LHC Run 3 and HL-LHC

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Layout

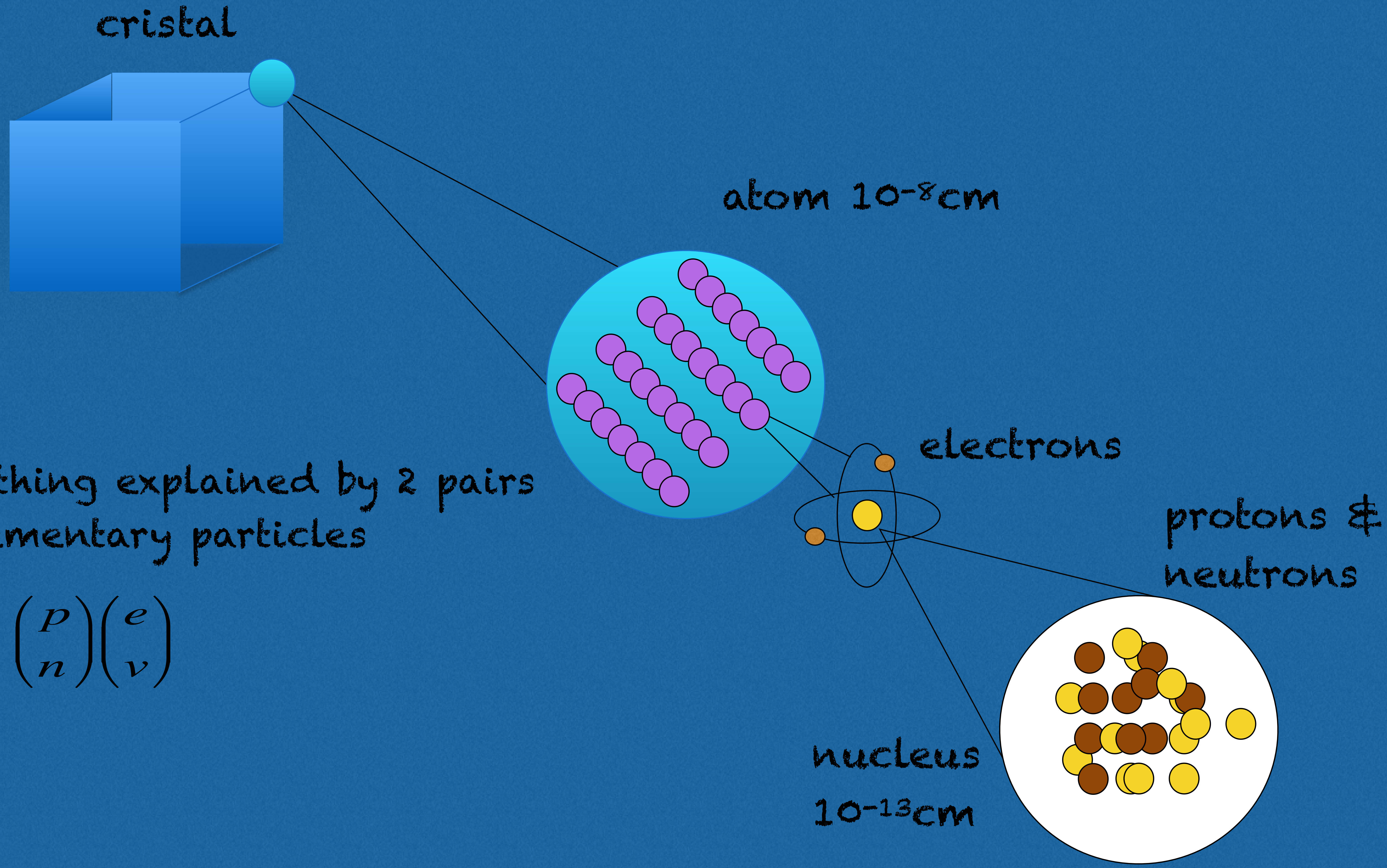
- Brief historical Introduction of SM
- overview of LHC and brief introduction of ATLAS and CMS experiments
- Overview of the event structure
- Challenges of the ATLAS and CMS experiments upgrades in Run3 and HL-LHC
- The lectures will concentrate on ATLAS and CMS physics.
- First Run 3 results
- Higgs physics in Run3 and HL-LHC
- Studying the EW symmetry breaking: di-higgs at Run3 and HL-LHC
- another way of studying the EW symmetry breaking: Vector Boson Scattering at Run3 and HL-LHC
- Effective Field Theories as a tool to discover new physics at Run3 and HL-LHC
- Few words on top physics at Run3 and HL-LHC
- Direct searches for new physics: the challenge for Run3

Historical background

Shortly introducing the Standard Model and its shortcomings to motivate our studies at the LHC

History

1930: The knowledge of matter



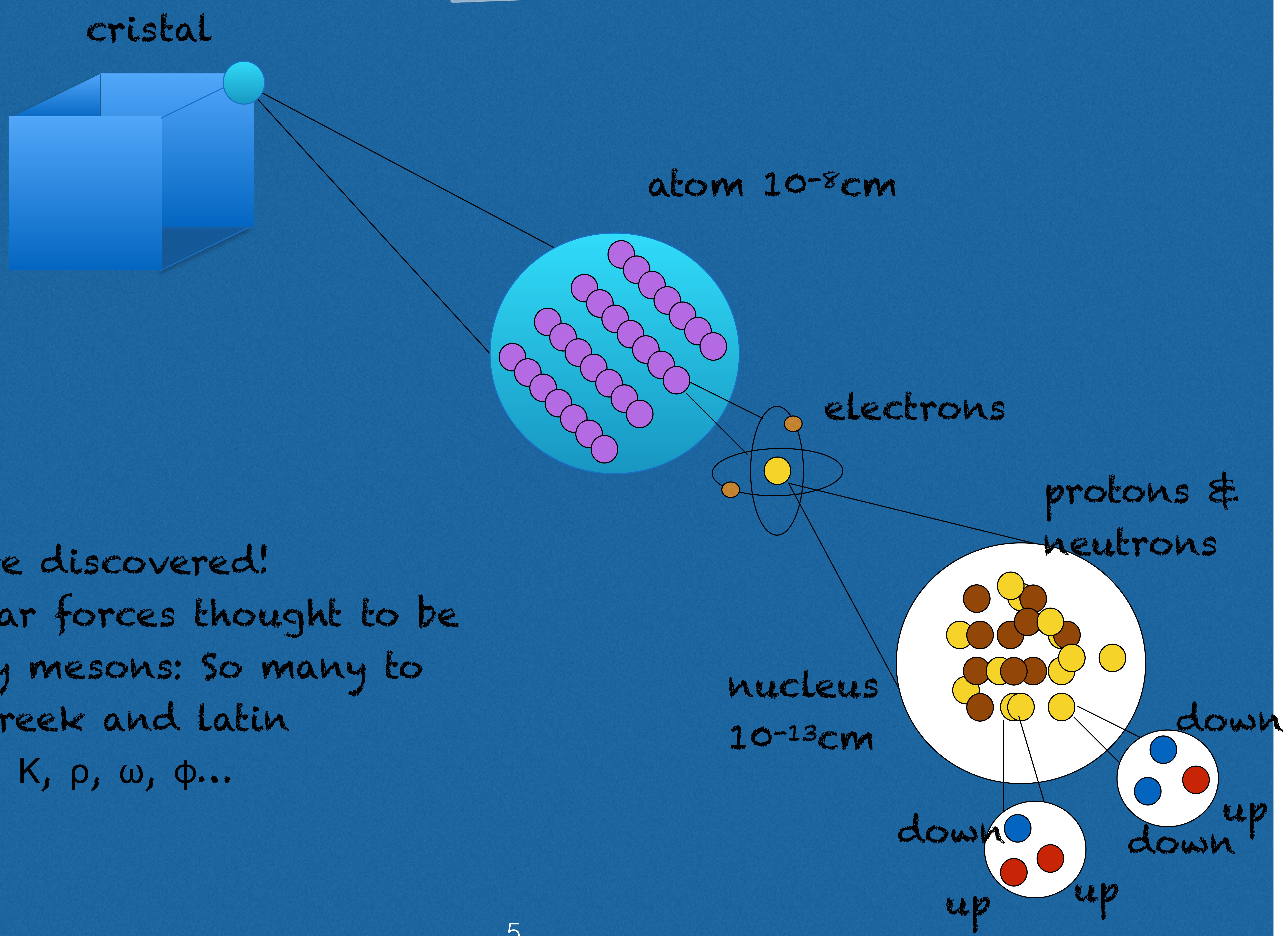
Everything explained by 2 pairs of elementary particles

$$\begin{pmatrix} p \\ n \end{pmatrix} \begin{pmatrix} e \\ \nu \end{pmatrix}$$

and the photon (quantum of light) and the Yukawa meson,
(e.g the pion π believed to carry nuclear forces)

History

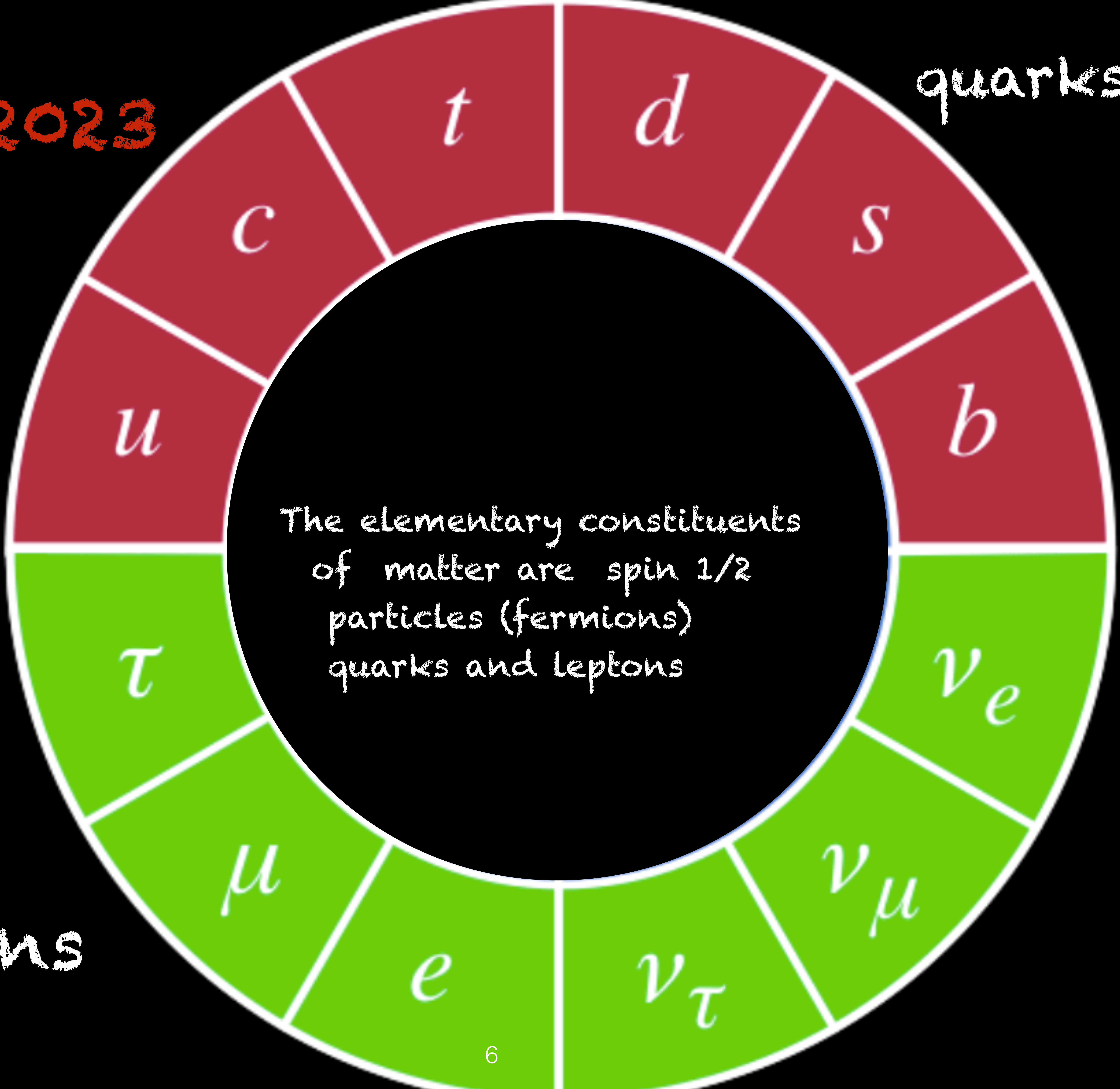
1960-70 new level: QUARKs



Quarks are discovered!
But nuclear forces thought to be carried by mesons: So many to exhaust greek and latin alphabets: K, ρ, ω, φ...

year 2023

quarks



The elementary constituents of matter are spin 1/2 particles (fermions) quarks and leptons

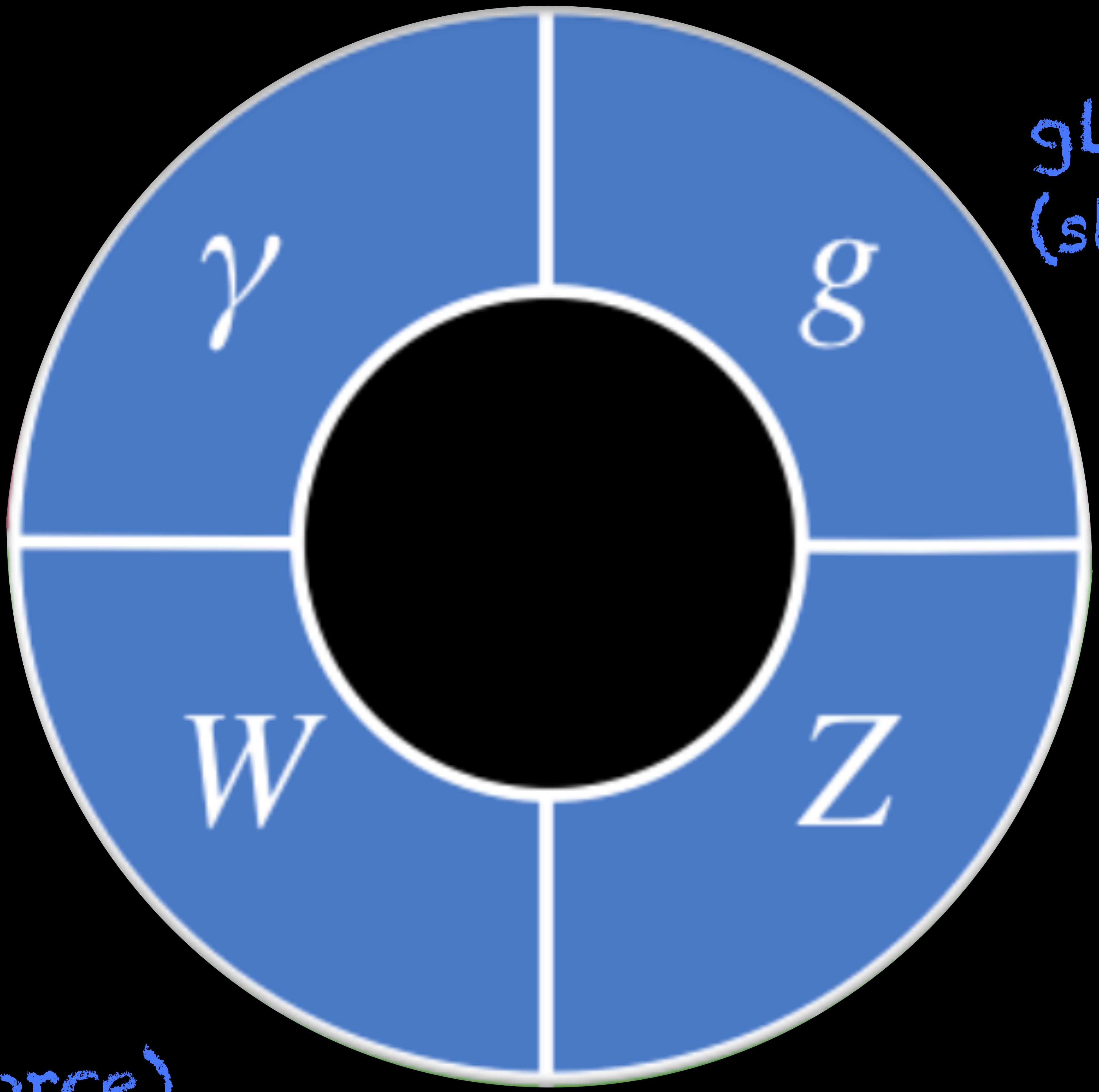
leptons

What about forces?

The force carriers are integer spin particles (bosons)

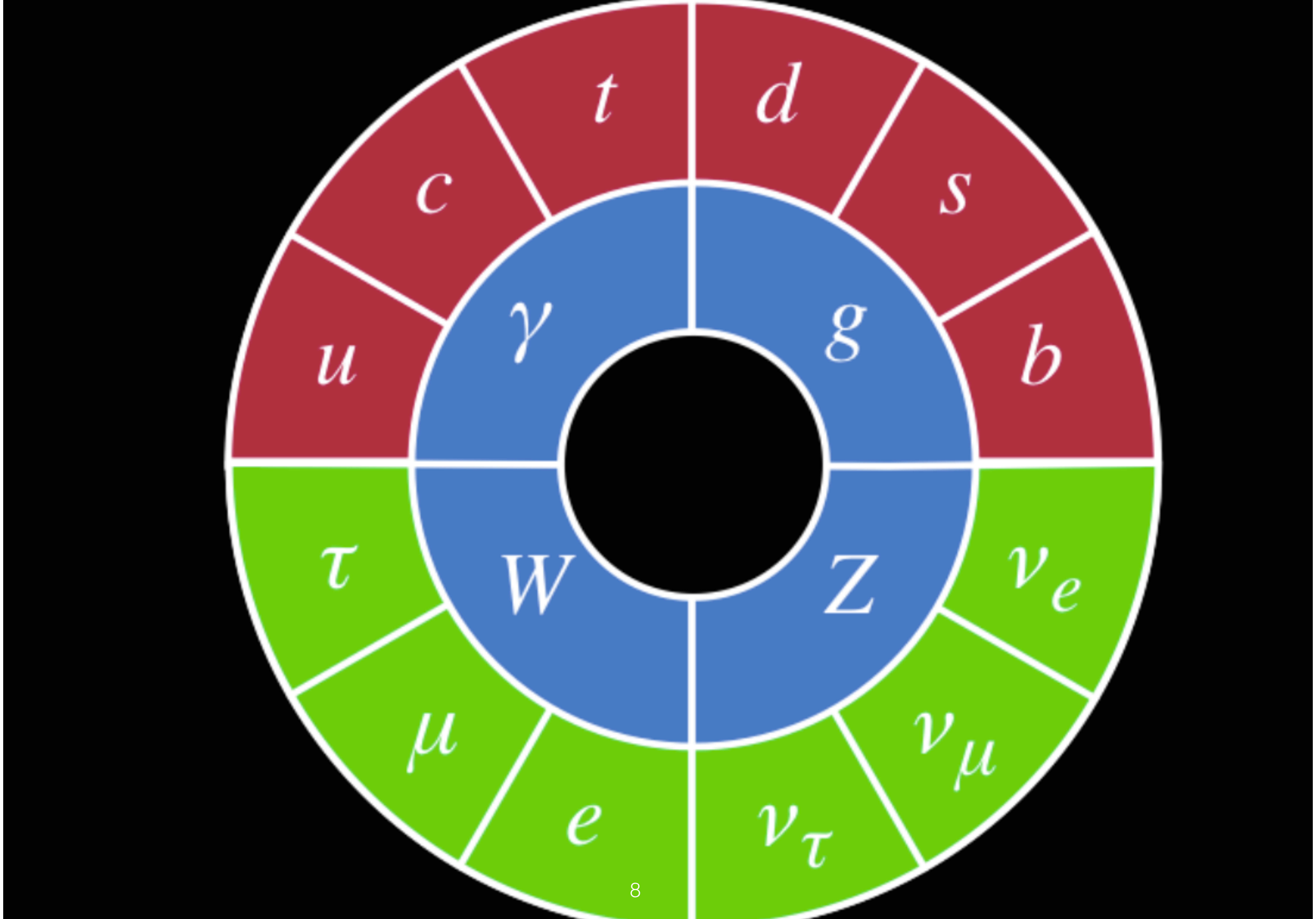
photon γ
(electromagnetic force)

gluon g
(strong force)



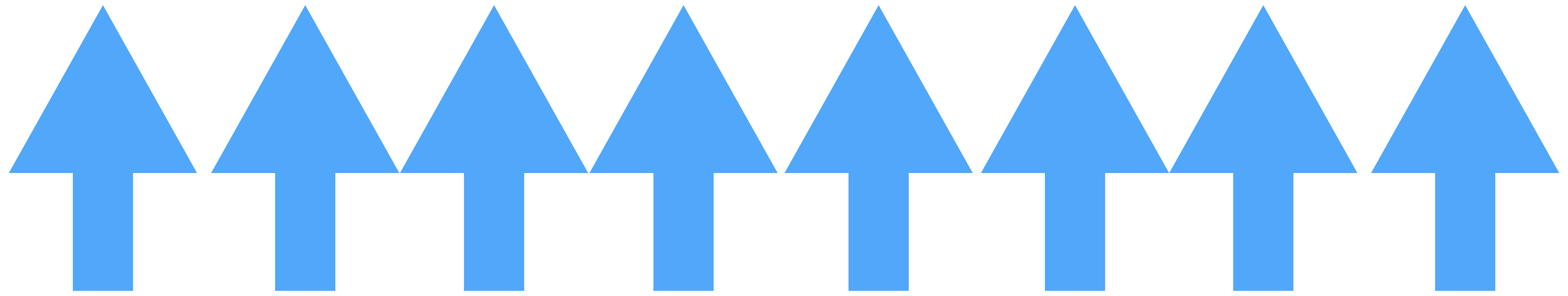
W/Z
(weak force)

History

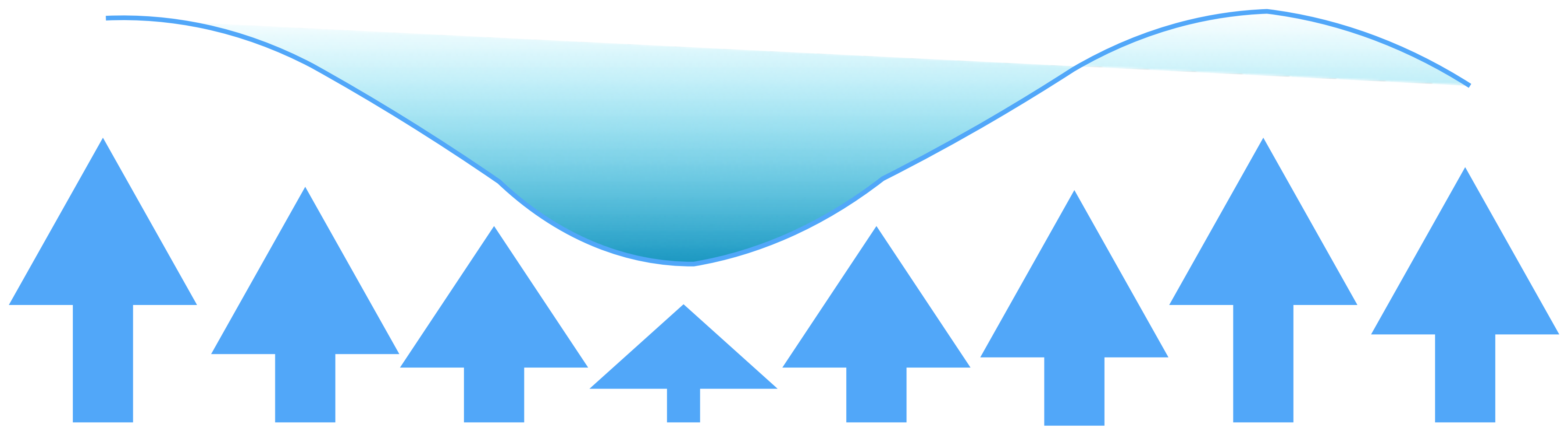


What is responsible of particles masses?

The Higgs field that fills the space. Particles get mass by interacting with it.



The vacuum is like the surface of still lake



collisions produce waves

(oscillation of field =particle)

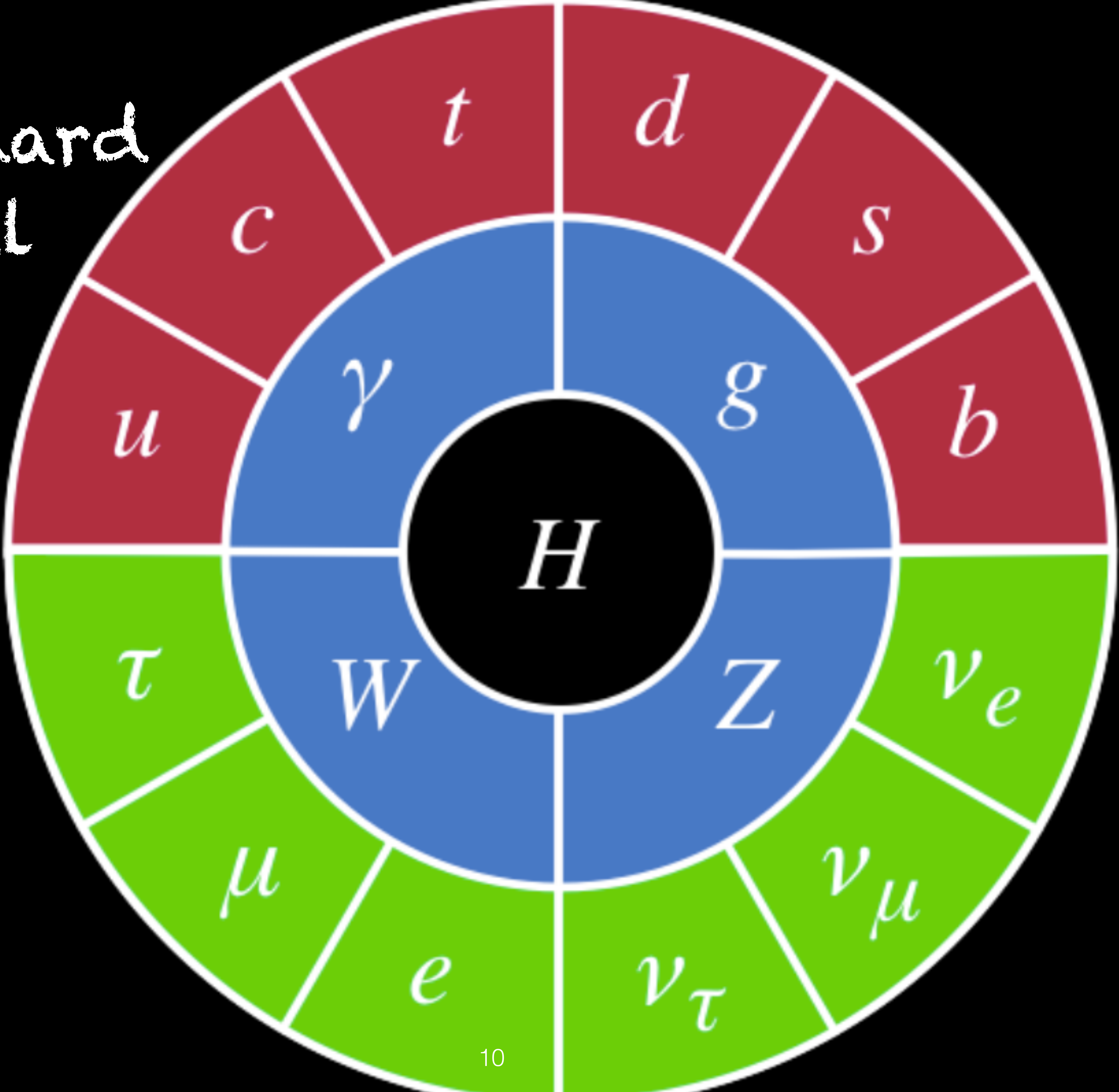
Higgs boson

spin zero particle, m~125 GeV

Vacuum is filled!

History

The Standard Model (SM)



- The Standard Model predicts that the Higgs boson and field acts as a sole player in the game of Electroweak symmetry breaking.

- This is a strong prediction that has yet to be verified experimentally.

- Answering this question is one of the pressing goals for the ATLAS and CMS experiments during Run 3 and Run 4 at the LHC.

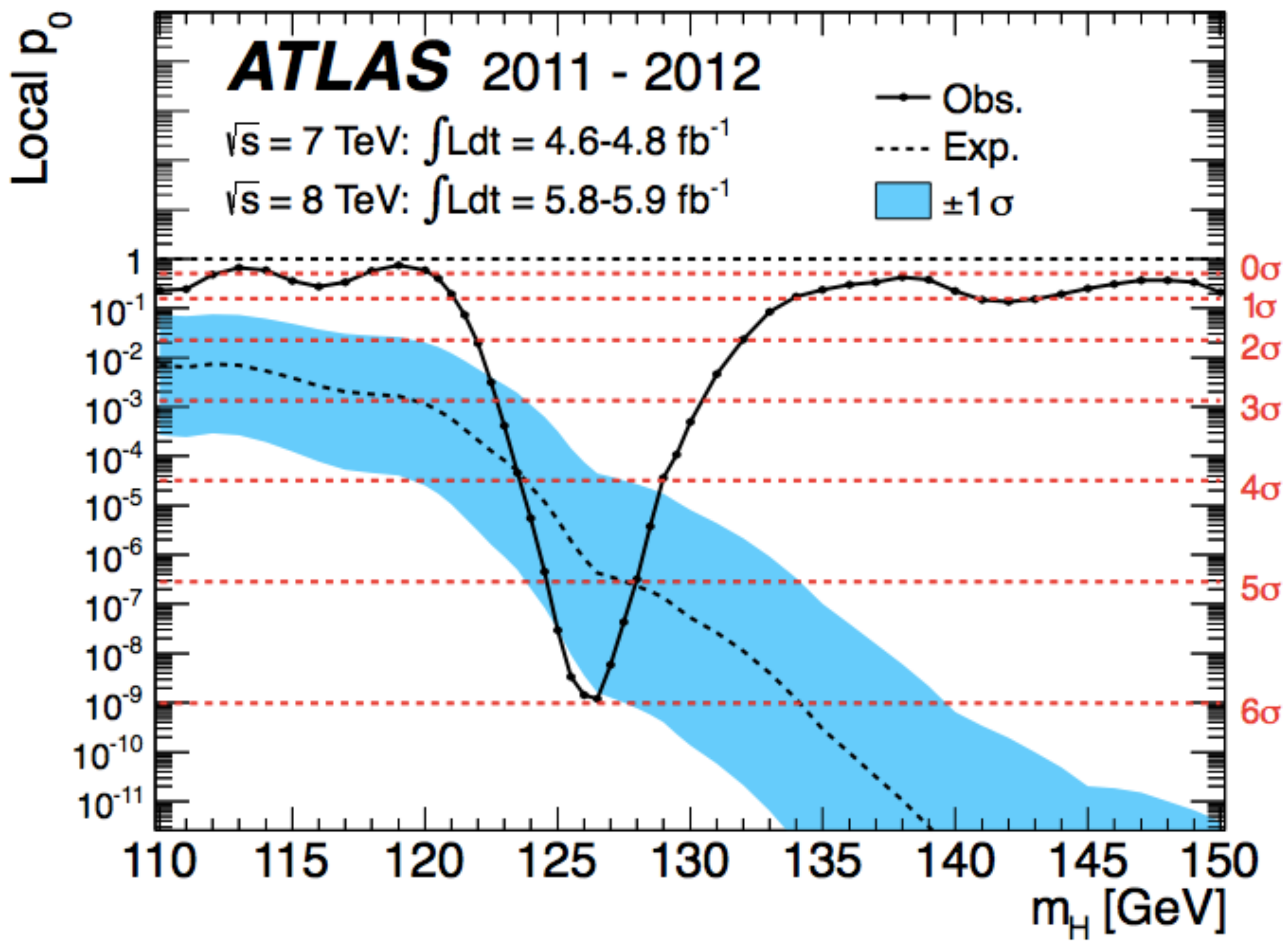
History

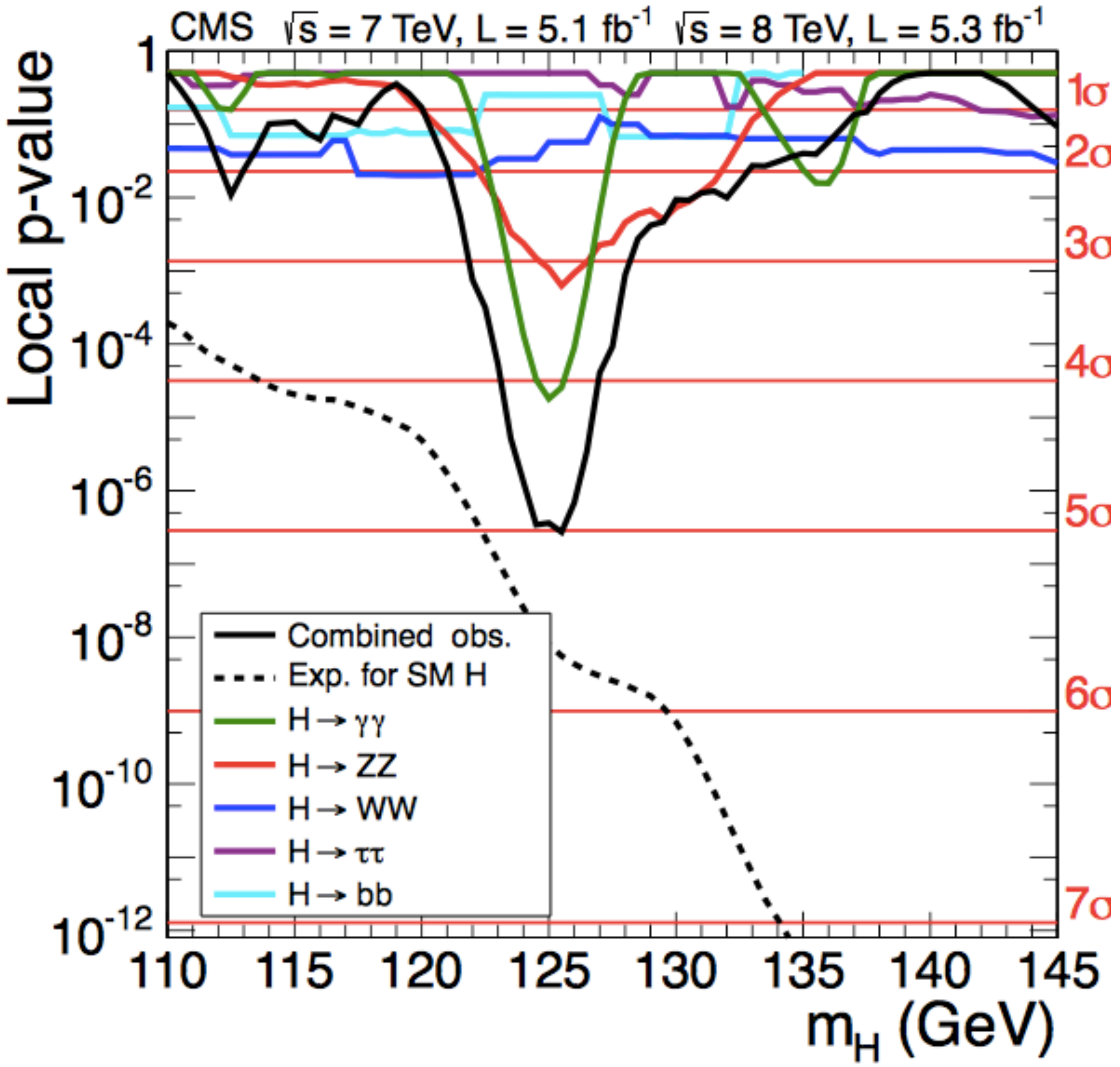
Higgs discovery at the LHC

A scalar boson compatible with the SM Higgs has been discovered in run I as shown by the combination of ATLAS and CMS run I results

Greatest achievement of run I

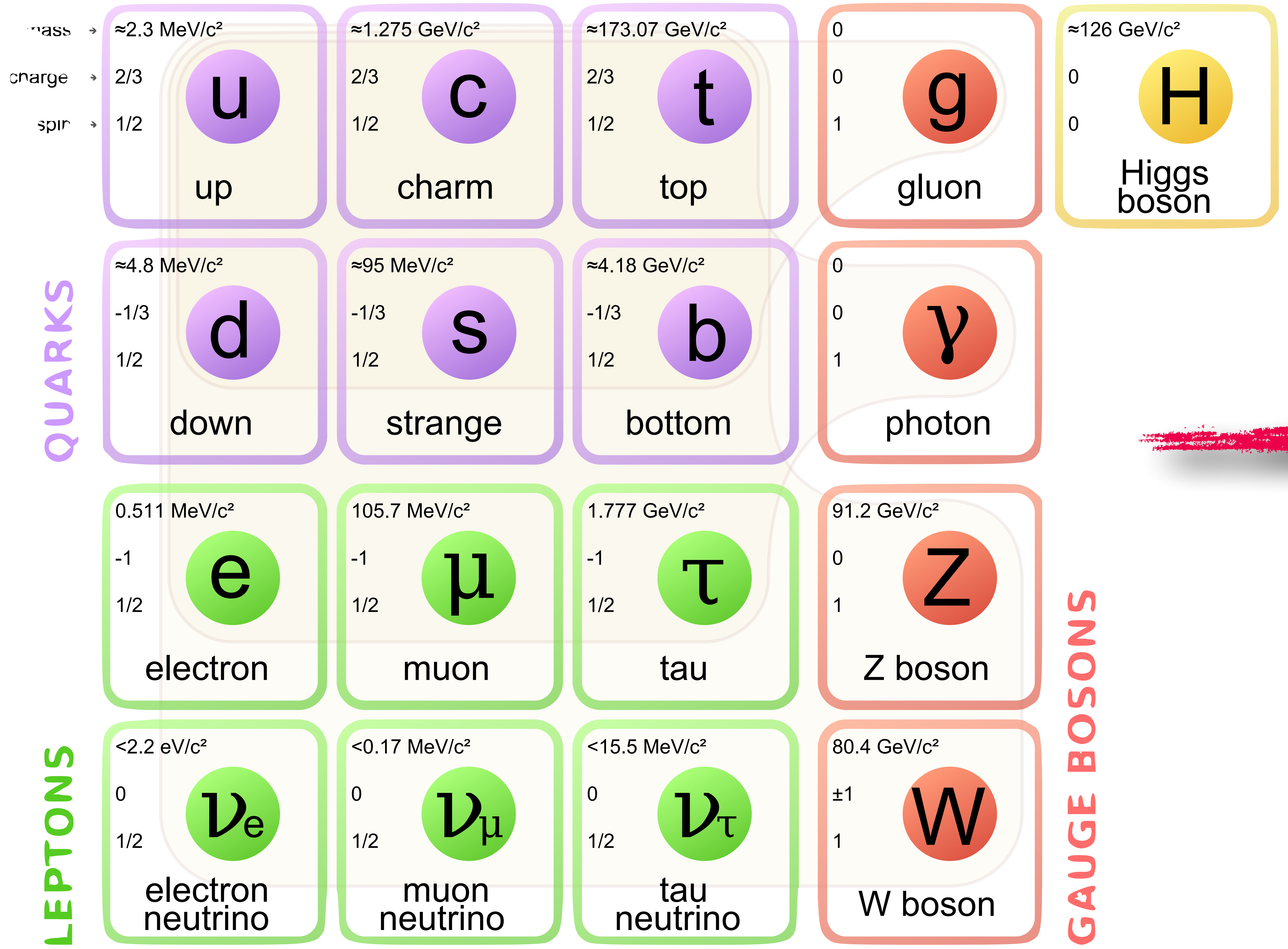
- concentrated effort on its properties:
  - magnitude of couplings
  - mass measurements
  - spin/CP





History

What is the mass/energy scale we are talking about?



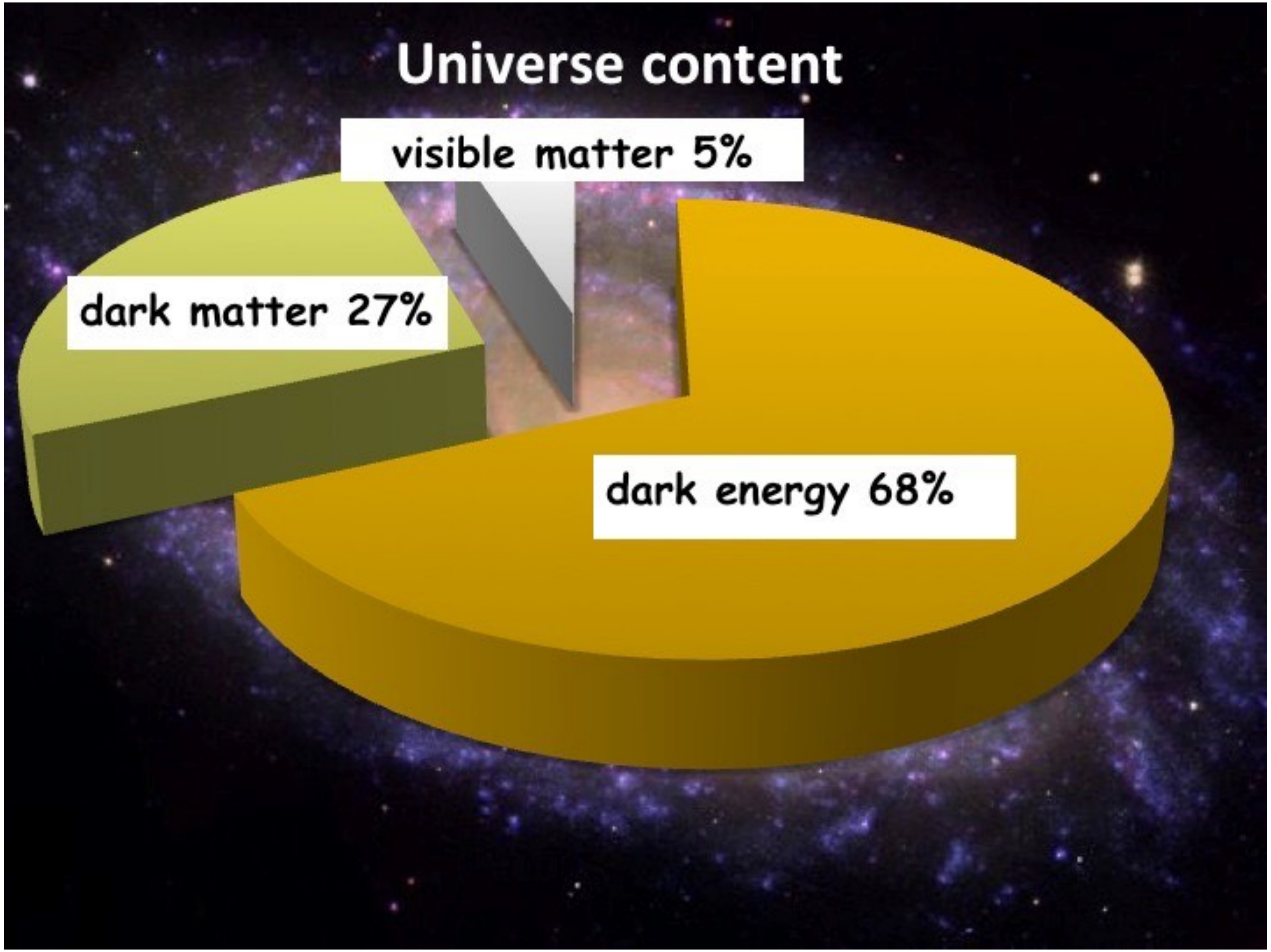
New physics may appear at higher scales

below 200 Giga-electronVolt = GeV

Dark Matter: the first puzzle

Stable Ordinary particles
Can they explain everything?

No!



History

Why is our universe made of matter and not anti-matter?

2. One of the major shortcomings of our understanding of particle physics is the matter over anti-matter asymmetry in the universe.

3. While the Standard Model does predict a matter vs. anti-matter asymmetry, it is much too small compared to what we observe.

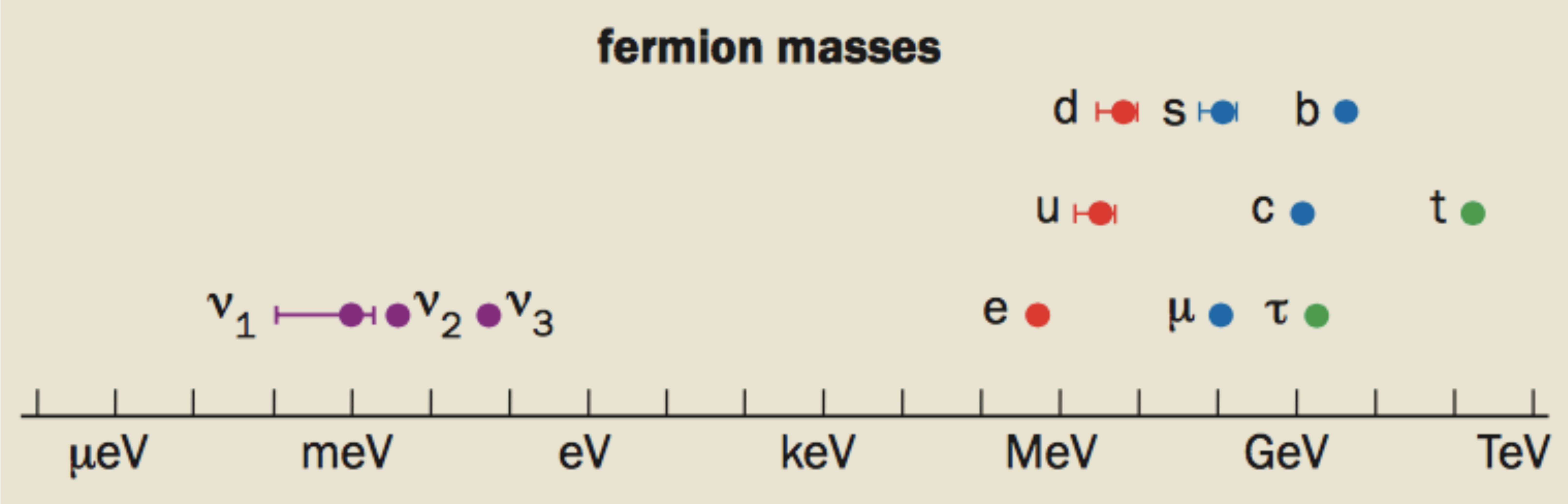
4. Moreover, the thermal history of electroweak symmetry breaking is important for particle physics and cosmology. If in the early universe, there was a first order electroweak phase transition (think boiling water), this could explain the matter vs. anti-matter asymmetry as well as sources for potentially observable gravitational radiation.

5. The Standard Model's prediction is again clear – no first- order transition. Therefore if such a transition took place, the Higgs doesn't act alone and some new physics is present.

History

The neutrino masses….

2. How to incorporate in SM neutrino masses?
   Why are they so small?



New physics should appear in the worst case at Planck scale where quantum gravity effects become important and quantum filed theory breaking down. Very large scale 1.22 x 10^{19} GeV!

