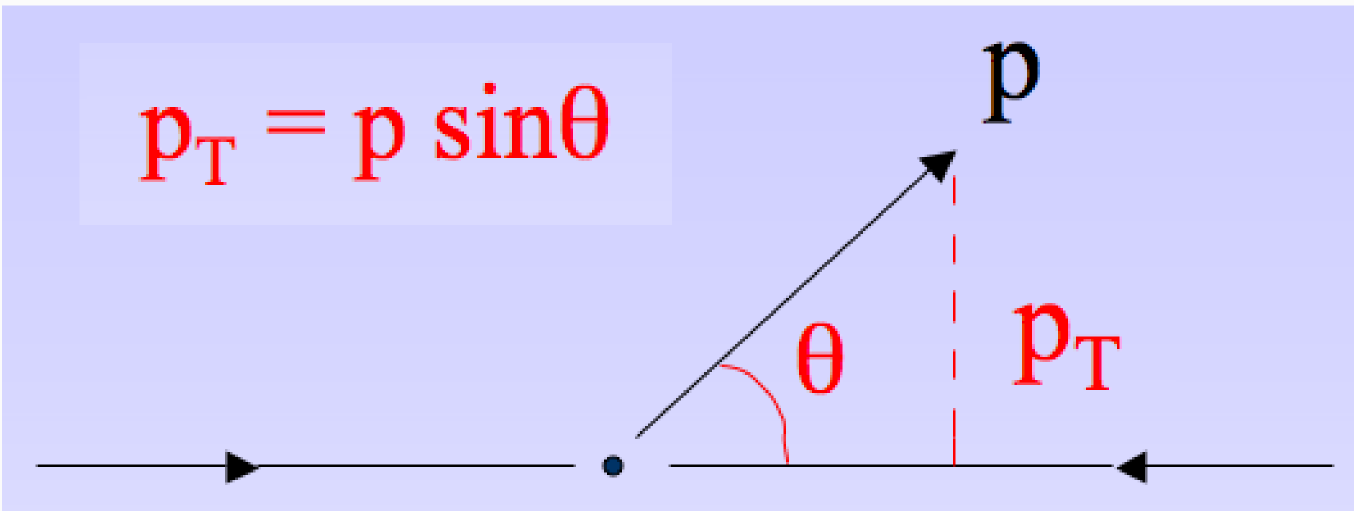
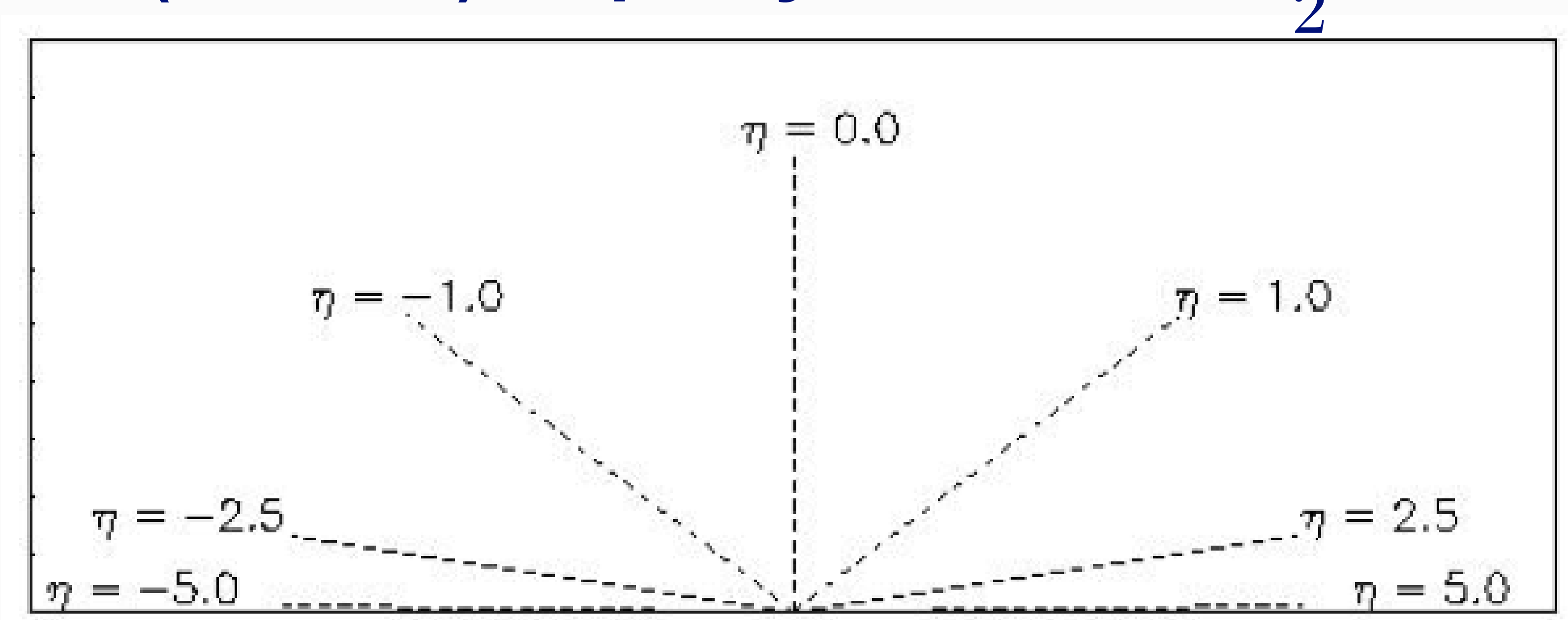


Transverse momentum

(in the plane perpendicular to the beam)

Rapidity $y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right)$

(Pseudo)-Rapidity $\eta = -\ln \tan \frac{\theta}{2}$



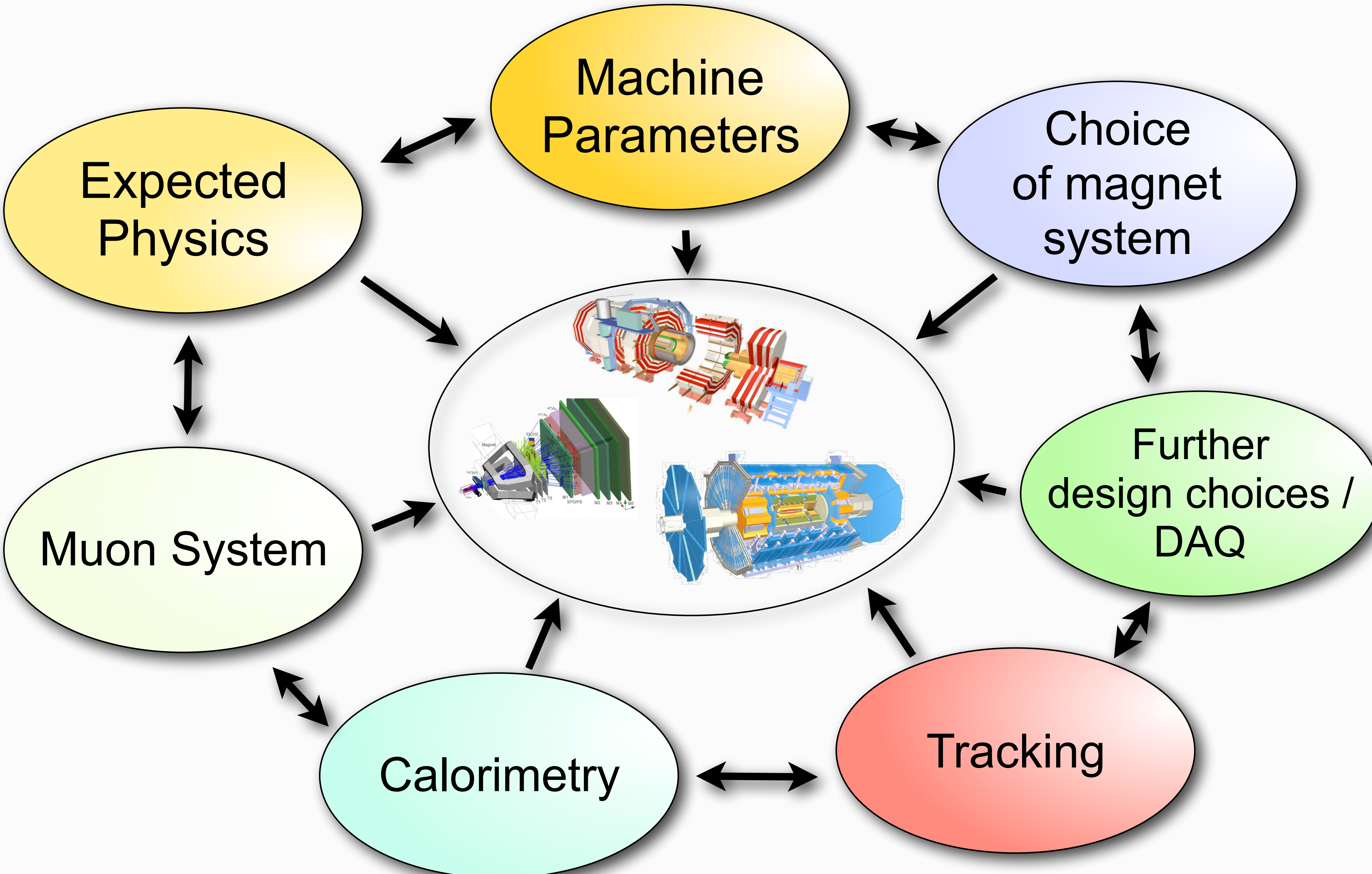
$\theta = 90^\circ \rightarrow \eta = 0$

$\theta = 10^\circ \rightarrow \eta \cong 2.4$

$\theta = 170^\circ \rightarrow \eta \cong -2.4$

$\theta = 1^\circ \rightarrow \eta \cong 5.0$

How to design your detector



Note : all numbers in the following are orders of magnitude!

pp-Interactions at the LHC

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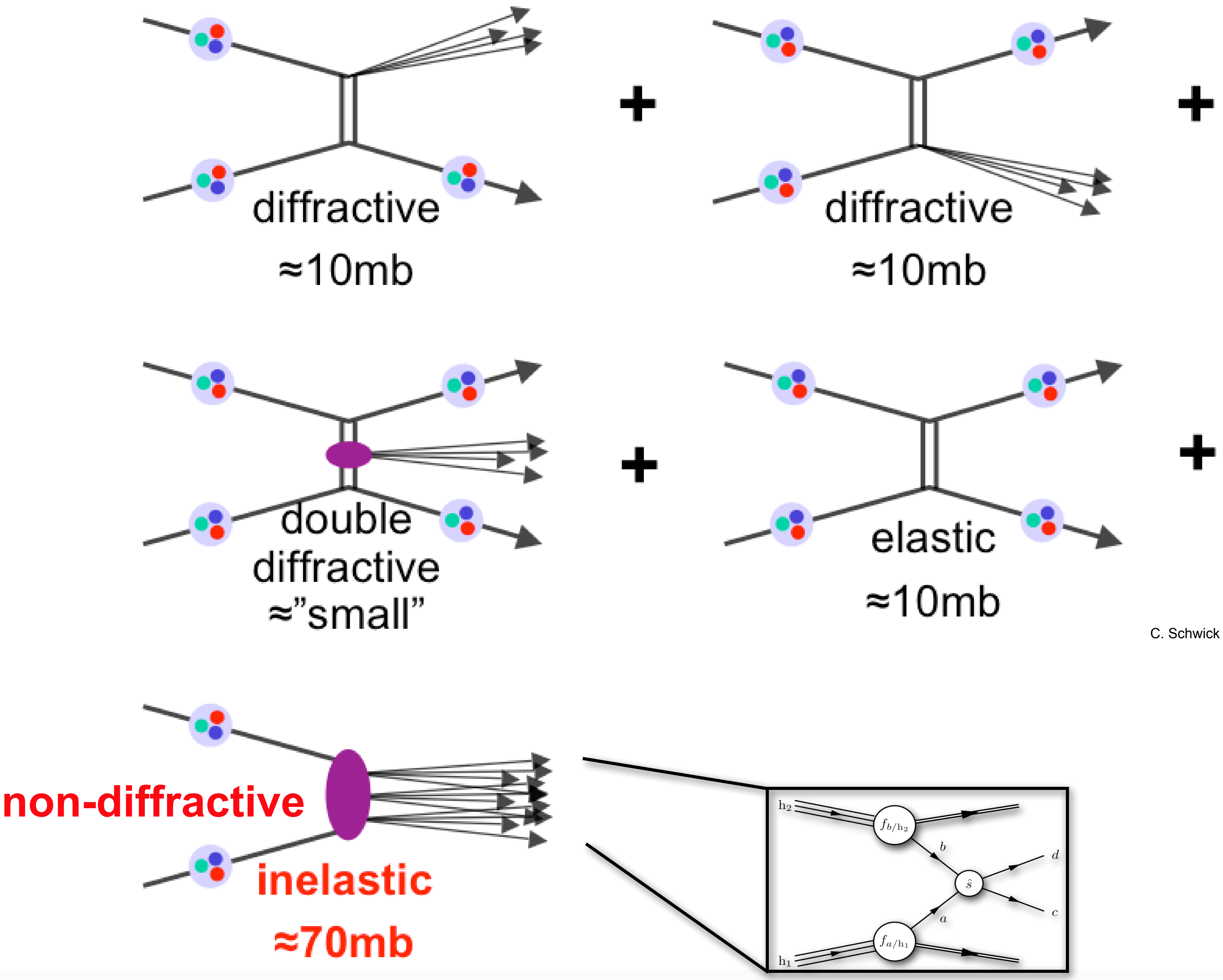
σ_{tot} =

≈100mb



Most of the focus: hard scattering

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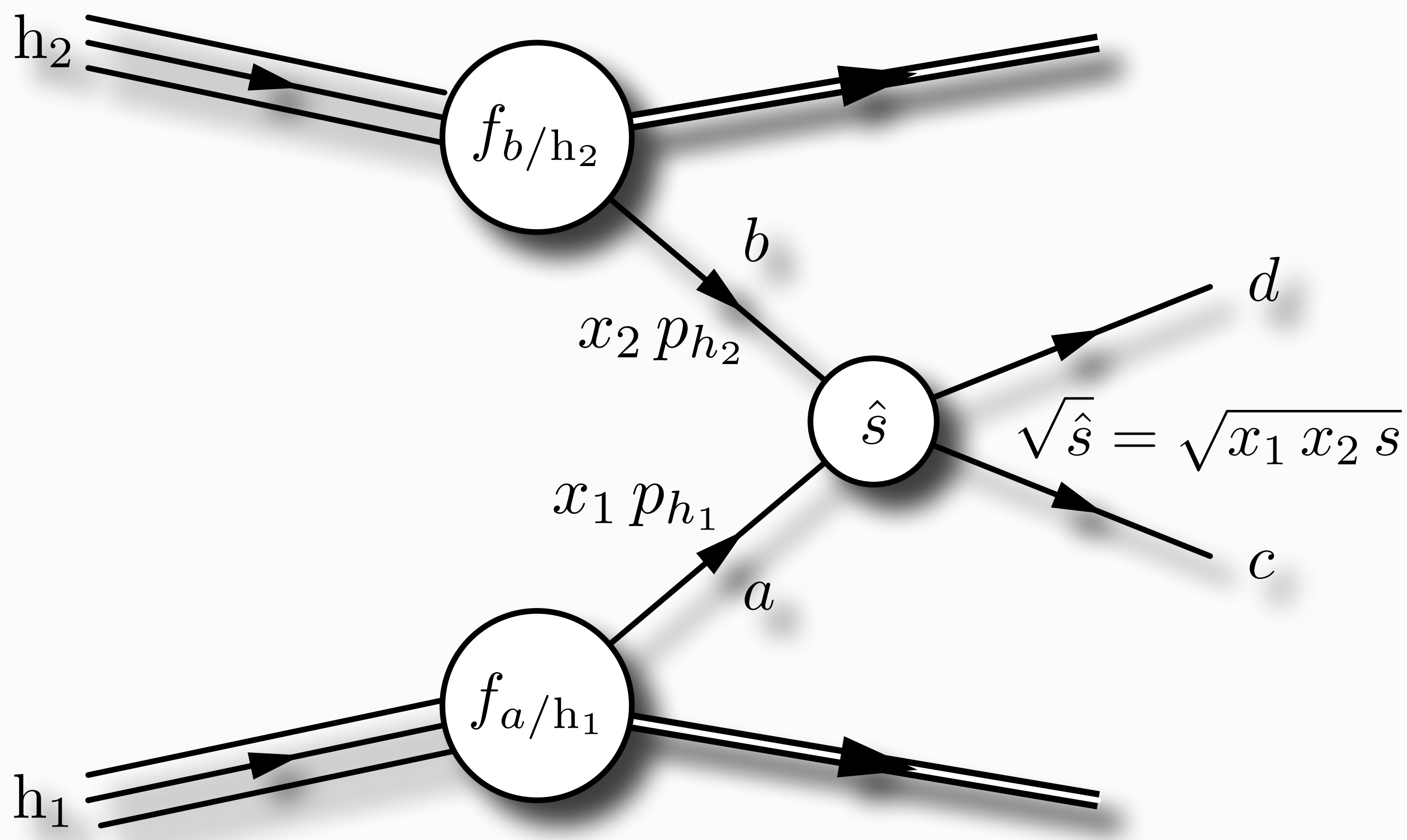


$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

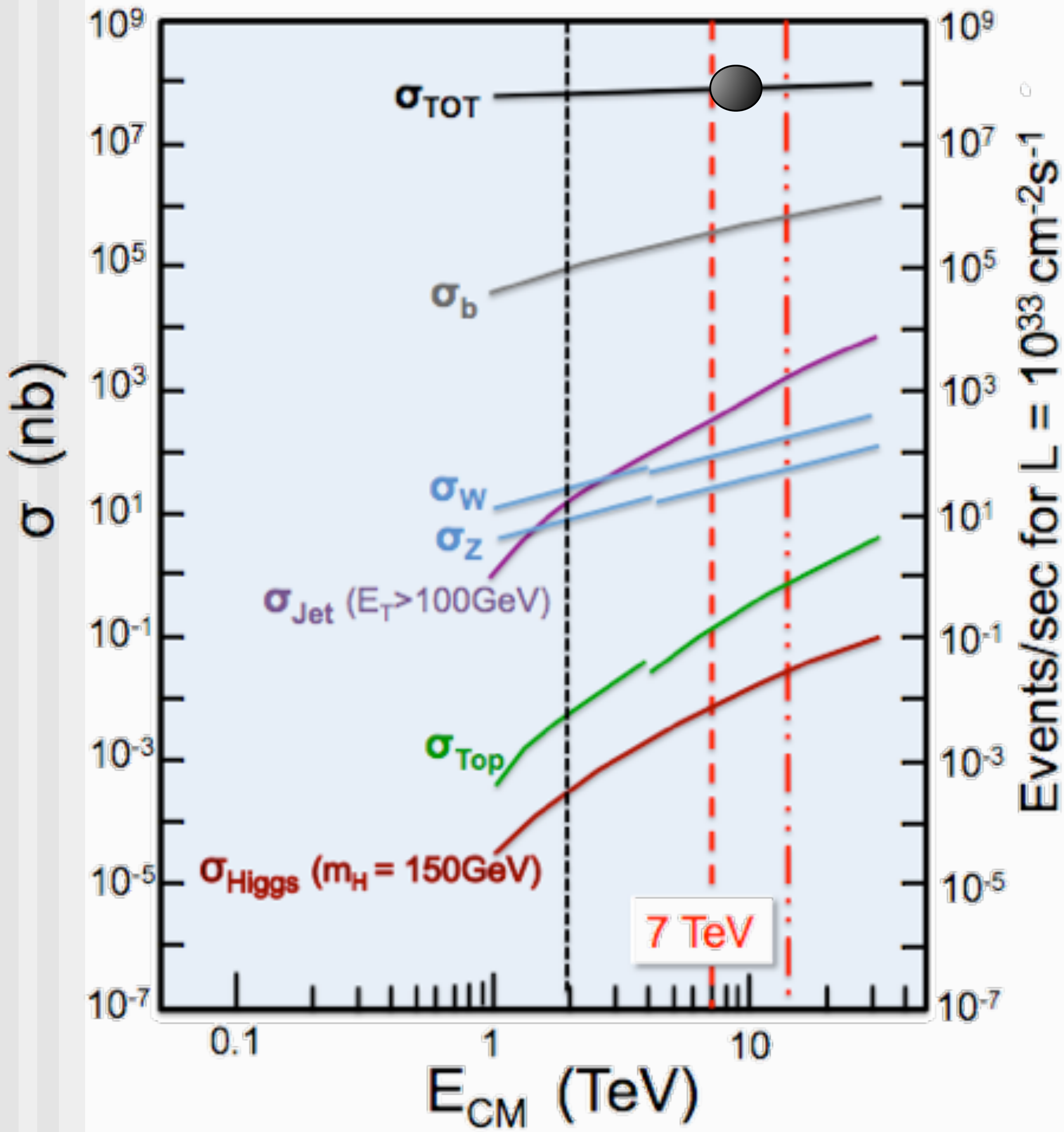
Hard Scattering = processes with large momentum transfer (Q^2)

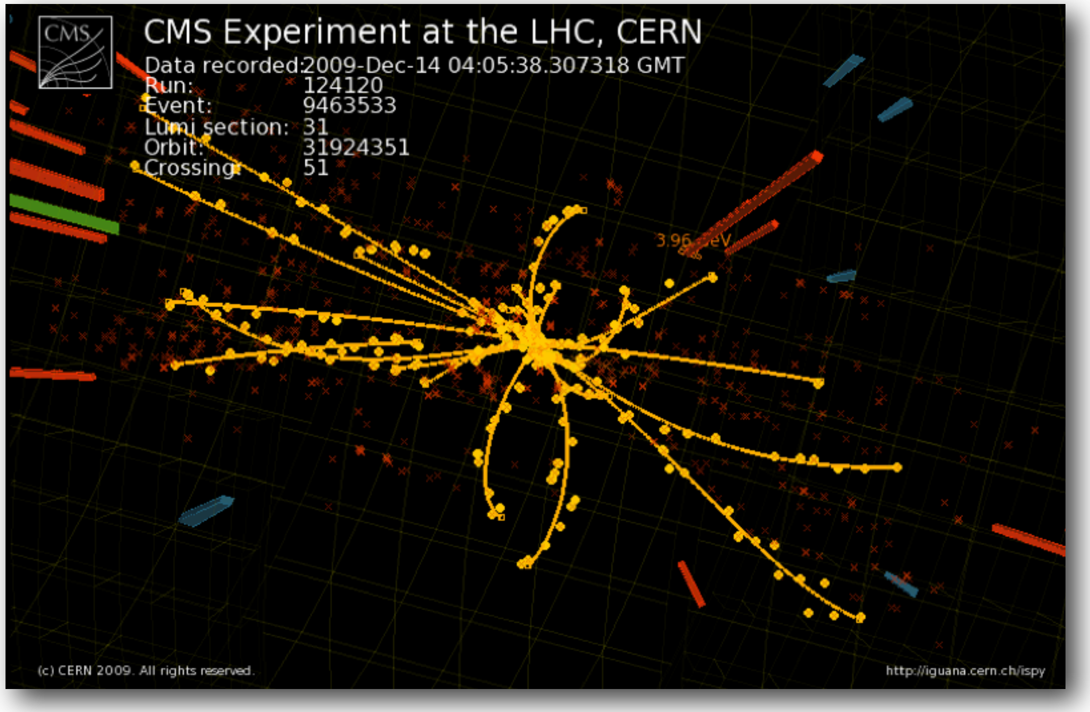
Represents only a tiny fraction of the total inelastic pp cross section (~ 70-80 mb)

eg. **σ(pp → W+X)** ~ 150 nb ~ **2 • 10^{-6} σ_{tot}(pp)**

Expected Physics was ... (1)

- Inelastic low-p_T pp collisions
  - Most processes are due to soft and semi-soft interactions between incoming protons
    - particles in the final state have large longitudinal, but small transverse momentum -> small momentum transfer:
      - several hundreds of MeV





Low-p_T inelastic pp-collisions:
"Minimum Bias events"
Parameters (multiplicity etc) poorly known!
Important for tuning MC simulations,
and understanding of Pile-Up effects

The impact on the detector design

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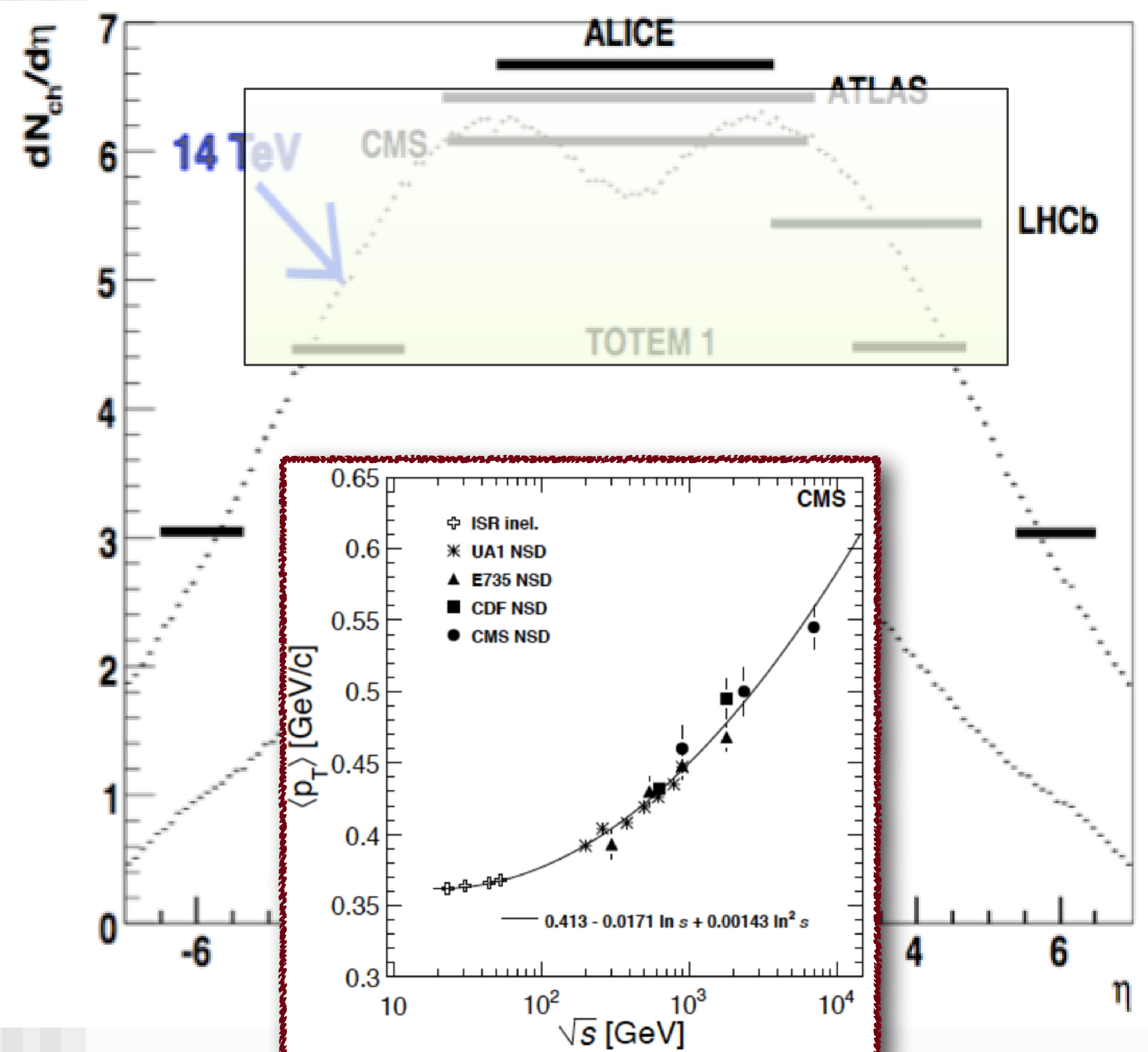


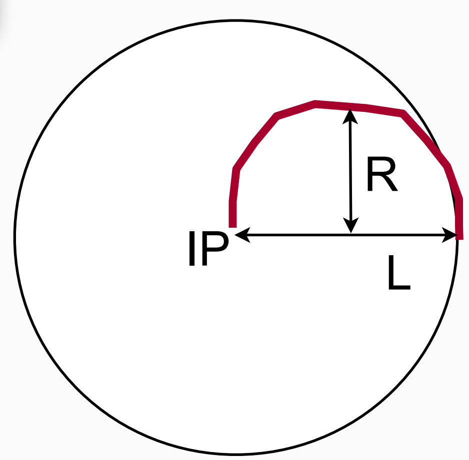
$$\frac{d^3p}{2E} = \frac{\pi}{2}\, dp_T^2\, dy$$

- for low-mass particles (eg. pions) : "flat" in (pseudo)-rapidity
- in order to collect most of them (also to ensure hermeticity, eg. for E_{Tmiss}): need detector up to $y_{\max} \approx 5$
- particle density: ~ 4 - 6 charged particles (pions) plus ~ 2 - 3 neutrals (π^0) per unit of pseudorapidity in the central detector region
- uniformly distributed in φ

$$\langle p_T \rangle \approx 500 - 600\,\mathrm{MeV}$$

$$p[\mathrm{GeV}] = 0.3\, R[\mathrm{m}]\, B[\mathrm{T}]$$

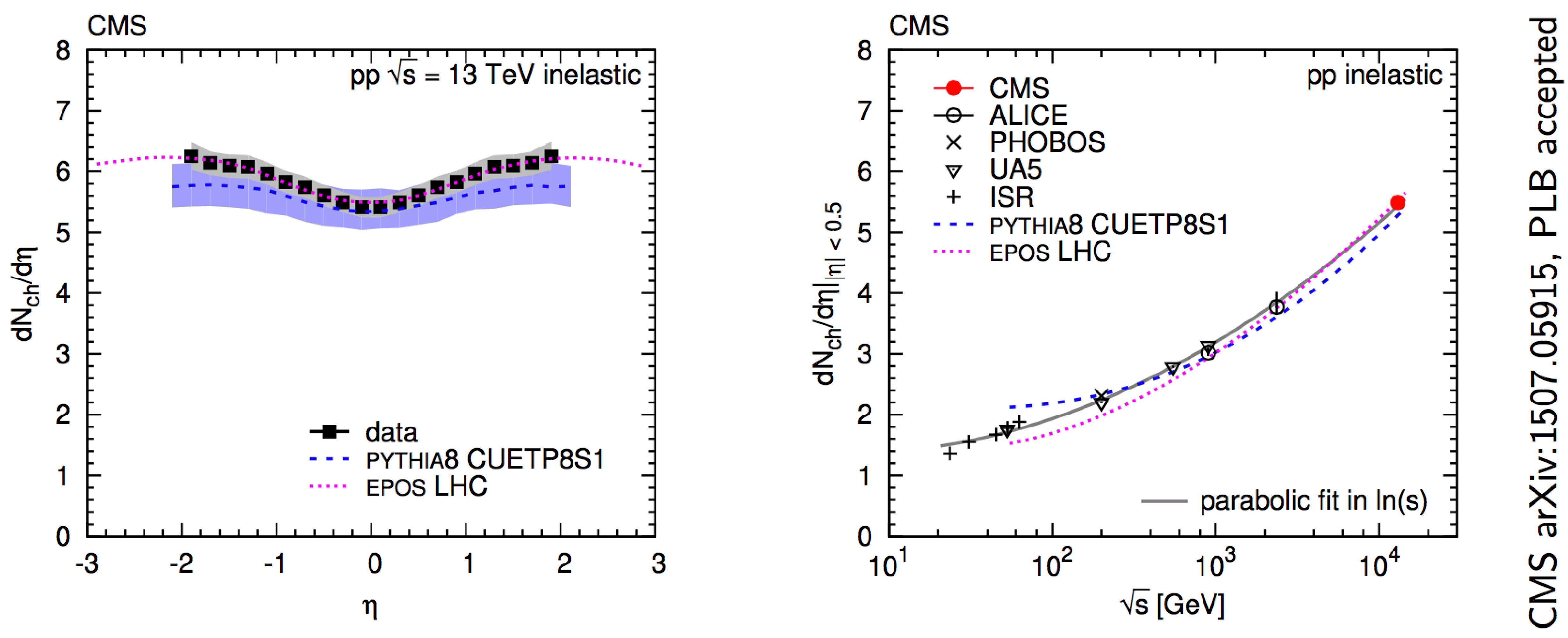
$$\Longrightarrow L \leq 2\,R = \frac{p}{0.15\,B}$$



