

Higgs physics and experimental results

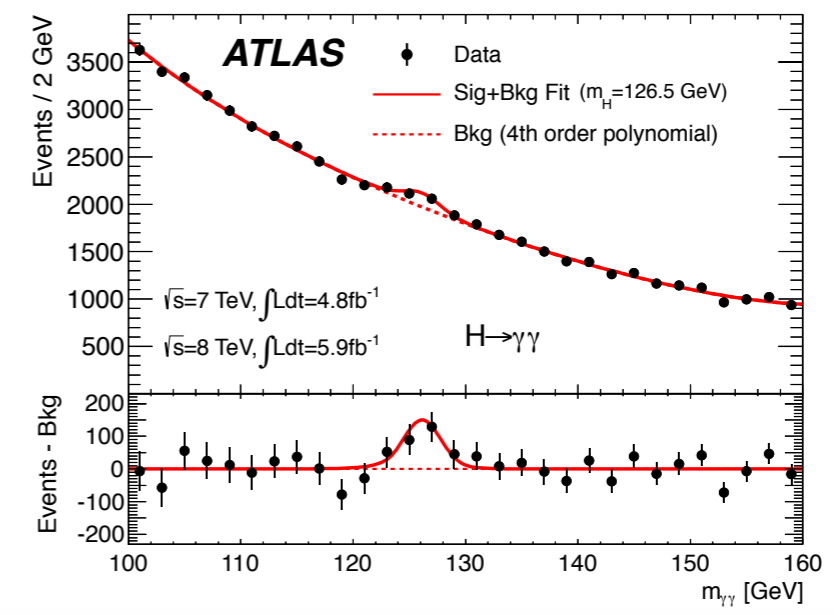
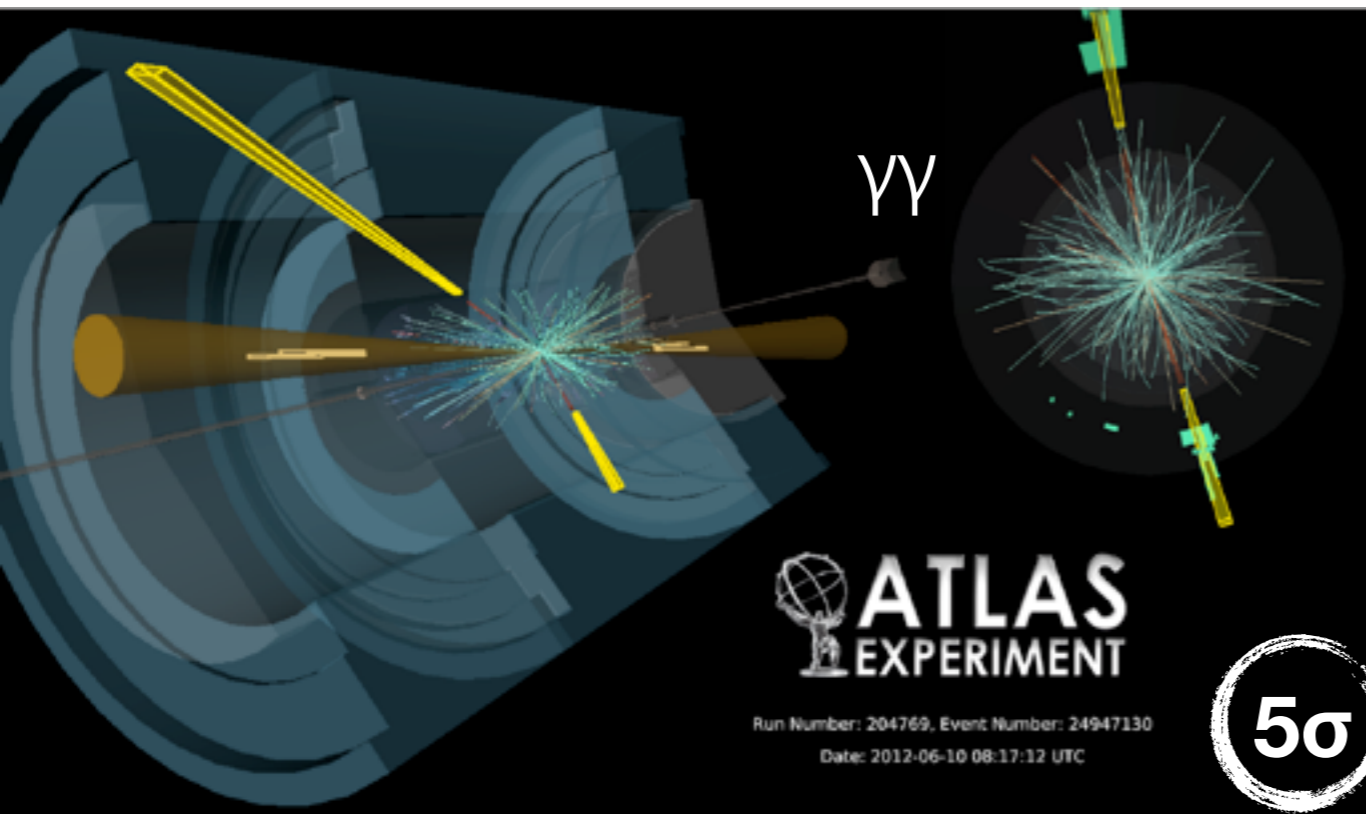
Bruno Lenzi



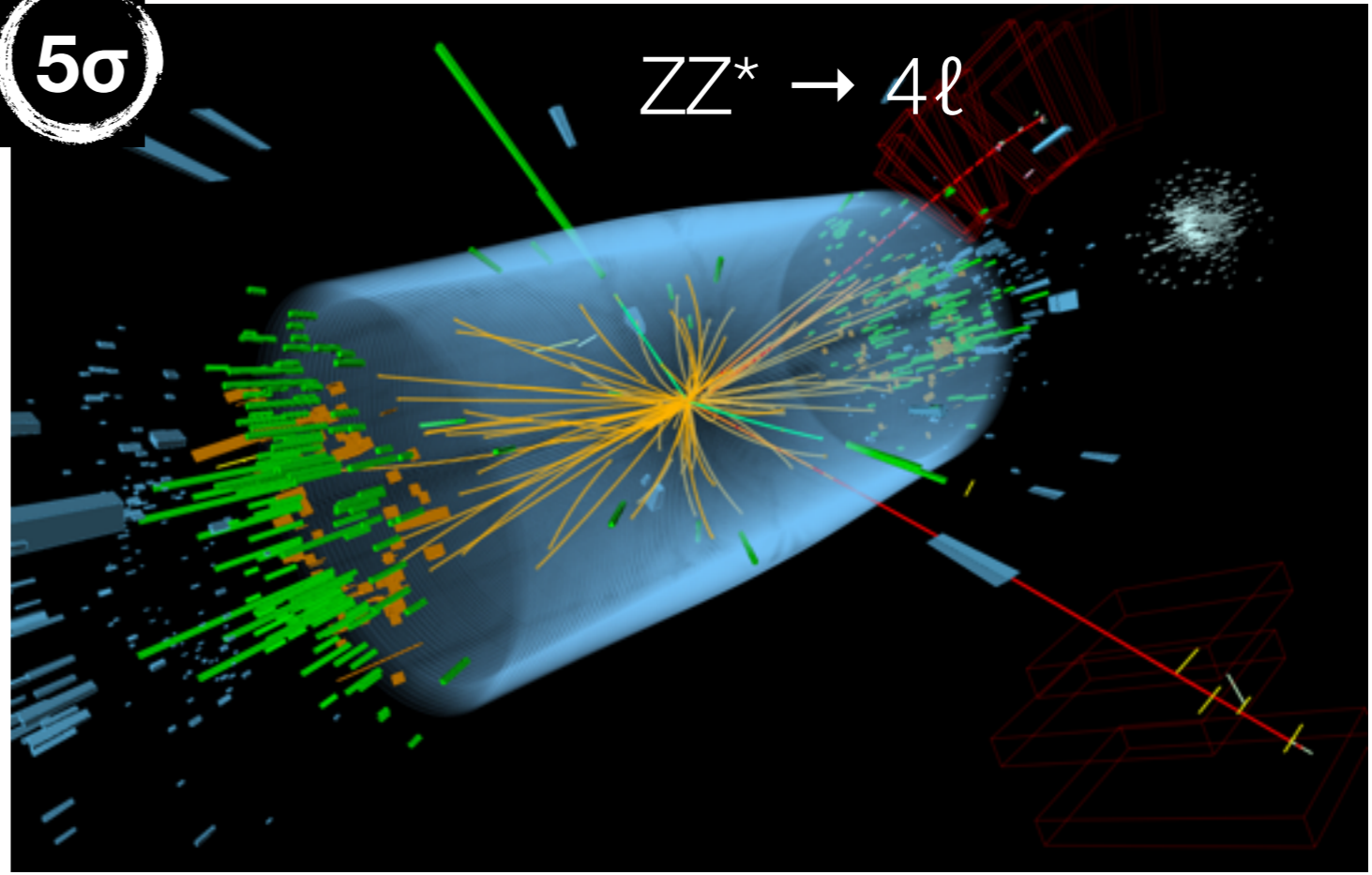
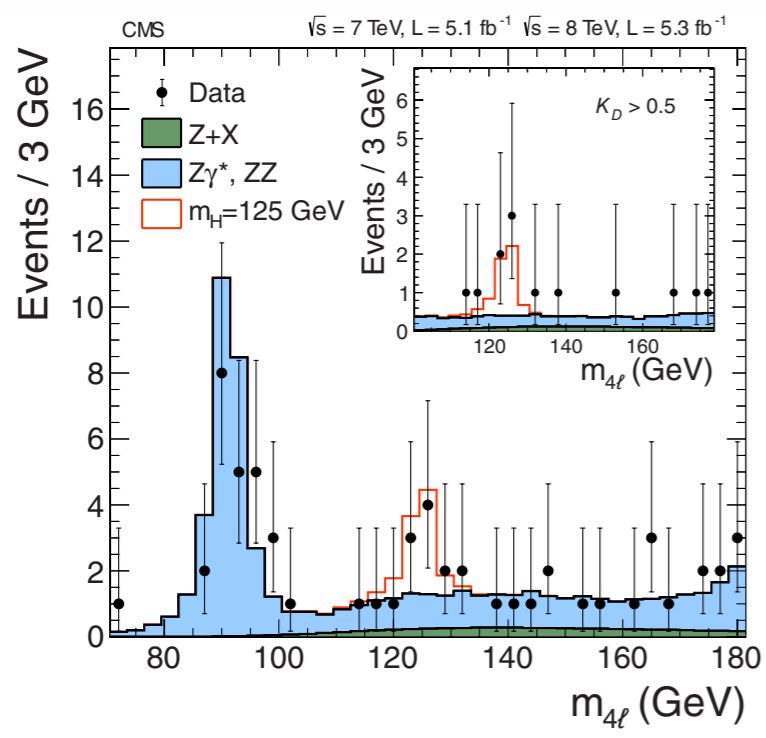
New Trends in High Energy Physics and QCD
School, Natal, Brazil

25/10/2014

The new particle



5 σ



The new particle

A visualization of a particle collision. Two yellow beams of particles enter from the left and right, meeting at a central point. From this point, a large number of smaller particles, represented by thin lines in various colors (blue, green, red, yellow), radiate outwards in all directions, creating a starburst effect. The background is dark with some blue and yellow circular patterns.

- Beyond any reasonable doubt, we have discovered a new particle
 - A boson since it decays to bosons!

The new particle

A visualization of a particle collision. A central point of impact is surrounded by a dense spray of blue and green lines radiating outwards, representing the decay products of a particle. The background is dark with some blue and yellow highlights, suggesting a laboratory or detector environment.

- Beyond any reasonable doubt, we have discovered a new particle
 - A boson since it decays to bosons!
- Is it a Higgs boson?
 - Scalar ($J^{PC} = 0^{++}$)
 - Its vacuum expectation value is responsible for EW symmetry breaking

Spin analyses

A visualization of particle tracks in a detector, showing a central point where many tracks radiate outwards, with some tracks highlighted in yellow and others in cyan.

“The outcome of the spin analysis has as much suspense as a football game between Brazil and Tonga” (theorist in 2012-3)

Spin analyses

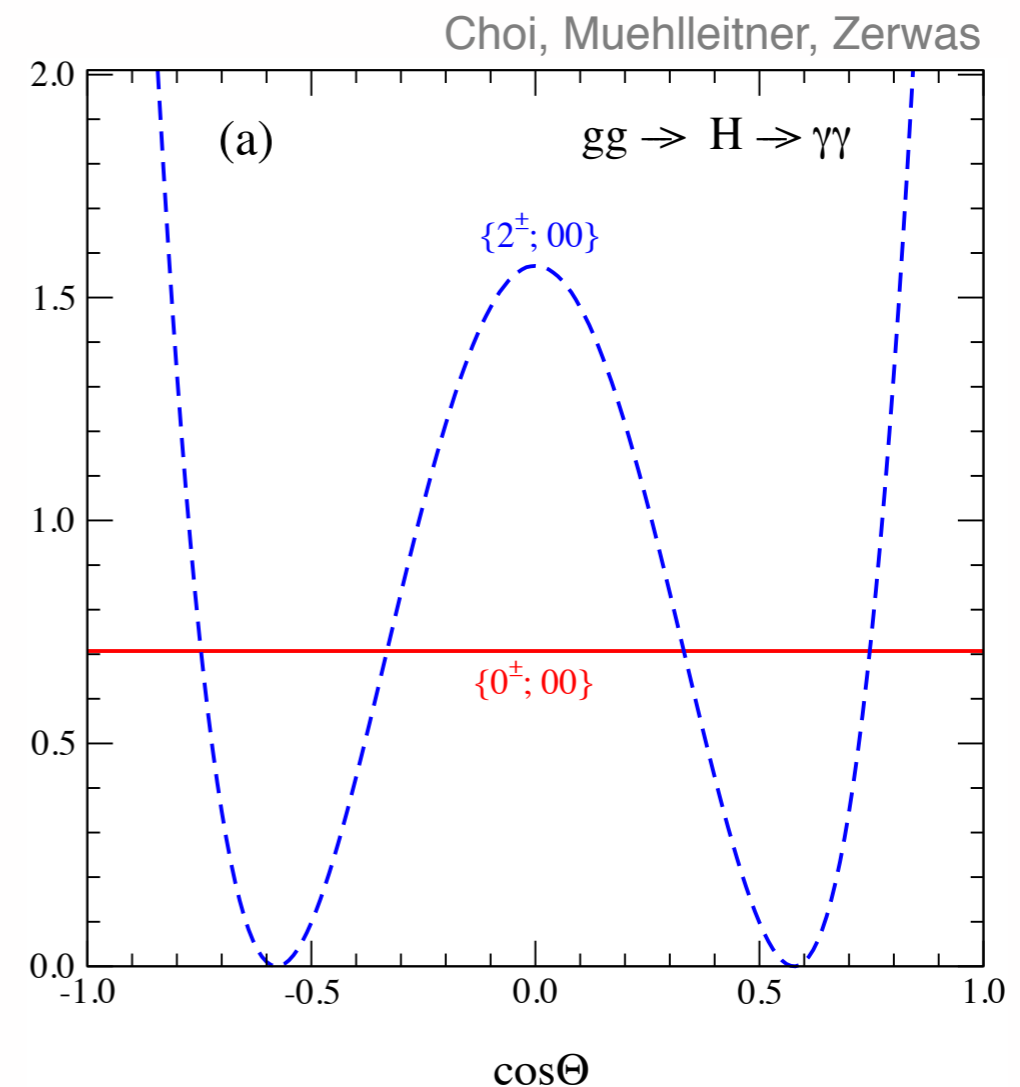
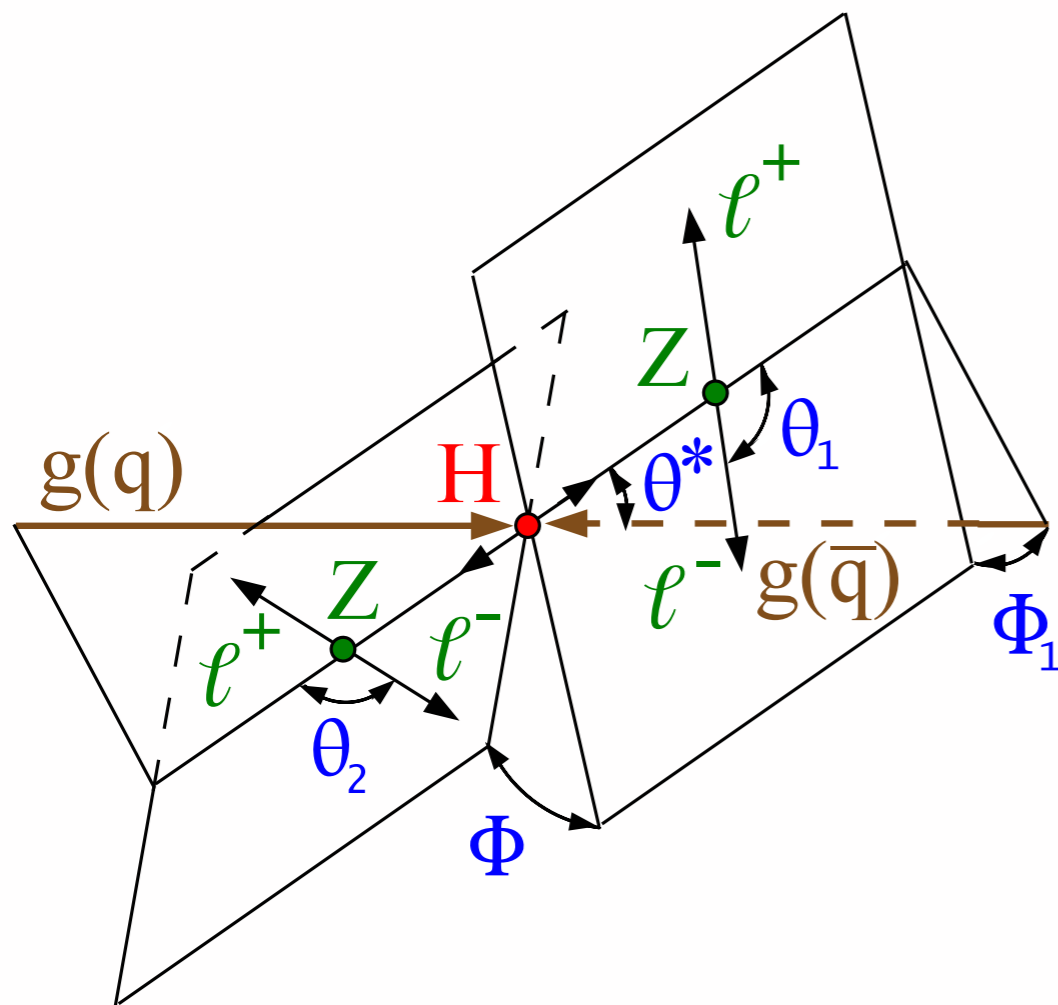
“The outcome of the spin analysis has as much suspense as a football game between Brazil and Tonga” (theorist in 2012-3)

Be prepared for the unexpected!



