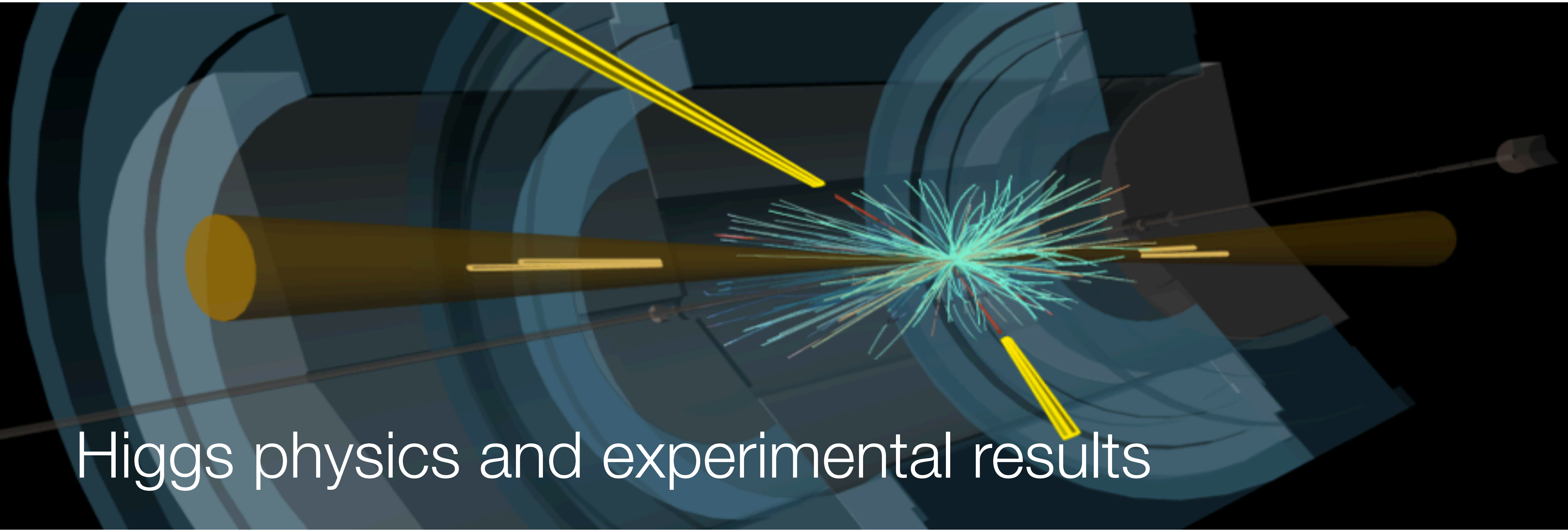


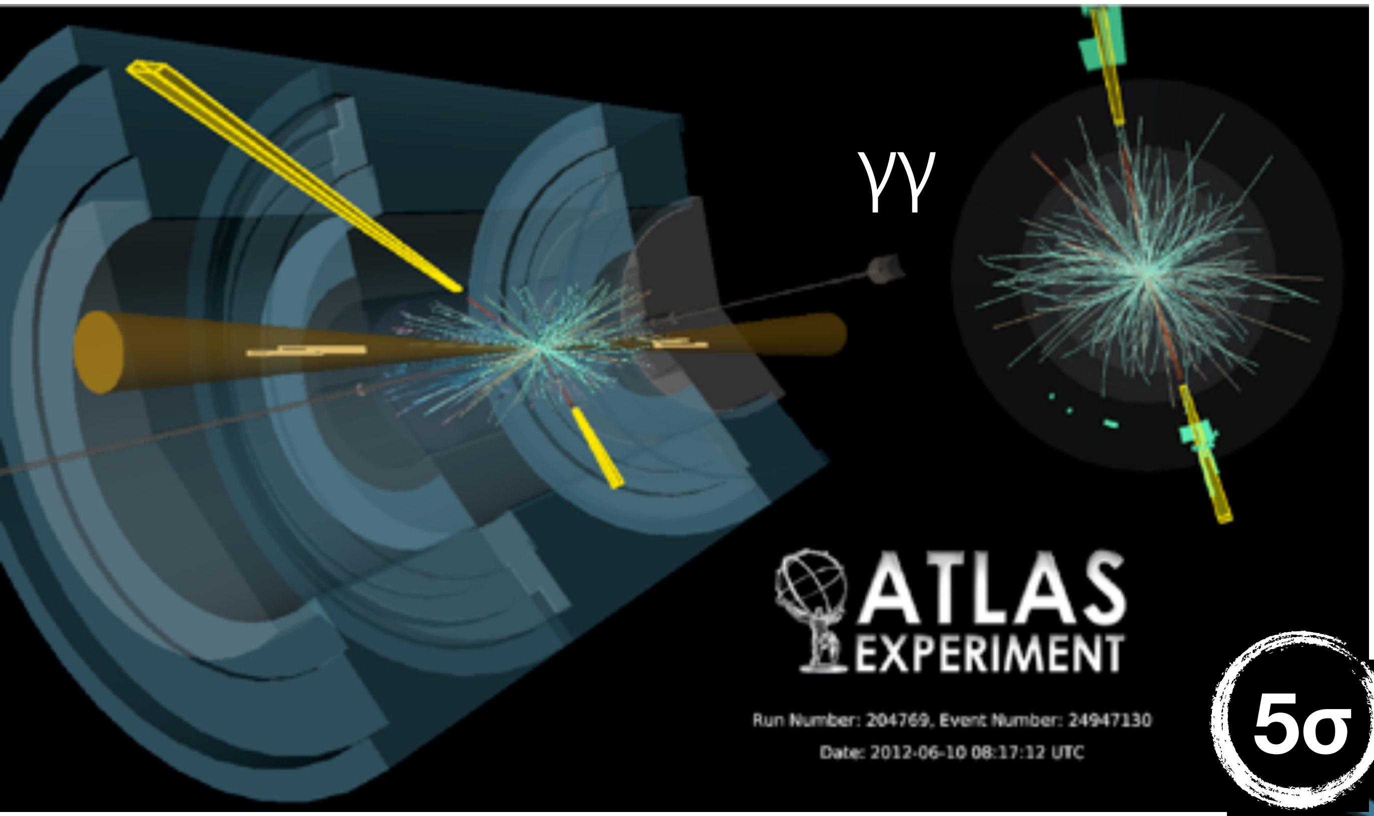
Higgs physics and experimental results

