A DECADE TURNING THE POSSIBLE INTO THE KNOWN

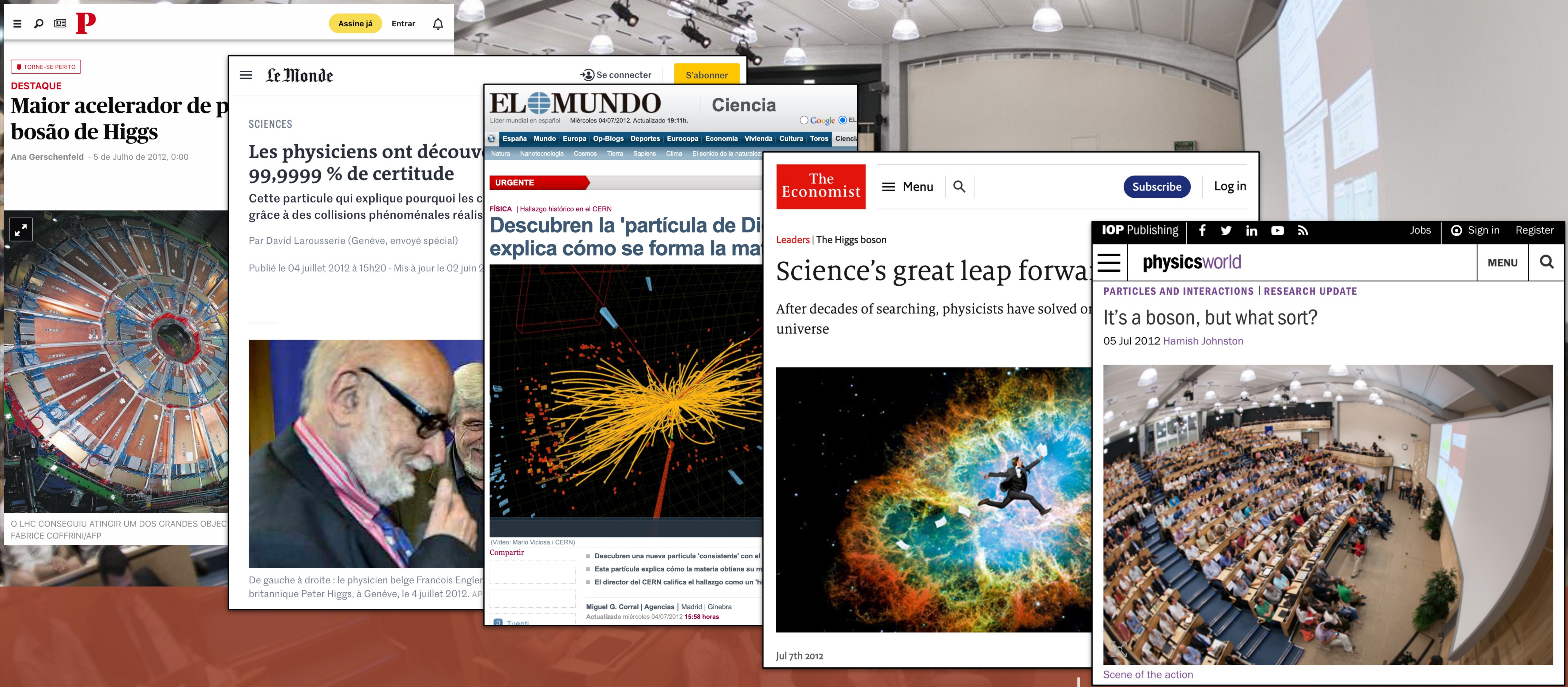
André David (CERN)
On behalf of the CMS and ATLAS Collaborations

CMS Compact Muon Solenoid

ATLAS EXPERIMENT

CERN 10 years HIGGS boson discovery

WHERE WE DISCOVERED A BOSON…


TORNE-SE PERITO
DESTAQUE
Maior acelerador de p
bosão de Higgs
Ana Gerschenfeld · 5 de Julho de 2012, 0:00
O LHC CONSEGUIU ATINGIR UM DOS GRANDES OBJEC
FABRICE COFFRINI/AFP

Le Monde
Se connecter
S'abonner
SCIENCES
Les physiciens ont découv
99,9999 % de certitude
Cette particule qui explique pourquoi les c
grâce à des collisions phénoménales réalis
Par David Larousserie (Genève, envoyé spécial)
Publié le 04 juillet 2012 à 15h20 - Mis à jour le 02 juin 2
De gauche à droite : le physicien belge Francois Engler
britannique Peter Higgs, à Genève, le 4 juillet 2012. AP

EL MUNDO
Ciencia
Líder mundial en español | Miércoles 04/07/2012. Actualizado 19:11h.
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Natura | Nanotecnología | Cosmos | Tierra | Sapiens | Clima | El sonido de la naturaleza
URGENTE
FÍSICA | Hallazgo histórico en el CERN
Descubren la 'partícula de Di
explica cómo se forma la ma
(Vídeo: Mario Viciosa / CERN)
Compartir
Descubren una nueva partícula 'consistente' con el
Esta partícula explica cómo la materia obtiene su m
El director del CERN califica el hallazgo como un 'hi
Miguel G. Corral | Agencias | Madrid | Ginebra
Actualizado miércoles 04/07/2012 15:58 horas

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Science's great leap forwa
After decades of searching, physicists have solved o
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Jul 7th 2012

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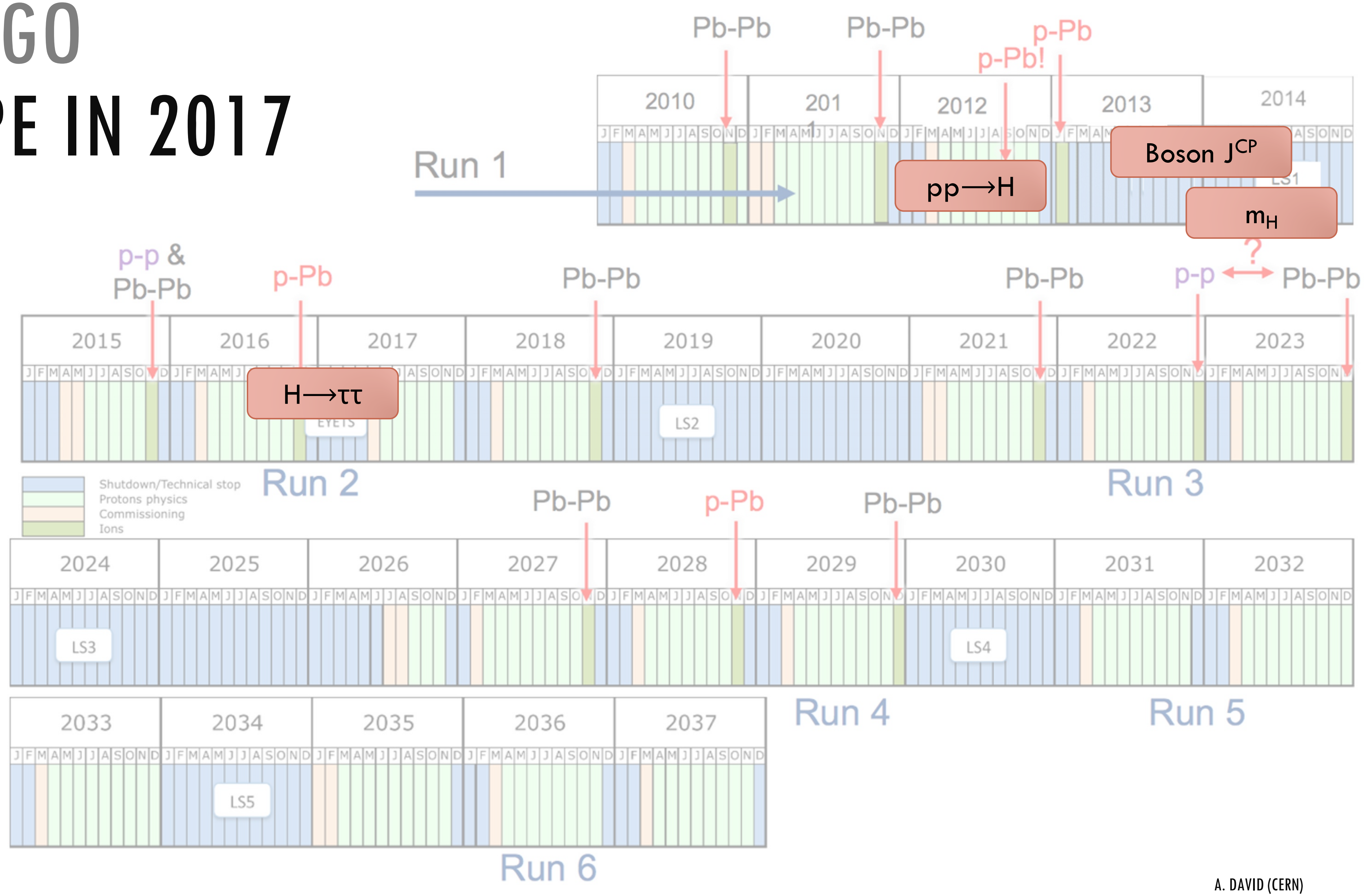
PARTICLES AND INTERACTIONS | RESEARCH UPDATE
It's a boson, but what sort?
05 Jul 2012 Hamish Johnston
Scene of the action

...BUT WHAT SORT OF BOSON?

5 YEARS AGO
LANDSCAPE IN 2017

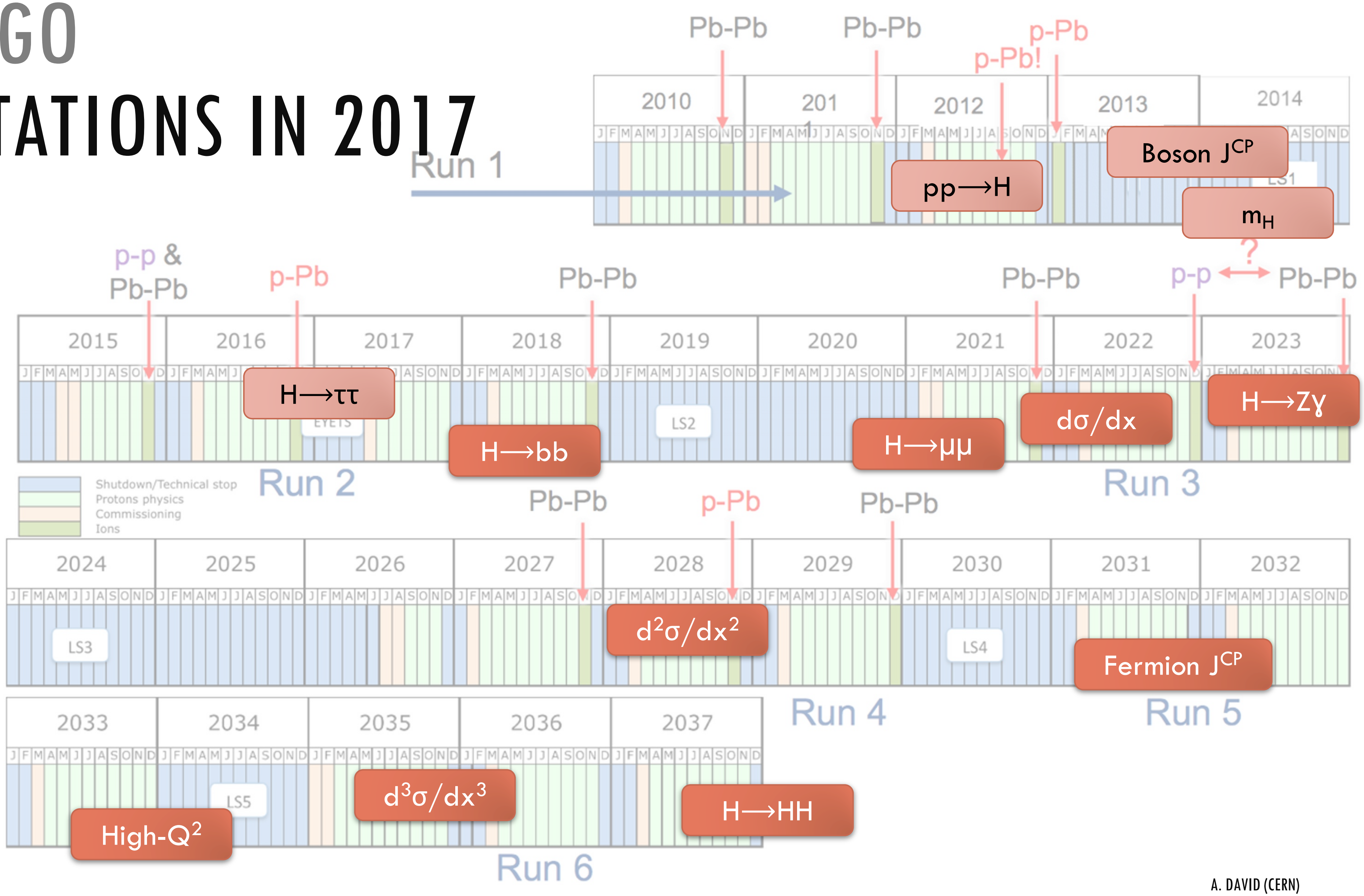
Explored by 2017



5 YEARS AGO
MY EXPECTATIONS IN 2017

Explored by 2017

I **expected** after 2017

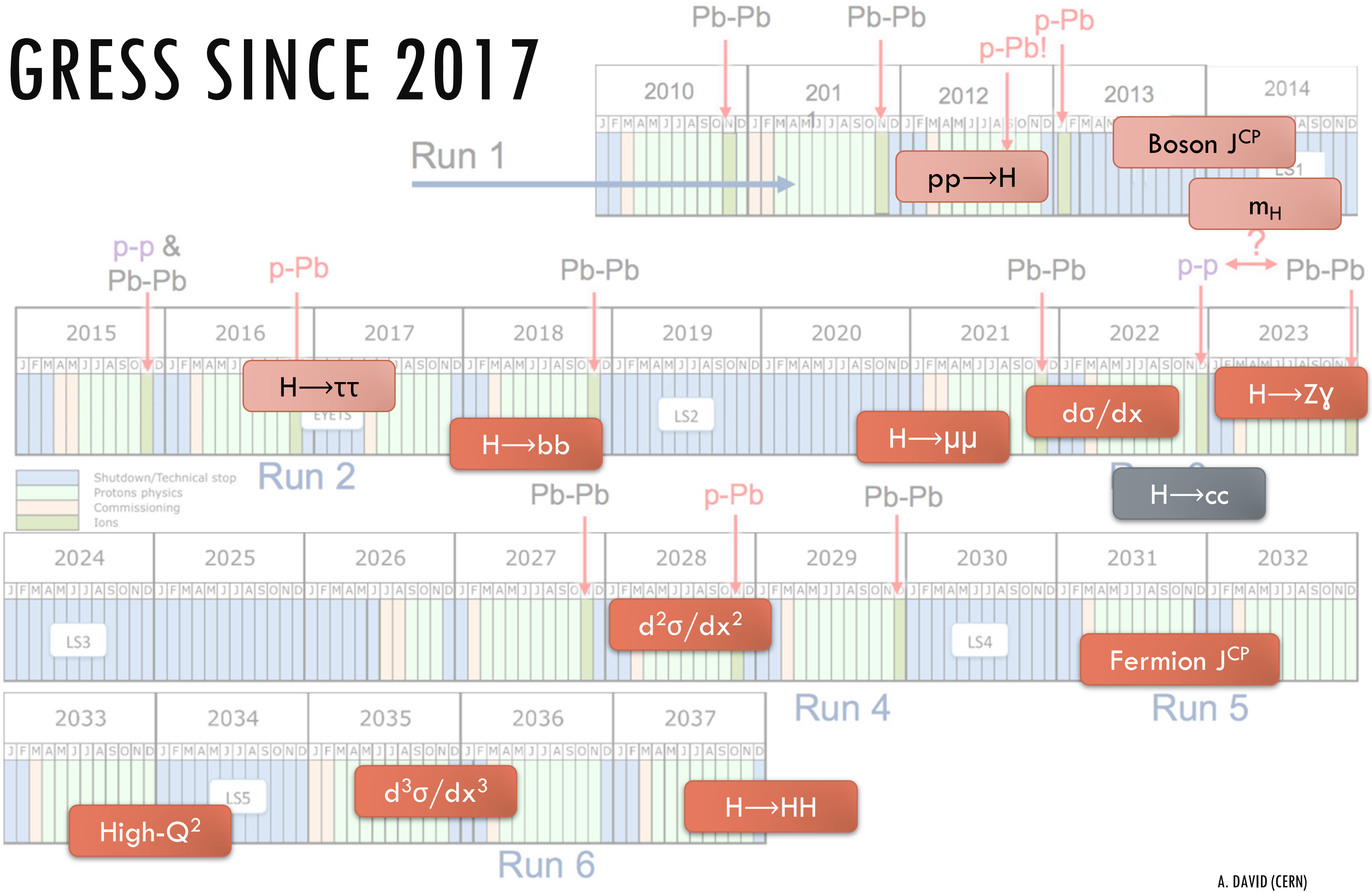


MUCH PROGRESS SINCE 2017

Explored by 2017

I **expected** after 2017

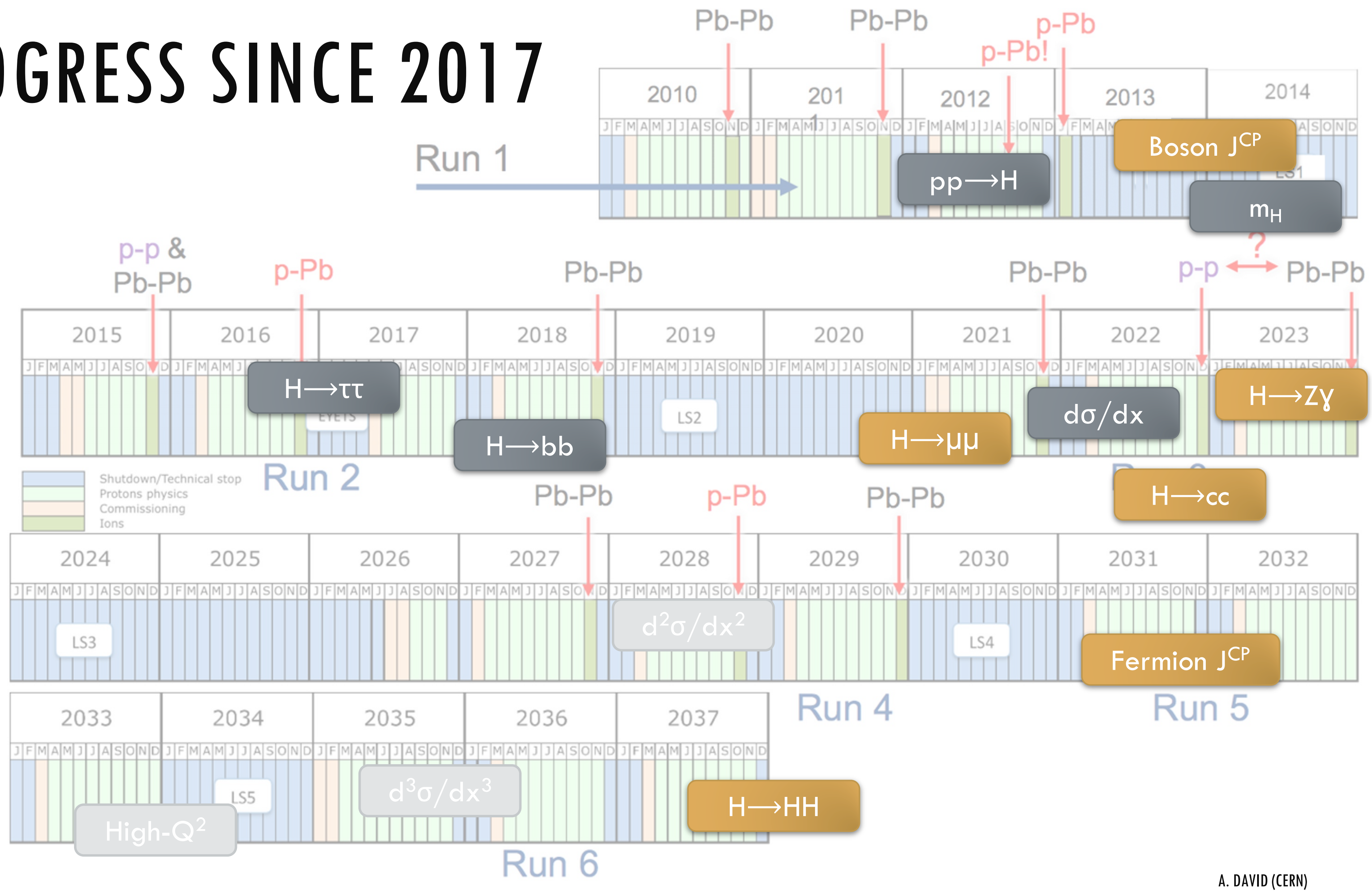
Beyond my expectations



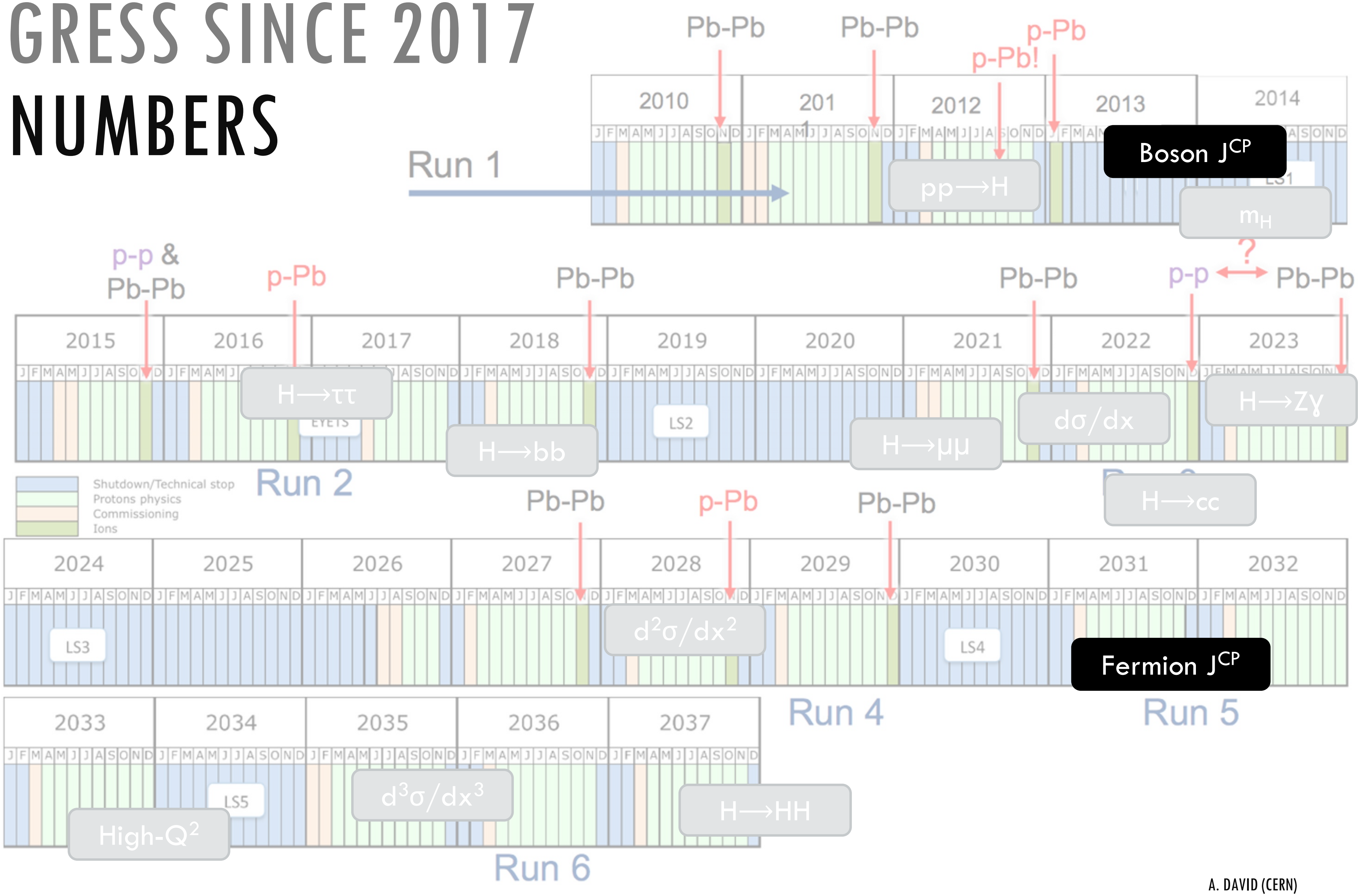
MUCH PROGRESS SINCE 2017

Previous talk

This talk



MUCH PROGRESS SINCE 2017
QUANTUM NUMBERS



Review of Particle Physics, Particle Data Group (2022)

QUANTUM NUMBERS
A PARTICLE'S FINGERPRINT

J = Spin angular momentum,

PC = Parity-Charge conjugation, and

q = Electric charge.

Each related to a symmetry.