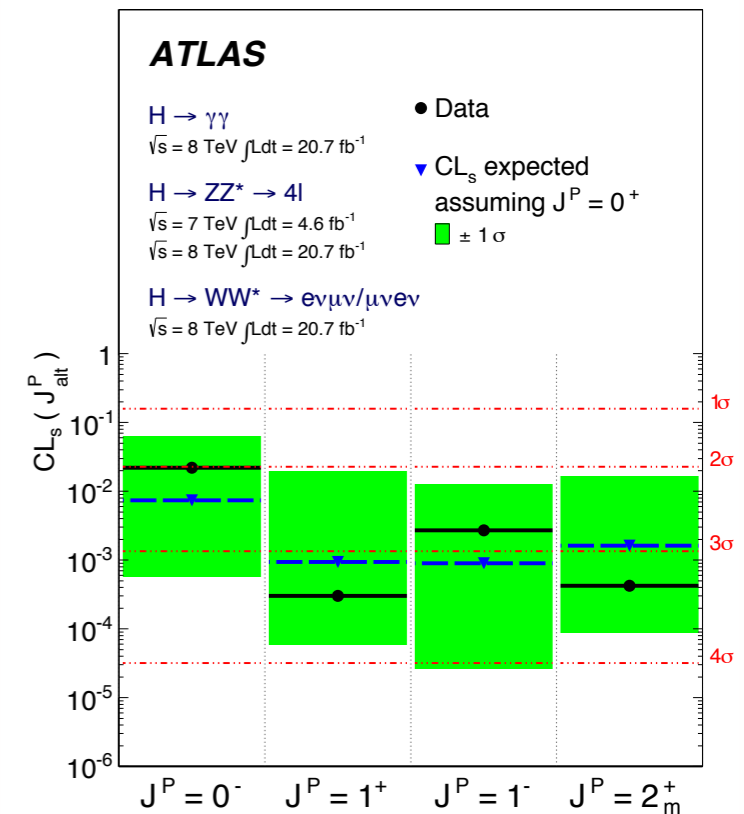
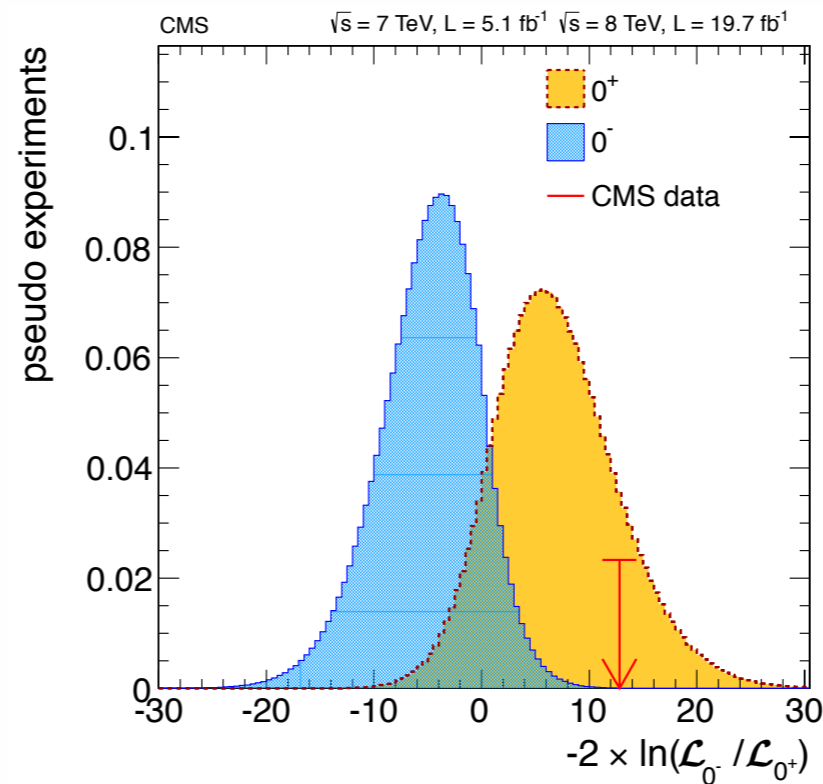
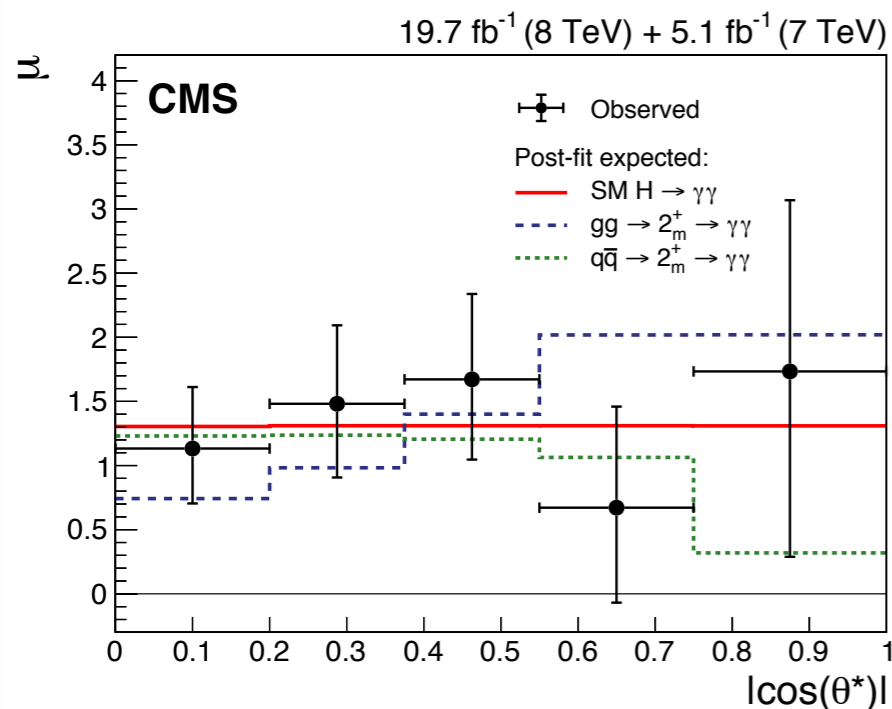
Spin analyses

- Observation of $H \rightarrow \gamma\gamma$ excludes spin-1 (Landau-Yang theorem)
- Compare SM 0^+ hypothesis with alternatives (0^- , 1^\pm , 2^+) via angular distributions / masses in $\gamma\gamma$, $ZZ^* \rightarrow 4\ell$, $WW^* \rightarrow \ell\nu\ell\nu$ final states



Spin analyses

- Observation of $H \rightarrow \gamma\gamma$ excludes spin-1 (Landau-Yang theorem)
- Compare SM 0^+ hypothesis with alternatives (0^- , 1^\pm , 2^+) via angular distributions / masses in $\gamma\gamma$, $ZZ^* \rightarrow 4\ell$, $WW^* \rightarrow \ell\nu\ell\nu$ final states



0^+ strongly favored, others excluded at $> 99\%$ CL

- Beyond any reasonable doubt, we have discovered a new particle
 - A boson since it decays to bosons!
- Is it a Higgs boson?
 - Scalar ($J^{PC} = 0^{++}$) ✓
 - Its vacuum expectation value is responsible for EW symmetry breaking
 - First evidence: large decay rates to WW , ZZ and small to $\gamma\gamma$ (and $Z\gamma$)

cfr: $f_0(980)$ $J^{PC}=0^{++}$ and $\Gamma(f_0 \rightarrow \gamma\gamma) = 290$ eV, but it's not "a" Higgs

The new particle

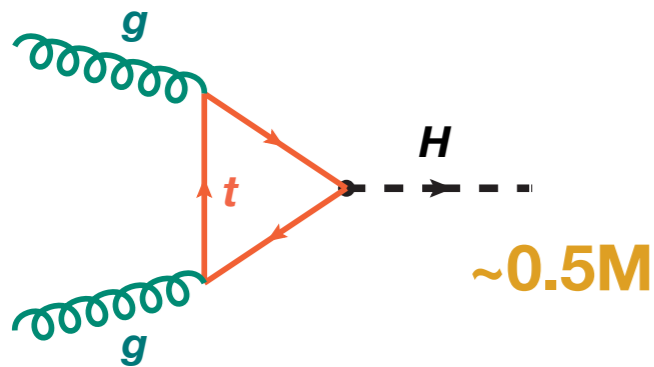
A visualization of a particle collision, showing a central point where multiple particles meet, with a large burst of energy and particles radiating outwards. The background is dark with some blue and yellow highlights.

- Beyond any reasonable doubt, we have discovered a new particle
 - A boson since it decays to bosons!
- Is it a Higgs boson?
 - Scalar ($J^{PC} = 0^{++}$) ✓
 - Its vacuum expectation value is responsible for EW symmetry breaking ✓
 - First evidence: large decay rates into WW , ZZ and small into $\gamma\gamma$ (and $Z\gamma$)
- Is it the SM Higgs boson?
 - Elementary particle, associated to the sole mechanism responsible for the masses of gauge bosons and fermions
 - Couplings, width (lifetime), self-interactions (potential) as predicted by the SM

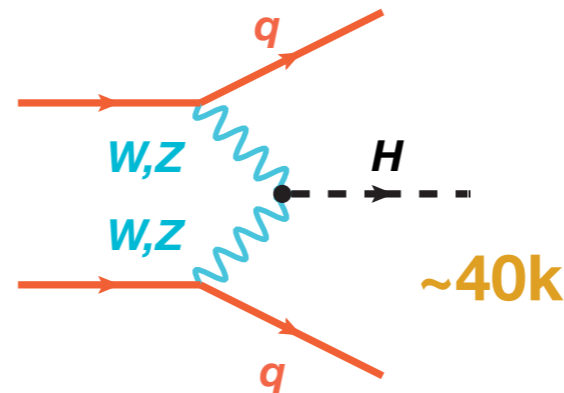
The SM Higgs boson at the LHC

Production mechanisms (events produced)

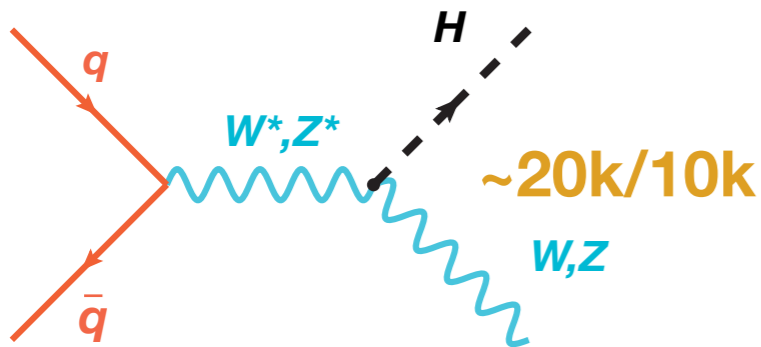
Gluon-fusion



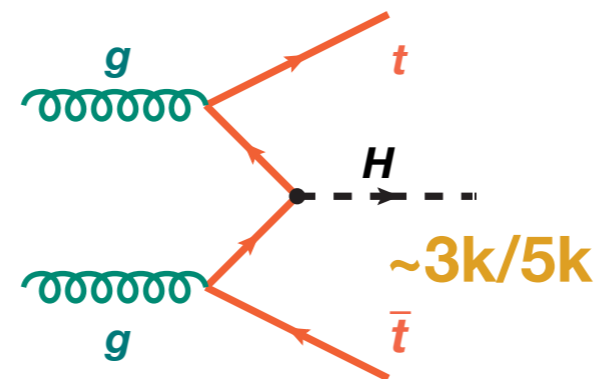
Vector boson fusion (VBF)



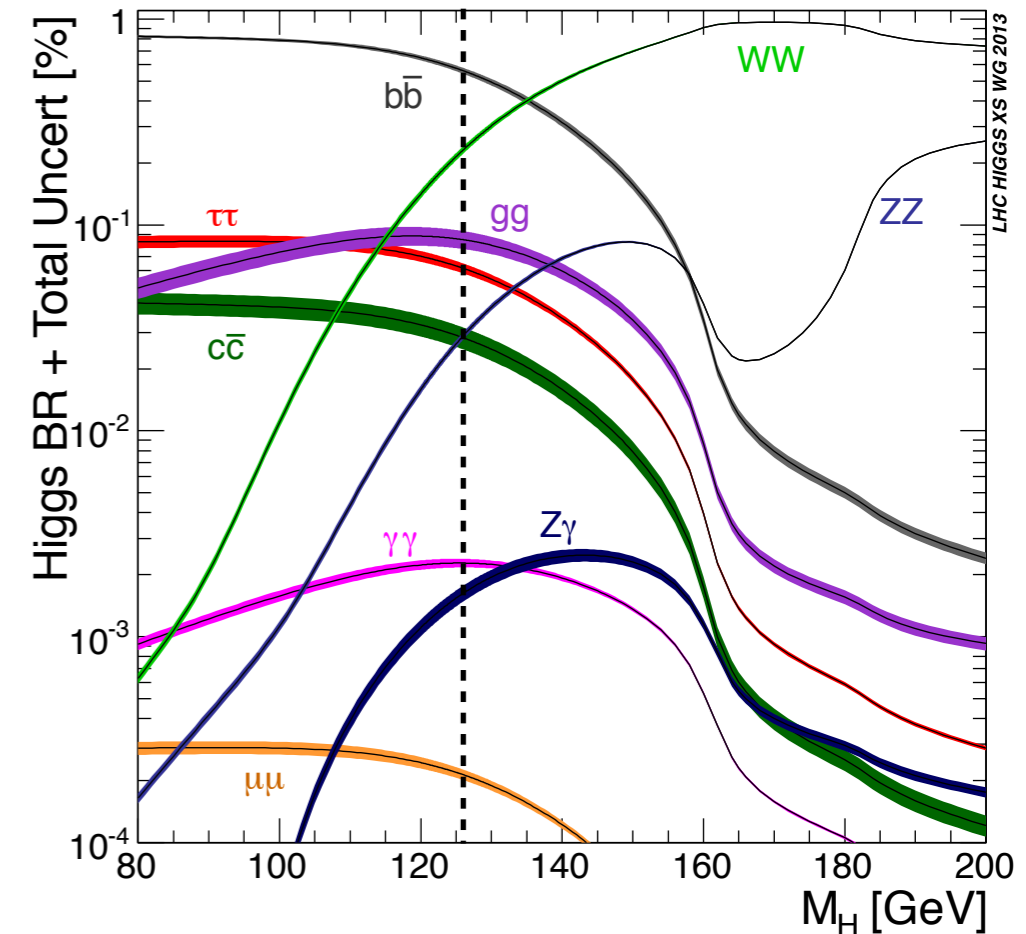
Associated with W / Z



Associated with tt (or bb)

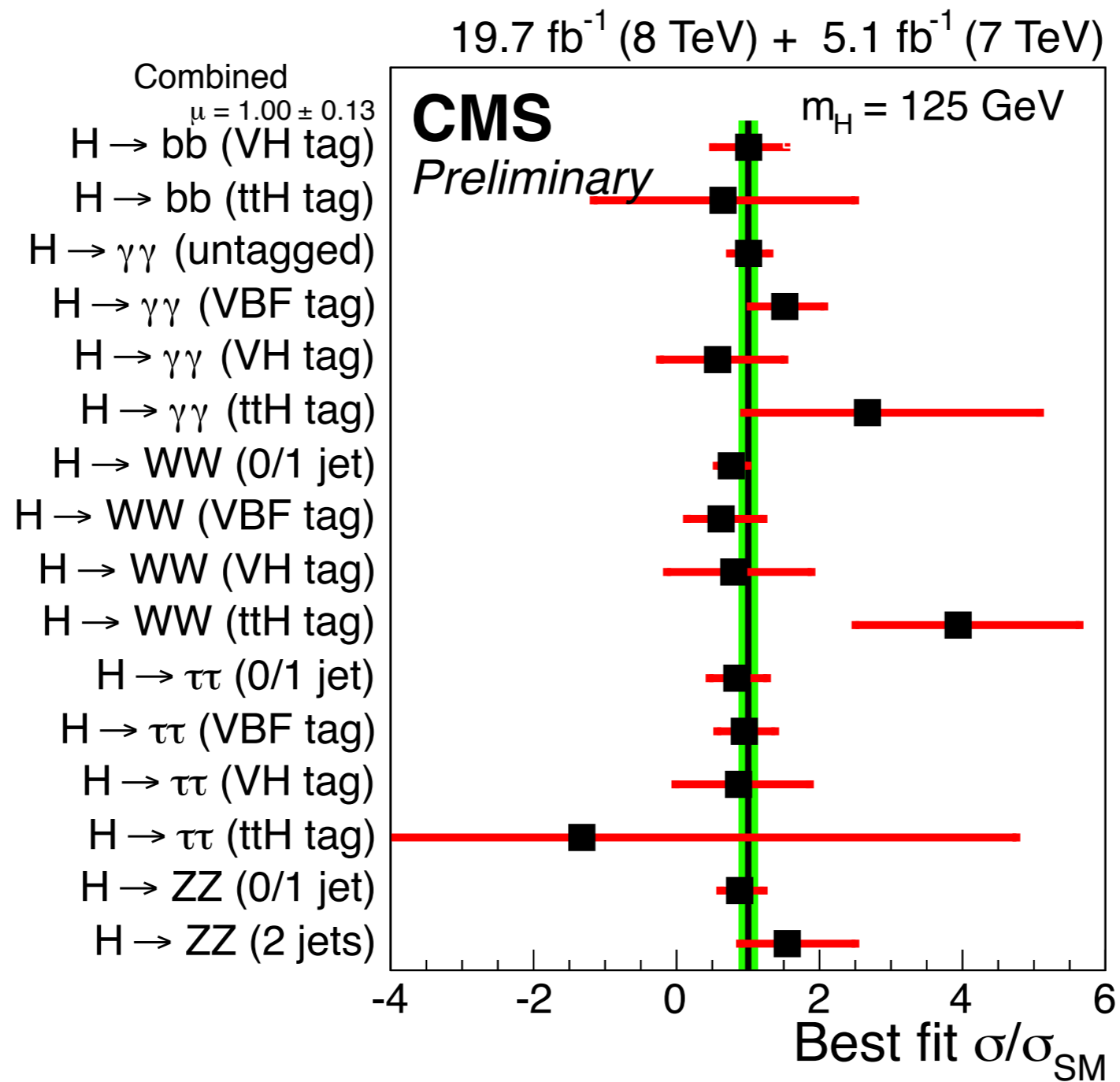


Decay modes



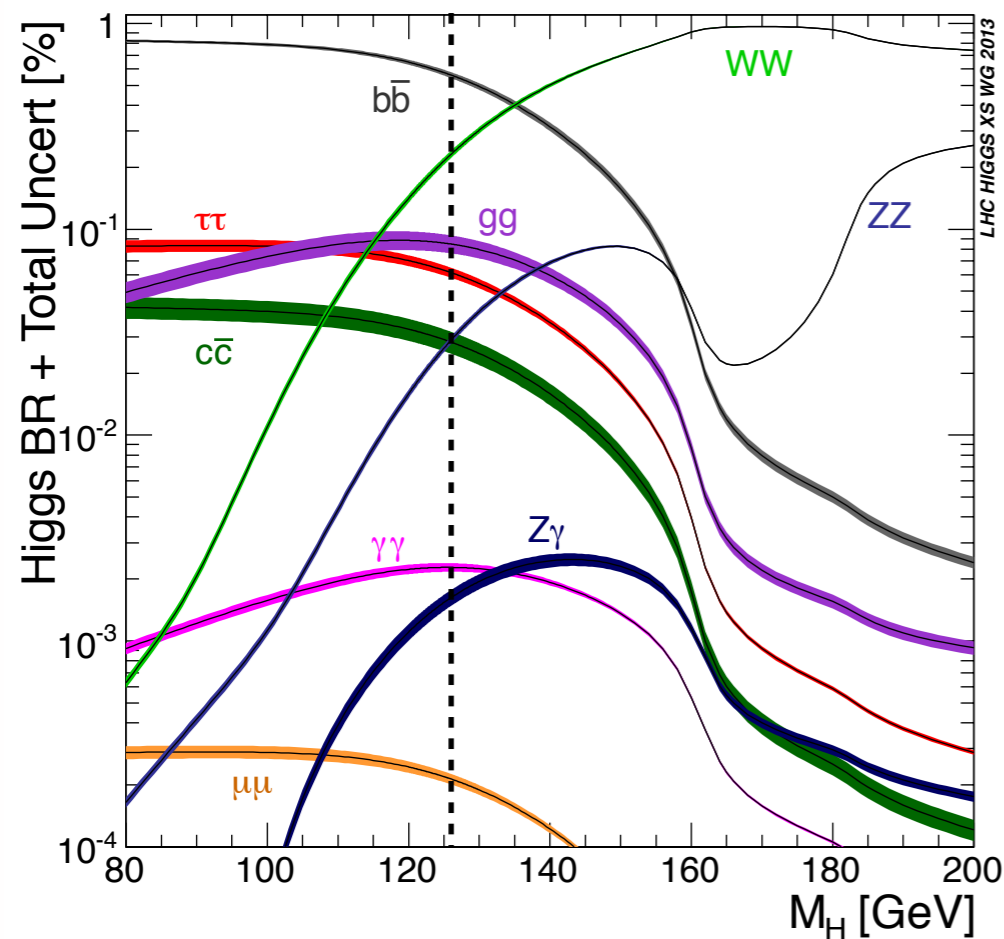
- Main channels (bosonic): $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
- Fermionic modes (associated production): (VBF) $H \rightarrow \tau\tau$, (W/Z) $H \rightarrow bb$
- Rare decays: $H \rightarrow Z\gamma$, $H \rightarrow \mu\mu$