- minimize too many "curling" tracks which do not reach the calorimeter: tracker/calo boundary at about **L ~ 1.2m for B = 4T**

By the way…

- first results on this at 13 TeV:



$$\text{Inelastic pp: } dN/d\eta|_{|\eta|<0.5} = 5.49 \pm 0.01(\text{stat}) \pm 0.17(\text{syst})$$

Expected Physics was ... (2)

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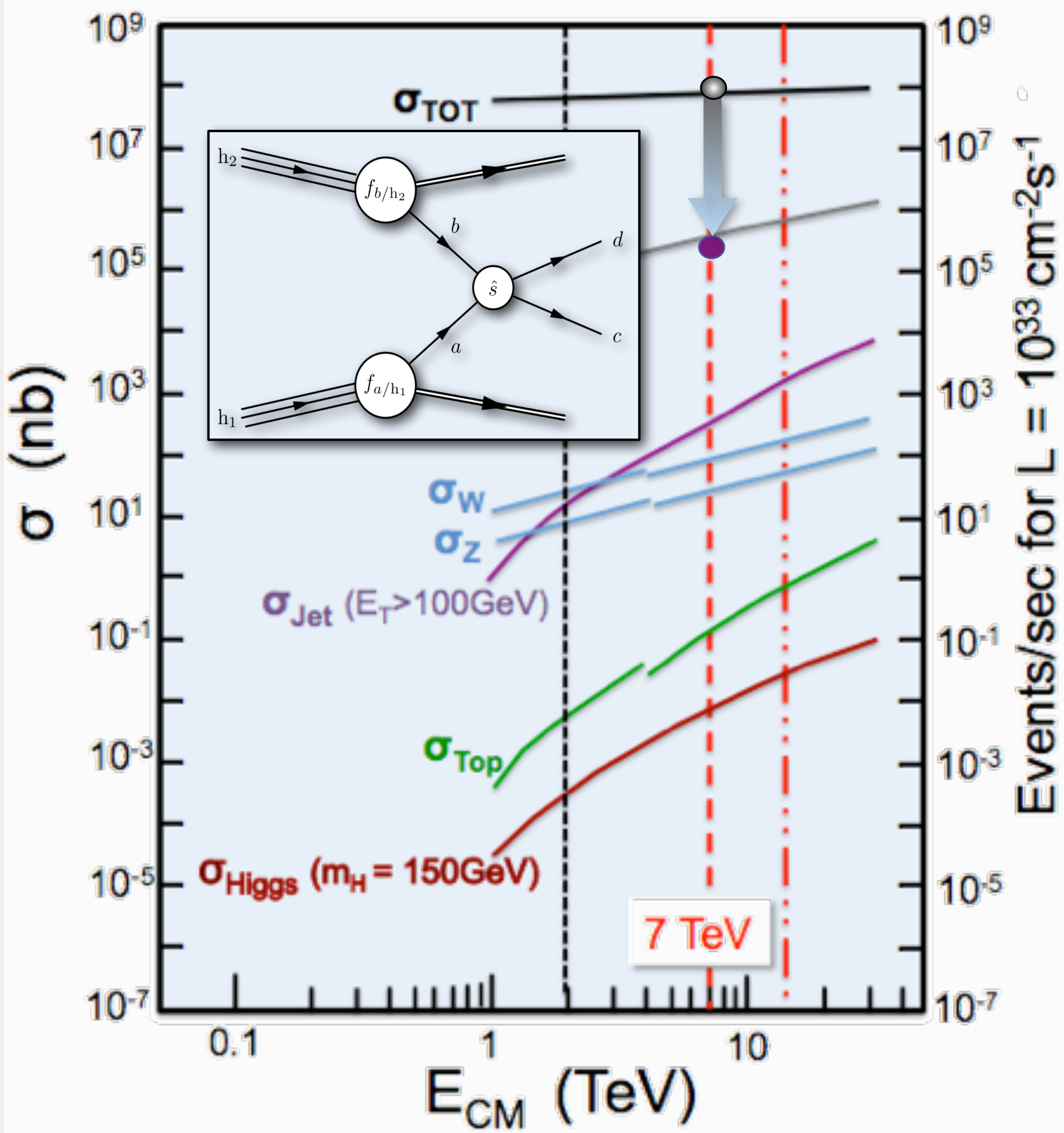
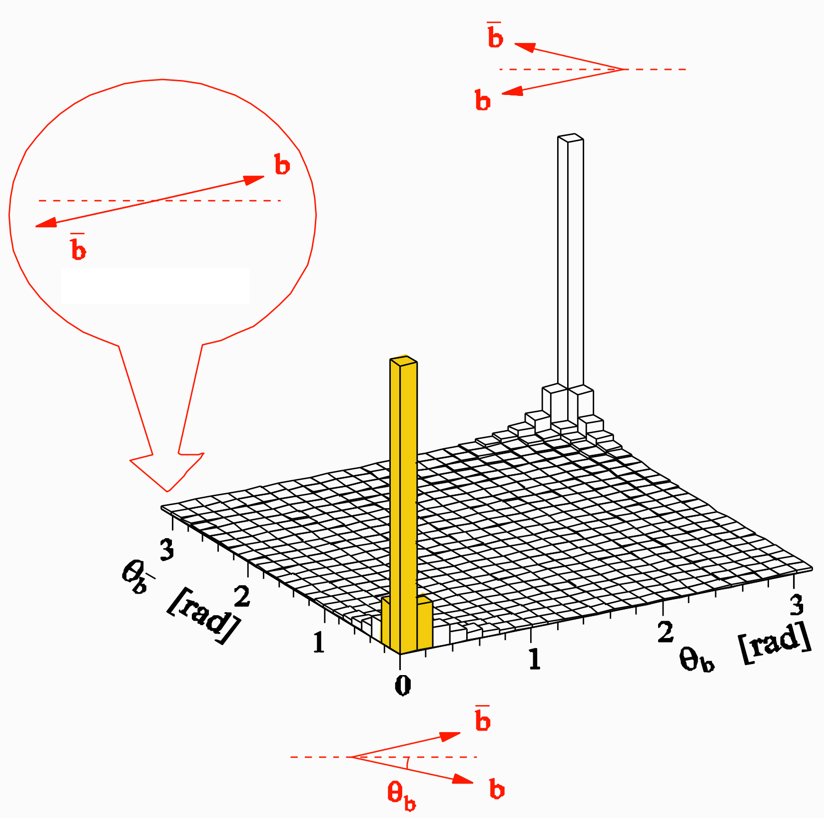


- **Huge** cross section for b-quark production (study CP viol., flavour problem)
  - about 0.5 mb (!) at 14 TeV
  - mostly gluon fusion, very asymmetric initial momenta, thus strongly boosted final state
    - b-hadrons with <p> ~ 80 GeV ==> 7mm mean decay distance



- no need for full “4PI” - coverage
- just built a “forward spectrometer”
- need: very good vertex detector and particle identification (to reconstruct b-hadrons)

Expected Physics was ... (3)

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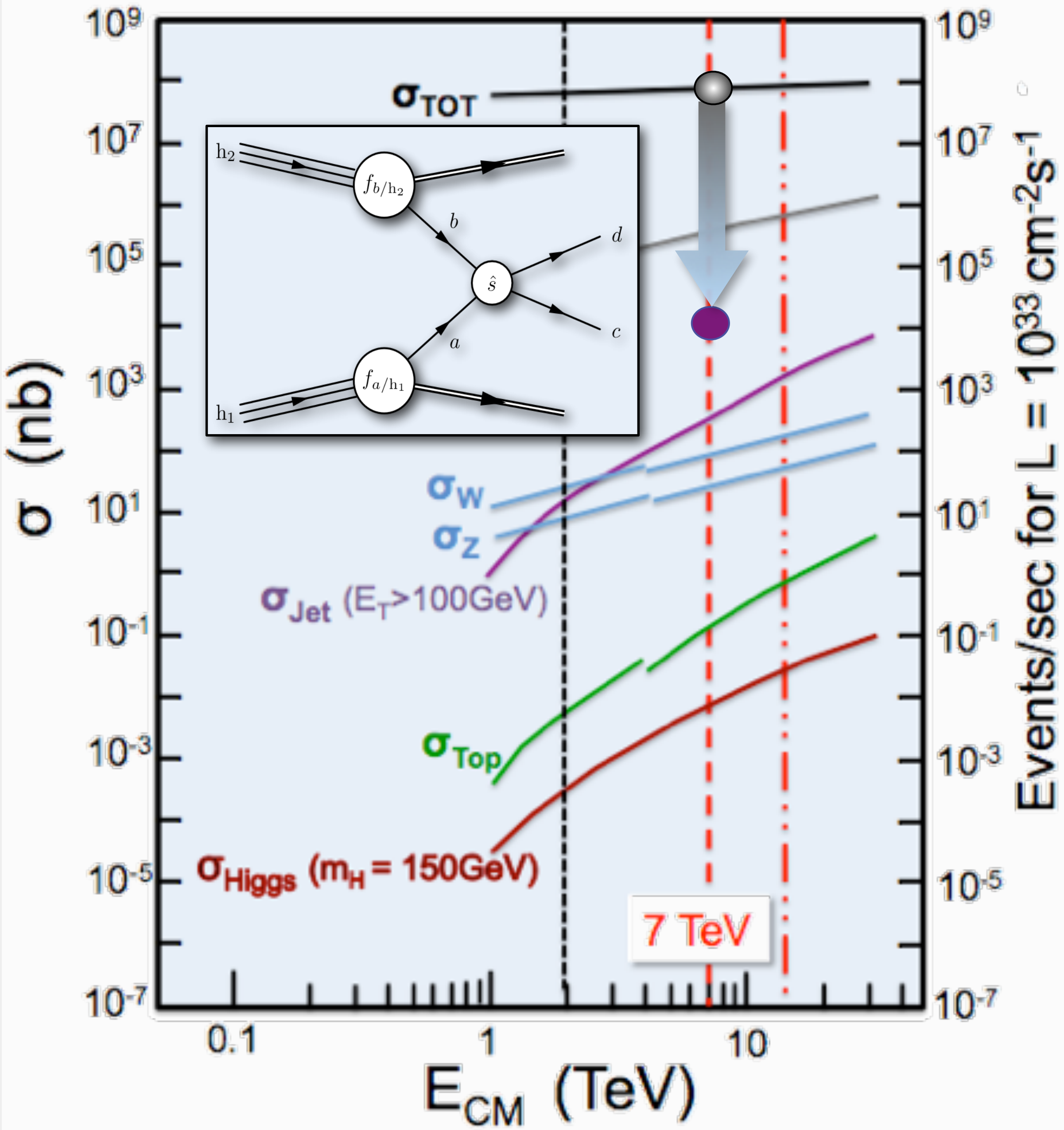
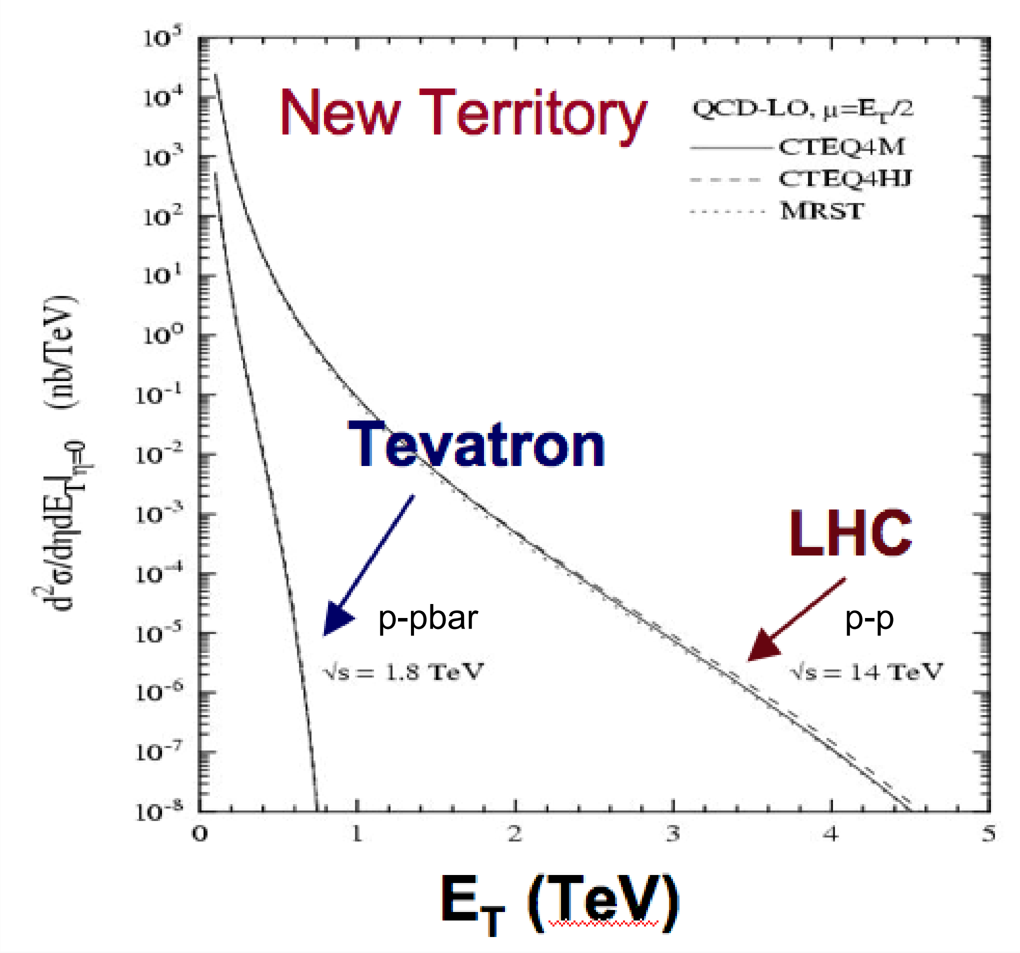


- Measure Jet cross sections
  - E_T^{Jet} > 500 GeV after a few months at startup
  - Going fast beyond the TEVATRON reach
    - early sensitivity to compositeness



- requires good understanding of jets (algorithms, production, jet energy scale), PDFs, pile-up, underlying event, ...
- Thus : good calorimetry!!
- Later came: the power of particle flow

Expected Physics was .... (4)

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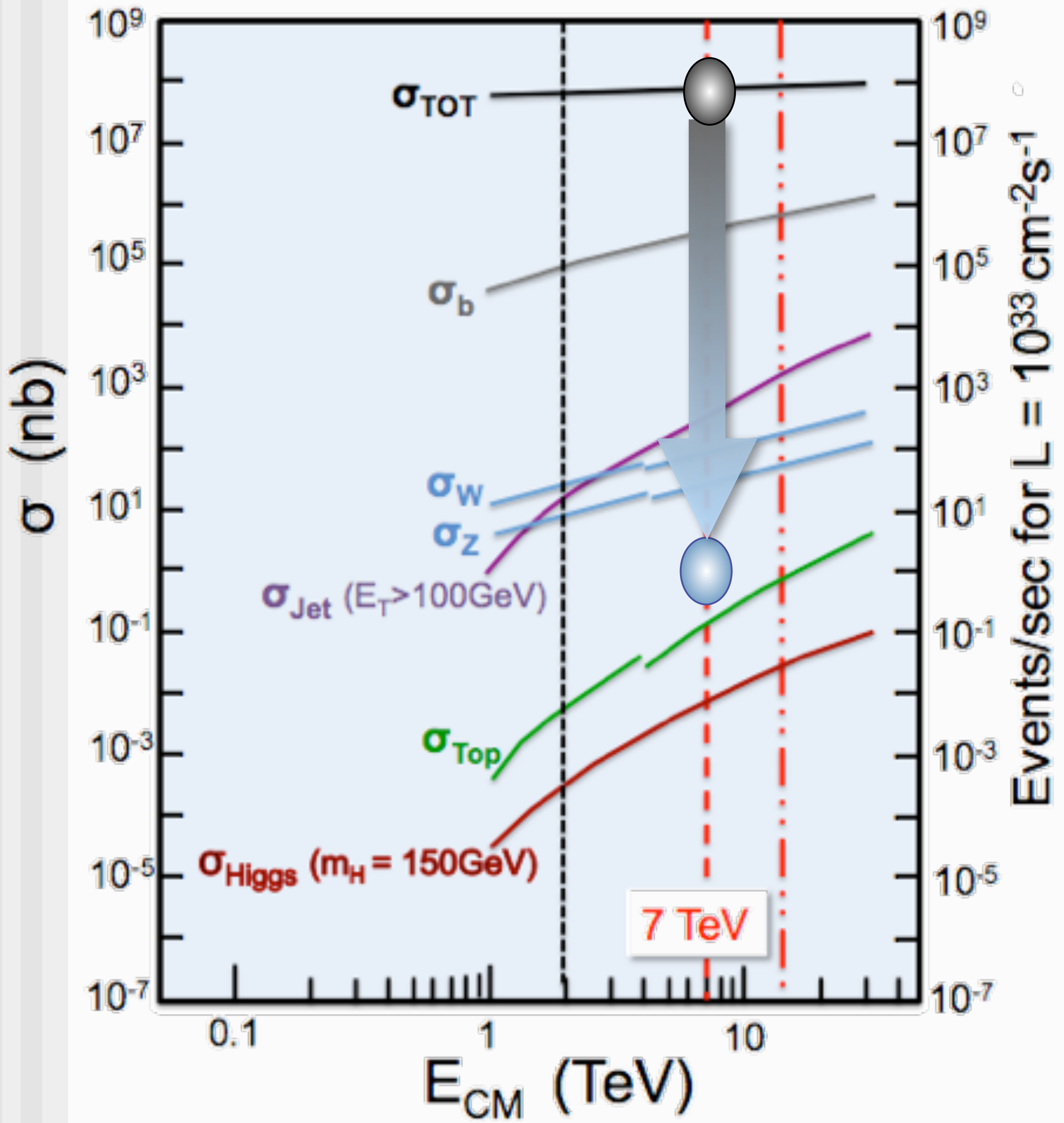

- The Electroweak Sector
  - test (re-establish the SM) and then go beyond
  - most SM cross sections are significantly higher than at the TEVATRON
    - eg. 100x larger top-pair production cross section
    - the LHC is a top, b, W, Z, ..., Higgs, ... factory

Important:
Concentrate on final states with high-p_T and isolated **leptons and photons** (+ jets)

Otherwise overwhelmed by QCD jet background!!

The benchmarks were ...

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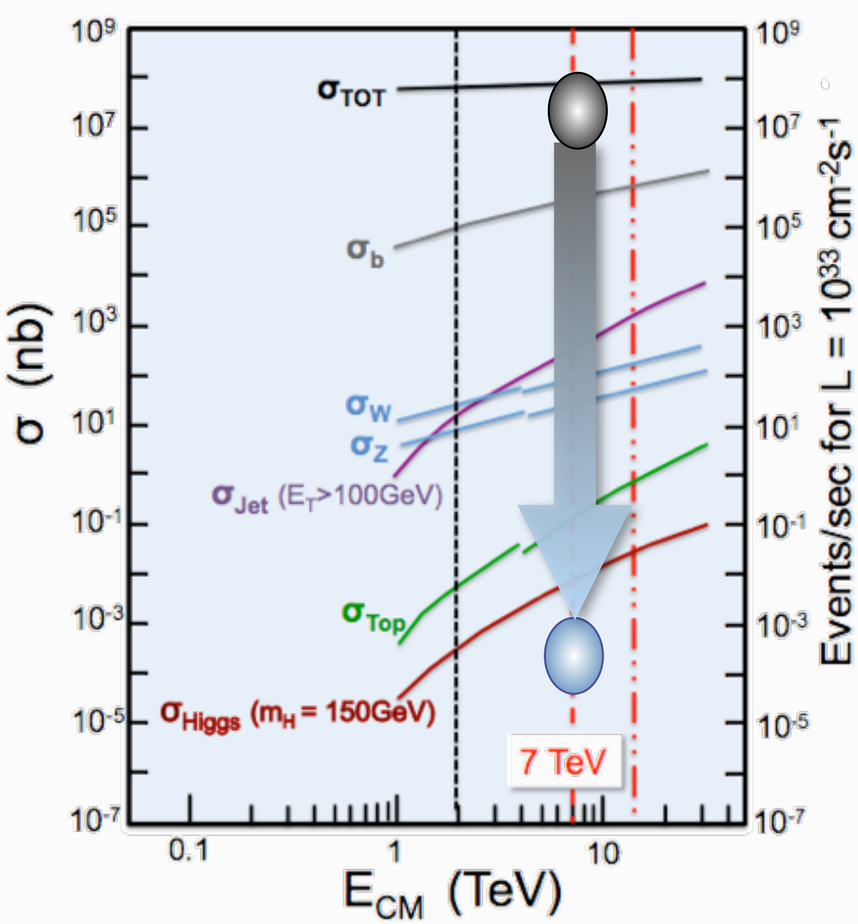
- Some benchmark processes of the early days, which influenced certain design parameters:
  - Basic processes relevant for studying electro-weak symmetry breaking (as seen in early days):



$$pp \to W^+W^- \to \mu^+\nu_\mu\,\mu^-\bar{\nu}_\mu$$
$$pp \to H \to ZZ \to \mu^+\mu^-\mu^+\mu^-$$
$$pp \to H \to ZZ \to \mu^+\mu^-\,\nu_\mu\bar{\nu}_\mu$$
$$pp \to H \to \gamma\gamma$$
$$pp \to H\ \text{jet jet}\ \ (\text{VBF})$$
$$pp \to Z' \to \mu^+\mu^-$$

  - All cross sections (times BR) of order **1 - 100 fb** : determines needed luminosities for sizeable statistics

Production of heavy states

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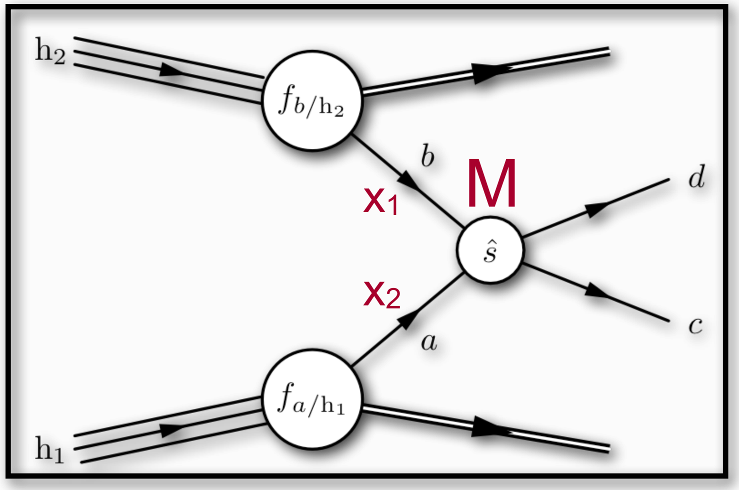
- Heavy particles are produced "more centrally"
  - example: single heavy resonance (eg. Z') of mass M, Energy E, rapidity y :

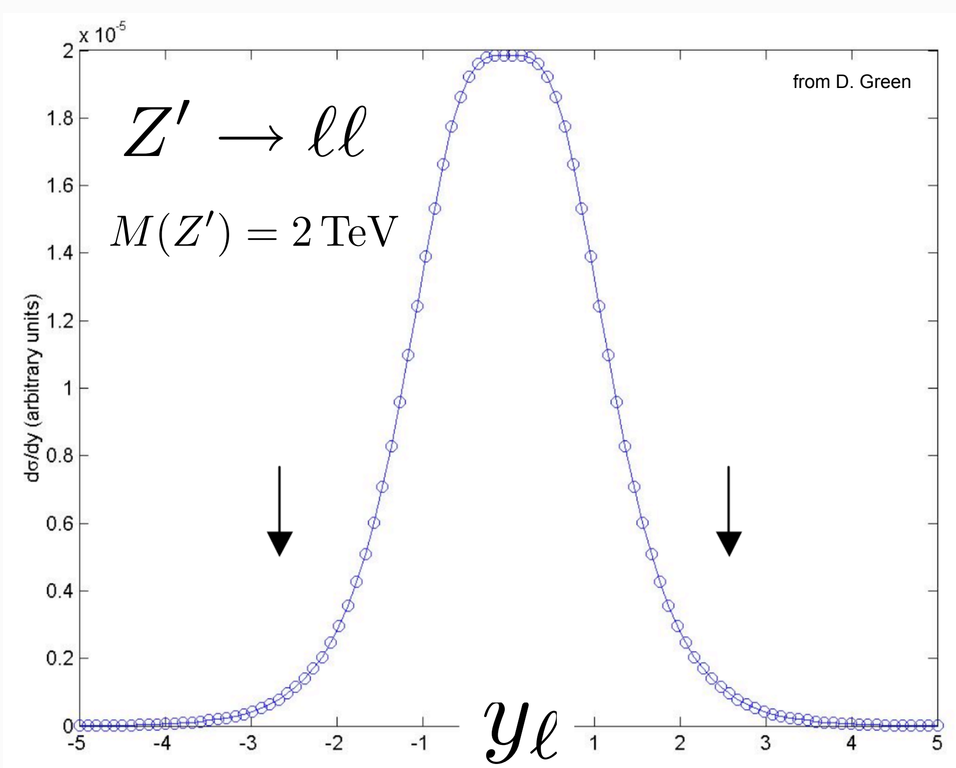


$$\hat{s} = x_1\, x_2\, s = M^2 \qquad x_1 \approx x_2 \rightarrow x_{1,2} = \frac{M}{\sqrt{s}}$$

$$E = \frac{\sqrt{s}}{2}(x_1 + x_2) \qquad p_L = \frac{\sqrt{s}}{2}(x_1 - x_2)$$

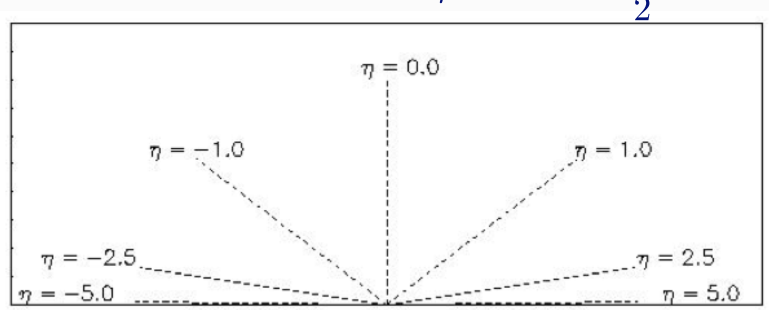
$$y = \frac{1}{2}\ln\frac{E + p_L}{E - p_L} \Rightarrow e^y = \sqrt{\frac{x_1}{x_2}} \Rightarrow y \rightarrow 0 \text{ for } x_1 \approx x_2$$

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



- Thus important to concentrate on precision tracking/calorimetry in area of approx. |y| < 2.5

$$\eta = -\ln\tan\frac{\theta}{2}$$



θ = 90° → η = 0

θ = 10° → η ≅ 2.4
θ = 170° → η ≅ -2.4

θ = 1° → η ≅ 5.0

Detector requirements

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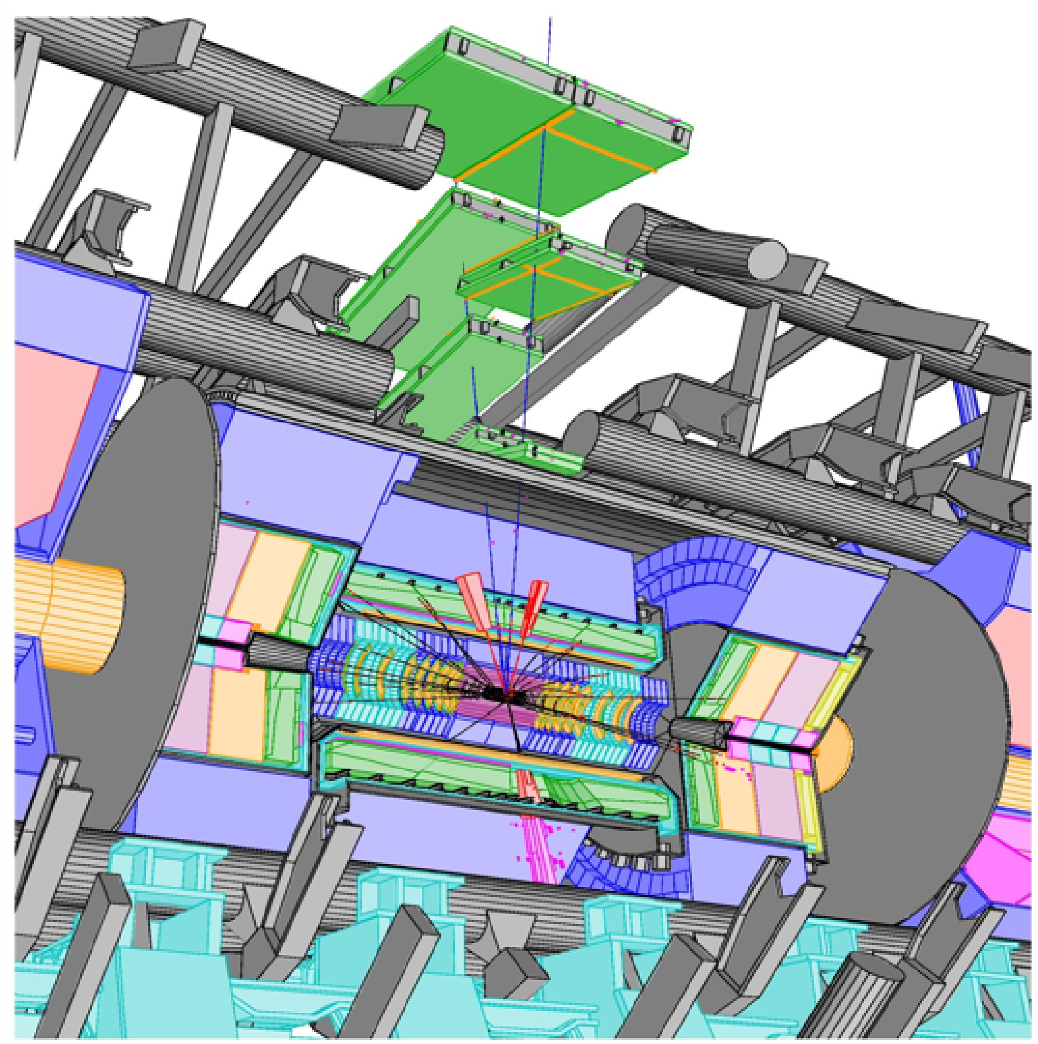
- Good measurement of leptons (e, μ) and photons with large transverse momentum p_T
  - electromagnetic calorimetry, muon systems
- Good jet reconstruction
  - good resolution, absolute energy measurement
- Good measurement of missing transverse energy ($E_{T\,miss}$)

  and
- energy measurements in the forward regions
  - thus, hermetic detector and
  - calorimeter coverage down to rapidity ~ 5