GAUGE AND HIGGS BOSONS

γ (photon) $I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-46}$ e (mixed charge)
Charge $q < 1 \times 10^{-35}$ e (single charge)
Mean life τ = Stable

g or gluon $I(J^P) = 0(1^-)$

Mass $m = 0$ [a]
SU(3) color octet

graviton $J = 2$

W $J = 1$

Charge $= \pm 1$ e

Z $J = 1$

Charge $= 0$

H^0 $J = 0$

ZERO ELECTRIC CHARGE

J = Spin angul

PC = Parity-Ch

q = 0.

Each related to

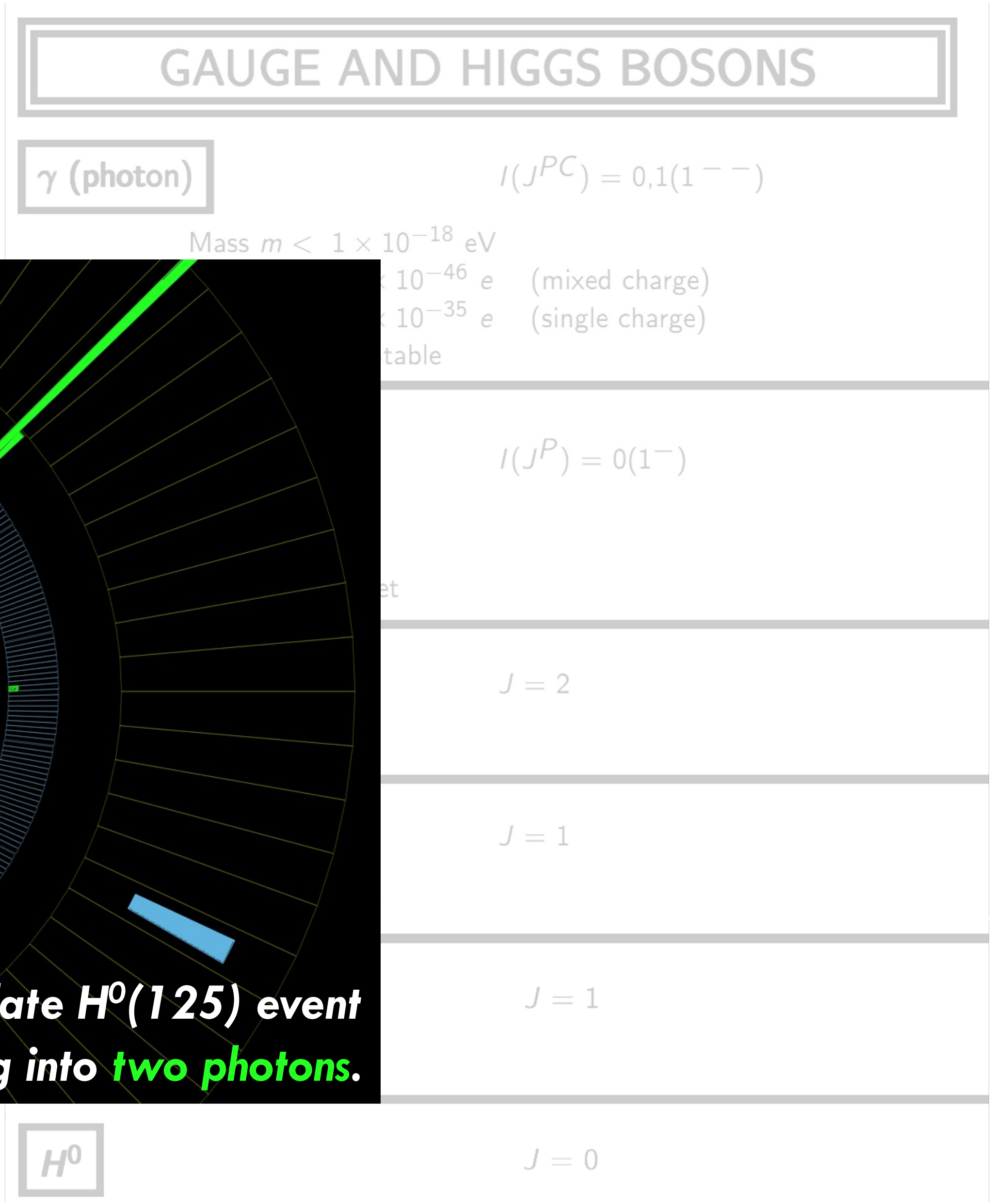

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table

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et

$J = 2$

$J = 1$

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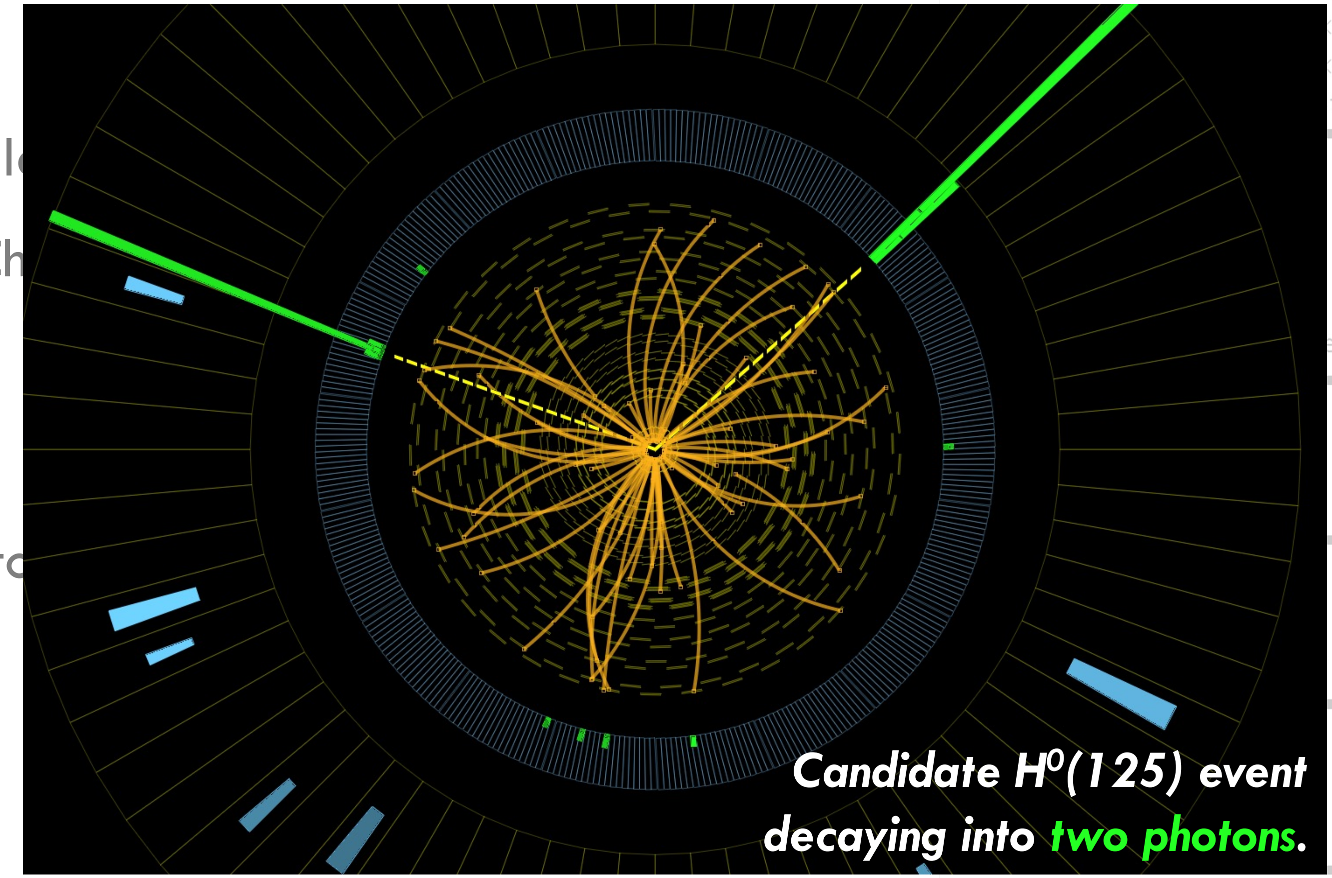
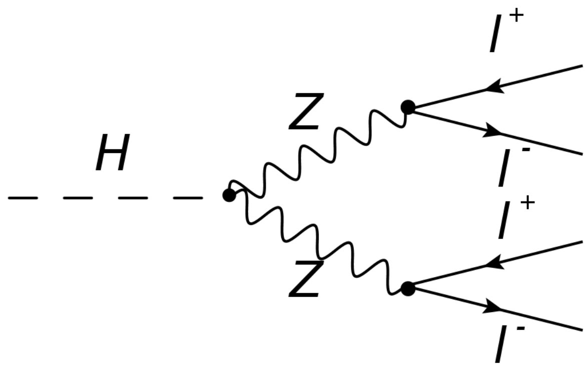
H^0 $J = 0$



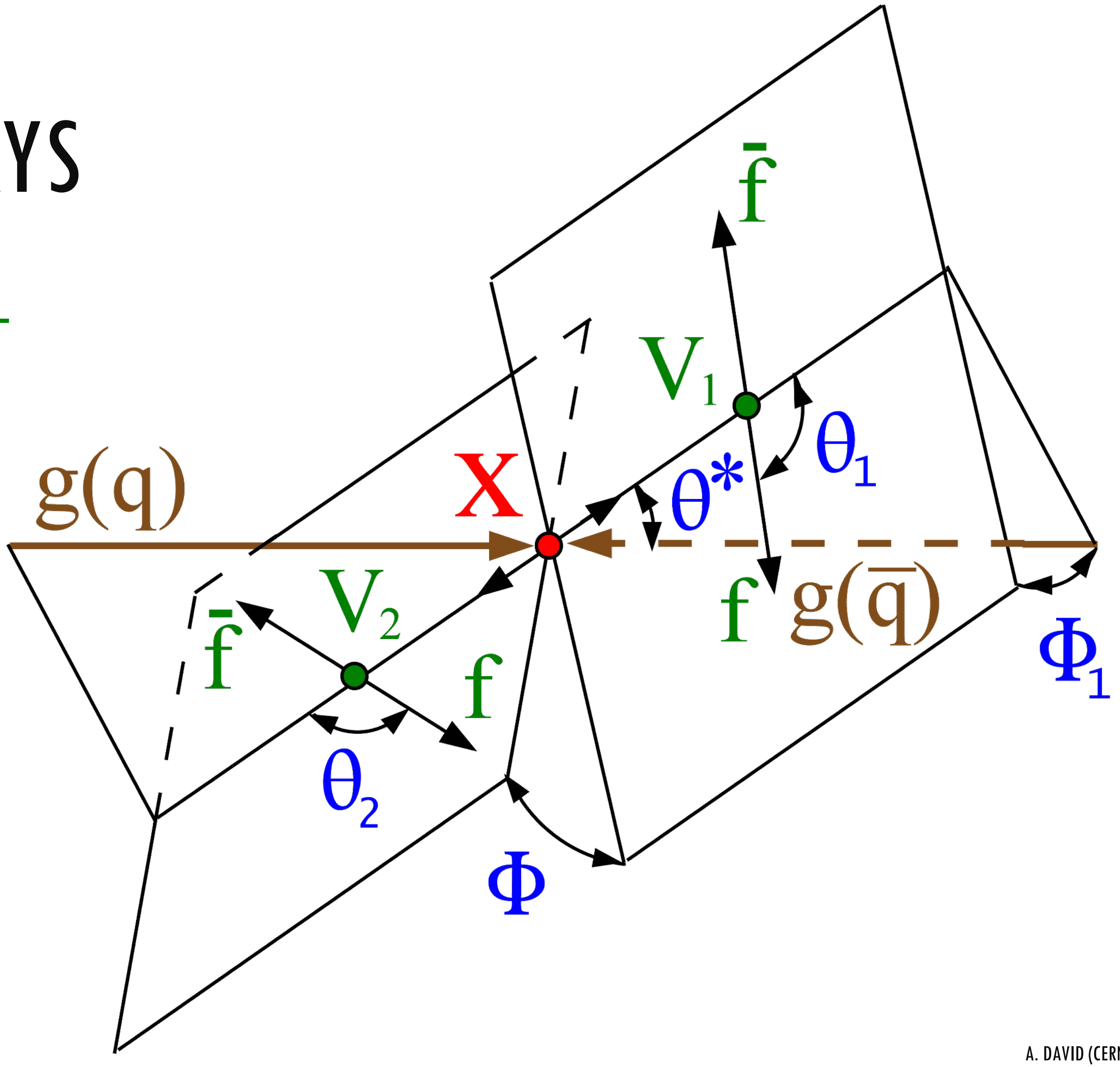
Candidate $H^0(125)$ event decaying into two photons.

SPIN-PARITY
FROM DI-BOSON DECAYS

Probed via **angular correlations** in di-boson decays (WW*, ZZ*, γγ).



Higgs decay to four charged leptons, an important channel for angular correlations.

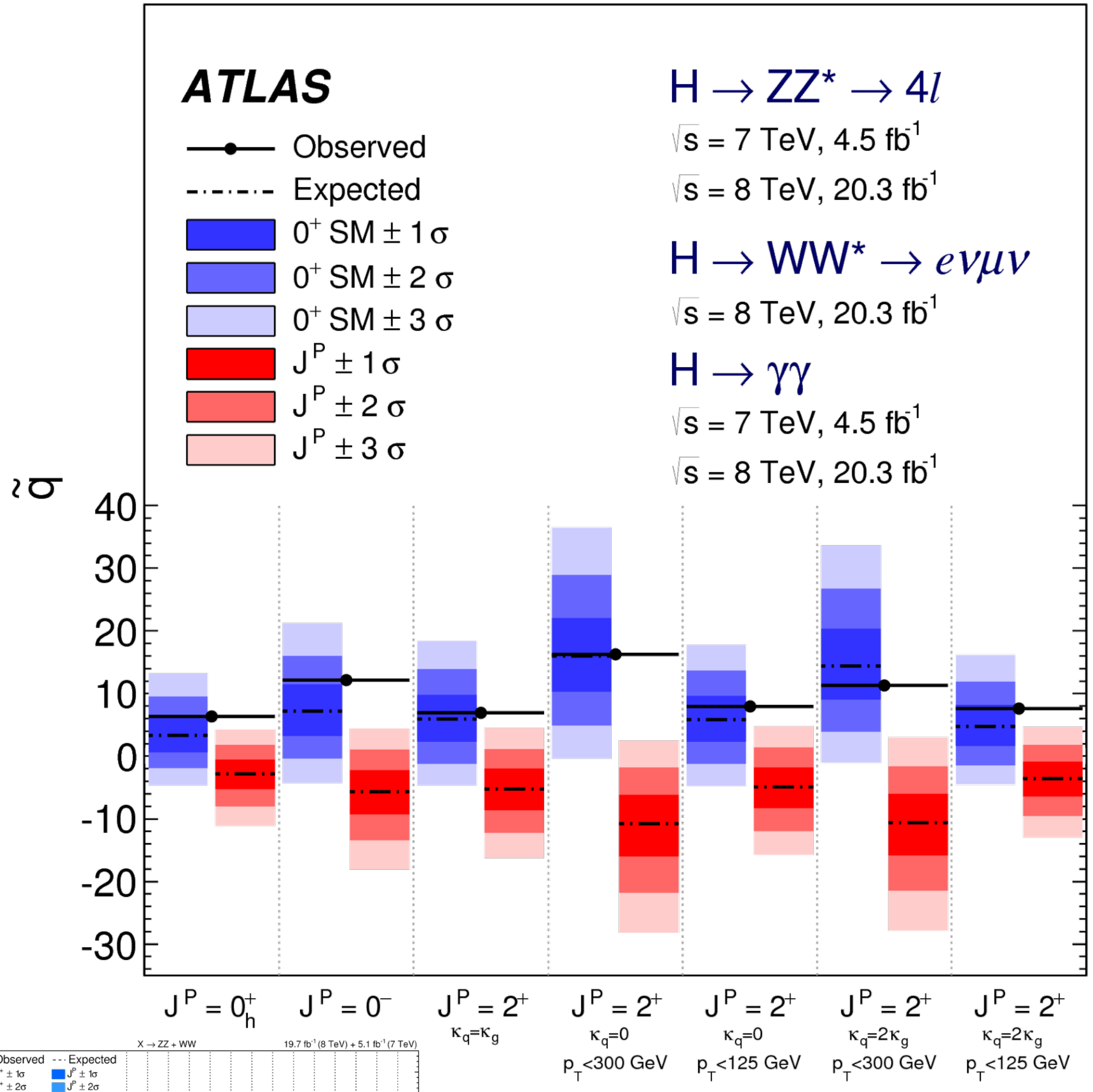


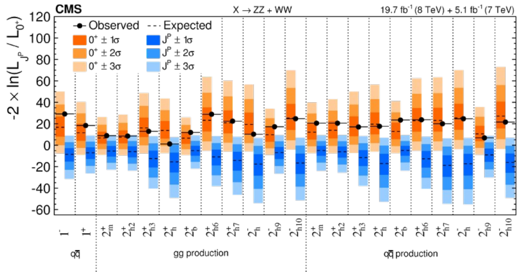
SPIN-PARITY FROM DI-BOSON DECAYS

Probed via angular correlations in di-boson decays (WW*, ZZ*, γγ).

Many **alternative spin-parity hypotheses** tested.

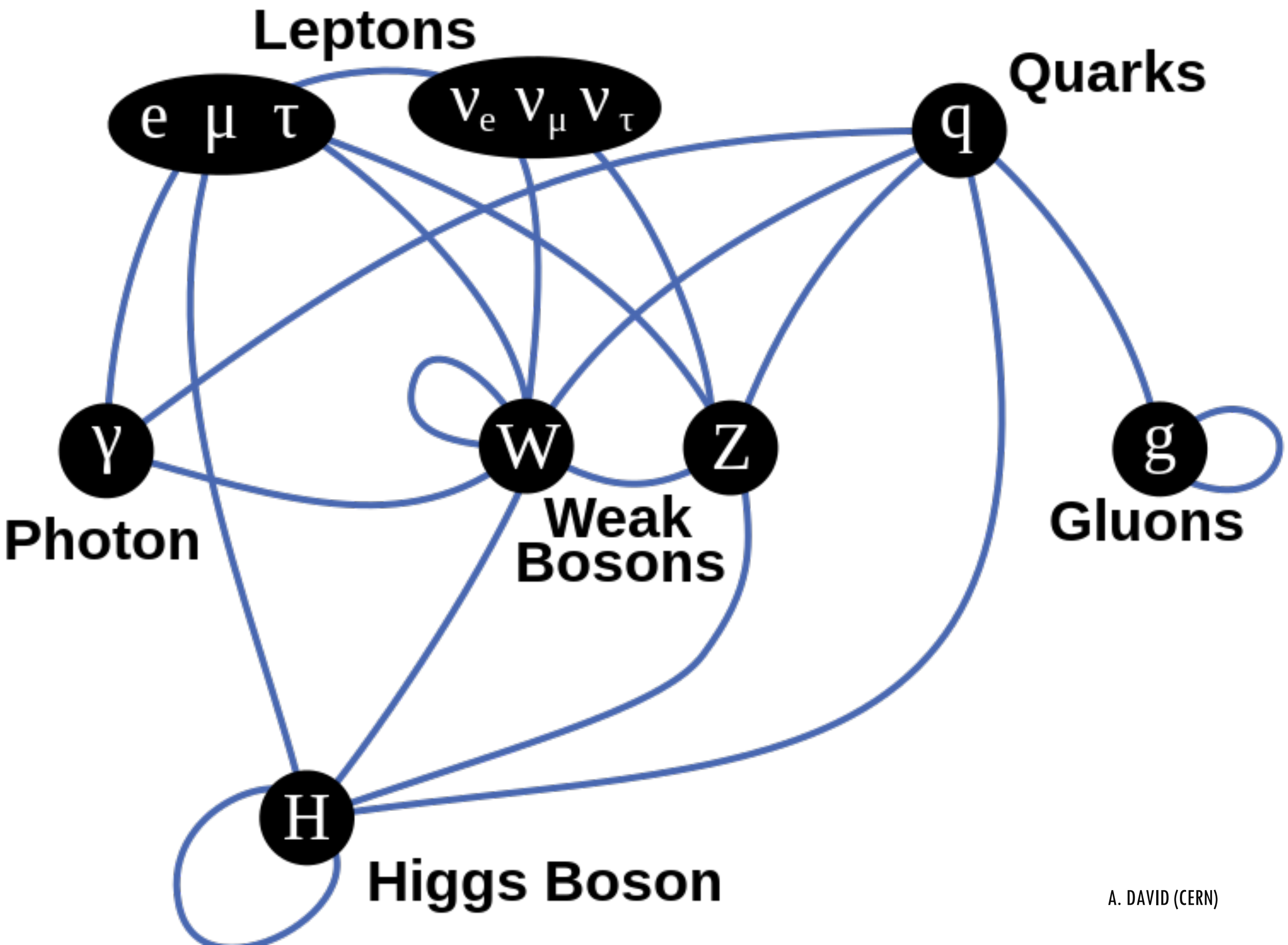
Data invariably compatible with spin zero and even parity, as predicted by **SM**.





PARITY
IN DI-TAU DECAYS

Higgs boson has many possible **interactions**.

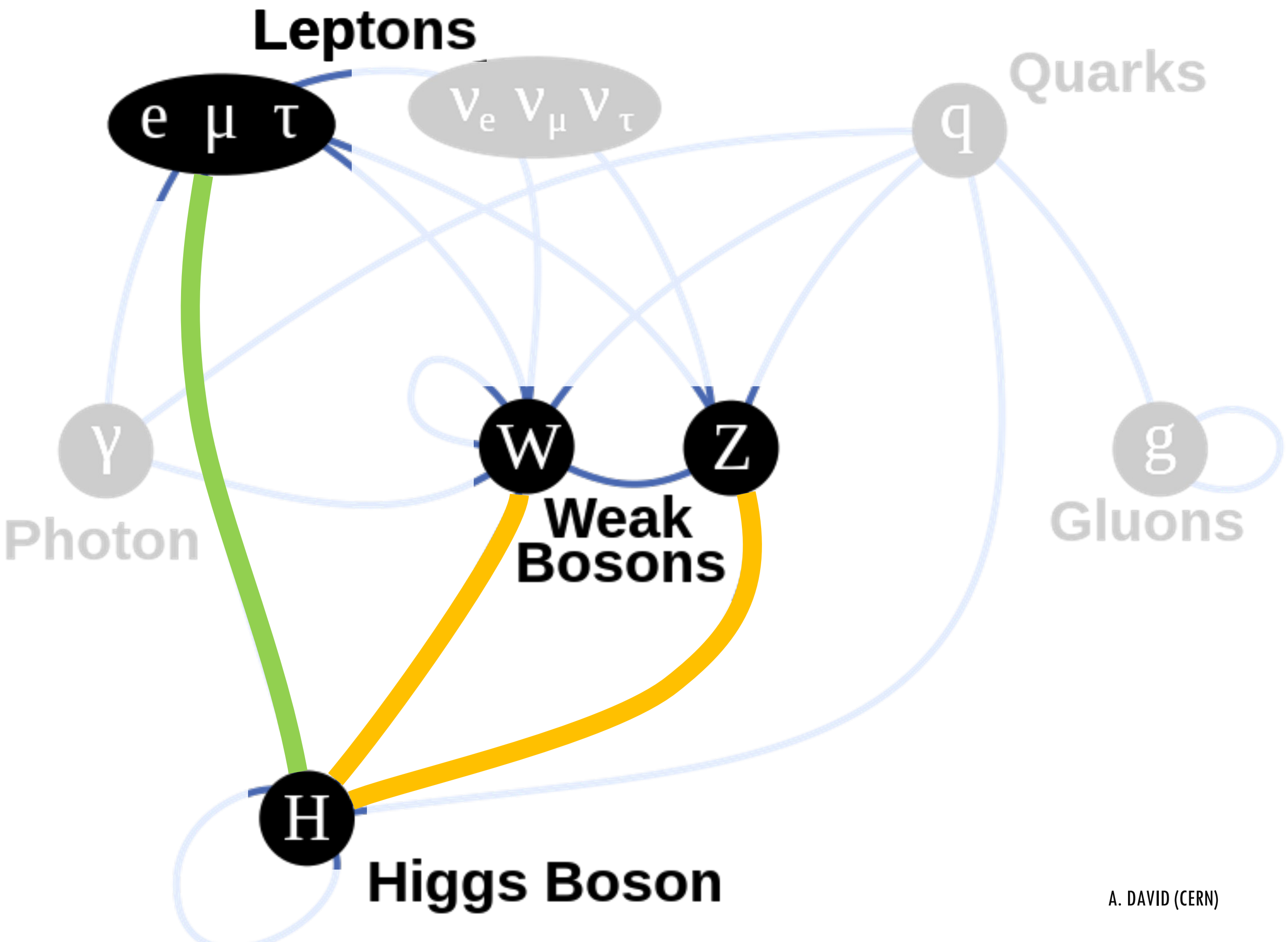


PARITY
IN DI-TAU DECAYS

Higgs boson has many possible interactions.