Higgs boson results: production / decays (CMS)



Higgs boson results: decays (ATLAS)

Decay modes

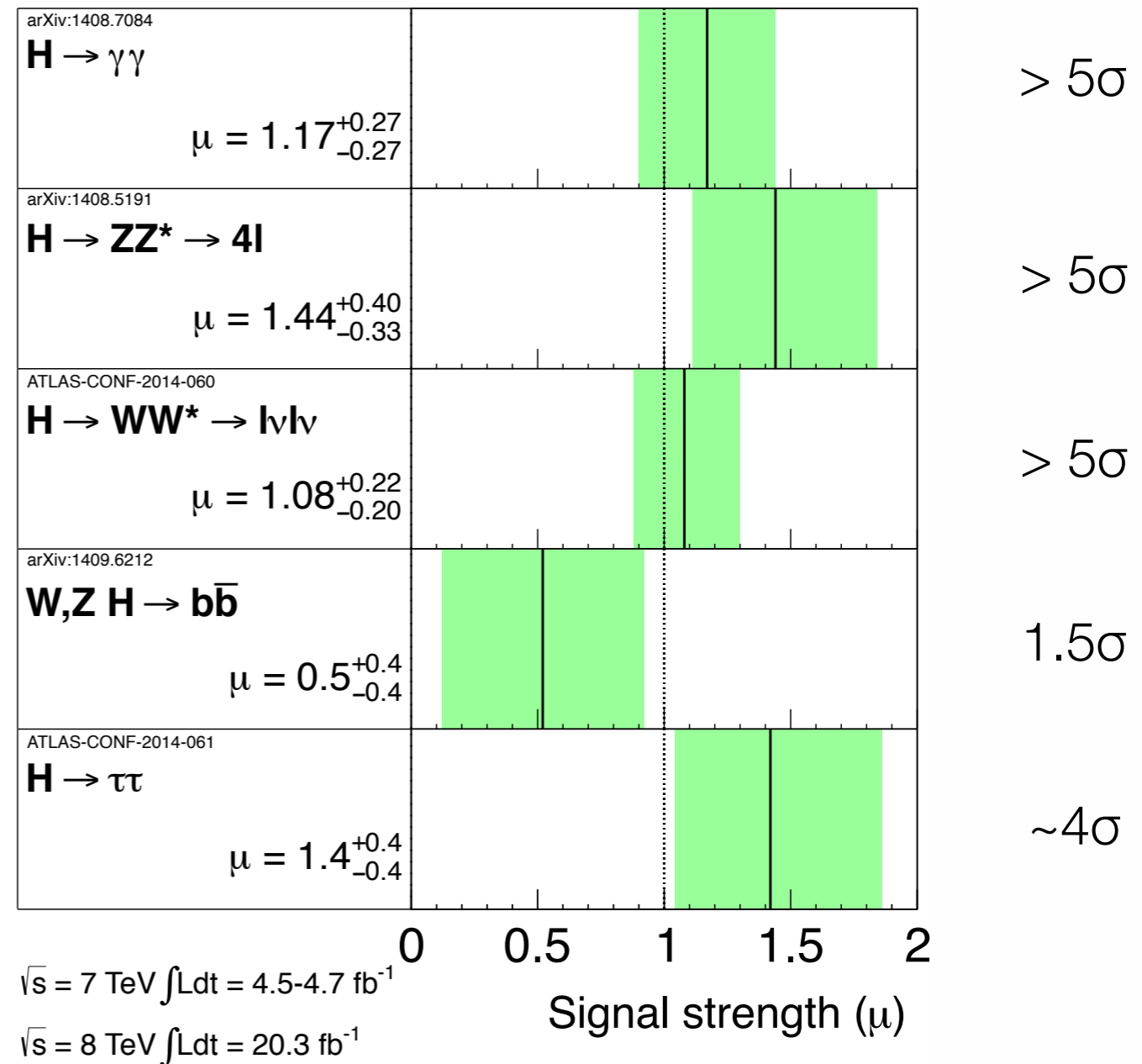


ATLAS Preliminary

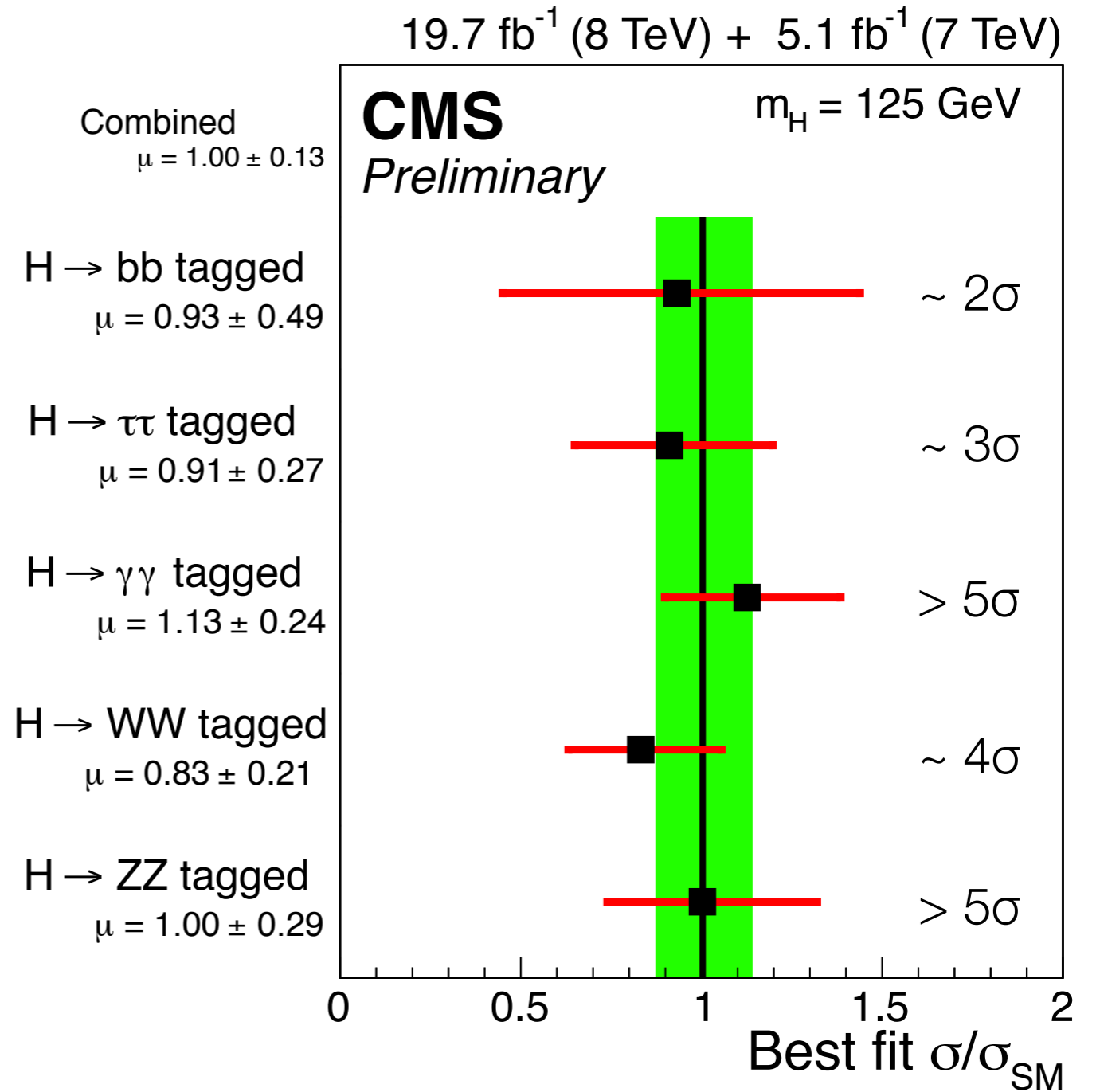
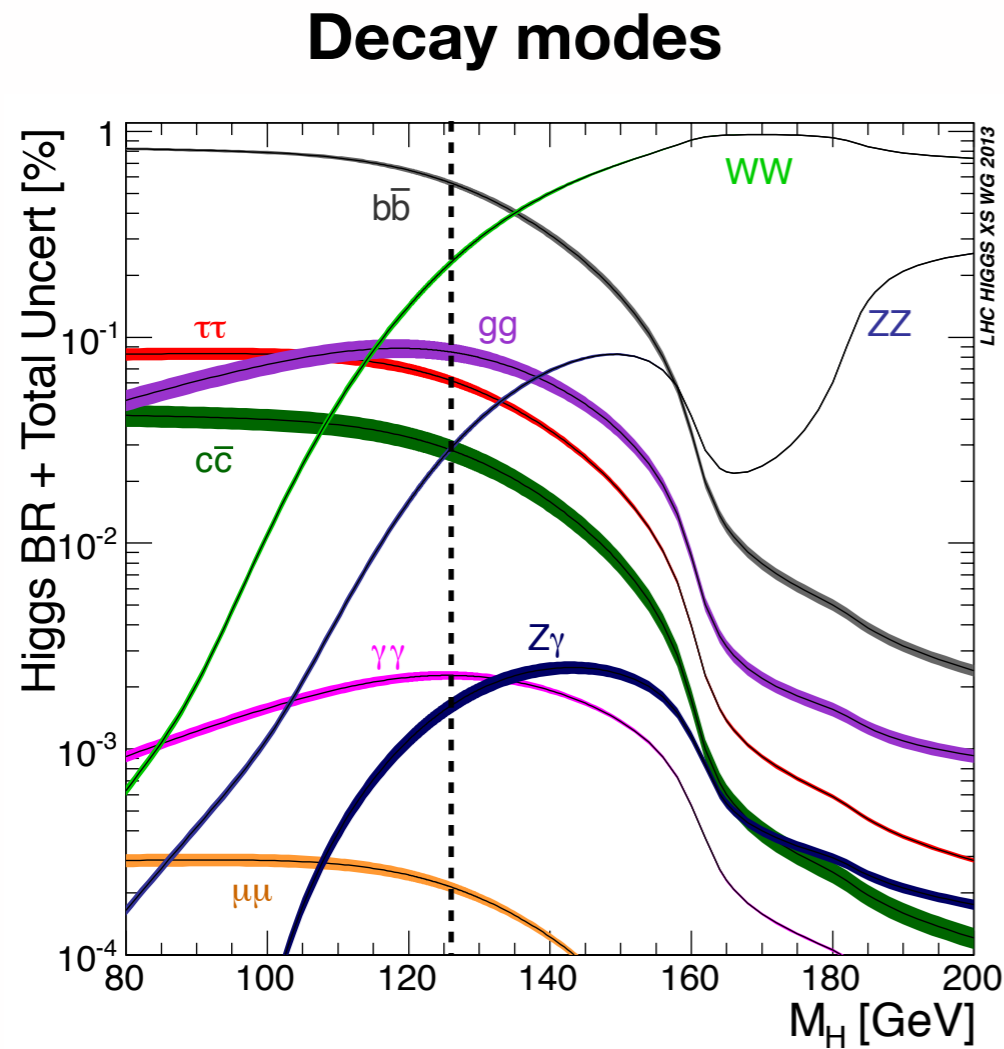
$m_H = 125.36$ GeV

Total uncertainty

■ $\pm 1\sigma$ on μ

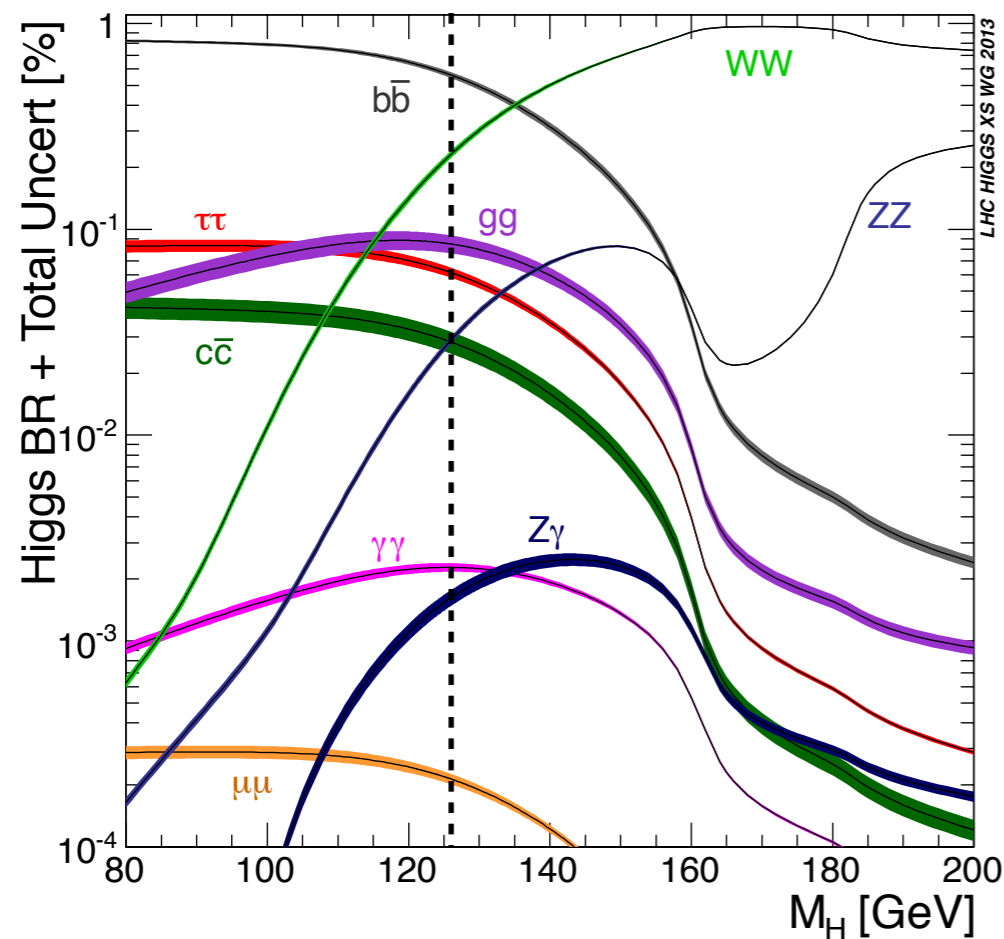


Higgs boson results: decays (CMS)



Higgs boson results: decays (ATLAS / CMS)

Decay modes



Combined
 $\mu = 1.00 \pm 0.13$

$H \rightarrow bb$ tagged
 $\mu = 0.93 \pm 0.49$

$H \rightarrow \tau\tau$ tagged
 $\mu = 0.91 \pm 0.27$

$H \rightarrow \gamma\gamma$ tagged
 $\mu = 1.13 \pm 0.24$

$H \rightarrow WW$ tagged
 $\mu = 0.83 \pm 0.21$

$H \rightarrow ZZ$ tagged
 $\mu = 1.00 \pm 0.29$

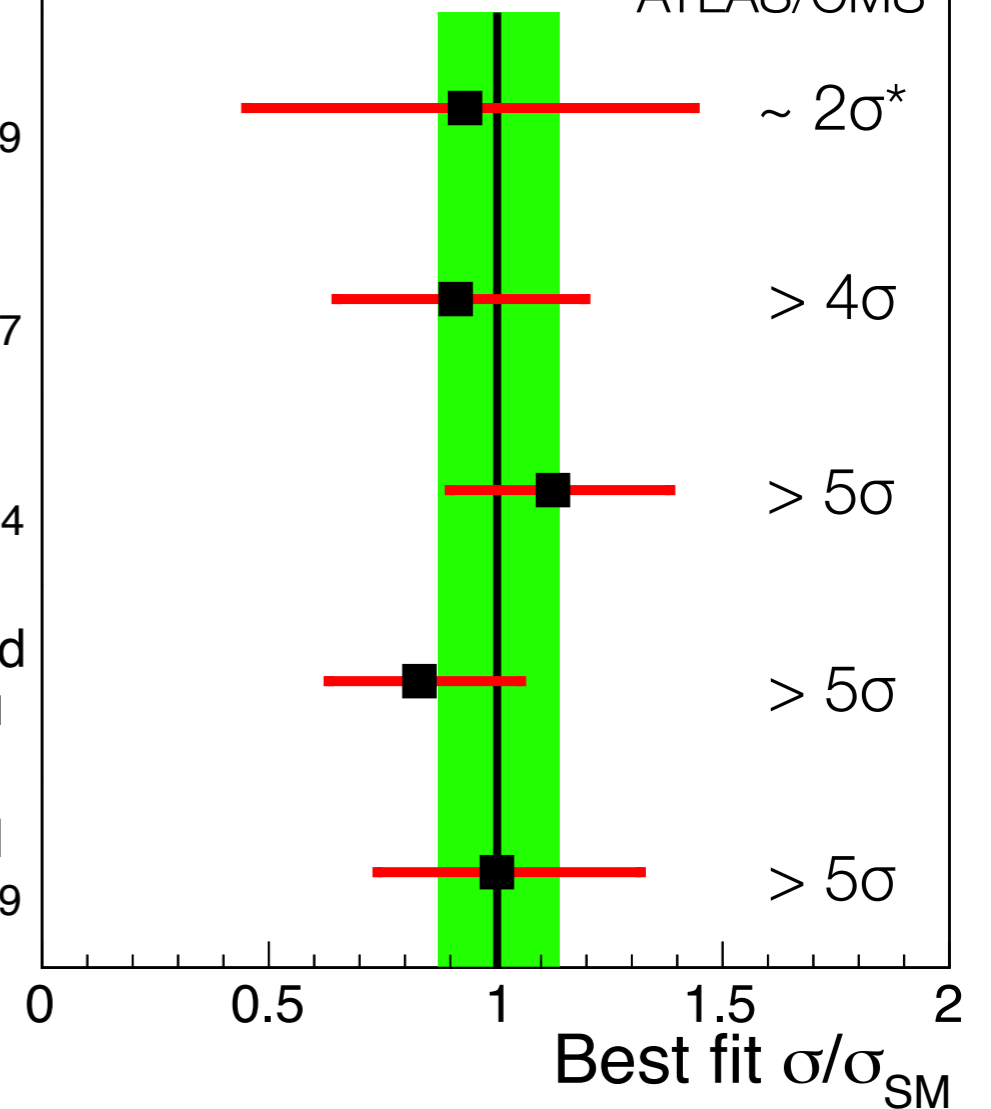
19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)