- Efficient b-tagging and tau identification (silicon strip and pixel detectors)
  - b-physics
  - top physics
  - Higgs couplings to b and tau

Examples of detector performance requirements

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Lepton measurement: $p_T \approx$ GeV → 5 TeV (b → l+X, W/Z, W'/Z', …)

achieved

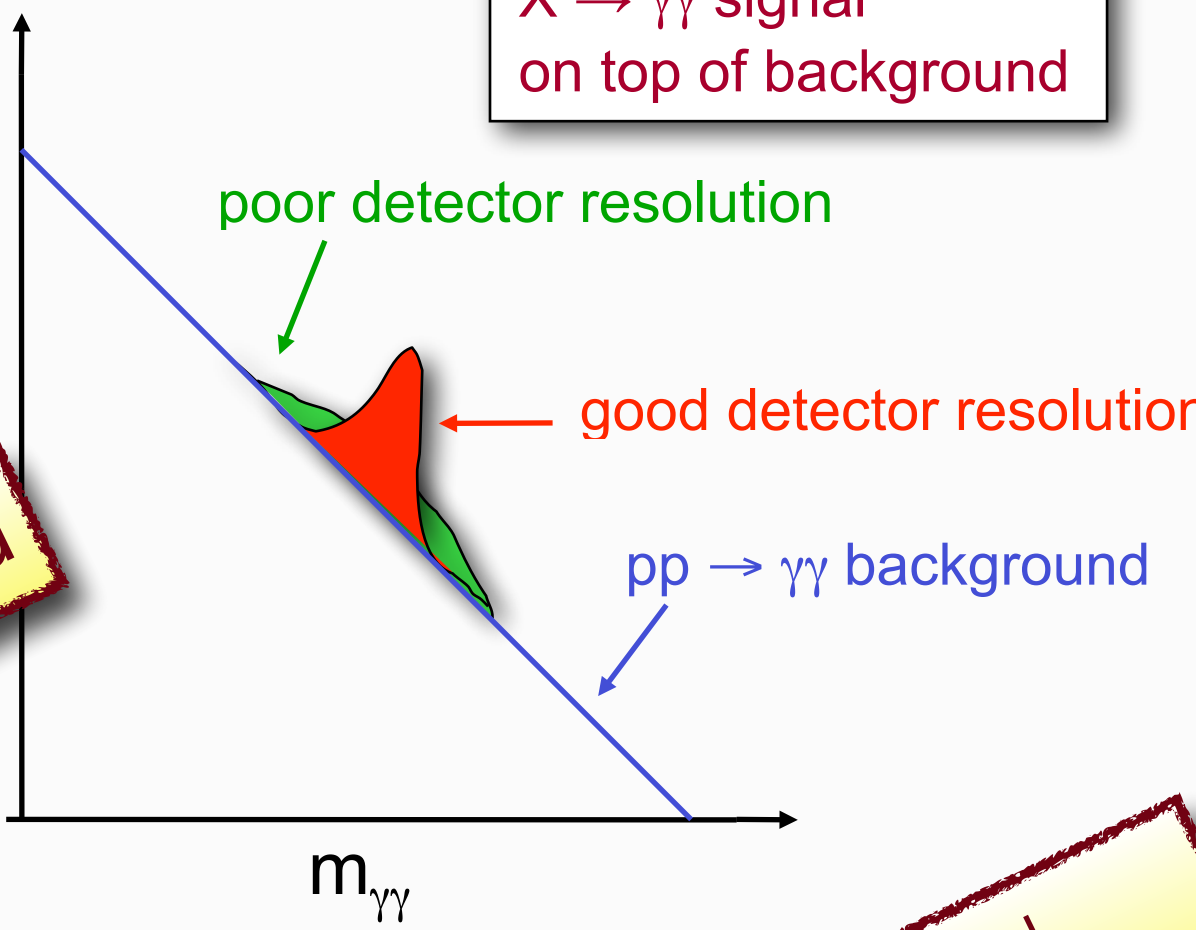
Mass resolutions:

≈ 1% decays into leptons or photons
(Higgs, new resonances)

≈ 10% W → jj, H → bb
(top physics, Higgs, …)

achieved

X → γγ signal
on top of background

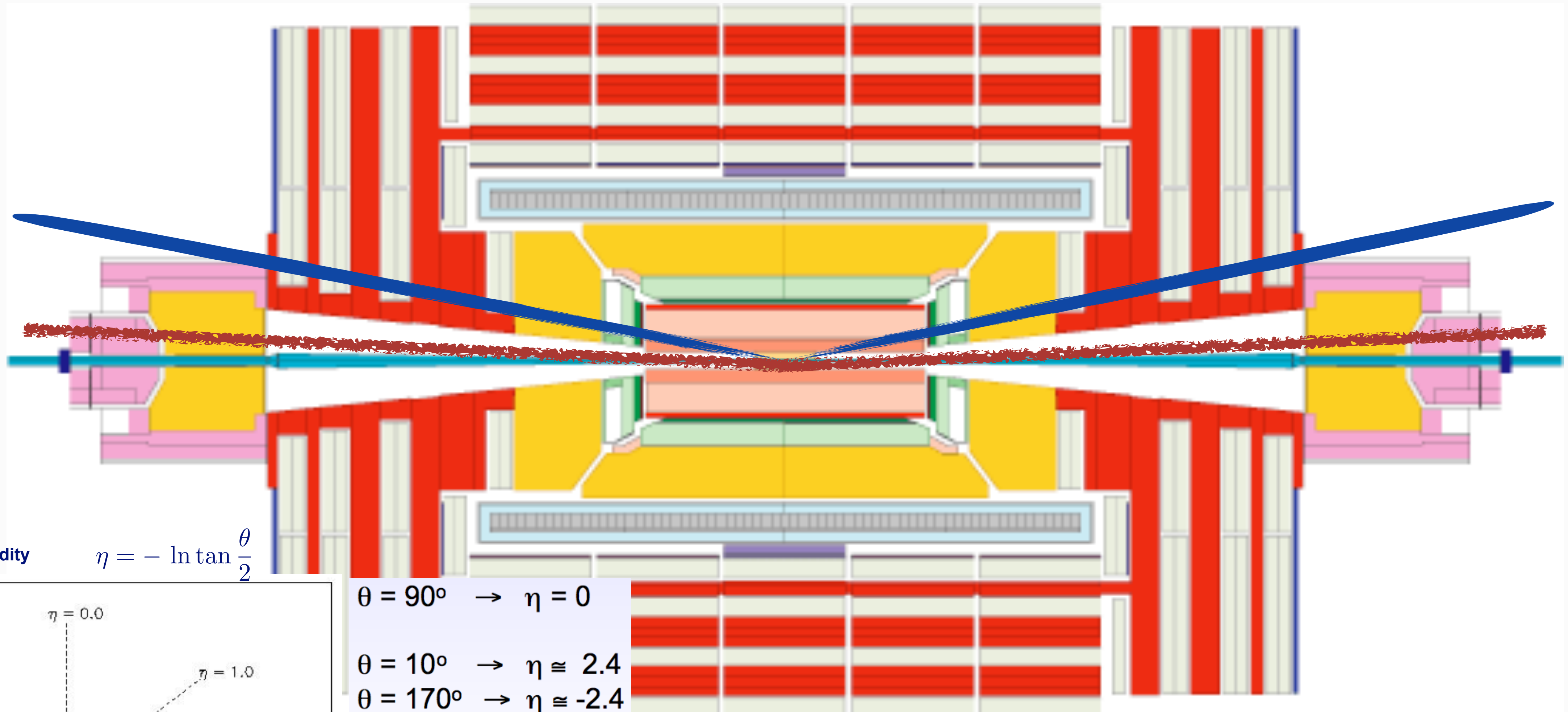


achieved
(or even better)

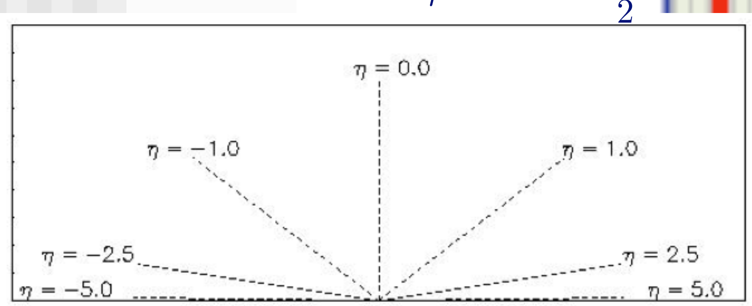
b/tau identification:

- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → ττ, SUSY, 3rd generation !!)

Typical detector acceptance



(Pseudo)-Rapidity $\eta = -\ln\tan\frac{\theta}{2}$



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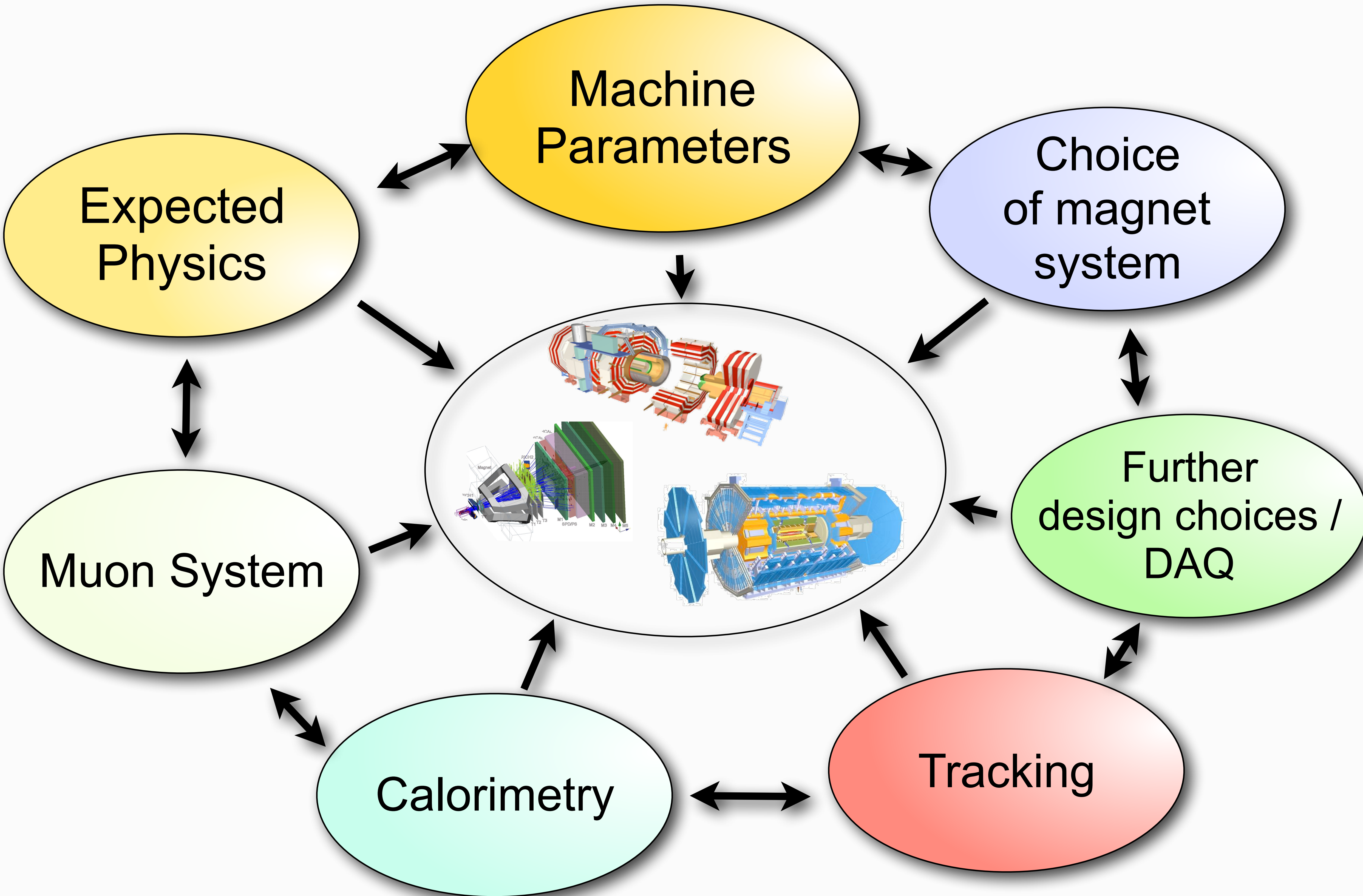
$\theta = 1^o \rightarrow \eta \cong 5.0$

- Precision tracking and **lepton** reconstruction up to rap~2.5
  - p_T thresholds for tracks ~ 100 MeV, for leptons 10-20 GeV
- **Jet and MET** reconstruction: include detectors up to rap~4.5-5
  - p_T thresholds for jets ~30 GeV, if tracking-based jets ~15 GeV

How to design your detector



The LHC parameters

- E_{cm} = 14 TeV (reached in steps 0.45 - 7 - 8 - 13 - 14? TeV)
  - basically fixed by LEP tunnel parameters (Radius) and superconducting magnets technologies
  - Was considerably lower than SSC (20 TeV / beam)
- Lumi :
  - by some considered to "must be 10x SSC" in order to compensate lower E_{CM}
  - RF bunch spacing = 25 ns (was 50 ns during the first 3 years)
  - relevant cross sections for testing of EWK symmetry breaking of order 1 - 100 fb^{-1}
  - Running time per year T ~ 10^7 secs (don't forget efficiency factors....)

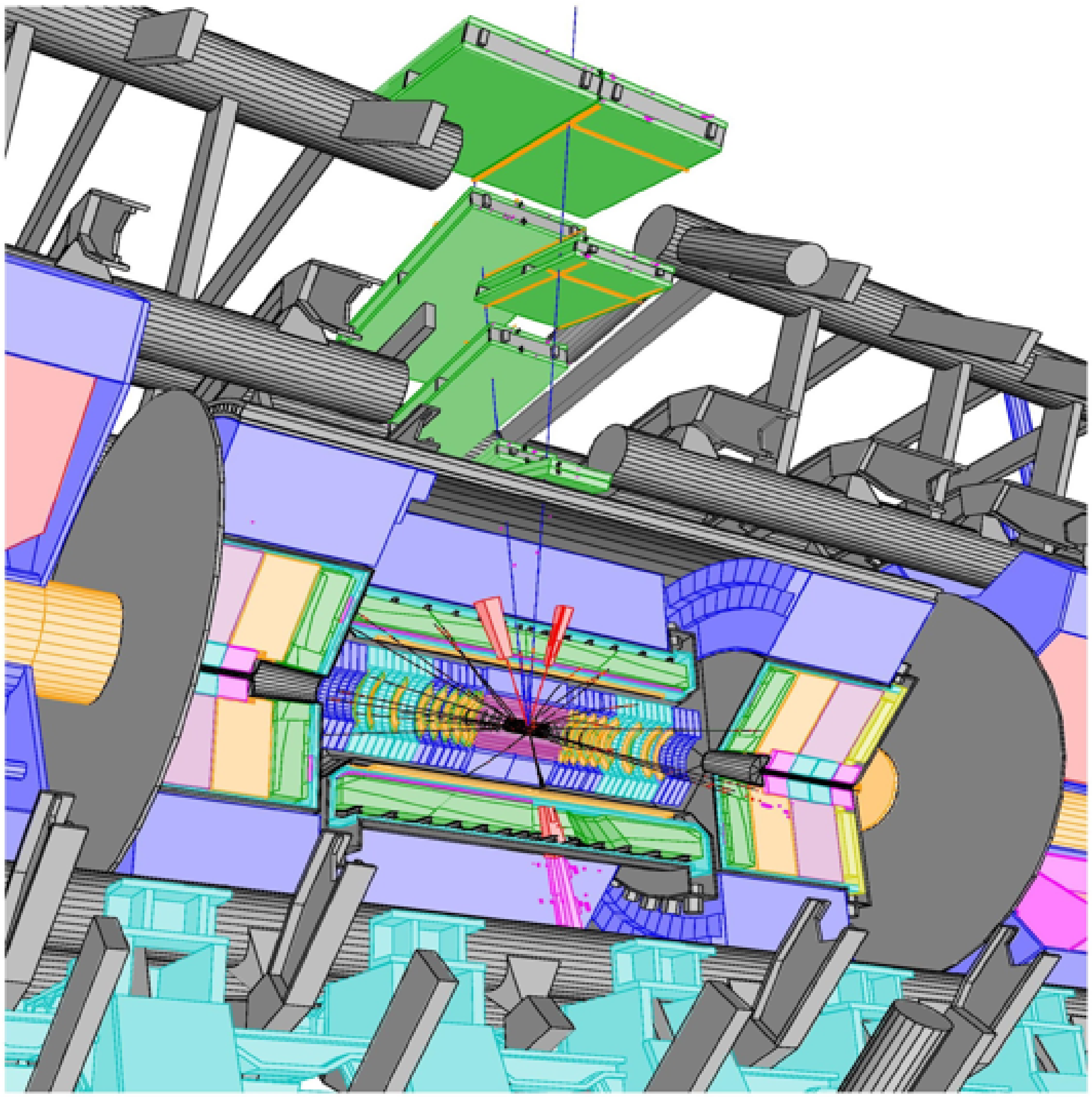
$$\text{for } \mathcal{L} = 10^{34}/\text{cm}^2/\text{sec} = 10^{-5}\,\text{fb}^{-1}/\text{sec}$$

$$N = (\mathcal{L} \cdot T)\,\sigma \Rightarrow 100\,\text{events per year for } \sigma = 1\,\text{fb}$$

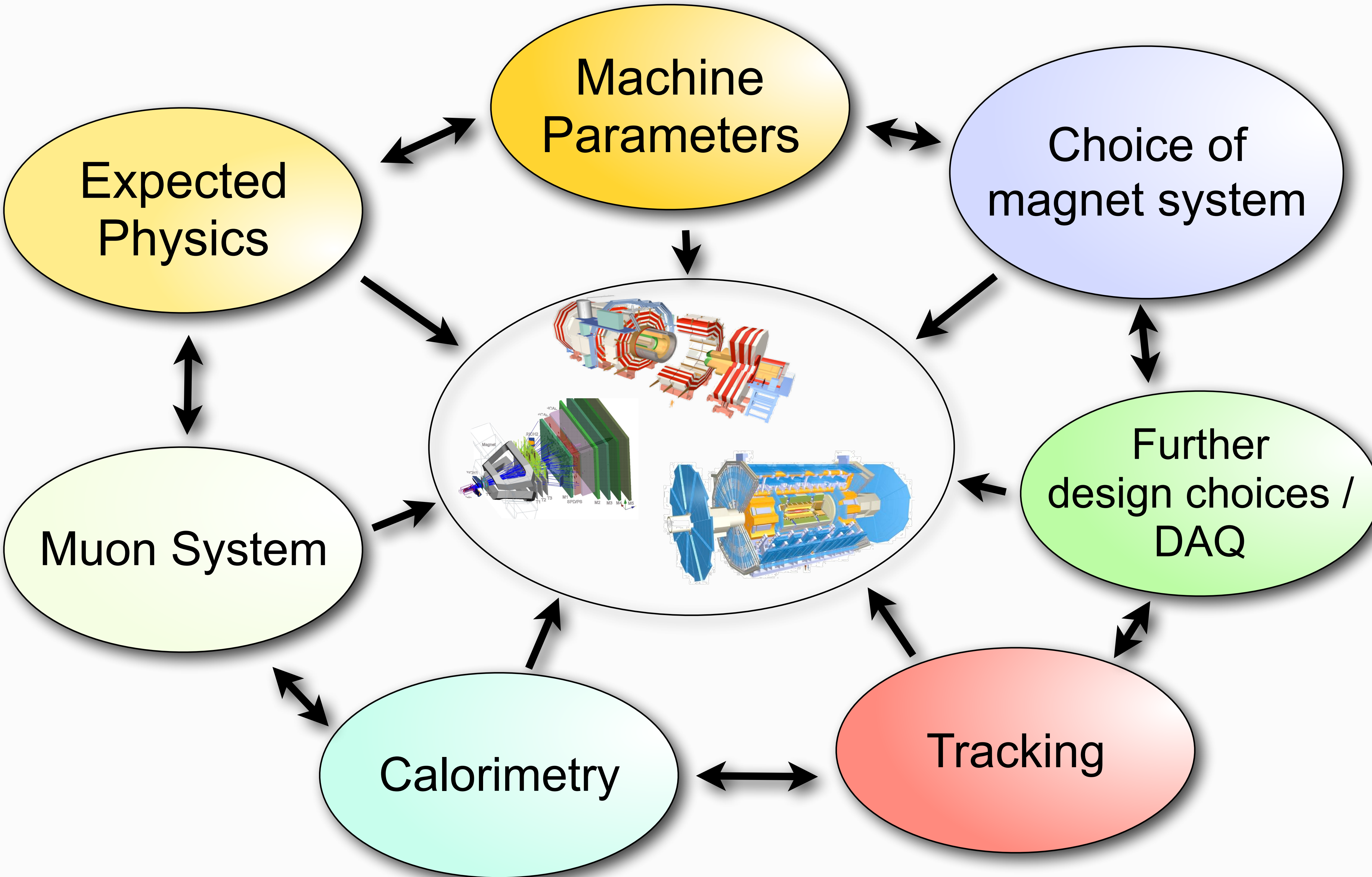
  - Total rate of inelastic events $R = \sigma_{\text{inel}}\,\mathcal{L} \approx (100\,\text{mb})\,(10^7\text{mb}^{-1}/\text{sec}) = 10^9\,\text{events/sec}$
  - Number of inelast. events per bunch crossing = 10^9/sec * 25 10^{-9} sec = 25 (pile-up)!
  - Number of chg. particles per bunch x-ing : 25 * N(pions)/rap * (2 y_{max}) >~ 1000 !!
  - Thus have an issue with **radiation levels**! (and pile up ...)

Detector requirements

- High granularity,
  fast readout,
  radiation hardness
  - minimize pile-up particles in same detector element
  - many channels
    eg. 100 million pixels,
    200'000 cells in electromagnetic calorimeter
  - cost !
  - 20-50 ns response time for electronics !
  - in pixel detector (forward calorimeters) :
    up to 10^{15-16} n/cm^2 over
    10 years of LHC operations



How to design your detector



Magnet Systems

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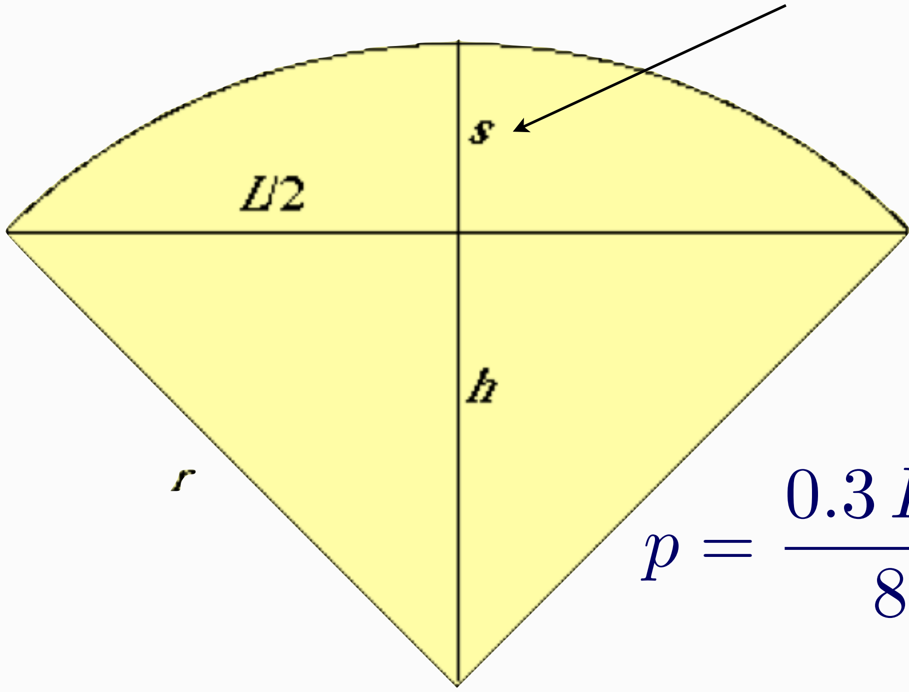
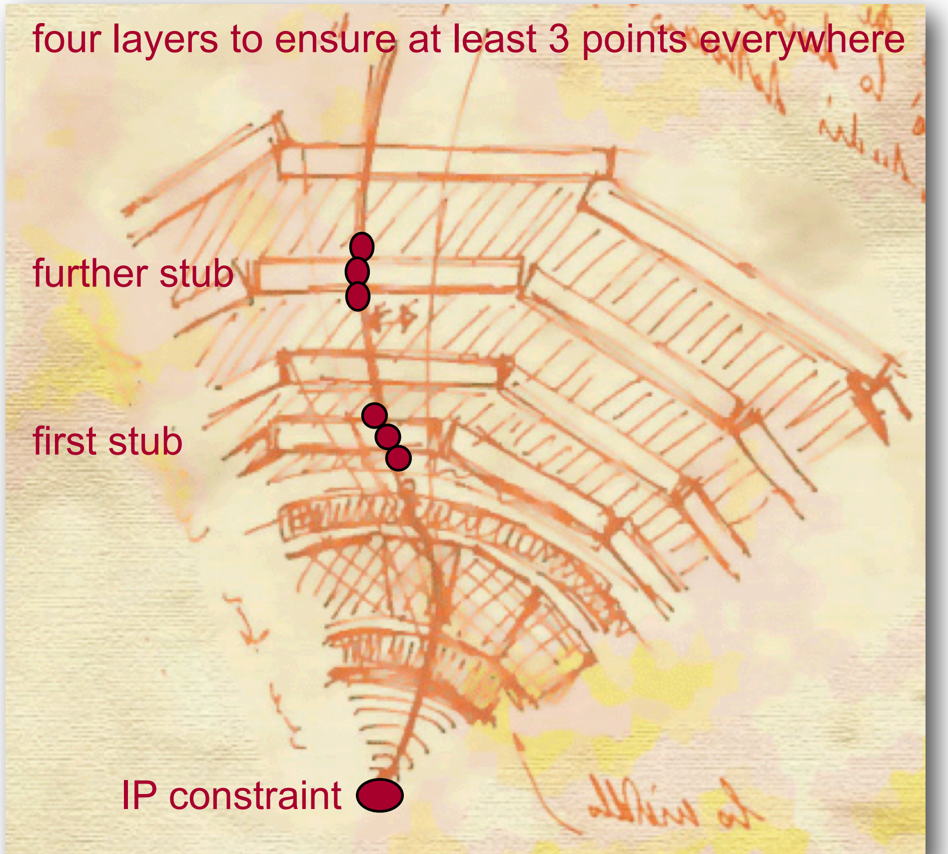
- Among the most important design choices
  - fixes many other parameters/sizes
- Example of CMS, early days:
  - assumed that a tracking system might not be possible (too harsh backgrounds), rad-hard Si-Detectors not yet sufficiently developed
  - so, put all effort on muons, in a robust manner; put absorber to get rid of the rest (a strong magnetic field also helps here) and try to get best possible muon measurement.

Momentum measurement via sagitta:



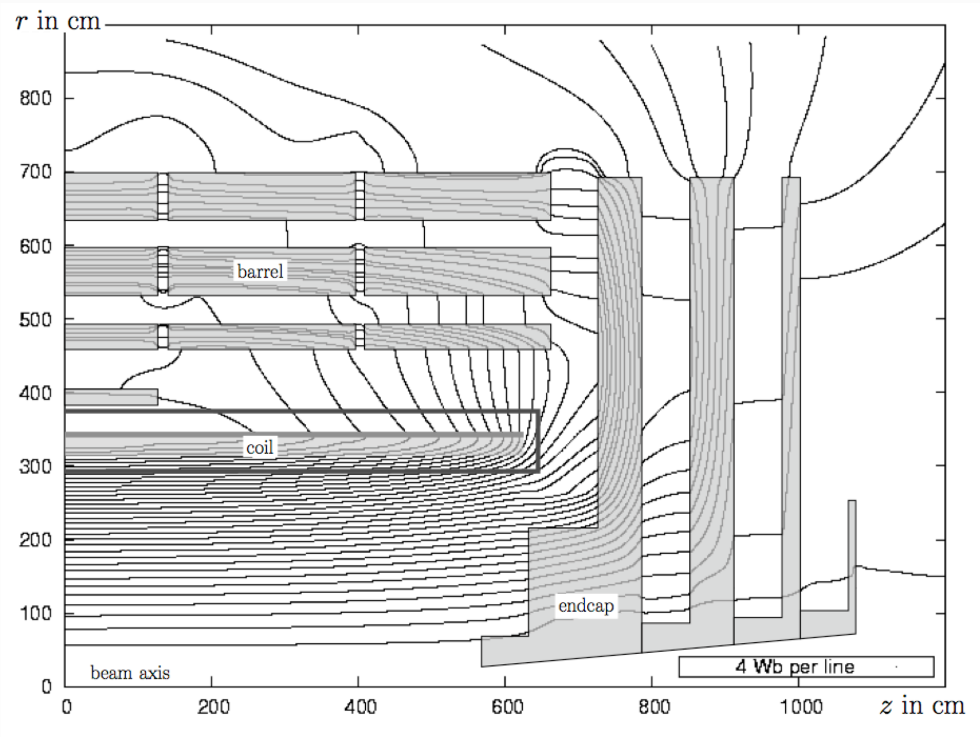
$$p = \frac{0.3\,L^2 B}{8s}$$



$$\frac{\delta p}{p} = \frac{8}{0.3\,L^2 B}\, p\,\delta s = \frac{\delta s}{s}$$

maximize... but note that L drives cost of detector very much.