H^0(125) may interact differently with **tau leptons** and **bosons**.

SM predicts same parity in both.



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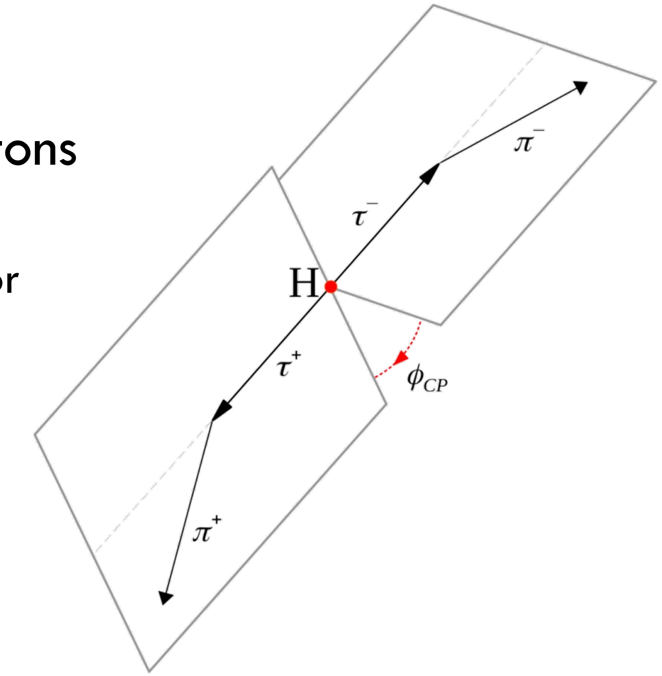


Probed via **angular correlations** in **$H^0(125)\to\tau\tau$ decays.**

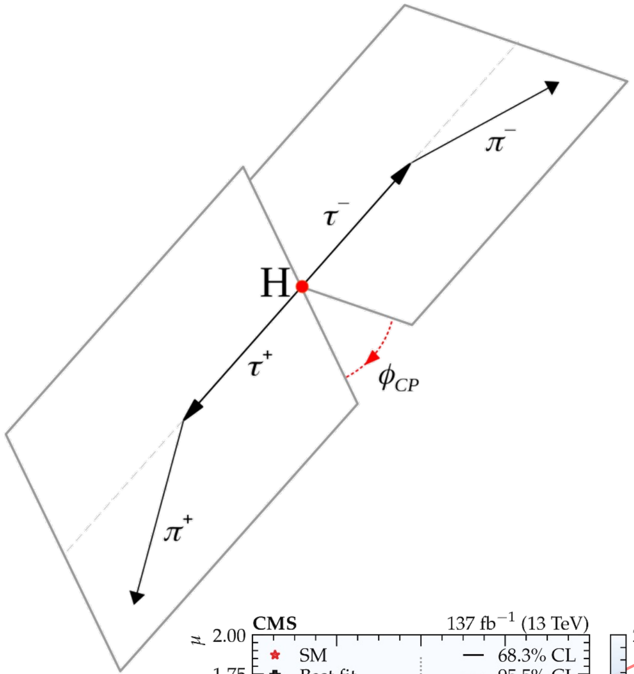
PARITY
IN DI-TAU DECAYS

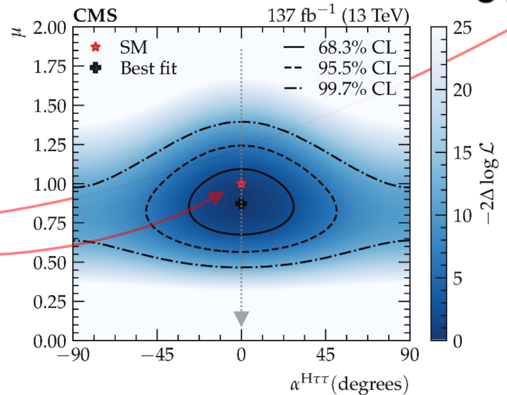
Tau leptons and bosons may interact differently with $H^0(125)$.

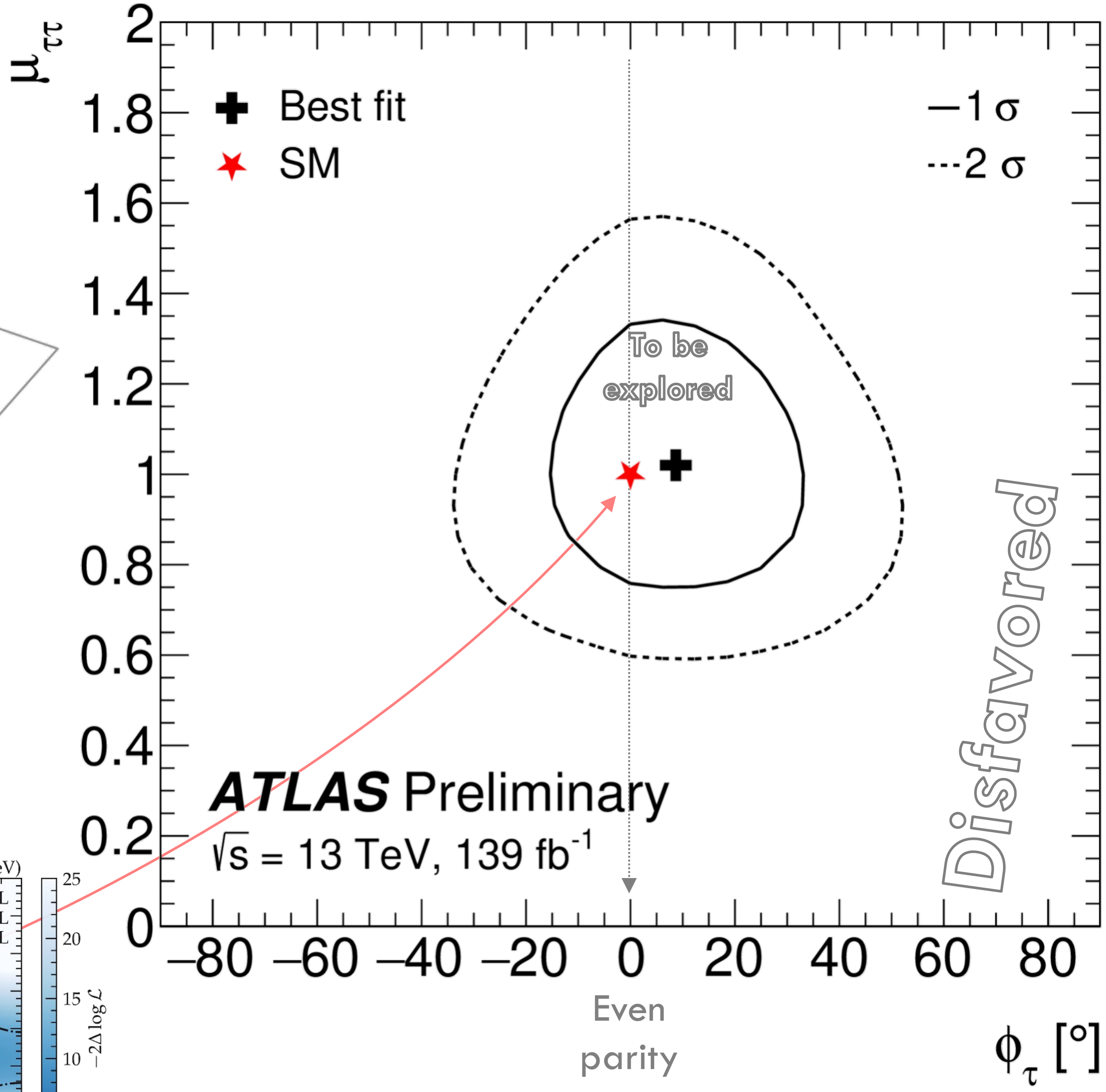
- SM predicts same parity for both.

Probed via angular correlations in $H^0(125) \rightarrow \tau\tau$ decays.

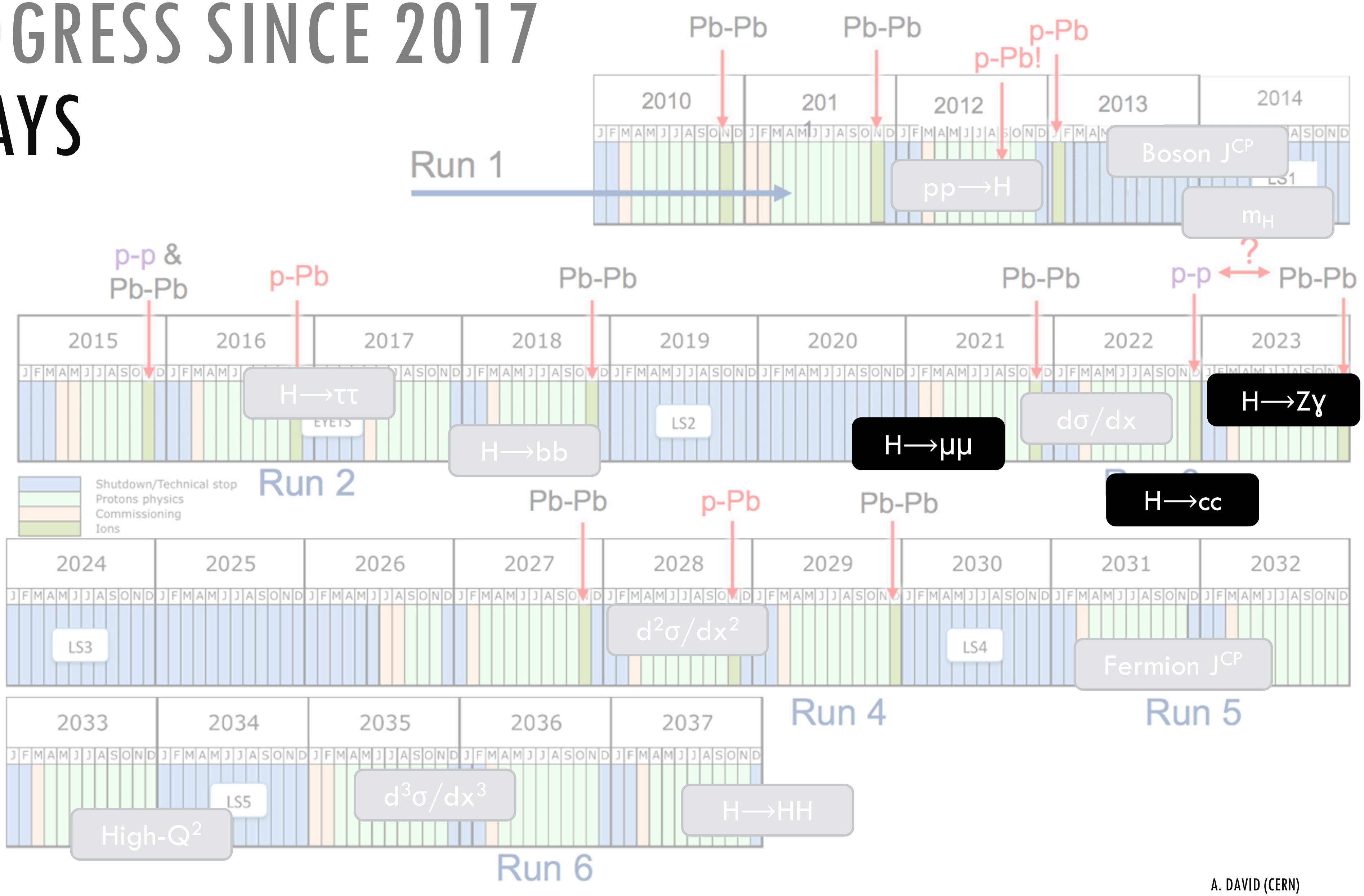
Data compatible with **even parity** and **SM** prediction.





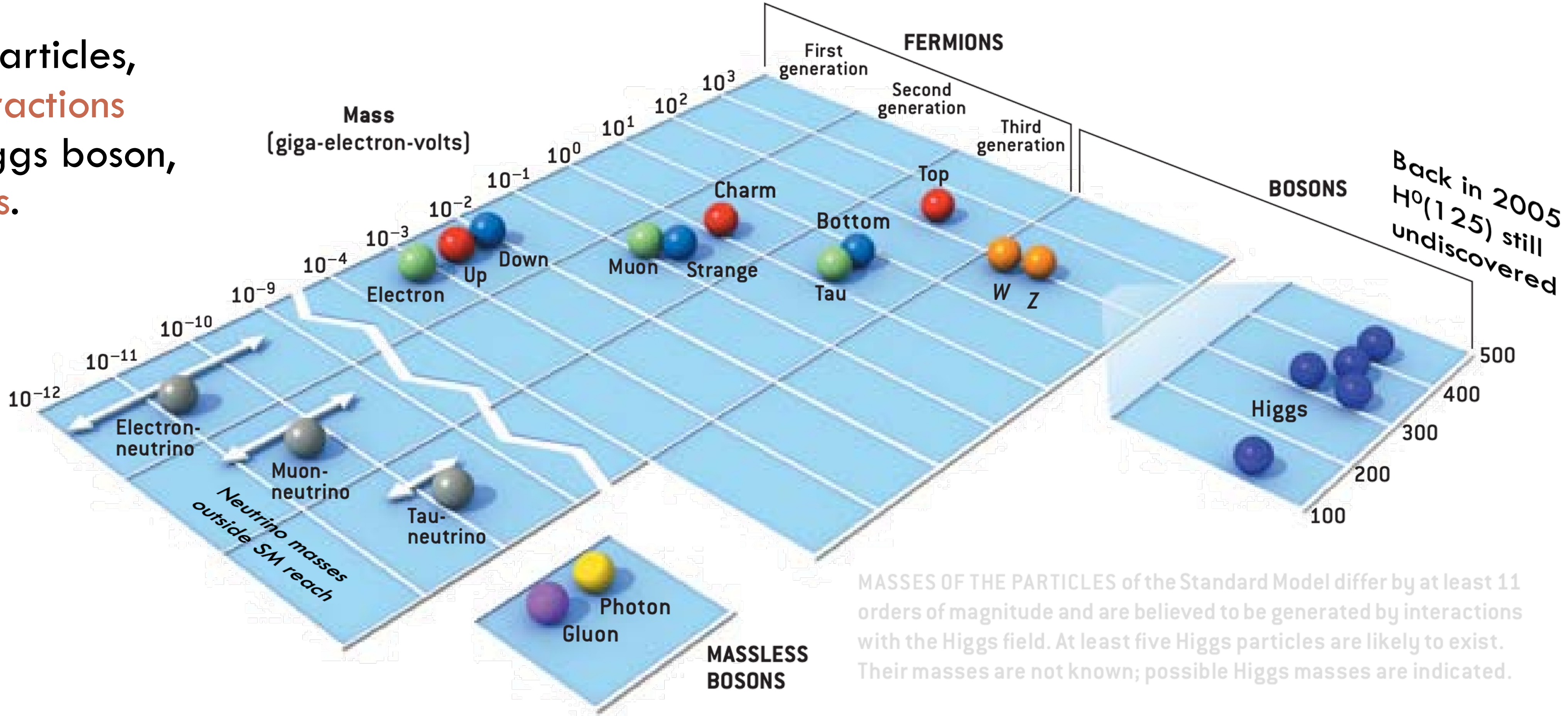


MUCH PROGRESS SINCE 2017
RARE DECAYS



RARE DECAYS

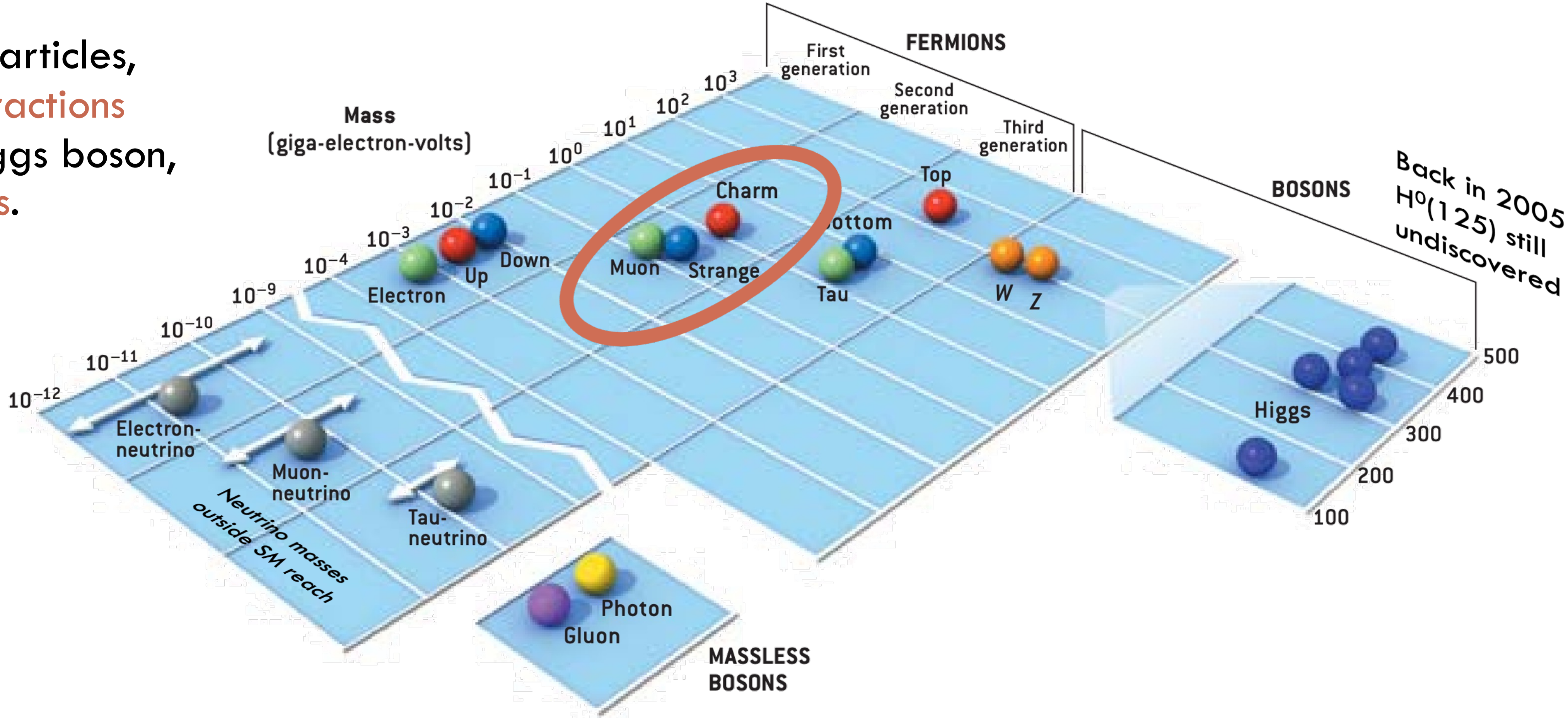
Low mass particles,
feeble interactions
with the Higgs boson,
rare decays.



MASSES OF THE PARTICLES of the Standard Model differ by at least 11 orders of magnitude and are believed to be generated by interactions with the Higgs field. At least five Higgs particles are likely to exist. Their masses are not known; possible Higgs masses are indicated.

RARE DECAYS – THE SECOND GENERATION

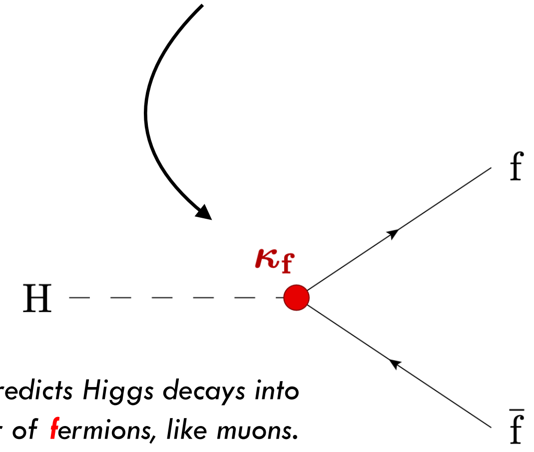
Low mass particles,
feeble interactions
with the Higgs boson,
rare decays.



HIGGS & MUONS

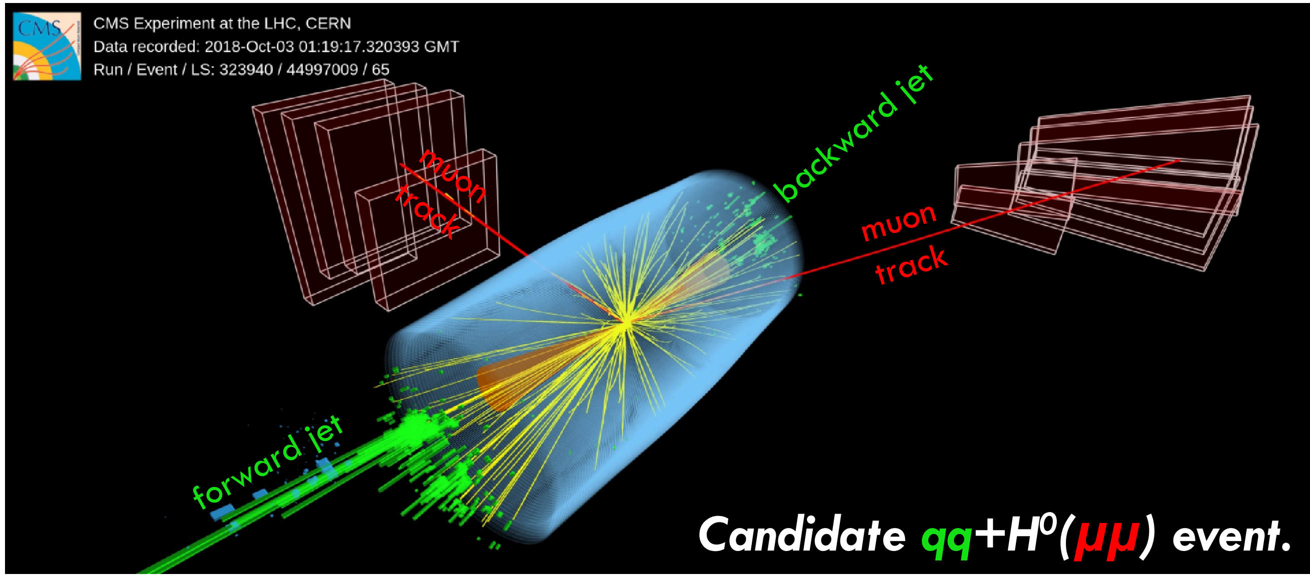
Exploit all production modes.

- Candidate events compatible with different associated production modes and a **$H^0(125)\rightarrow\mu\mu$ decay**.



SM predicts Higgs decays into a pair of fermions, like muons.