CMS

Preliminary

$m_H = 125 \text{ GeV}$

ATLAS/CMS

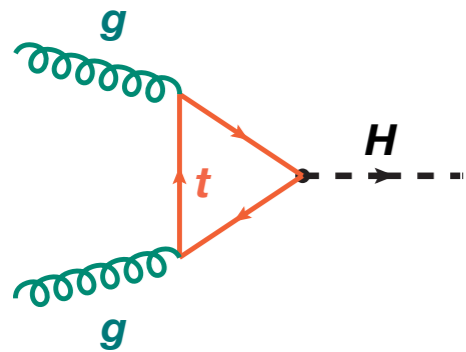


* 3σ at Tevatron

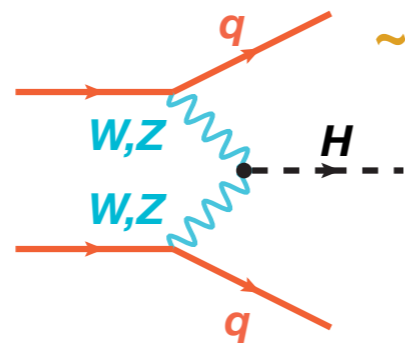
The SM Higgs boson at the LHC

Production mechanisms (events produced)

Gluon-fusion **~0.5M**



Vector boson fusion (VBF) **~40k**



Combined
 $\mu = 1.00 \pm 0.13$

Untagged
 $\mu = 0.87 \pm 0.16$

VBF tagged
 $\mu = 1.14 \pm 0.27$

VH tagged
 $\mu = 0.89 \pm 0.38$

ttH tagged
 $\mu = 2.76 \pm 0.99$

19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)

CMS
Preliminary

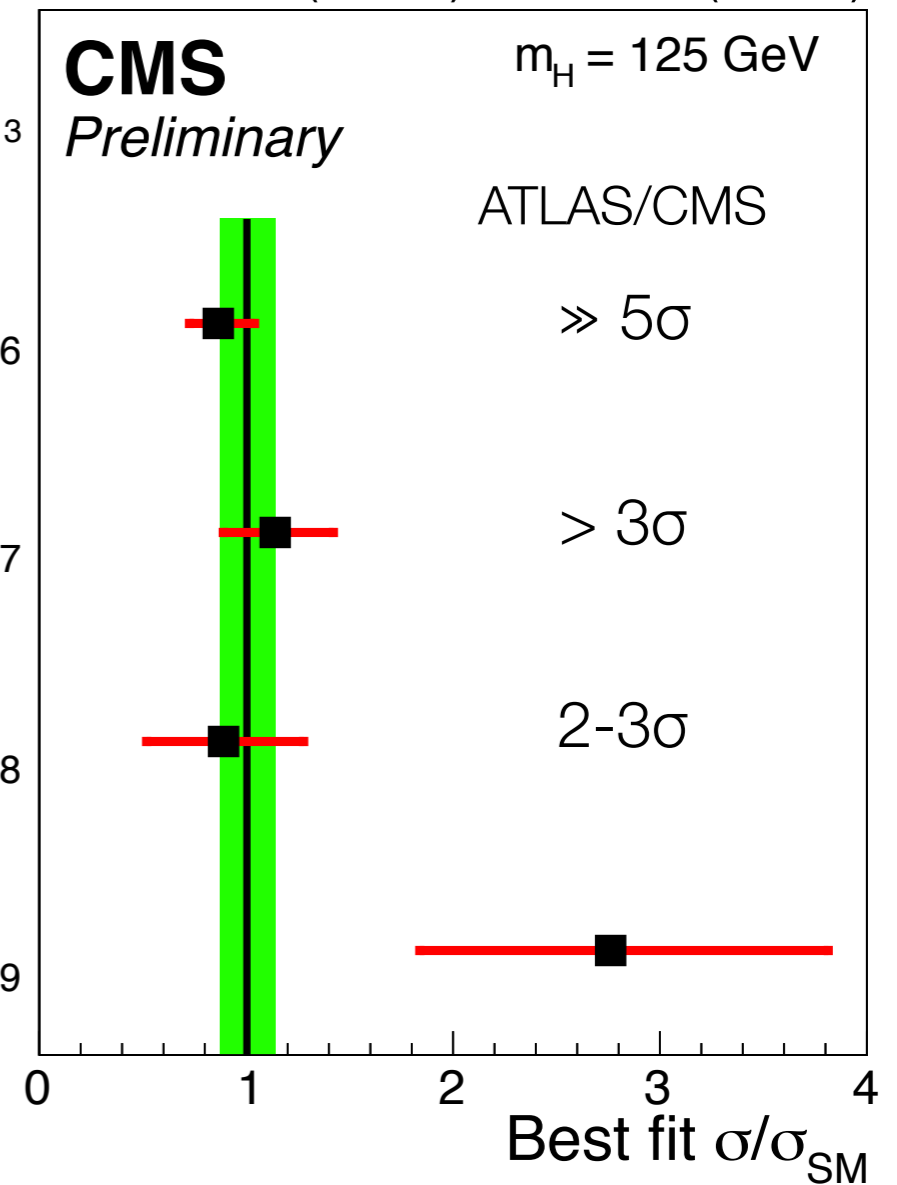
$m_H = 125$ GeV

ATLAS/CMS

$\gg 5\sigma$

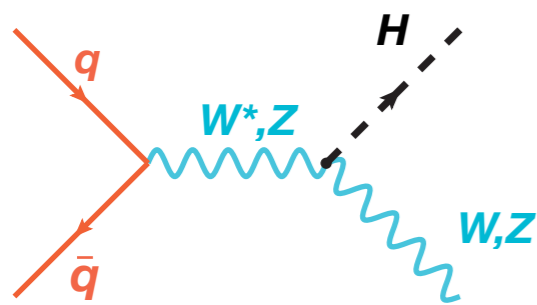
$> 3\sigma$

2-3 σ

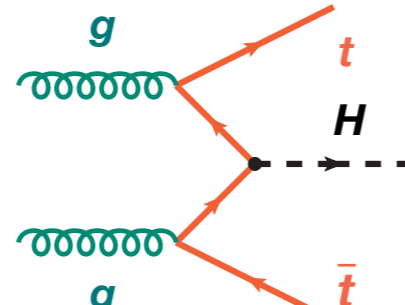


~20k/10k

Associated with W/Z (VH)

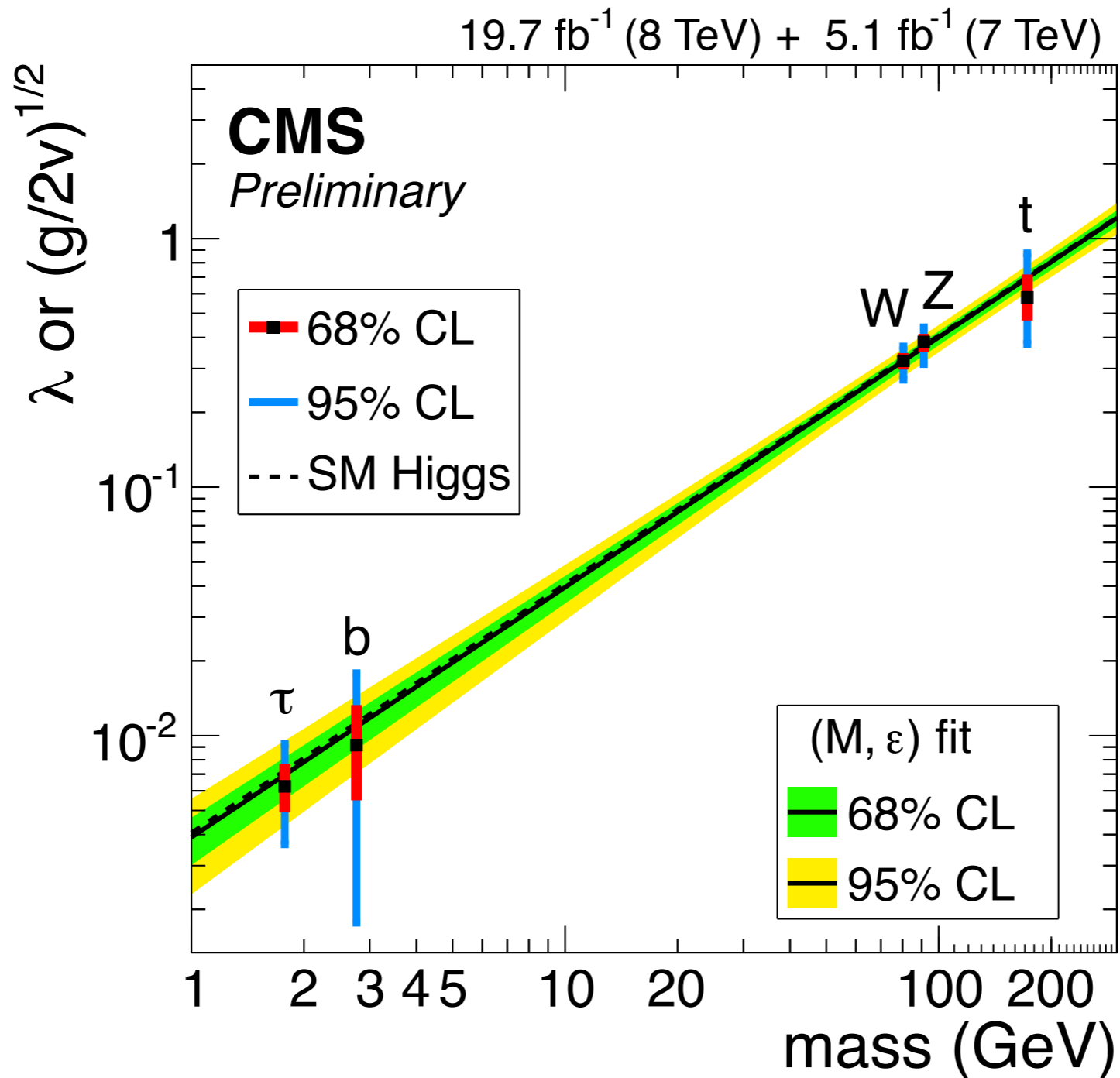


Associated with tt (or bb)

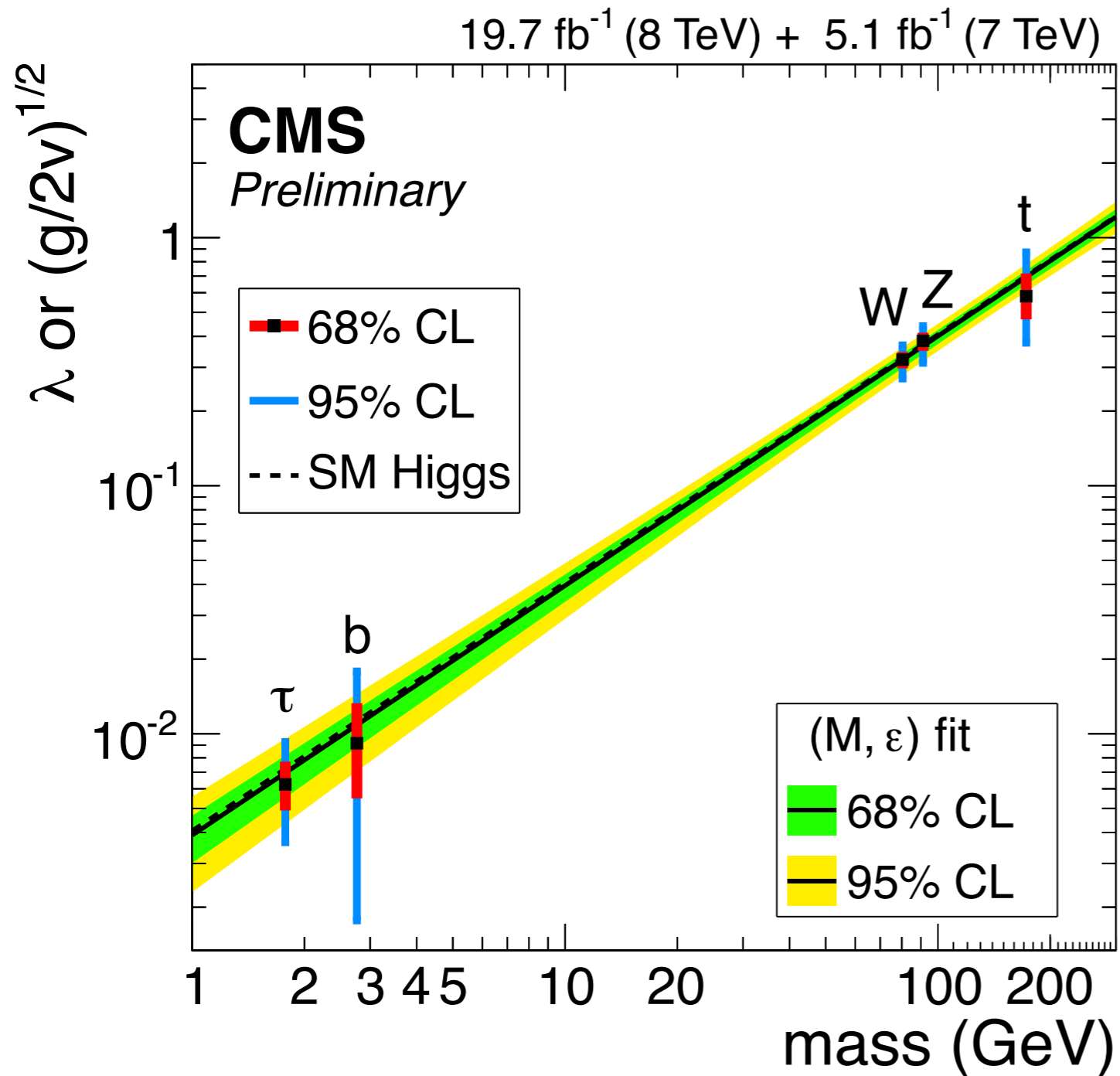


~3k/5k

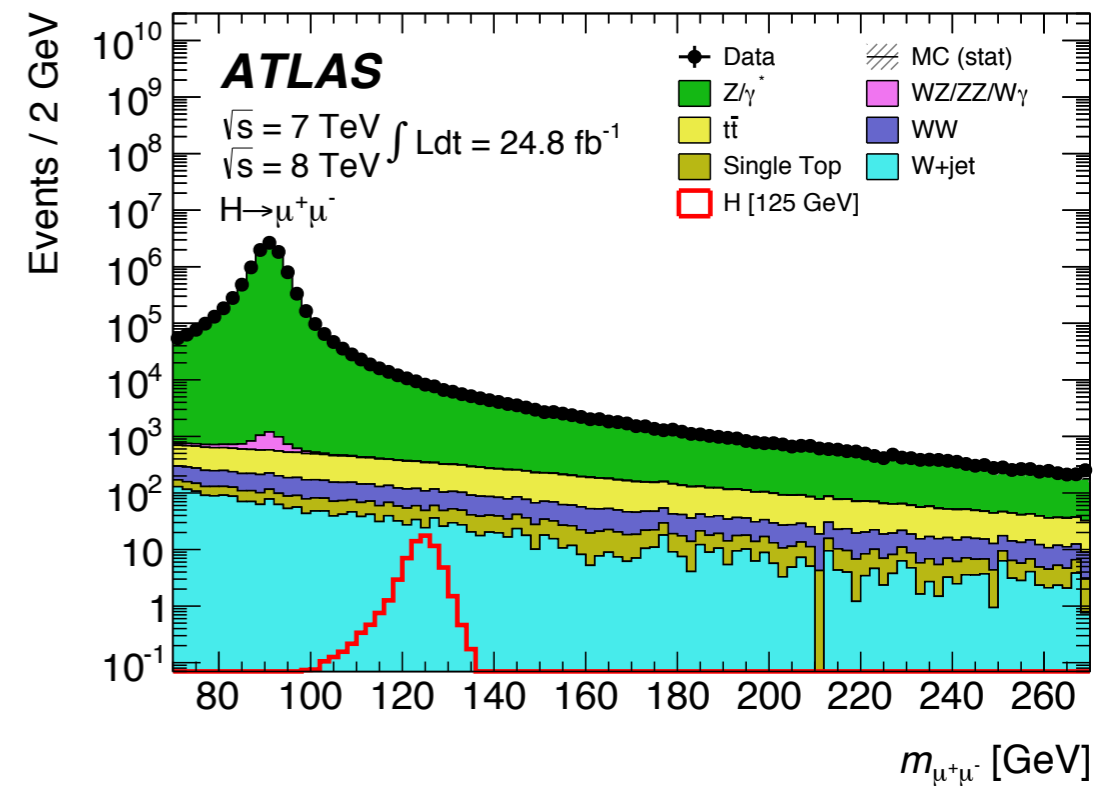
Higgs couplings scale with mass



Higgs couplings scale with mass



Evidence for $H \rightarrow \tau^+\tau^-$
 no sign of $H \rightarrow \mu^+\mu^-$ (or e^+e^-)
 (no lepton universality)



Higgs width

A visualization of a particle collision, likely at the LHC. A central point of interaction is shown with a burst of colorful particles (red, blue, green, yellow) radiating outwards. The background is dark with some blue and yellow highlights, suggesting a complex detector environment.