Various topologies...

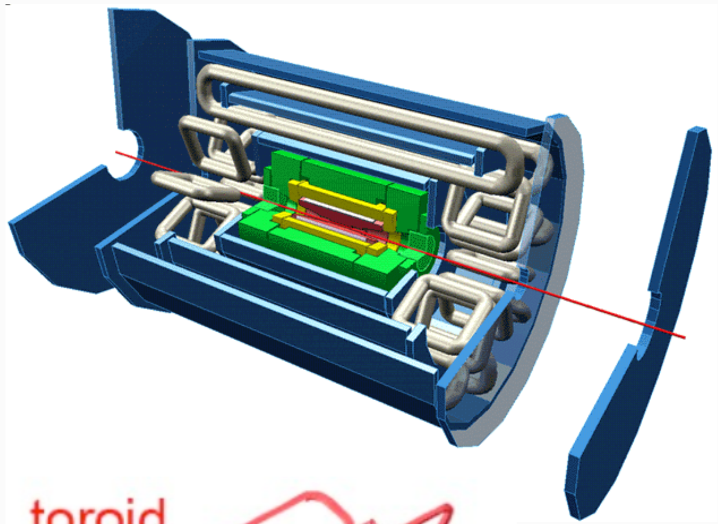


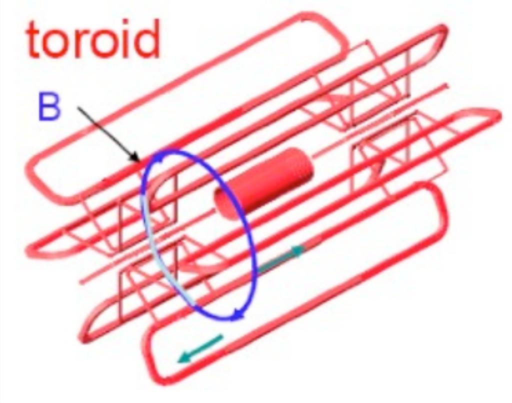
- But : Pending power prop.to. $\int Bdl$ of path perpendicular to B field.
- Solenoid not optimal in forward direction
- For large solenoid radius: have to make it long in order to cover large rapidity
- if large enough: place calorimetry inside,

  eg. with R_{sol}=3m, $R_{Tracker}$=1.2-1.3m,

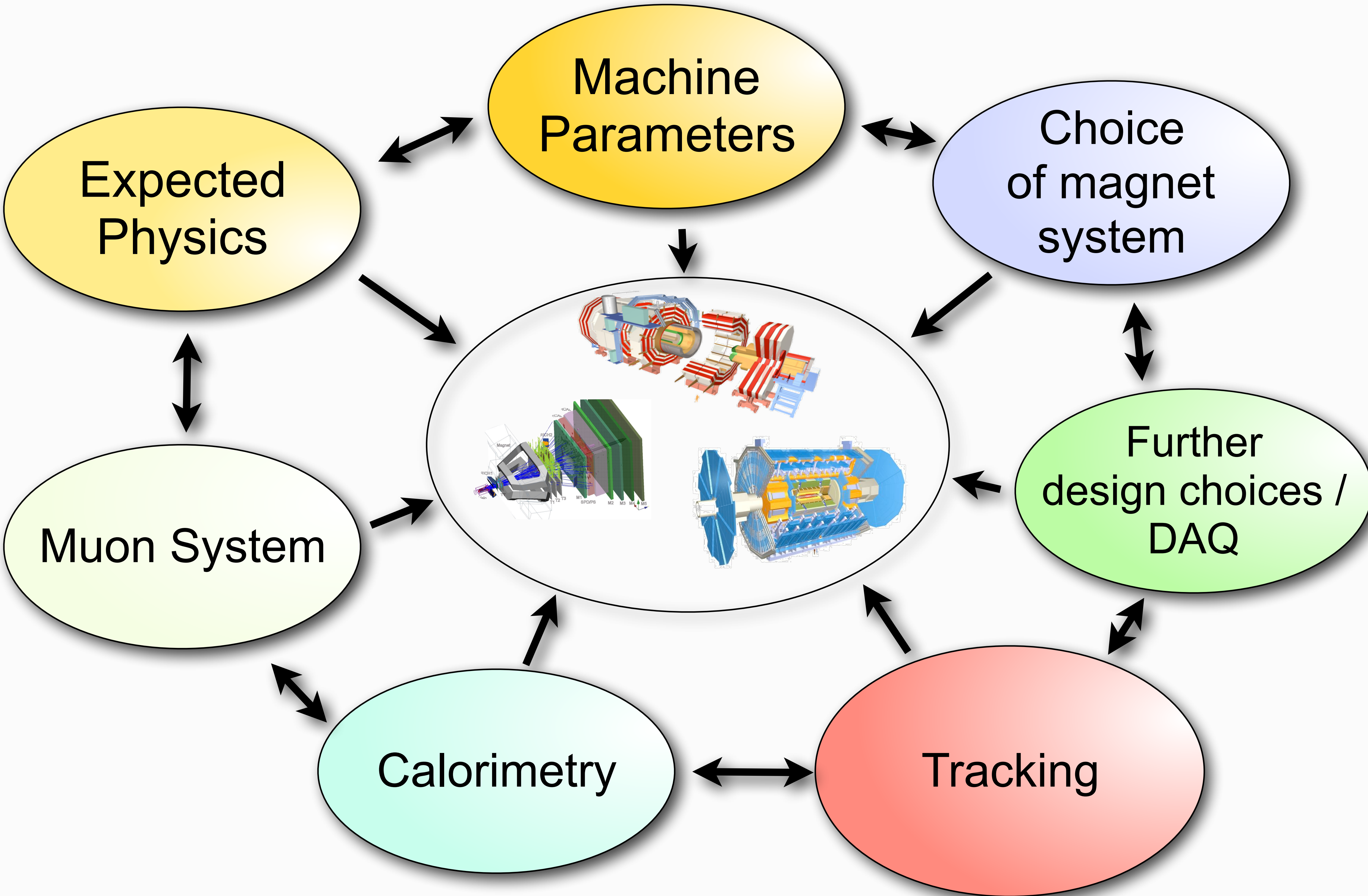
  < 2 m left for ECAL+HCAL !

- Alternative: Toroid system. Large BL^2. Good pending power also in forward direction
- Keeps detectors inside toroids free of B field
- But : for large system: becomes expensive, needs very precise knowledge of (complicated) B-field, difficult alignment
- For tracking near IP: additional solenoid





How to design your detector



Basic tracking requirements

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- Robust and redundant pattern recognition
  - efficient / precise reco of all charged particles with p_T > 0.1-1 GeV, up to rapidity ~ 2.5
- Reconstruction of secondary vertices, impact parameters
  - heavy flavours, b-jets, B decays
- Reconstruction of hadronic tau decays (one-prong, three-prong, thin jets)
- **"Conflict of interest" :**
  - many layers (many hits) for robust track reco -->
    many channels; lots of supports (cables, cooling, ...)
  - but not too much material, bad for ECAL resolution and multiple scatt.
- Remember: momentum resolution

$$\frac{\delta p}{p} = \frac{\delta s}{s} = \frac{8}{q}\,\frac{1}{L^2 B}\,p\,\delta s$$

$$\text{for } L = 1\,\mathrm{m}\ ,\ B = 4\,\mathrm{T}\ ,\ p = 100\,\mathrm{GeV}$$

$$\frac{\delta p}{p} = 1\,\%\ \text{ for }\ \delta s \approx 15\,\mu\mathrm{m}$$

➡ need hit reconstruction at this level of prec. !

➡ e.g. Si-Tracker : optimize carefully pitch vs. strip length vs. # channels (material) vs. occupancy

Basic layout

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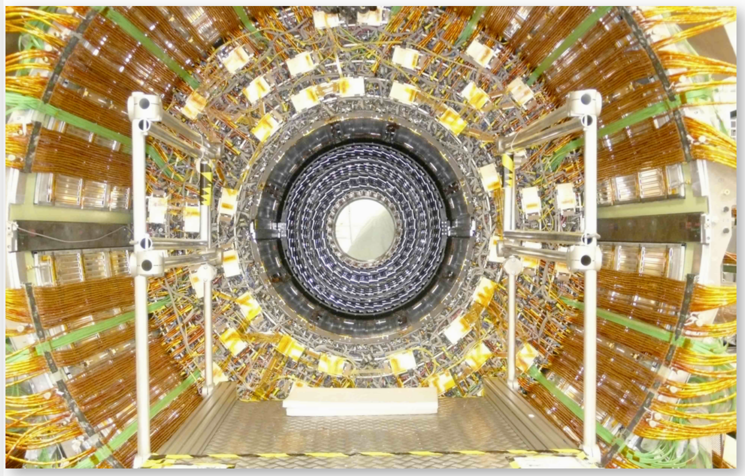
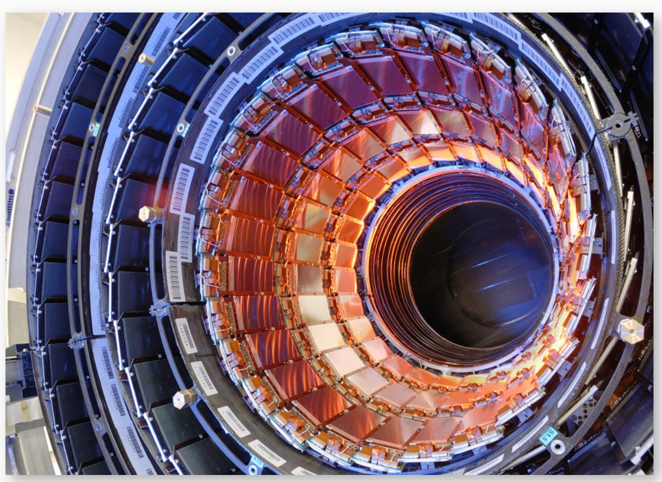
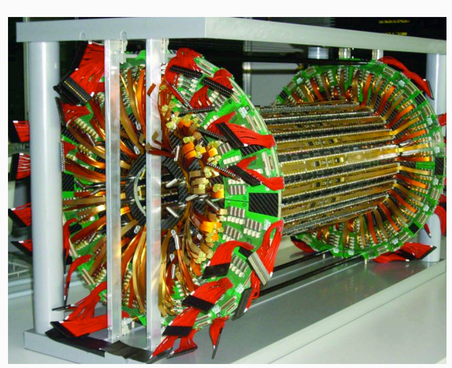
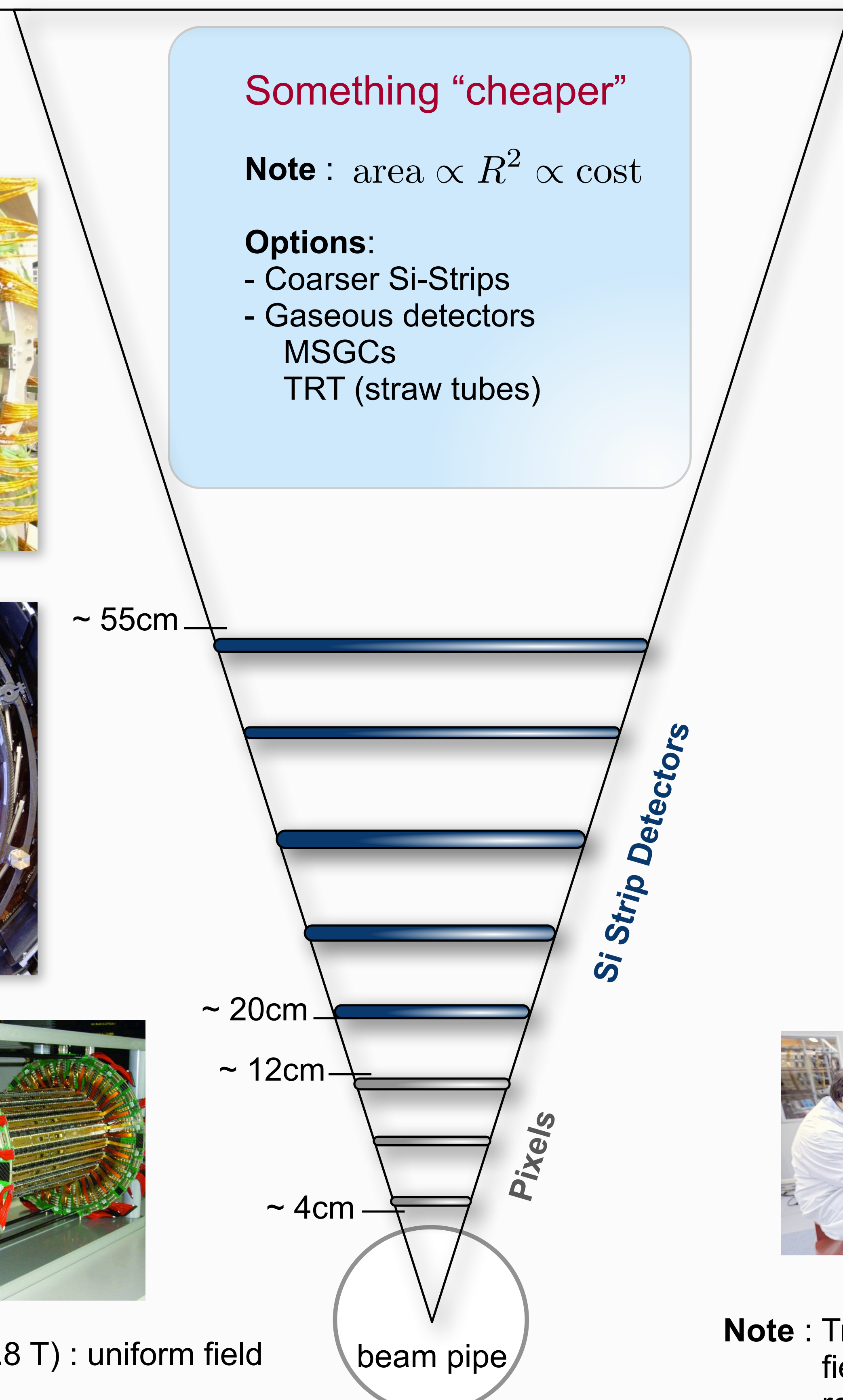
CMS







Note : Tracker well within solenoid (3.8 T) : uniform field



Something "cheaper"

Note : $\text{area} \propto R^2 \propto \text{cost}$

Options:
- Coarser Si-Strips
- Gaseous detectors
  MSGCs
  TRT (straw tubes)

ATLAS

Note : Tracker slightly longer than solenoid (2 T) : field non-uniformities and worse momentum resolution at each end

For LHCb

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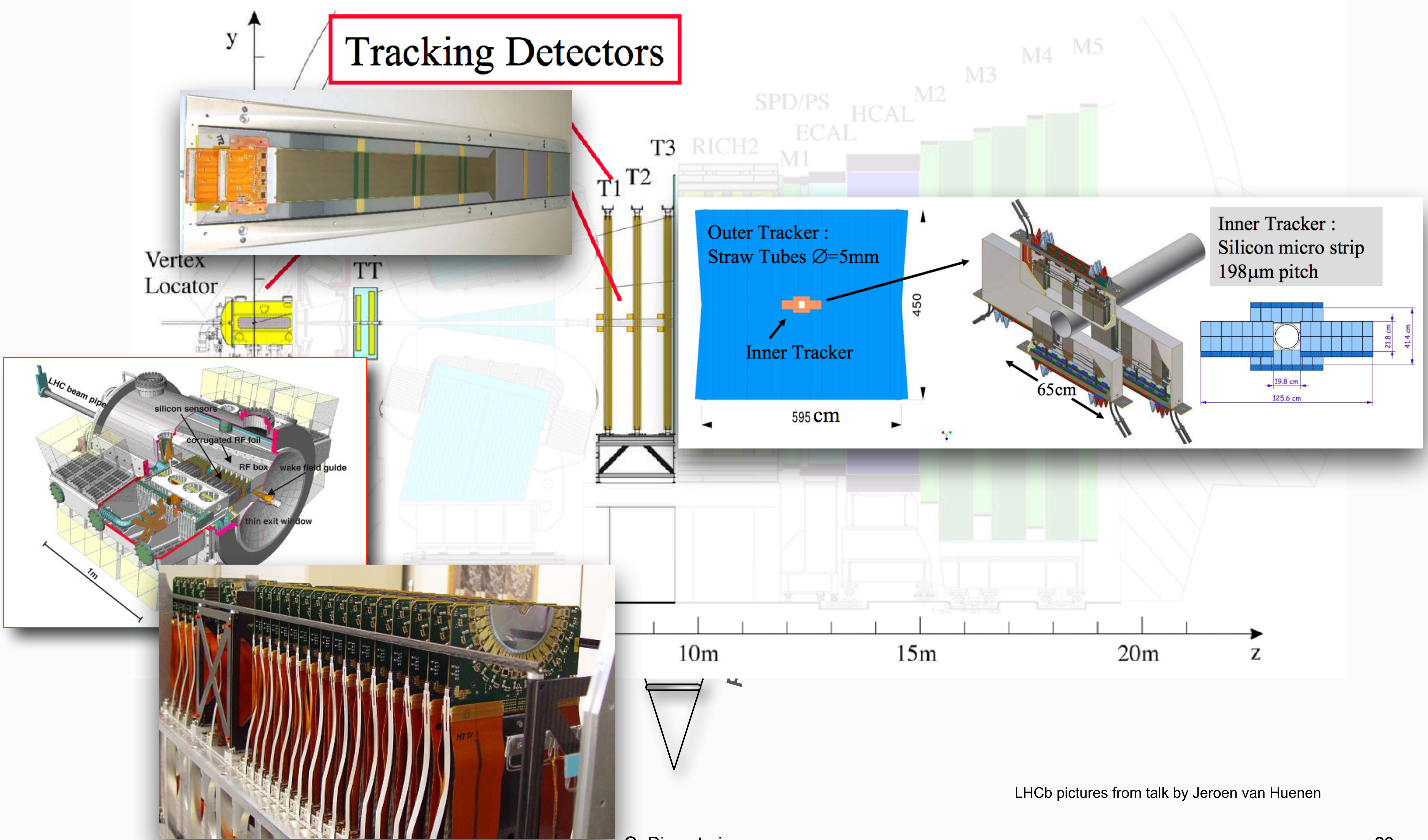
Something “cheaper”

Note : $\text{area} \propto R^2 \propto \text{cost}$



LHCb pictures from talk by Jeroen van Huenen

How to design your detector

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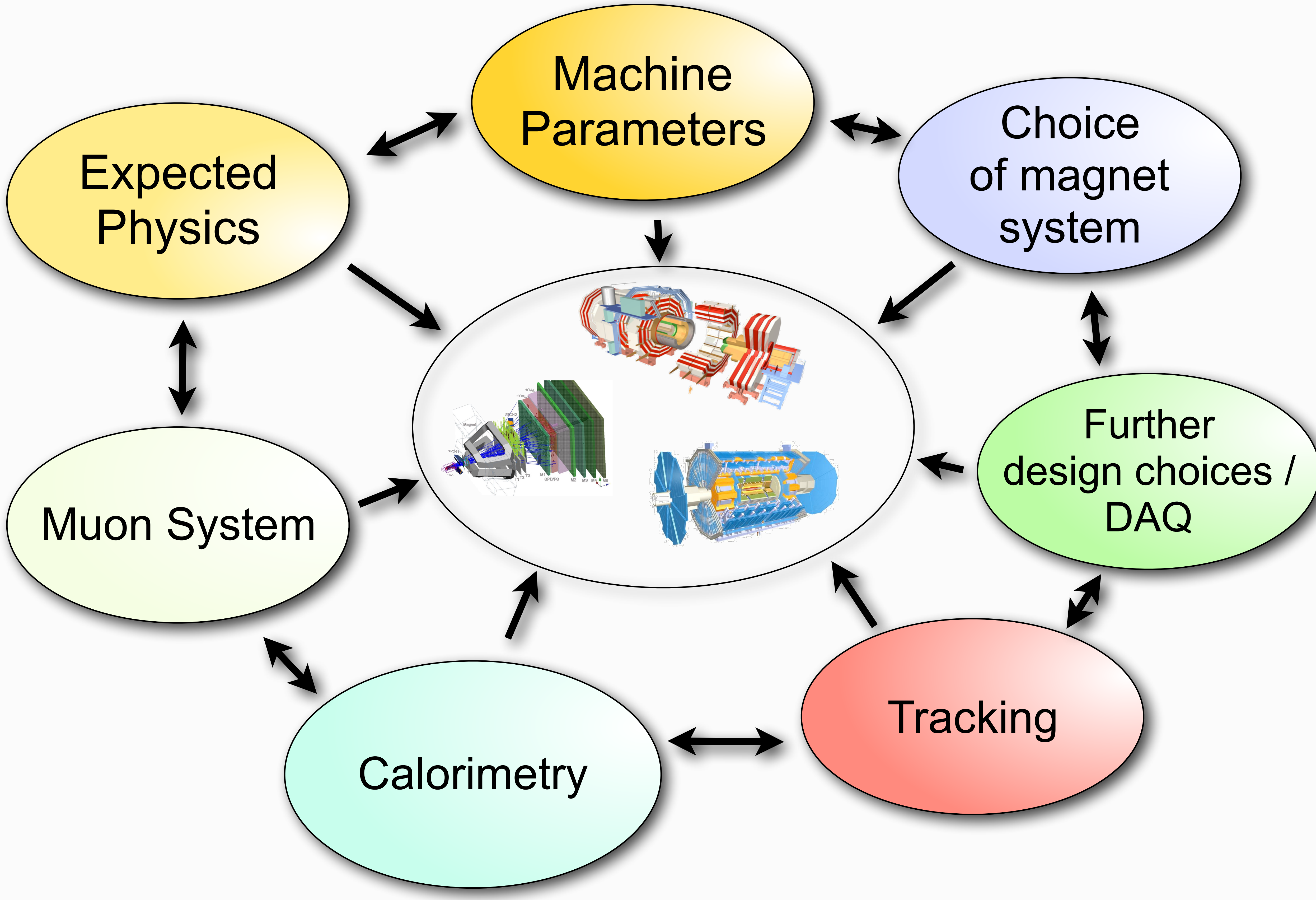

Calorimetry: Main principles

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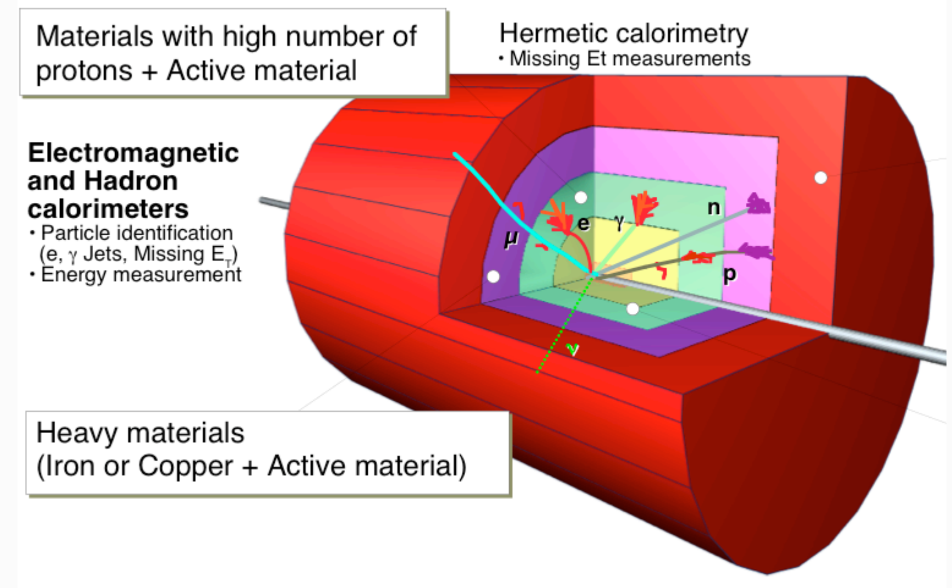
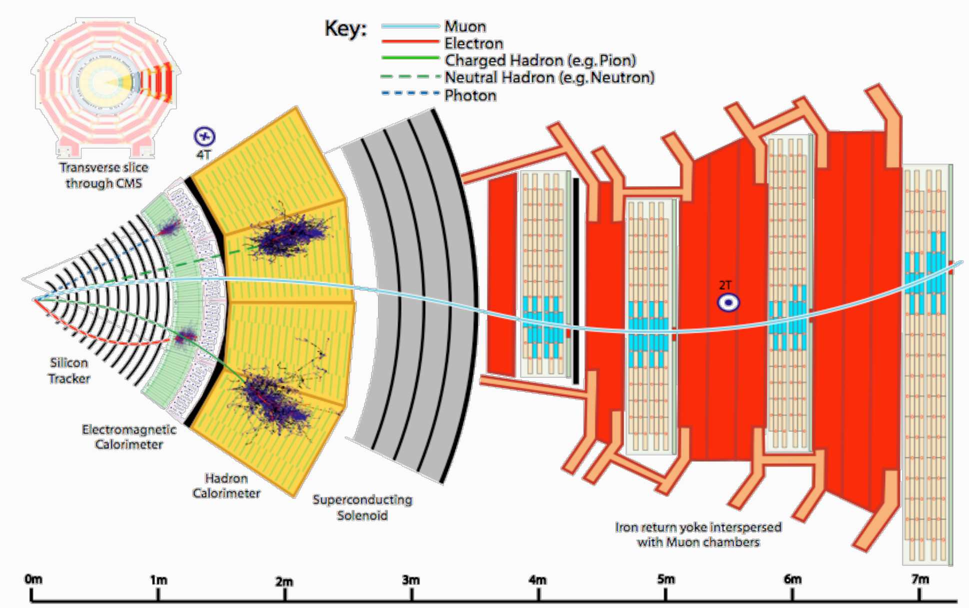
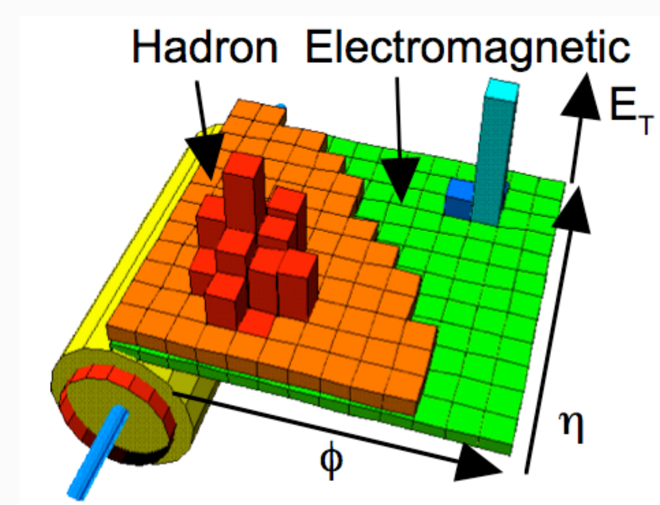
- Excellent energy measurement of electrons, photons, jets
  - good coverage up to $\eta \sim 5$, also for E_{Tmiss}

$$\text{Calorimeter} \quad \frac{\delta E}{E} \propto \frac{1}{\sqrt{E}} \qquad \text{Spectrometer} \quad \frac{\delta p}{p} \propto p$$

- Trigger on high-p_T objects
- Fine segmentation (lateral, longitudinal) for shower analysis
- Have to absorb ~ TeV objects (e,gamma,jets)
  - shower max position $x_{\max} \propto x_0 \ln E$
  - to cover elmg. shower of ~ 1 TeV : ~ 25 X_0
  - to contain hadronic jets of ~ 1 TeV : 11 λ_0
  - take $(X_0)_{PbWO4}$ = 0.89 cm
    - plus space for electronics : need ~ 50 cm
  - take $(\lambda_0)_{Fe}$ = 16.8 cm : would need ~ 180 cm
- CMS : R_{coil} - $R_{tracker}$ - ECAL (+electronics) ~ 1 m !!
  - only space for 6 λ_0 , 7 λ_0 including ECAL
  - added tail catcher (HO) after coil
- Further considerations
  - Homogenous vs. sampling calorimeter
  - Very forward calo : at large distance (less radiation) or closer (better uniformity of rap coverage)
  - Projective Tower sizes
    - relevant parameters: Moliere Radius, Occupancy
    - eg. $\Delta\eta \times (\Delta\Phi/2\pi) = 0.1 \times 0.1 \quad \text{over} \quad 2 \cdot y_{\max} = 10 \;\Rightarrow \mathcal{O}(10000)$ towers