HIGGS & MUONS



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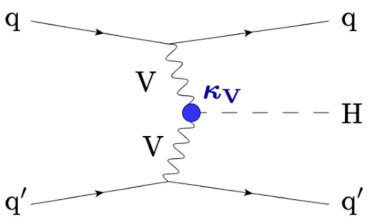

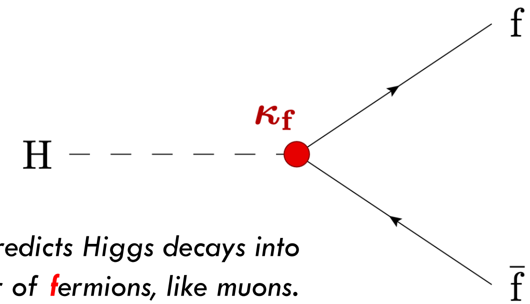

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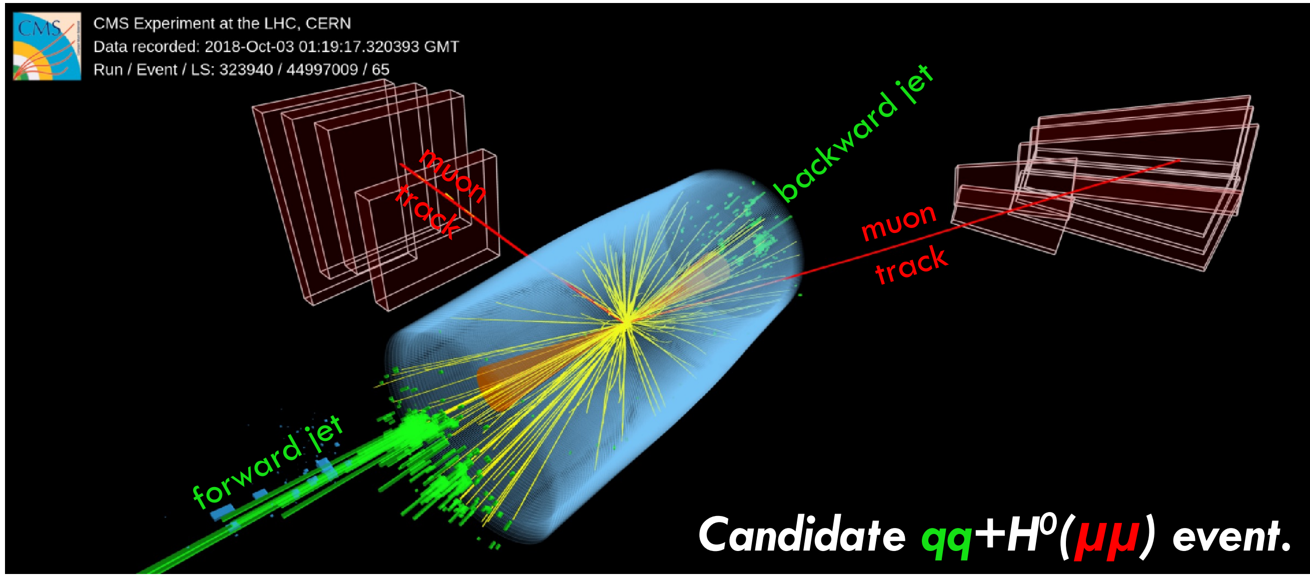

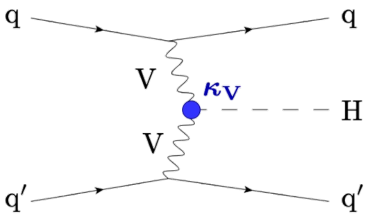

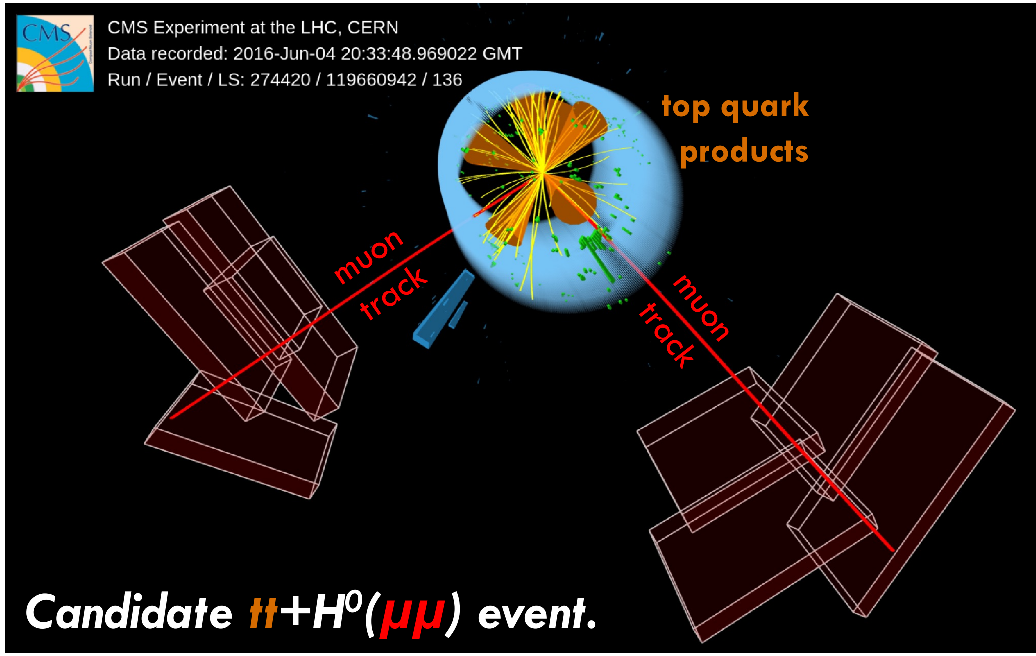

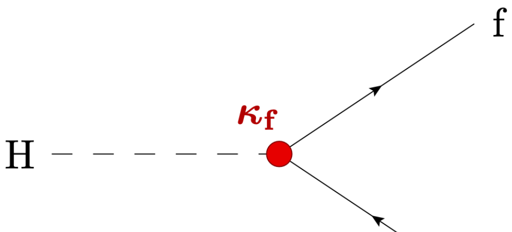

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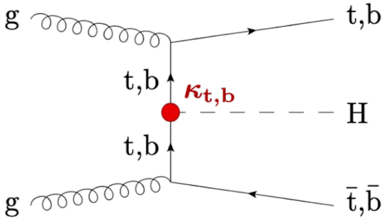
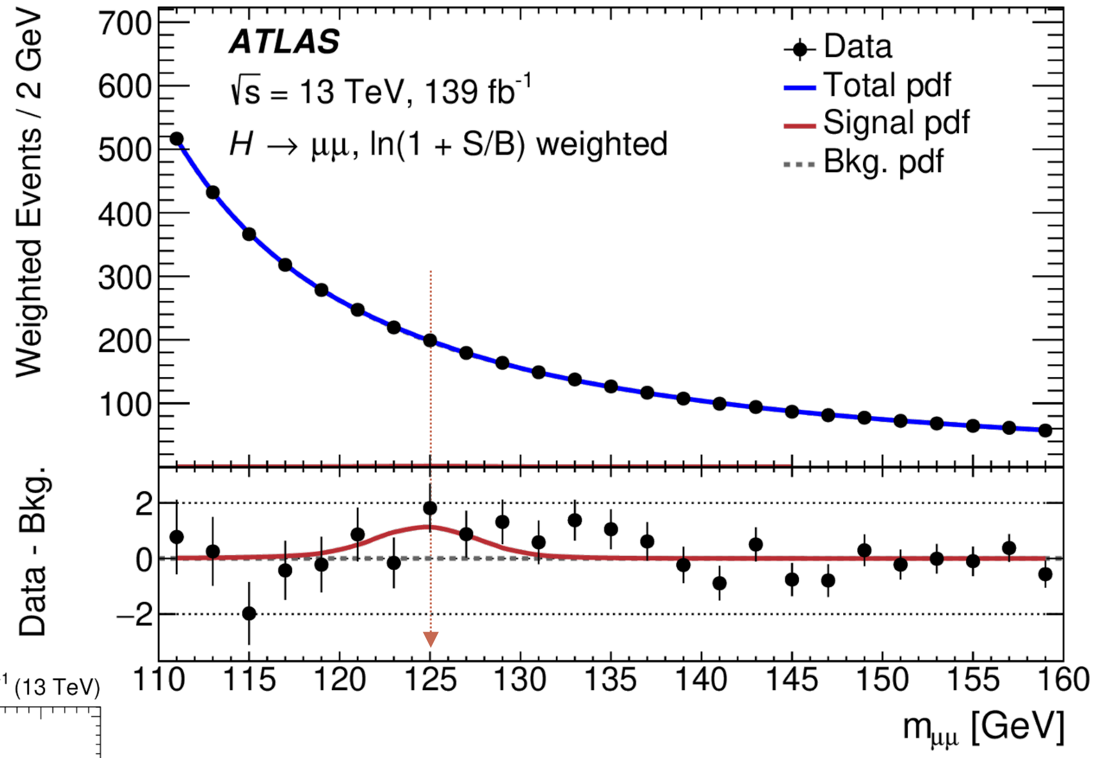
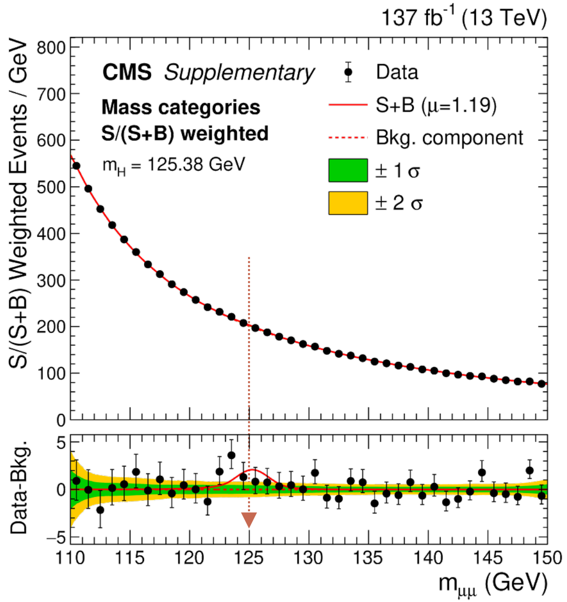


HIGGS & MUONS

Exploit all production modes.

Exquisitely small signal.





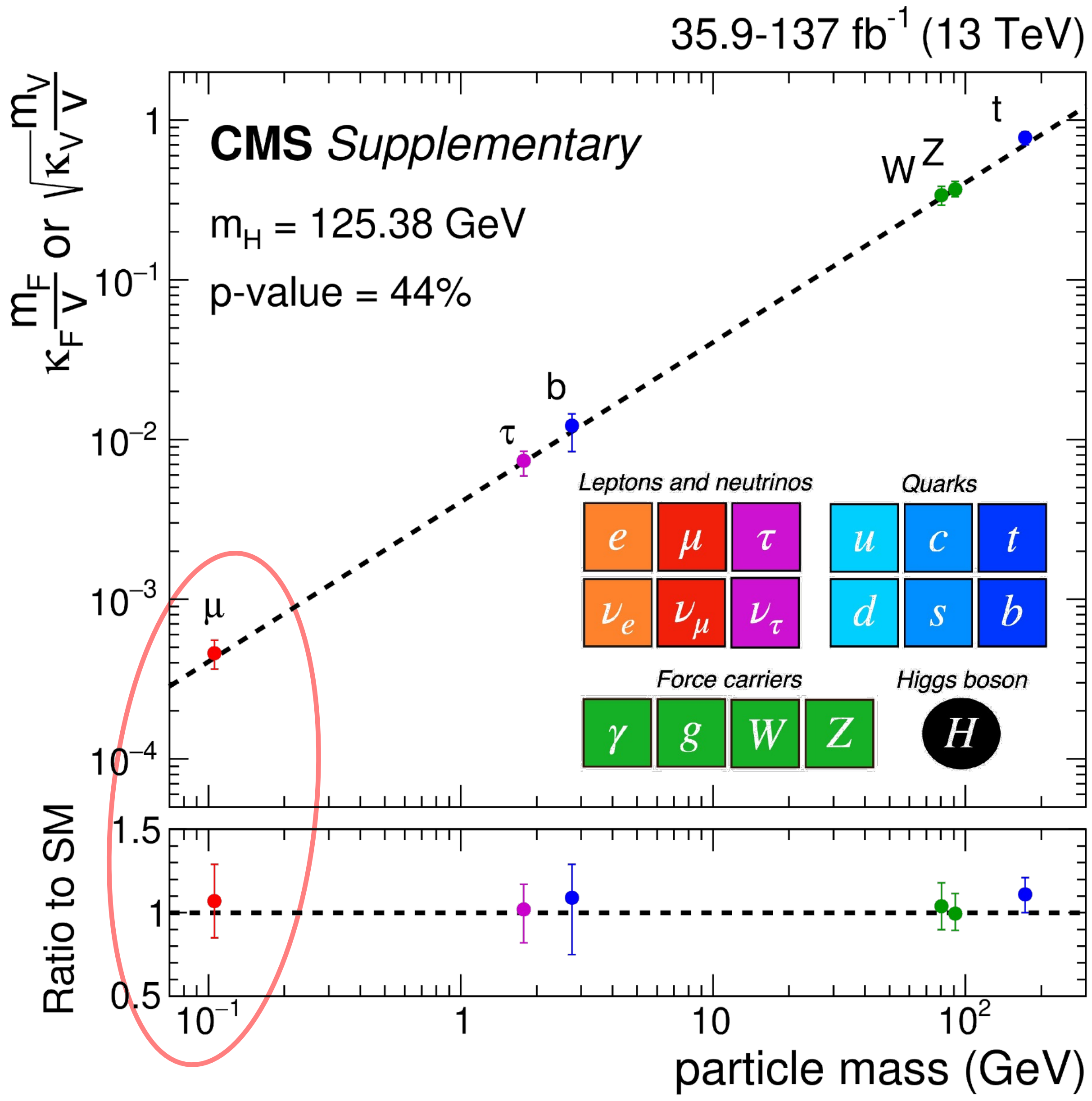
HIGGS & MUONS

Exploit all production modes.

Exquisitely small signal.

A **new data point**.

Evidence-level measurement at the LHC.



HIGGS & MUONS

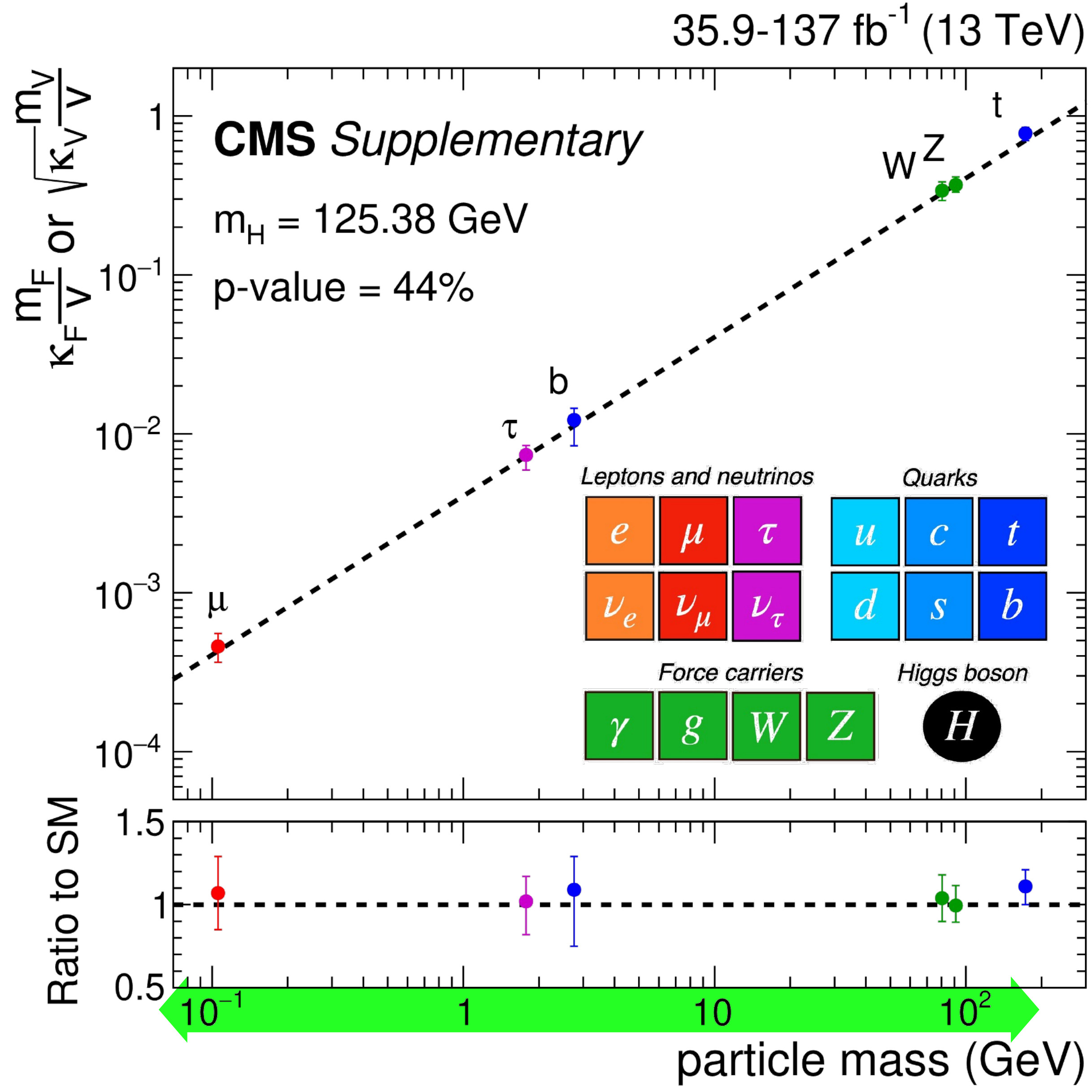
Exploit all production modes.

Exquisitely small signal.

A new data point.

Evidence-level measurement at the LHC.

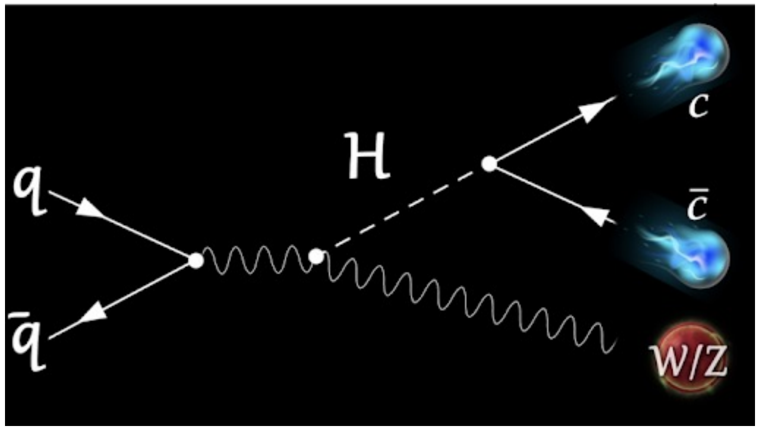
Mass range probed covers 3 orders of magnitude !

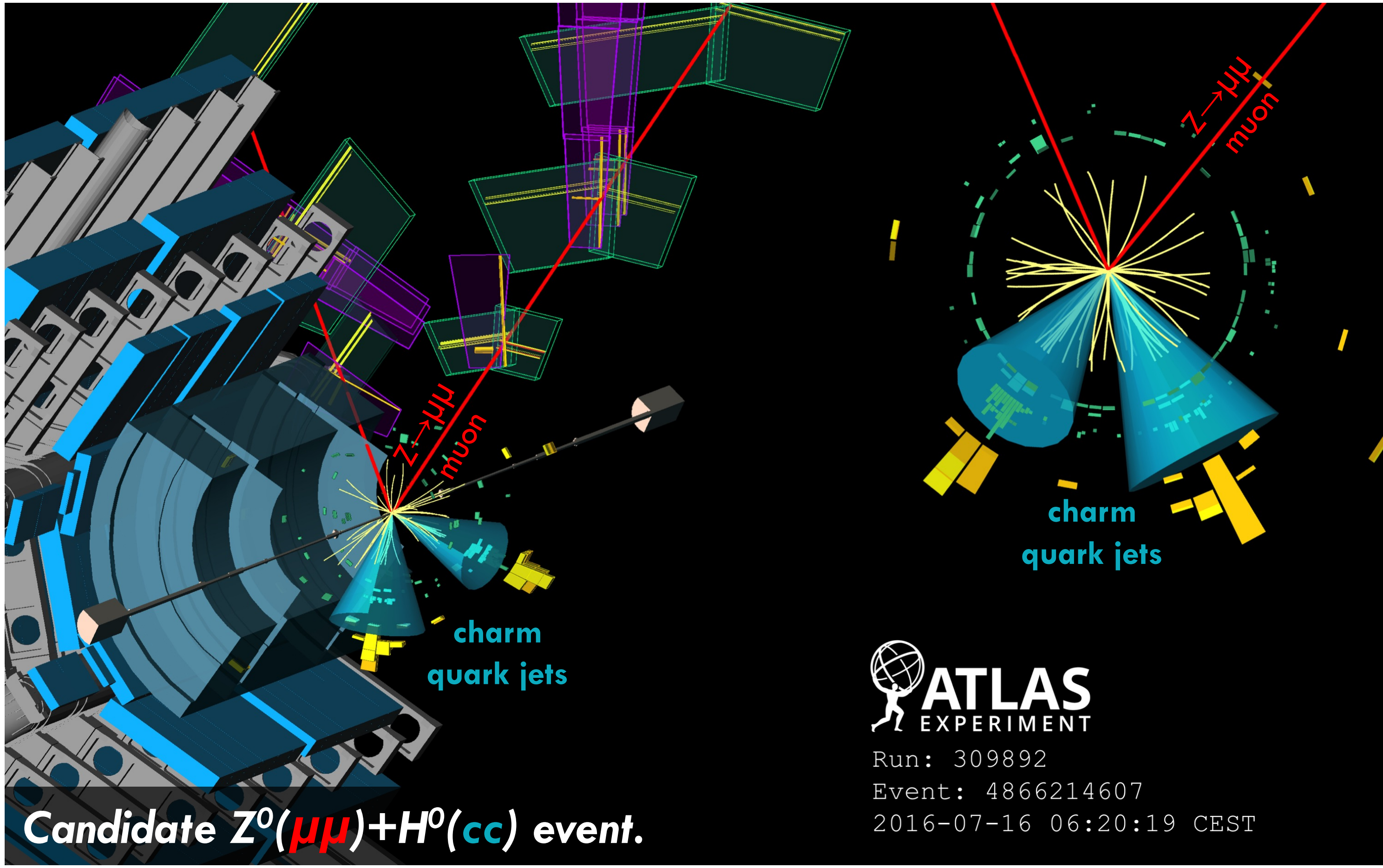


HIGGS & CHARM QUARKS

Charm quarks harder to individuate than muons.

- Exploit associated production with a vector boson.





CMS: arxiv:2205.05550
ATLAS: arxiv:2201.11428

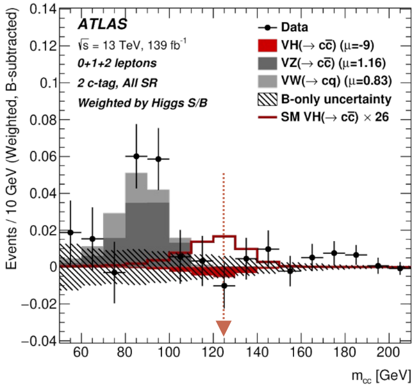
HIGGS & CHARM QUARKS

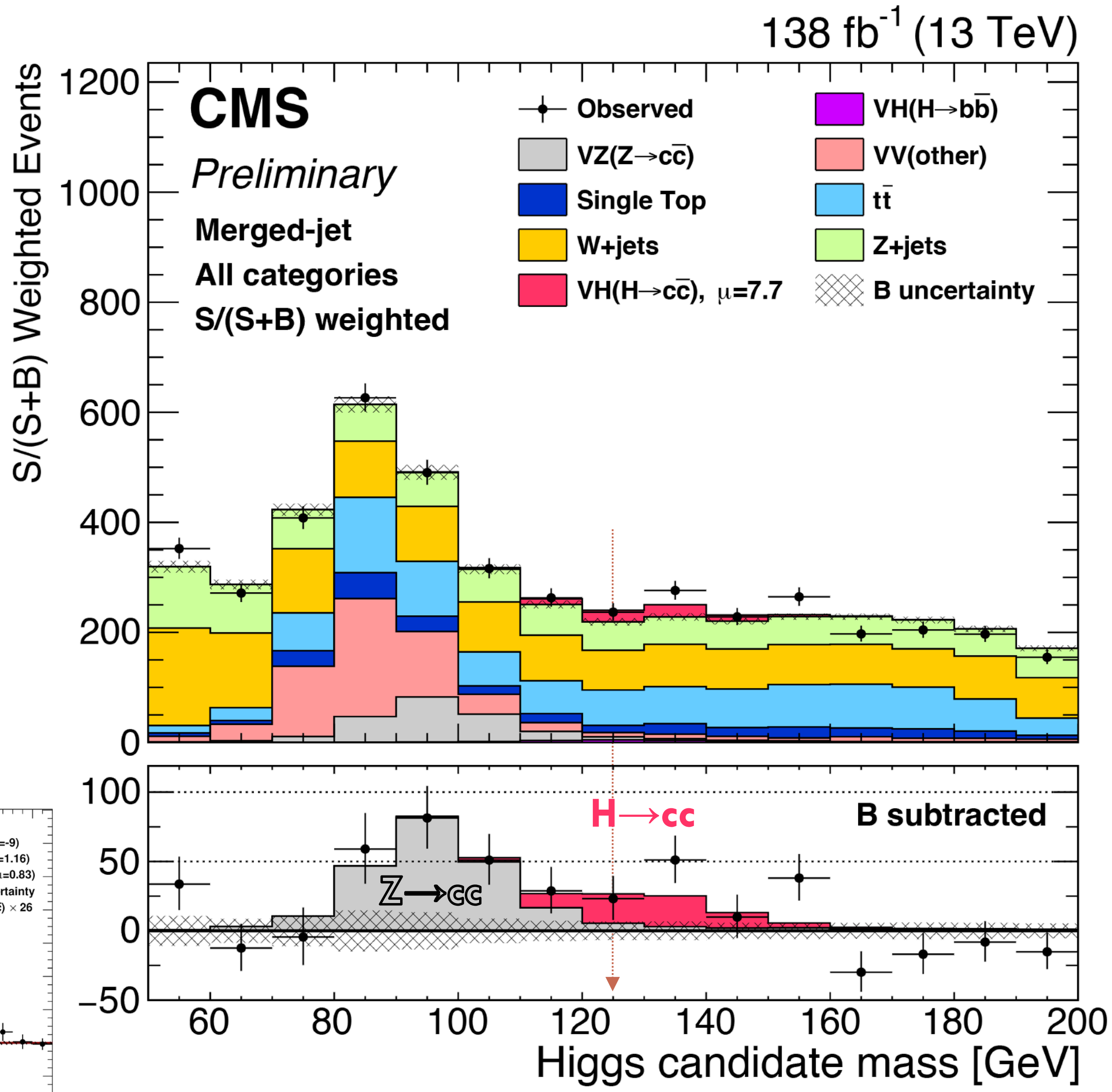
Charm quarks harder to individuate than muons.

Use **advanced machine learning** techniques.

Sensitivity to H→cc < 10× SM.

