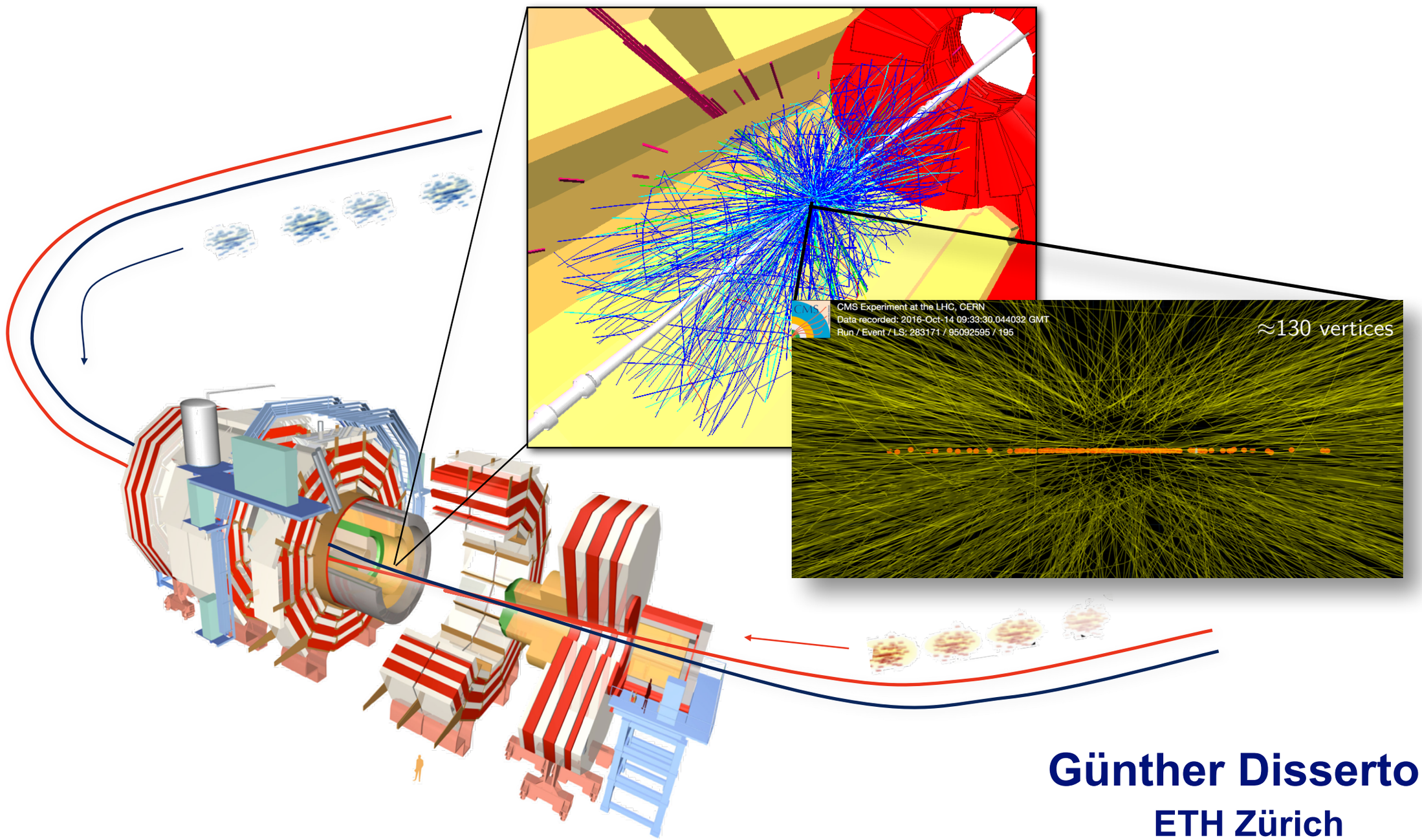
The LHC endeavour

ETH zürich

achievements and future plans



Günther Dissertori
ETH Zürich

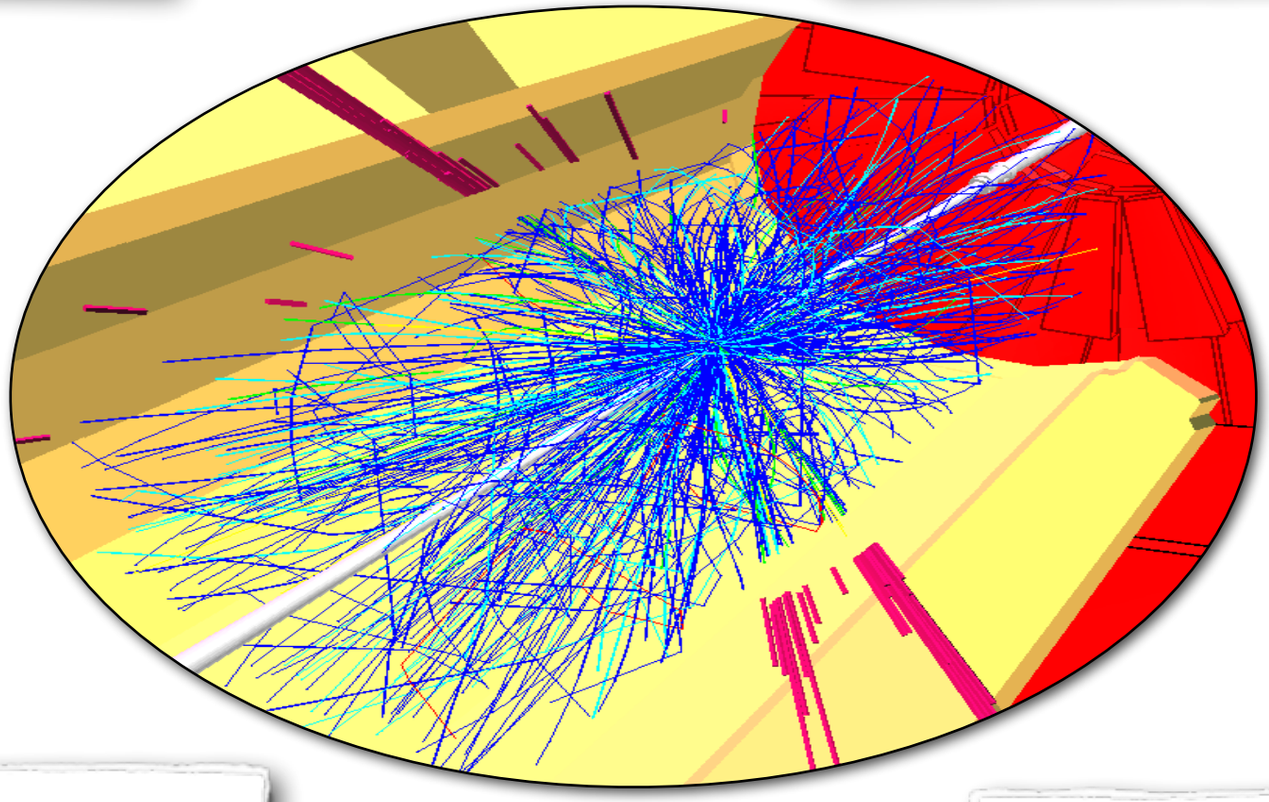
MPI Munich, 25 Sep 2018

Outline:

ETH zürich

General intro

LHC physics and achievements so far

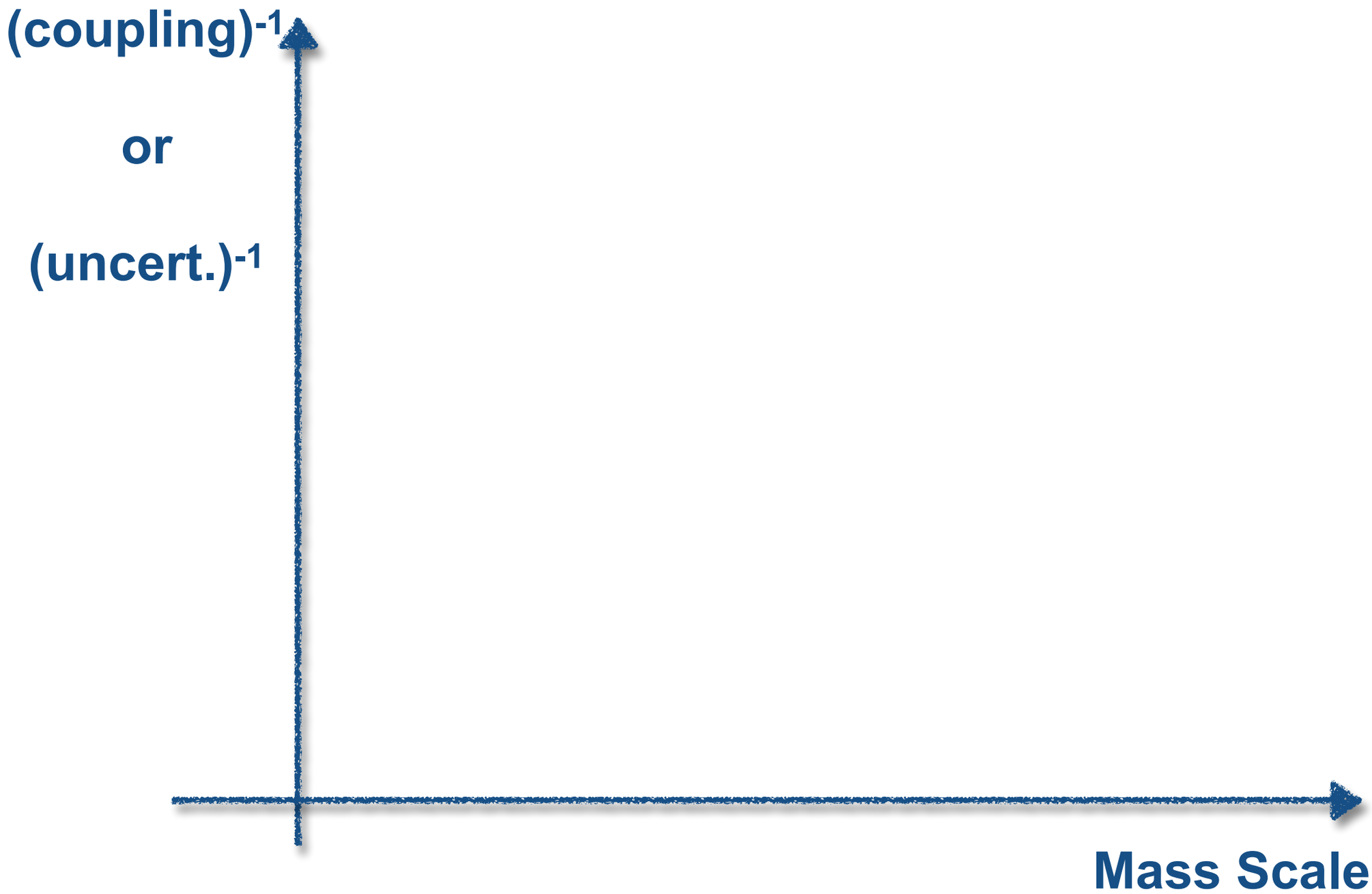


The challenges ahead

How to face these challenges

The (not so small) print:
focus on the CMS experiment, for “practical” reasons….

How to explore the unkown



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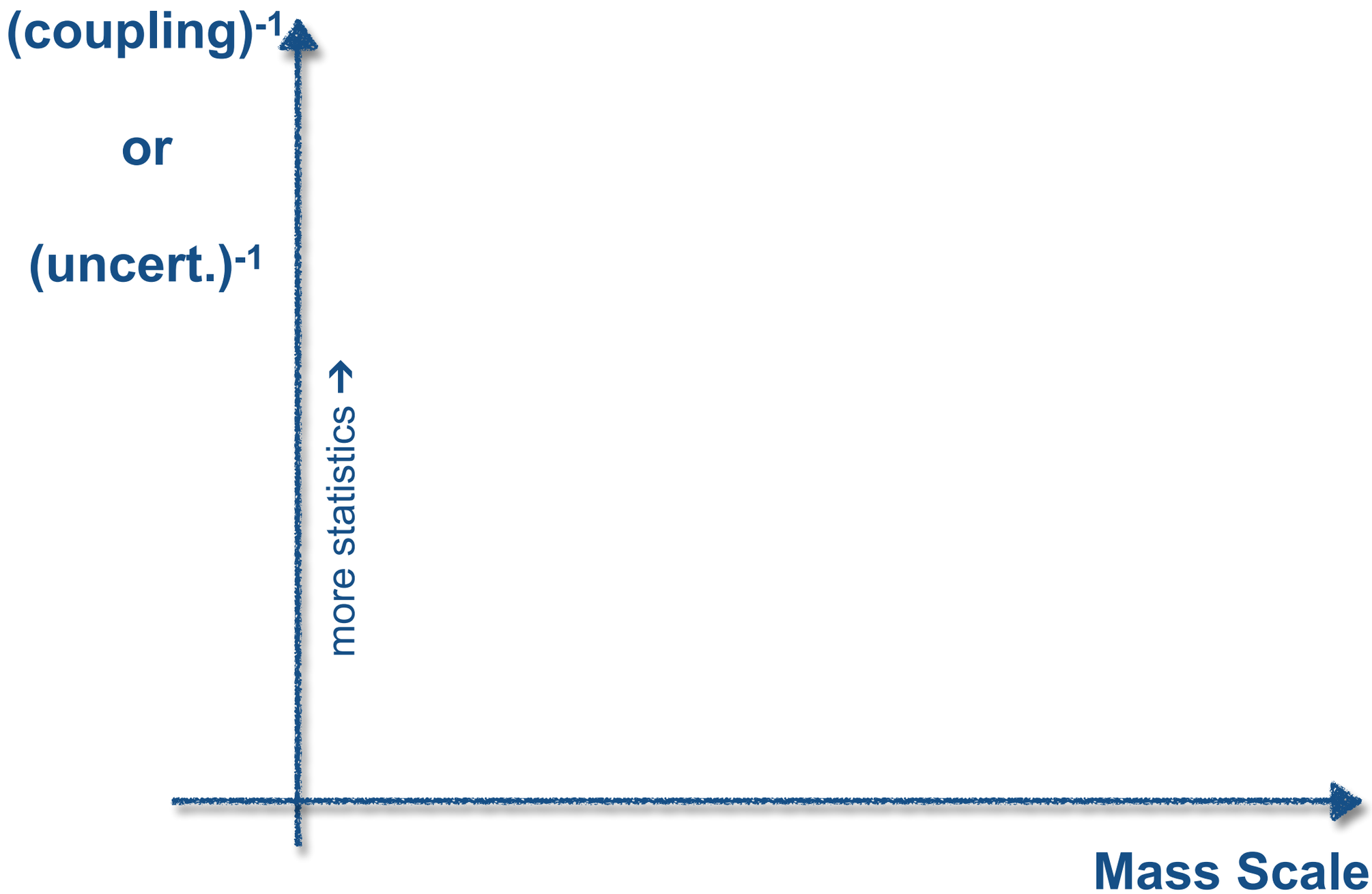

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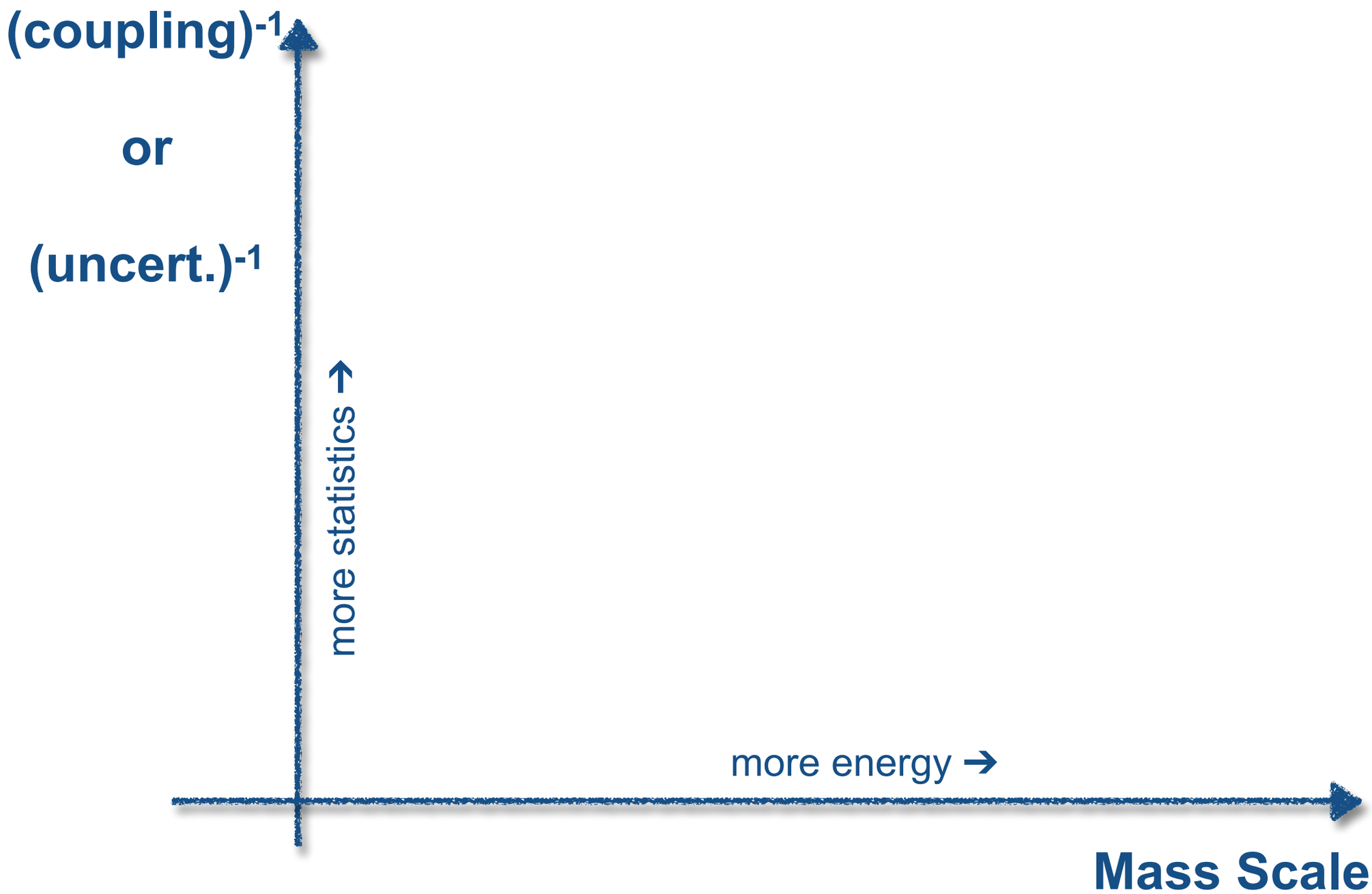

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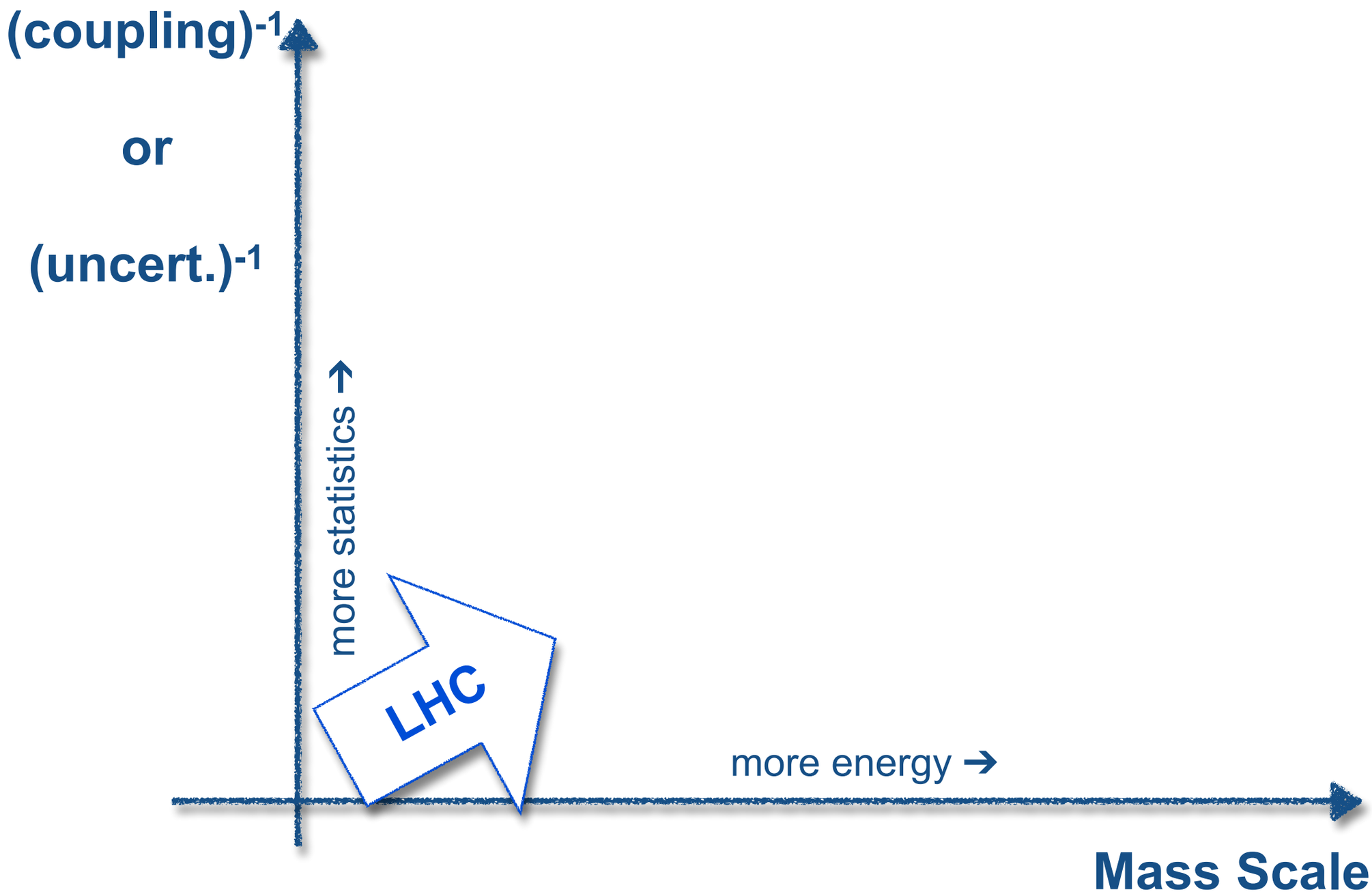

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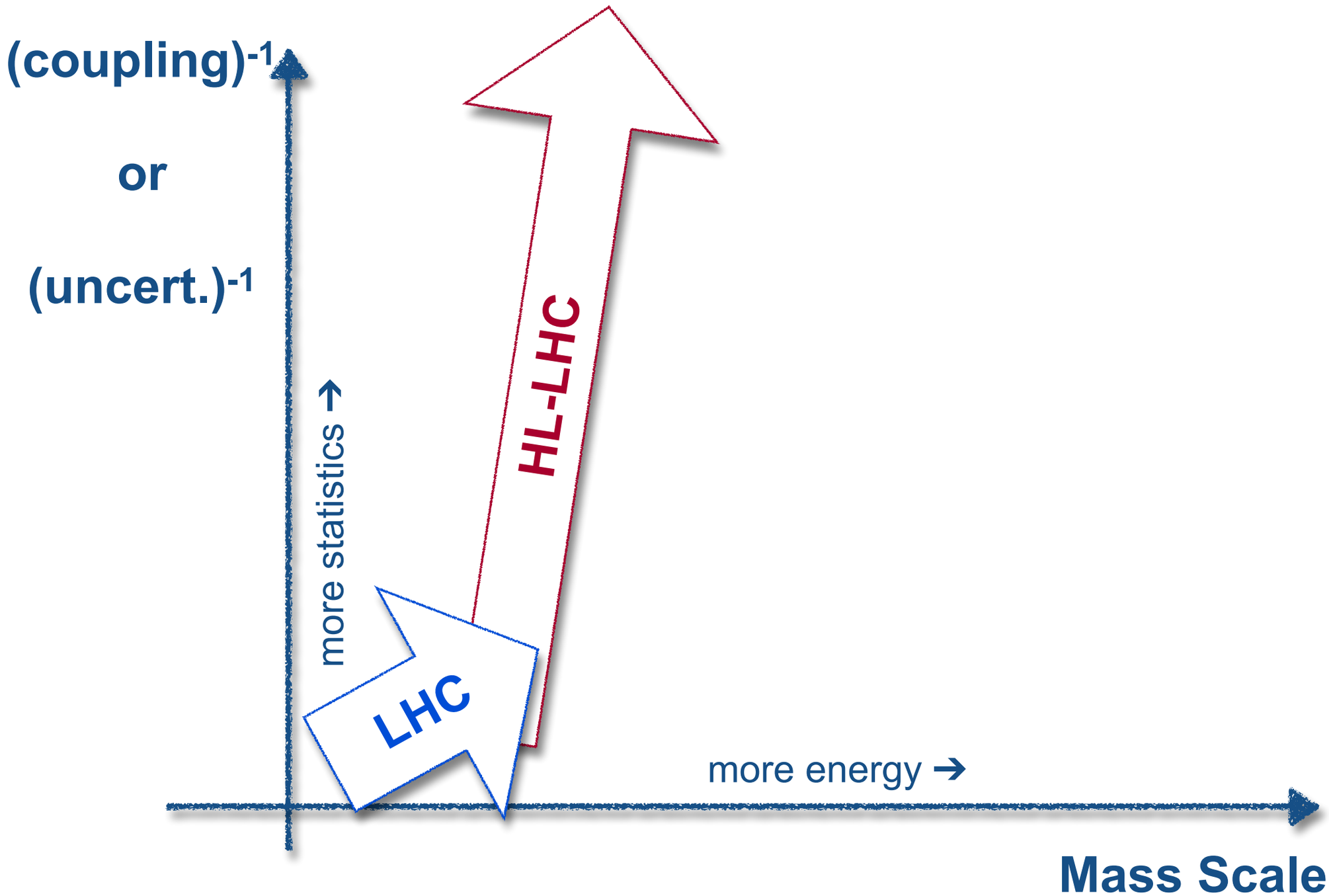

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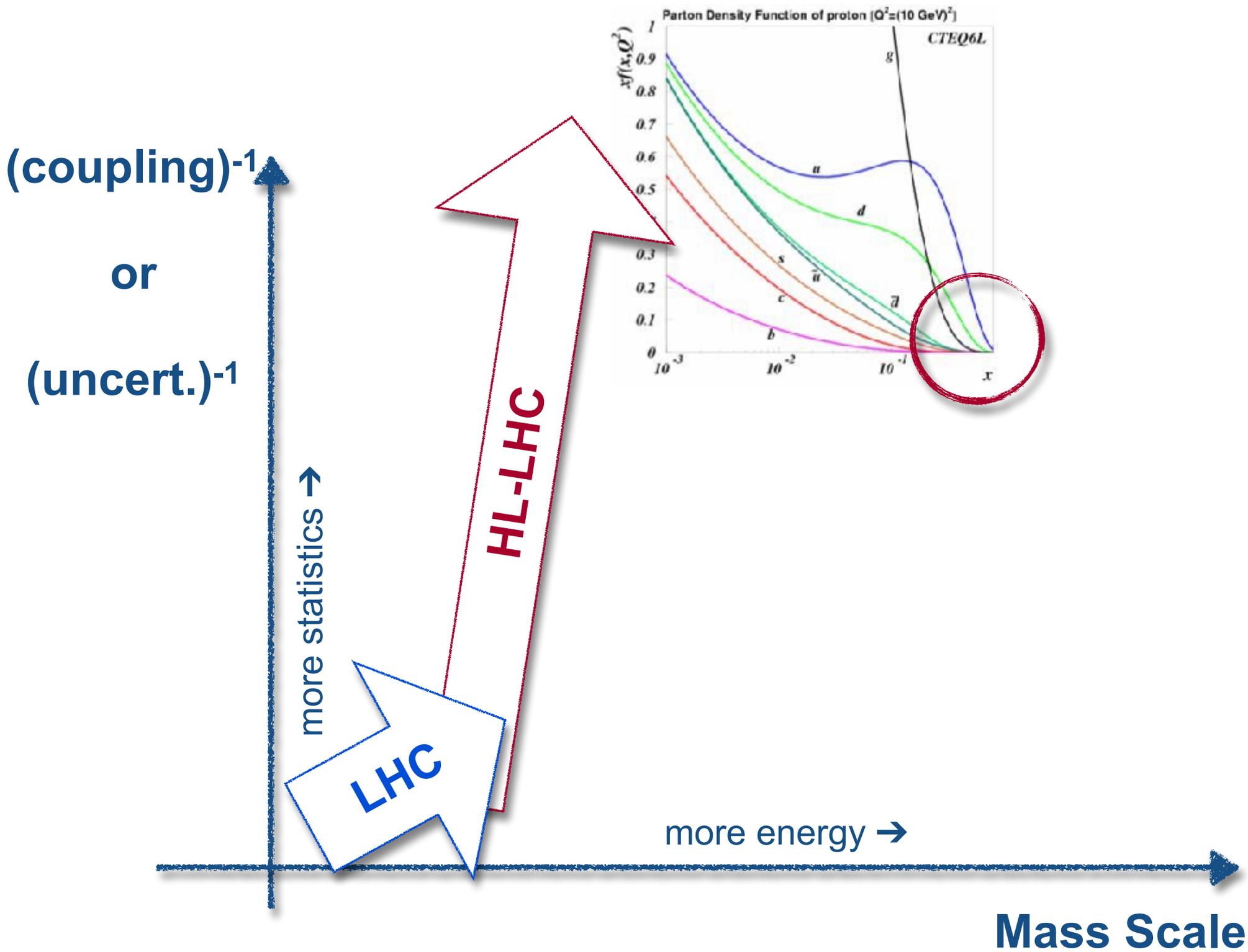

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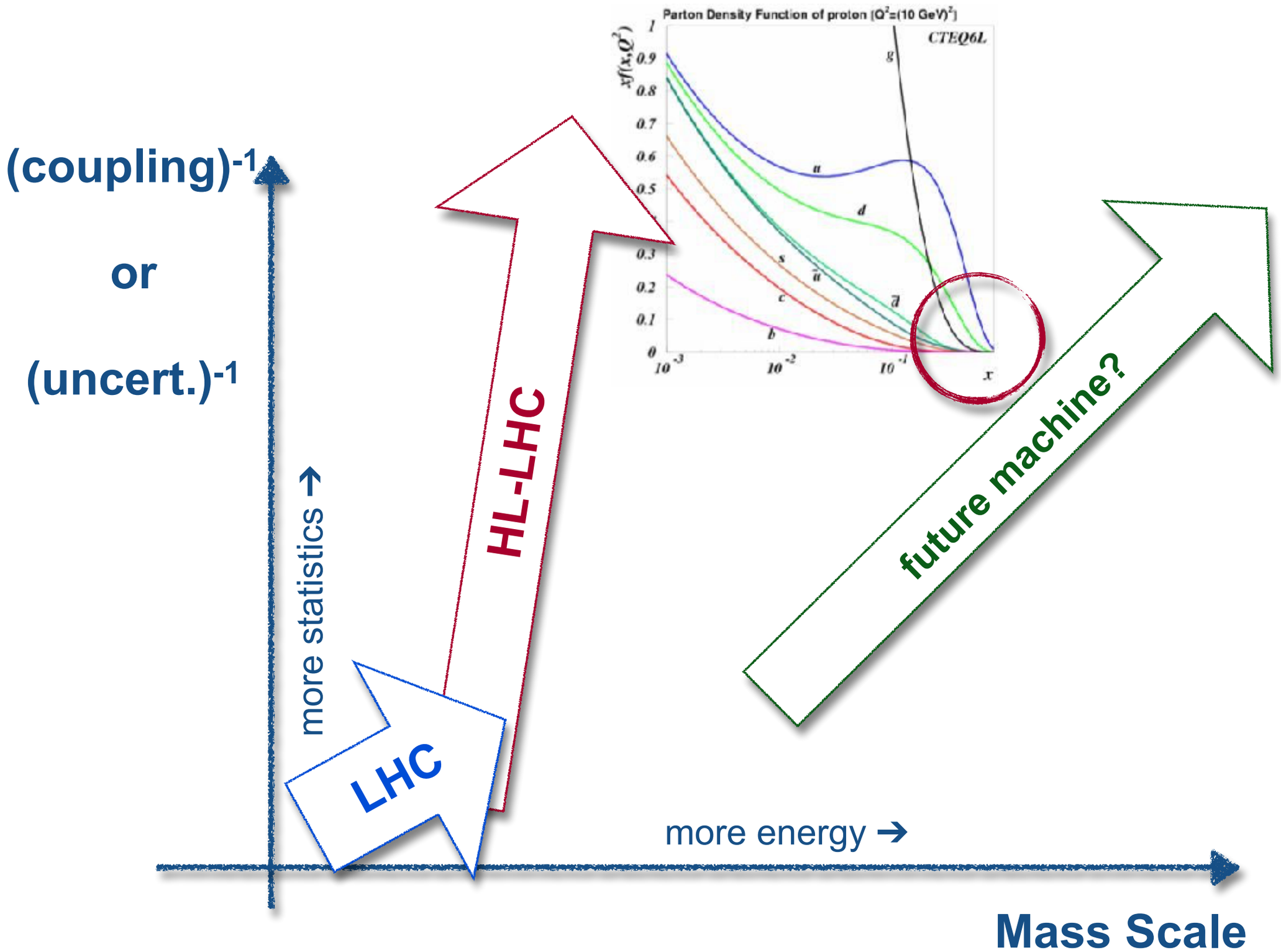
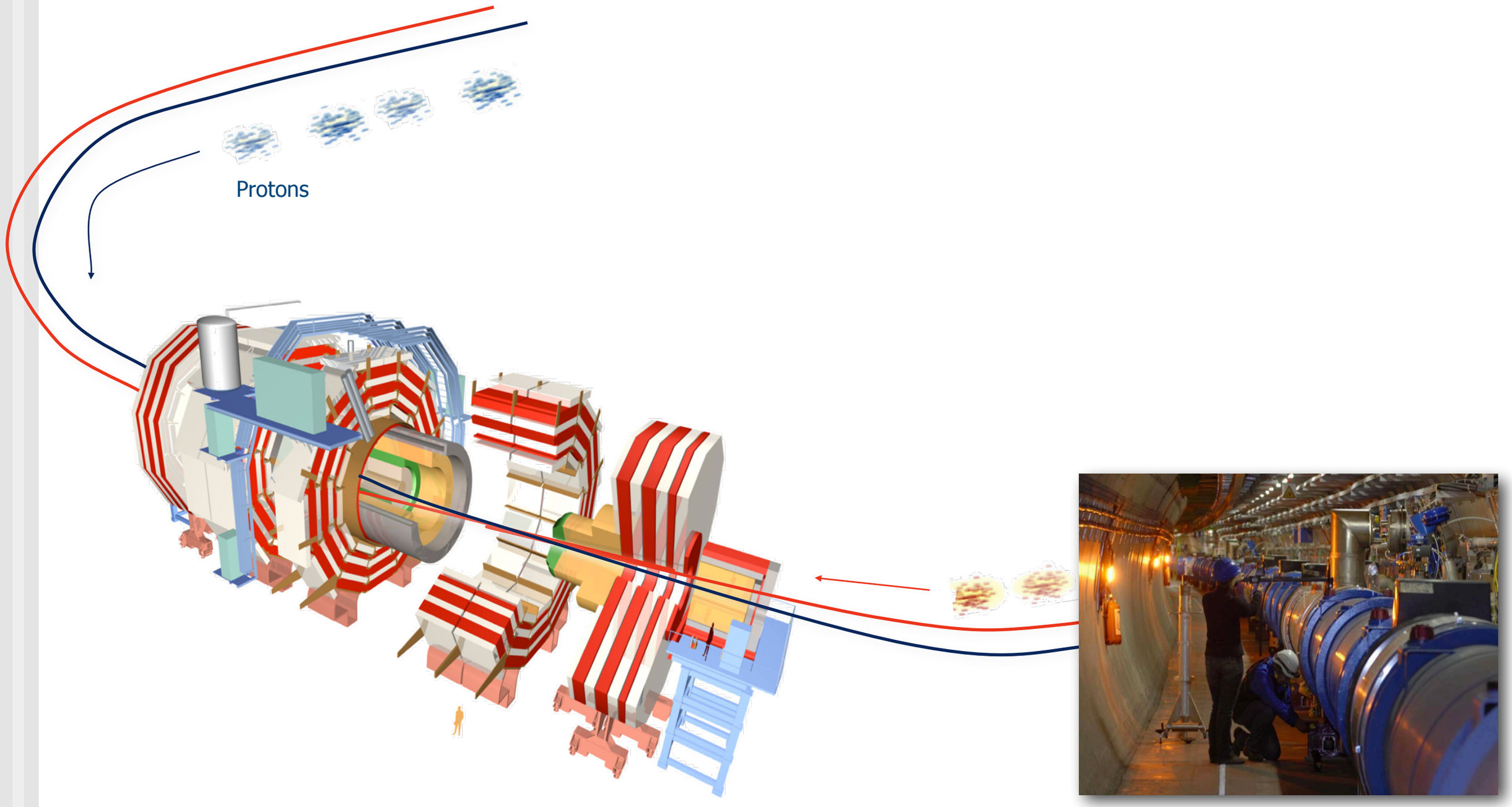


Collisions at the LHC

Centre-of-Mass Energy = 0.9 - 2.36 - 5 - 7 - 8 - 13/14 TeV
Bunch separation : 50 - 25 ns
Beam crossings : 20-40 Million / sec
p p - Collisions : ~1 Billion / sec
Events to tape : ~1000 / sec



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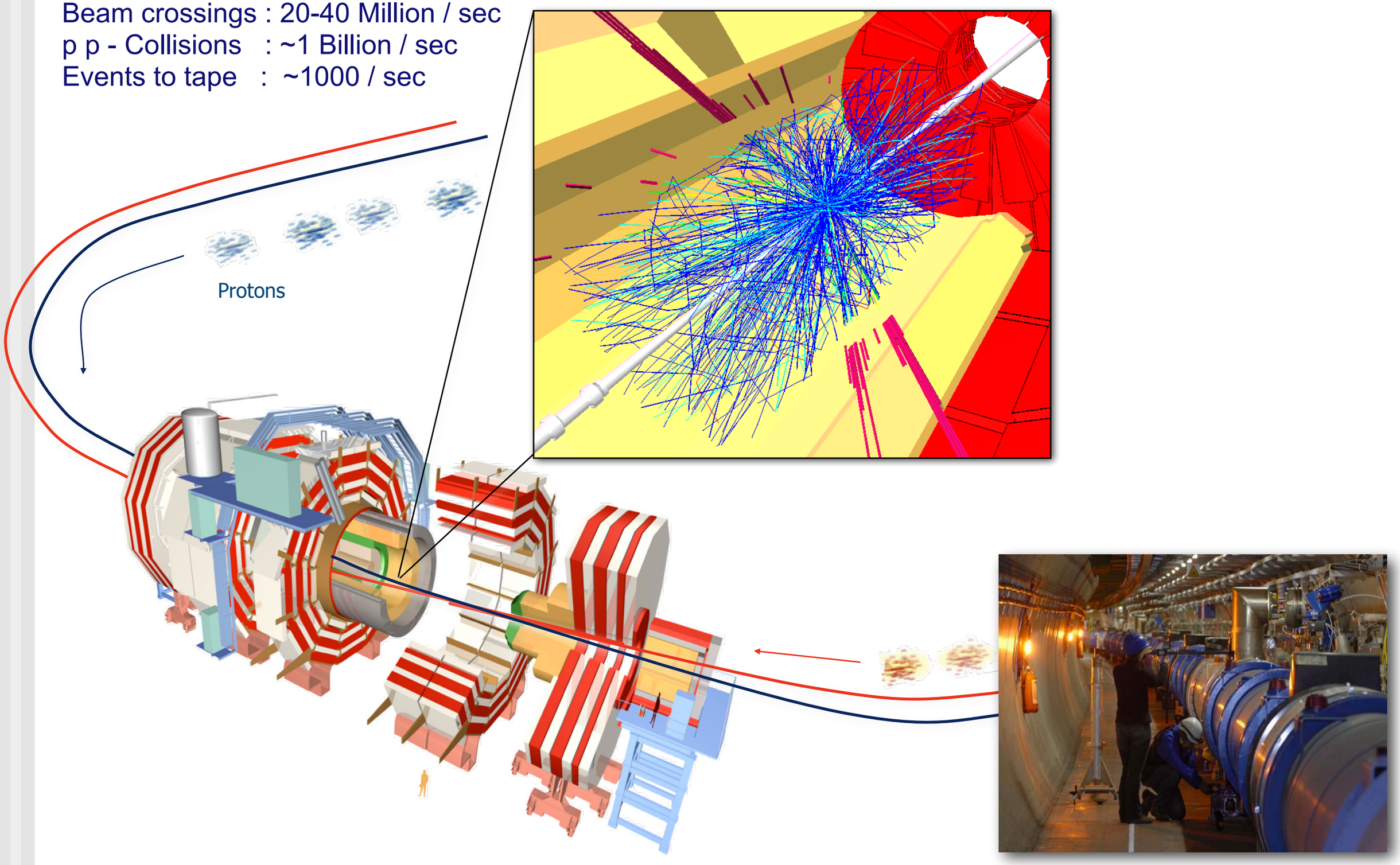

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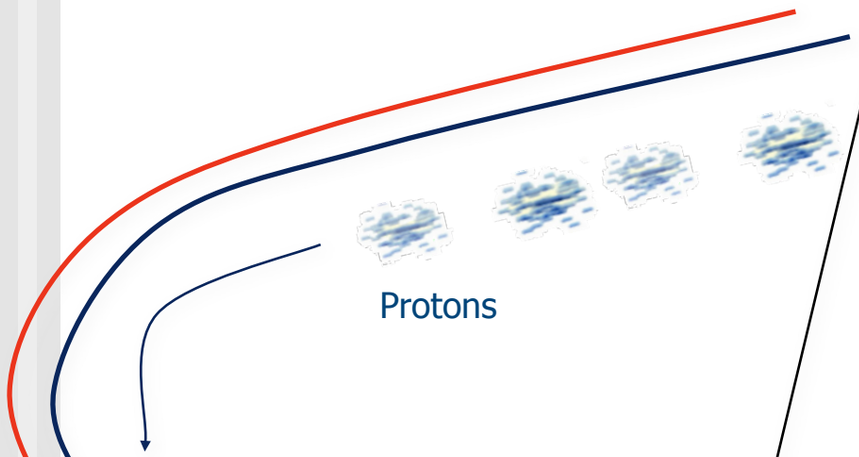
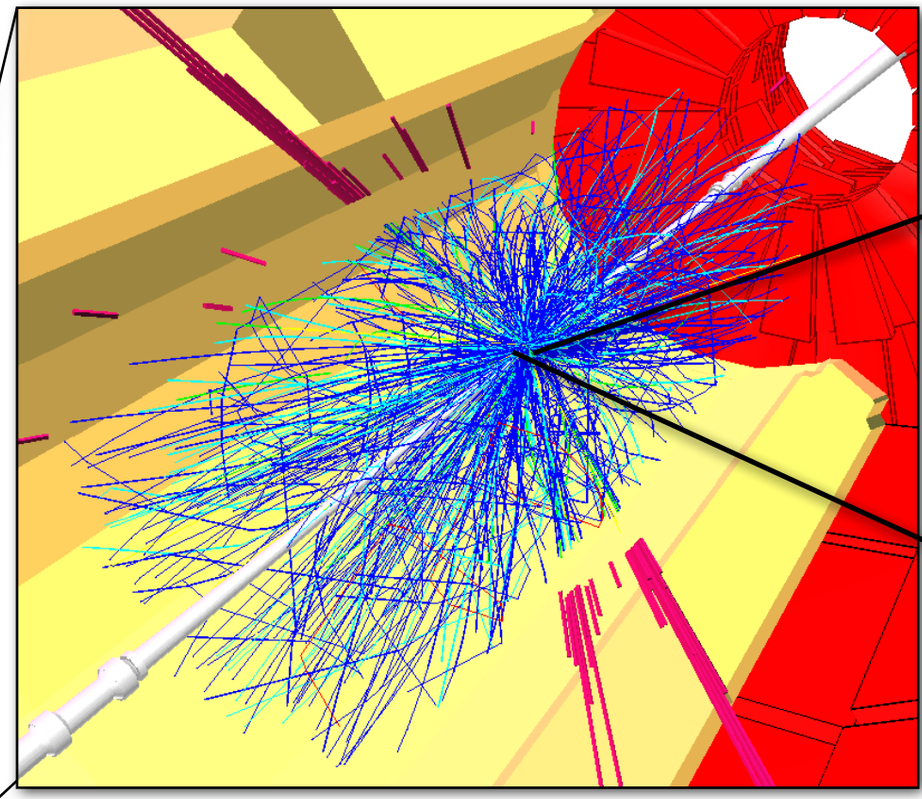
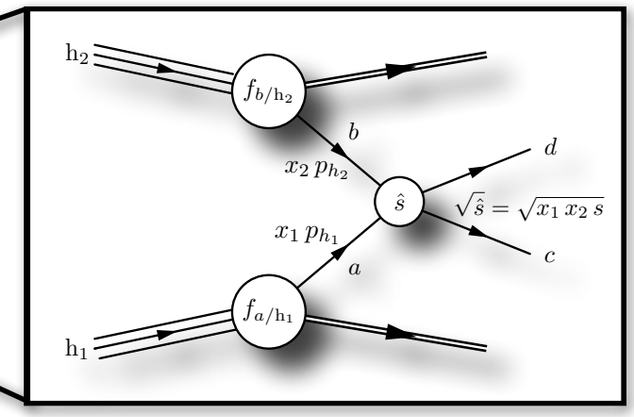
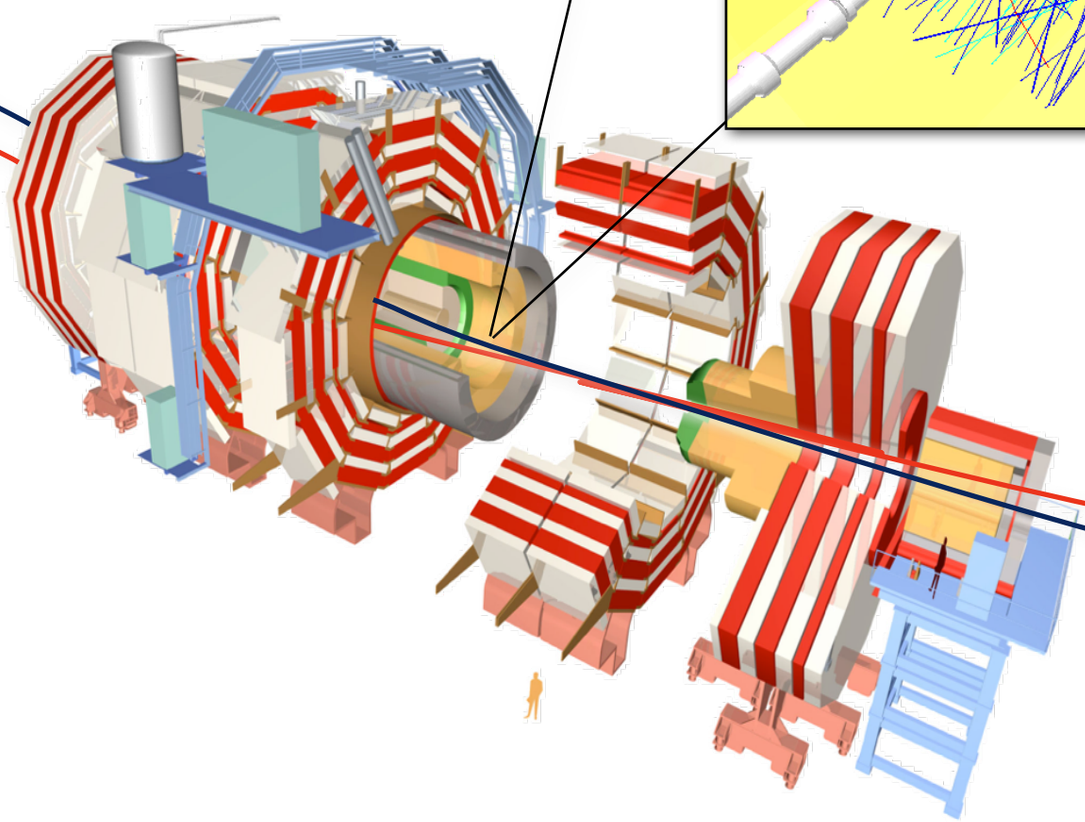
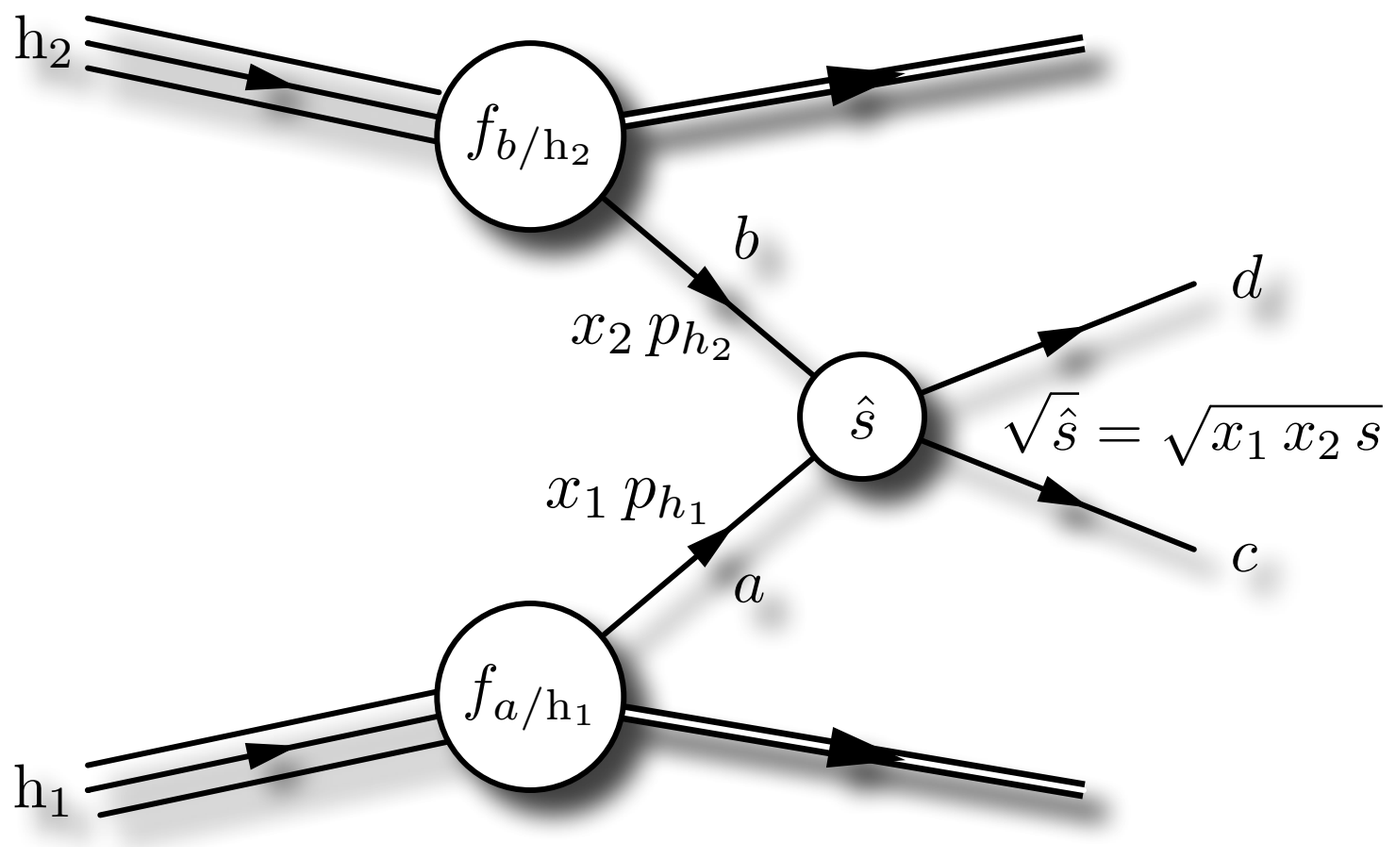








