HL-LHC and Beyond

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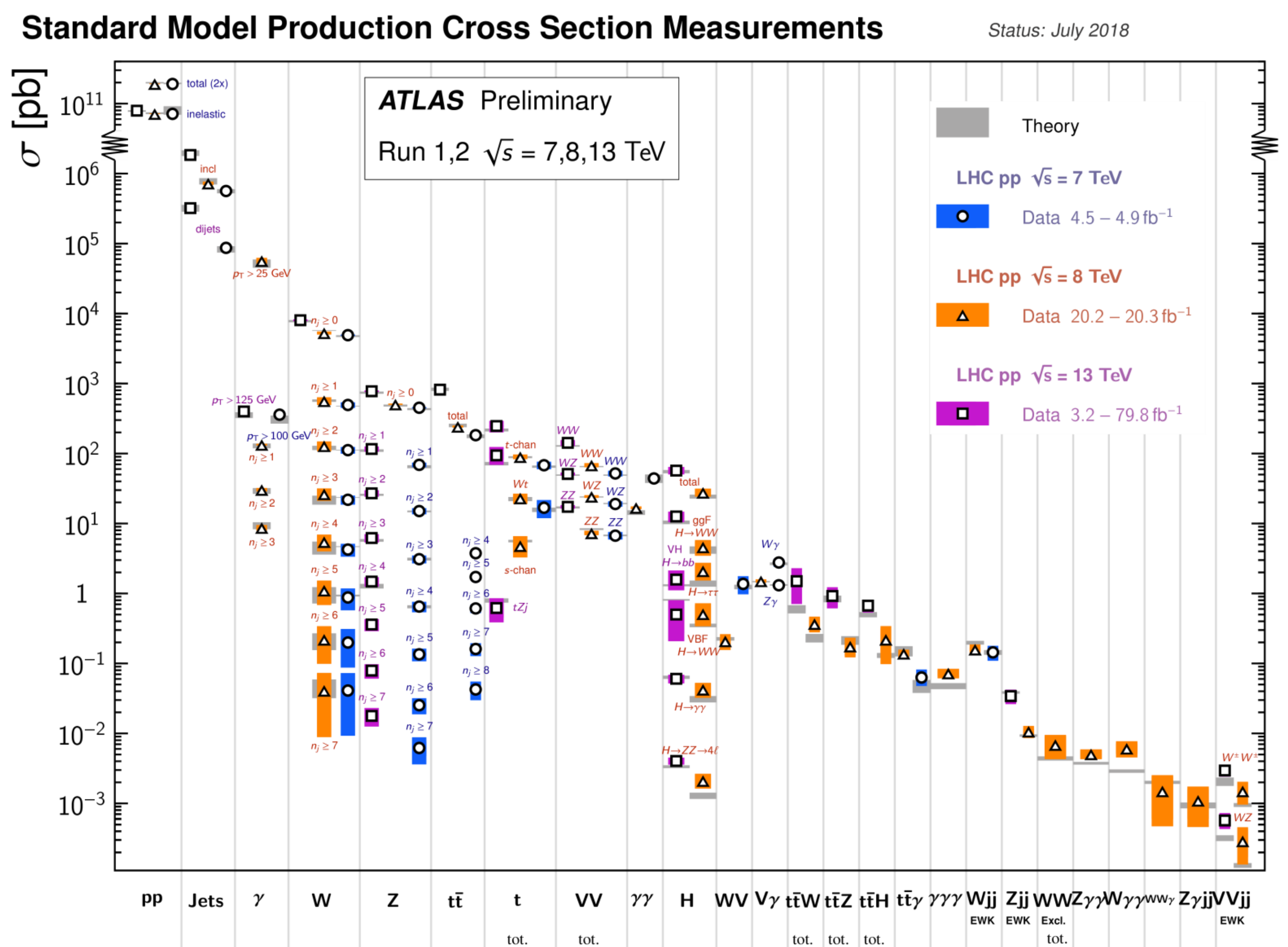
6/7 October 2024

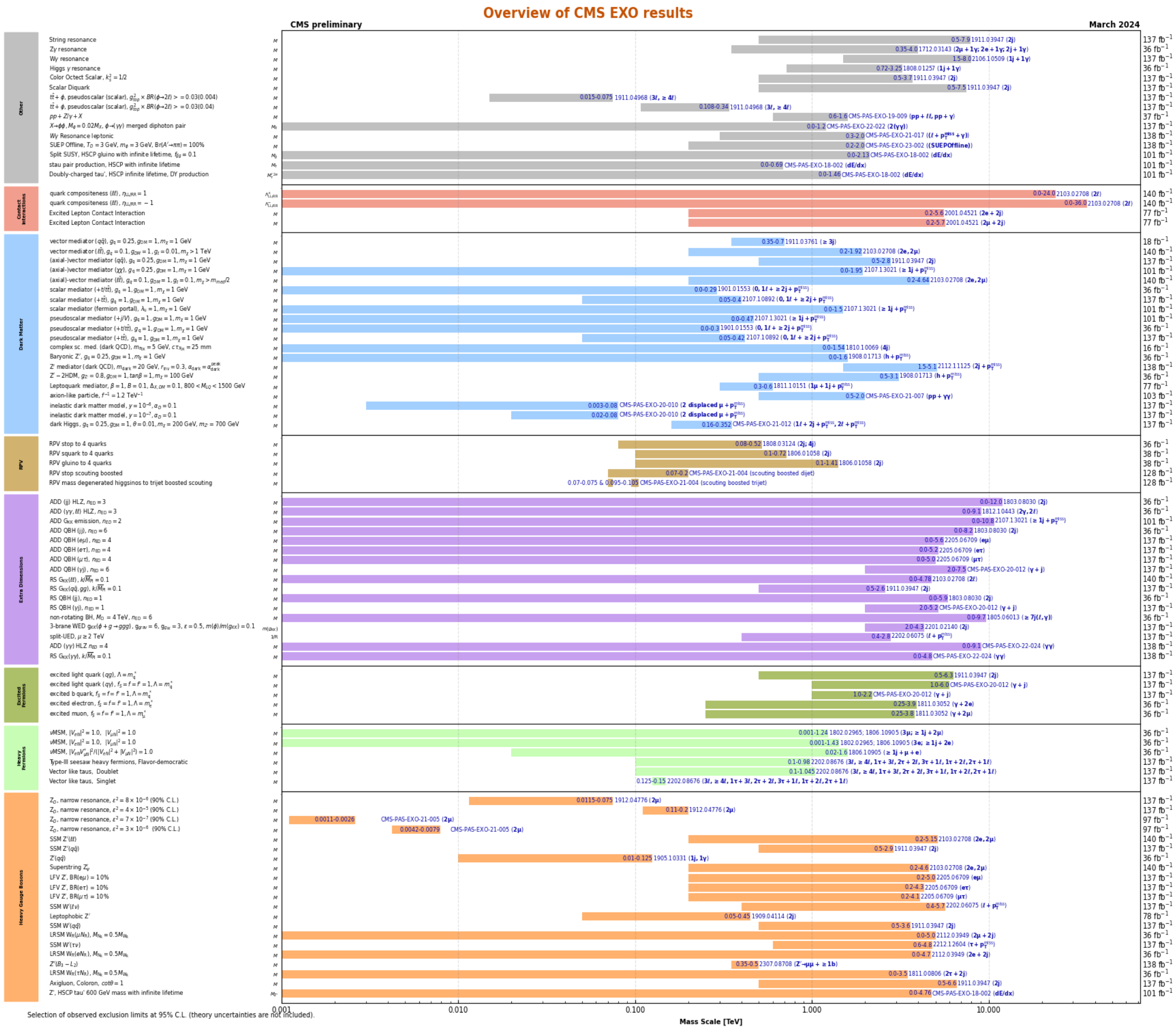
Two Lectures

1) Today: LHC, collider physics, HL-LHC prospects
2) Tomorrow: “Beyond”: Future colliders

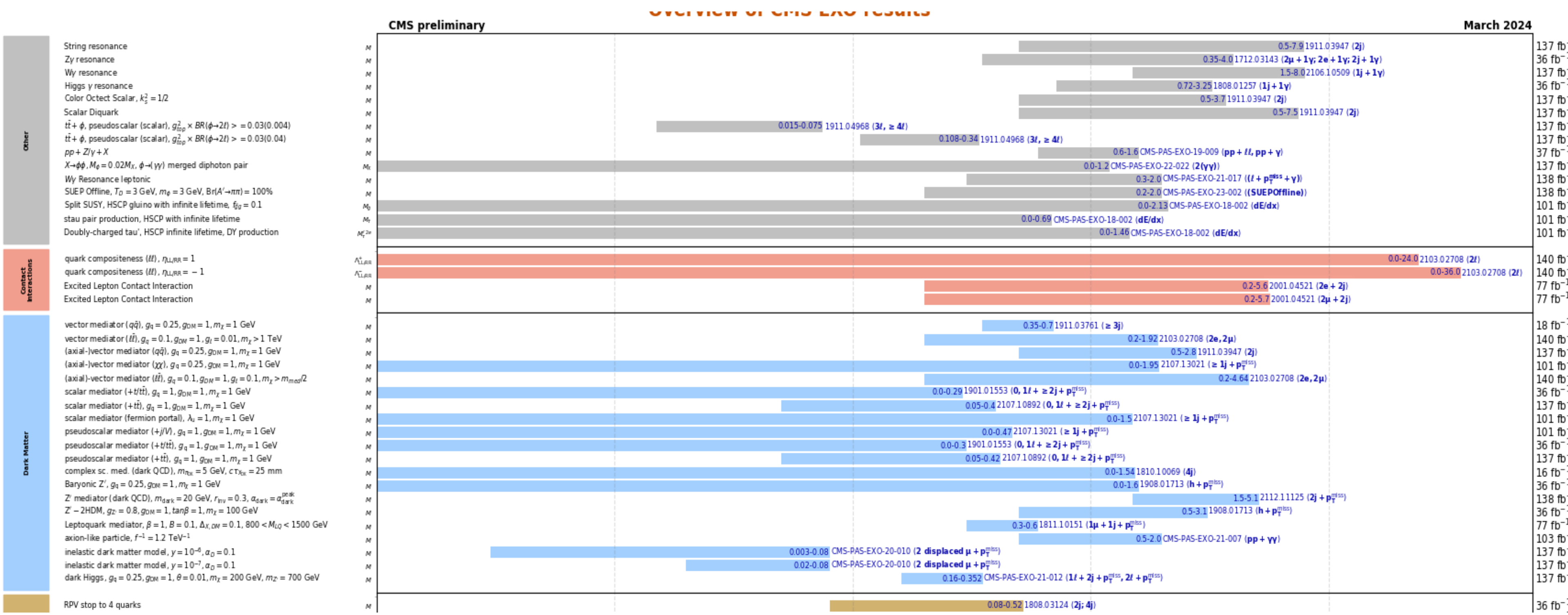
Now


Standard Model Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
σ [pb]
total (2x)
inelastic
incl
dijets
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Wjj
Zjj
WW
Zγγ
Wγγ
WWγ
Zγjj
VVjj
EWK
Excl.
tot.

Now…


Overview of CMS EXO results
CMS preliminary
March 2024
Other
Contact Interactions
Dark Matter
RPV
Extra Dimensions
Excited Fermions
Heavy Fermions
Heavy Gauge Bosons
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
Mass Scale [TeV]

Now…

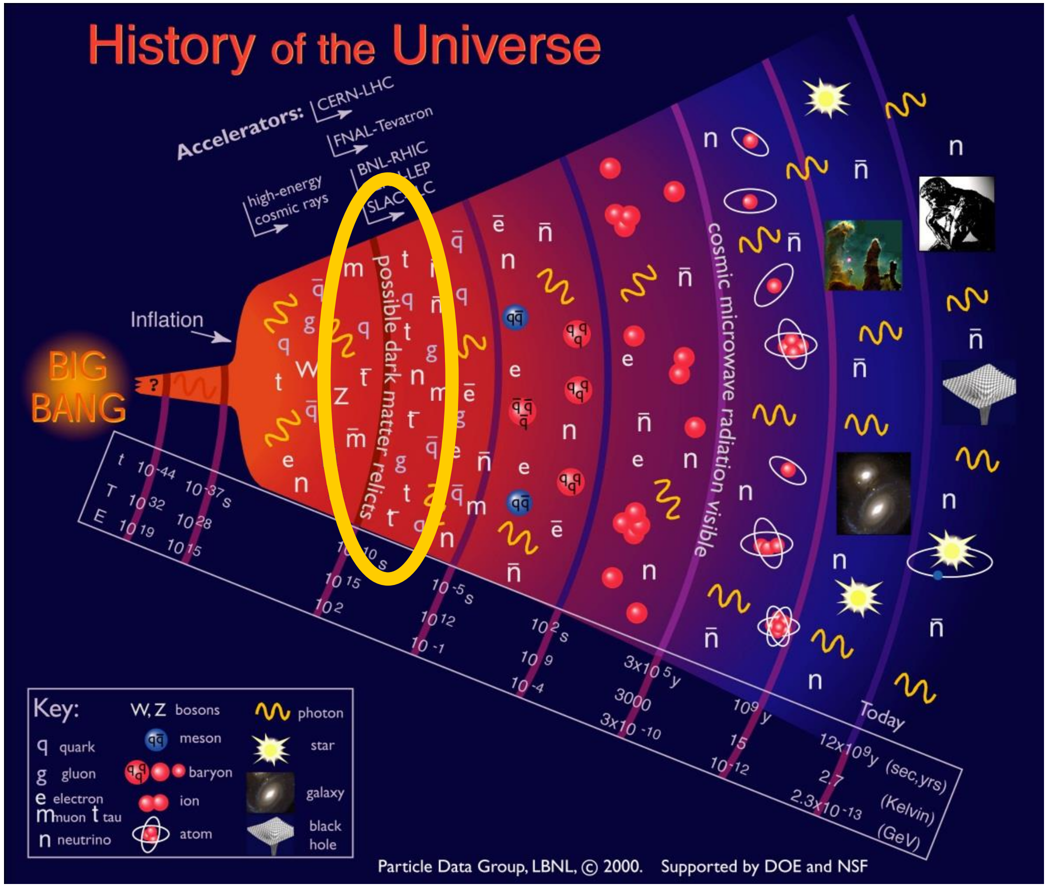


CMS preliminary
March 2024
Other
String resonance 0.5-7.9 1911.03947 (2j) 137 fb
Zγ resonance 0.35-4.0 1712.03143 (2μ + 1γ; 2e + 1γ; 2j + 1γ) 36 fb
Wγ resonance 1.5-8.0 2106.10509 (1j + 1γ) 137 fb
Higgs γ resonance 0.72-3.25 1808.01257 (1j + 1γ) 36 fb
Color Octect Scalar 0.5-3.7 1911.03947 (2j) 137 fb
Scalar Diquark 0.5-7.5 1911.03947 (2j) 137 fb
0.015-0.075 1911.04968 (3ℓ, ≥ 4ℓ) 137 fb
0.108-0.34 1911.04968 (3ℓ, ≥ 4ℓ) 137 fb
pp + Z/γ + X 0.6-1.6 CMS-PAS-EXO-19-009 (pp + ℓℓ, pp + γ) 37 fb
merged diphoton pair 0.0-1.2 CMS-PAS-EXO-22-022 (2(γγ)) 137 fb
Wγ Resonance leptonic 0.3-2.0 CMS-PAS-EXO-21-017 138 fb
SUEP Offline 0.2-2.0 CMS-PAS-EXO-23-002 (SUEPOffline) 138 fb
Split SUSY, HSCP gluino with infinite lifetime 0.0-2.13 CMS-PAS-EXO-18-002 (dE/dx) 101 fb
stau pair production, HSCP with infinite lifetime 0.0-0.69 CMS-PAS-EXO-18-002 (dE/dx) 101 fb
Doubly-charged tau', HSCP infinite lifetime, DY production 0.0-1.46 CMS-PAS-EXO-18-002 (dE/dx) 101 fb
Contact Interactions
quark compositeness 0.0-24.0 2103.02708 (2ℓ) 140 fb
quark compositeness 0.0-36.0 2103.02708 (2ℓ) 140 fb
Excited Lepton Contact Interaction 0.2-5.6 2001.04521 (2e + 2j) 77 fb
Excited Lepton Contact Interaction 0.2-5.7 2001.04521 (2μ + 2j) 77 fb
Dark Matter
0.35-0.7 1911.03761 (≥ 3j) 18 fb
0.2-1.92 2103.02708 (2e, 2μ) 140 fb
0.5-2.8 1911.03947 (2j) 137 fb
0.0-1.95 2107.13021 101 fb
0.2-4.64 2103.02708 (2e, 2μ) 140 fb
0.0-0.29 1901.01553 36 fb
0.05-0.4 2107.10892 137 fb
0.0-1.5 2107.13021 101 fb
0.0-0.47 2107.13021 101 fb
0.0-0.3 1901.01553 36 fb
0.05-0.42 2107.10892 137 fb
0.0-1.54 1810.10069 (4j) 16 fb
0.0-1.6 1908.01713 36 fb
1.5-5.1 2112.11125 138 fb
0.5-3.1 1908.01713 36 fb
0.3-0.6 1811.10151 77 fb
axion-like particle 0.5-2.0 CMS-PAS-EXO-21-007 (pp + γγ) 103 fb
inelastic dark matter model 0.003-0.08 CMS-PAS-EXO-20-010 (2 displaced μ) 137 fb
inelastic dark matter model 0.02-0.08 CMS-PAS-EXO-20-010 (2 displaced μ) 137 fb
dark Higgs 0.16-0.352 CMS-PAS-EXO-21-012 137 fb
RPV stop to 4 quarks 0.08-0.52 1808.03124 (2j; 4j) 36 fb

Why?

Understanding the Universe

Big Bang

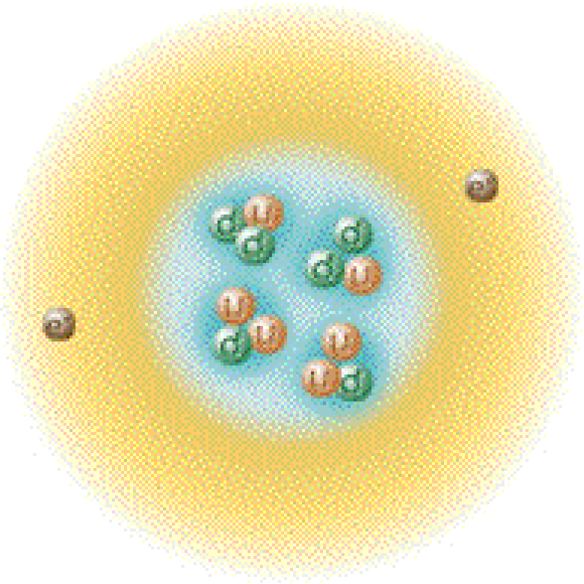


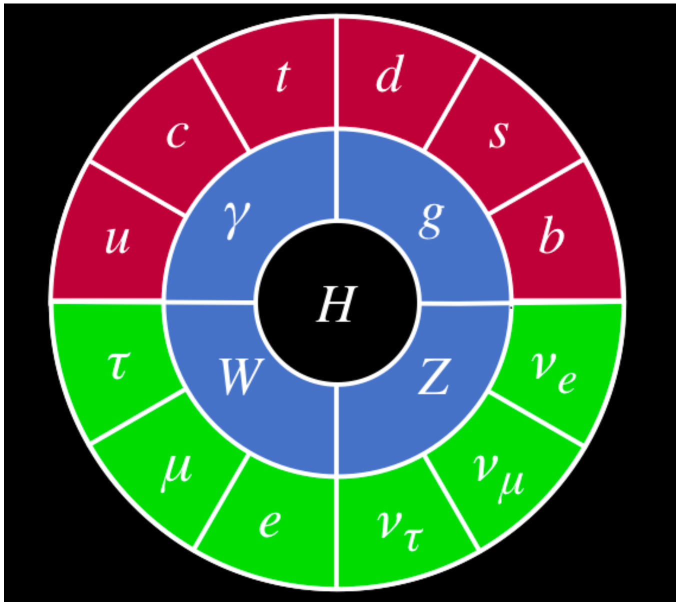
now

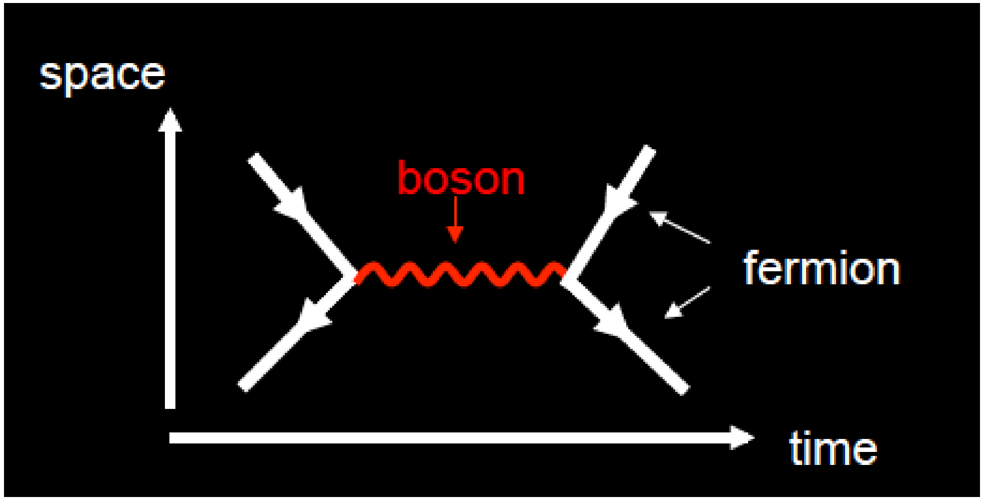
Older ….. larger … colder ….less energetic

Standard Model of Particle Physics

- Strong, weak and Electromagnetic forces
- Describes interaction of matter particles by the means of force carrier particles







Goals of Particle Physics

- **Measuring Standard Model parameters precisely**
  - It has 26 free parameters
- **Understanding the generation of mass (is the Higgs mechanism the right answer?)**
- **Searching for new phenomena to rule in or out new theories**
  - Standard Model has some shortcomings
  - Joining up our understanding of the very large (galaxies) with the very small: what is dark matter?
- **CP violation**

The Collider Approach (in the present)

The Energy Frontier

- Mass of new particles that can be produced:

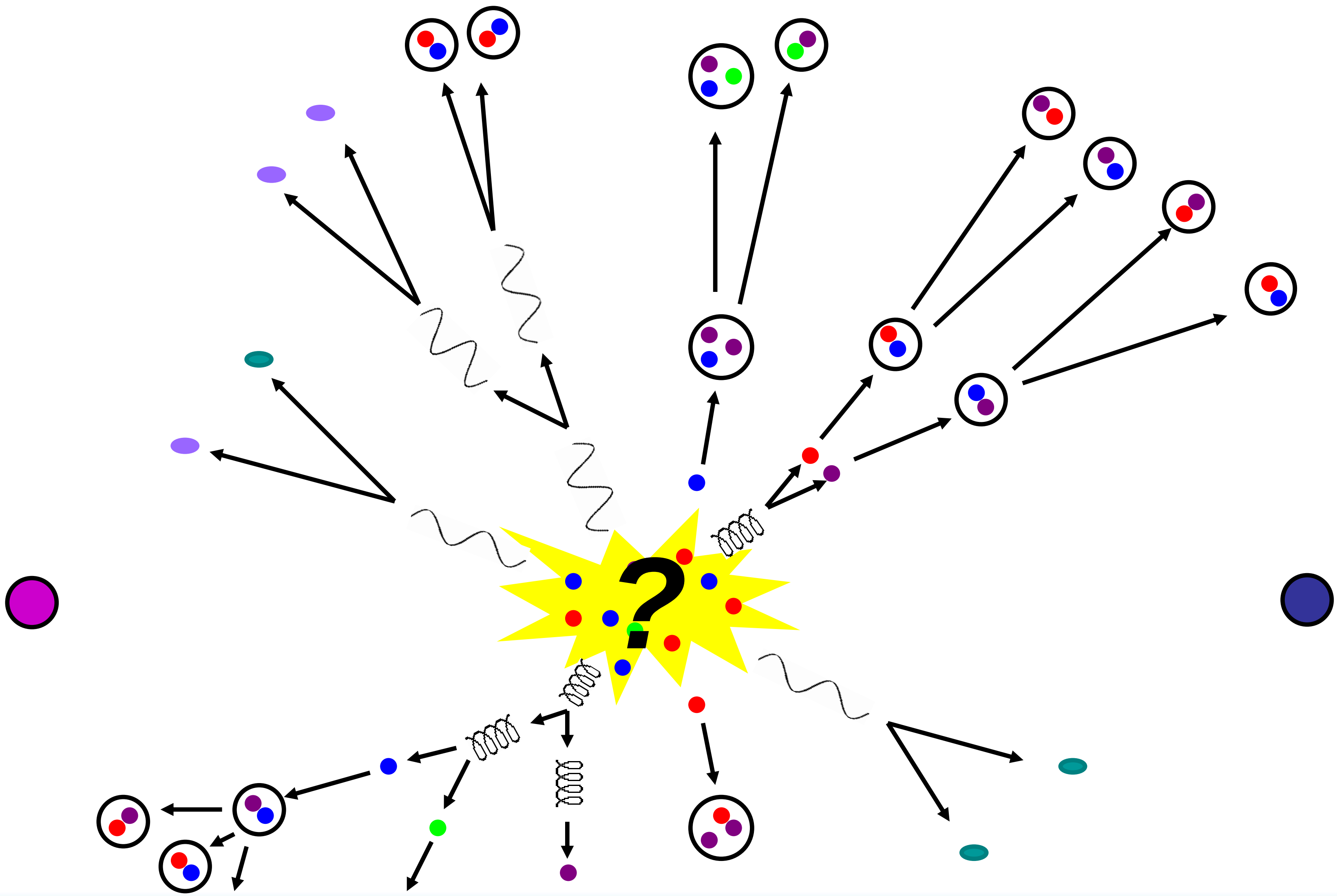
$$E=mc^2$$

- The larger the collision momentum (energy), the higher the mass of new particles that can be produced
  - And the higher the process cross-section

Particle Collisions

Two particles collide at very high energy

New particles are produced which we detect and study

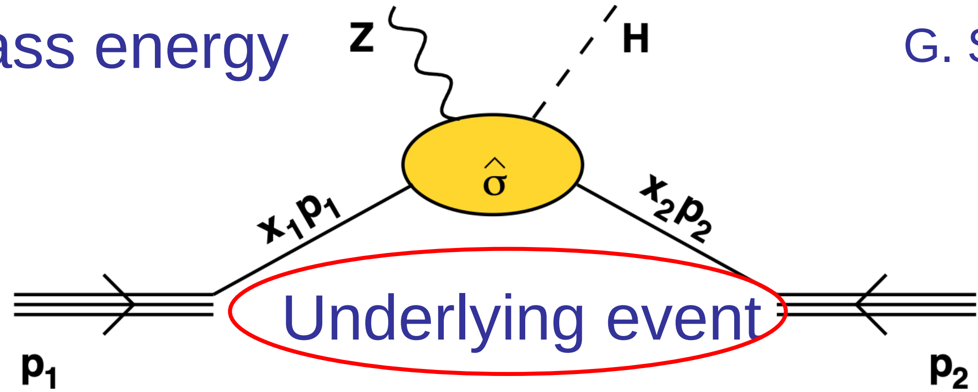


Proton Proton Collisions

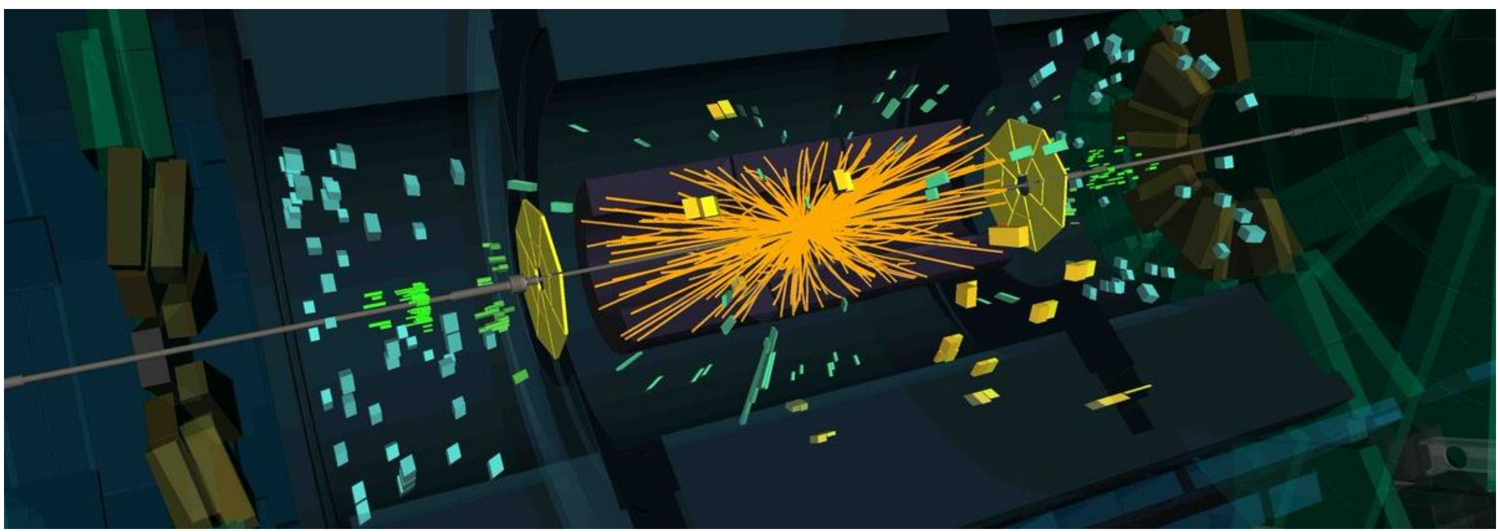
LHC 13 TeV centre of mass energy

G. Salam

Cross section for some hard process in hadron-hadron collisions

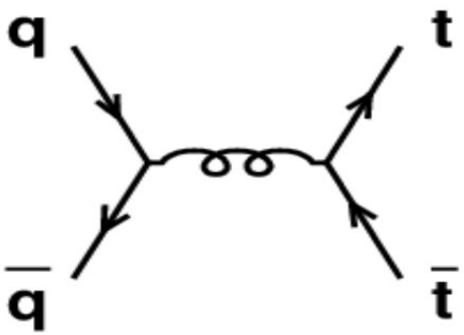


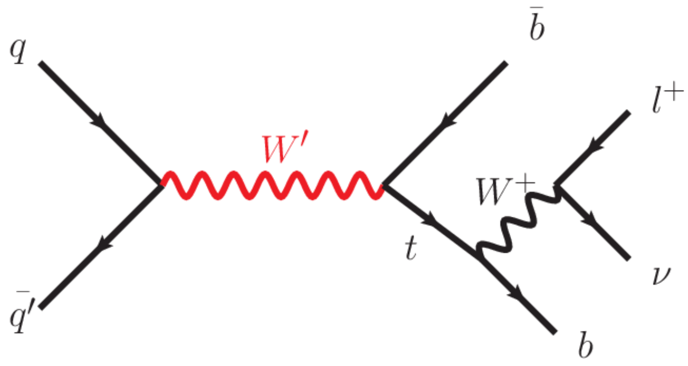
$$\sigma = \int dx_1 f_{q/p}(x_1,\mu^2) \int dx_2 f_{\bar{q}/\bar{p}}(x_2,\mu^2)\, \hat{\sigma}(x_1p_1, x_2p_2, \mu^2)\,, \quad \hat{s} = x_1x_2s$$



Proton Proton Collisions

- Example production diagrams: top, exotic W'



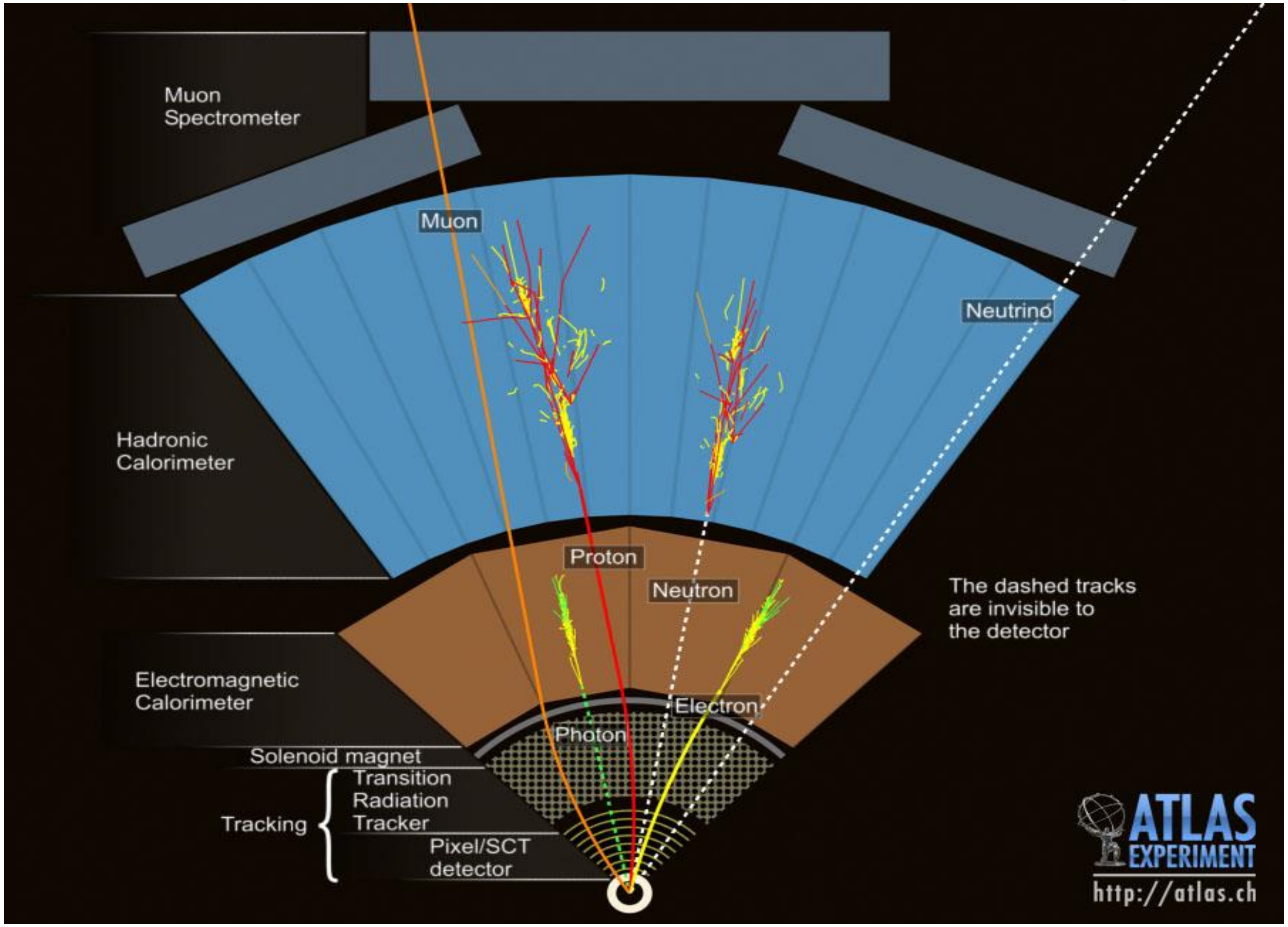


- Leads to multitude of signatures (leptons, jets…)
- Motivates a *General Purpose Detector* with capabilities for all these particles (ATLAS and CMS)

- Dedicated b-physics detector: LHCb, (Tim Gershon)
- Dedicated heavy-ion detector: ALICE

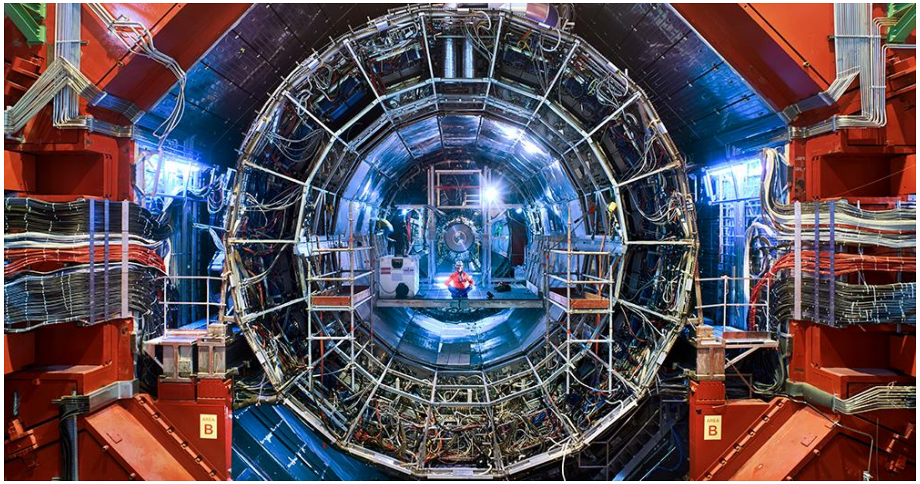
A Particle Detector

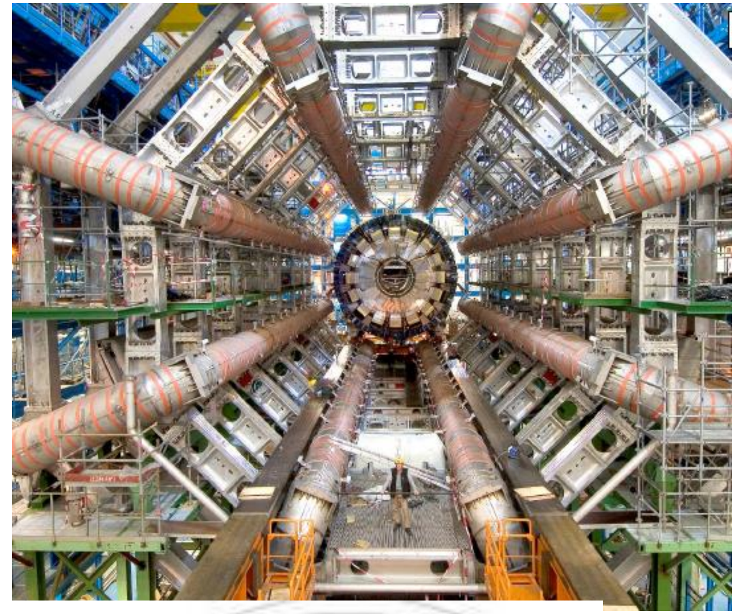
"Onion shell" structure enables reconstruction of particles

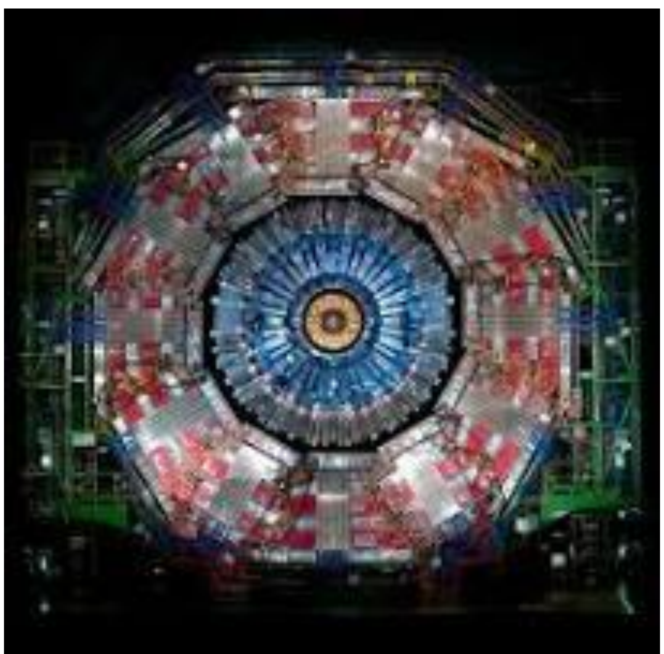


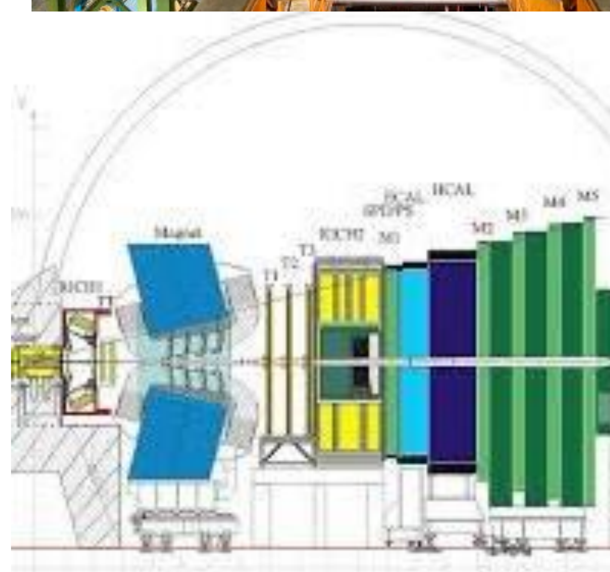
Use this capability to reconstruct particle interactions of special interest