History

Hierarchy Problem

If SM is a complete description of Nature

↓

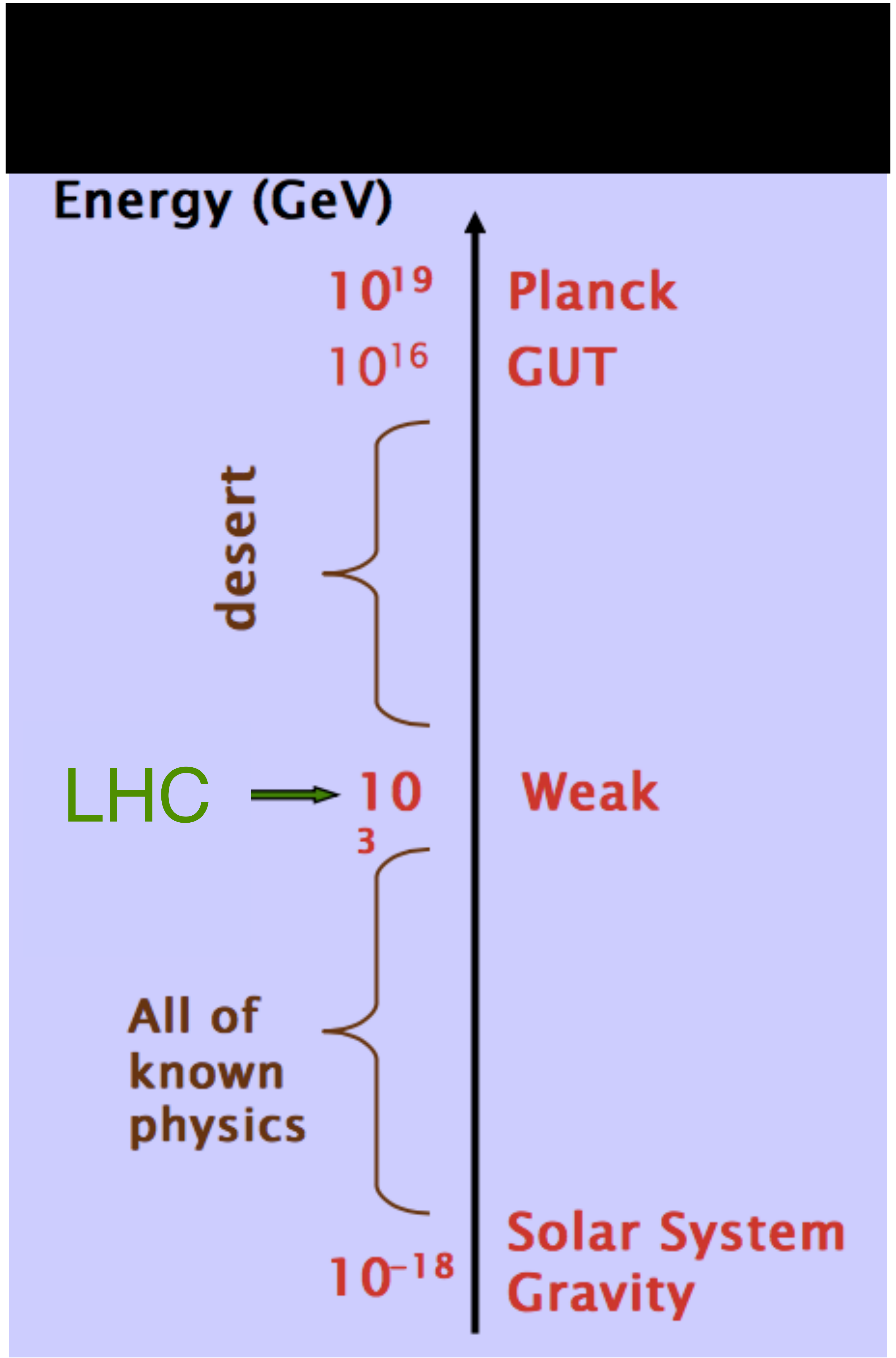
no hierarchy problem.

But the SM has unresolved issues which point to New Physics (NP)
If NP appears at Planck scale unnatural large difference wrt EW Scale

Most accredited models predict NP @TeV scale.
1TeV=1000GeV

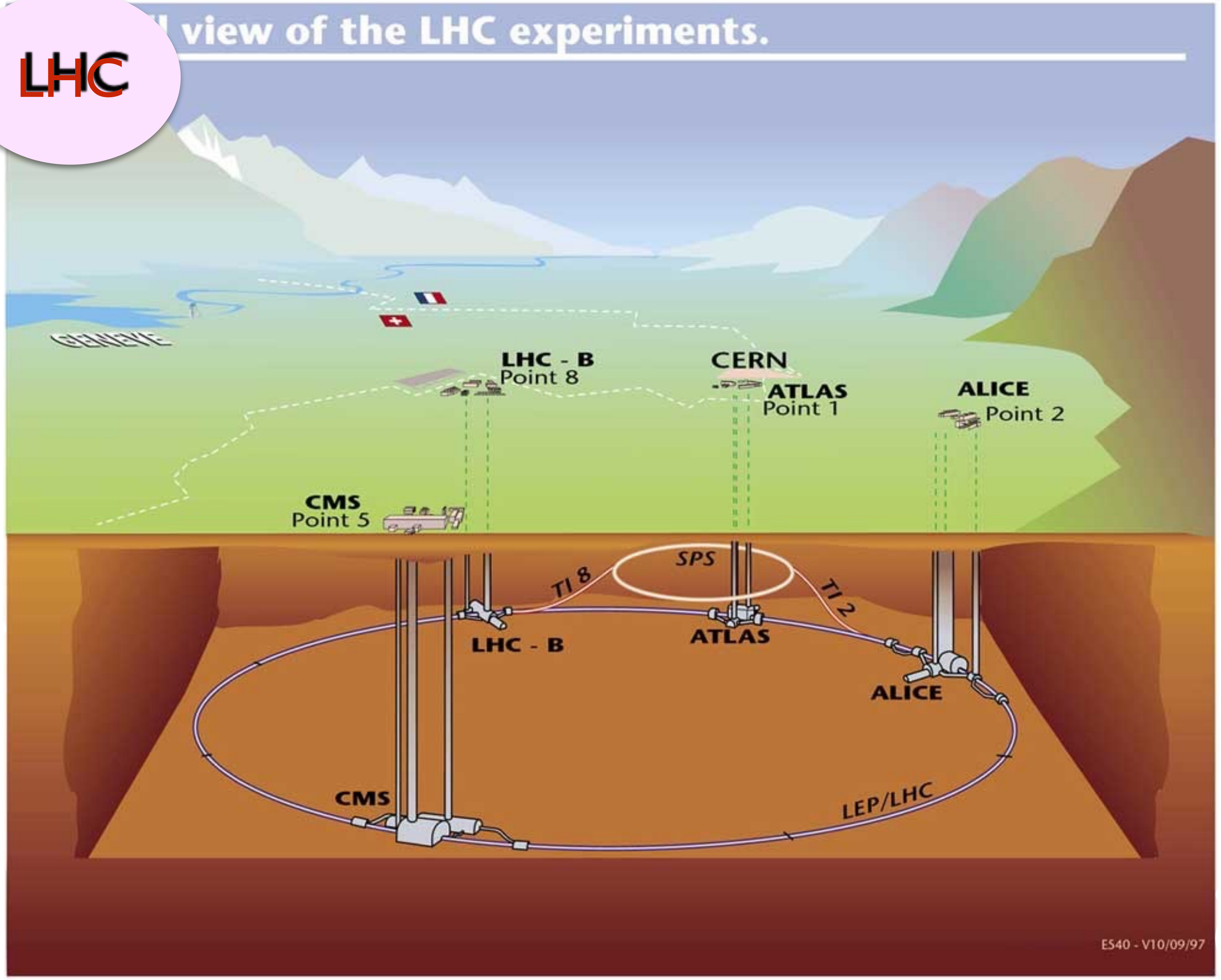
↓

LHC range



The LHC accelerator and the ATLAS and CMS detectors

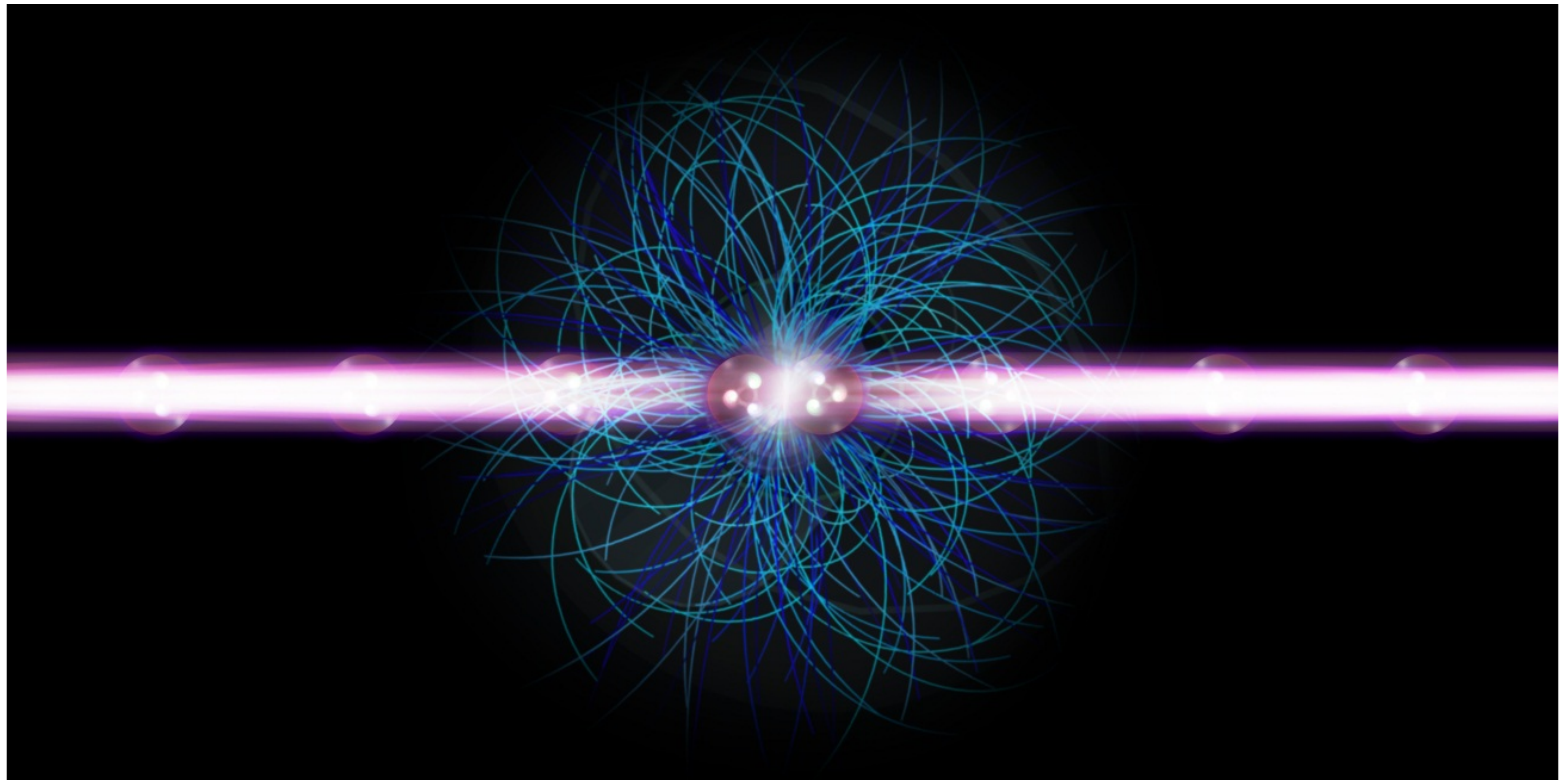
Explaining the main features of the LHC and the detectors



LHC

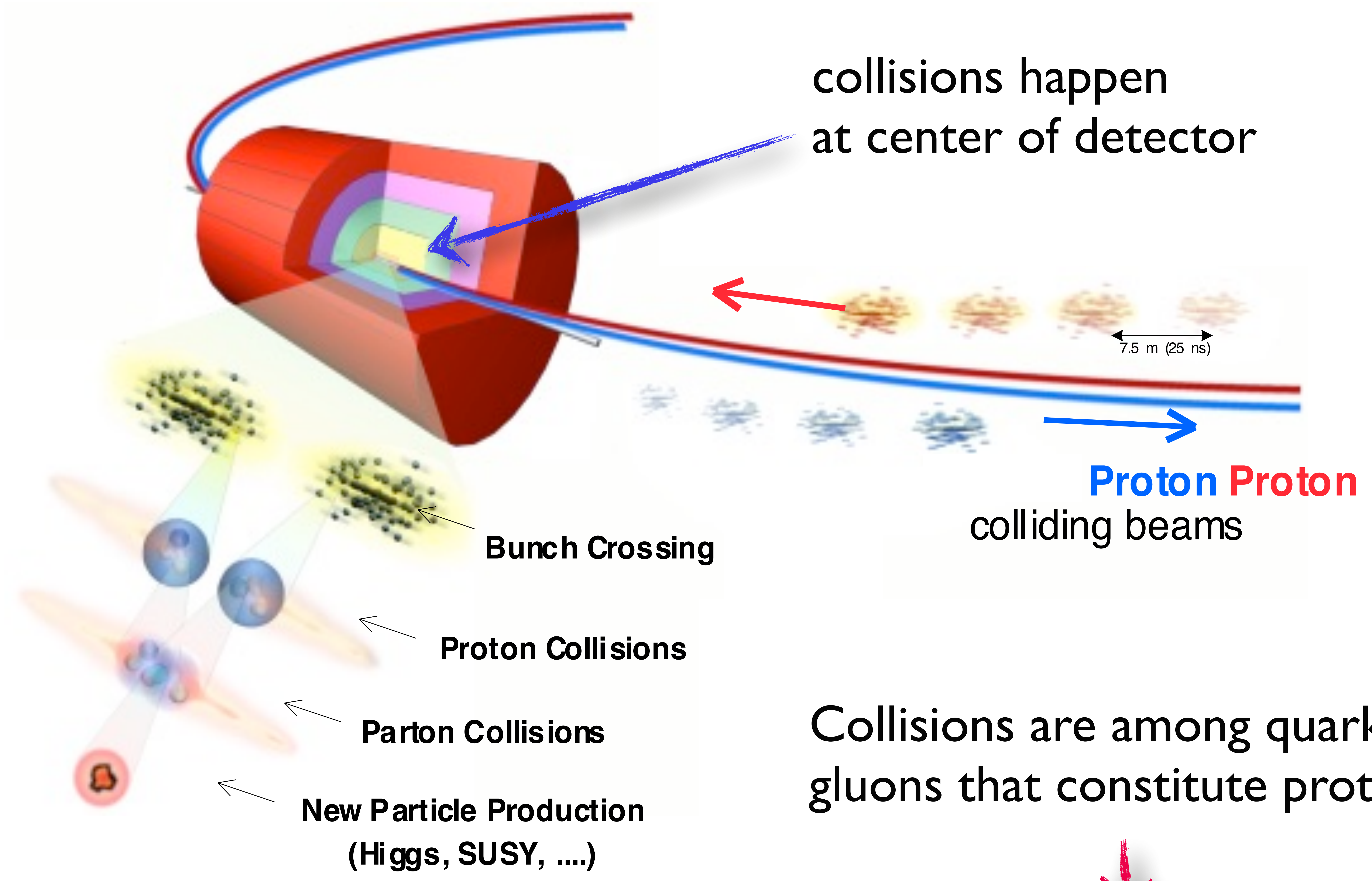
LHC accelerates
protons in opposite directions along
28km ring.

Protons collided at experiments @7,8,13 TeV
and at 13.6 at Run3



Collisions bring us back to Big
Bang producing particles
abundant at that time

TeV collisions



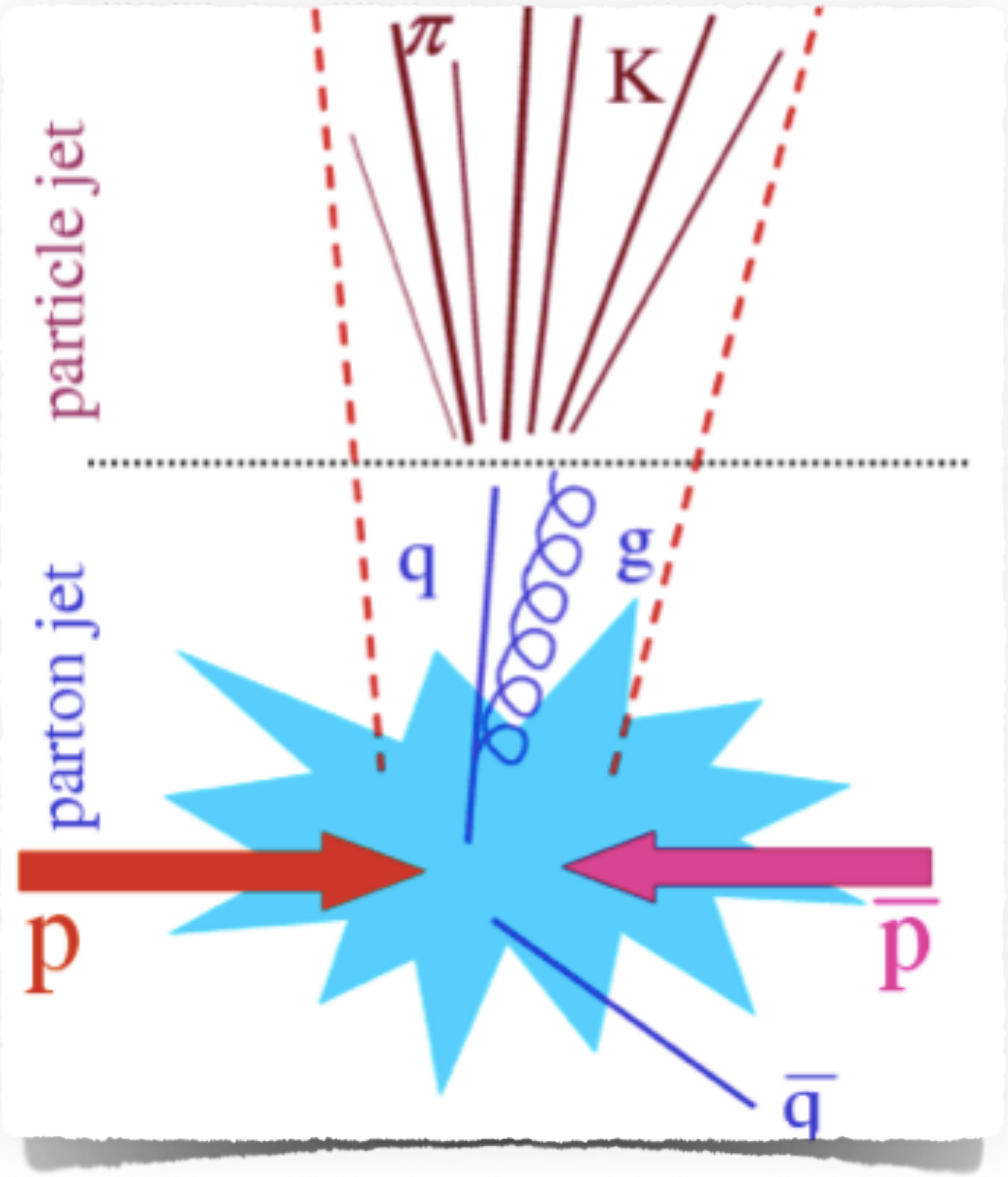
Collisions are among quarks and gluons that constitute protons

↓

Produce new particles in final state

detector

Typical detector



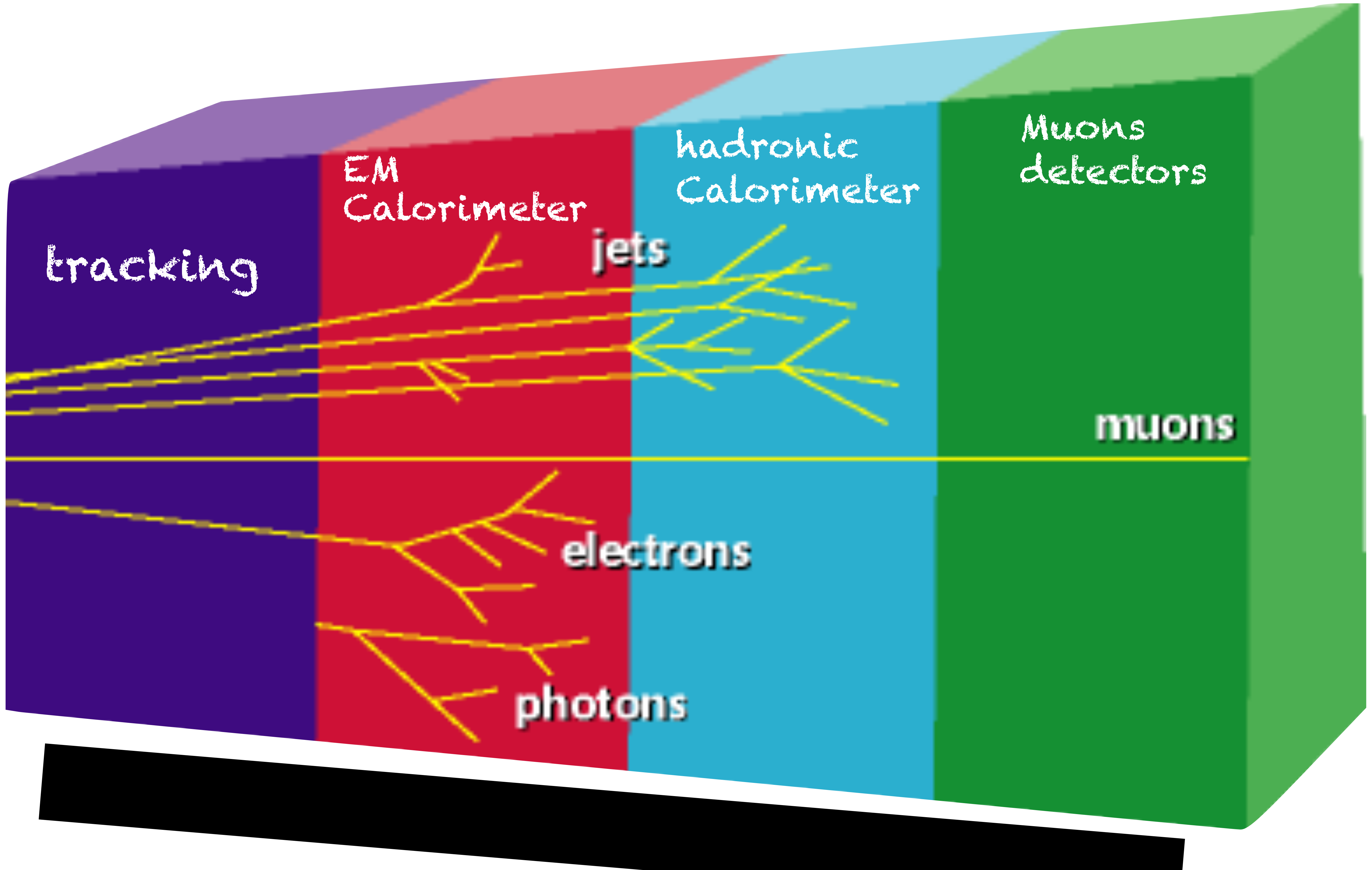
Detectors built to observe particles produced in collisions

quark/gluons seen as jets of particles in a narrow cone

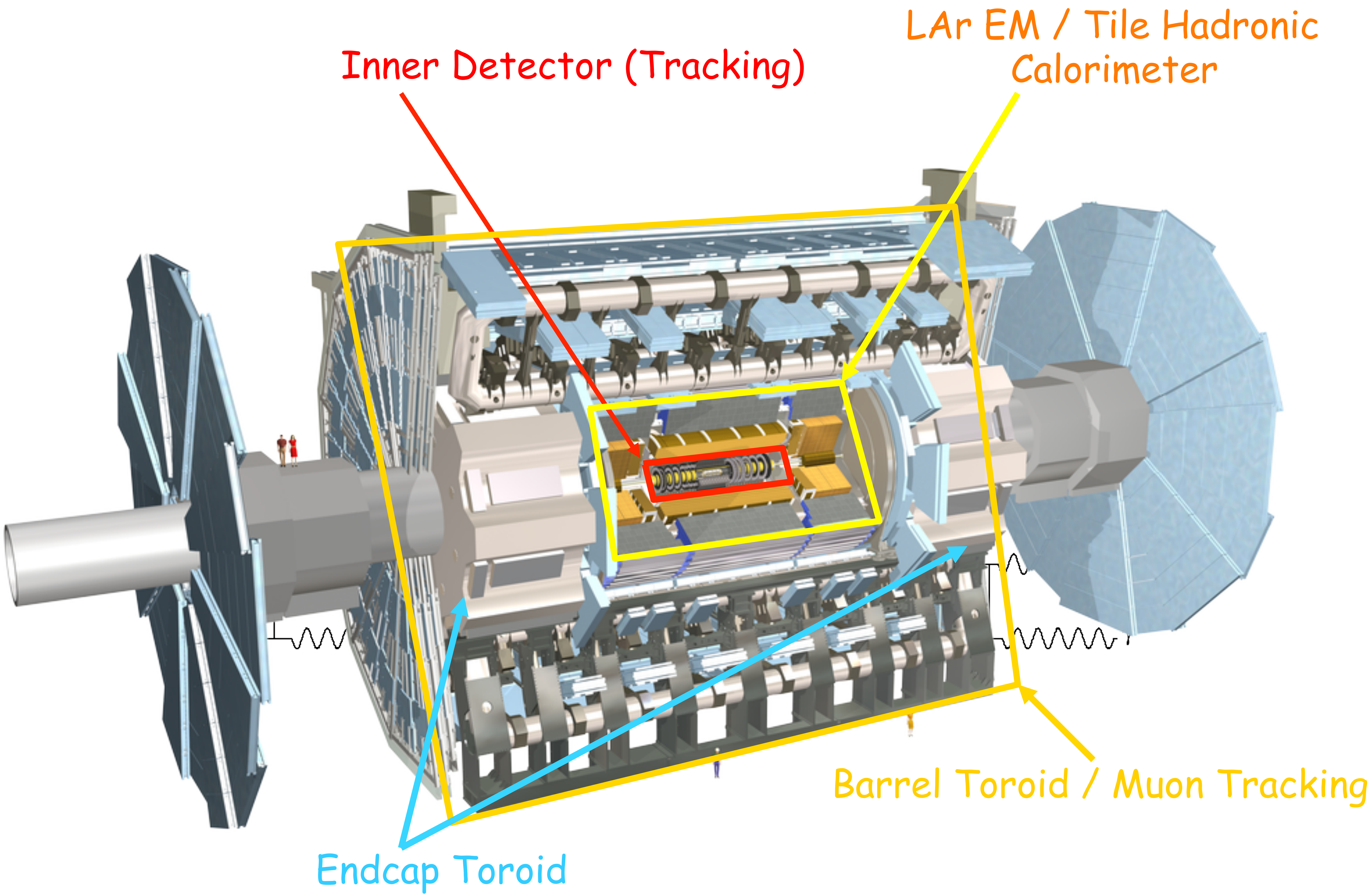
particles interact differently with detector

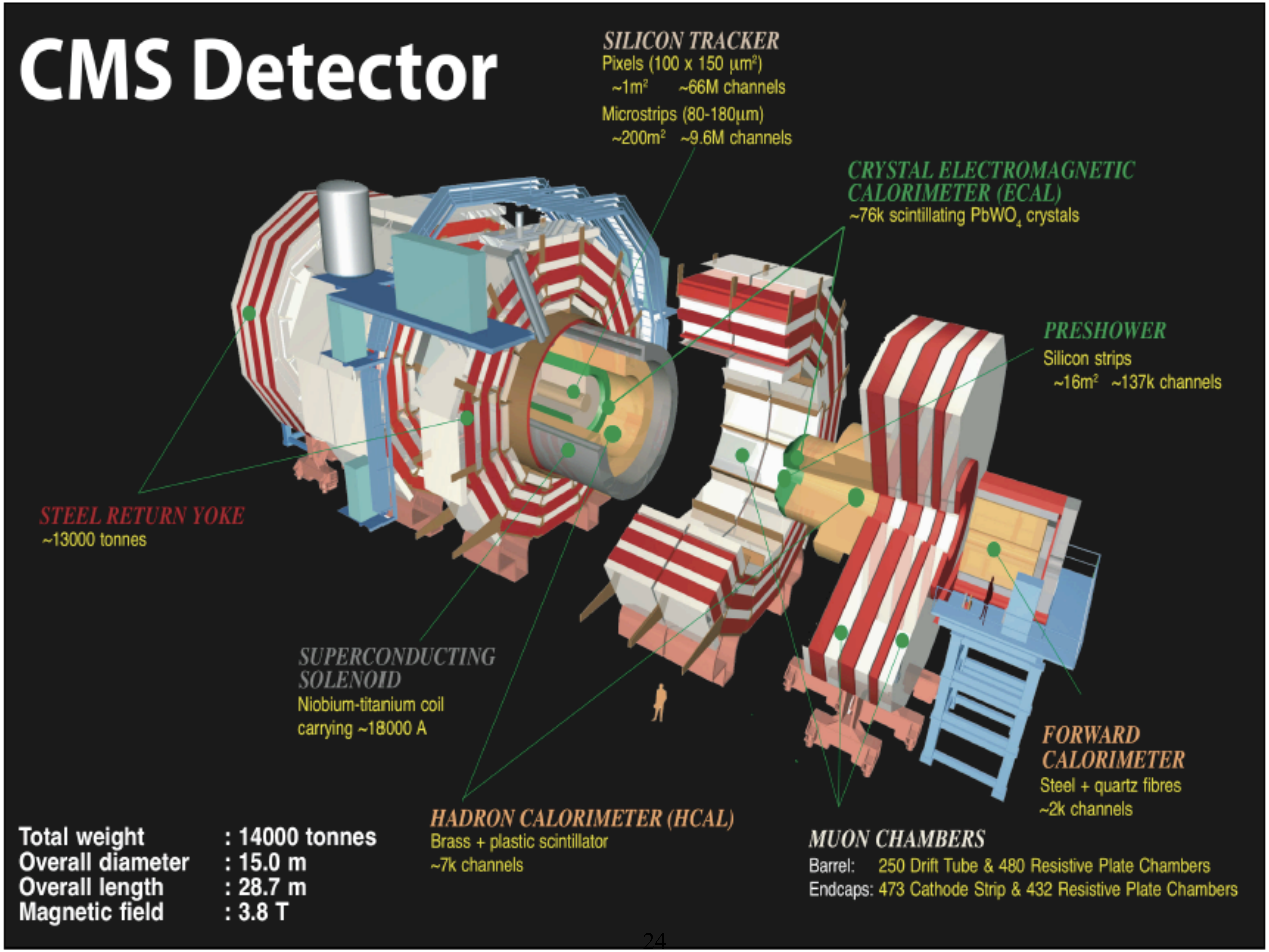
↓

used to disentangle them



ATLAS Detector

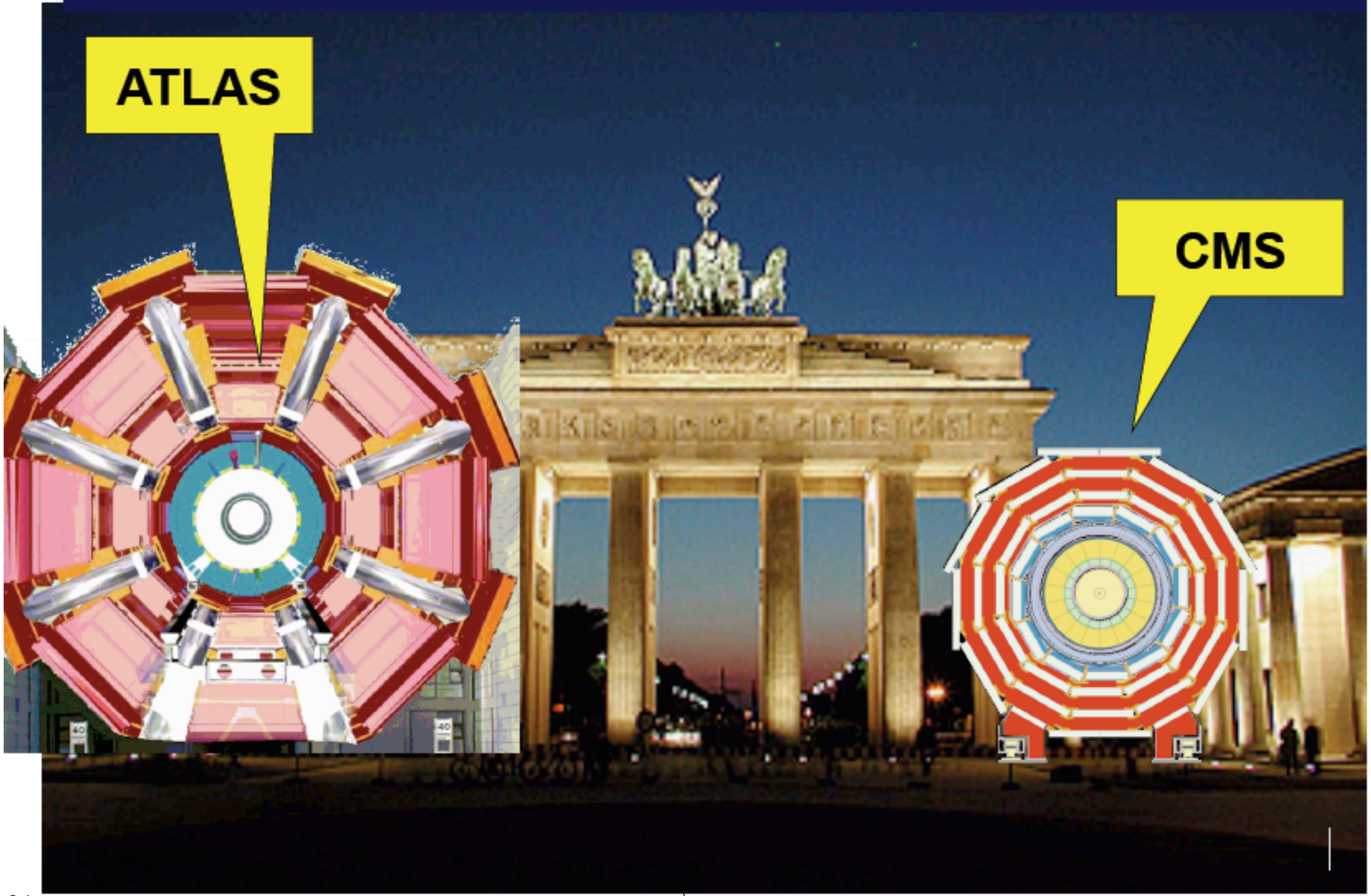




CMS Detector
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

detector

ATLAS and CMS in Berlin



detector

ATLAS Detector Trigger

- Trigger (online event selection for permanent storage) is of paramount importance since is the first cut applied any physics analysis

- Two level trigger system

↓ 40 MHz

Level-1 (L1)
- Hardware-based trigger
- Inputs from Calorimeter and Muon systems with coarse detector granularity defining Regions of Interest (RoIs)
- Latency: $< 2.5\ \mu s$

↓ 100 kHz

High Level Trigger (HLT)
- Software-based trigger
- Full detector granularity
- Latency: ~ 0.5 s average

↓ 1 kHz average $\times$ 1 MB/event = 1 GB/s

The Structure of an event

I will here introduce few concepts by showing what happens when two protons interact, i.e:

- hard process
- Radiation: ISR/FSR
- Pile-up
- Parton Density Functions (PDF's)

The event structure

Few useful reminders on hadron collider kinematics

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons

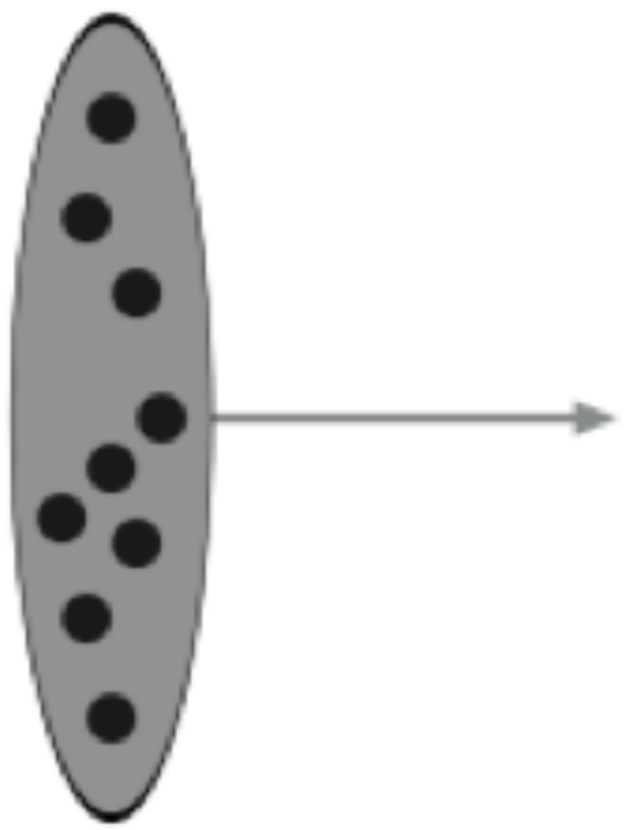
The energy of each beam is carried not by the entire proton, but by one of its constituents

$E_{collision} < 2E_b$

Pros: with a single energy possible to scan different processes at different energies

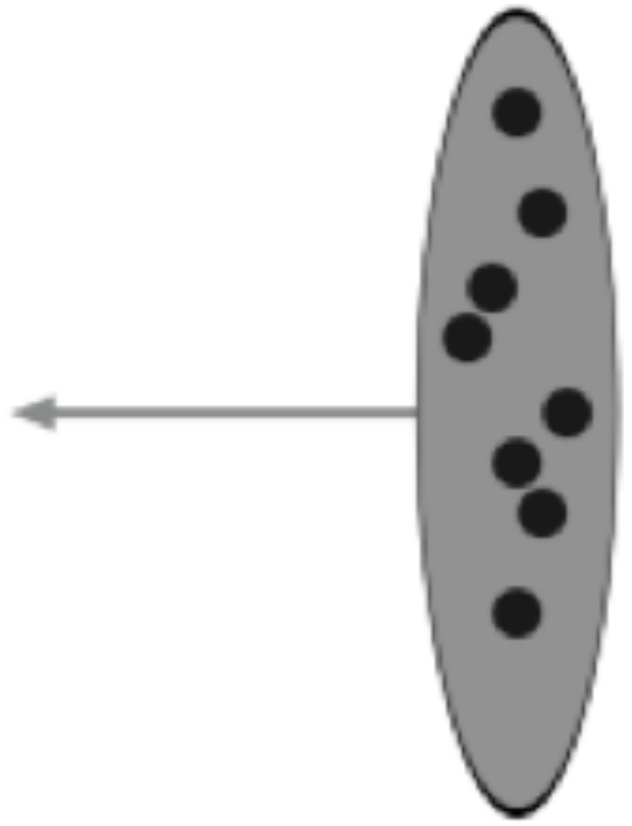
Cons: the energy available for the collision is lower than the accelerator energy

The Structure of an event: PDFs



p

Initially two beam particles are coming in towards each other. Normally each particle is characterized by a set of parton distributions, which defines the partonic substructure in terms of flavour composition and energy sharing. This determines the energy of the interacting partons (x_1, x_2)



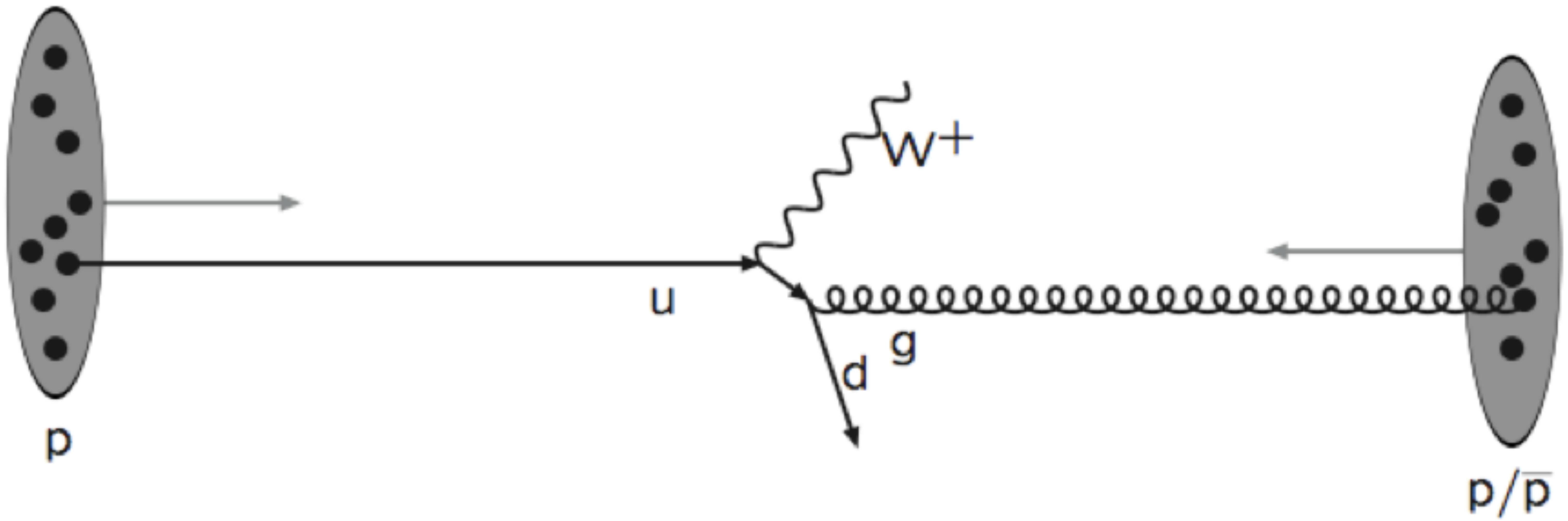
$p/\bar{p}$

$$\sigma(p(P_1) + p(P_2) \to Y) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \to Y)$$

partonic x-section:
phase space* matrix element

Incoming beams: parton densities

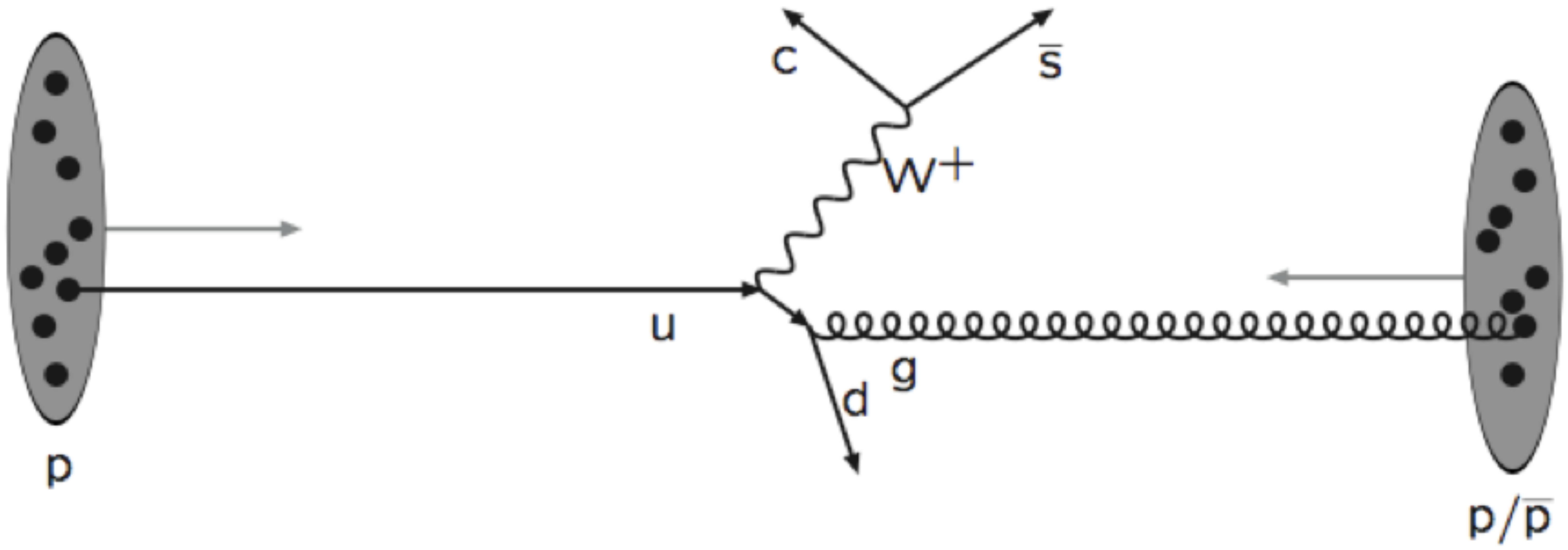
The Structure of an event



→ One incoming parton from each of the protons enters the hard process, where then a number of outgoing particles are produced. It is the nature of this process that determines the main characteristics of the event.

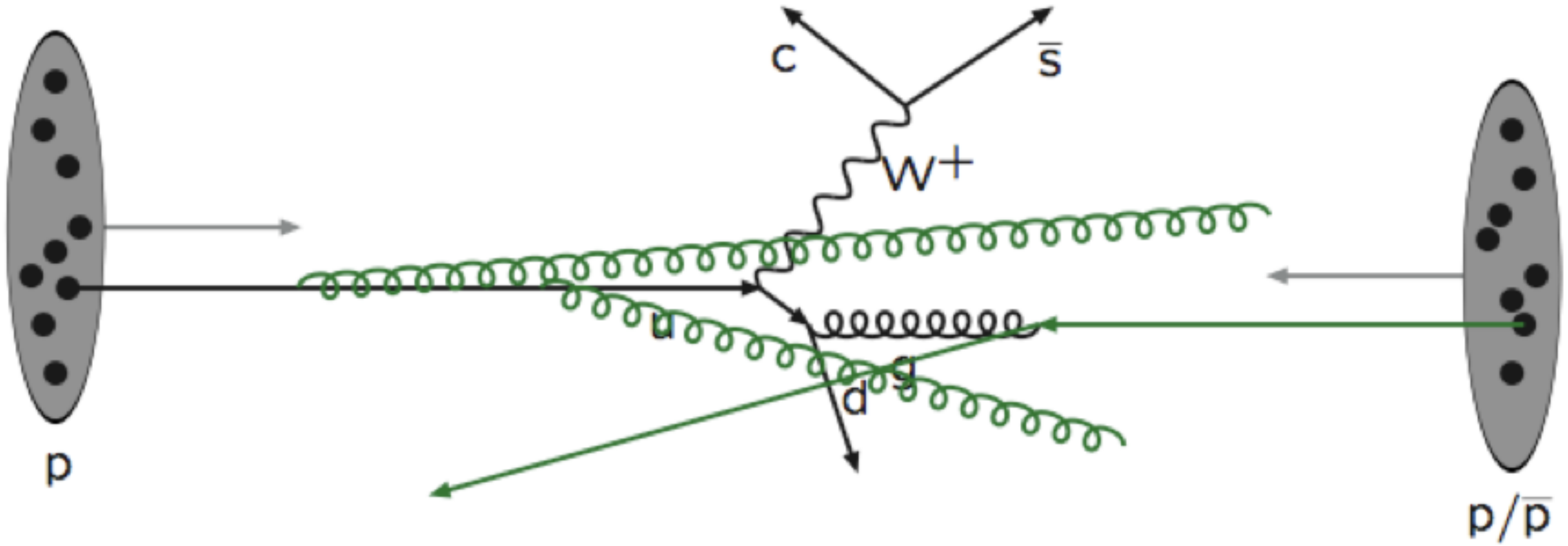
Hard subprocess: described by matrix elements

The Structure of an event: resonances



The hard process may produce a set of short-lived resonances, like the $Z^0/W^{\pm}$ gauge bosons.