- SM: $\Gamma_H(125 \text{ GeV}) \sim 4 \text{ MeV}$. Detector resolution $\sim 1 \text{ GeV}$
- Need to look for other observables sensitive to width

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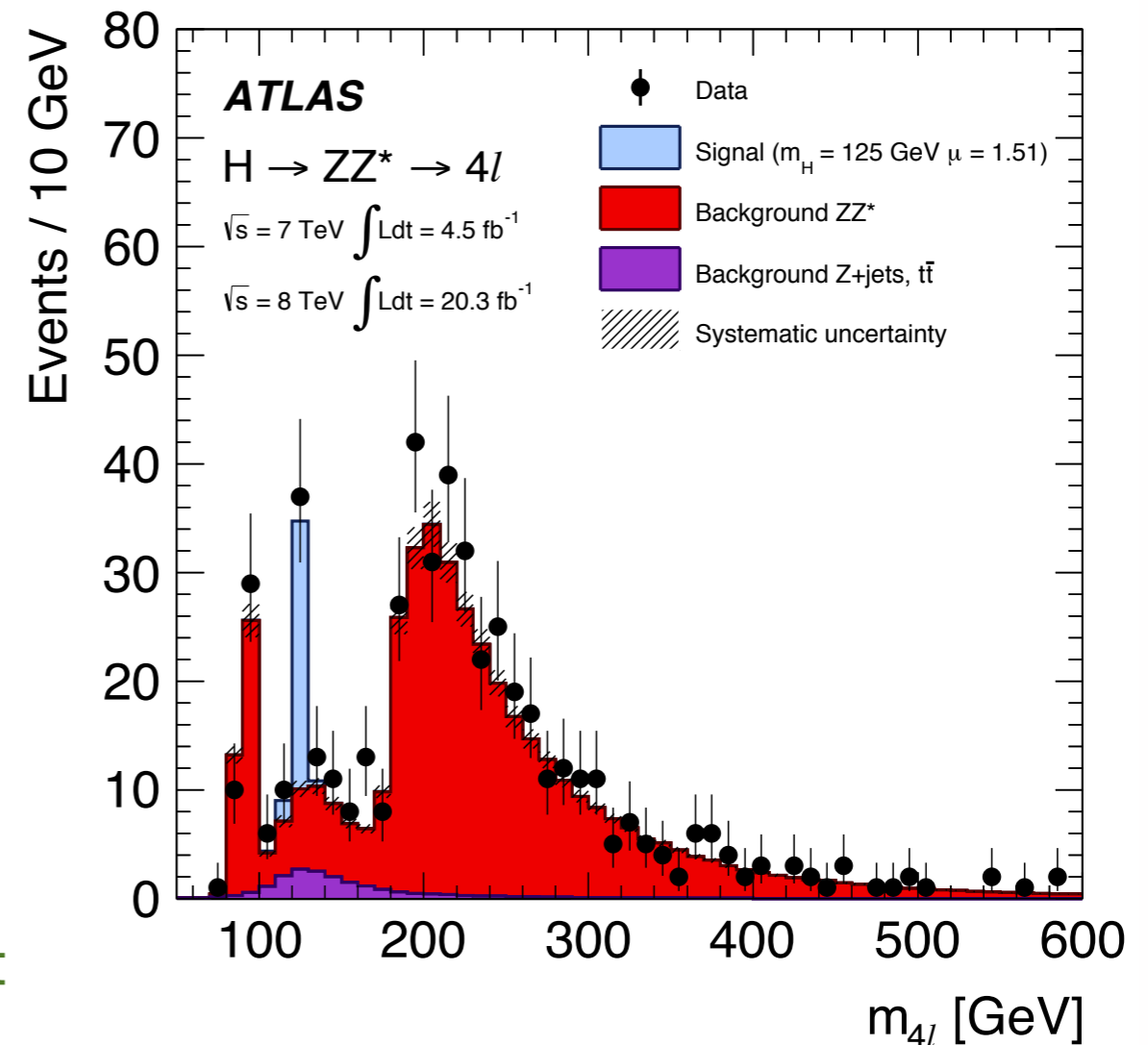
- On-shell / off-shell $gg \rightarrow H \rightarrow ZZ$

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ^*}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

$$\sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$

- Background from SM ZZ, dominated by qq production
- Suppressed by matrix element based discriminants



Higgs width

- SM: $\Gamma_H(125 \text{ GeV}) \sim 4 \text{ MeV}$. Detector resolution $\sim 1 \text{ GeV}$
- Need to look for other observables sensitive to width

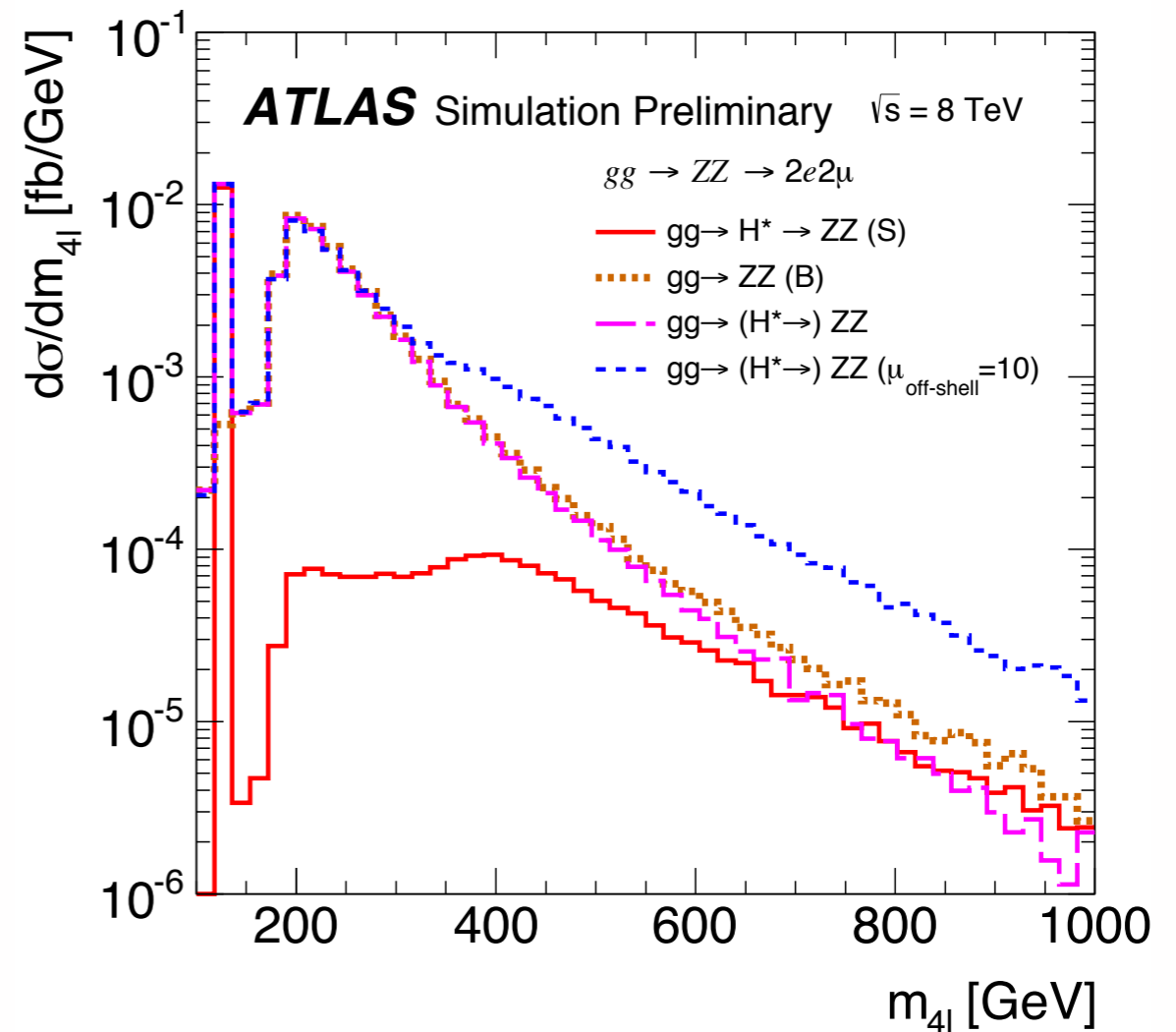
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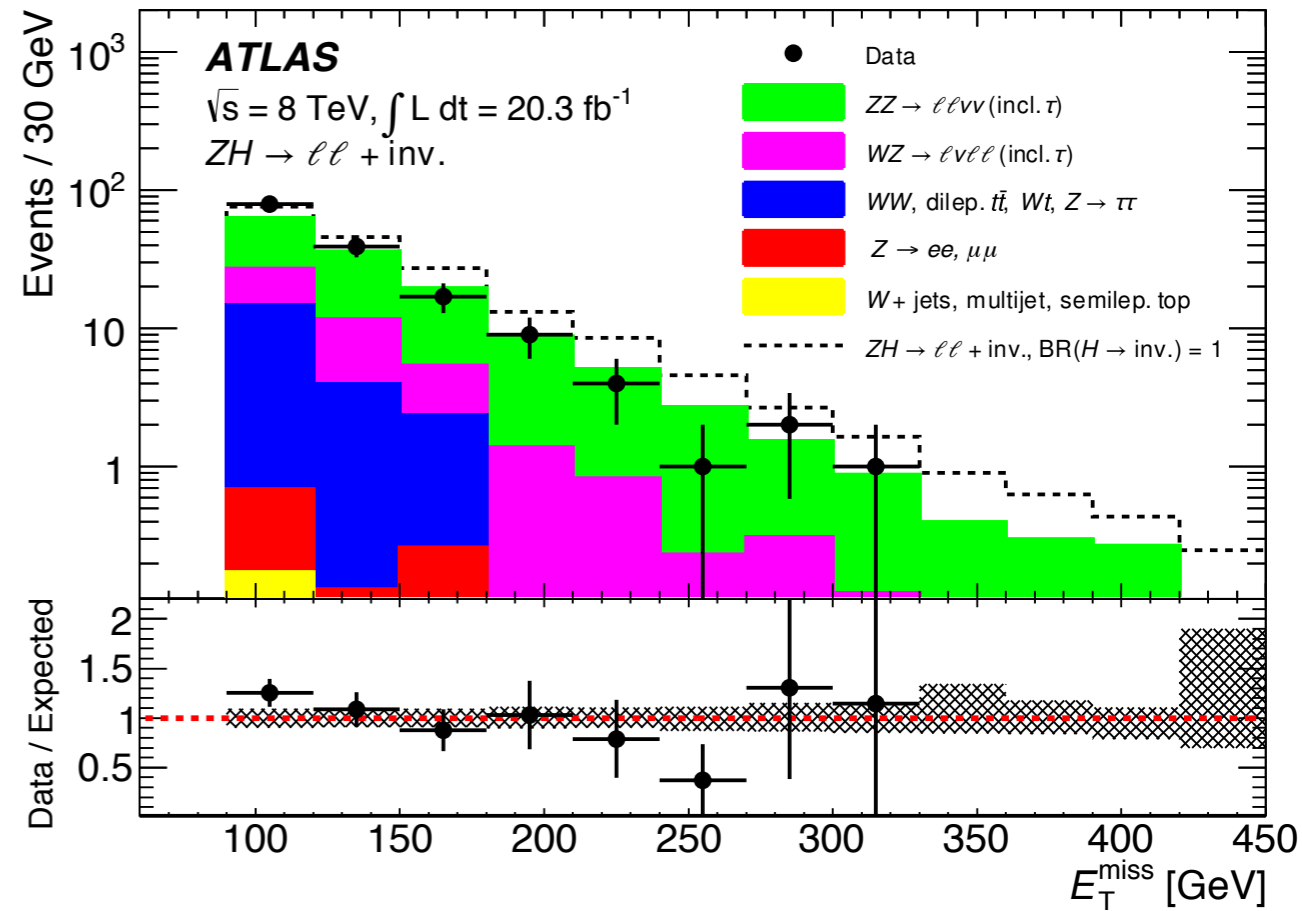
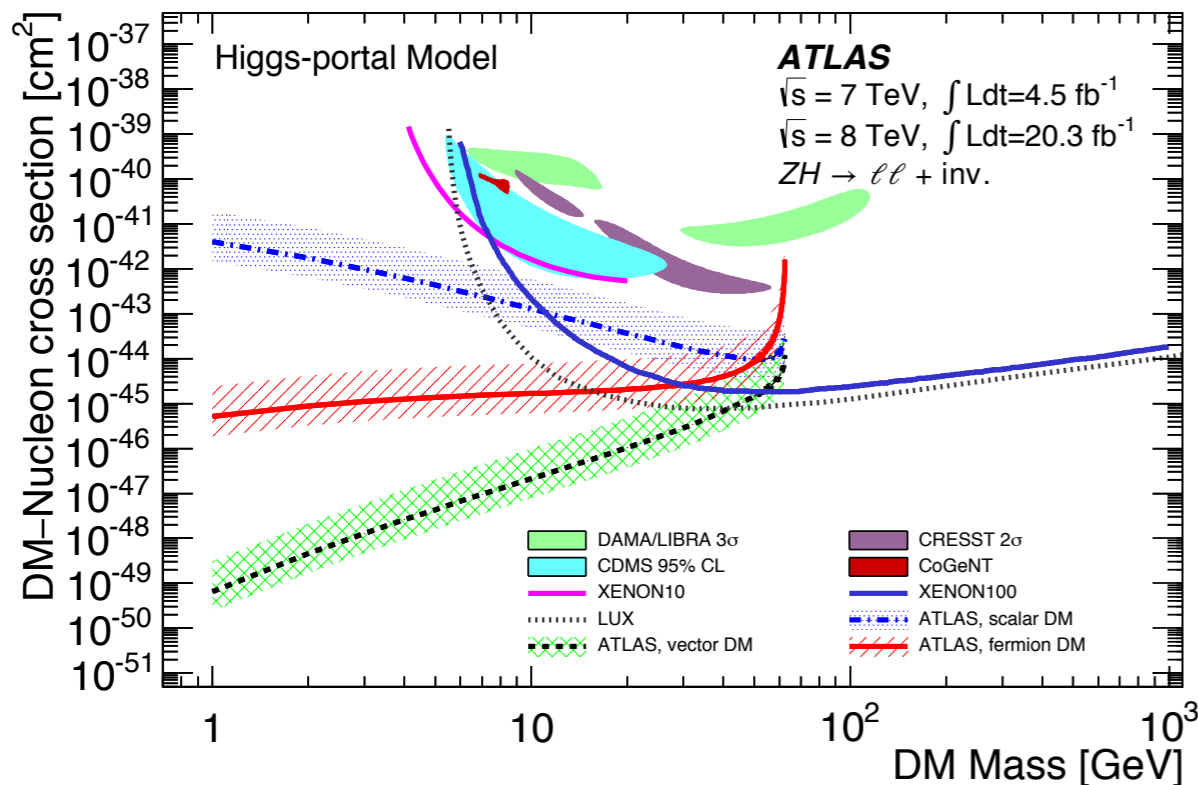
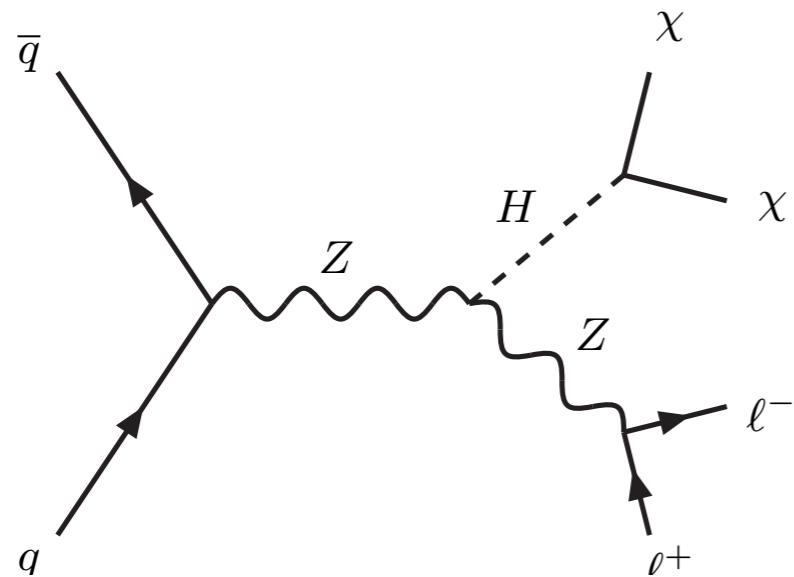
- Interference with $gg \rightarrow ZZ$, assumes no new physics there



ATLAS/CMS: $\Gamma/\Gamma_{\text{SM}} \lesssim 5$ @ 95% CL

Higgs decays to invisible particles

Look for $H \rightarrow$ missing energy



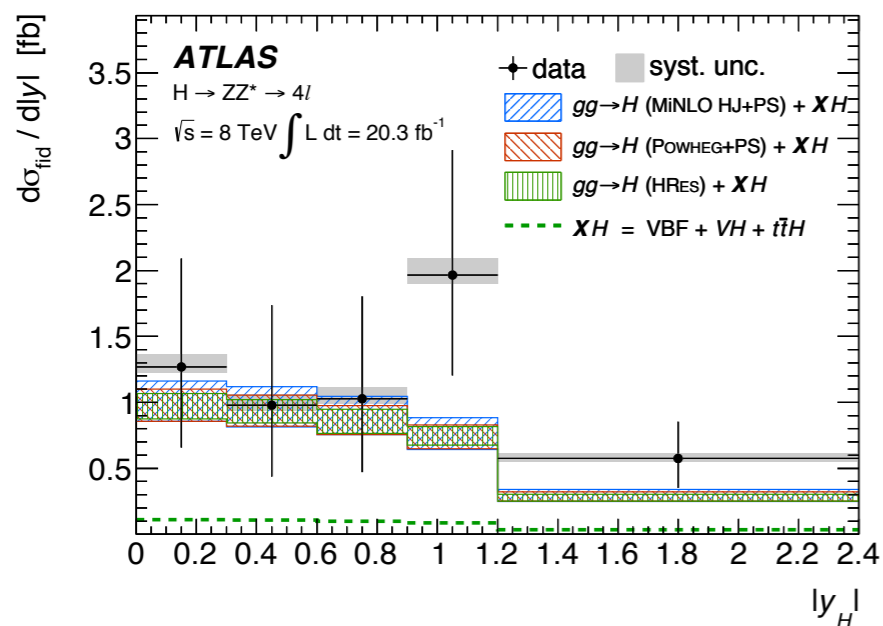
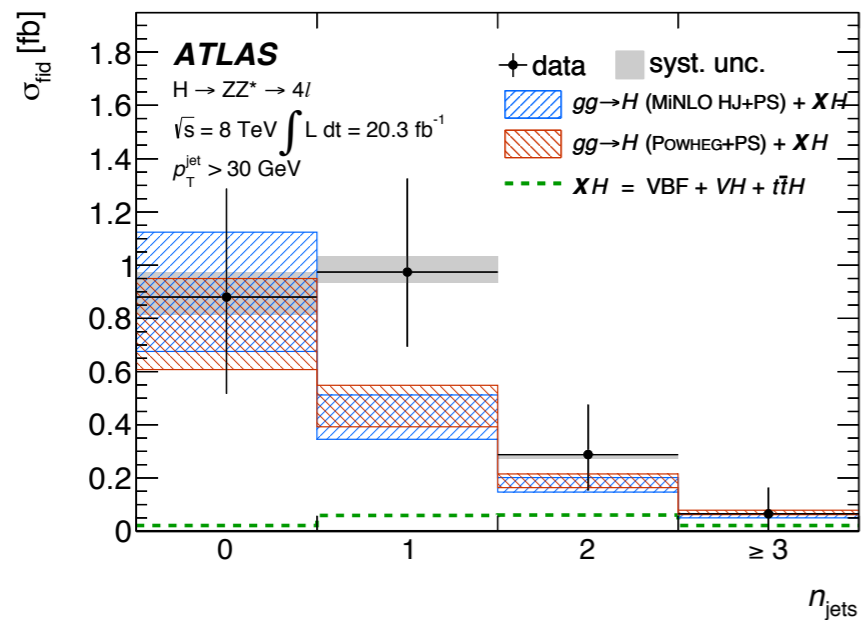
ATLAS: $\text{BR}(\text{inv}) < 0.75$ (0.62) @ 95% C.L.

CMS: $\text{BR}(\text{inv}) < 0.58$ (0.44) @ 95% C.L.

