The CMS experiment

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Kern- und Teilchenphysik II
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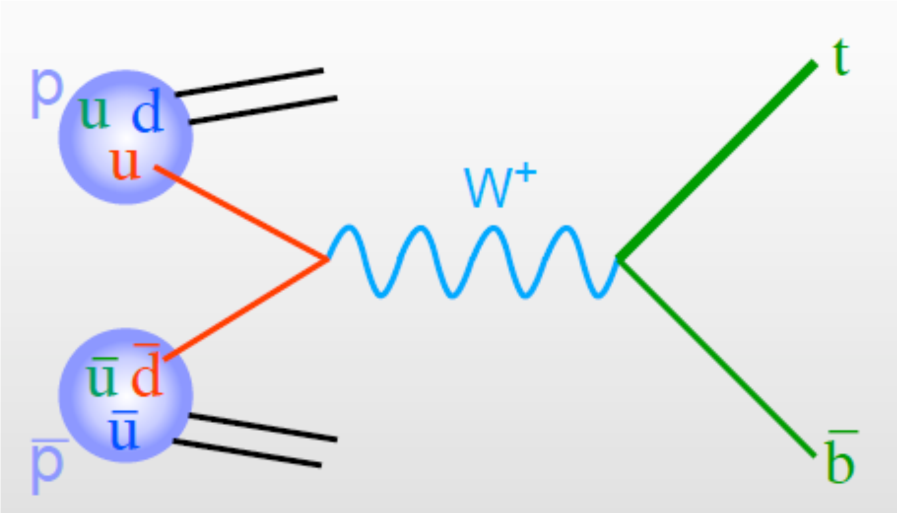
Overview

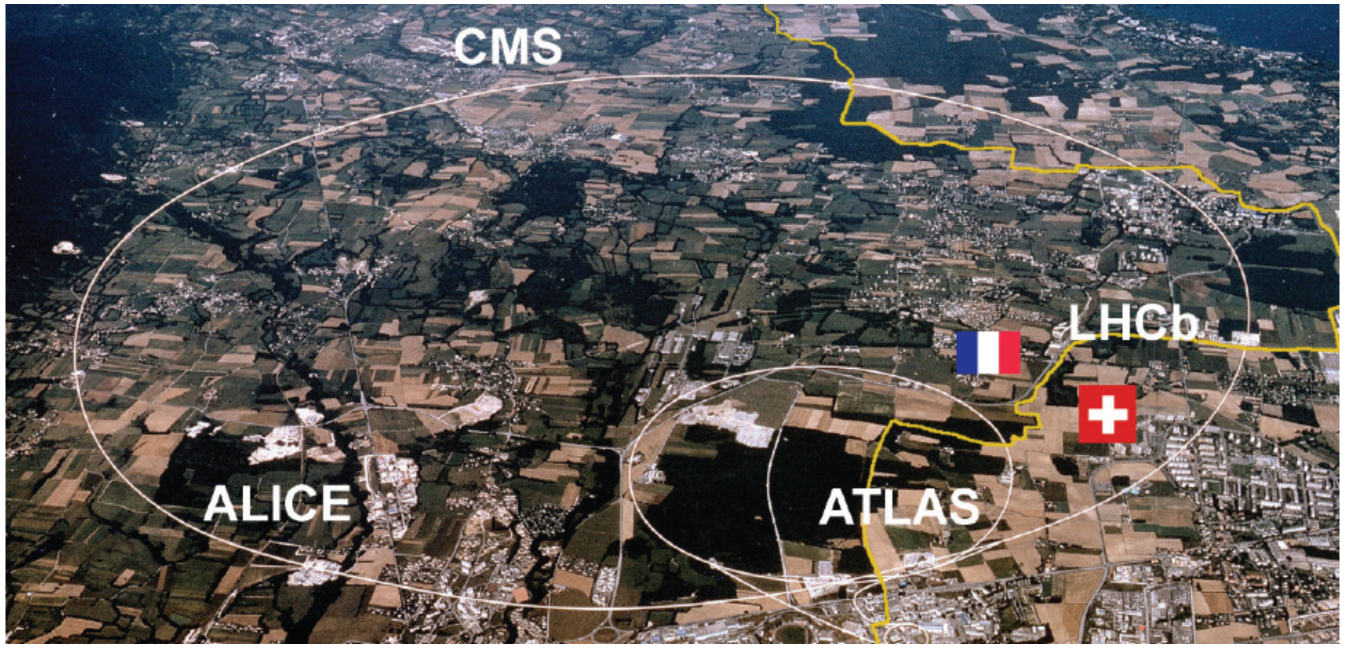
- LHC
- Collisions
- Basic principles of CMS
- CMS Higgs analysis overview

* for simplicity most numbers are approximate

LHC in a nutshell - pt1

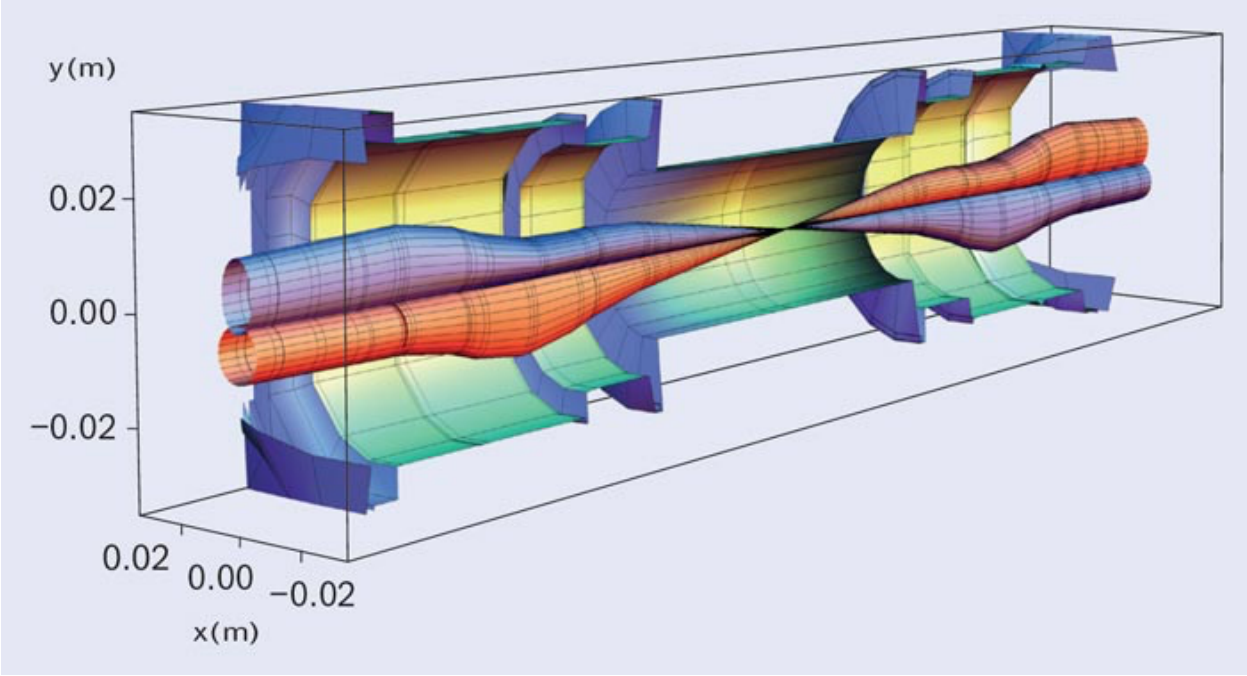
- Goal at CERN's Large Hadron Collider is to accelerate particles to high energies and make them collide
  - producing new particles
- High mass particles → high energies ($E=mc^2$)
  - very important as in proton collisions quarks and gluons entering the hard scattering carry a fraction of the proton's energy



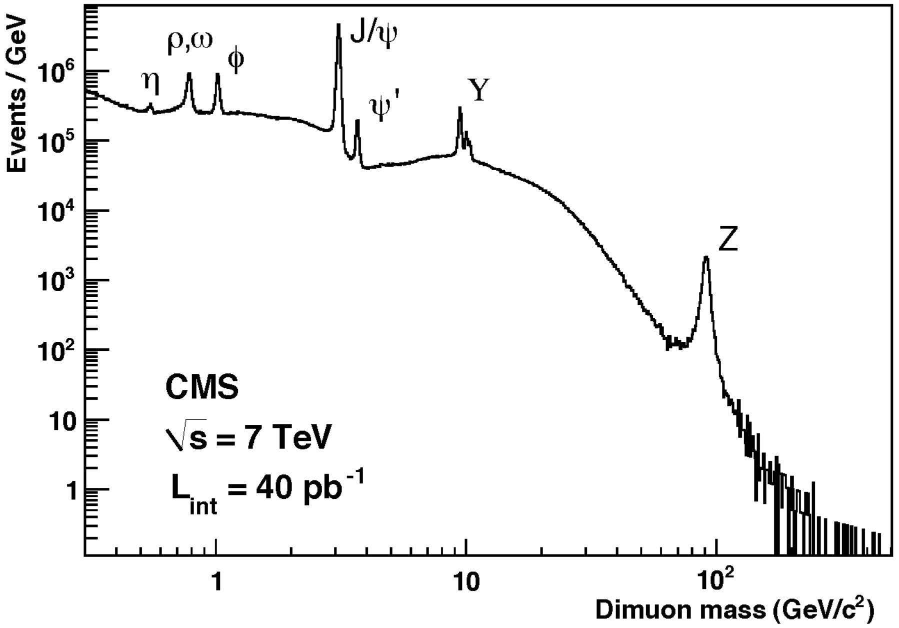


LHC in a nutshell - pt2

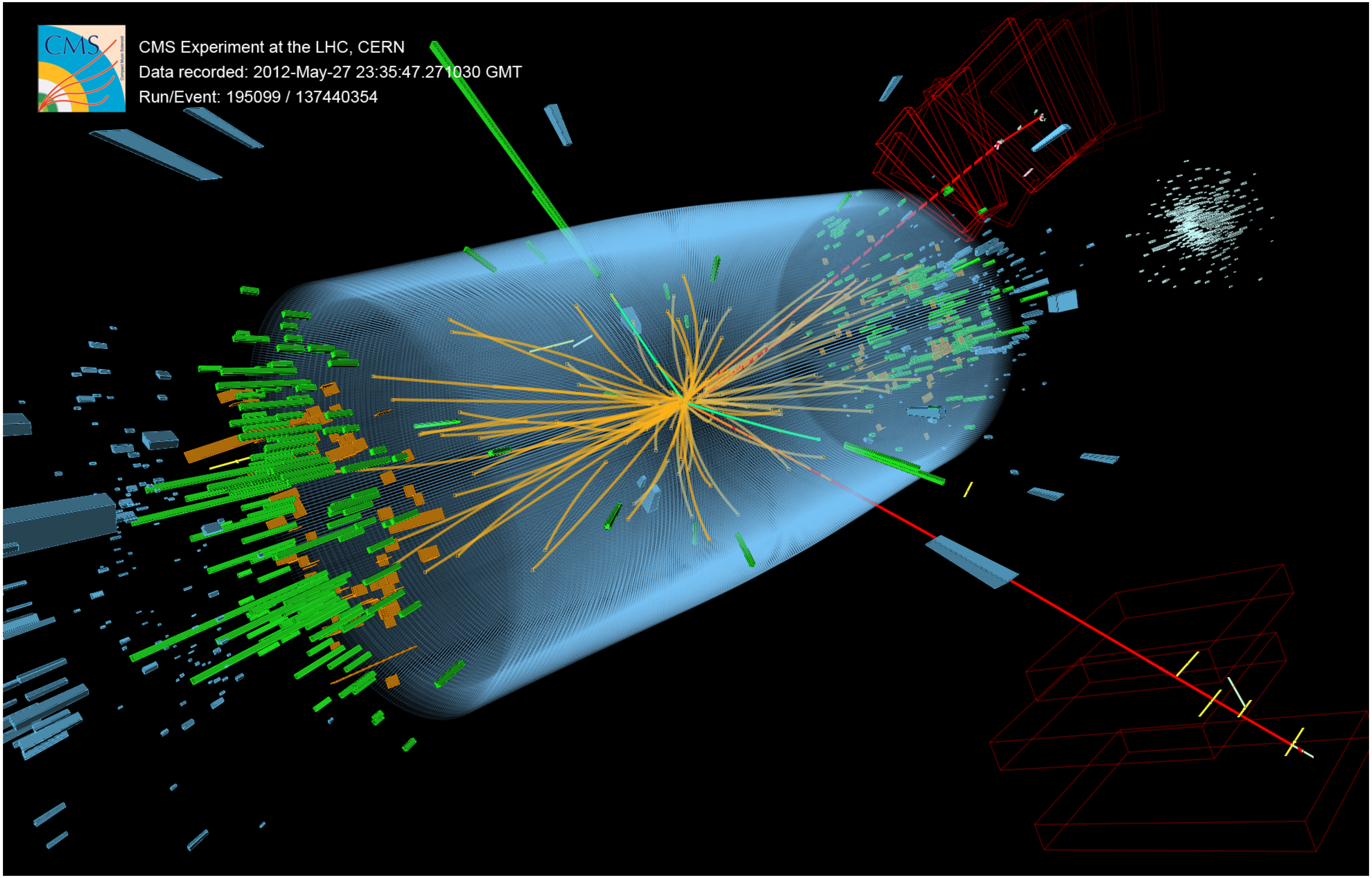
- LHC accelerates protons at $\sqrt{s}$=13 TeV
- Collision frequency 40 MHz
- Current instantaneous luminosity at CMS ~10^{34} $cm^{-2}s^{-1}$
- Effective year t = 10^7 s
- integrated luminosity L = 10^{41} cm^{-2} = 100 fb^{-1}
- LHC beams cross at the interaction point
  - ~2.5k bunches per beam
  - ~3x10^{14} protons per bunch



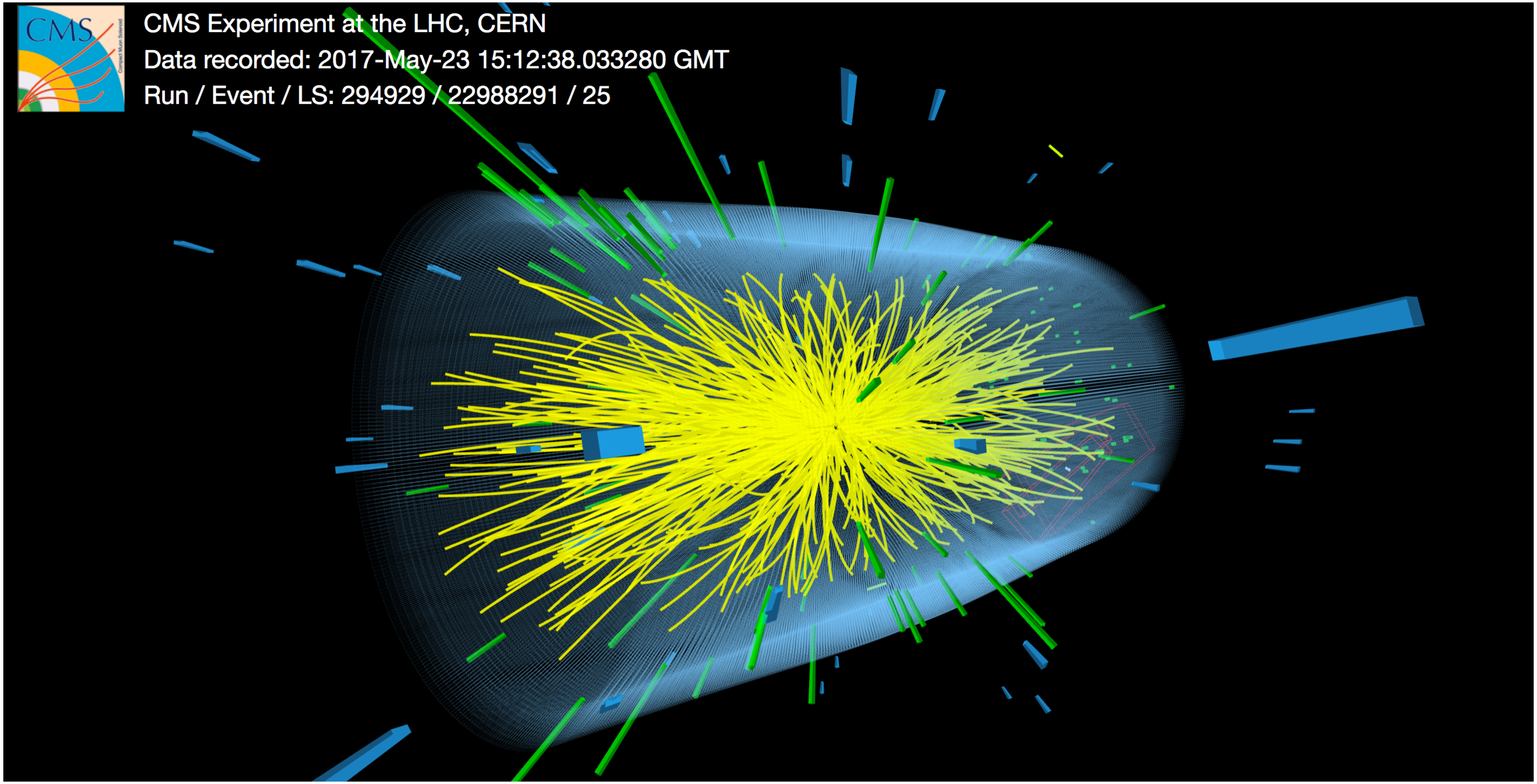
- Inverse femtobarn (fb^{-1}) measures particle collision events per femtobarn (10^{-43} m^2)
- 1 fb^{-1} ~ 10^{12} pp collisions
- Looking at a particular process (for now)
  - N_{events} = L x σ



How an event looks like

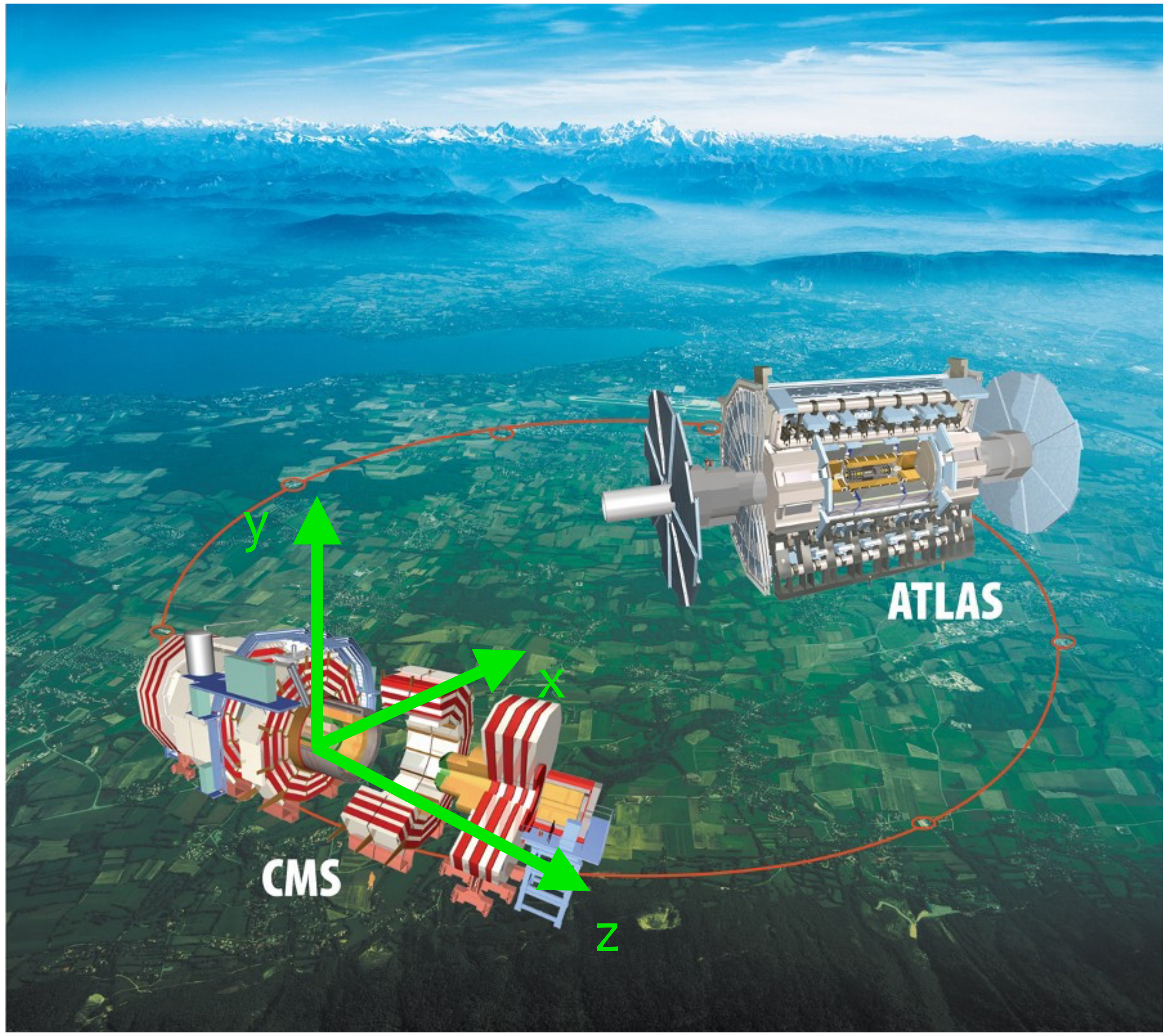


Another example

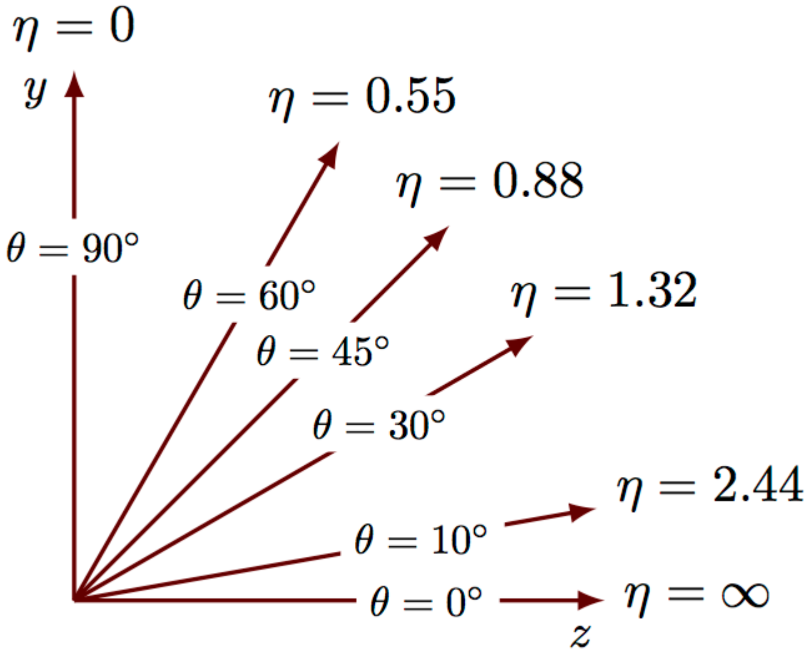


LHC in a nutshell - pt3

- Coordinate system
    - x-axis: point to the Interaction Point
    - y-axis: upwards
    - z-axis: along the beam axis

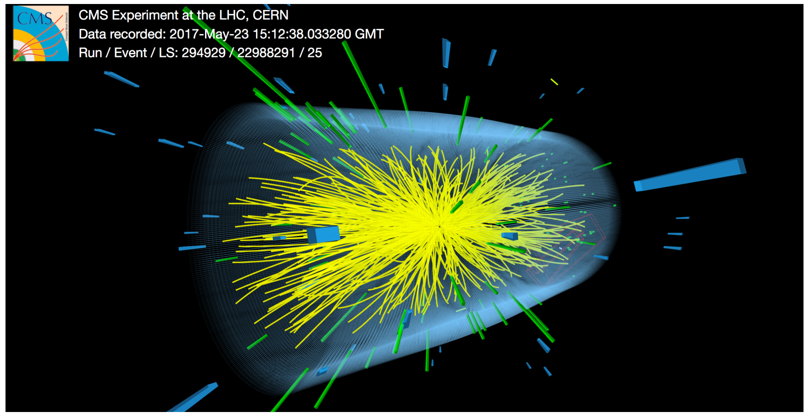


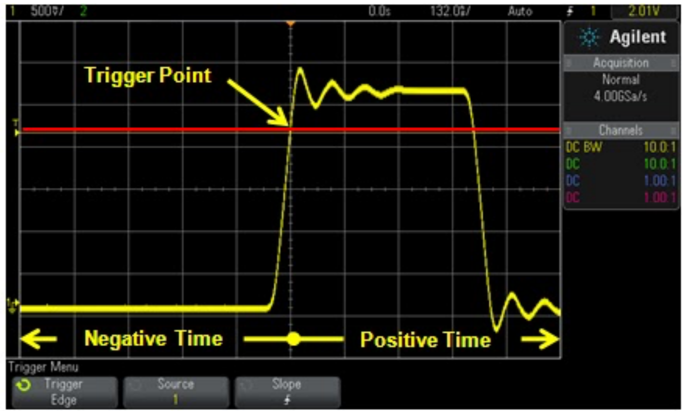
- instead of polar θ
    - pseudo-rapidity $\eta = -\ln\tan(\theta/2)$