The LHC Detectors



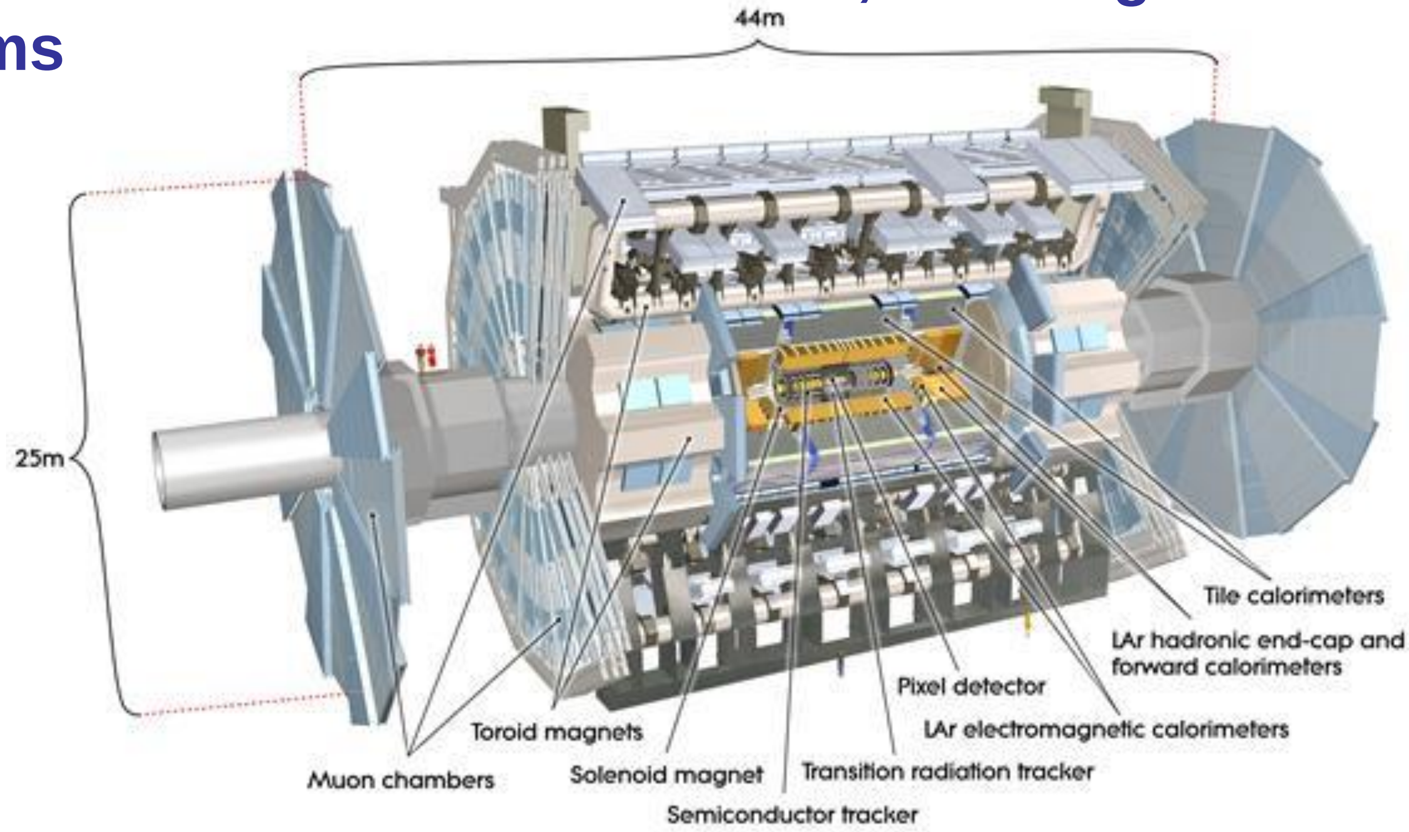




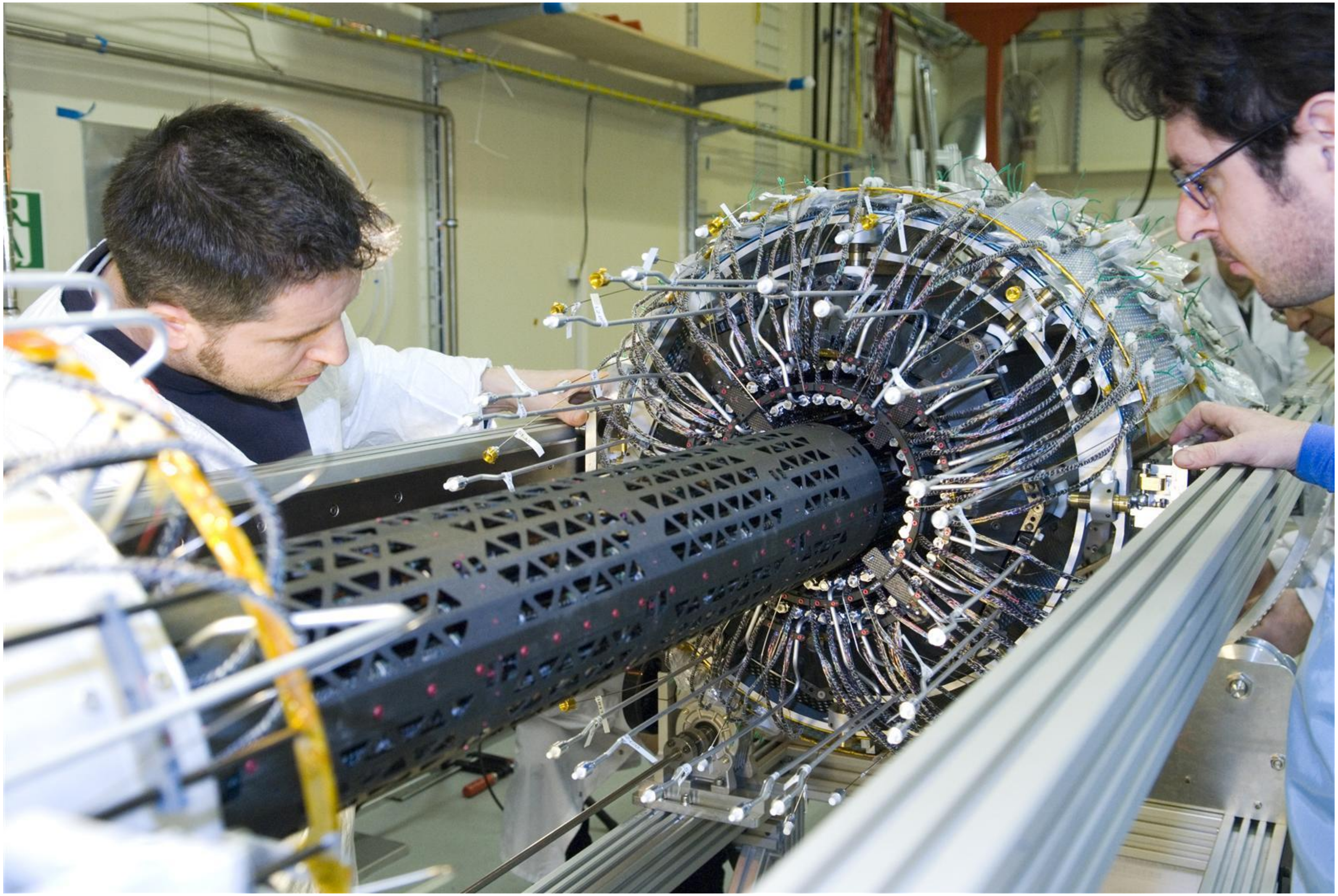


The ATLAS experiment

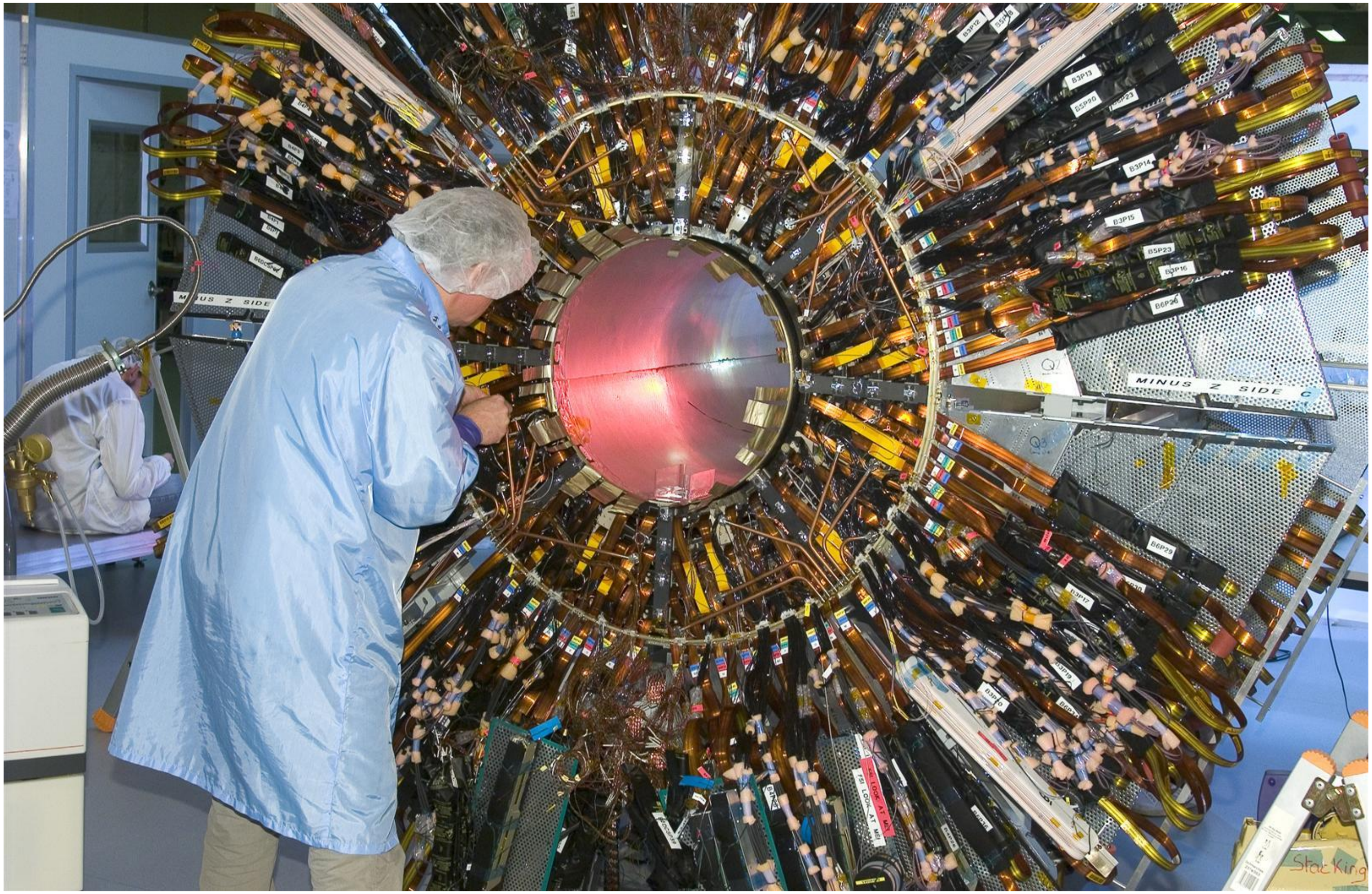
- **40M readout channels**
- **Finely instrumented tracking detectors, then deep calorimeters then muon chambers, two magnet systems**



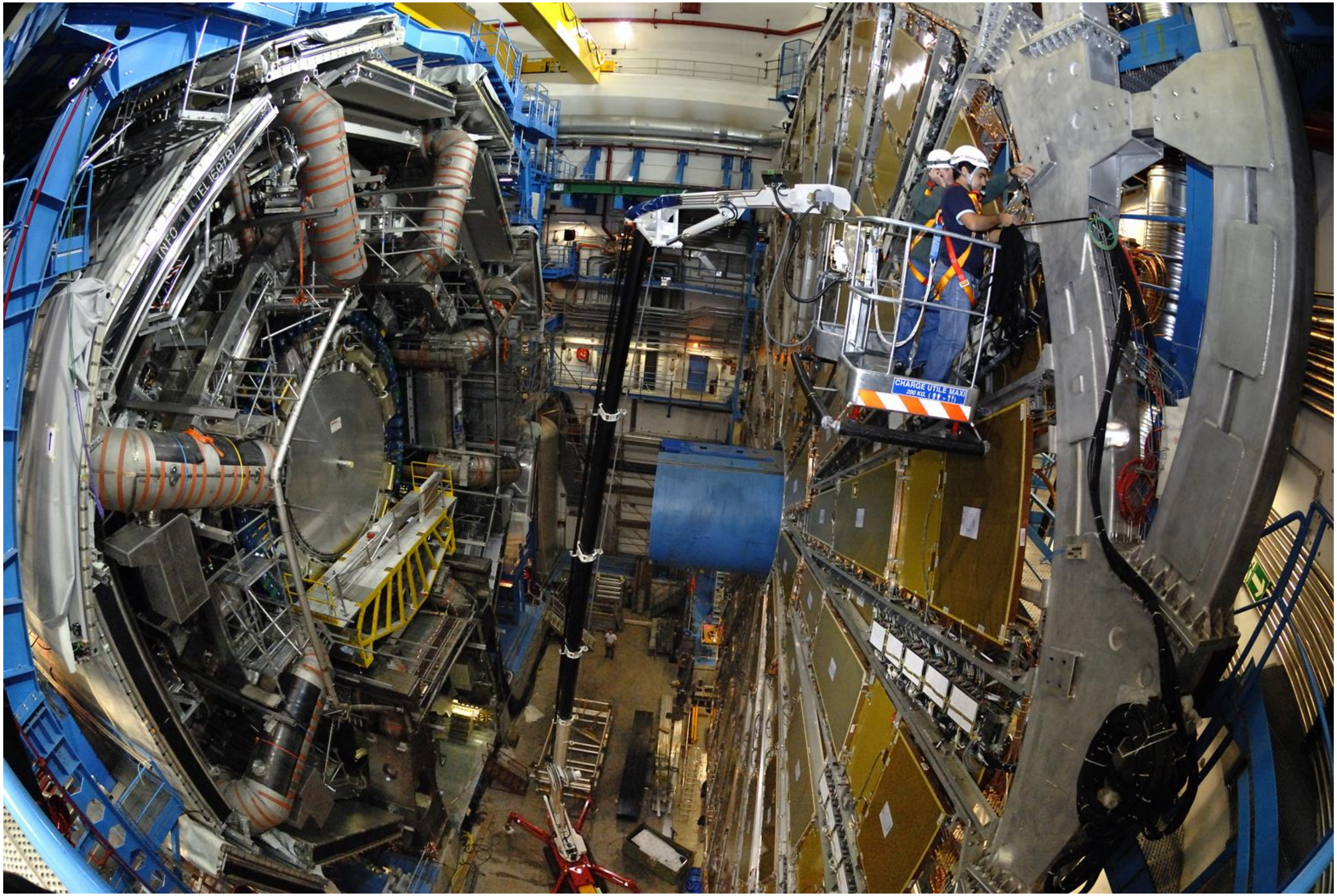
Precision silicon tracking



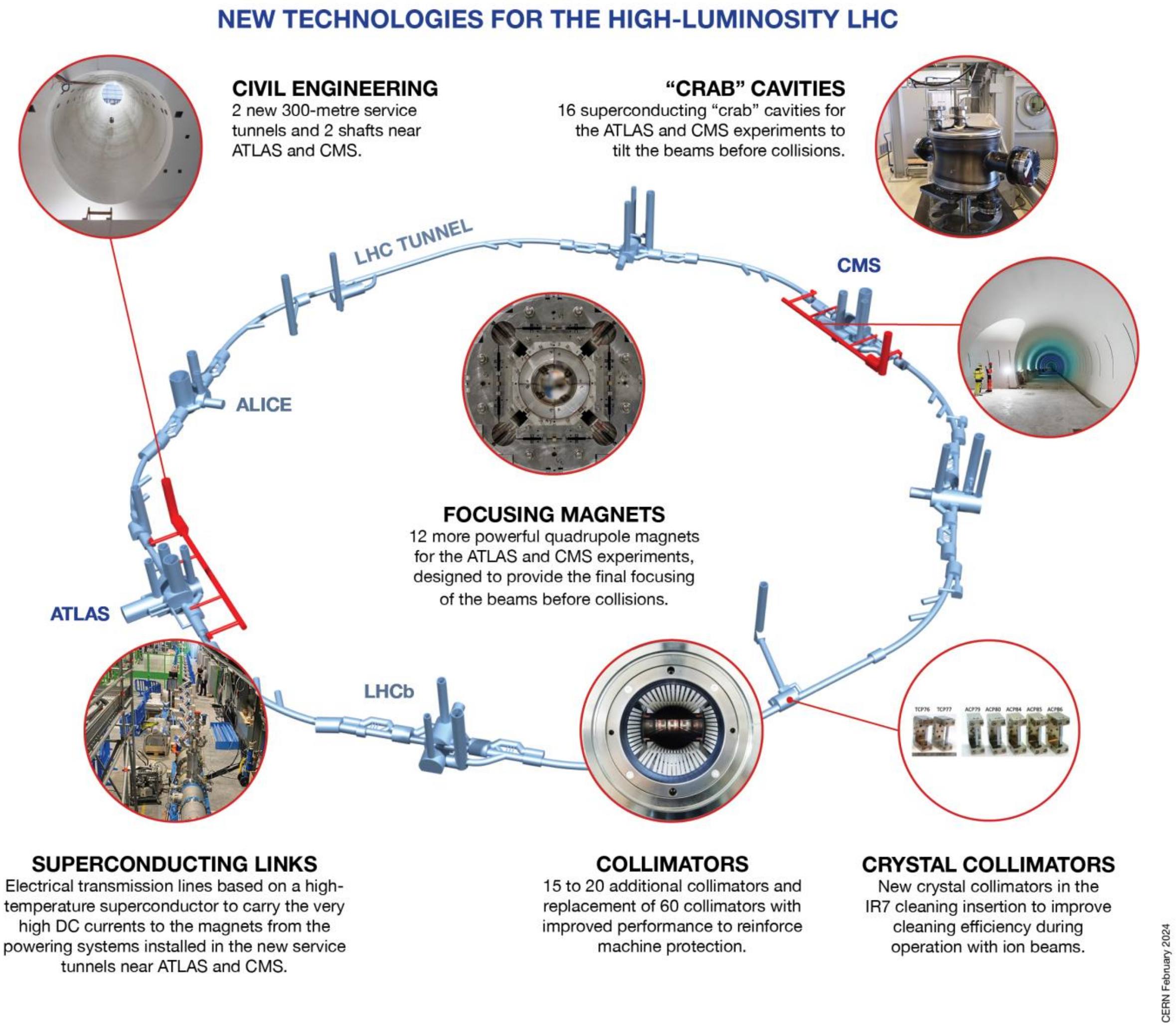
100's millions readout channels



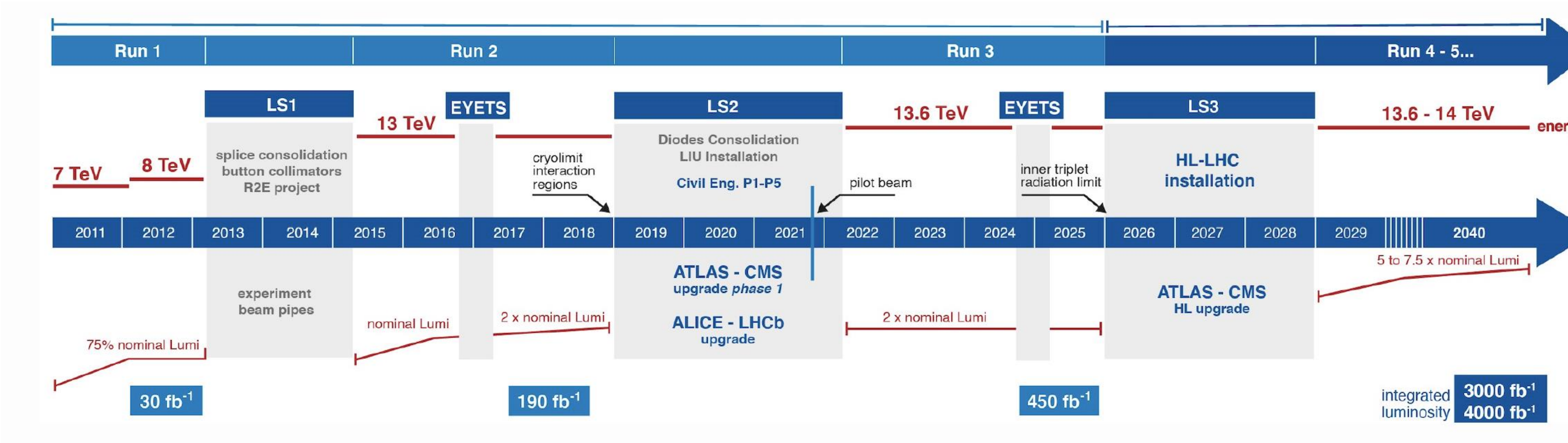
Large scale magnets and muon detection



LHC Collider Upgrades

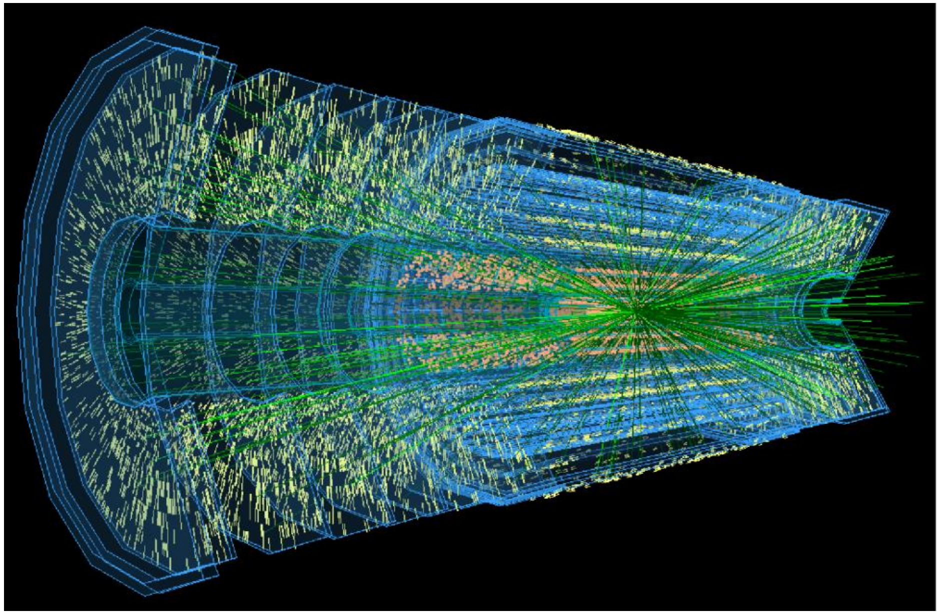


LHC Collider Upgrades



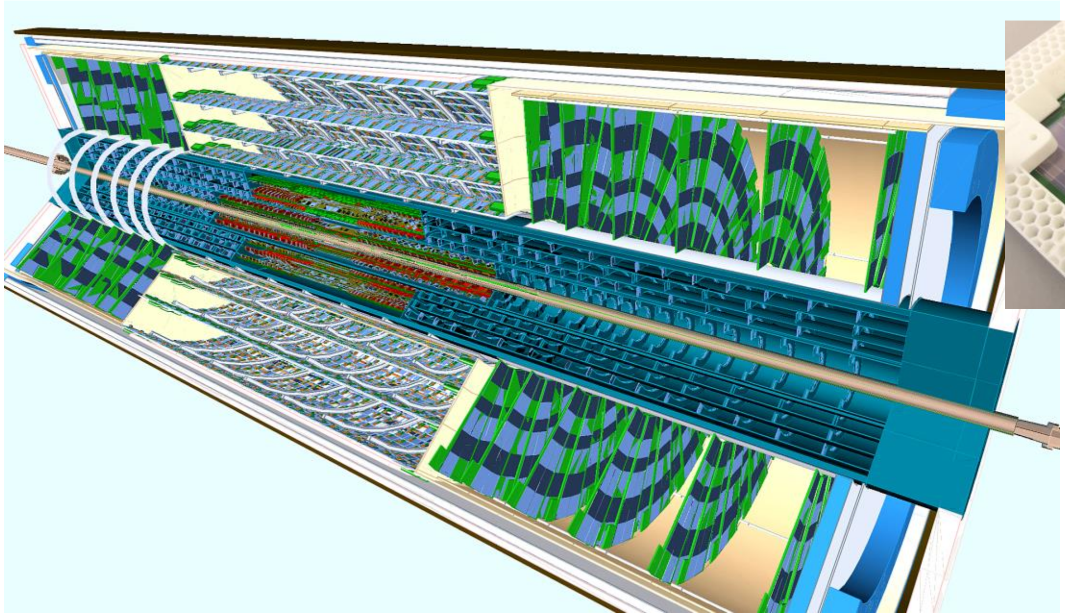
LHC Upgrades

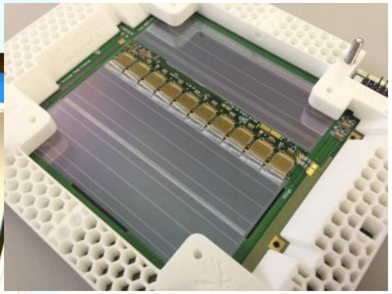
- **~10x instantaneous luminosity**
- **Pile-up of ~200 (c.f. 60 now) at ATLAS/CMS**
- **High Luminosity-LHC detector occupancy would overwhelm existing detectors**
  - Require finer-grained silicon detectors, new tracking detectors

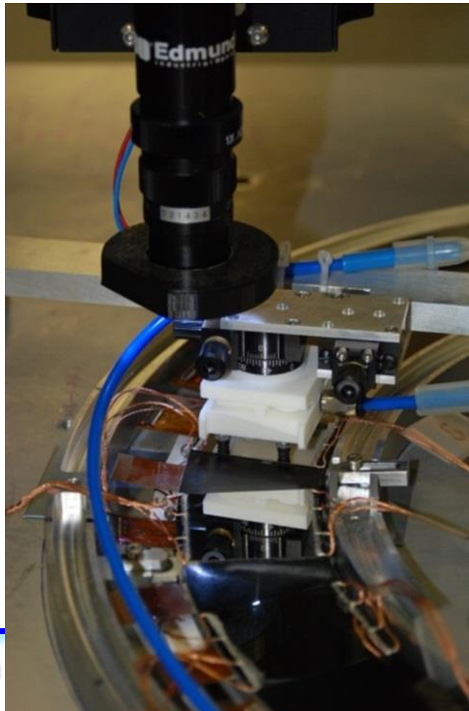


LHC Upgrades

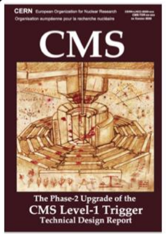
- **Construction work is taking place around the world**
- **All new silicon detectors for ATLAS/CMS**
  - In addition to substantial software developments in data-recording
  - Challenging projects, large scale pixel detector. Much to do!
- **ALICE and LHCb propose upgrades after LS4**







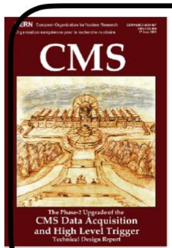
CMS upgrades



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

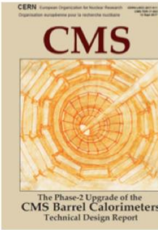
https://cds.cern.ch/record/2759072

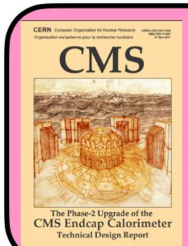
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