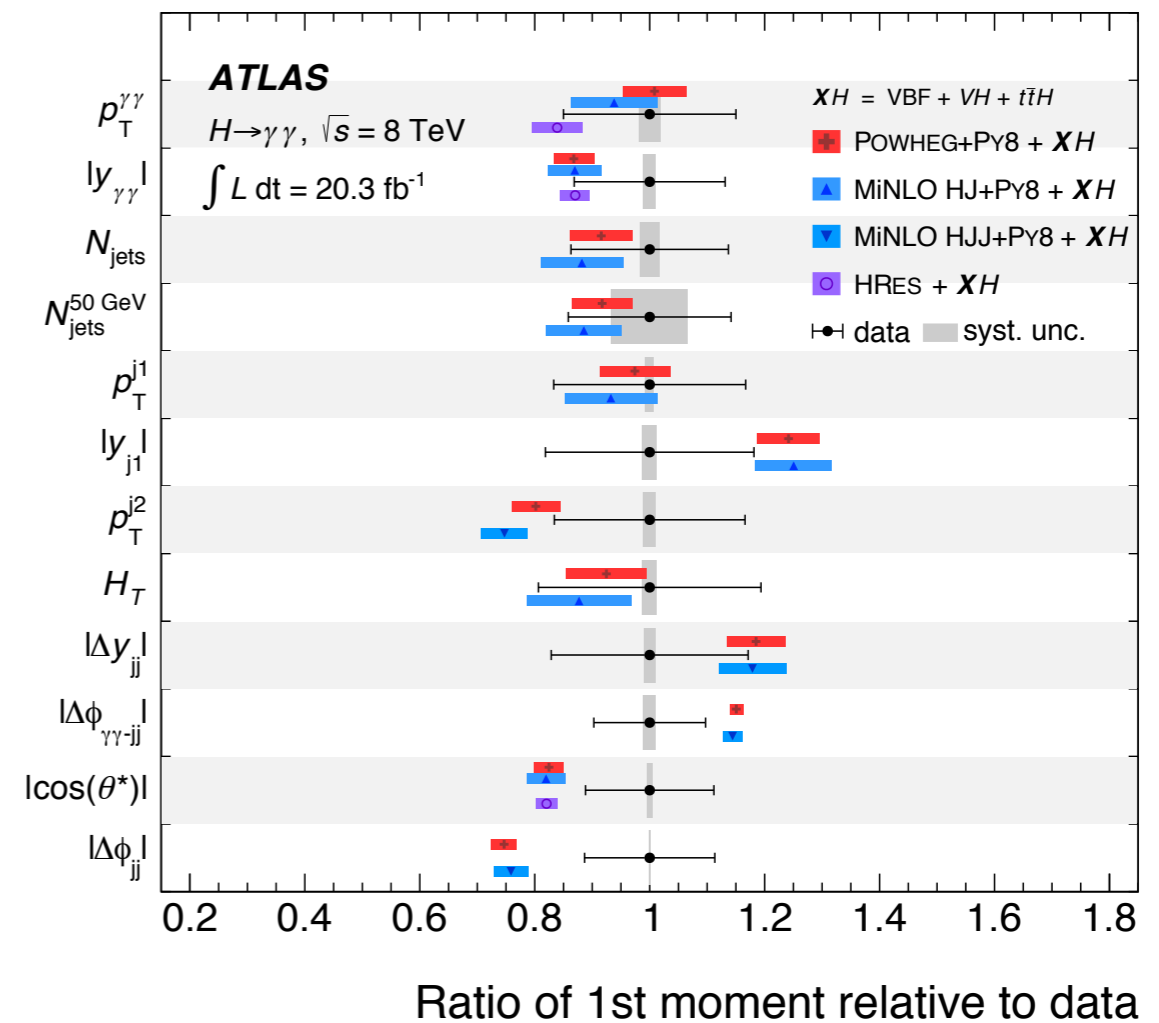
Differential distributions

Kinematics of Higgs production / decay corrected for detector effects
(validate theoretical calculations)

$$H \rightarrow ZZ^* \rightarrow 4\ell$$



$$H \rightarrow \gamma\gamma \text{ (summary)}$$



No significant deviations from SM



Prospects

Prospects



- All the measurements seem to indicate that this particle is consistent with the SM Higgs boson
 - Couplings measured to $\sim 30\%$ precision
 - Deviations in the most attractive scenarios of physics beyond the SM $\lesssim 10\%$

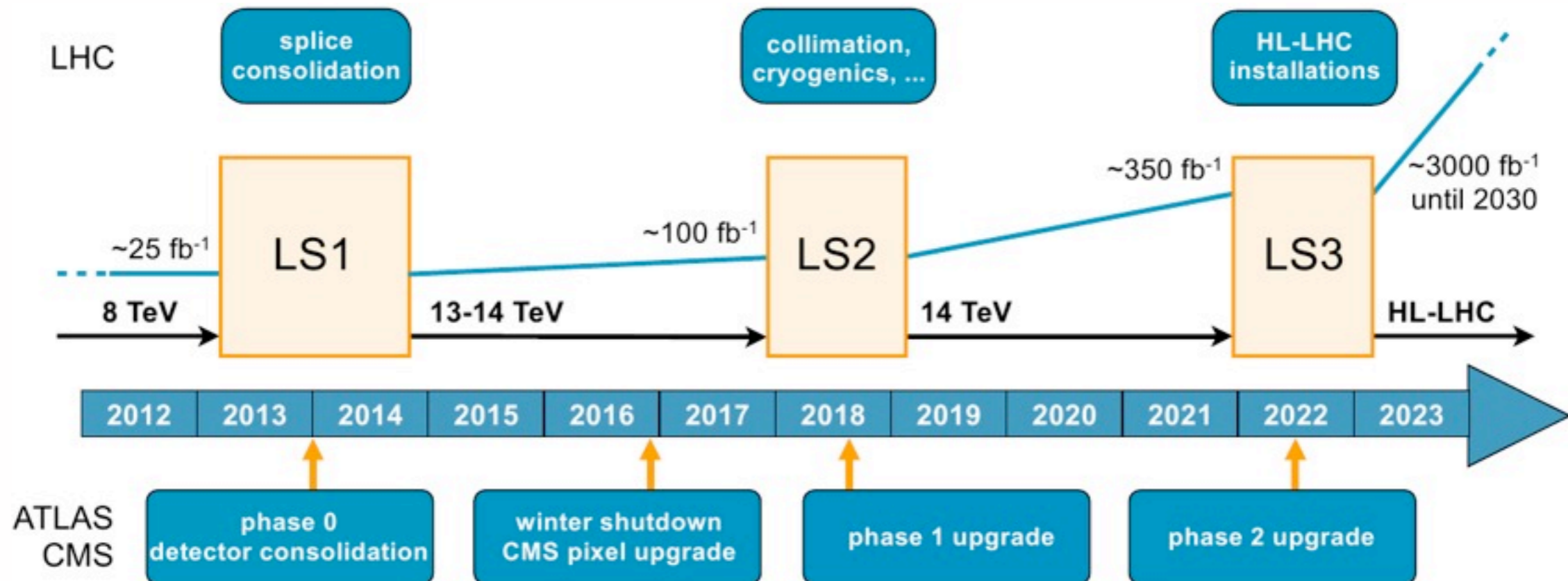
Prospects

A visualization of a particle collision, showing a central point where multiple particles meet, with a large burst of energy and particles radiating outwards. The background is dark with some blue and yellow highlights.

- All the measurements seem to indicate that this particle is consistent with the SM Higgs boson
 - Couplings measured to $\sim 30\%$ precision
 - Deviations in the most attractive scenarios of physics beyond the SM $\lesssim 10\%$
- How to go beyond ?
 - Better experimentalists (and theorists) ?
 - More data (luminosity) ?
 - More energy ?
 - Collide different particles ?

Higgs prospects: LHC / HL-LHC

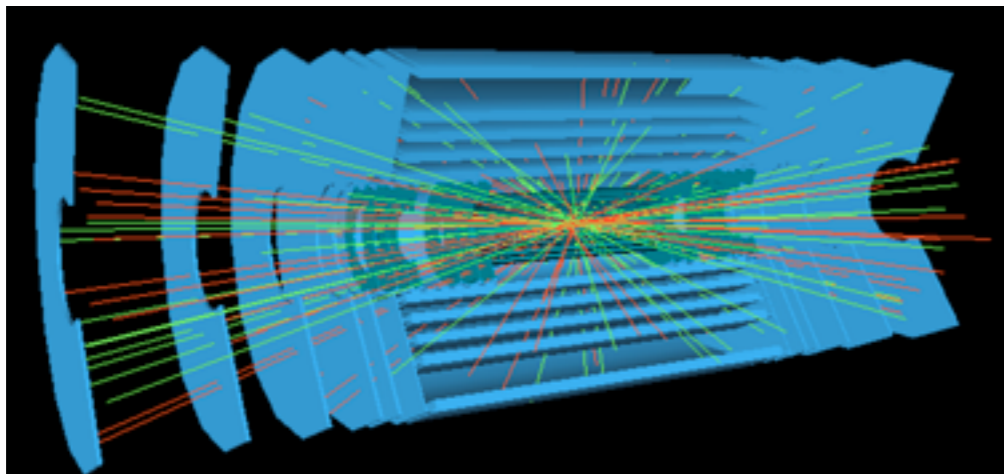
- LHC is expected to operate for another ~ 15 y and produce ~ 100 x more data



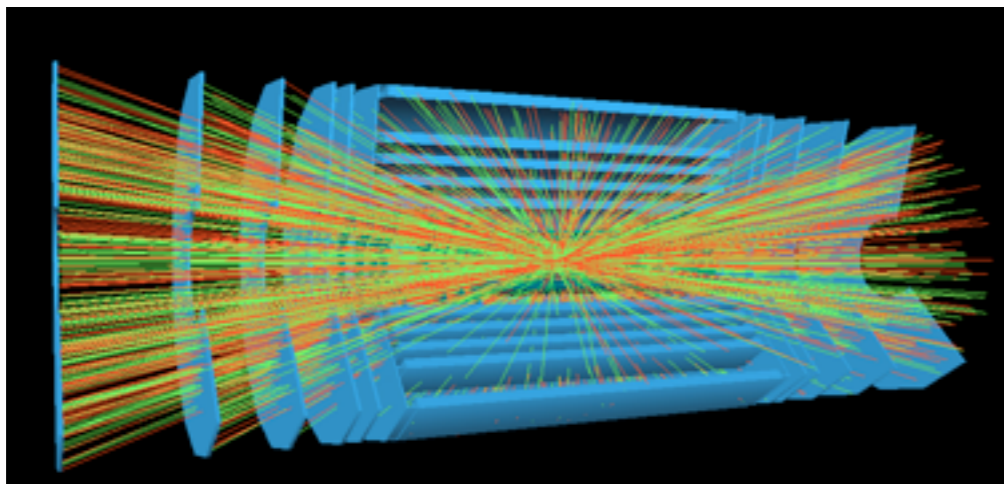
Higgs prospects: LHC / HL-LHC

- LHC is expected to operate for another ~ 15 y and produce ~ 100 x more data
 - Naively would lead to 10x better coupling determinations but with higher luminosities comes higher pileup \rightarrow challenging for the detectors

23 additional interactions

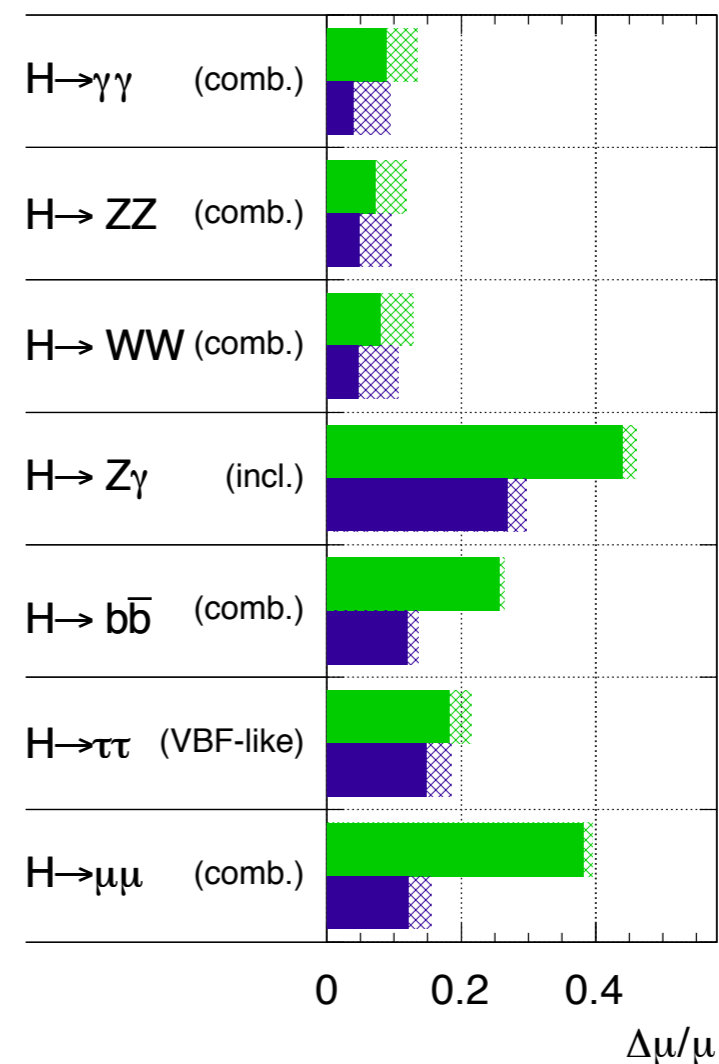


230 additional interactions



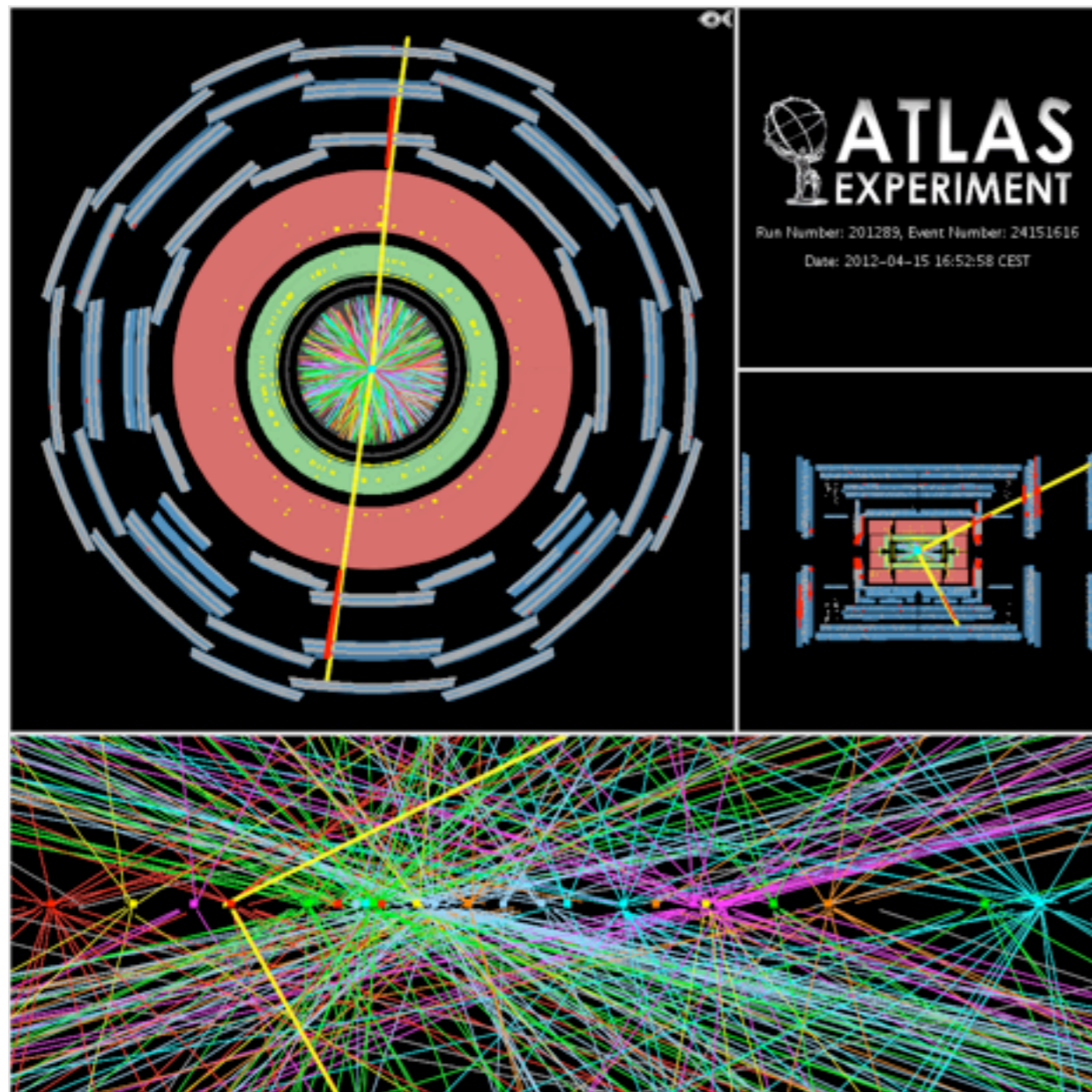
ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$