CMS/ATLAS coverage up to ~here

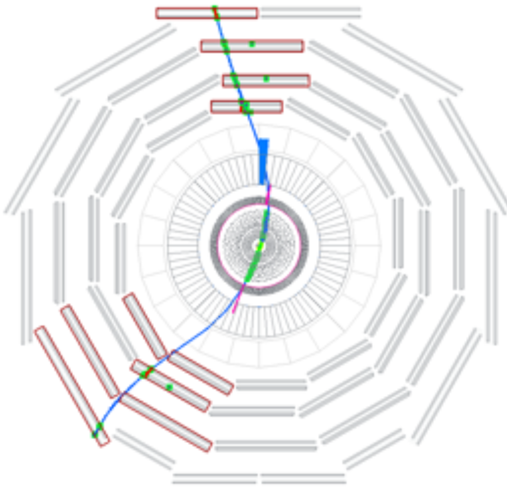
From collisions to bytes



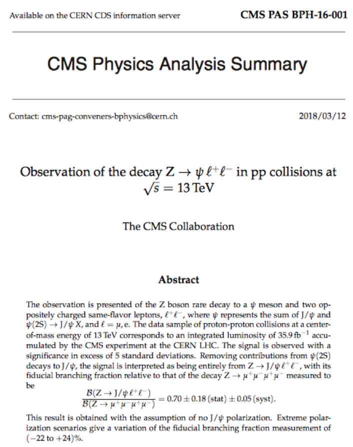


online

- Trigger on physics is crucial
  - LHC collision rate 40 MHz
  - Hardware trigger (aka L1) ~100kHz
  - Software trigger (aka HLT) ~1kHz
- Here you can find raw data
  - what does it contain?



offline



Available on the CERN CDS information server — CMS PAS BPH-16-001

CMS Physics Analysis Summary

Contact: cms-pag-conveners-bphysics@cern.ch — 2018/03/12

Observation of the decay $Z \to \psi \ell^+\ell^-$ in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

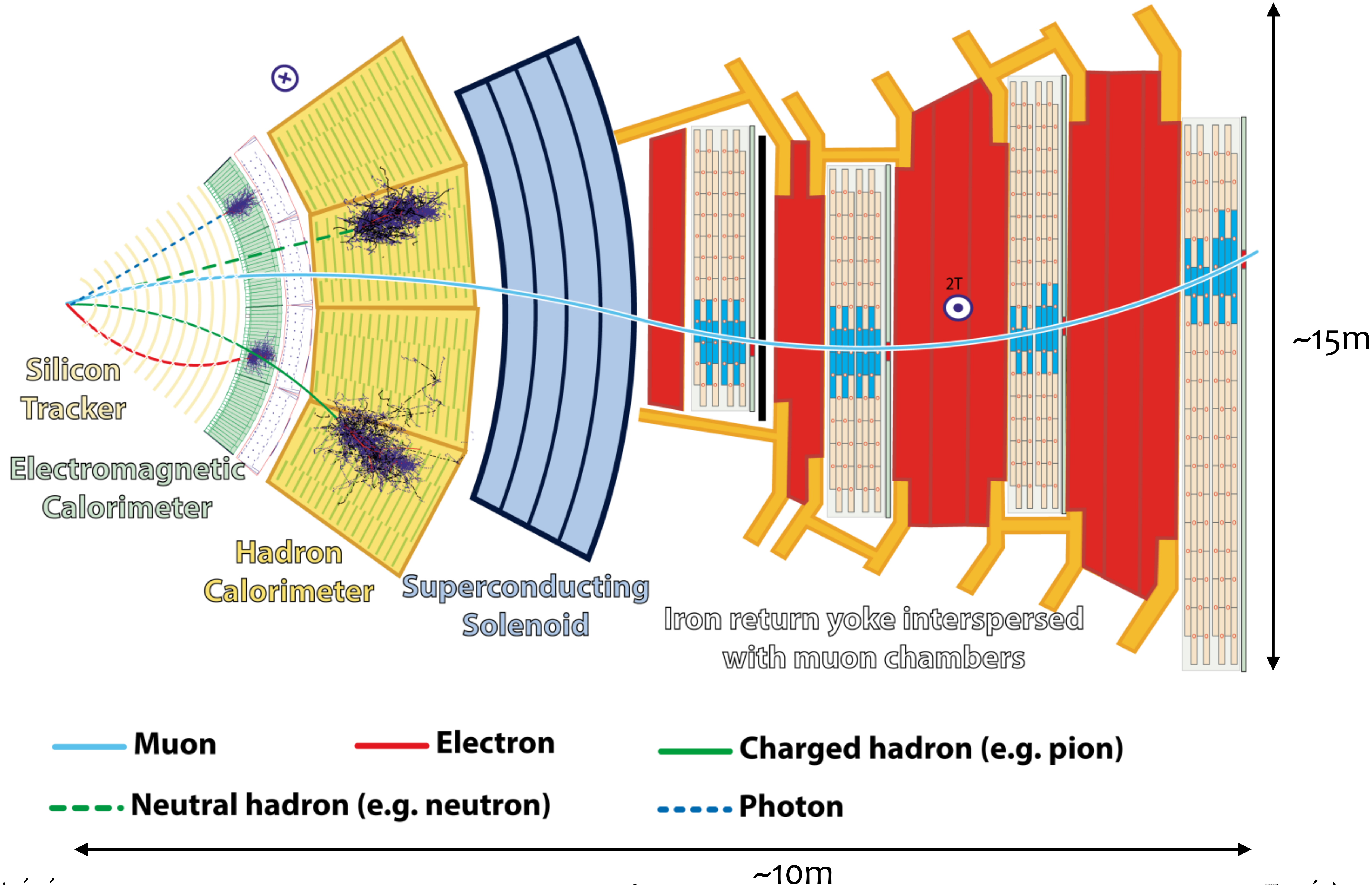
Abstract

The observation is presented of the Z boson rare decay to a ψ meson and two oppositely charged same-flavor leptons, $\ell^+\ell^-$, where ψ represents the sum of J/ψ and $\psi(2S) \to J/\psi X$, and $\ell = \mu, e$. The data sample of proton-proton collisions at a center-of-mass energy of 13 TeV corresponds to an integrated luminosity of 35.9 fb^{-1} accumulated by the CMS experiment at the CERN LHC. The signal is observed with a significance in excess of 5 standard deviations. Removing contributions from $\psi(2S)$ decays to J/ψ, the signal is interpreted as being entirely from $Z \to J/\psi \ell^+\ell^-$, with its fiducial branching fraction relative to that of the decay $Z \to \mu^+\mu^-\mu^+\mu^-$ measured to be

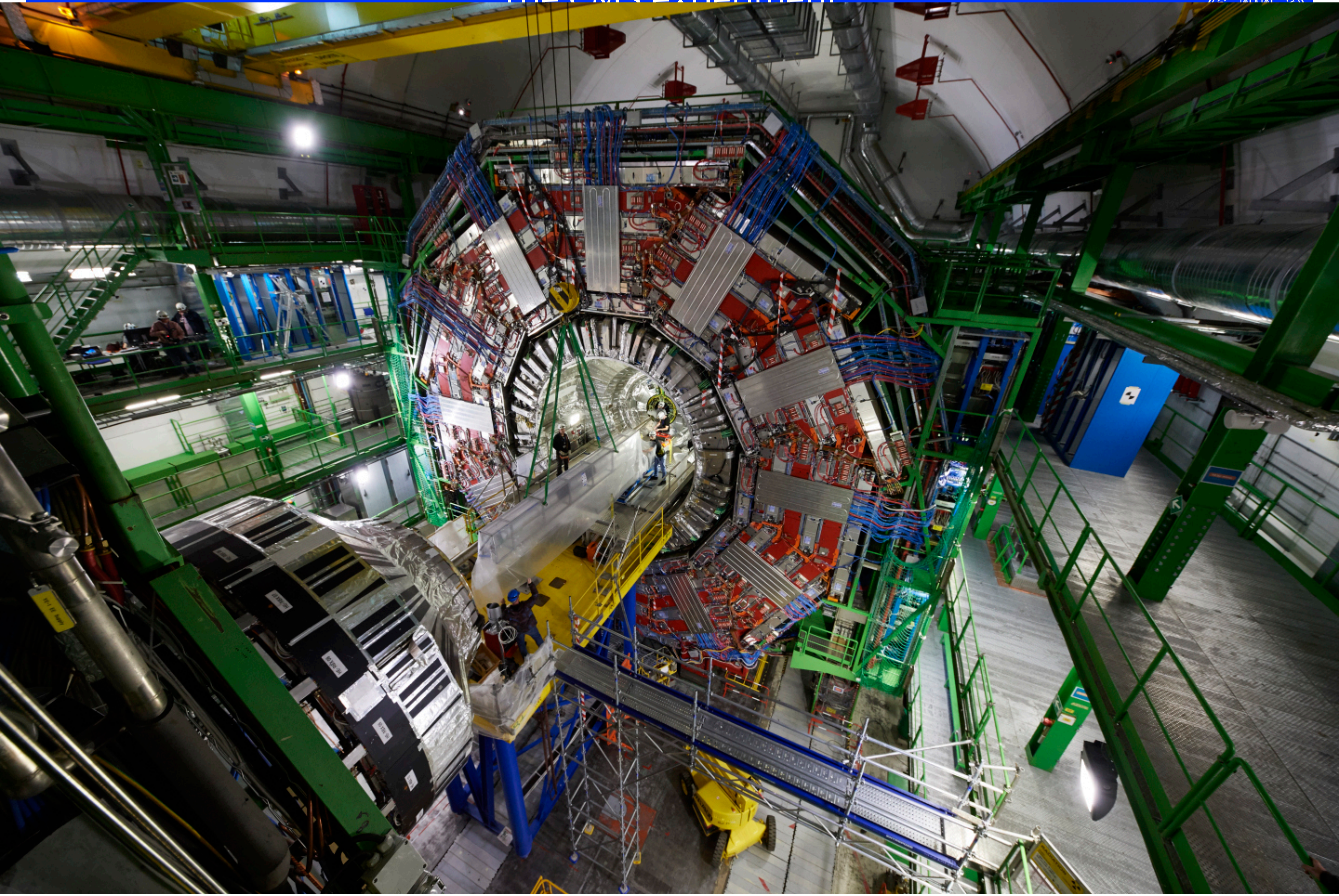
$$\frac{\mathcal{B}(Z \to J/\psi \ell^+\ell^-)}{\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-)} = 0.70 \pm 0.18\,(\text{stat}) \pm 0.05\,(\text{syst}).$$

This result is obtained with the assumption of no J/ψ polarization. Extreme polarization scenarios give a variation of the fiducial branching fraction measurement of (−22 to +24)%.

Basic principle of a HEP detector



The CMS experiment



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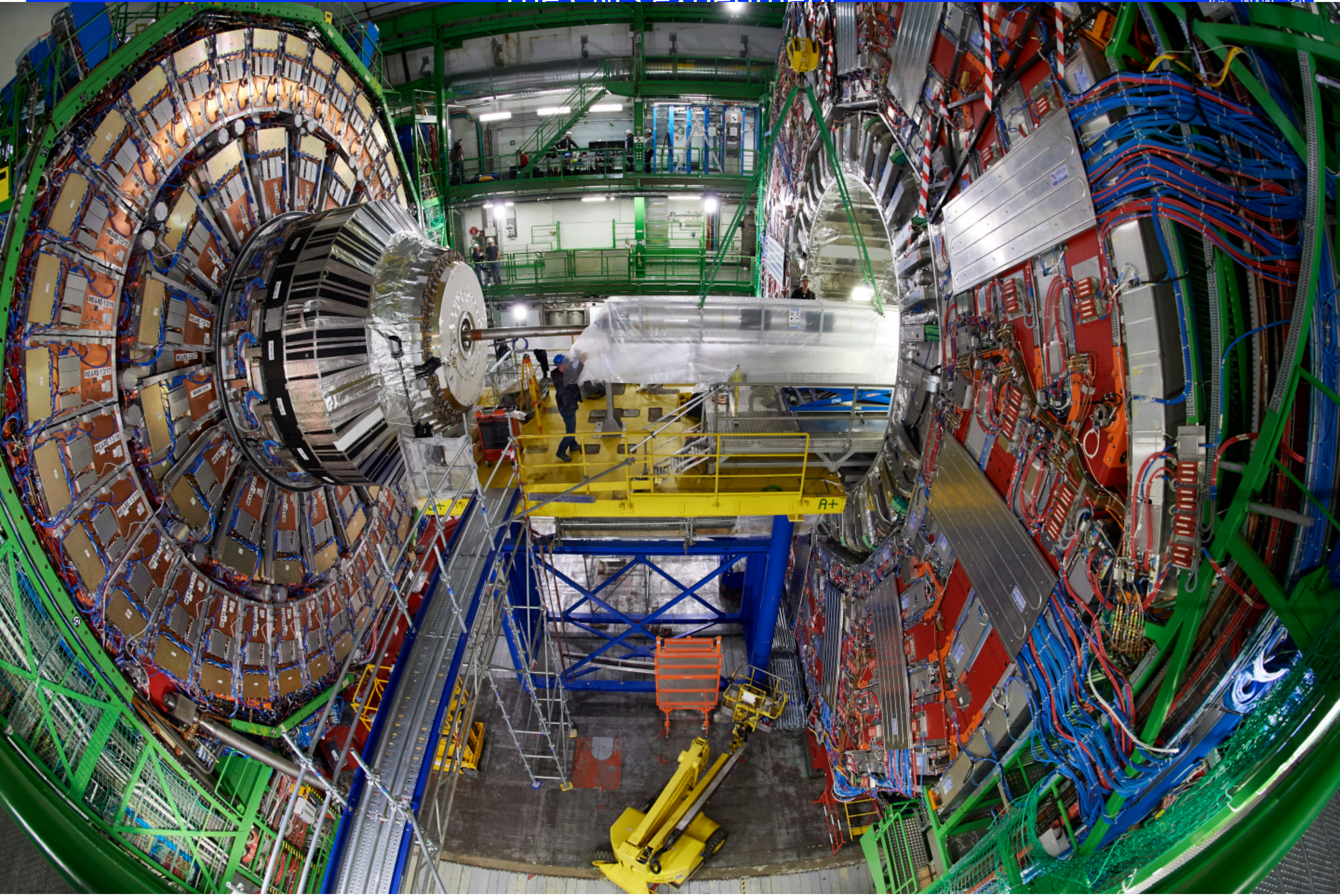
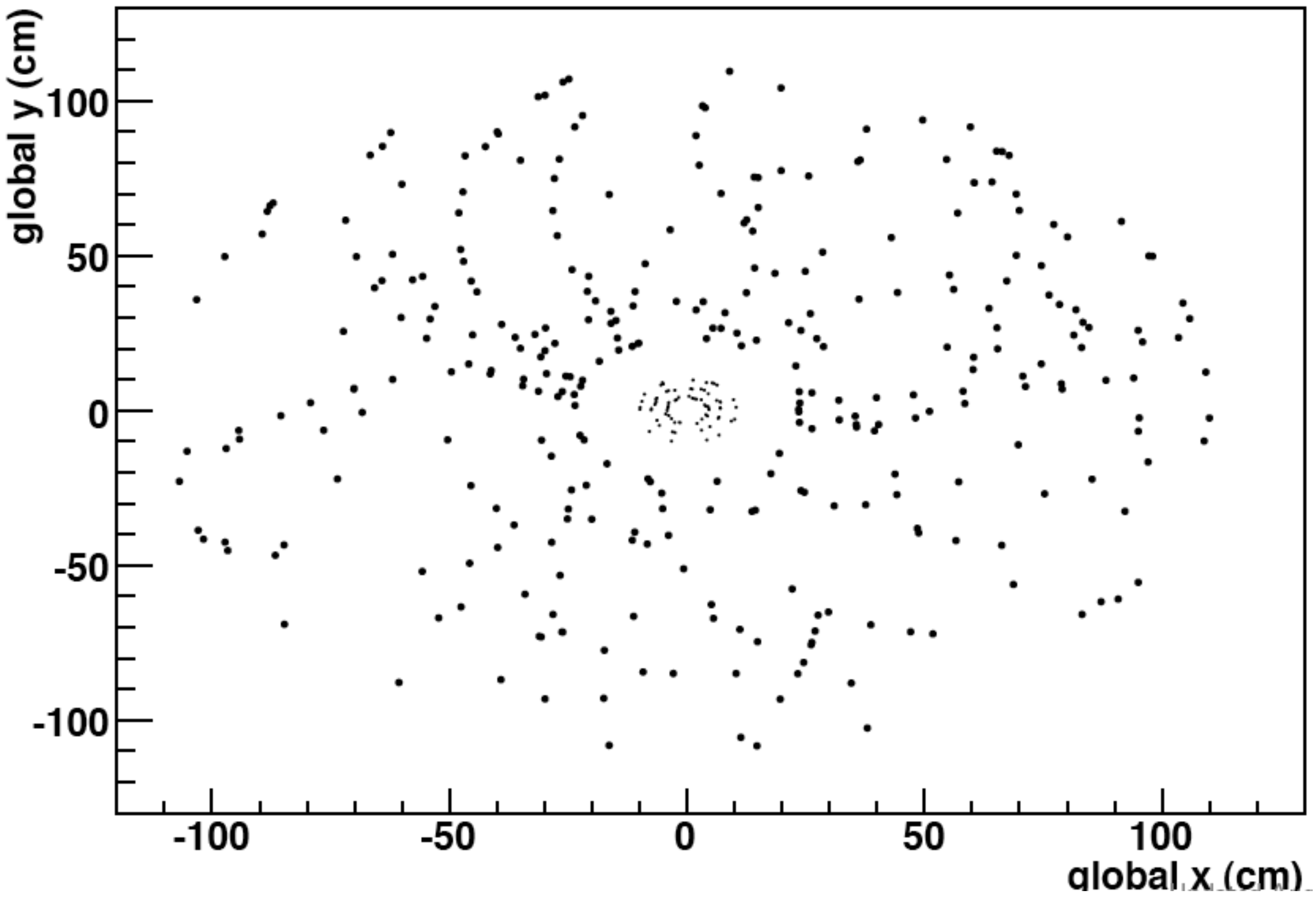


Tracking is not easy!

Where is the 50 GeV track?



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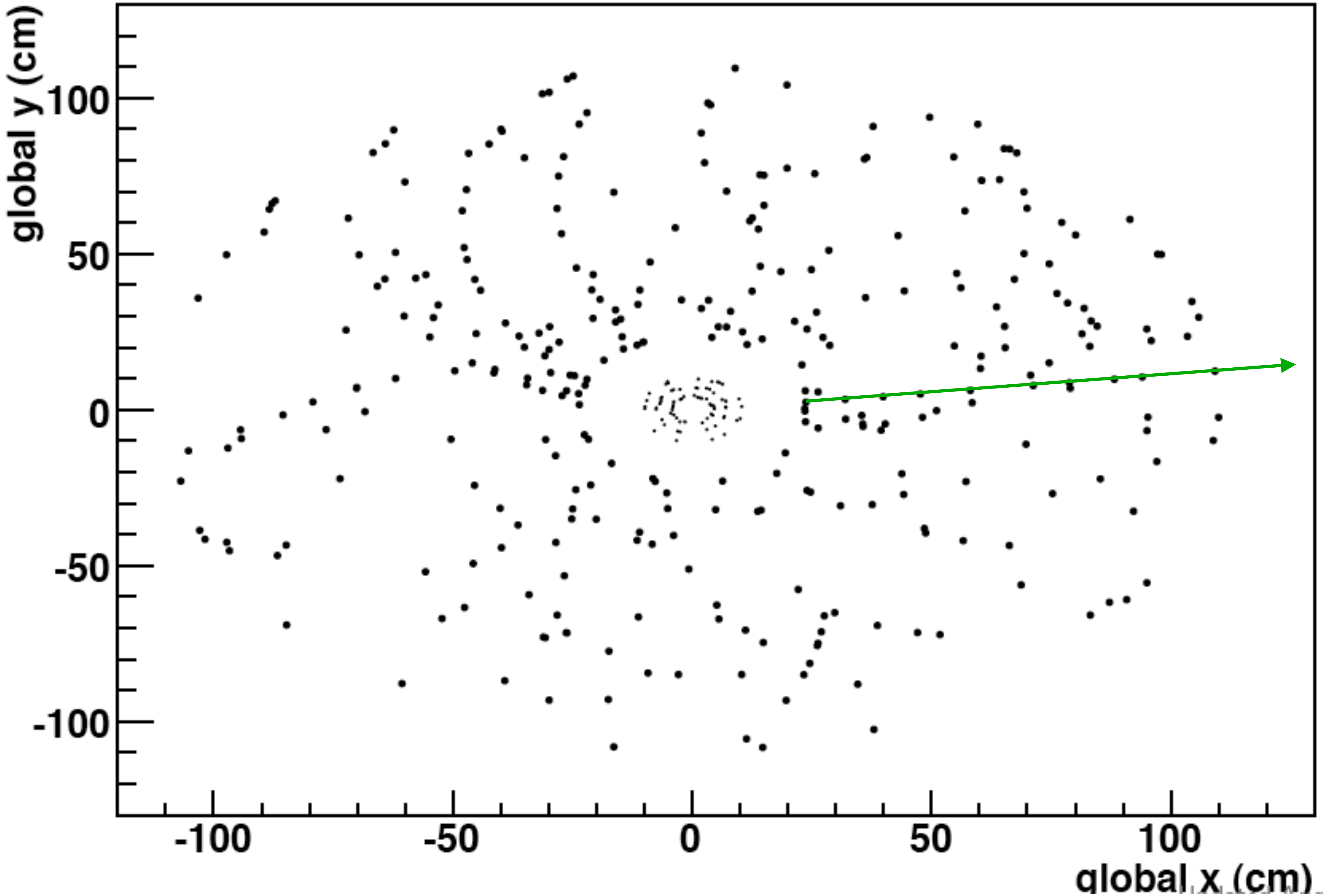