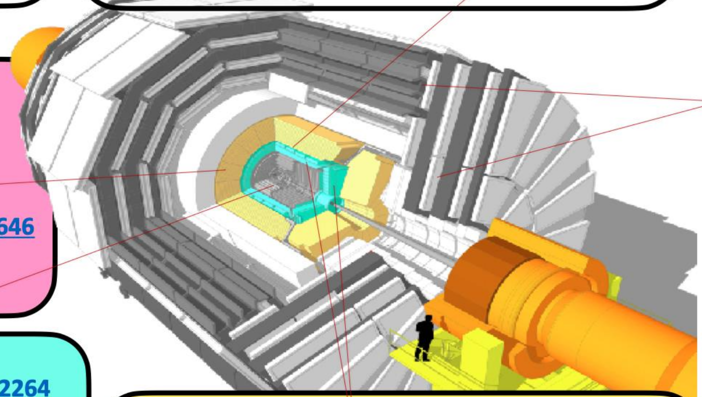




Calorimeter Endcap

https://cds.cern.ch/record/2293646

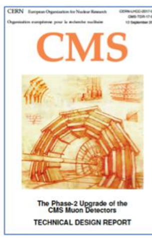
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

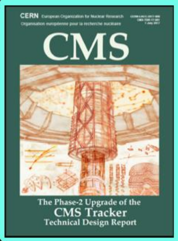


Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

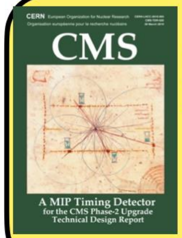




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



MIP Timing Detector

https://cds.cern.ch/record/2667167

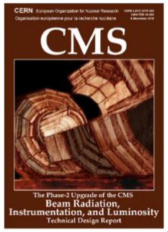
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors



6

P. McBride

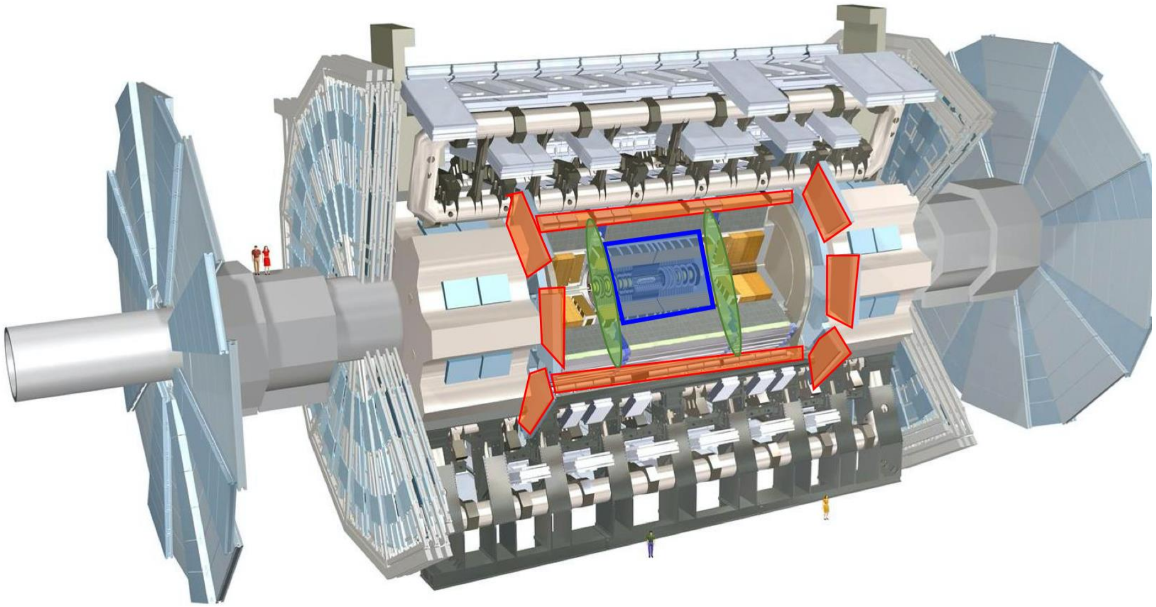
ATLAS upgrades

New Inner Tracking Detector (ITk)
- All silicon with 9 layers up to |η| = 4
- Less material, finer segmentation
- Improve vertexing, tracking, b-tagging

New High Granularity Timing Detector (HGTD)
- Precision track timing (30 ps) with LGAD in the forward region
- Improved pile-up separation and bunch-by-bunch luminosity

Calorimeter Electronics
- On-detector/off-detector electronics upgrades of LAr and Tile Calorimeter
- Provide 40 MHz readout for triggering

New Muon Chambers and electronics
- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate



Upgraded Trigger and Data Acquisition System
- Single Level Trigger with 1 MHz output (x 10 current)
- Improved DAQ system with faster FPGAs

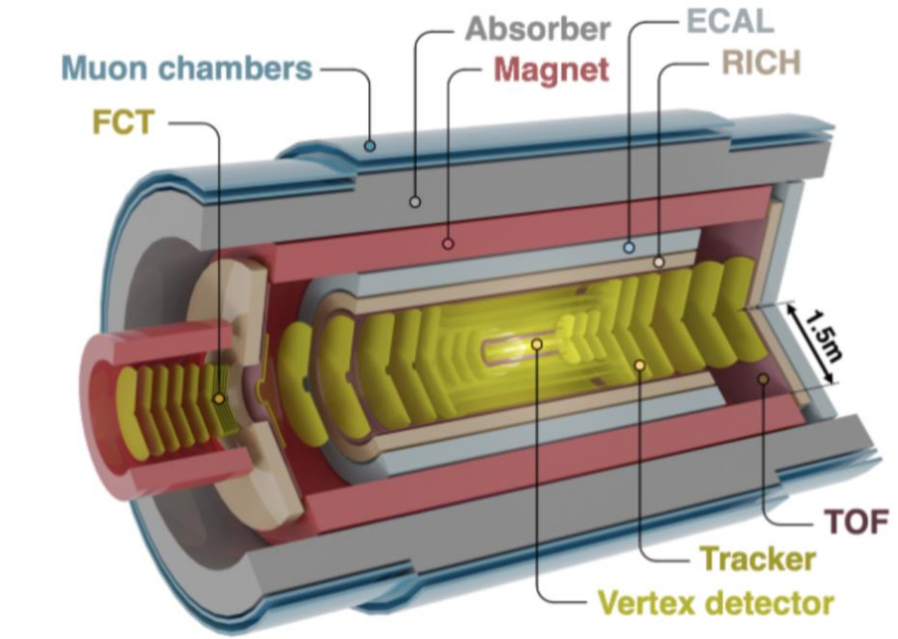
Additional small upgrades
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

K. Tariq

LHCb and ALICE Proposed Upgrades

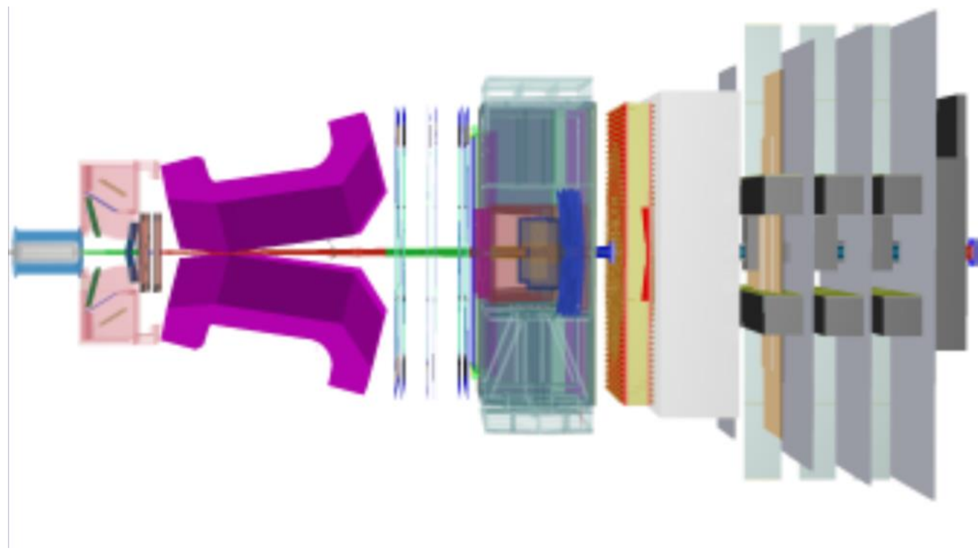
ALICE: very light tracker

- MAPS technology
- Enable 20-50xhigher lumi



LHCb: magnet stations

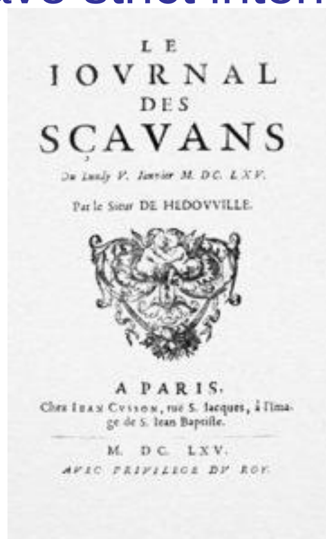
PID, calorimetry…

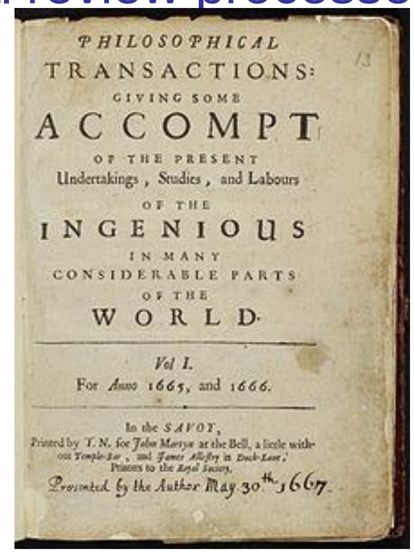


What is a scientific paper?

- Original work
- Peer-reviewed – adversarial process
  - Collaborations have strict internal review processes in addition

(savants)



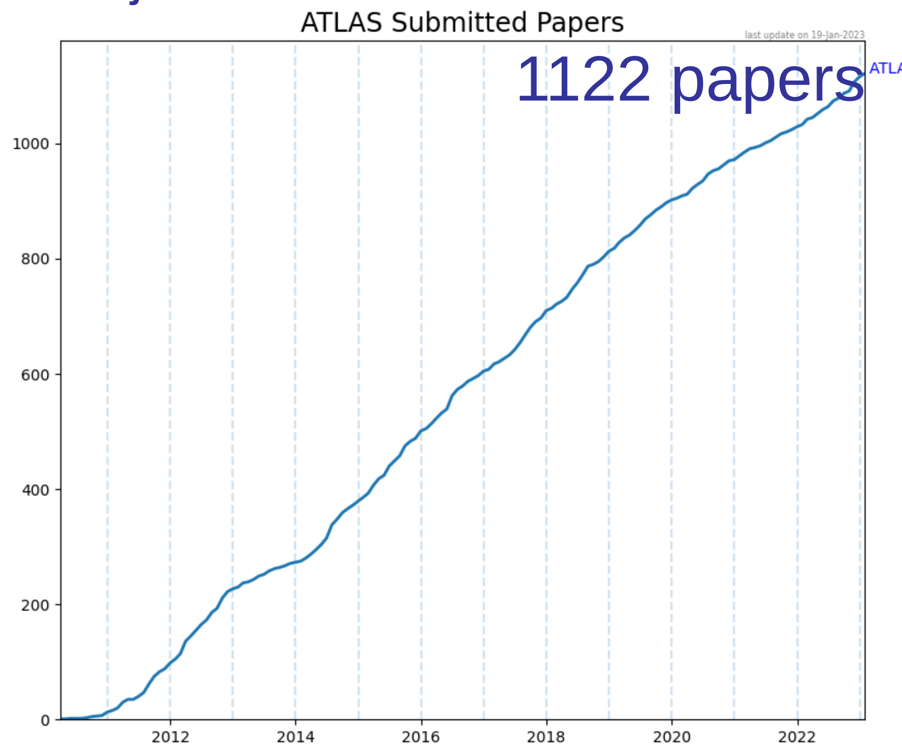


1665

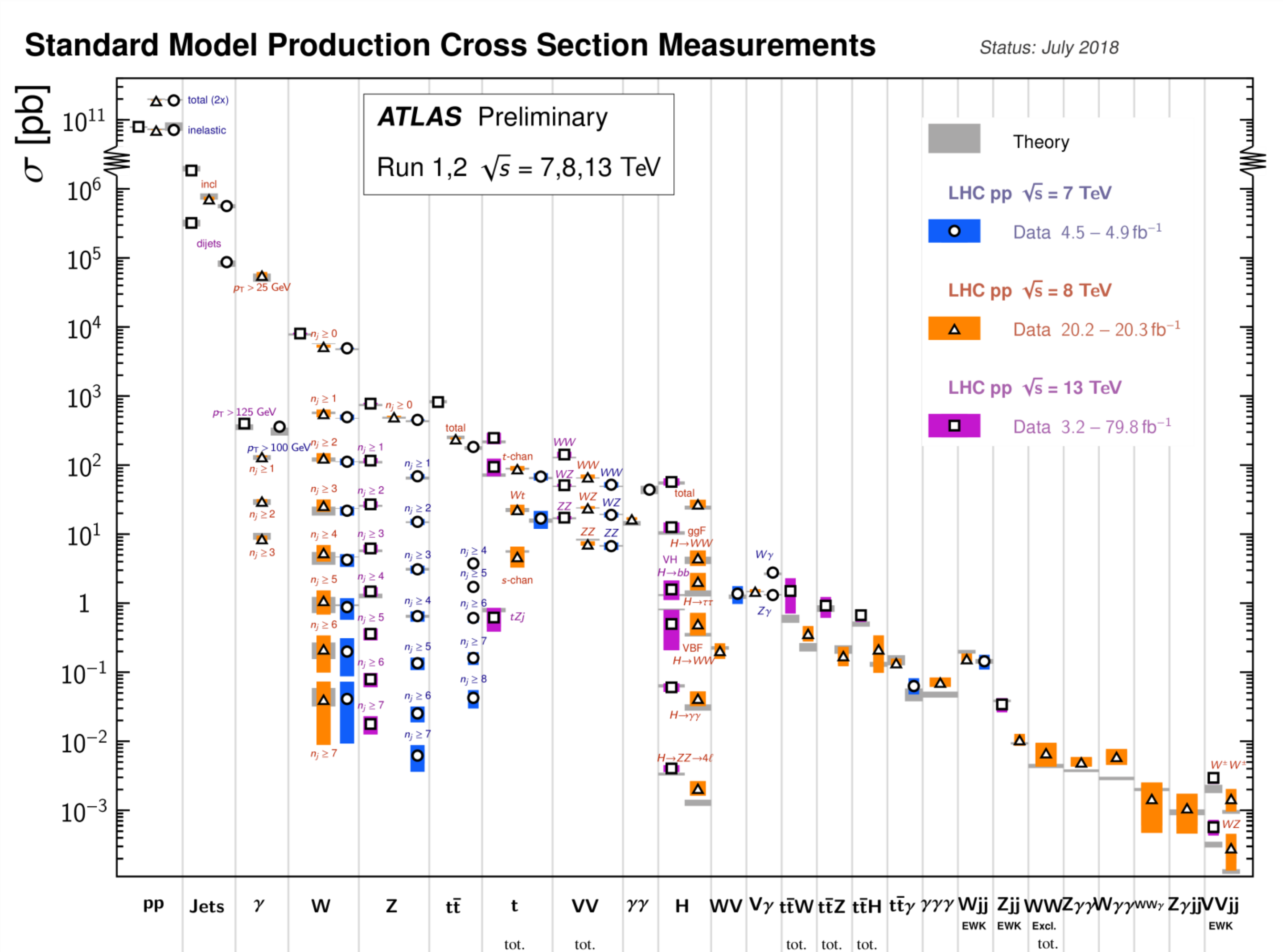
"Giving some Account of the present Undertakings, Studies, and Labours of the Ingenious in many considerable parts of the World" (Royal Society journal)

Celebrate

- Each paper is the result of the collaboration's work to
  - construct the detector
  - read data out
  - calibrate the data
  - process the data to reconstruct the objects
  - analyse the data…
- Hence large authorship papers

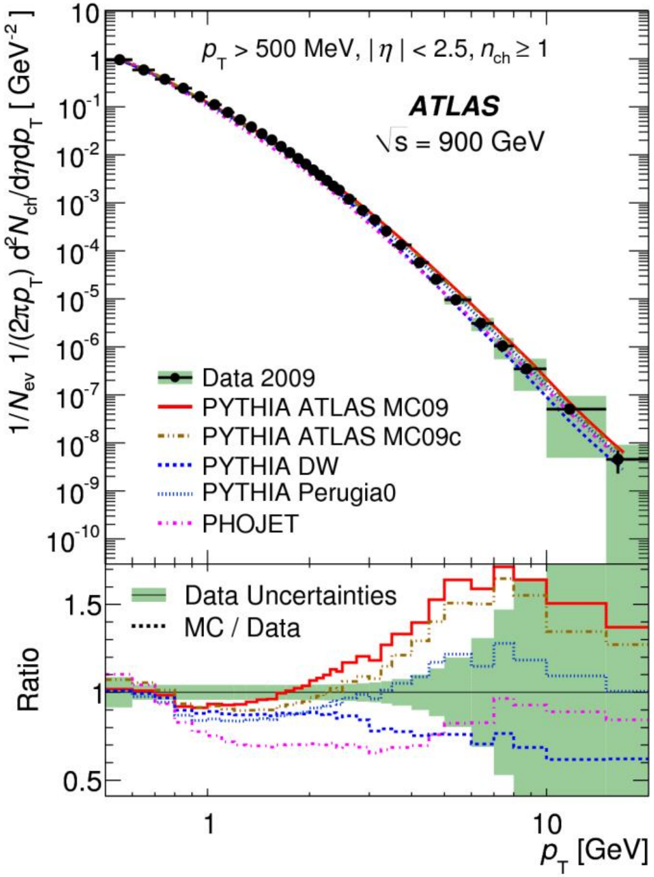


Which processes can we probe?



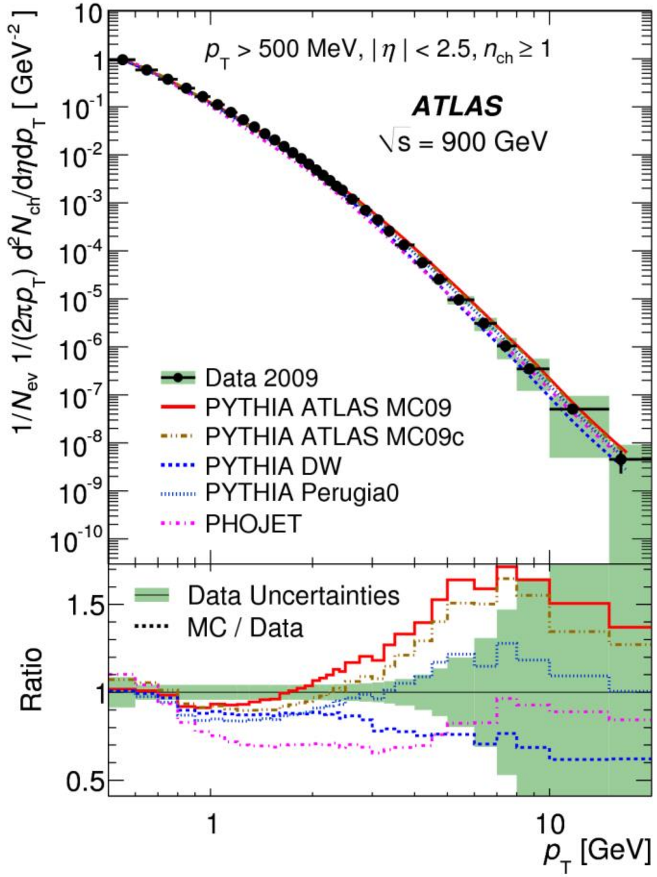
Which processes can we probe?: QCD

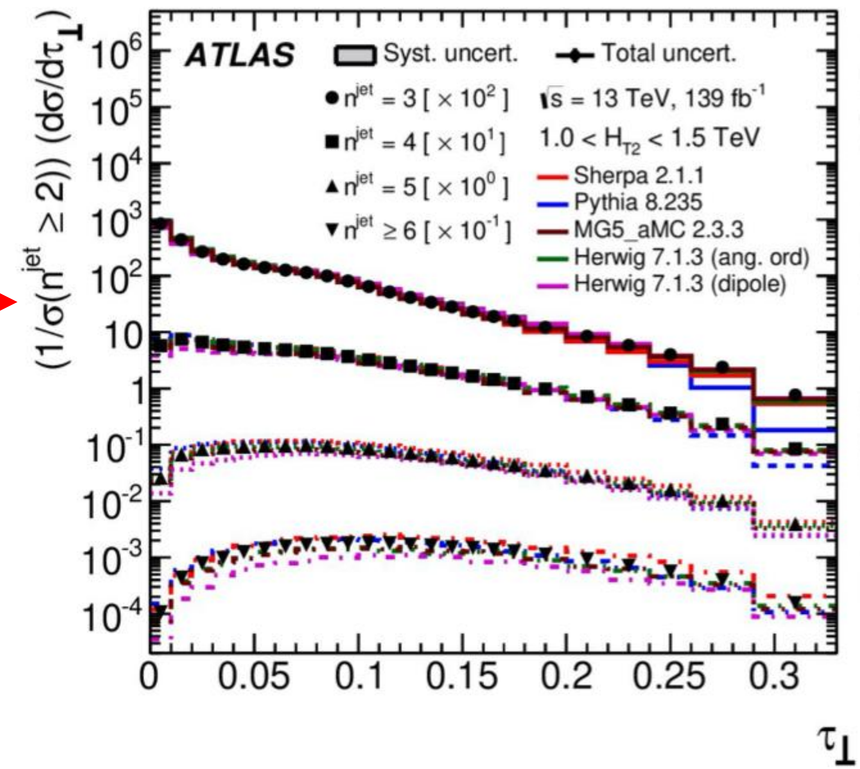
- First thing to understand with collisions at a new centre of mass energy: what are the bulk of the collisions and do they look as we would expect, extrapolating from lower energies?