The basics…



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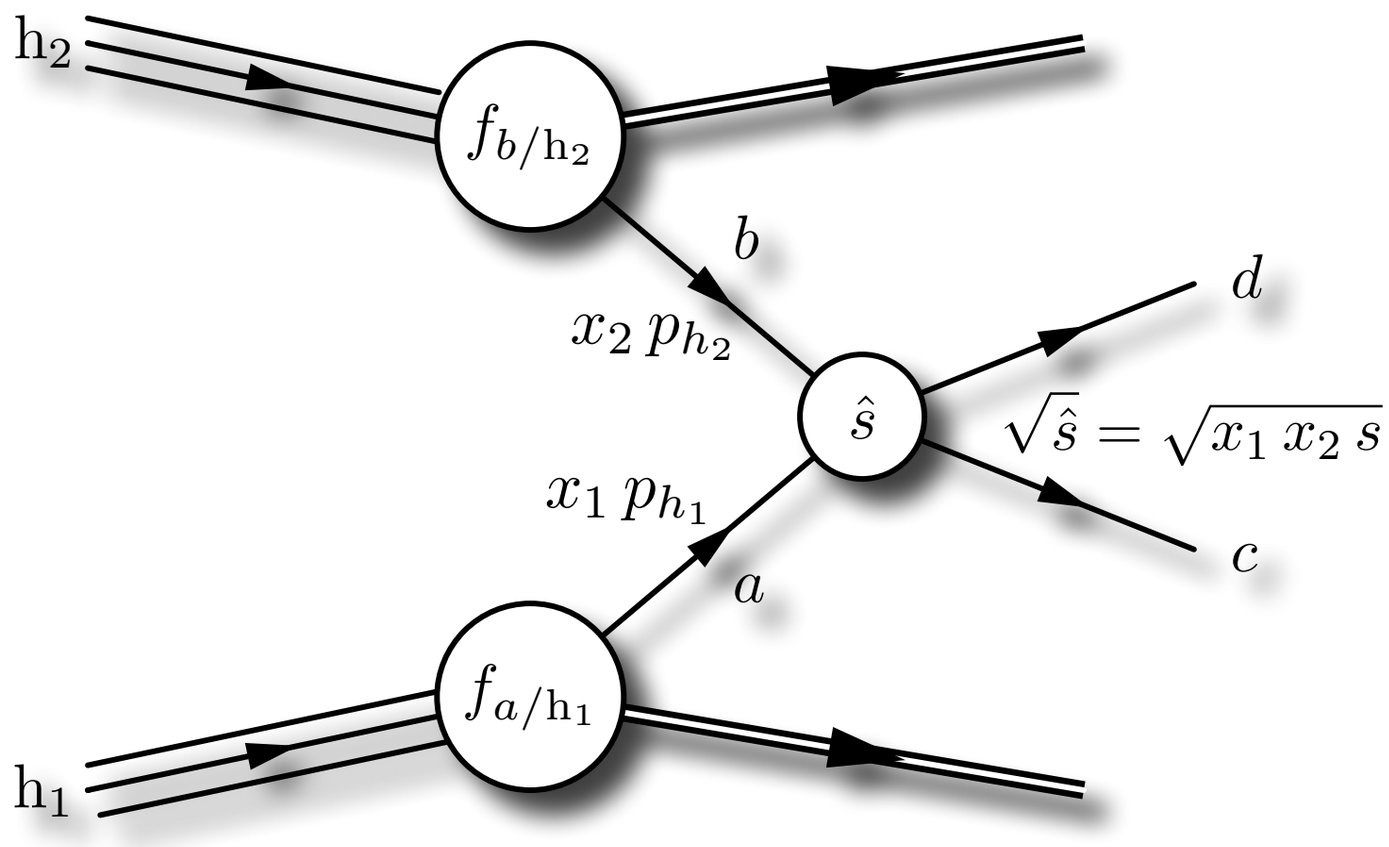

$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

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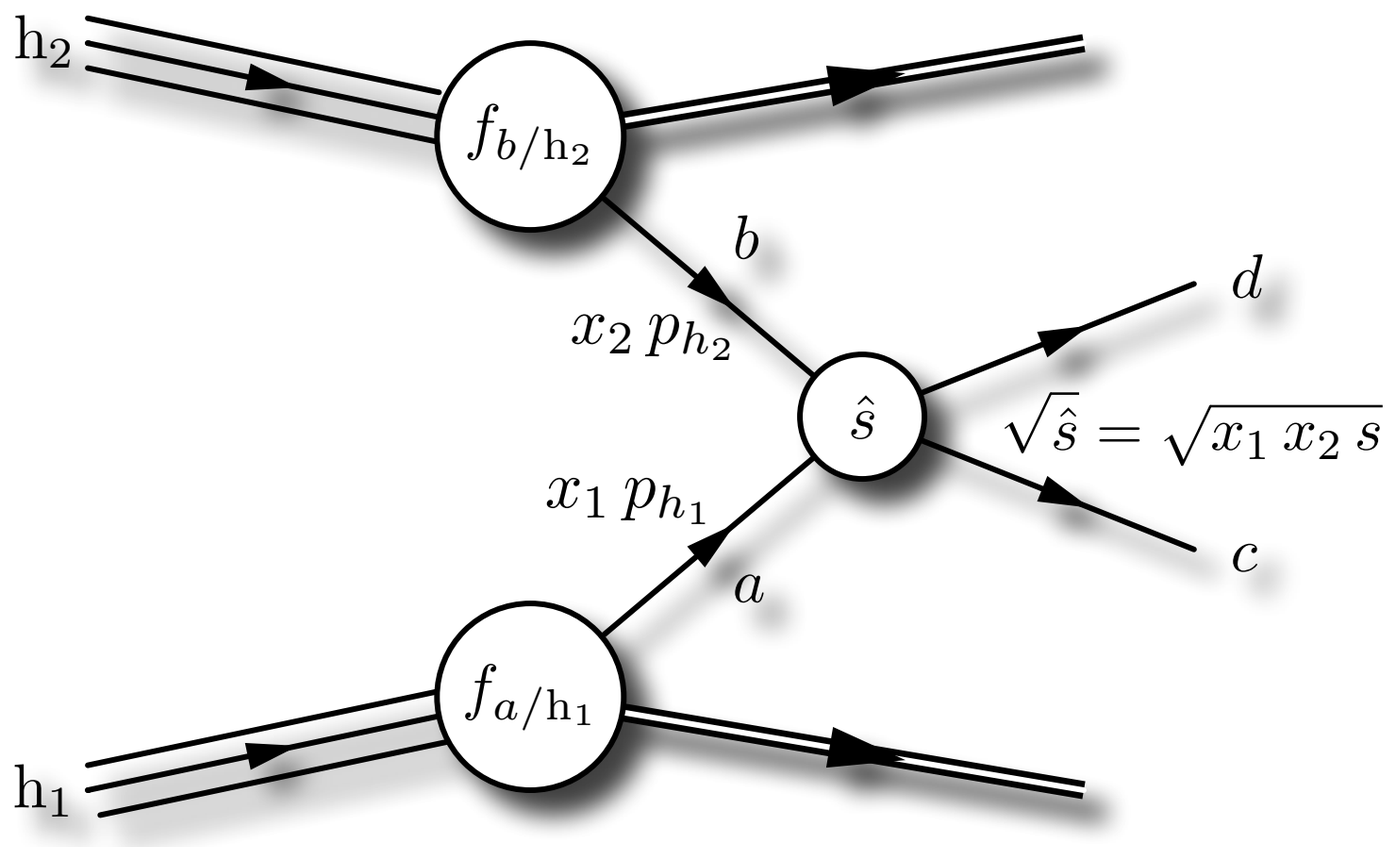

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Hard Scattering = processes with large momentum transfer (Q^2)

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

eg. **σ(pp → W+X)** ~ 150 nb ~ **$2 \cdot 10^{-6}\ \sigma_{tot}$(pp)**

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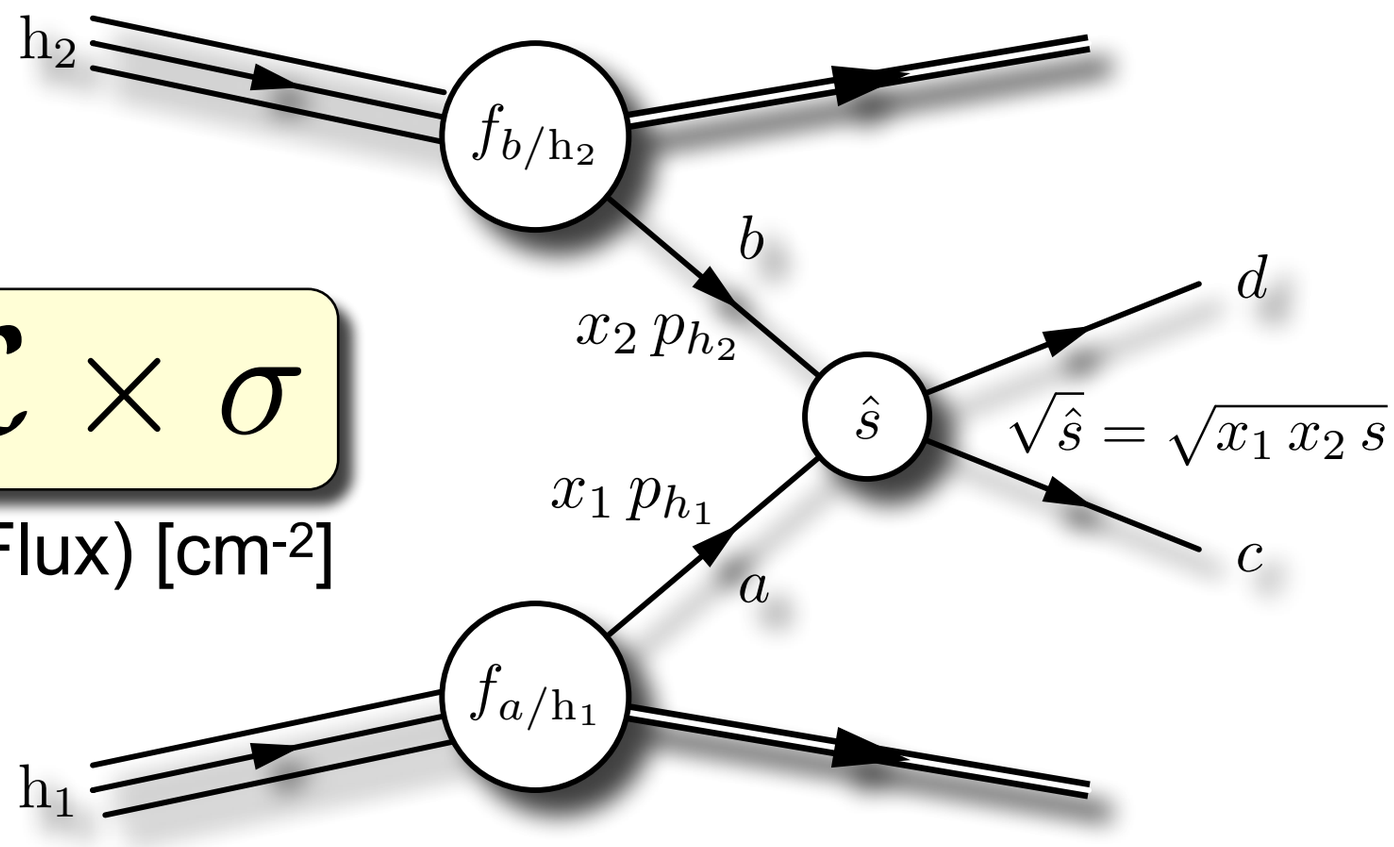

$$N_{\rm ev} = \mathcal{L} \times \sigma$$

Luminosity (Flux) [cm^{-2}]

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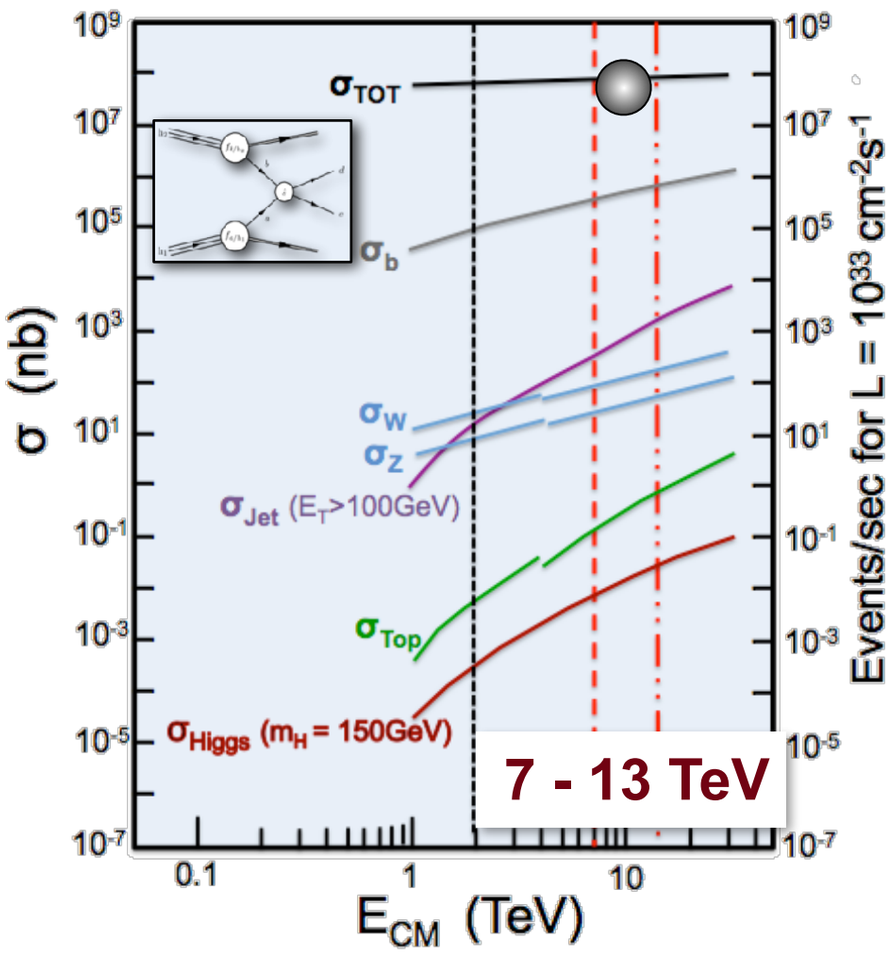

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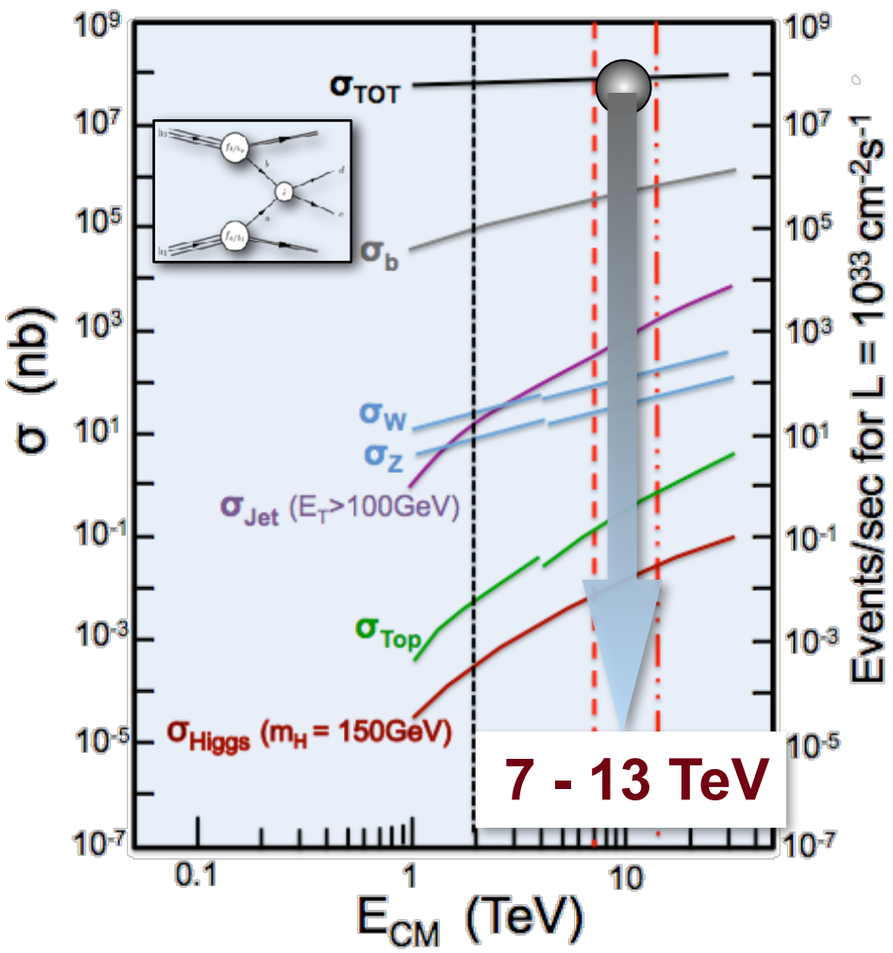

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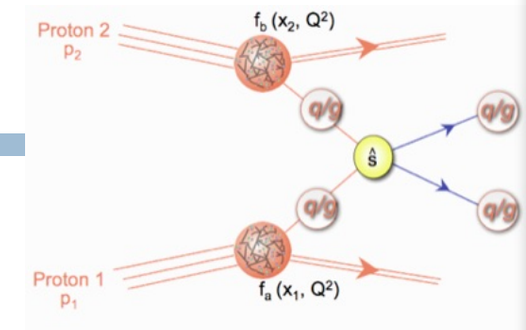

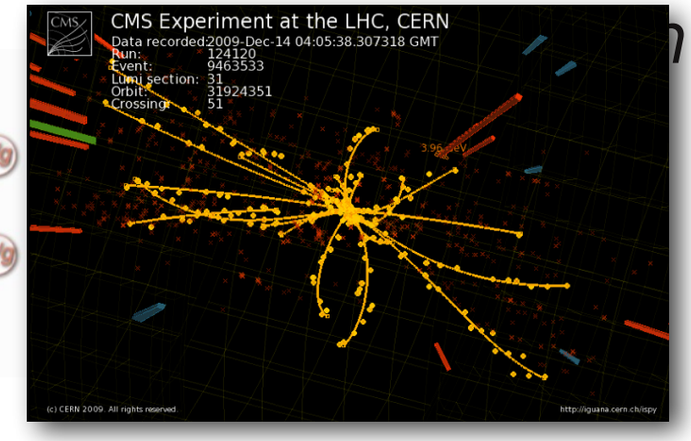

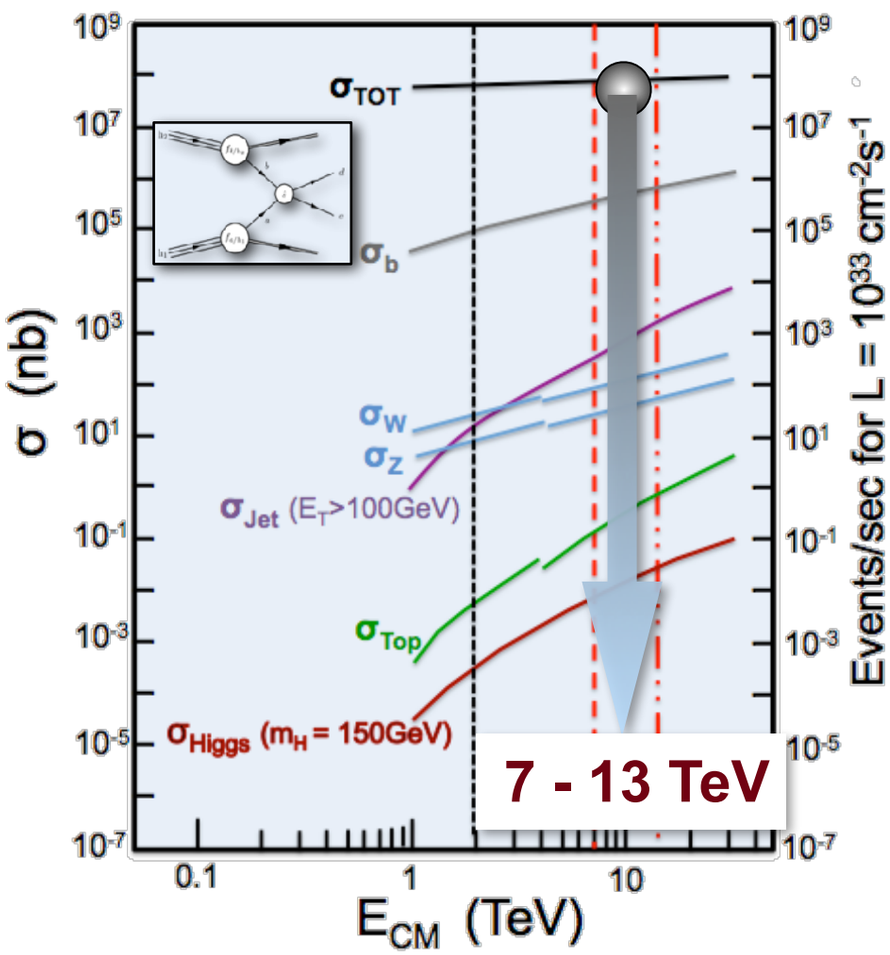

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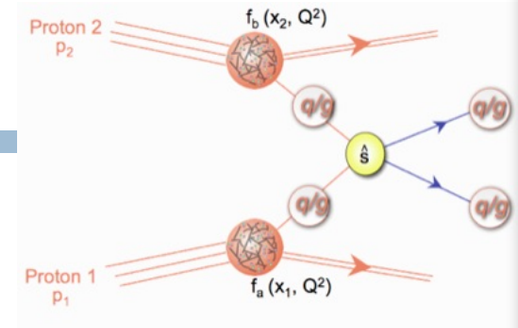

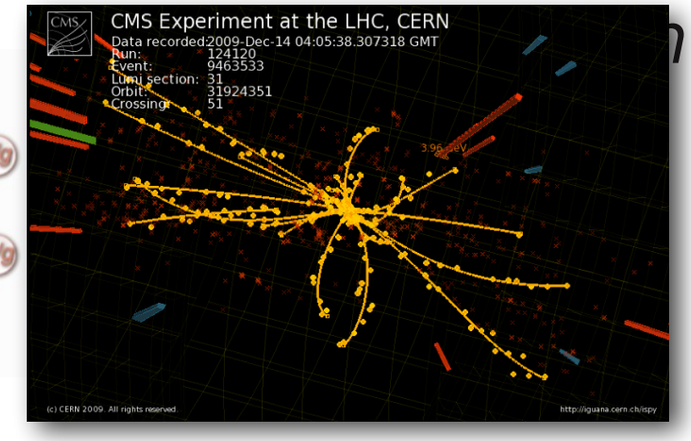

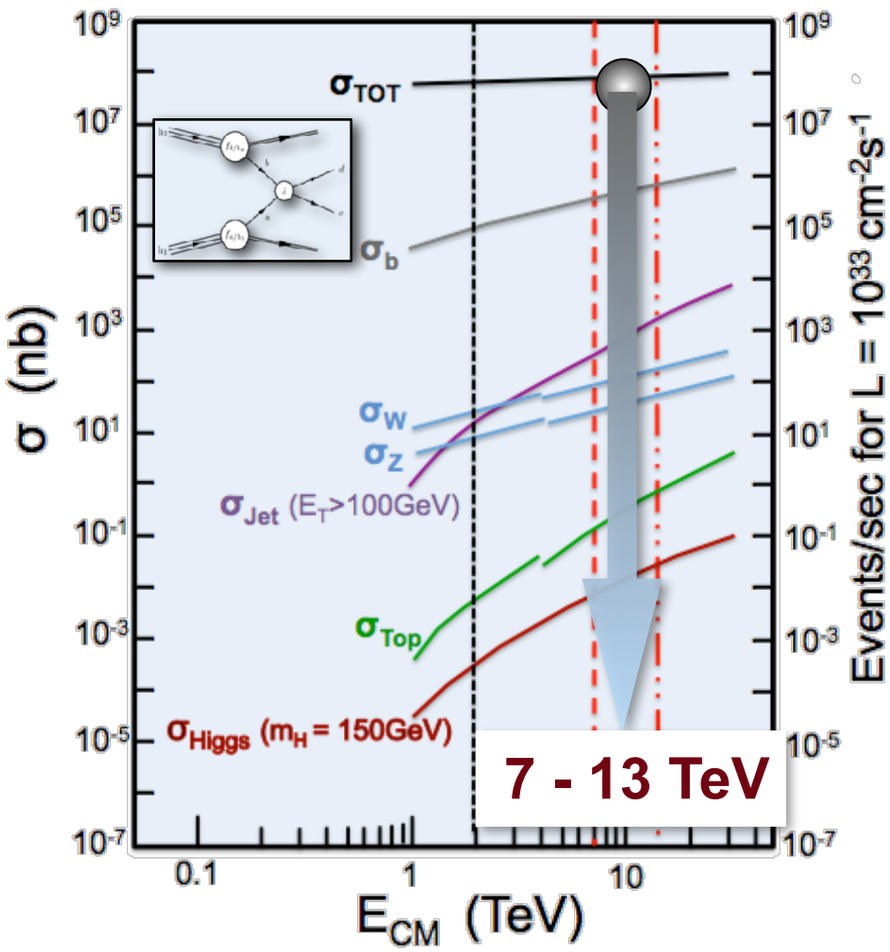

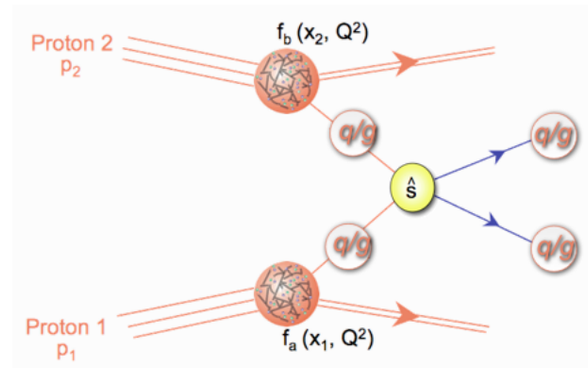

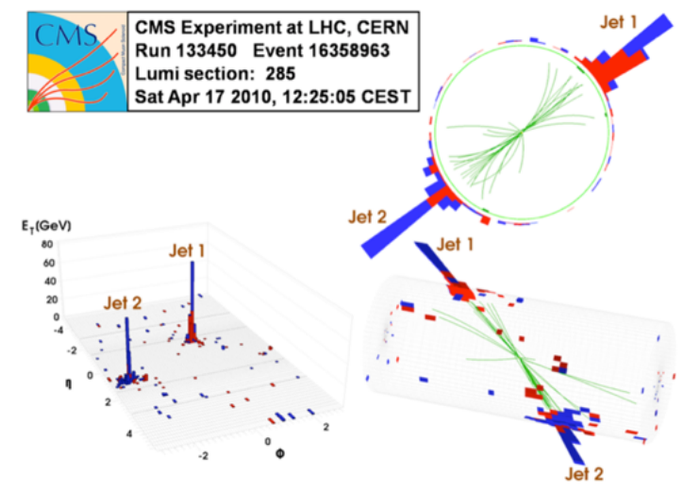

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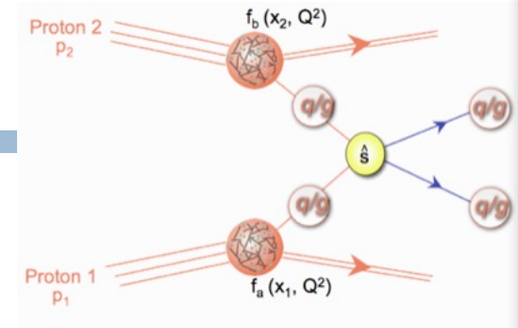

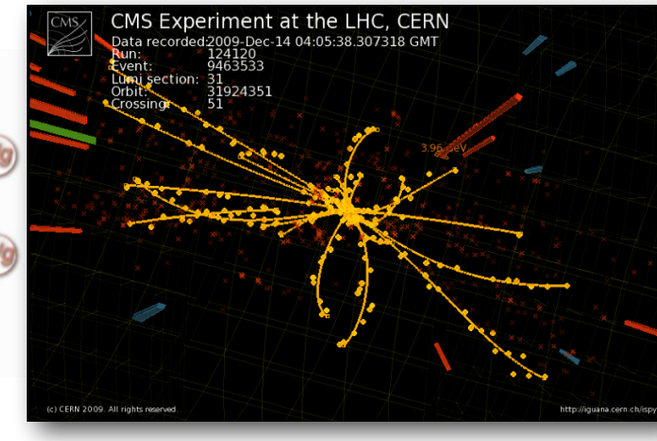

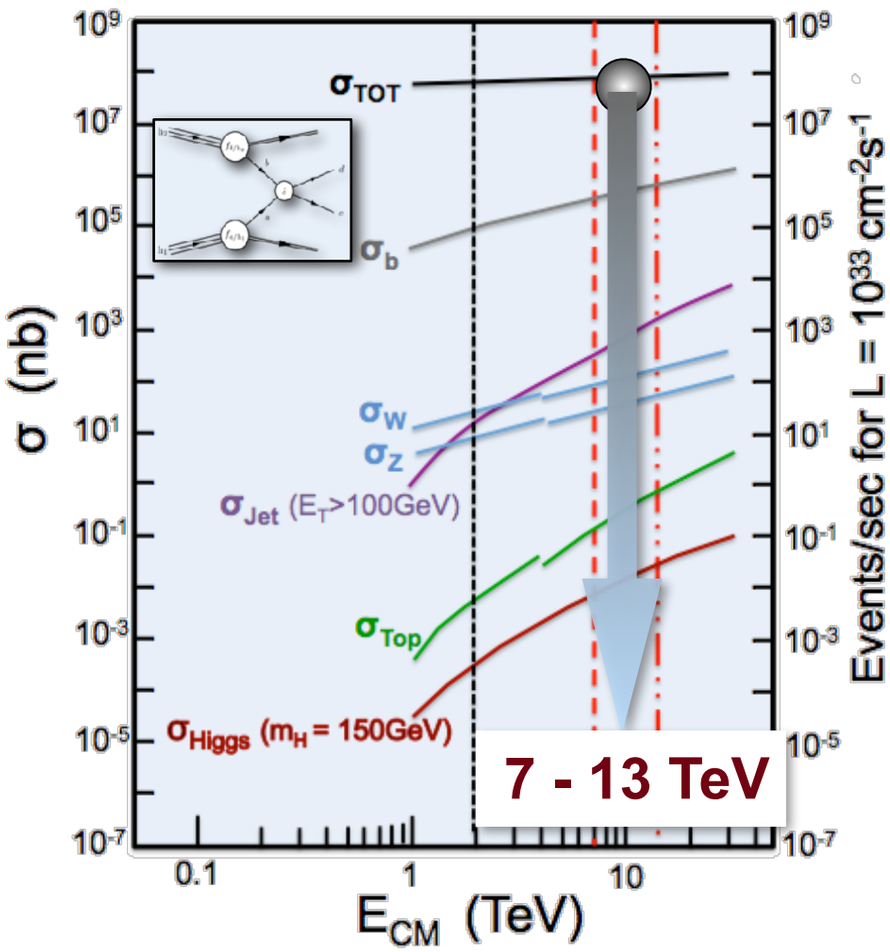

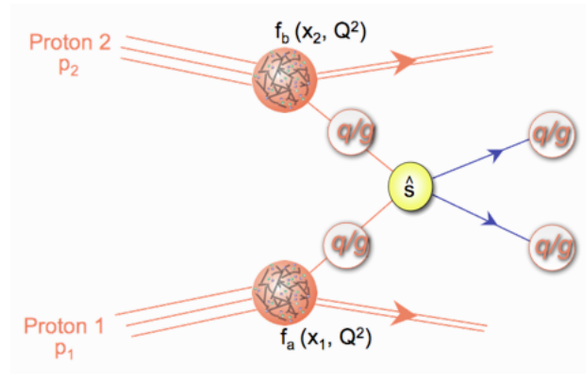

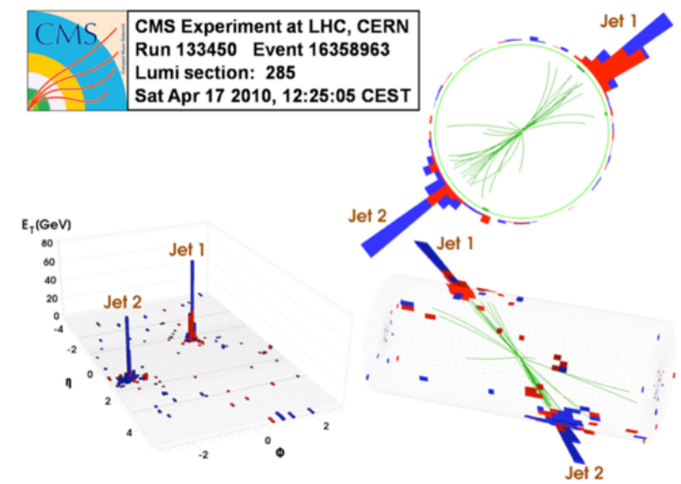

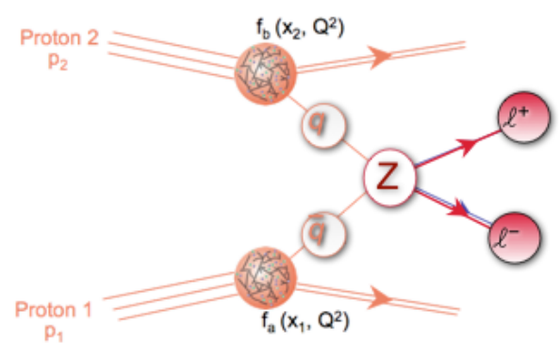

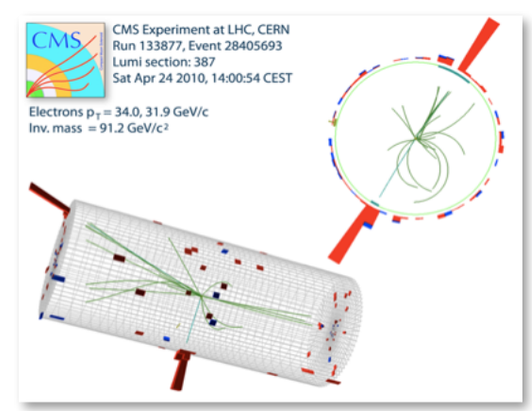

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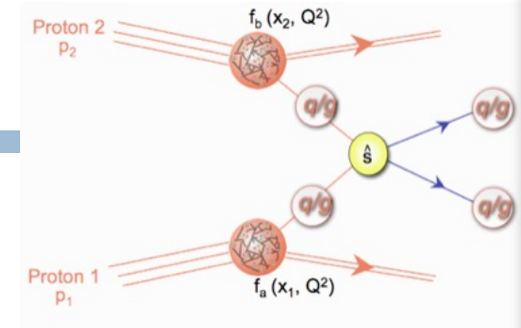

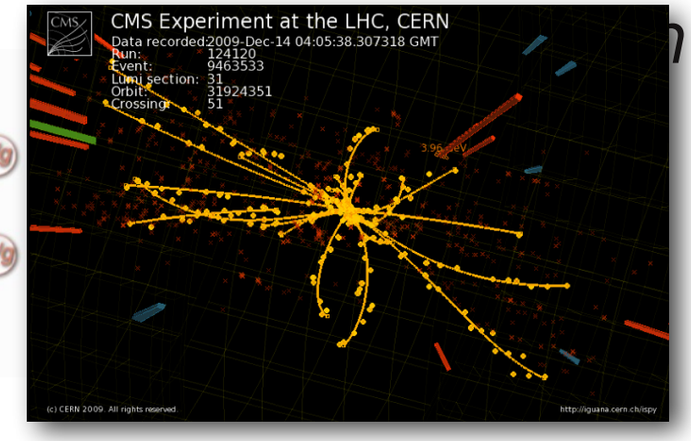

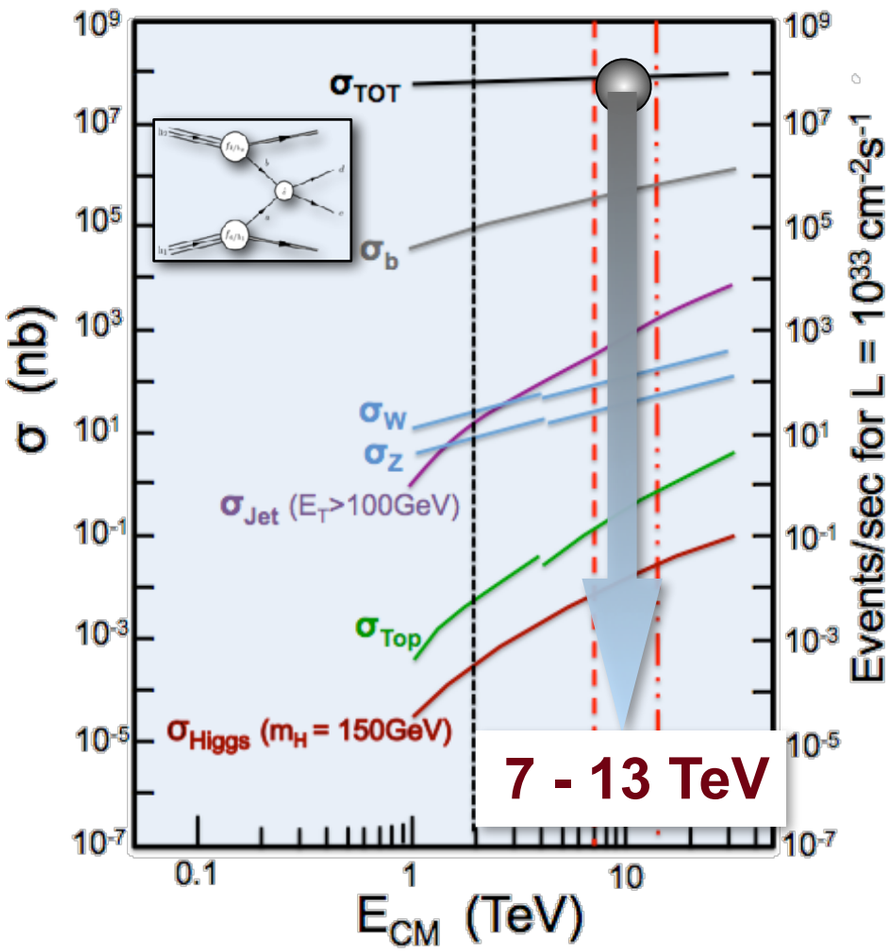

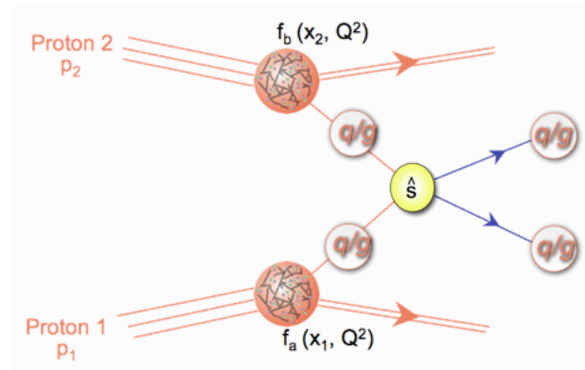

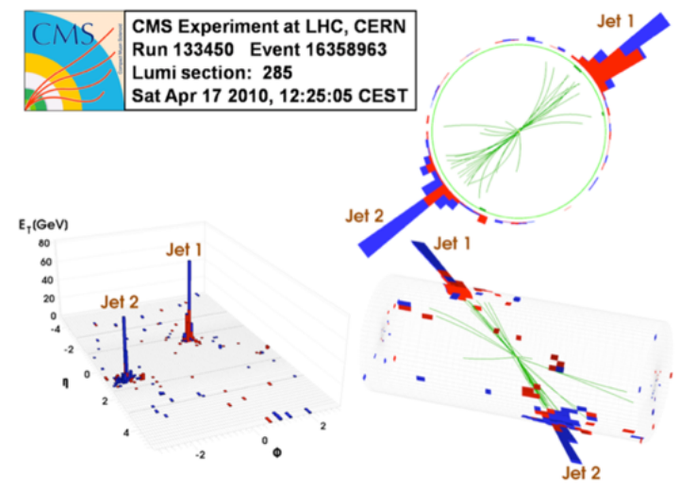

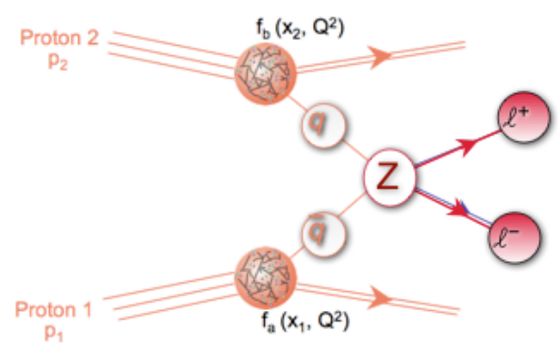

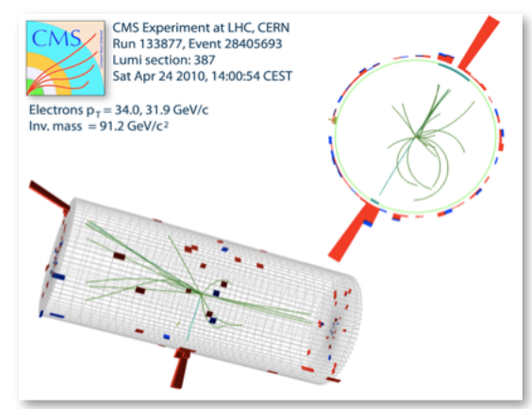

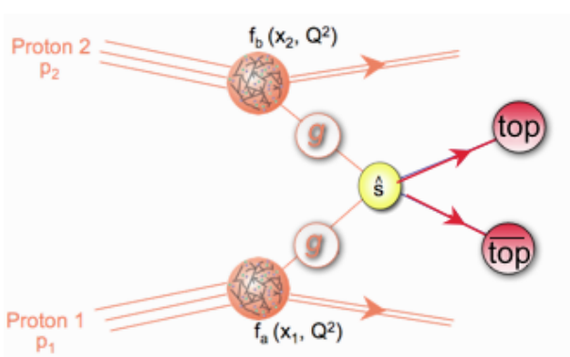

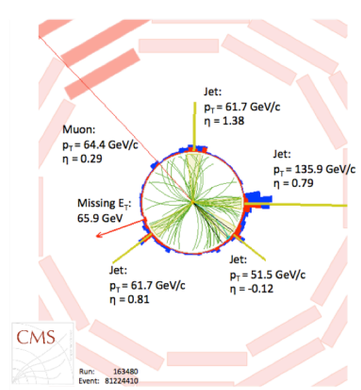

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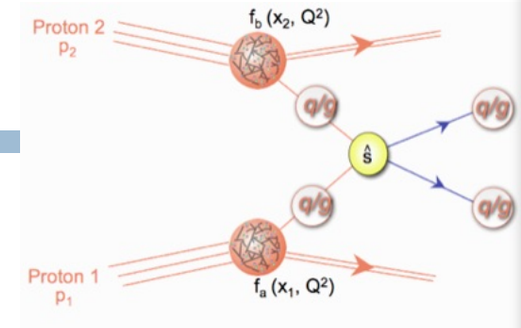
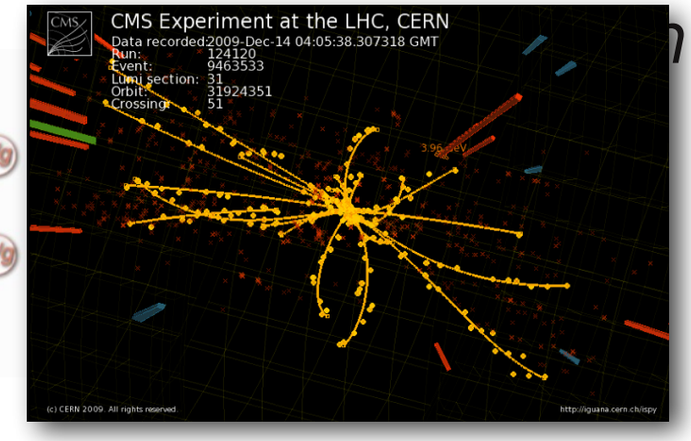
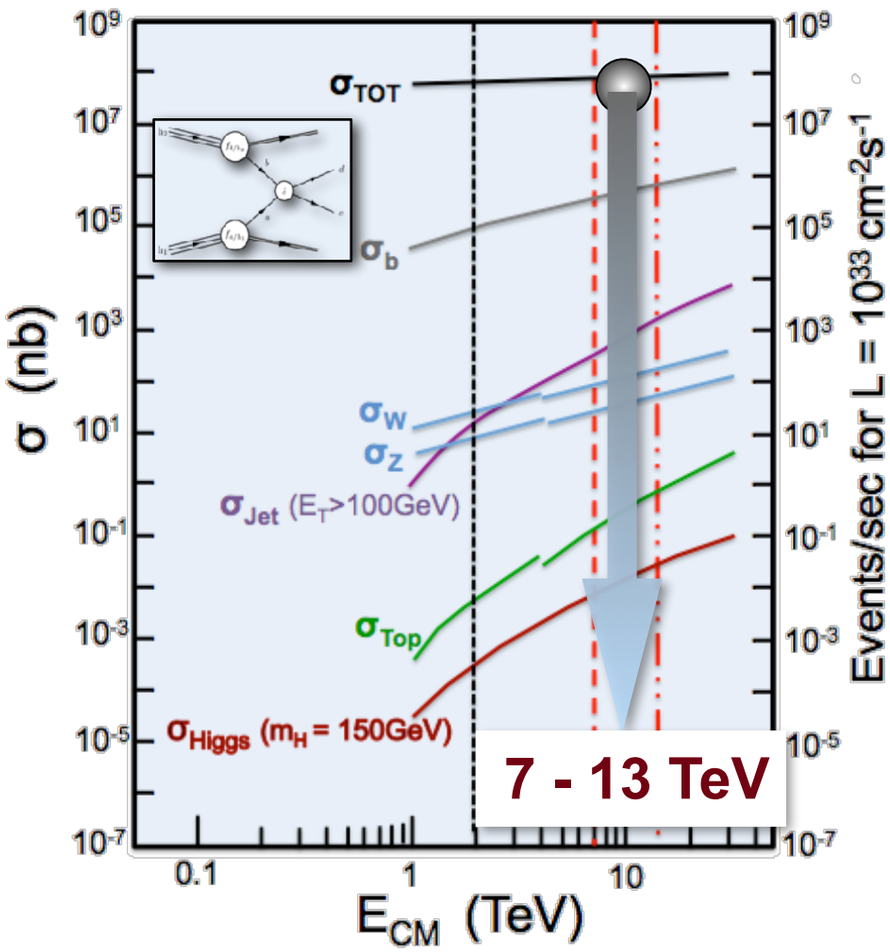
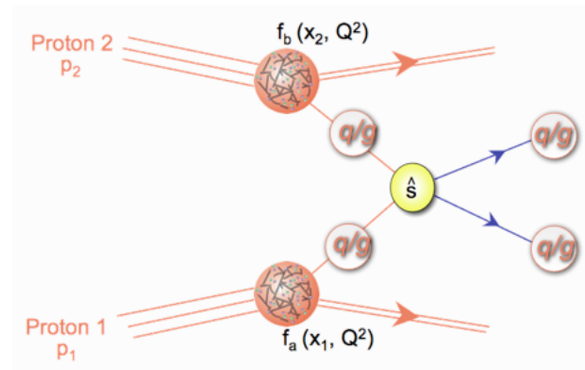
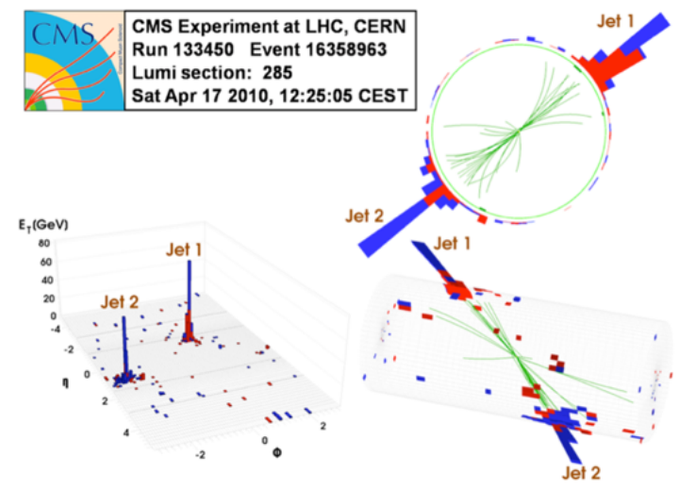
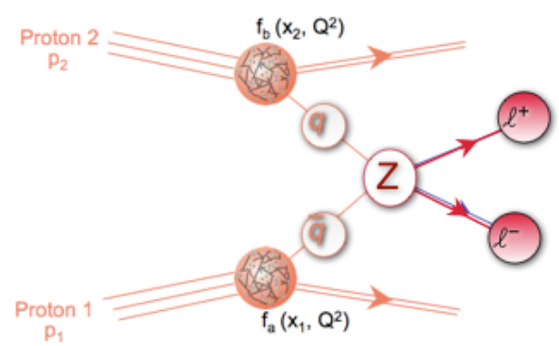