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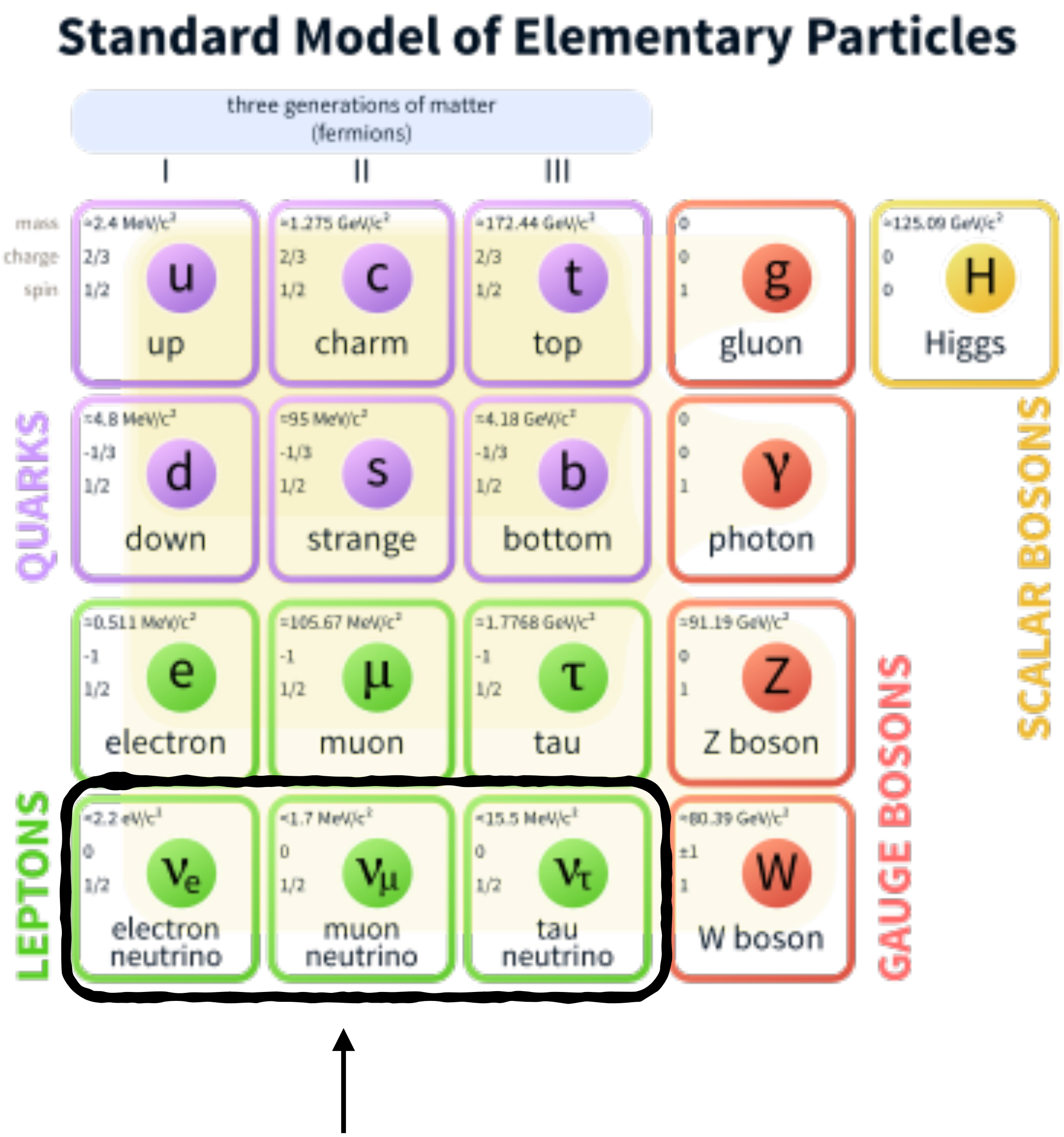
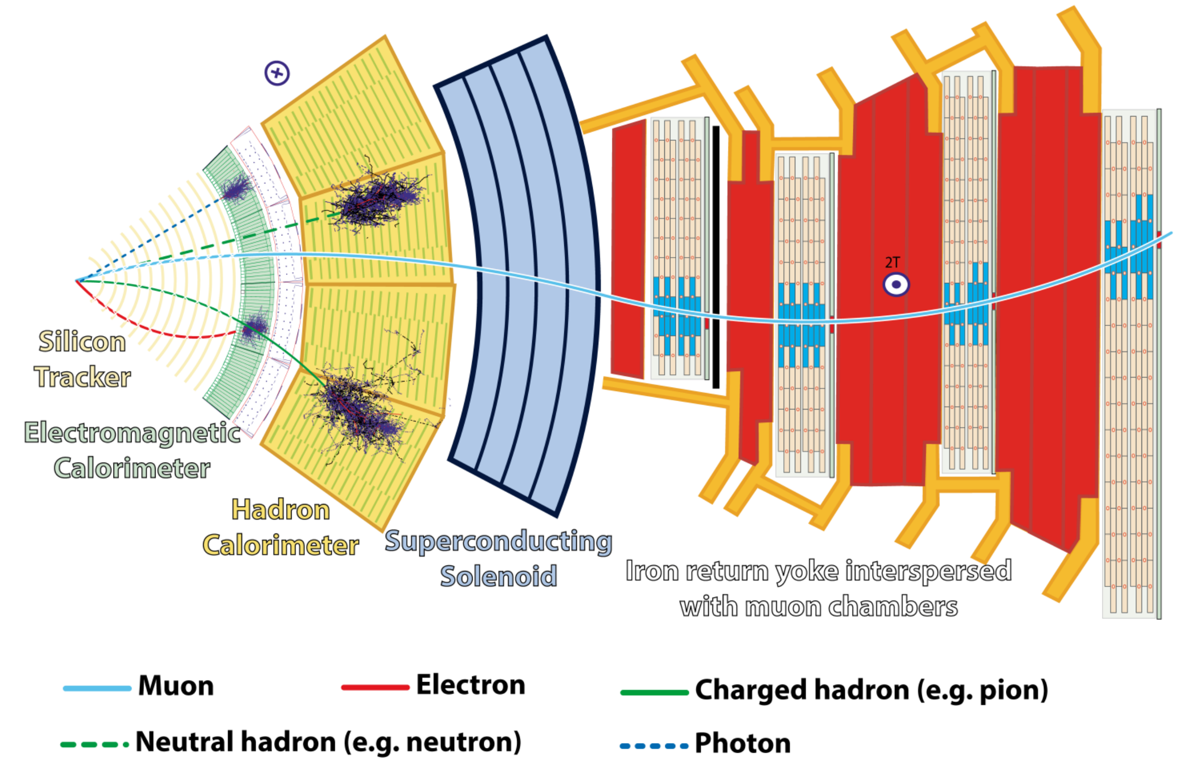
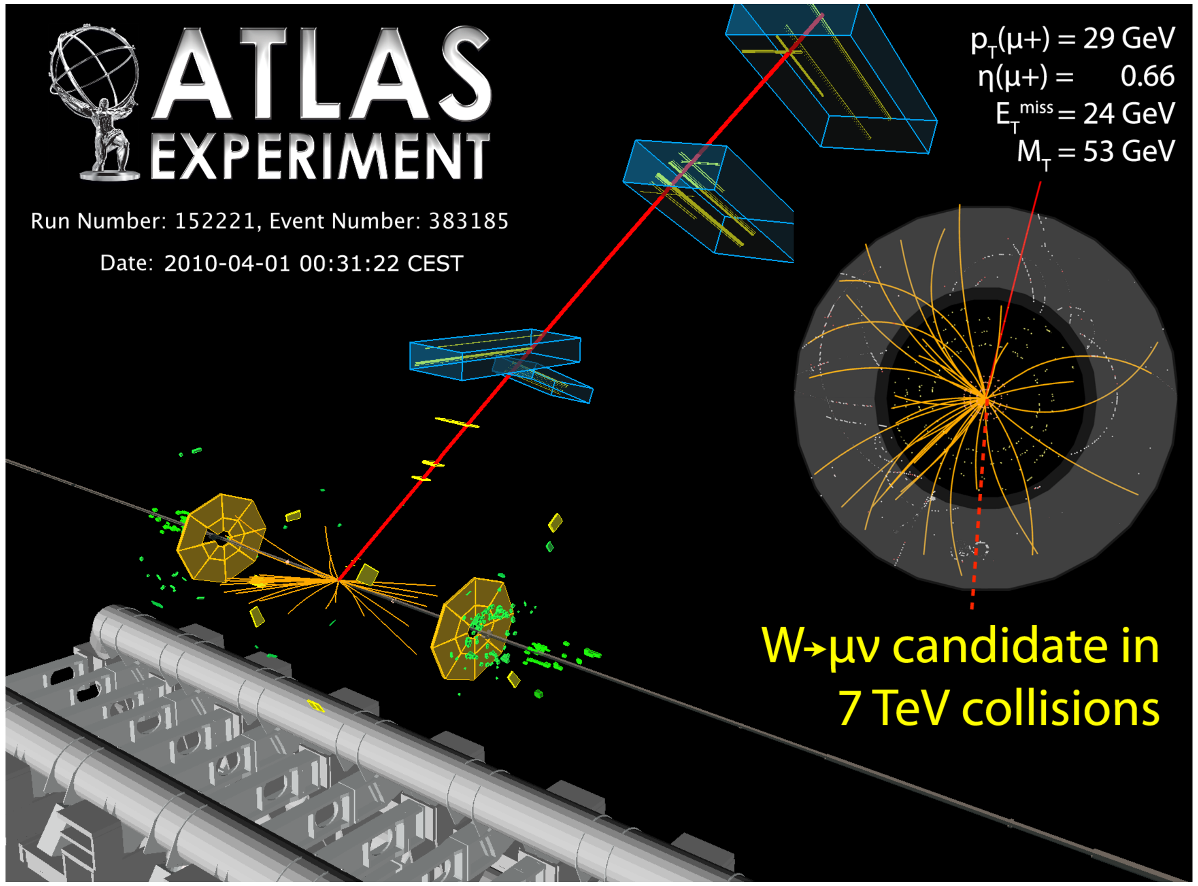


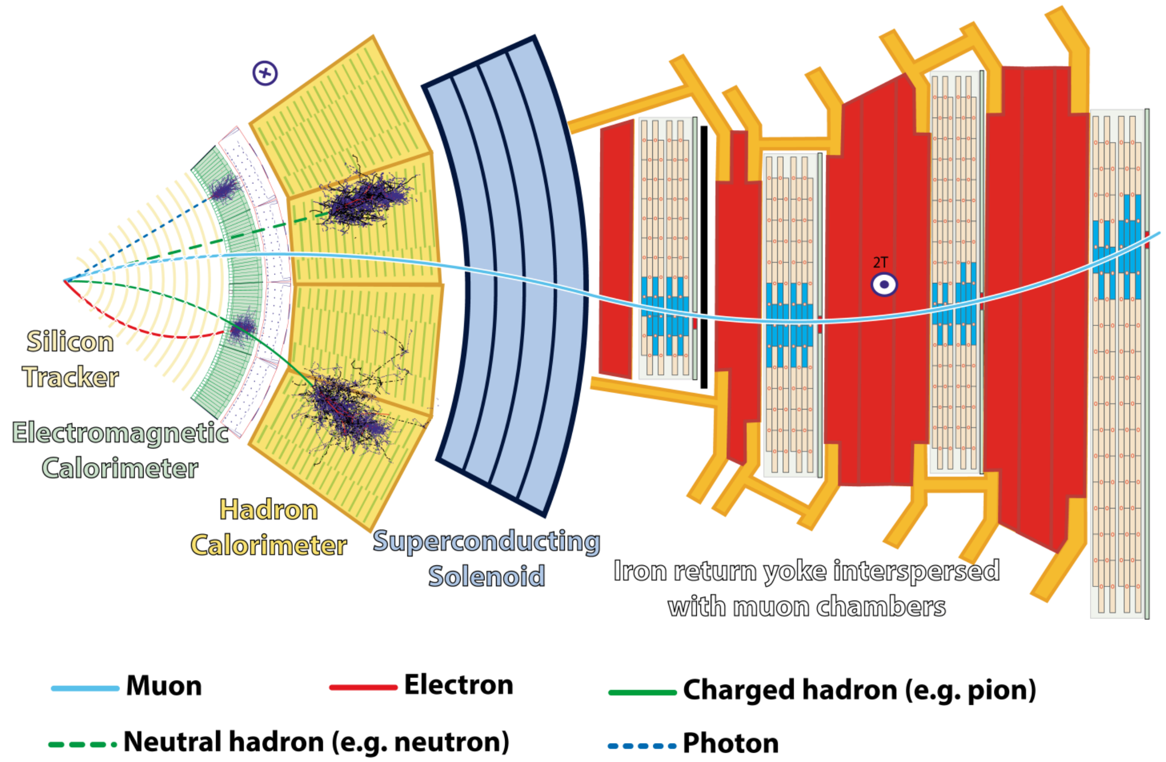


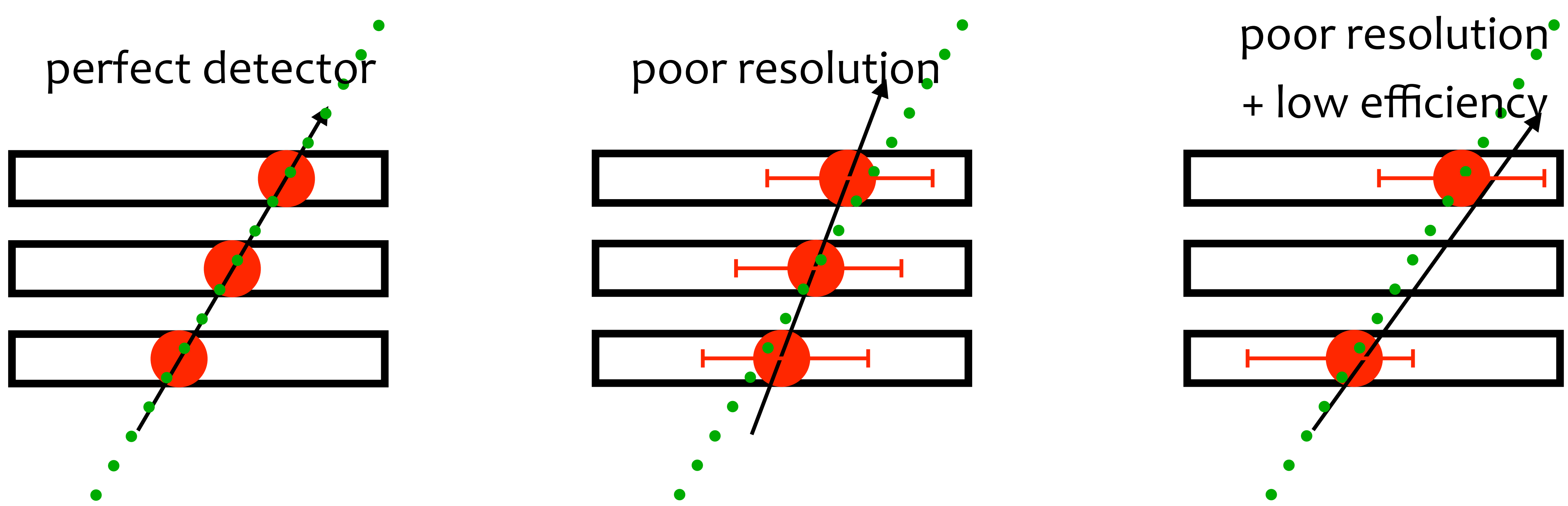


- In the transverse plane
  - $\Sigma p_T = 0$
  - aka Missing Transverse Momentum (MET)

Basic principle of a HEP detector

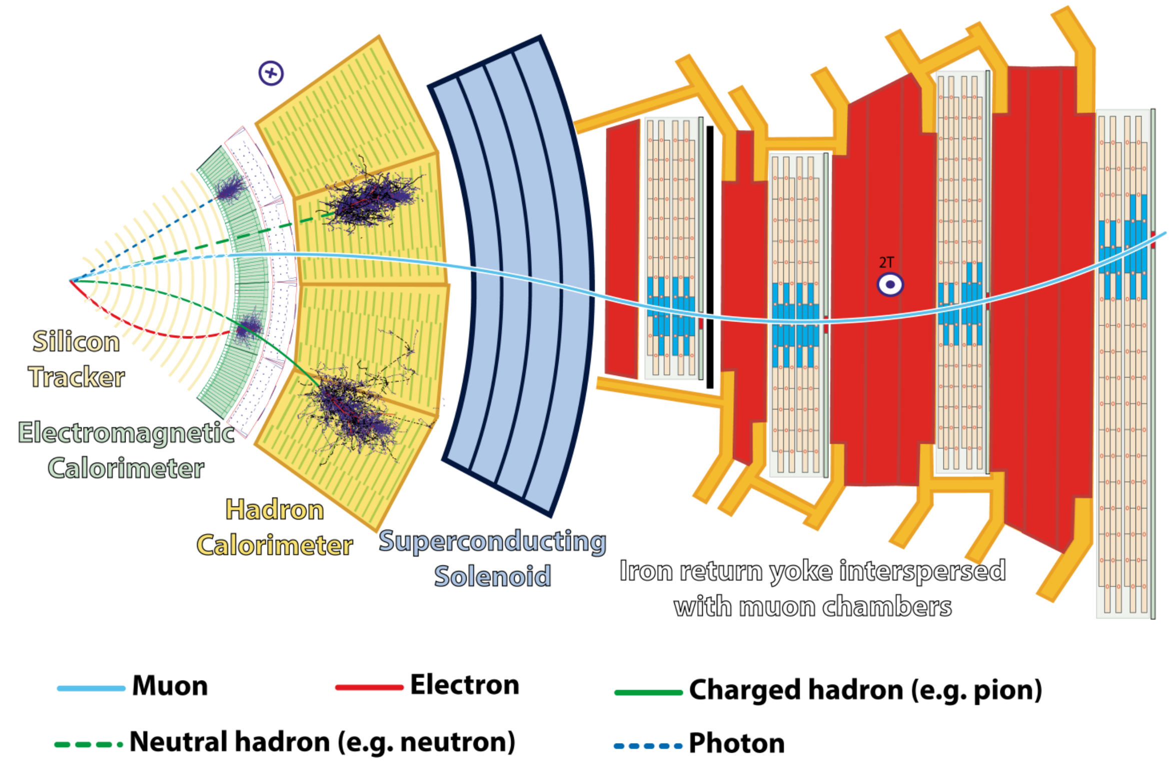
- 3 key characteristics of a good detector
  - high efficiency
  - good resolution
  - low fake rate
- Big advantage of CMS
  - high magnetic field (3.8 T)
    - good pT resolution
    - good separation of charged and neutral particles

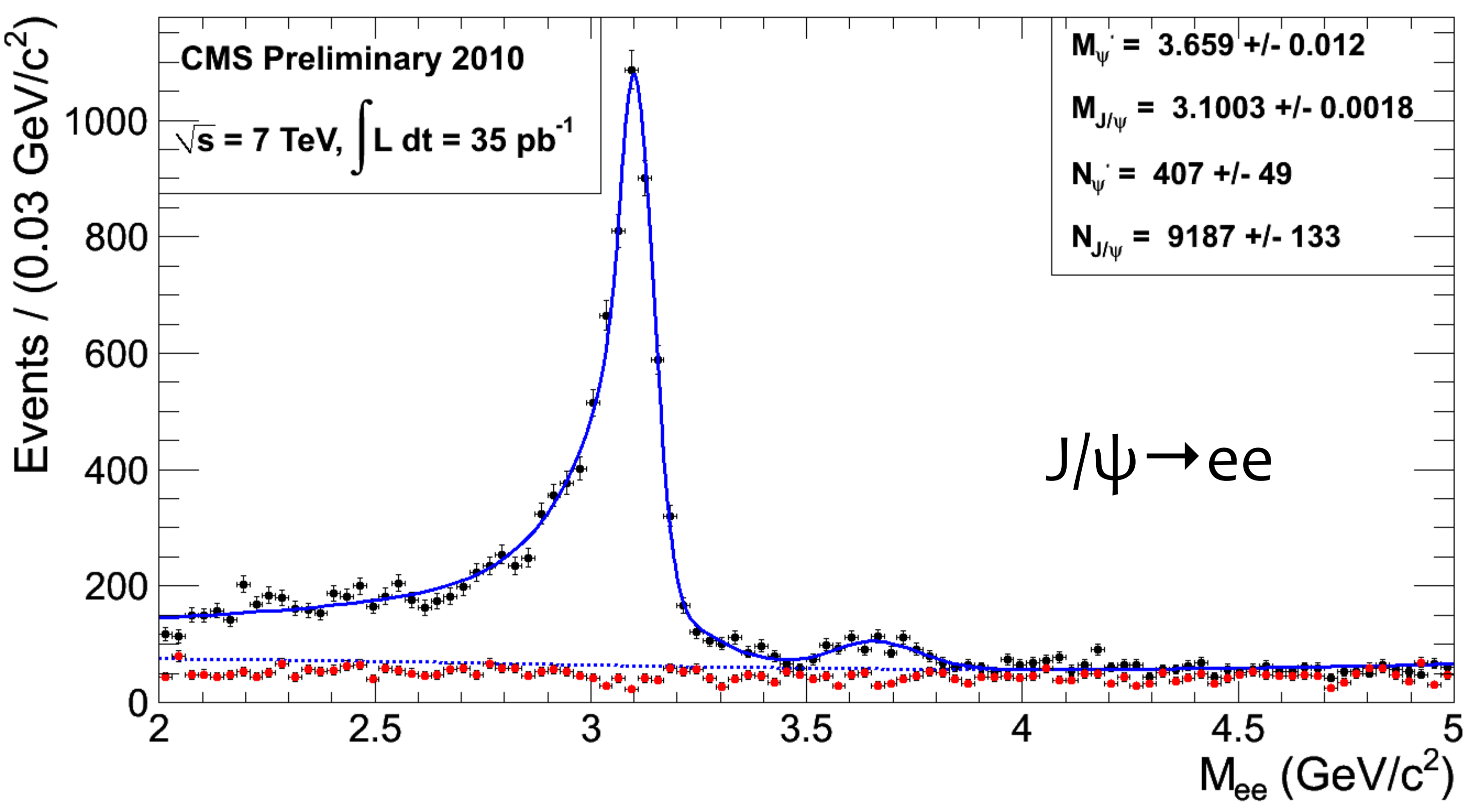


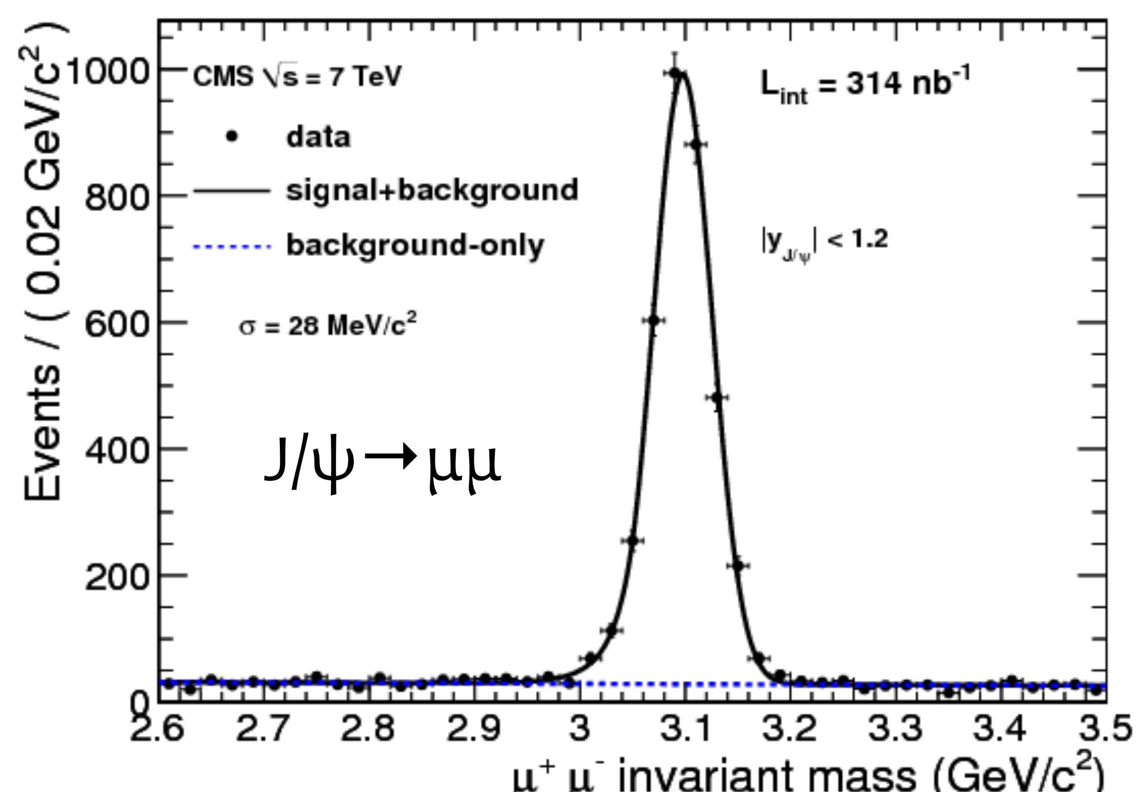


Basic principle of a HEP detector

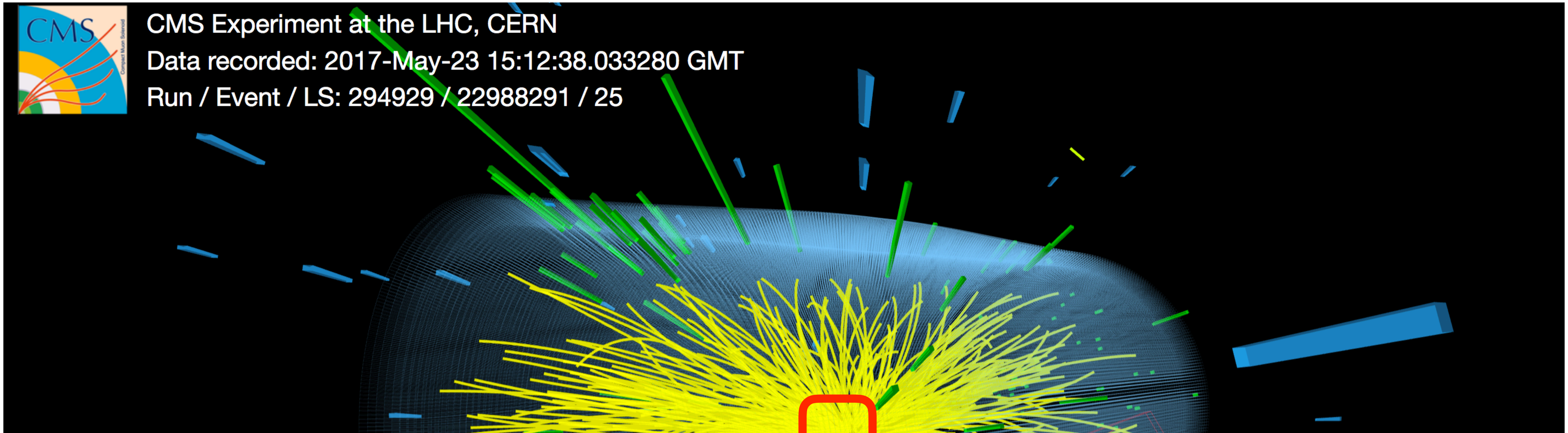
- Tracks and hits are turned into objects
  - electrons
  - muons
  - MET
  - photons
  - jets