The Structure of an event: ISR

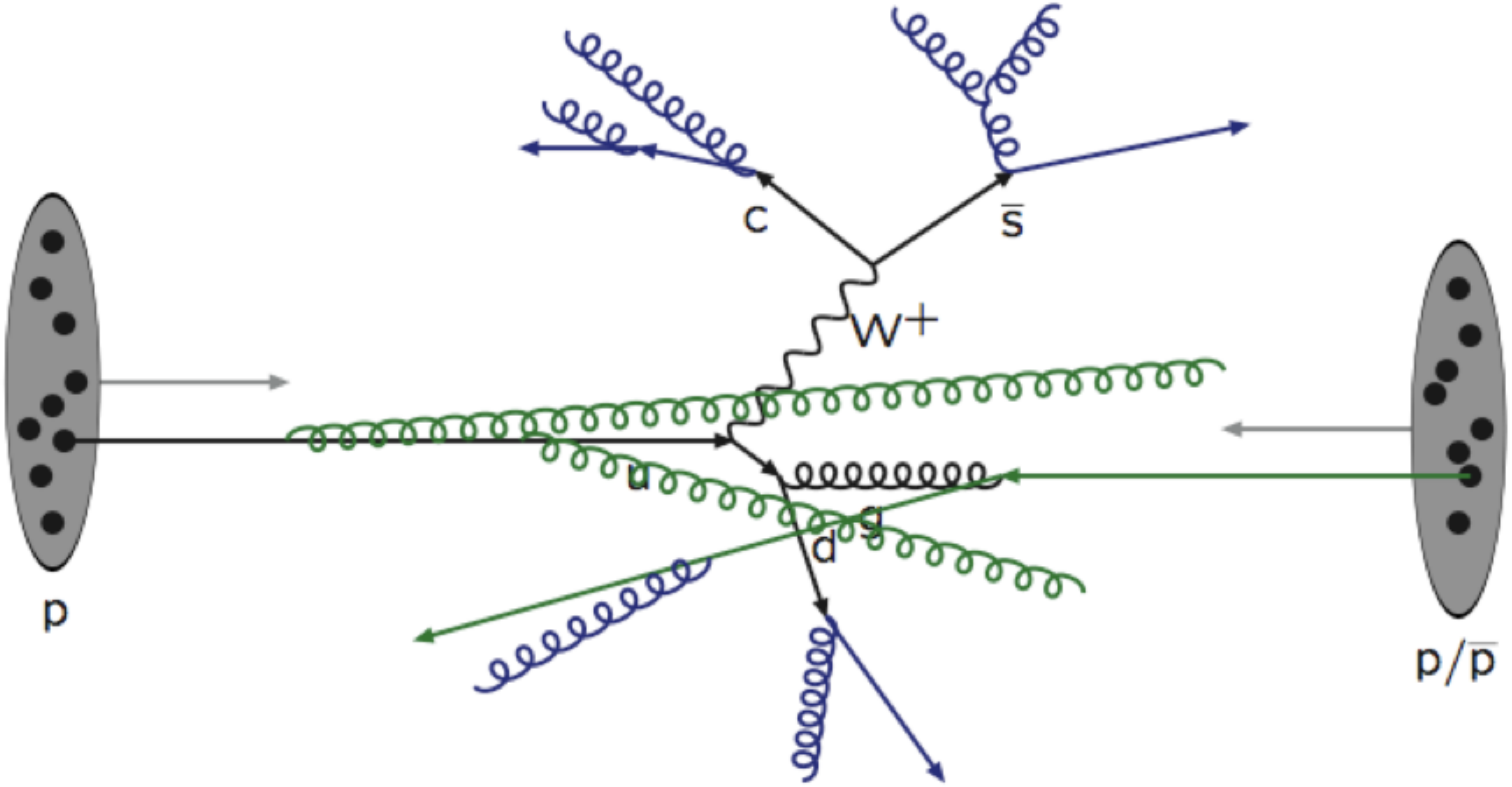


One shower initiator parton from each beam may start off a sequence of branchings, such as q → qg, which build up an initial-state shower.

Initial-state radiation: spacelike parton showers

The event structure

The Structure of an event: FSR



The outgoing partons may branch, just like the incoming did, to build up final-state showers.

Final-state radiation: timelike parton showers

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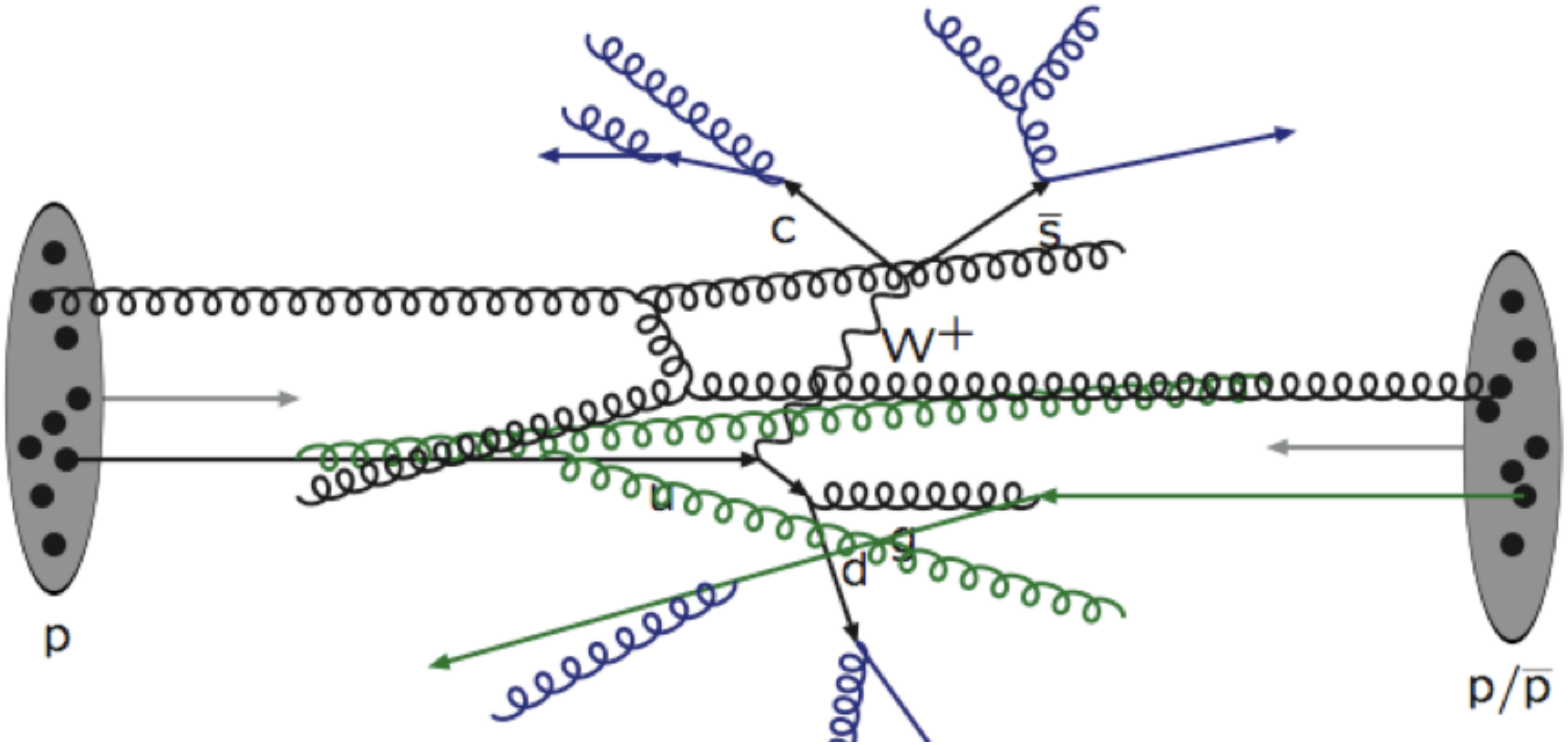
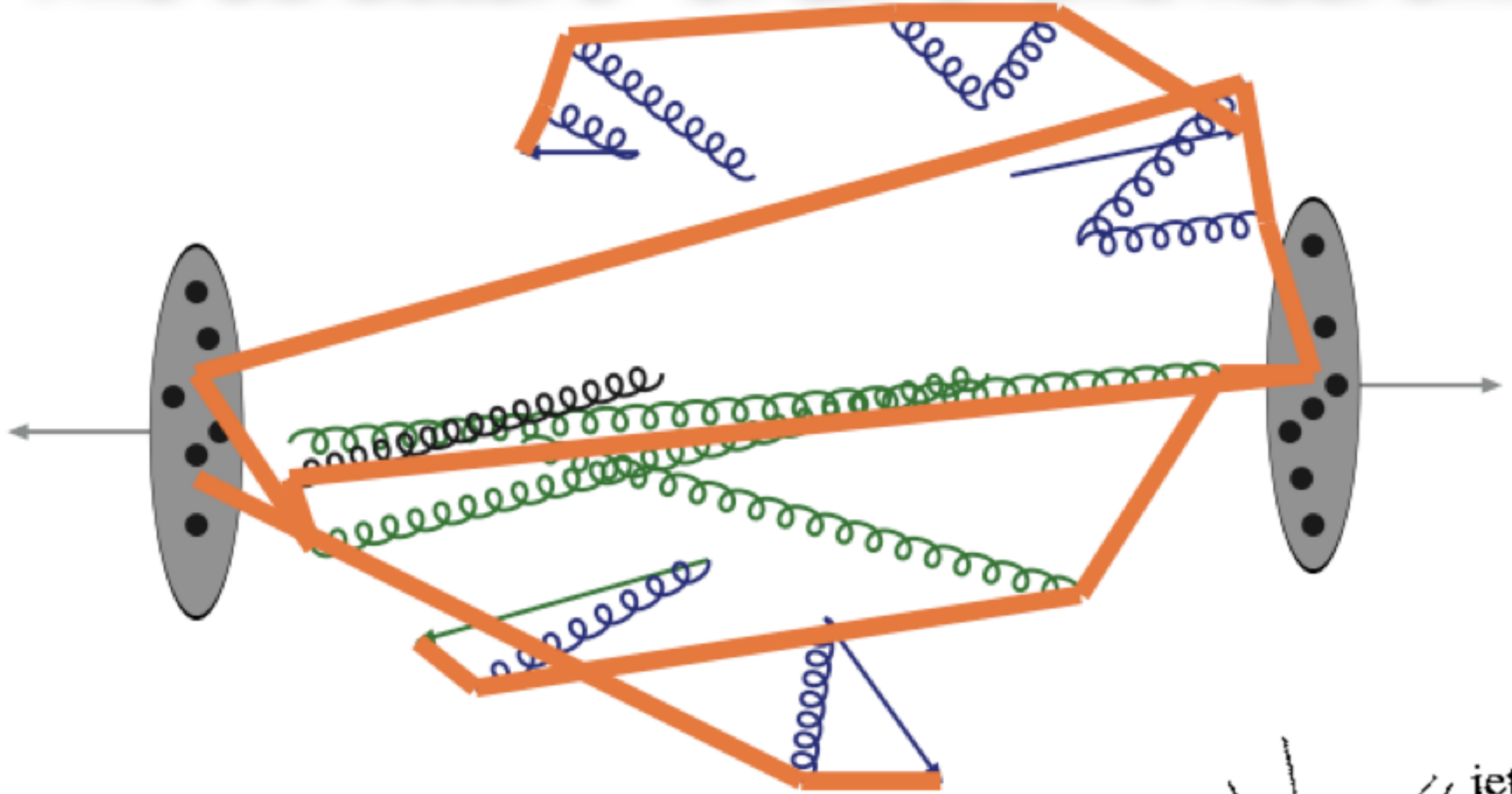
The Structure of an event: pile-up



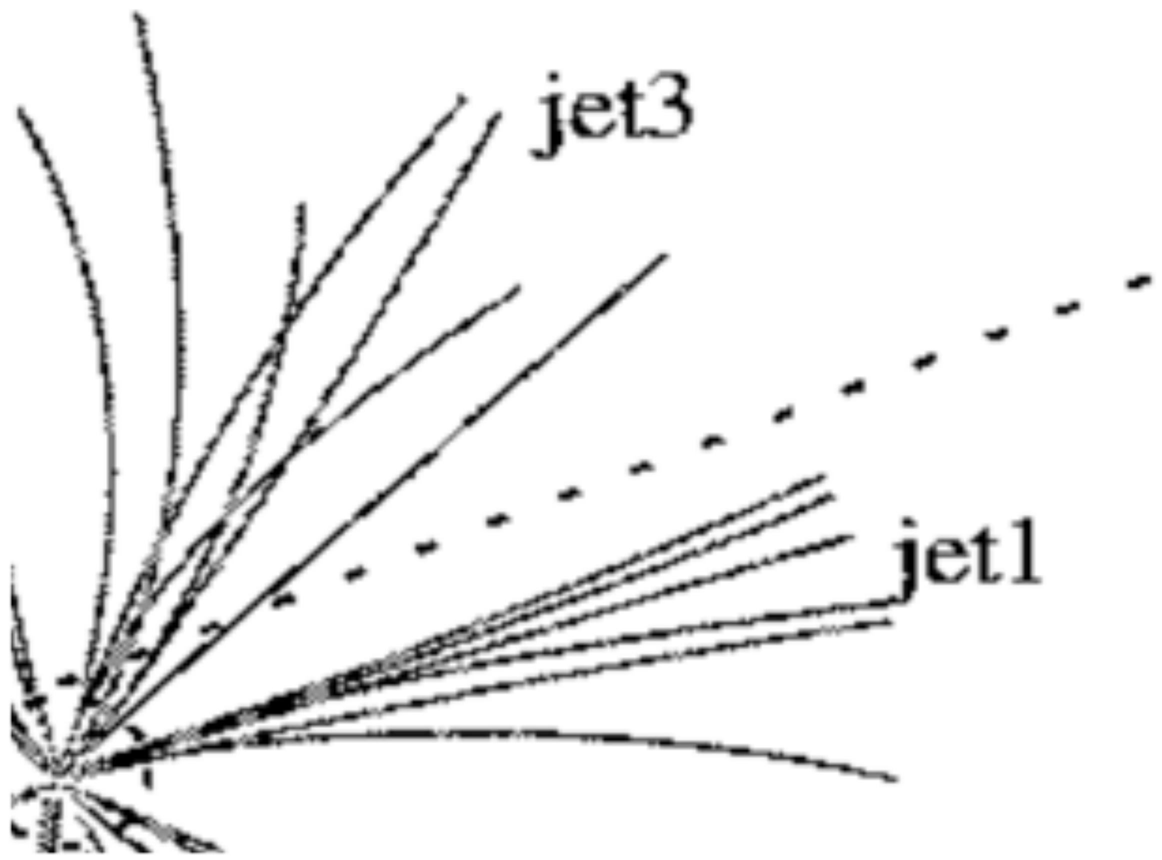
In addition to the hard process, further semihard interactions may occur between the other partons of two incoming hadrons.
There is in time pile-up which comes from the same bunch of protons from the interaction of interest, and can be resolved by setting the interaction points location by identifying vertices.
The second type is out-time pile-up, which which comes from other proton bunches when the detector has not yet recorded the signal completely due to dead time, the time needed for a certain detector to be able to record an event after a previous one

The event structure

The Structure of an event: hadronisation



The result of the hadronization is that quark and gluons are not observed as free particles but as Hadrons, and actually in the detector as jets of particles in a narrow cone



The event structure

Pile-up

2010

O(2) Pile-up events

150 ns inter-bunch spacing

2011

O(10) Pile-up events

50 ns inter-bunch spacing

Design value (expected to be reached at $L=10^{34}$!)

2012

O(20) Pile-up events

50 ns inter-bunch spacing

The event structure

The Cross-section

the cross-section

number of observed events

background contamination in the sample

cross section:
$$\sigma = \frac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

analysis efficiency

$$\varepsilon = \varepsilon_{tr} \cdot \varepsilon_{reco} \cdot \varepsilon_{ID} \cdot \varepsilon_{sel}$$

luminosity delivered by LHC

$$1 \text{ barn} = 10^{-28} \text{ m}^2 = 10^{-24} \text{ cm}^2$$

Number of observed events is proportional to

1) Luminosity
2) analysis efficiency
3) cross section of the process

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

The luminosity is a parameter of the LHC and can be increased

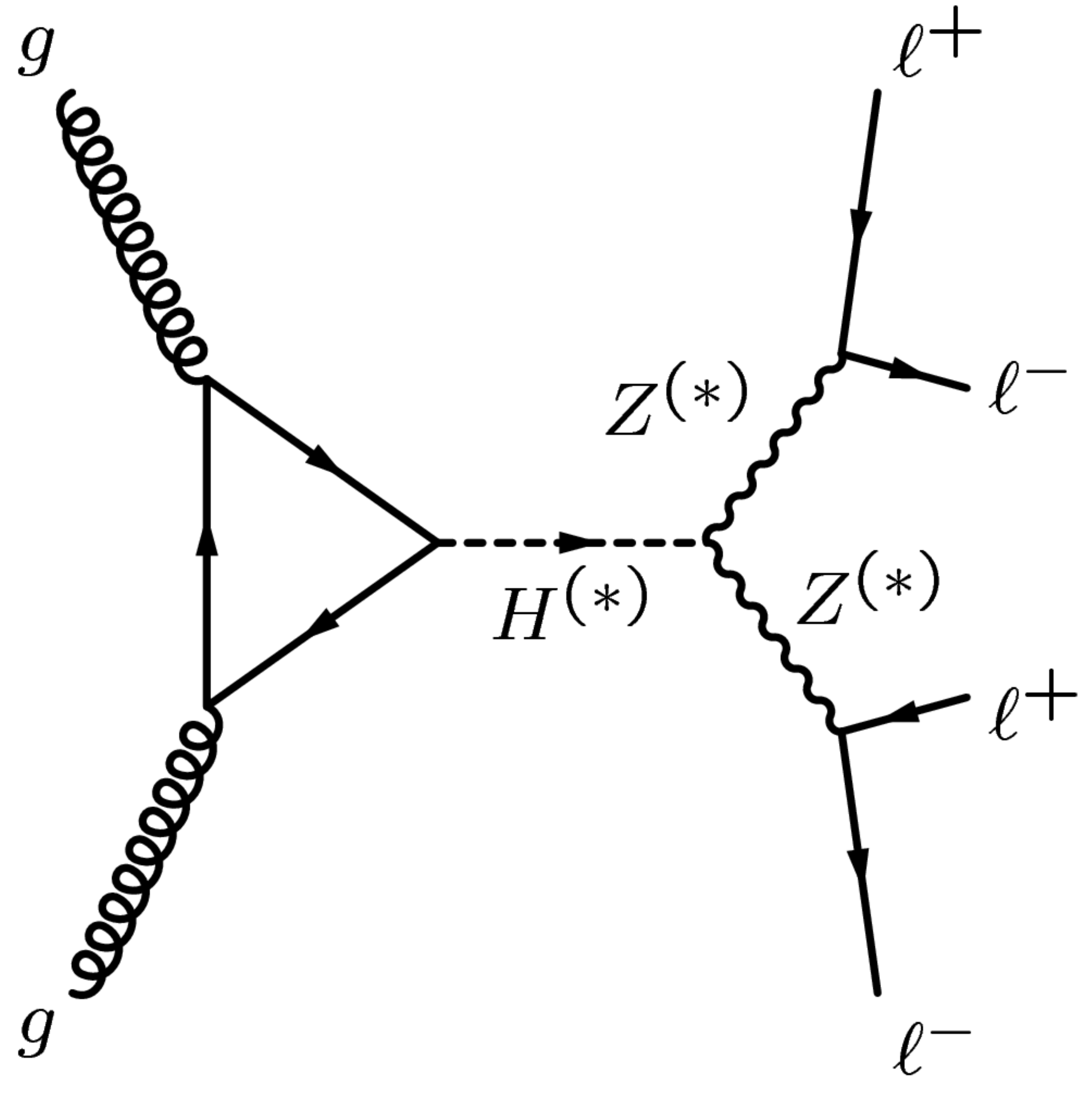
$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi\sigma_x\sigma_y}$$

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

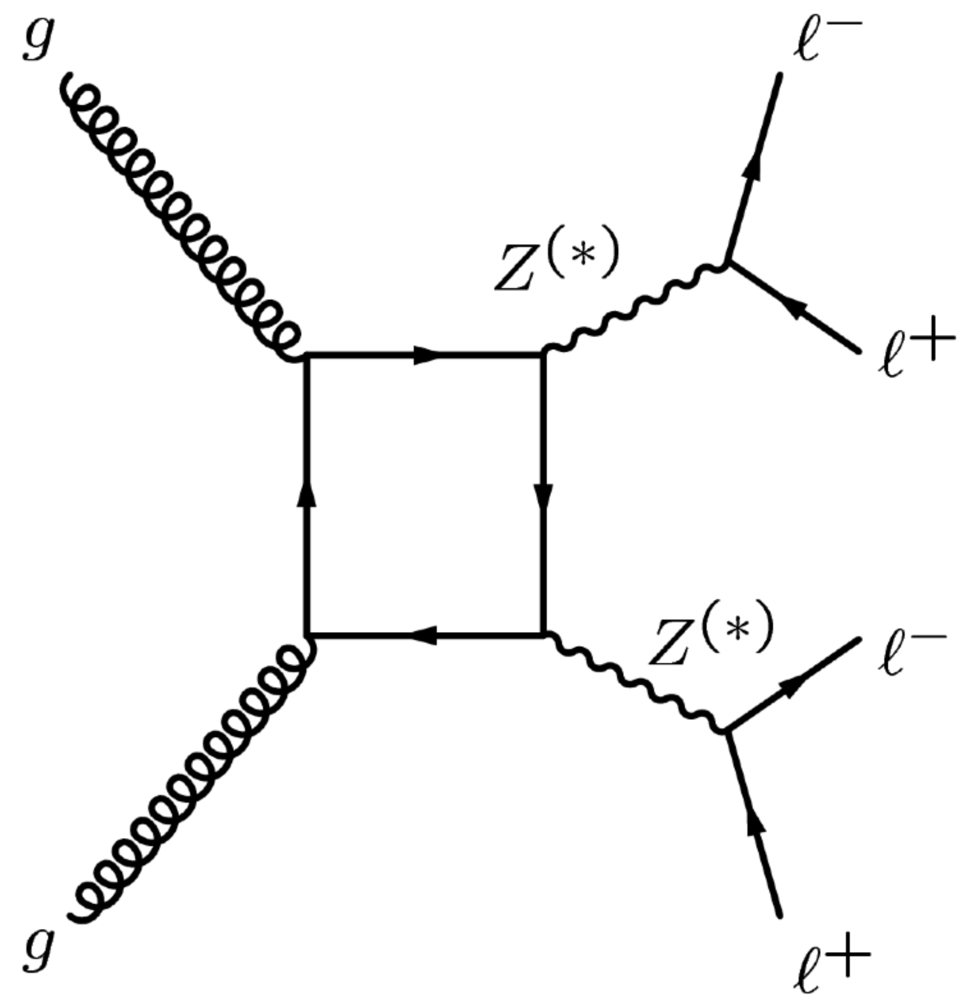
Signal and backgrounds

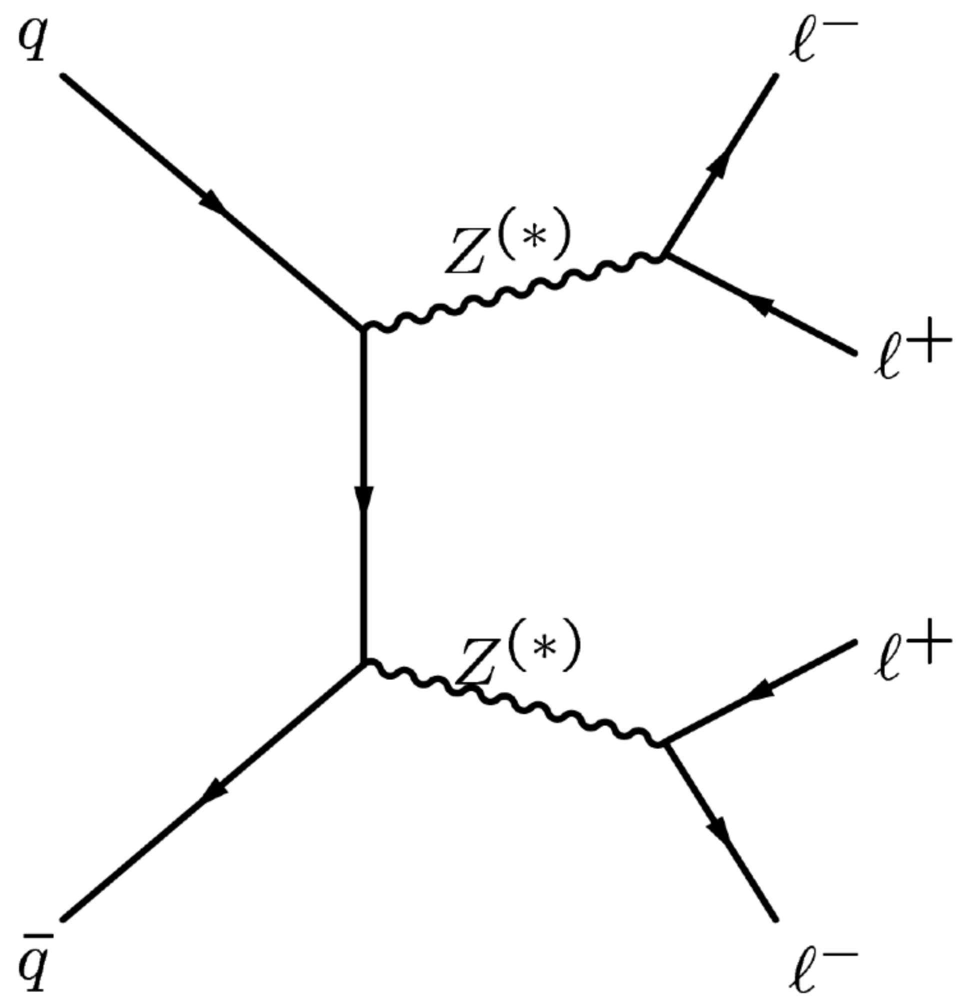
Other processes (background) can mimic signal final state.
Same particles in the final state!

HIGGS Signal



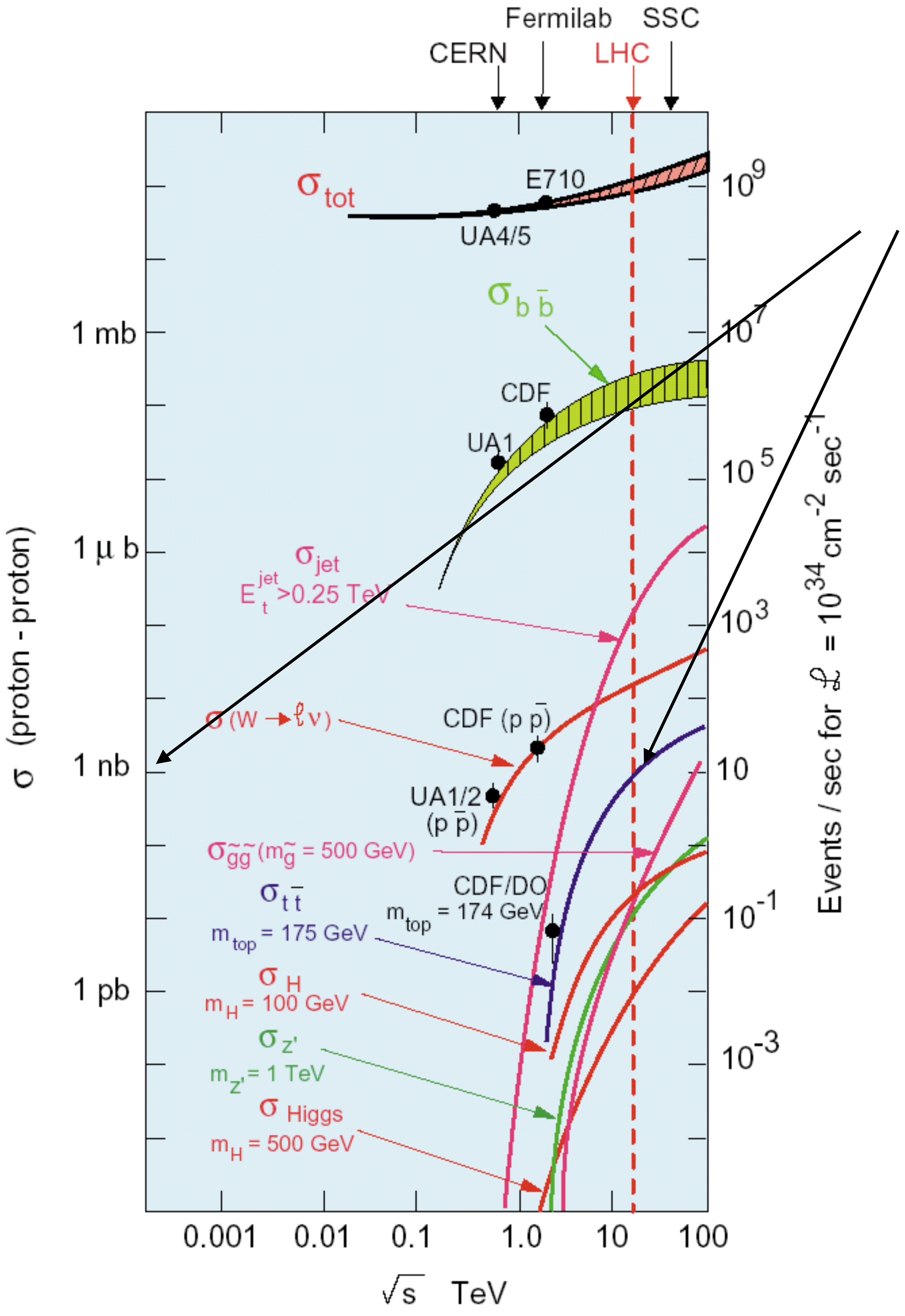
SM backgrounds





The event structure

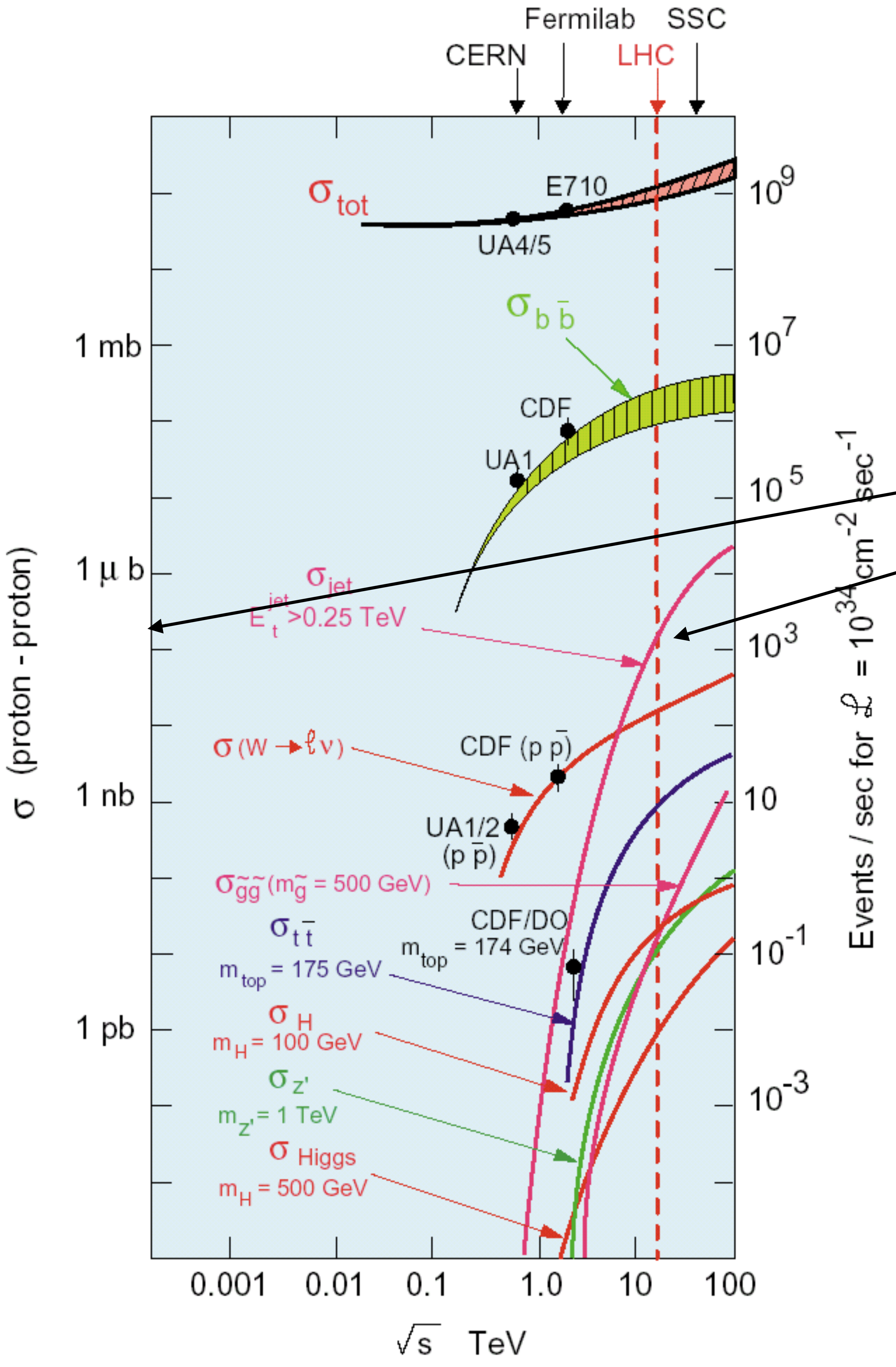
Cross-sections/ number of Events



Large cross-sections and what is interesting is rare:

- x-section ttbar ~ 1nb (800pb)

Cross-sections/ number of Events



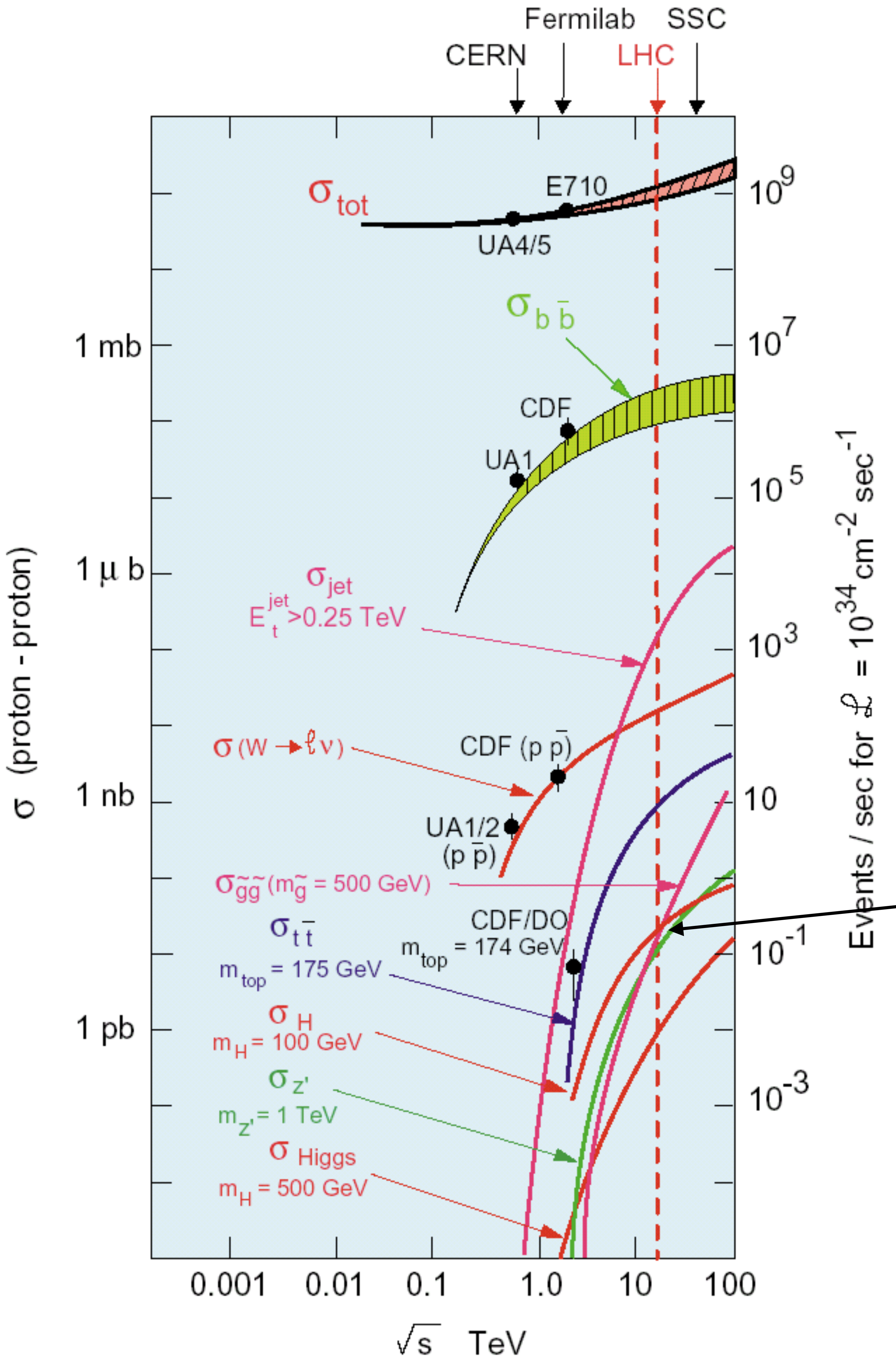
Large cross-sections and what is interesting is rare:

- x-section ttbar ~ 1nb (800pb)

- x-section jet production ~ 100nb (100000pb)

The event structure

Cross-sections/ number of Events

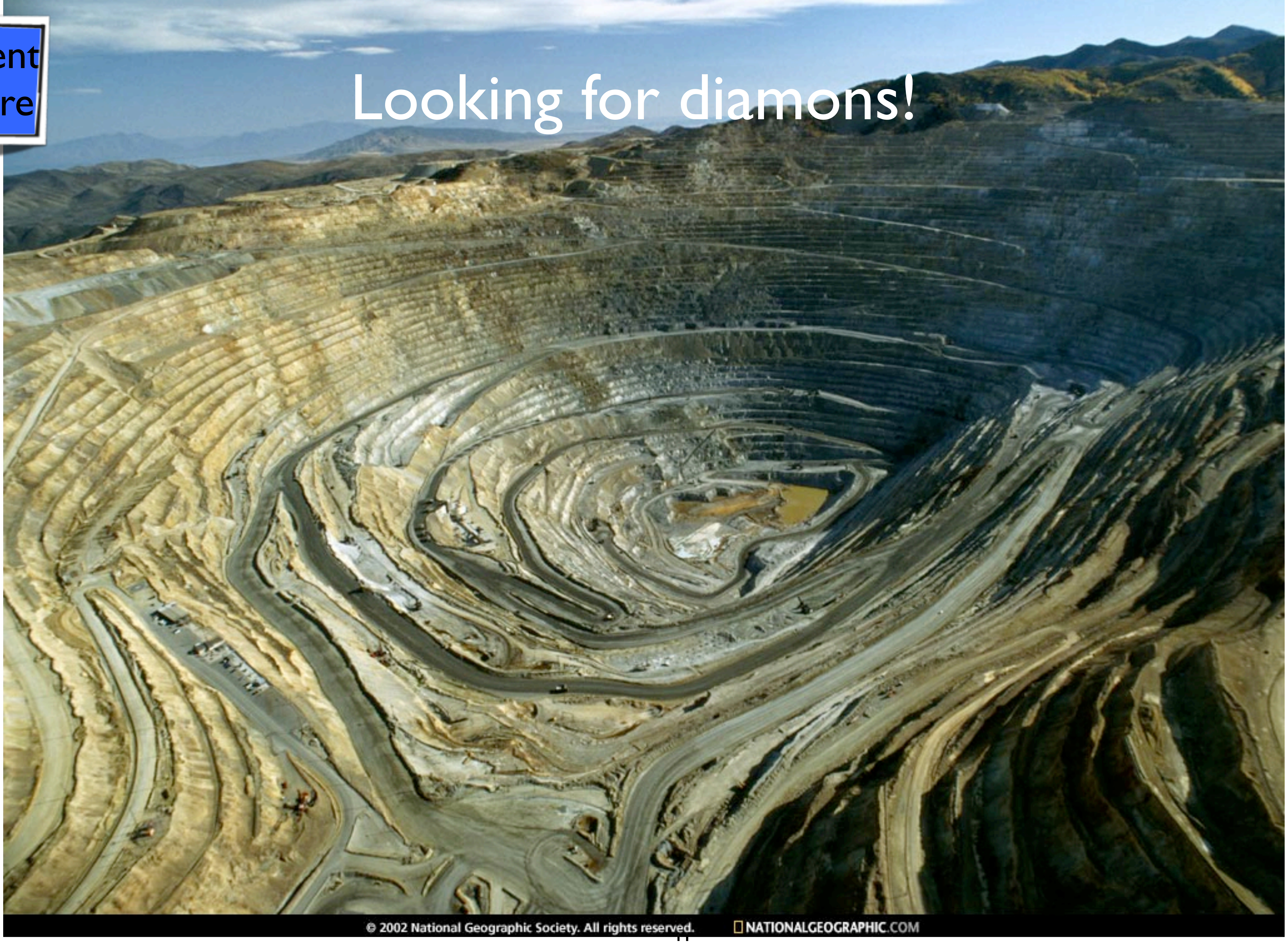


Large cross-sections and what is interesting is rare:

- x-section ttbar ~ 1nb (800pb)
- x-section jet production ~ 100nb (100000pb)
- x-section Higgs production ~ 10pb

The event structure

Looking for diamons!