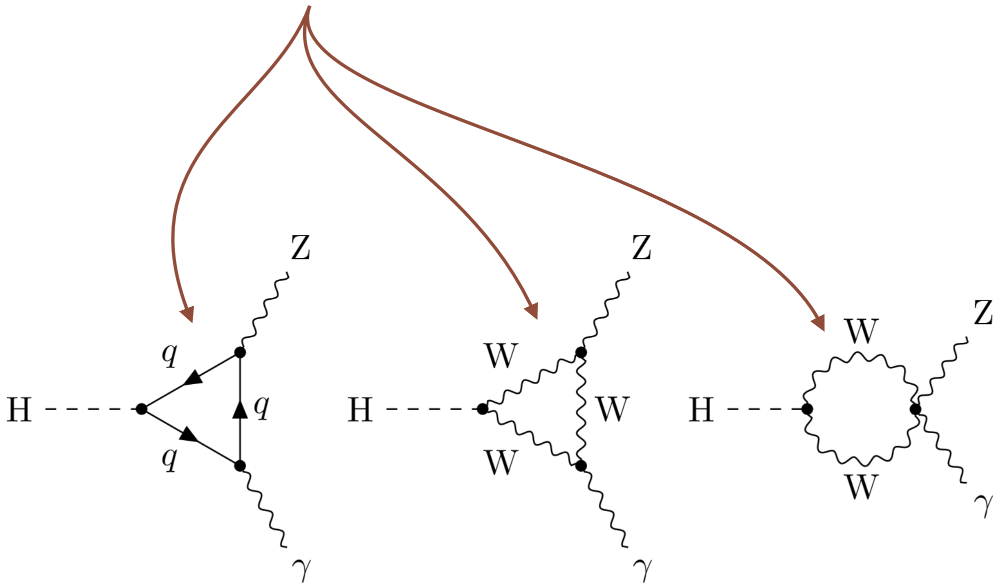
- A testament to the ingenuity of experimentalists.
- *Beyond my 2017 expectations !*





RARE LOOPS – Z+PHOTON

New particles can contribute
in quantum loops.



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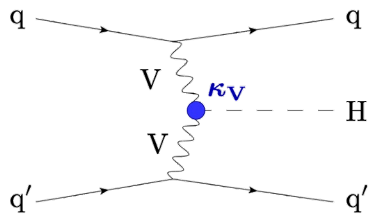
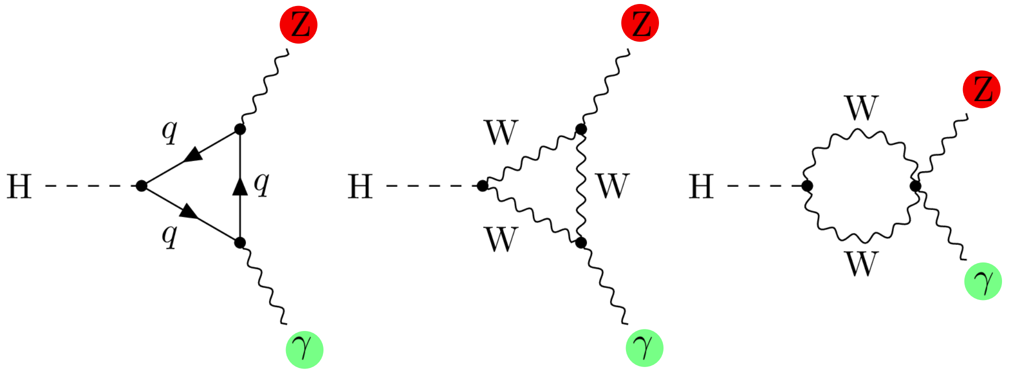
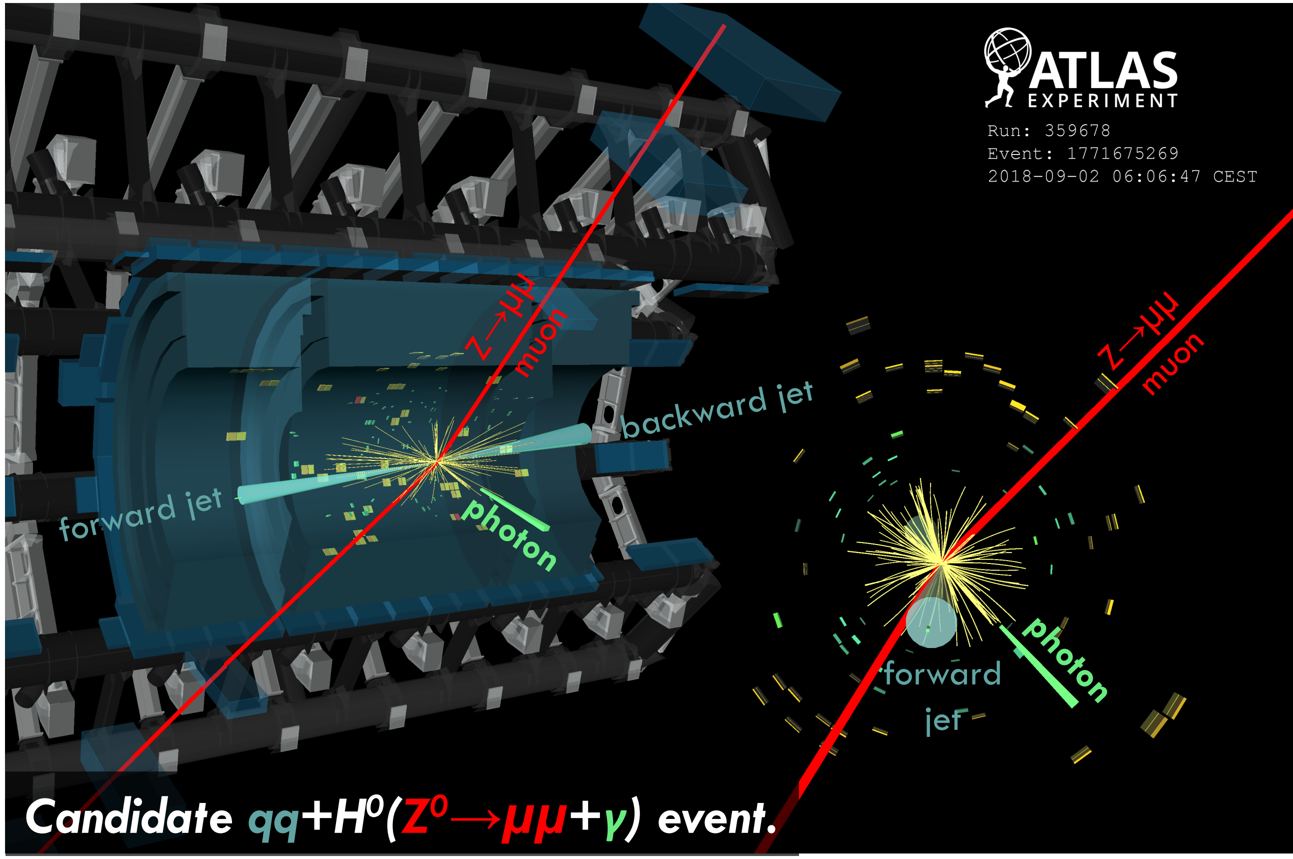


New particles can contribute in quantum loops.

Exploit different production modes to tease out small signal.



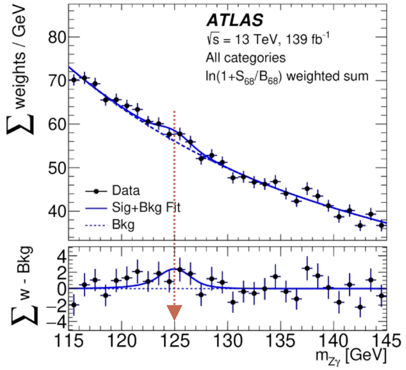


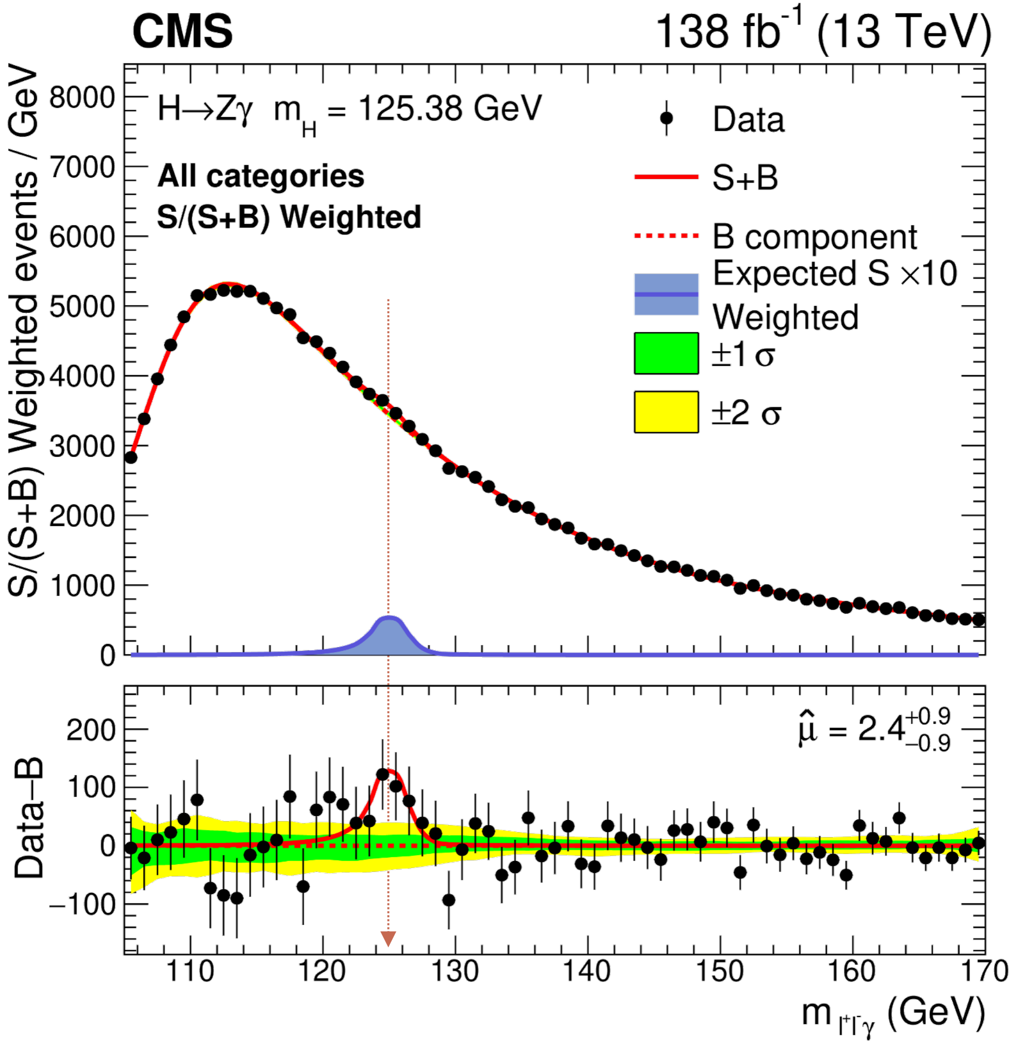
RARE LOOPS – Z+PHOTON

New particles can contribute in quantum loops.

Exploit different production modes to tease out small signal.

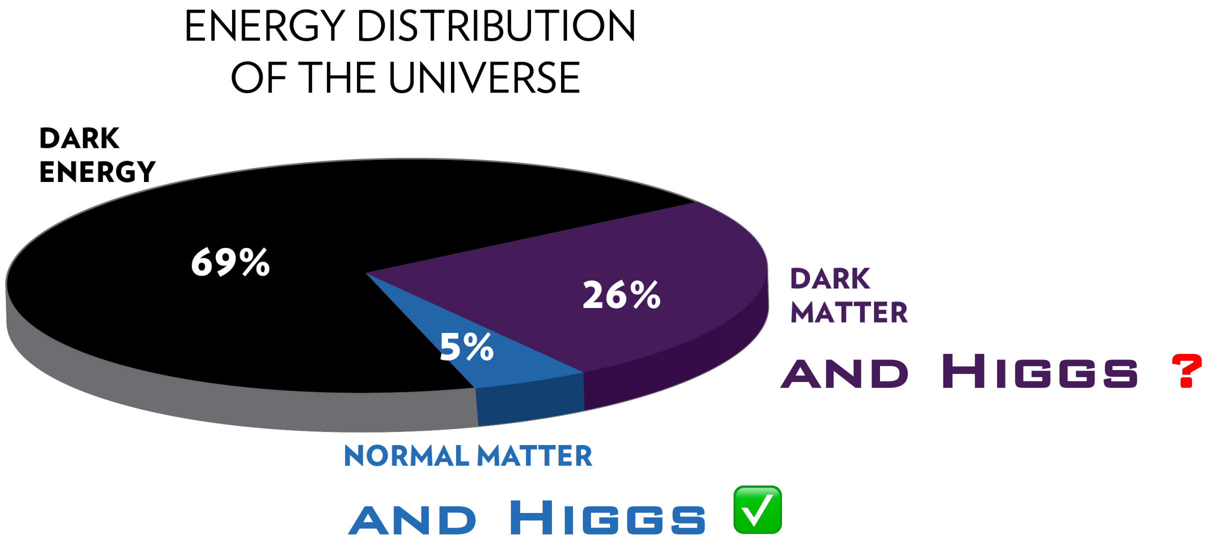
Both experiments seeing intriguing results.





DARK MATTER CONNECTION?

Dark Matter particles ***could*** have mass from Brout-Englert-Higgs mechanism.



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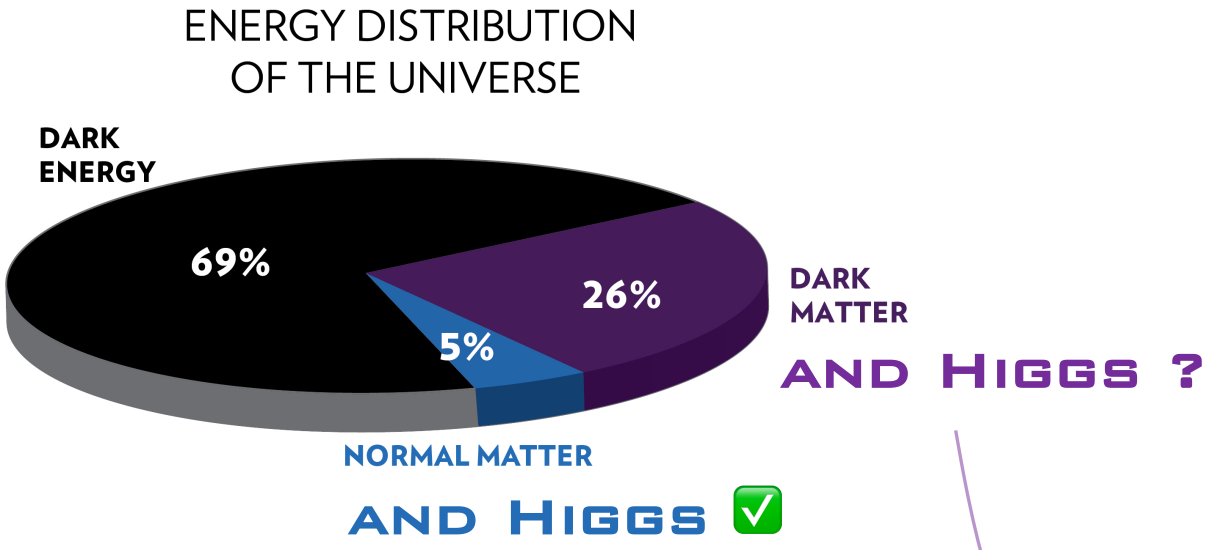

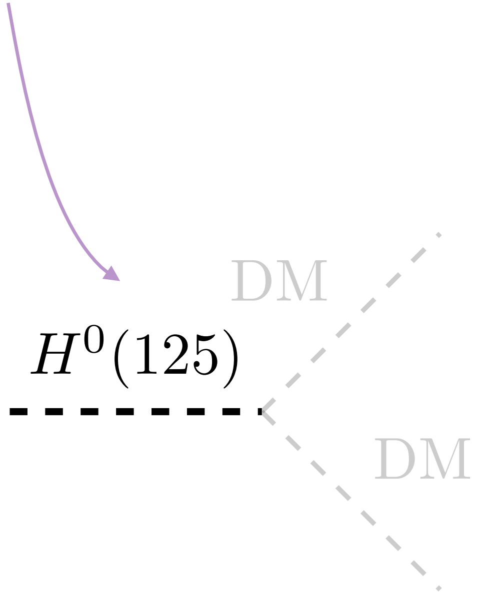

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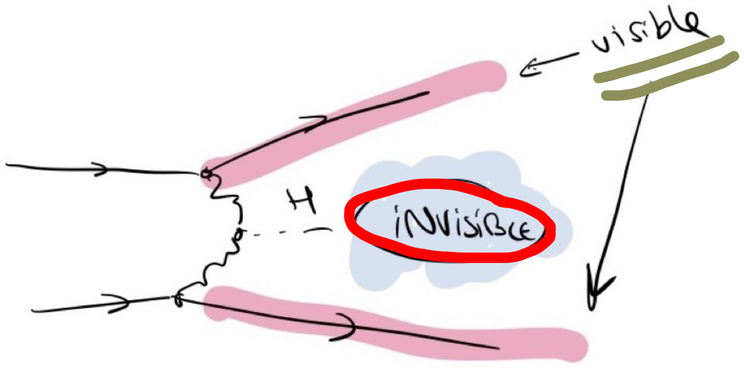
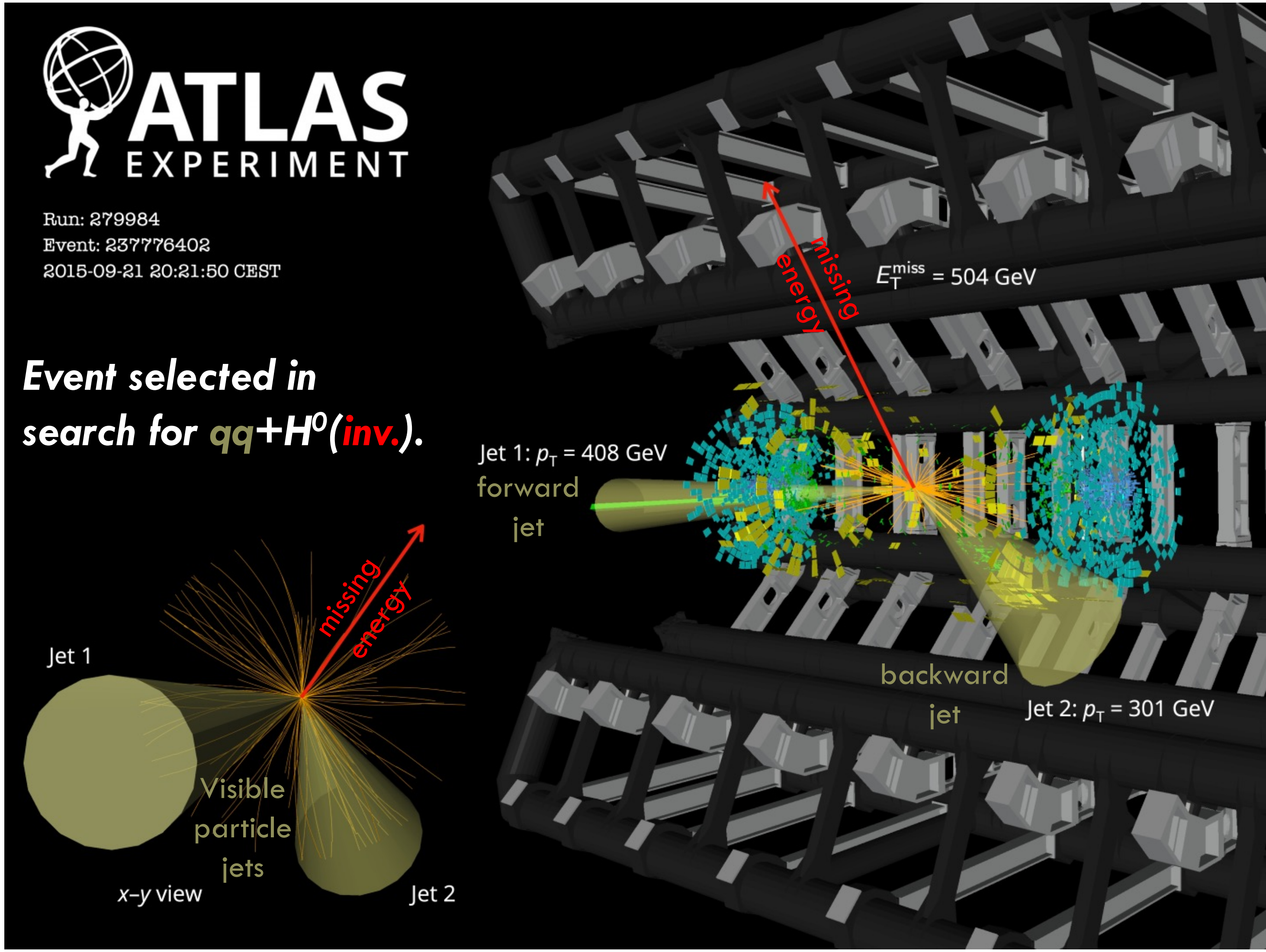
Search for invisible Higgs decays (into DM particles).





ATLAS: ATLAS-CONF-2020-052
CMS: PRD 105 (2022) 092007

DARK MATTER CONNECTION?

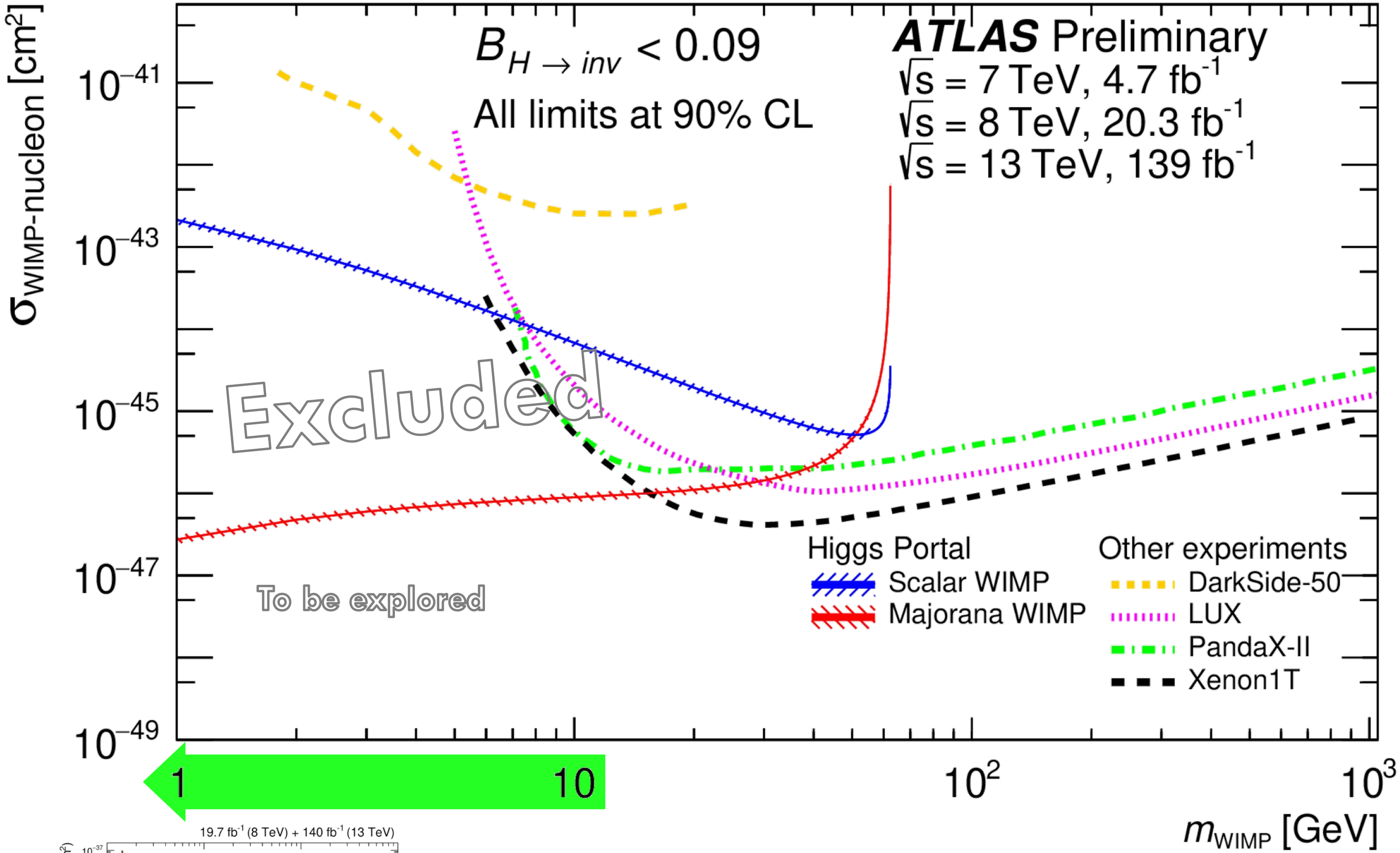
Dark Matter particles *could* have mass from Brout-Englert-Higgs mechanism.