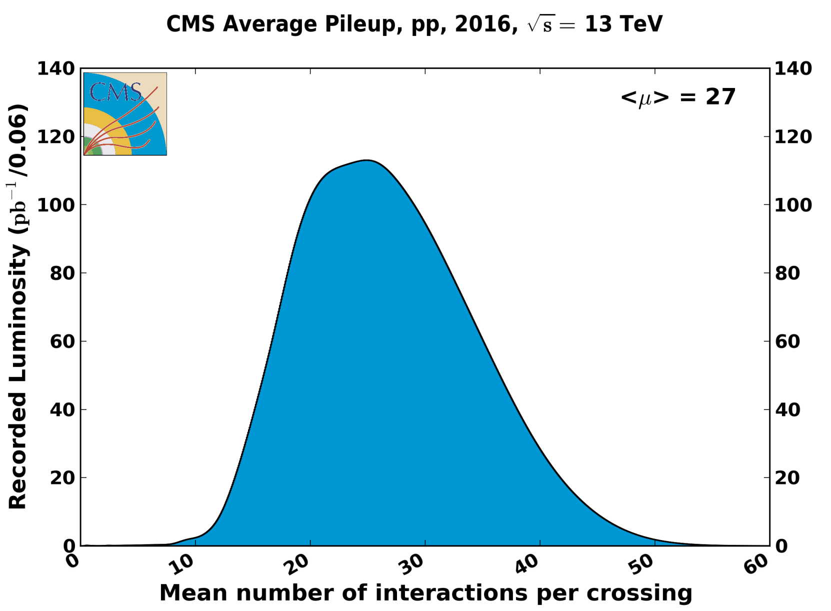


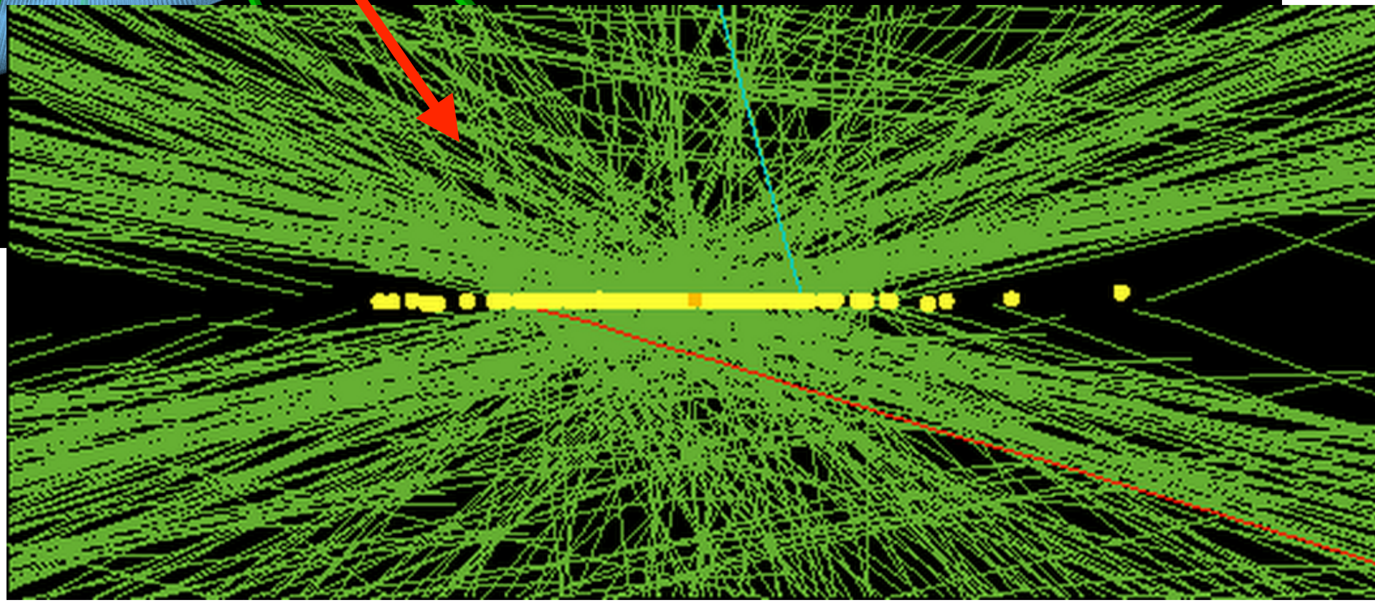




Pileup



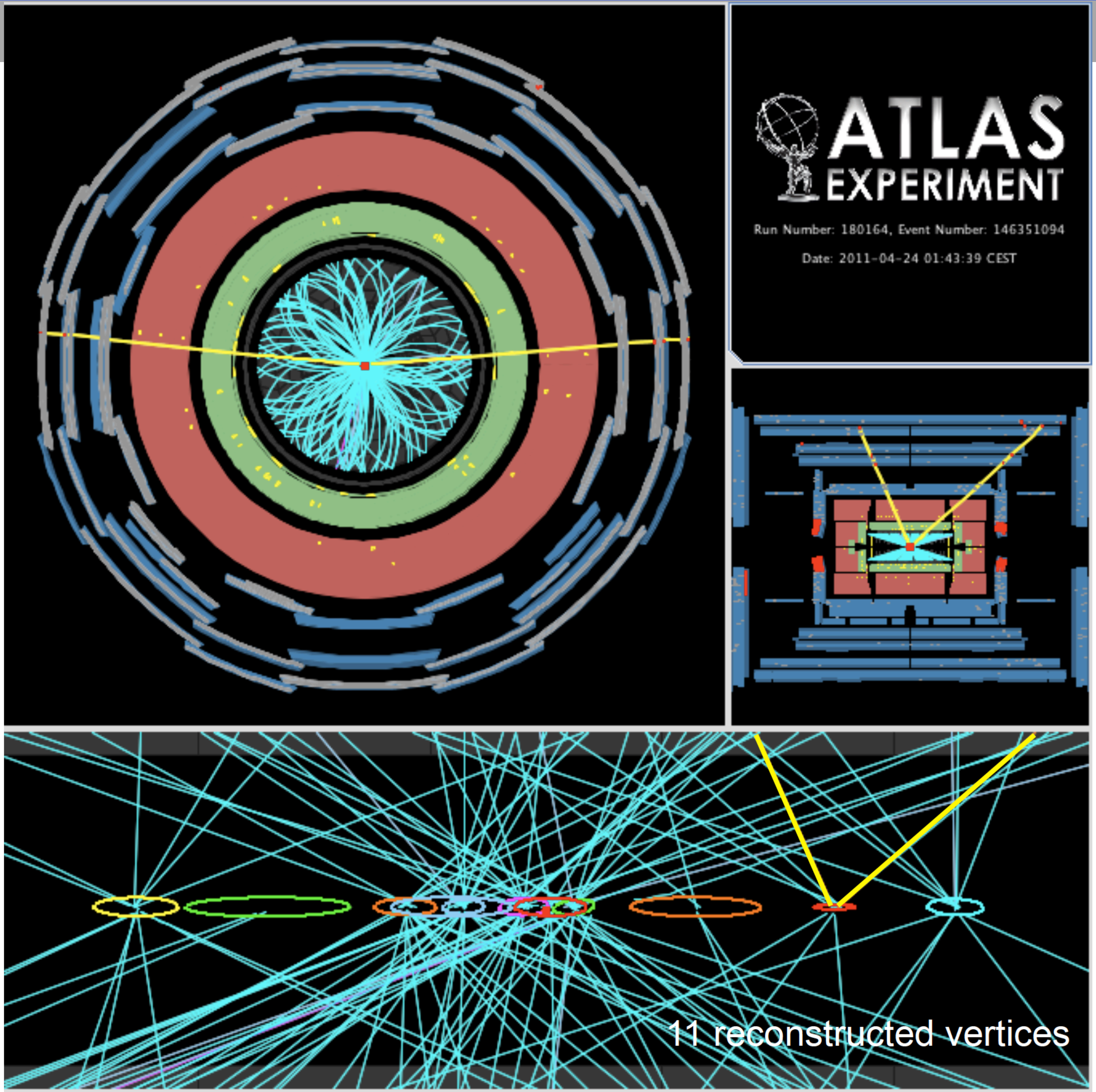




- Average condition per event
  - ~27 vertices spread in ~20mm per bunch crossing

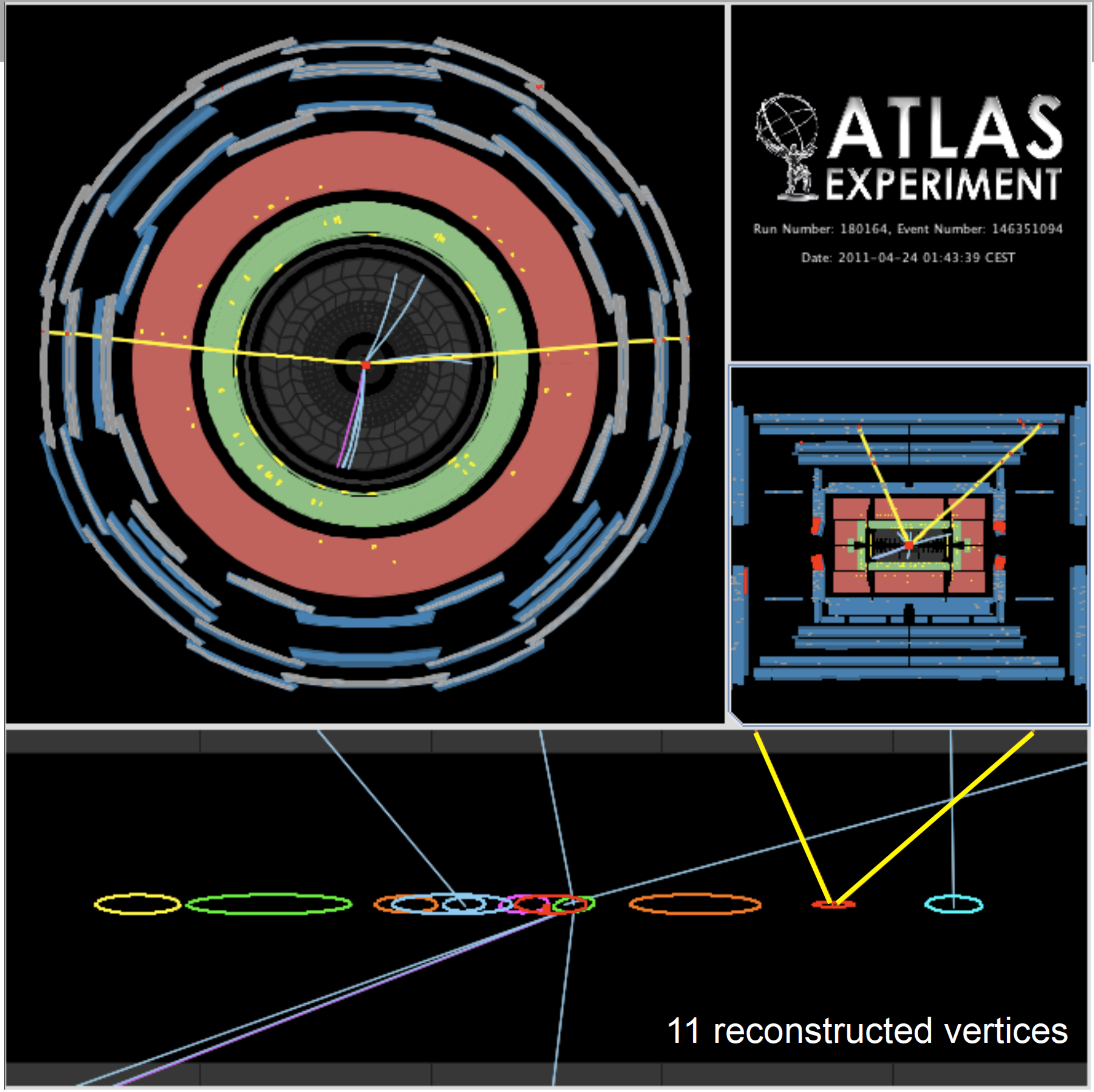
Pileup

$p_T > 0.5$ GeV



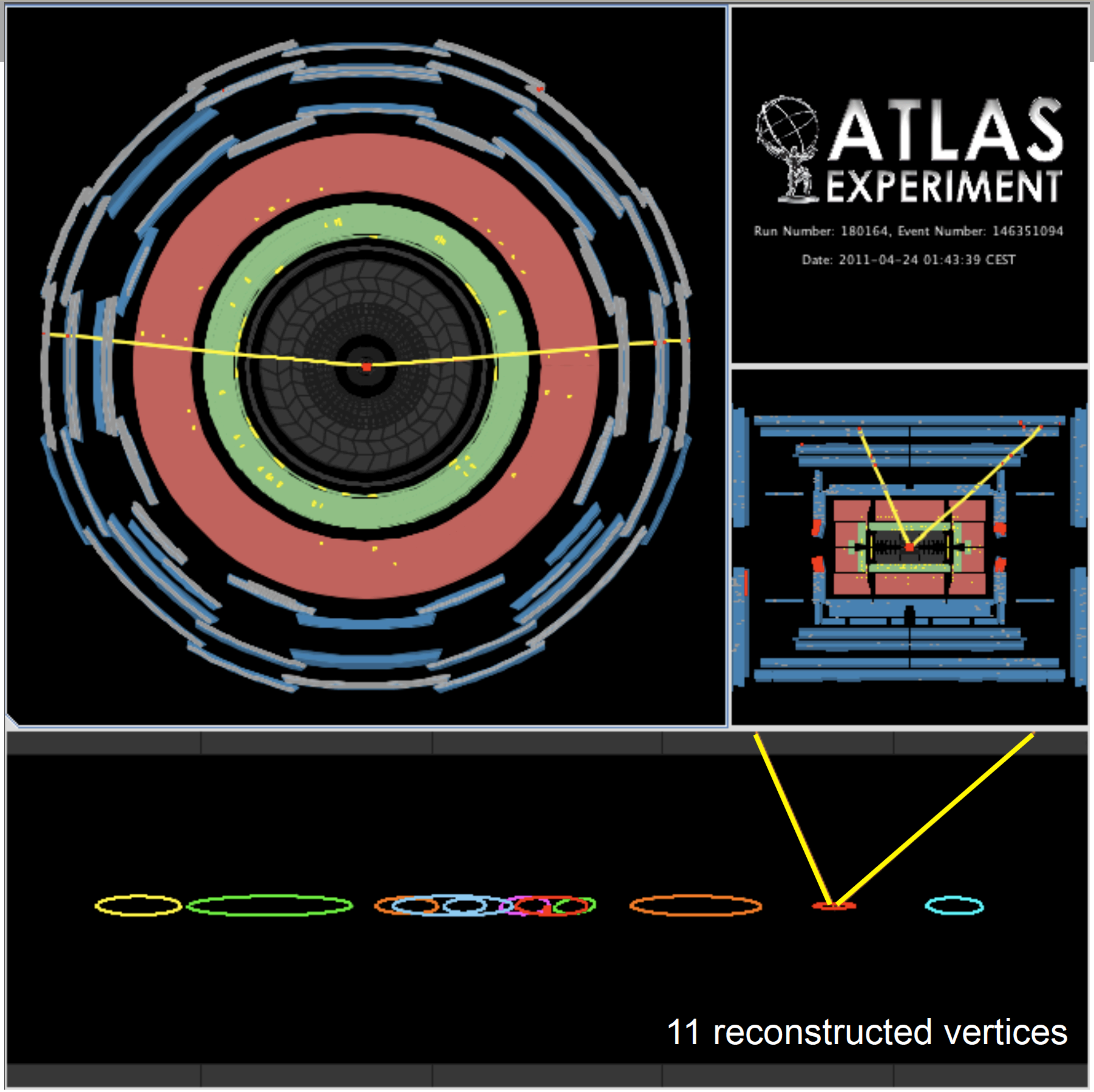
Pileup

$p_T > 2.0$ GeV



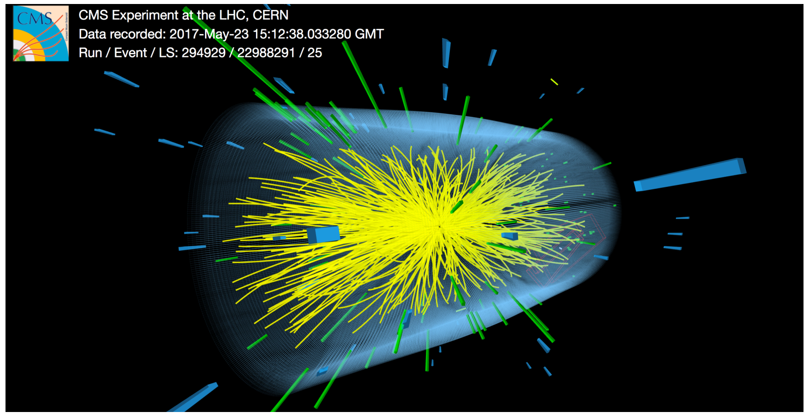
Pileup

$p_T > 10$ GeV

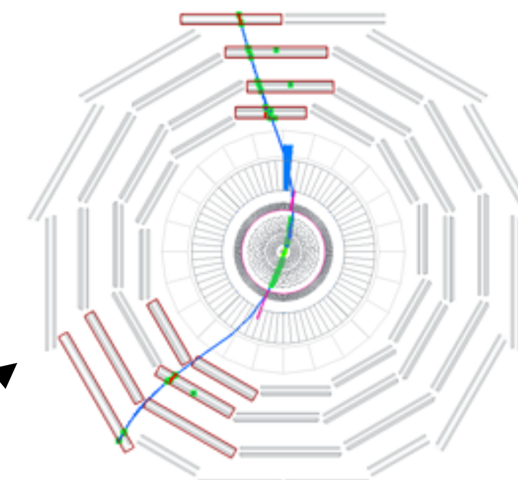


The CMS experiment

From collisions to bytes



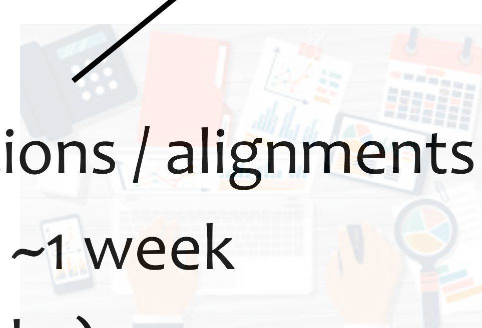
online

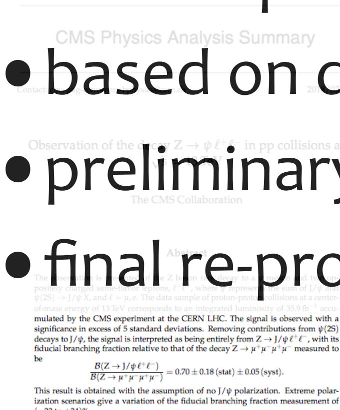


offline

- Trigger on physics is crucial
  - LHC collision rate 40 MHz
  - Hardware trigger (aka L1) ~100kHz
  - Software trigger (aka HLT) ~1kHz

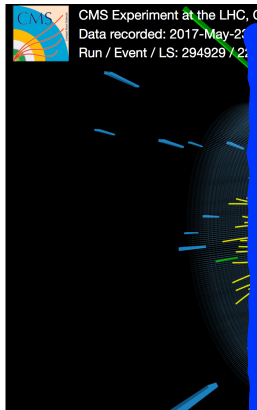
- Here you can find raw data
  - what does it contain? - now you know

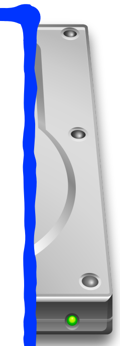




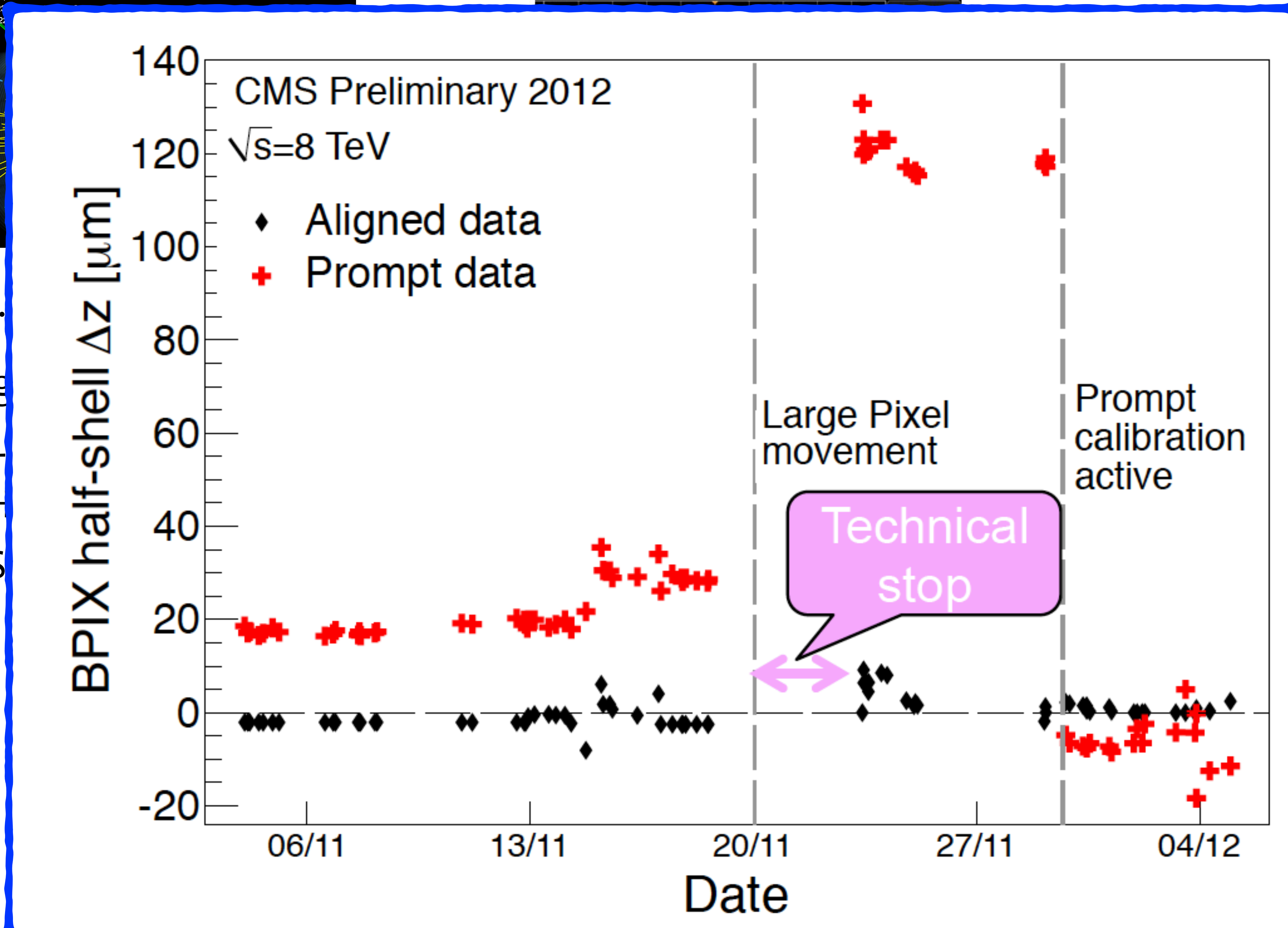
- Data are reprocessed
  - based on detector calibrations / alignments / other corrections
  - preliminary samples ready ~1 week
  - final re-processing O(months)