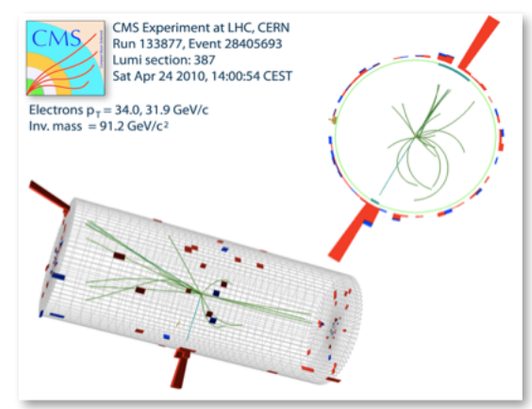


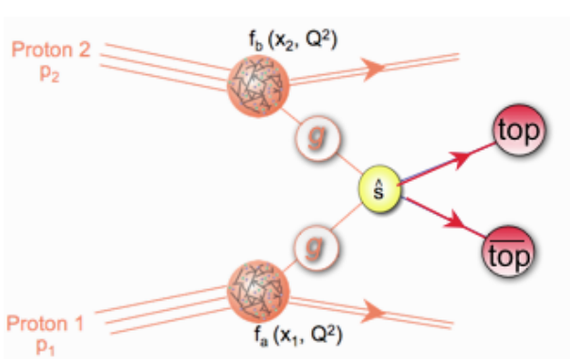


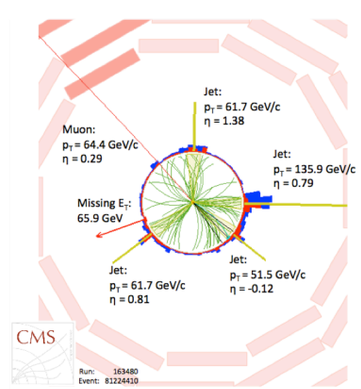


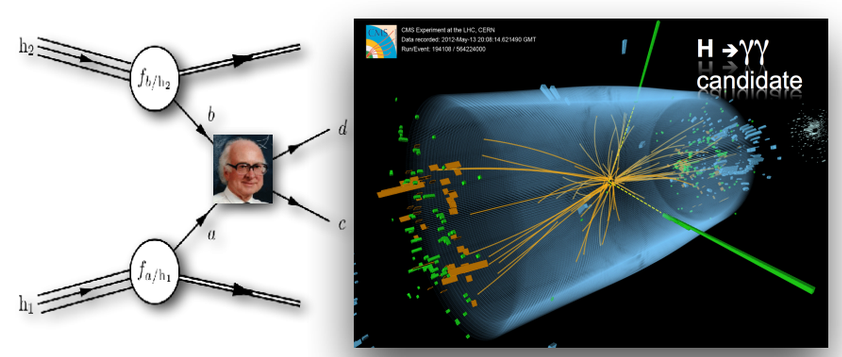




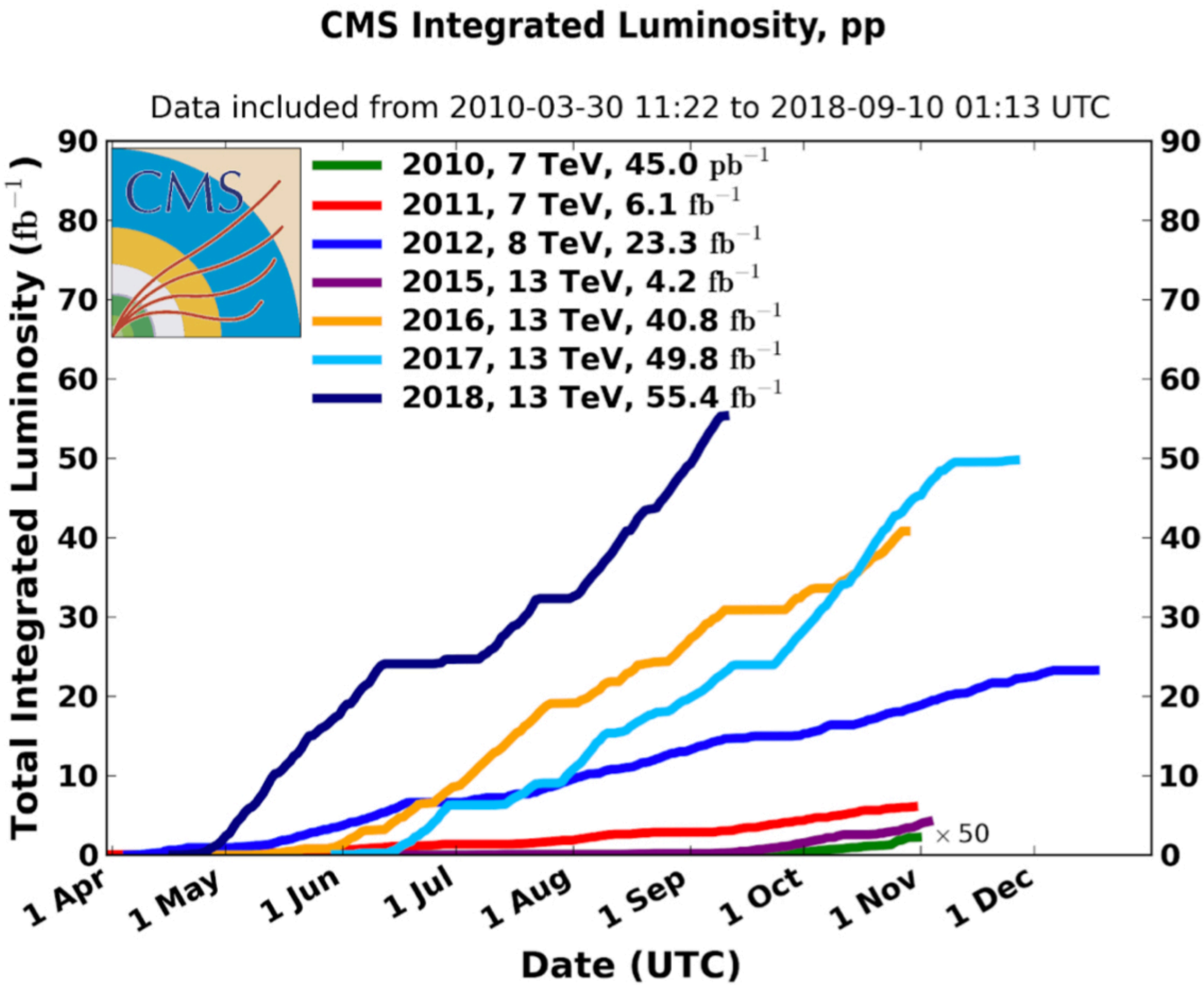




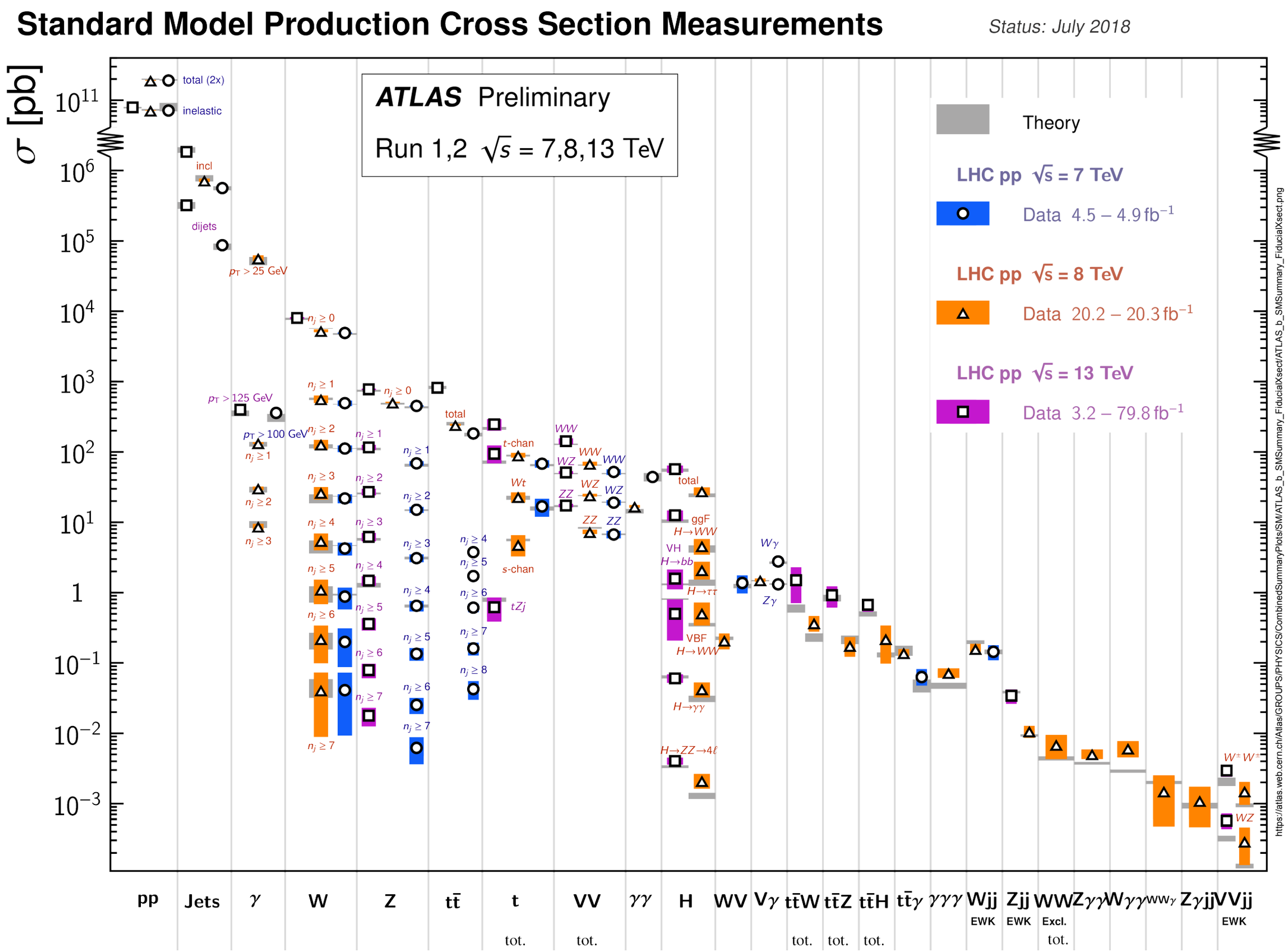




Delivery of (lots of) data



Stairway to ….


Standard Model Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Wjj EWK
Zjj EWK
WWZγγWγγWWγ
Zγjj
VVjj EWK
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_b_SMSummary_FiducialXsect/ATLAS_b_SMSummary_FiducialXsect.png

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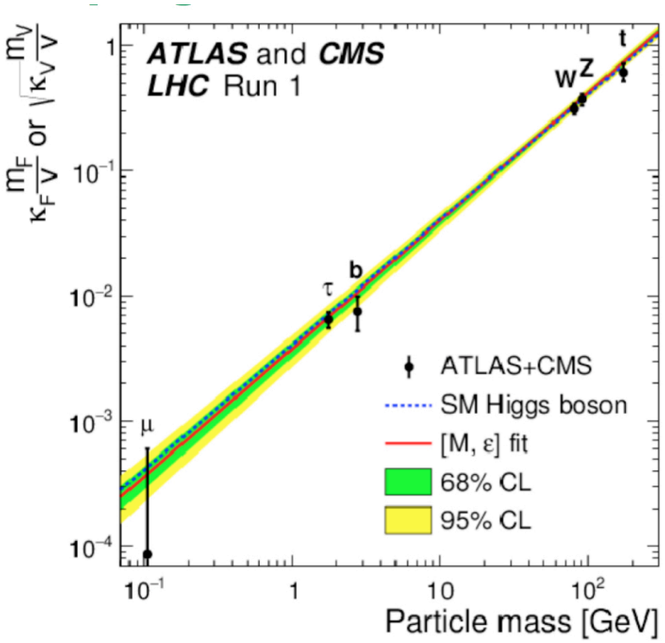

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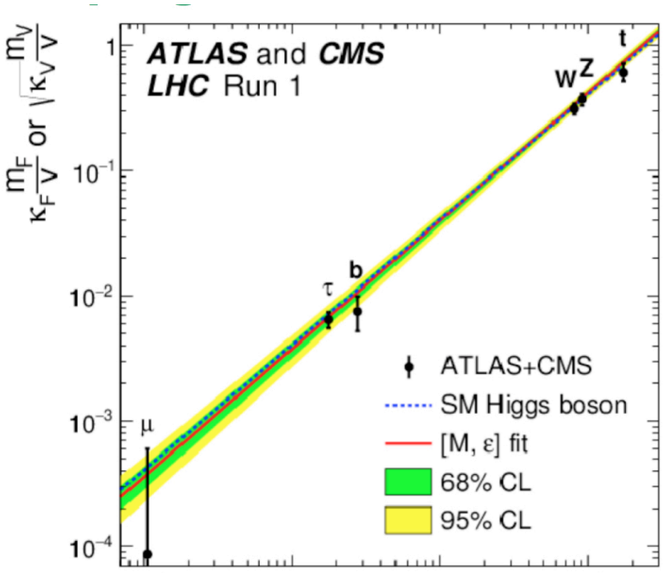

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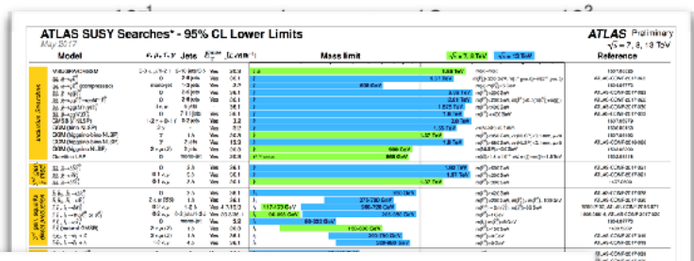

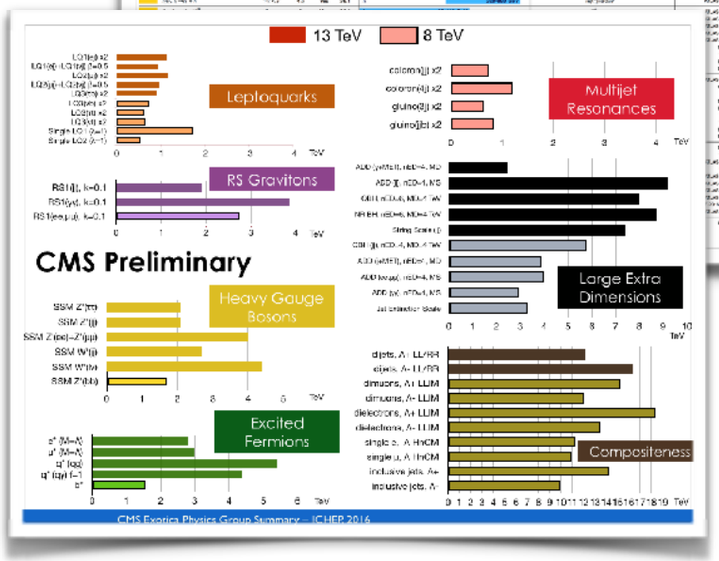

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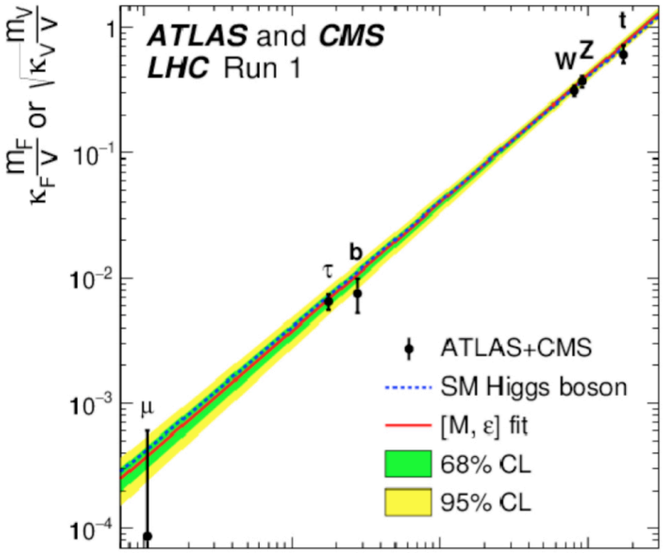

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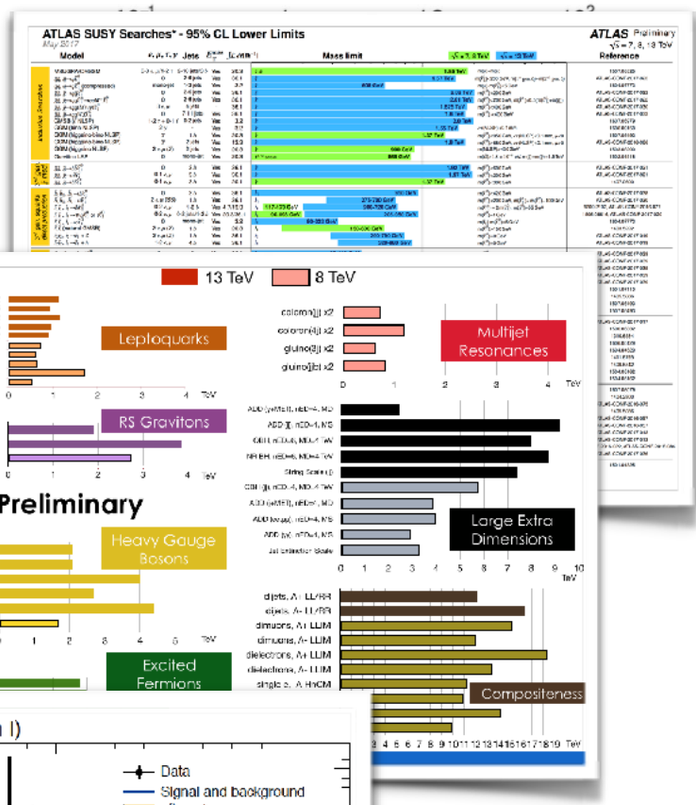

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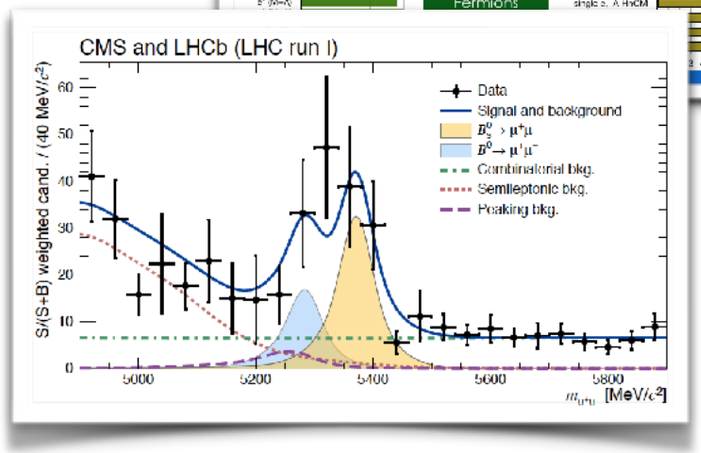
  - eg. $B_s \rightarrow \mu\mu$ (at 10^{-9} level)



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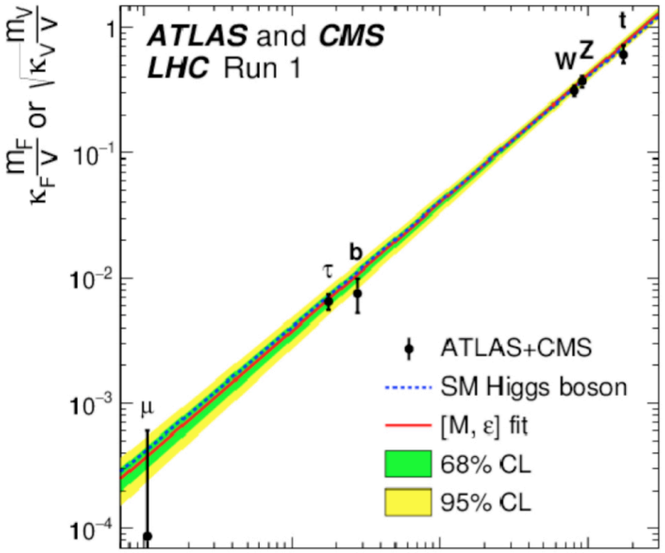

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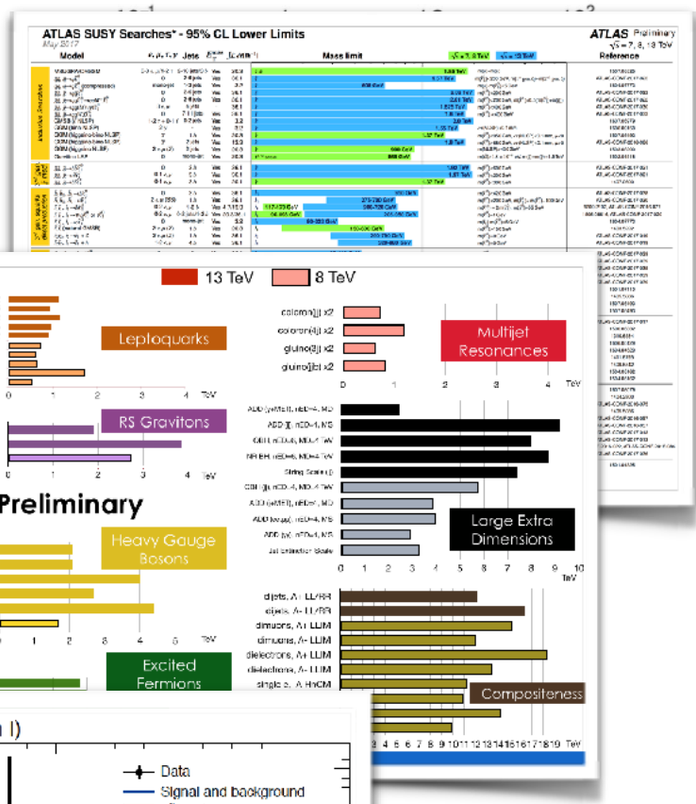

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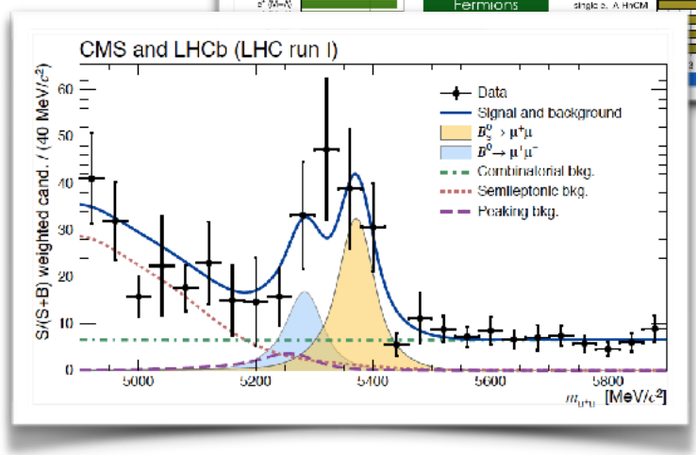

- **Some anomalies in the flavour sector? coupled to LFV?**

A (incomplete) list of open questions

inspired by talk by M. Mangano

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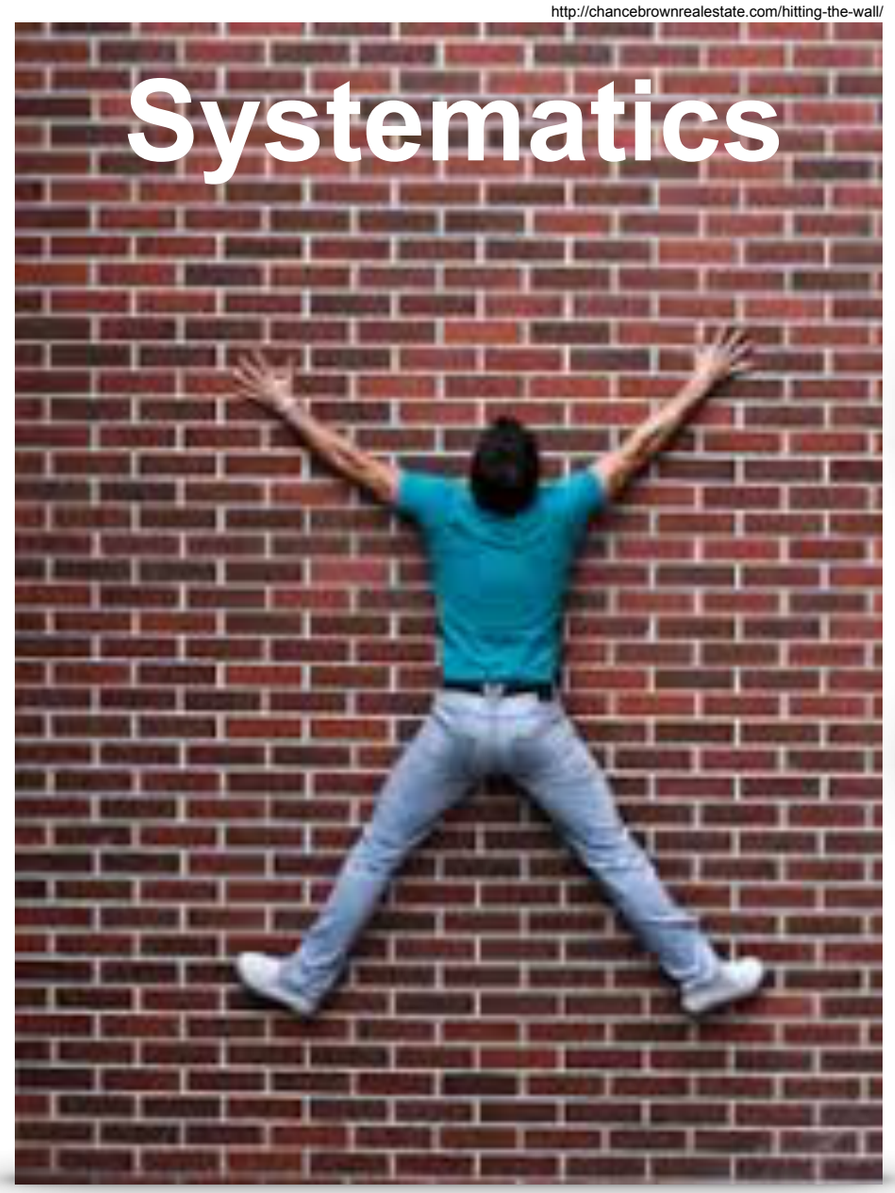
However:



http://chancebrownrealestate.com/hitting-the-wall/

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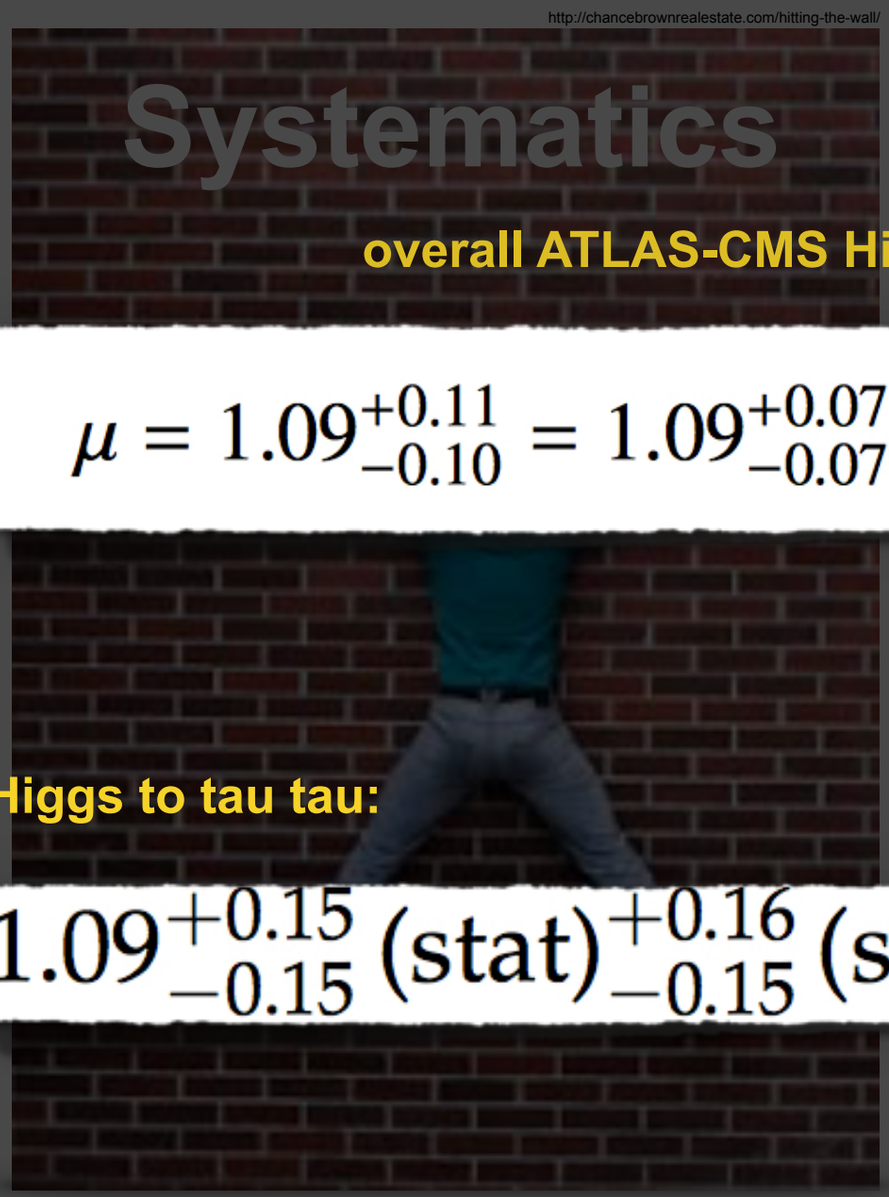

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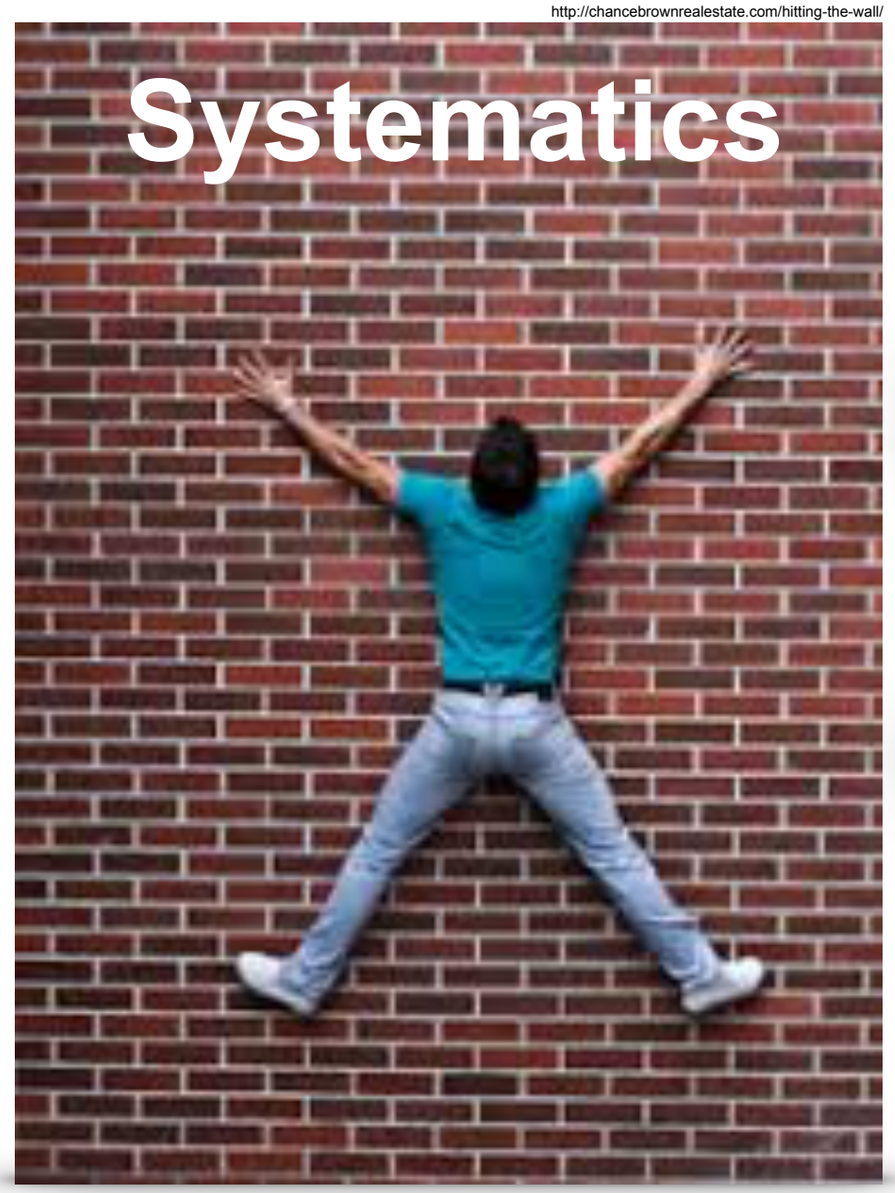

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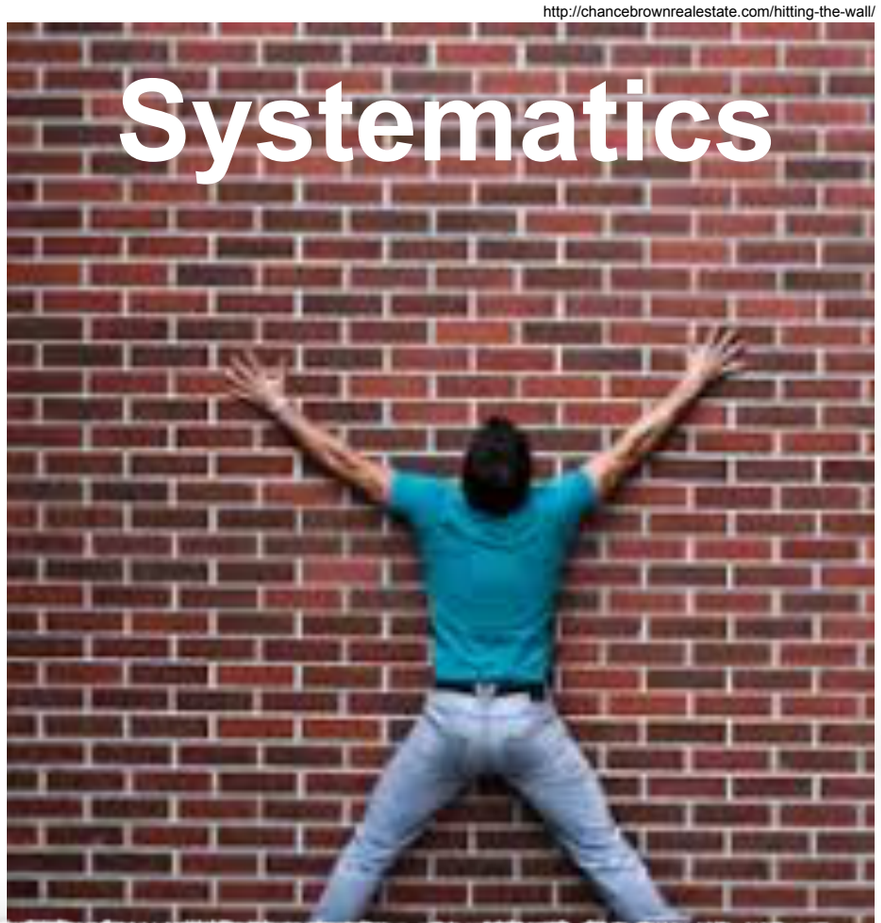

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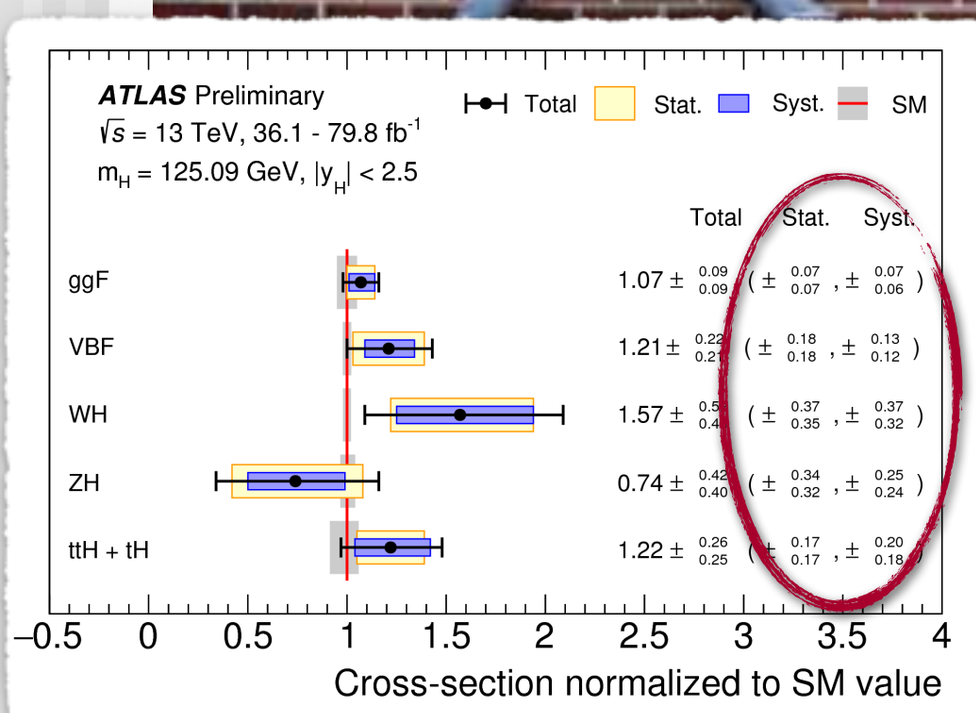

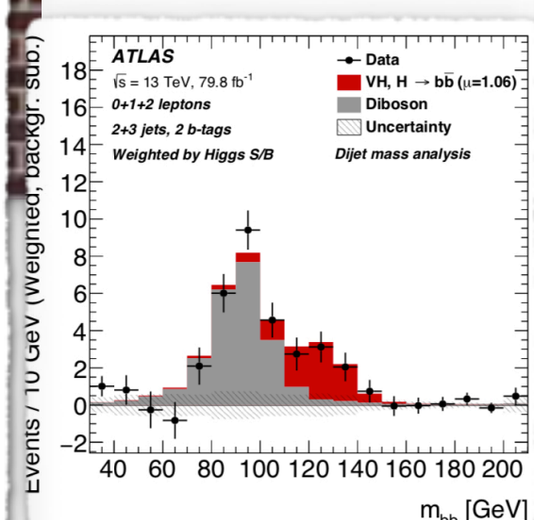

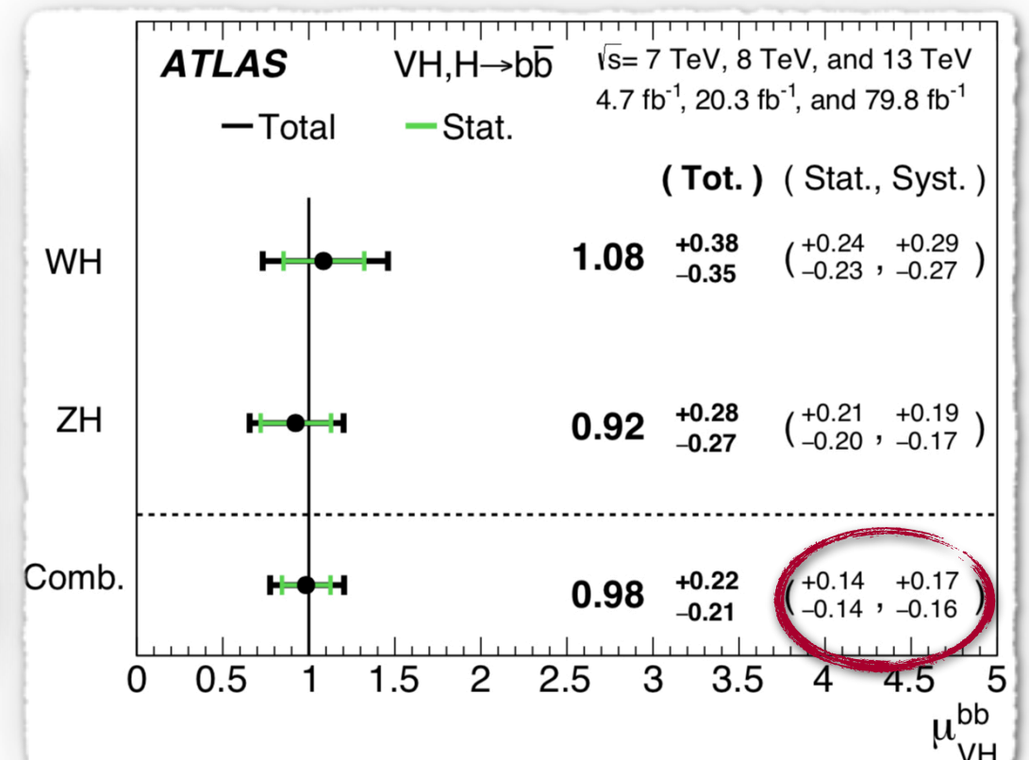

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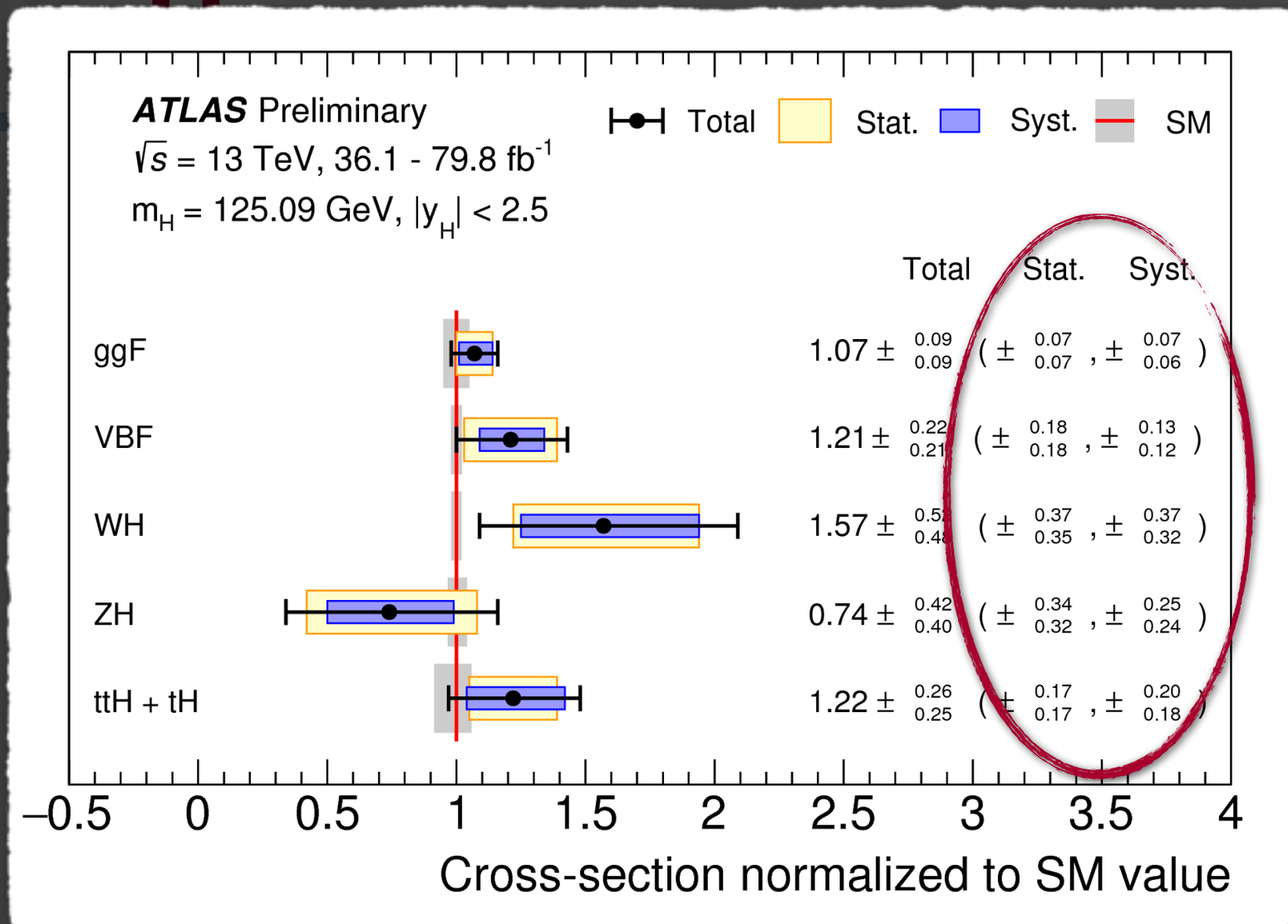