Coverage

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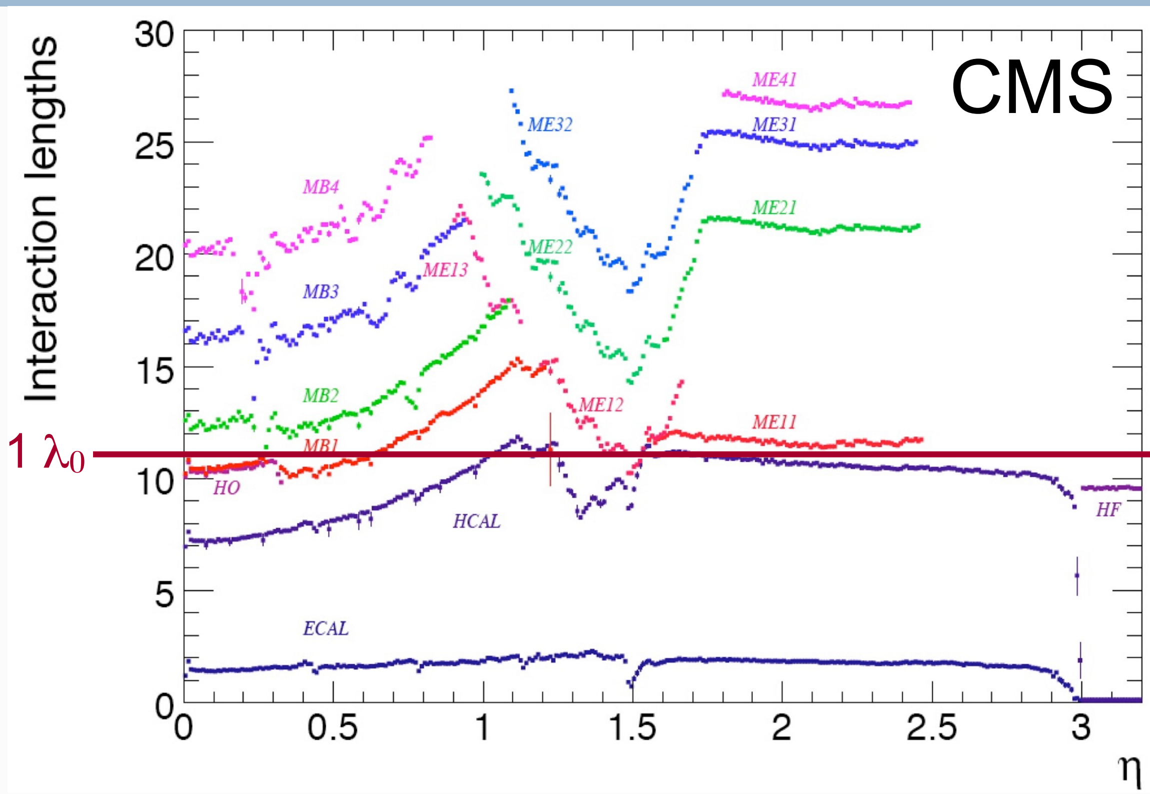
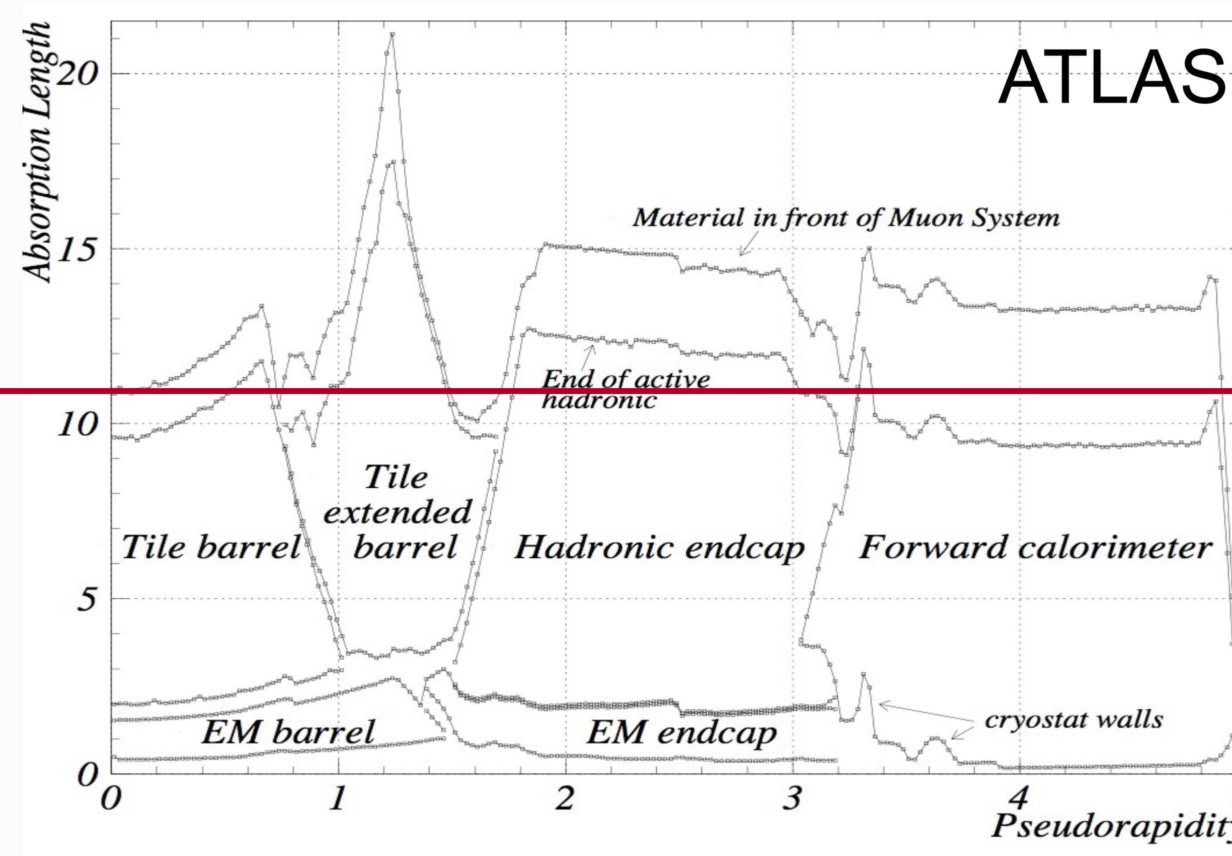
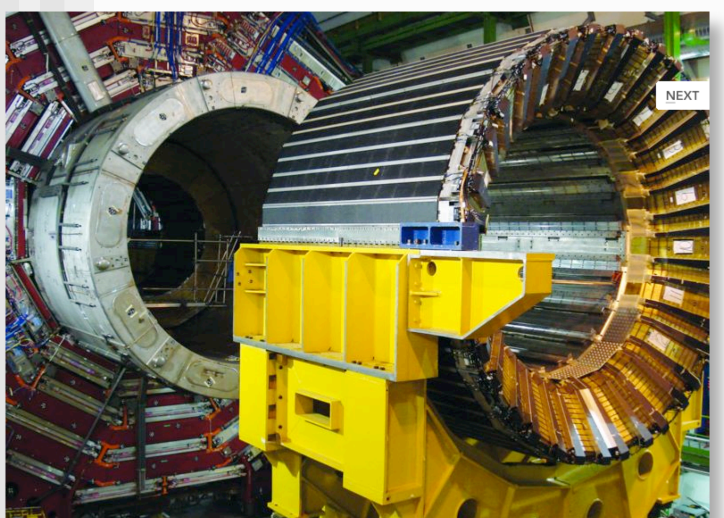
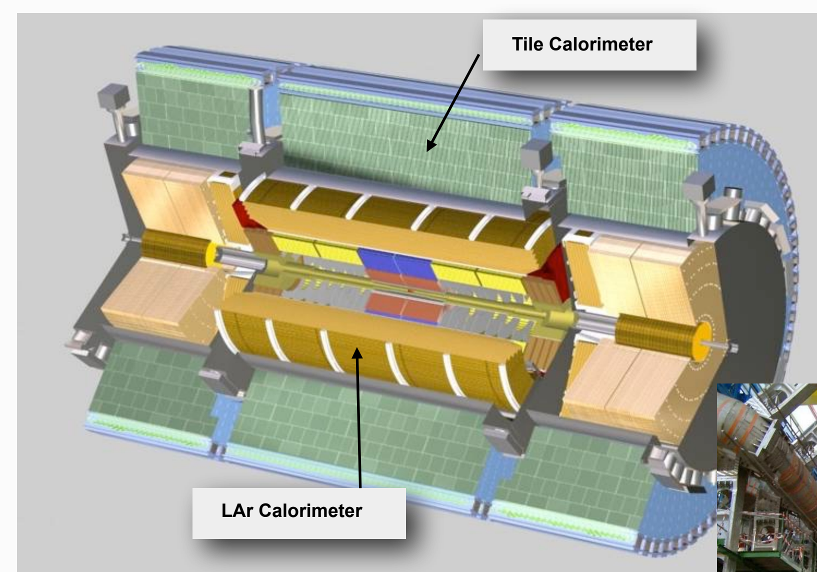
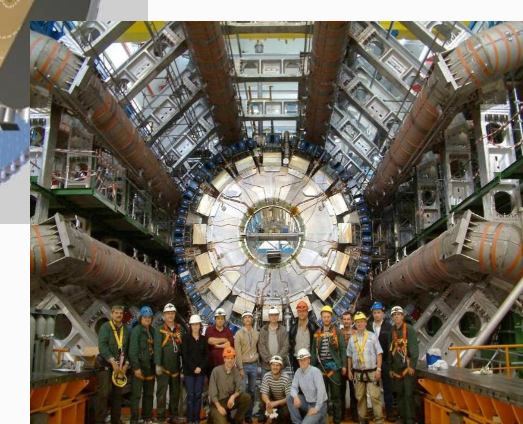


11 λ_0

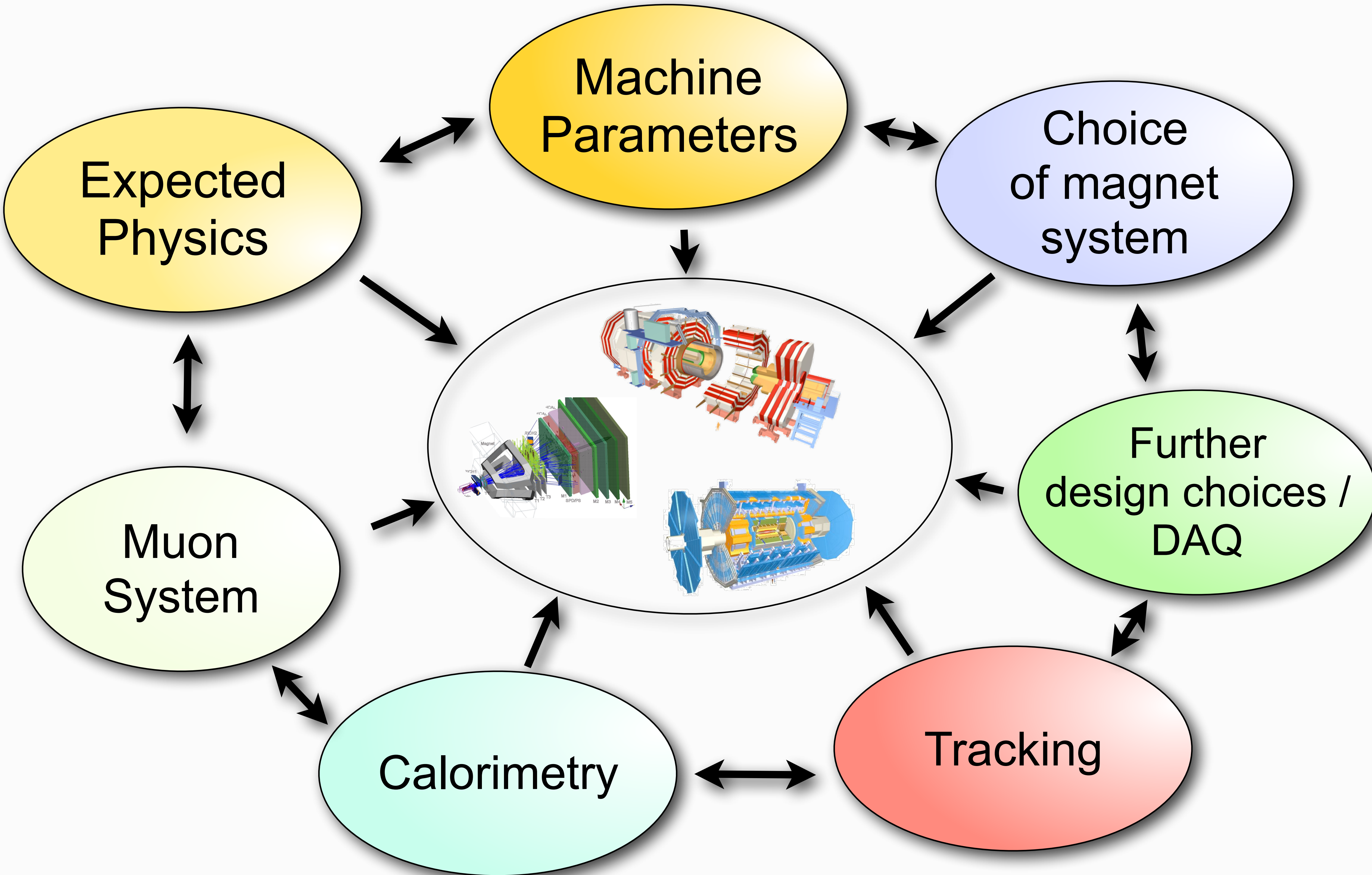






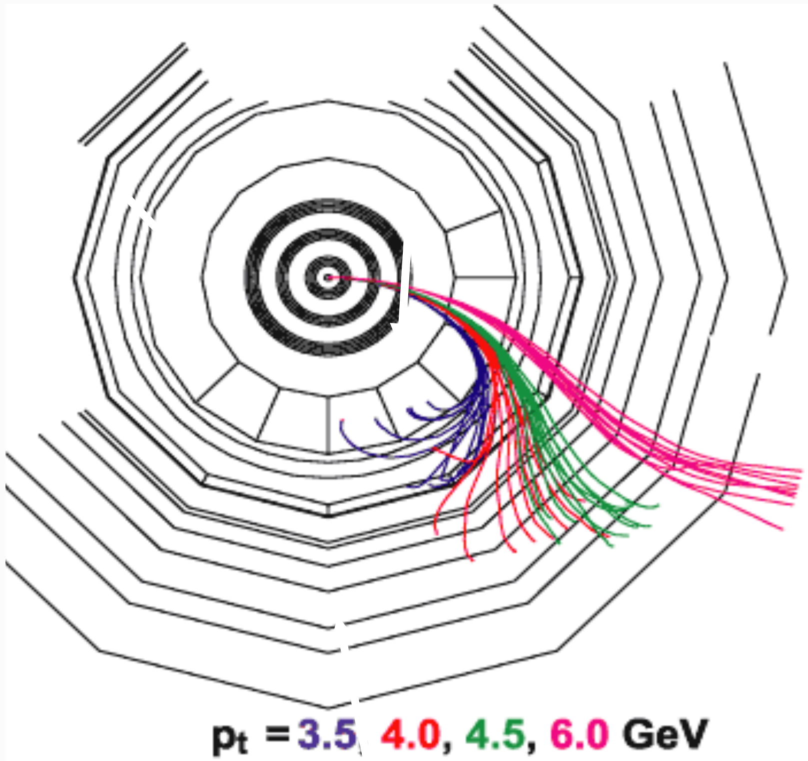


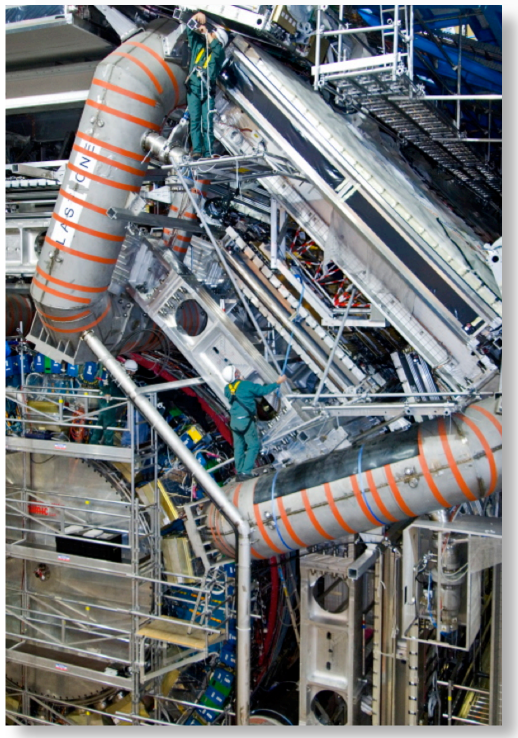
How to design your detector

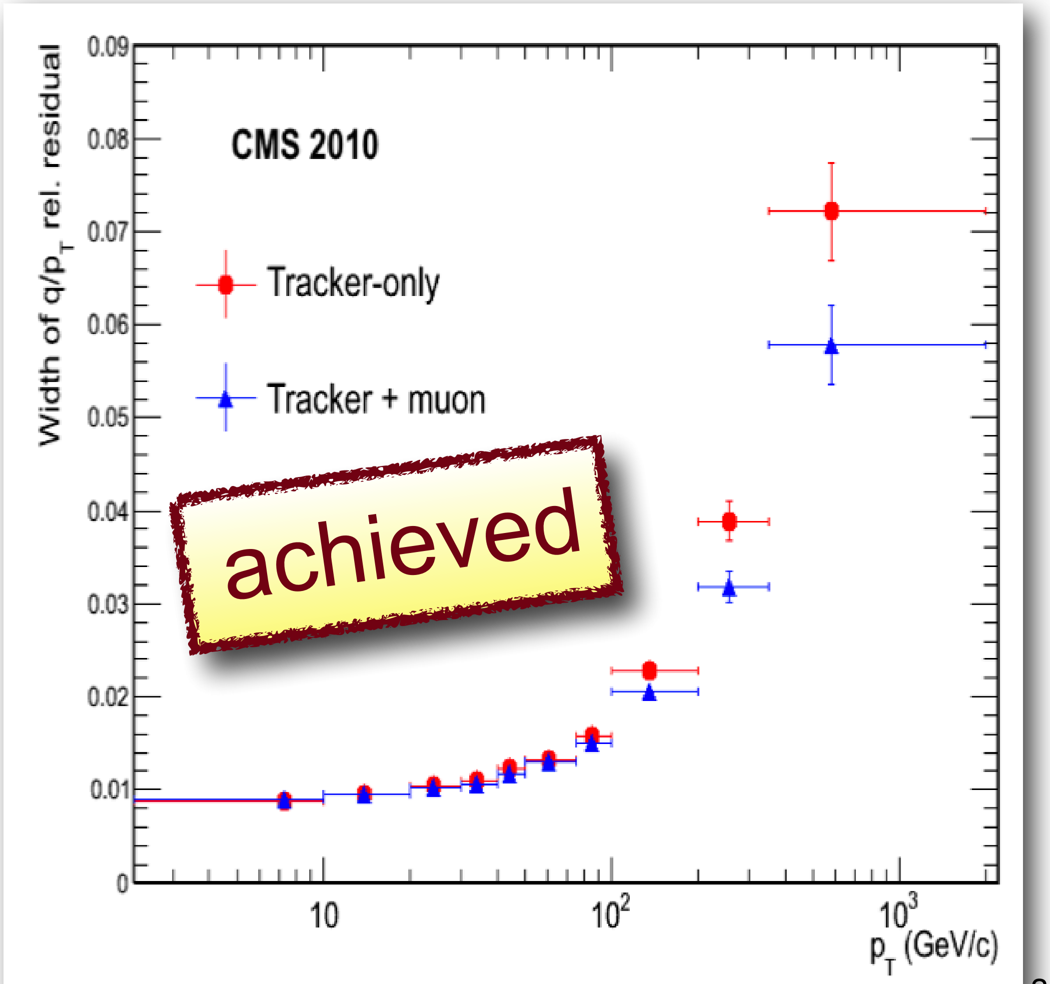


Muons : Requirements were

- Reconstruct mass of narrow 2-muon state (eg. Z mass) at 1% precision
- Reconstruct 1 TeV muons with 10% precision
- Over wide rapidity range
- Identification in dense environment
- Measure and trigger on muons in standalone mode, for momenta above ~ 5 GeV
  - CMS can use IP as further constraint
  - ATLAS has much less multiple scattering
- Combine different technologies for chambers
  - redundancy, robustness, radiation hardness, different speed
- Issues
  - Alignment (30 micron! for ATLAS)
  - Punch-through
  - Multiple scattering $\frac{\delta p_{\mathrm{MS}}}{p} \approx \frac{52 \cdot 10^{-3}}{\beta \, B \sqrt{L \, x_0}}$

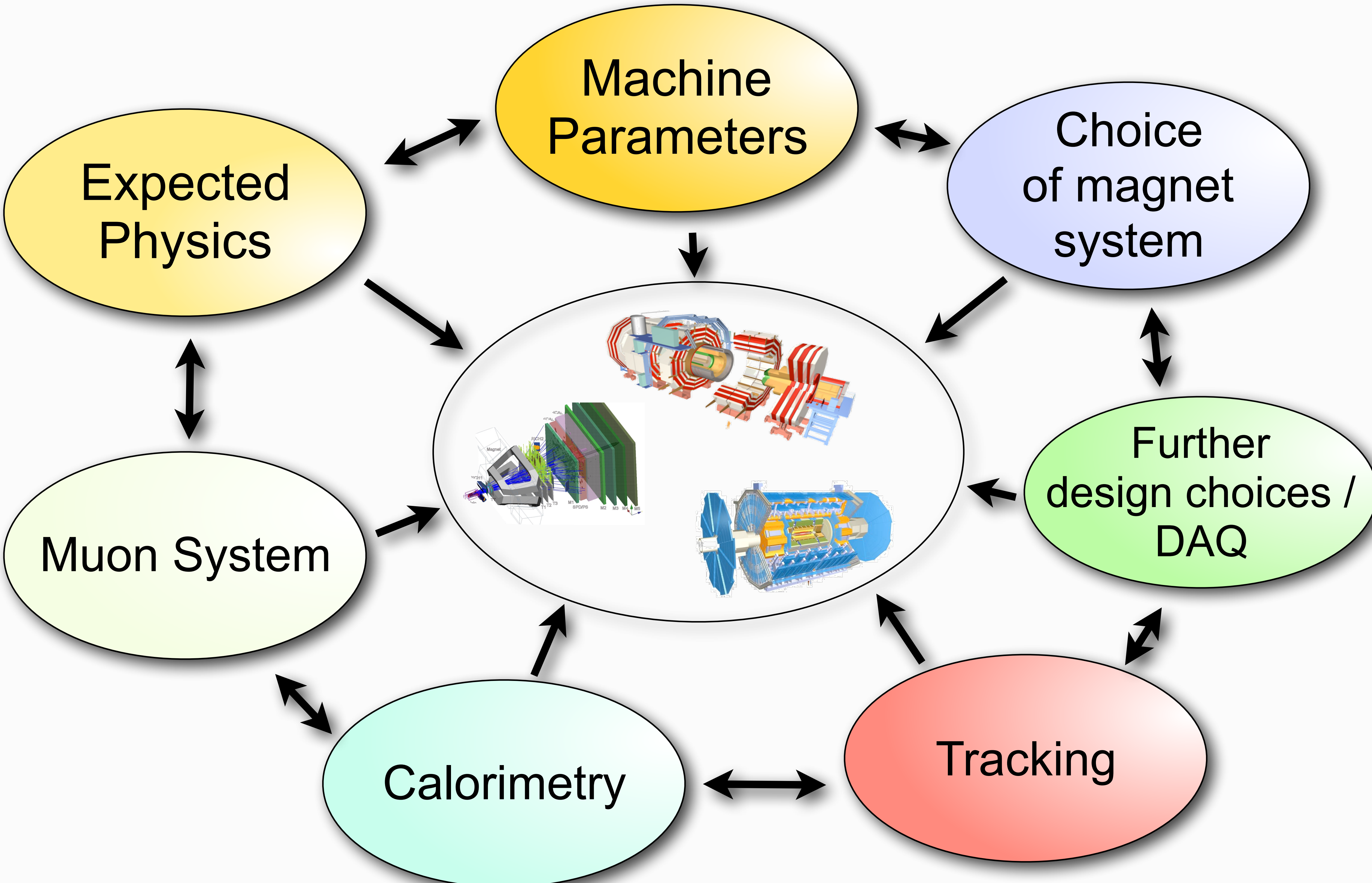






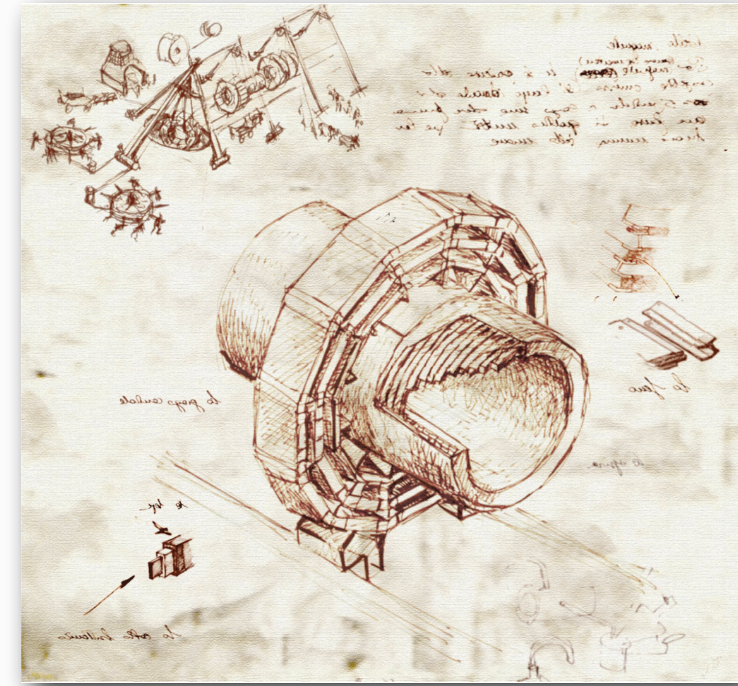
$$\text{for } \beta \approx 1 \, , \; B = 2\,\mathrm{T} \, , \; L \approx 2\,\mathrm{m} \, , \; x_0 = 0.14\,\mathrm{m} \quad \Rightarrow \frac{\delta p_{\mathrm{MS}}}{p} \approx 5\,\%$$

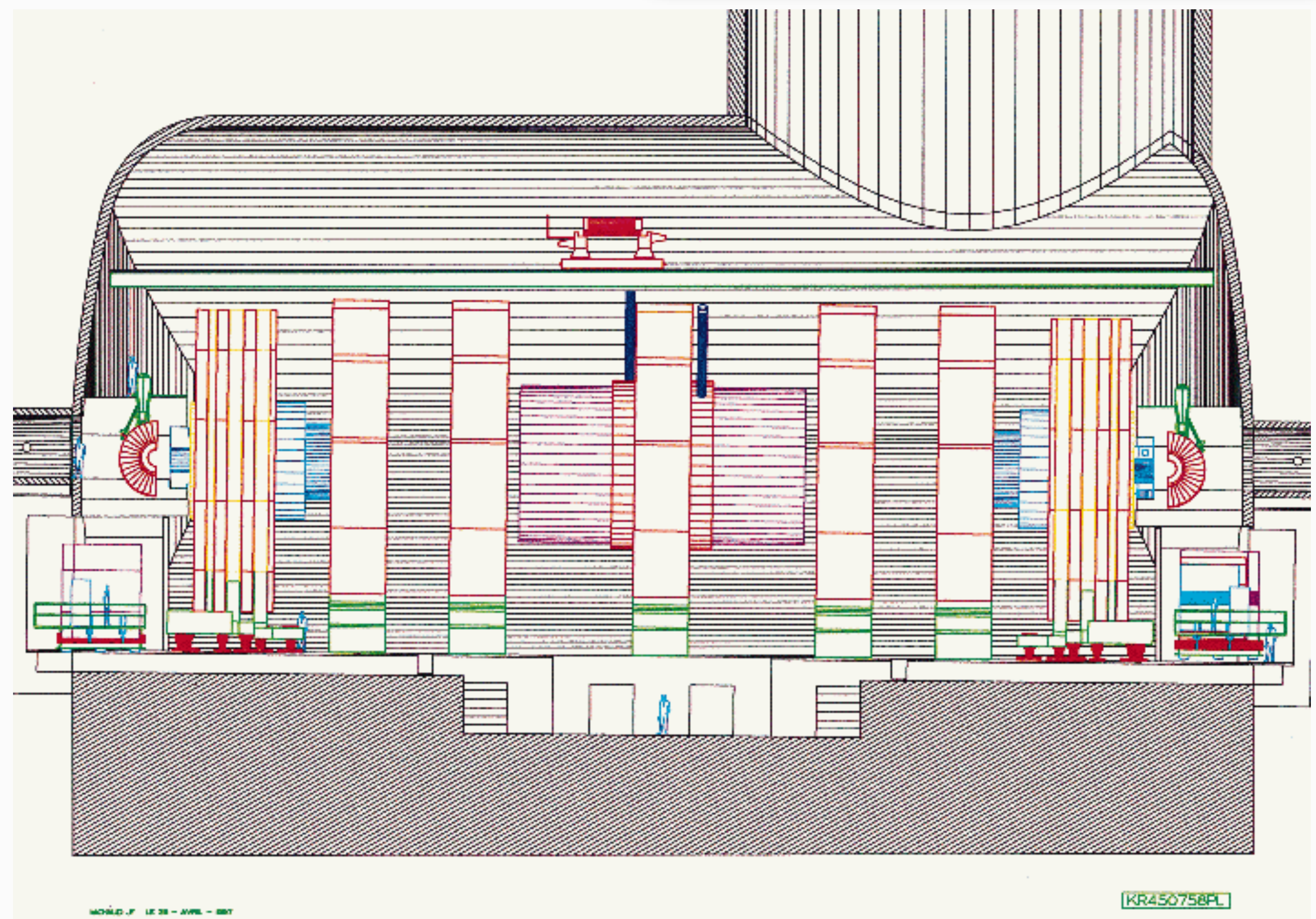
How to design your detector



Some examples...