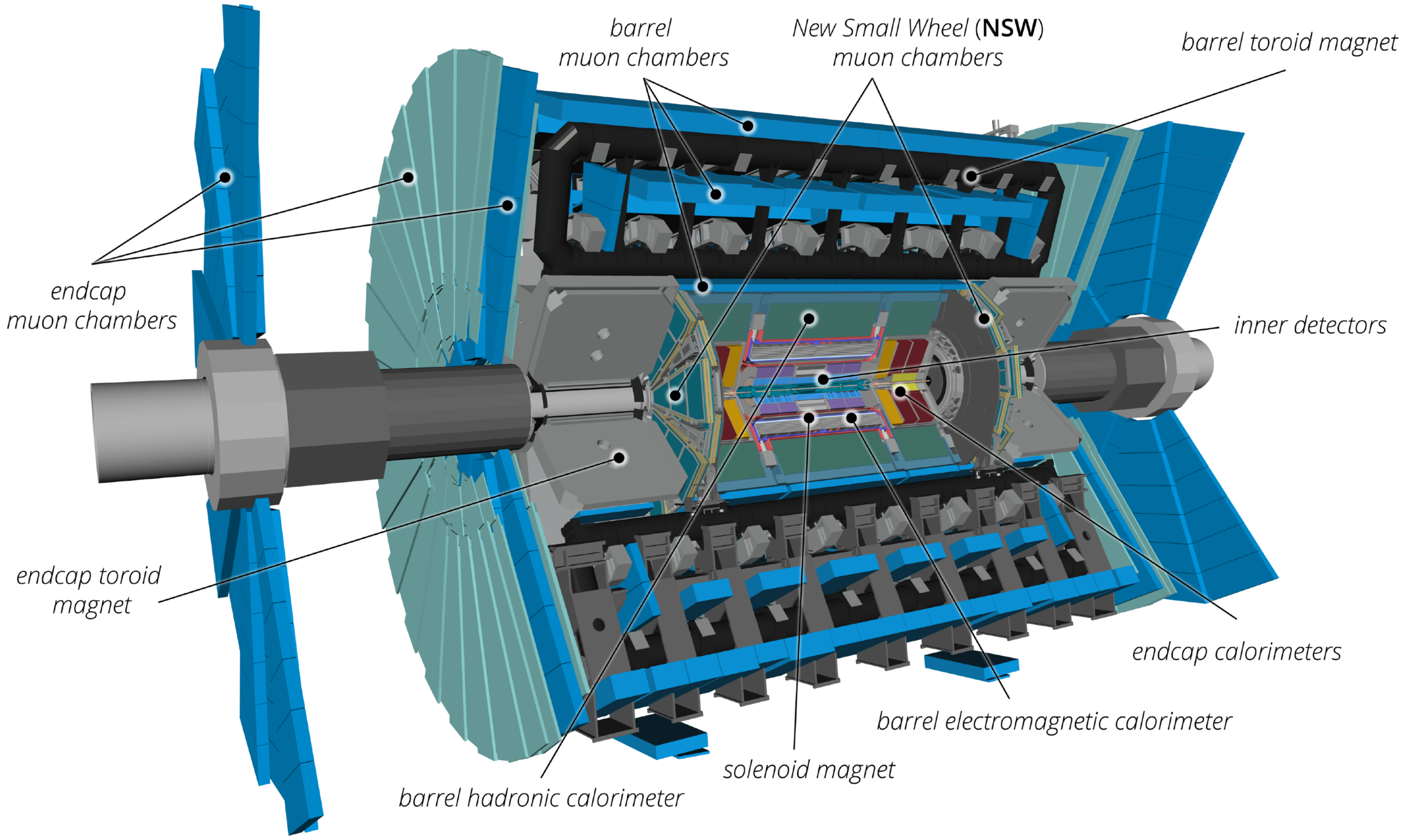


The evolution of the detectors

- description of the detectors upgrades in run 3 mainly driven by physics needs
- Run 3 detectors as a first step towards the HL-LHC

Run 3 detector evolution in preparation for HL-LHC

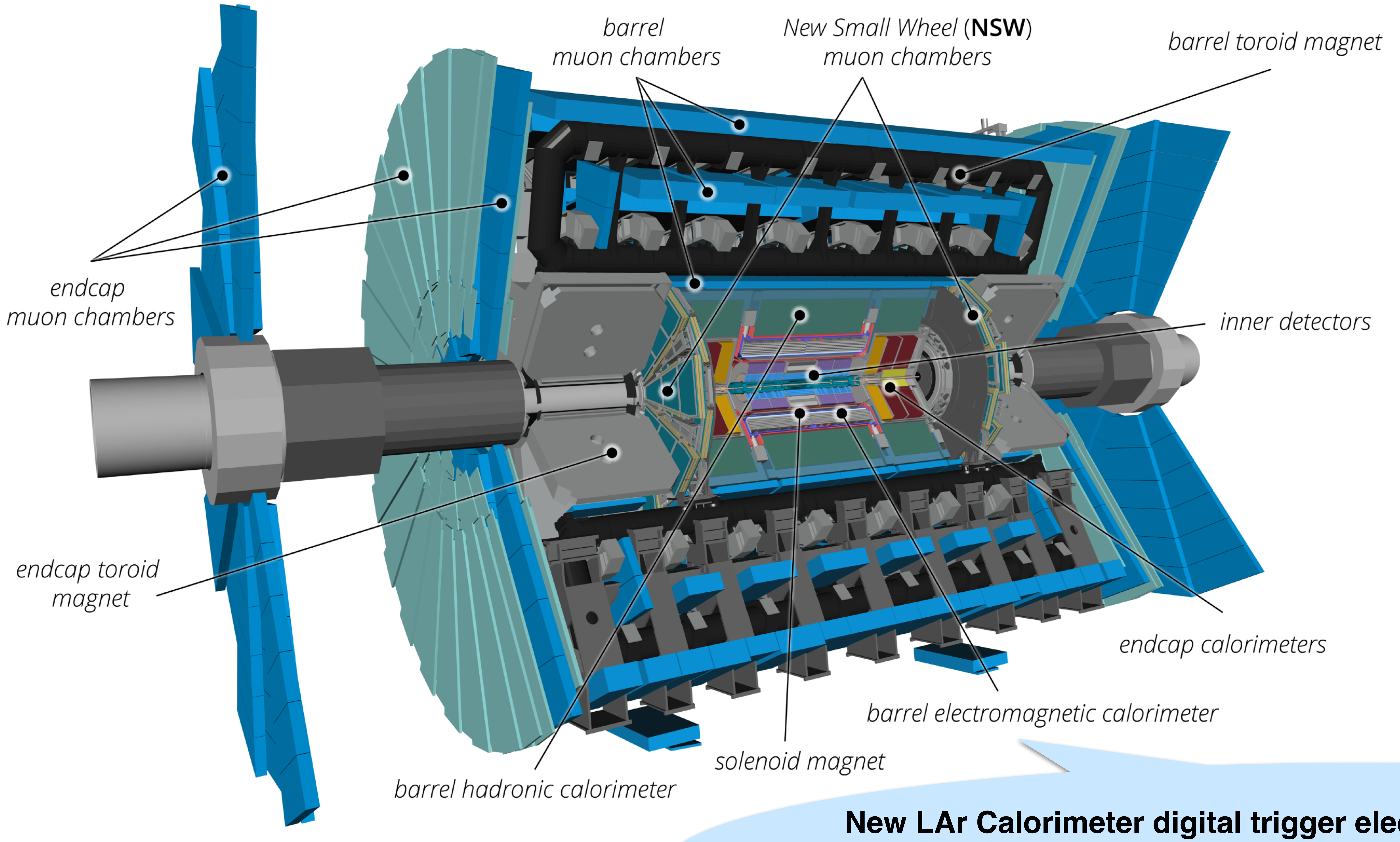
arXiv:2305.16623



Detectors upgrades

Run 3 detector evolution in preparation for HL-LHC

arXiv:2305.16623

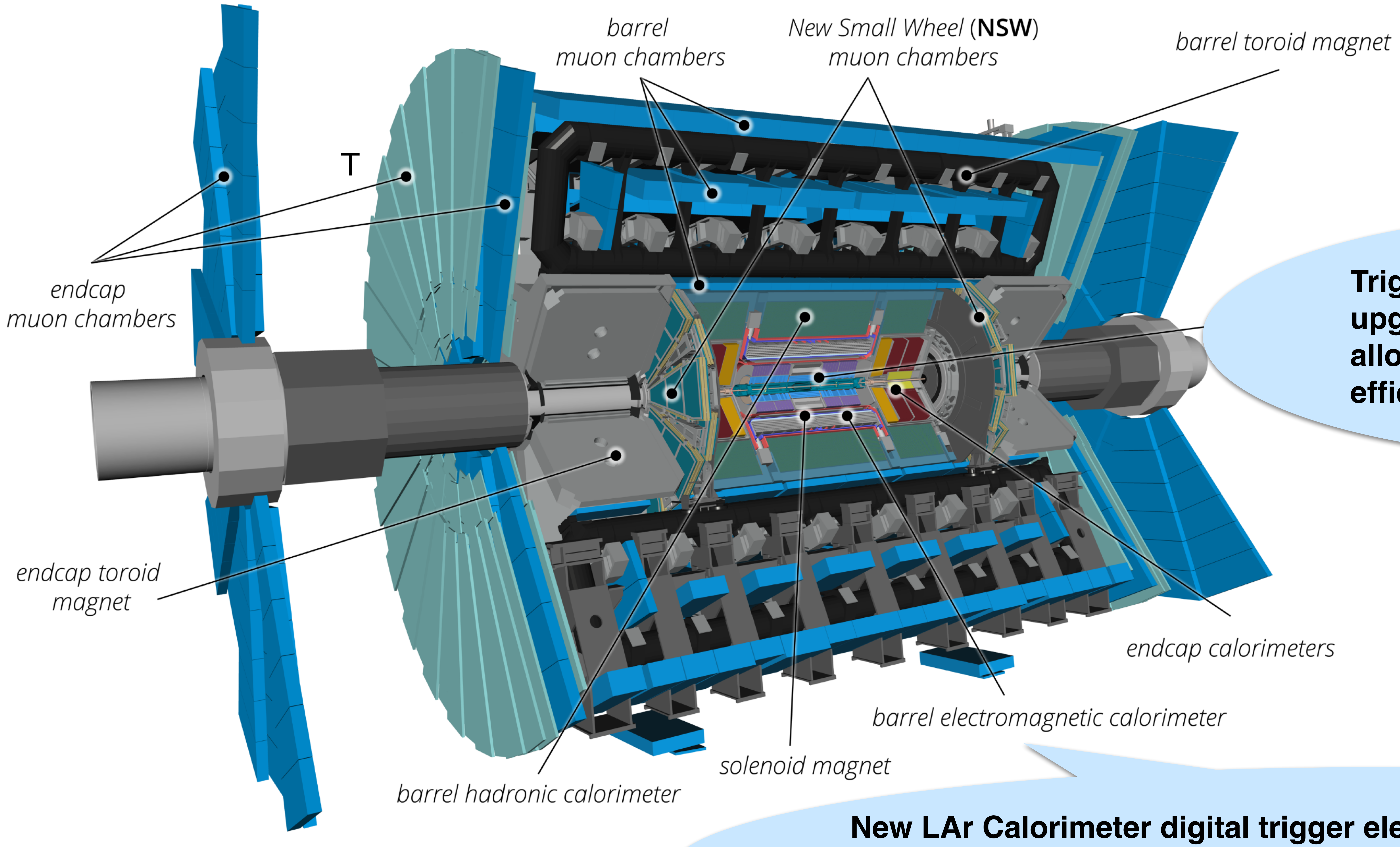


Detectors upgrades

New LAr Calorimeter digital trigger electronic boards: improved first level trigger granularity!
towards HL-LHC runs to deal with high background rates

Run 3 detector evolution in preparation for HL-LHC

arXiv:2305.16623



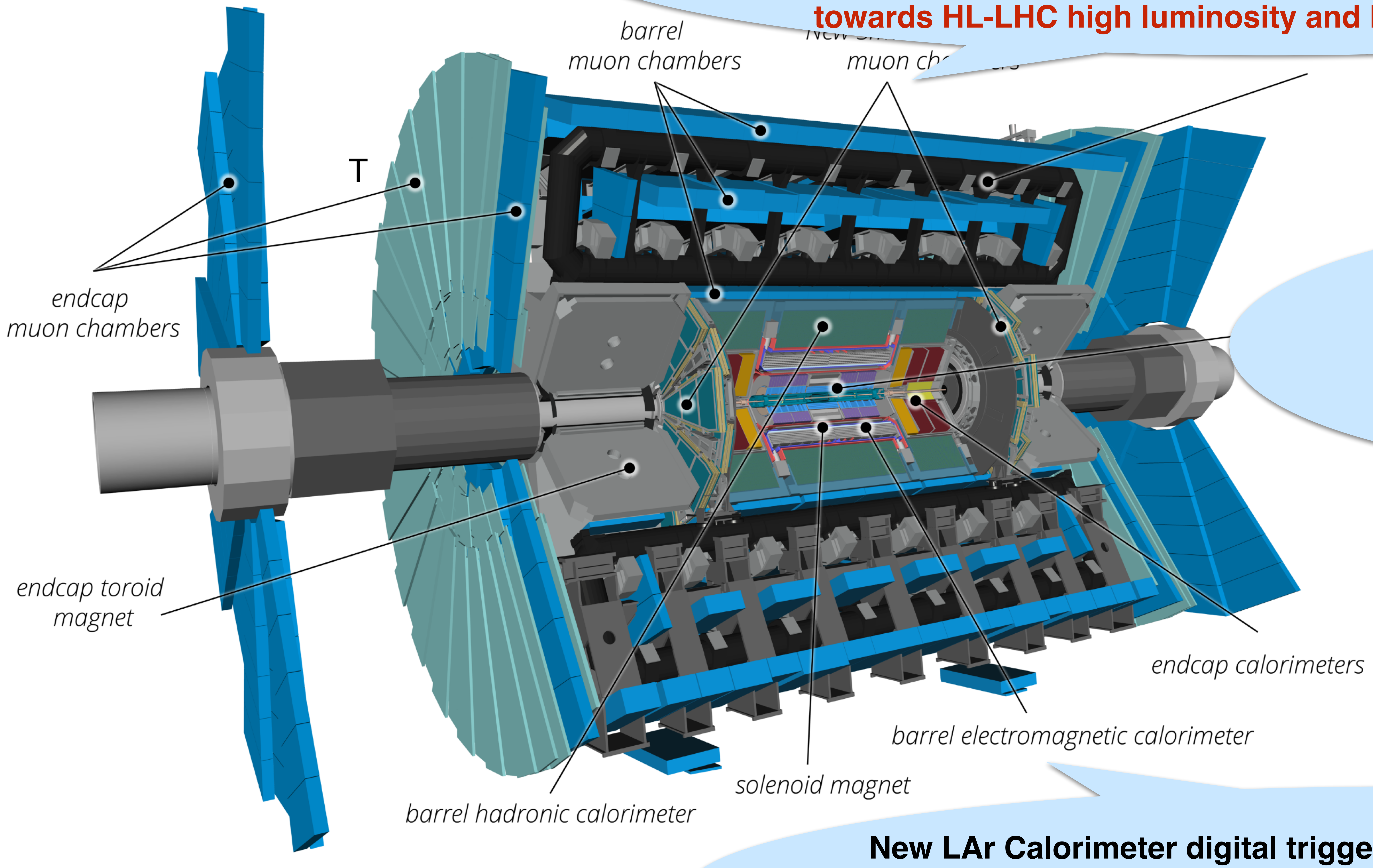
Detectors upgrades

Trigger & data acquisition have upgraded hardware & software allowing the trigger to select events more efficiently & reduce background rates

New LAr Calorimeter digital trigger electronic boards: improved trigger granularity!
towards HL-LHC runs to deal with high background rates

Run 3 detector ev … for HL-LHC

arXiv:2305.16623

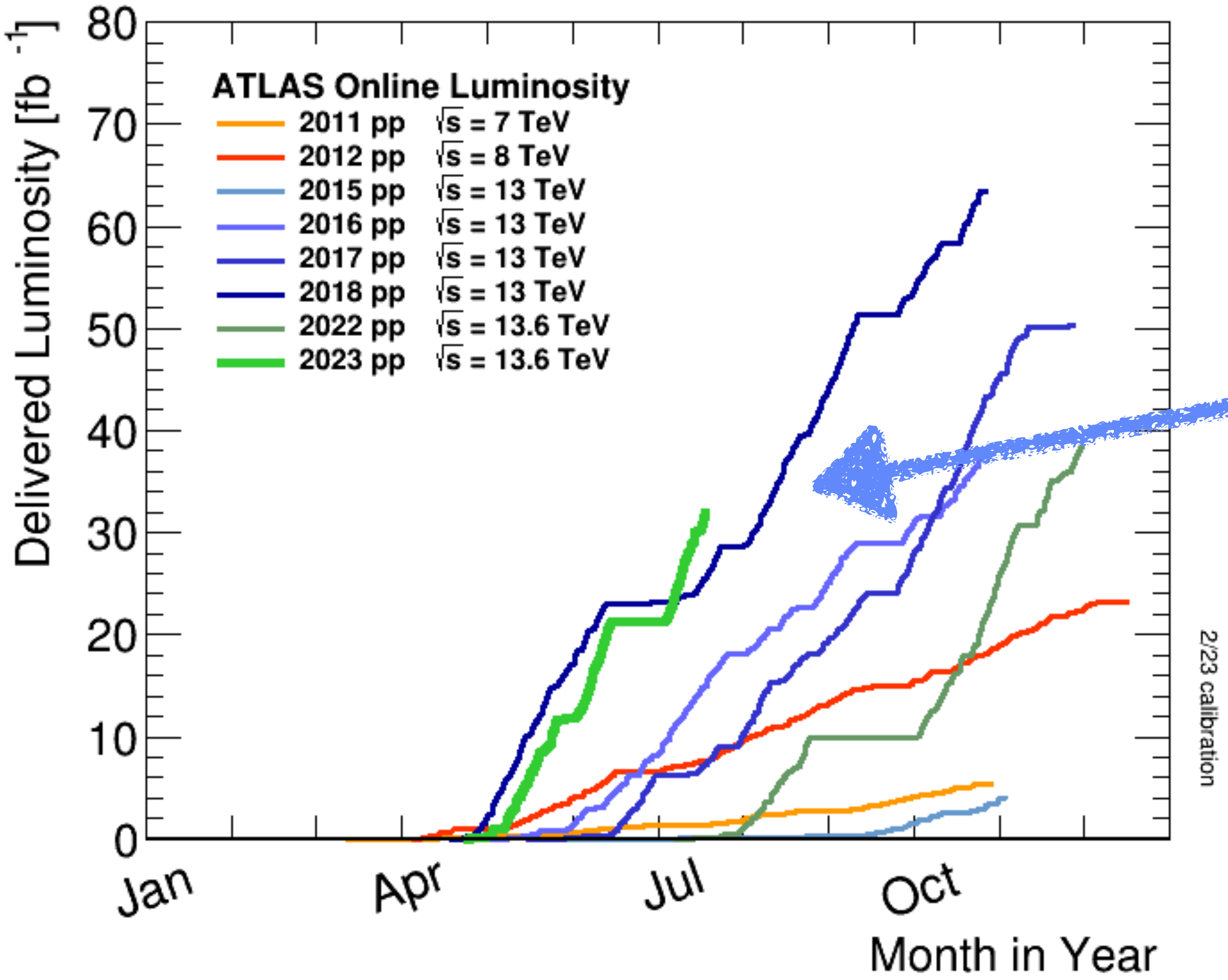


Muon New Small Wheels to replace innermost forward Muon station to
1) improve Level 1 trigger (high granularity, fast response)
2) maintain good tracking in end-cap region
towards HL-LHC high luminosity and high background rates

Detectors upgrades

Trigger And data acquisition systems have upgraded hardware ad software allowing the trigger to spot a wide range of collision events (with same acceptance)

New LAr Calorimeter digital trigger electronic boards: improved trigger granularity!
towards HL-LHC high luminosity and high background rates



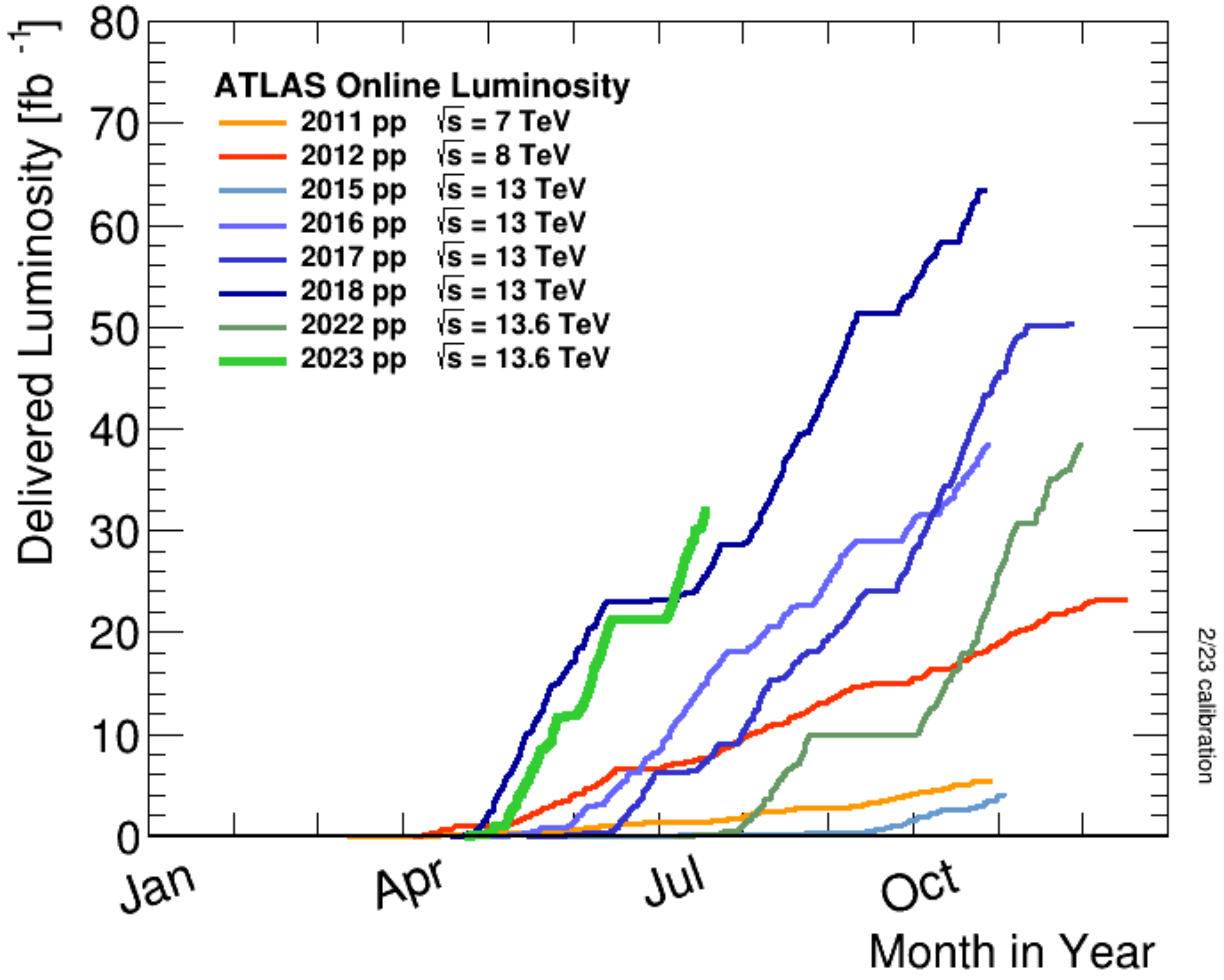
Detectors upgrades

- faster rise ever!

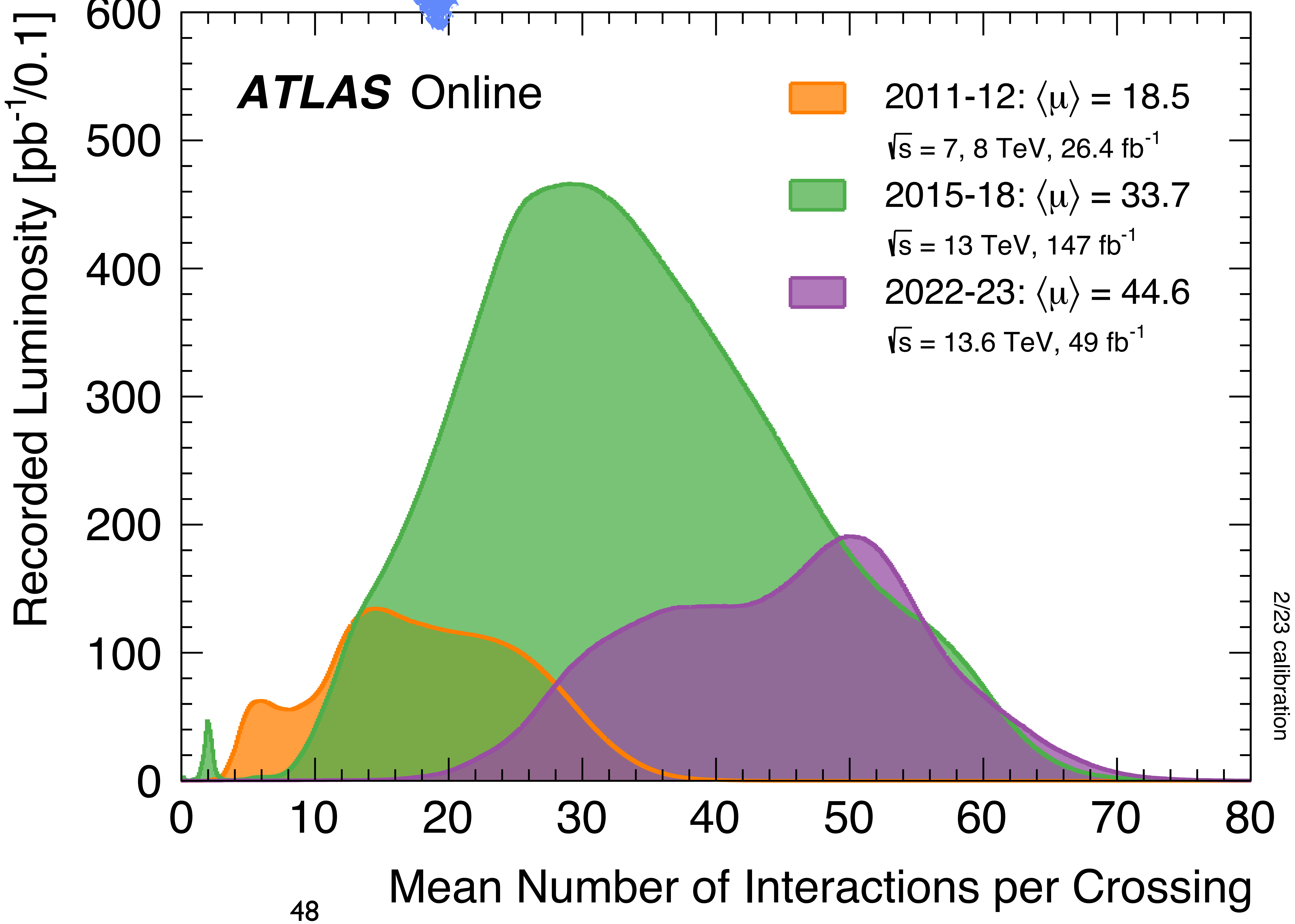
Run 3

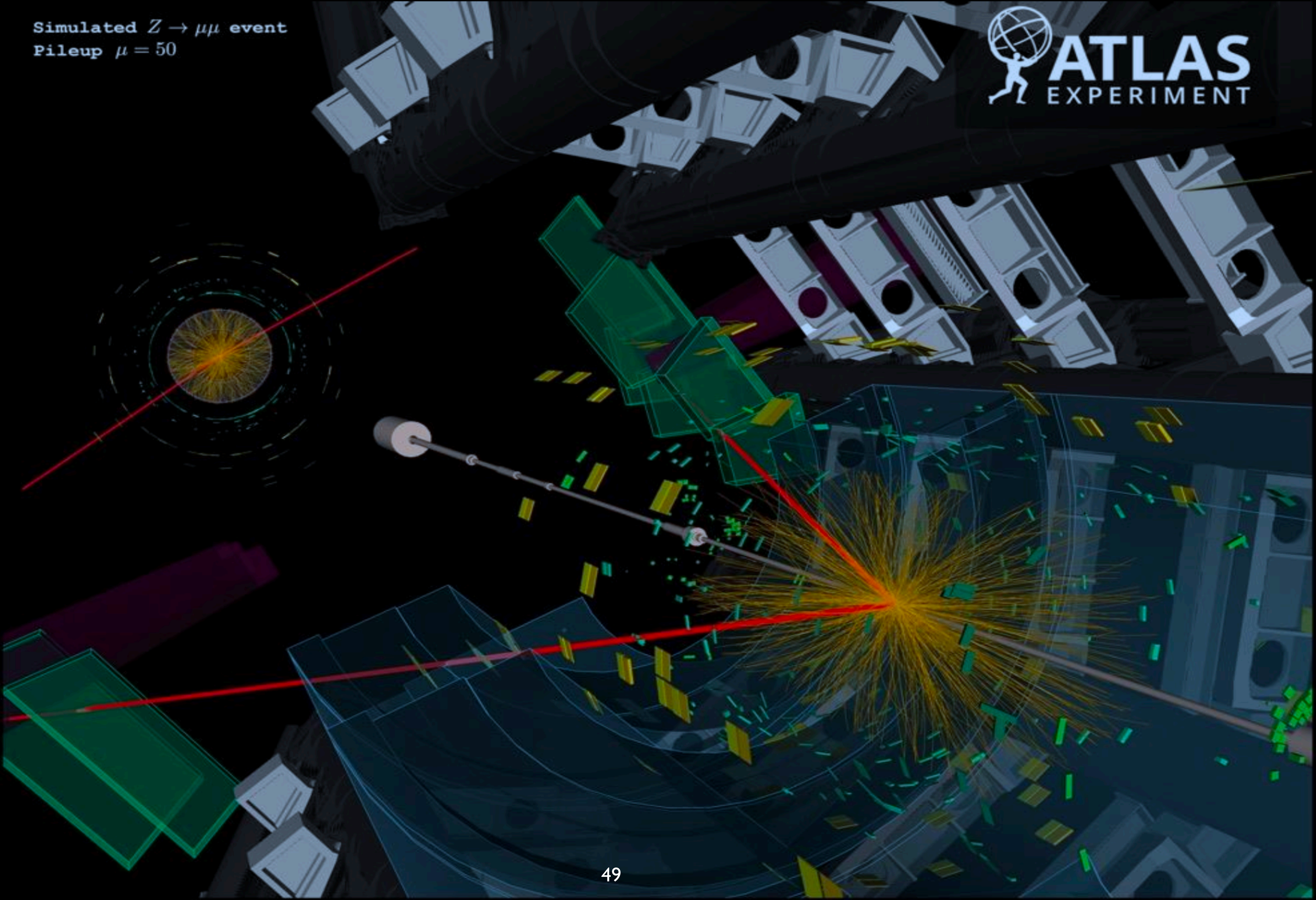
ATL-DAPR-PUB-2023-001

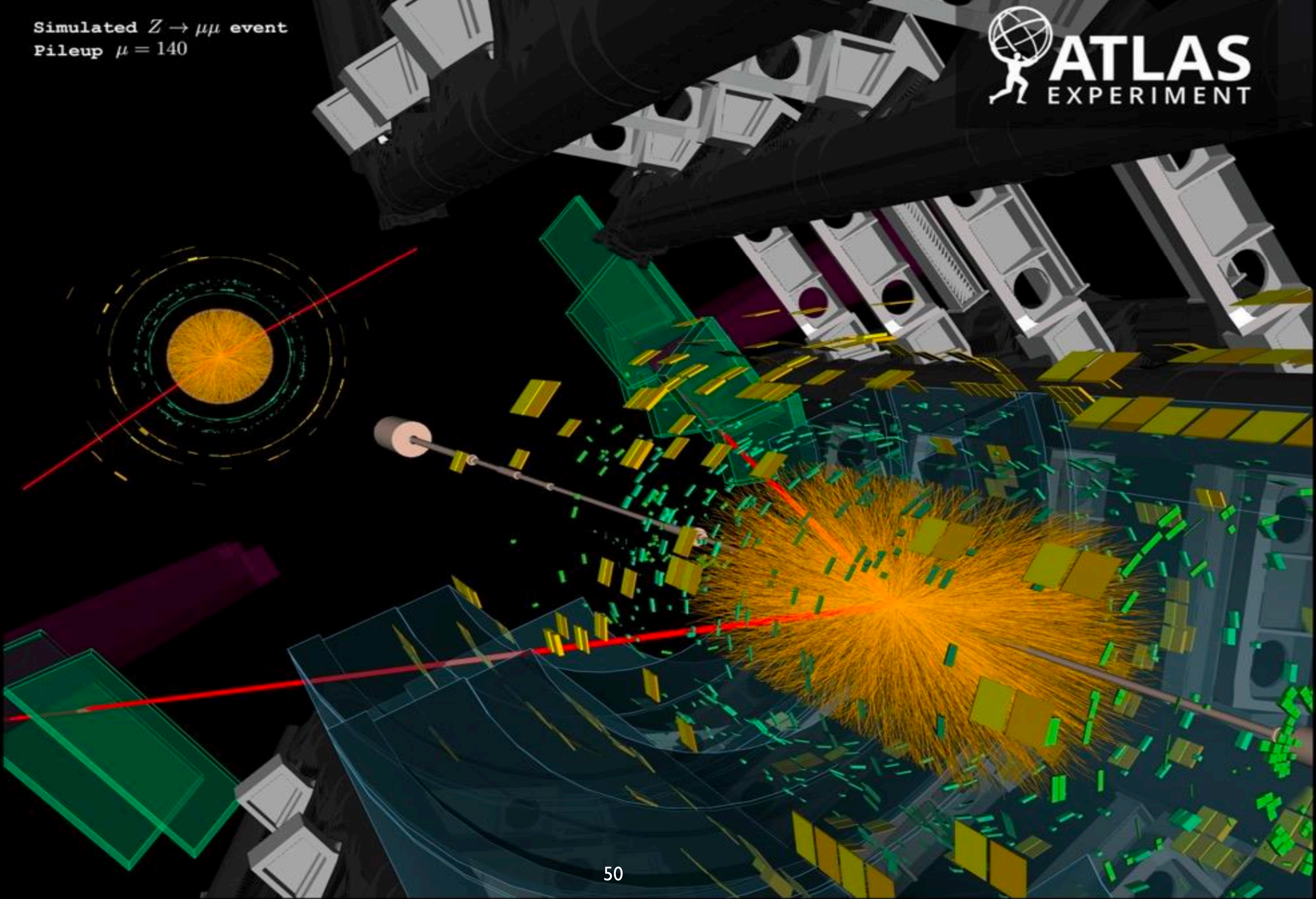
Detectors upgrades



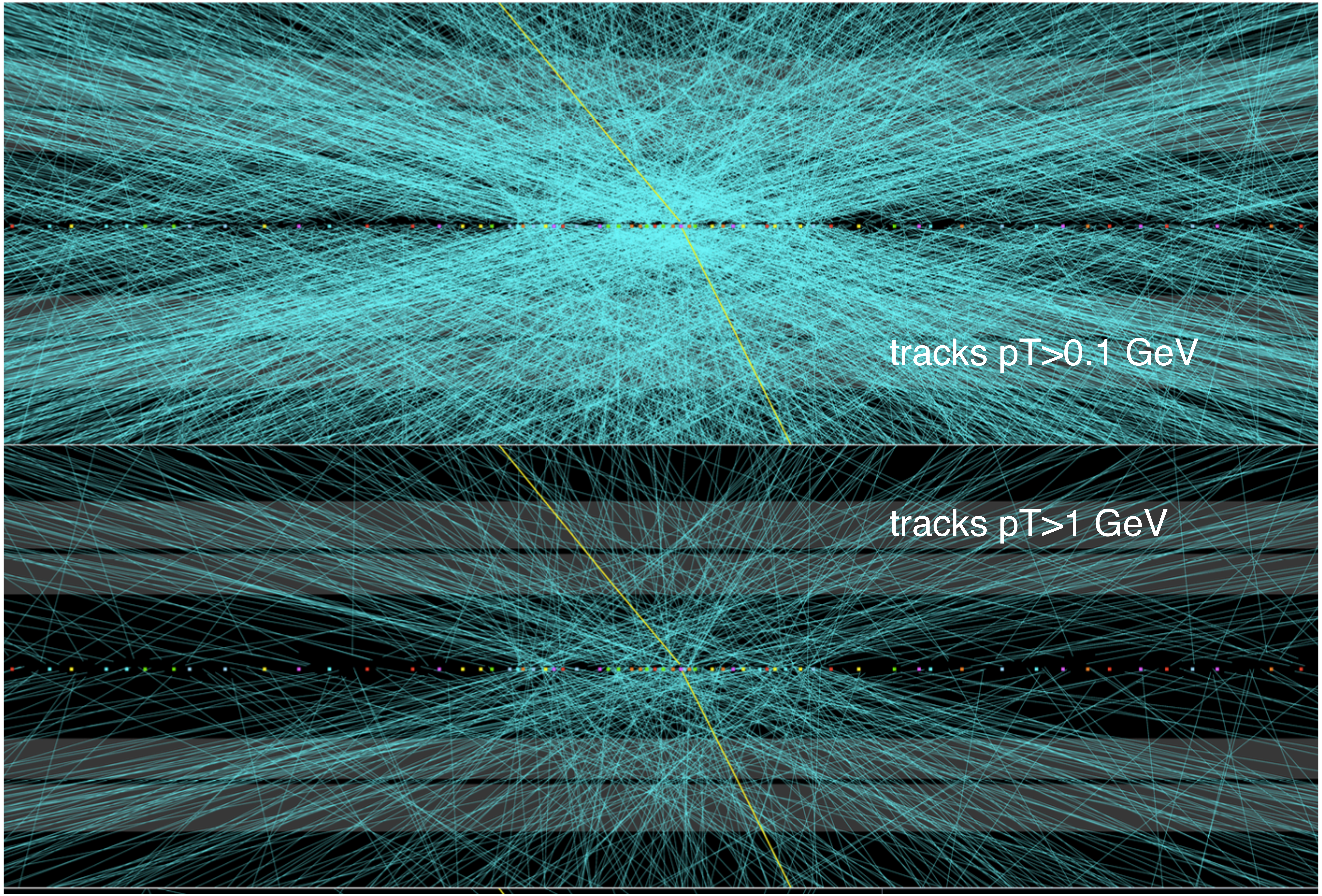
# of interactions per beam crossing = pile-up increasing with Luminosity




Simulated $Z \to \mu\mu$ event
Pileup $\mu = 50$
ATLAS
EXPERIMENT


Simulated $Z \to \mu\mu$ event
Pileup $\mu = 140$
ATLAS
EXPERIMENT

Pile-up



1)Z->μμ event with 65 interaction vertices

LHC / HL-LHC Plan

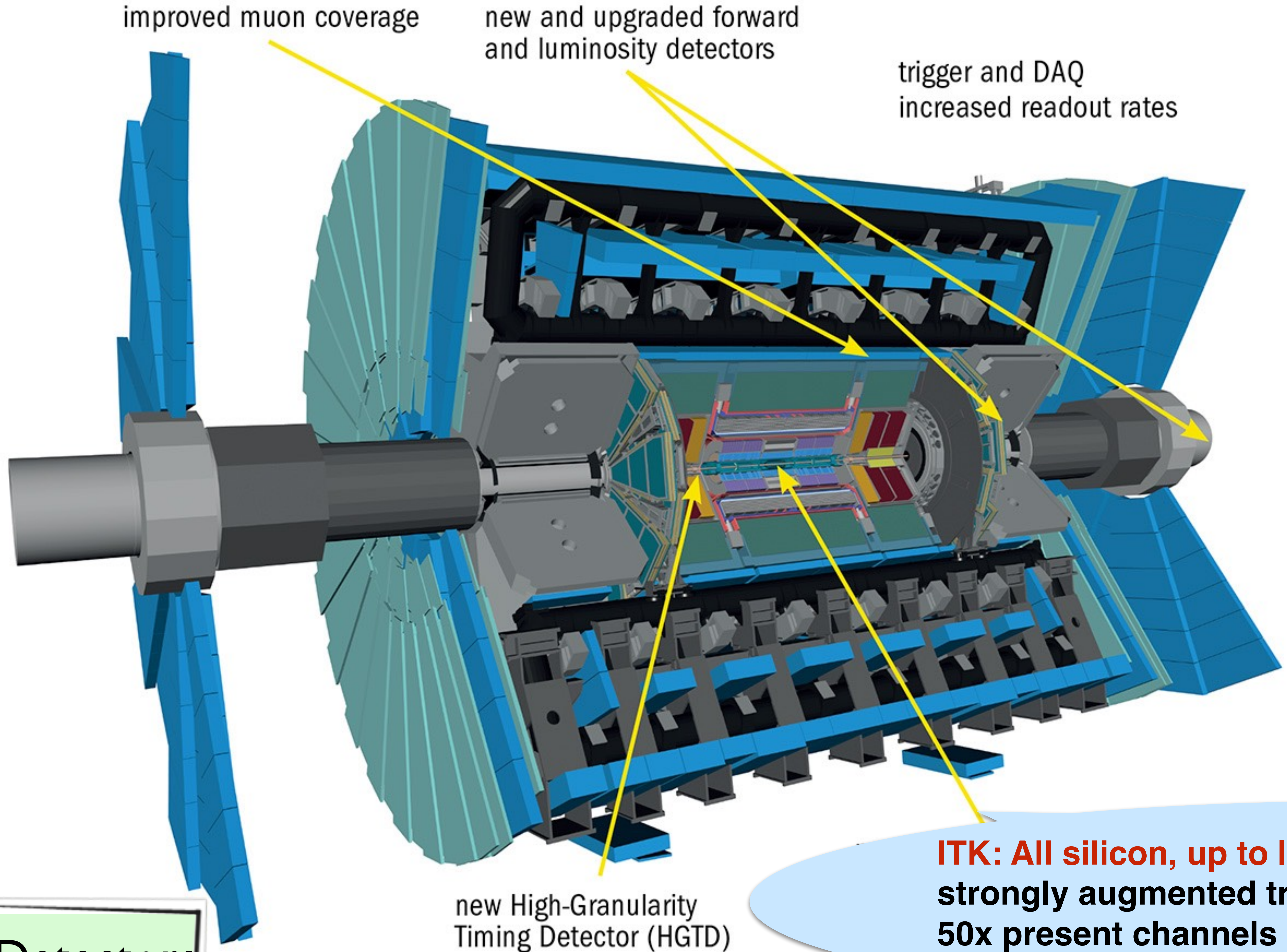
HL-LHC upgrade: The challenges

Unprecedented opportunities come with great challenges

- HL-LHC promises to provide 15 times the present data sample
- instantaneous luminosity a factor of 5-7 larger than LHC nominal value.
- Up to 200 p-p interactions per bunch crossing !

ATLAS GOAL: at least as good / better performance (depending on feature) than the current detector in the much harsher HL-LHC environment

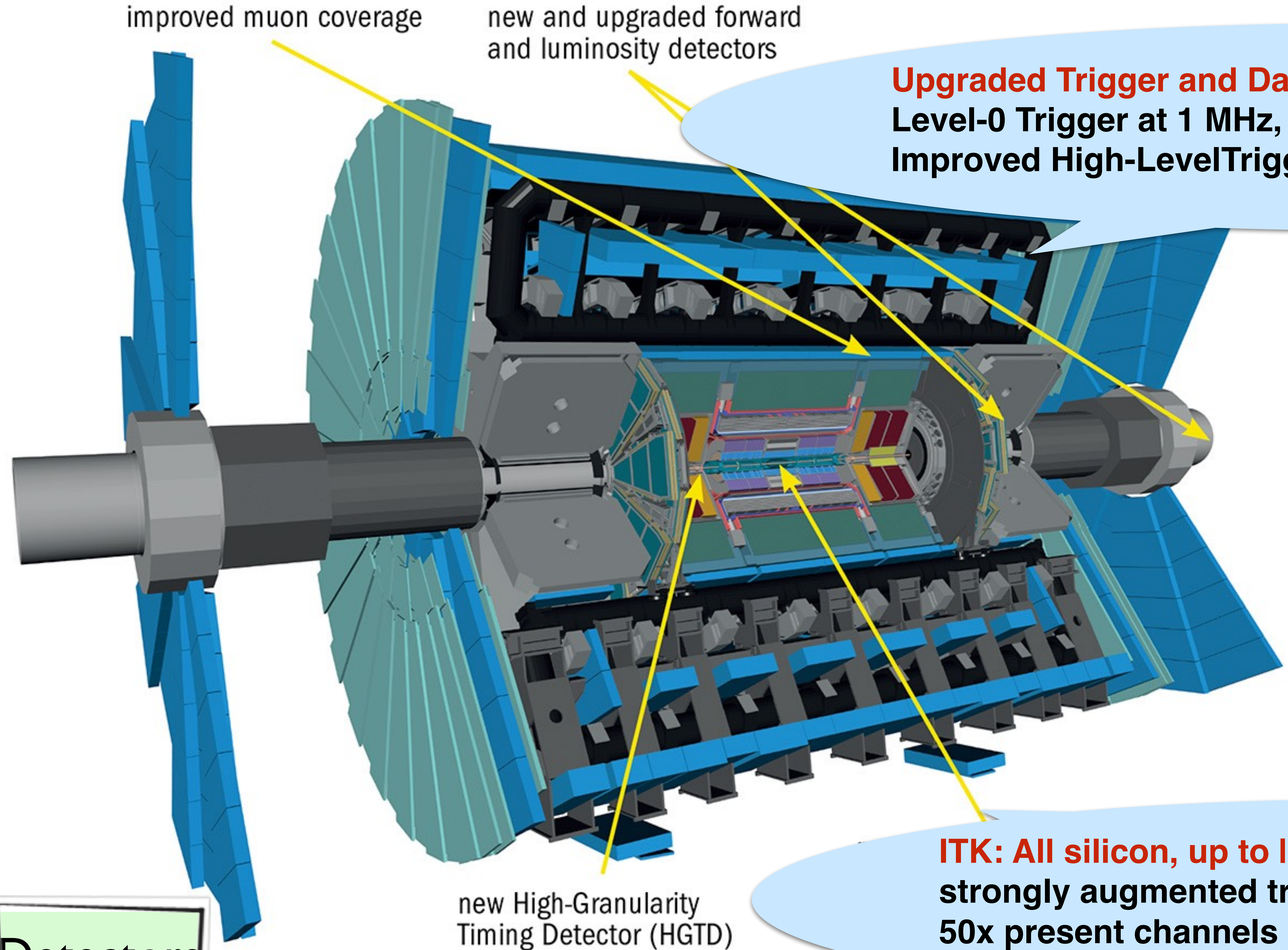
HL-LHC upgrade



ITK: All silicon, up to $|\eta| = 4$
strongly augmented tracking acceptance,
50x present channels → to cope with high occupancy

Detectors upgrades

HL-LHC upgrade

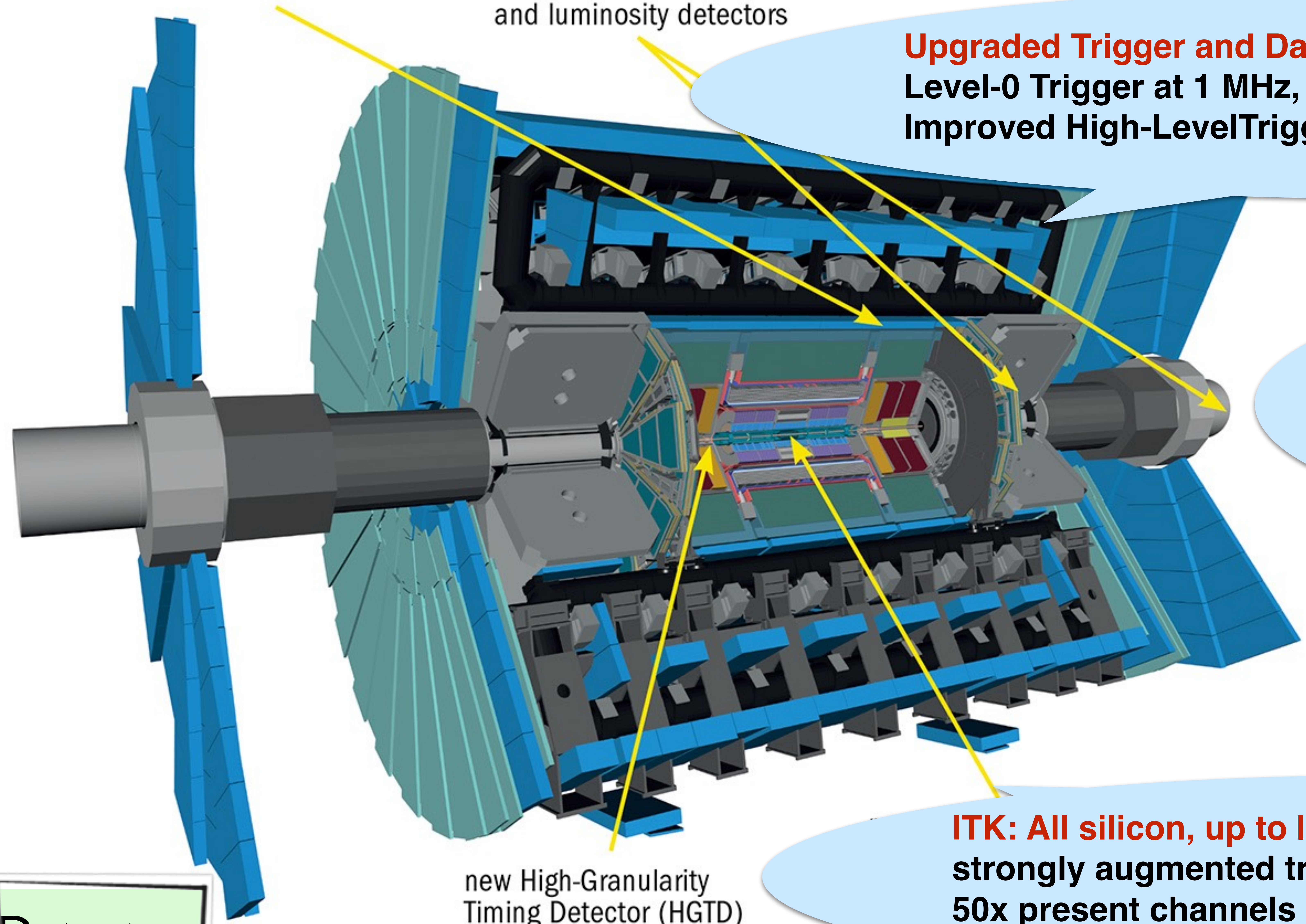


Upgraded Trigger and Data Acquisition system
Level-0 Trigger at 1 MHz, Full-feature global trigger
Improved High-LevelTrigger (150 kHz full-scan tracking)

ITK: All silicon, up to |η| = 4
strongly augmented tracking acceptance,
50x present channels → to cope with high occupancy