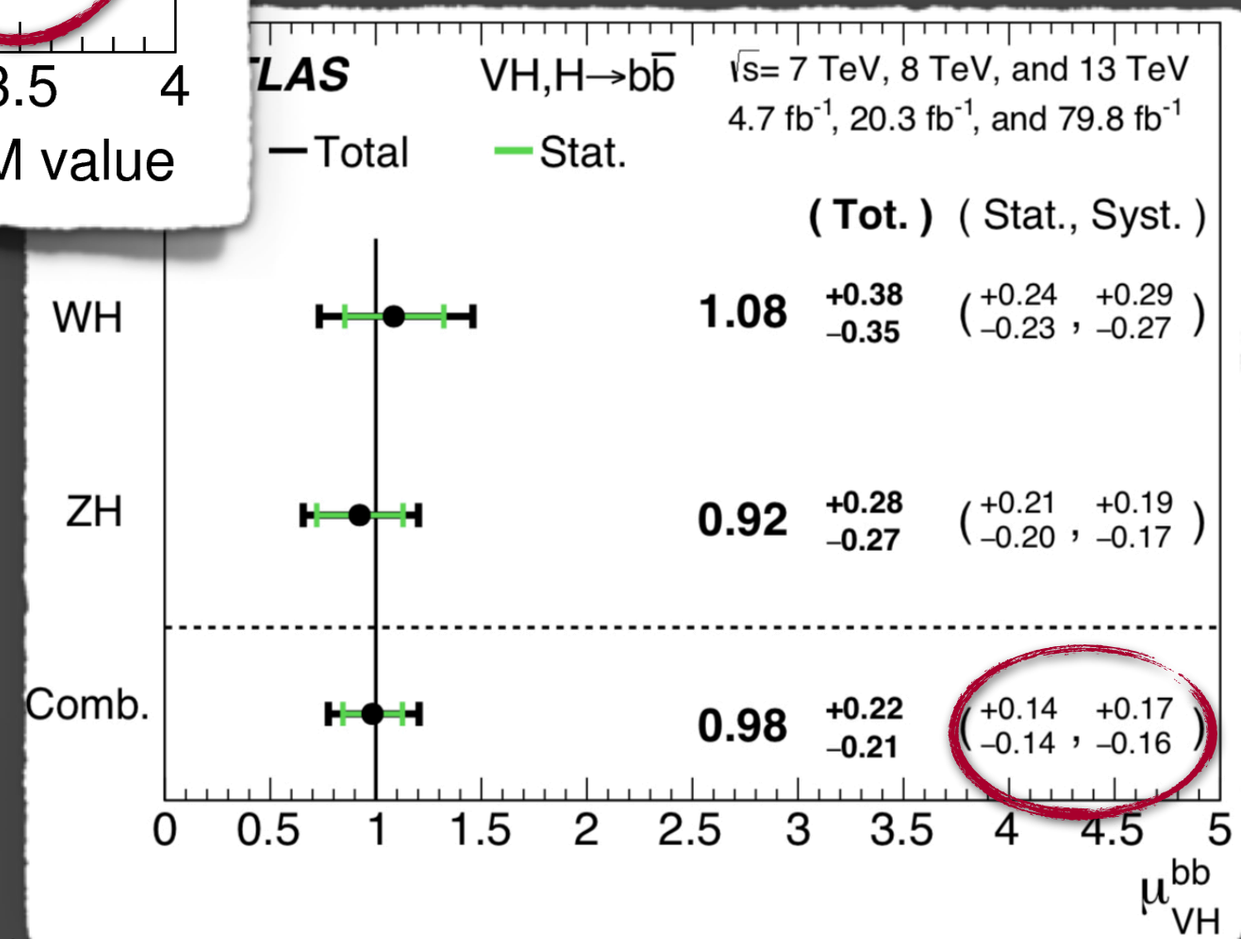

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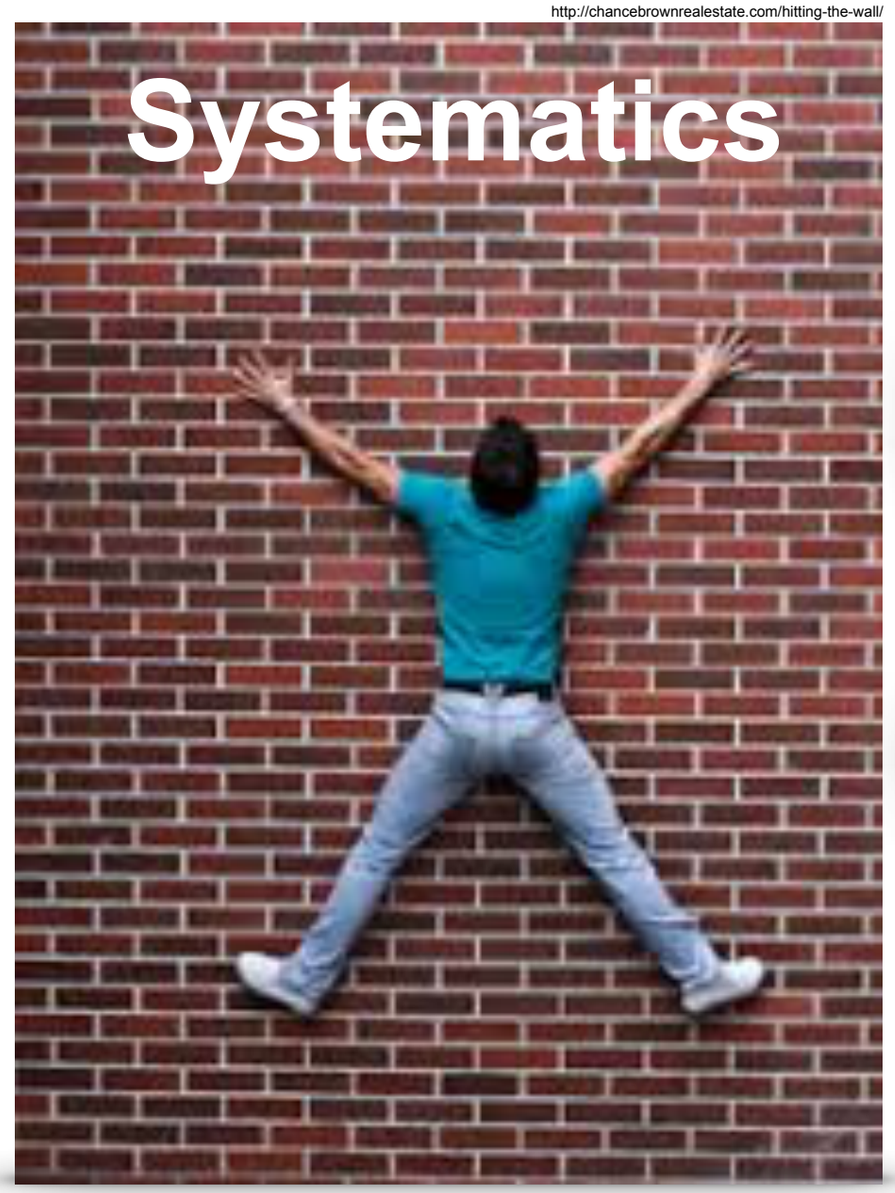

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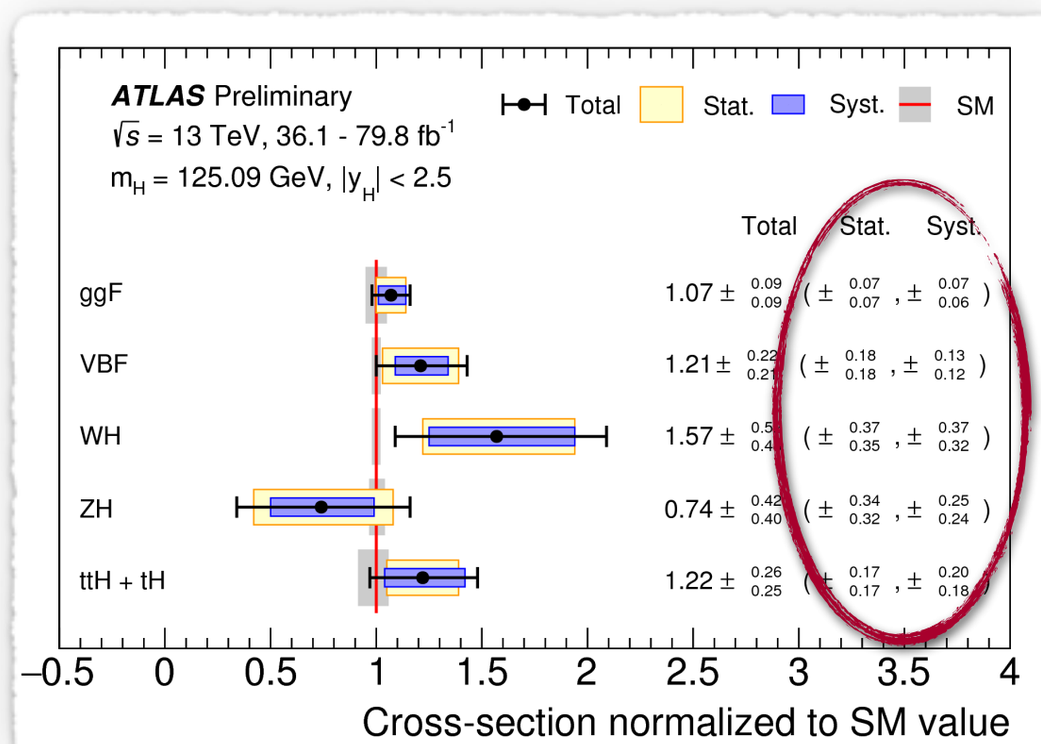

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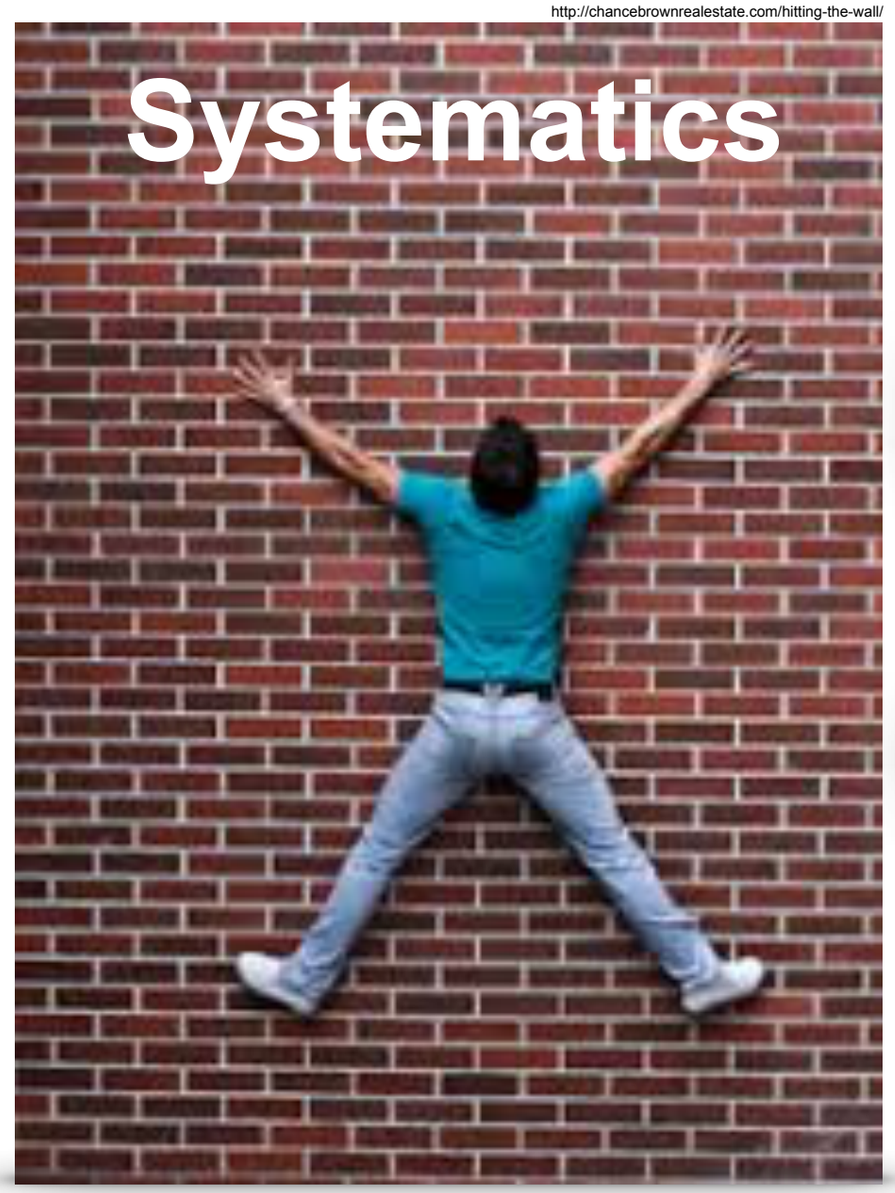

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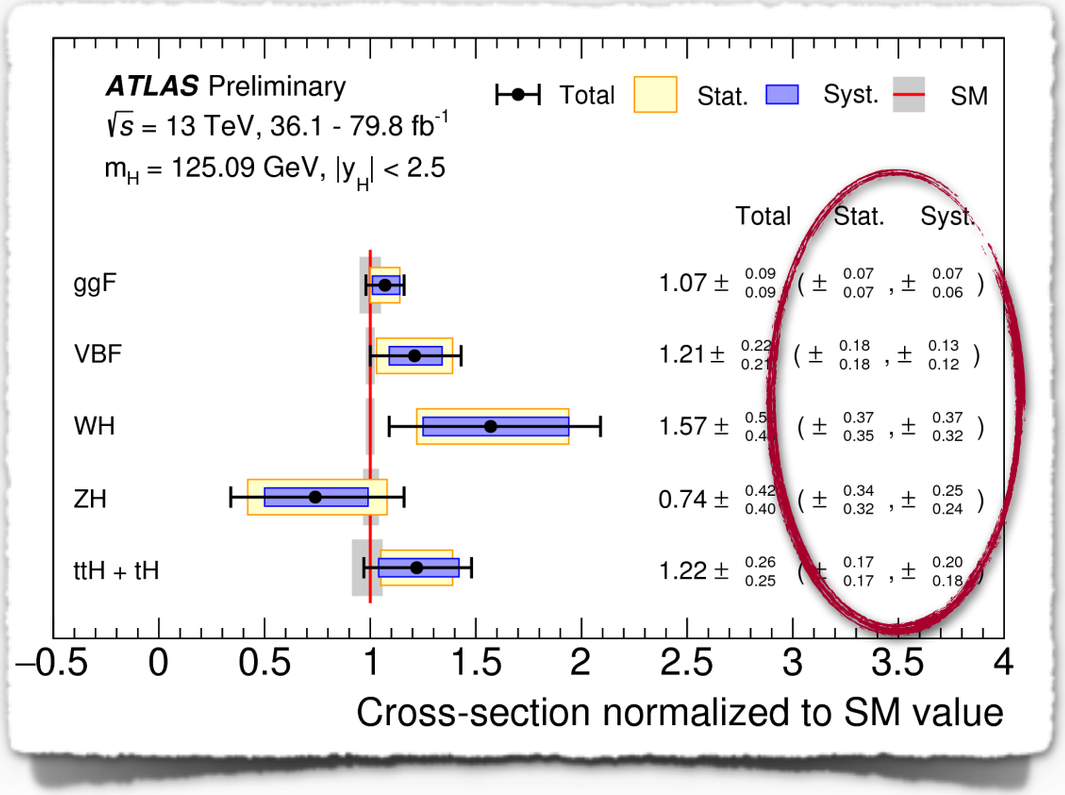

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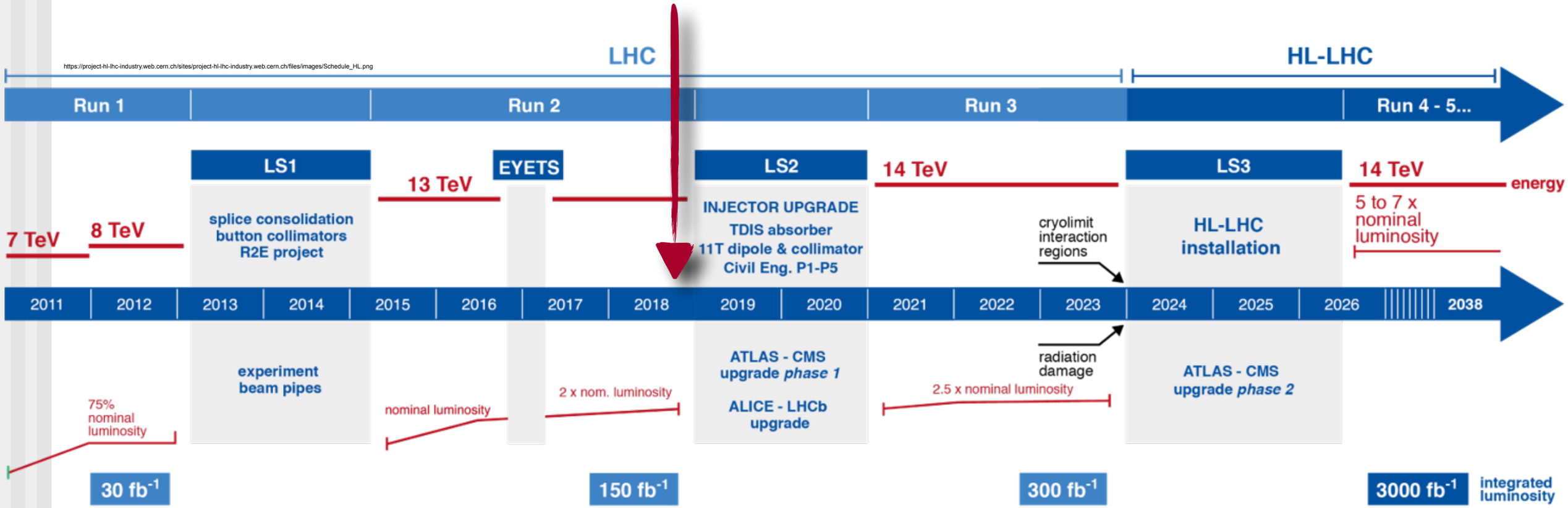
- **And of course:**
  make sure you have an excellent detector!

The Plan


https://project-hl-lhc-industry.web.cern.ch/sites/project-hl-lhc-industry.web.cern.ch/files/images/Schedule_HL.png
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2038
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
upgrade phase 2
75%
nominal
luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

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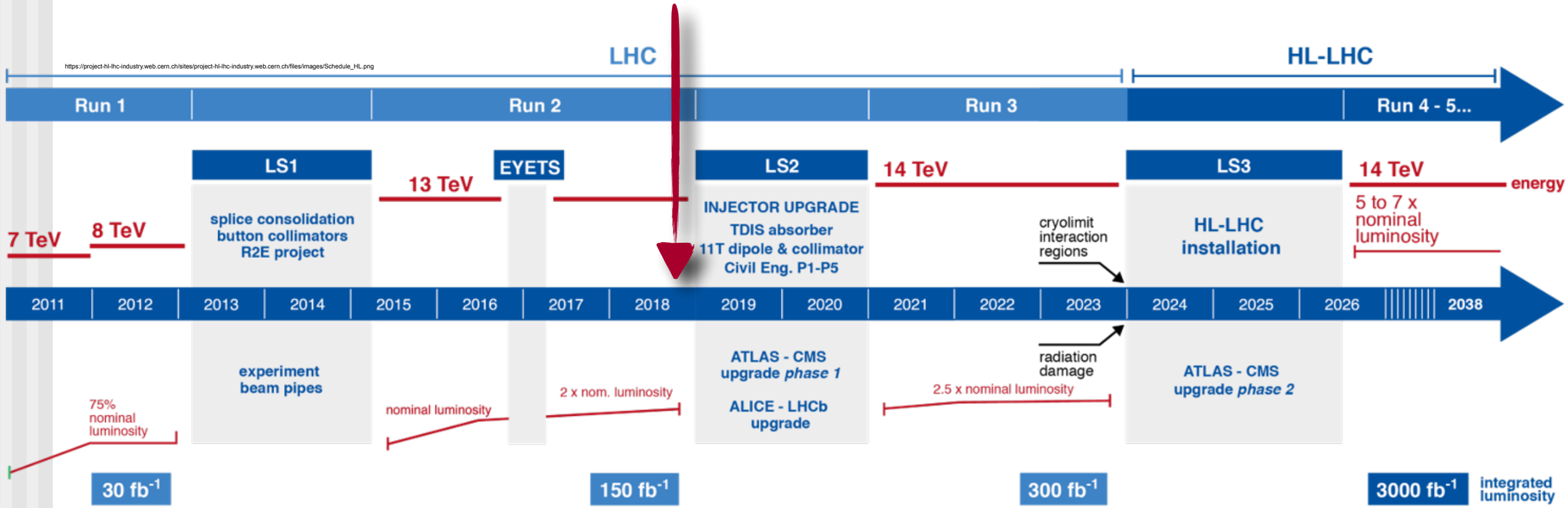
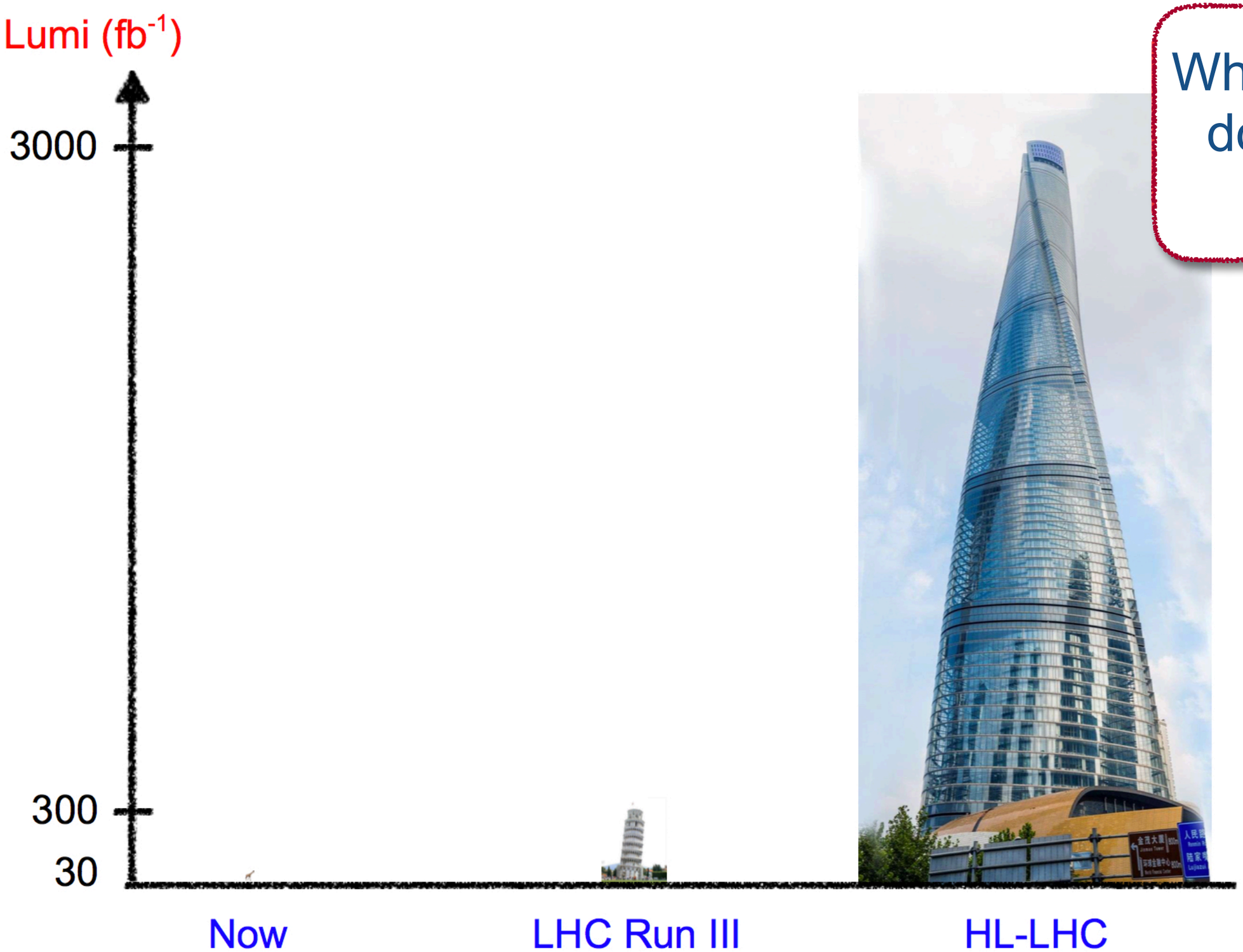


Notice, this is the Nominal Scenario:
L = **5.0**x10 e^{34} $cm^{-1}s^{-1}$ up to 3000 fb^{-1} (140 PU)
The Ultimate Scenario forsees:
L = **7.5**x10 e^{34} $cm^{-1}s^{-1}$ up to 4000 fb^{-1} (200 PU)

so far, recorded only ~5% of total expected data set !

Another look at the plan

from: S. Gori, LP17



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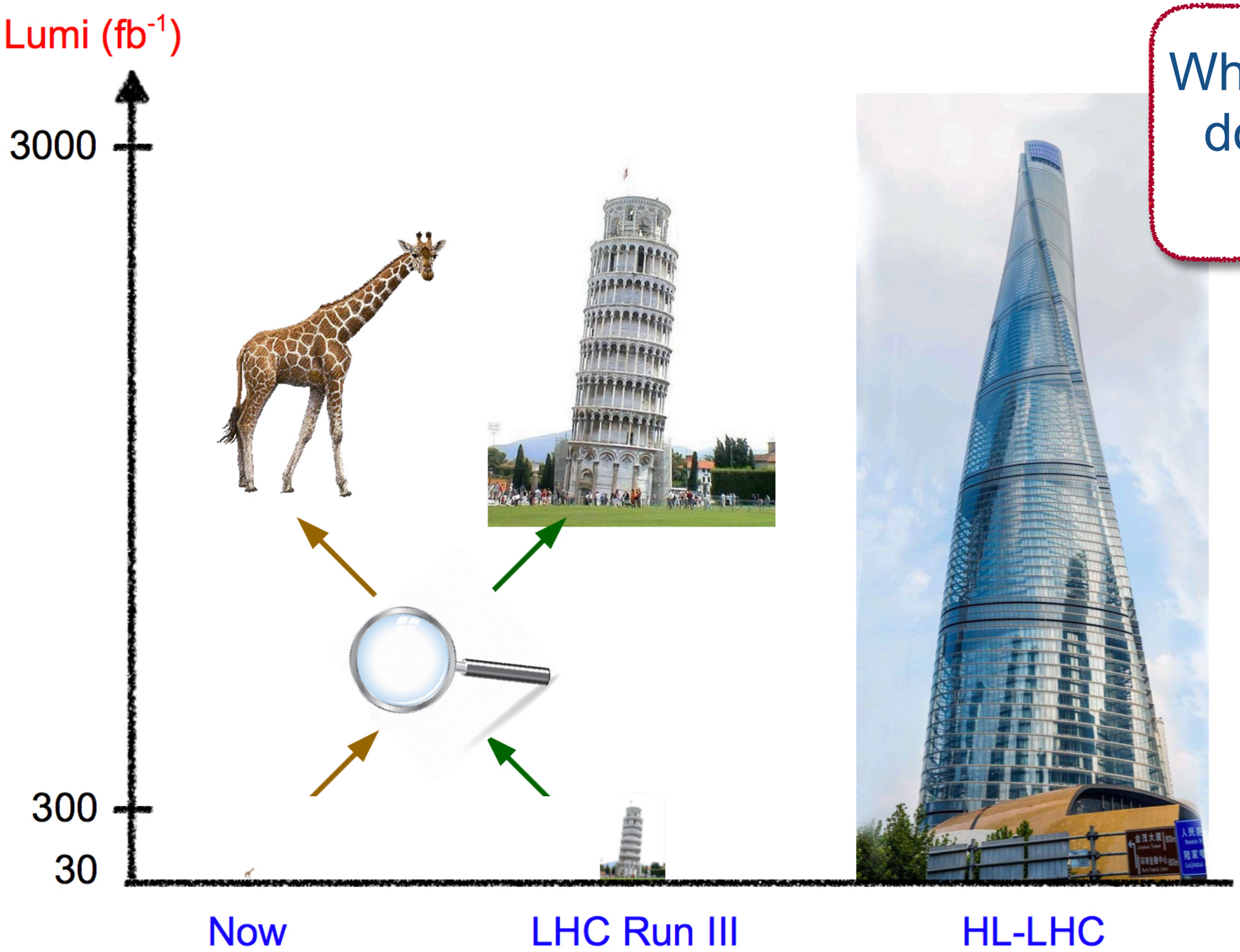

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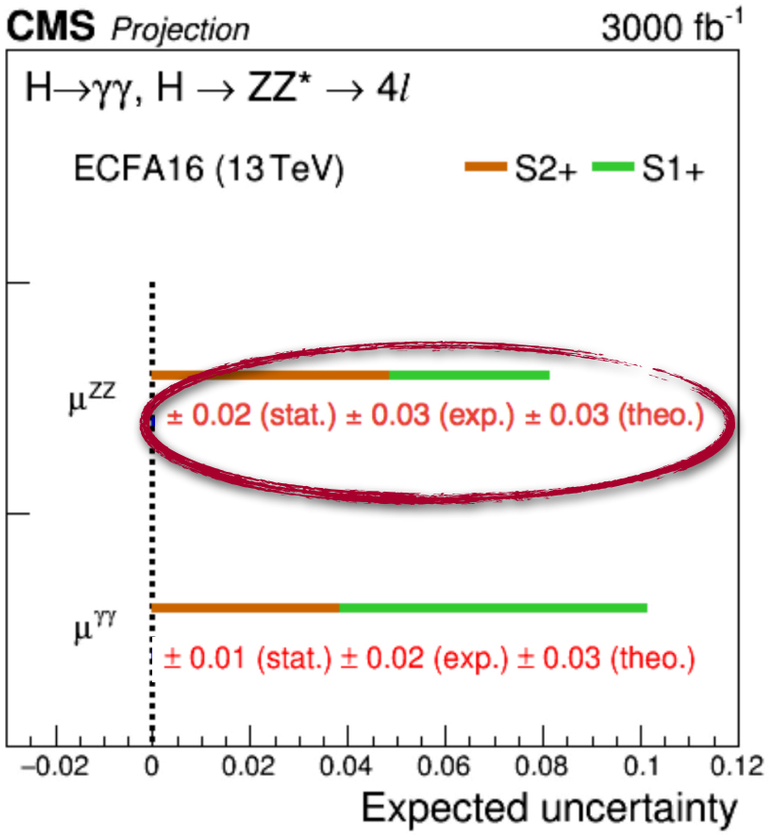
HL-LHC Physics Objectives in a nutshell

ETH zürich

- **Higgs boson**
  - Push the couplings measurements to the **few-% level**
  - Study Higgs production at **large transv. mom.**
  - A key deliverable**: Higgs self-coupling!**



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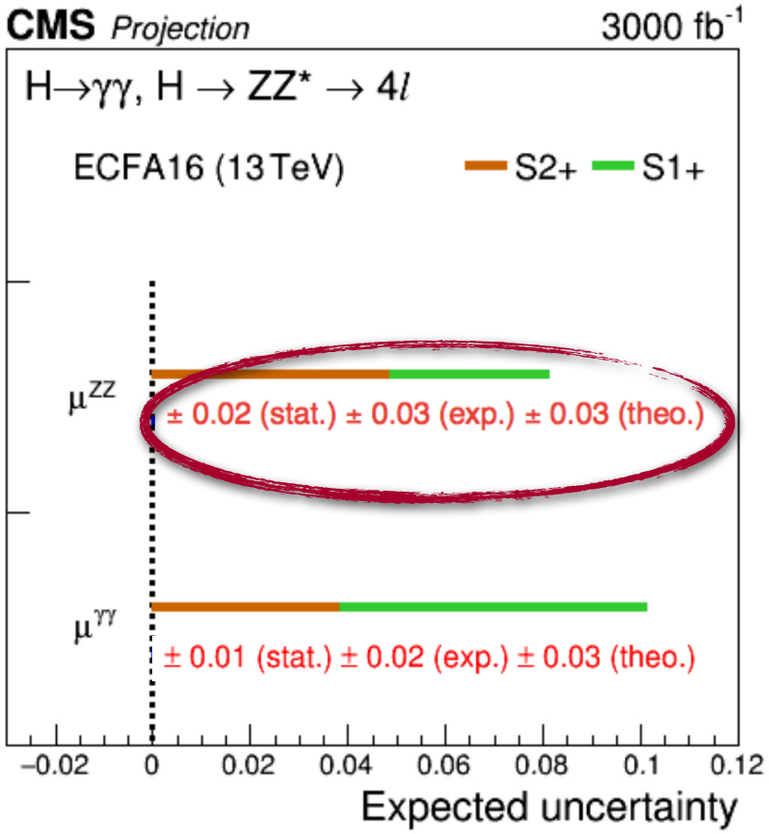

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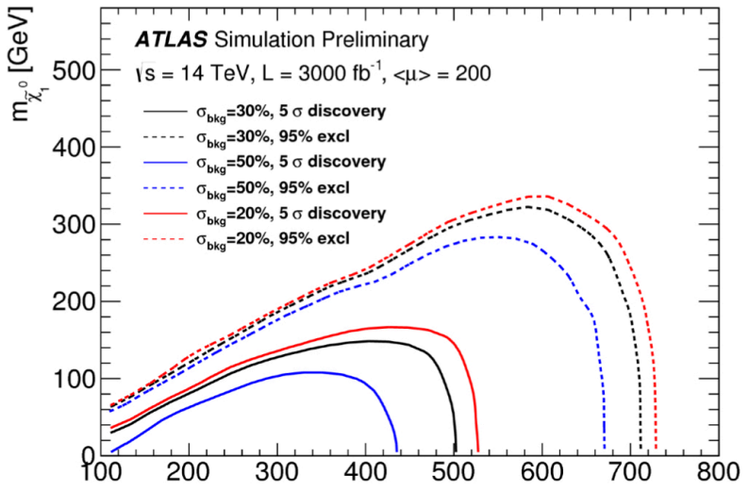

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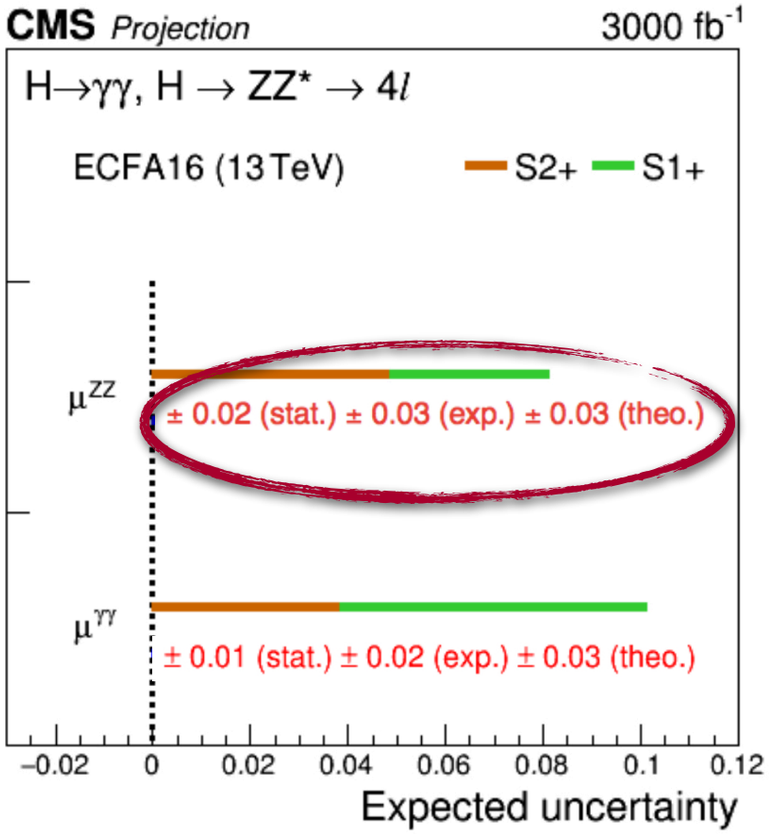

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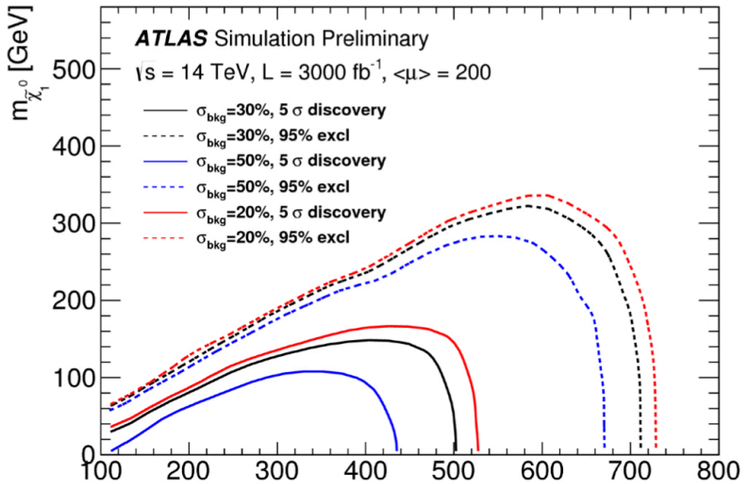

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- **Use (rare) flavour processes to look for the new**
  - eg. anomalous top couplings, FCNC
  - $B_d \to \mu\mu$ at the 5σ level, $\delta(B_d\mu\mu/B_s\mu\mu) \sim 20\%$
  - closing-in on (excluding or confirming) the recent flavour anomalies?

The power of large p_T

from: M. Mangano

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

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$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

$\Rightarrow$ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

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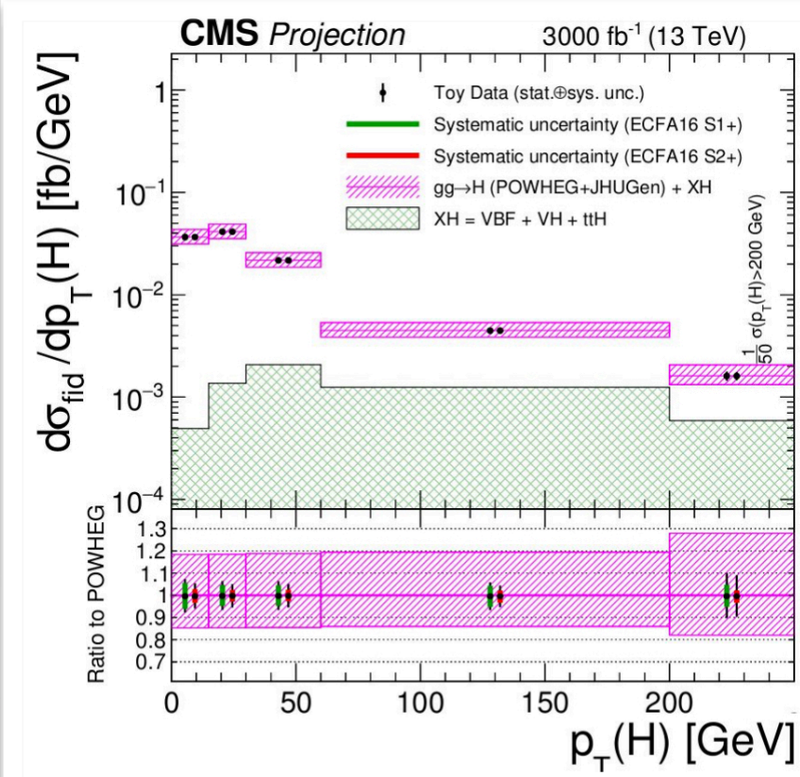

Ultra-precise measurements of differential cross sections (ZZ channel shown) ~ 4-9% (stat.)

CMS-DP-2016-064

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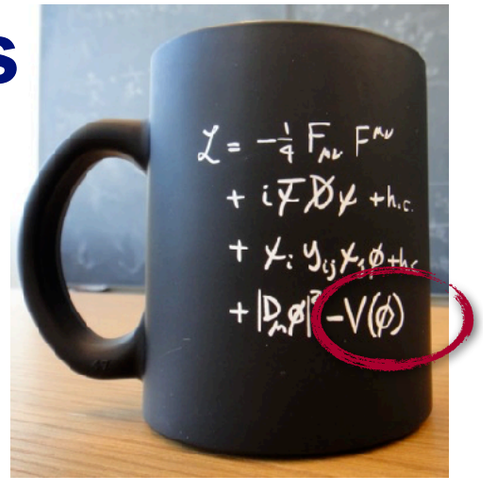
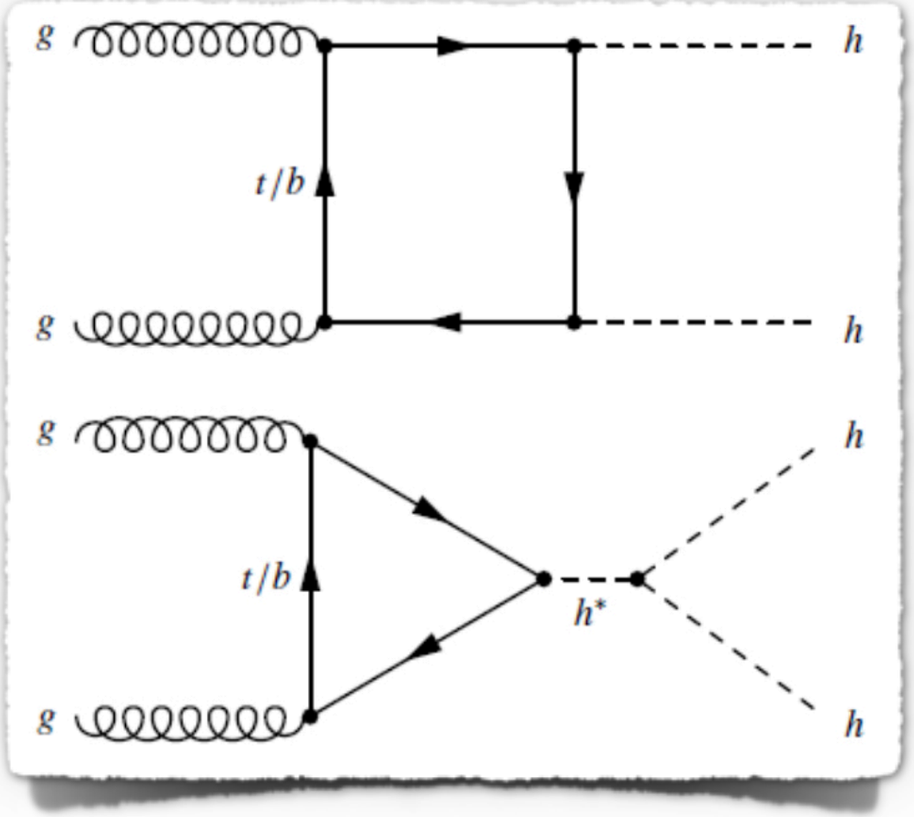
Rare processes: examples

ETH zürich

- **Di-Higgs production: a key process**
  - Probe the Higgs potential!
  - Cross section very small: ~33 fb^{-1}
    (~1000 smaller than single Higgs prod !)
  - **Current projections:**
    - ~**30%** precision on signal yield (assuming SM)
    - expect to exclude zero self-coupling at 95% C.L.