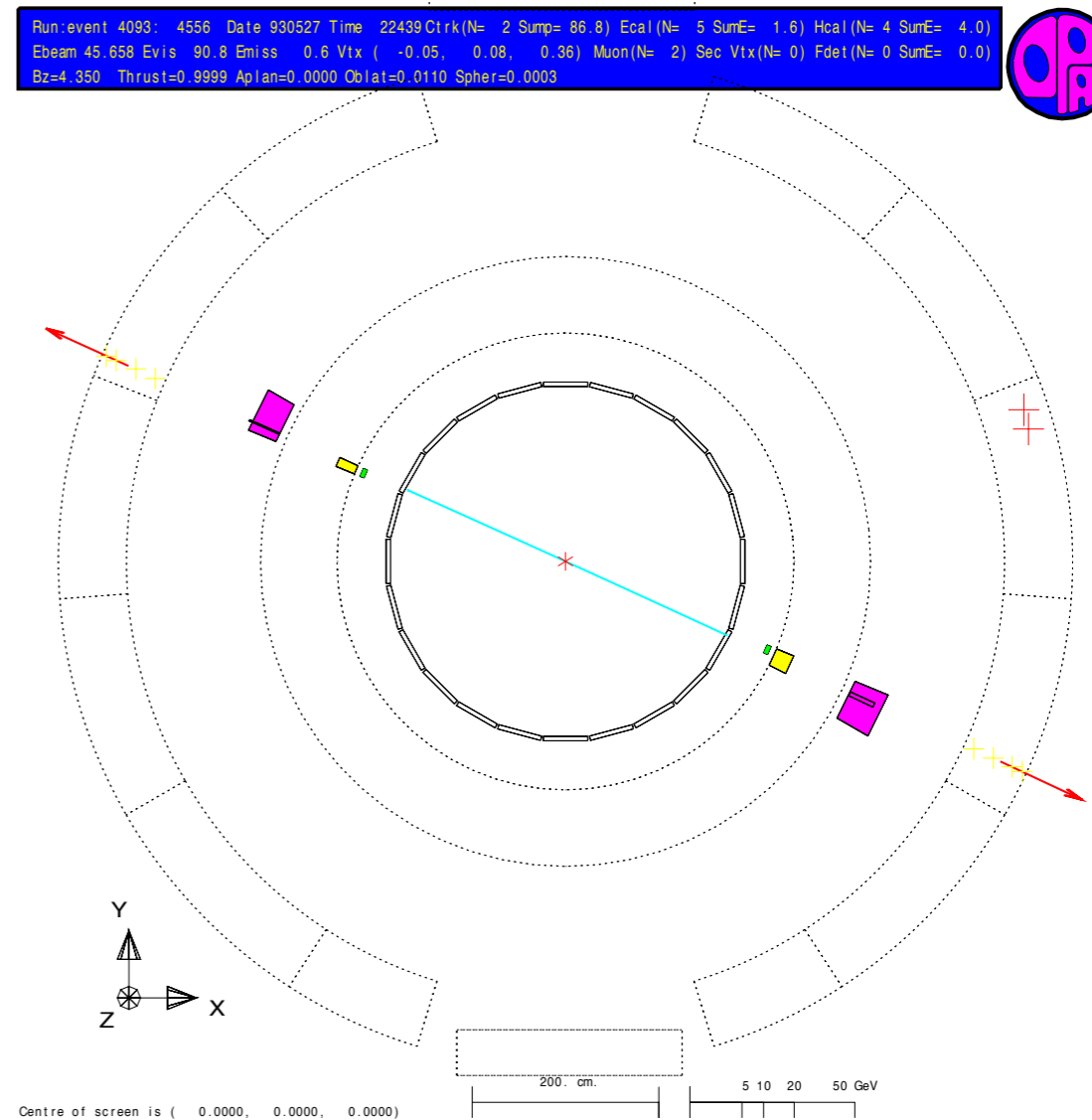


pp vs. e^+e^- colliders

$pp \rightarrow Z \rightarrow \mu\mu + \sim 25$ interactions

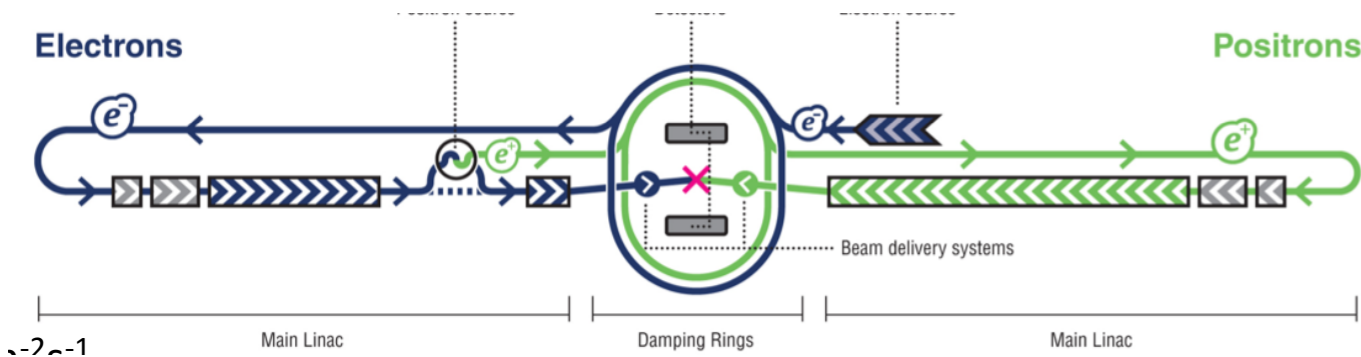


$e^+e^- \rightarrow Z \rightarrow \mu\mu$

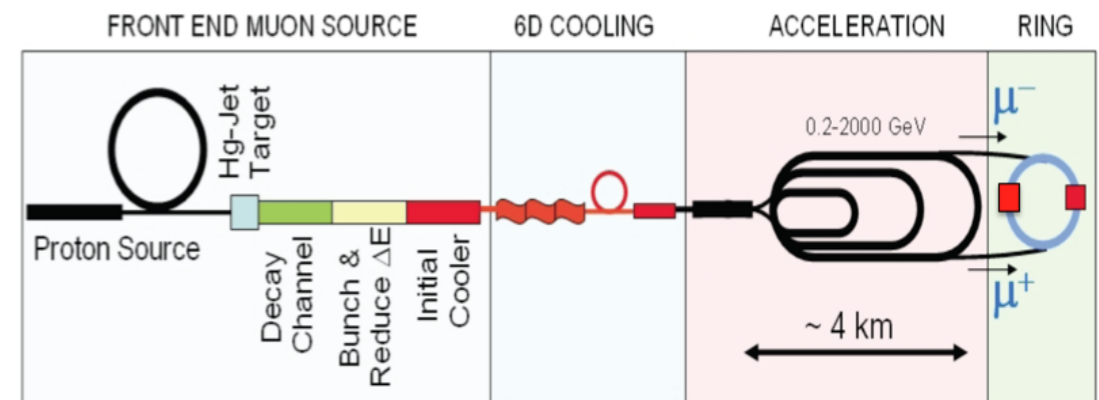


Future projects: lepton or photon colliders

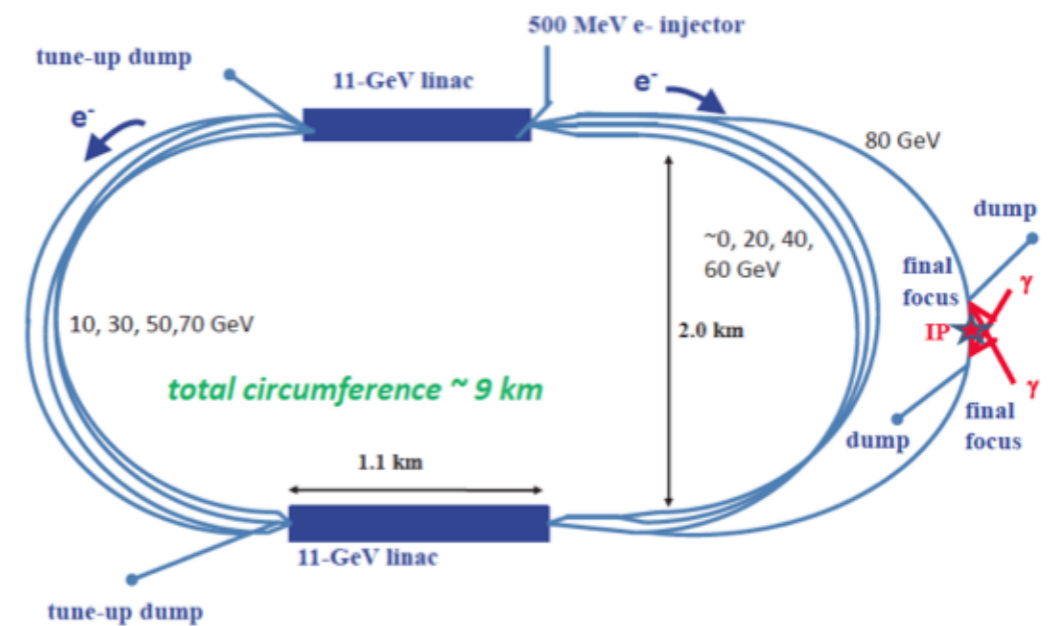
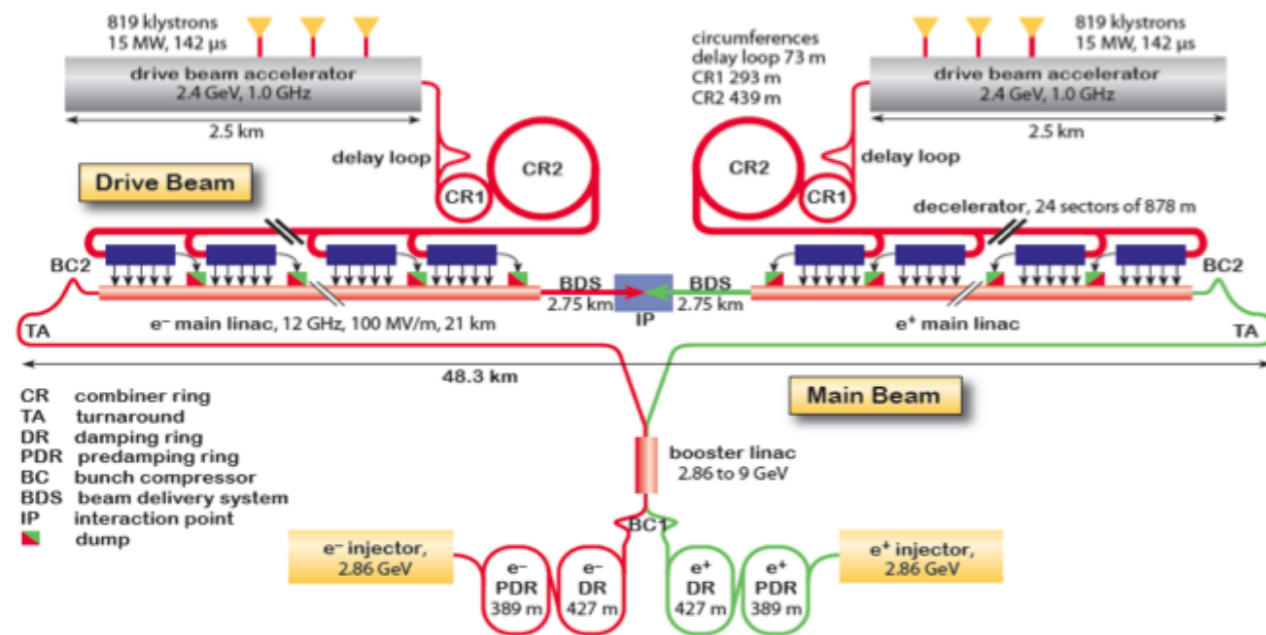
e^+e^- colliders



$\mu\mu$ collider

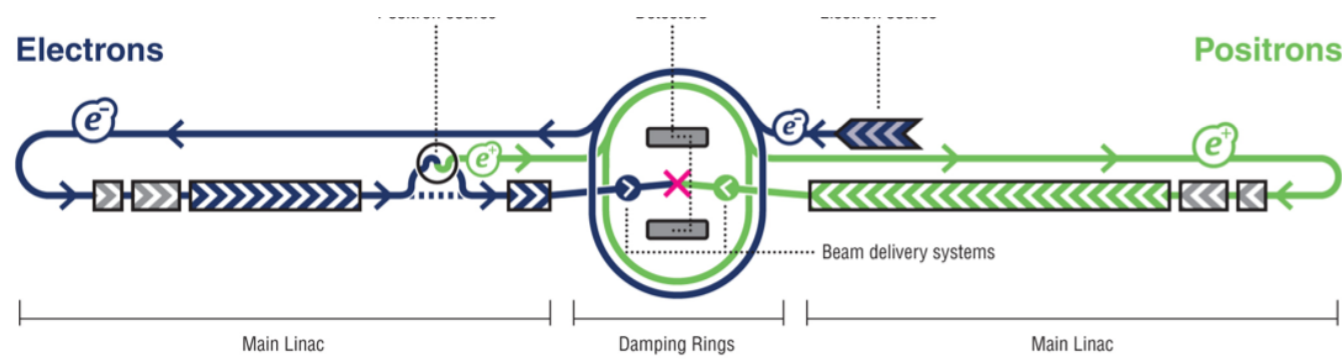


$\gamma\gamma$ collider

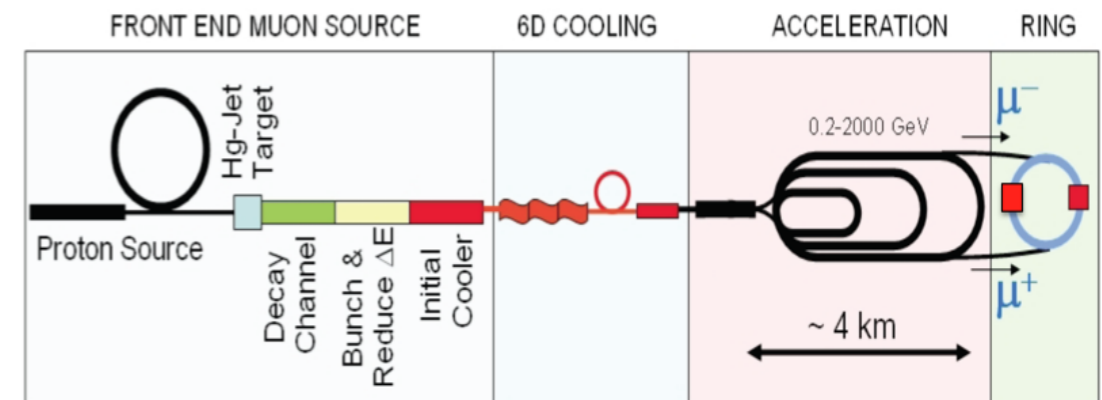


Future projects: lepton or photon colliders

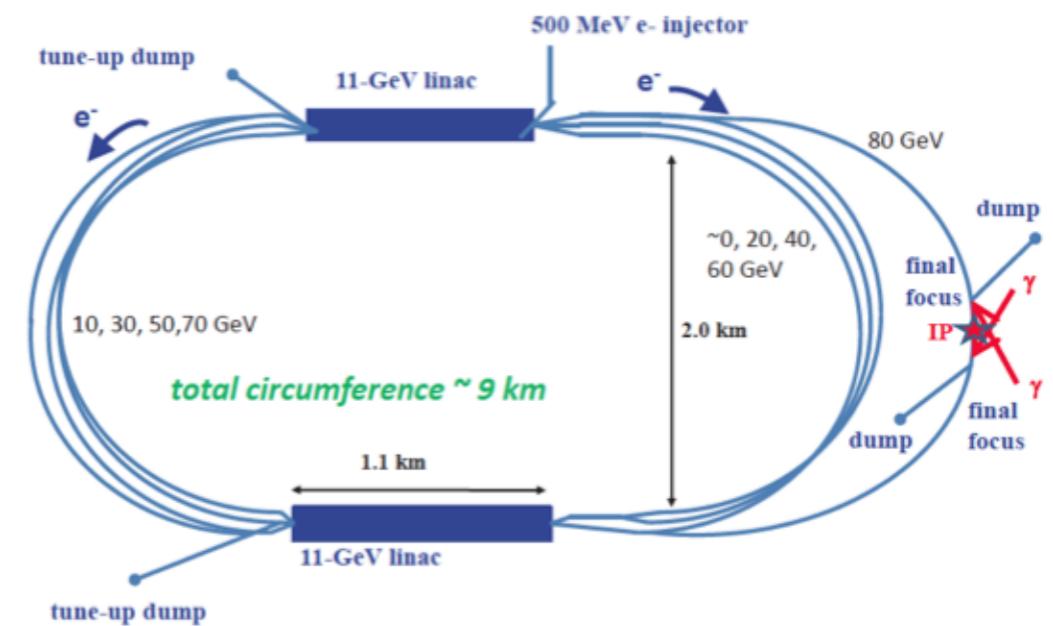
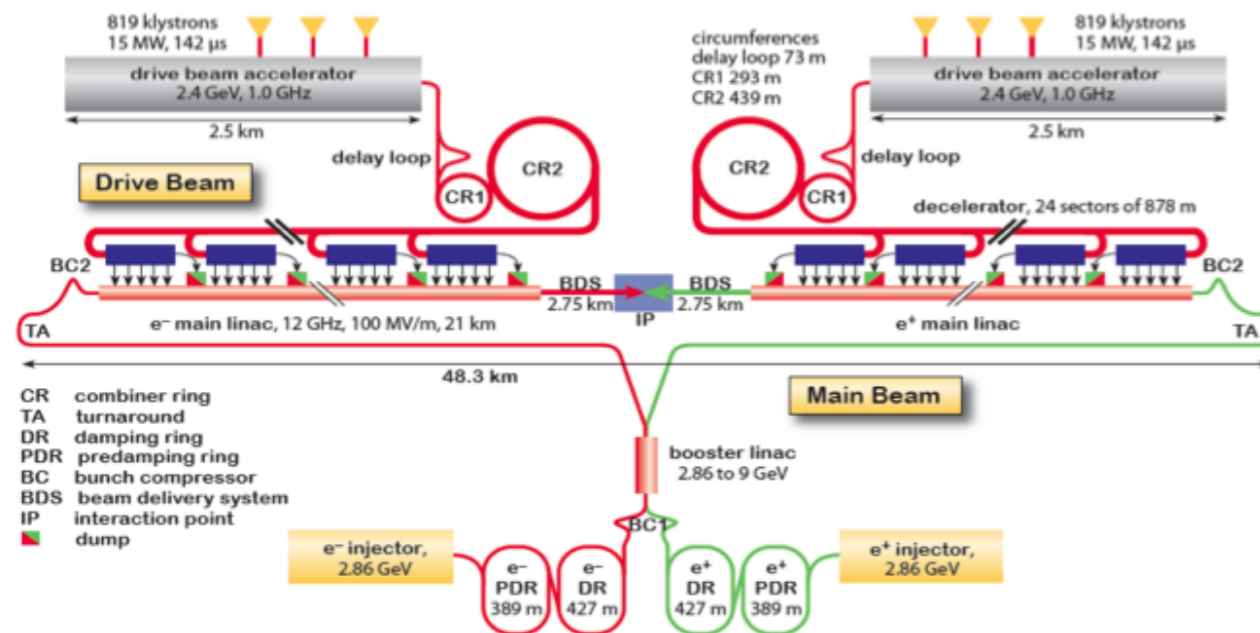
e^+e^- colliders