- CMS: Modular structure
  - eg. CMS Barrel 13m long:
    not possible to build such long muon-chambers
  - Idea of wheels. All cabling independent. Flexibility.
  - Original idea: build/test everything at surface.
  - Every part of detector “easily” accessible during shutdowns
  - CMS Pixel detector is dramatic example





Finally:
The Detectors
ATLAS and CMS
and LHCb

ATLAS

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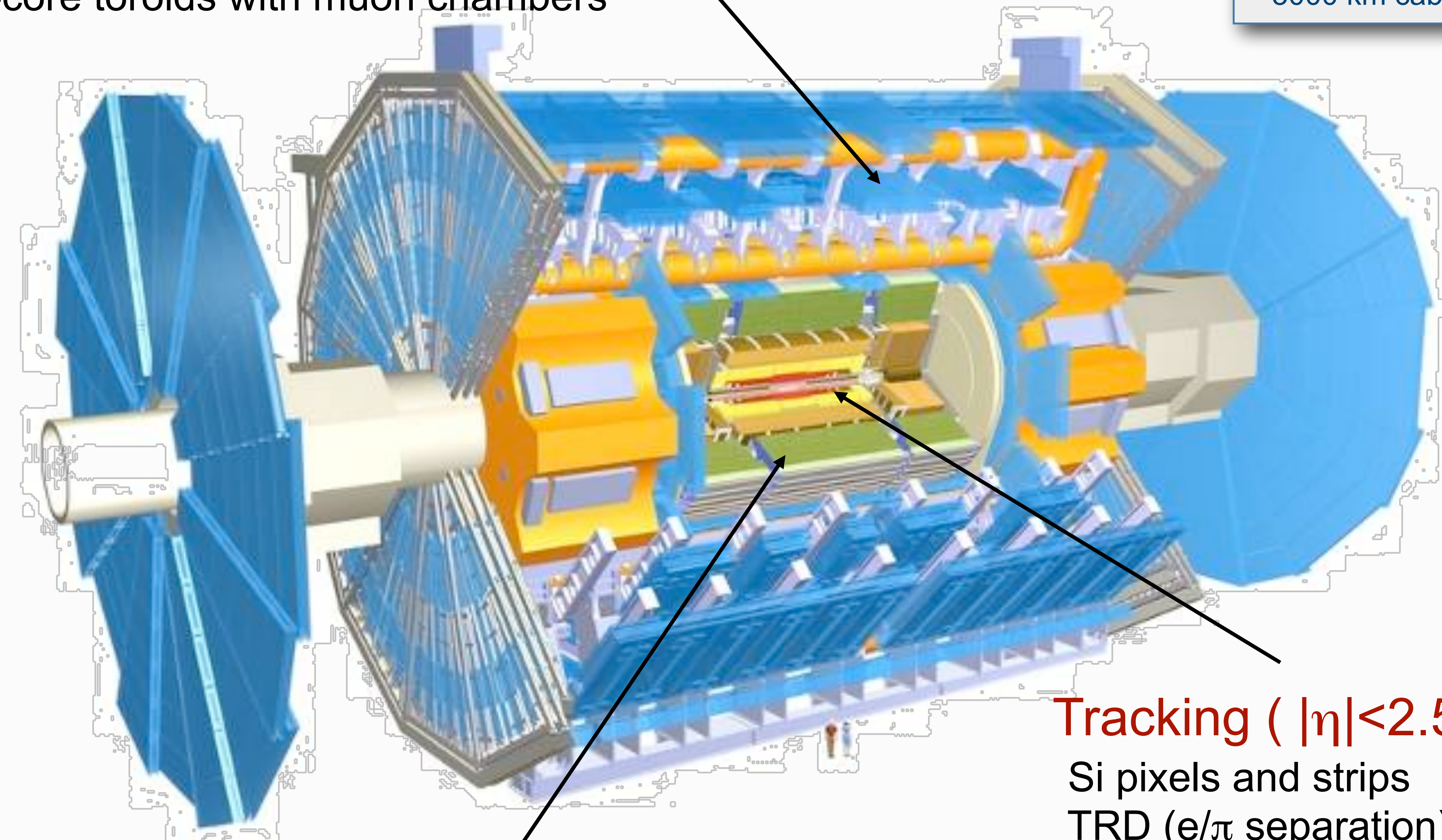
Muon Spectrometer ($|\eta|<2.7$)

air-core toroids with muon chambers

~10^8 electronic channels
~3000 km cables



Tracking ($|\eta|<2.5$, B=2T)

Si pixels and strips
TRD (e/π separation)

Calorimetry ($|\eta|<5$)

EM : Pb-LAr
HAD : Fe/scintillator (central),
Cu/W-Lar (fwd)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 tons

Compact Muon Solenoid

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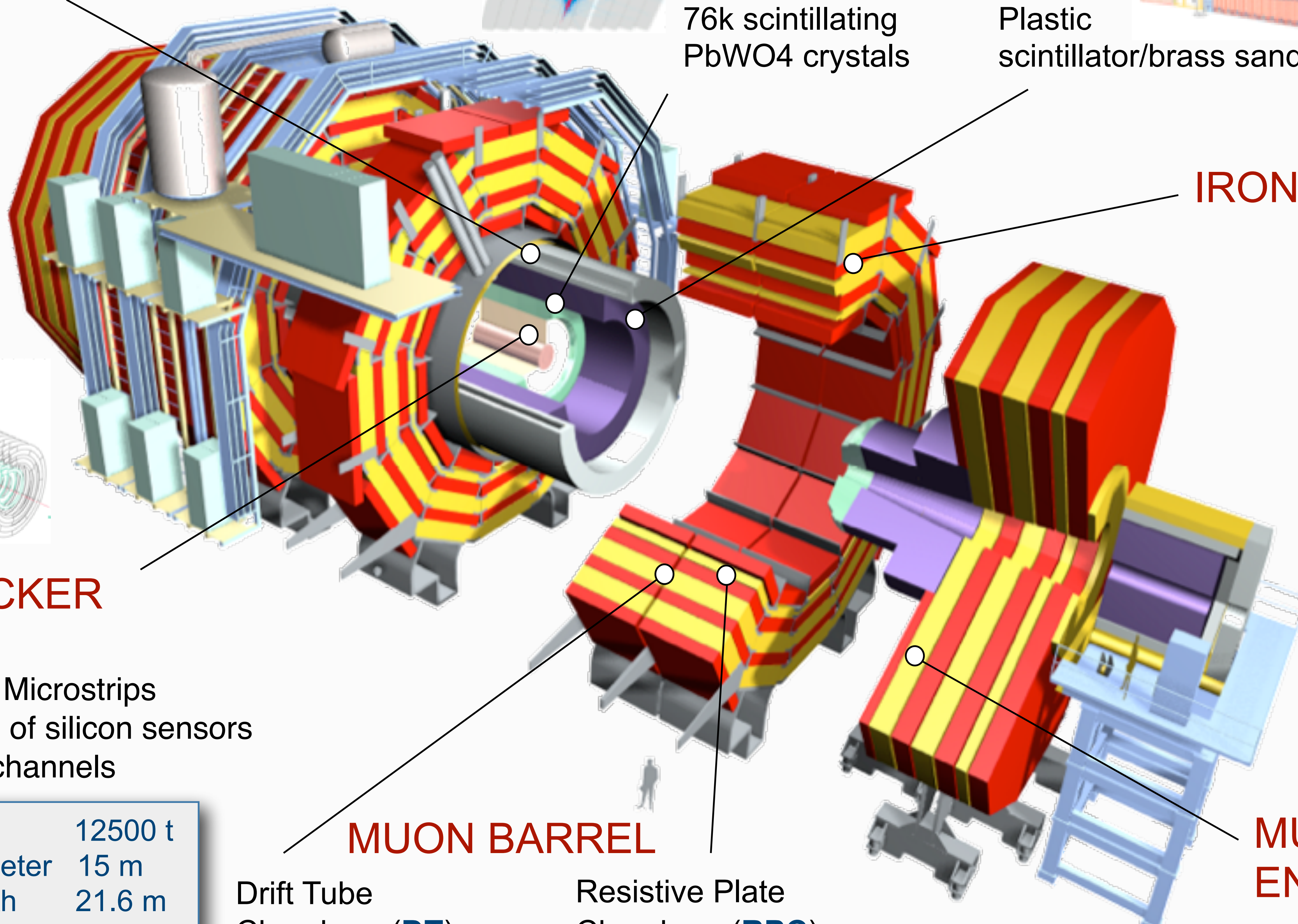
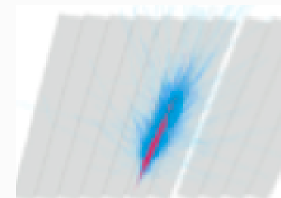




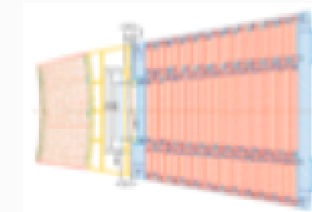
CALORIMETERS

ECAL

76k scintillating PbWO4 crystals

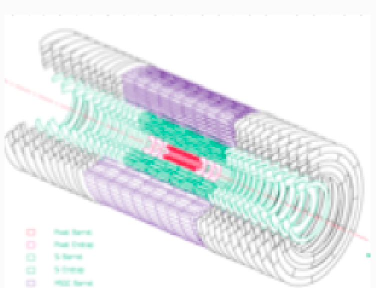
HCAL

Plastic scintillator/brass sandwich



Superconducting Coil, 4 Tesla

IRON YOKE



TRACKER

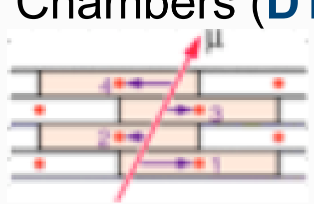
Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6 M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

2900 scientists from
183 Institutes from
38 countries

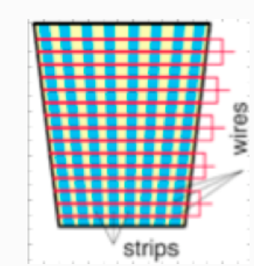
MUON BARREL

Drift Tube Chambers (**DT**)



Resistive Plate Chambers (**RPC**)

MUON ENDCAPS



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

ATLAS vs CMS

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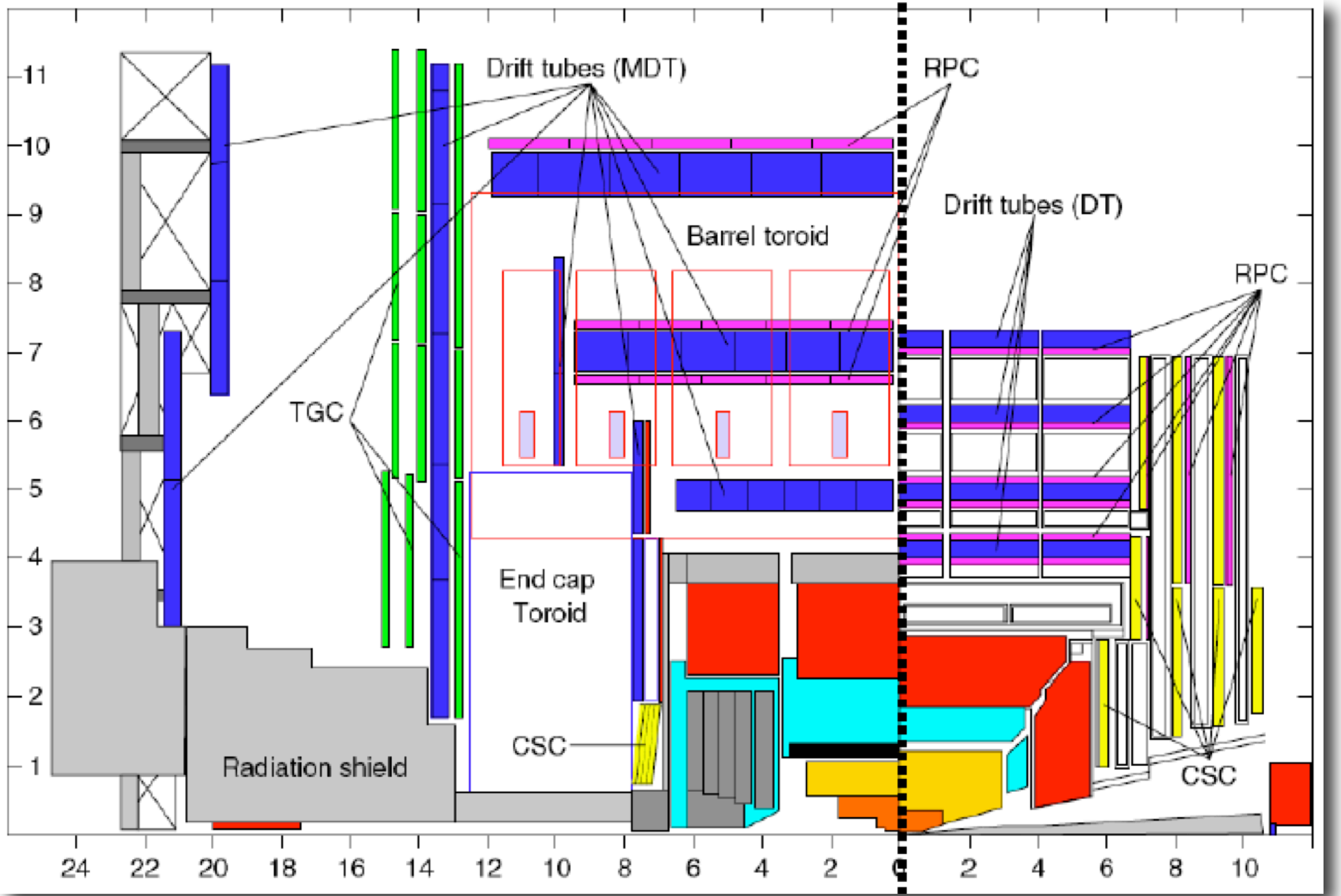
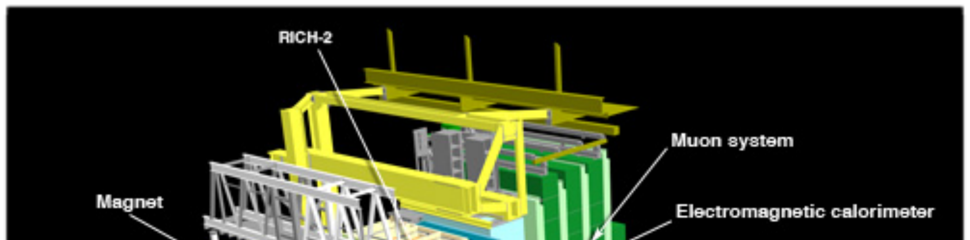


from W. Riegler

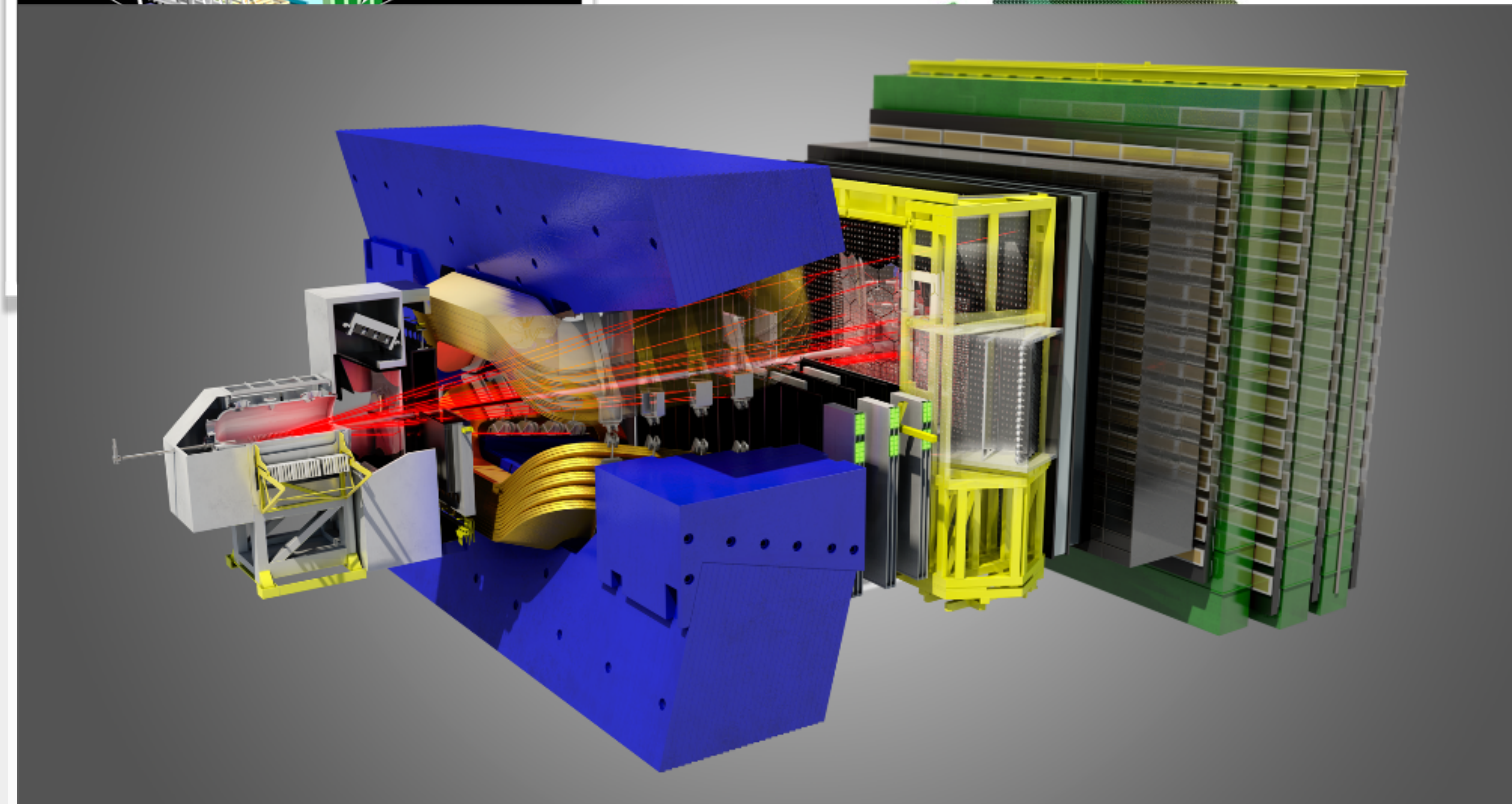
Comparison (of design values)

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E} + 0.007$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\%/\sqrt{E} + 0.003$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (~7 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim$ 2%(@50GeV) to 10% (@1 TeV) standalone	Fe → $\sigma/p_T \sim$ 1% (@50 GeV) to 10% (@1 TeV) combining with tracker

LHCb



not covered here: particle ID, eg. with RICH systems



http://lhcb-public.web.cern.ch/lhcb-public/en/LHCb-outreach/multimedia/LHCbDetectorpnglight1.png

Particle Flow and Consequences

Use of global event description

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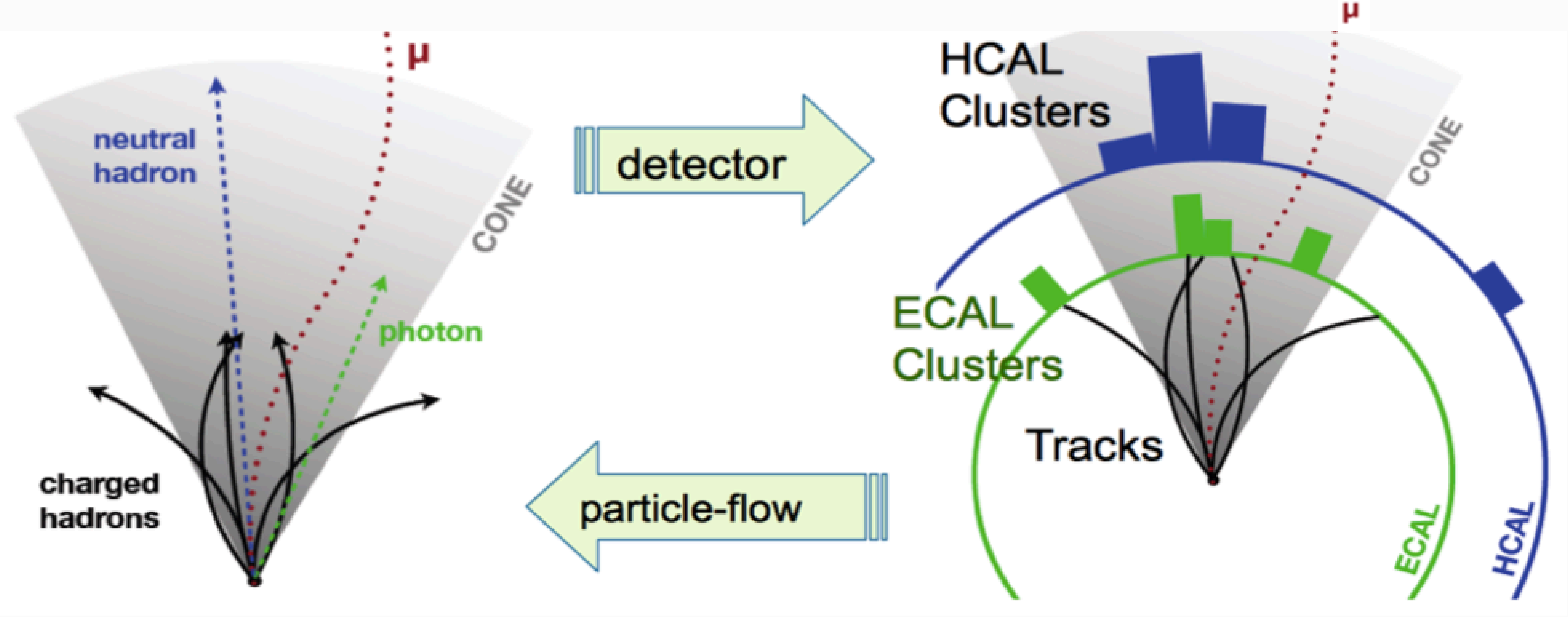
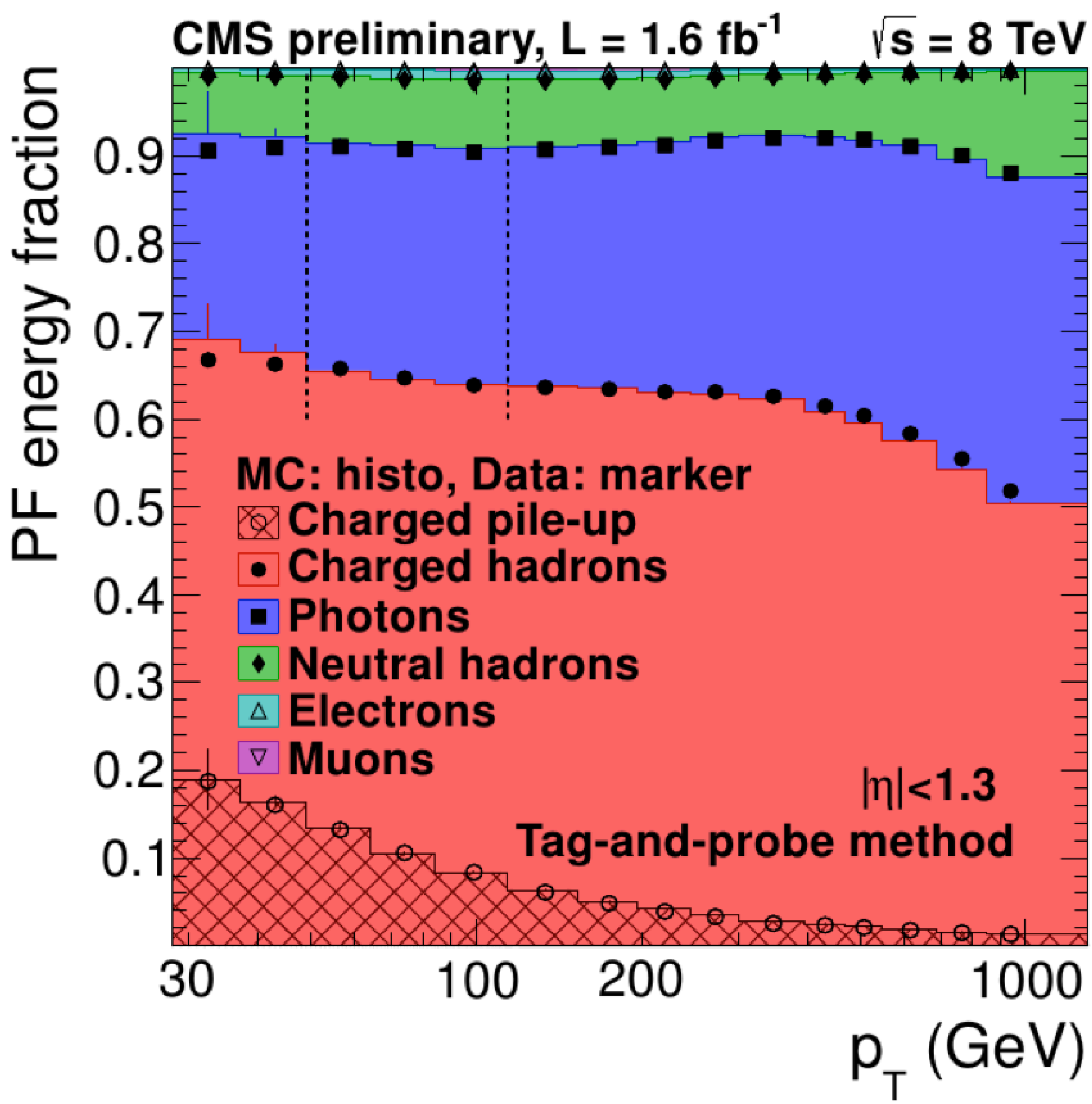
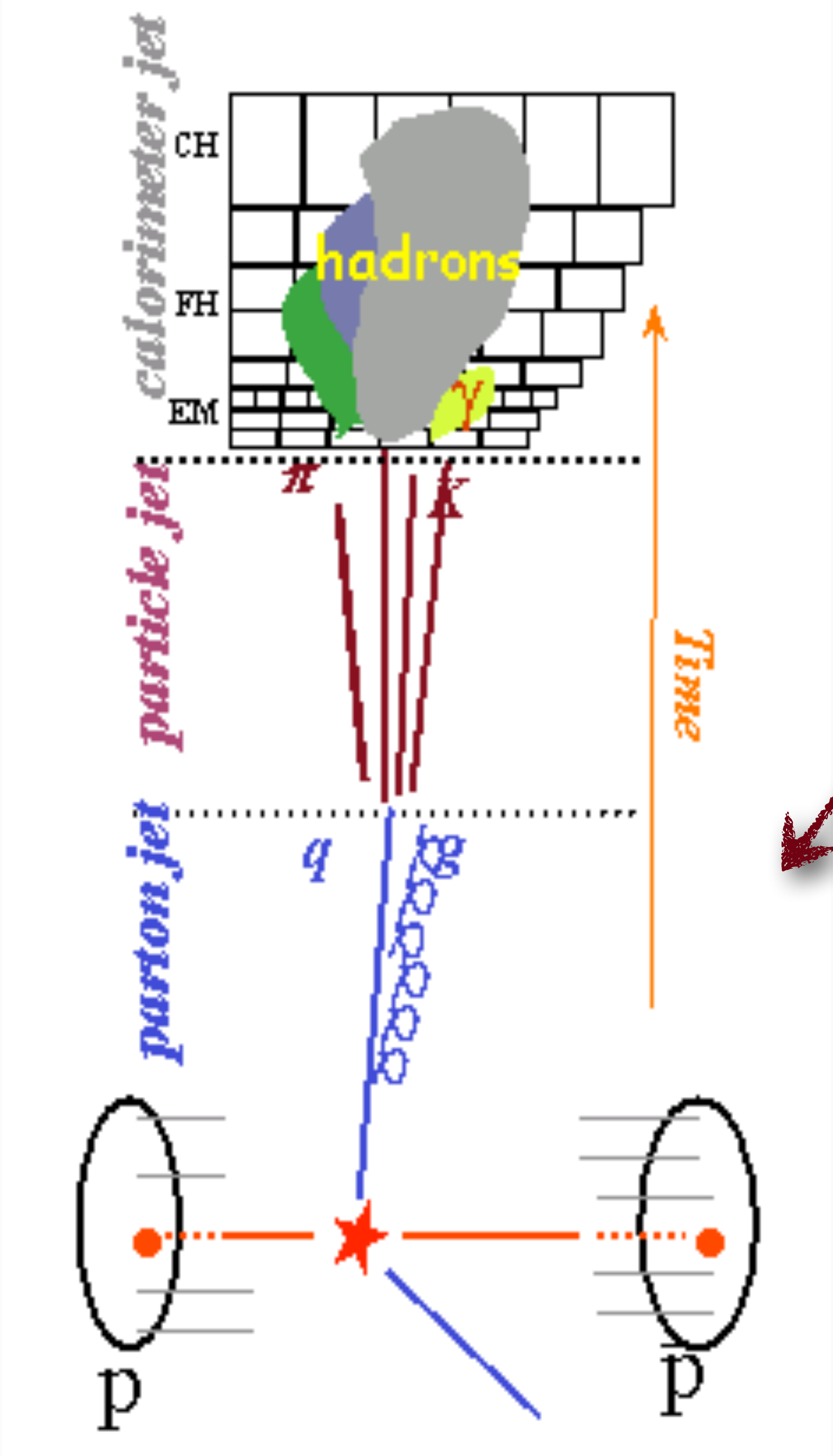


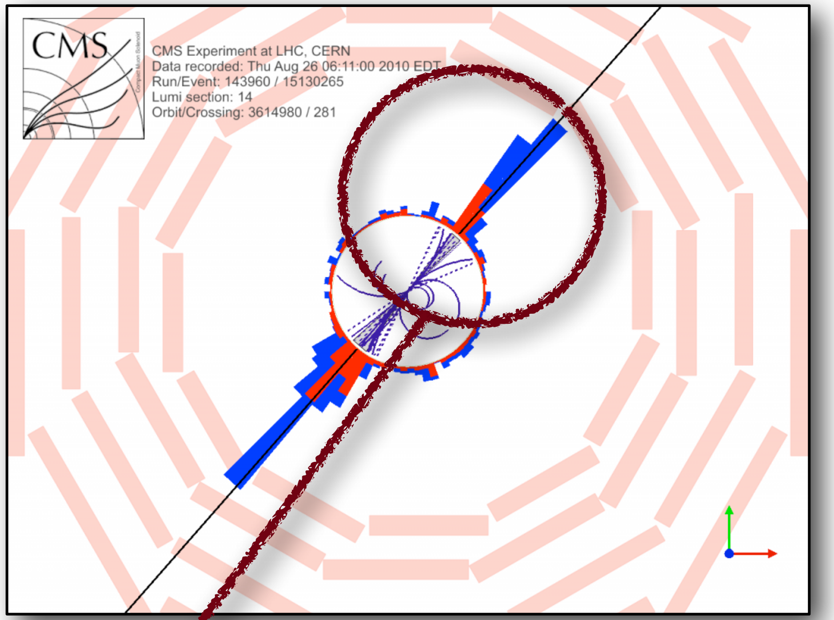
- Charged particles well separated in large tracker volume & 3.8T B field
- Excellent tracking, able to go to down to very low momenta (~100 MeV)
- Granular electromagnetic calorimeter with excellent energy resolution
- In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)
- Therefore: **Use a global event description** :
  - Optimal combination of information from all subdetectors
  - Returns a list of reconstructed particles (e,mu,photons,charged and neutral hadrons)
  - Used as building blocks for jets, taus, missing transverse energy, isolation and PU particle ID