Which processes can we probe?: QCD

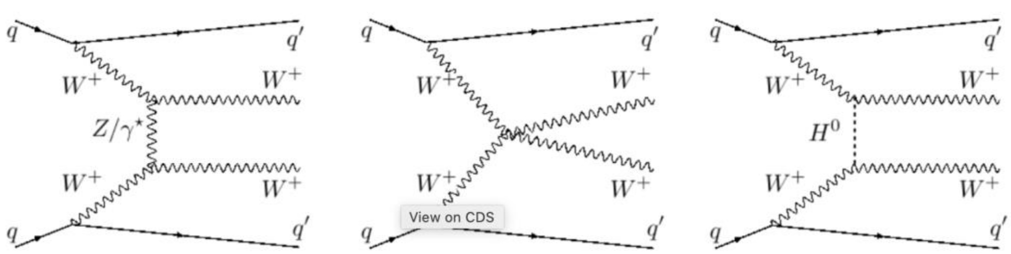
- **First thing to understand with collisions at a new centre of mass energy: what are the bulk of the collisions and do they look as we would expect, extrapolating from lower energies?**

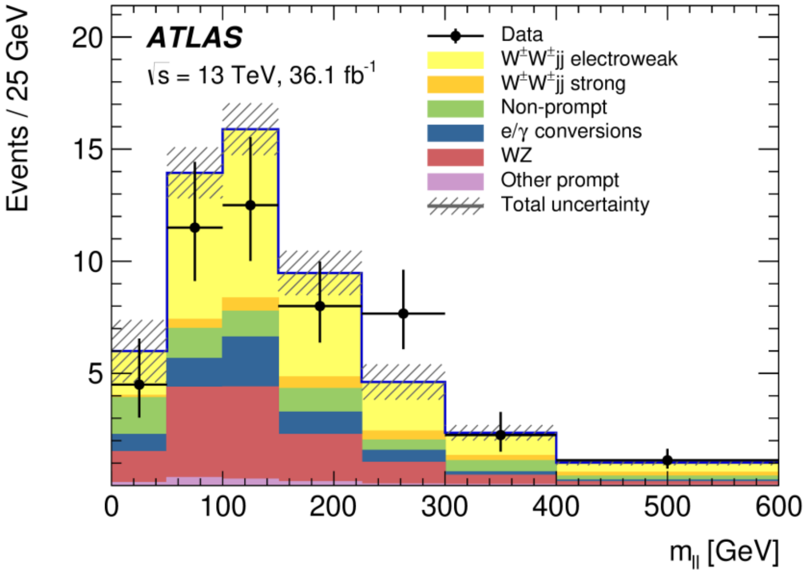




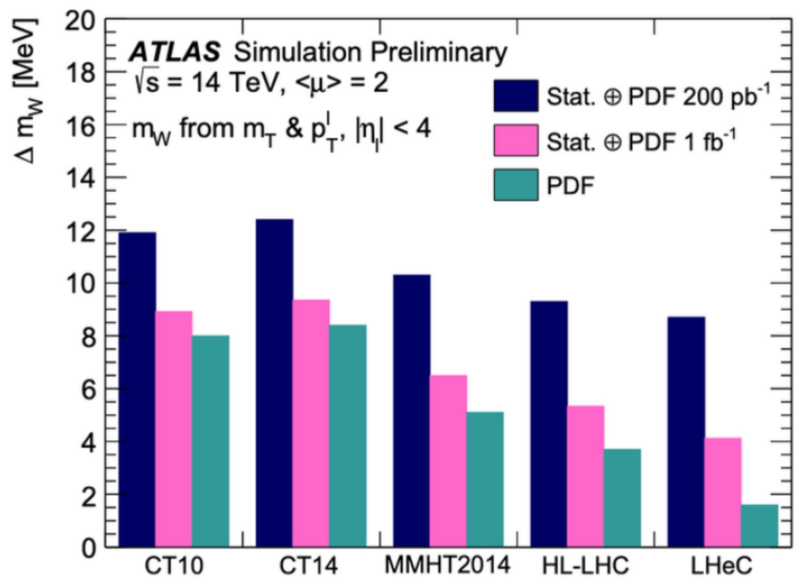
Which processes can we probe?: EW

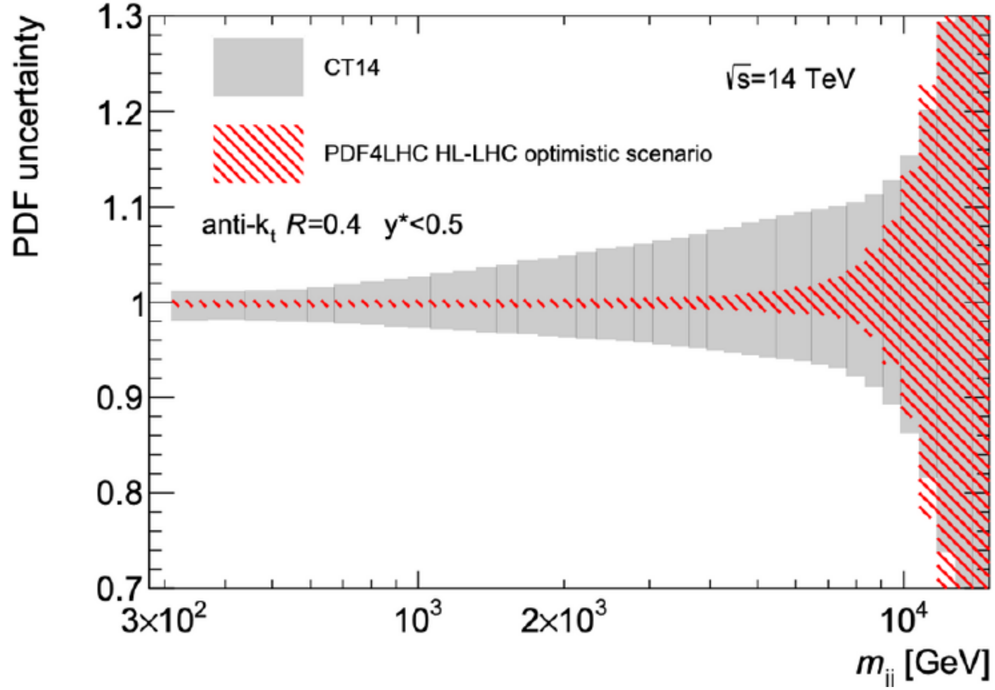
- **Many parameters and processes to explore**
- **Example: WW scattering**
  - Significant and delicate test of the Electroweak theory with the Higgs boson at the heart of it – deviation from exact SM Higgs predictions would alter WW cross-section potentially fatally for the SM, but it agrees with predictions so far.

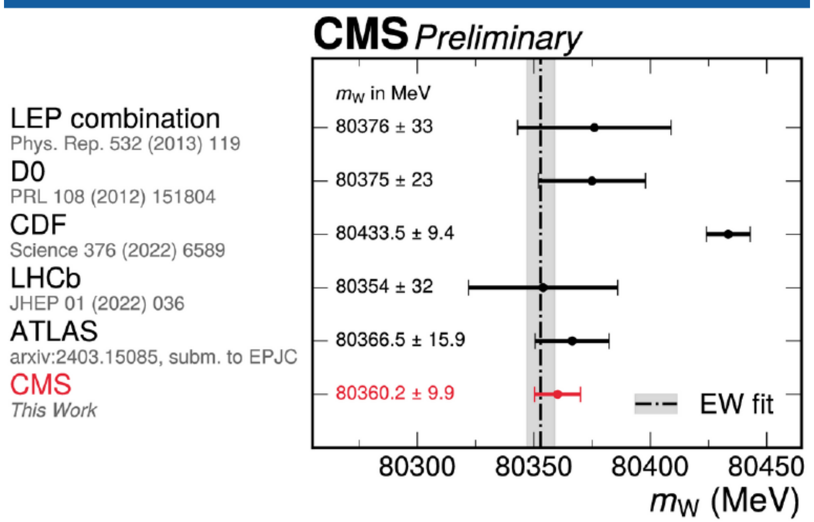




SM prospects





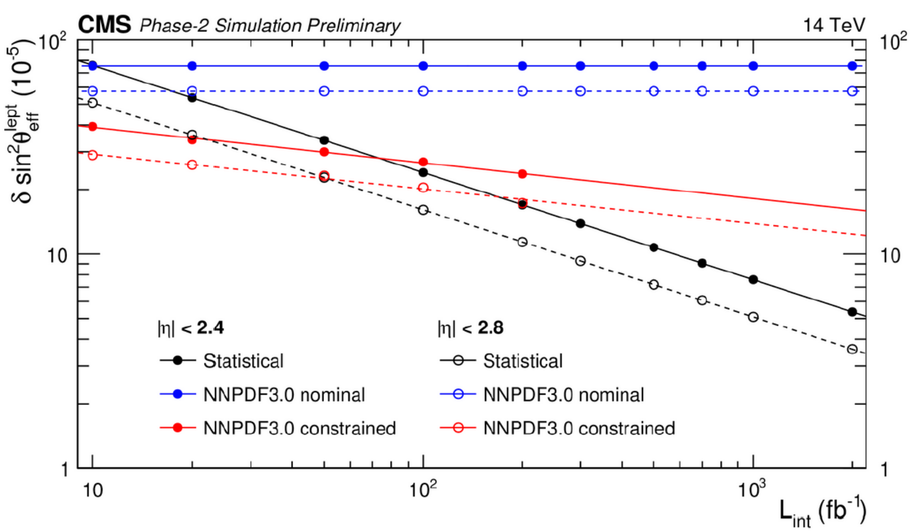


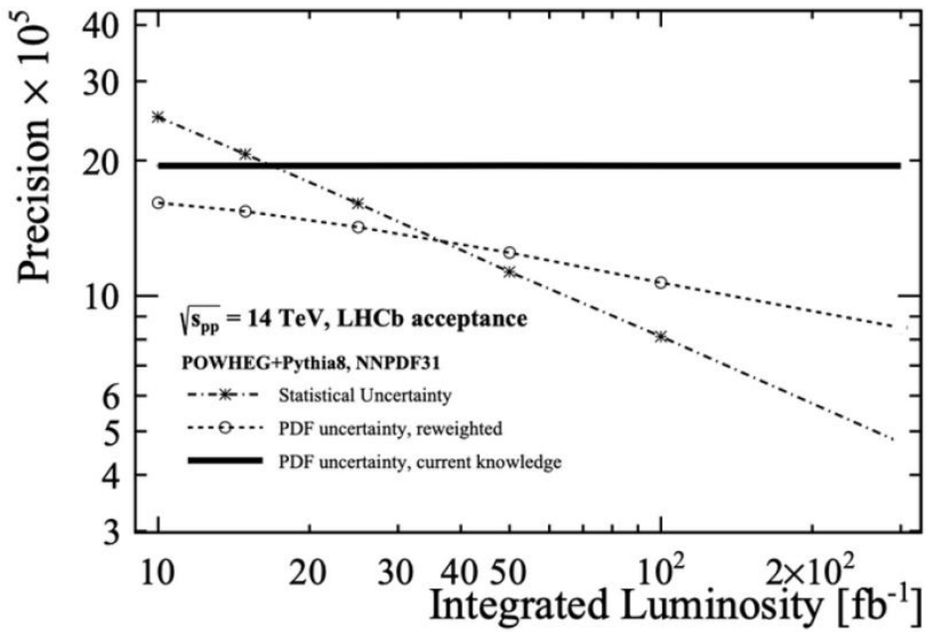
W mass: precision at hadron collider

$\sin^2\theta W$

Weak Mixing angle

- **LHCb benefit from forward acceptance**





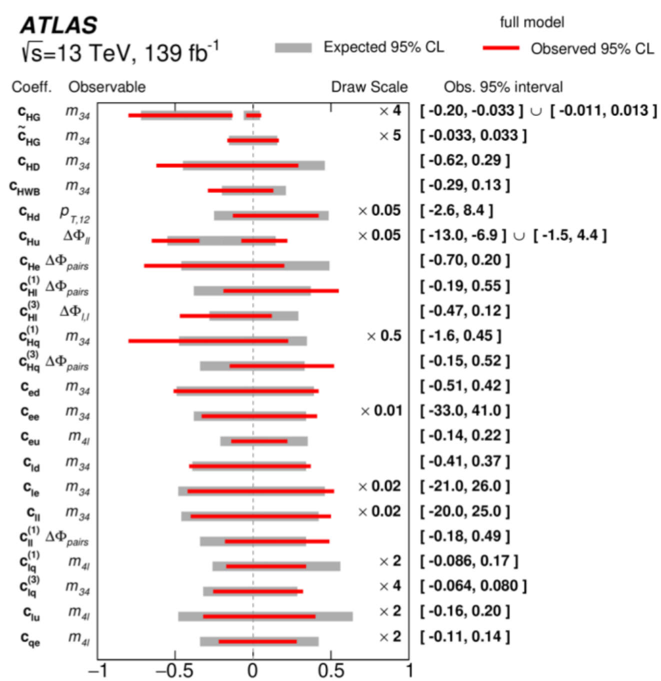
$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

ATL-PHYS-PUB-2018-037
LHCb-PUB-2018-013

Effective Field Theory

- **Not a model as such, but an equation with terms additional to the SM, that modify it in specific ways**

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\sigma_i^{\text{dim-6, lin.}} + \sum_{i,j} \frac{c_i c_j}{\Lambda^4}\sigma_{ij}^{\text{dim-6, quad.}} + \sum_i \frac{c_i}{\Lambda^4}\sigma_i^{\text{dim-8, lin.}} + \ldots$$

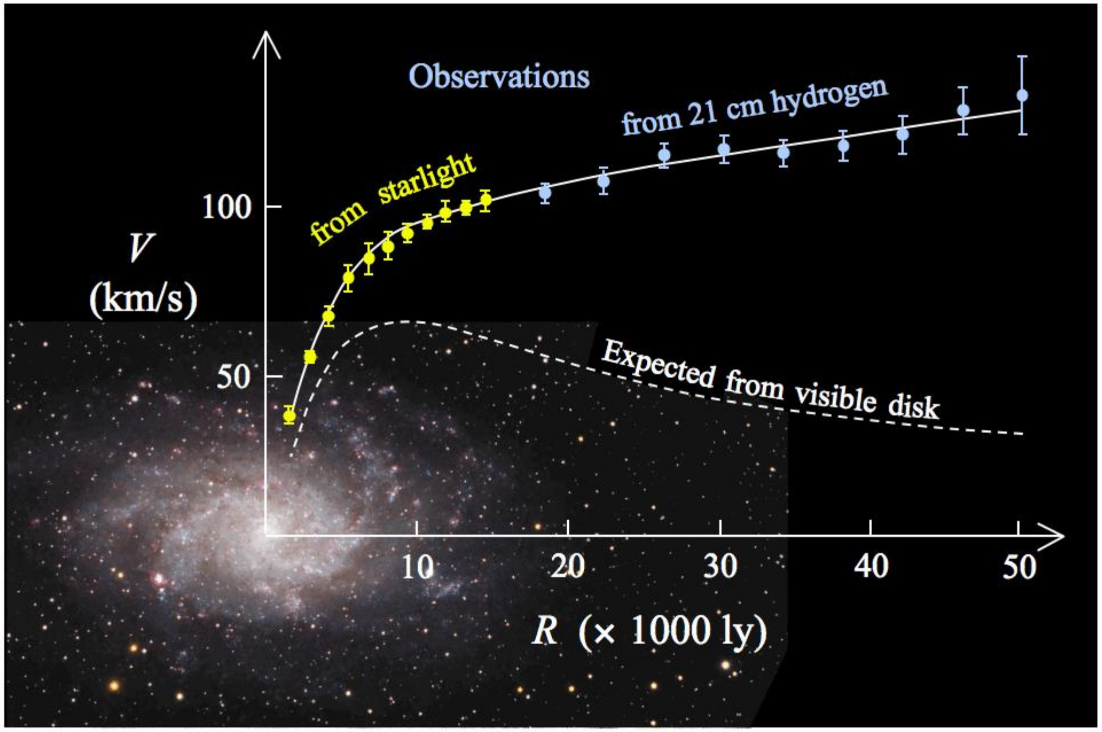


Standard Model Shortcomings

- Remarkable self-consistency and predictive power… but…
- Couplings of different scales – partial unification through Electroweak theory, but not unified with QCD
- Nothing to say about gravity
- (Too?) many free parameters
- Hierarchy problem (difference in scales of fundamental forces)
- Naturalness problem (Higgs mass fine—tuned)
- No dark matter candidate

- … and so we are driven to look Beyond the Standard Model

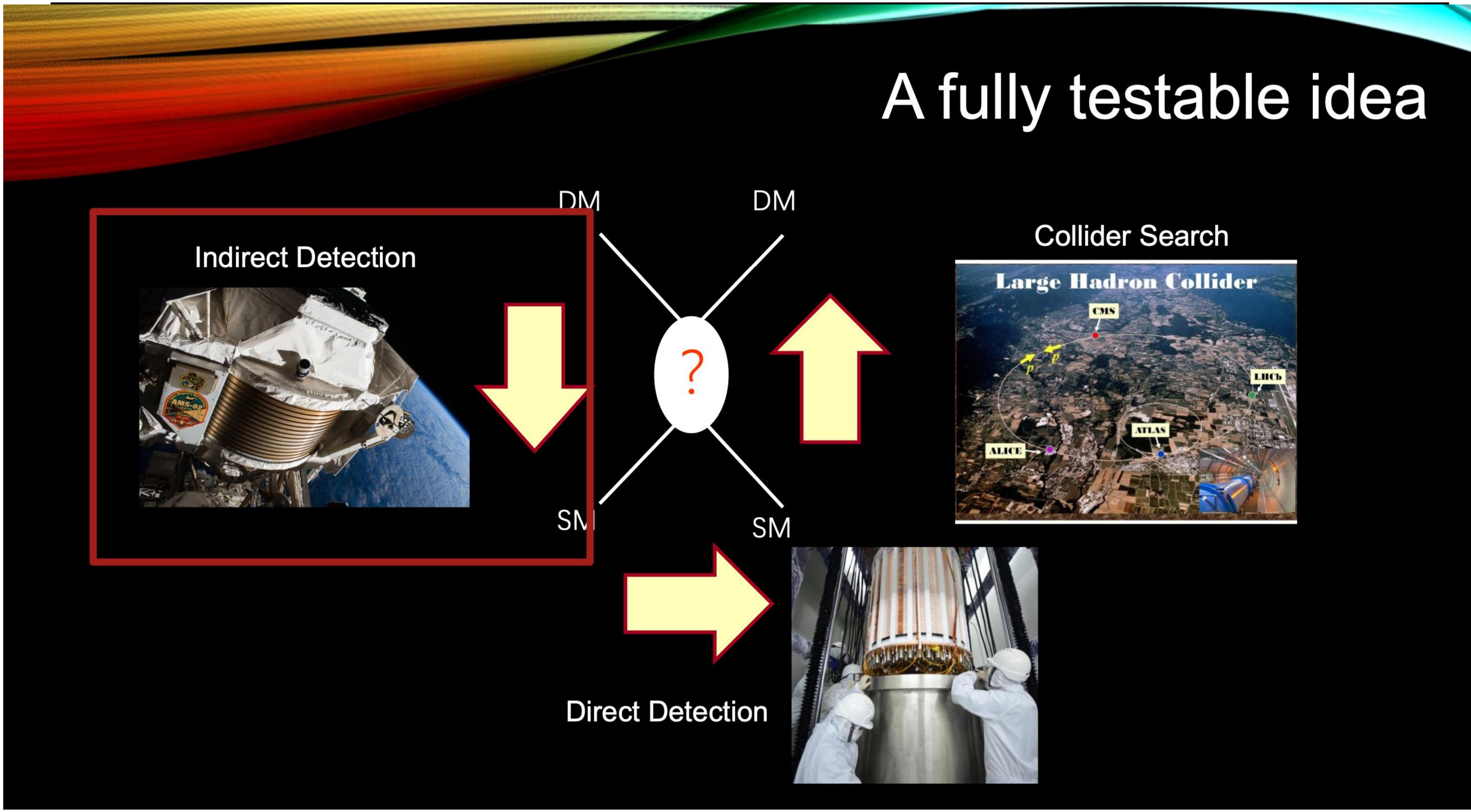
Dark Matter



Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

Dark Matter

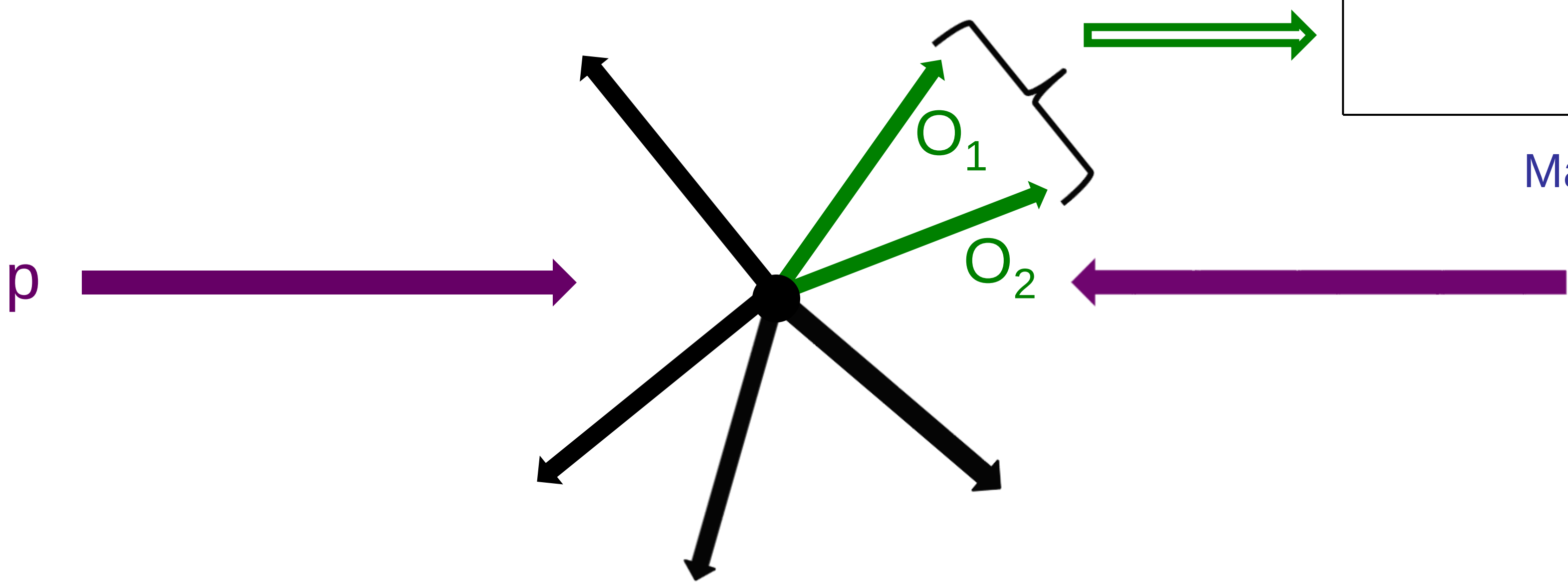
- **There are specific theories**
- **But even better than looking for specific theories:**
  - go and map out the phase space = what can we see (or not)?
    - organise by experimental signature
    - divide the parameter space up into “fiducial volumes” – well-defined regions, separated by cuts
    - Say what you saw or didn’t see in that region
      - This constrains the theories

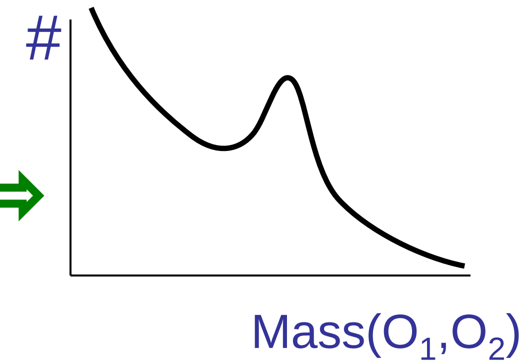

A fully testable idea
DM
DM
?
SM
SM
Indirect Detection
AMS-02
Collider Search
Large Hadron Collider
CMS
LHCb
ATLAS
ALICE
Direct Detection

J. Liu

Dark Matter / BSM in colliders?