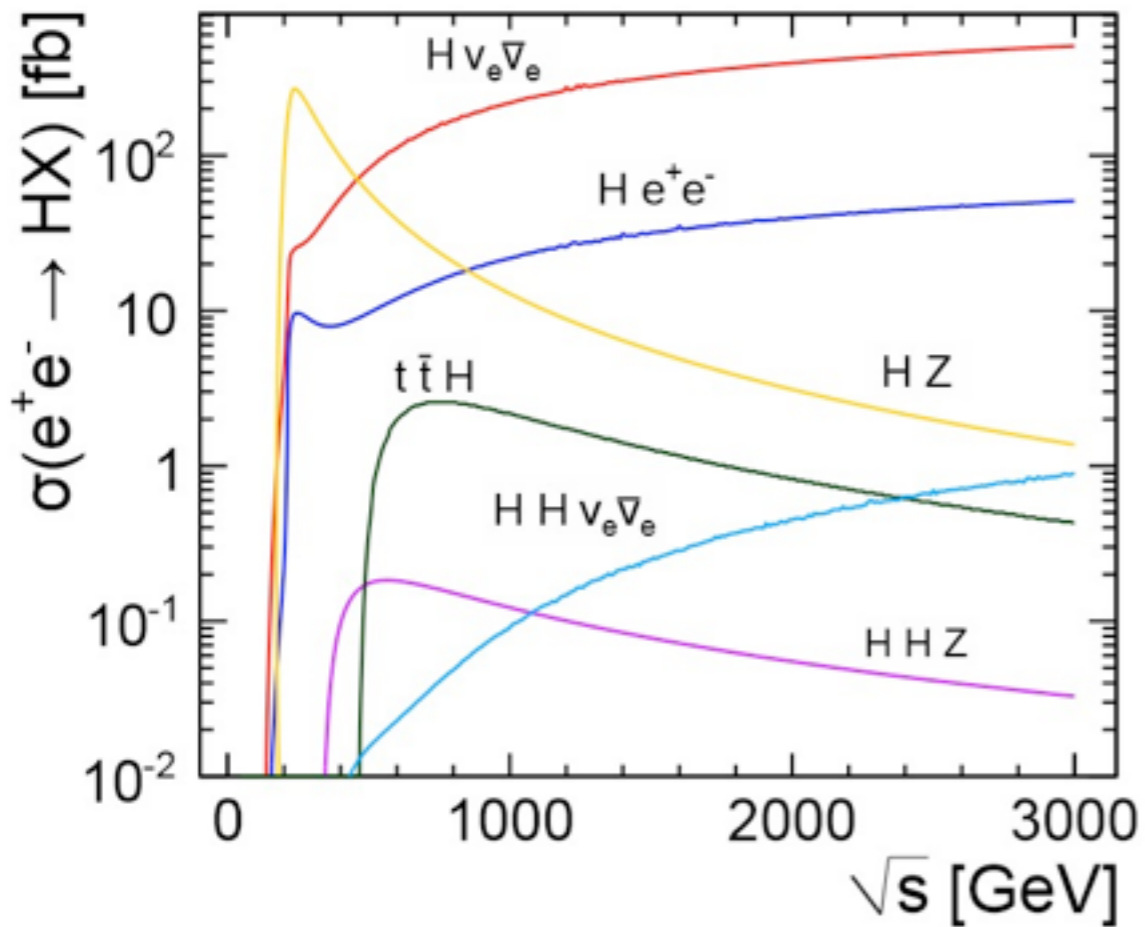
$\mu\mu$ collider



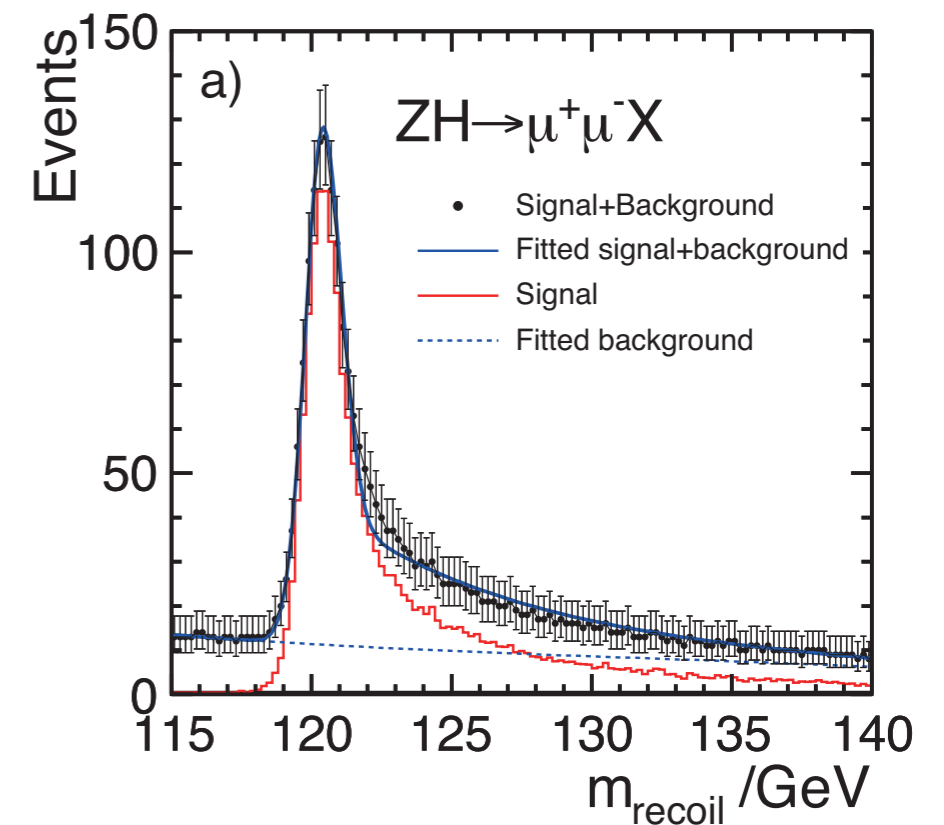
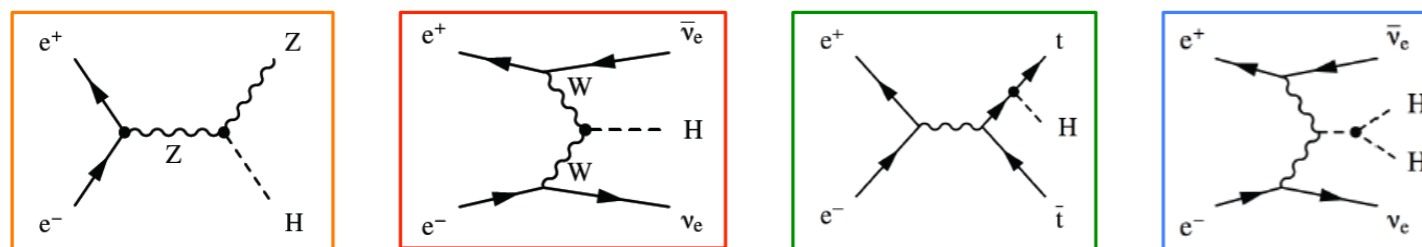
$\gamma\gamma$ collider



Higgs at e⁺e⁻ colliders



- Hadronic final states (bb, cc, gg)
- Mass measurement (40 MeV)
- Width
- ...



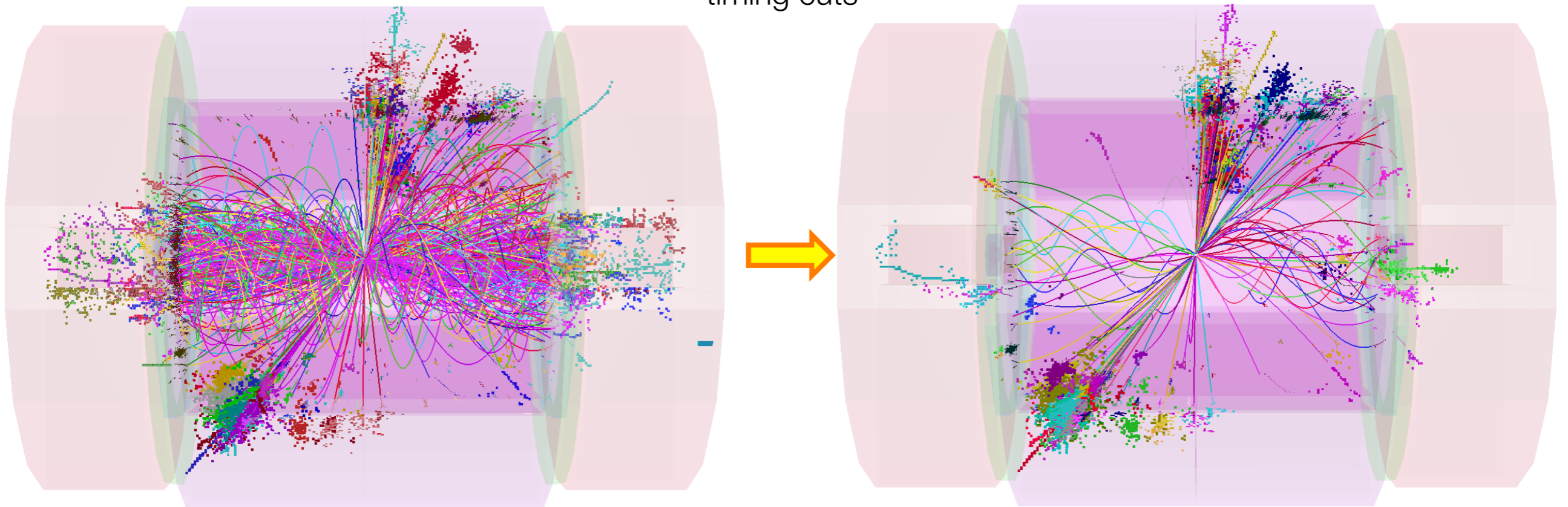
e^+e^- collision at high energies

Background energy in the detector:

1.2 TeV

100 GeV

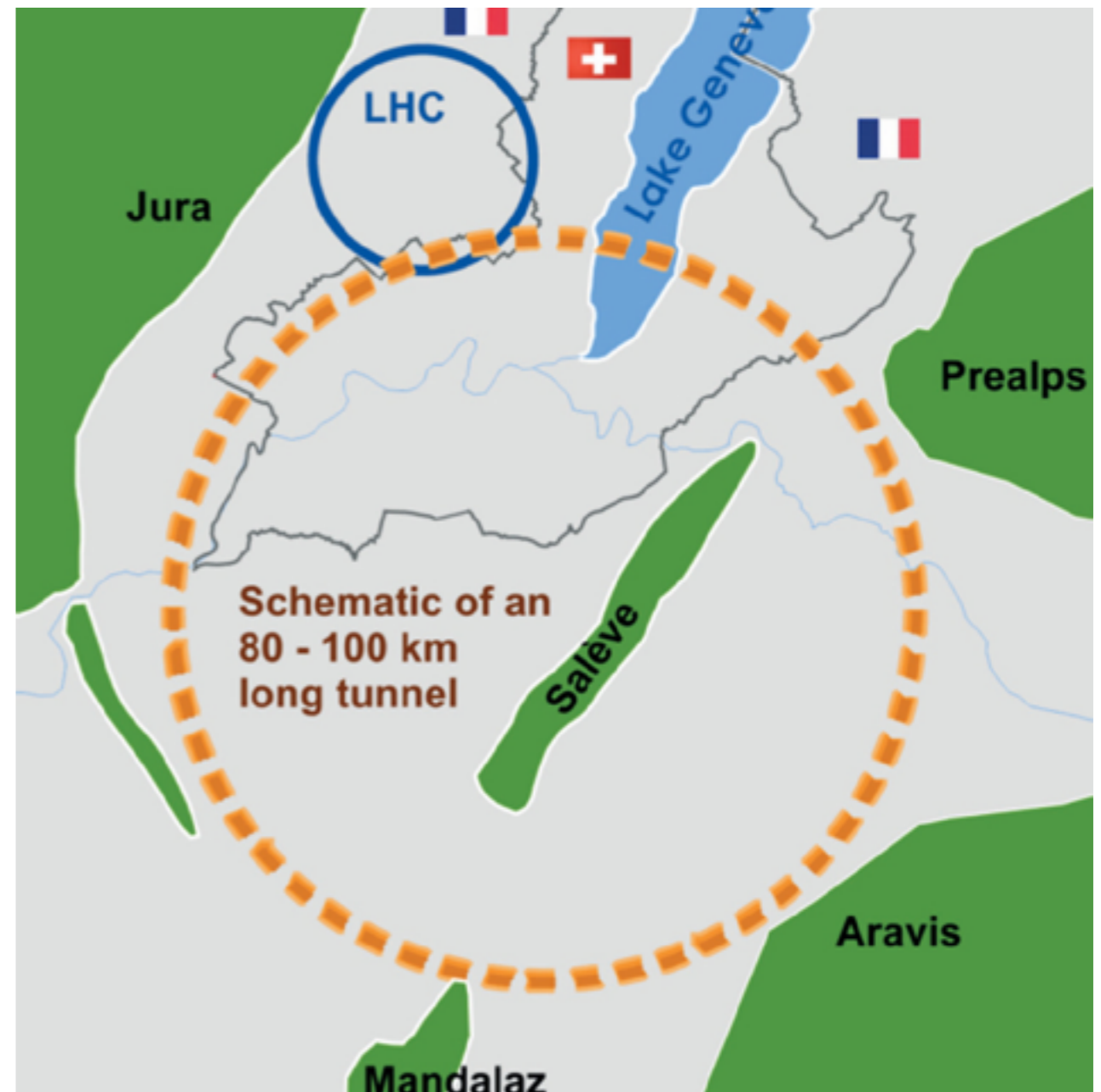
timing cuts



Not so clean anymore but manageable with fast detectors

Future circular colliders (FCC, previously TLEP, VLHC)

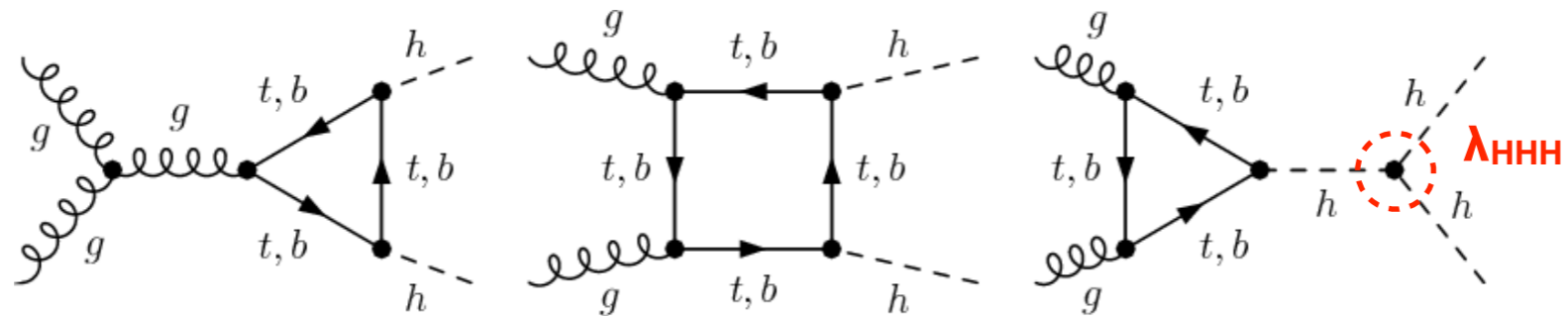
- 80 - 100 km tunnel
- 4 interaction points
- e^+e^- : $\sqrt{s} \sim 240$ and 350 GeV
 - Need top-up injection
- pp : \sqrt{s} up to 100 TeV
 - 20T magnets
- Higgs factory and increased reach for new physics
- Detailed studies of physics case starting



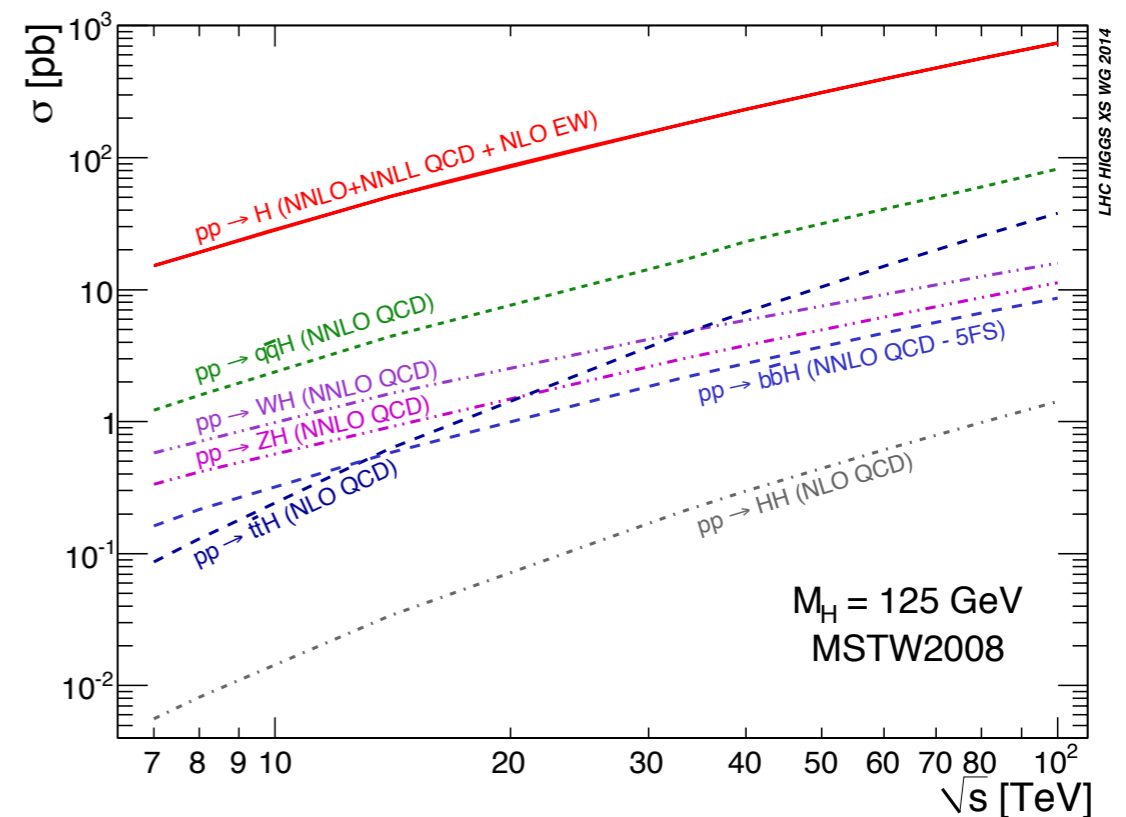
Higgs prospects at LHC and e^+e^- colliders

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
\sqrt{s} (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L} dt$ (fb $^{-1}$)	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

pp colliders: Higgs self-coupling

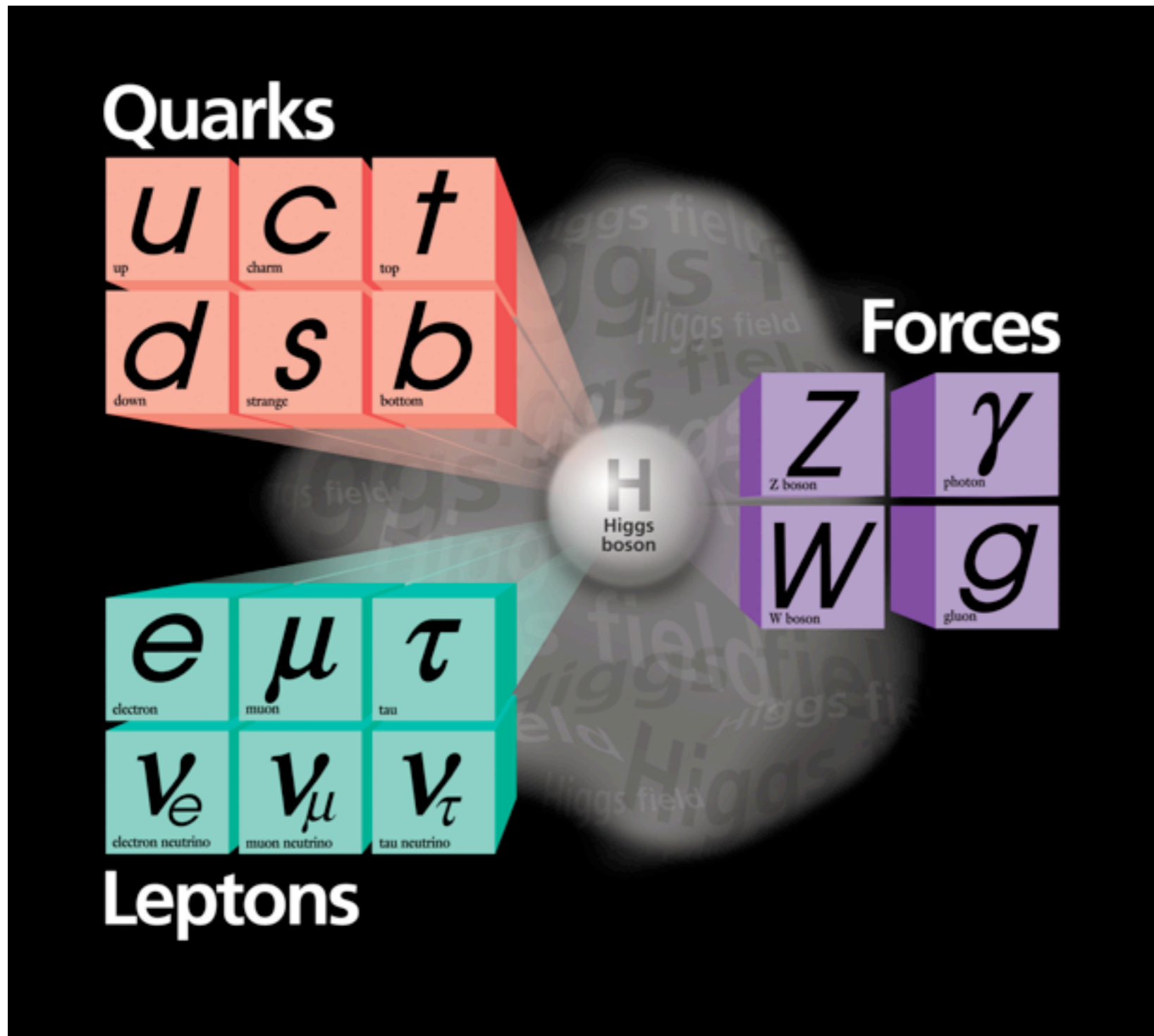


- Cross sections increase with \sqrt{s}
 - Important for HH production
 - Destructive interference between diagrams
 - Need to explore many final states: $bb\gamma\gamma$, $bb\tau\tau$, $bbWW$, ...



	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
\sqrt{s} (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L} dt$ (fb^{-1})	3000/expt	500	1600 [‡]	500+1000	1600+2500 [‡]	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

The Standard Model (SM) of particle physics



- Unifies special relativity, quantum mechanics and field theory
- Describes electroweak and strong interactions between all known particles
- BEH mechanism gives mass to W,Z bosons (+ fermions)
- Survived last decades of experimental verification
 - Higgs boson was (?) the only missing piece

100 years after the discovery of cosmic rays...

The discovery of the Higgs boson completes the Standard Model

It is a triumph for the imagination and rigour of the human mind

It is a triumph for the greatest experimental undertaking ever:

Frontier of accelerator & detector technologies

Global data sharing, analysis & collaboration