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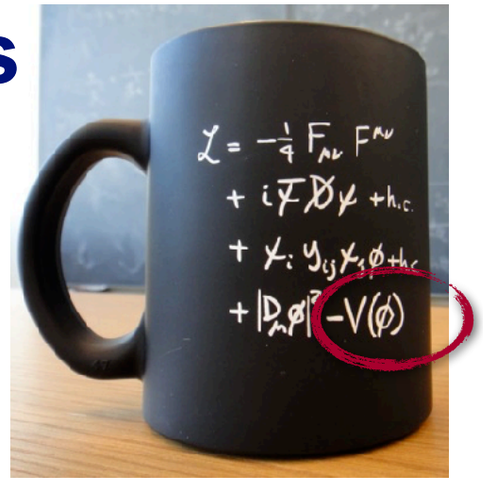
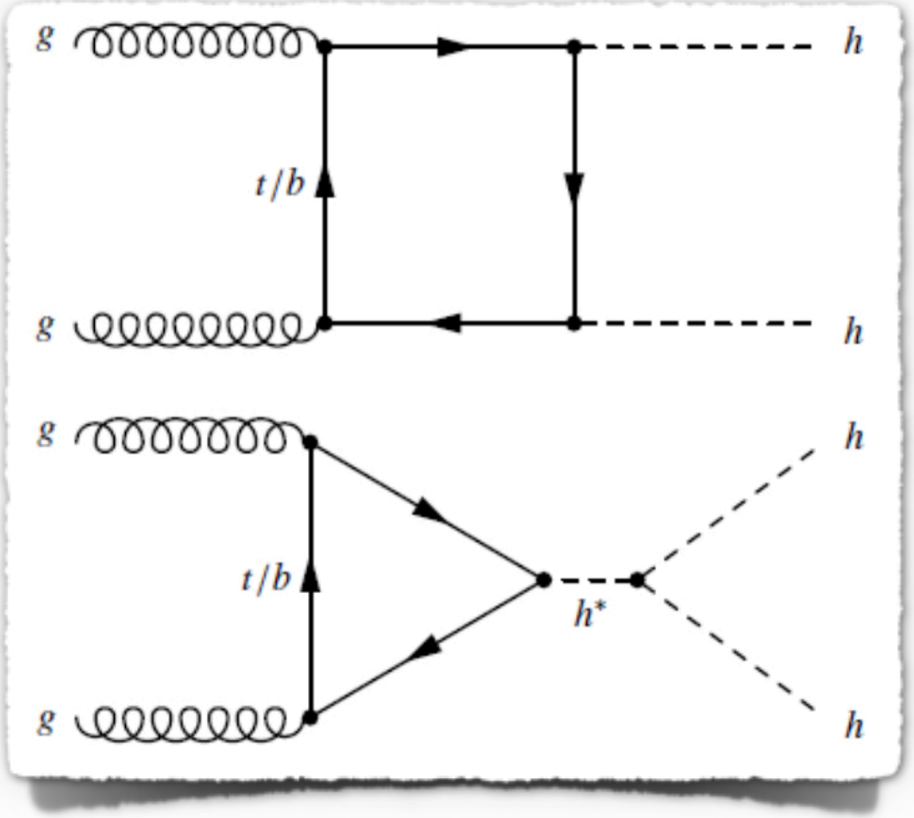
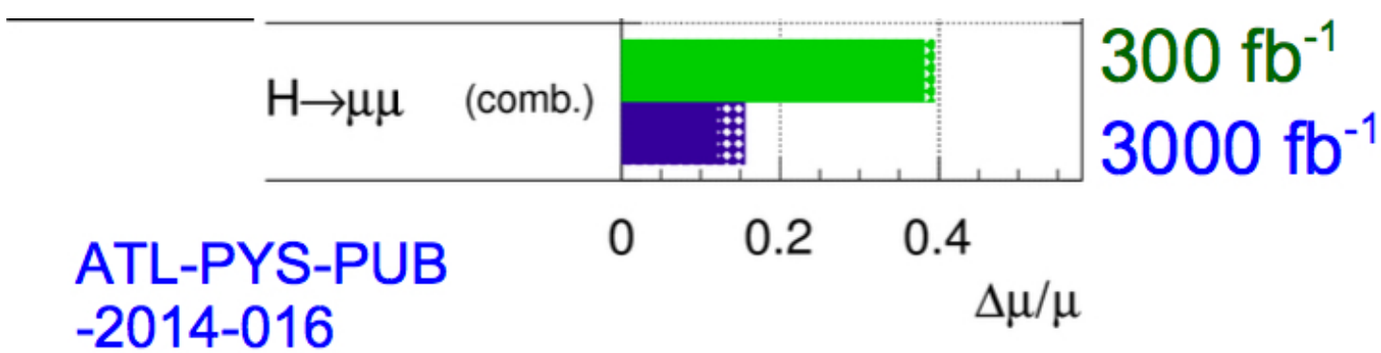




- **Rare (or new) Higgs decays**
  - **Higgs to two muons** (at ~15% level)
  - **Higgs to Zγ** (at ~10% level)
  - (VBF) **Higgs to "invisible"**

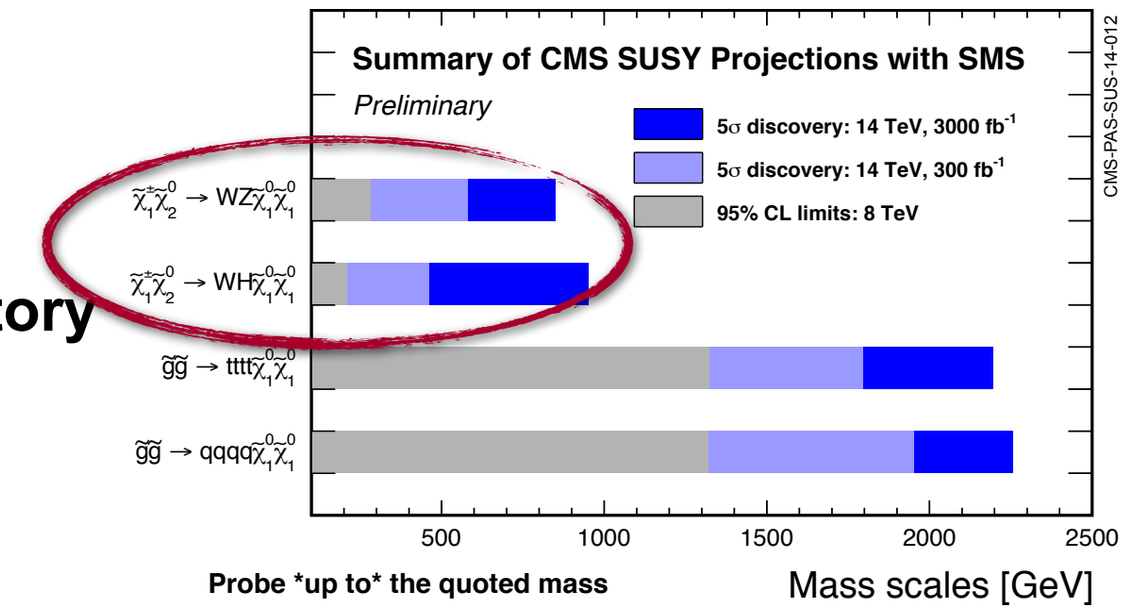


ATL-PYS-PUB -2014-016

Searches: the new frontiers

following S. Gori, LP17 and J. Alcaraz, IMFP17

- Leave no stone unturned
  - important focus on **electro-weak** particles (eg Winos, Higgsinos, Binos)
    - could be part of the **Dark Matter story**



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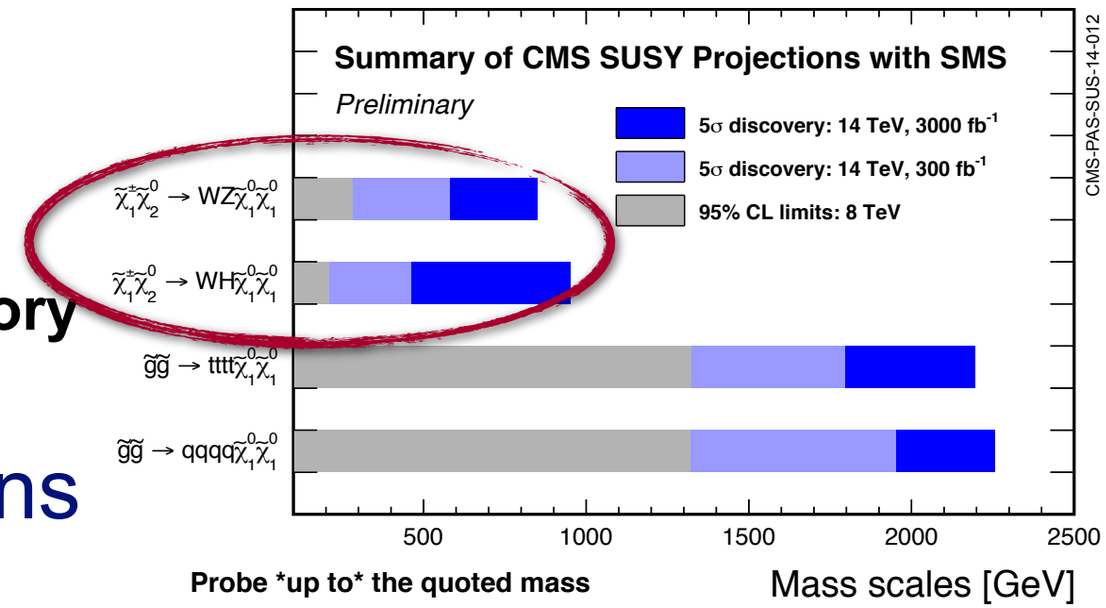

- SUSY: difficult parameter regions
  - example: $\tilde{t}_1\tilde{t}_1$ production
    $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 173$ GeV
  - 300 to 3000 fb^{-1} ⇒

    difference between
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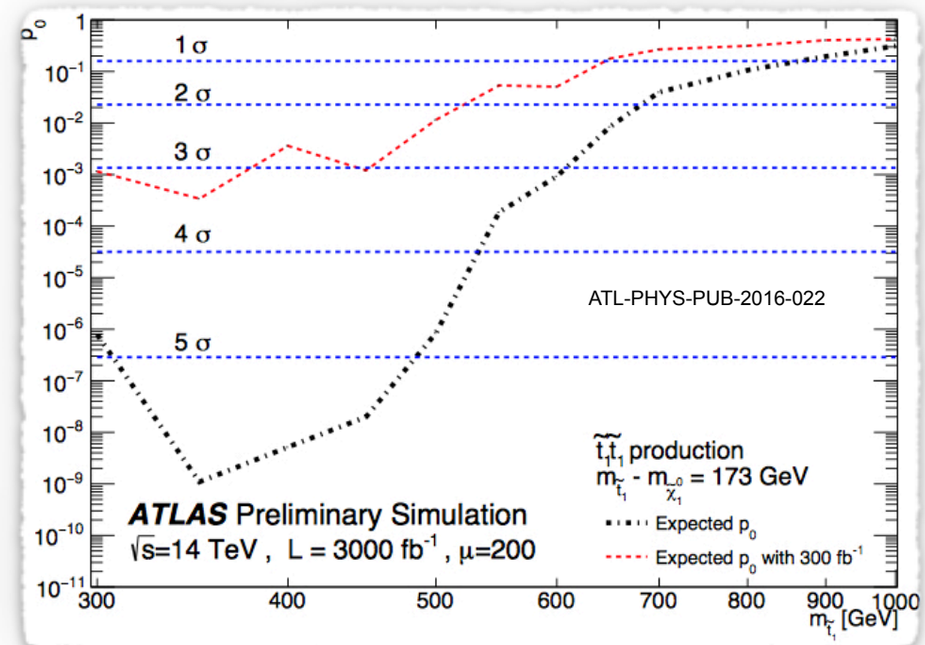

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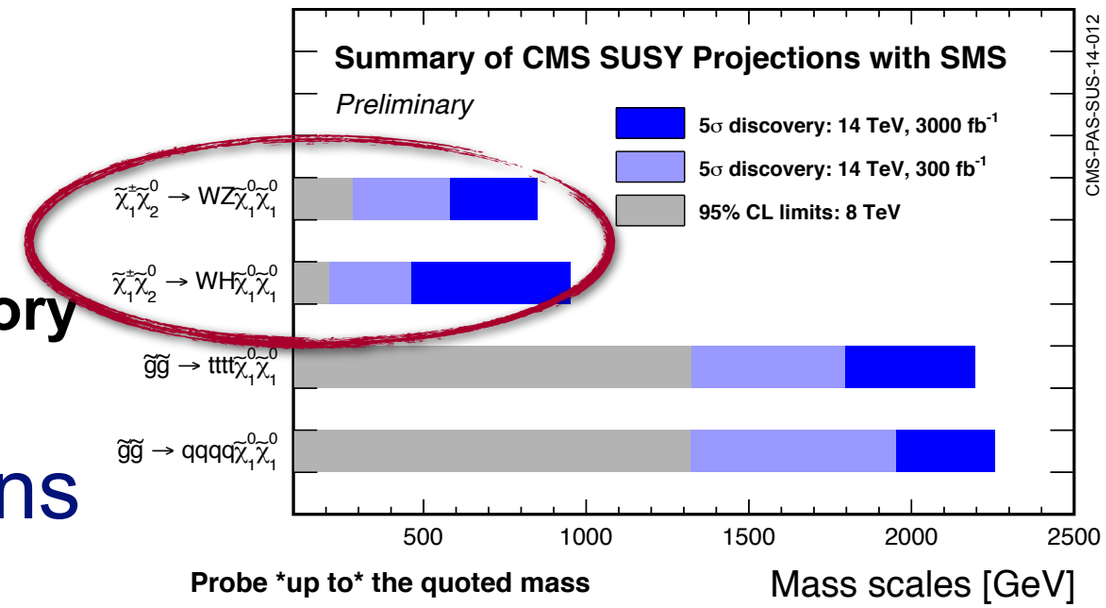

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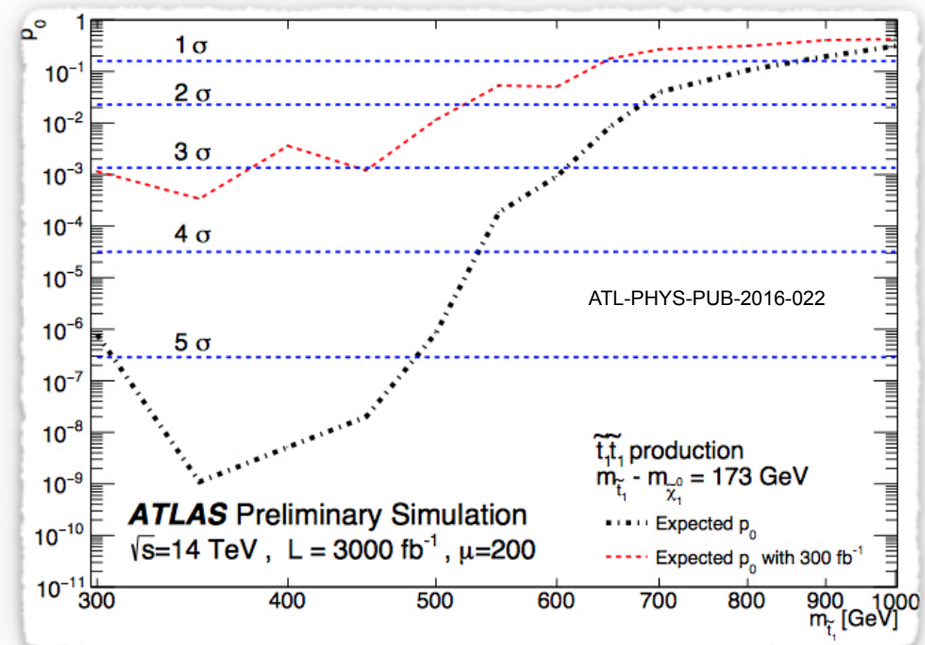


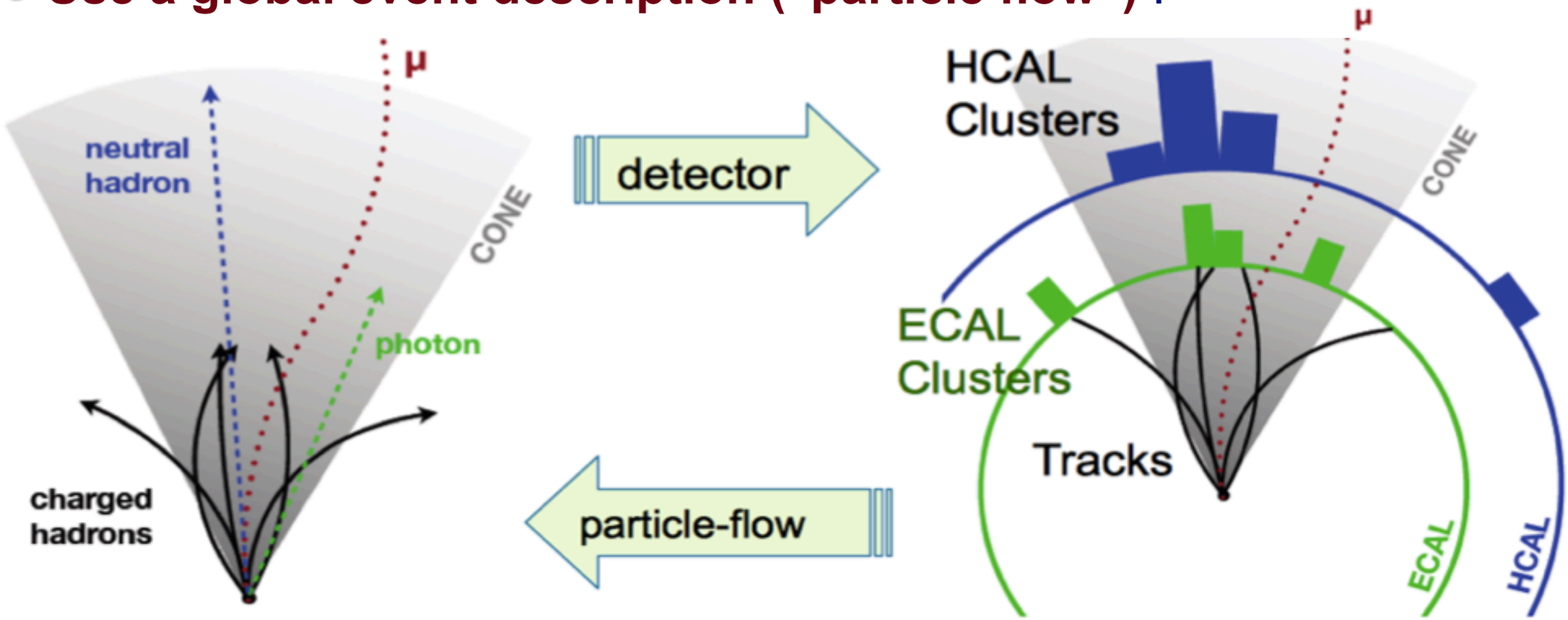
- Heavy Vector Bosons
  - decays to leptons: reach up to **~6 TeV**
  - decays to top quarks: up to **~4 TeV** (limits today: 2 TeV)

The experimental challenges (and proposed solutions)

but first a short pre-amble

The Particle-Flow concept

- **Use a global event description ("particle flow") :**



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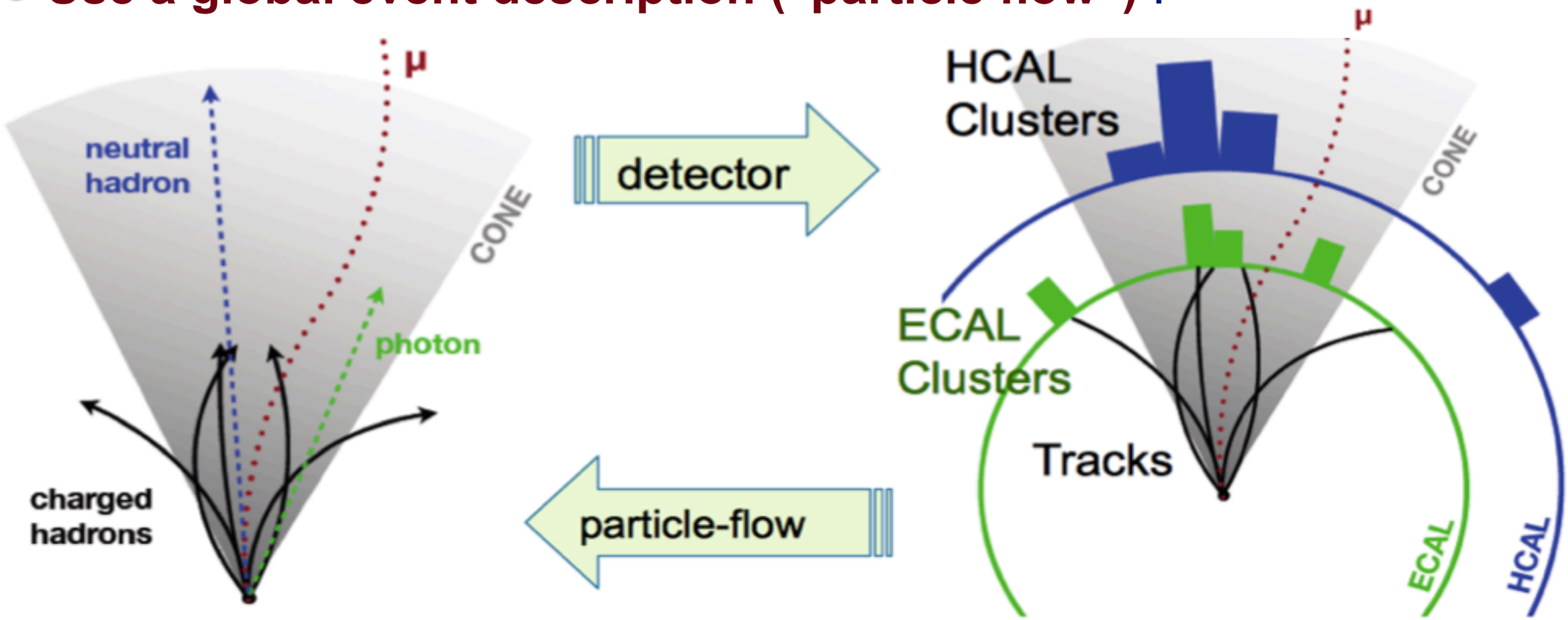

- In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)
- **Use a global event description** :
  - Optimal combination of information from all subdetectors
  - Returns a list of reconstructed particles (e,mu,photons,charged and neutral hadrons)
  - Used as building blocks for jets, taus, missing transverse energy, isolation and PU particle ID

Pile-up (1)

Luminosities of

$L \sim 5 - 7.5 \times 10^{34}\ cm^{-2}s^{-1}$

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Number of simultaneous proton-proton collisions per bunch crossing:

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$\sim (5 - 7.5)\ 10^{34}\ cm^{-2}s^{-1} \times 100\ mb \times 25\ ns \sim$

125 - 190 !

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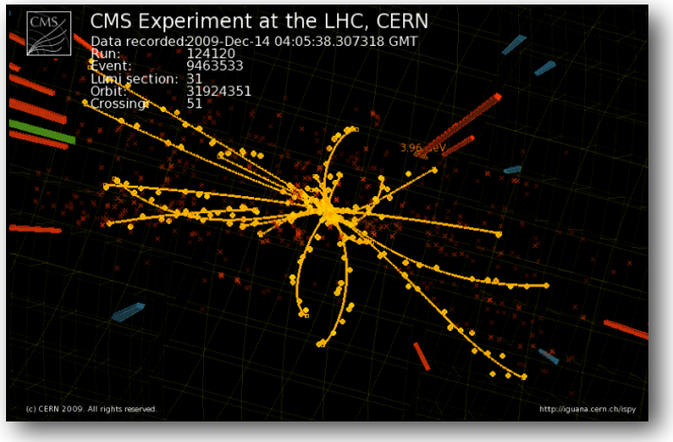
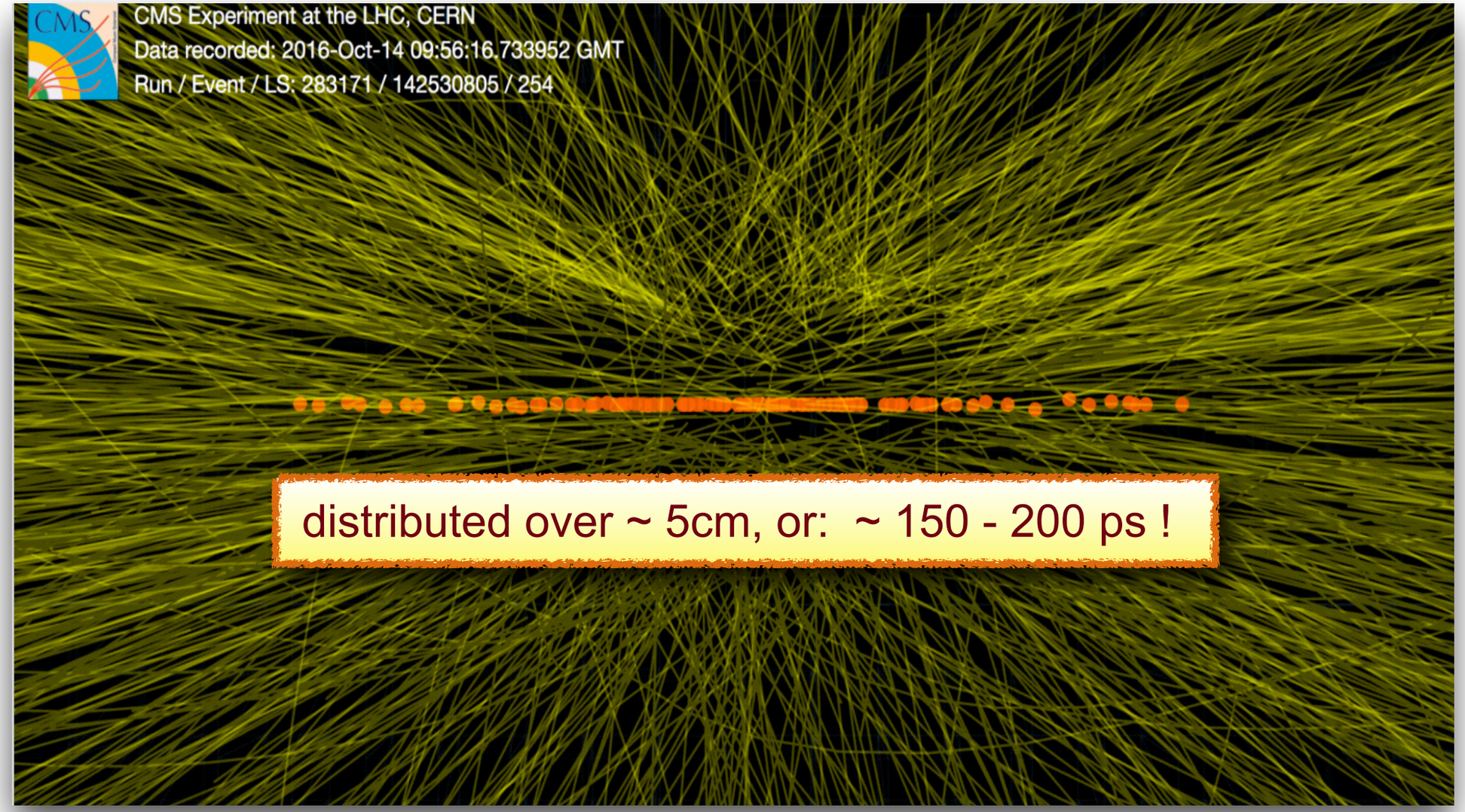


Each of these:
~ 6 charged particles per unit rapidity,
over range of +- 5 units in rapidity:
O(10000) particles per collision !!

Pile-up (2)



distributed over ~ 5cm, or: ~ 150 - 200 ps !

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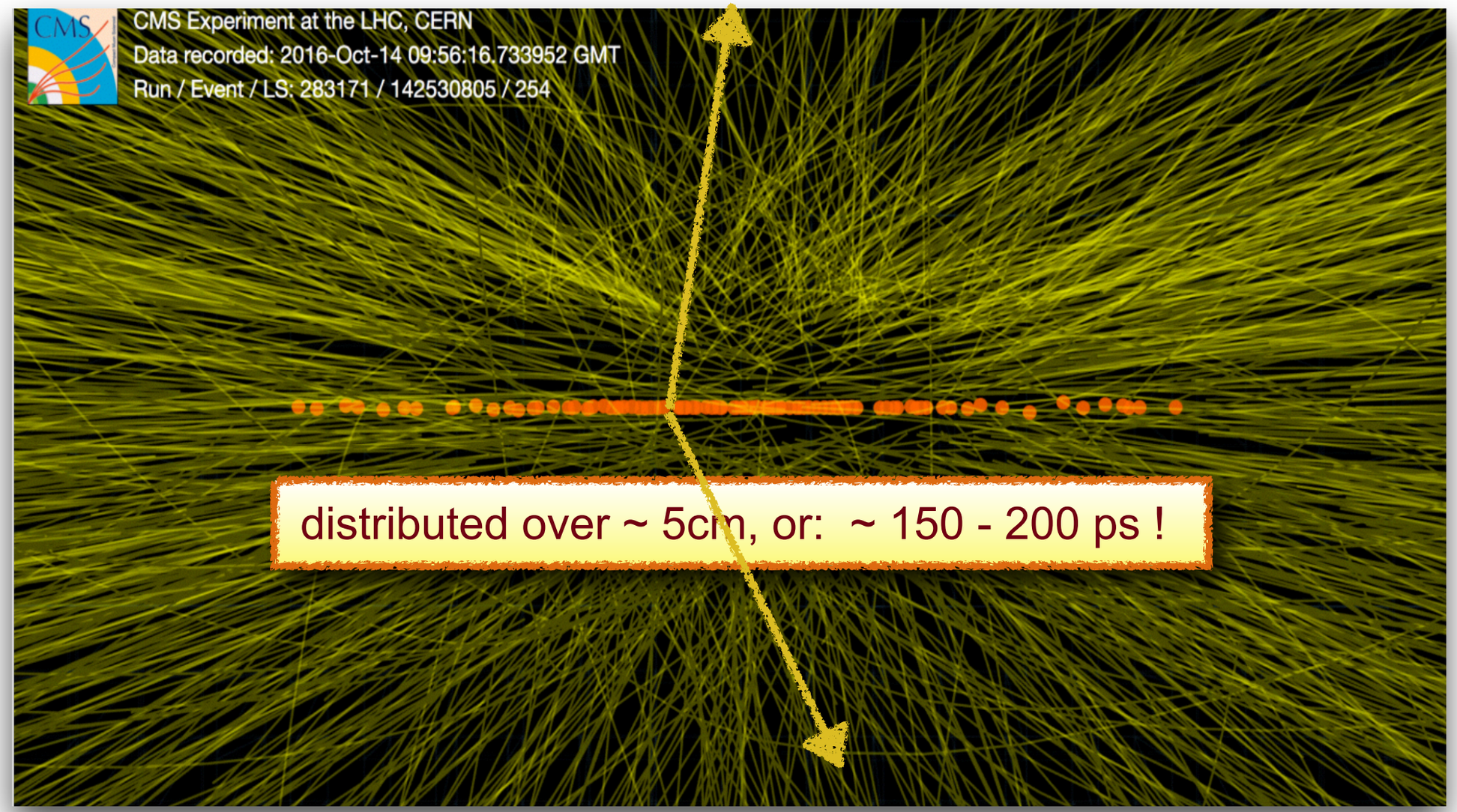
CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-14 09:56:16.733952 GMT
Run / Event / LS: 283171 / 142530805 / 254
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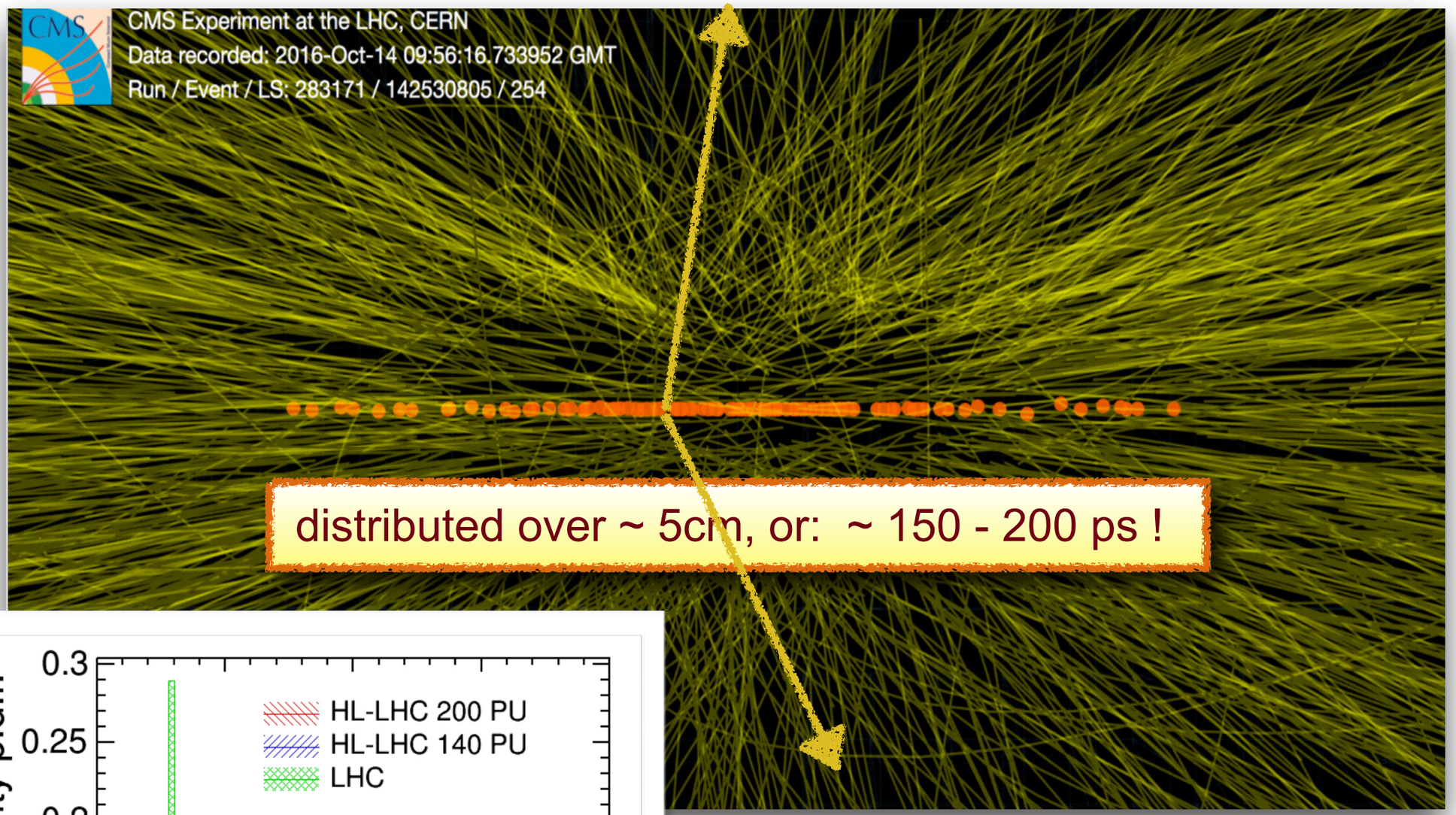
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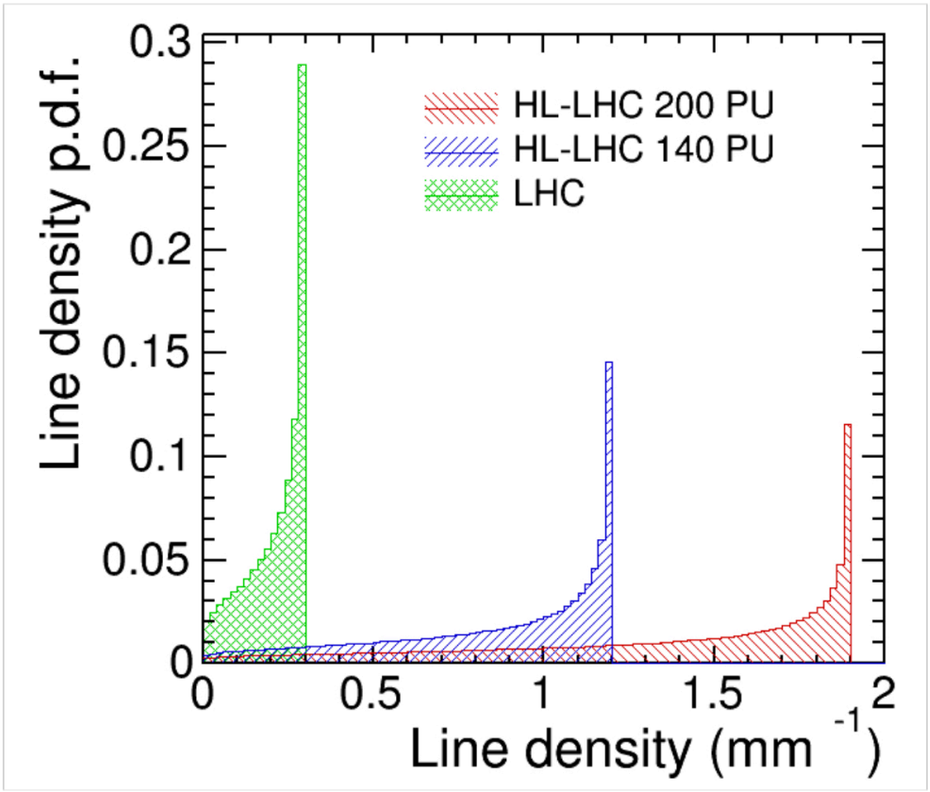
Line density p.d.f.
0.3
0.25
0.2
0.15
0.1
0.05
0
HL-LHC 200 PU
HL-LHC 140 PU
LHC
0
0.5
1
1.5
2
Line density (mm -1)

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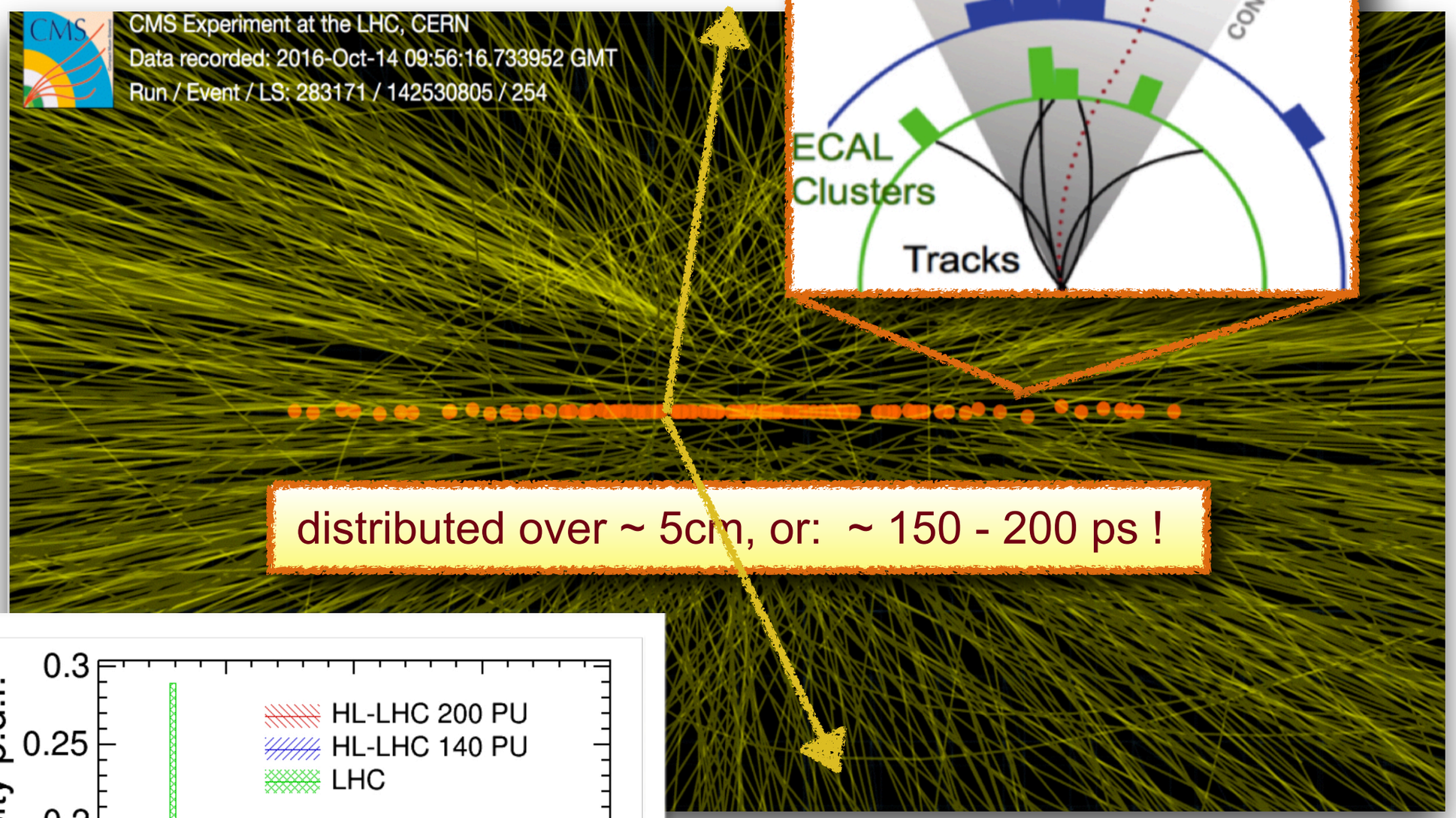

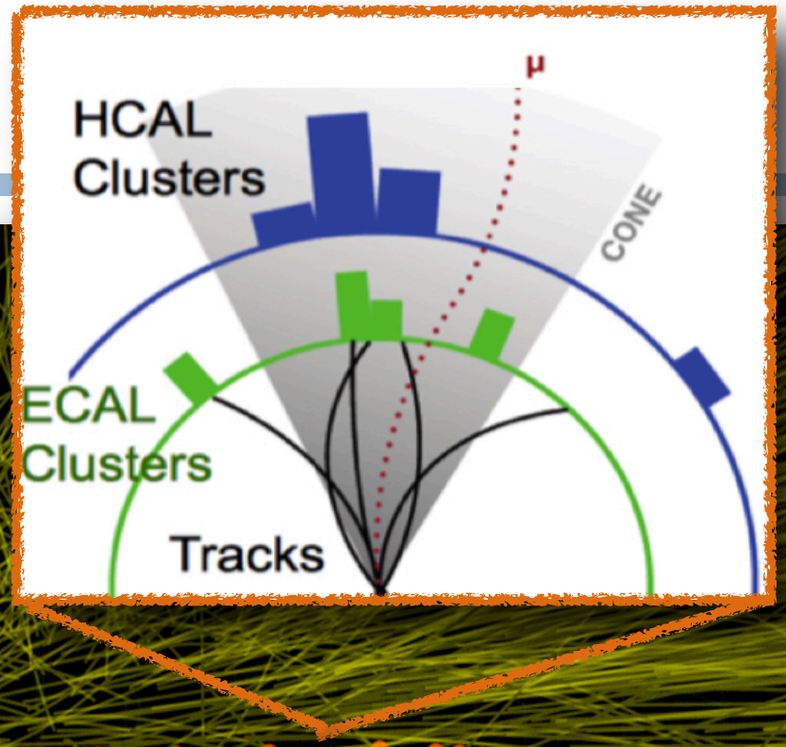

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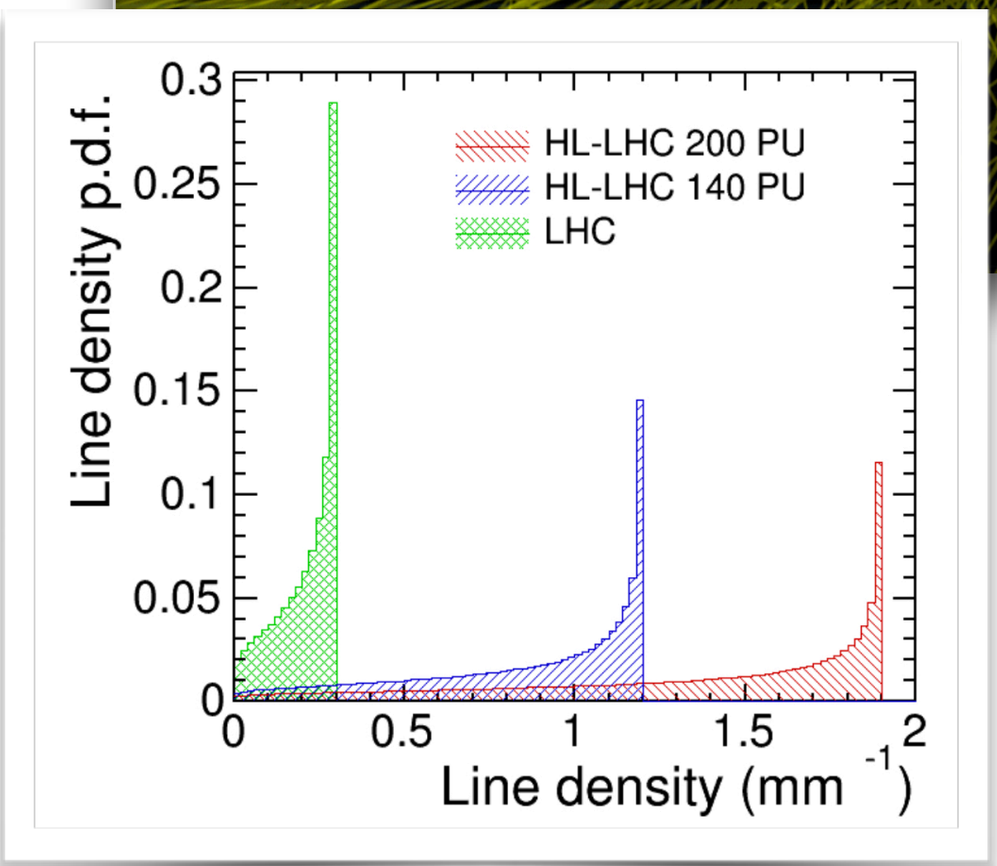

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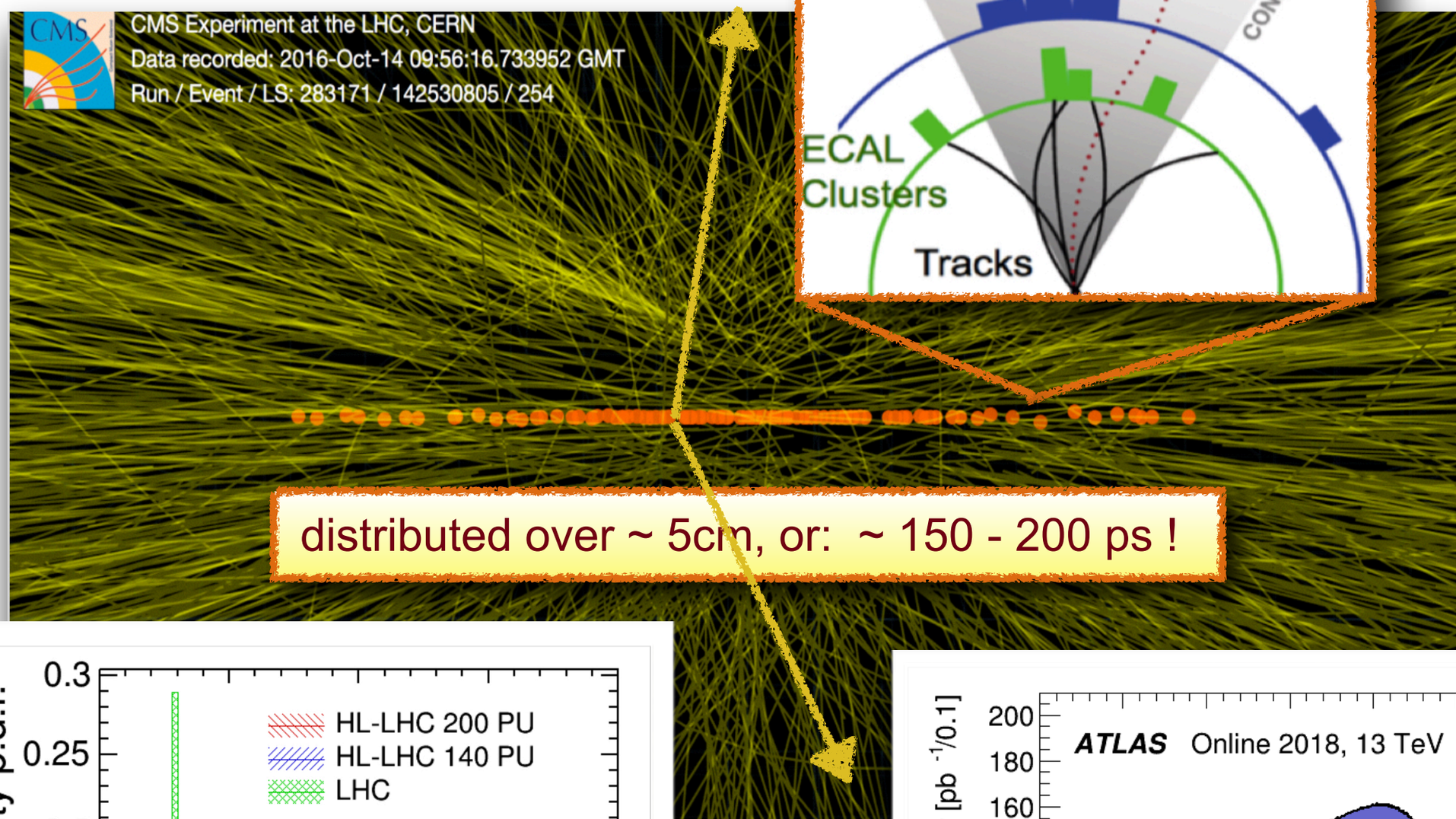