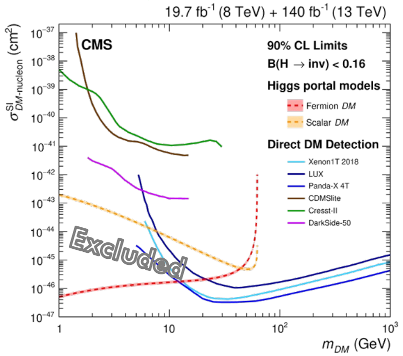
Search for invisible Higgs decays (into DM particles).

- Exclude invisible branching fractions larger than about 10%.

Set limits on DM models.

- Competitive limits for **low mass** DM candidates.

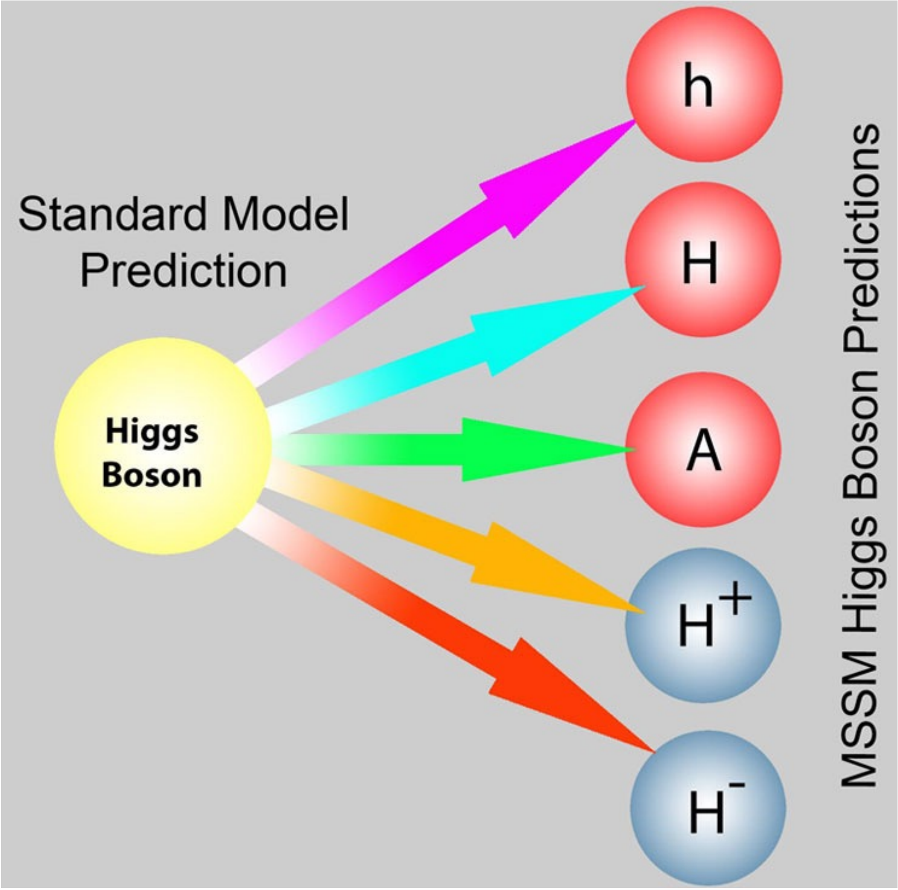




OTHER HIGGS BOSONS

SM extensions easily predict more Higgs bosons.

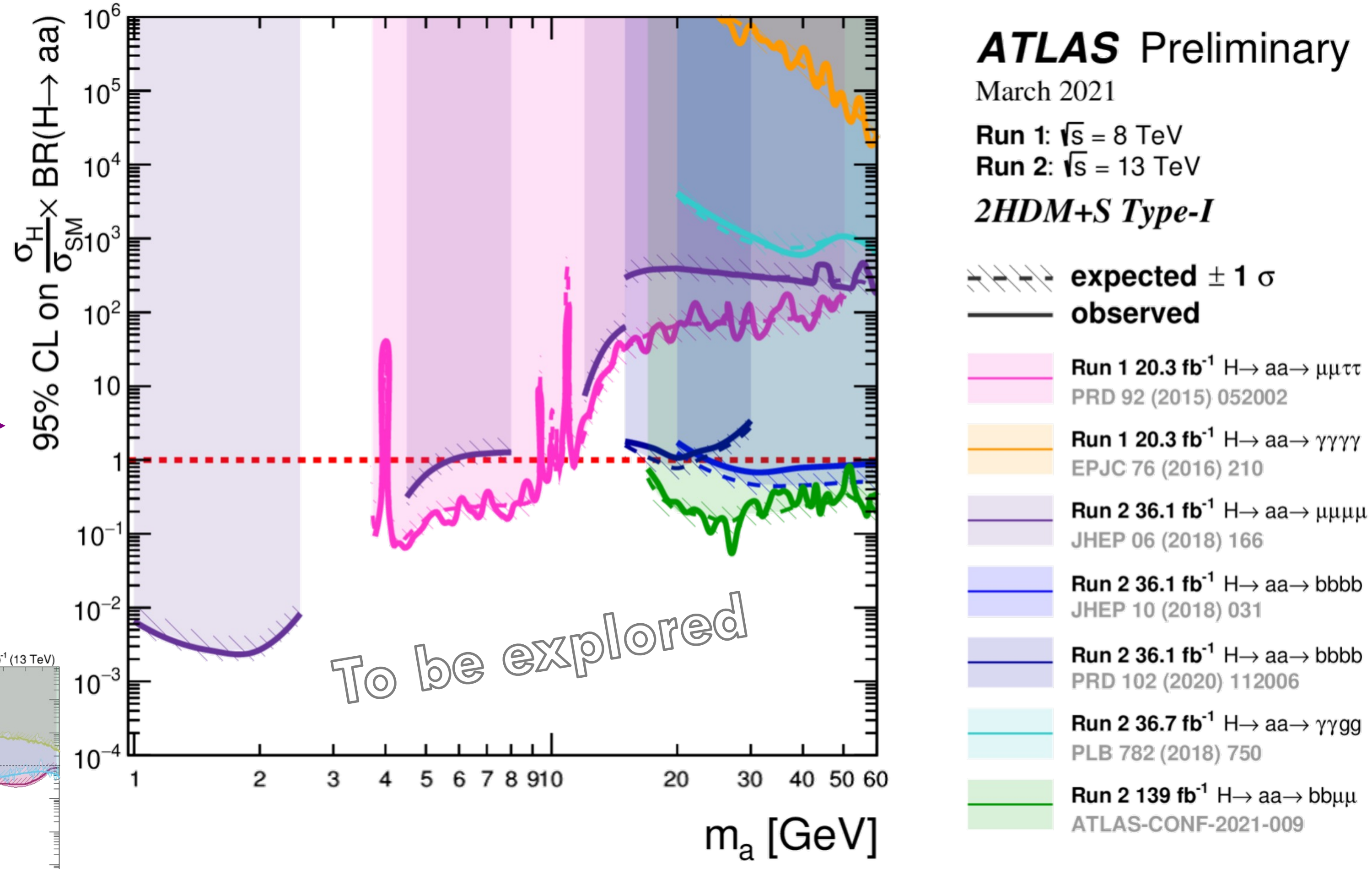
- SM is remarkably minimalist in this respect.

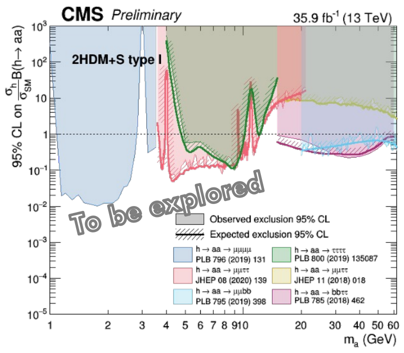


OTHER HIGGS BOSONS

SM extensions easily predict more Higgs bosons.

Vigorous effort **using many signatures,** excluding many **low mass** and high mass scalars.

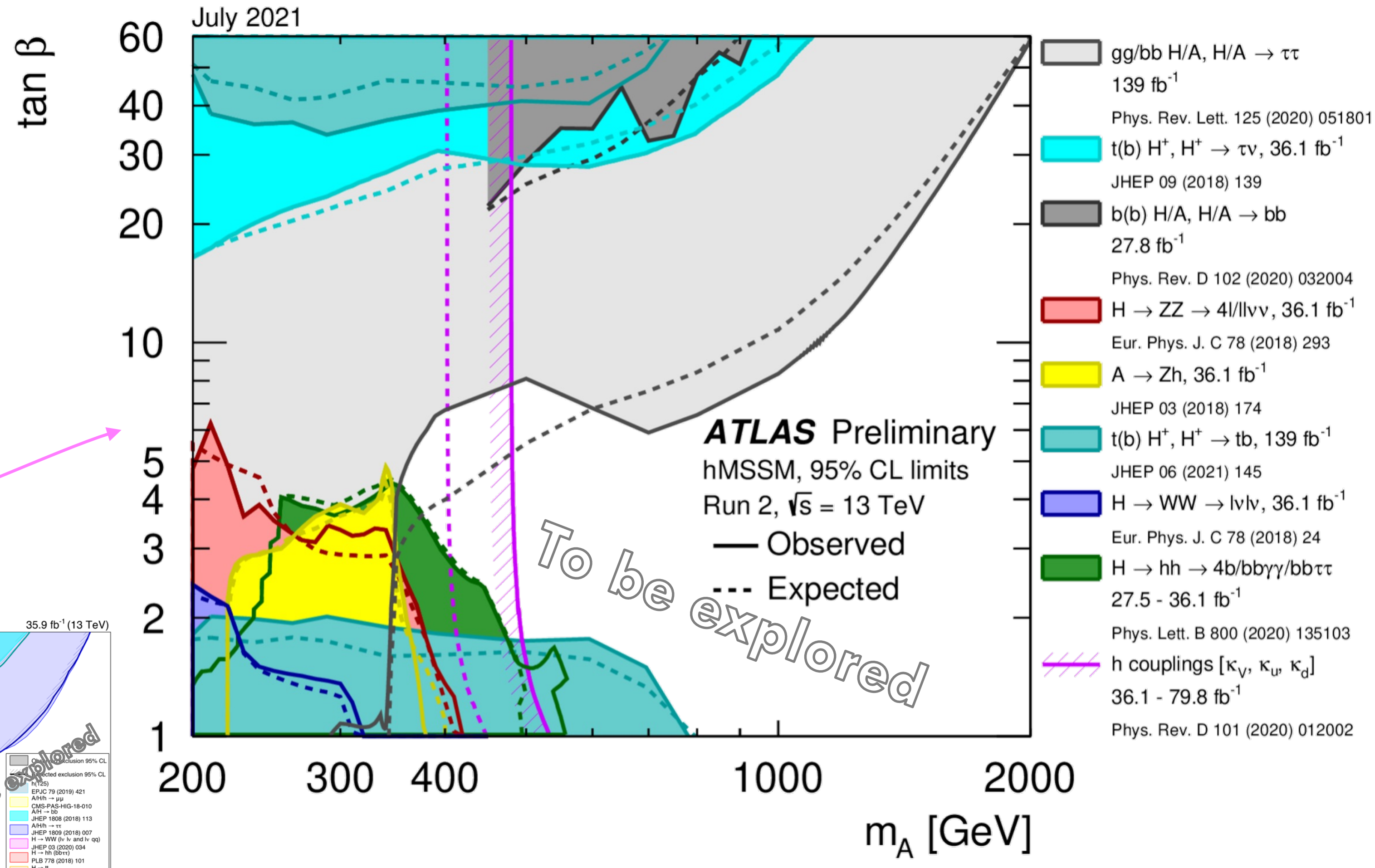


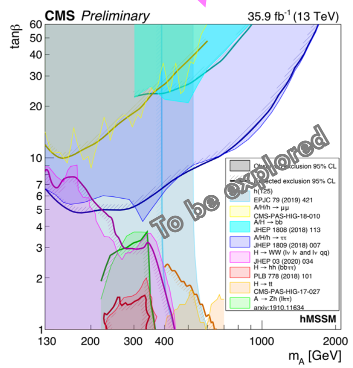


OTHER HIGGS BOSONS

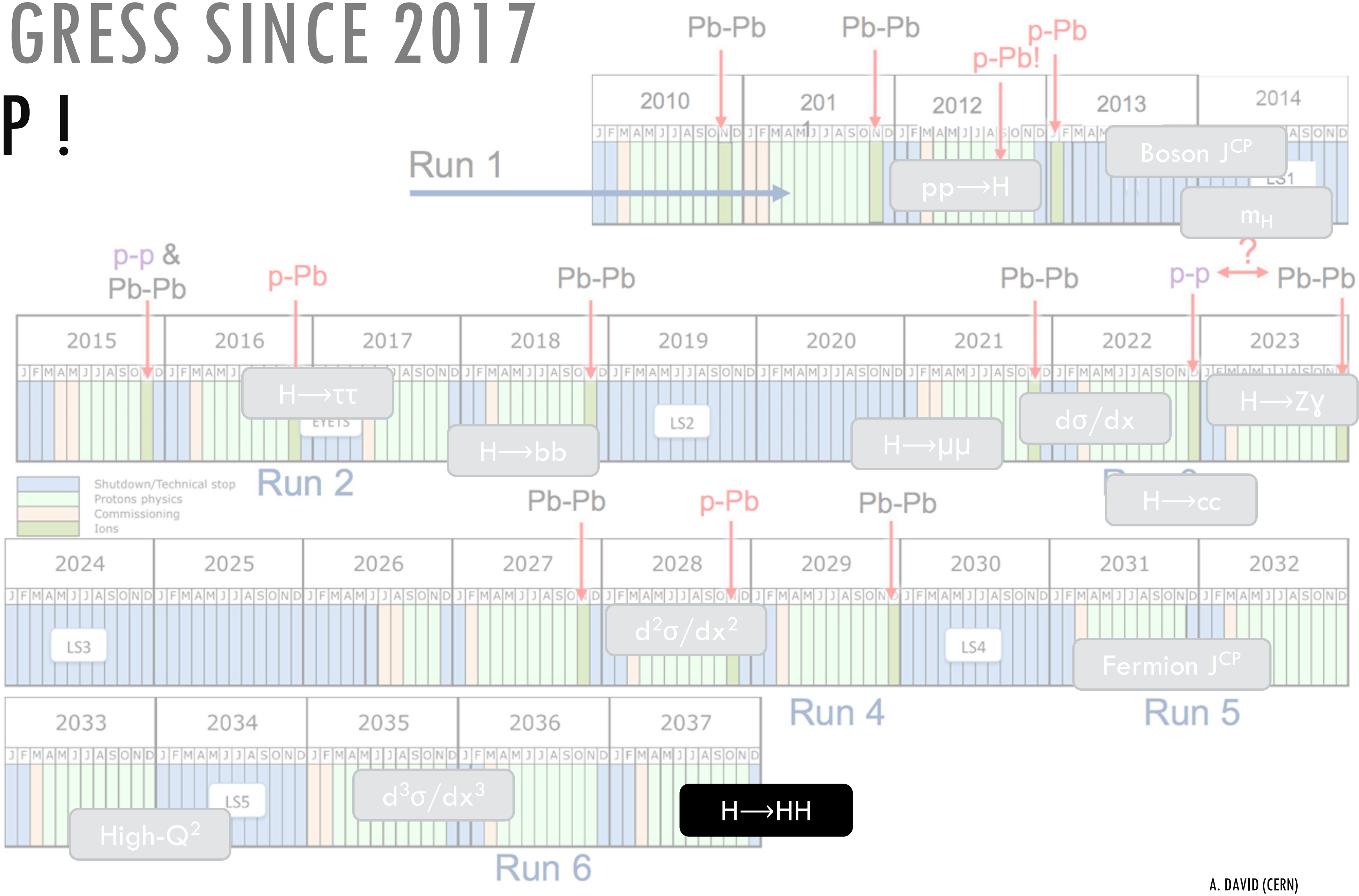
SM extensions easily predict more Higgs bosons.

Vigorous effort **using many signatures,** excluding many low mass and high mass scalars.



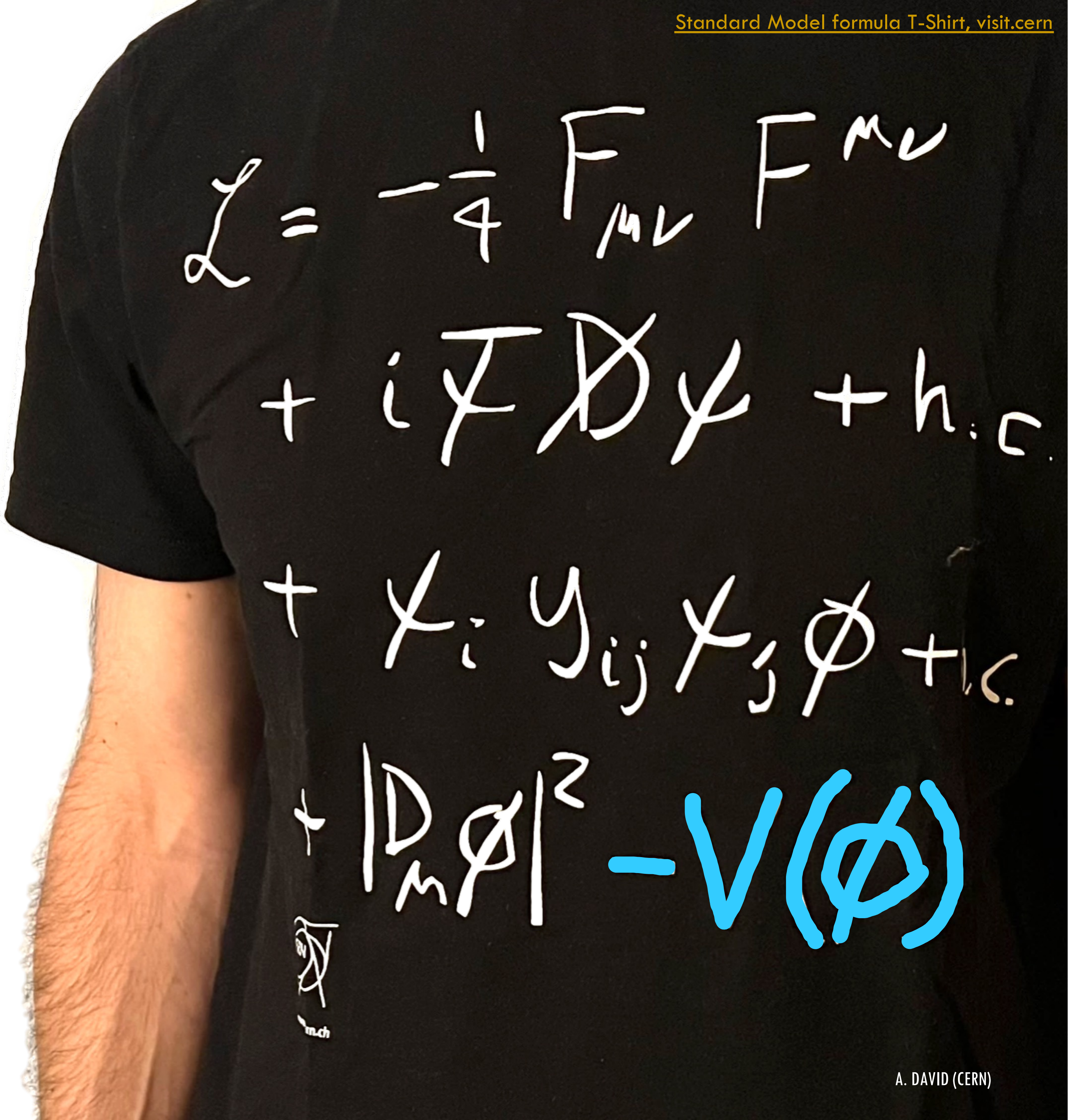


MUCH PROGRESS SINCE 2017
PAIRING UP !



THE SHAPE OF THE VACUUM

In the SM, the structure of the vacuum of the universe is intimately related to how the Higgs boson interacts with… itself.



Standard Model formula T-Shirt, visit.cern

[Standard Model formula T-Shirt, visit.cern](#)
[Phys. Educ. 52 (2017) 034001](#)

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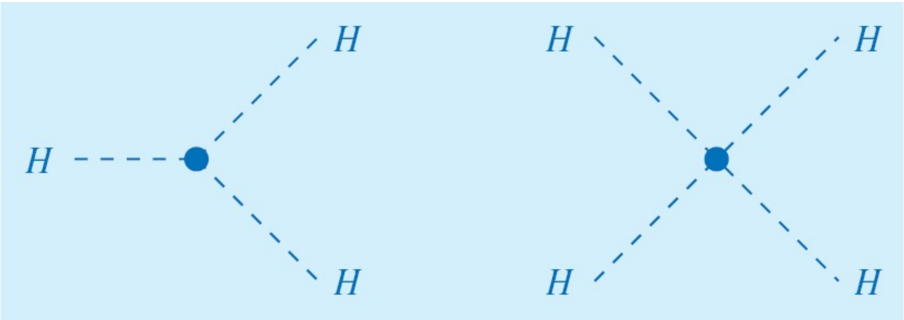
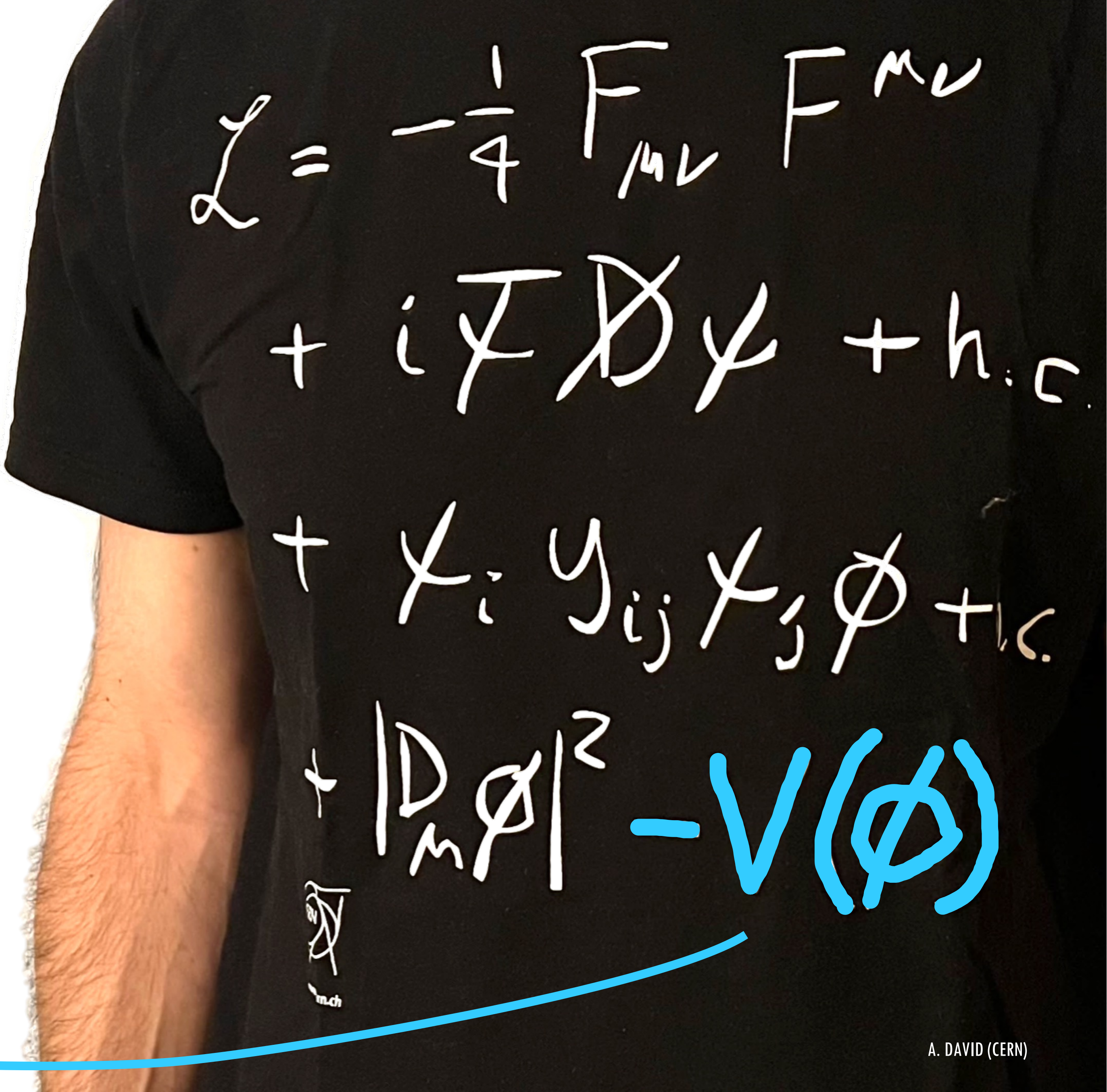
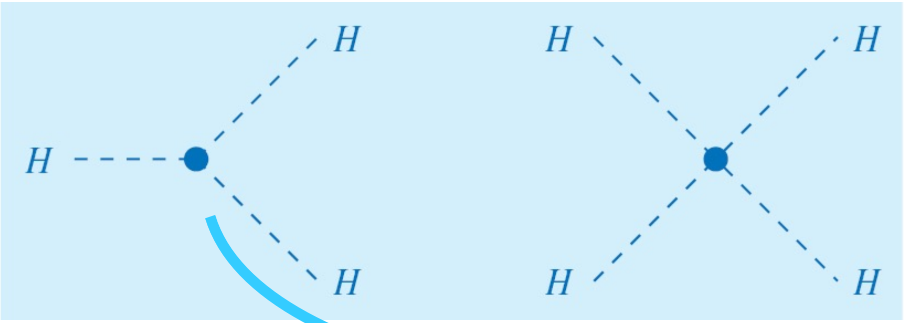


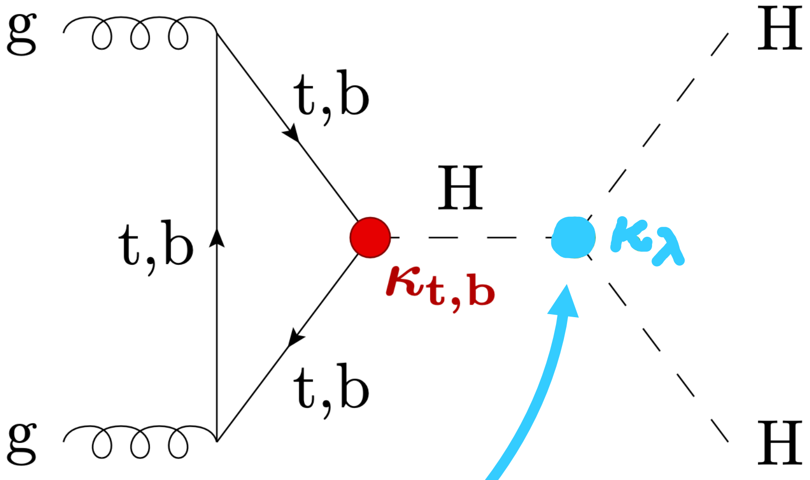


HIGGS BOSON PAIR PRODUCTION

In the SM, the structure of the vacuum of the universe is intimately related to how the Higgs boson interacts with… itself.