- Typically search for a mass resonance

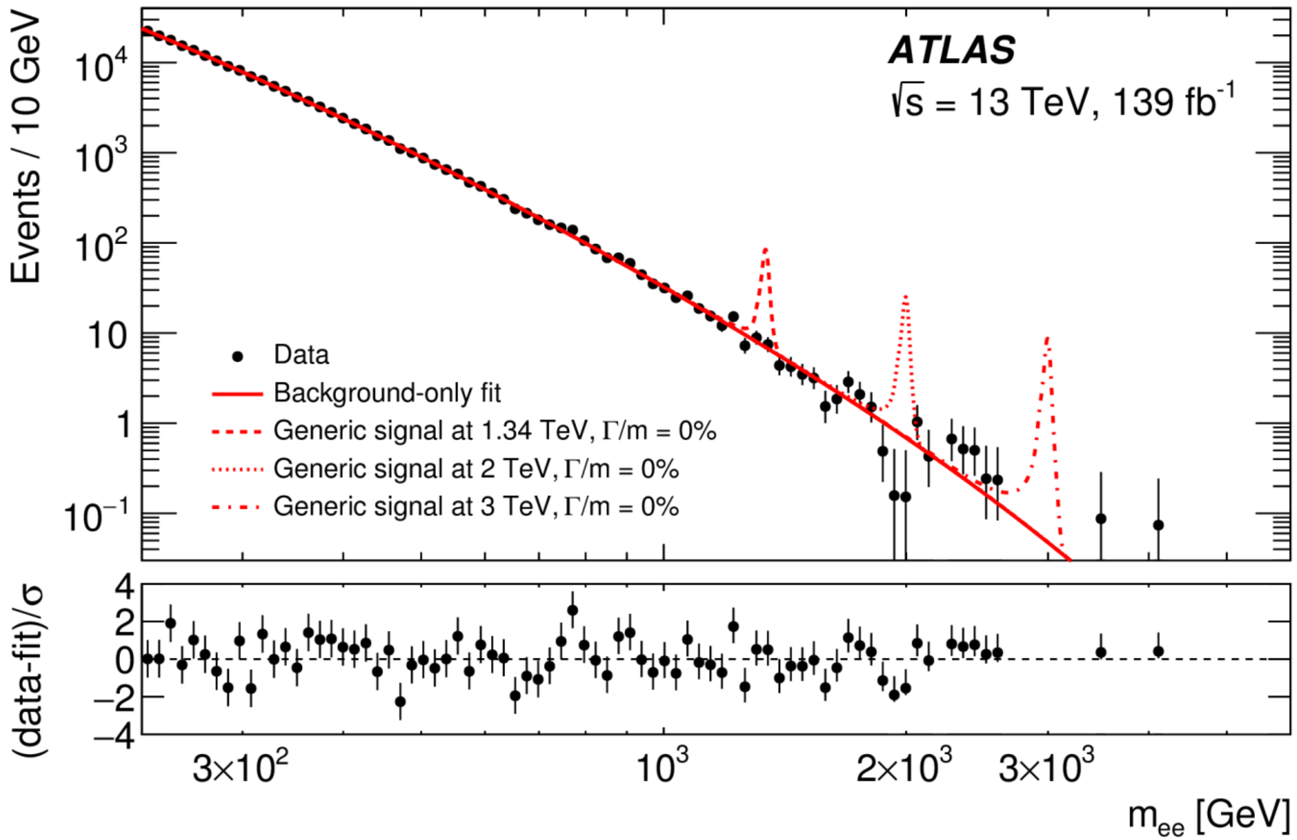




  - Higher energy ➔ Access higher mass states
  - Higher luminosity ➔ Access rarer production processes
- This has worked: ...J/ψ, ϒ, Z, Higgs, ...
  - But no evidence for resonances Beyond the Standard Model
    Ruled out phase-space: e.g. mass(Z□➔ $\tau^+\tau^-$) is > 2.4 TeV

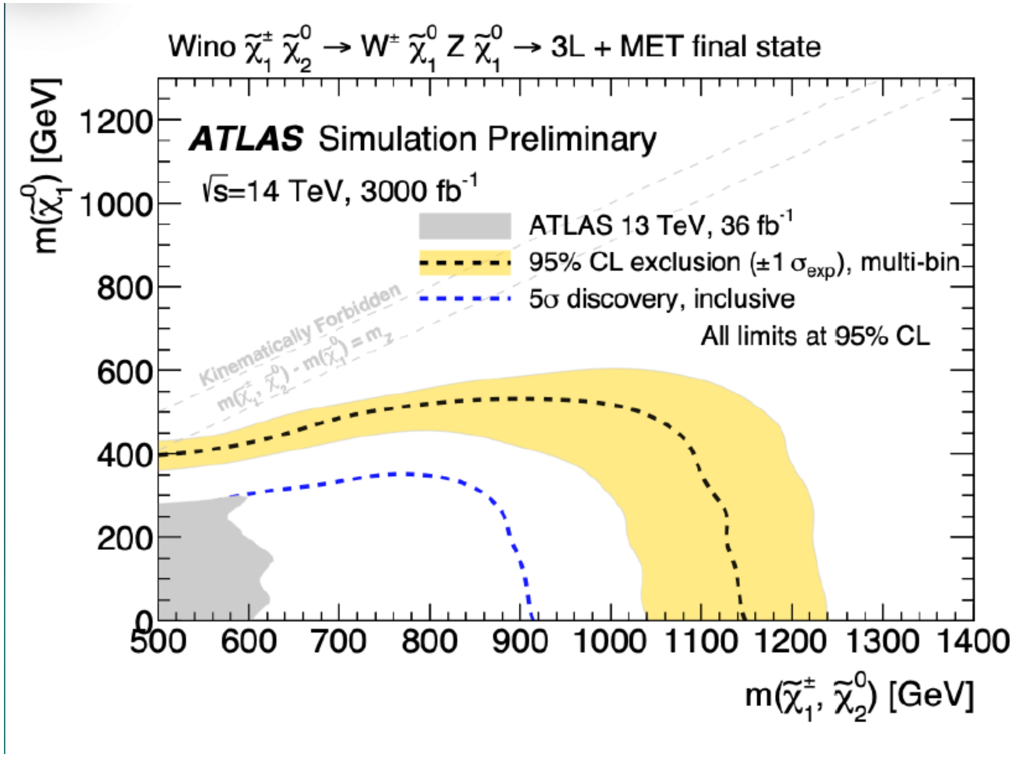
Which processes can we probe?: Searches

- For example, rule out new particles decaying to two leptons up to around 4.5 TeV in mass

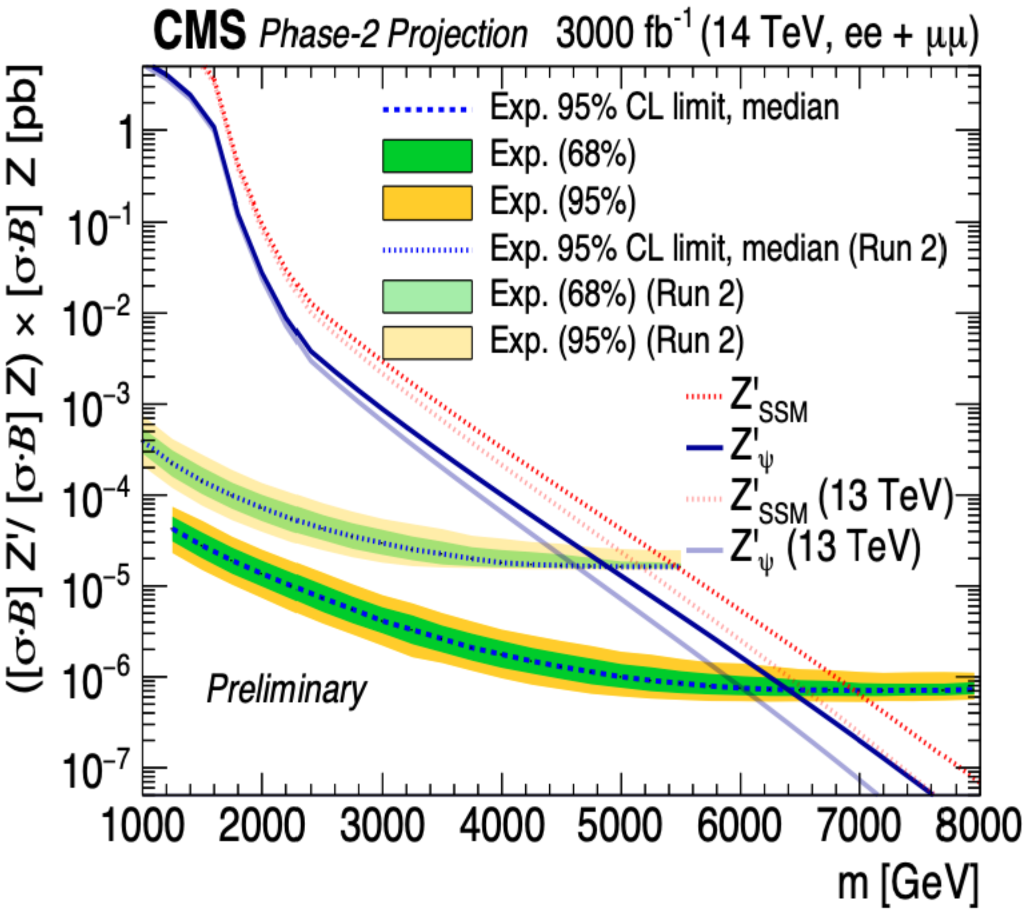


Dark matter candidates at (HL-)LHC

- **SUSY neutralino**

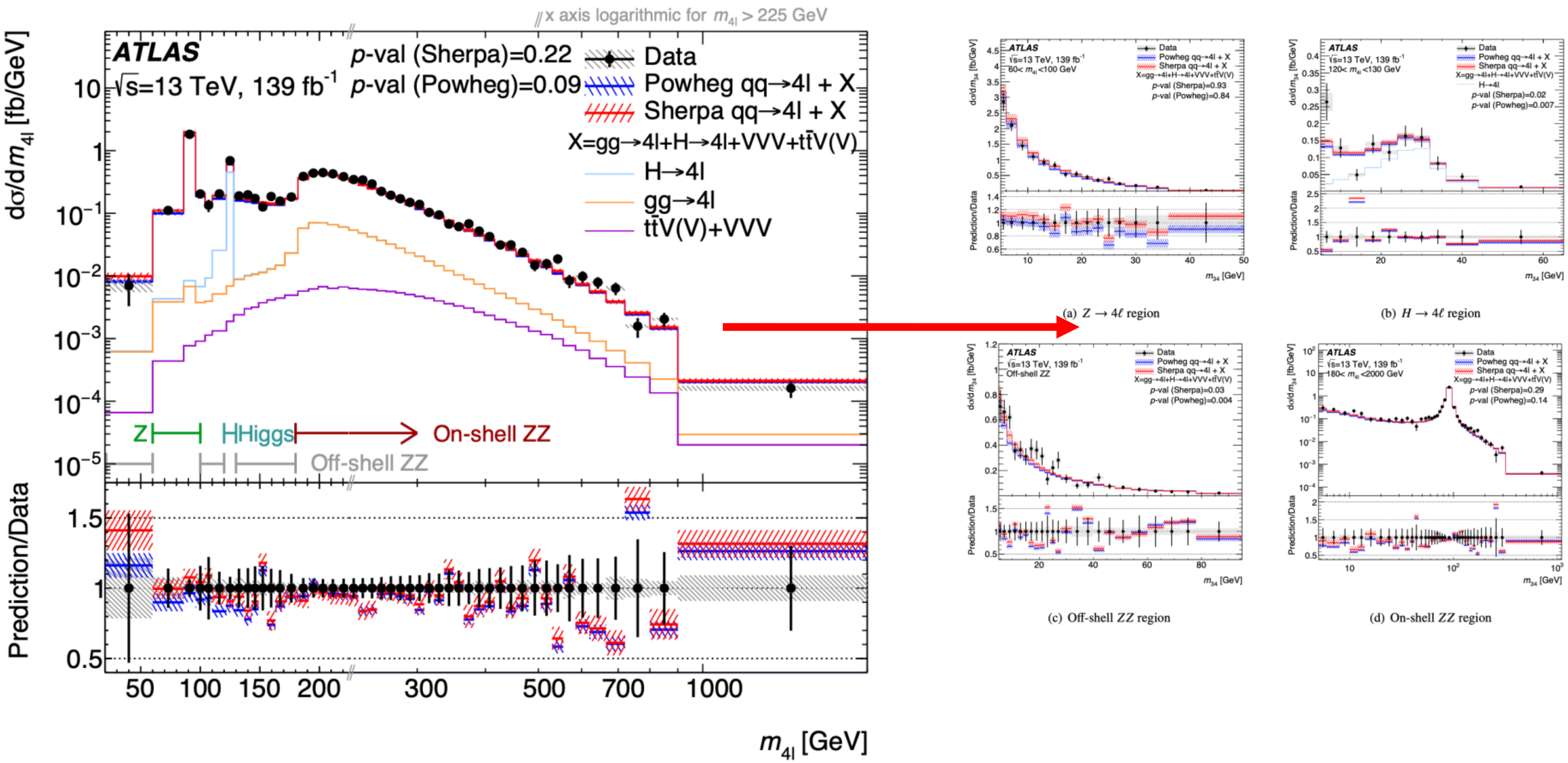


Z’ Prospects



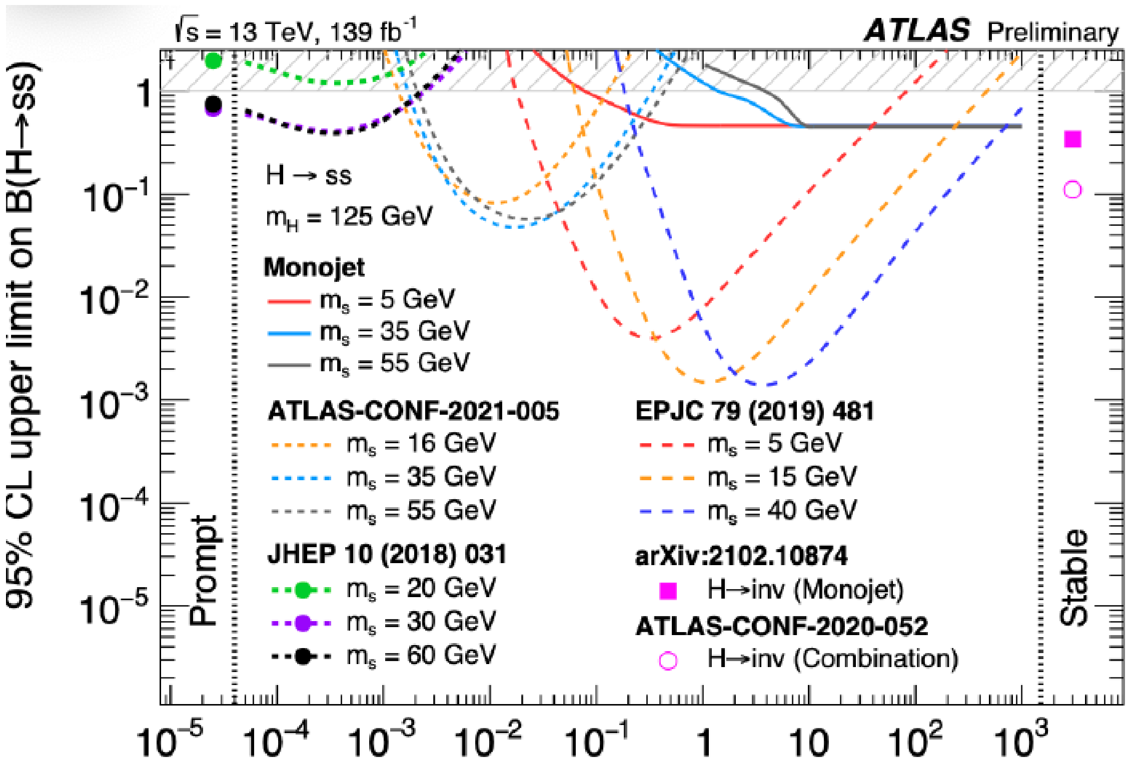
CMS Phase-2 Projection 3000 fb-1 (14 TeV, ee + μμ)
Exp. 95% CL limit, median
Exp. (68%)
Exp. (95%)
Exp. 95% CL limit, median (Run 2)
Exp. (68%) (Run 2)
Exp. (95%) (Run 2)
Z'SSM
Z'ψ
Z'SSM (13 TeV)
Z'ψ (13 TeV)
Preliminary
([σ·B] Z'/ [σ·B] Z) × [σ·B] Z [pb]
1
10−1
10−2
10−3
10−4
10−5
10−6
10−7
1000
2000
3000
4000
5000
6000
7000
8000
m [GeV]

Legacy: Cross sections in fiducial regions



Reinterpretation

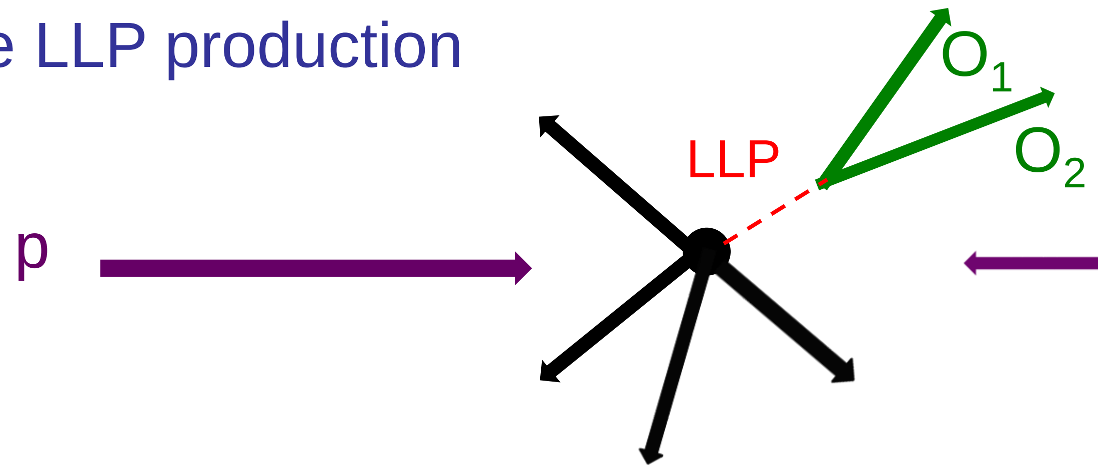
Exemplar:

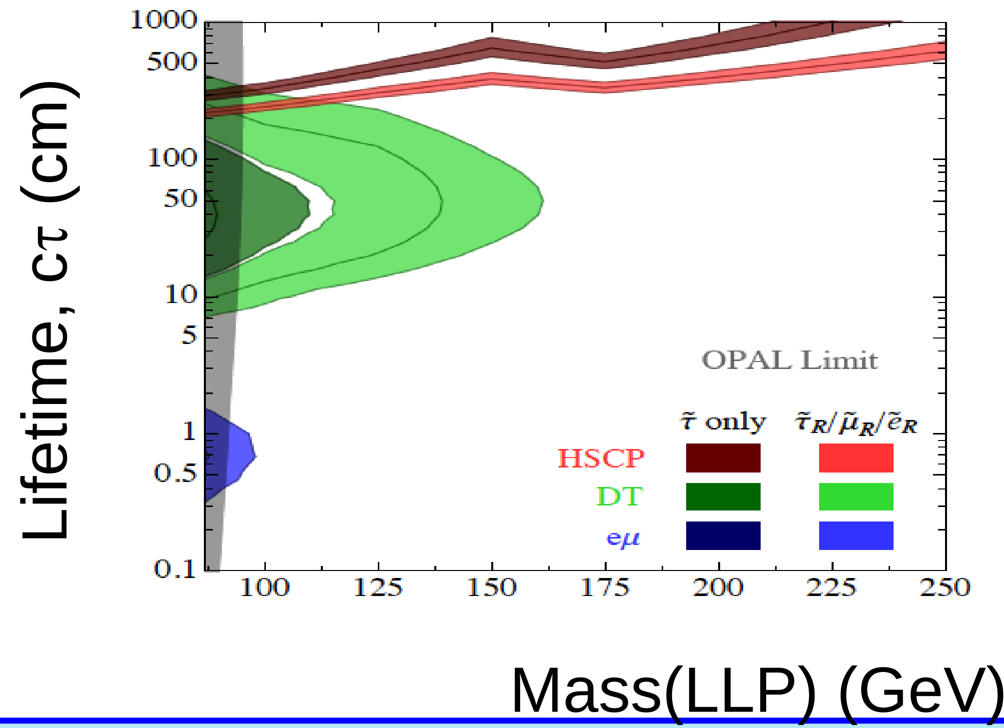


Alternative Axis: Lifetime

Single LLP production

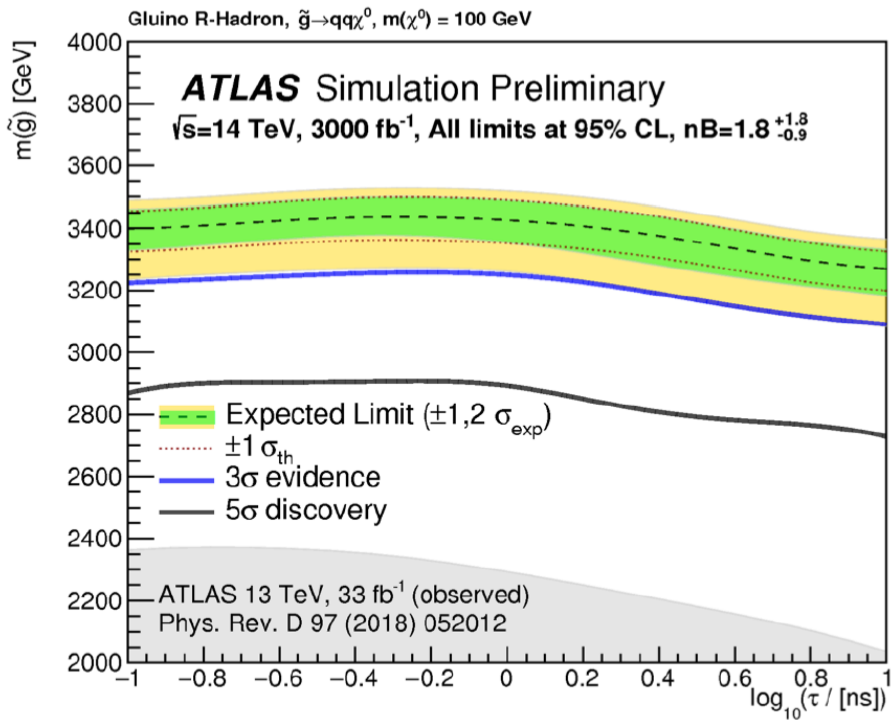
LLP = Long Lived Particle





Dark matter candidates at (HL-)LHC

- **SUSY long-lived gluino**



The Higgs b
particle for t
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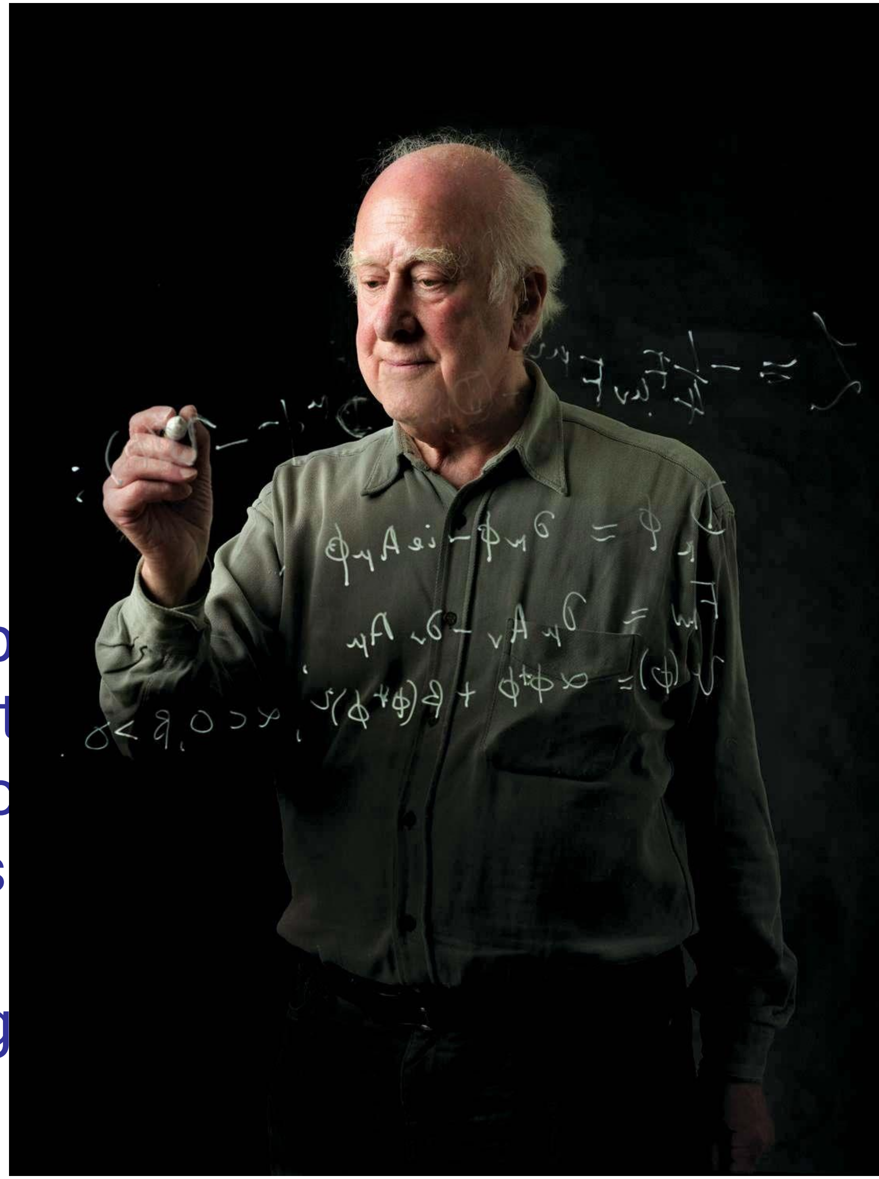
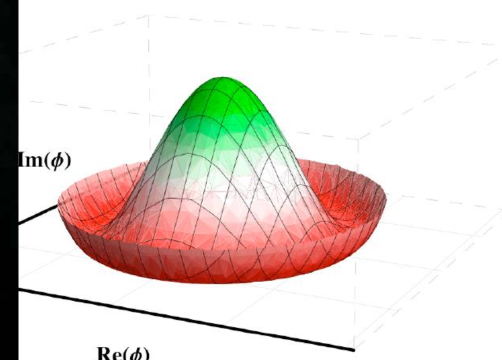
which gives
The more a
with the Hig
its mass.

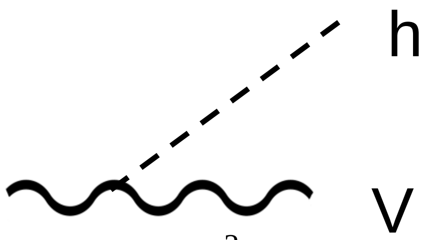




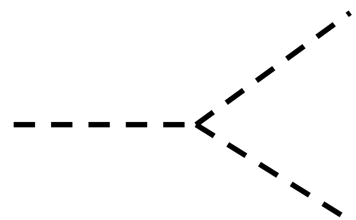
SM Higgs Boson Couplings

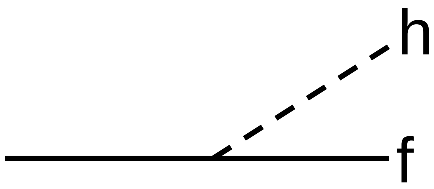
- **Standard Model Higgs: h: $J^{PC}=0^{++}$**

$$D_m F^* D^m F \qquad + \qquad V(F^* F) \qquad + \qquad \bar{D}_L Y_D D_R F$$



$$2i\frac{M_V^2}{v}$$



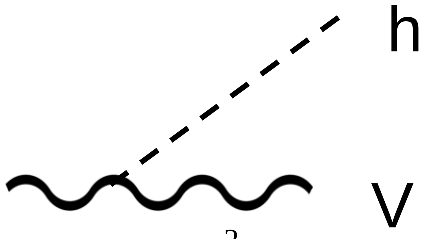


$$-i\frac{m_f}{v}$$

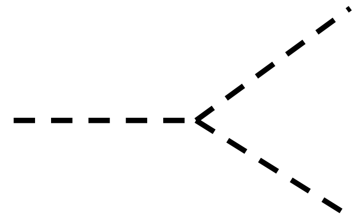
SM Higgs Boson Couplings

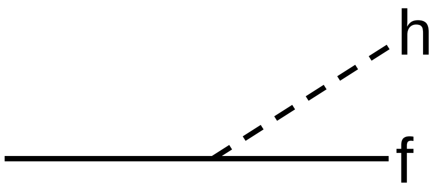
- **Standard Model Higgs: h: $J^{PC}=0^{++}$**

$$D_\mu \Phi^* D^\mu \Phi \quad + \quad V(\Phi^*\Phi) \quad + \quad \overline{D}_L Y_D D_R \Phi$$



$$2i\frac{M_V^2}{v}$$

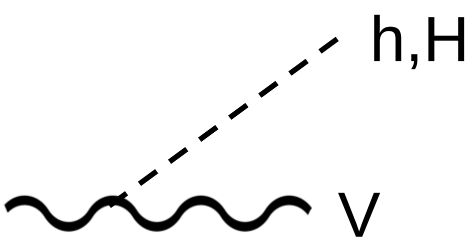




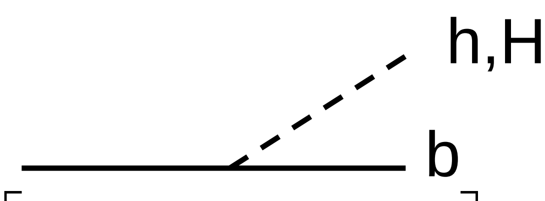
$$-i\frac{m_f}{v}$$

- **2HDM (SUSY) Higgs: h^0, H^0: 0^{++}; A^0: 0^{-+}; $H^\pm$**

$$D_\mu \Phi^*_{1,2} D^\mu \Phi_{1,2} \quad + \quad V(\Phi_1,\Phi_2) \; + \; \overline{D}_L Y_D D_R \Phi_1 \quad + \quad \overline{U}_L Y_D U_R \Phi_2$$



$$2i\frac{M_V^2}{v}\left[\sin(\beta-\alpha)h^0+\cos(\beta-\alpha)H^0\right]$$

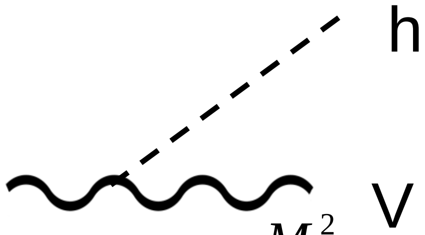


$$-i\frac{m_f}{v}\left[-\frac{\sin\alpha}{\cos\beta}h^0+\frac{\cos\alpha}{\cos\beta}H^0\right]$$

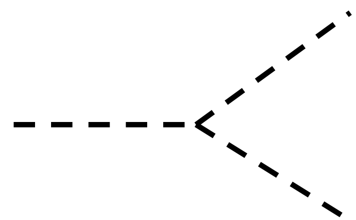
SM Higgs Boson Couplings

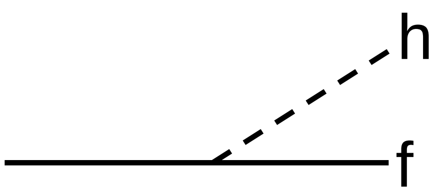
- **Standard Model Higgs: h: $J^{PC}=0^{++}$**

$$D_m F^* D^m F \quad + \quad V(F^* F) \quad + \quad \bar{D}_L Y_D D_R F$$



$$\kappa_V \; 2i \frac{M_V^2}{v}$$

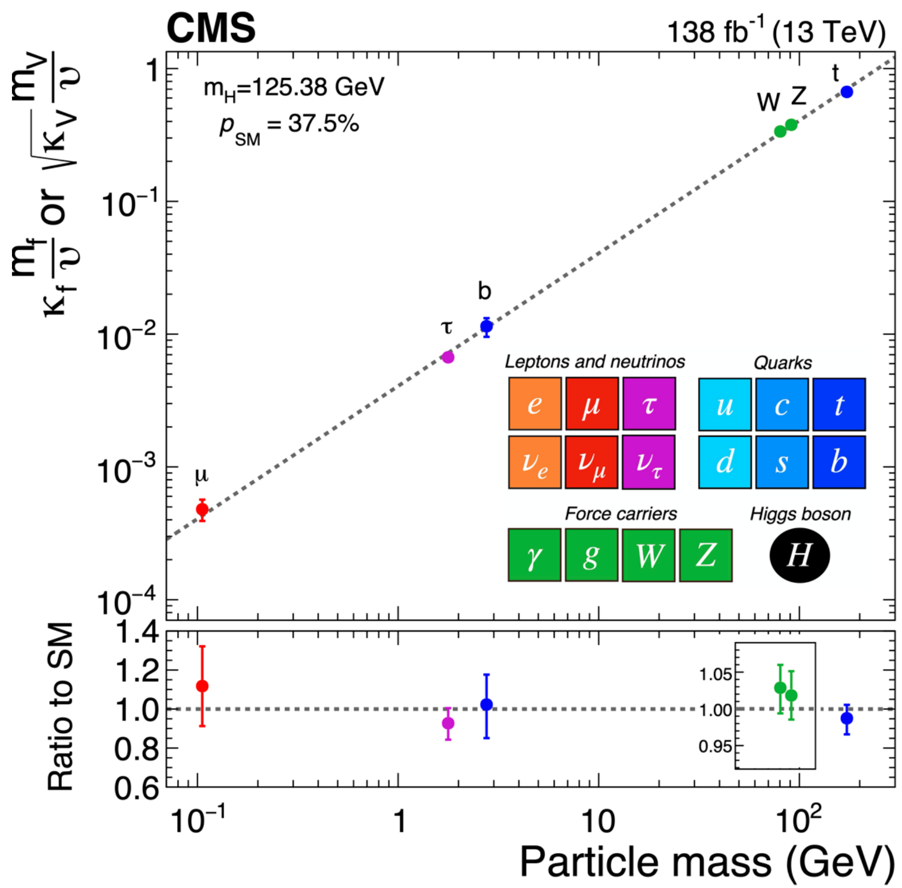




$$\kappa_f \; -i \frac{m_f}{v}$$

Standard Model Agreement with Data

- **Within uncertainties the data agree with the Standard Model**



$$g_V \sim \frac{\kappa_V \cdot m_V^2}{v}$$

$$\lambda_f \sim \frac{\kappa_f \cdot m_f}{v}$$

What precision is necessary?

- **SM couplings can be modified by new physics**

$$\Gamma_i = \kappa_i^2\ \Gamma_i^{SM}$$

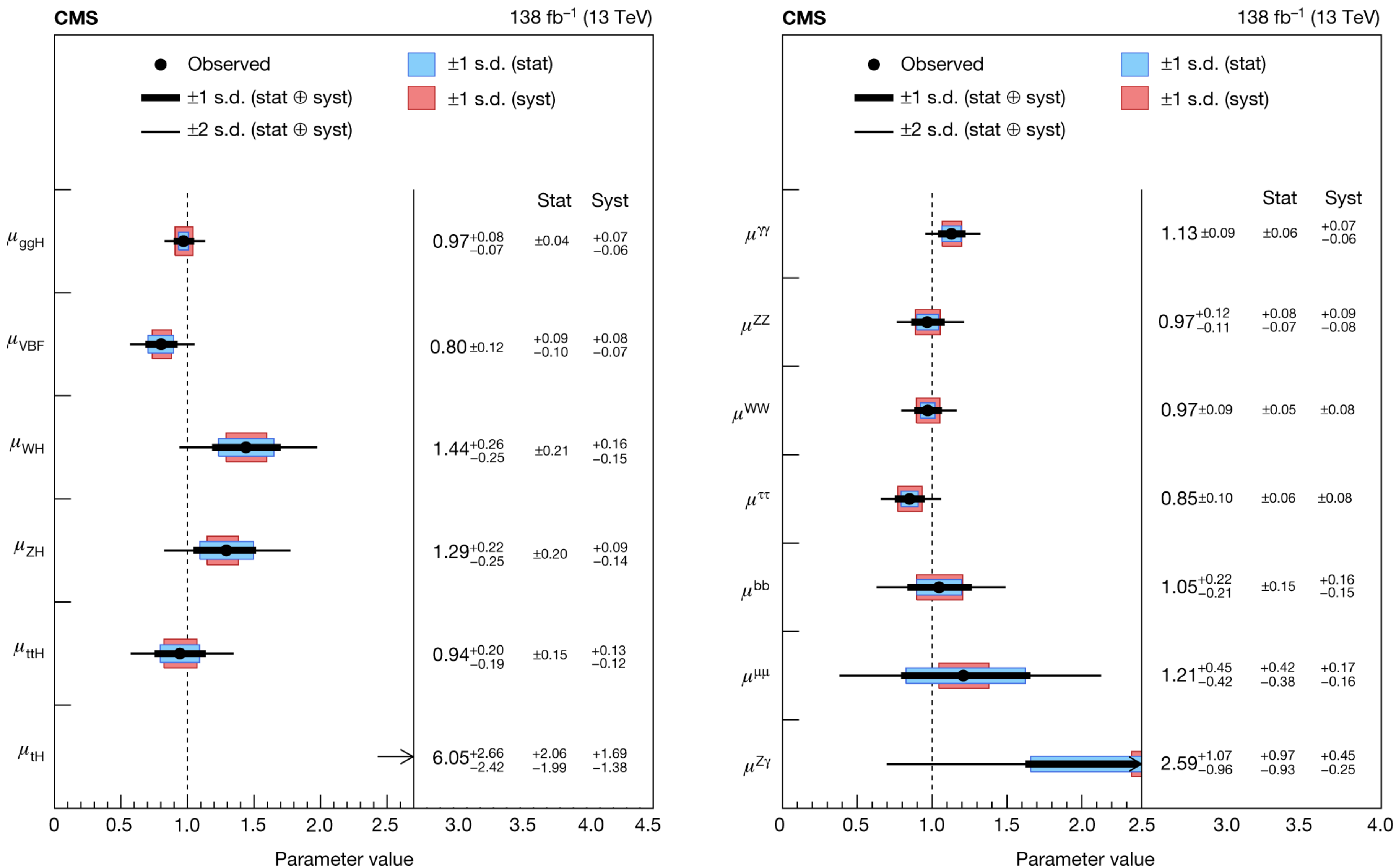
- **Modifications can be small depending on the BSM scenario (Snowmass report)**
  - For new physics at the 1TeV mass scale:

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

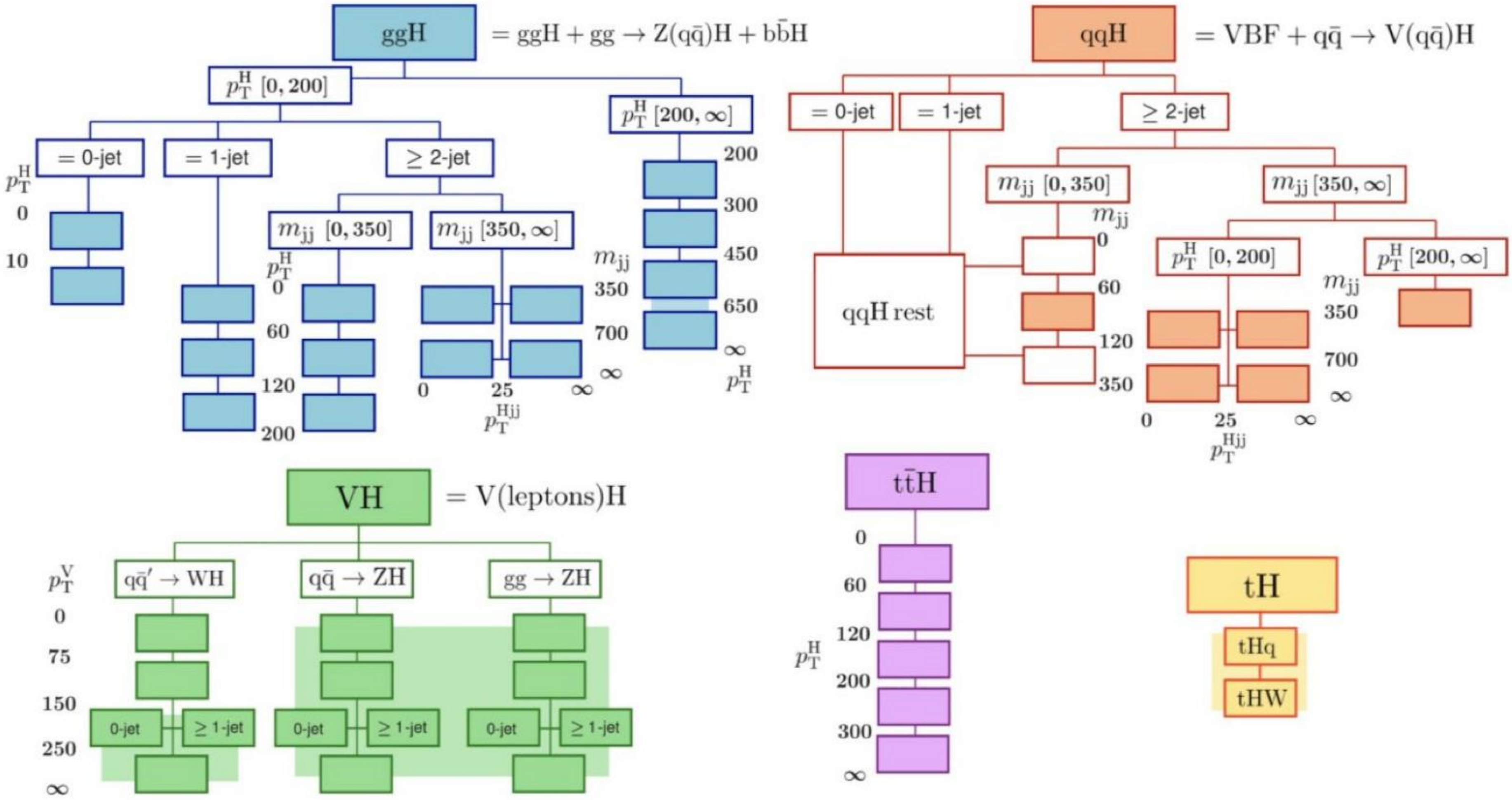
arXiv:1310.8361

  - Higher scales imply smaller effects

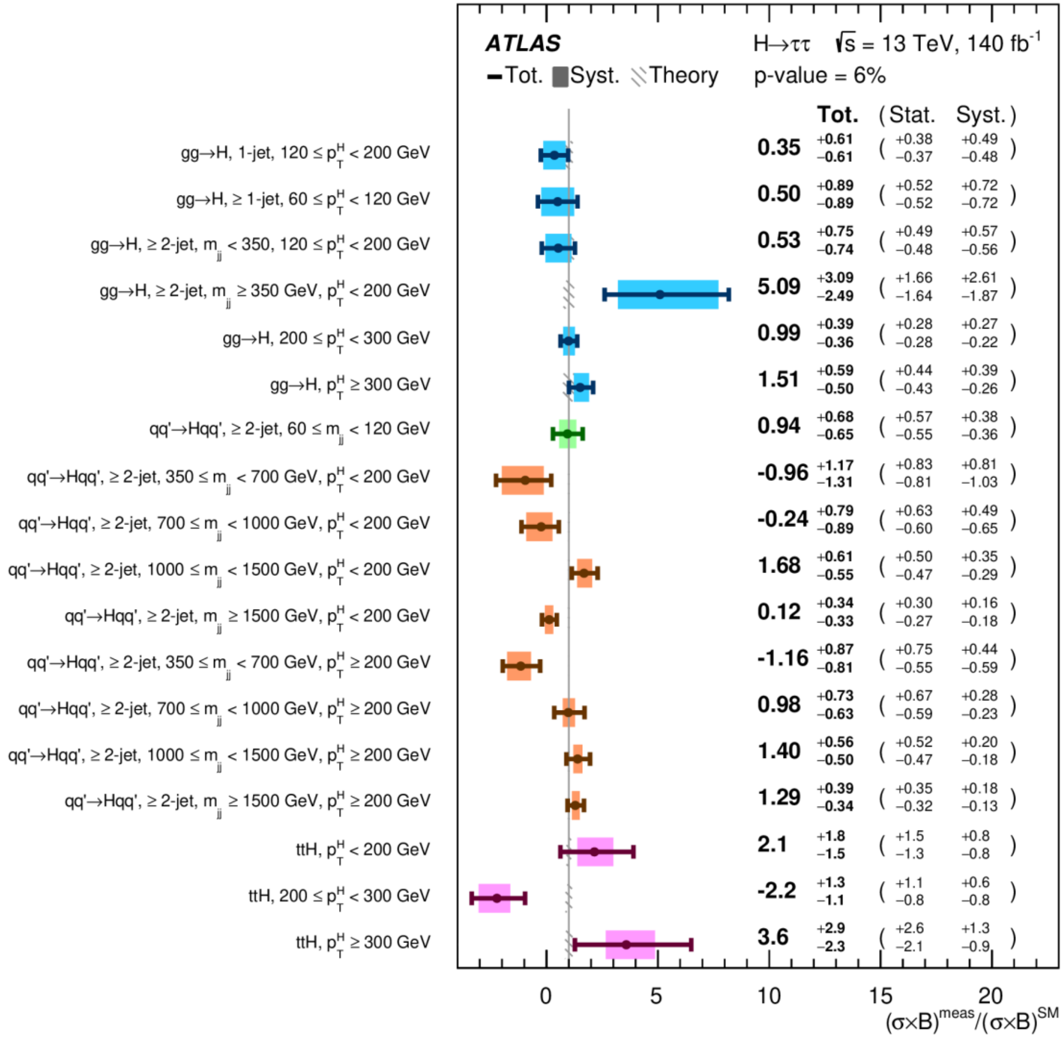
What did we discover?