Detectors upgrades

HL-LHC upgrade



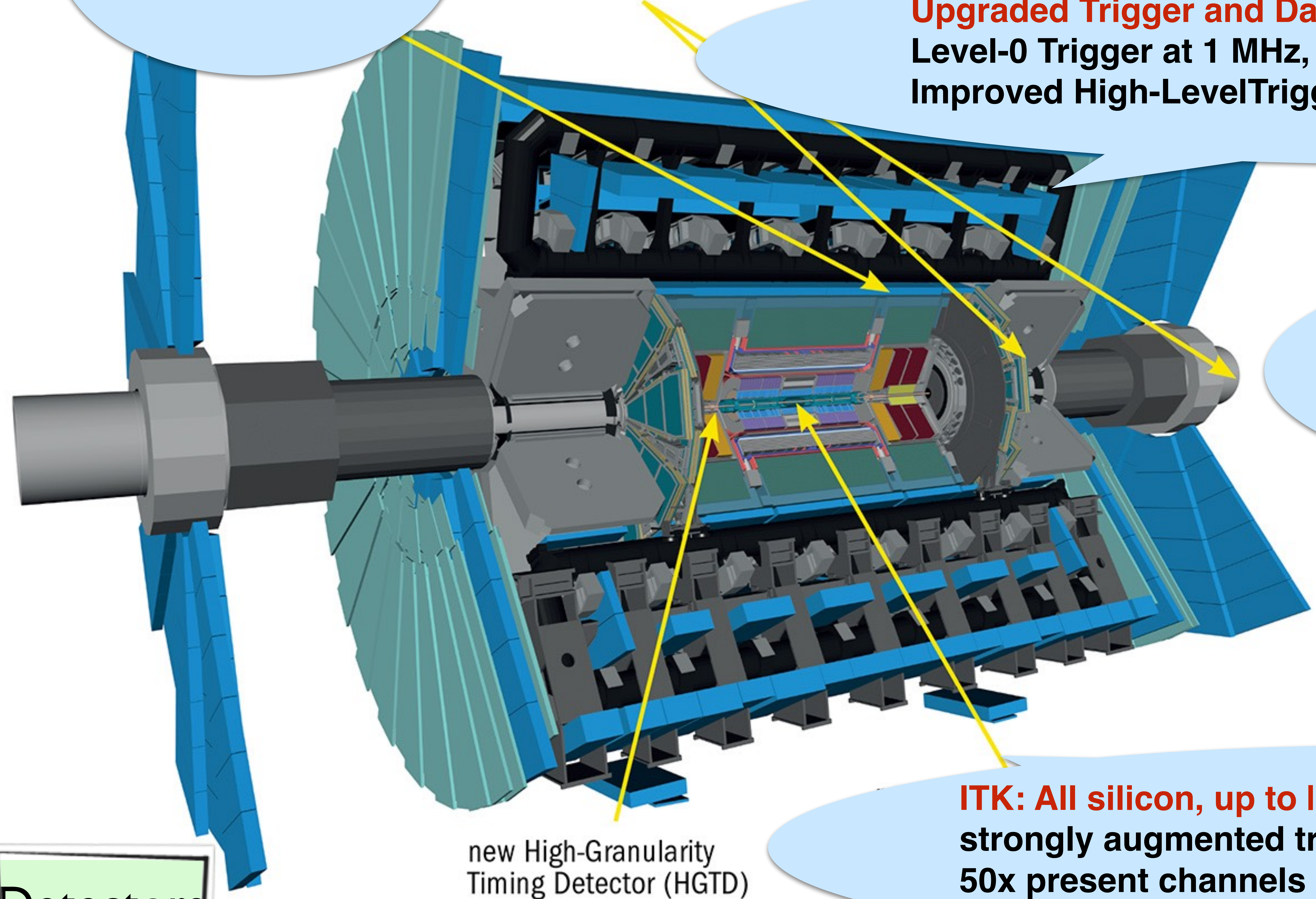
Upgraded Trigger and Data Acquisition system
Level-0 Trigger at 1 MHz, Full-feature global trigger
Improved High-LevelTrigger (150 kHz full-scan tracking)

Electronics Upgrades
- **LAr Calorimeter**
- **Tile Calorimeter**
- **Muon system**

ITK: All silicon, up to |η| = 4
strongly augmented tracking acceptance,
50x present channels → to cope with high occupancy

Detectors upgrades

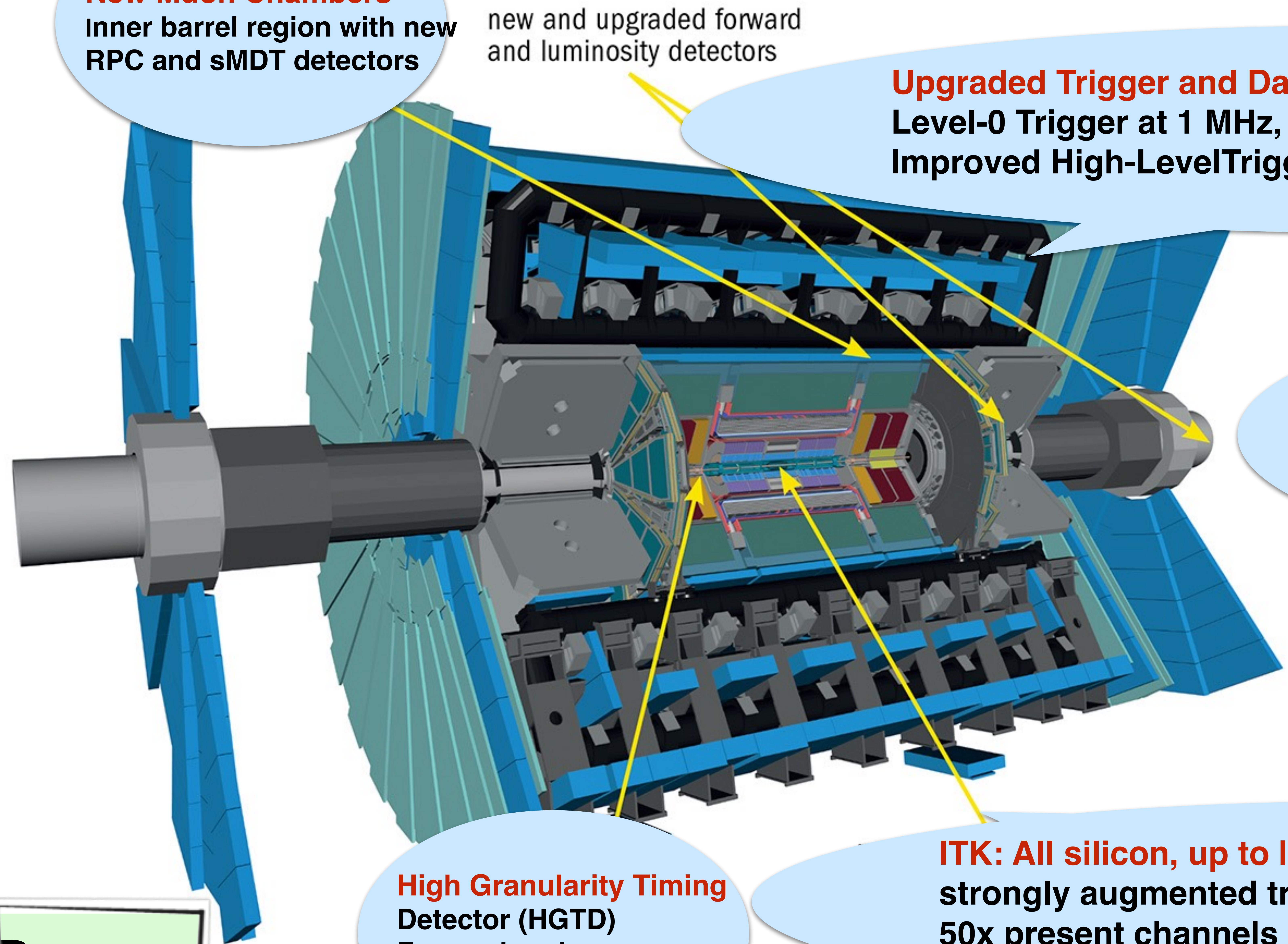
HL-LHC upgrade



Detectors upgrades

HL-LHC upgrade

New Muon Chambers
Inner barrel region with new RPC and sMDT detectors



Upgraded Trigger and Data Acquisition system
Level-0 Trigger at 1 MHz, Full-feature global trigger
Improved High-LevelTrigger (150 kHz full-scan tracking)

Electronics Upgrades
- **LAr Calorimeter**
- **Tile Calorimeter**
- **Muon system**

High Granularity Timing Detector (HGTD)
Forward region
(2.4 < lηl < 4.0) to reduce Pile-up

ITK: All silicon, up to lηl = 4
strongly augmented tracking acceptance,
50x present channels → to cope with high occupancy

Detectors upgrades

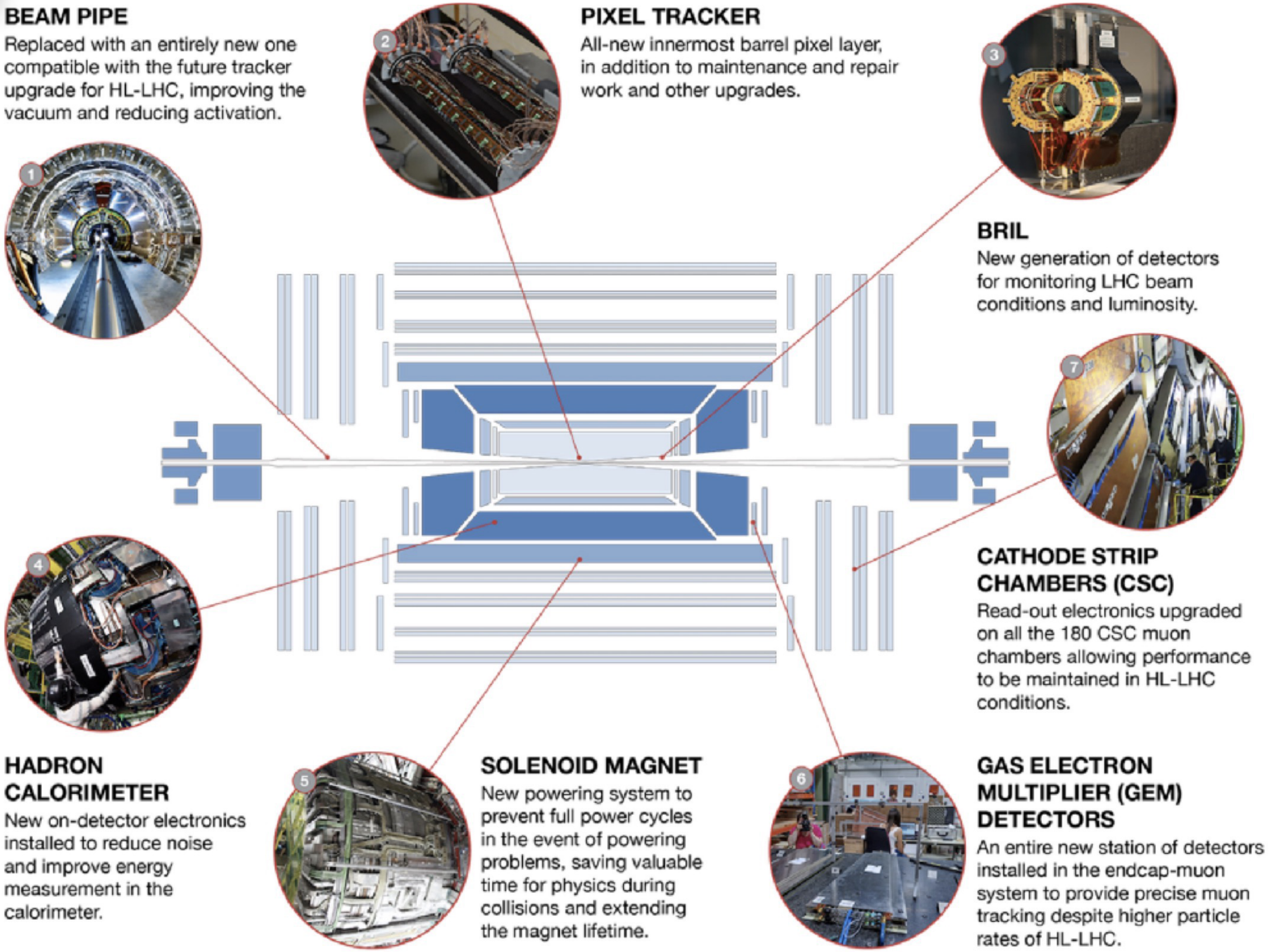
CMS upgrade

During Long Shutdown 2 (2018-2022), CMS completed the Phase 1 upgrades and started the Phase 2 upgrades. Some highlights :

- Phase 1: HCAL barrel readout, new barrel inner pixel (layer 1)

- Phase 2: First of GEM chambers installed, upgraded CSC electronics for HL-LHC, new beam pipe.

- GPU at HLT and transitioned to a hybrid CPU + GPU in trigger software (HLT nodes) : A Graphics Processing Unit (GPU) is a programmable architecture, offering large number of parallel independent streams of instructions, originally designed for image processing. Accelerate online processing



Detectors upgrades

But in the meantime Run 3 is ongoing

Where can we expect to improve with Run3?

1) more luminosity, and higher cross-section

2) experimental techniques are improving fast: reconstruction improvement have been key for important measurements, I will show you a couple of important examples for Run 3 and discuss more in the following

3) advanced analysis techniques

4) better theoretical calculations and PDFs

ATLAS EXPERIMENT

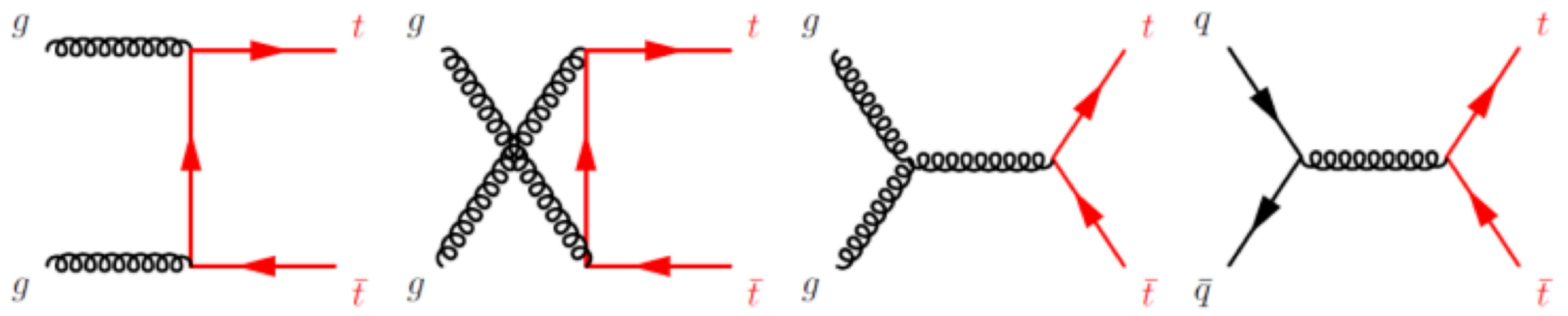
top pair production event @13.6 TeV Run3

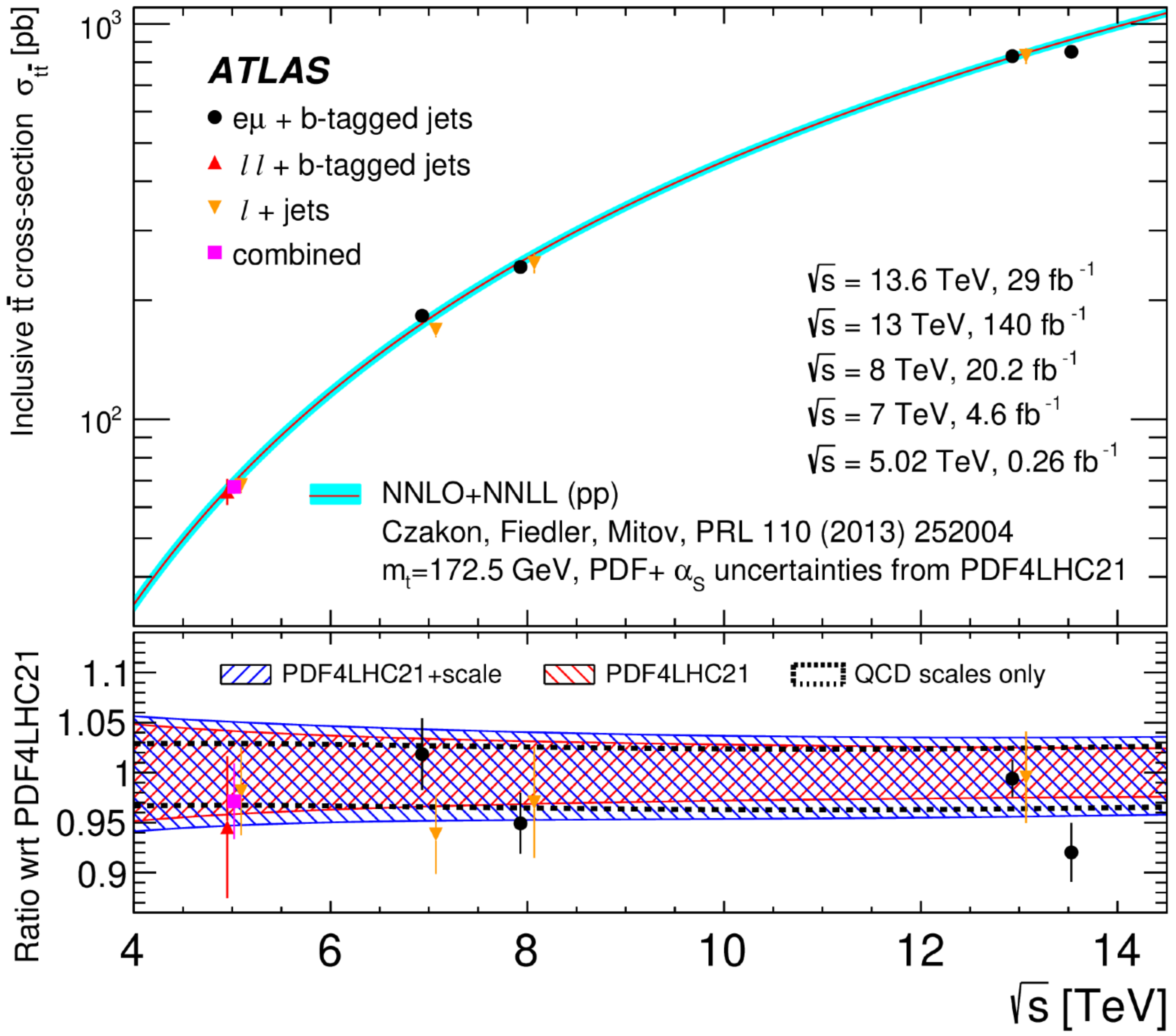
top quark decays in Wb ~100%

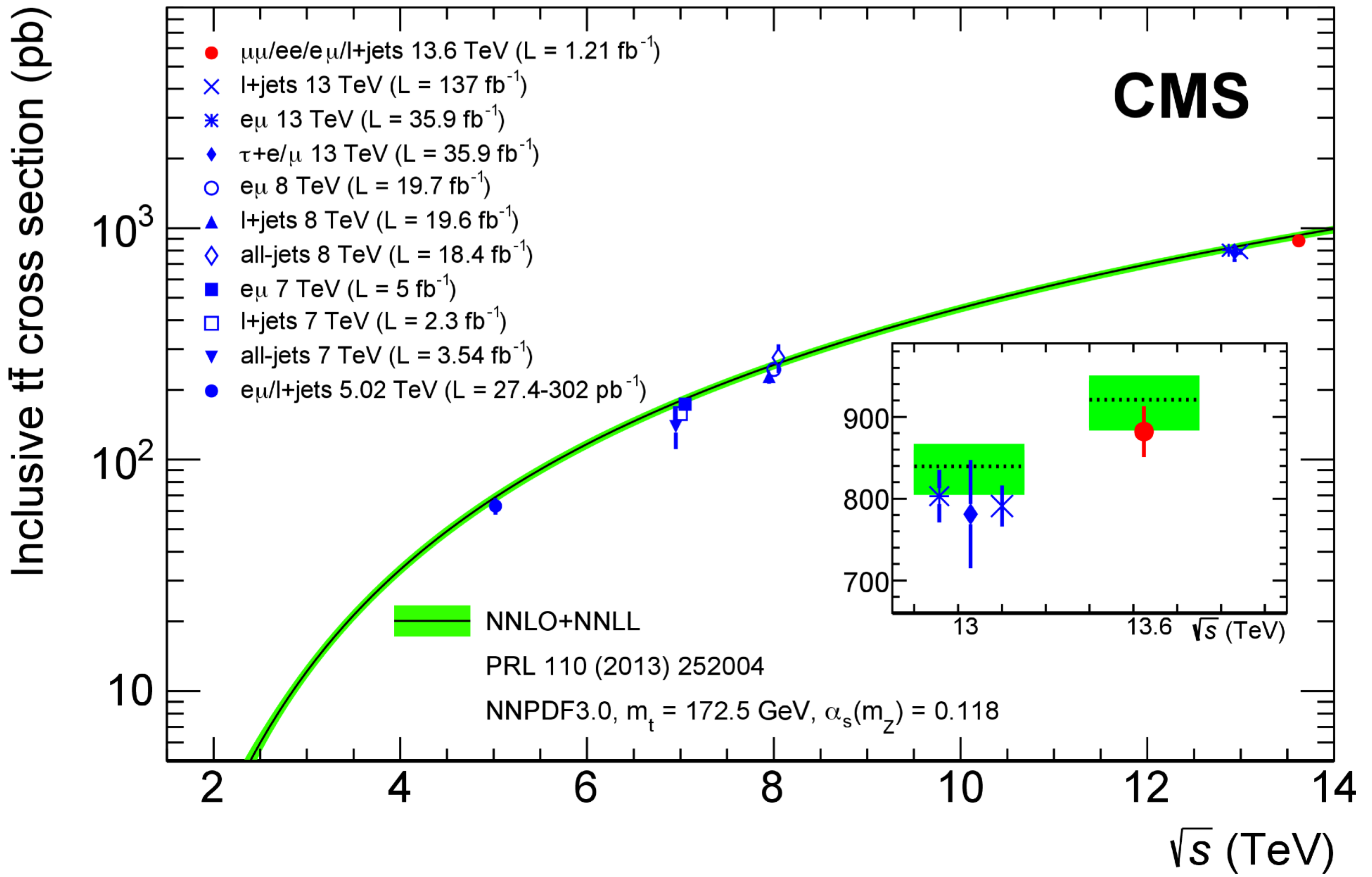
Run3

Run 3 first measurements: top production

Cross-sections are expected to be slightly higher at 13.6 TeV, for example we expect a 12% increase of the ttbar x-section at 13.6 TeV



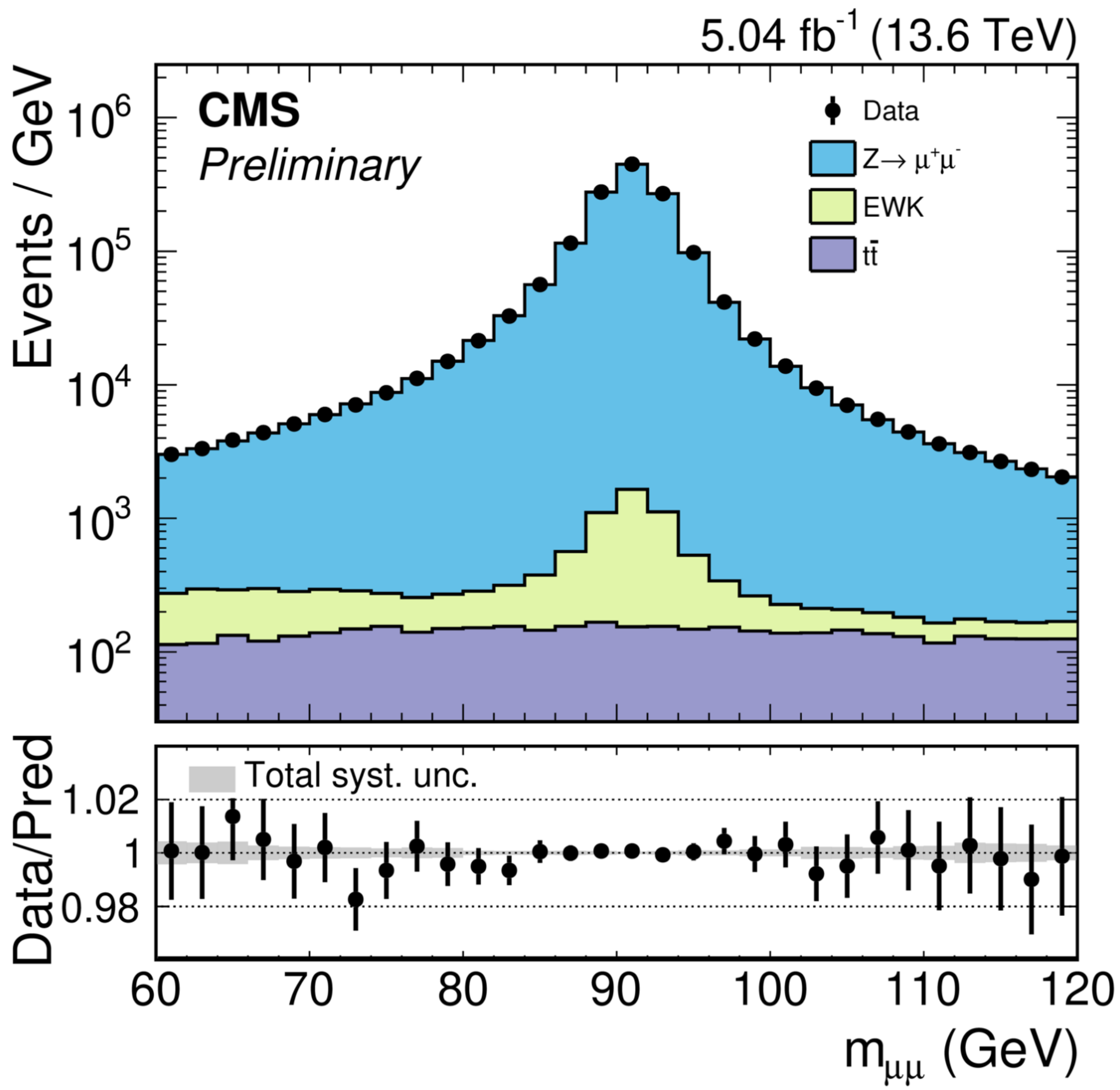


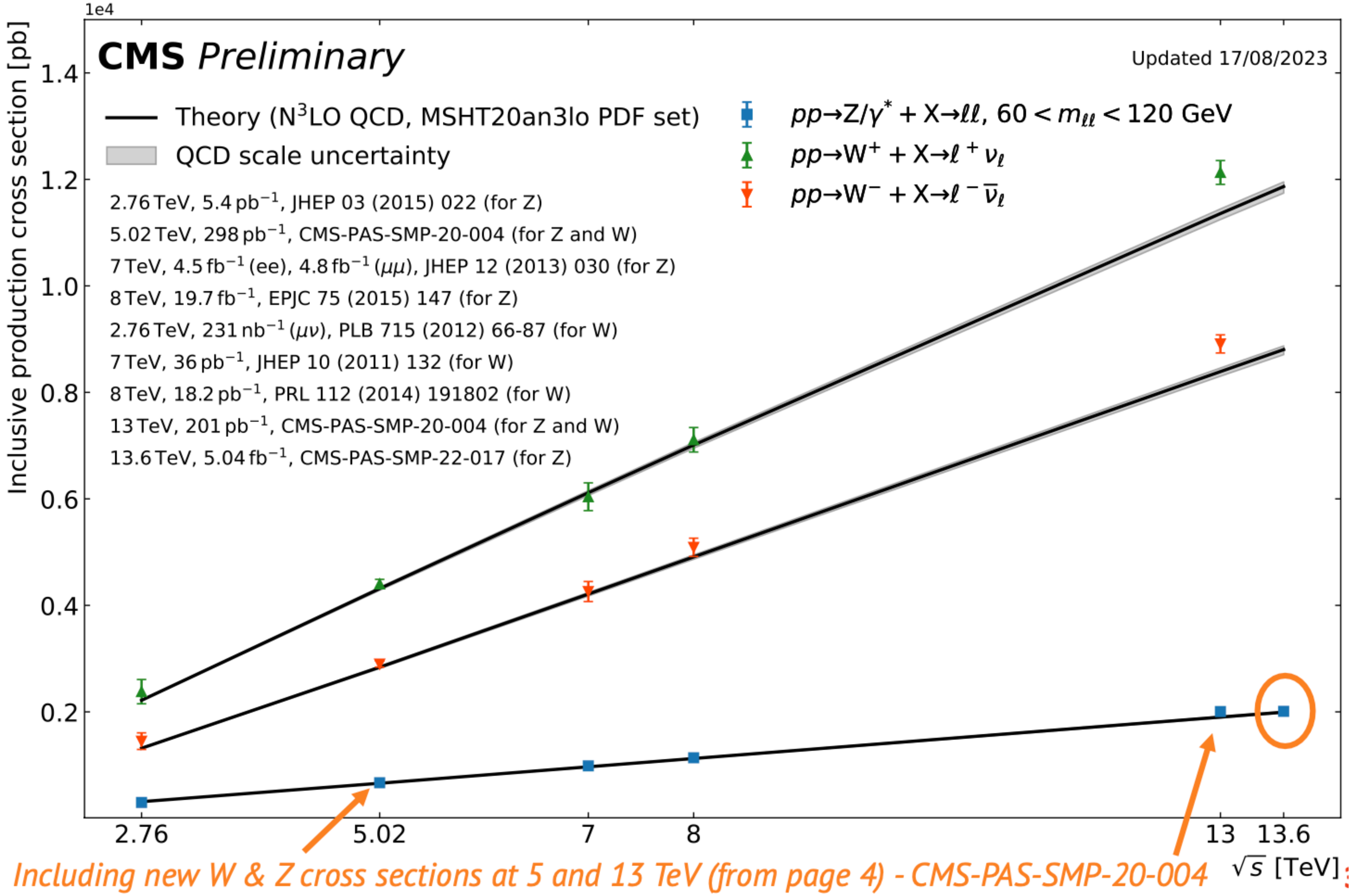


Run 3 first measurements: Z boson

Run3

Z into muon pairs





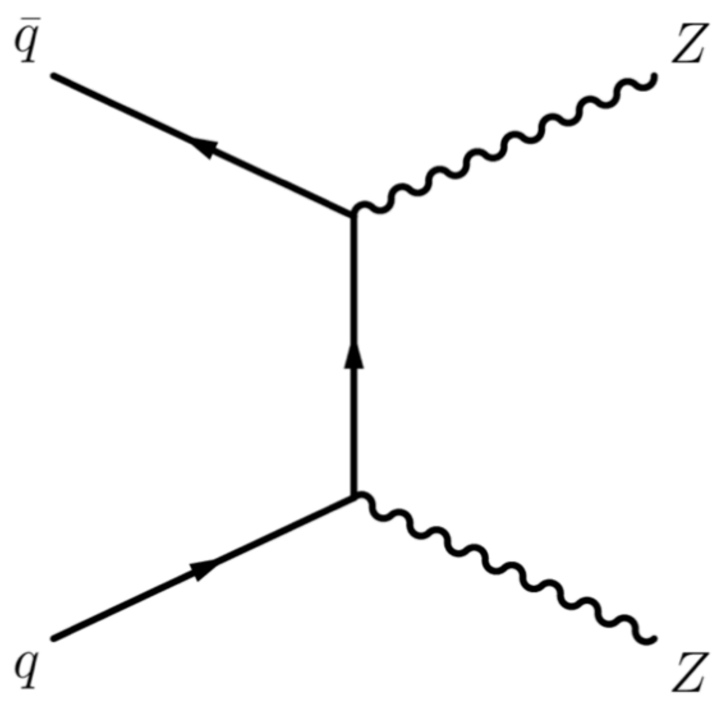
Run3

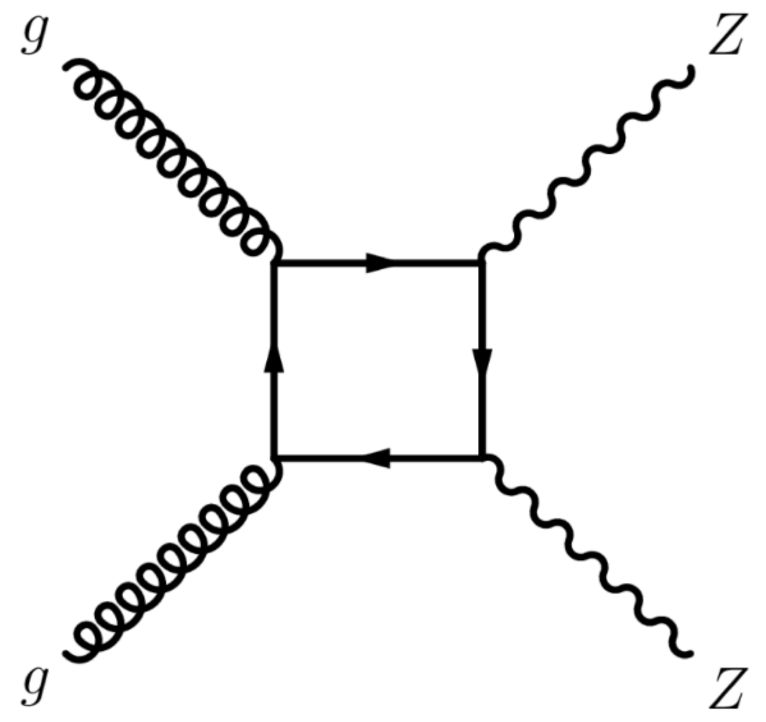
ZZ on-shell production Run3 @13.6 TeV

ATLAS-CONF-2023-062

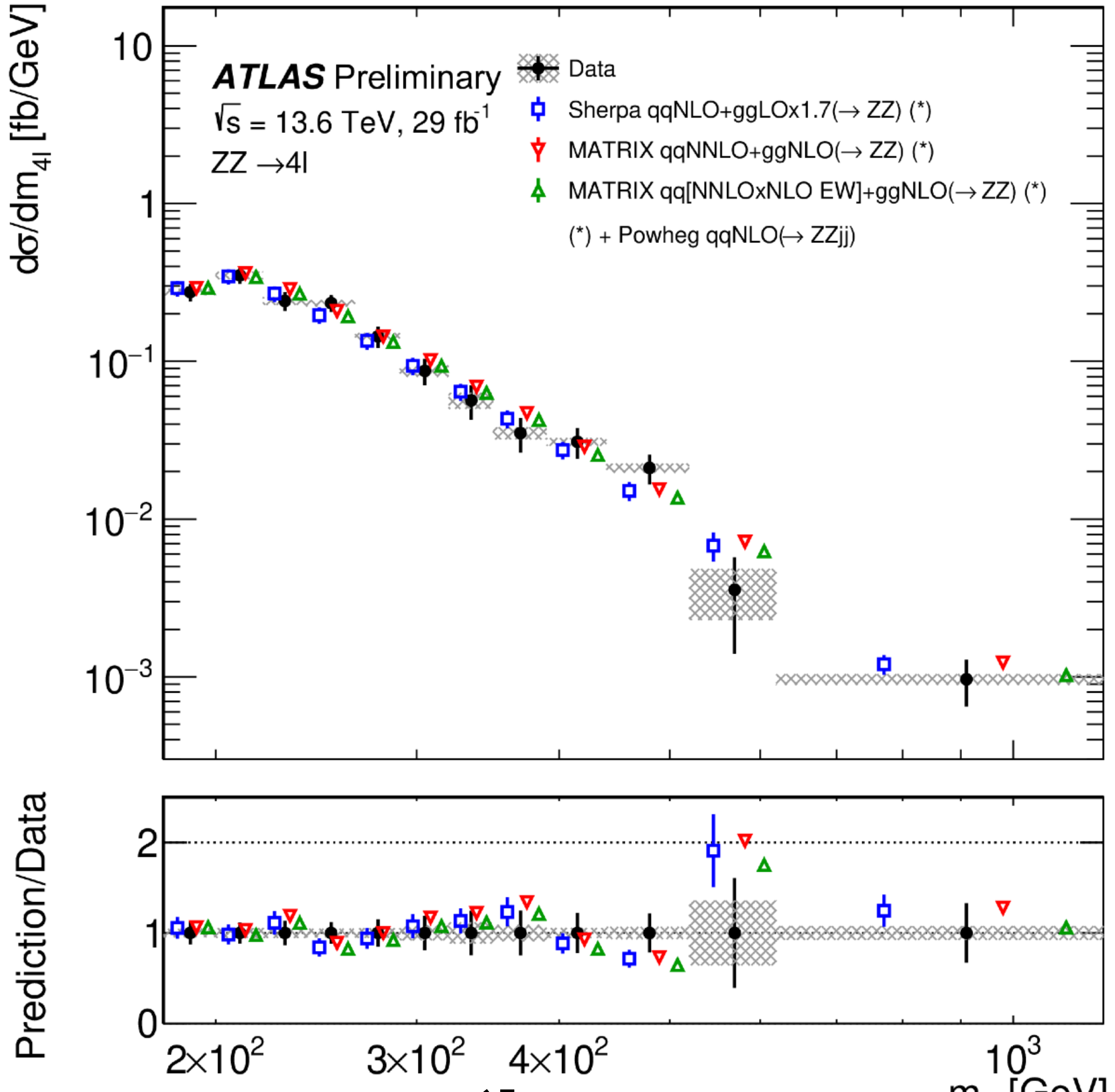
	Measurement	MC prediction	MATRIX prediction
Fiducial	$36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})$ fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.6 fb
Total	$16.9 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.4 pb

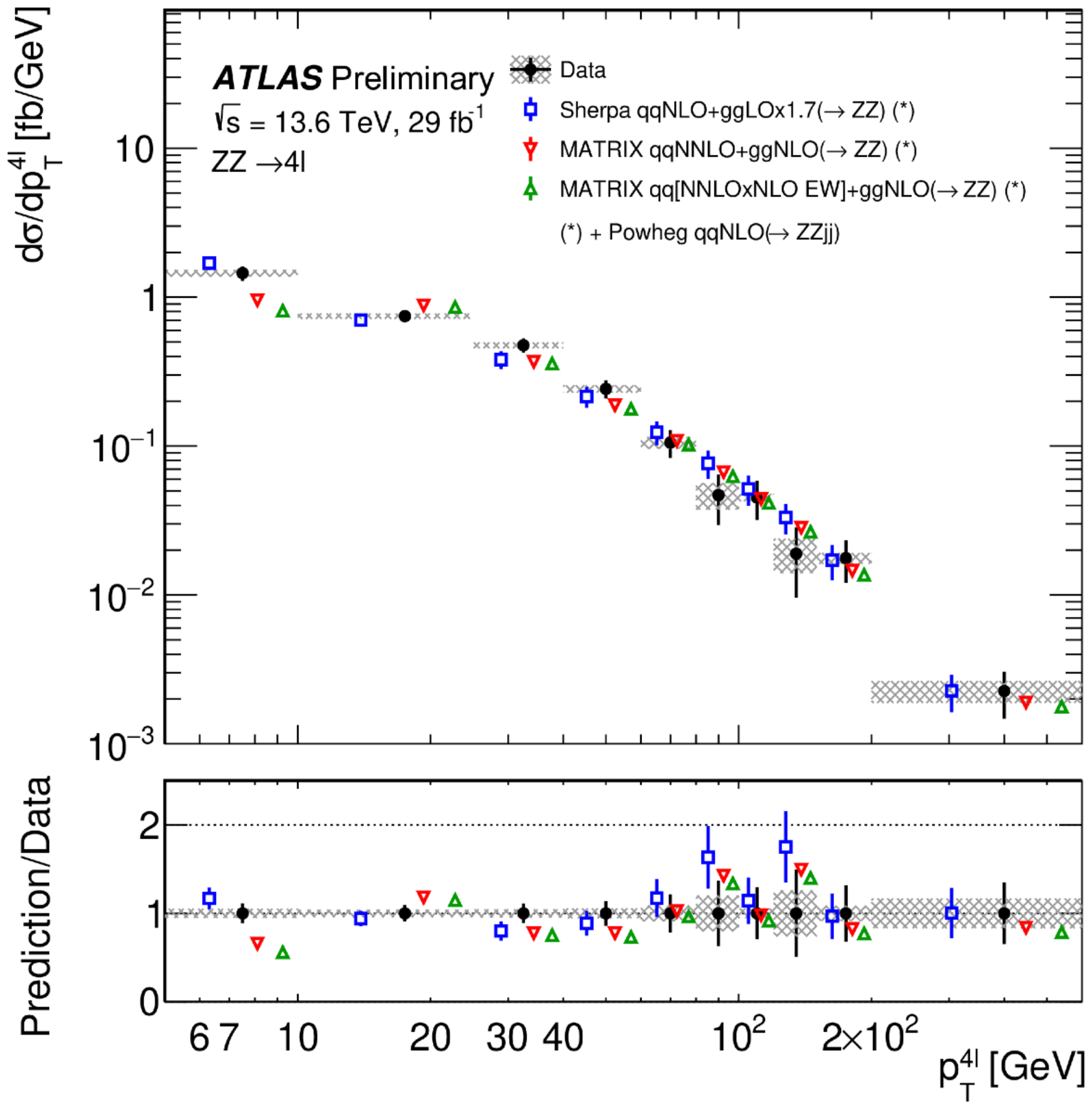
- Inclusive & differential measurements
- Compares to state-of-art MC
- Well in agreement with SM predictions