From collisions to bytes - example of reprocessing

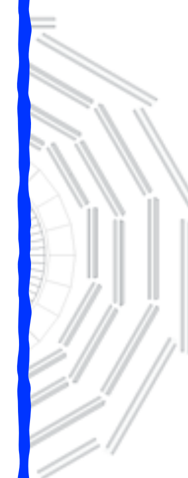




online



- Trigg
  - L
  - H
  - S



offline

ections

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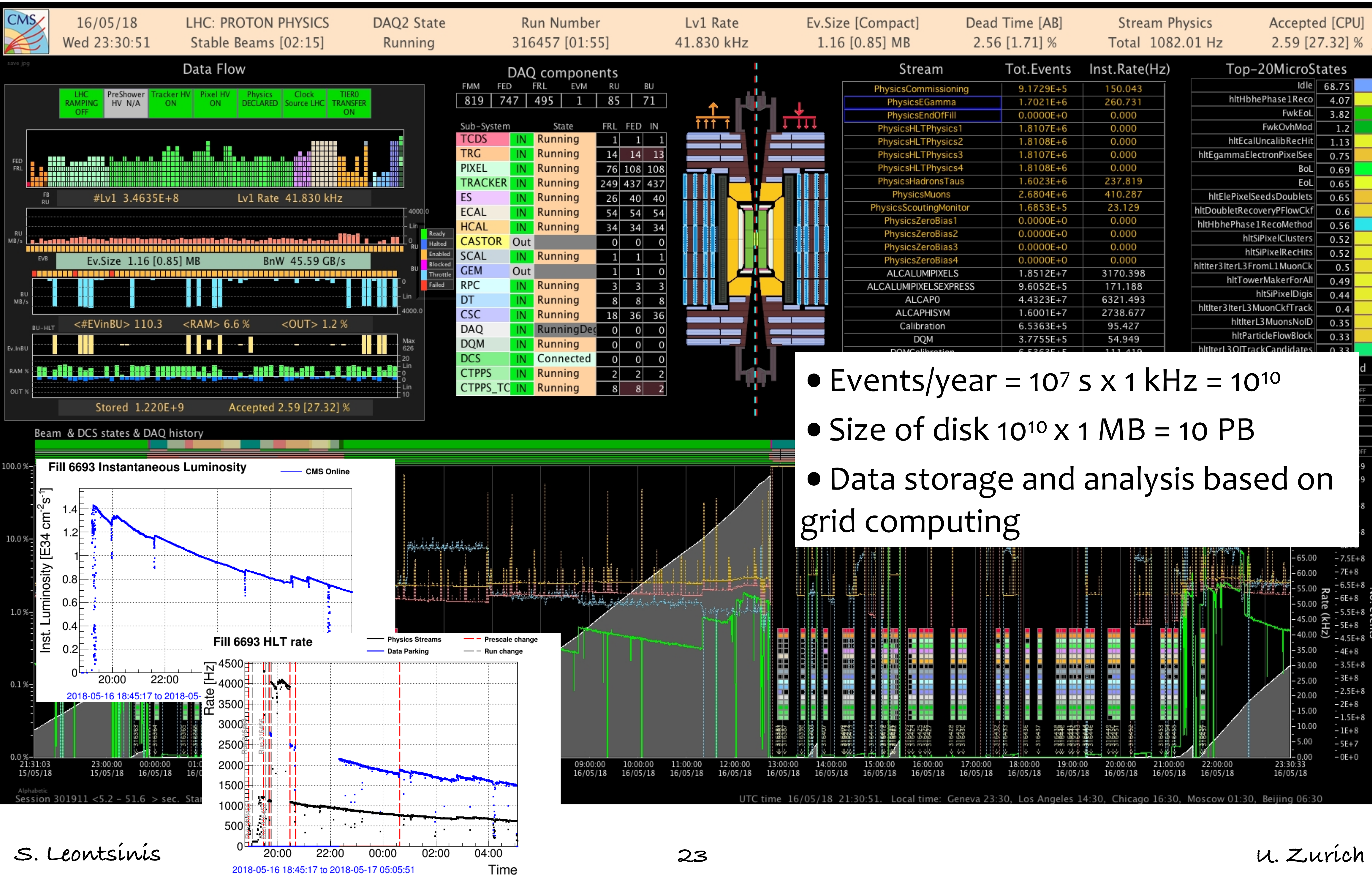
Data taking…



- Events/year = 10^7 s x 1 kHz = 10^{10}
- Size of disk 10^{10} x 1 MB = 10 PB
- Data storage and analysis based on grid computing

What can we do with the collisions recorded?

- Standard Model
  - W/Z production cross-sections
  - WW/ZZ production cross-sections
  - WWW/ZZZ production cross-sections
  - …
- New physics, beyond the Standard Model
  - Supersymmetry
  - Extra dimensions
  - Dark matter
  - Charged Higgs
  - …

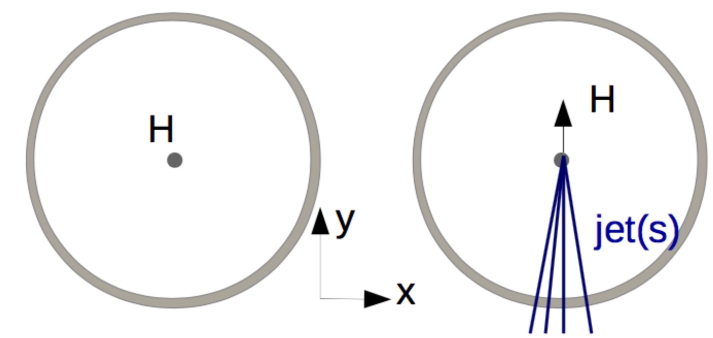
- Measurements
  - cross-sections
  - mass / lifetime
  - …
- Searches
  - bump
  - distributions - tails

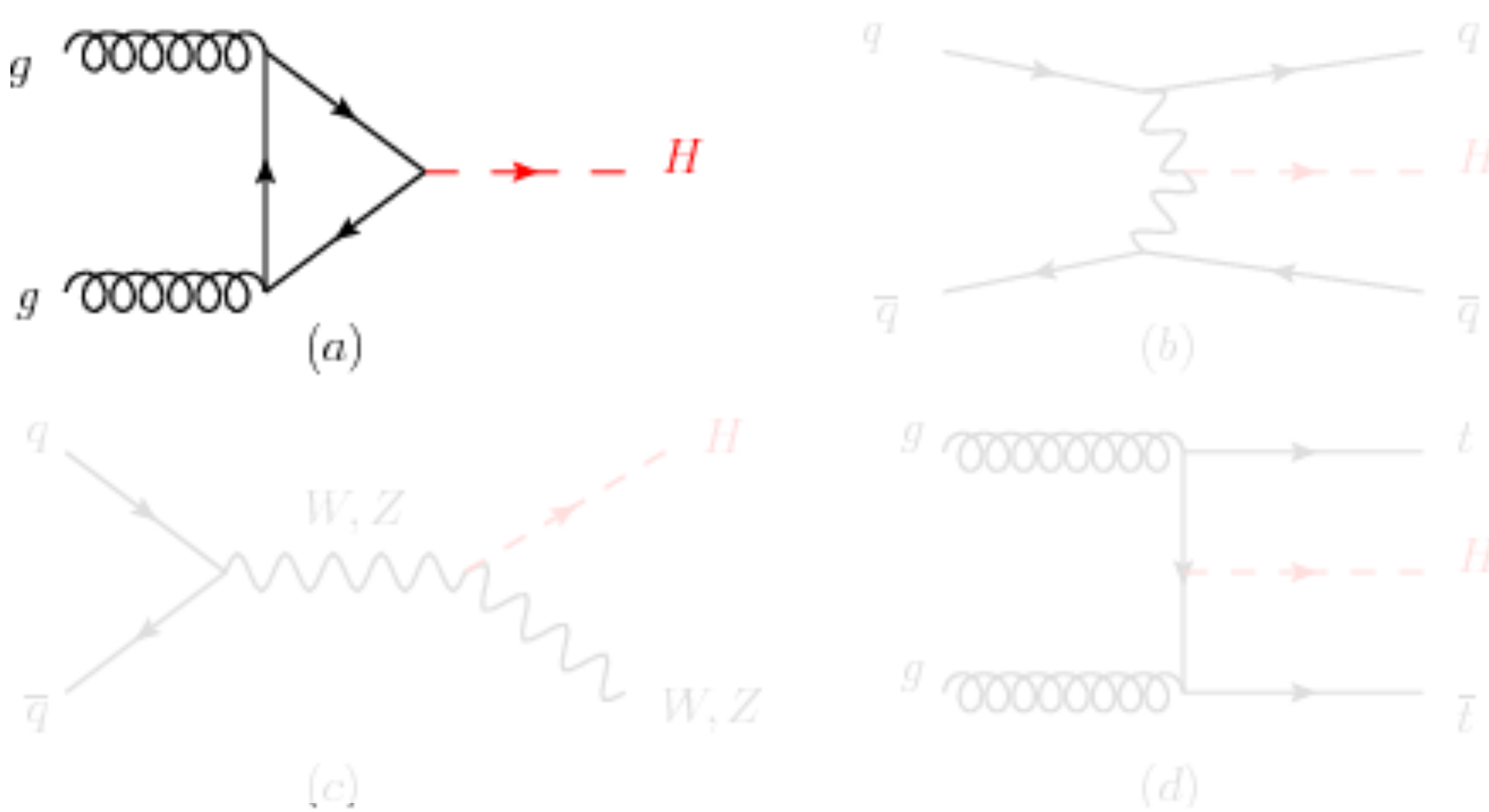
Higgs physics as a prime example of a standard analysis

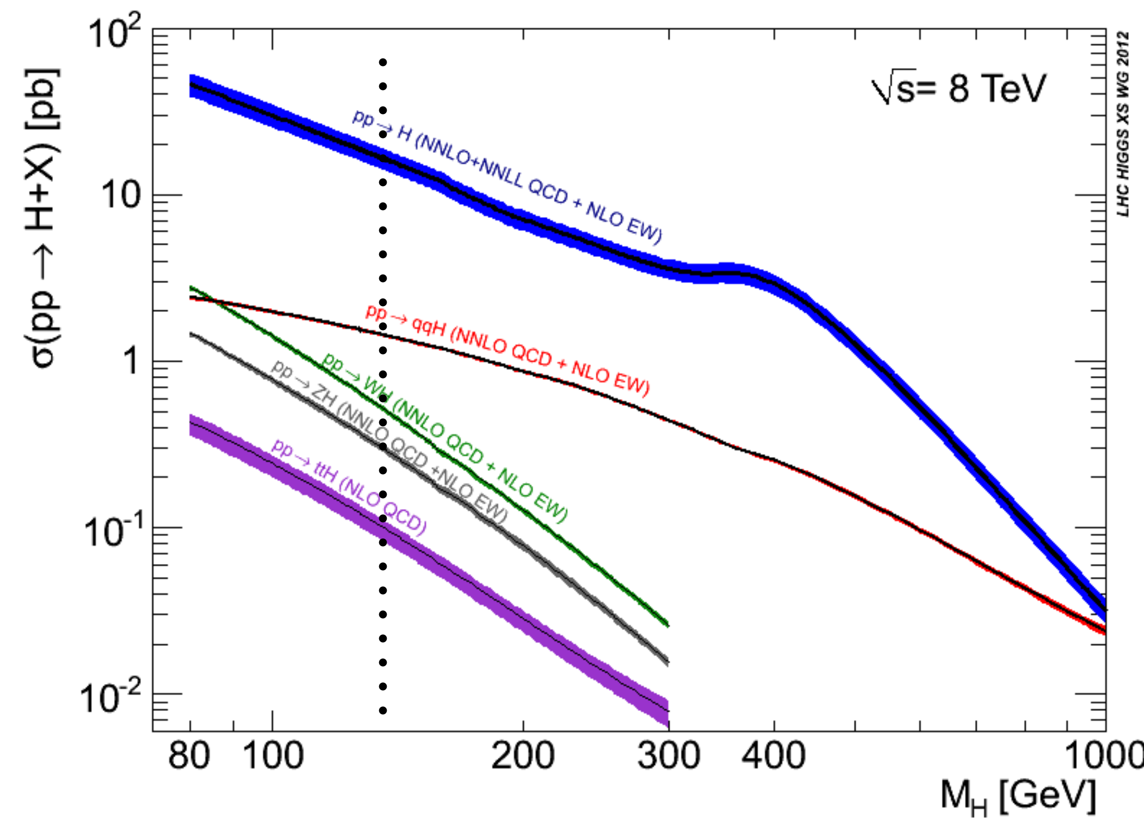
(reminder $N_{events} = L \times \sigma$)

Higgs **production** at the LHC

- Gluon gluon fusion
    - σ = 19.3 pb $\sqrt{s}$=8 TeV
    - loop dominated by top quark
    - often accompanied by jets in the final state





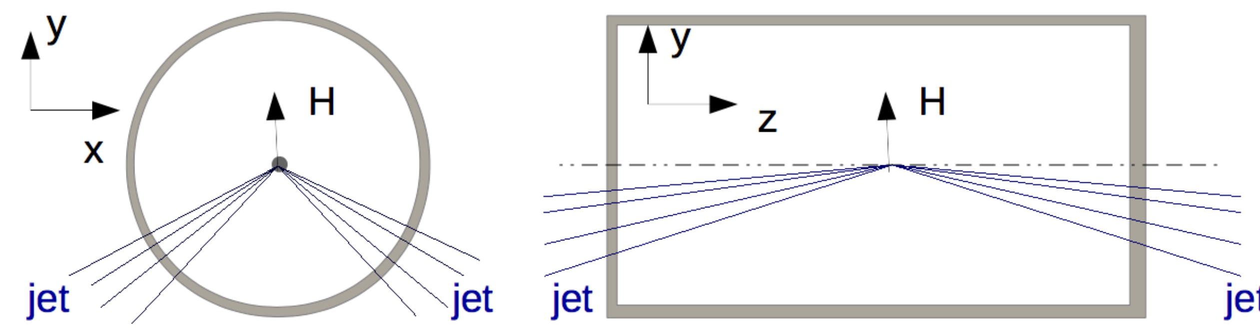


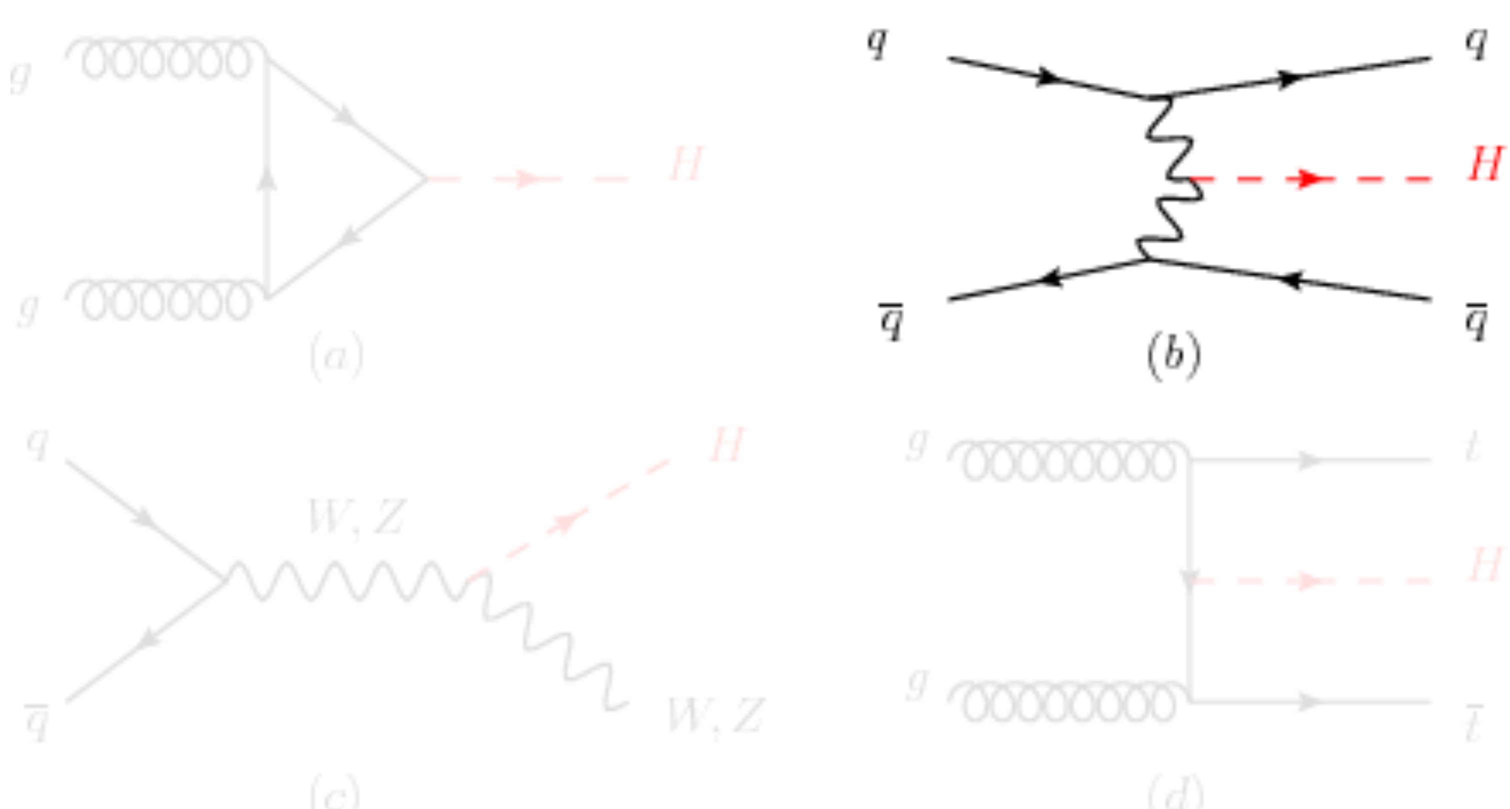
dominant production mechanism

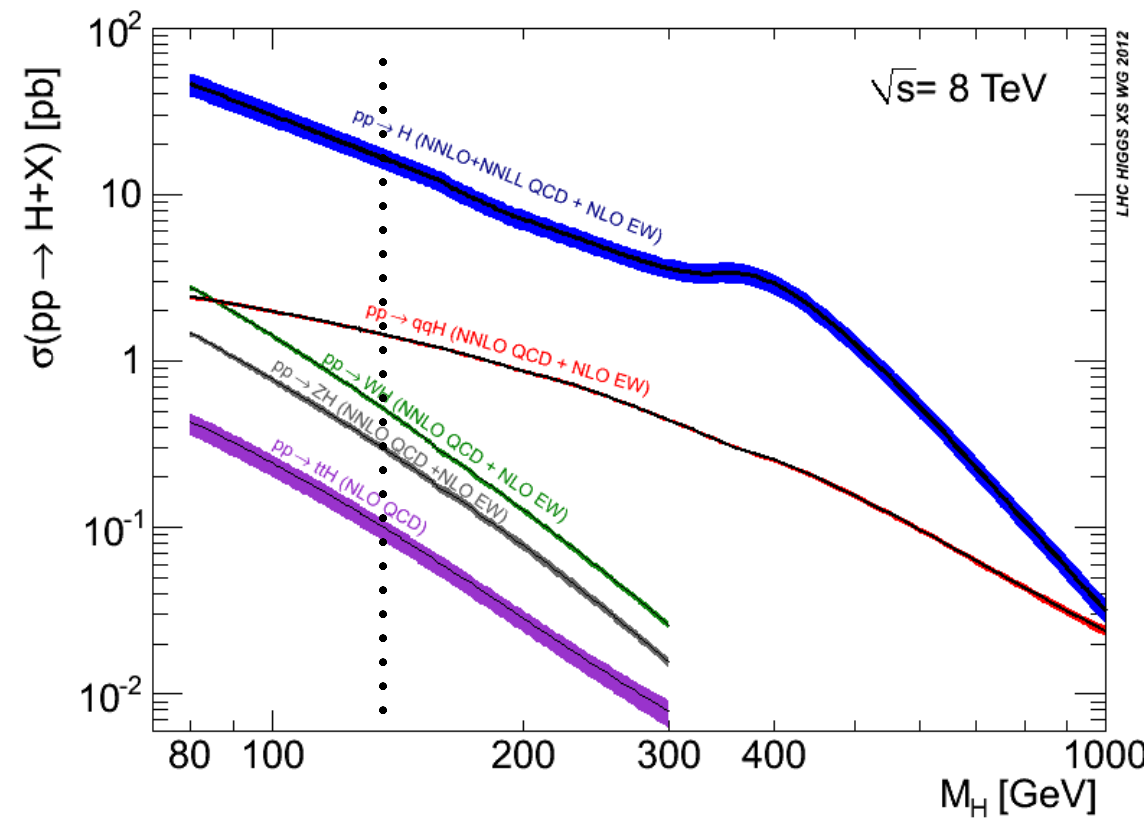
N_{events} = L x σ = 20 fb^{-1} x 19.3 pb = 4×10^5

Higgs **production** at the LHC

- Vector boson fusion
  - σ = 1.6 pb √s=8 TeV
  - 10x lower cross-section compared to ggF





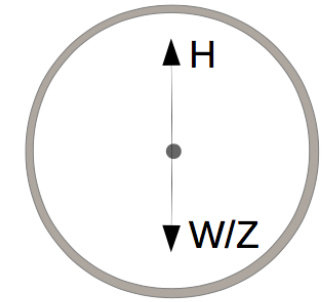


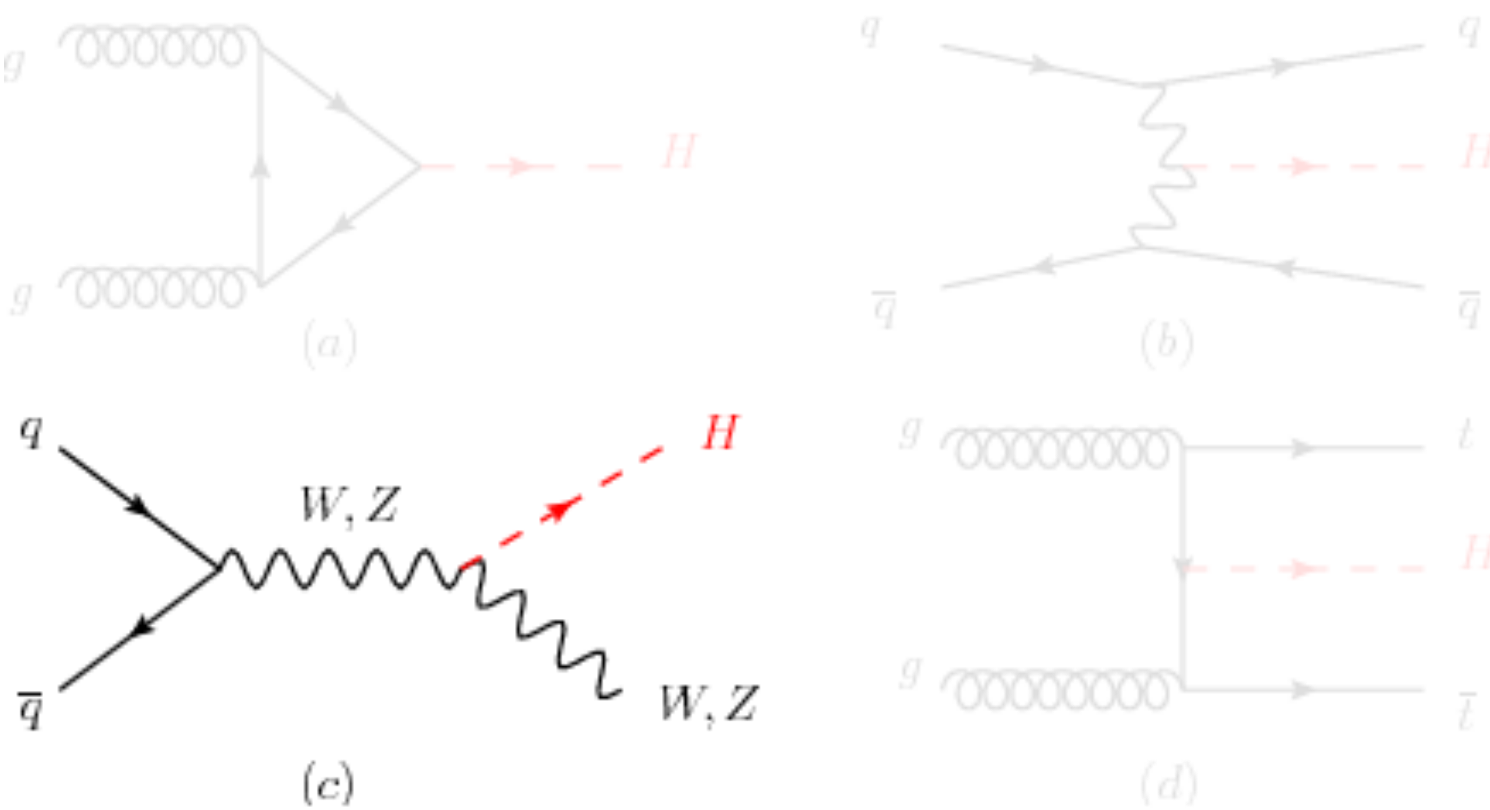
Disting experimental signature

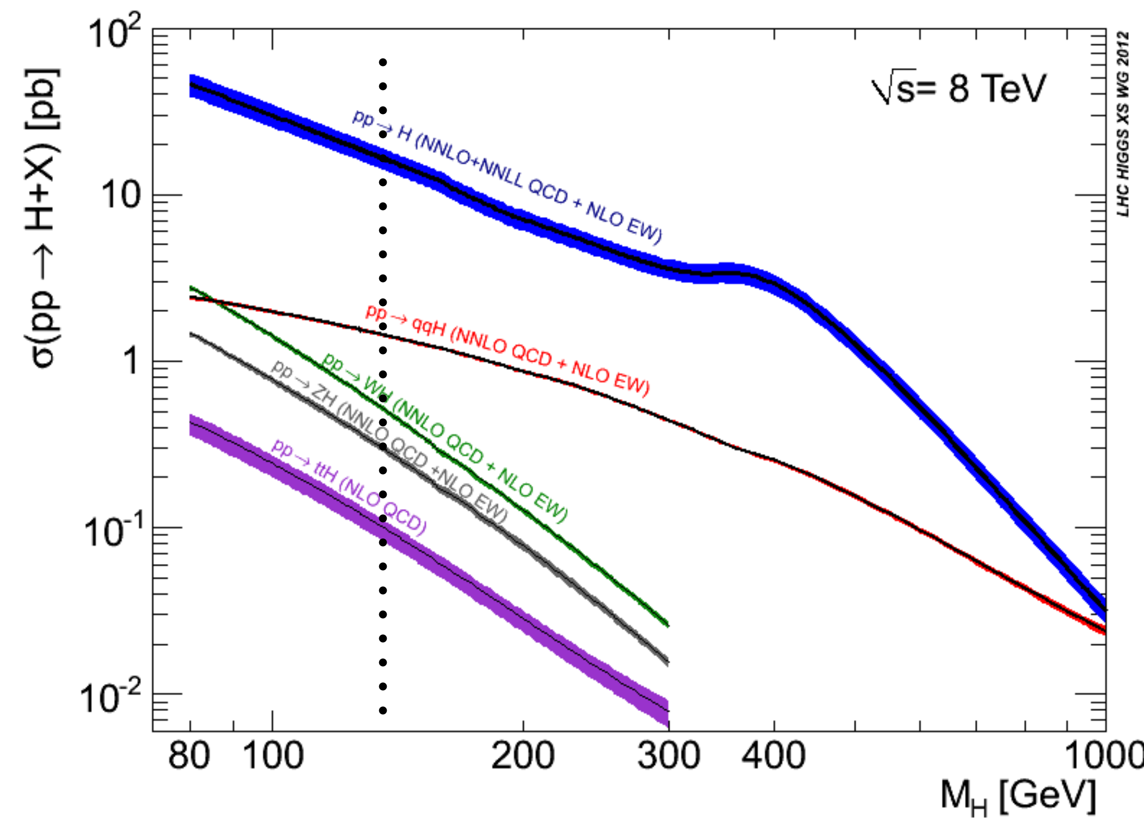
$N_{events} = L \times \sigma = 20\ fb^{-1} \times 1.6\ pb = 3\times10^{4}$