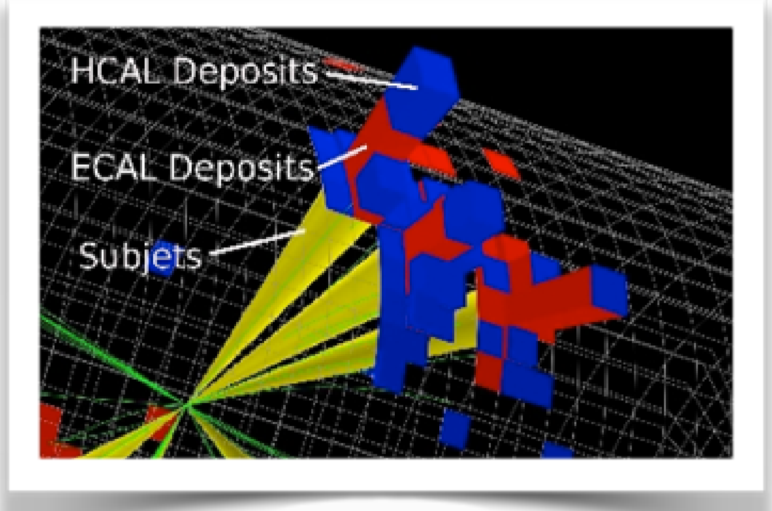
The Pflow jet composition

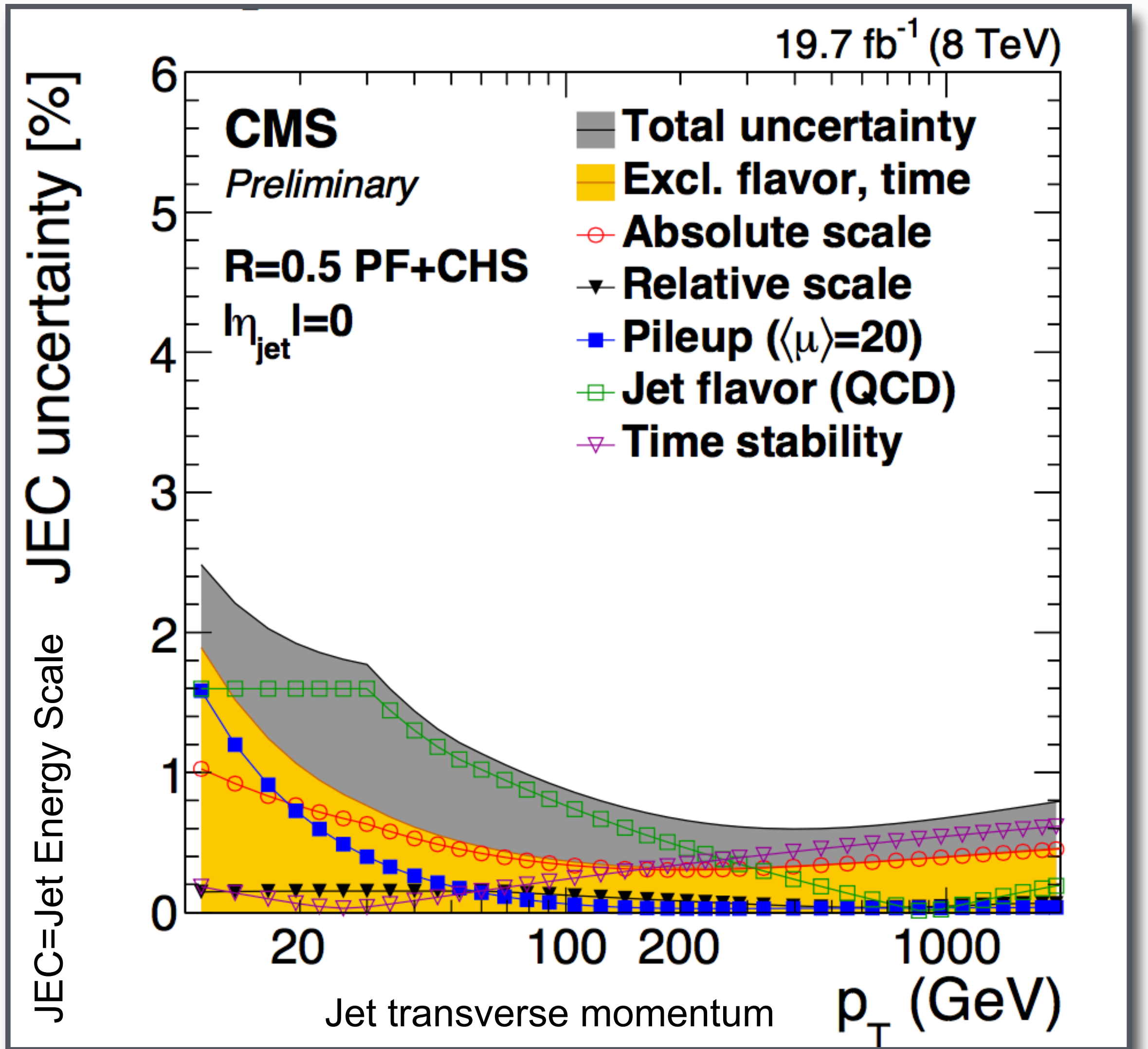


Impact on Jet Calibration





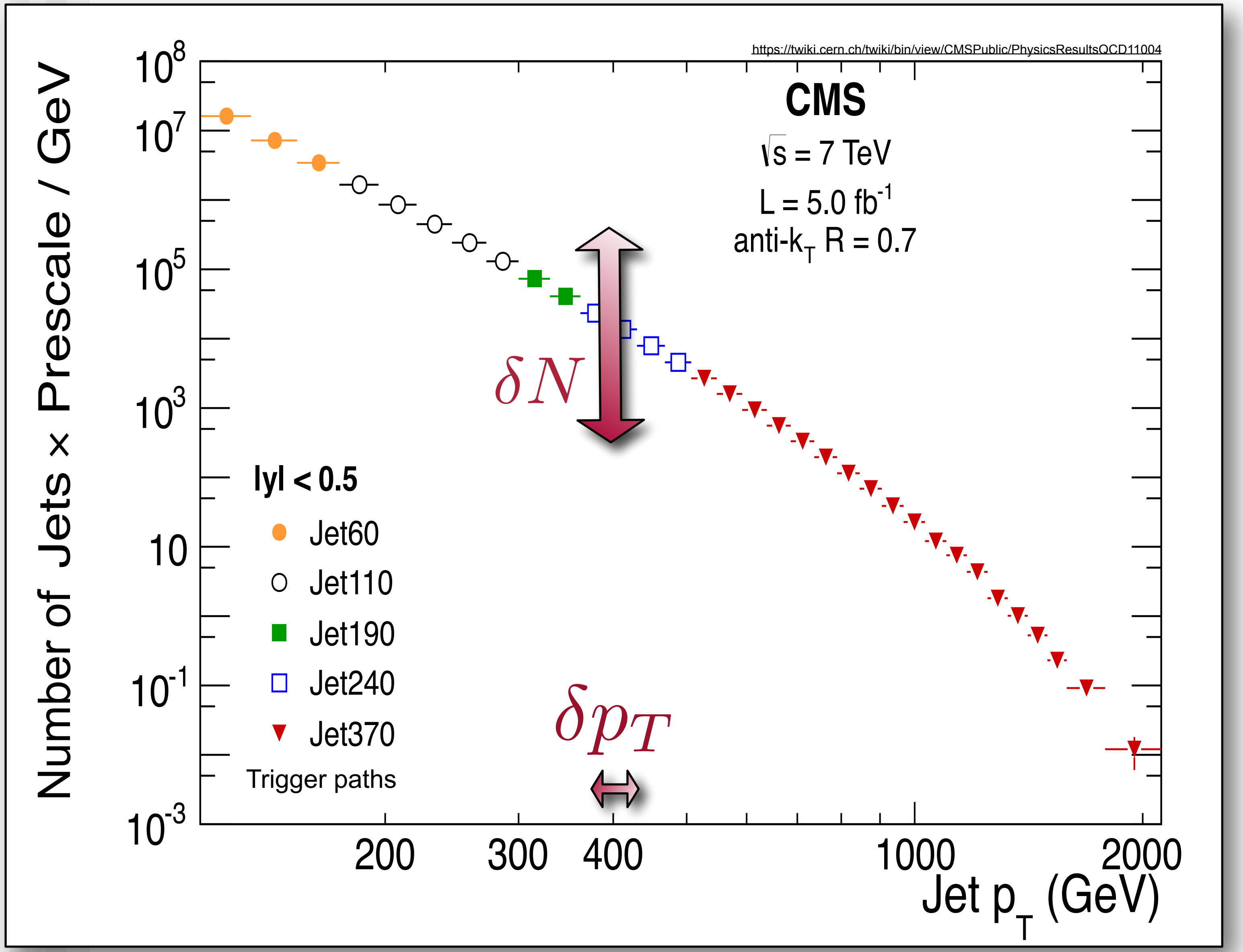




JES uncertainty <2% for most of the p_T range, JER about 10%

Jet energy calibration

- Question : how well do we know the calibration of the variable on the x-axis, eg. jet energy?
- A general problem for a very steeply falling spectrum!
- It makes a **big** difference if the jet energy scale uncertainty is 1%, 2% or 5%



$$\frac{d\sigma}{dp_T} \approx \mathrm{const} \cdot p_T{}^{-n}$$

n large, eg. $n \approx 6$

relative uncertainties

$$\frac{\delta N}{N} \approx 6 \cdot \frac{\delta p_T}{p_T}$$

so beware:

eg. an uncertainty of **5%** on absolute energy scale (calibration)

→ an uncertainty of **30%** (!) on the measured cross section

Our milestones:

1. Why do ATLAS and CMS look like they look like today?
2. **Some highlights, and achievements**

The speed, at which things appeared....

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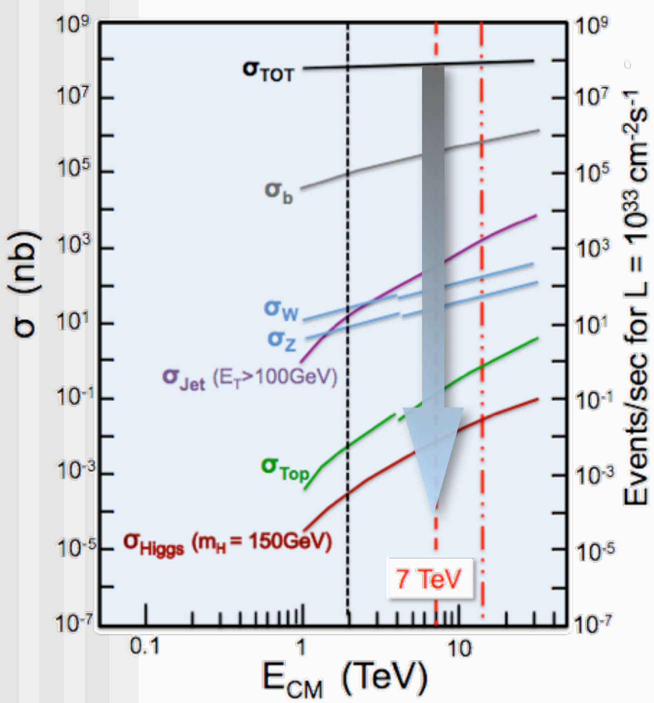
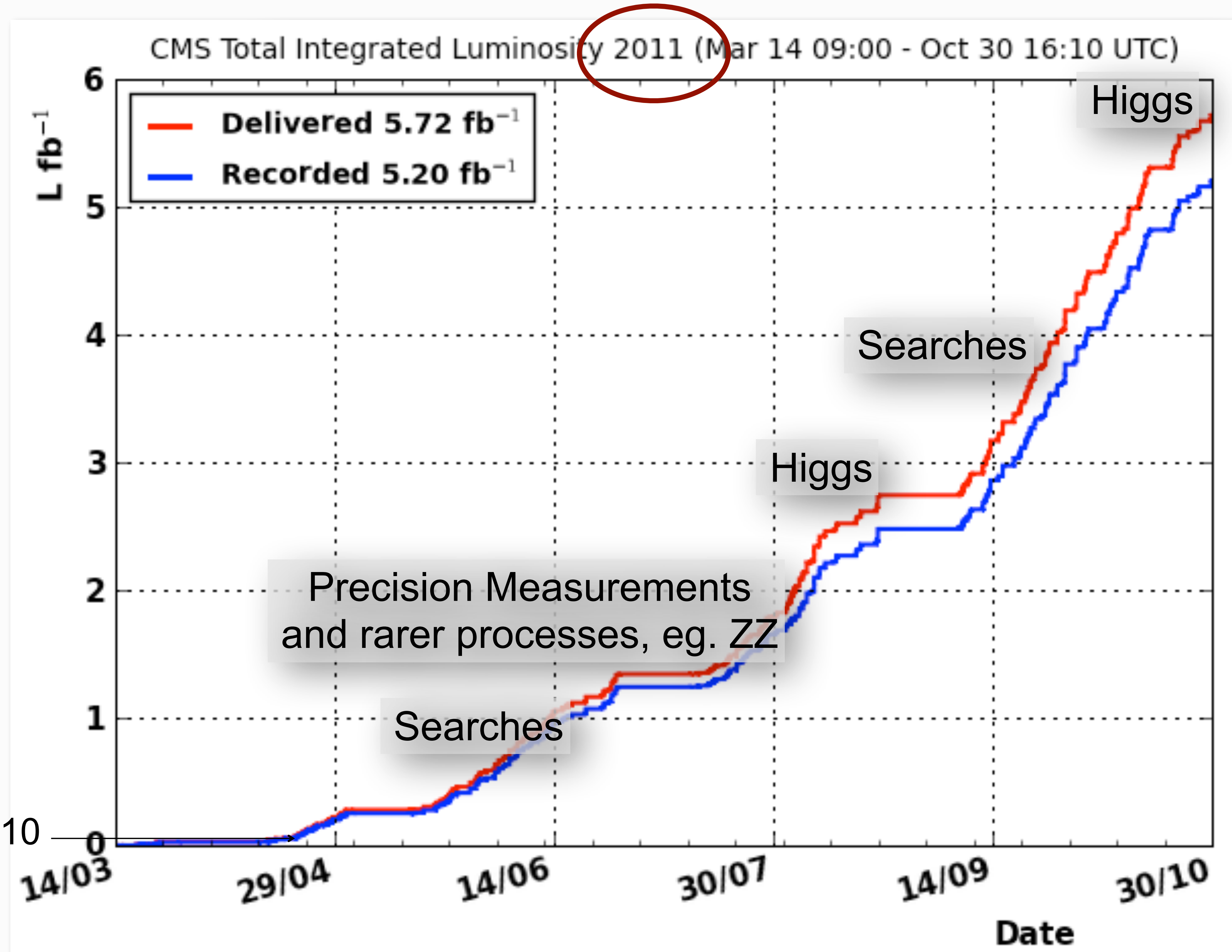


2010



The speed, at which things appeared....

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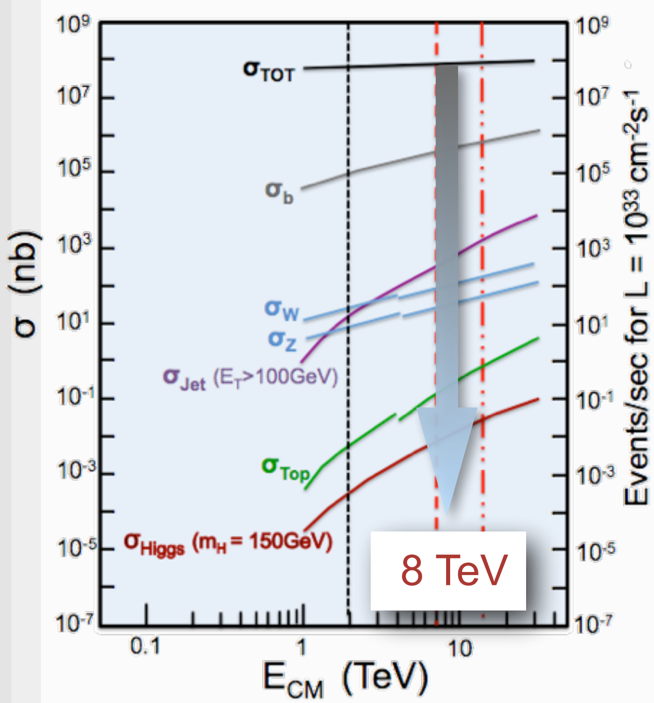
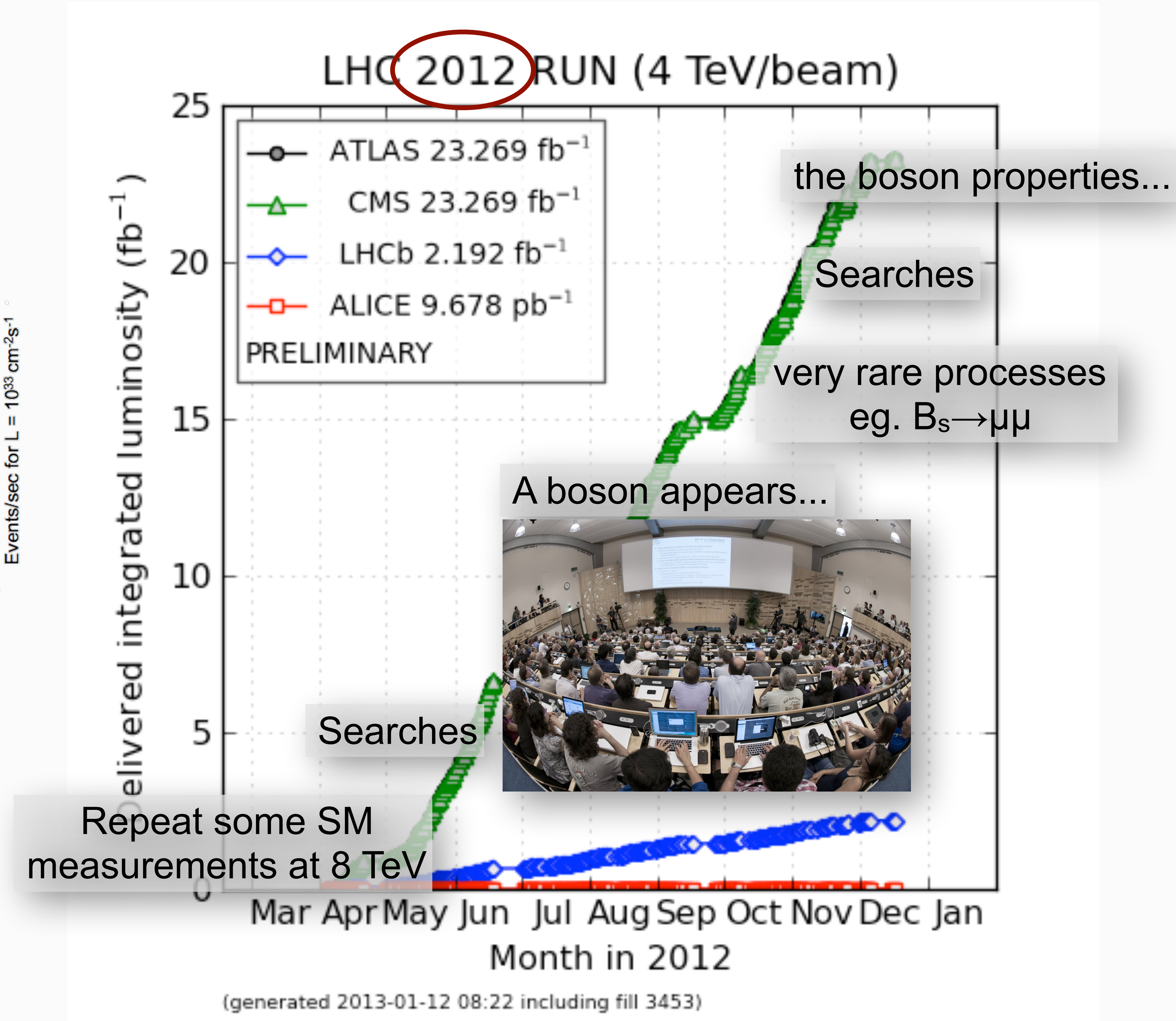
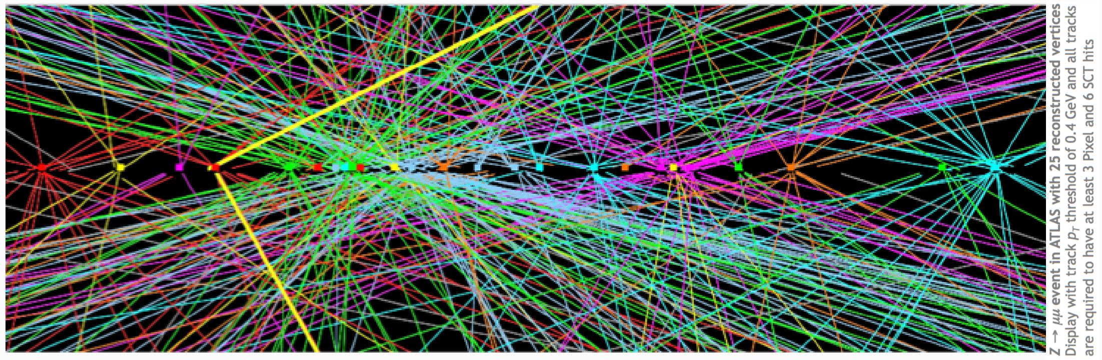
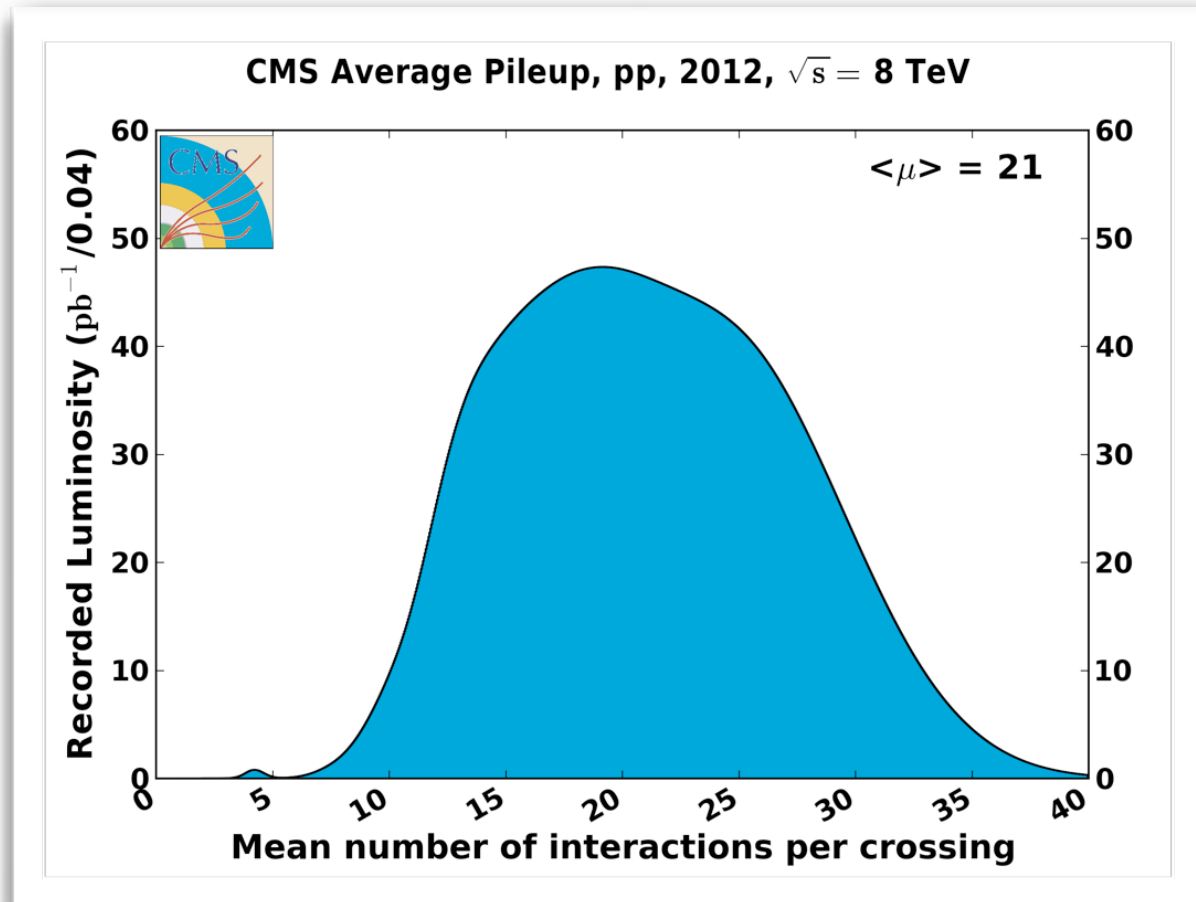




The environment...

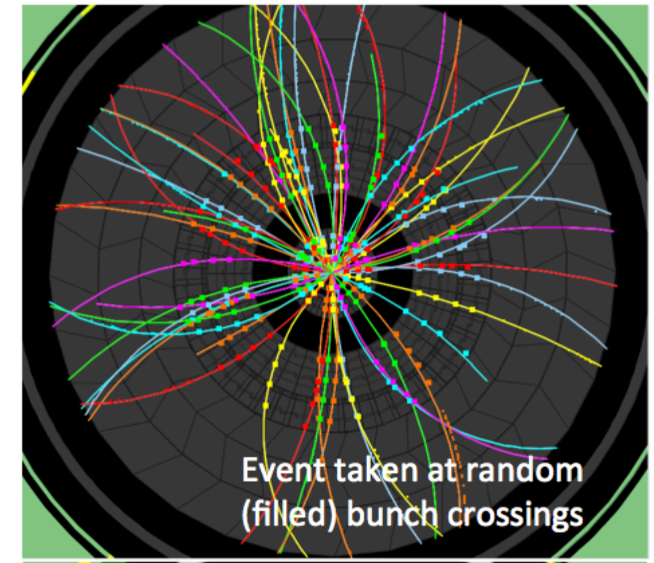
A. Hoecker, Dec 2012





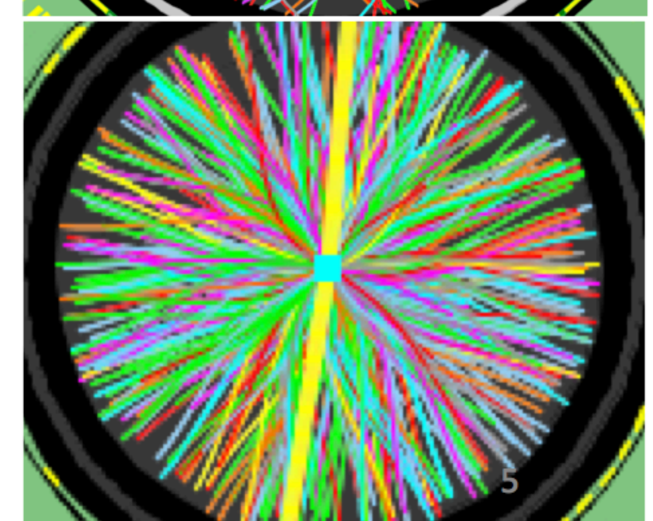
Data taking efficiencies ~94%
At or above 90% used for physics.
Kept the performance, despite high PU!