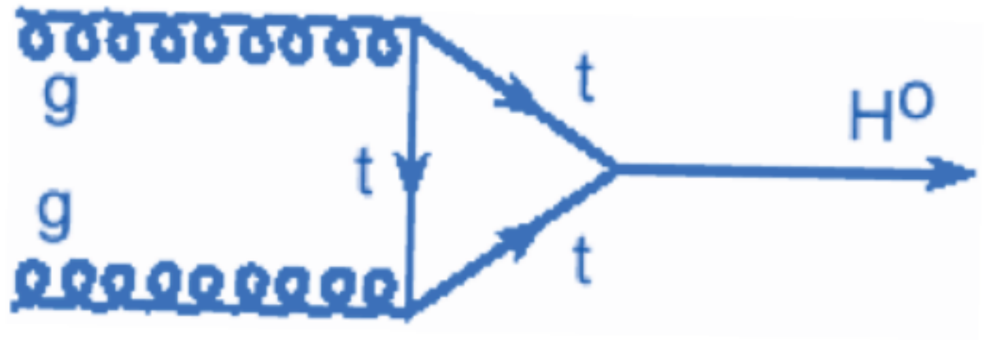


$q\bar{q} \rightarrow ZZ$, $gg \rightarrow ZZ$, and EW $qq \rightarrow ZZ + 2j$

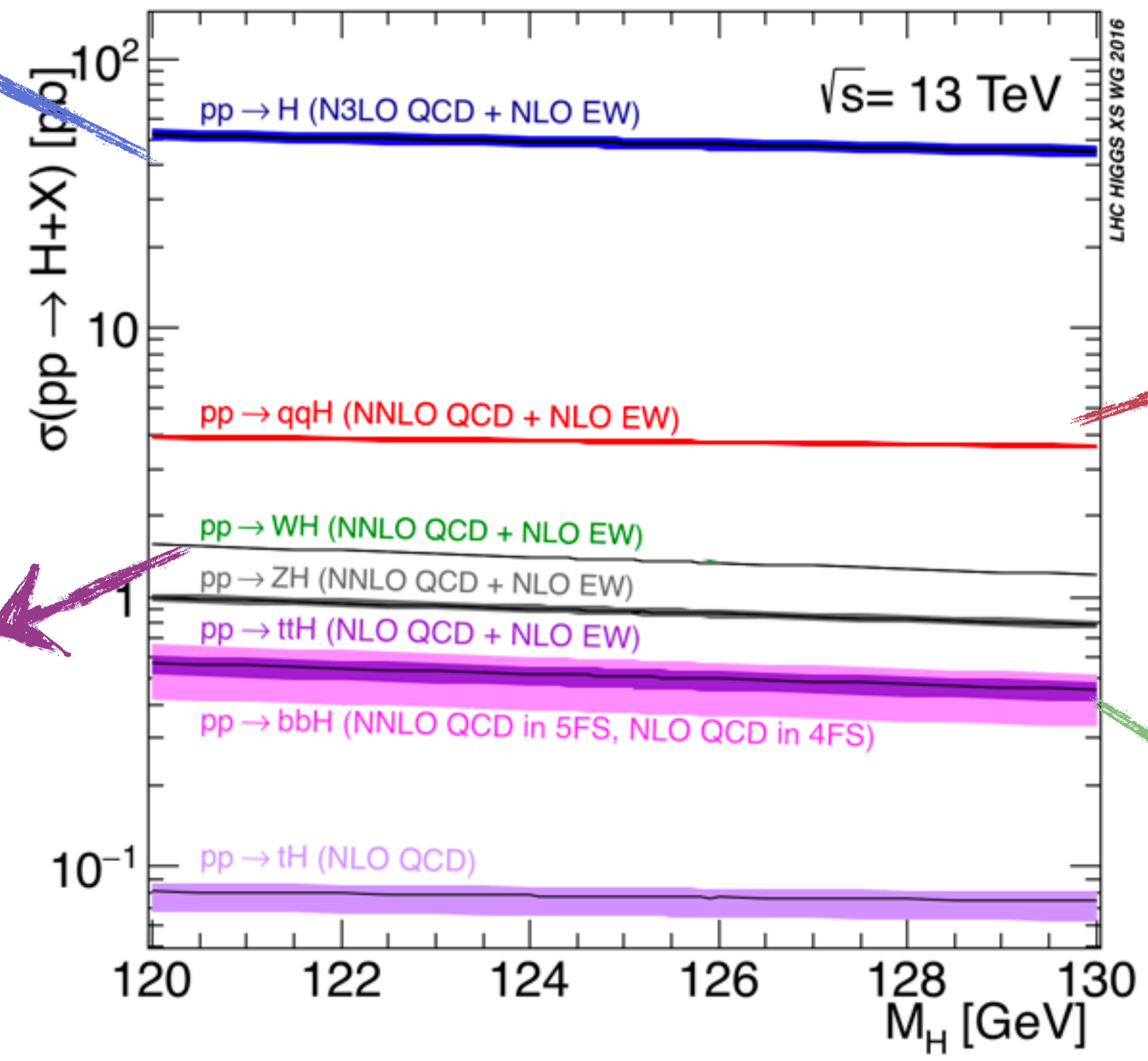




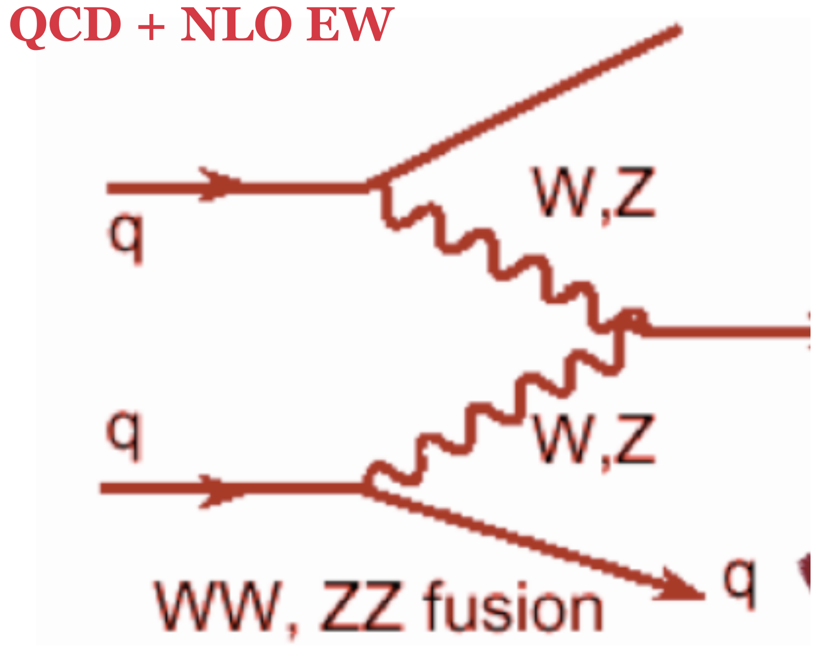
Higgs production



ggF: NNNLO+NNLL QCD
+ NLO EW

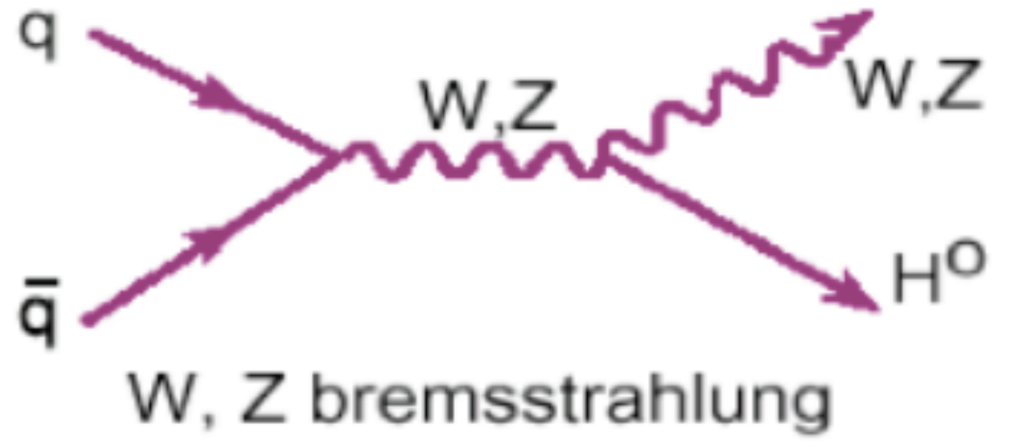


NNLO QCD + NLO EW

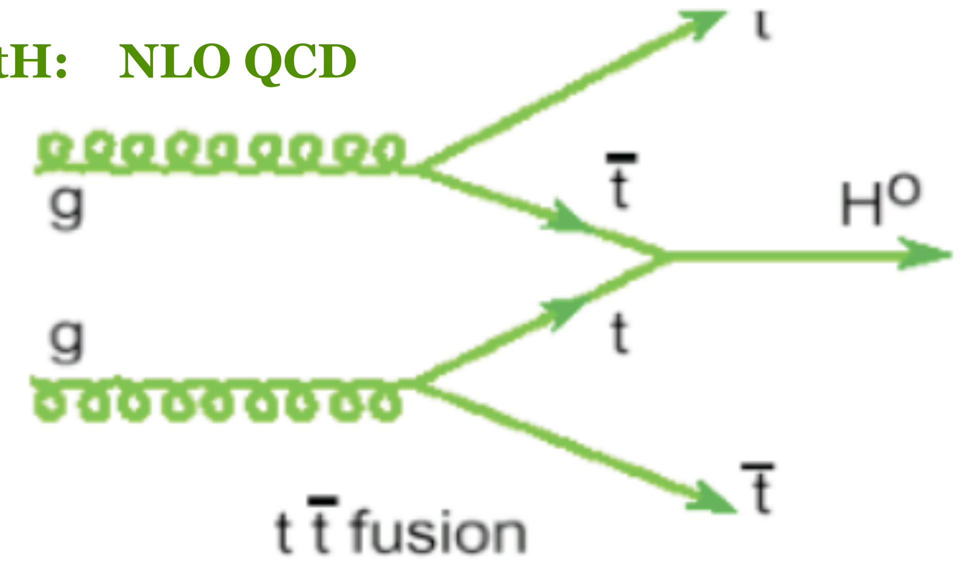


WH: NNLO QCD + NLO EW

ZH: NNLO QCD + NLO EW



ttH: NLO QCD

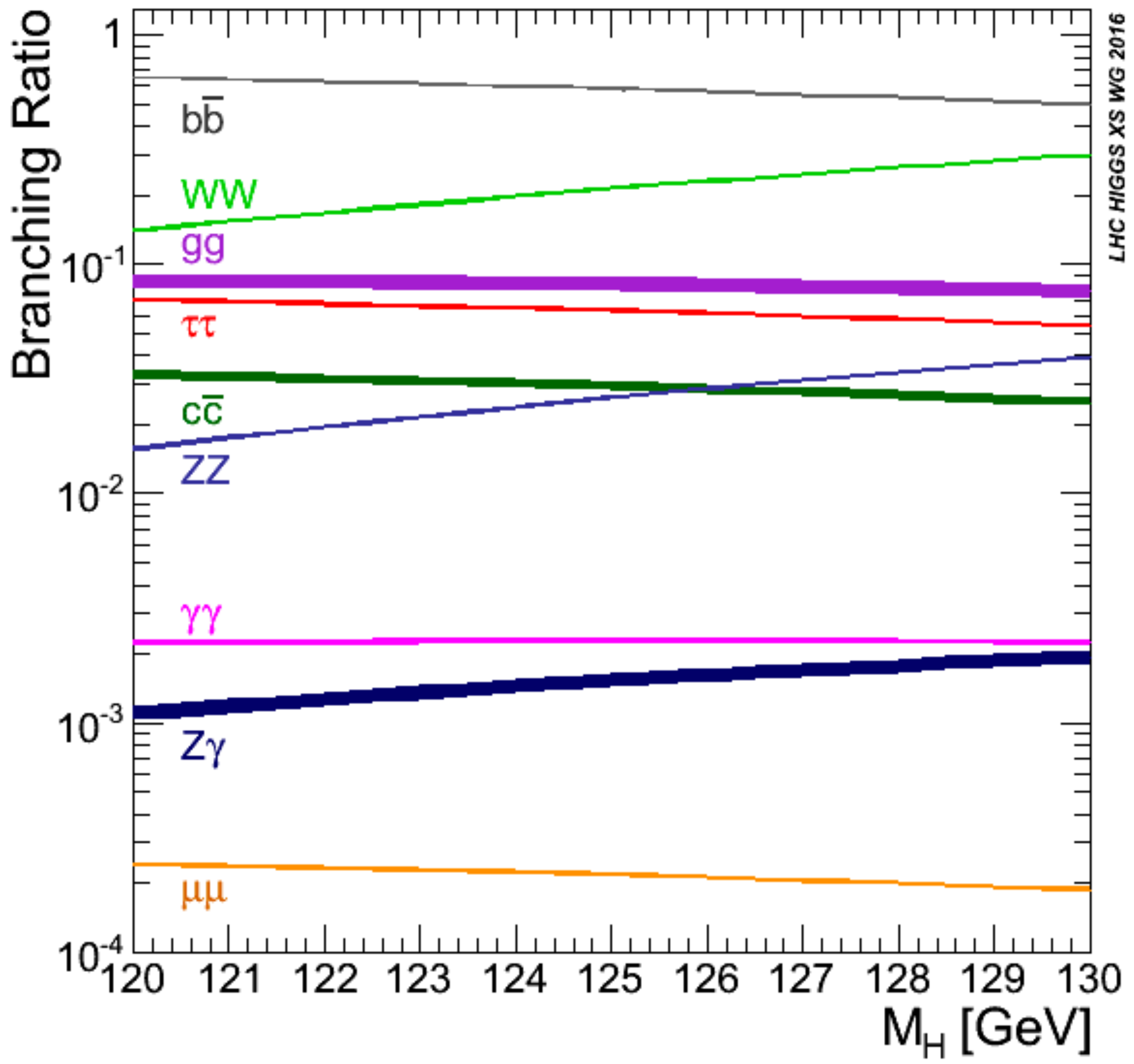


Increase in run 3 @ 13.6 TeV

ggF	+7.5%
VBF	+7.9%
WH	+6.2%
ZH	+6.9%
ttH	+12.6%
HH	+11%

Higgs

Higgs decay

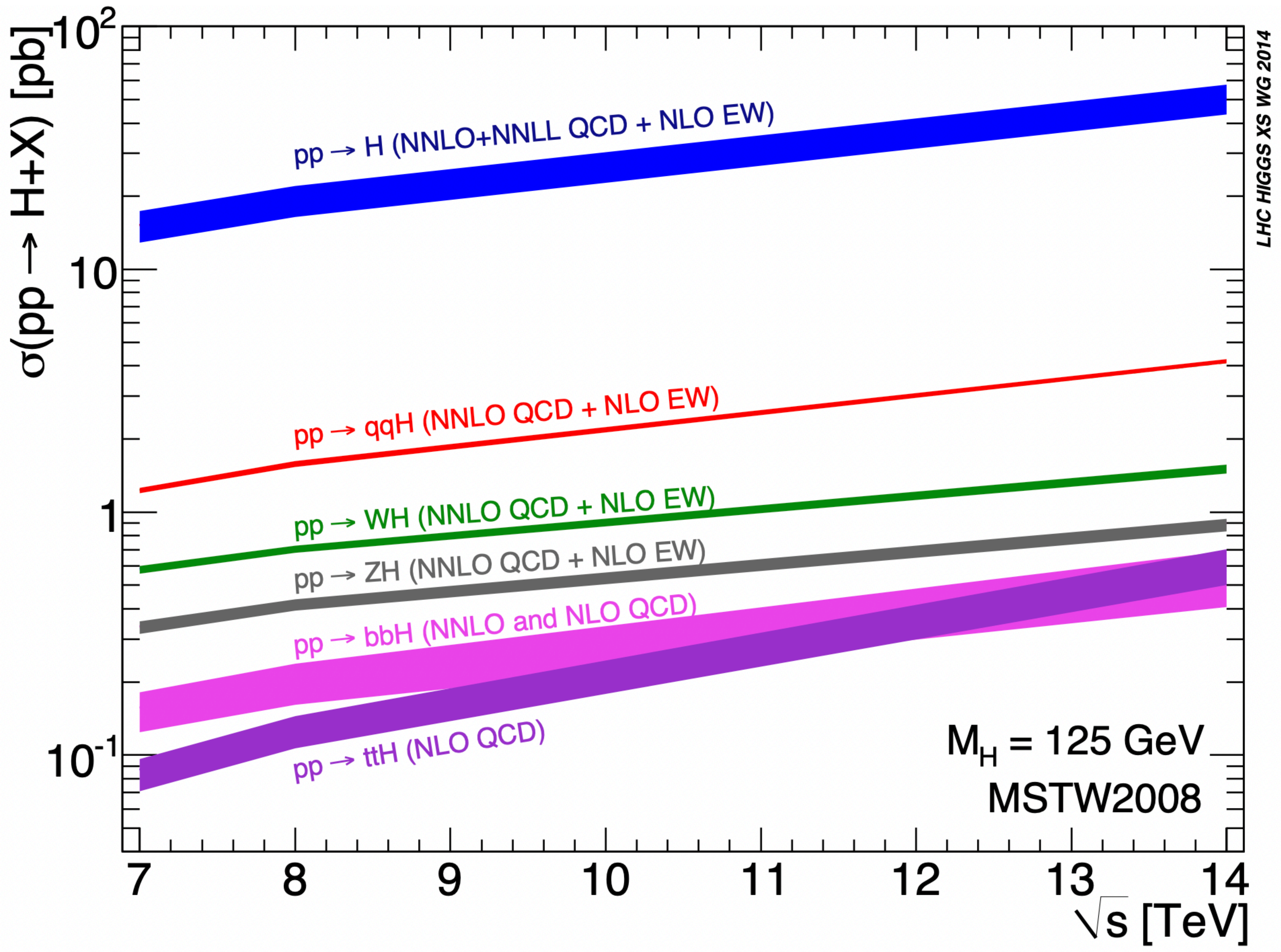


	BR(%)
bb	57
WW	22
$\tau\tau$	6.2
ZZ	2.8
$\gamma\gamma$	0.23
$Z\gamma$	0.15

BR= decay Branching Ratio

Run3

Run 3 Higgs x-sections

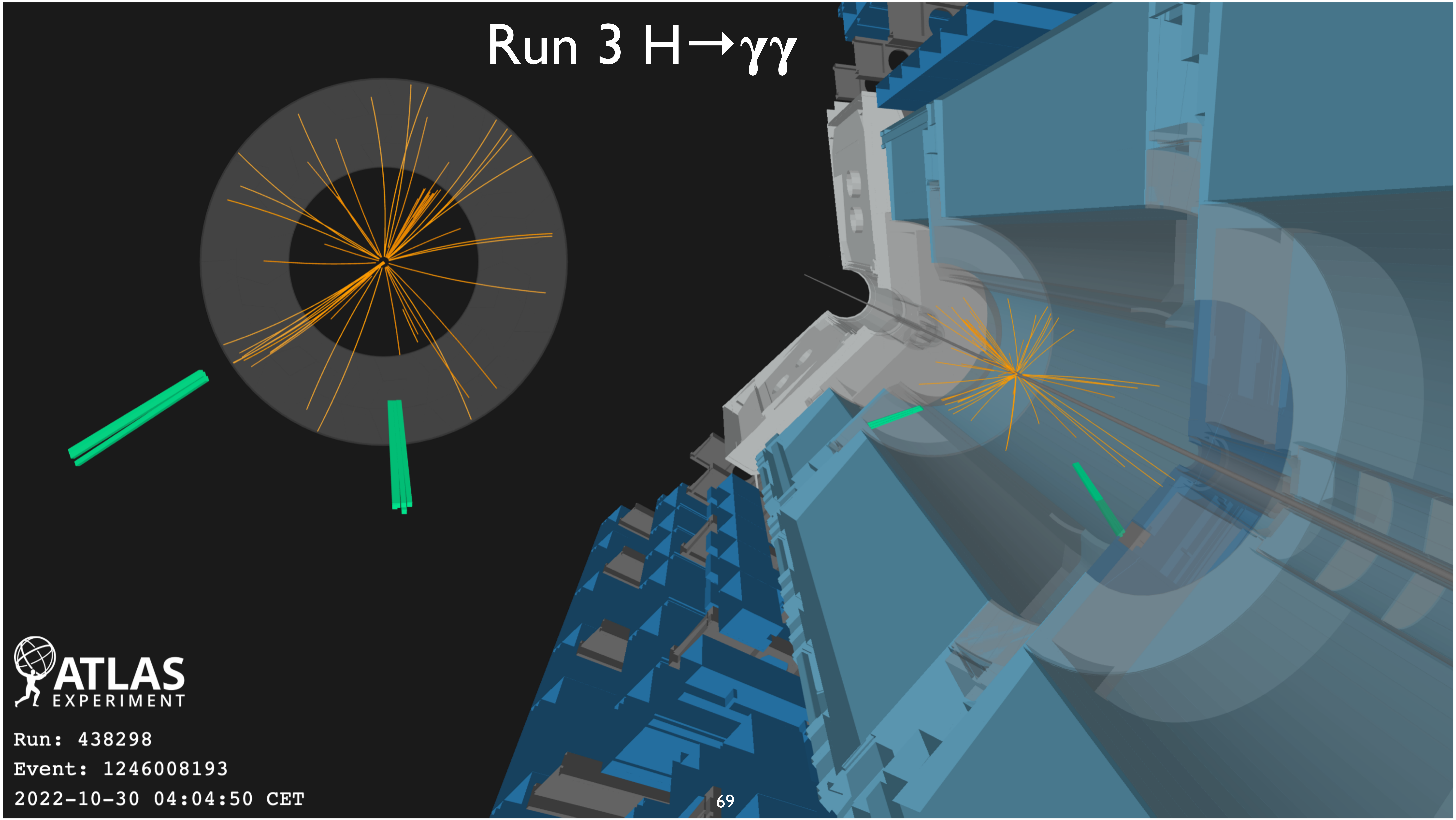


Increase by

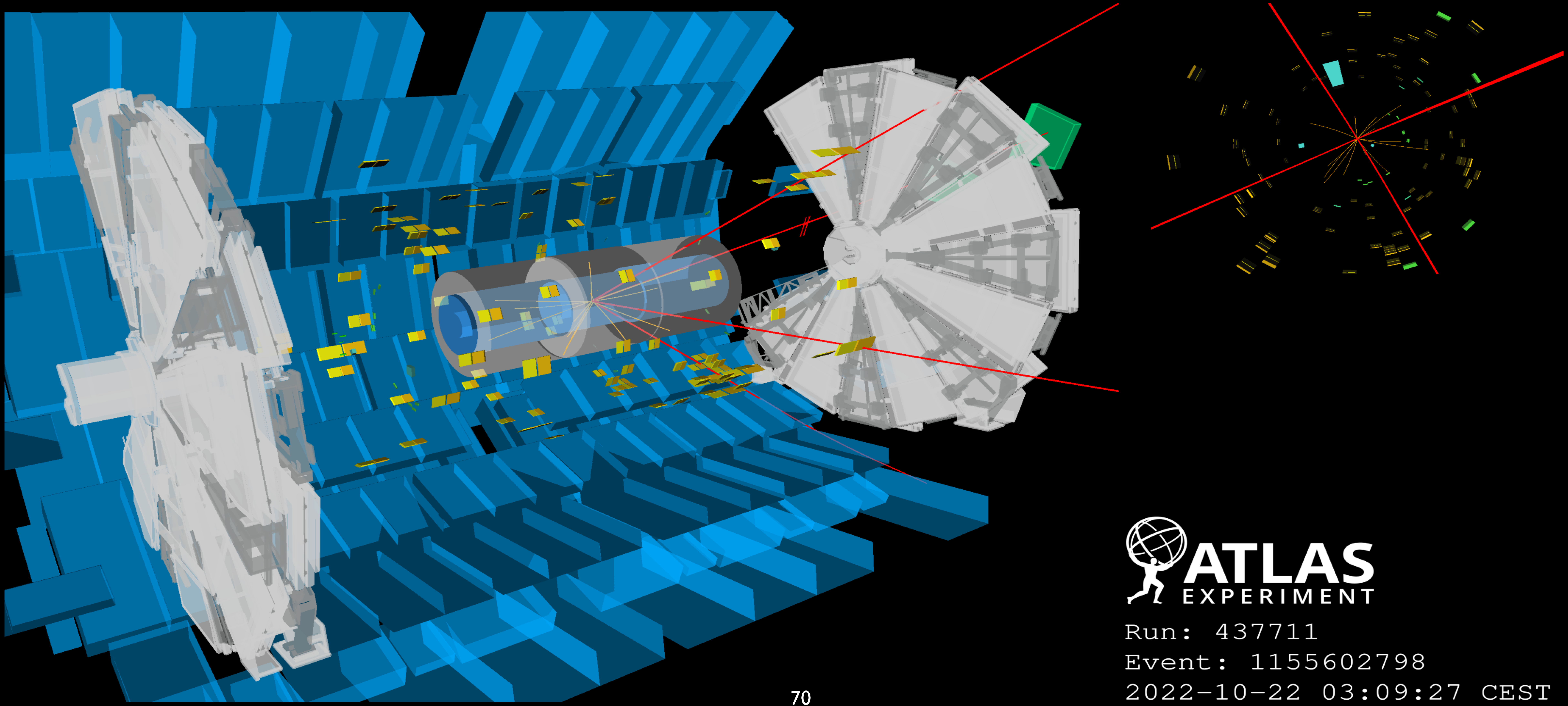
7% for ggH, 11% for HH and

13% for ttH

Run 3 $H \rightarrow \gamma\gamma$

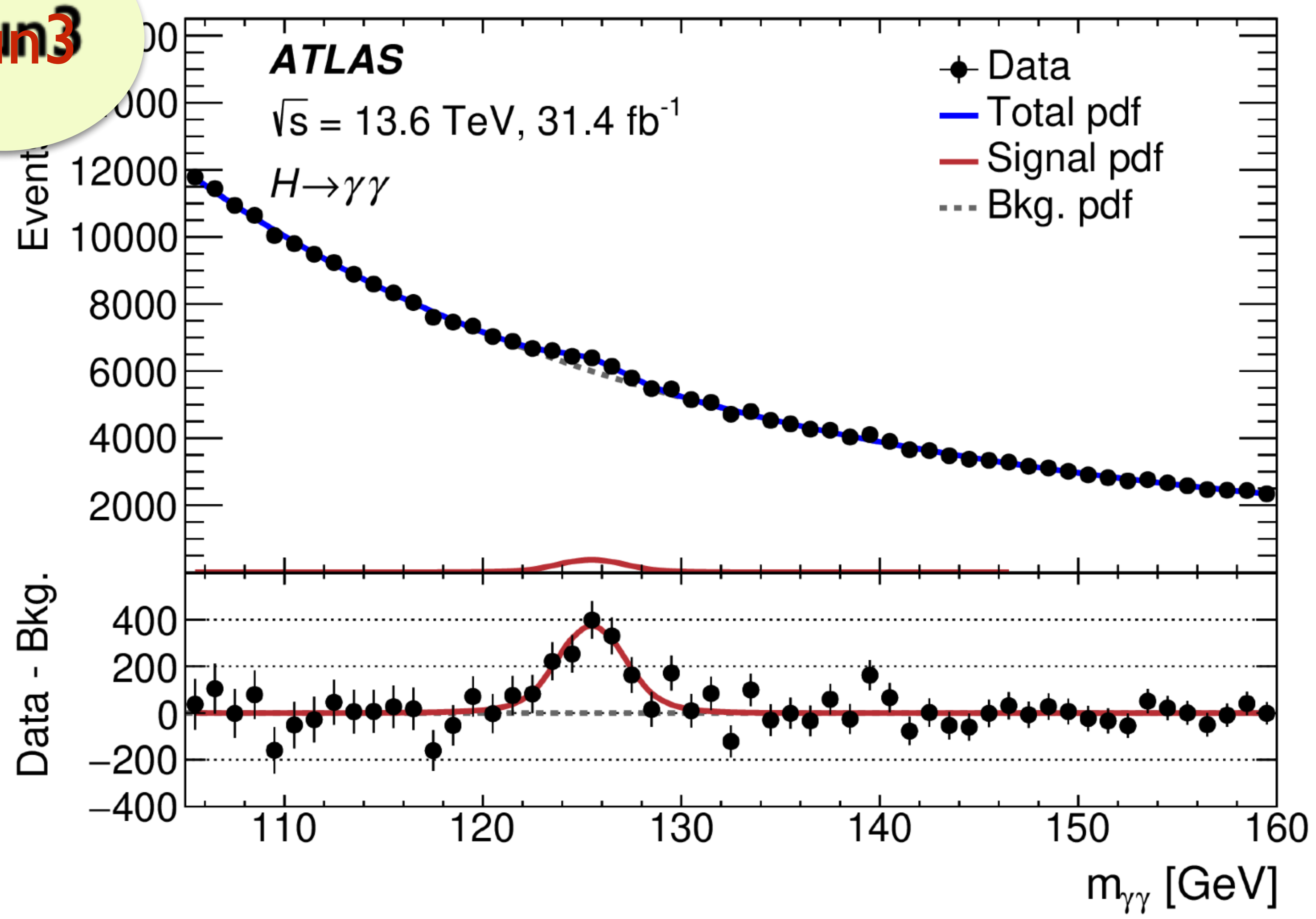


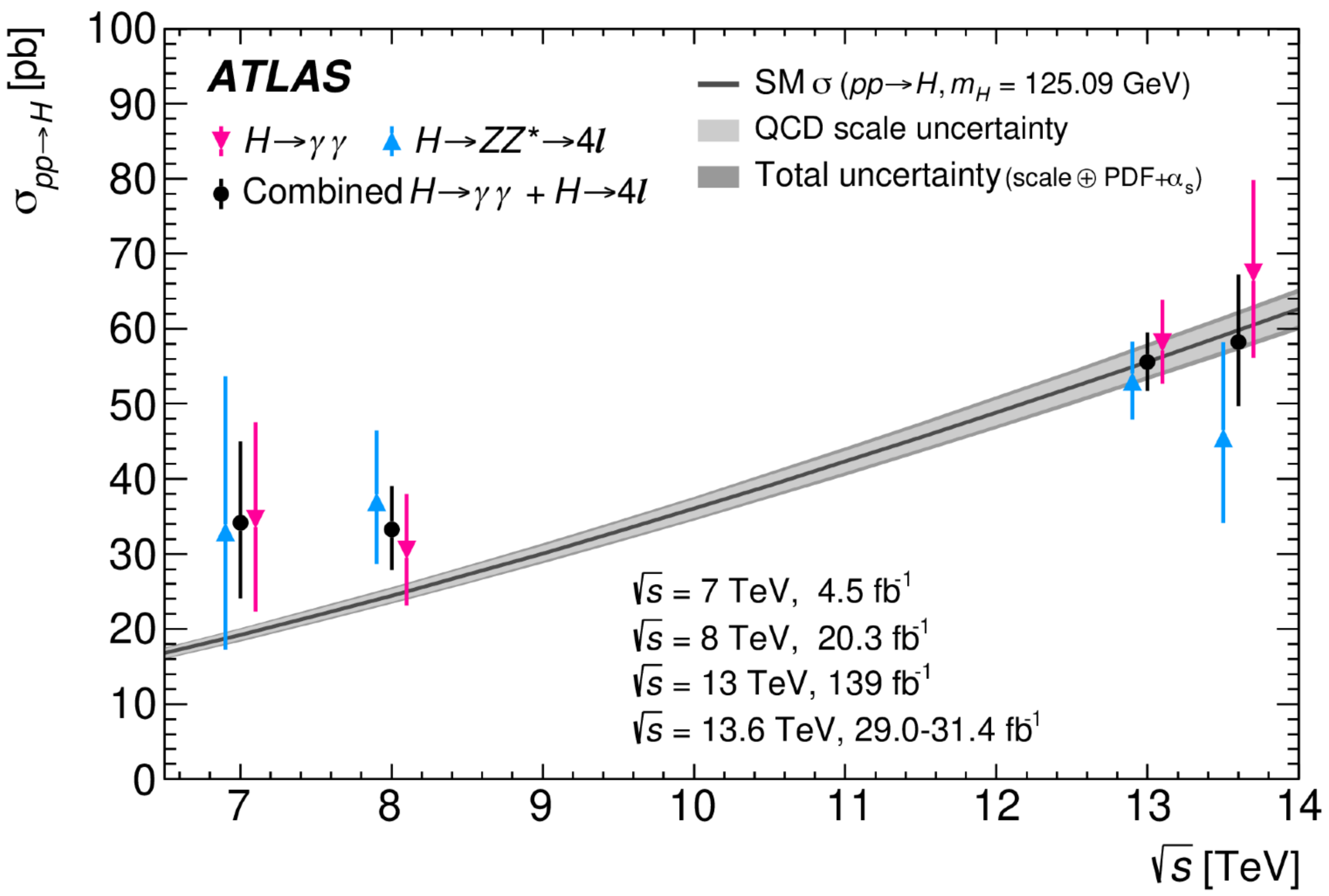
Run 3 $H \to ZZ^*$ with hits in NSW



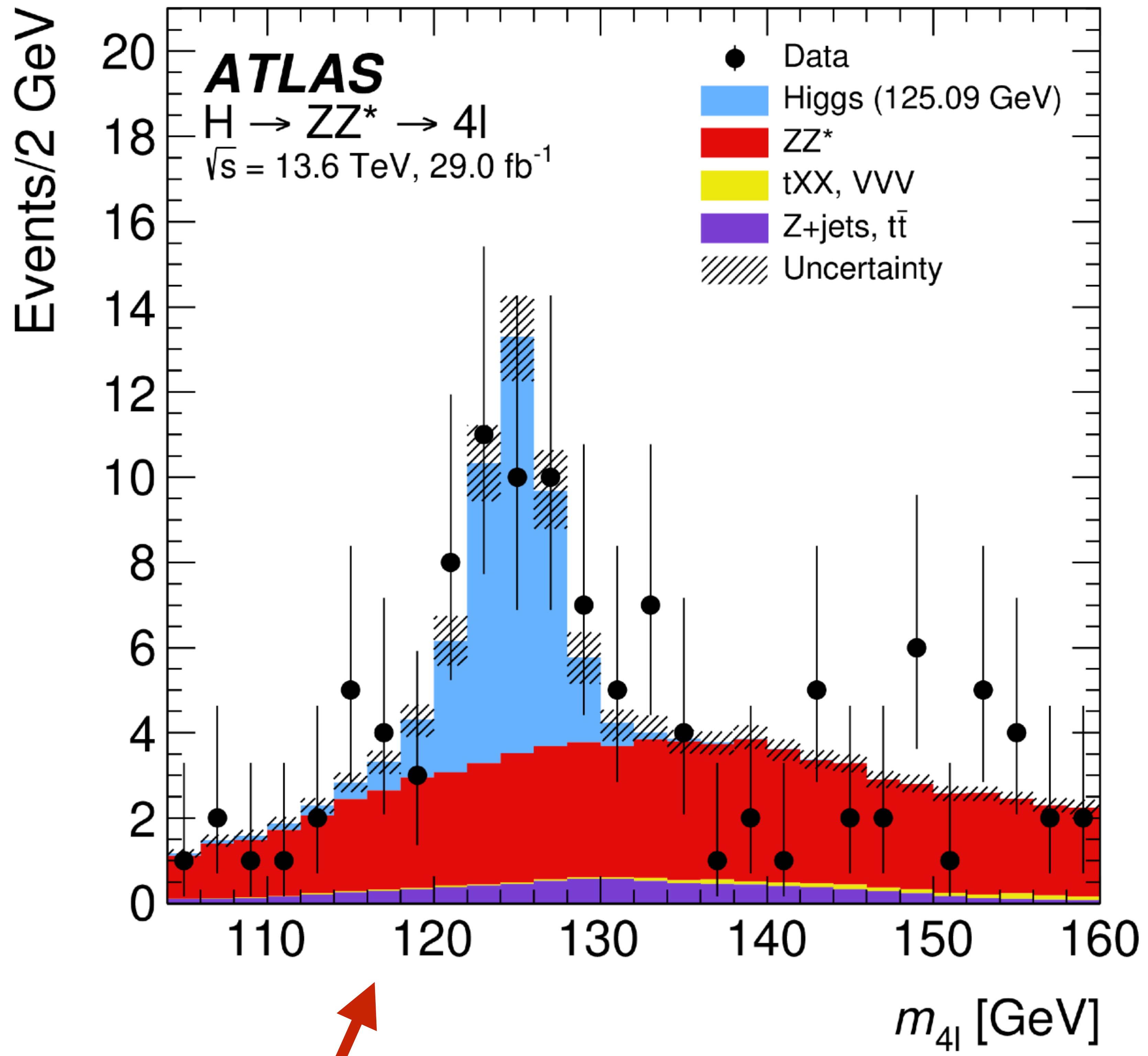
$H\to\gamma\gamma$ and $H\to ZZ^*\to 4l$ Run3 @13.6 TeV

Run3





arXiv:2306.11379



Excellent performance for muons, electrons, and photons in Run3!

Re-observation of the Higgs boson!

But what are the prospects for Higgs Physics?

Prospects for Run 3 and HL-LHC

- Higgs physics
- di-Higgs
- Vector Boson Scattering
- precision measurements as a tool to search for new physics
- top quark physics + SM physics

Higgs: where are we?

- Since the discovery we have a factor 30 more statistical power
- we have a permil precision on the Higgs mass
- its width measured at ~2 MeV precision

We are :

- measuring Higgs couplings to bosons and fermions
- investigating the Higgs couplings to the second generation
- measuring the signal strength for Higgs production with a 6% precision
- a precision on various couplings that ranges from 3-10%
- evidence that the Higgs couples with the particle mass and that it has spin 0
- at the level of sensitivity of testing x-sections at the level of 2-3 times the SM for the di-higgs production

Let's walk through all of this together!

Higgs terminology

- in Higgs physics we talk of signal strength, defined as the μ parameter.
- μ is the ratio of the measured cross-section with respect to the SM expectation.
- μ=1 means that we measure back the SM

Higgs

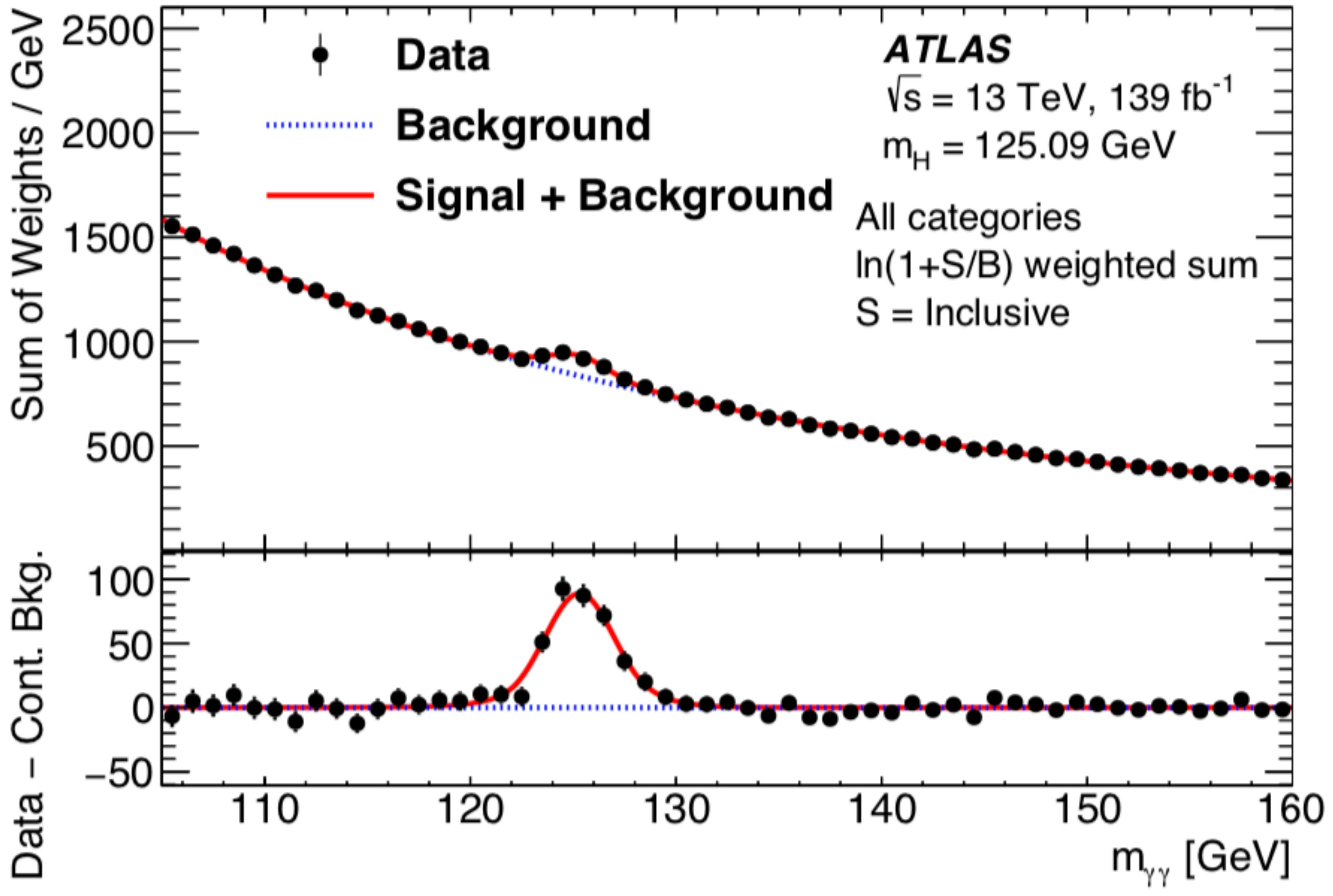
$H \rightarrow \gamma\gamma$

ArXiv:2207.00348

10 % precision

$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{theory syst.})\ ^{+0.05}_{-0.04}\ (\text{exp. syst.}).$$

Please note that theoretical error is at level of other errors!



Higgs

$H \to \gamma\gamma$

ArXiv:2207.00348

10 % precision

$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\,(\text{stat.})^{+0.06}_{-0.05}\,(\text{theory syst.})\;^{+0.05}_{-0.04}\,(\text{exp. syst.}).$$

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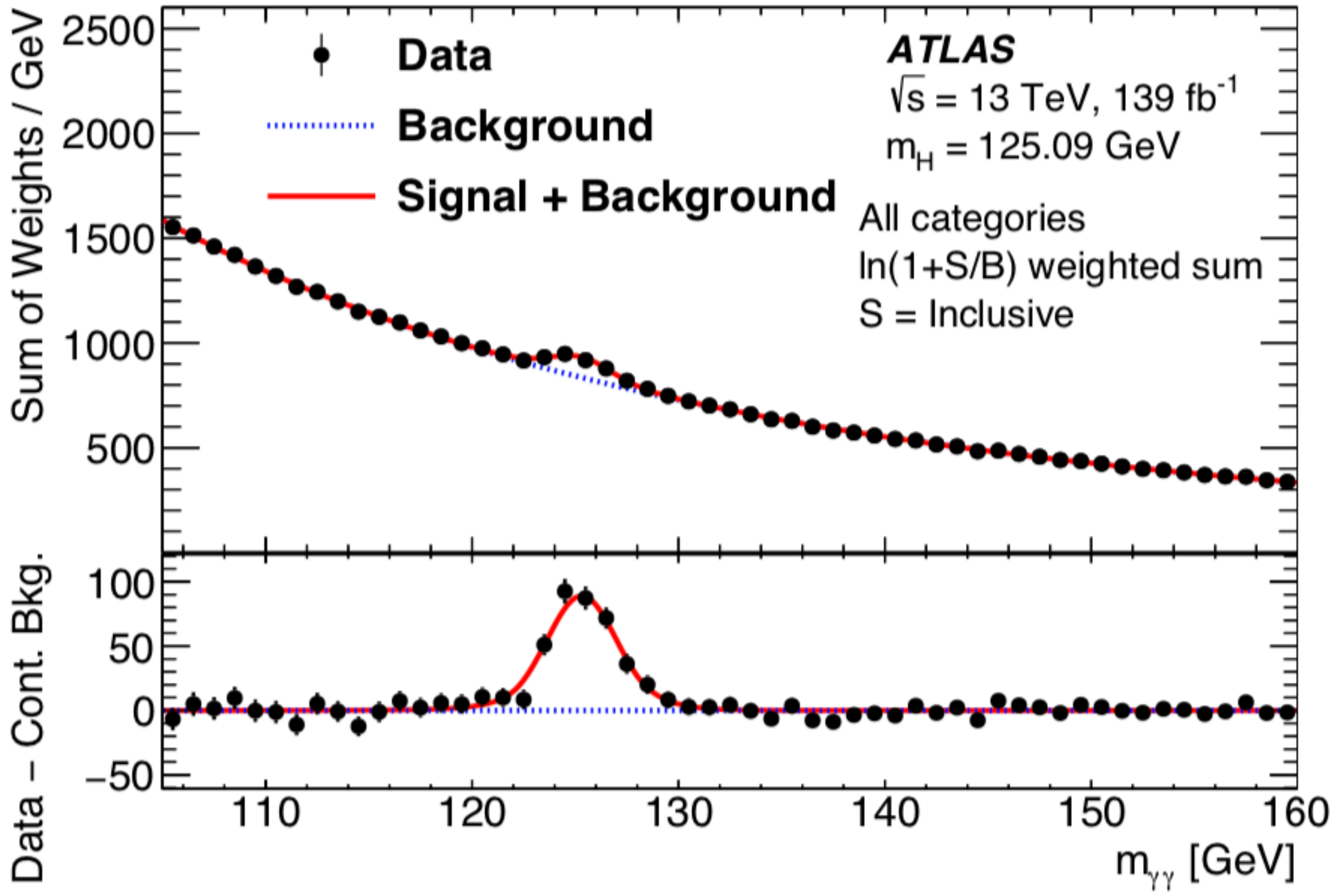
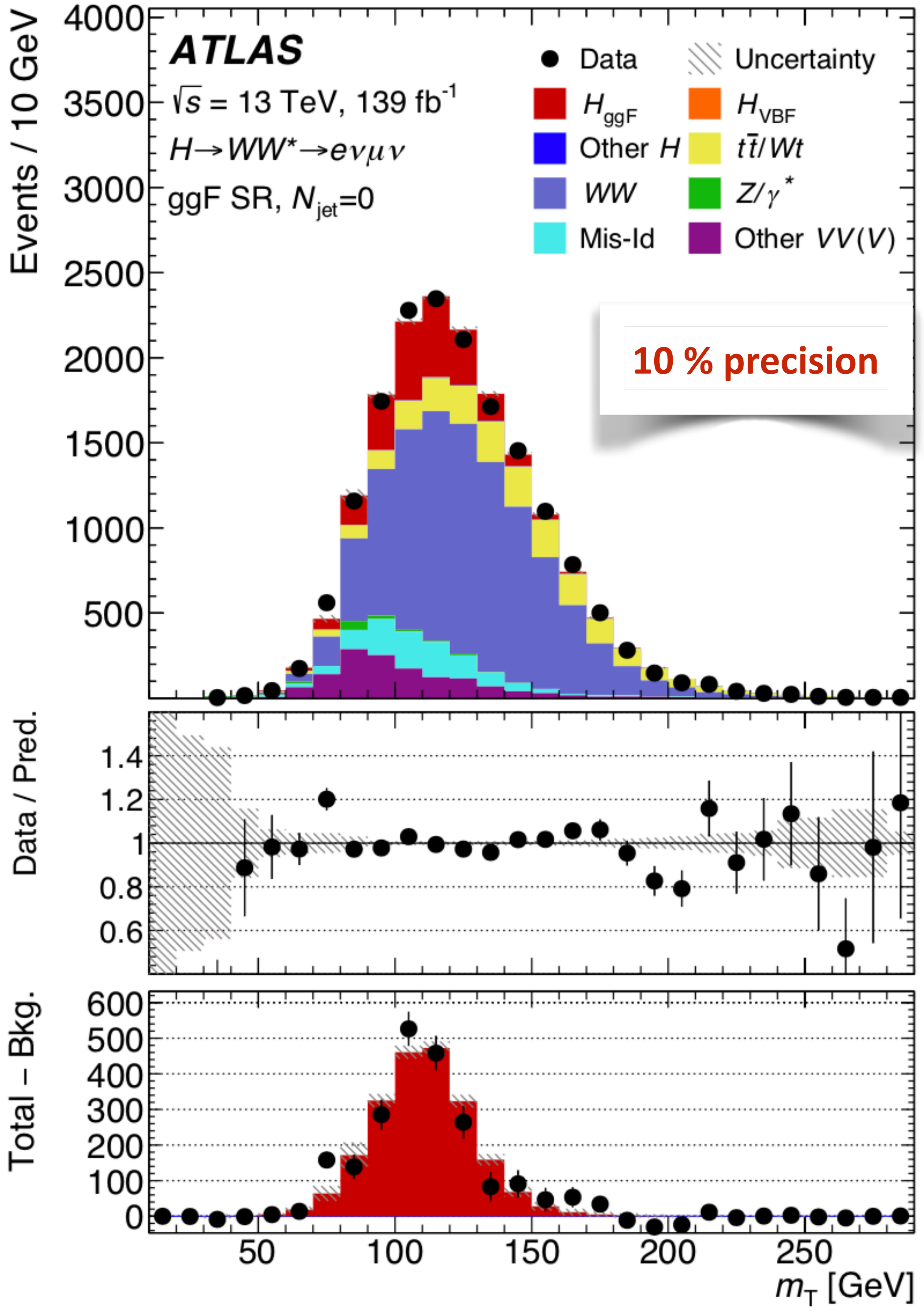


$H \to WW^*$



	Total	(Stat., Syst.)	SM Unc.
1.09	$^{+0.11}_{-0.11}$	($^{+0.06}_{-0.06}$, $^{+0.10}_{-0.09}$)	± 0.07

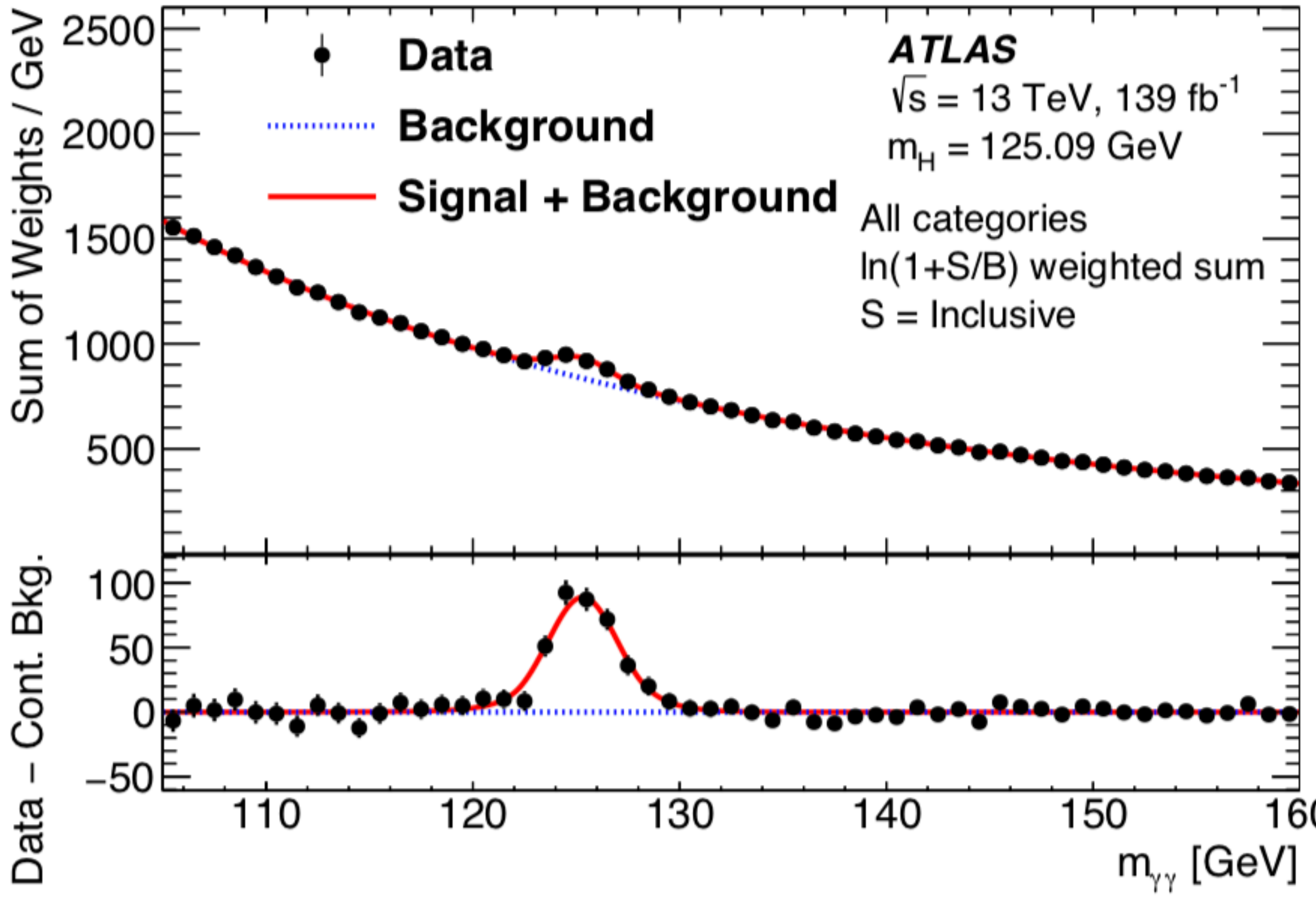
Higgs

$H \to \gamma\gamma$

10 % precision

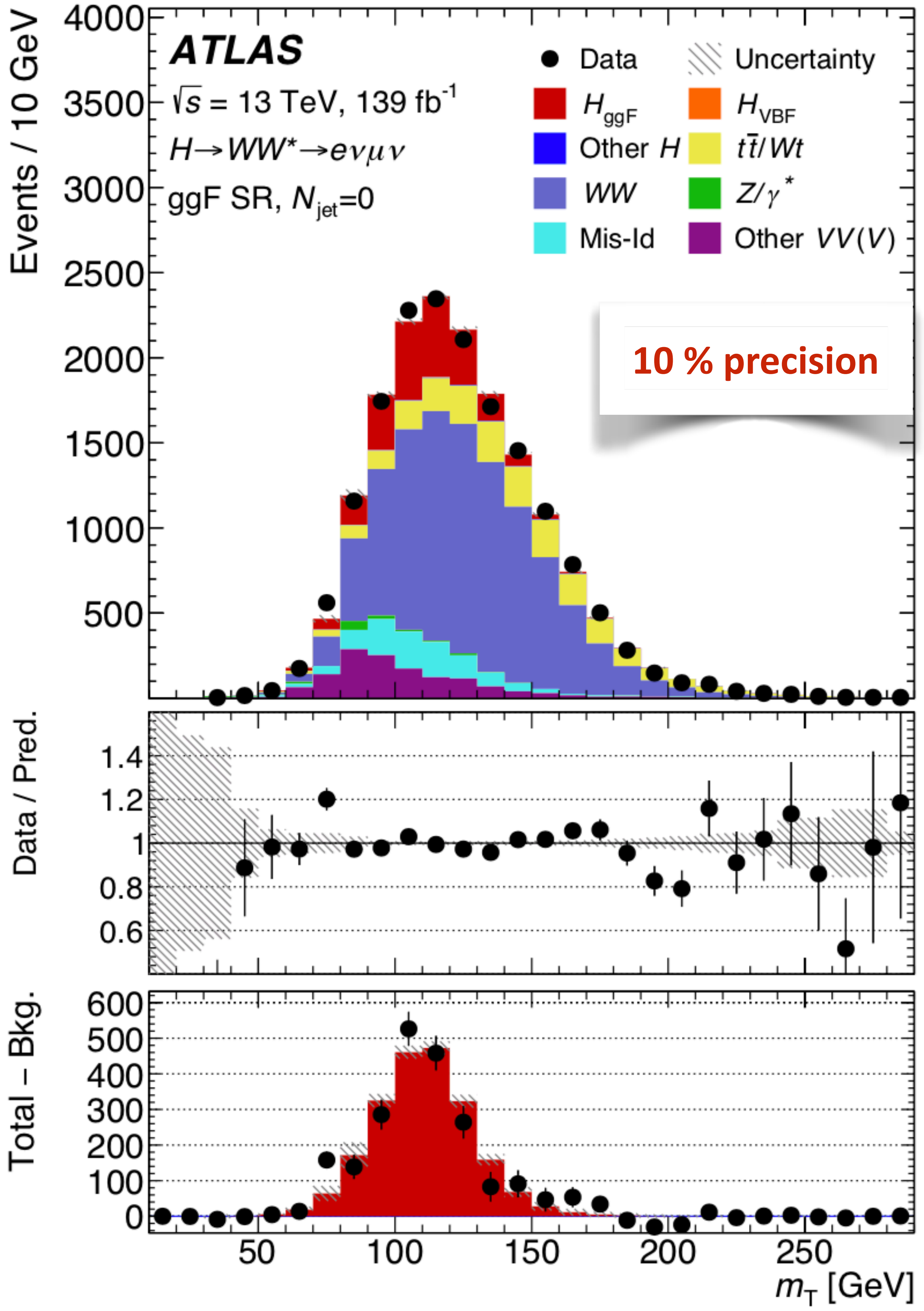
$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{theory syst.})\ ^{+0.05}_{-0.04}\ (\text{exp. syst.}).$$

Please note that theoretical error is at level of other errors!