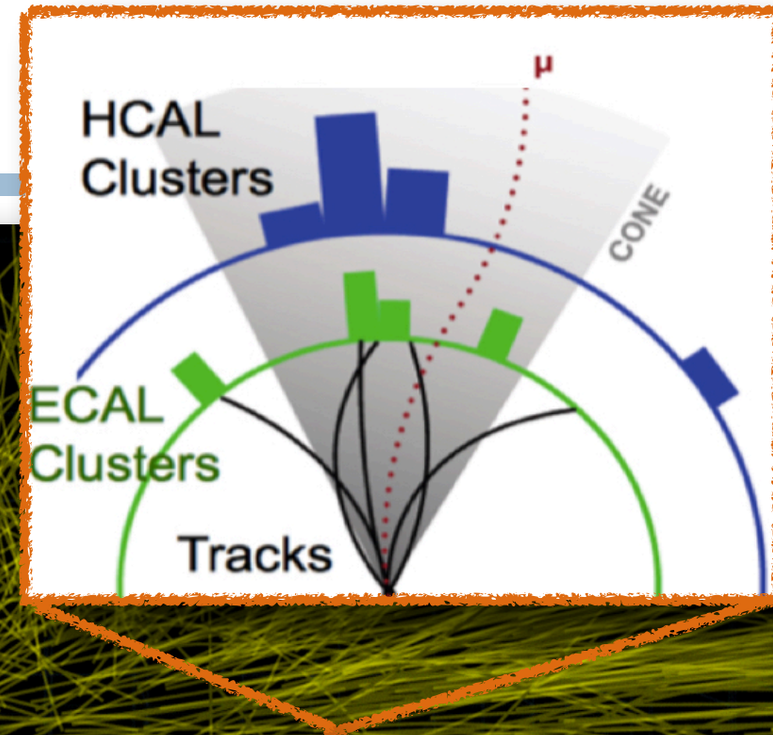

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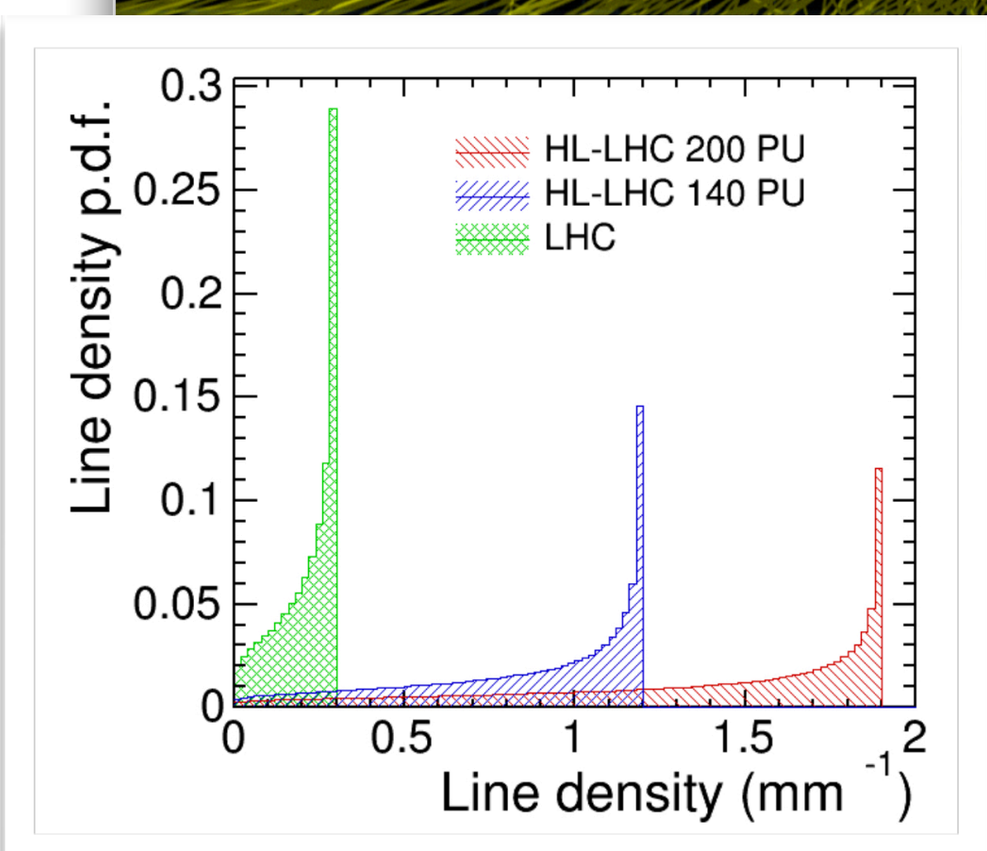
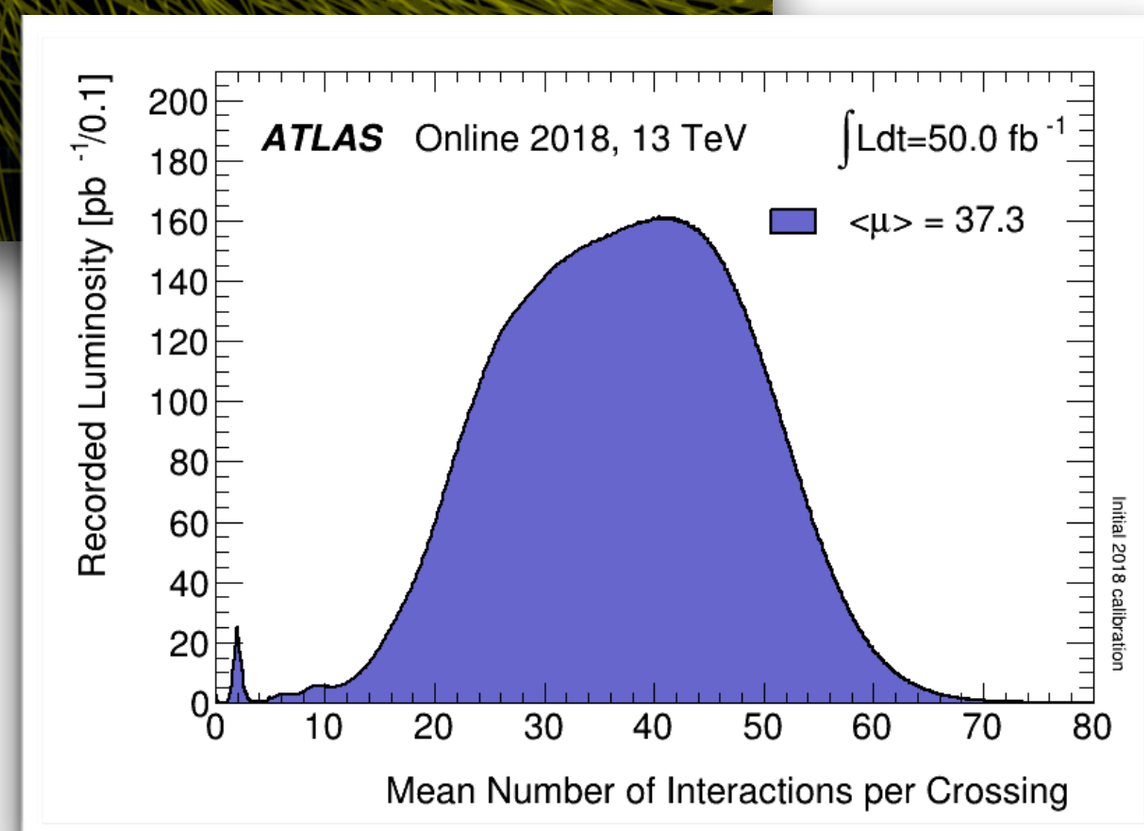
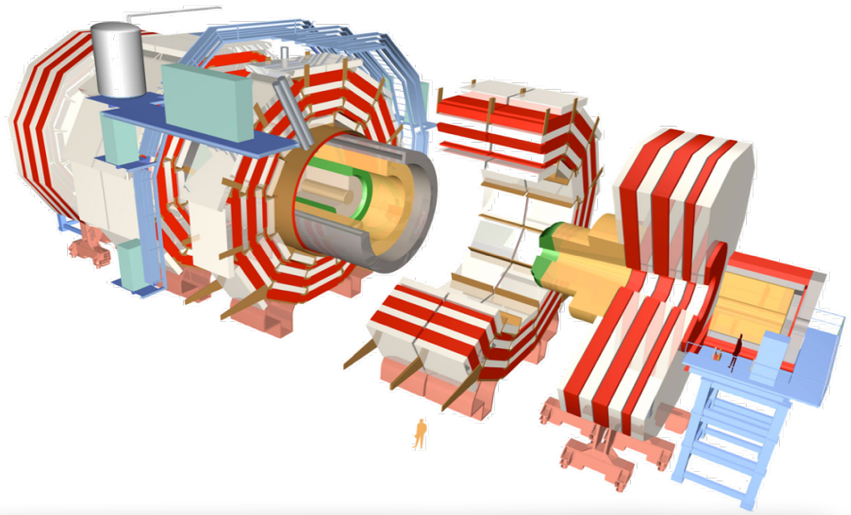
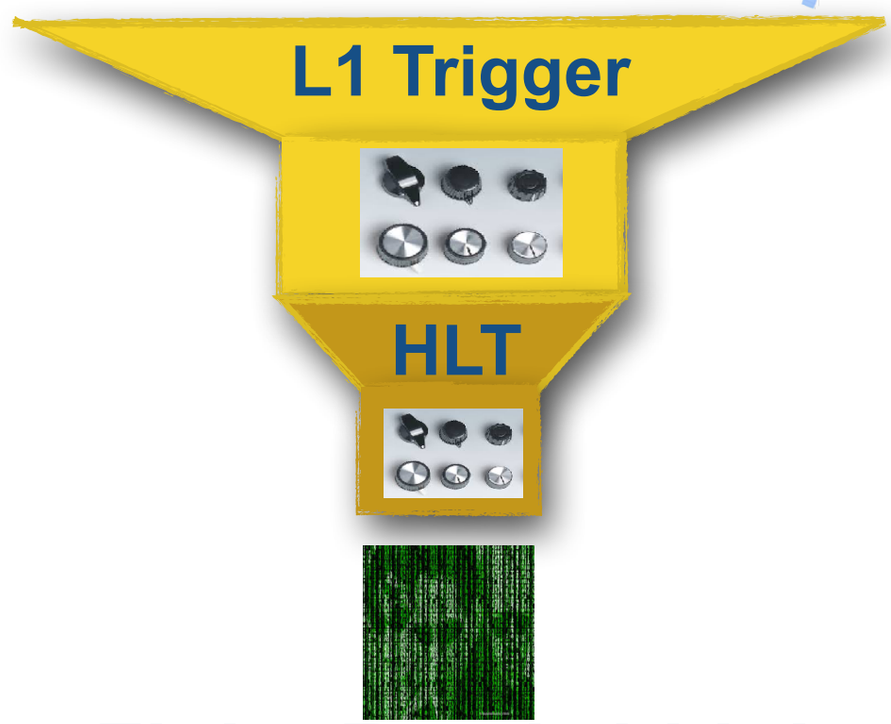




The Trigger Challenge (1)





Finite Bandwidth !

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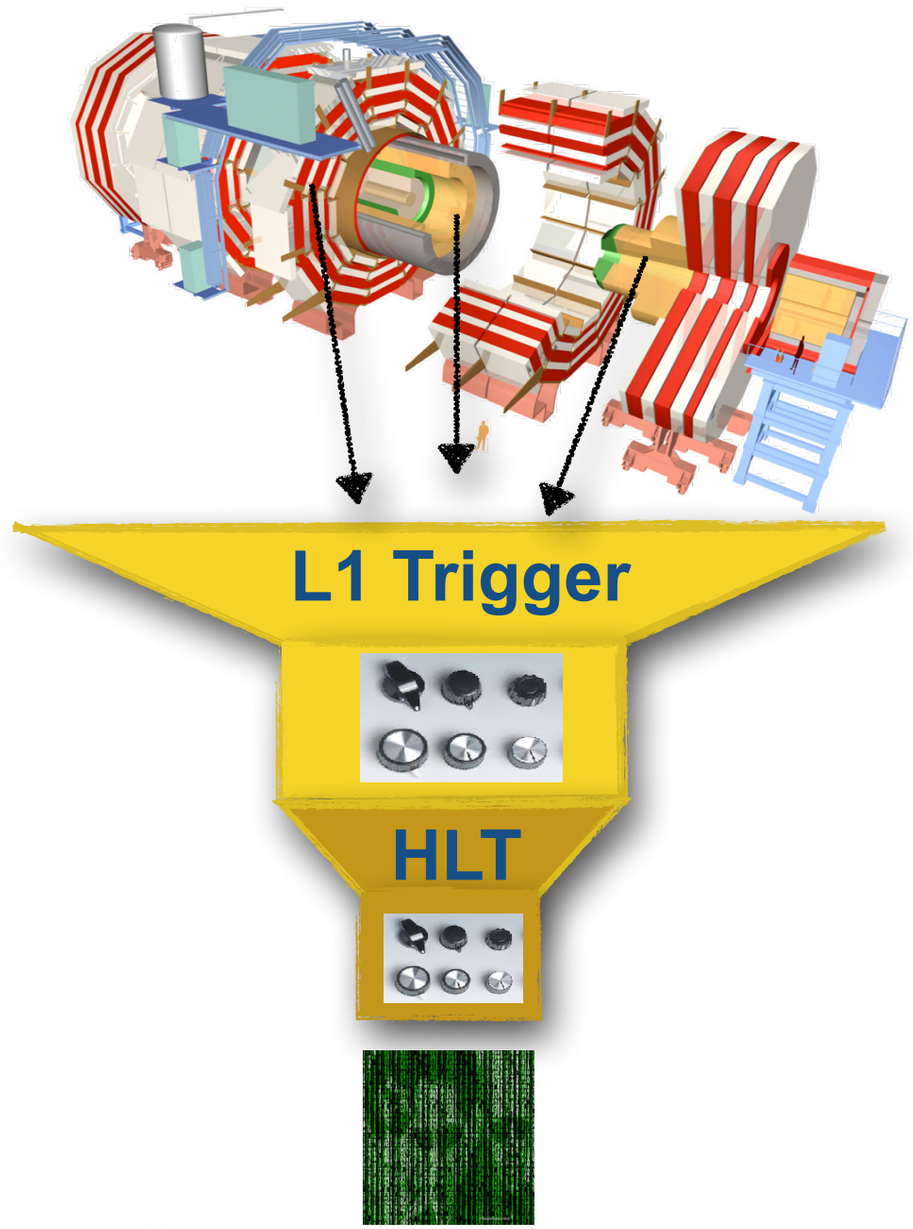

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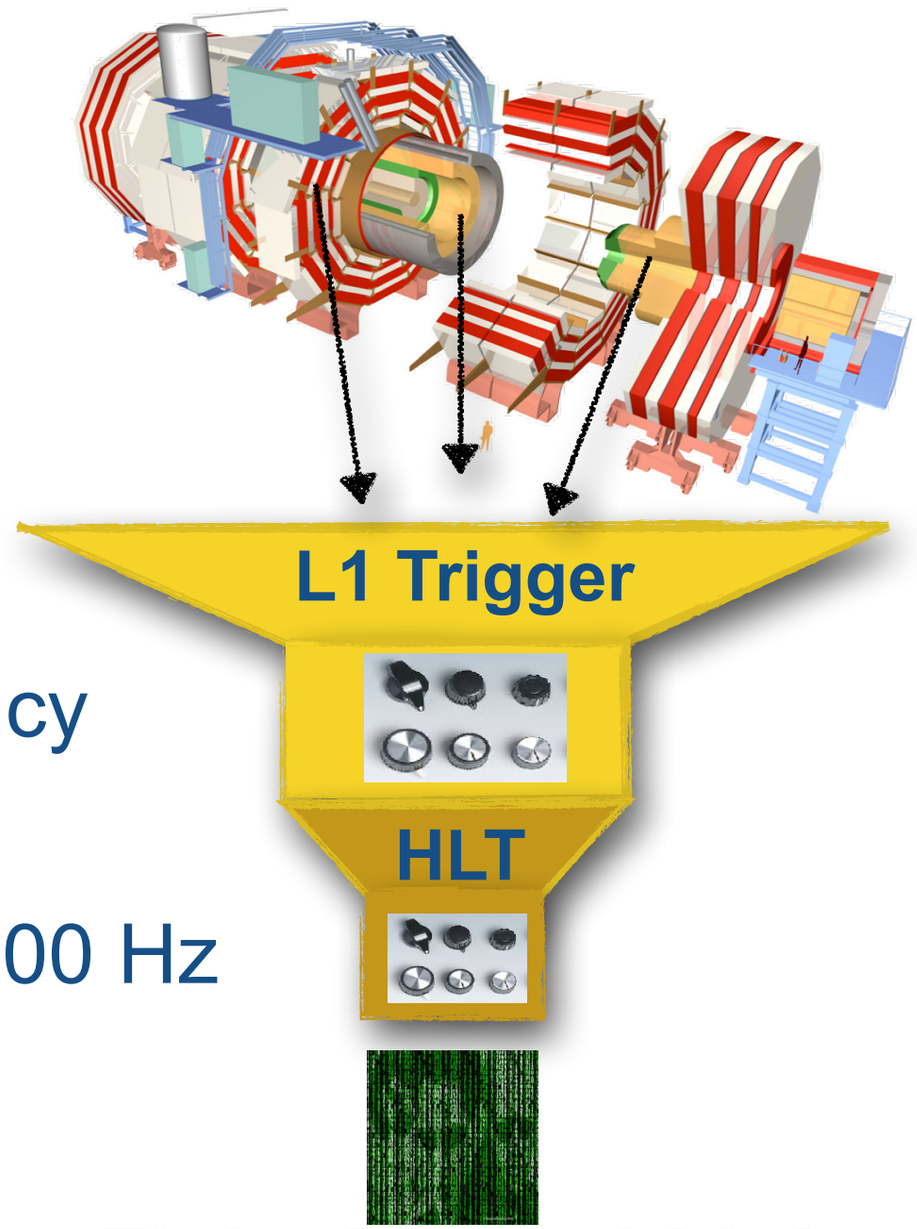

LHC:

~100 kHz
3.6 μs latency

~1000 Hz

Finite Bandwidth !

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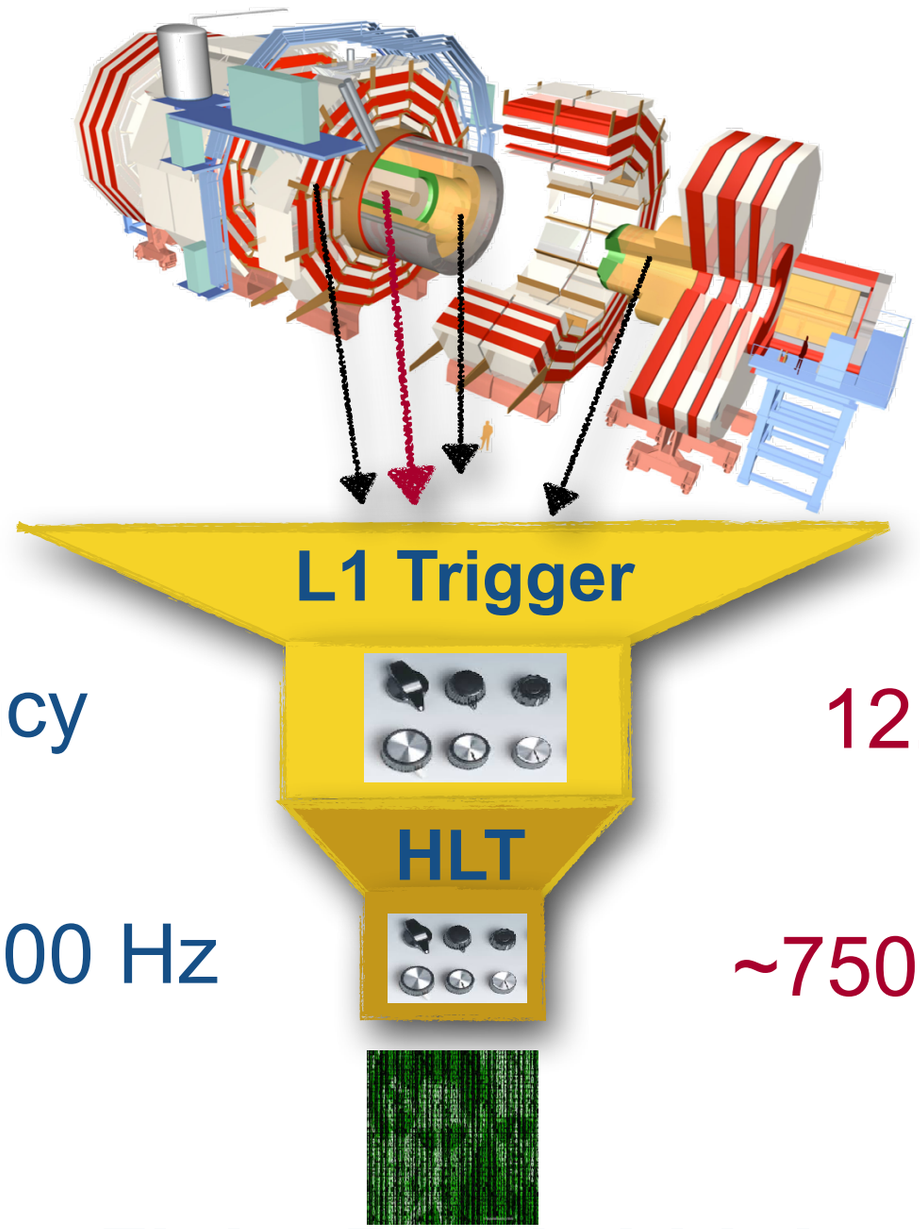


LHC:

~100 kHz
3.6 μs latency

~1000 Hz

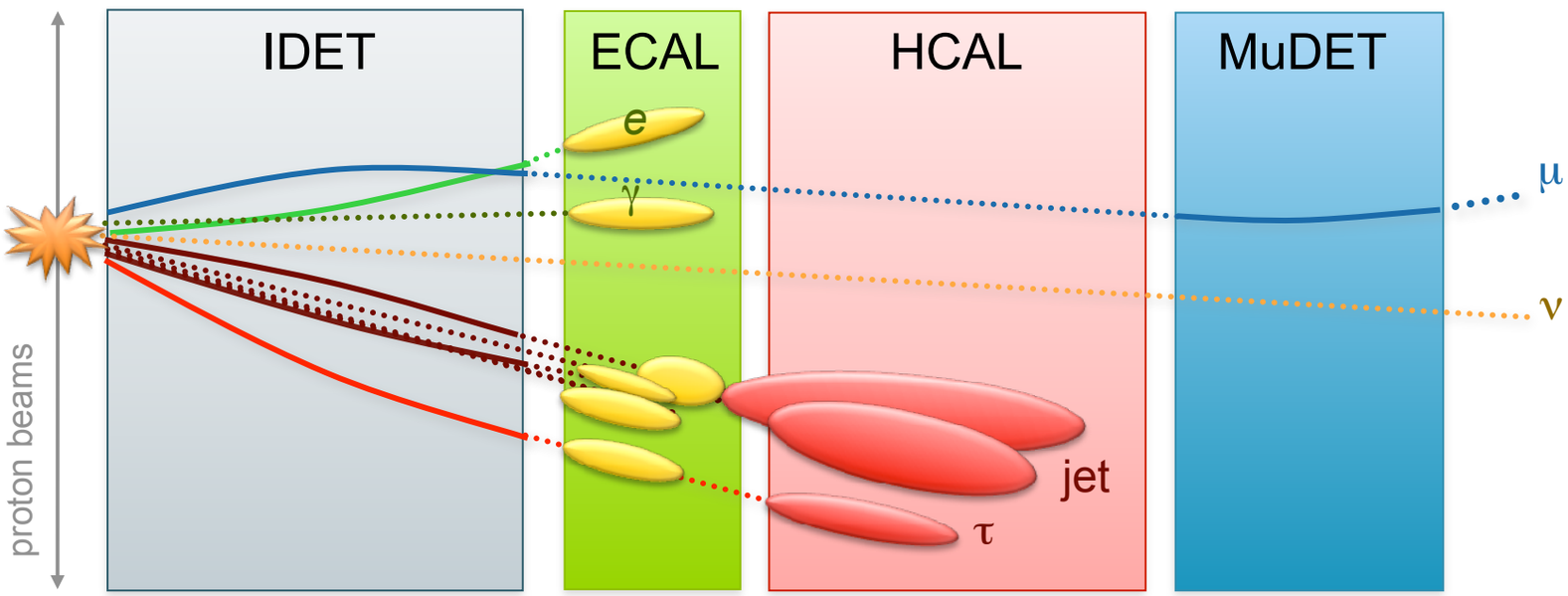
HL-LHC:

~750 kHz
12.5 μs latency

~7500 Hz

Finite Bandwidth !

The Trigger Challenge (2)



e.g.
"Interesting" muons
from, eg.
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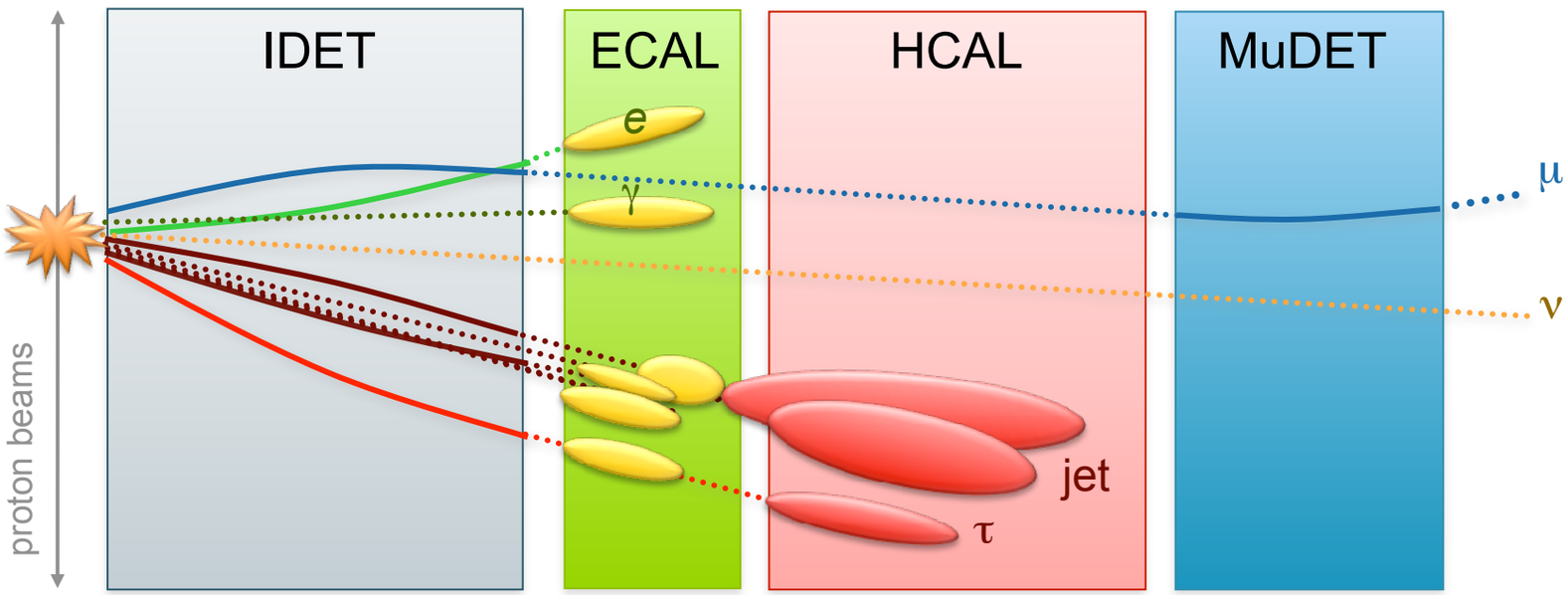

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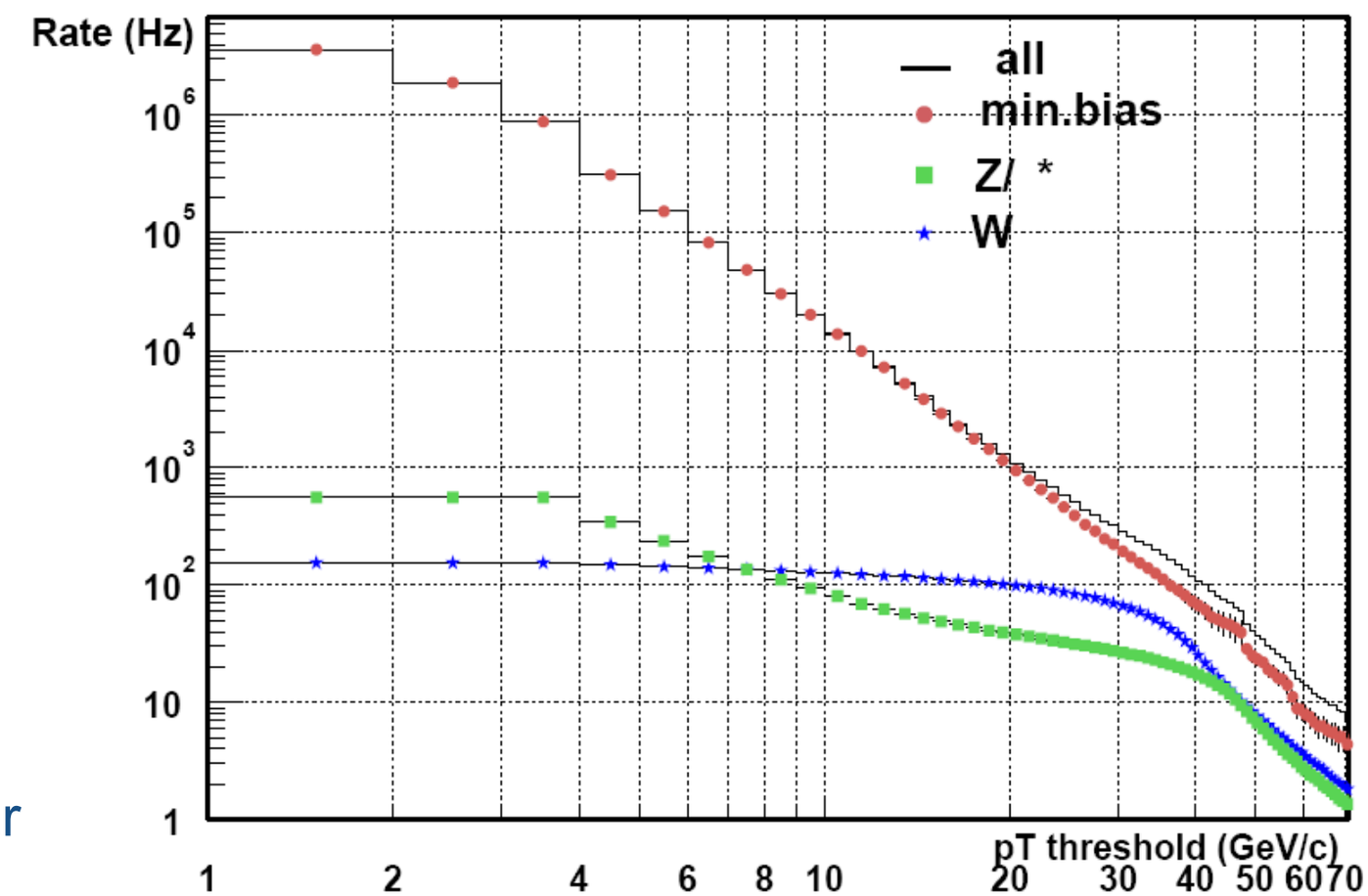
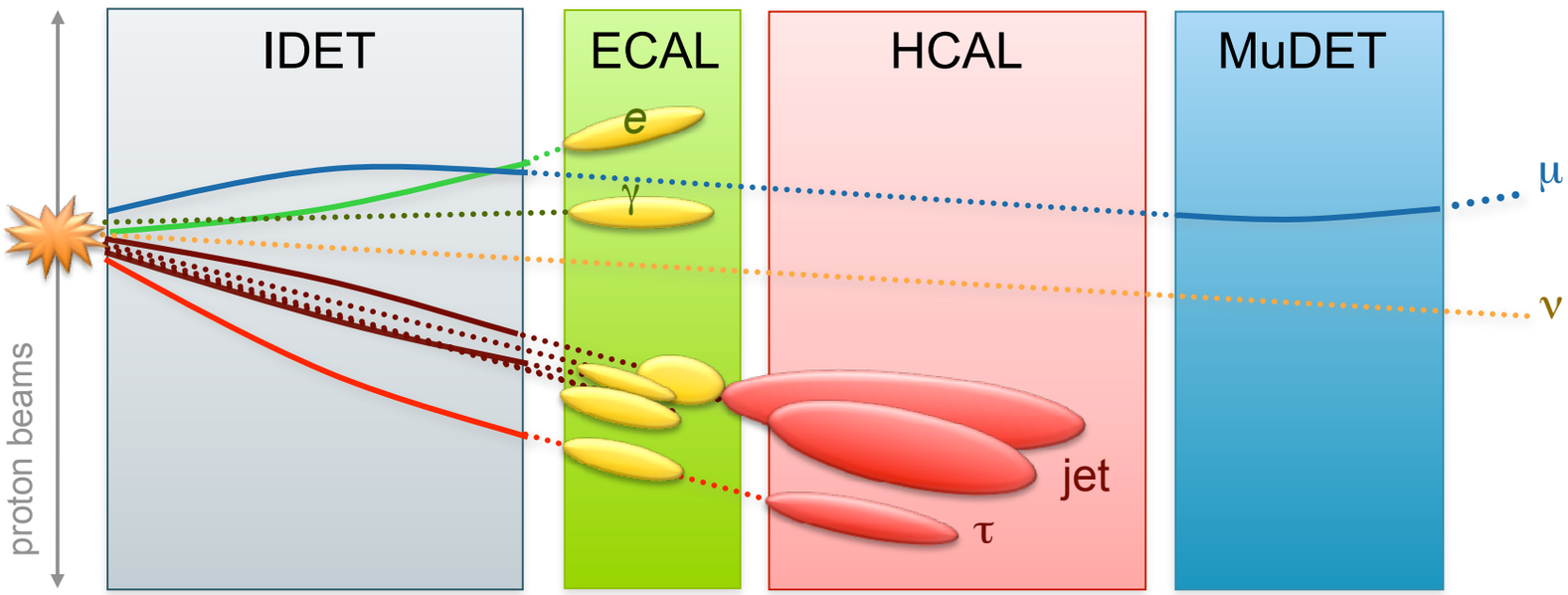
Example: Muon rate

~power law



Also: Trigger rate highly non-linear
with pile-up!

The Trigger Challenge (2)



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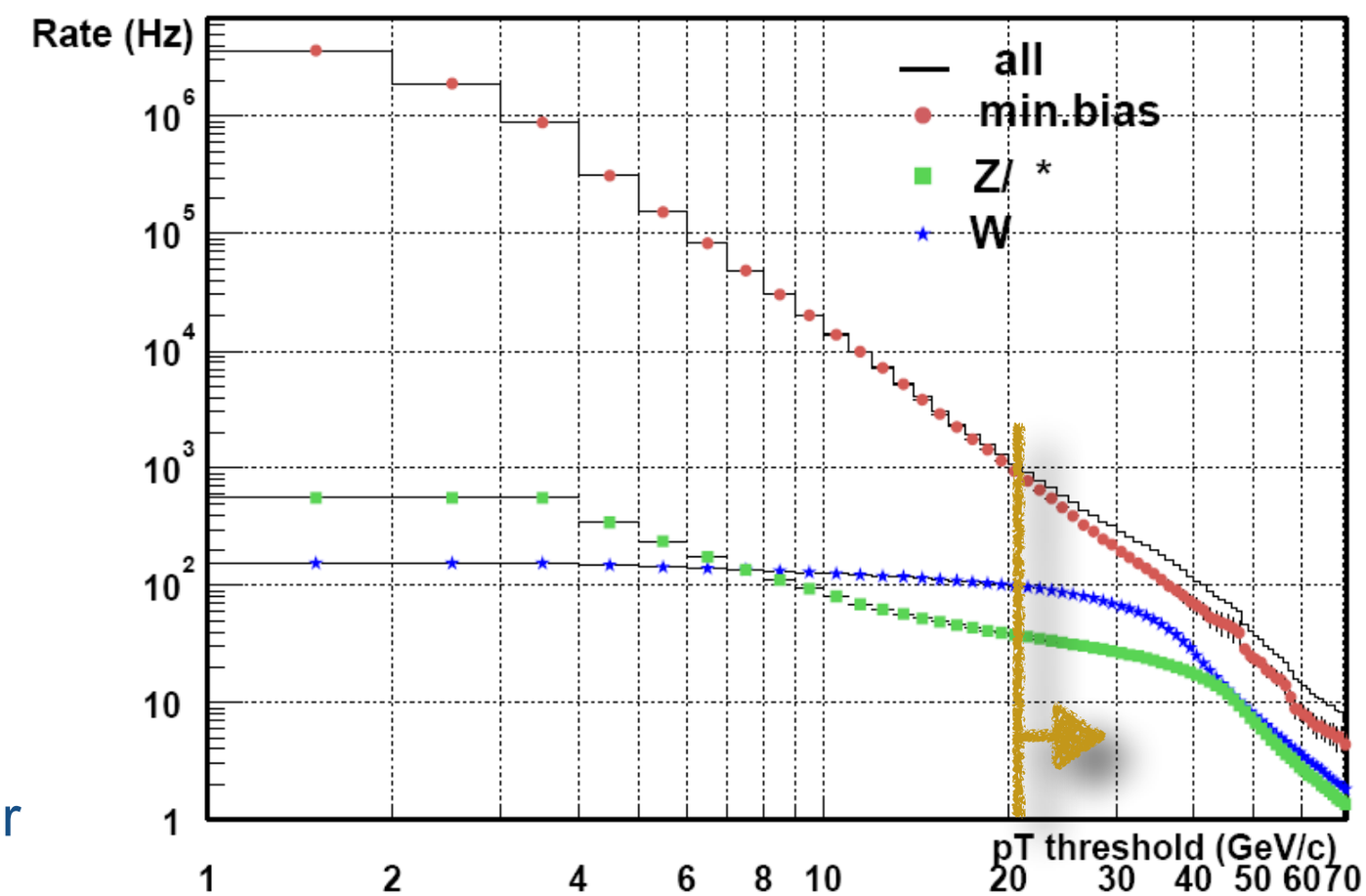
Example: Muon rate

~power law



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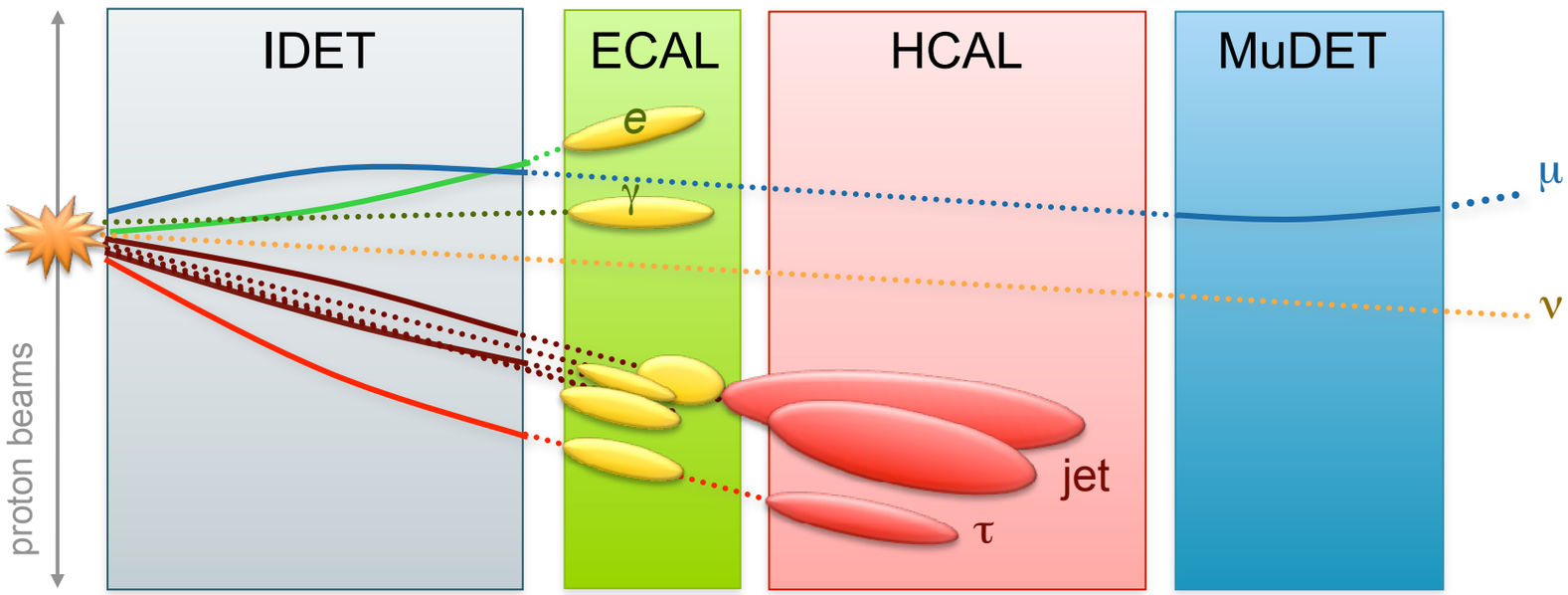

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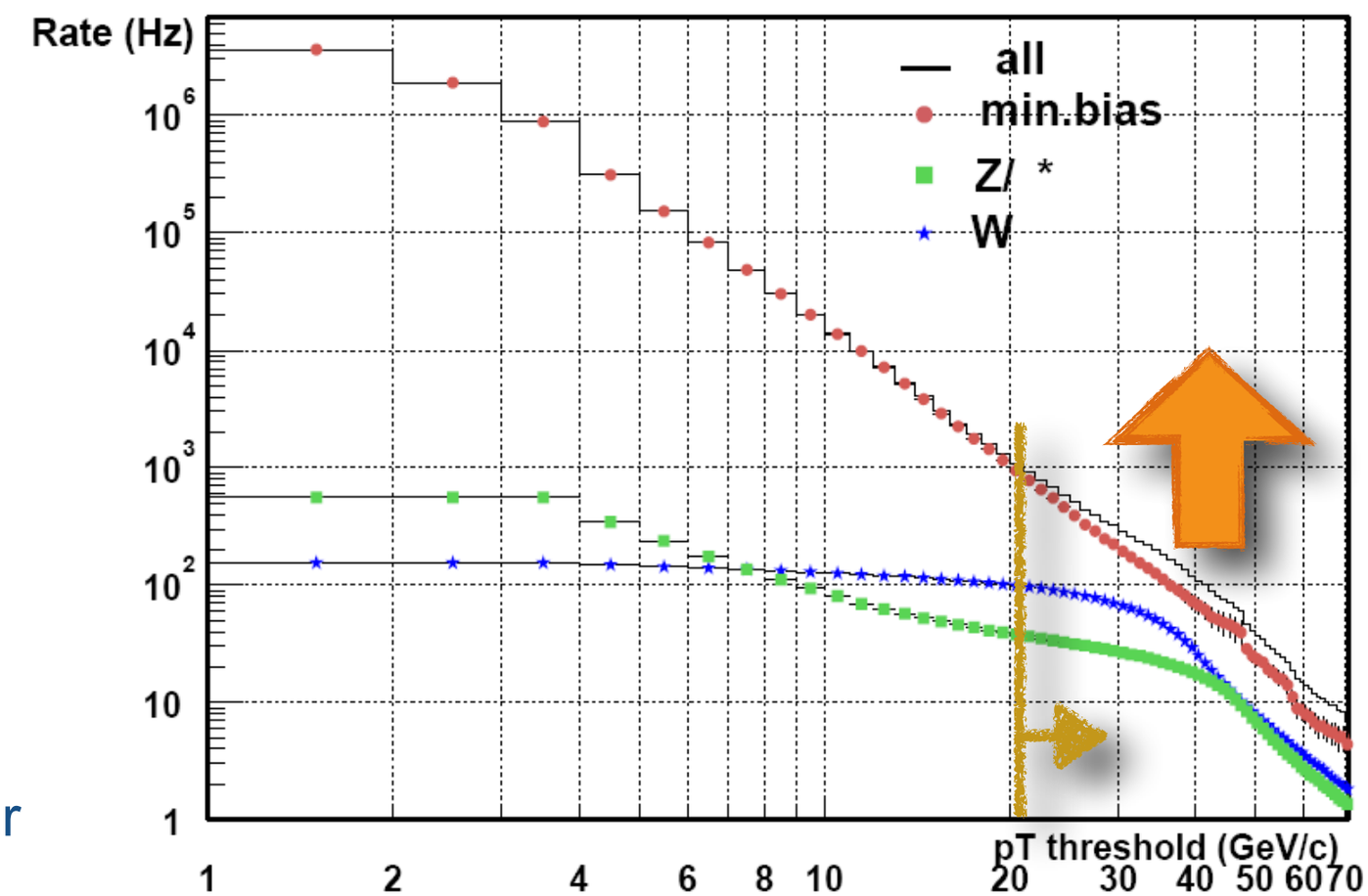

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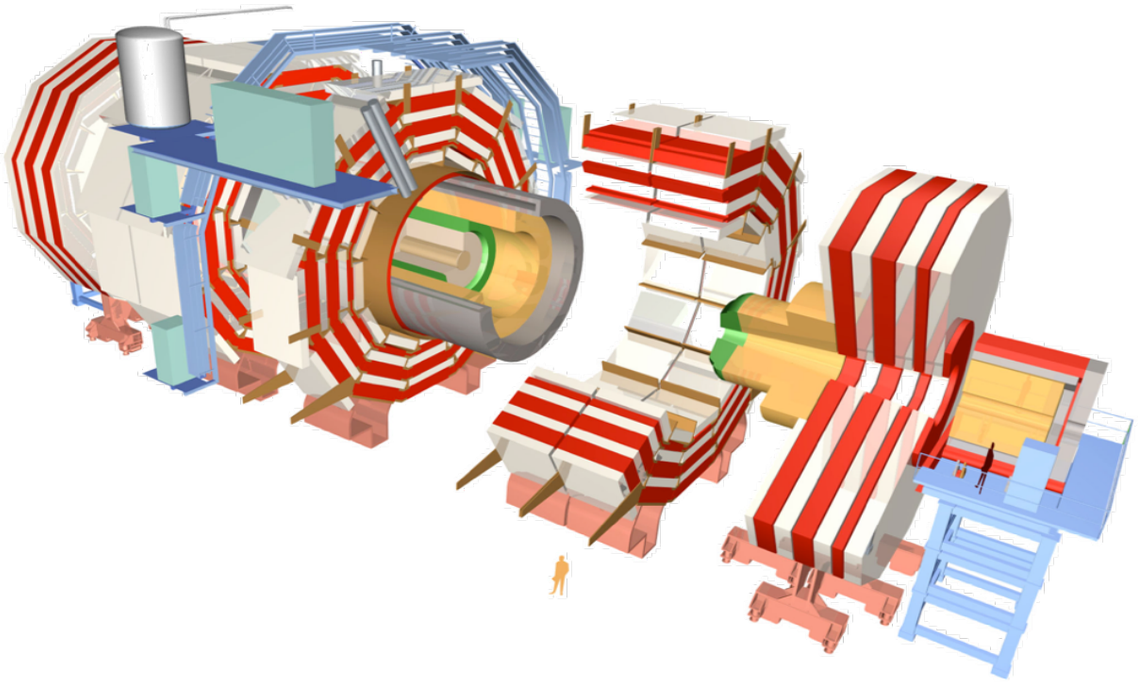