Higgs **production** at the LHC

- Associated production with W/Z
  - σ = 0.7 pb $\sqrt{s}$=8 TeV for WH
  - σ = 0.4 pb $\sqrt{s}$=8 TeV for ZH
  - very low cross-section





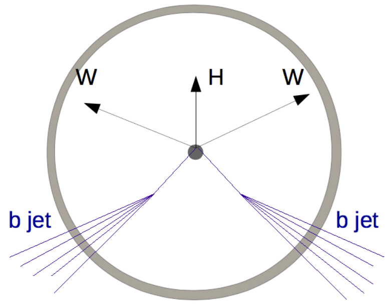


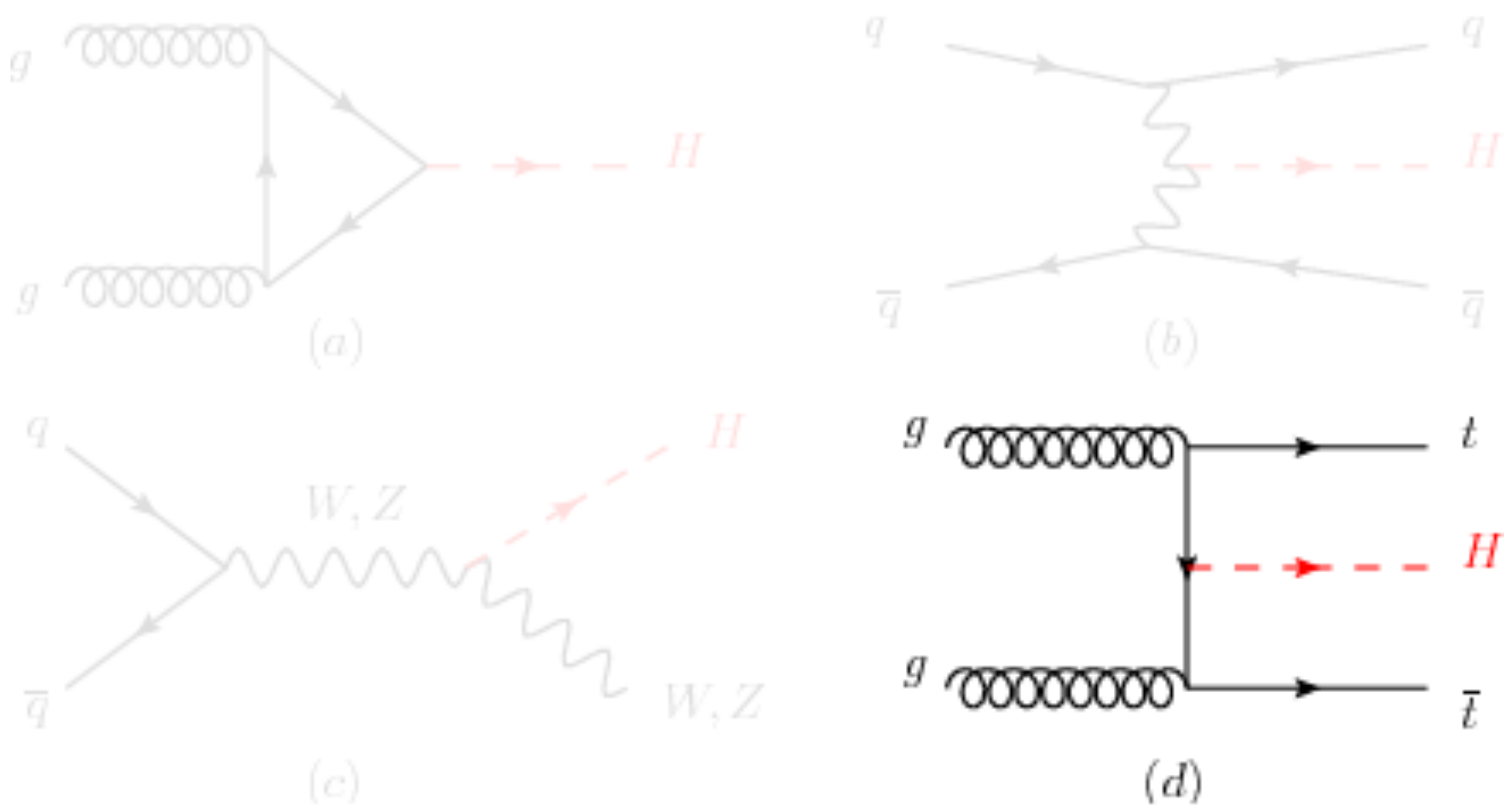
Very clean final state

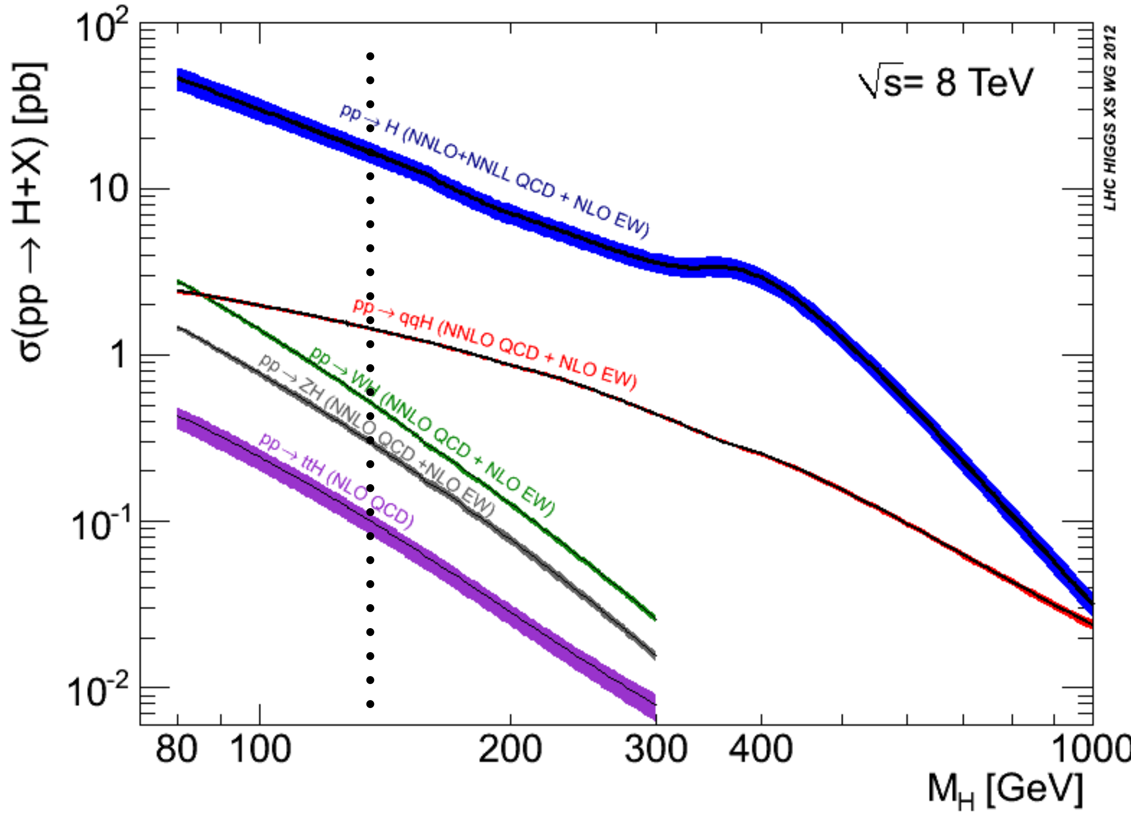
$N_{events} = L \times \sigma = 20\ fb^{-1} \times 1.1\ pb = 2\times10^{4}$

Higgs **production** at the LHC

- Associated production with top pair
  - σ = 0.12 pb √s=8 TeV
  - very² low cross-section







Unique final state with 2 b-jets, 2 W bosons and a Higgs

$N_{events} = L \times \sigma = 20\ fb^{-1} \times 0.12\ pb = 2\times10^3$

Higgs **decays** at the LHC

Highest branching ratio, but high QCD background

Not fully reconstructed state

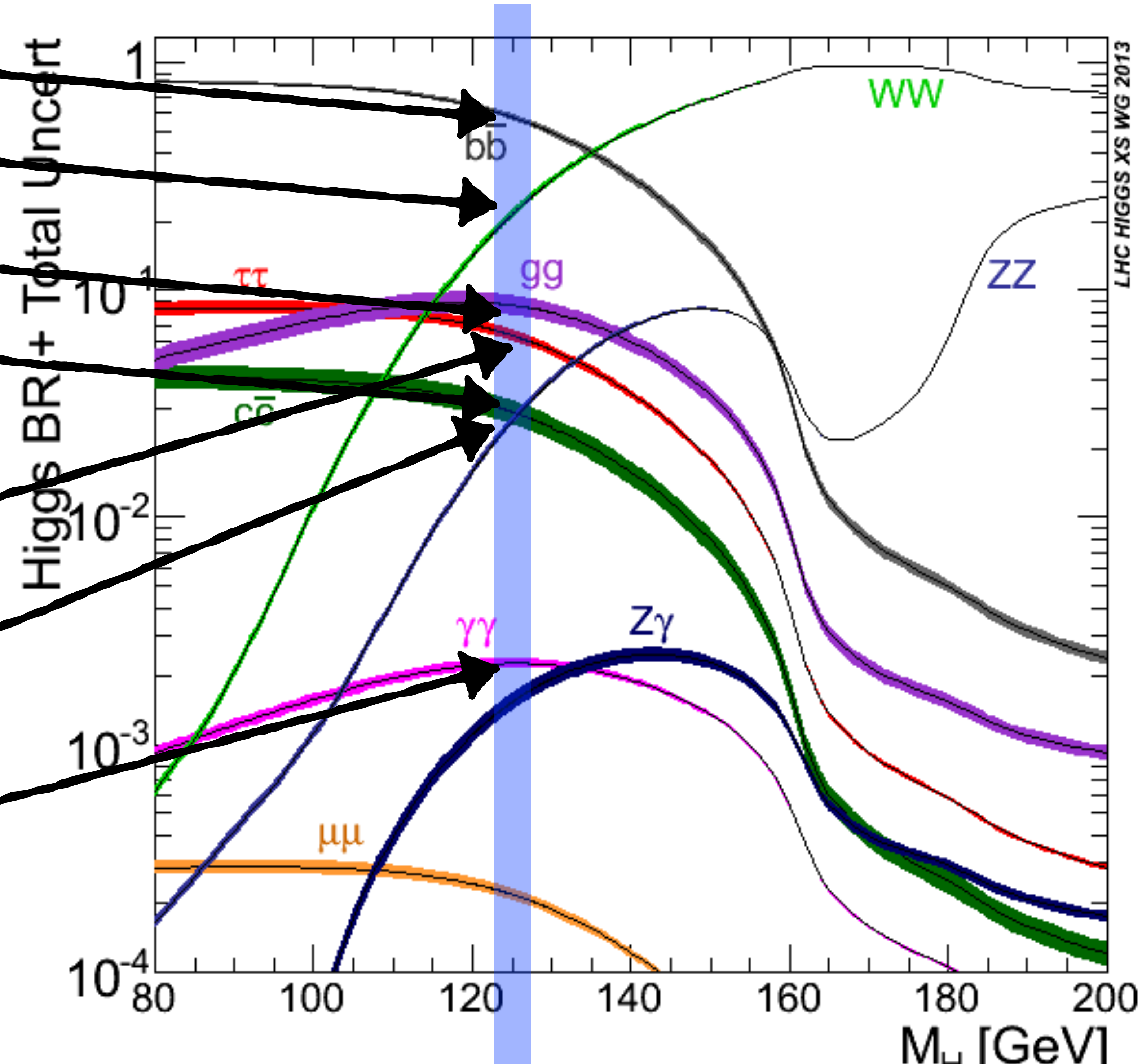
Impossible due to jet backgrounds

Very difficult.. Poor performance of c jet tagging

Only accessible final state with leptons

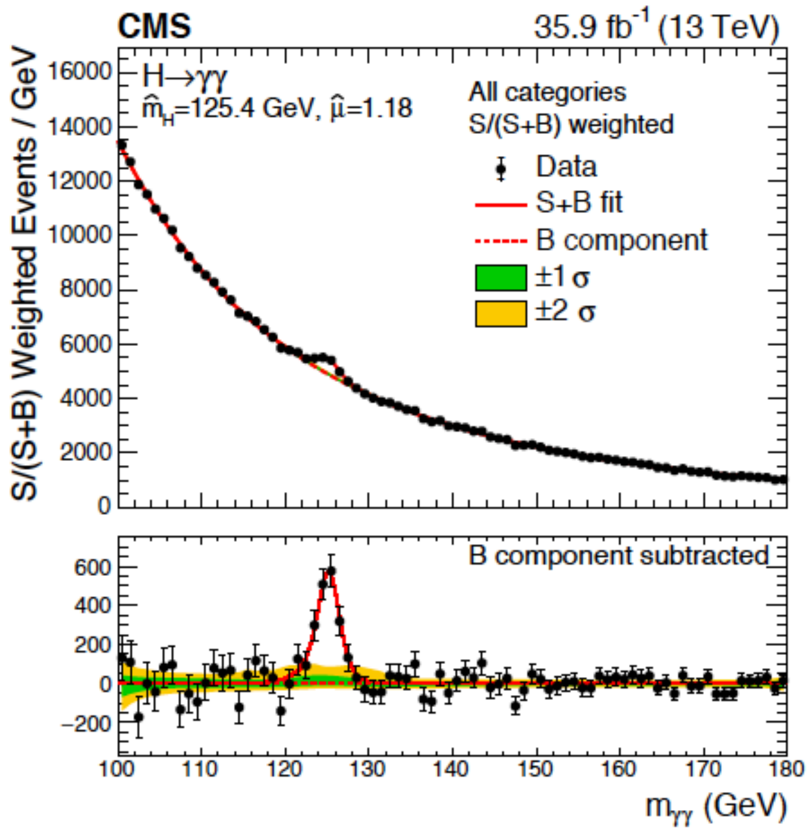
Fully reconstructed final state with excellent resolution

Fully reconstructed final state with excellent resolution



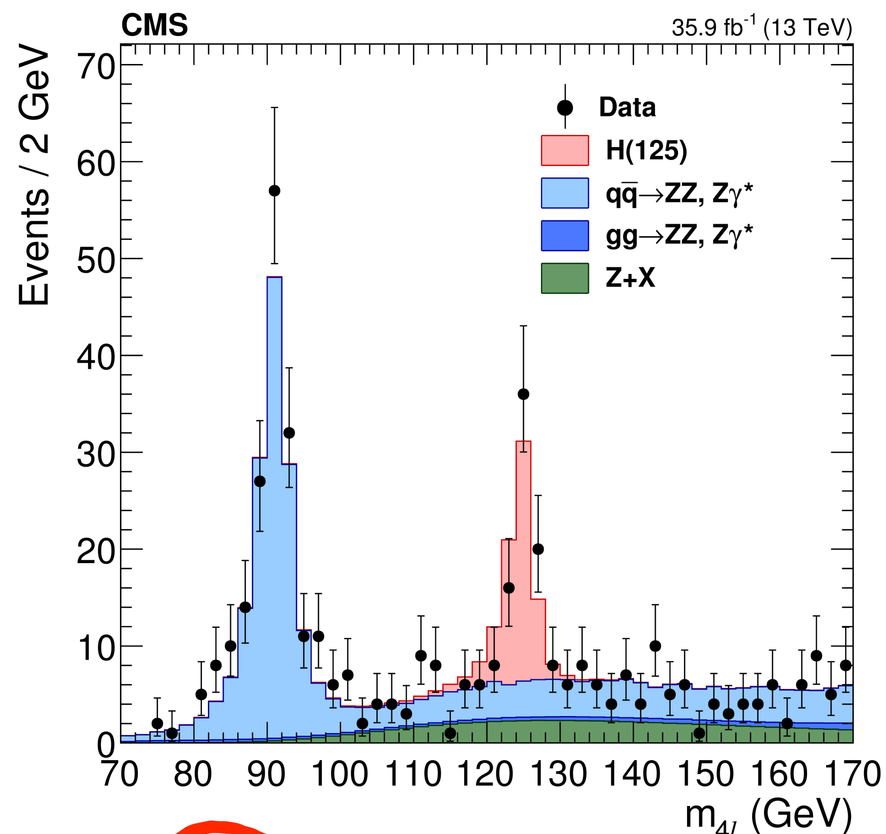
H→gg and H→cc can be studied in ee collider