Total	(Stat., Syst.)		SM Unc.
1.09 $^{+0.11}_{-0.11}$	($^{+0.06}_{-0.06}$,	$^{+0.10}_{-0.09}$)	± 0.07

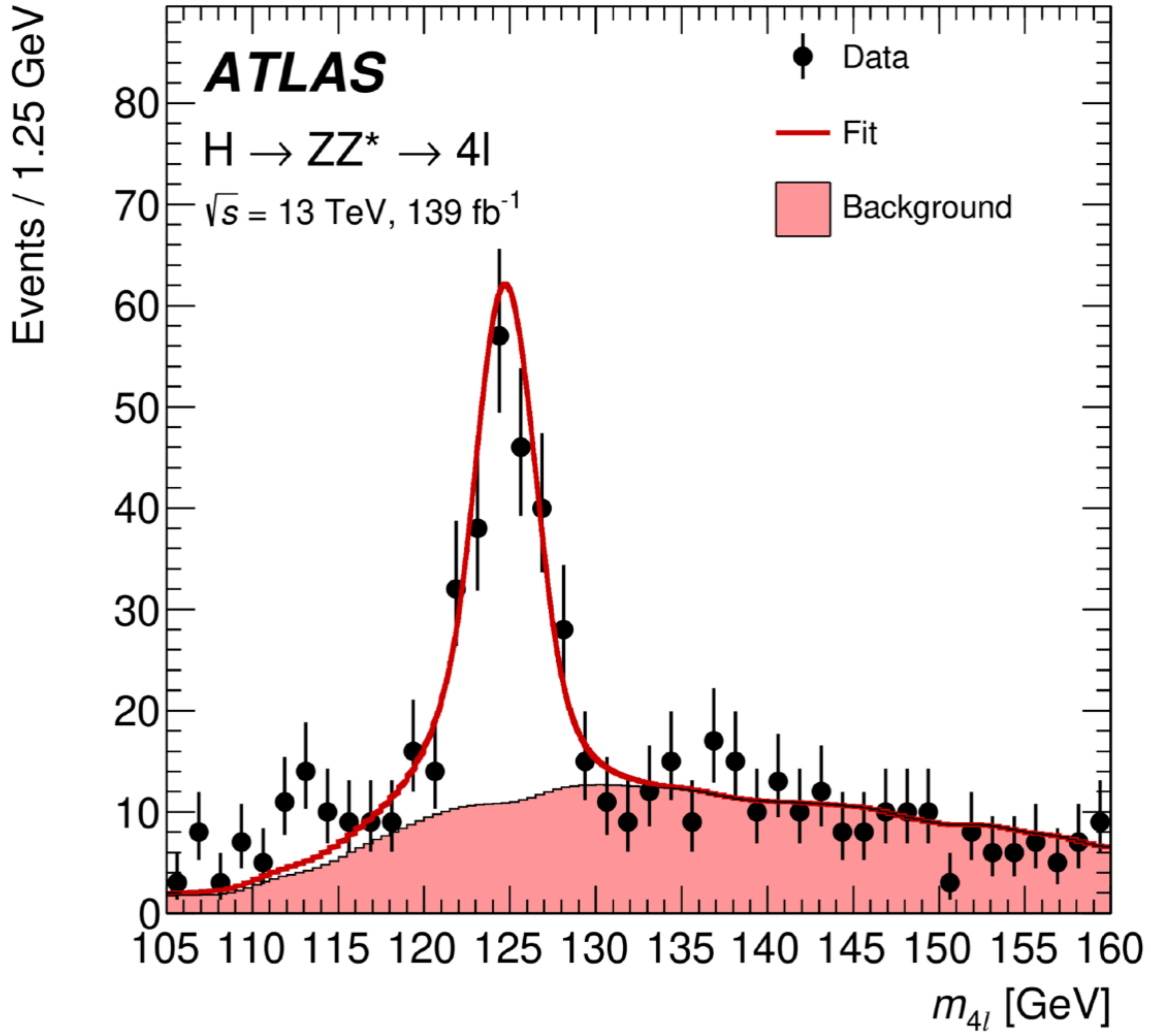
$H \to WW^*$



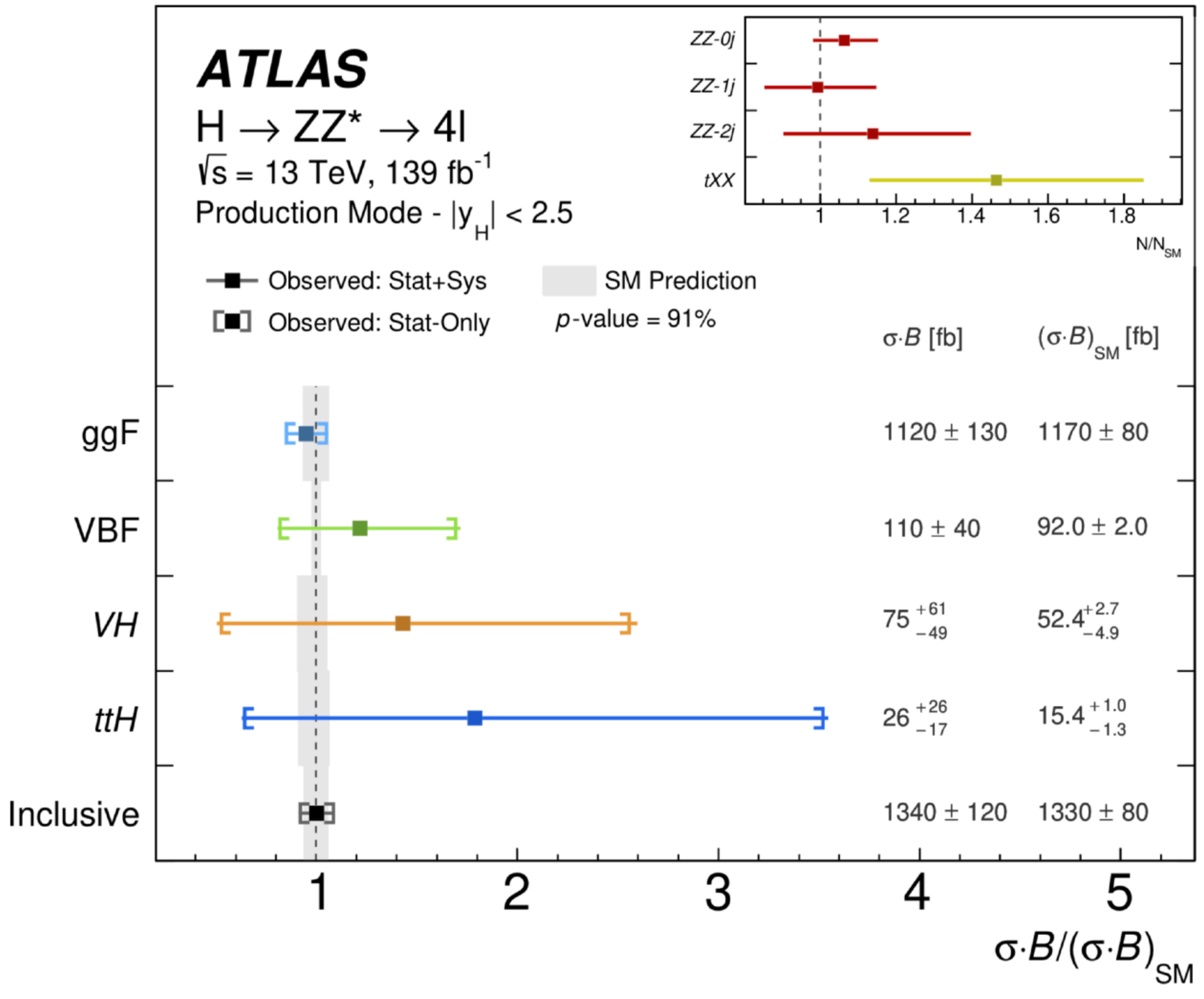
$H \to ZZ \to 4l$

precision on μ ~ 10%

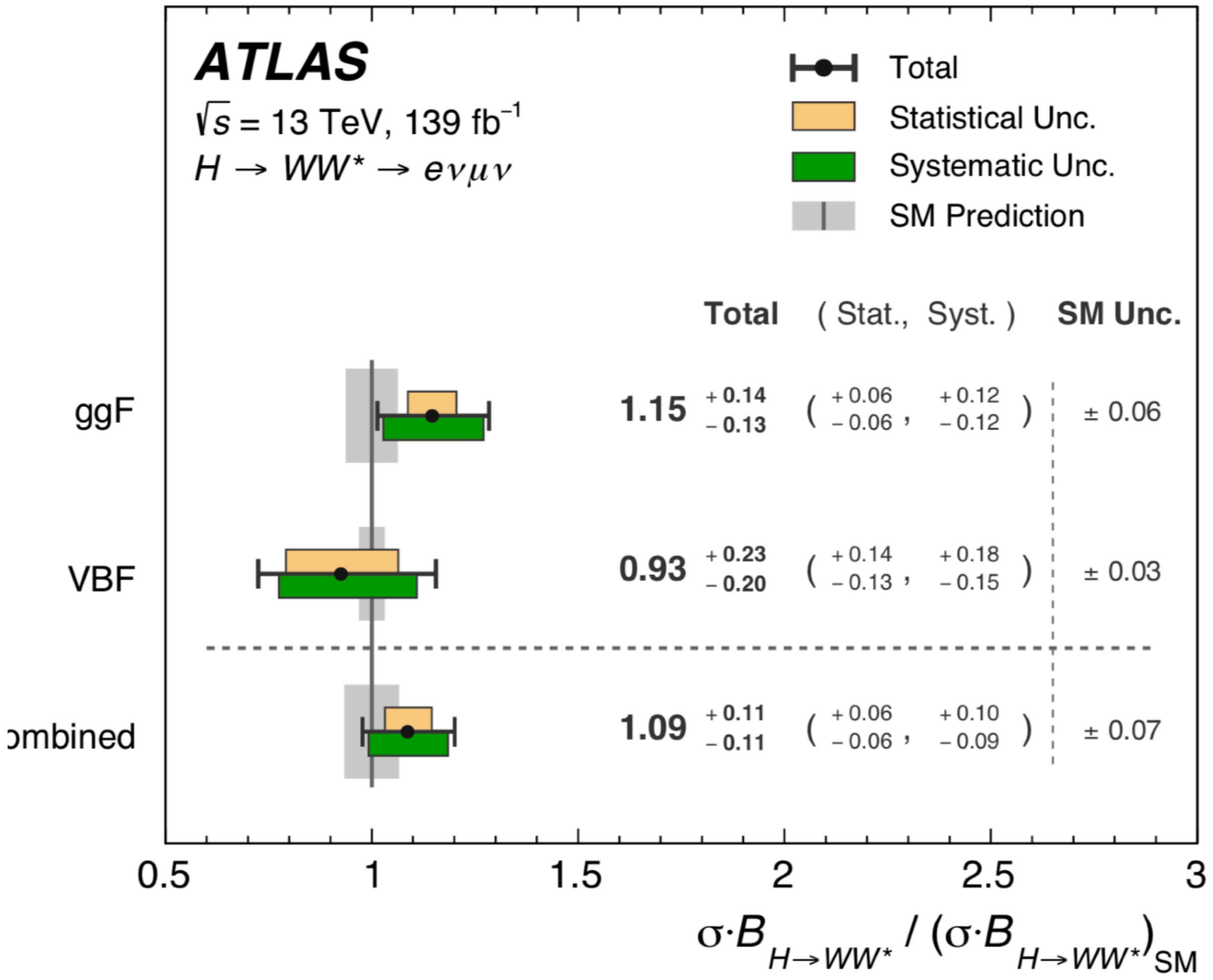
$$\mu = 1.01 \pm 0.08(\text{stat.}) \pm 0.04(\text{exp.}) \pm 0.05(\text{th.})$$

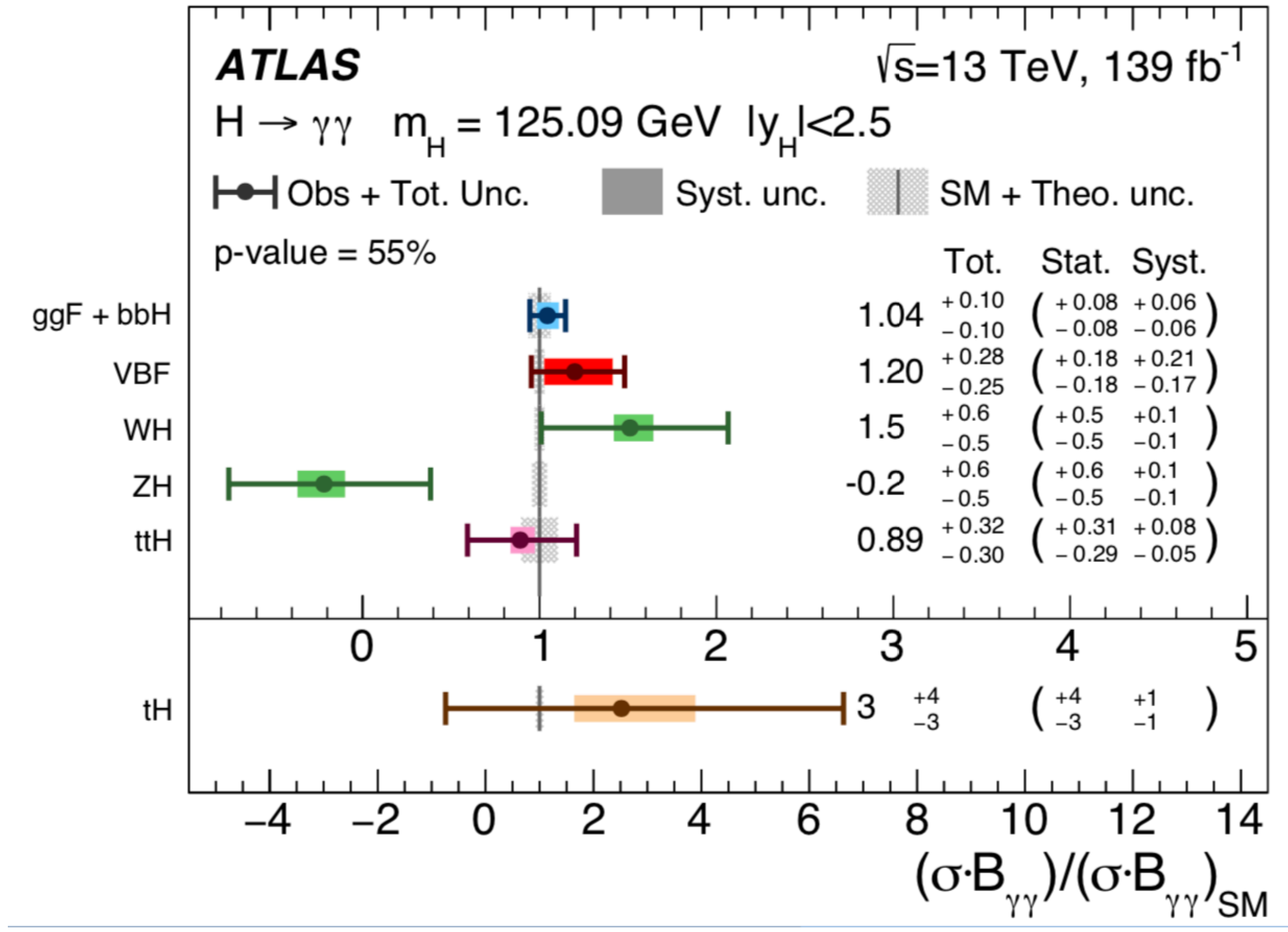


Production modes



→ theory uncertainties start to matter





Measurement precision

- 10% uncertainty on ggF
- 20-30% on VBF
- 35% ttH(γγ)

Run 3 will bring 20-30% improvements

Decay modes

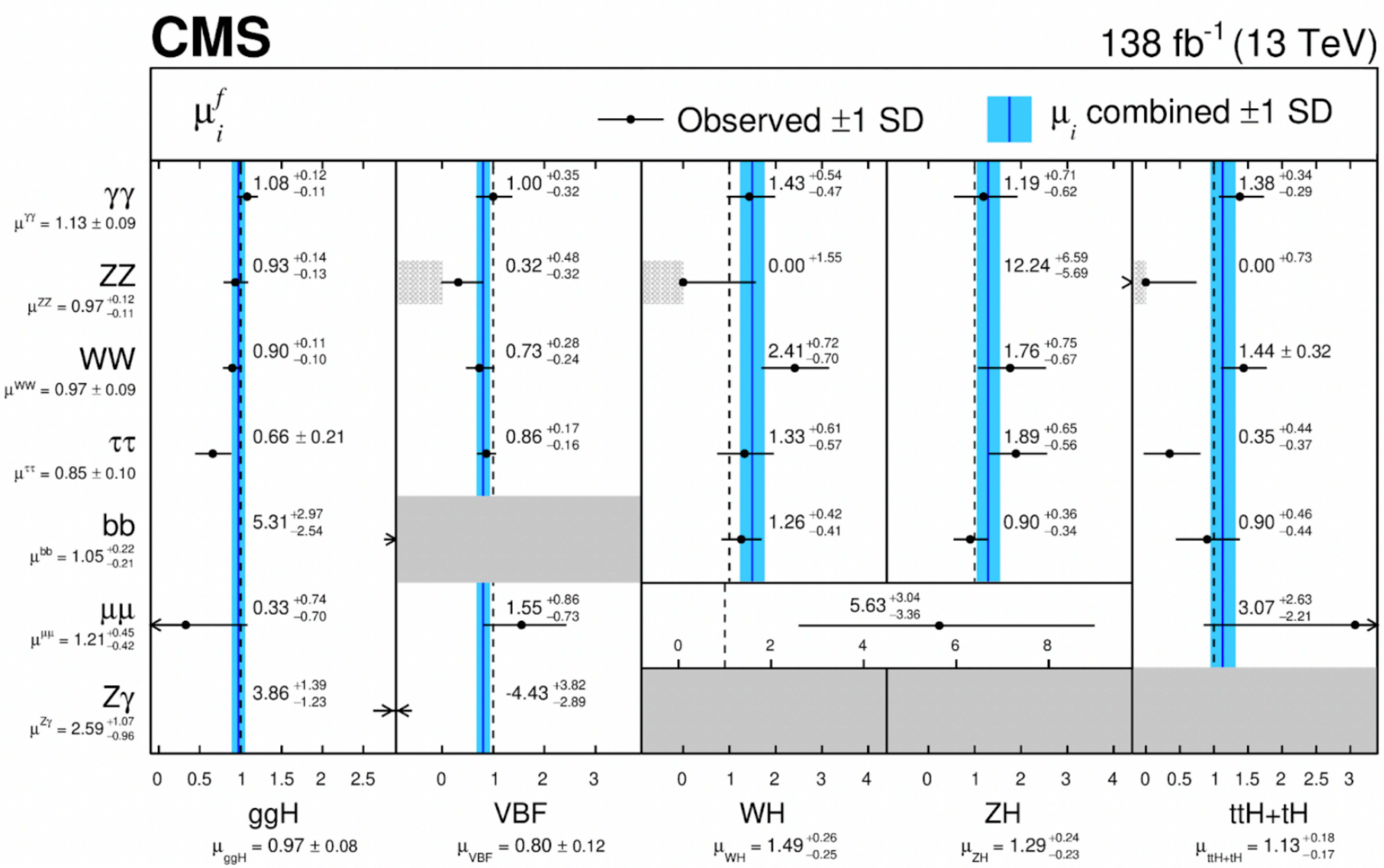
Run 3 will bring 20-30% improvements also on decay modes

All major decay modes have been observed:

- BR(bb) precision of <20%
- BR(ττ), BR(WW), BR(ZZ) and BR(γγ) now at precision of 10-12%

Not everything is observed though!

H->μμ single experiment evidence

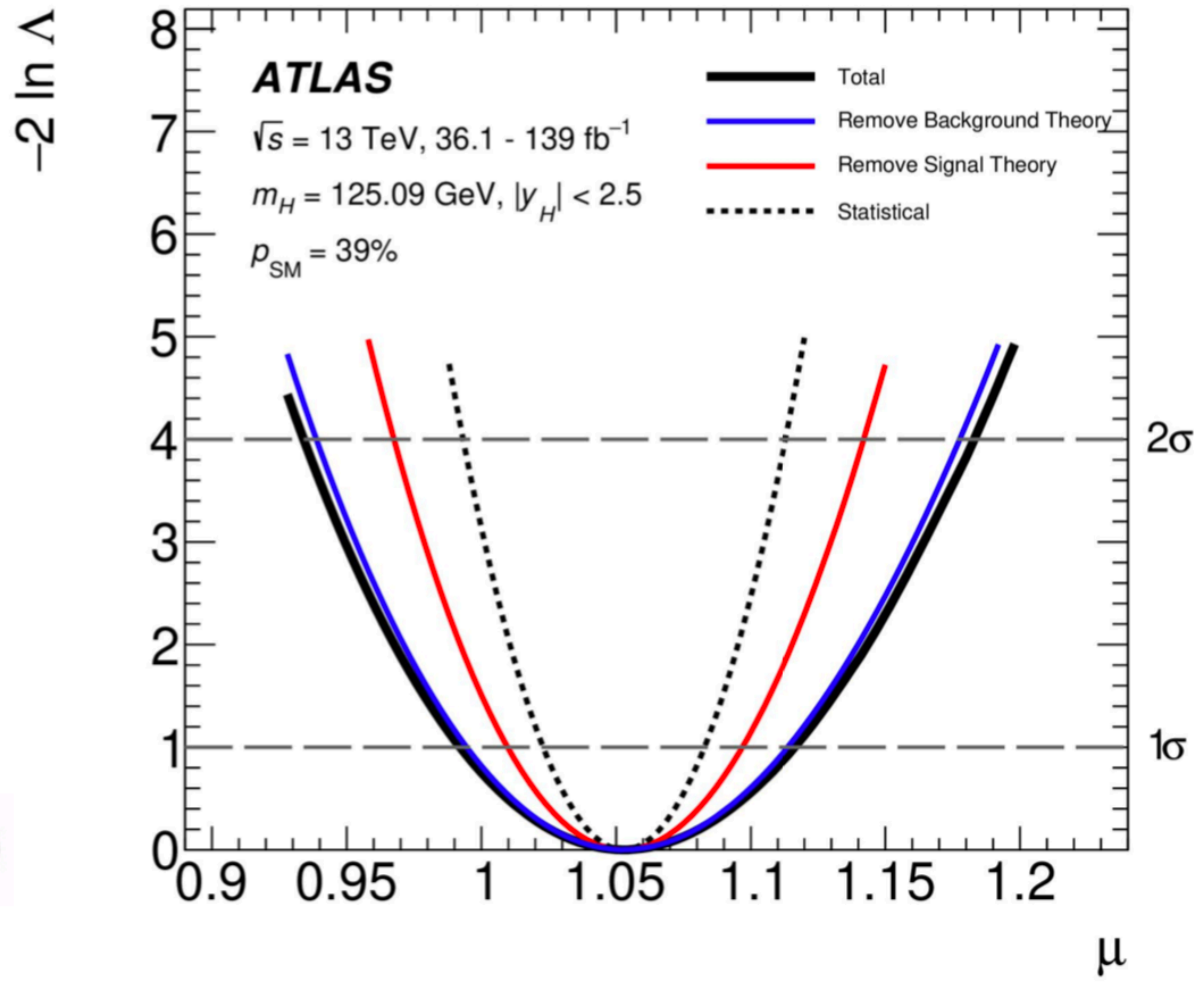


Zy we have now evidence in ATLAS+CMS combination

Higgs Combination

Nature 607, 52–59 (2022)

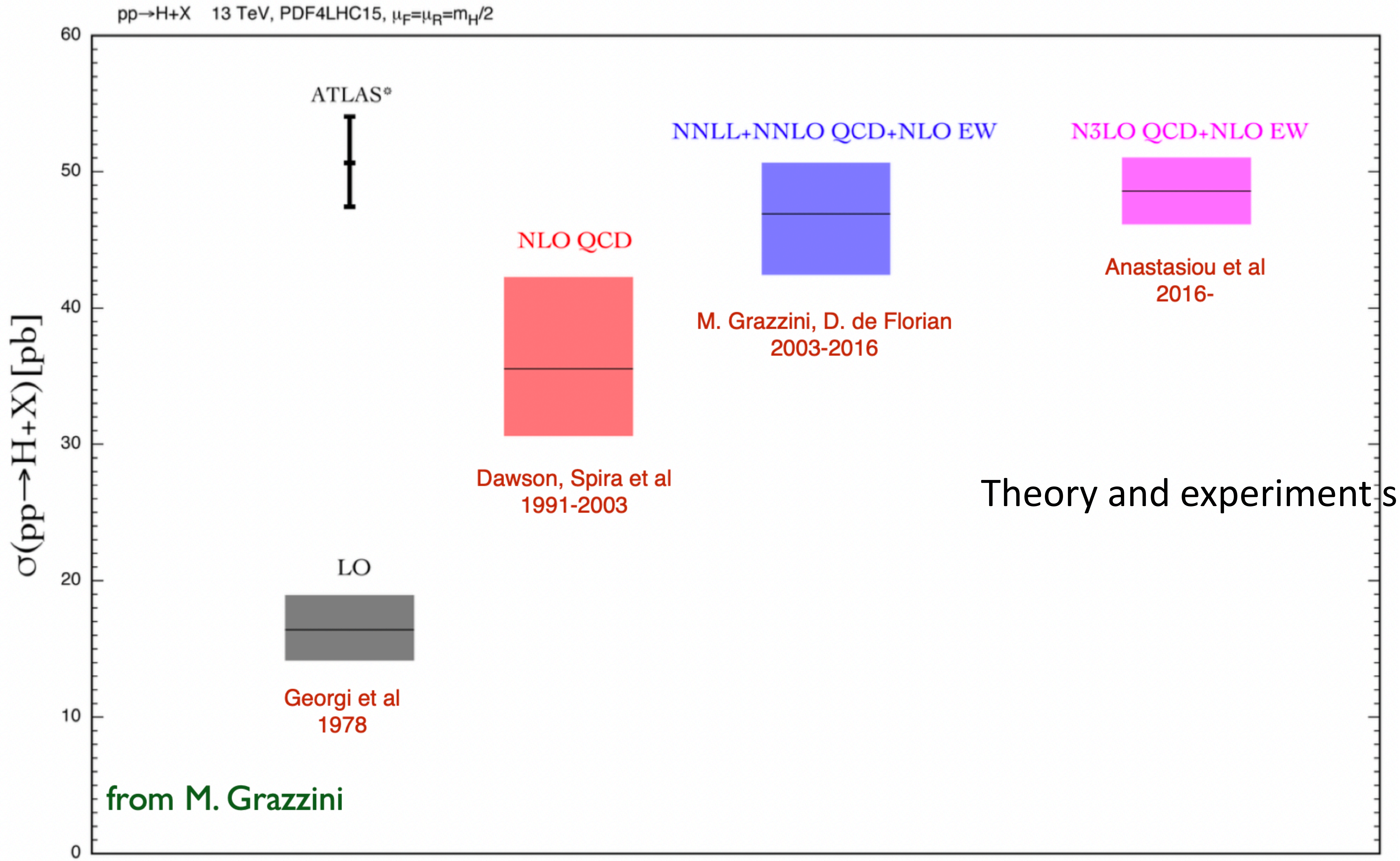
	ggHb	qqH	VH	ttH/tH
$H\to\gamma\gamma$	✔	✔	✔	✔
H→ZZ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
$H\to\tau\tau$	✔	✔	✔	✔
H→bb	✔	✔	✔	✔
$H\to\mu\mu$	✔	✔	✔	✔
H→cc			✔	
$H\to Z\gamma$	✔	✔	✔	✔
H→inv		✔	✔	



Measurement at 6%!

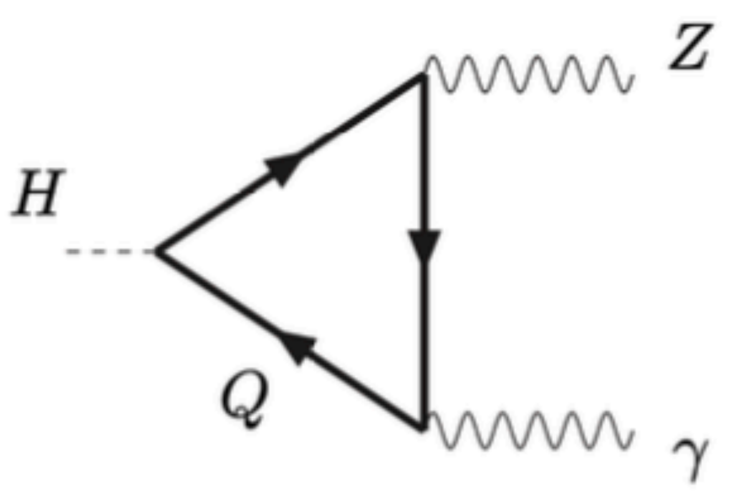
$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

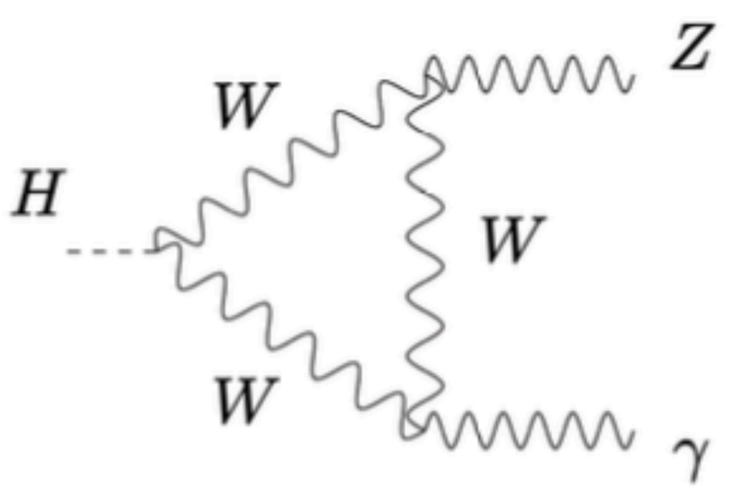
Inclusive Higgs x-section theoretical improvements

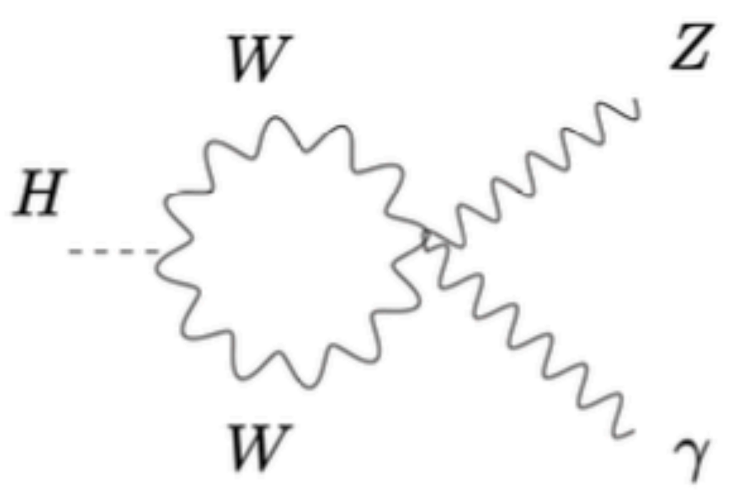


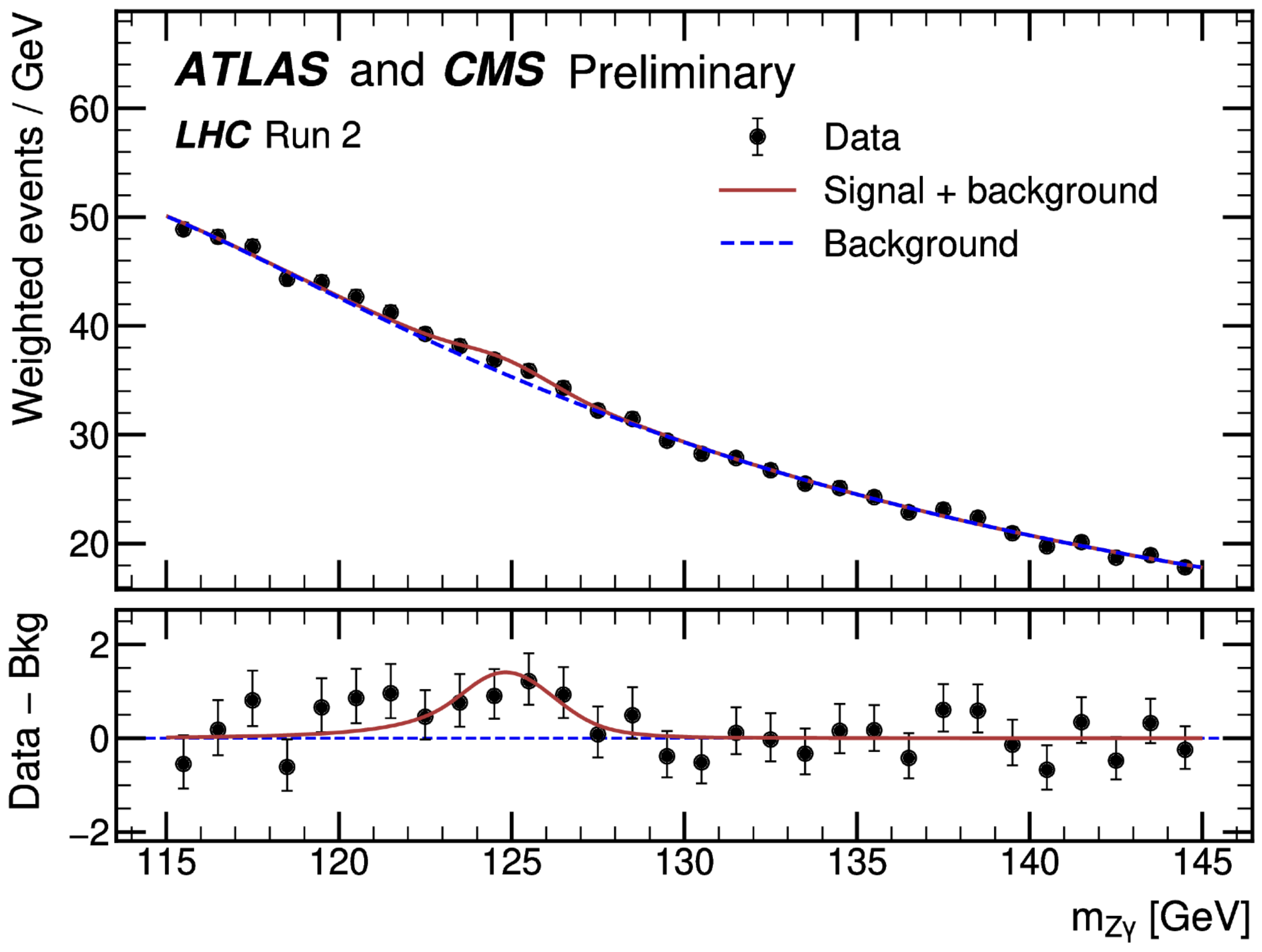
Theory and experiment should go hand to hand

ATLAS + CMS combination: First Evidence for $H \to Z\gamma$









First evidence of this process!

3.4σ evidence from combination of independent 2.2σ ATLAS and 2.6σ CMS observed sensitivity

Observed signal is 2.2 ± 0.7 times the SM prediction (compatible at 1.9σ)

With the additional 200 fb-1 Run 3 would give observation in the combination, while single experiments would fall slightly short of observation.

This of course in the hypothesis that the observed signal is higher than the expectation

Higgs

Rare processes: back on the envelope calculation based on SM expectations

run3 Lumi→ expected sensitivity↓	H->μμ		H->γγ*		H->Zγ		HH	
	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb
ATLAS	2.8	2.6	3.5	3.3	2.0	1.9	1.2	1.1
CMS	4.2	4.0	-	-	2.0	1.9	1.3	1.2
Combined	5.0	4.8	5.0	4.7	2.8	2.6	1.8	1.6

Back of the envelope calculation (no official source)

Following SM expectations

Higgs couplings to second generation

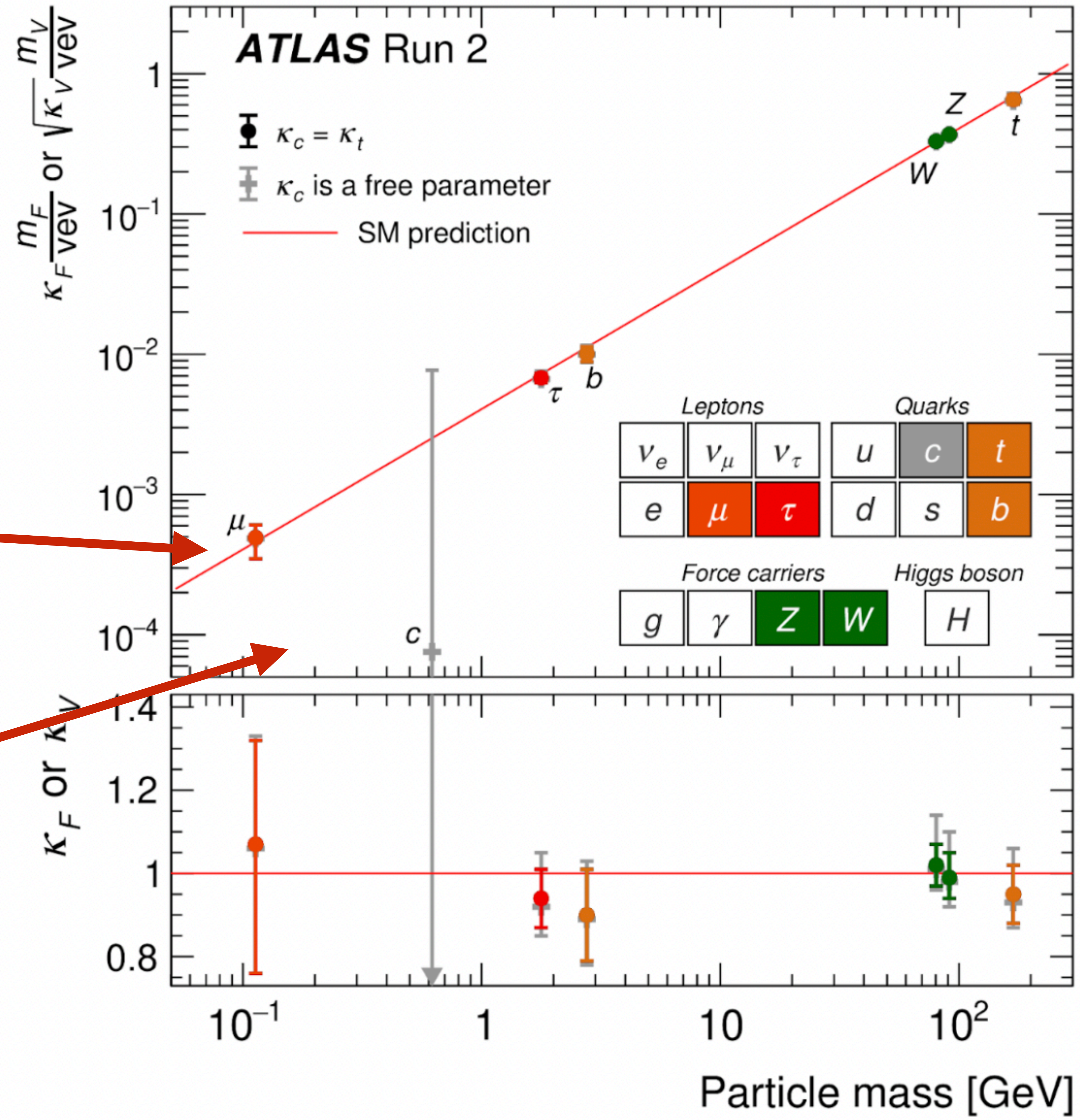
Particle masses span almost six orders of magnitude,
from 0.5 MeV/c2 for electrons in the first generation
to 173,000 MeV/c2 for the top quark in the third generation.

These masses correspond to a range in Higgs interaction strengths from 0.000003 to 1, assuming that a single Higgs field generates the mass in all particle generations.

That assumption is so far experimentally untested as only the interactions with 3rd generation particles have been established.

With the increased data volume of LHC Run 2+3, constraints on couplings to the 2nd generation come into reach, allowing a first ever test of the universality of the mass generation mechanism.

Anticipated during Run 3 is a major breakthrough in Higgs physics: the observation of Higgs Boson decays to muons.



Higgs

Rare processes: back on the envelope calculation based on SM expectations

run3 Lumi→ expected sensitivity↓	H->μμ		H->γγ*		H->Zγ		HH	
	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb
ATLAS	2.8	2.6	3.5	3.3	2.0	1.9	1.2	1.1
CMS	4.2	4.0	-	-	2.0	1.9	1.3	1.2
Combined	5.0	4.8	5.0	4.7	2.8	2.6	1.8	1.6

Following SM expectations

ATLAS has significance 2.0σ (with an expectation of 1.7σ) CMS has evidence 3.0σ (with an expectation of 2.5σ).
The precision of this result is currently limited by the statistics of the data sample;
Run3, both experiments fall slightly short of an observation significance with 200 fb-1.
Combination should provide an unambiguous discovery
It is a goal for both experiments to reach an observation sensitivity independently.

Higgs couplings to 2nd generation: c quarks

Higgs

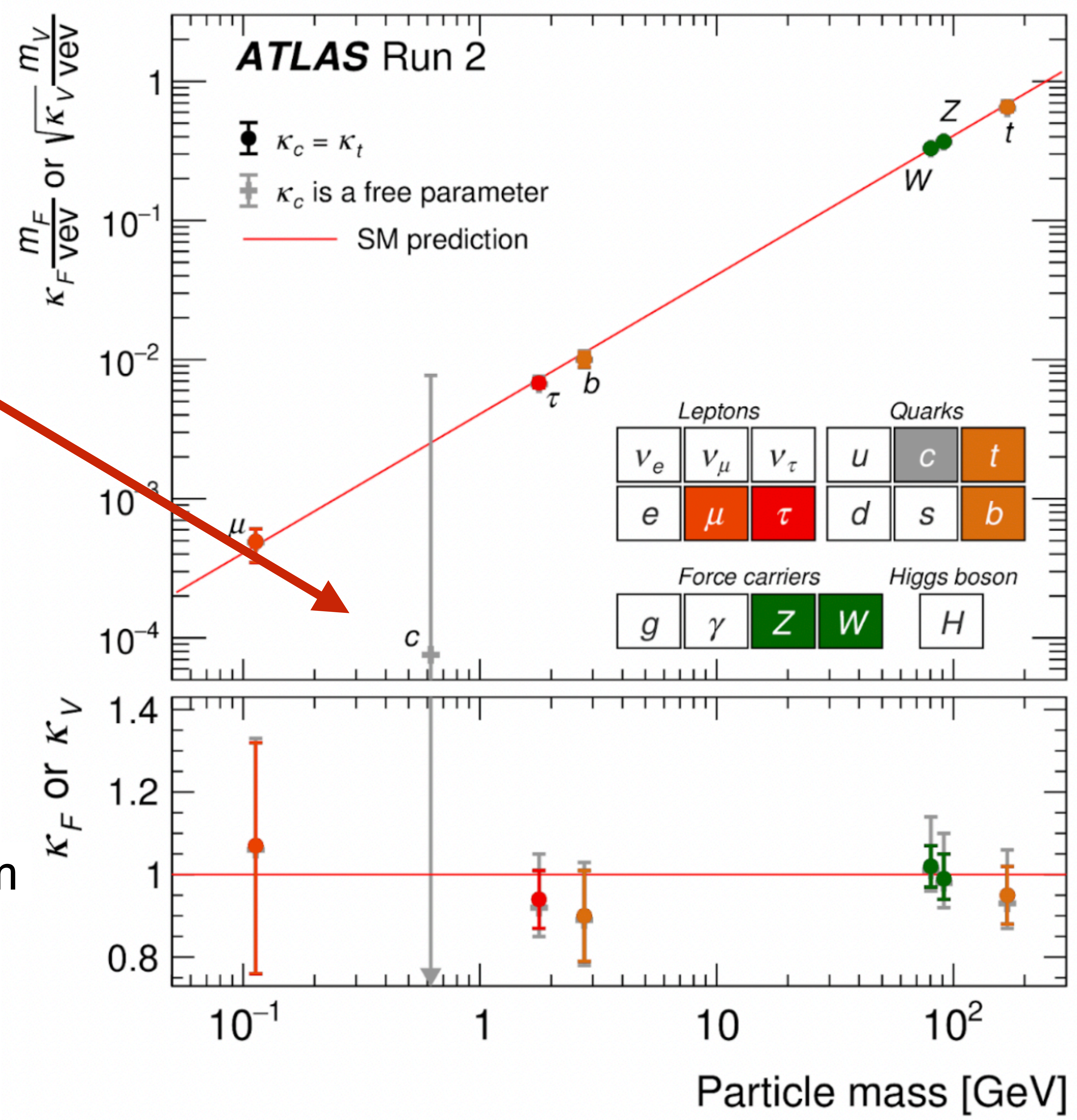
Run 3 will serve as a fundamental benchmark for studying the coupling to second-generation quarks, specifically the charm quark.