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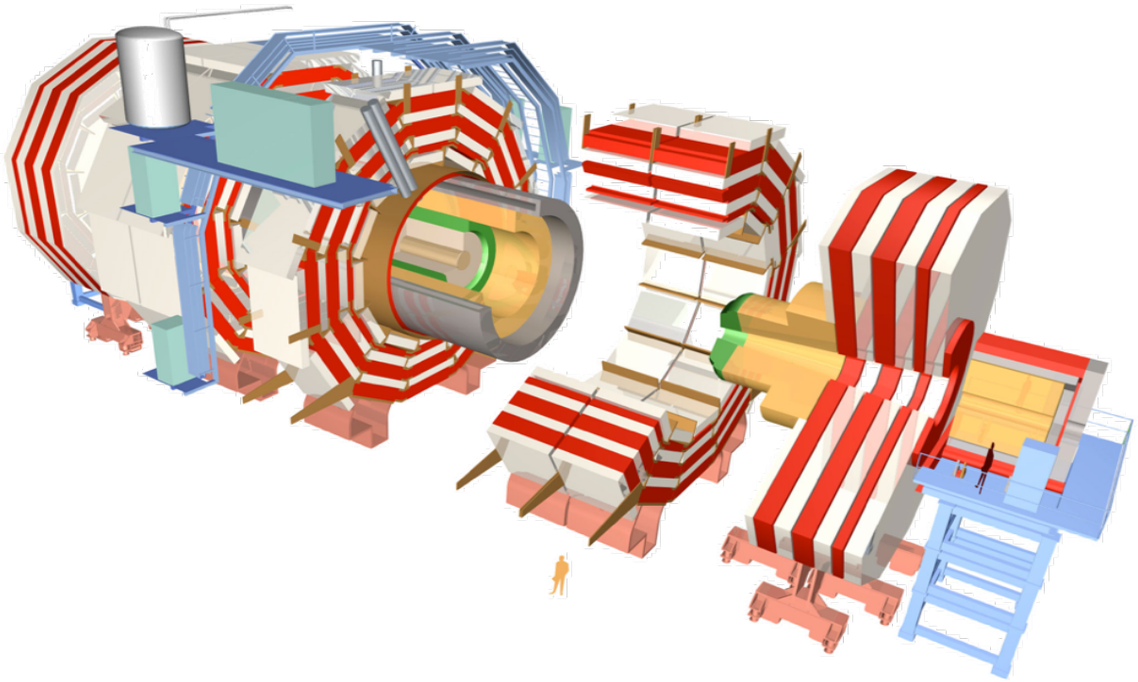

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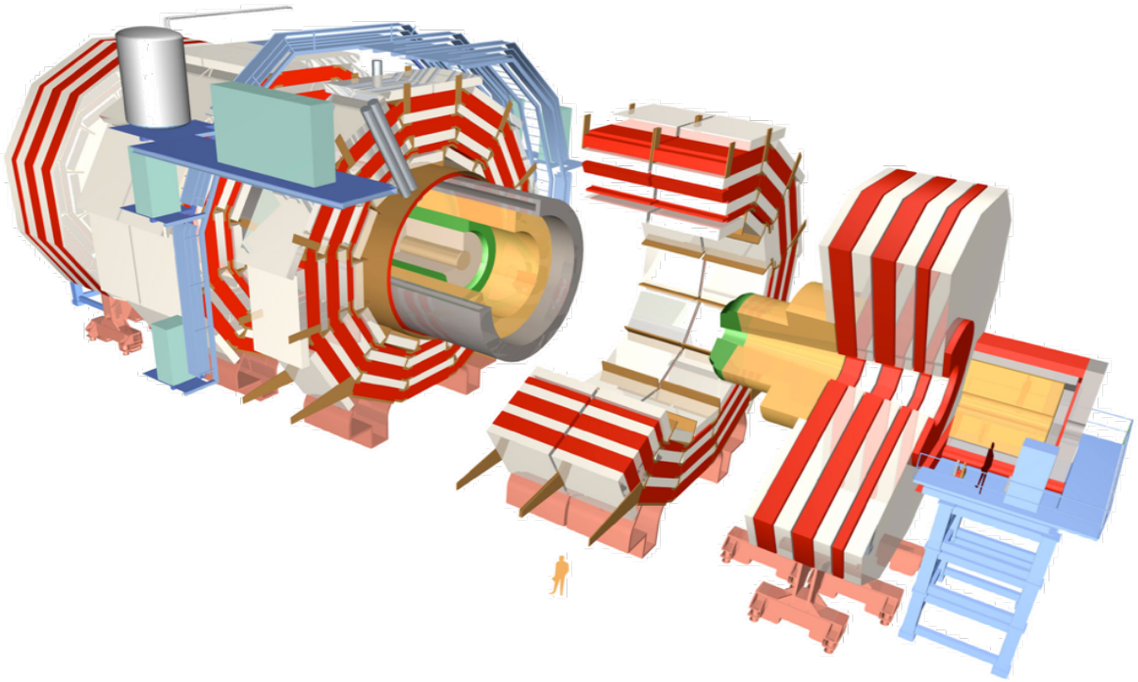

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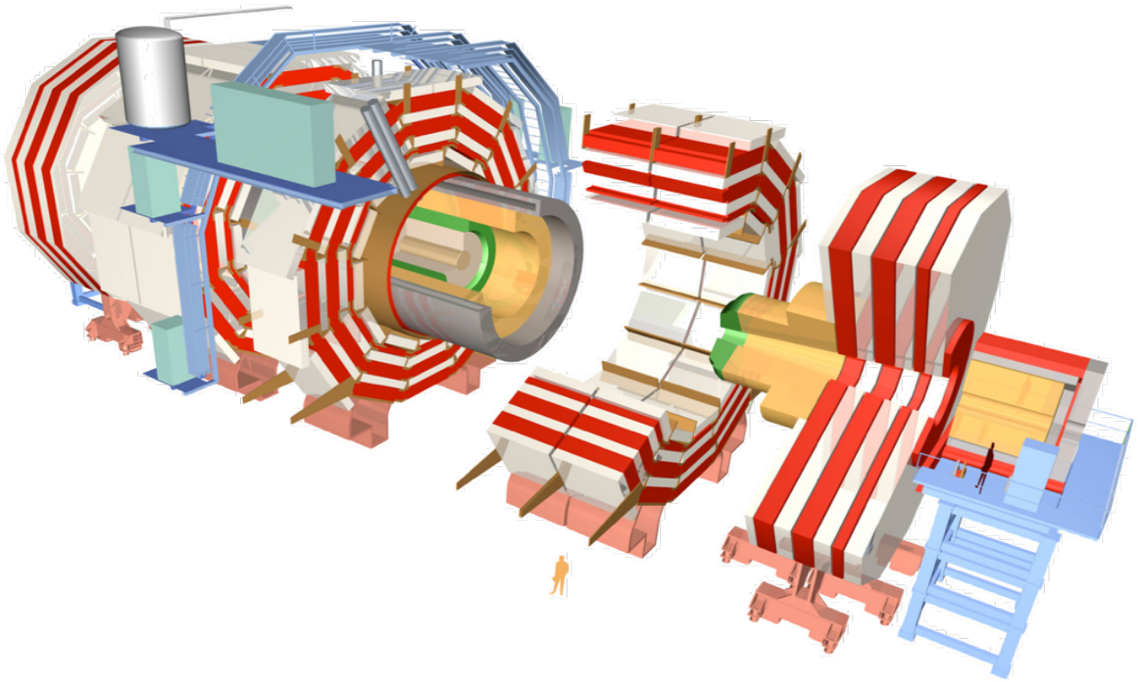

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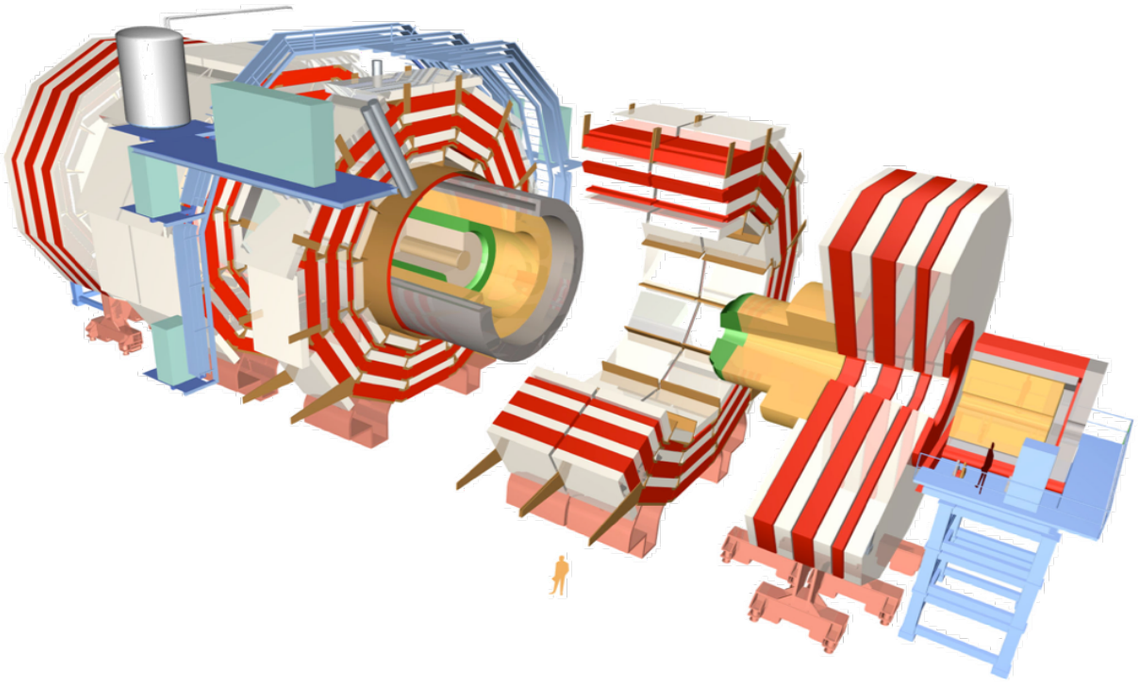

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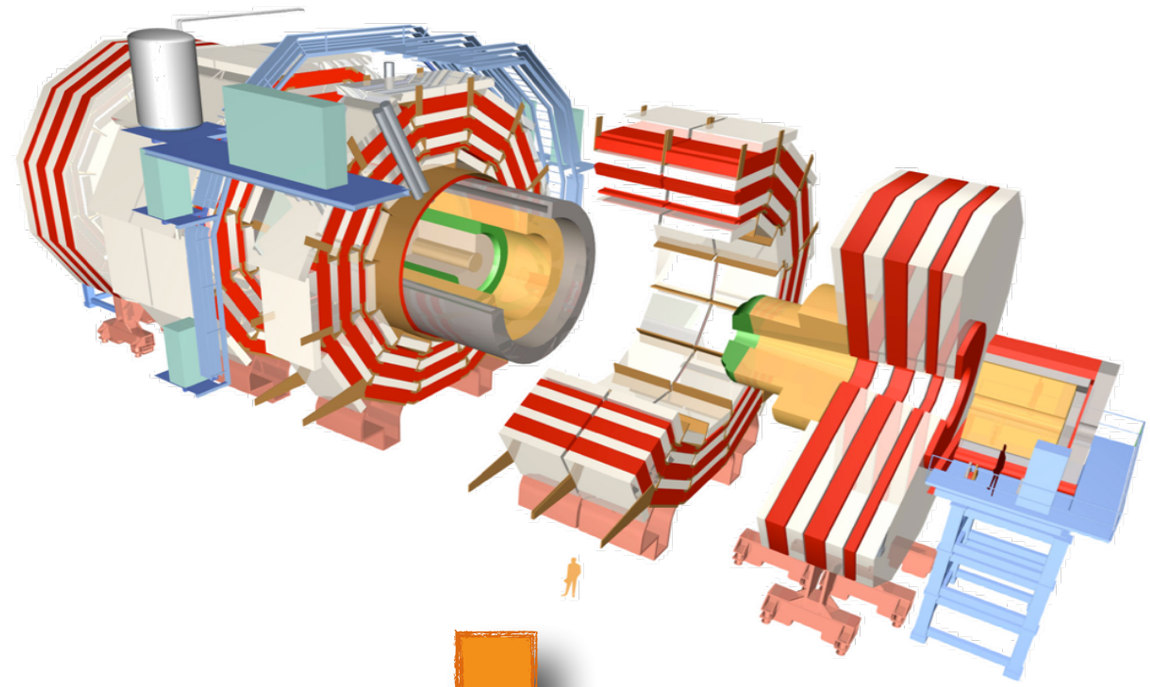
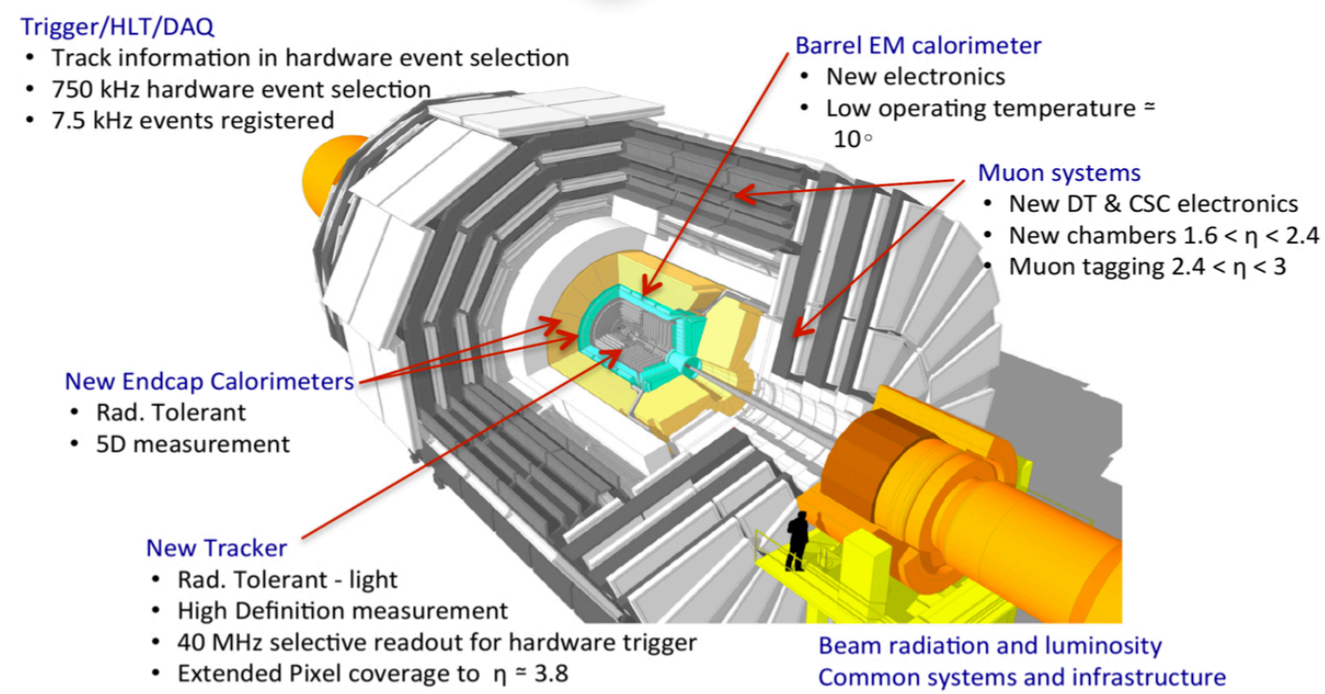
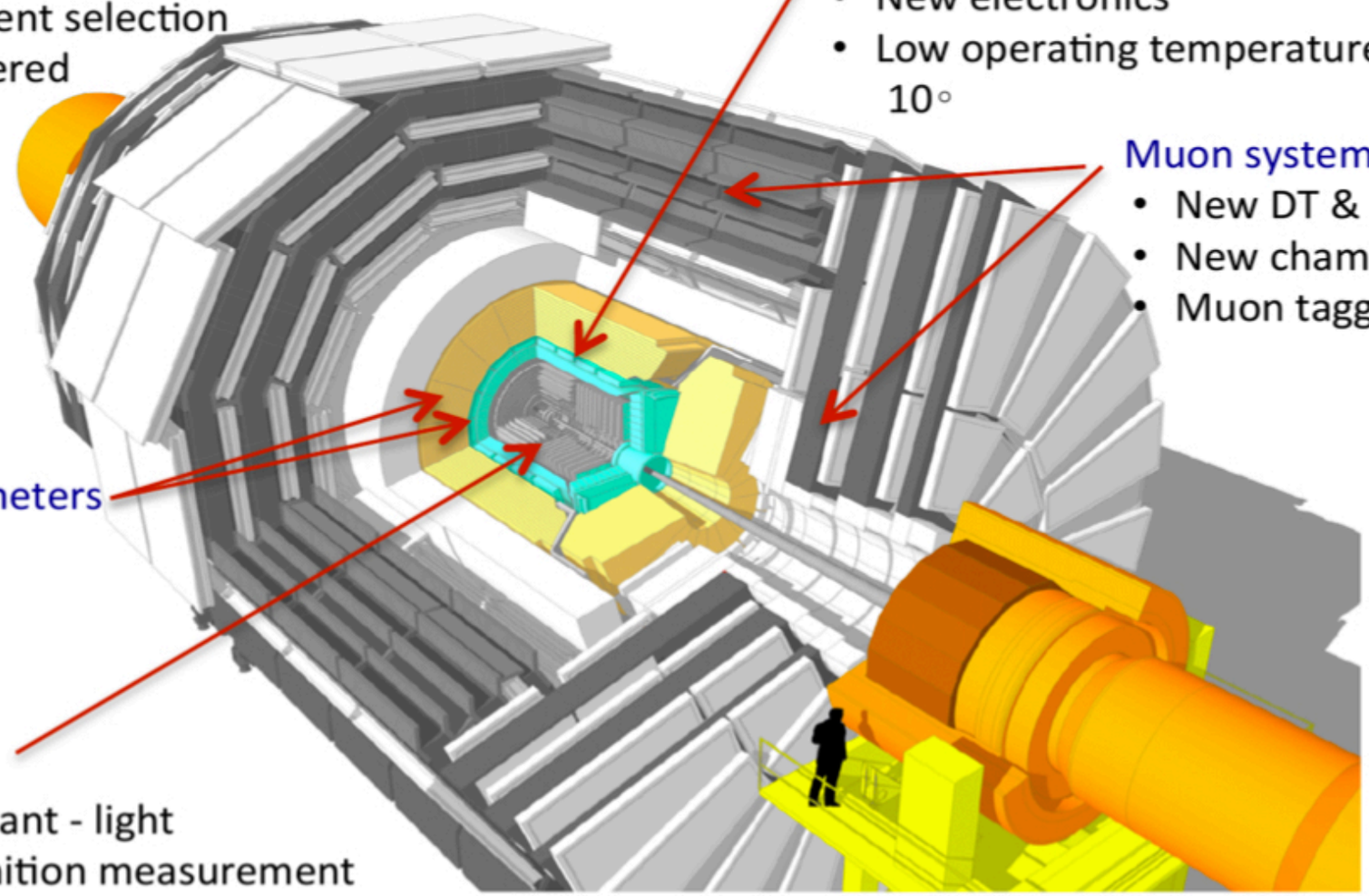




In a nutshell….



Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ 10°

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \approx 3.8$

Beam radiation and luminosity
Common systems and infrastructure

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ETH zürich

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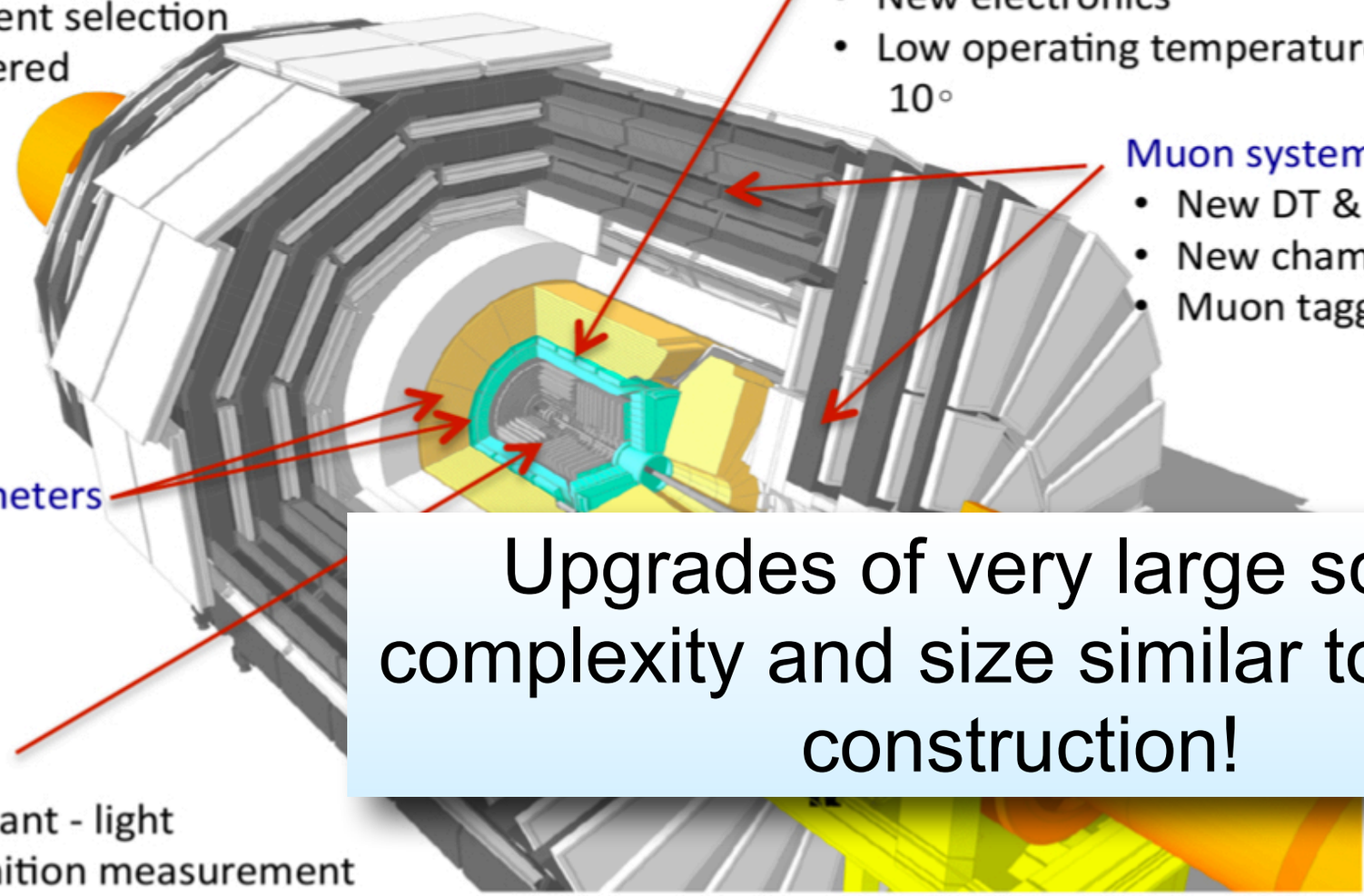

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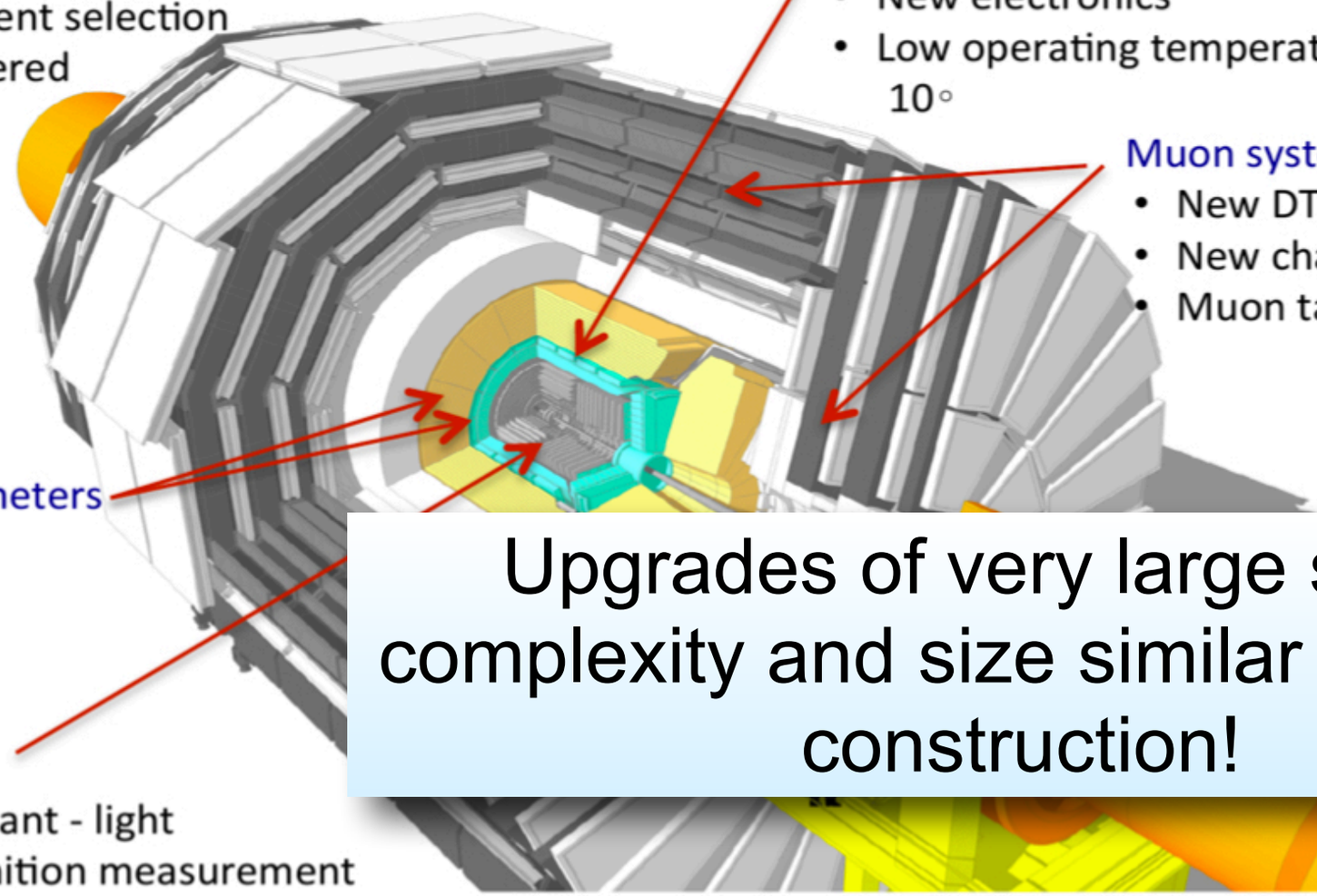

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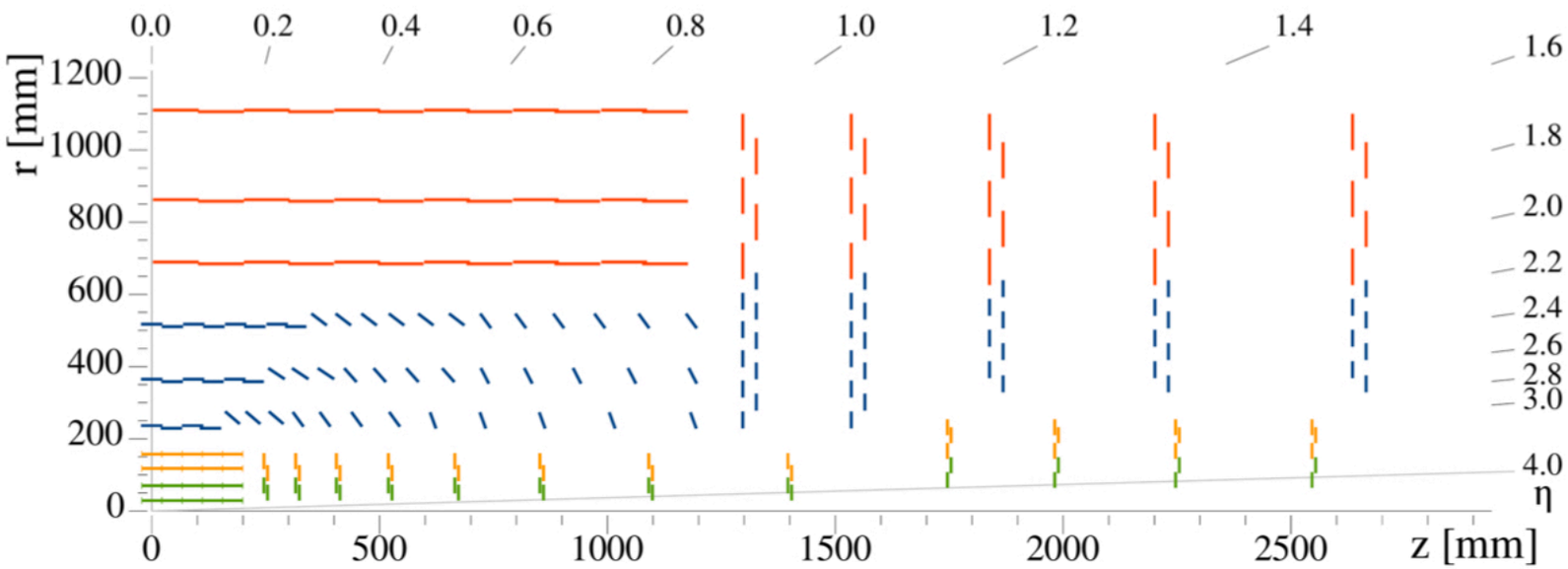
"*CMS likes to do bold projects….*" (J. Butler)
Obviously, just the same is true for the ATLAS upgrades…

A new Tracker, with Trigger



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(>2 billion pixels and strips!)

less material, large angular coverage.

Will maintain and even improve the excellent tracking performance of CMS

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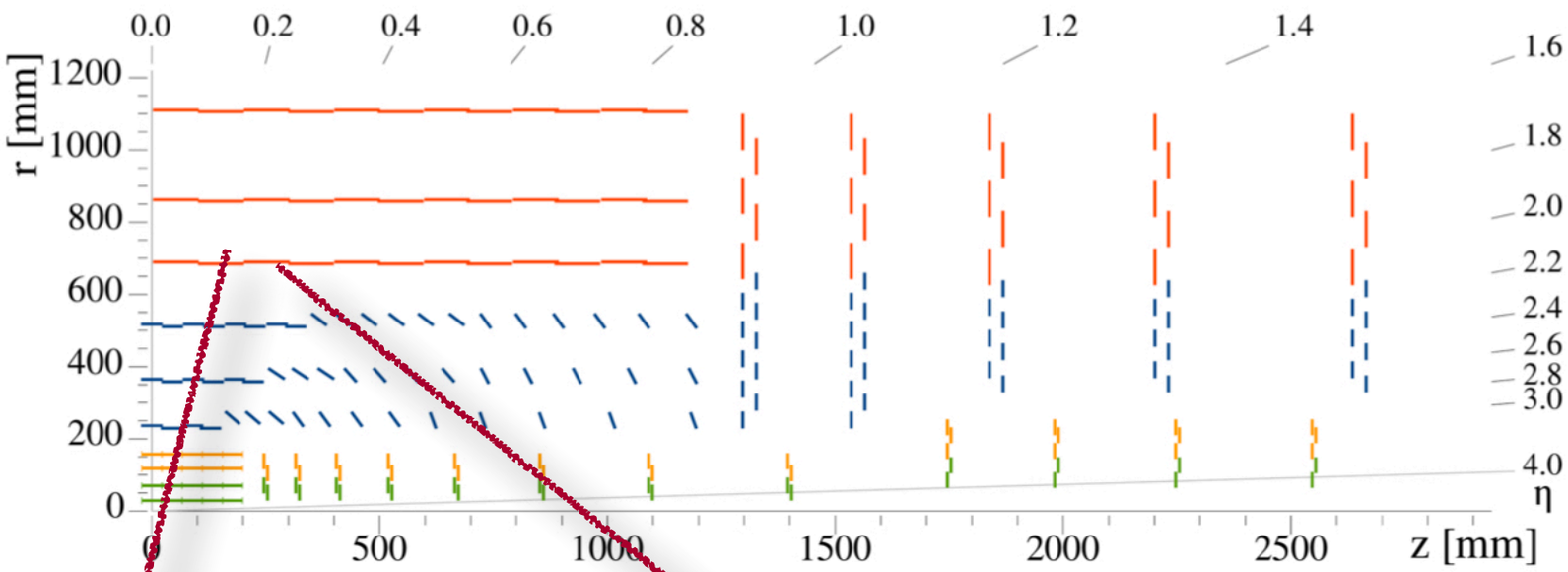

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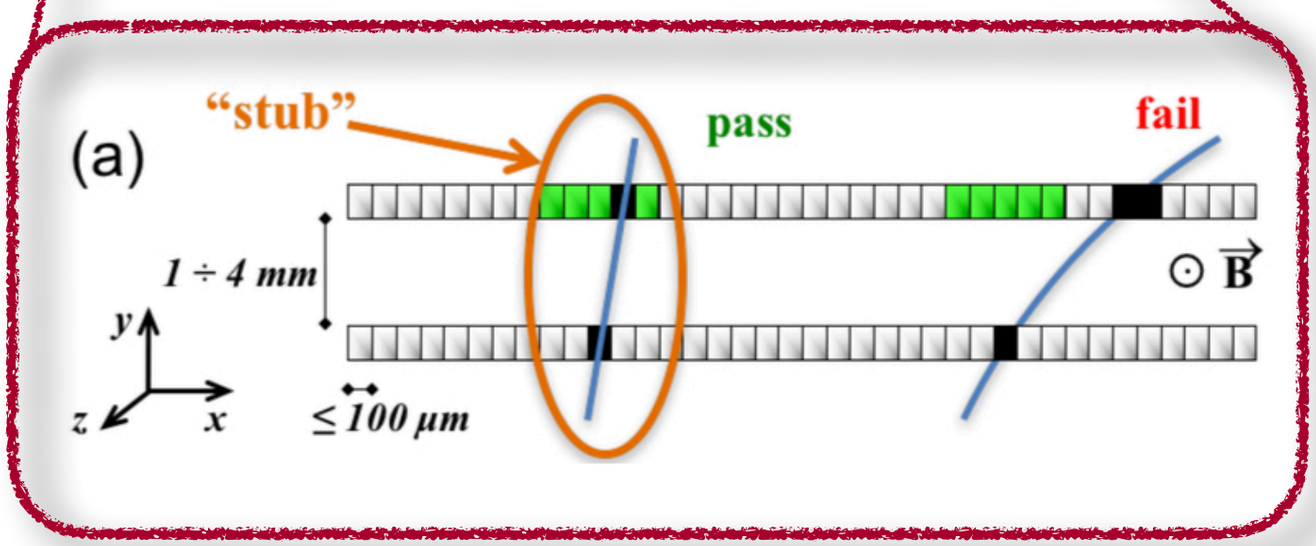

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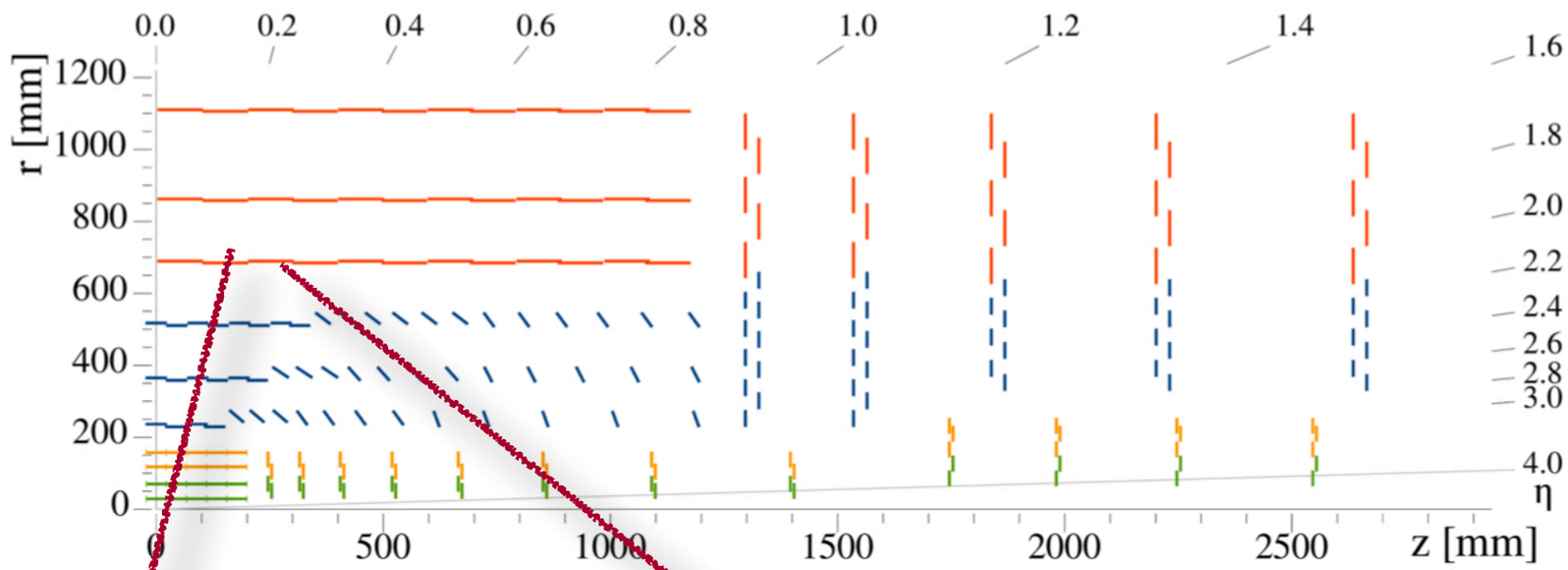

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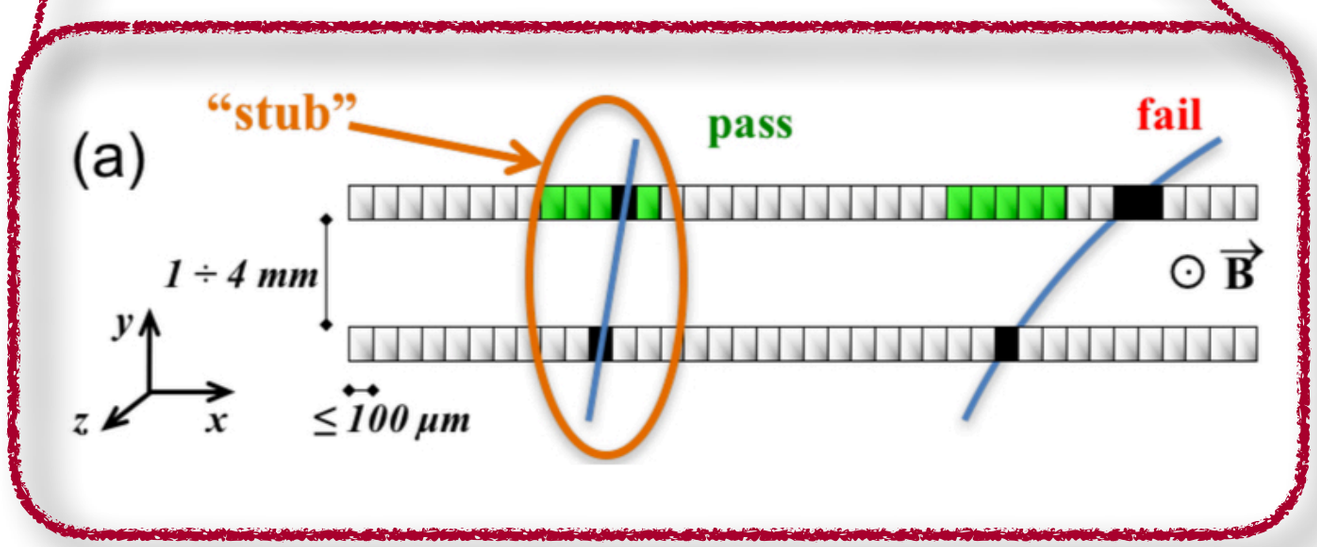
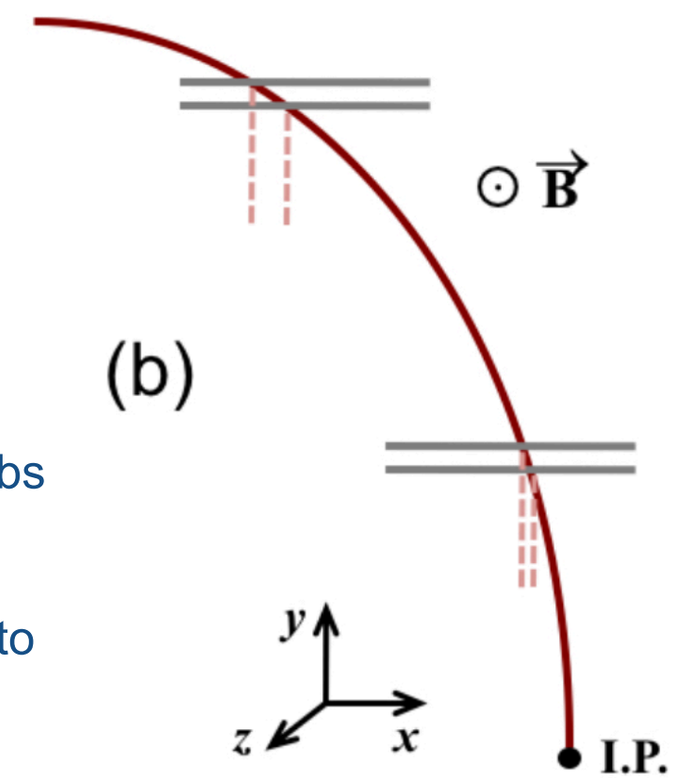
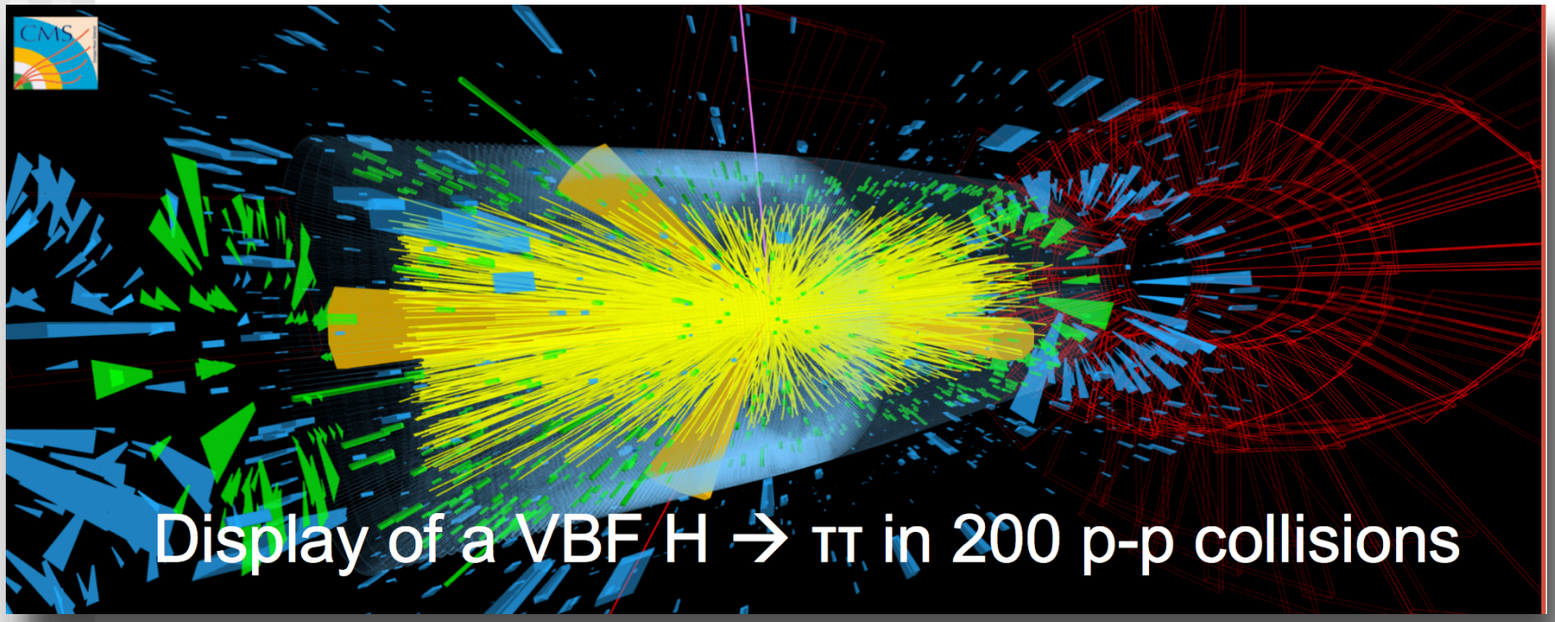


Up to 15k stubs at 40 MHz; 5 μsec to find tracks; down to p_T~2GeV, $|\eta|$<2.4



A new forward calorimeter



Display of a VBF H → ττ in 200 p-p collisions

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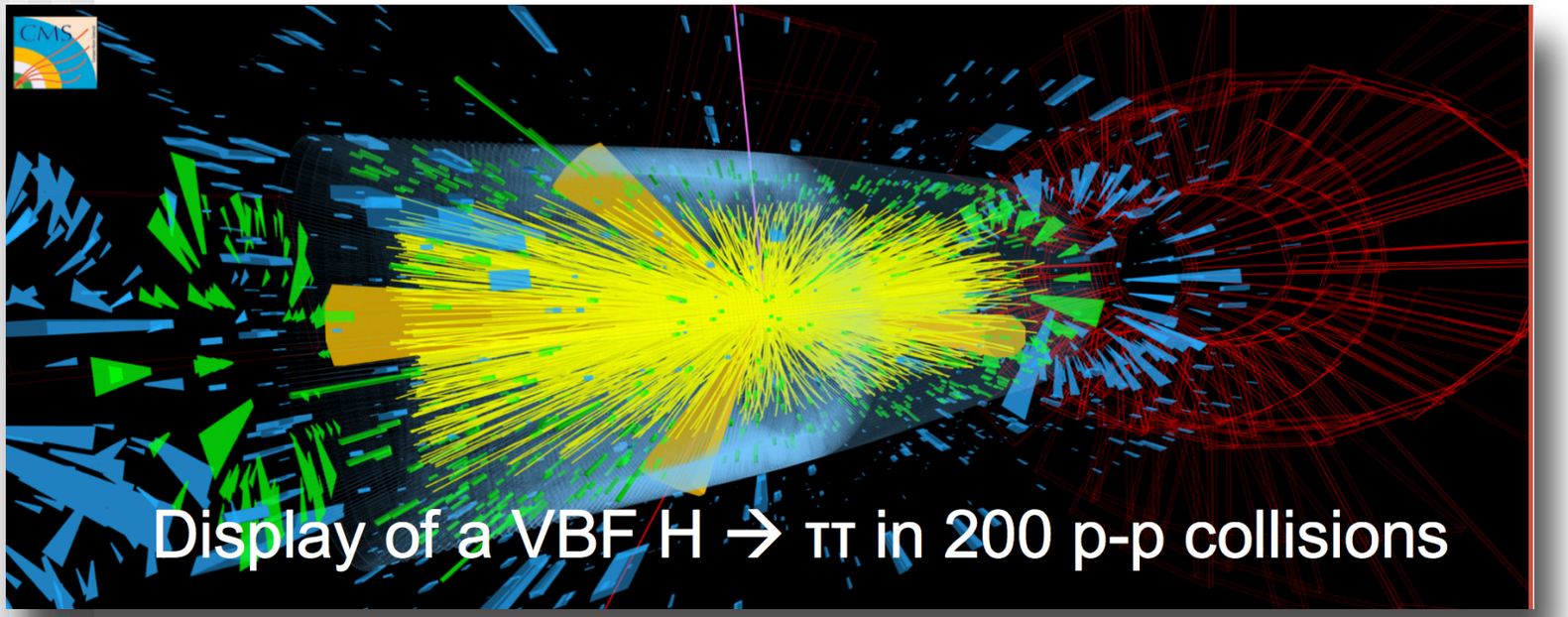

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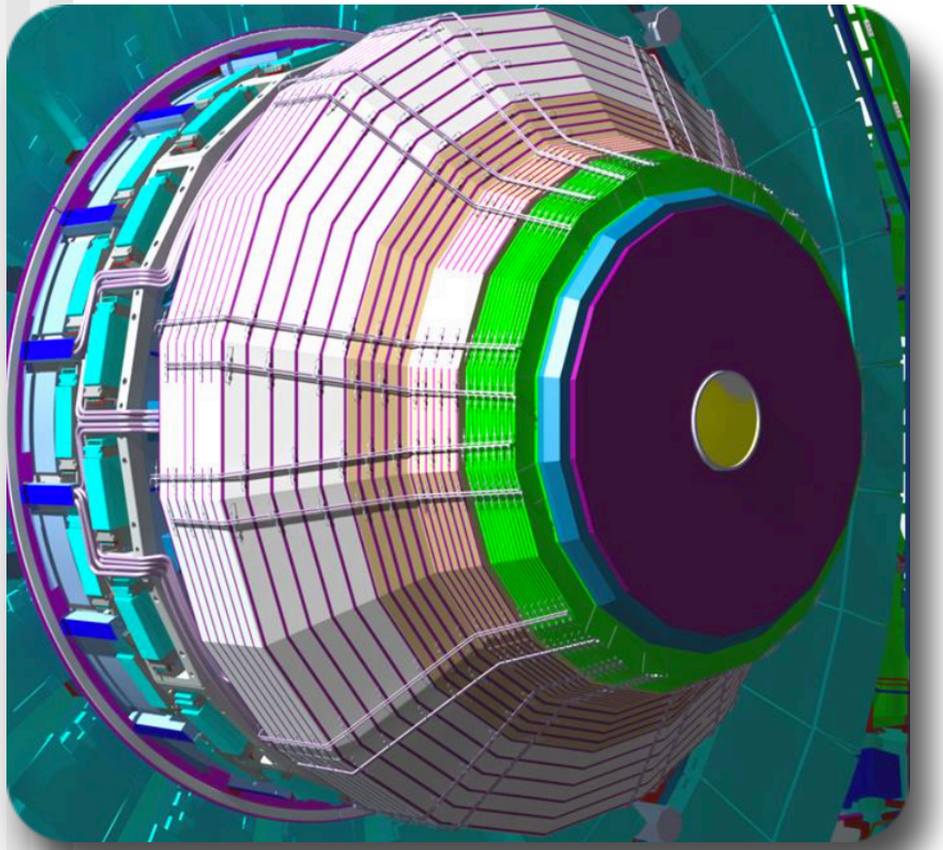
High granularity **silicon detector with tungsten/brass absorber** (plastic scintillator and brass absorber in back part)

a "first" for a hadron collider exp.!