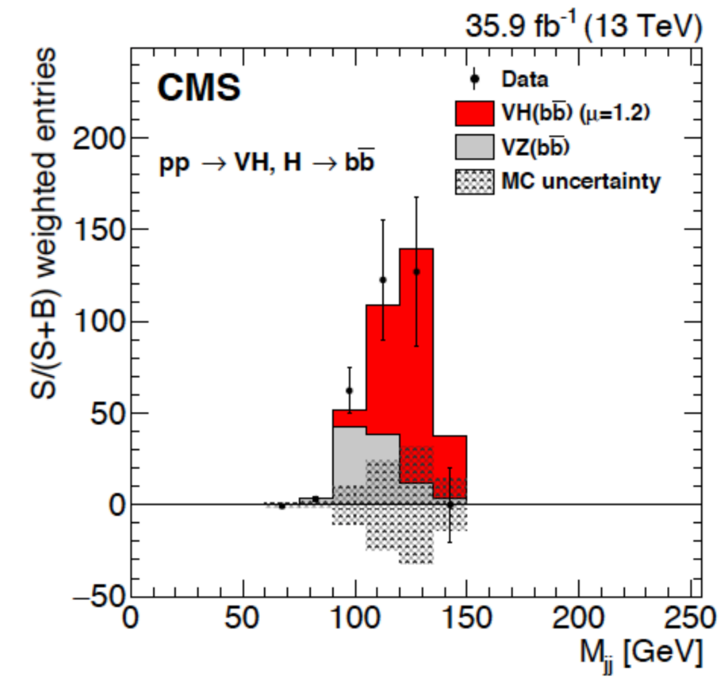
Higgs **decays** at CMS

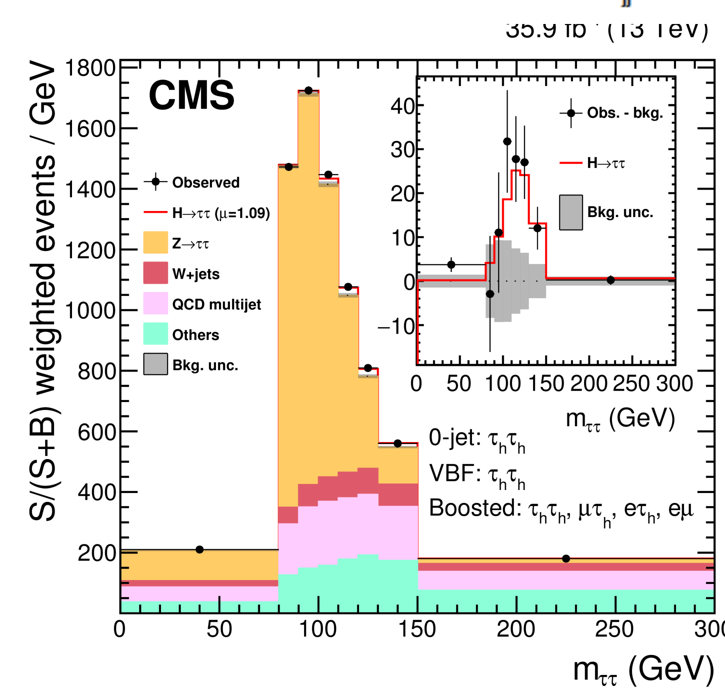


$$M(x,p,q) = N_s/(N_s+N_b)\, S(x;p) + N_b/(N_s+N_b)\, B(x;q)$$

$$N_{total} = N_s + N_b$$

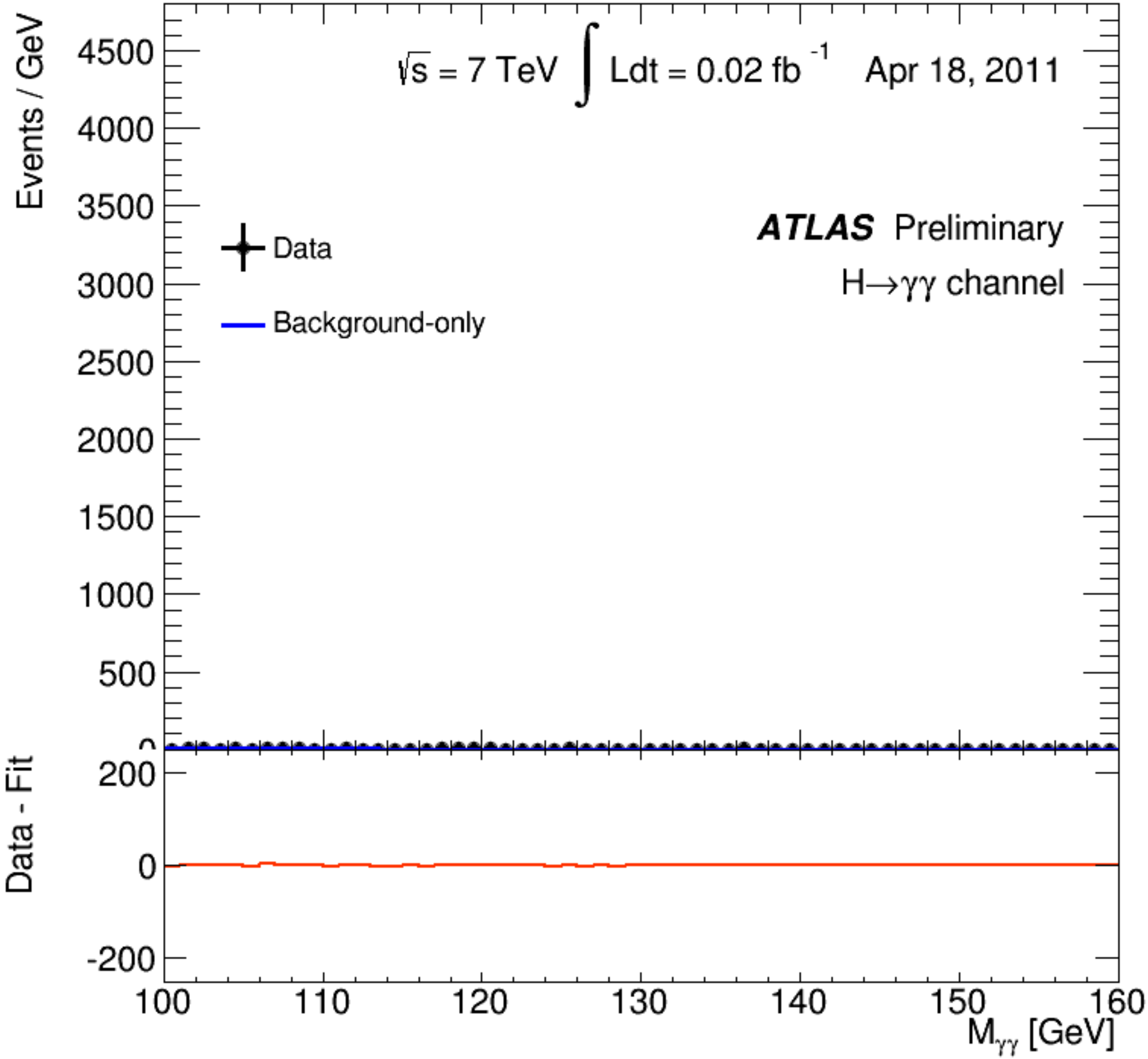






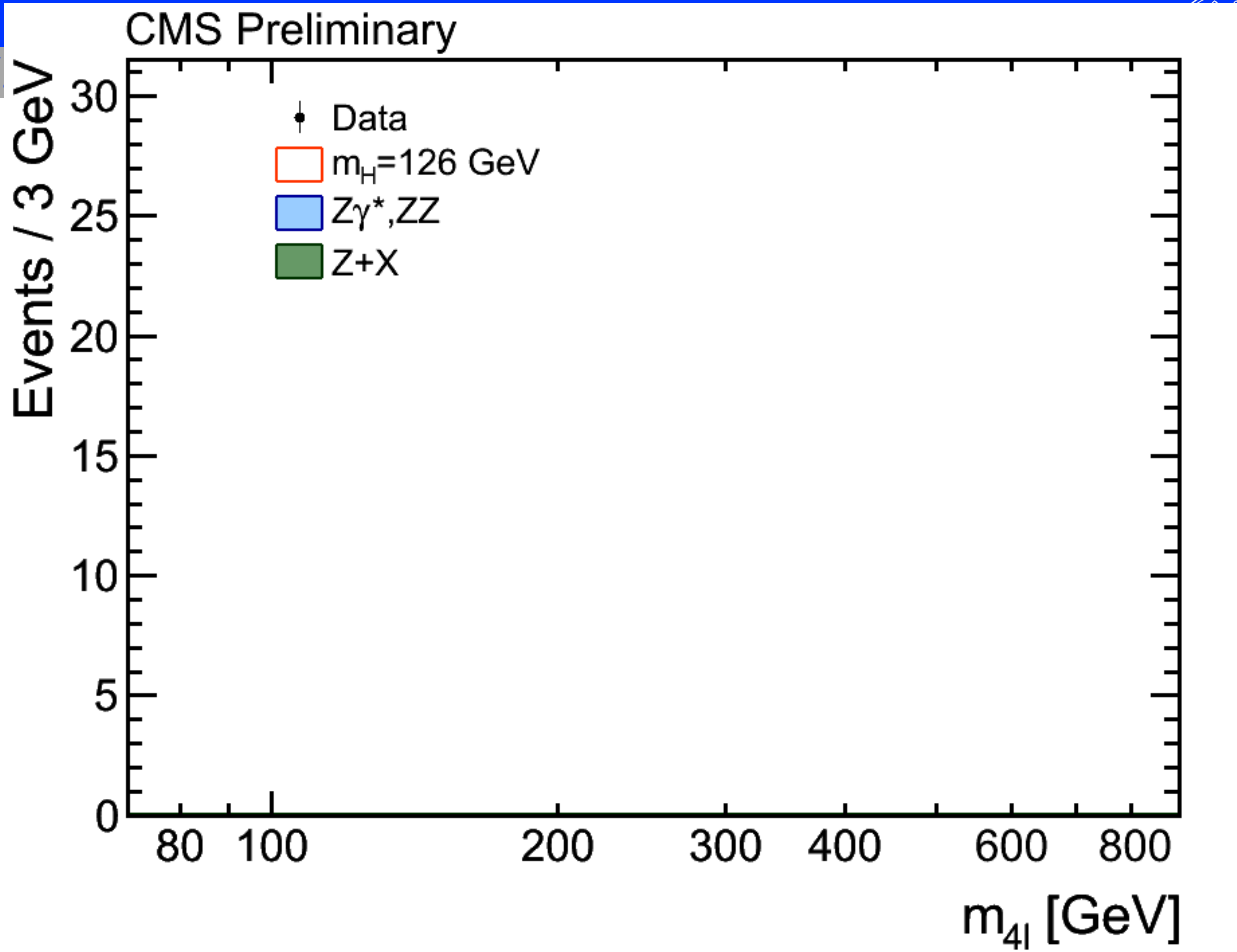
$$N_{events} = L \times \sigma \times B(H\rightarrow ?) \times B(? \rightarrow ?') \times \varepsilon \times A$$

for $H\rightarrow ZZ\rightarrow 4l$, $e \times A = (20\text{-}40)\%$



$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

Hi

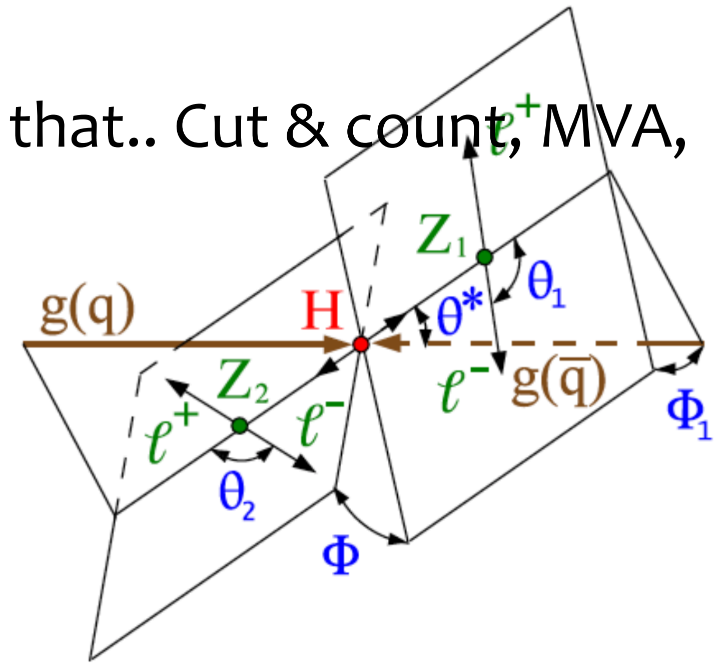


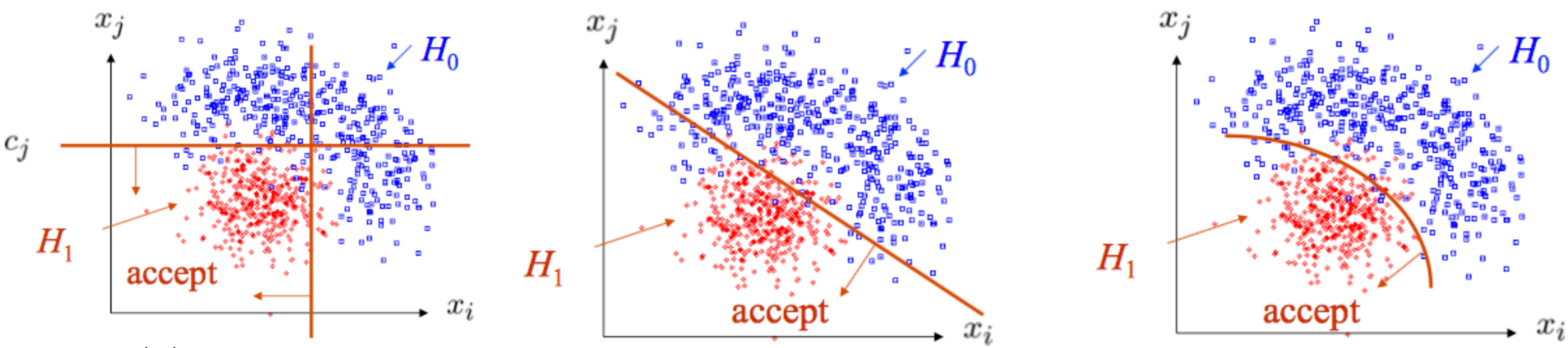
CMS Preliminary
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Events / 3 GeV
0
5
10
15
20
25
30
80
100
200
300
400
600
800
m_4l [GeV]

$H \rightarrow ZZ \rightarrow 4l$ simplified

- Choose decay mode of the Z
  - $Z \rightarrow qq$
  - $Z \rightarrow ee/\mu\mu/\tau\tau$
  - $Z \rightarrow \nu\nu$
- $H \rightarrow ZZ \rightarrow llll$, $l=e,\mu$ is the easiest by far
  - aka the golden mode
  - high-pt leptons are clean!
  - have high efficiency
  - very good momentum resolution

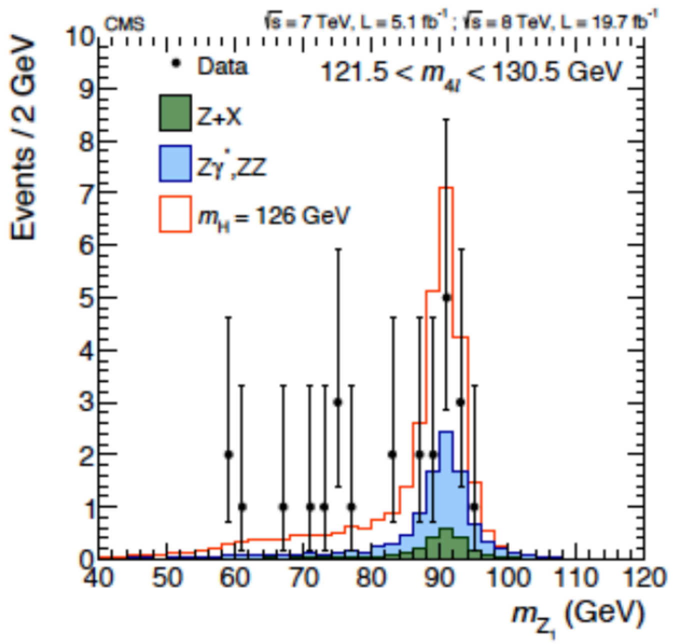
- Select events containing
  - 2electrons and 2muons OR
  - 4 electrons OR
  - 4 muons
- Various approaches on that.. Cut & count, MVA, MELA, …

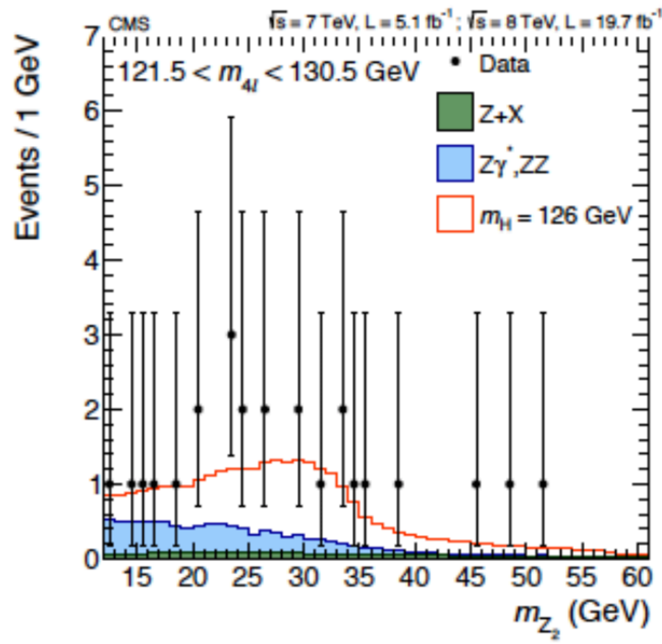


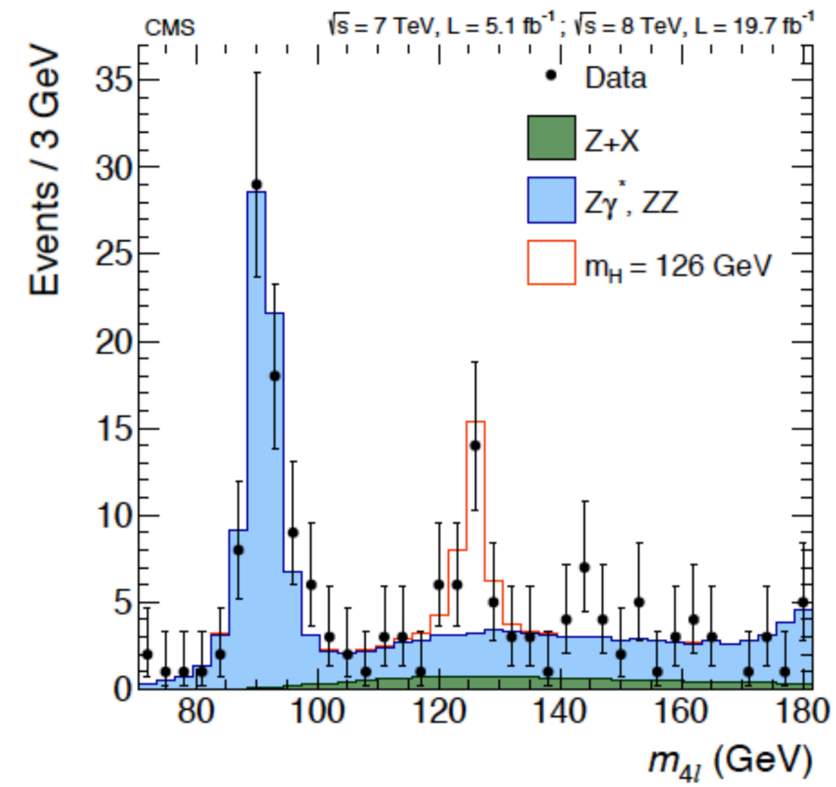


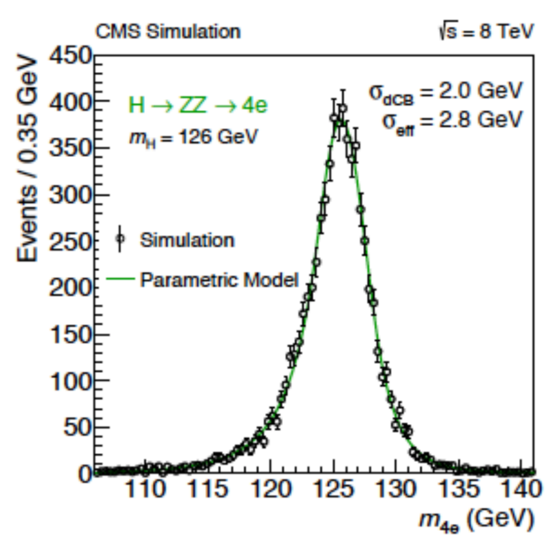
H→ZZ→4l simplified

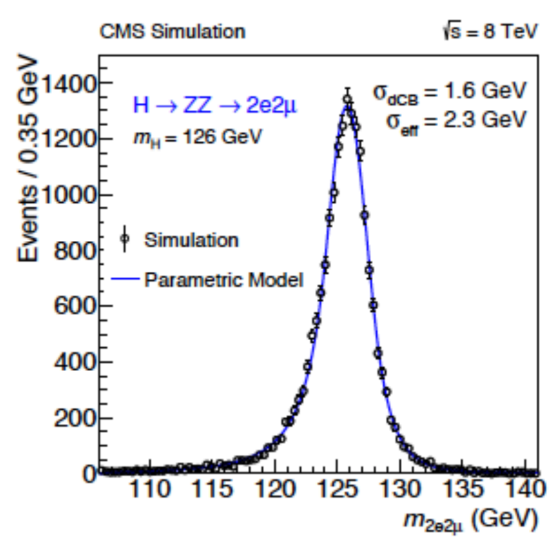
- Check that one of the di-lepton pair is consistent with a Z
    - one is real, one is off-shell
- Check that the 4 leptons are compatible with the Higgs