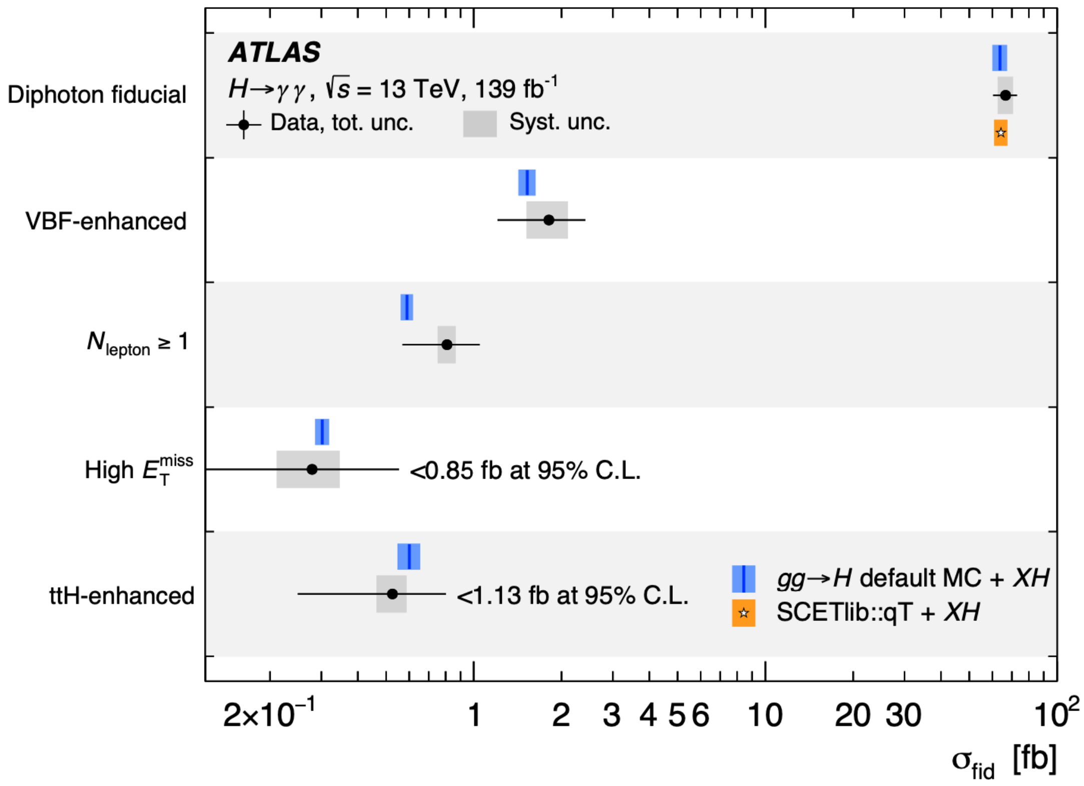
Cross Section in exclusive regions



H→ττ in regions



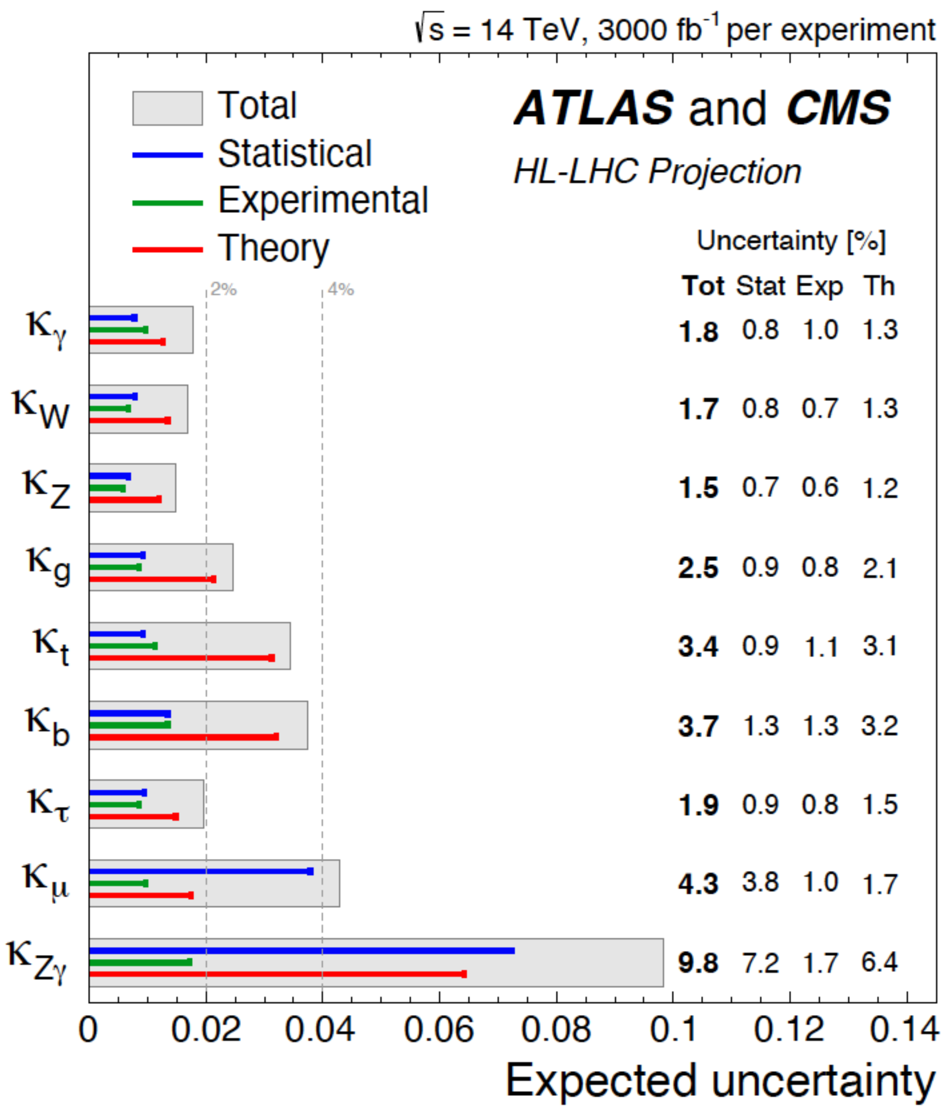
Cross Section in exclusive regions



Agreement across three orders of magnitude

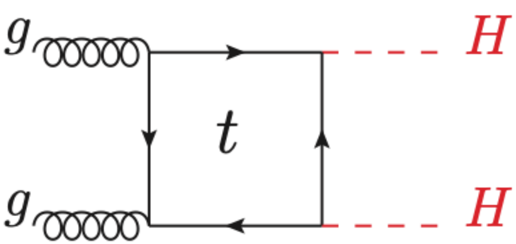
HL-LHC Prospects: Higgs

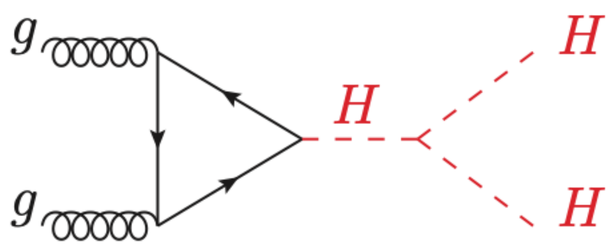
Single Higgs Couplings



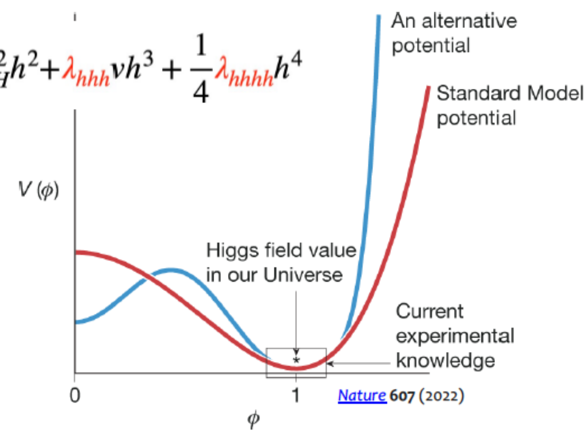
Di-Higgs

- **Total production cross section is very small ~30fb**
- **Currently set limits on HH production (inclusive of both diagrams)**





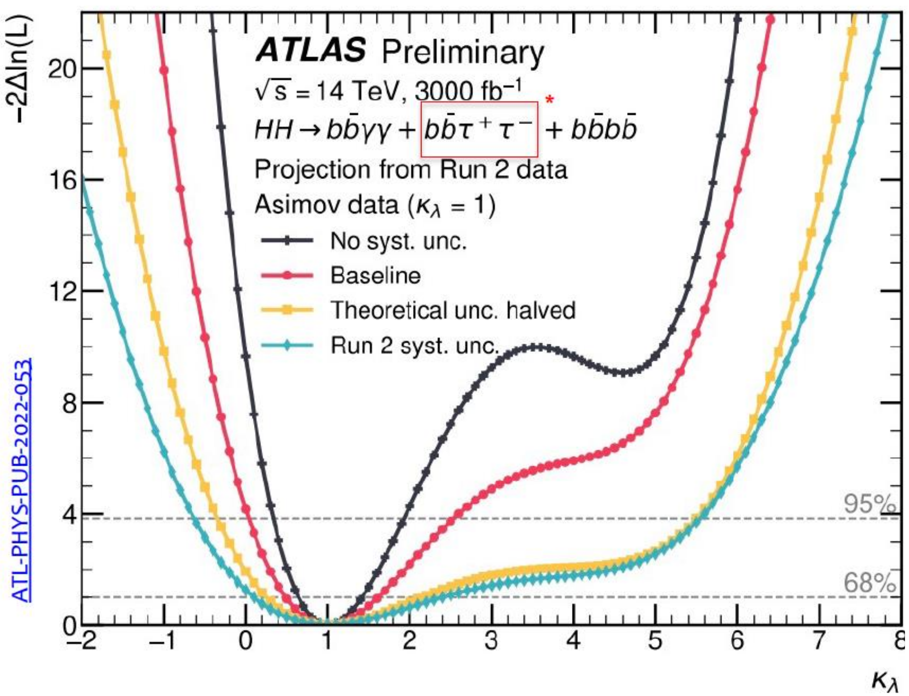
$$V(h) = V_0 + \frac{1}{2}m_H^2 h^2 + \lambda_{hhh} v h^3 + \frac{1}{4}\lambda_{hhhh} h^4$$



Nature 607 (2022) 60-68

Di-Higgs

- **Getting close to SM: both experiments set limits on cross-section at ~2.5 x SM cross-section**
- **Theory systematics: parton shower up to 13%; PDF up to 12%; scale variations up to 8%**



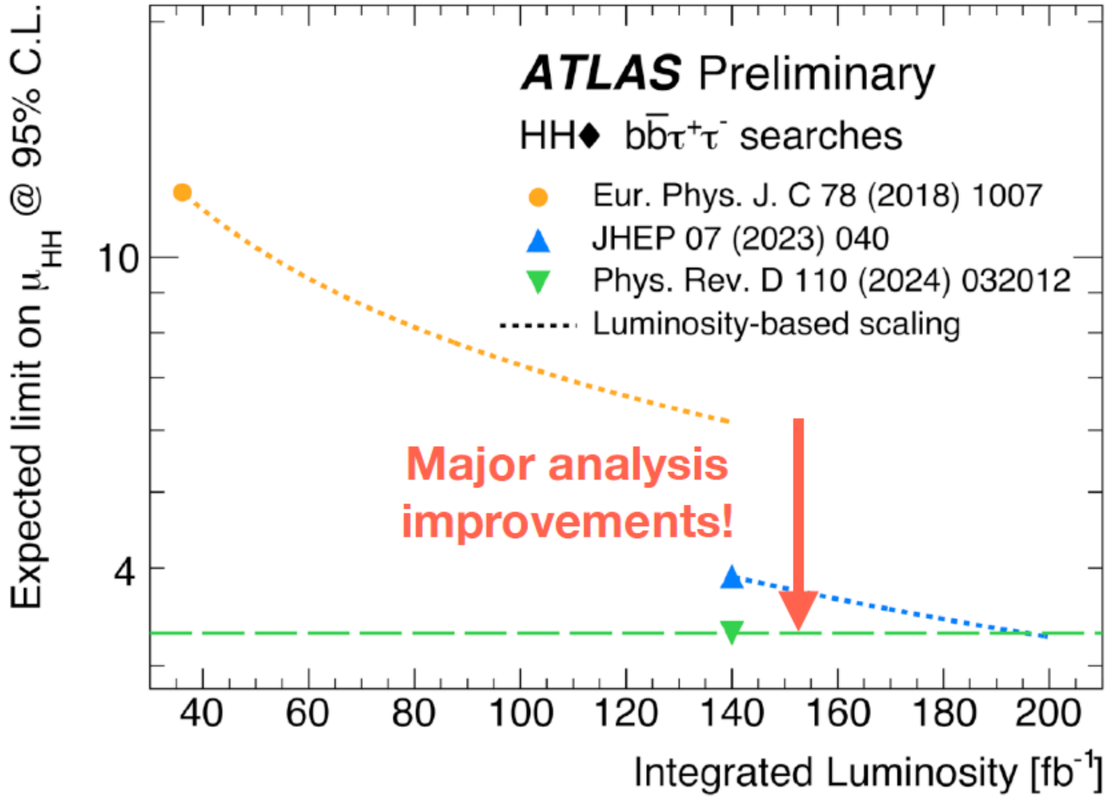
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

ATLAS 3 ab^{-1}

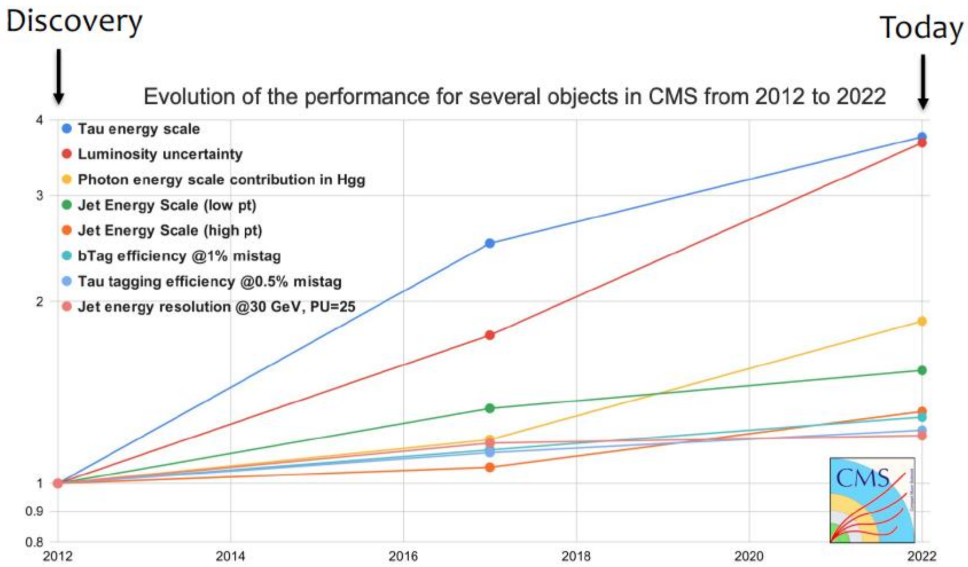
→ Uncertainty in **κ_λ ~ 20% with LHC combination!**

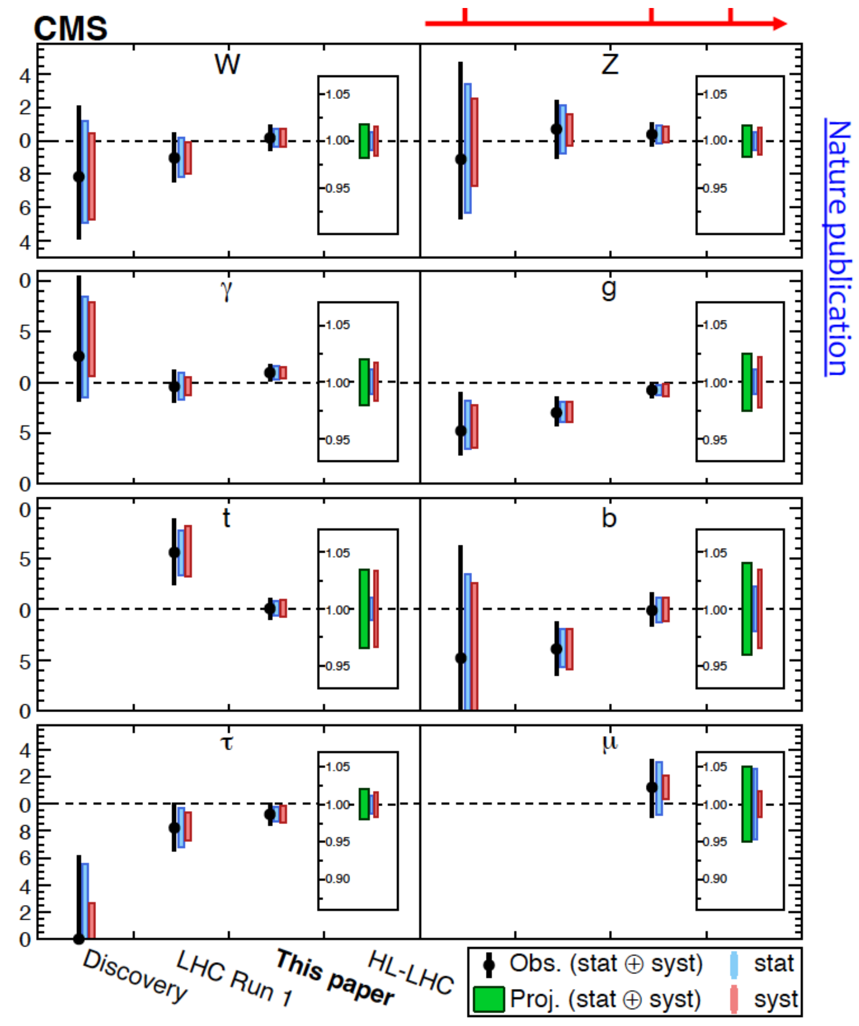
But



ATLAS Preliminary
HH→ $b\bar{b}\tau^+\tau^-$ searches
Eur. Phys. J. C 78 (2018) 1007
JHEP 07 (2023) 040
Phys. Rev. D 110 (2024) 032012
Luminosity-based scaling
Major analysis improvements!
Expected limit on μ_{HH} @ 95% C.L.
10
4
40
60
80
100
120
140
160
180
200
Integrated Luminosity [fb^{-1}]

Technique improvements

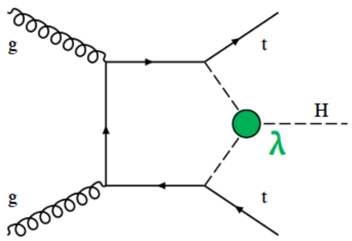


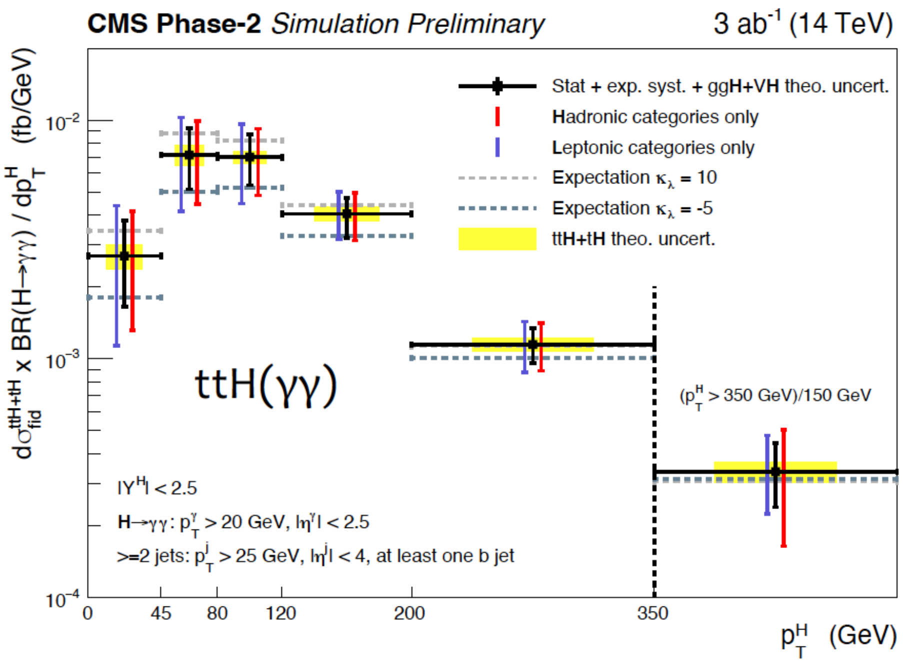


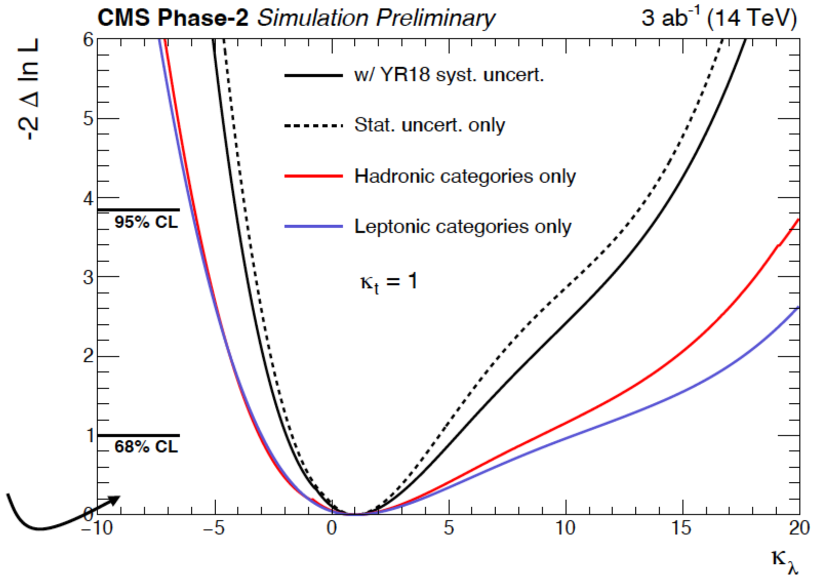
Kinematic Distributions

Kinematic distributions

Differential Higgs boson measurements also expected to yield sensitivity to Higgs boson self-coupling → **combine with HH searches for ultimate sensitivity to κ_λ**







N. Wardle

Future up to 2040

- HL-LHC is a major part of our field until 2040 (or until we reach $3ab^{-1}$ at ATLAS/CMS)

The next 1000 papers from the HL-LHC?

- New triggers are in place to record new signatures, so even with the same LHC run configuration, we can say new things
- Higgs boson established, it's the only fundamental spin 0 particle we know of, explore its properties and those of W/Z/top more precisely
- Higgs Self coupling?
- Map out phase space as far as our ingenuity allows us

What might we know in 2040?

- **Higgs self-coupling to 20% (if SM value…)**
- **Higgs single couplings to % level (2^{nd} generation to a few %; light quarks? Get smart on that too?)**
- **Top mass to 0.1%?**
- **W mass to a few MeV**
- **pdf constraints improved by several factors**

- **Constraints on event rates for a huge signature phase space**
  - (know which models not to consider…)
- **All this -> EFT fits – hints?**
- **Or something direct and anomalous?**