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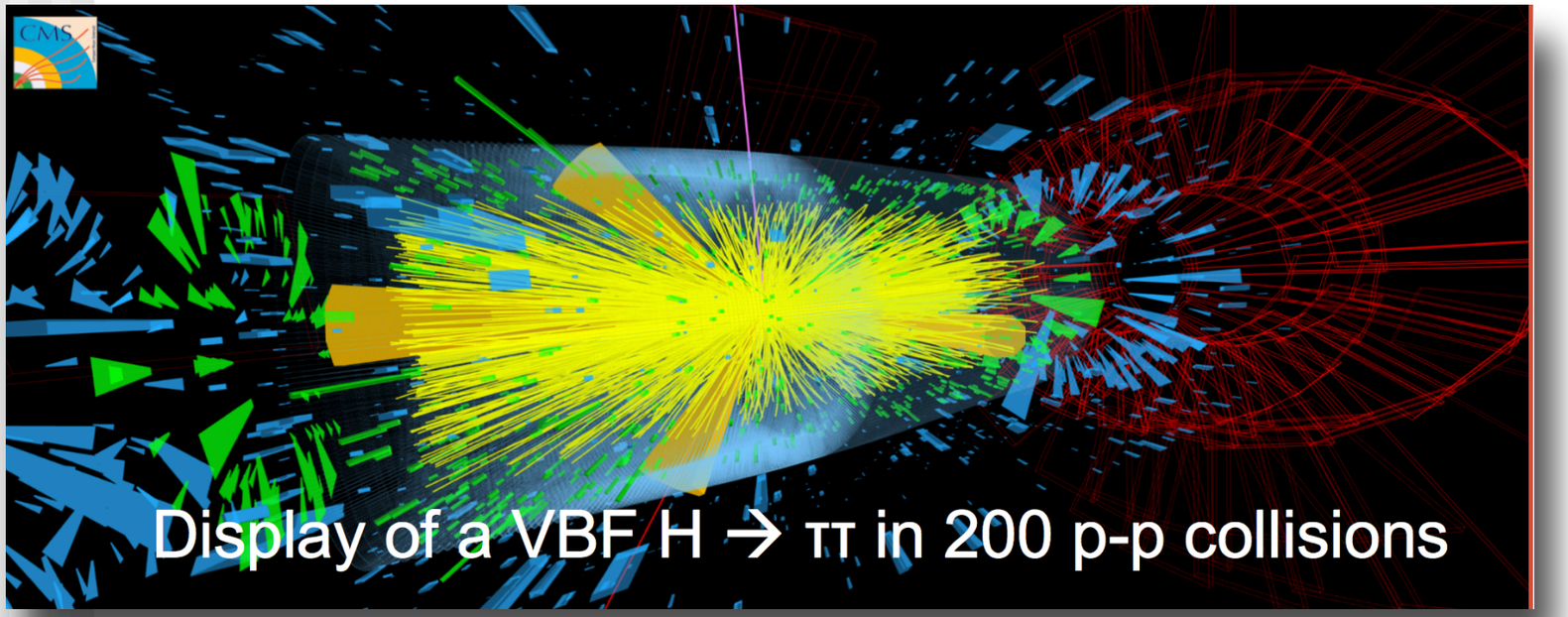

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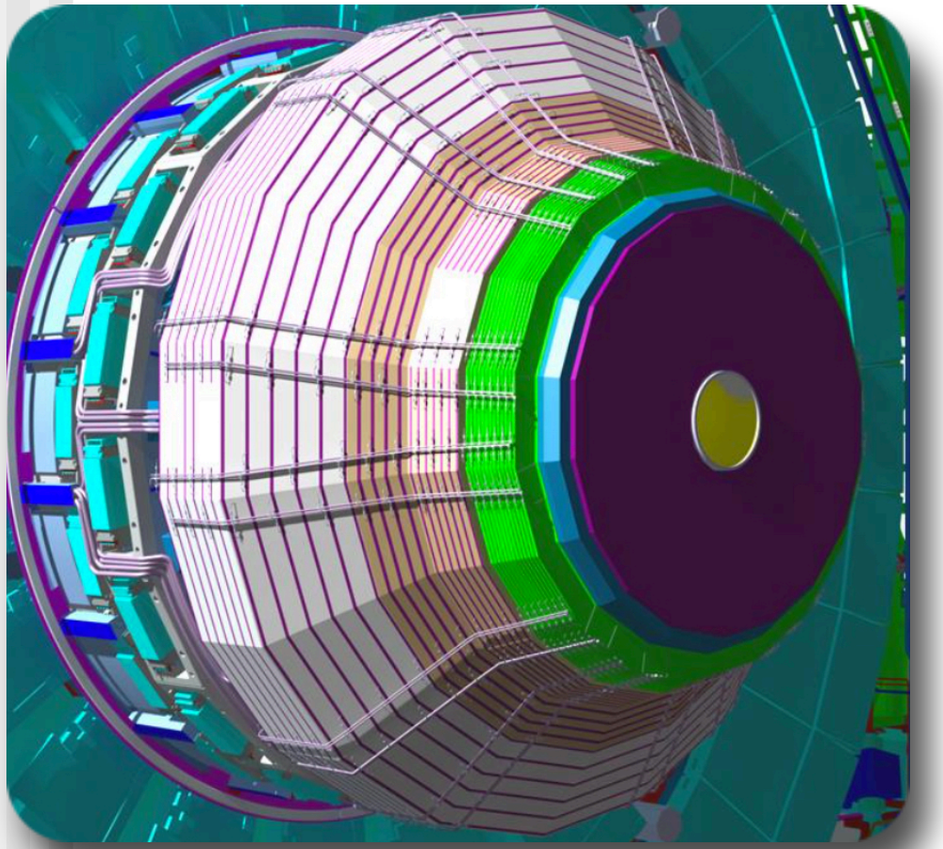
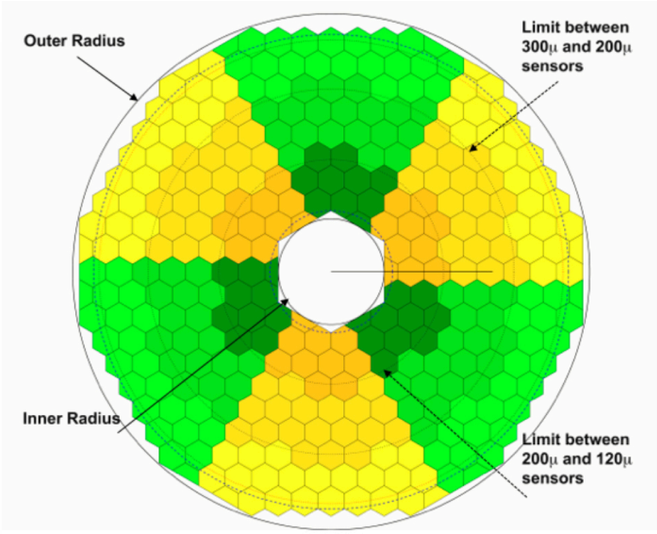
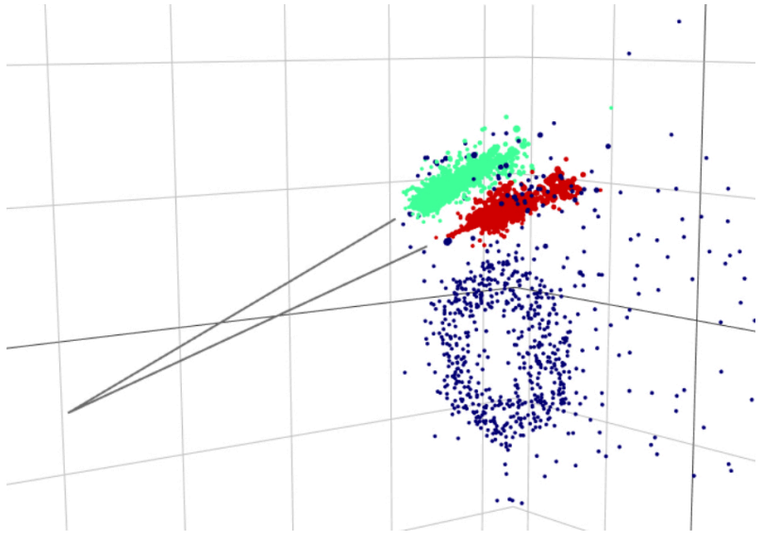
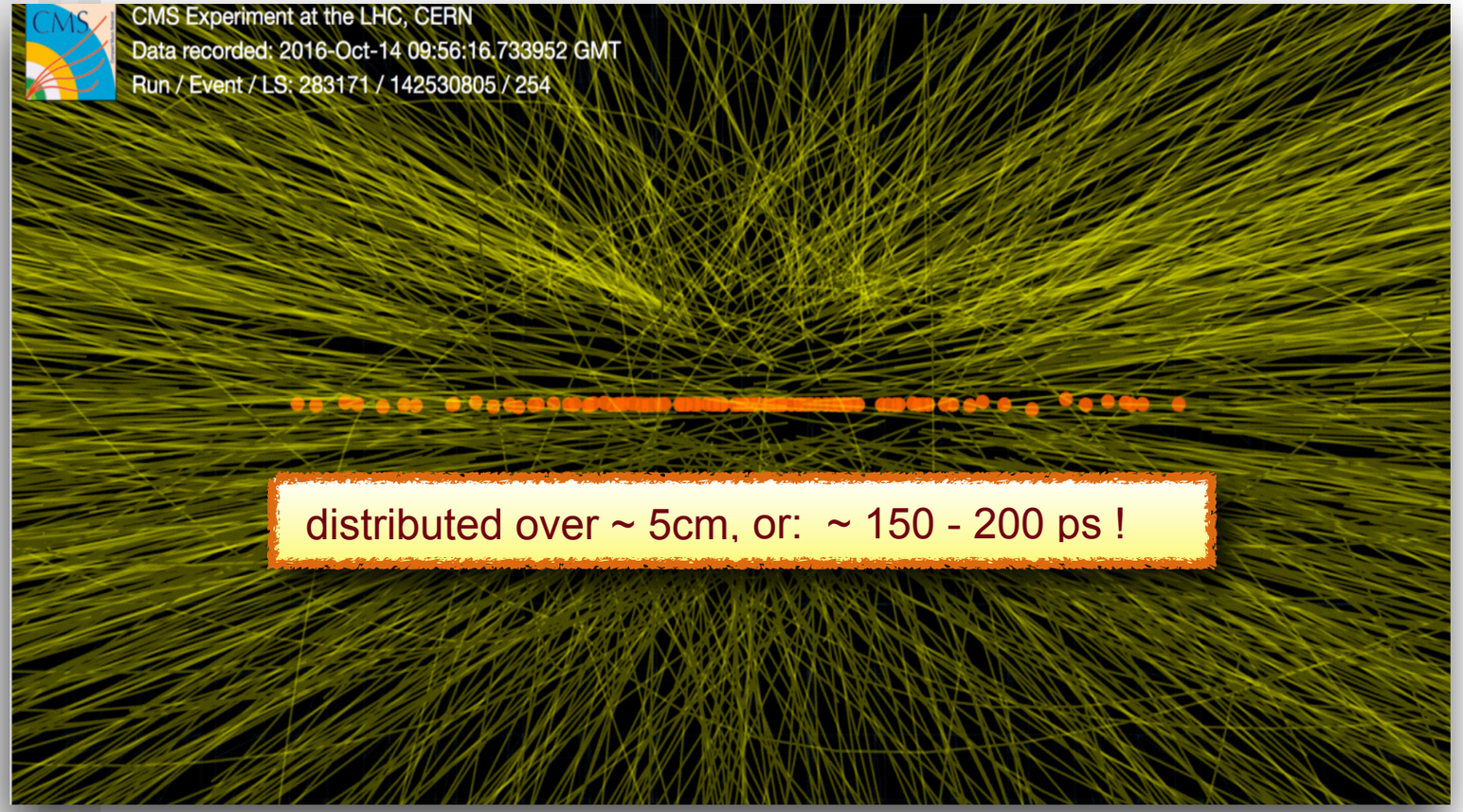




600 m² Si
6M channels



Timing information



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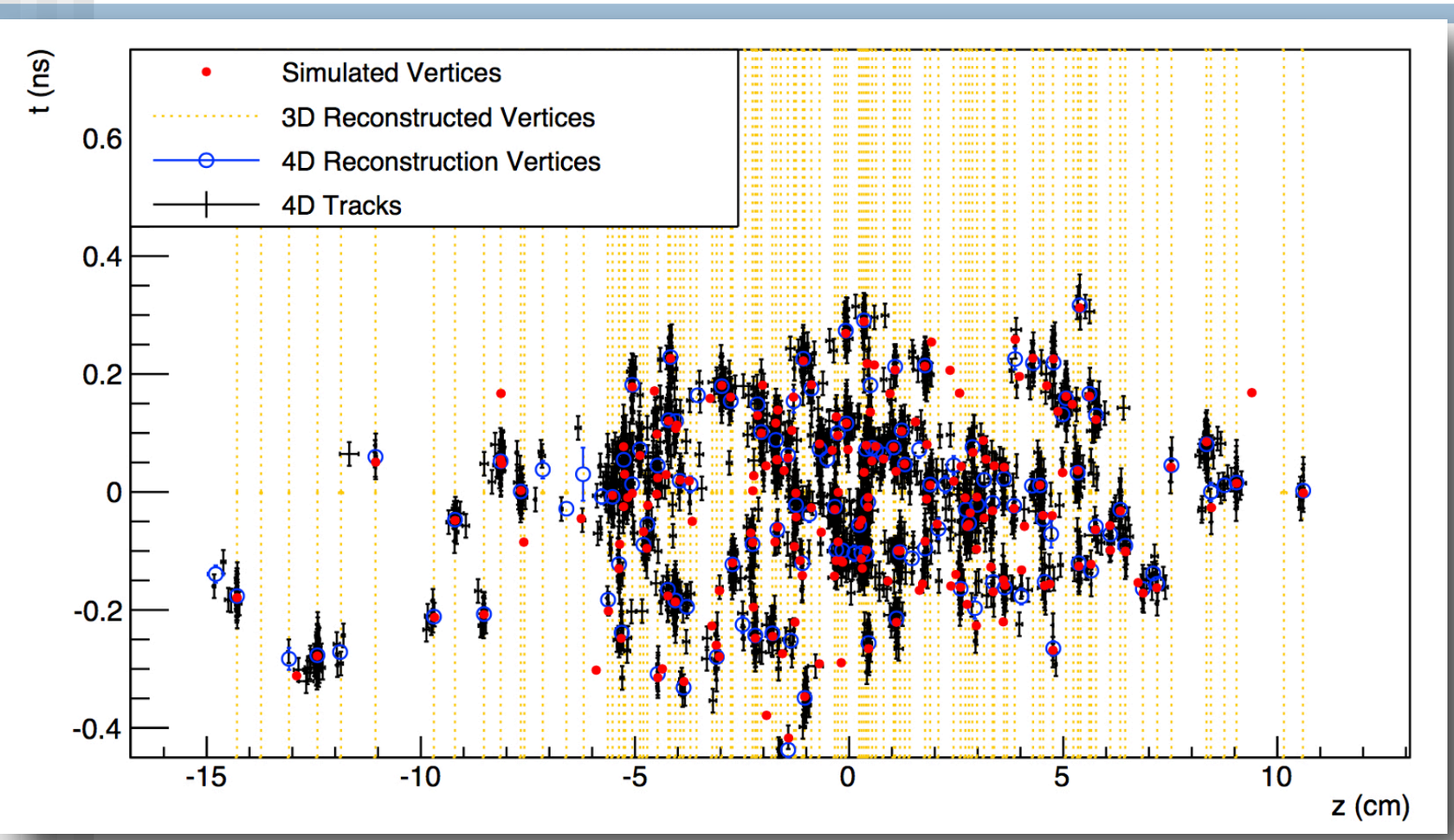

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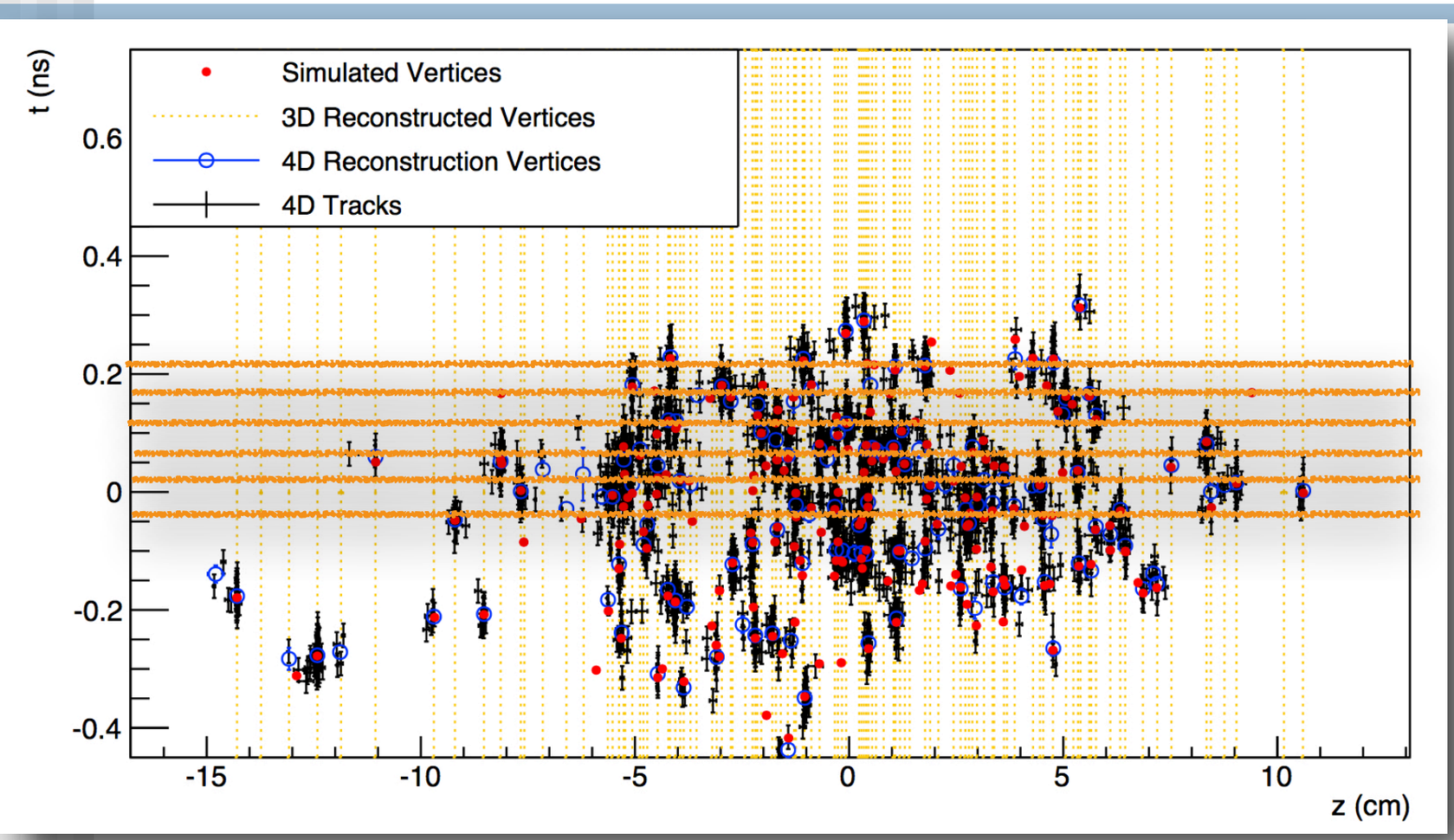

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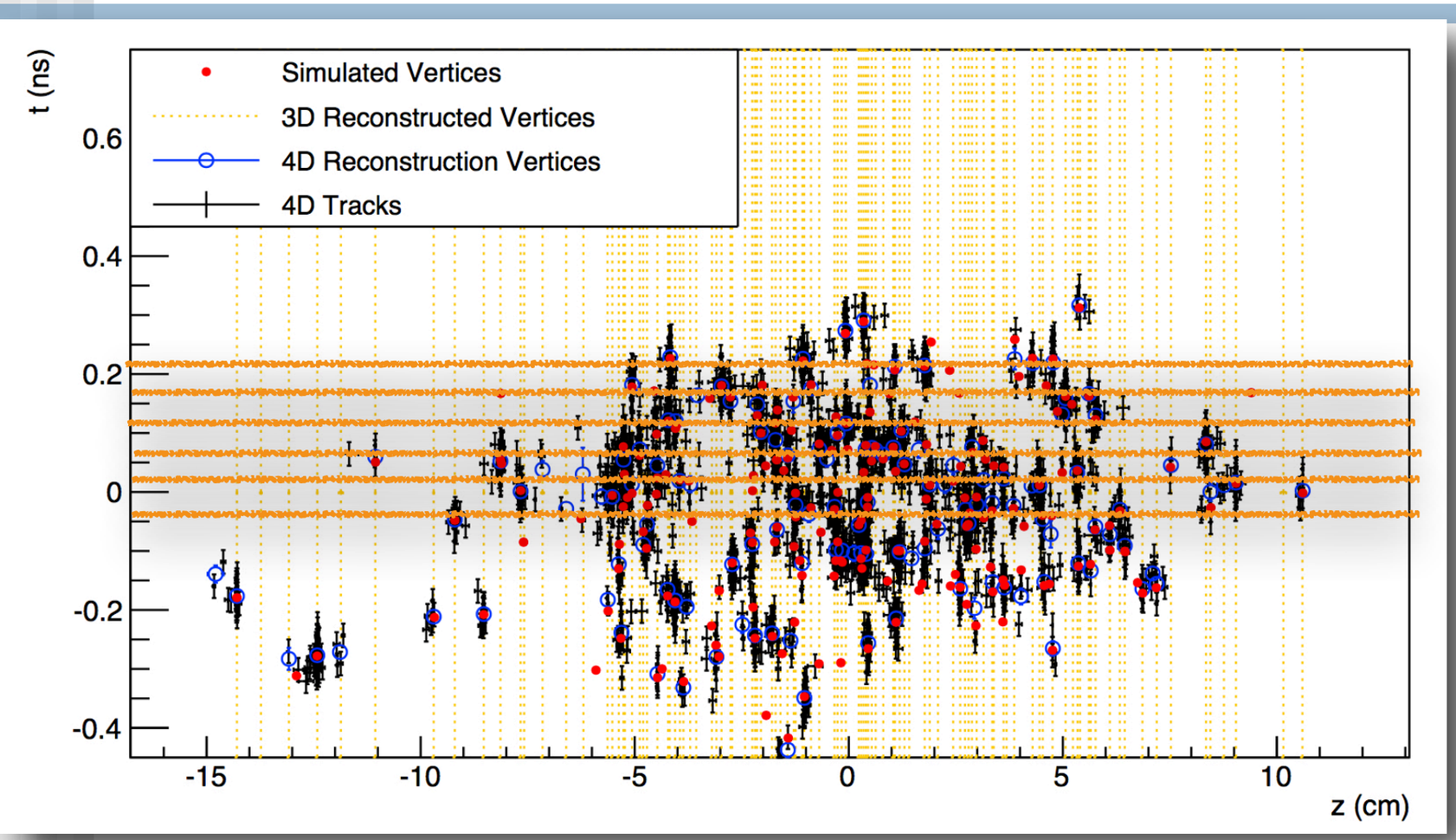

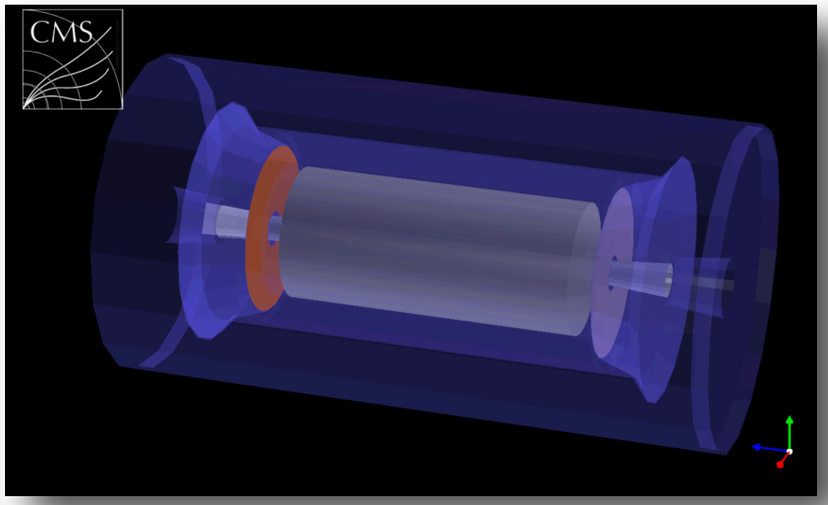

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Aim: resolution of **~30 ps**

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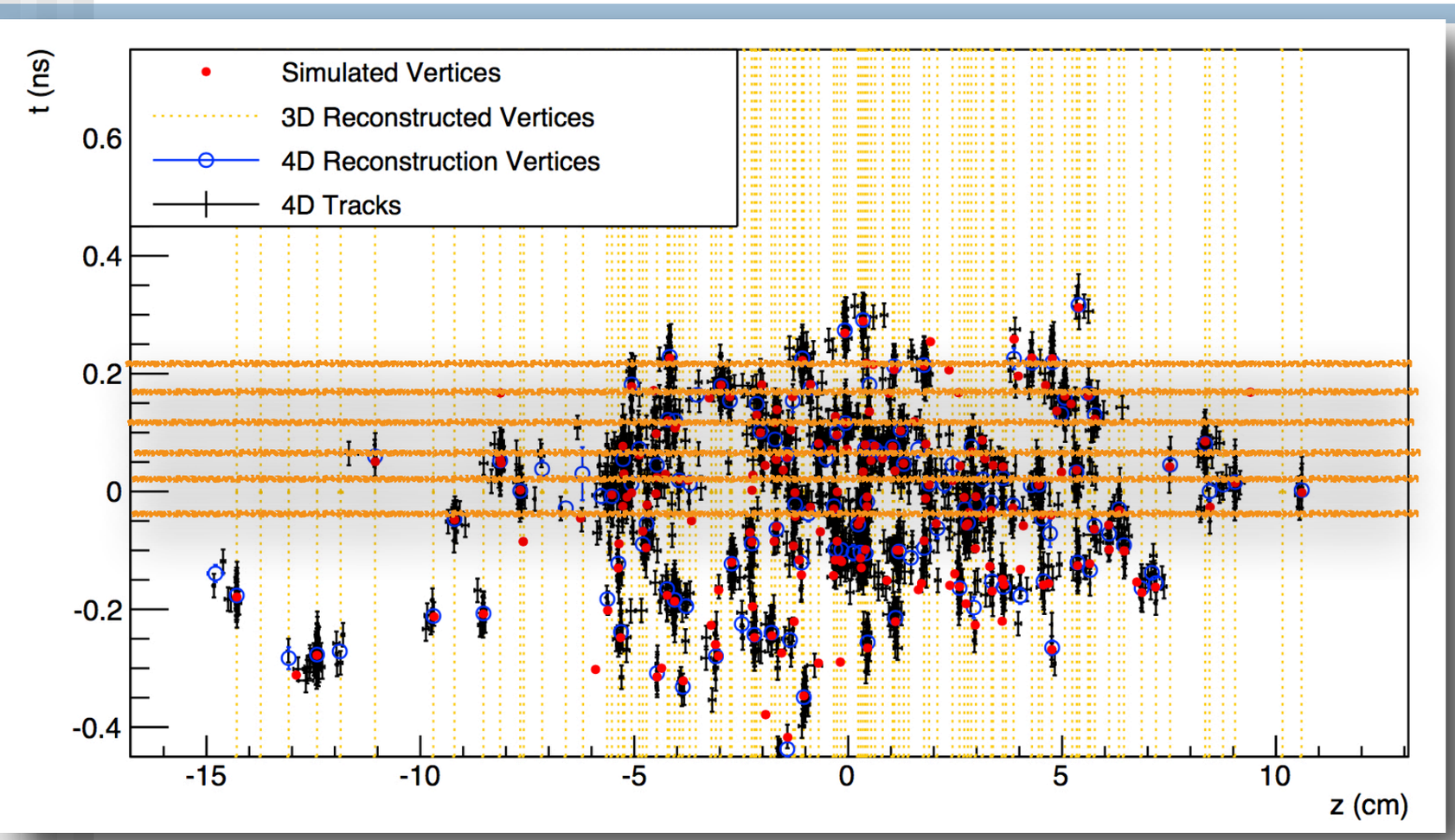

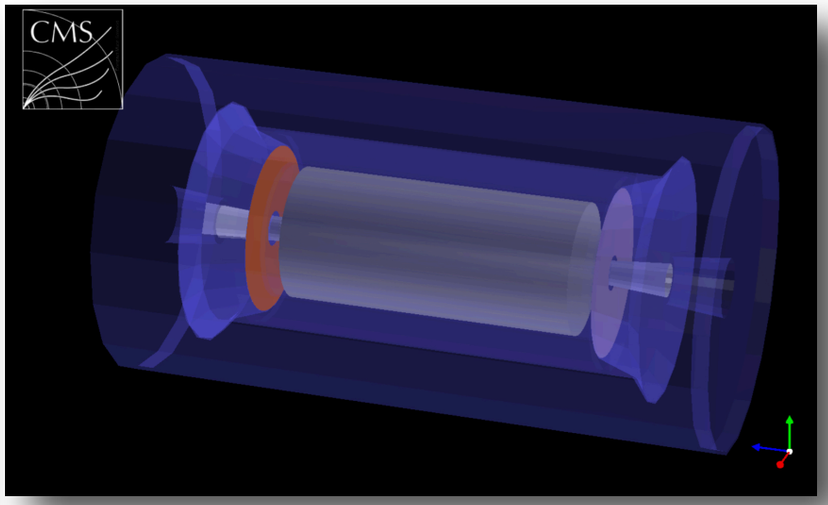

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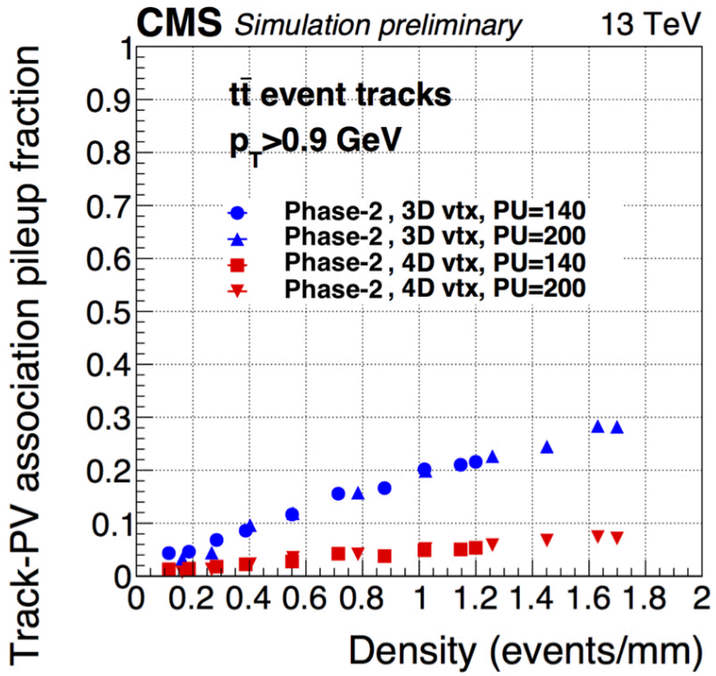
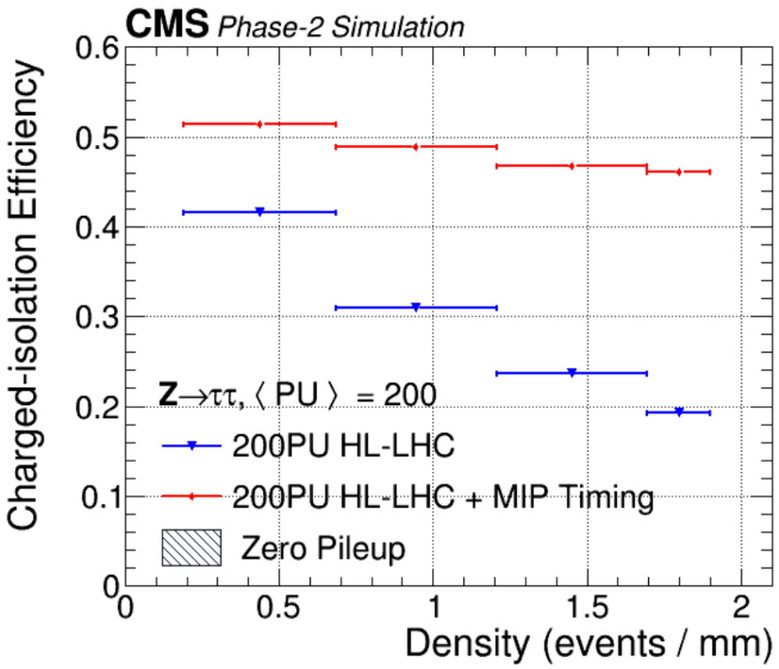
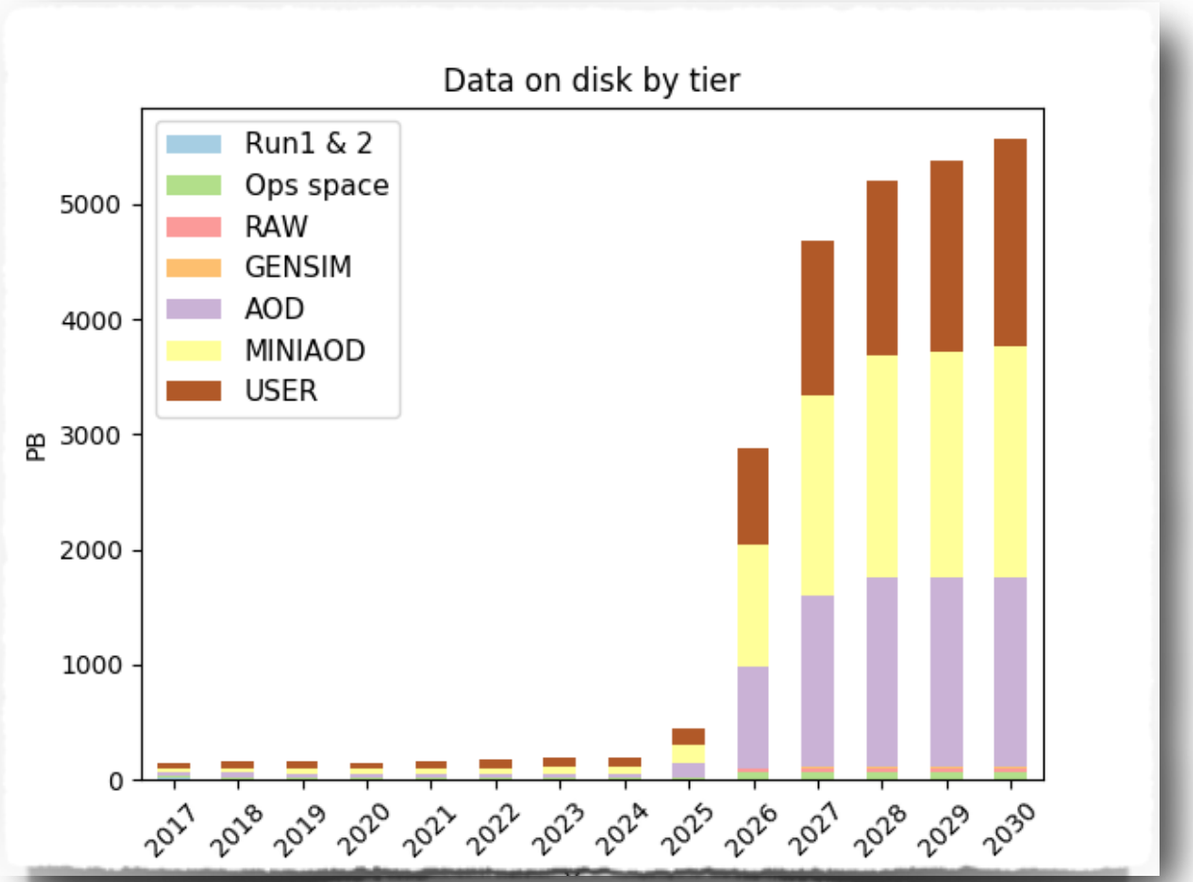




For example:
enhancement by
~20 % (!)
in signal yield of
HH (bbγγ)

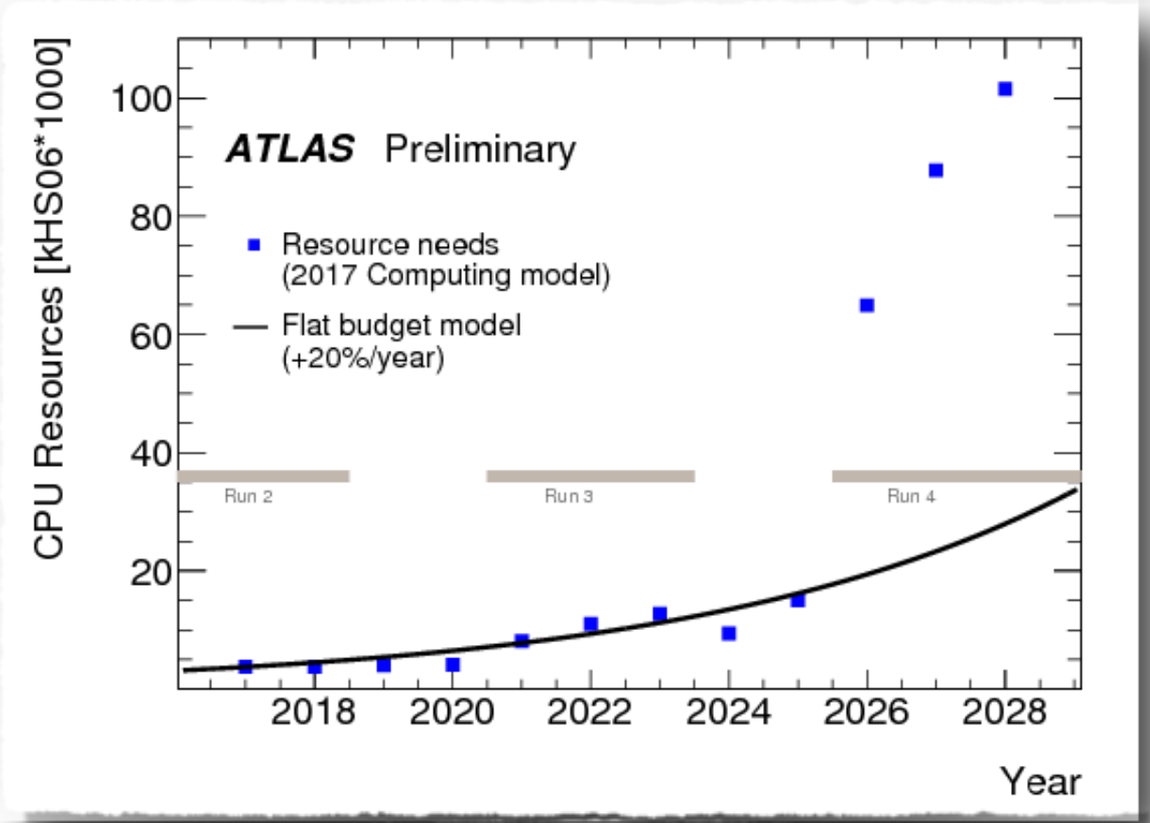
And not to be forgotten: the computing challenge!

https://cds.cern.ch/record/2298968/plots



Just scaling what we have doesn't work!

Community is working on this intensively
HSF Community White Paper
WLCG Strategy Document



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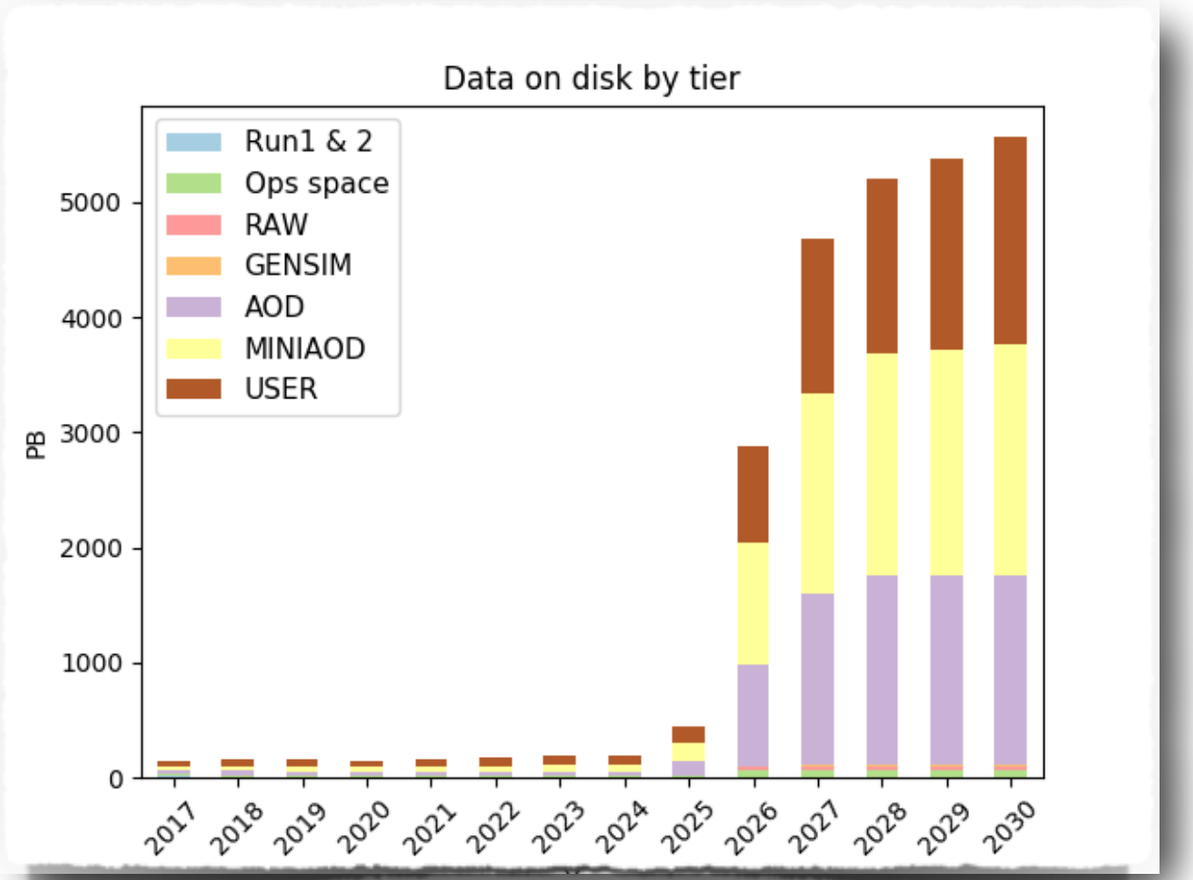

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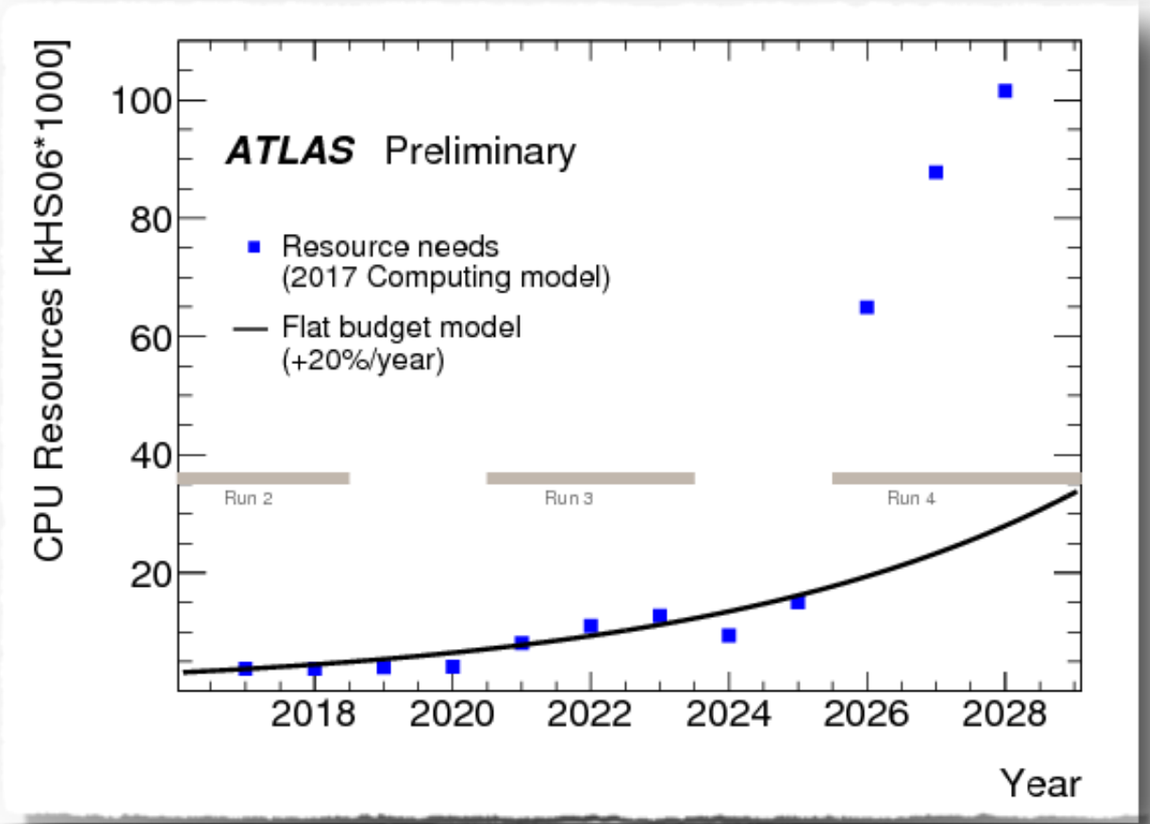

Intensive R&D and follow industry developments
(both hardware and software)

particularly "hot topic"
Machine learning (deep learning)
applications in all areas
(simulation, reconstruction, monitoring, analysis…)

Concluding…

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from: M. Mangano

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ETH zürich

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- **The "*still-don't-know-what's-next*" scenario**
  - LHC is the only guaranteed machine we have. If nothing else is approved within the next 10-15 years, we must rely on HL-LHC and possible further evolutions of the LHC complex to guarantee the future of our exploration

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- **The detector upgrades address the challenges posed by the LHC machine conditions and the requirements from physics**

Thank you for your attention!