To probe this phenomenon we can study the production of **Higgs boson pairs**.





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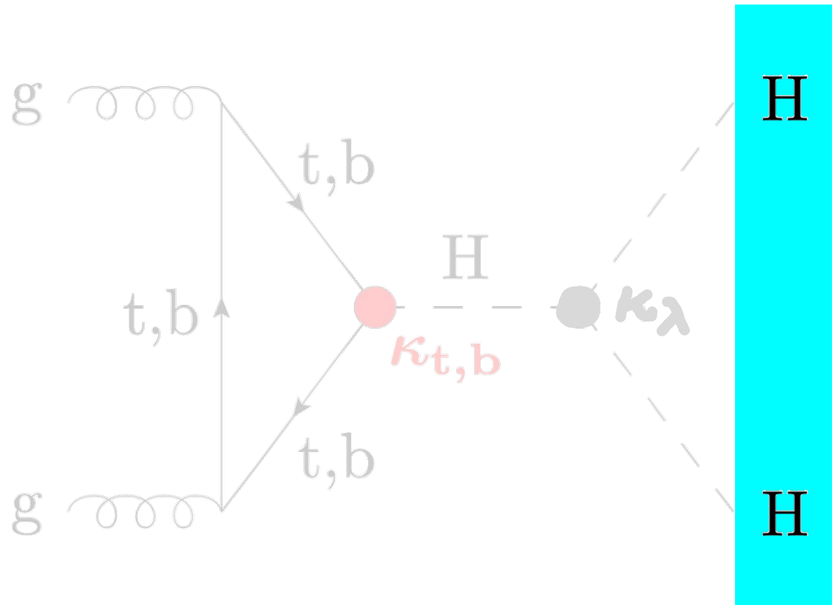
Higgs pairs are predicted to be 1000× rarer than single Higgs.



CMS: Nature 607, 60 (2022)
ATLAS: ATLAS-CONF-2022-050

HIGGS BOSON PAIRS

Higgs pairs are predicted to be 1000× rarer than single Higgs.

Must **bring together many channels** to achieve the best sensitivity.

bb ZZ
Expected: 40
Observed: 32

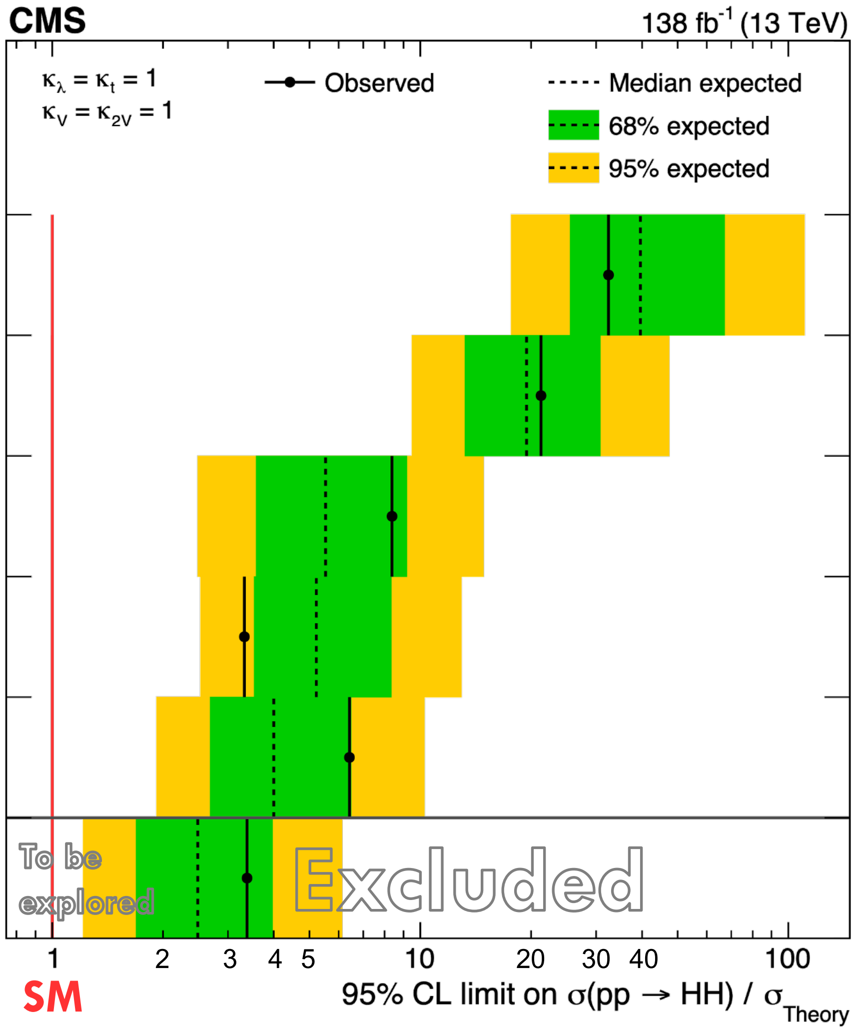
Multilepton
Expected: 19
Observed: 21

bb γγ
Expected: 5.5
Observed: 8.4

bb ττ
Expected: 5.2
Observed: 3.3

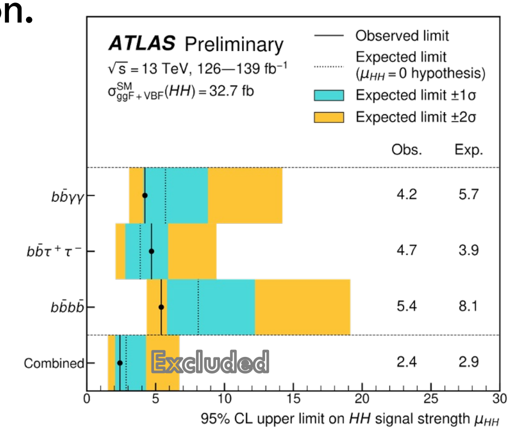
bb bb
Expected: 4.0
Observed: 6.4

Combined
Expected: 2.5
Observed: 3.4



Sensitivity better than 3× SM.

- On the way to challenge SM prediction.



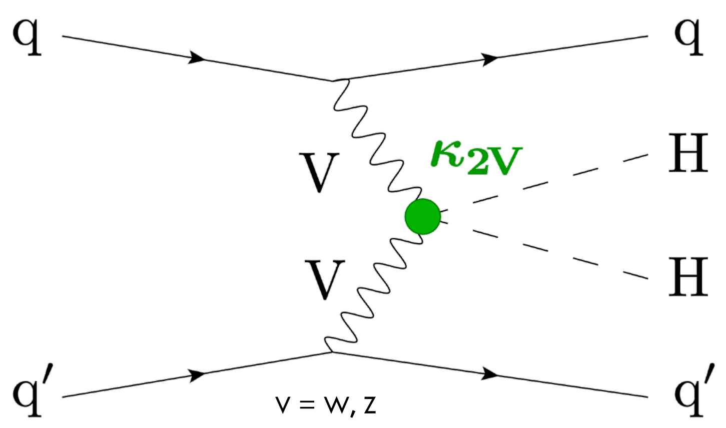
CMS: Nature 607, 60 (2022)
ATLAS: ATLAS-CONF-2022-050

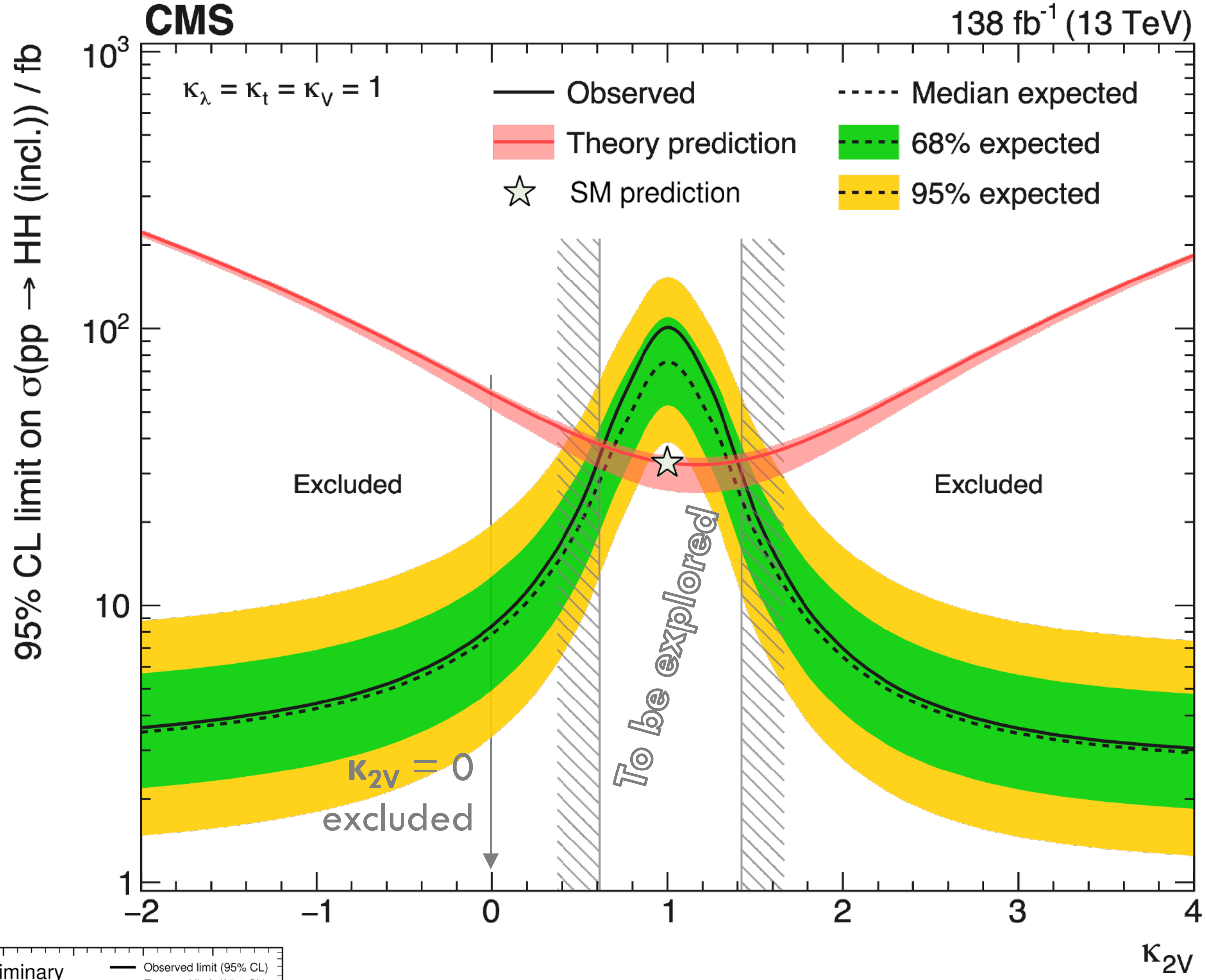
HIGGS BOSON PAIRS

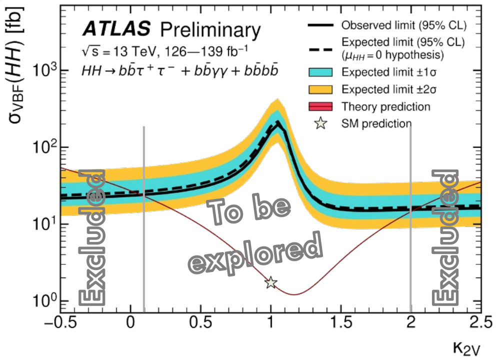
HH production searches allow to **probe other rare interactions.**

E.g., the **VVHH 4-particle interaction** seems to exist in nature.

- I.e., $\kappa_{2V} = 0$ excluded.







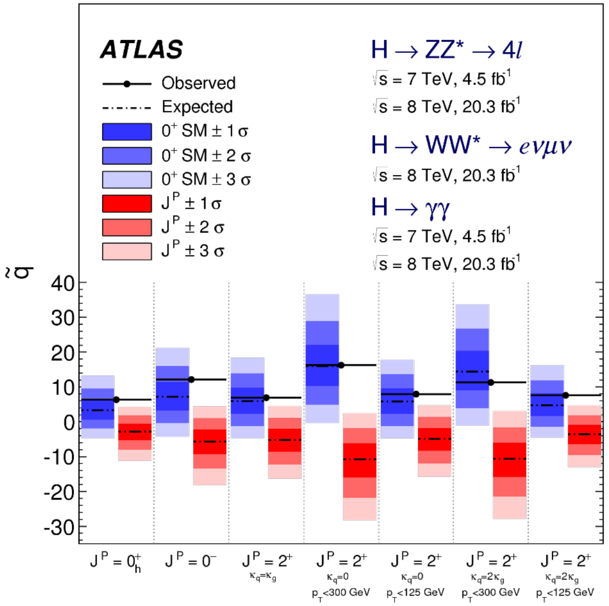
10 YEARS ON, WE'VE ONLY STARTED WITH THE $H^0(125)$

A fundamentally different kind of particle, a new player in our team probing nature.

CMS and ATLAS have **steadily accrued knowledge** about this Higgs boson.

- $H^0(125)$ remains compatible with SM predictions.
- Many more details in the afternoon session !

The *coming decades* are crucial to understand it and make use of it in exploring nature.



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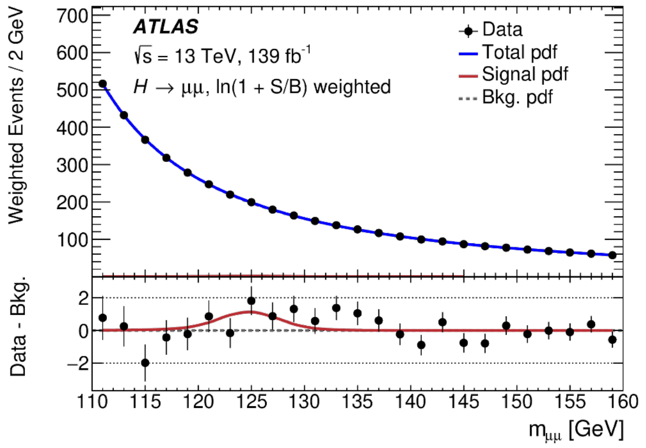

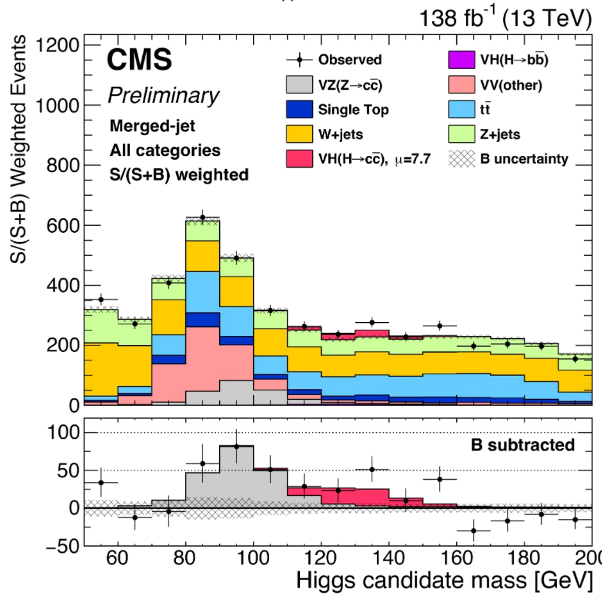

Longer term LHC schedule (2022)
CMS: Nature 607, 60 (2022)

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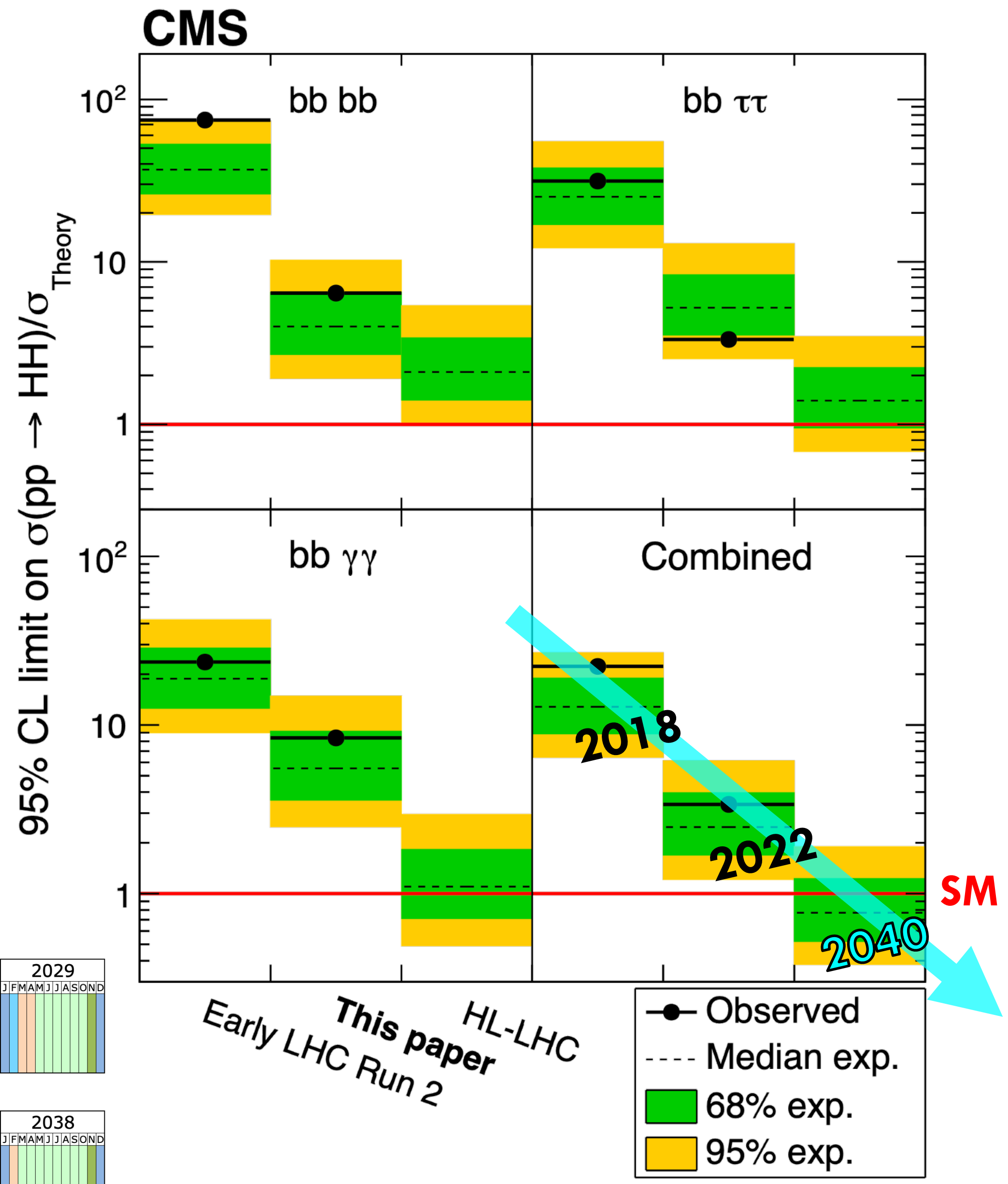
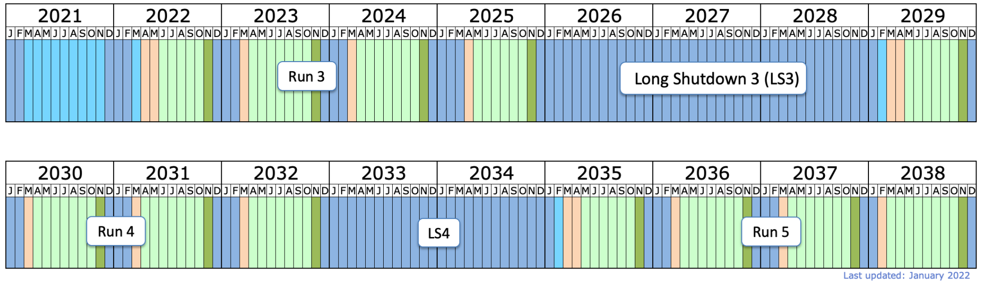




THANK YOU !

…all who contributed to the accelerator, theory, experiments, and computing, and all supporters of science.

ATLAS: ATLAS-CONF-2022-032
CMS: JHEP 06 (2022) 012

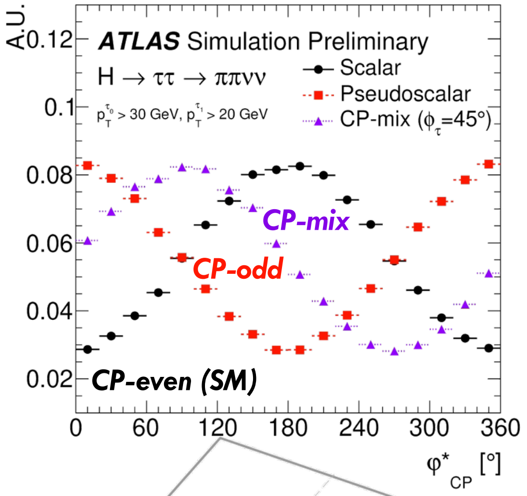
PARITY
IN DI-TAU DECAYS

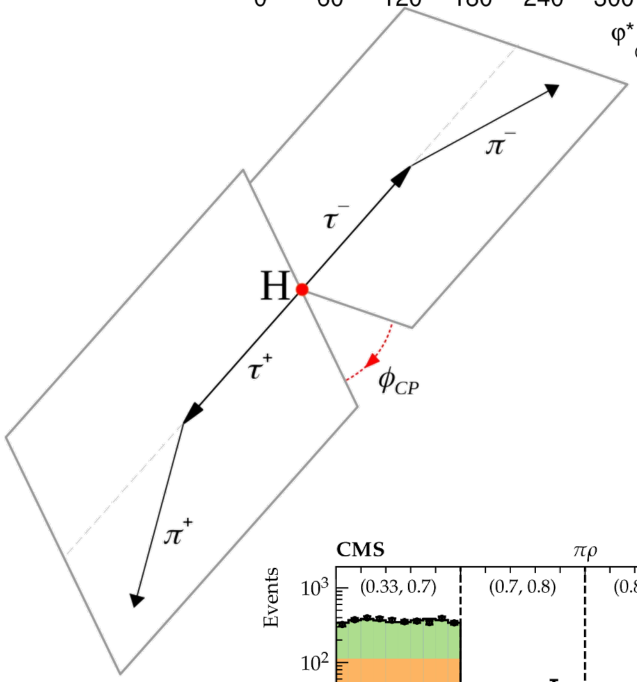
Tau leptons and bosons may interact differently with $H^0(125)$.