2010
O(2) Pile-up events
150 ns inter-bunch spacing



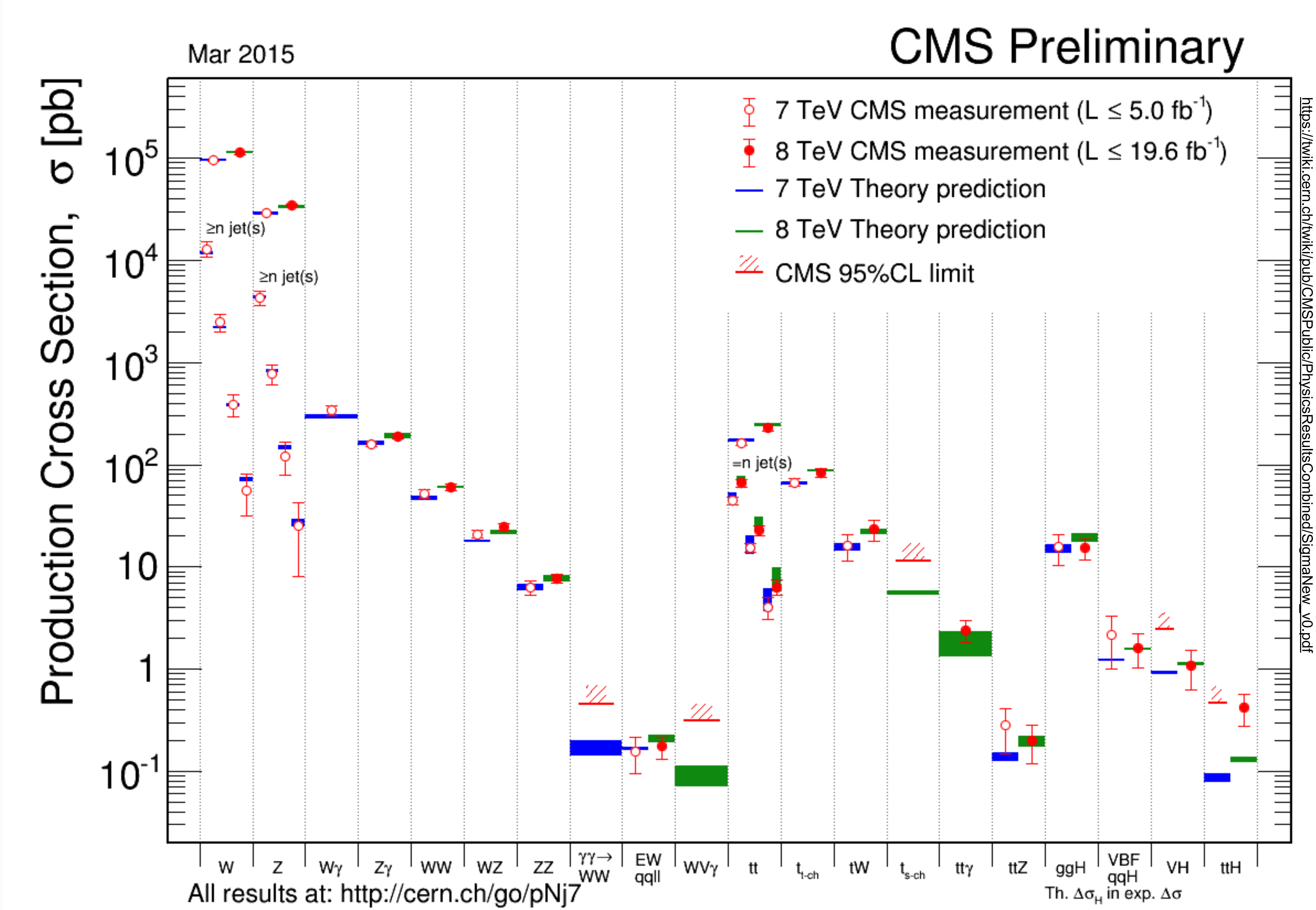
2011
O(10) Pile-up events
50 ns inter-bunch spacing

2012
O(20) Pile-up events
50 ns inter-bunch spacing



Marumi Kado, Dec 2012

Good performance leads to good results



Picking "at random"…

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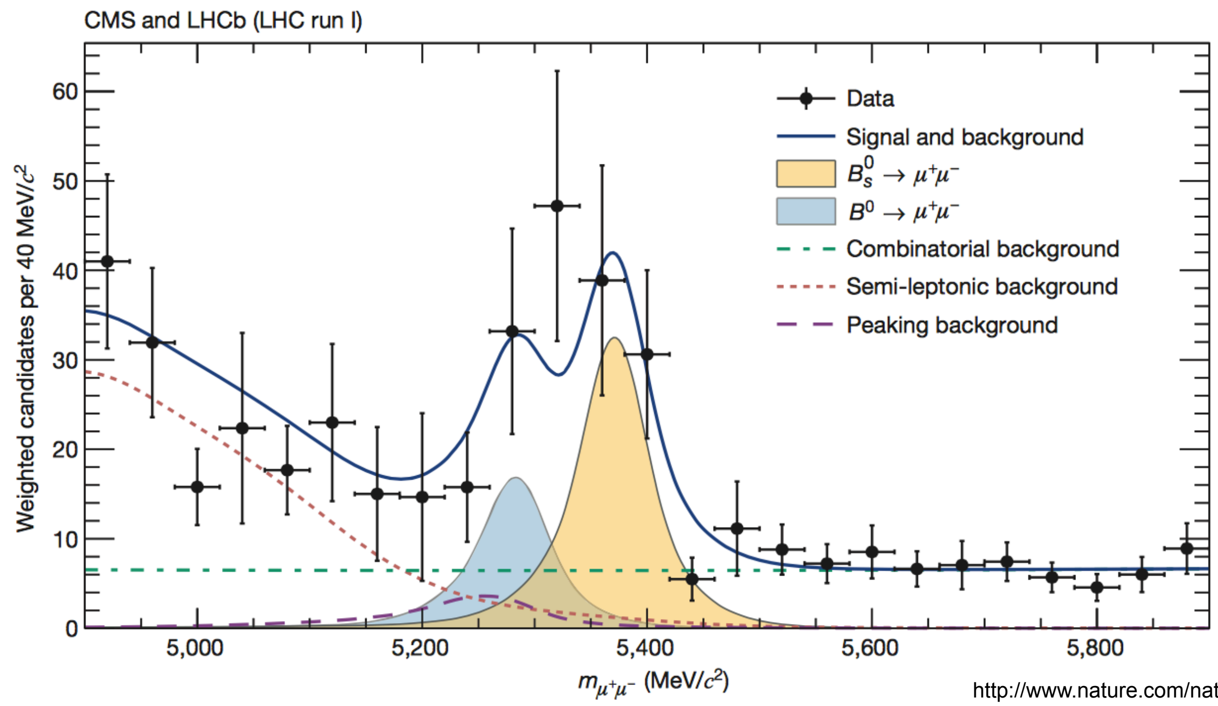
- … a very rare process…

$B^0_{(s)} \to \mu^+\mu^-$



http://www.nature.com/nature/journal/v522/n7554/pdf/nature14474.pdf

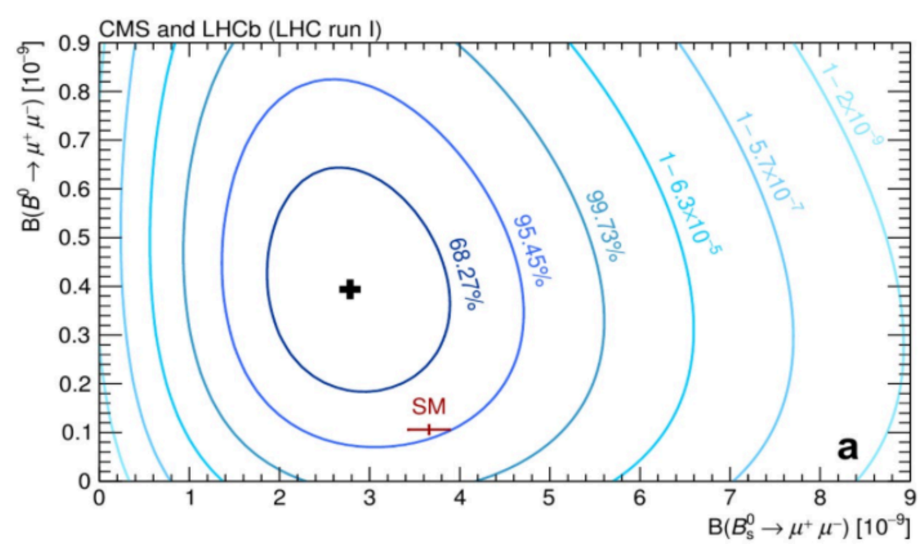
- **combination with CMS measurement**

$$BF(B^0_s \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

$$BF(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

[arXiv:1411.4413]

- **$B^0_s \to \mu^+\mu^-$ agrees with Standard Model**
- **$B^0 \to \mu^+\mu^-$ 2.2 σ above Standard Model**



13.05.2015 **Particle Physics Seminar Bern (38/64)** **O. Steinkamp**

This plot really depresses me…

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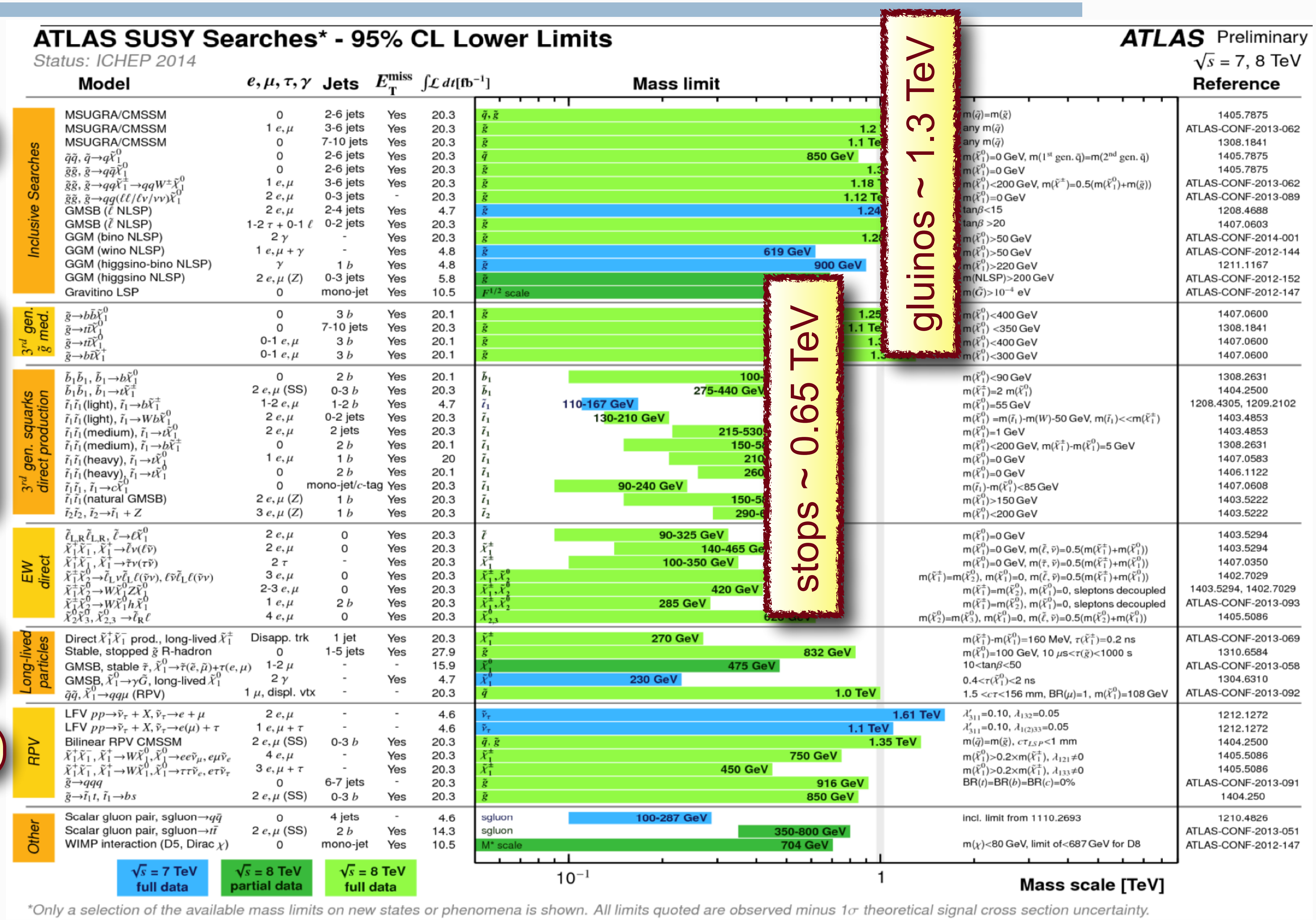
inclusive searches

Natural SUSY

long-lived particles, eg. split SUSY

RPV



- impressive list, similar plethora of results from CMS
- but: **read the fine-print** !!
  - most of the time, limits are based on (many) assumptions, simplified models

Exotica: Executive summary

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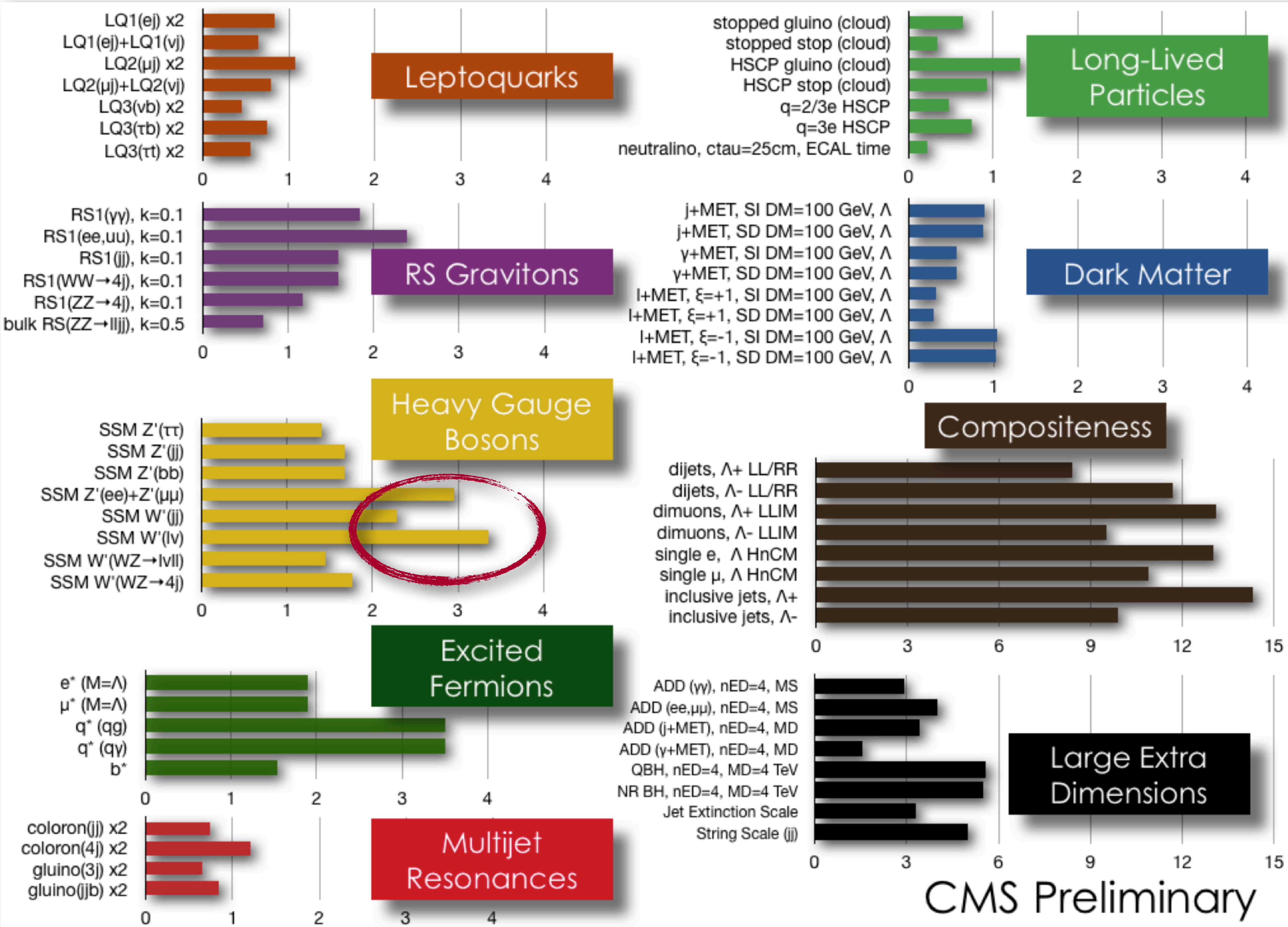
- also this plot depresses me…



Conclusion

1. This was (at most) an appetizer, a glimpse, a flash, a ….
2. no way to do justice to all the fantastic achievements, the details, …
3. and I didn’t even mention the upgrades!

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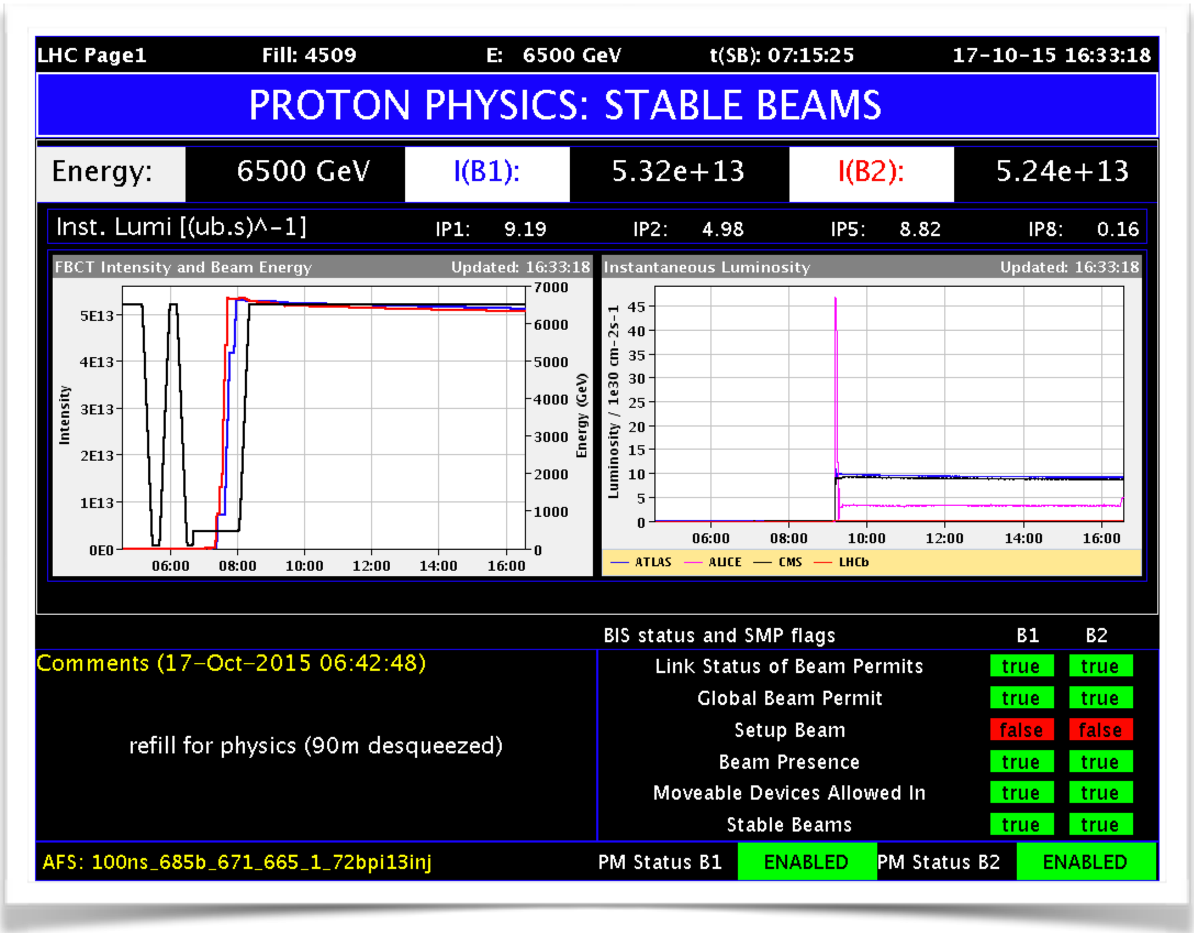
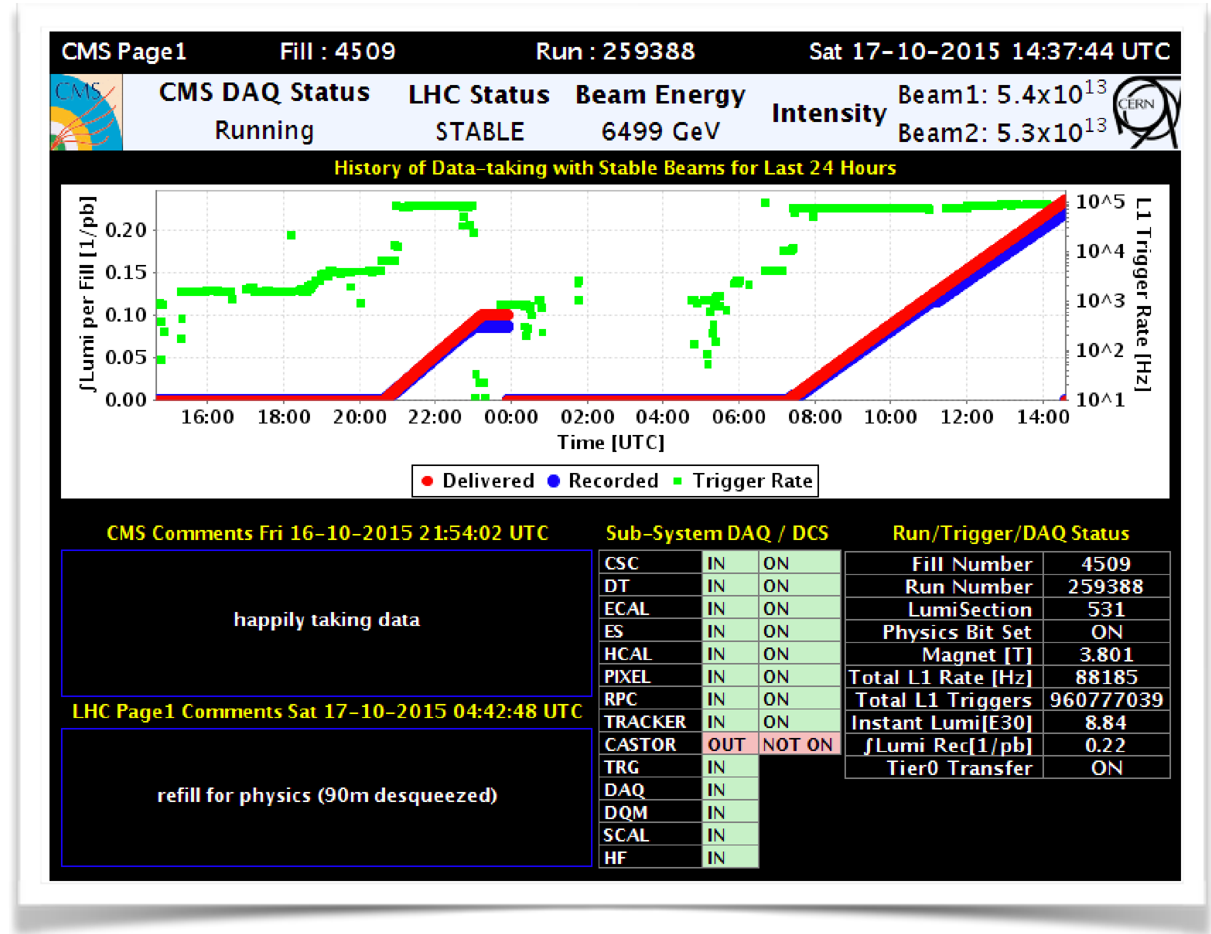
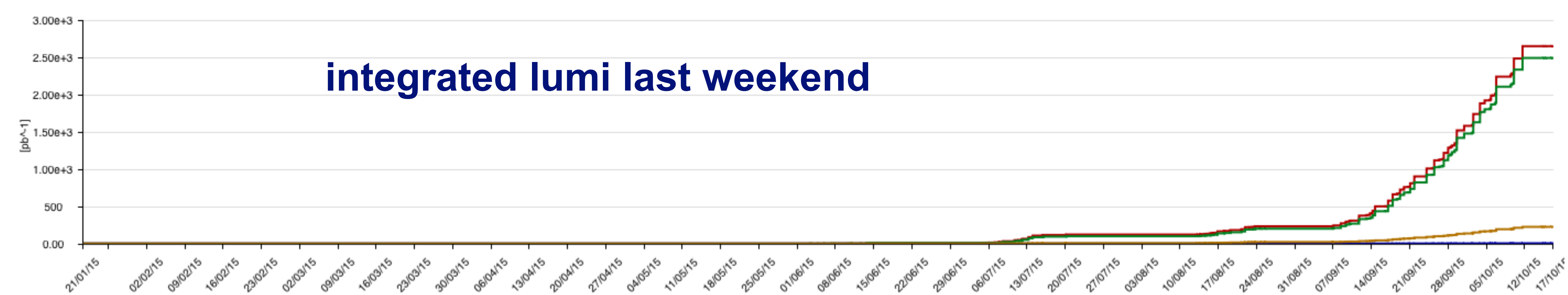
Run 2 is in full swing







https://acc-stats.web.cern.ch/acc-stats/#lhc/overview-panel

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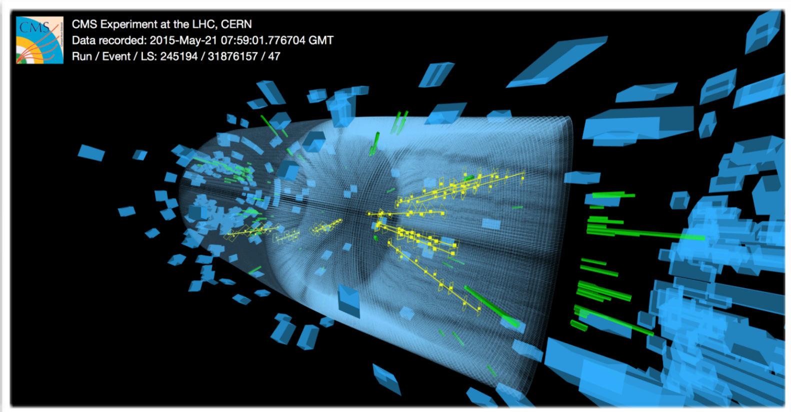
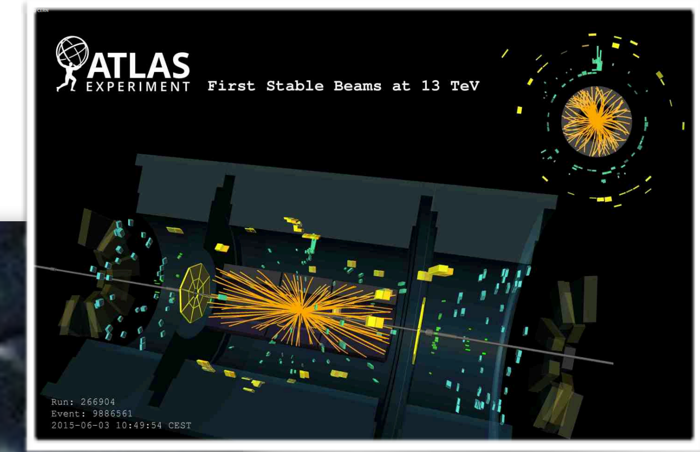
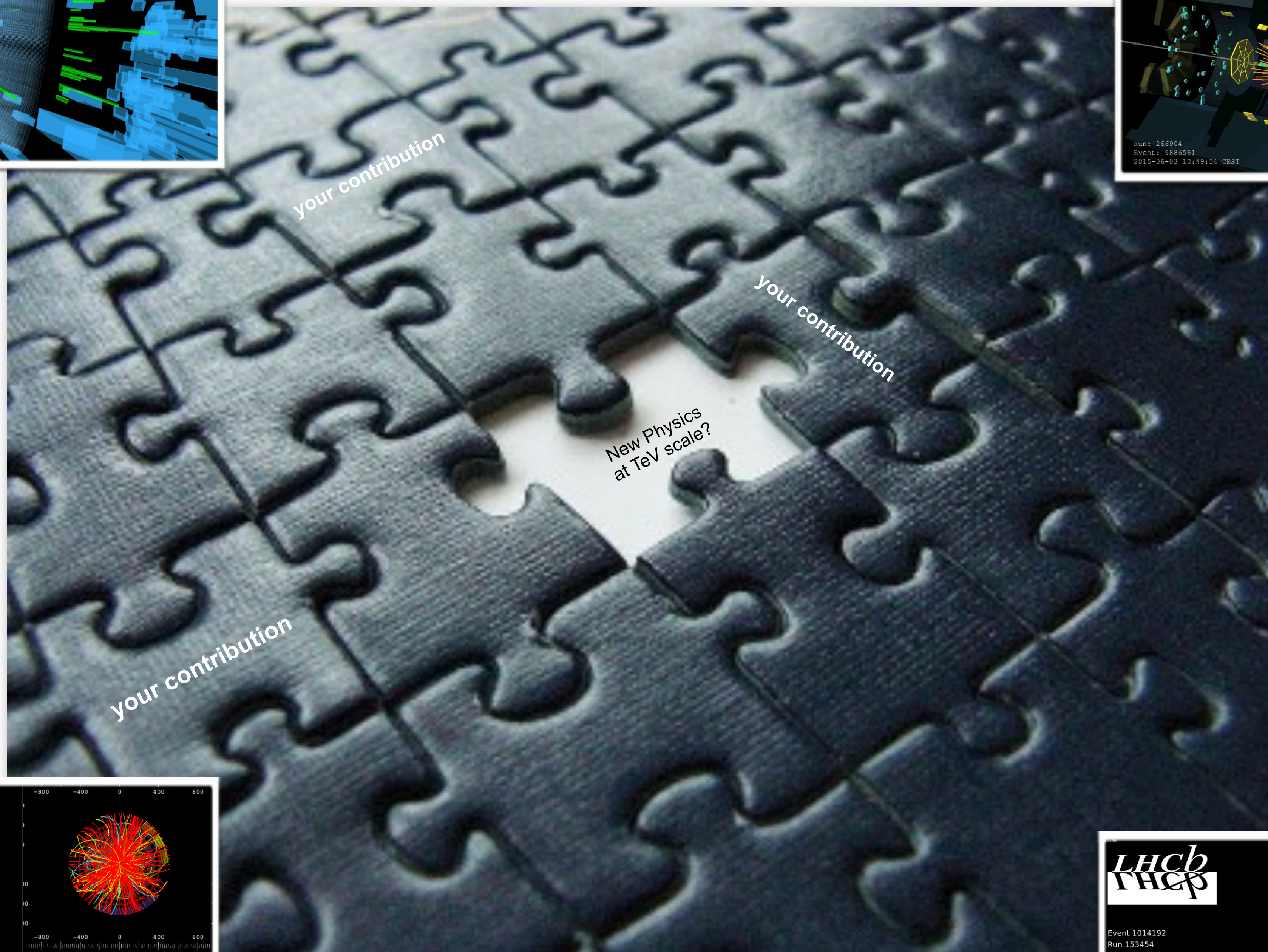
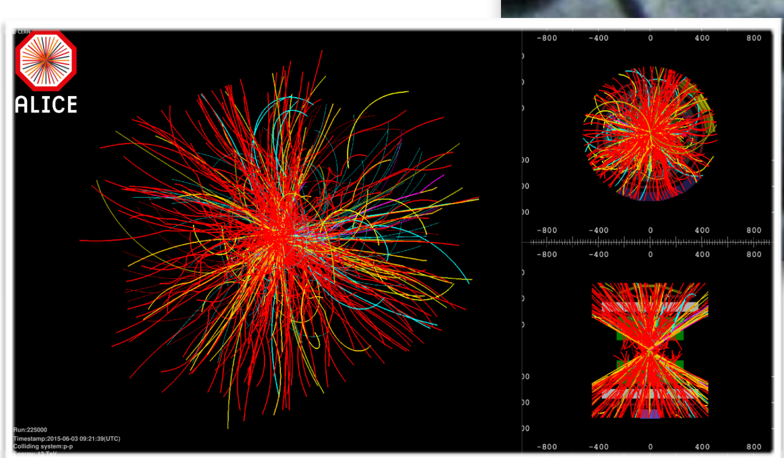
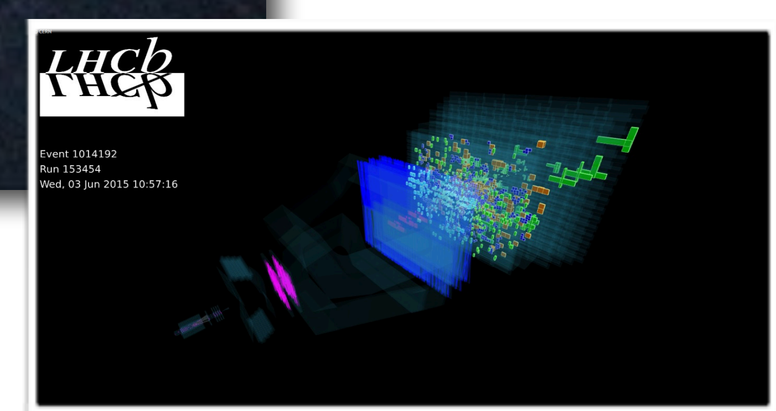
Summary











Doing something ordinary is a waste of time.

Madonna

Where to look....

ETH Institute for Particle Physics

- Recent (big) conferences:
  - Rencontres de Moriond in 2015: http://moriond.in2p3.fr
  - EPS-HEP2015 : http://eps-hep2015.eu
  - Lepton-Photon 2015 : http://indico.cern.ch/event/325831/
  - LHCP 2015 : http://lhcp2015.com
  - Physics at the LHC and beyond, Vietnam, 2014: http://events.lal.in2p3.fr/Physics-LHC-2014/

- Of course, the experiment's websites:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - http://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results.html
  - https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults

- Review articles, such as
  - Dissertori, *LHC detectors and early physics*, http://inspirehep.net/record/848687?ln=en
  - Butterworth, Dissertori, Salam, Hard Processes in pp collisions at the LHC, http://inspirehep.net/record/1087377?ln=en
  - J. Ellis, *Theory Summary and prospects*, http://inspirehep.net/record/1312173?ln=en
  - D. Froidevaux, P. Sphicas, Ann. Rev. Nucl. Part. Sci. 56 (2006) 375
  - T. Carli, K. Rabbertz, S. Schumann, *Studies of QCD at the LHC*, arXiv:1506.03239
  - P. Bechtle, T. Plehn, C. Sander, The Status of Supersymmetry after the LHC Run 1, arXiv:1506.03091
  - of course, there are many more on the market....