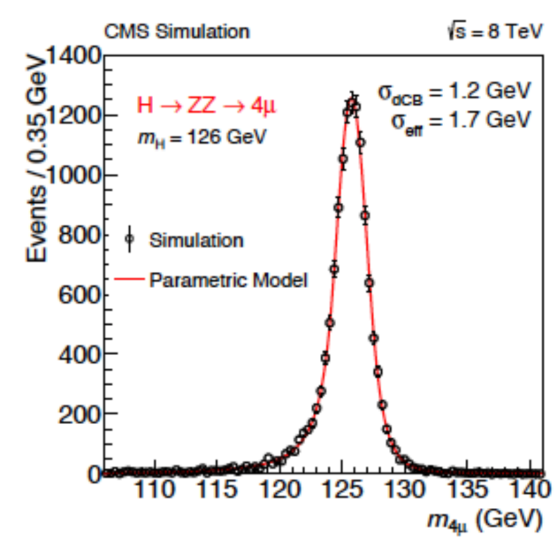






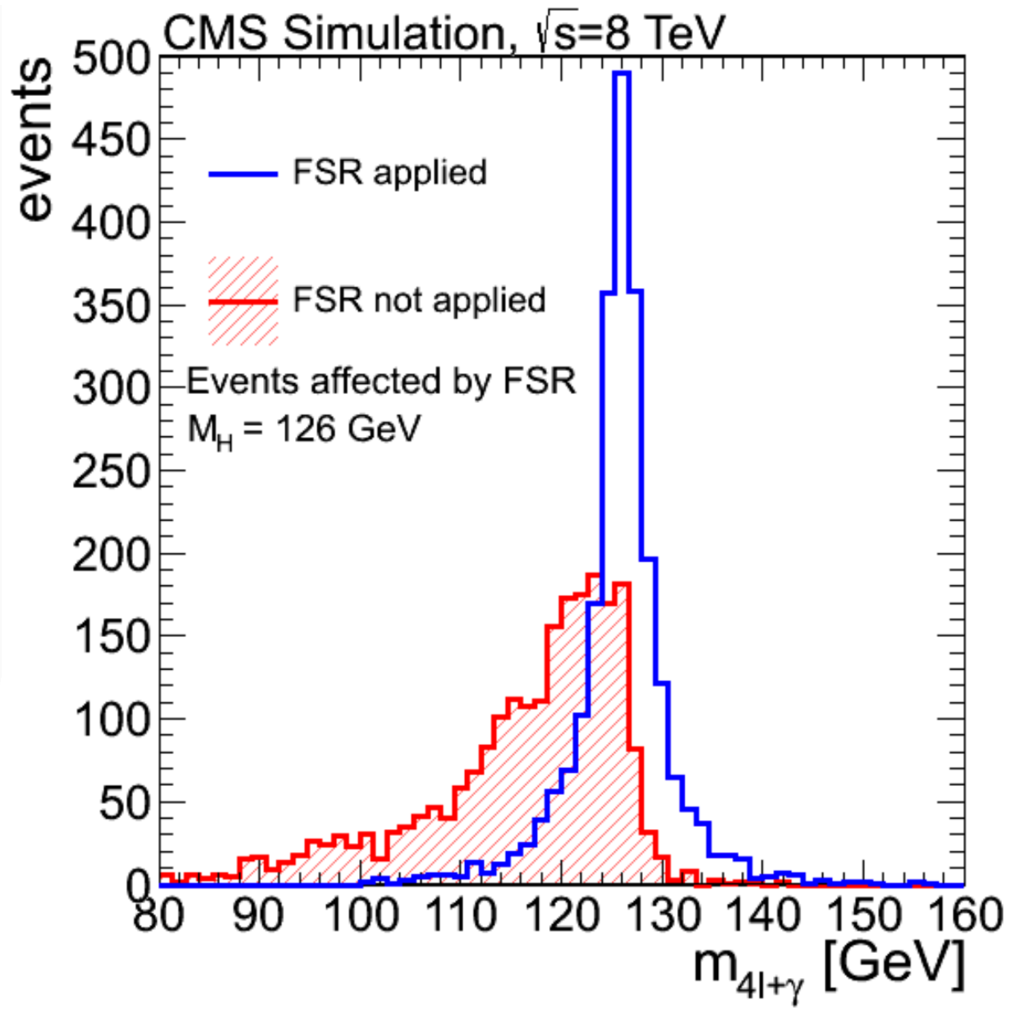


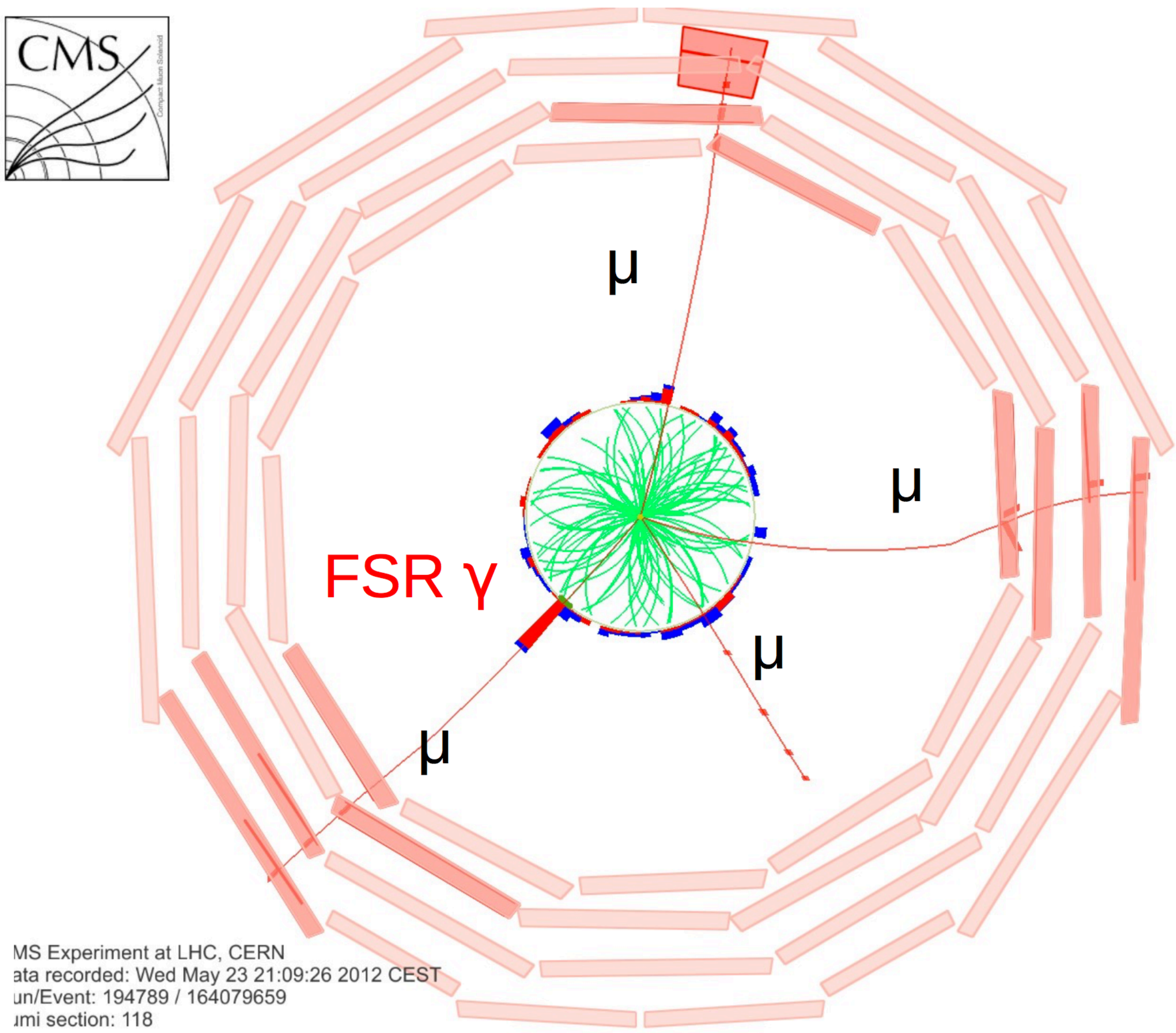




How to recover

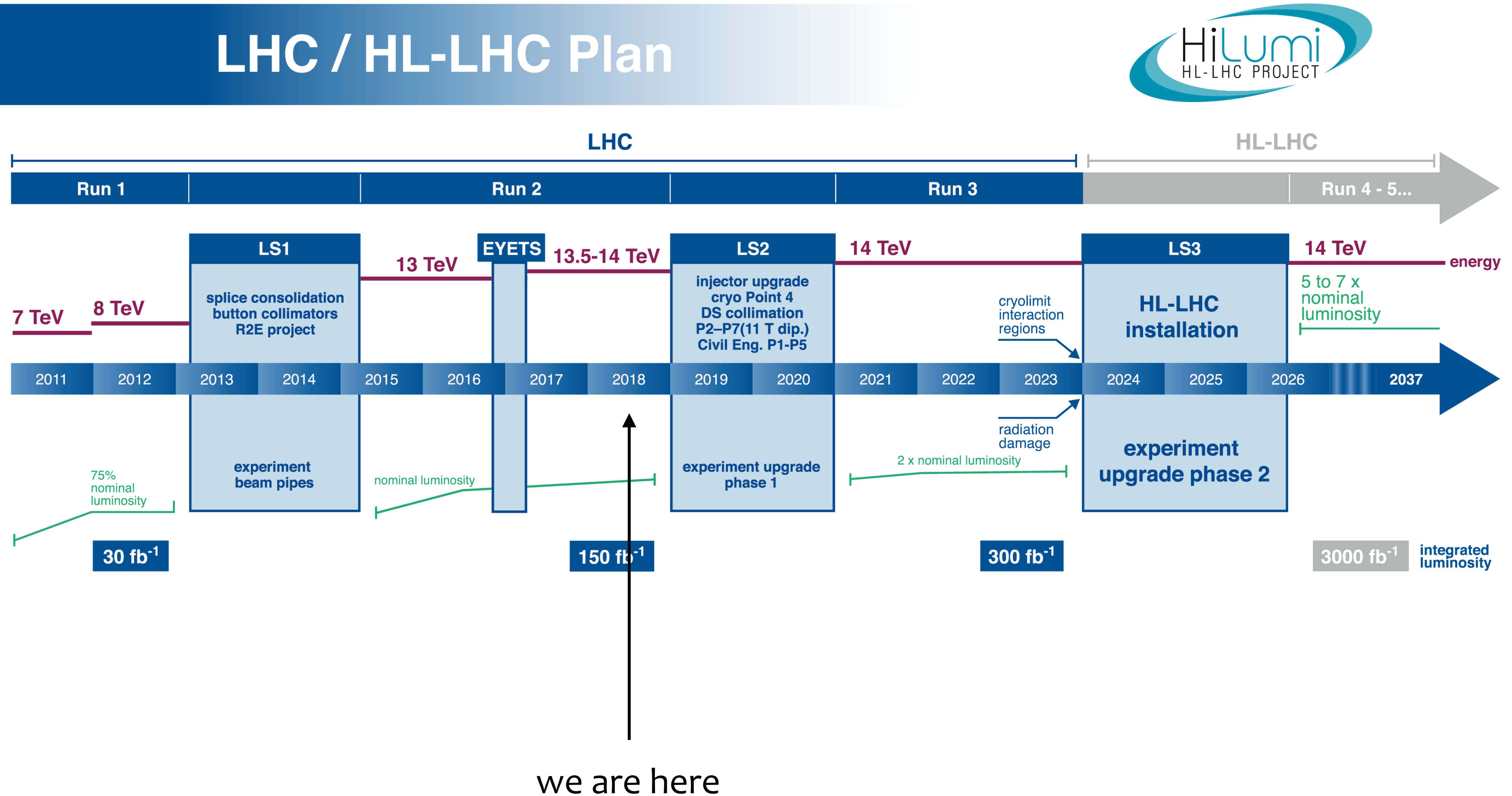
- Final state radiation recovery
  - leptons radiate photons
  - high energy photons can be detected and recombined with the muon





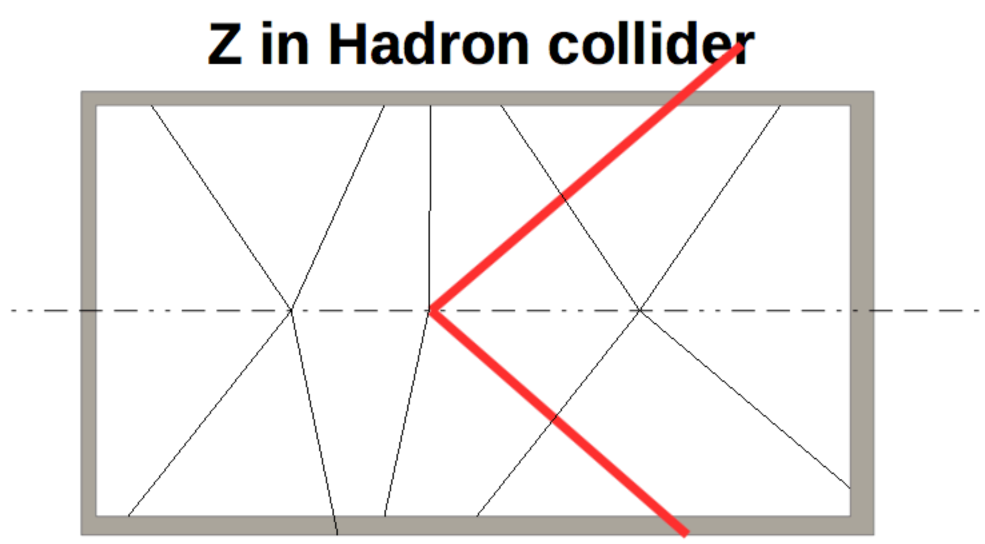
The CMS experiment

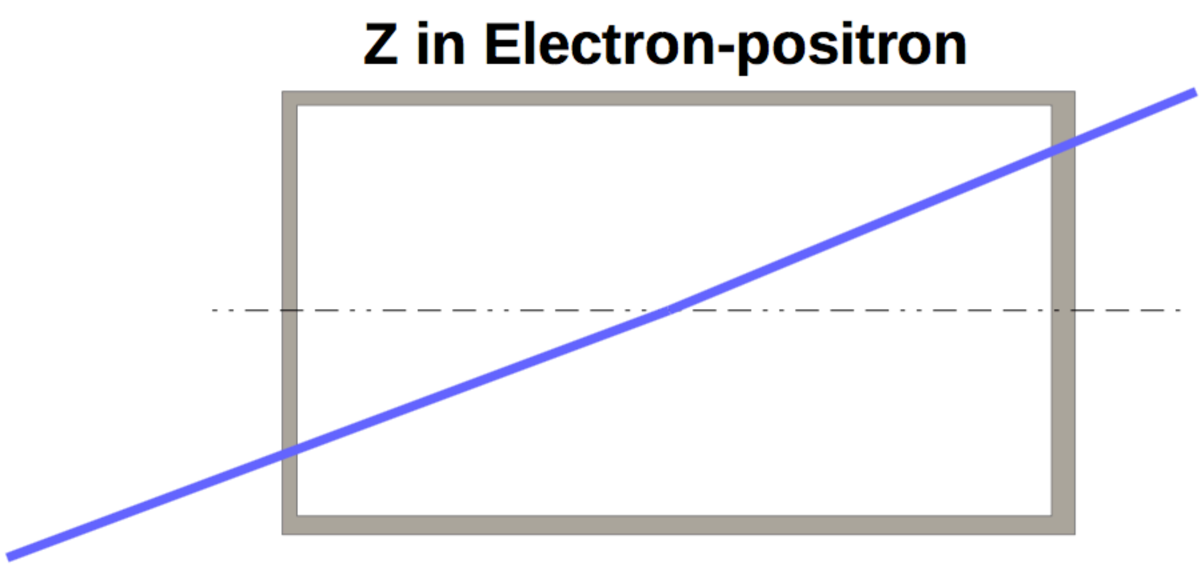
Looking towards the future aka what you are going to work on



Looking towards the future aka what your students will work on

- In case no new physics found
  - would make sense to go to an e+e- collider
  - make it a Higgs factory and study principles of the new boson





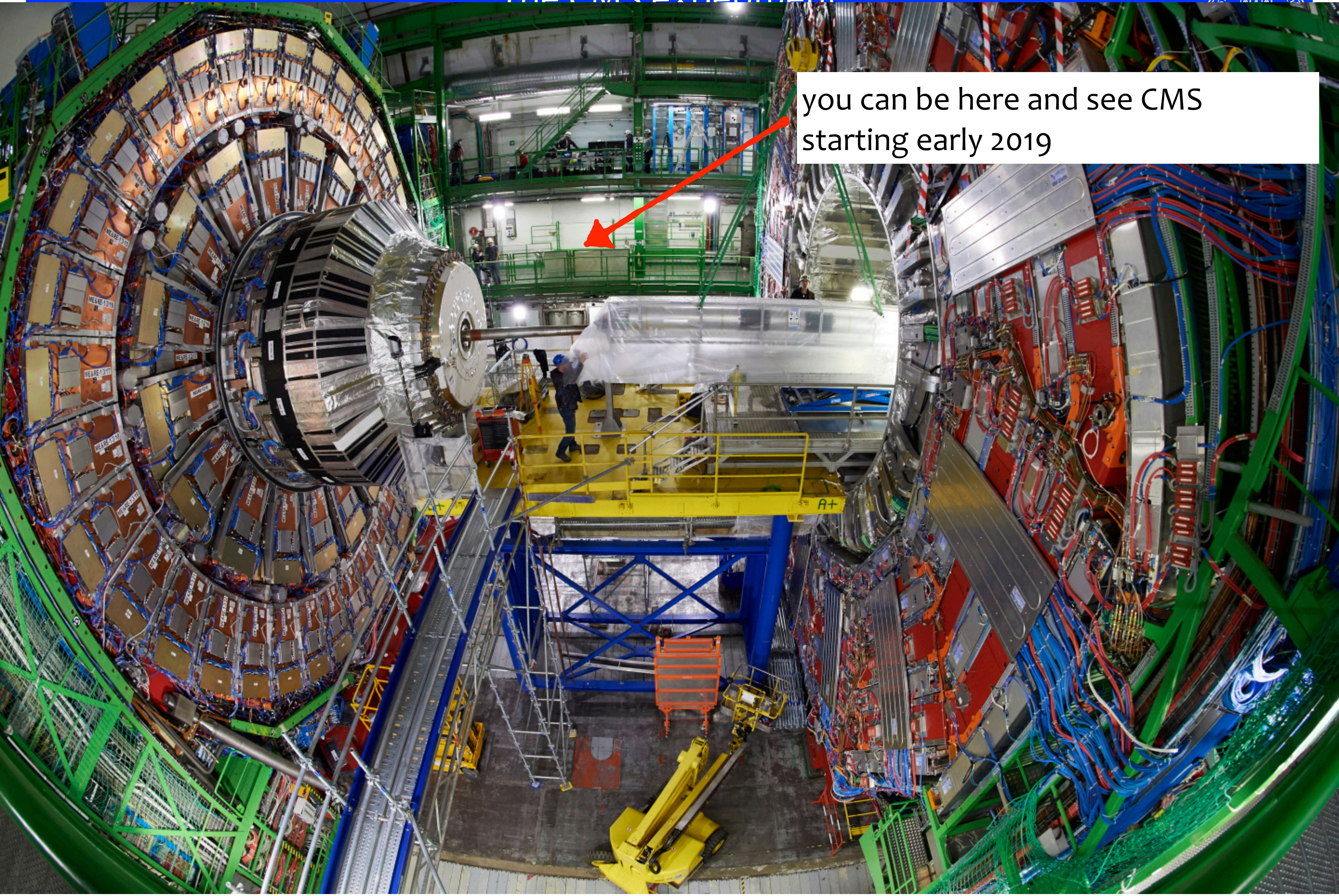

you can be here and see CMS
starting early 2019
A+

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Diagram simplified

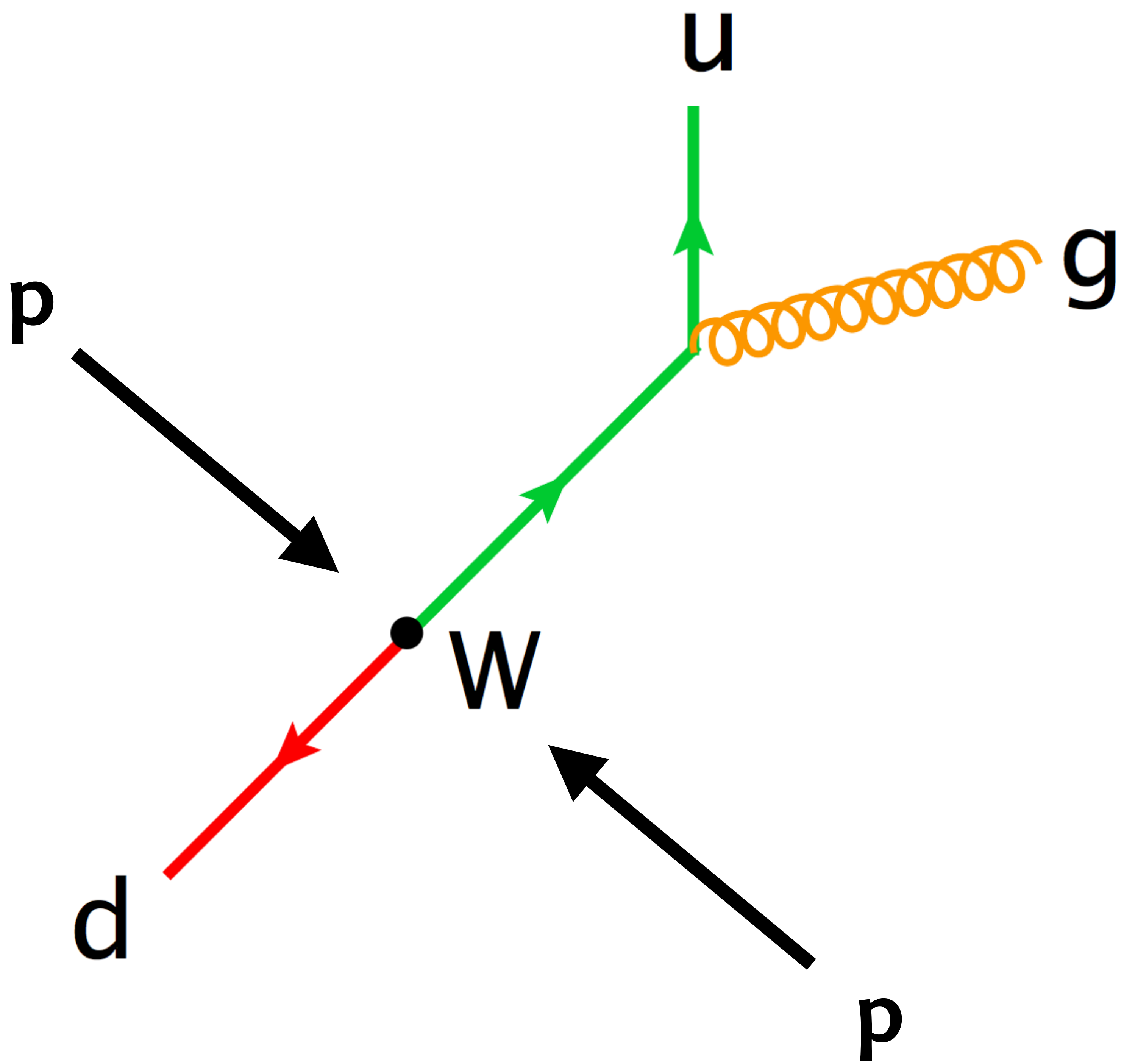
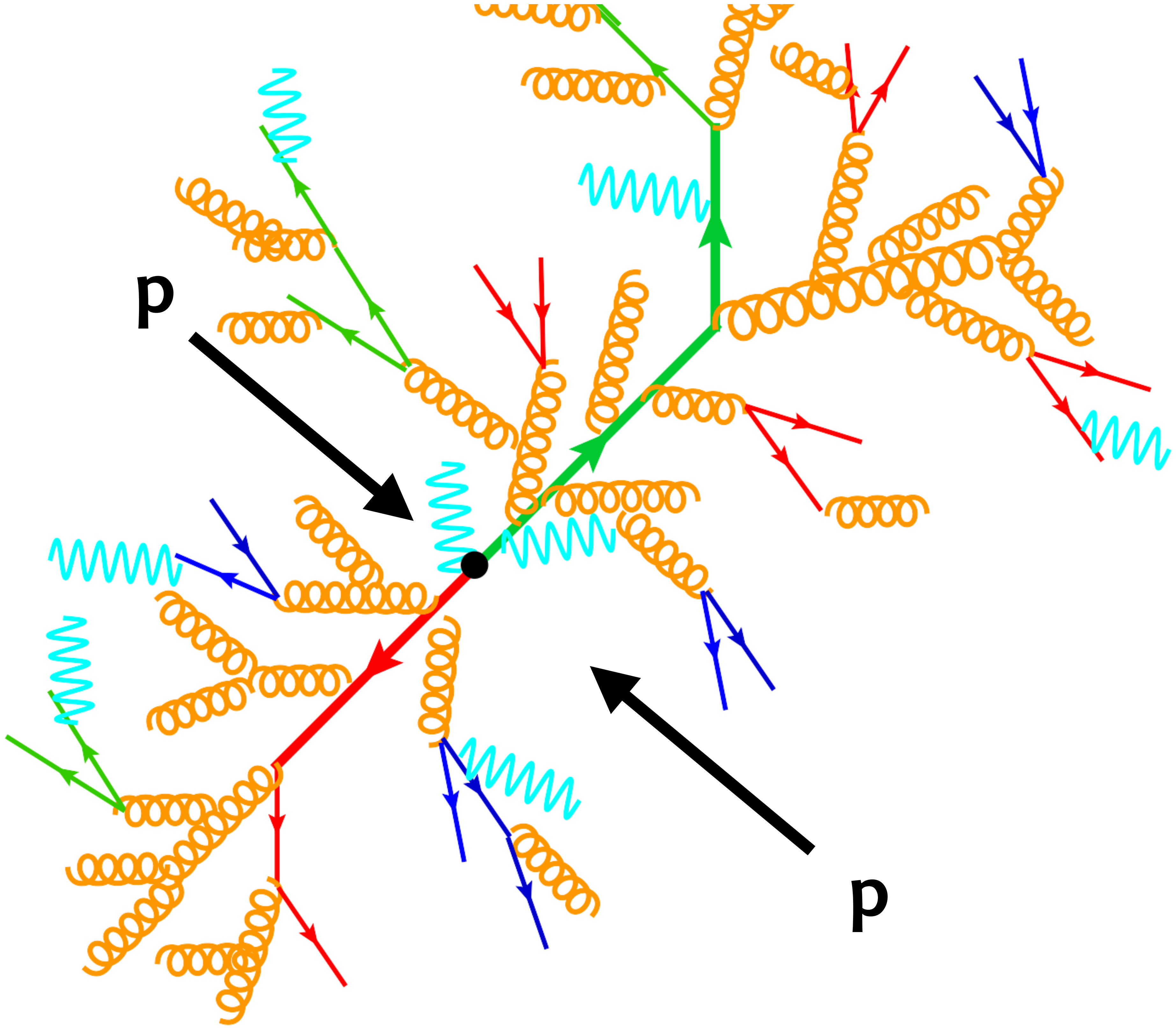
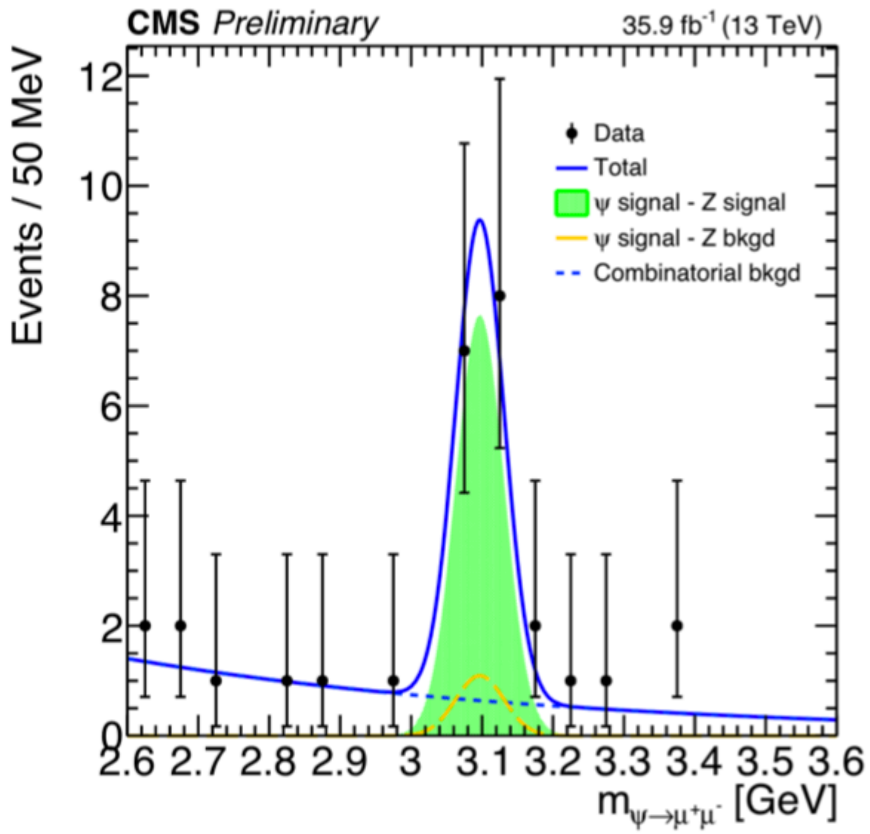
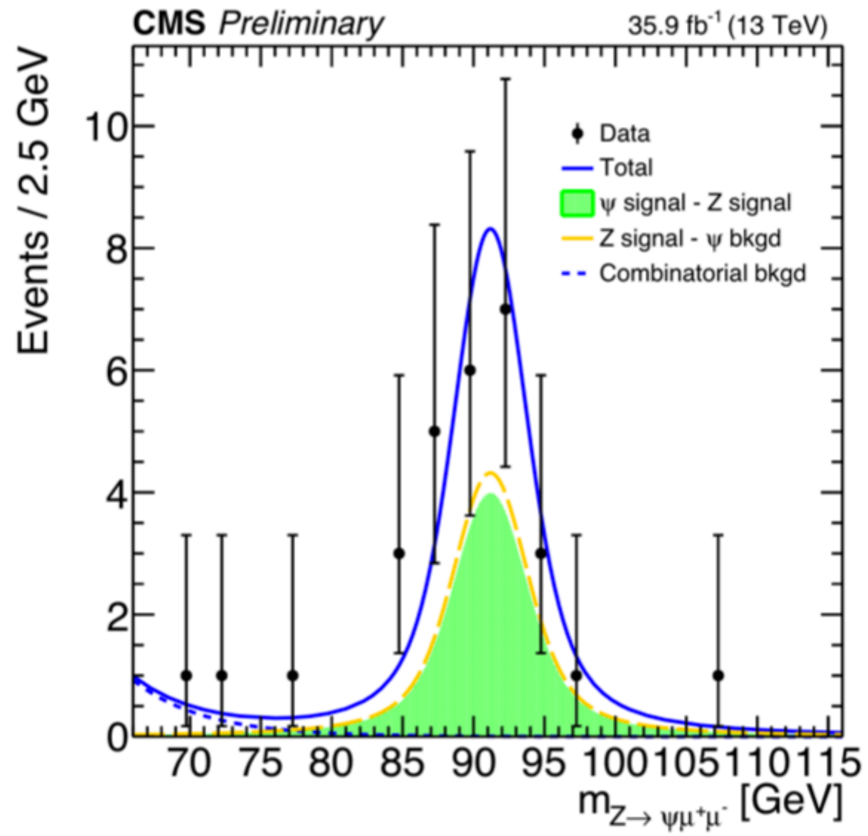


Diagram in reality



Significance of observation





Z (σ)	p
1.00	1.59×10^{-1}
1.28	1.00×10^{-1}
1.64	5.00×10^{-2}
2.00	2.28×10^{-2}
2.32	1.00×10^{-2}
3.00	1.35×10^{-3}
3.09	1.00×10^{-3}
3.71	1.00×10^{-4}
4.00	3.17×10^{-5}
5.00	2.87×10^{-7}
6.00	9.87×10^{-10}