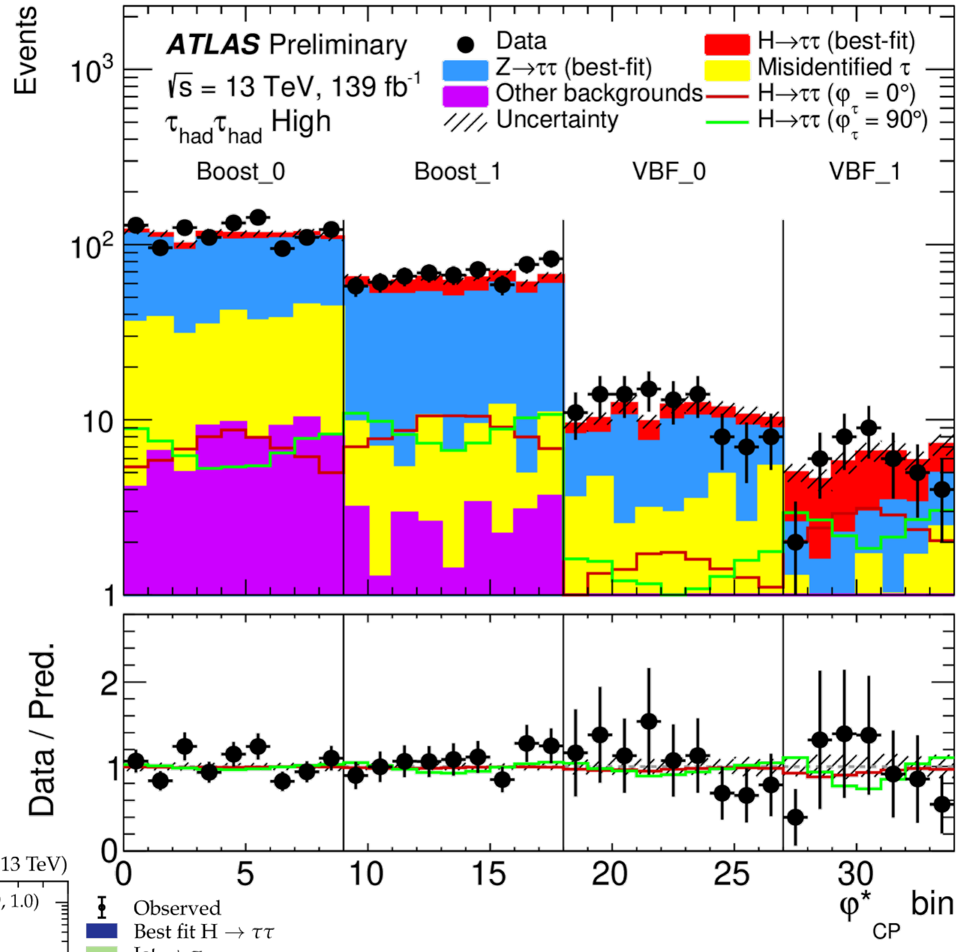
- SM predicts same parity for both.

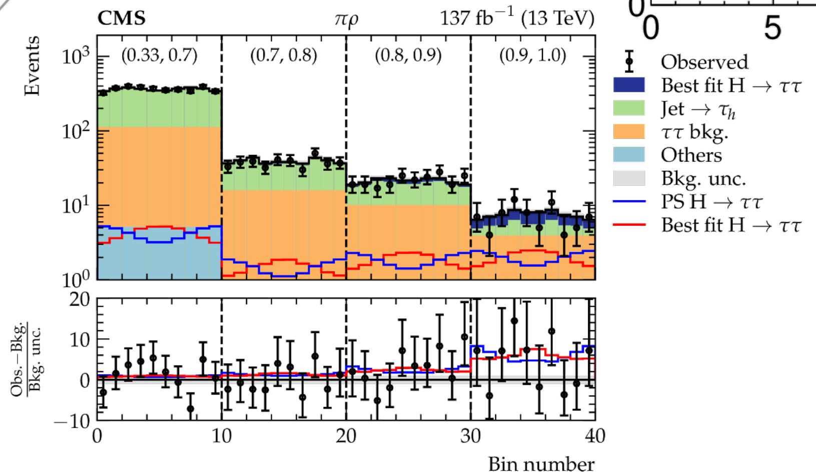
Probed via angular correlations in $H^0(125)\to\tau\tau$ decays.

Data compatible with **even parity** and SM prediction.







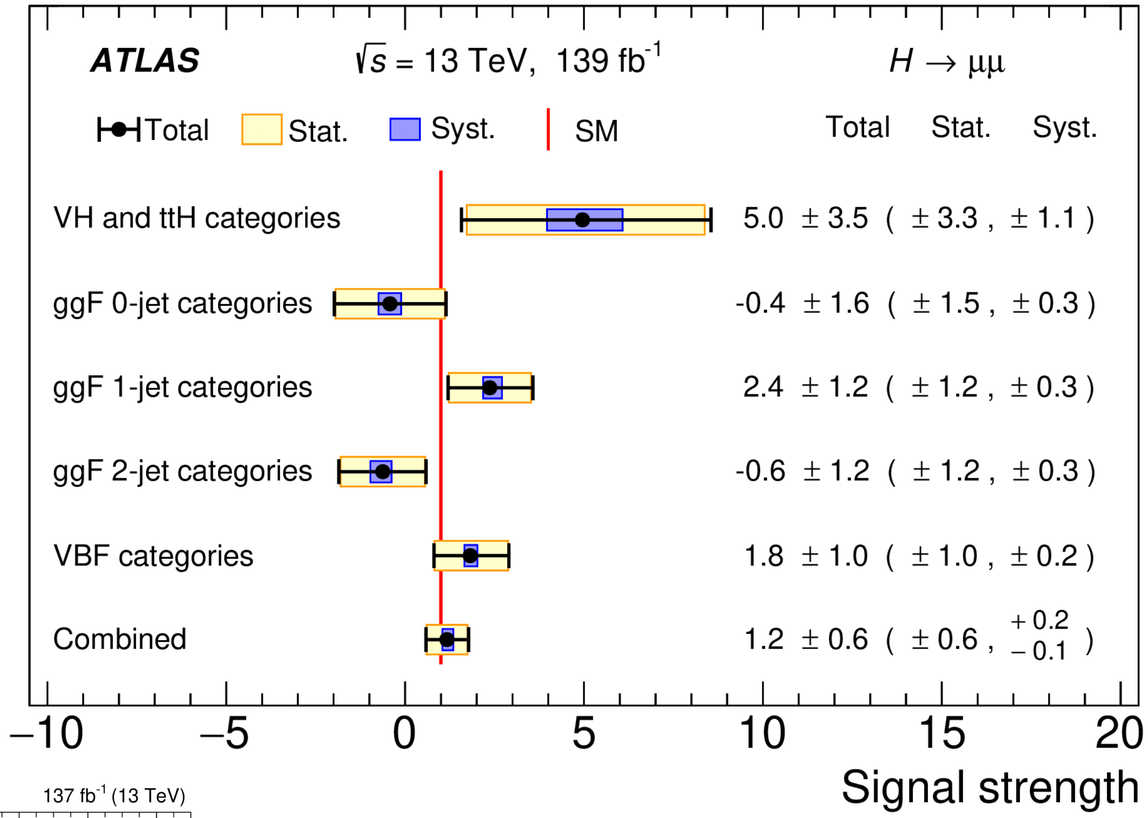


HIGGS & MUONS

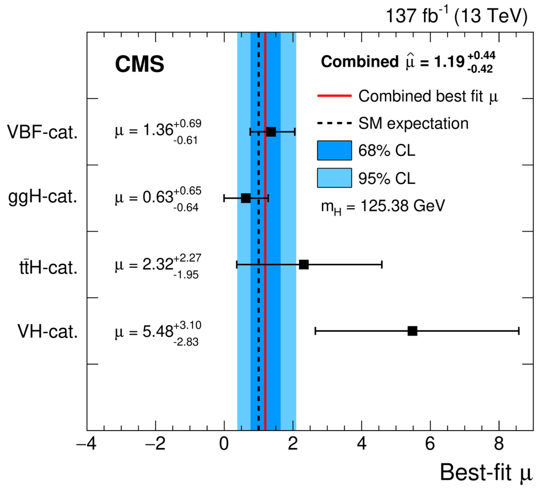
Exploit all production modes.

Exquisitely small signal.

Evidence-level measurement at the LHC.



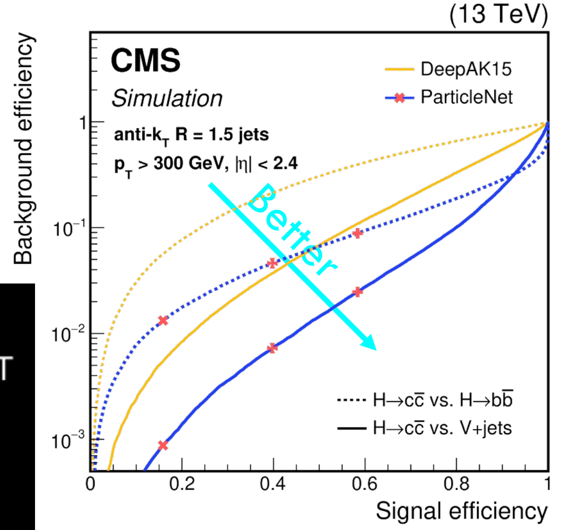
SM ⇒ Signal strength = μ = 1



CMS: arxiv:2205.05550

Increased confidence for the Higgs boson coupling to the charm quark

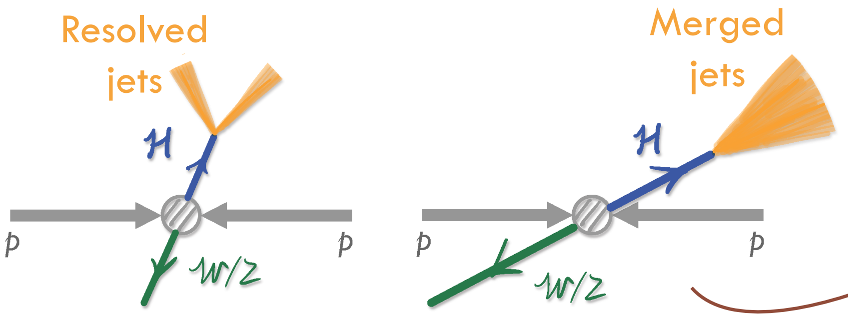
HIGGS & CHARM QUARKS

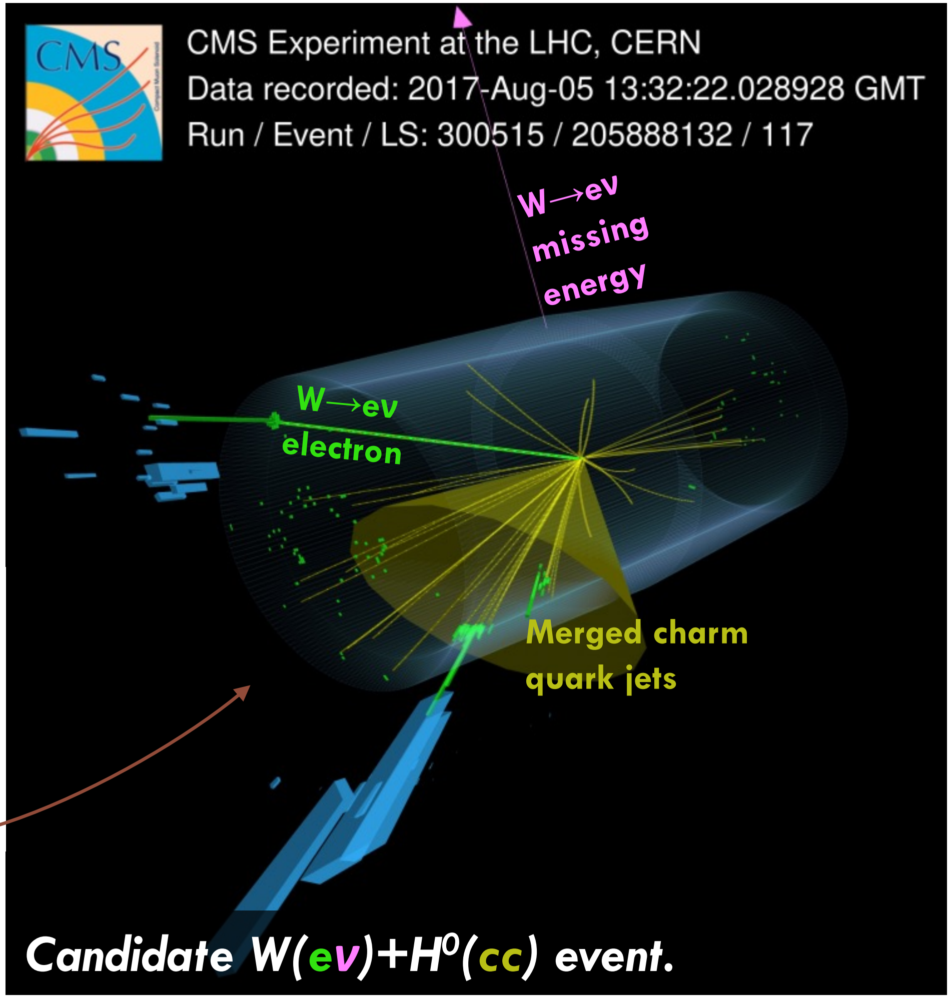


Charm quarks harder to individuate than muons.

Use **advanced machine learning** techniques.

- Charm identification in merged jets.
- Charm jet mass regression.





CMS: arxiv:2205.05550
ATLAS: arxiv:2201.11428

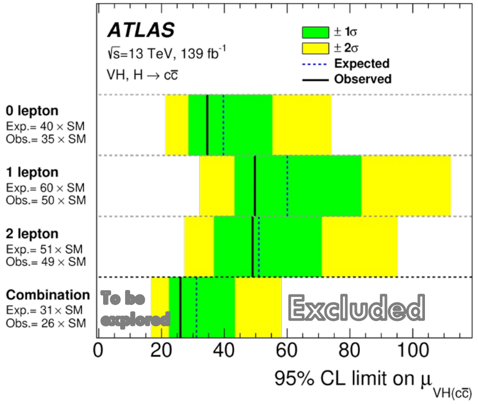
HIGGS & CHARM QUARKS

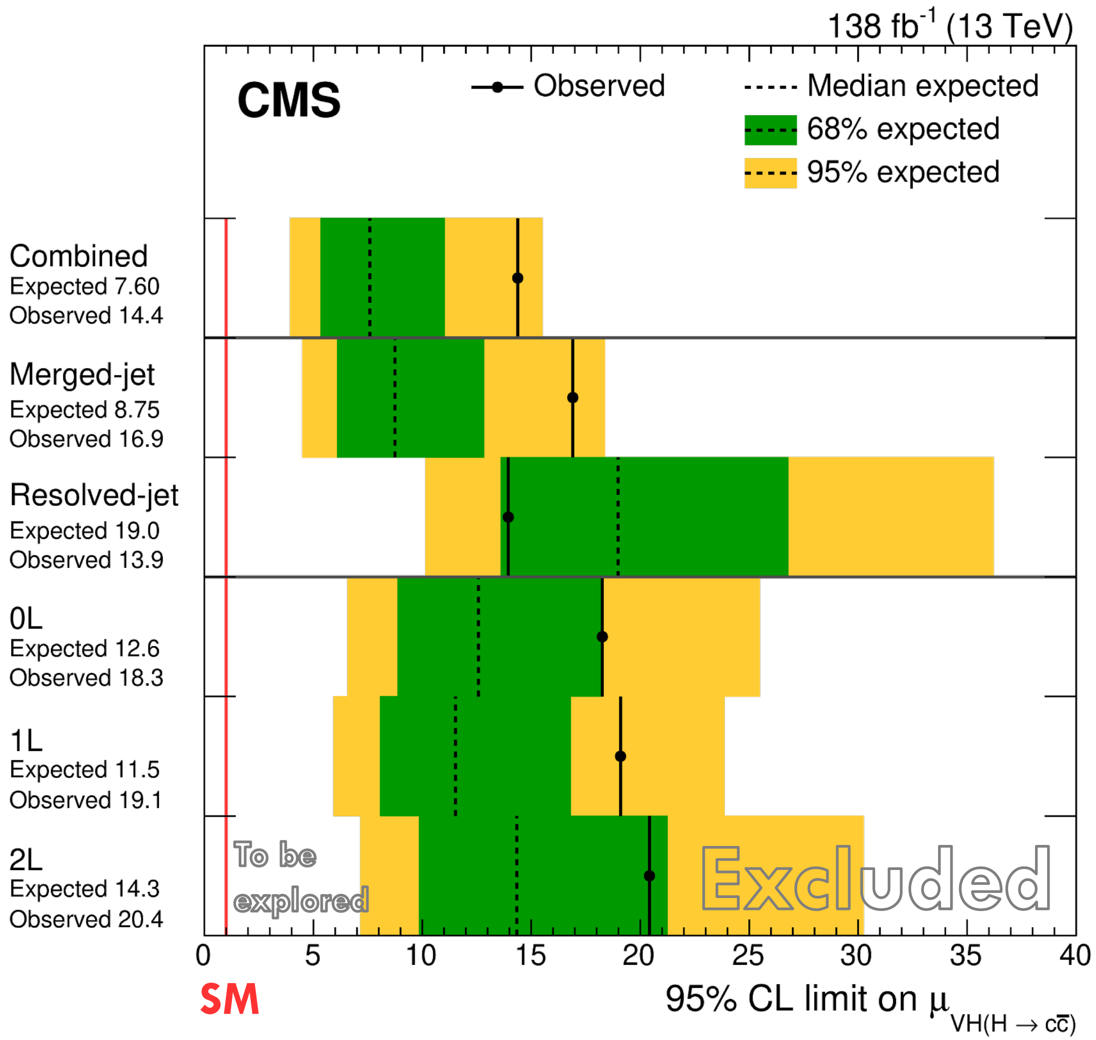
Charm quarks harder to individuate than muons.

Use **advanced machine learning** techniques.

Sensitivity to H→cc < 10× SM.

- A testament to the ingenuity of experimentalists.
- *Beyond my 2017 expectations !*



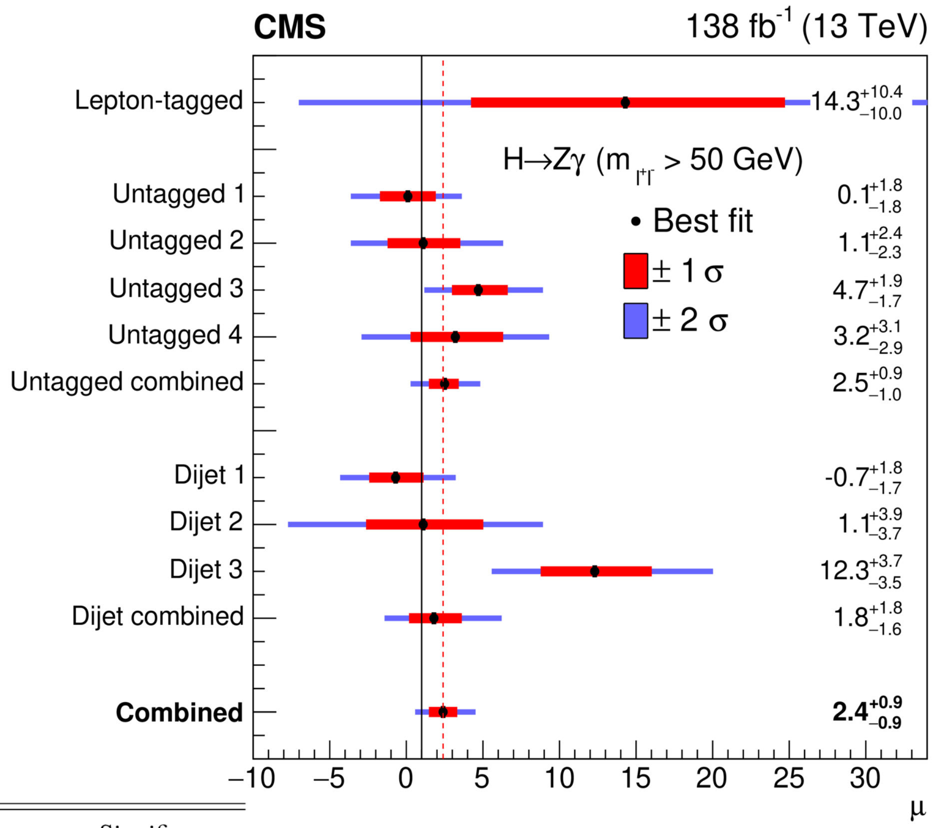


RARE LOOPS – Z+PHOTON

New particles can contribute in quantum loops.

Exploit different production modes to tease out small signal.

Both experiments seeing intriguing results.



ATLAS

Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

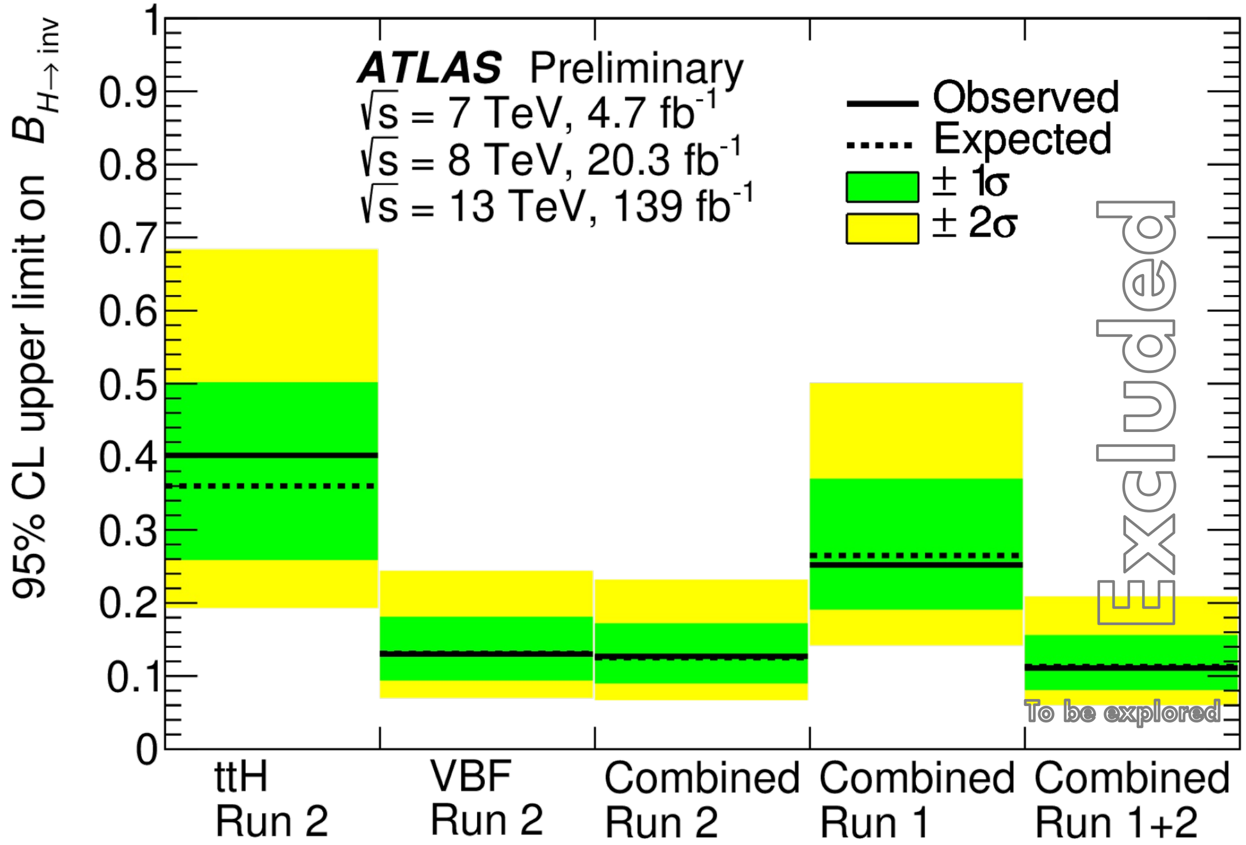
SM ⇒ Signal strength = μ = 1

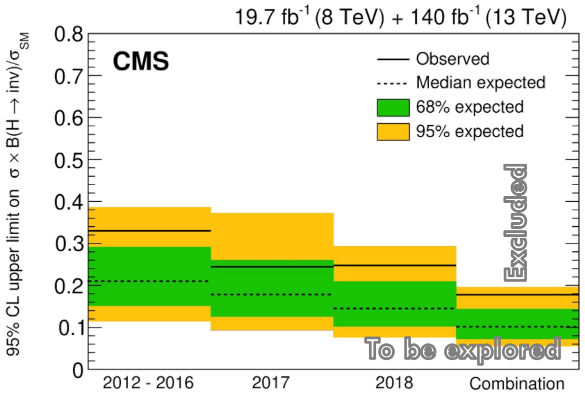
DARK MATTER CONNECTION?

Dark Matter particles could have mass from Brout-Englert-Higgs mechanism.

Search for invisible Higgs decays (into DM particles).

- **Exclude invisible branching fractions larger than about 10%.**





SM predicts $H^0(125)\to 4\nu$ invisible decay branching fraction to be ~0.1%.

HIGGS BOSON PAIRS

HH production searches allow to **probe other rare interactions.**

E.g., the **VVHH 4-particle interaction** seems to exist in nature.

- I.e., $\kappa_{2V} = 0$ excluded **for a large range of self-interaction values, κ_λ.**