Decays of the Higgs boson into a pair of c ("charm") quarks are relatively common; however, the challenge lies in accurately identifying them based on their detector signature.

When high-energy quarks transform into collimated jets of bound states known as hadrons, those originating from b or c quarks travel a finite distance before decaying (D lifetime 10^{-15} s, B lifetime 10^{-12} s)

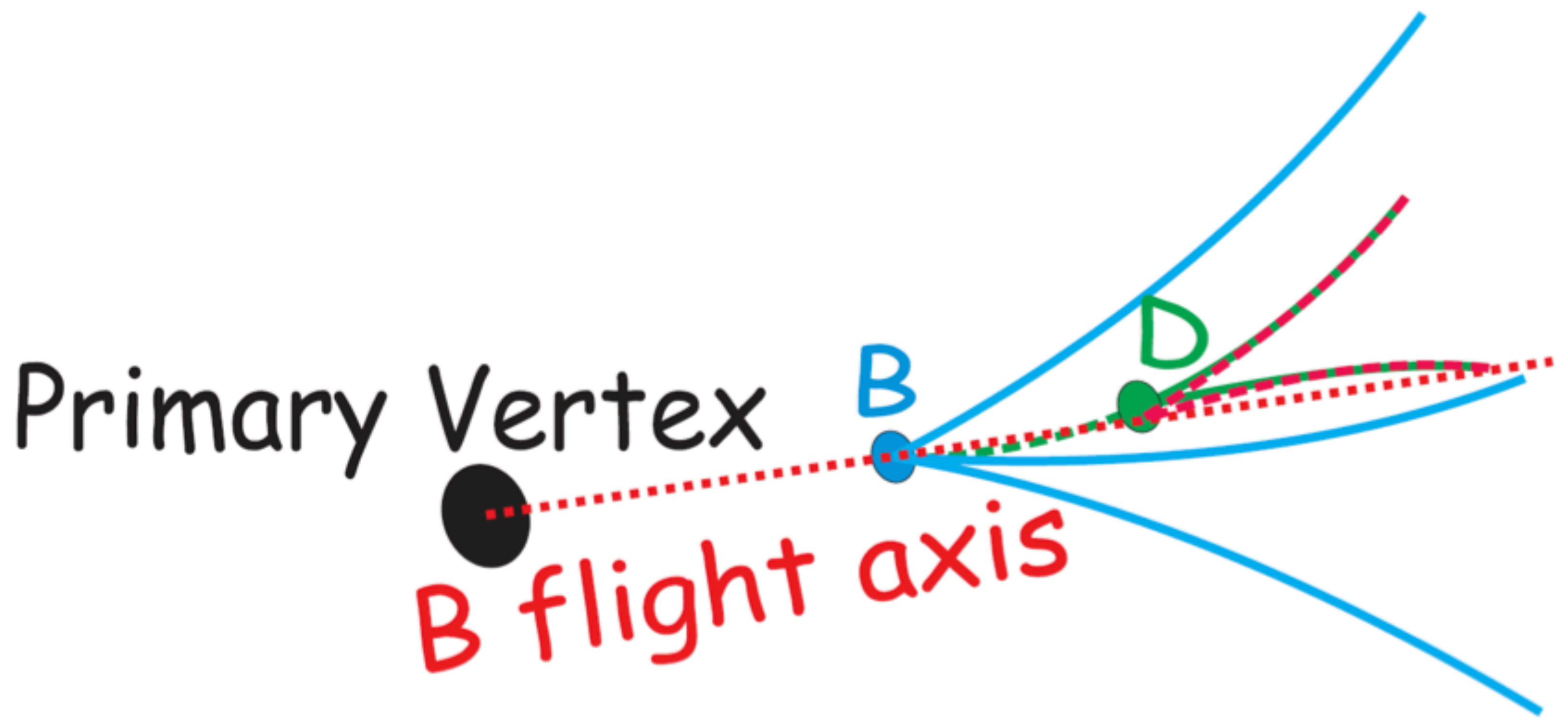
Techniques based on distance measurements have proven effective in identifying the long-lived and heavy b quarks of the third generation.

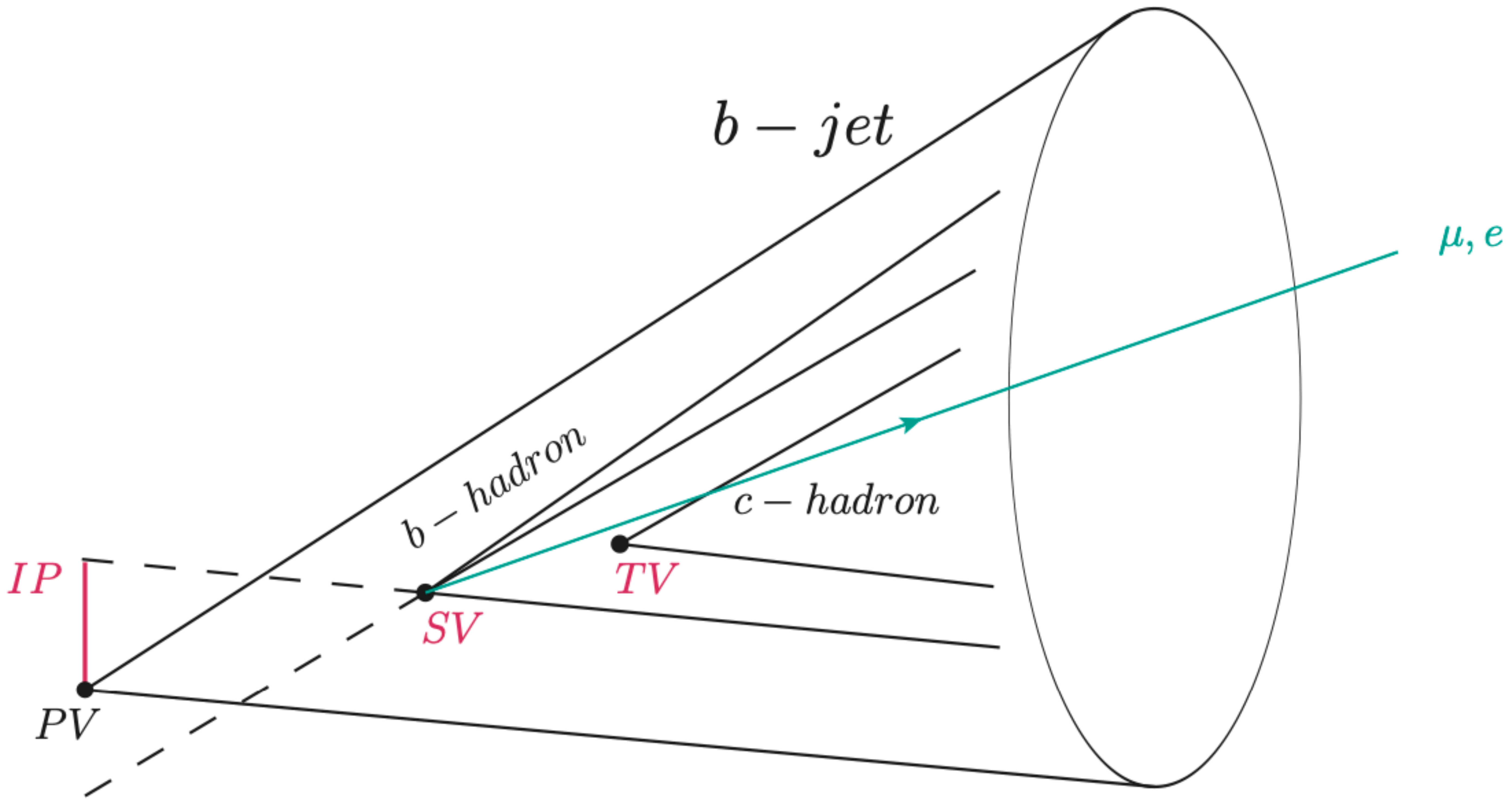
To address the more challenging scenario of the shorter-lived and lighter charm quarks, innovative analysis techniques and the utilization of boosted Higgs decays have brought the charm quark within reach for the High-Luminosity phase of the LHC. Run 3 will be instrumental in testing and establishing new analysis strategies to pave the way forward.



Flavor tagging

We tag b-hadrons and c-hadrons thanks to the fact that there is a secondary vertex

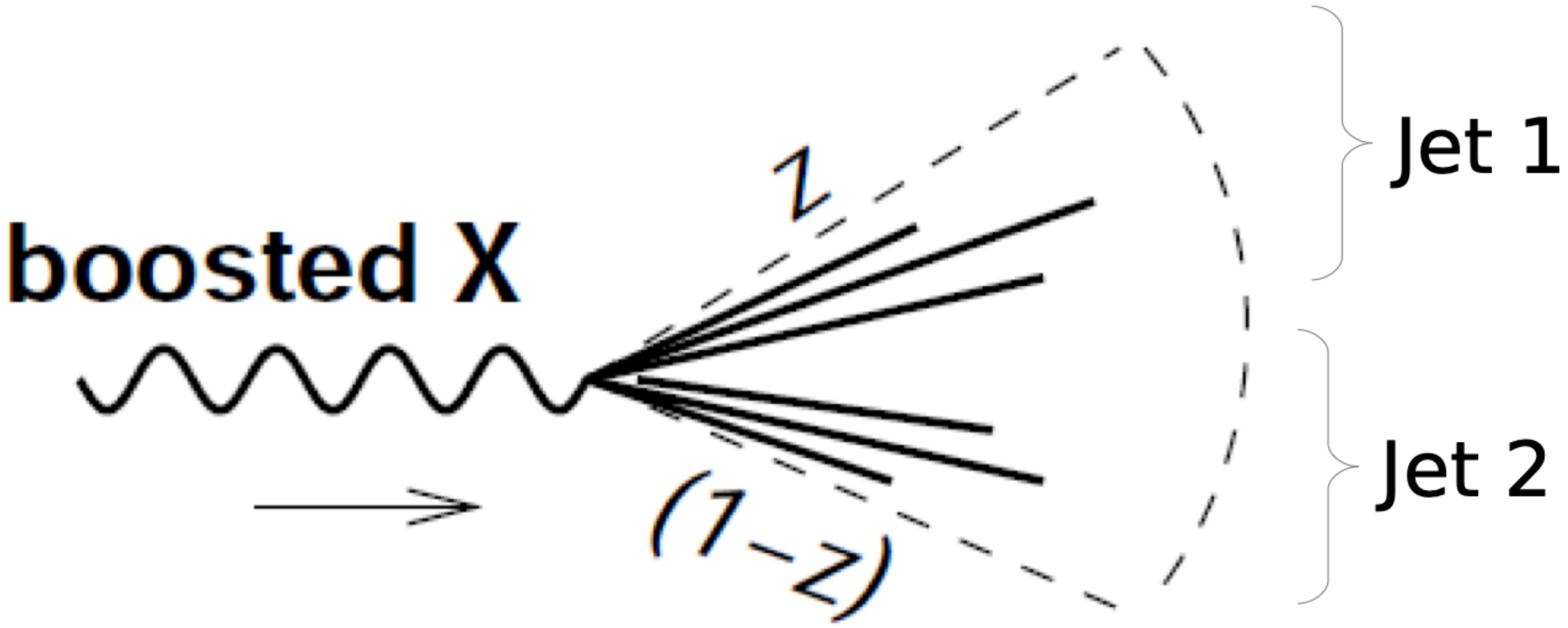




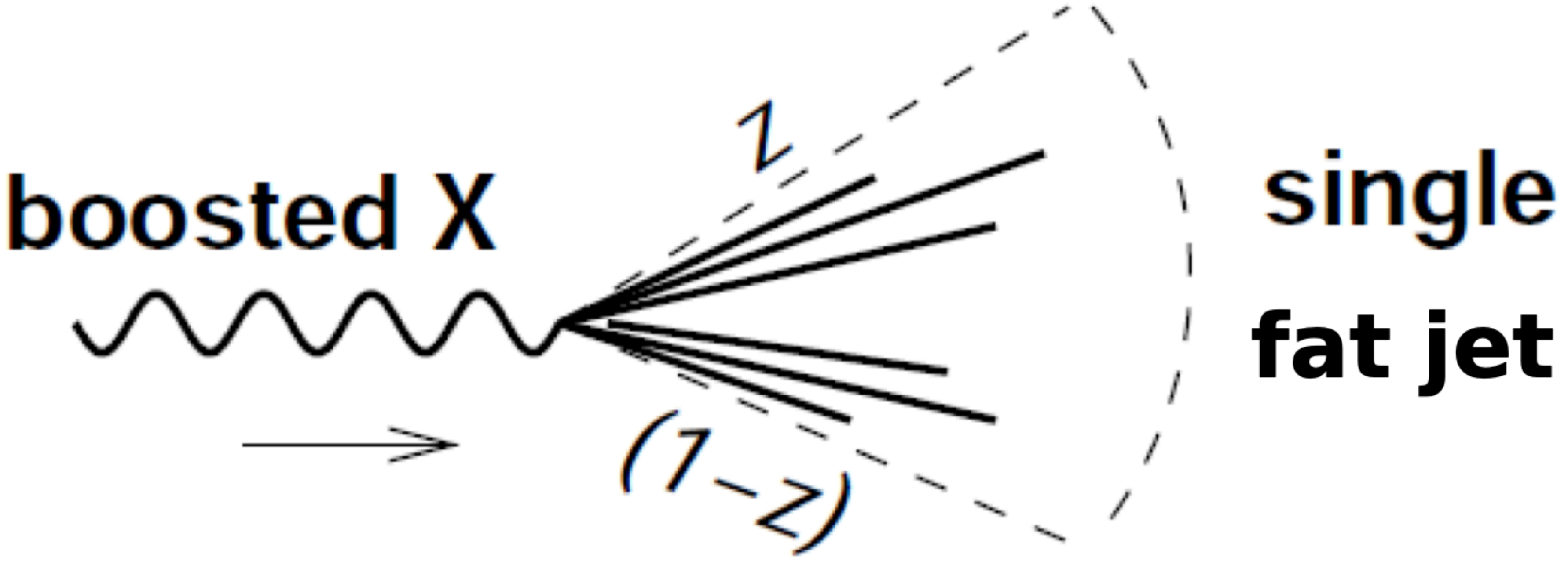
Boosted objects

At the LHC given the large center of mass energy and given that the SM particles have masses below 200 GeV, also the heaviest SM particles often acquire large momentum >> m → production of “boosted objects”

Normally we reconstruct jets with R=0.4,
if the object is boosted the jets in which it decays cannot be resolved in small r-jets

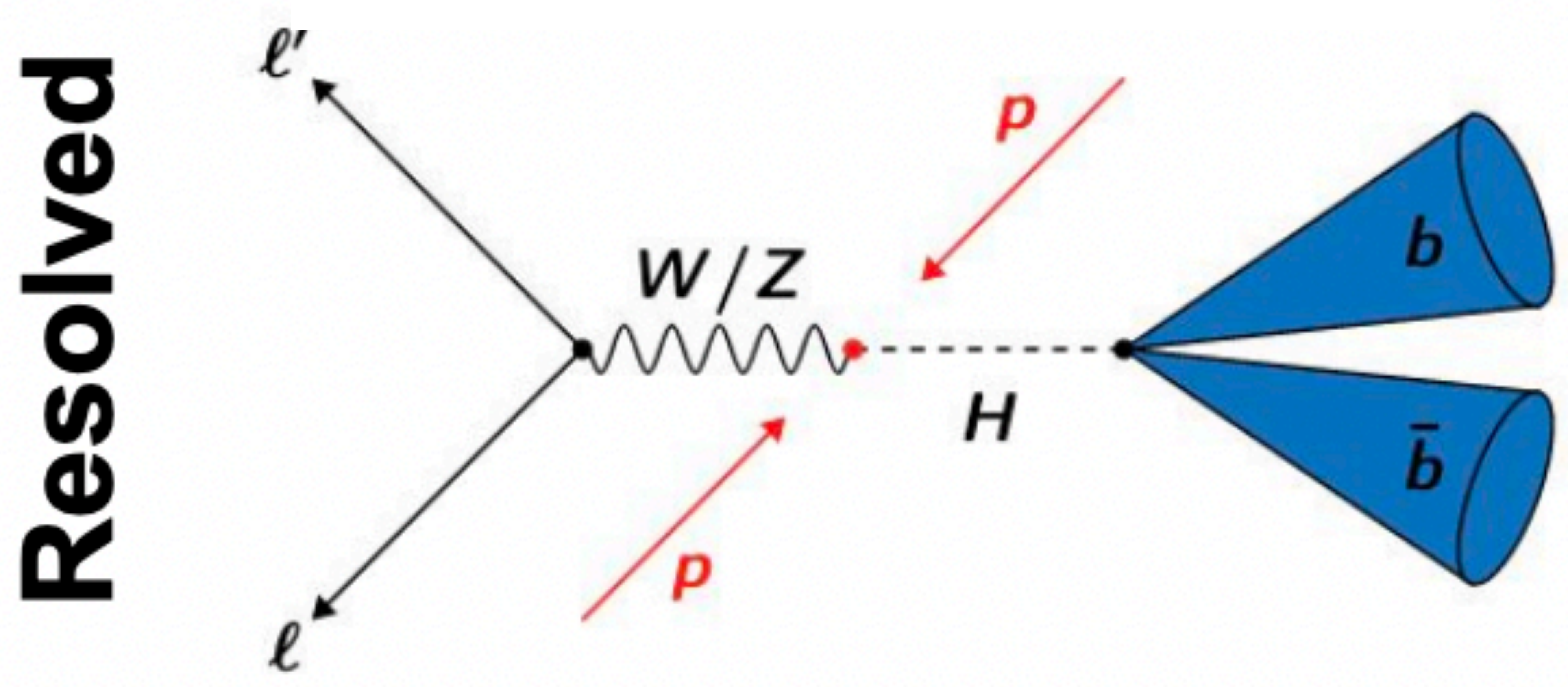


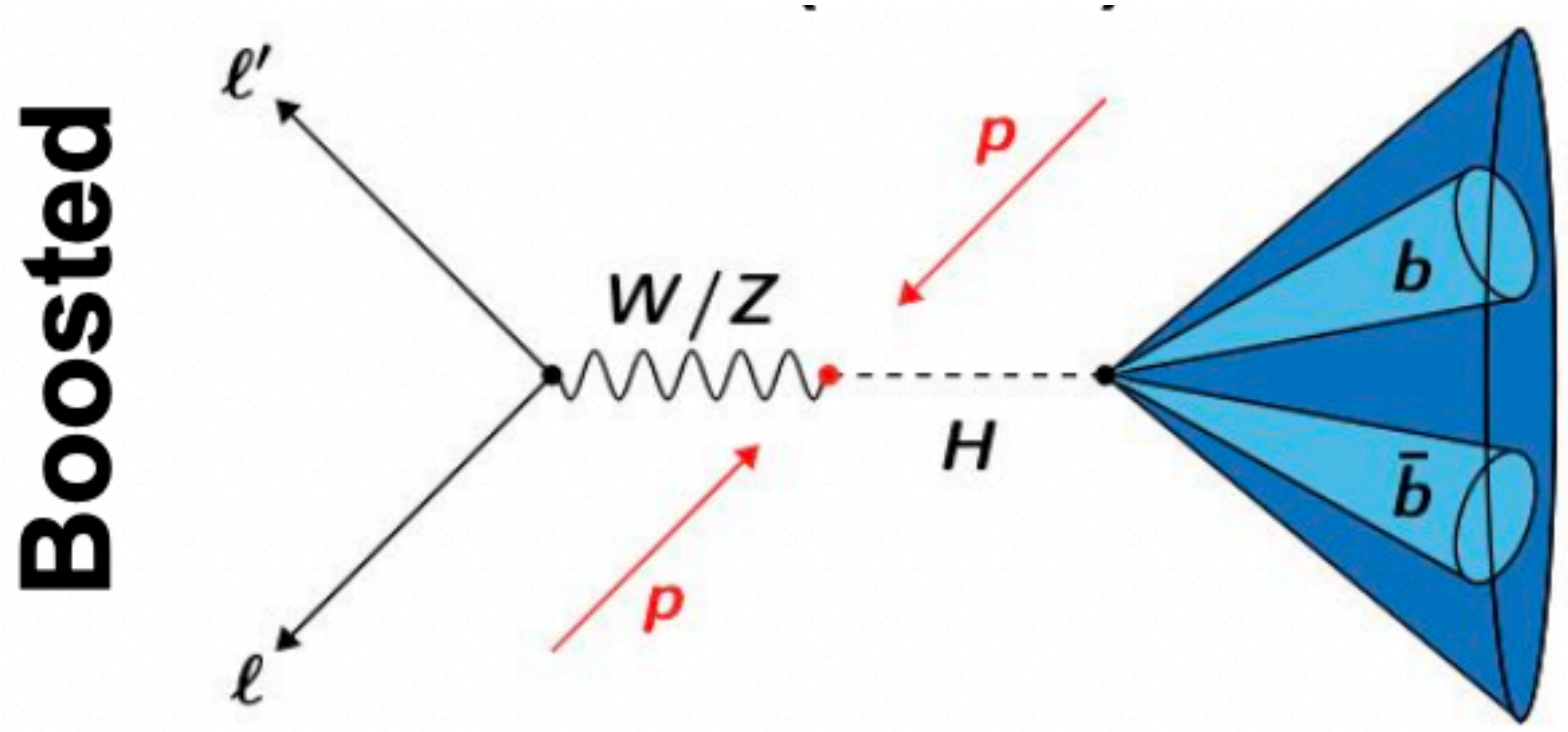
Recover sensitivity to boosted objects by developing boosted taggers, using larger R



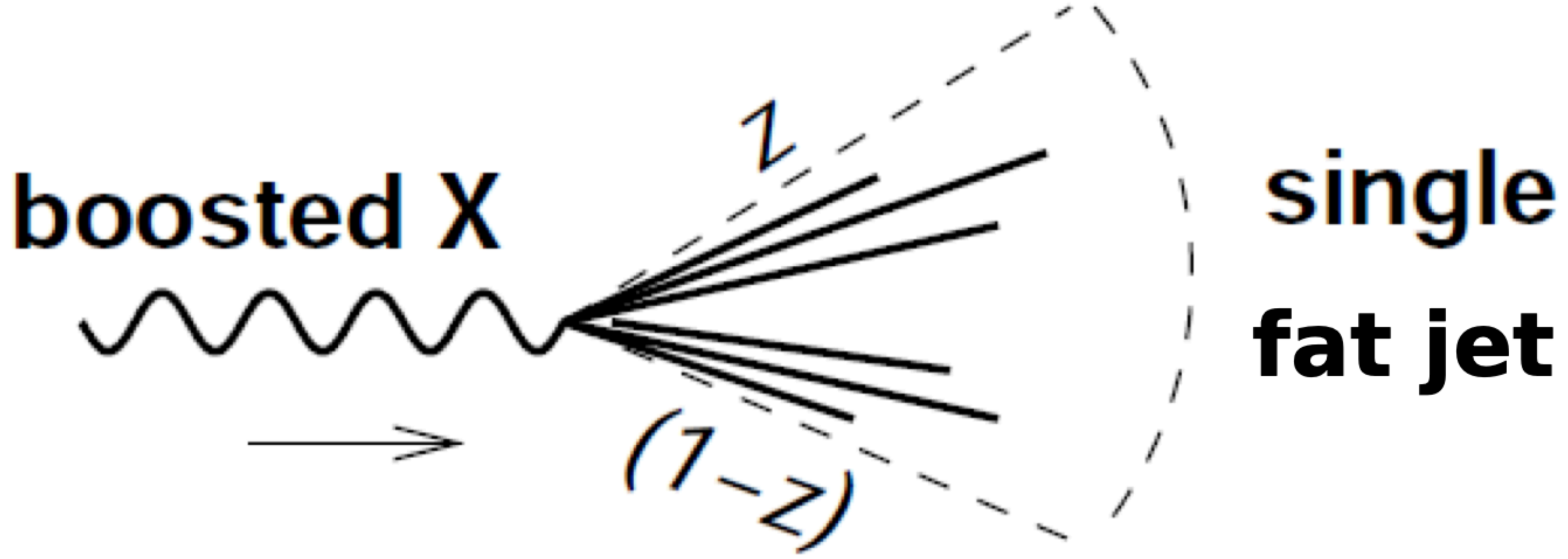
Boosted objects

At the LHC given the large center of mass energy and given that the SM particles have masses below 200 GeV, also the heaviest heaviest SM particles often acquire pT >> m → production of “boosted objects”





Recover sensitivity to boosted objects by developing boosted taggers, using larger R



Higgs boosted taggers for H→cc

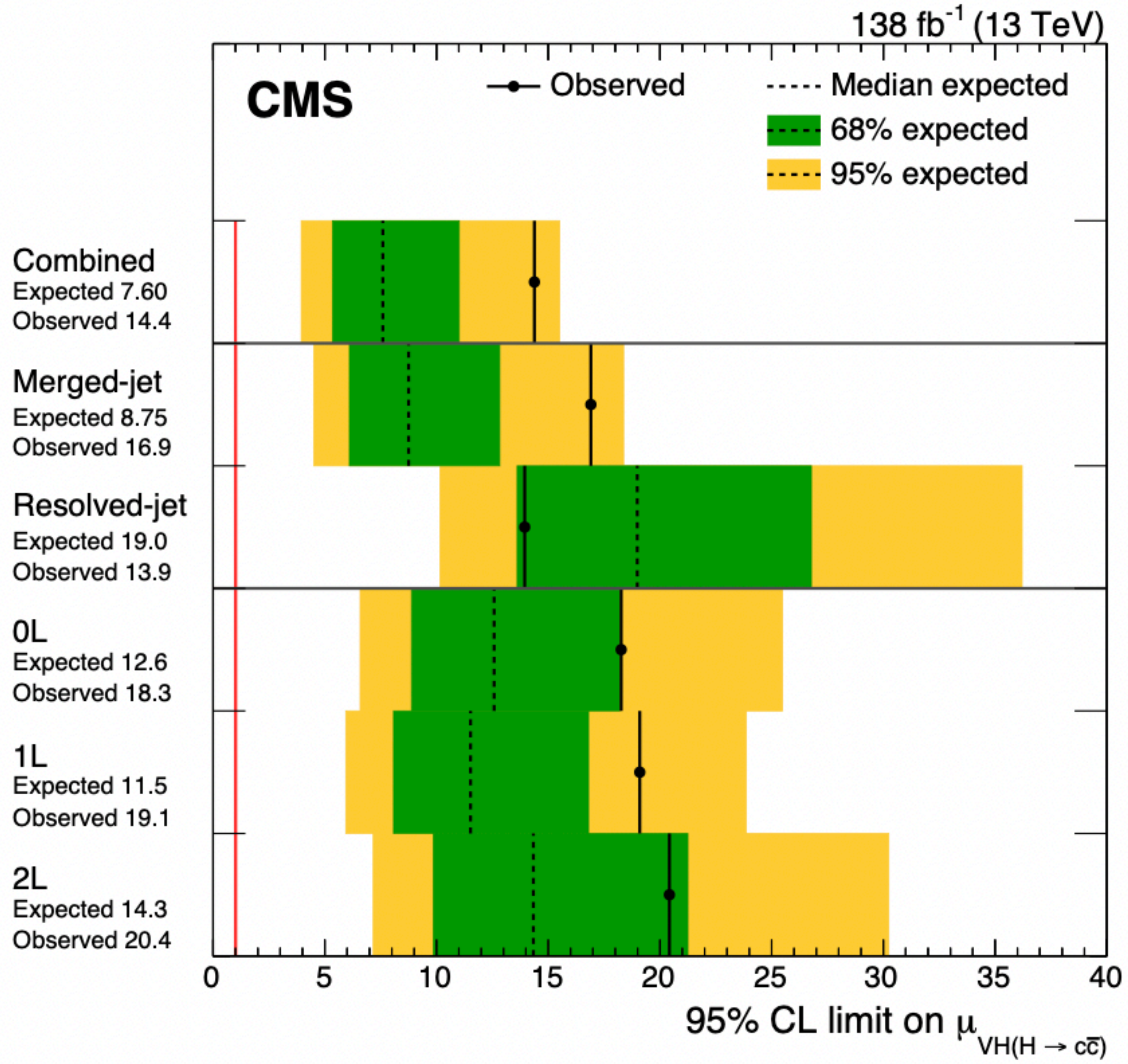
arXiv:2205.05550

Latest CMS Run 2 results (dataset 20 times smaller than HL-LHC) has sensitivity of 3.4 times the SM coupling in VH (WH,ZH) production mode. When the V has a large pT, the Higgs is boosted.

expected $|\kappa_c| < 3.4$ observed $1.1 < |\kappa_c| < 5.5$ @95% CL

thanks to exploitation of flavour tagging + reconstruction of the m_Higgs through boosted large R-jet using modern Machine learning techniques.

HL-LHC Lumi→ Expected sensitivity↓	VH(→ cc)	
	3 ab^{-1}	2.5 ab^{-1}
ATLAS	-	-
CMS	1.3	1.2
Combined	1.9	1.7



Adding inclusive Higgs and the VBF production modes +various improvements could lead to first direct evidence for the Yukawa coupling of the Higgs boson to charm at HL-LHC

It is therefore extremely important as an intermediate goal of Run 3 that progress is shown by all experiments in improving their sensitivity in this channel:

Graph nets

Graph nets

- Graph nets can be neural networks operating on graphs, but can be implemented with functions very different from neural networks. arXiv:1806.01261v3
  Networks acting on a “graph” rather than a vector of inputs, with output being a graph: Lot of activity on this in the past years in industry

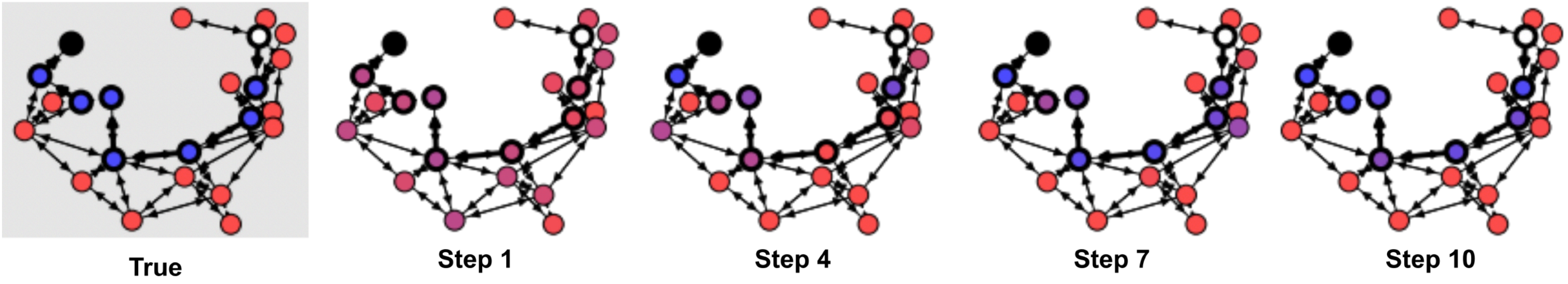
  Here one can find open-source software library for building graph nets, with demonstrations on how to use them:
  https://github.com/deepmind/graph_nets

- Quite some possibile applications: they have been used already for a variety of cases:
  - to learn the dynamics of physical systems (Battaglia et al., 2016; Chang et al., 2017; Watters et al., 2017; van Steenkiste et al., 2018; Sanchez-Gonzalez et al., 2018)
  - to predict the chemical properties of molecules (Duvenaud et al., 2015; Gilmer et al., 2017)
  - to predict traffic on roads (Li et al., 2017; Cui et al., 2018)
  - to classify and segment images and videos (Wang et al., 2018c; Hu et al., 2017)
  - to perform semi-supervised text classification (Kipf and Welling, 2017)
  - in machine translation (Vaswani et al., 2017; Shaw et al., 2018; Gulcehre et al., 2018)…

Graph nets: demo

- Find the shortest path in a graph: demo: tinyurl.com/gn-shortest-path-demo
  This demo creates random graphs, and trains a GN to label the nodes and edges on the shortest path between any two nodes. Over a sequence of message-passing steps (as depicted by each step's plot), the model refines its prediction of the shortest path.

Shortest path: predictions at each message-passing step

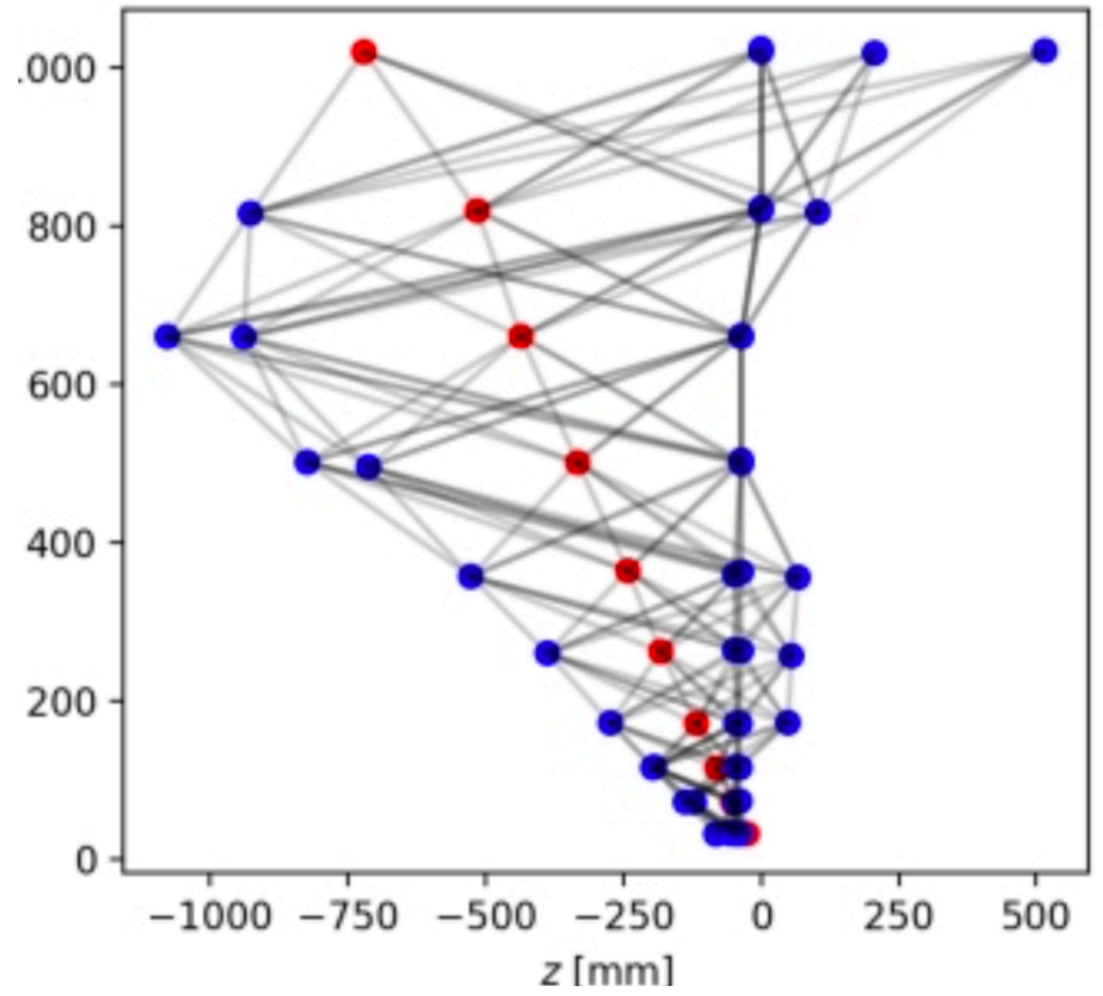


Where could we apply graph-nets?

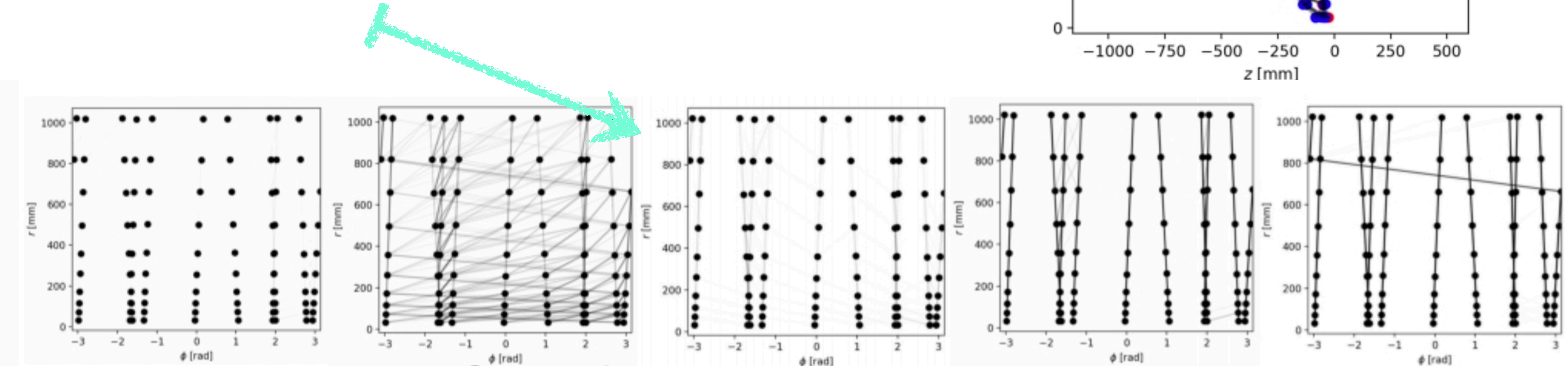
- A great improvement could be achieved by applying graph-nets to tracking

- Tracking is a very time consuming reco task at LHC (most consuming?)

- When applying graph-nets
  to track building one
  could for example use them to pair hits



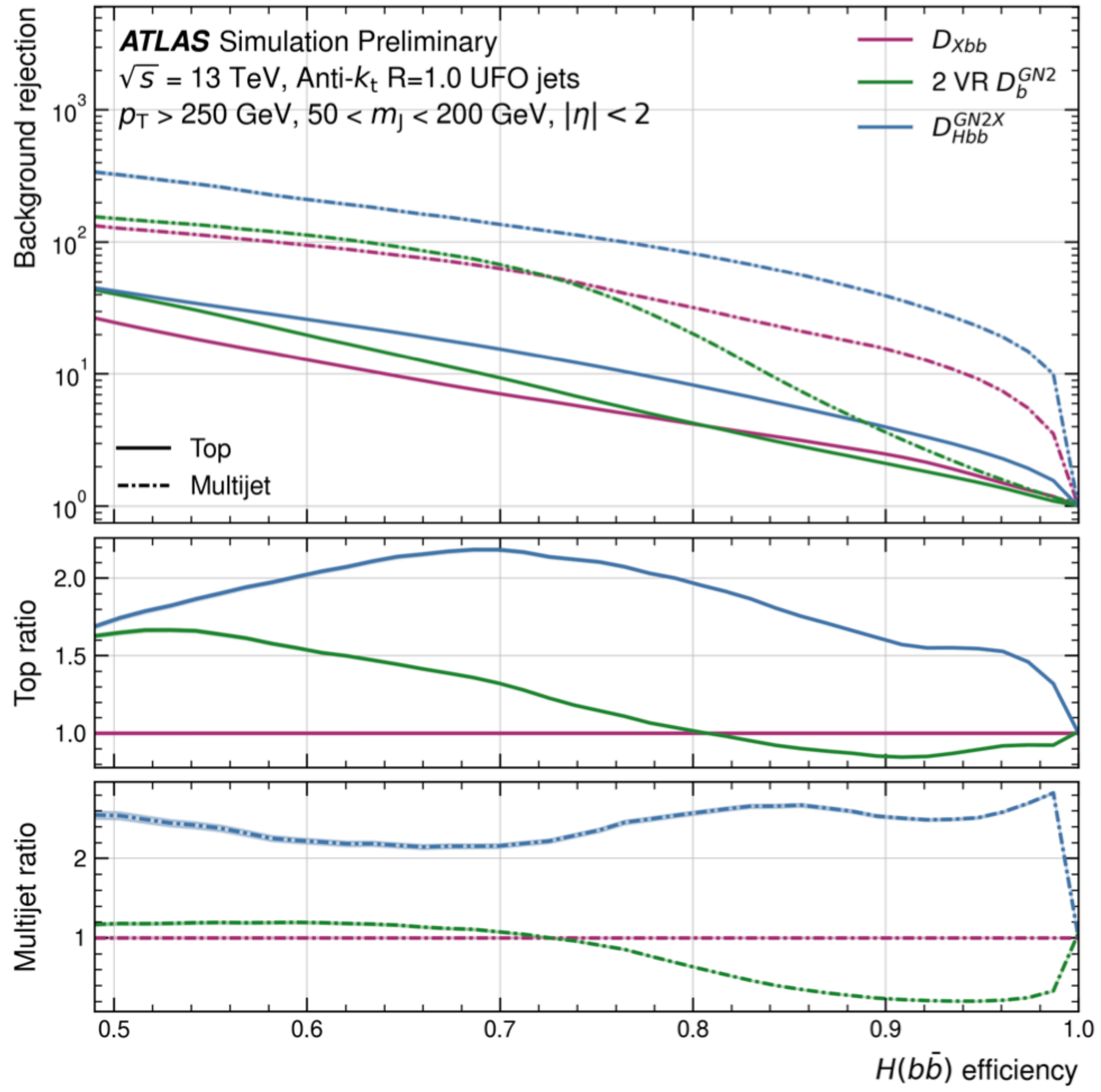
Successive iterations on an event



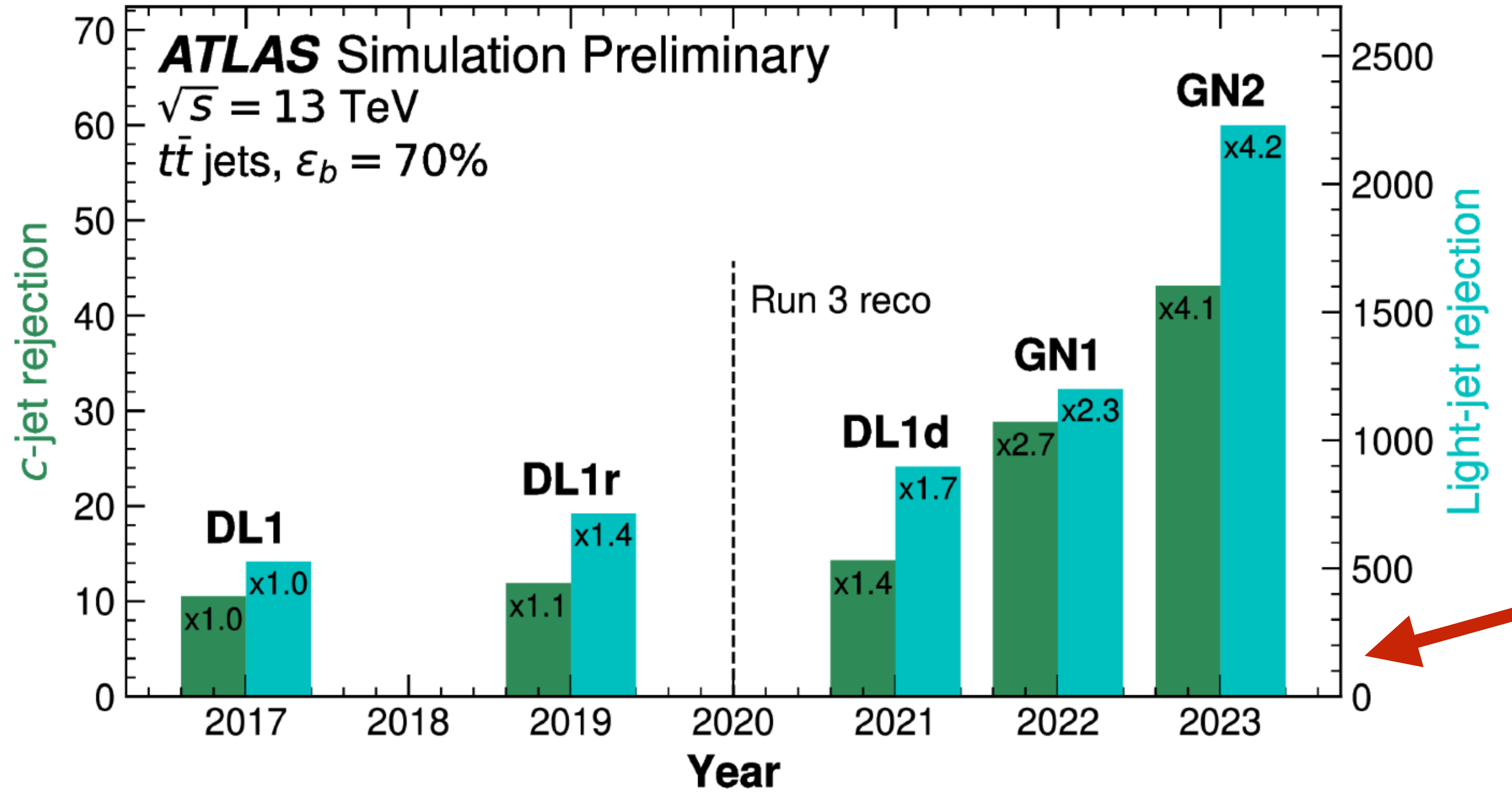
Flavor tagging in continuous evolution

Boosted H->bb/cc tagging
ATL-PHYS-PUB-2023-021

- Boosted b-tagging: new algorithm, GN2X for large-radius jets: tagging boosted H(bb) jets and H(cc) jets.



small R-jet tagging
Jet Flavour Tagging With GN1 and DL1d



- GN2X benefits from advances in flavour tagging of small-radius jets with Graph Neural Networks (GNNs)