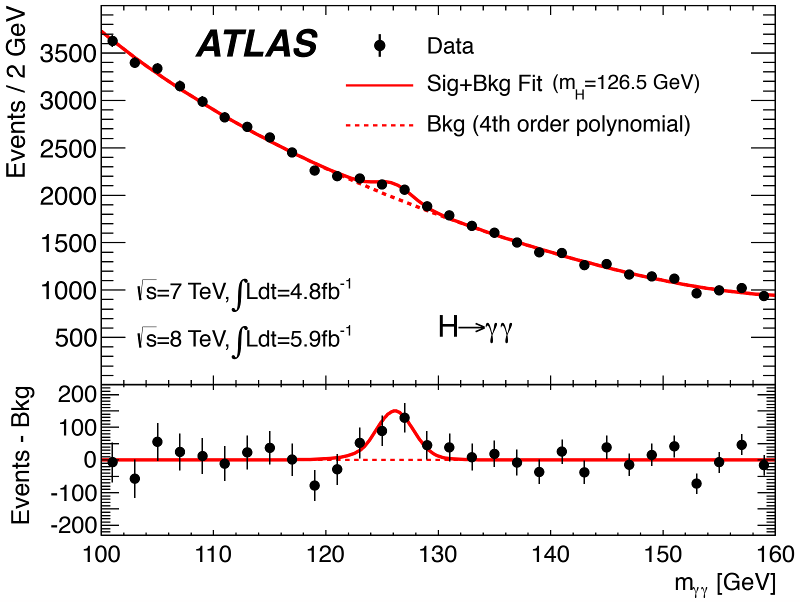
Bruno Lenzi

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

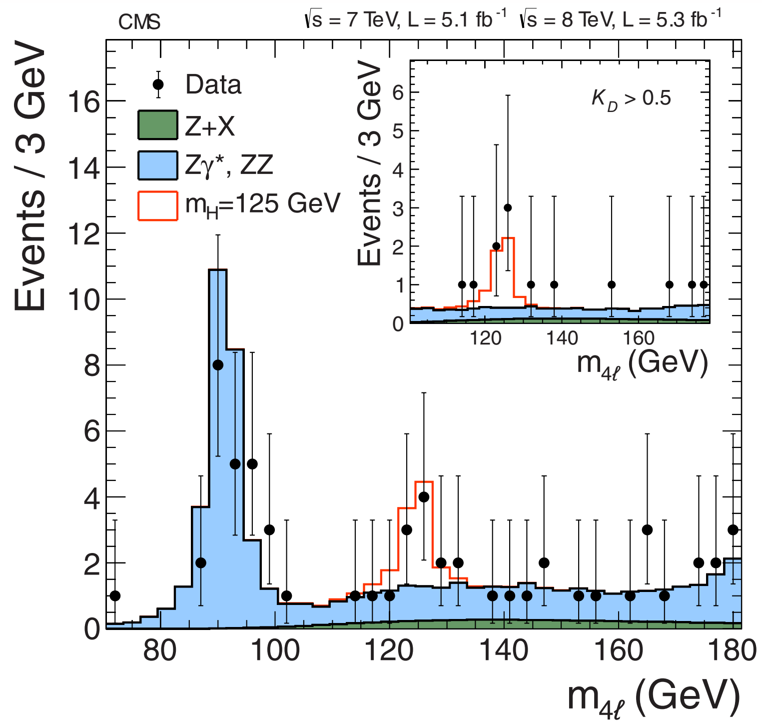
25/10/2014

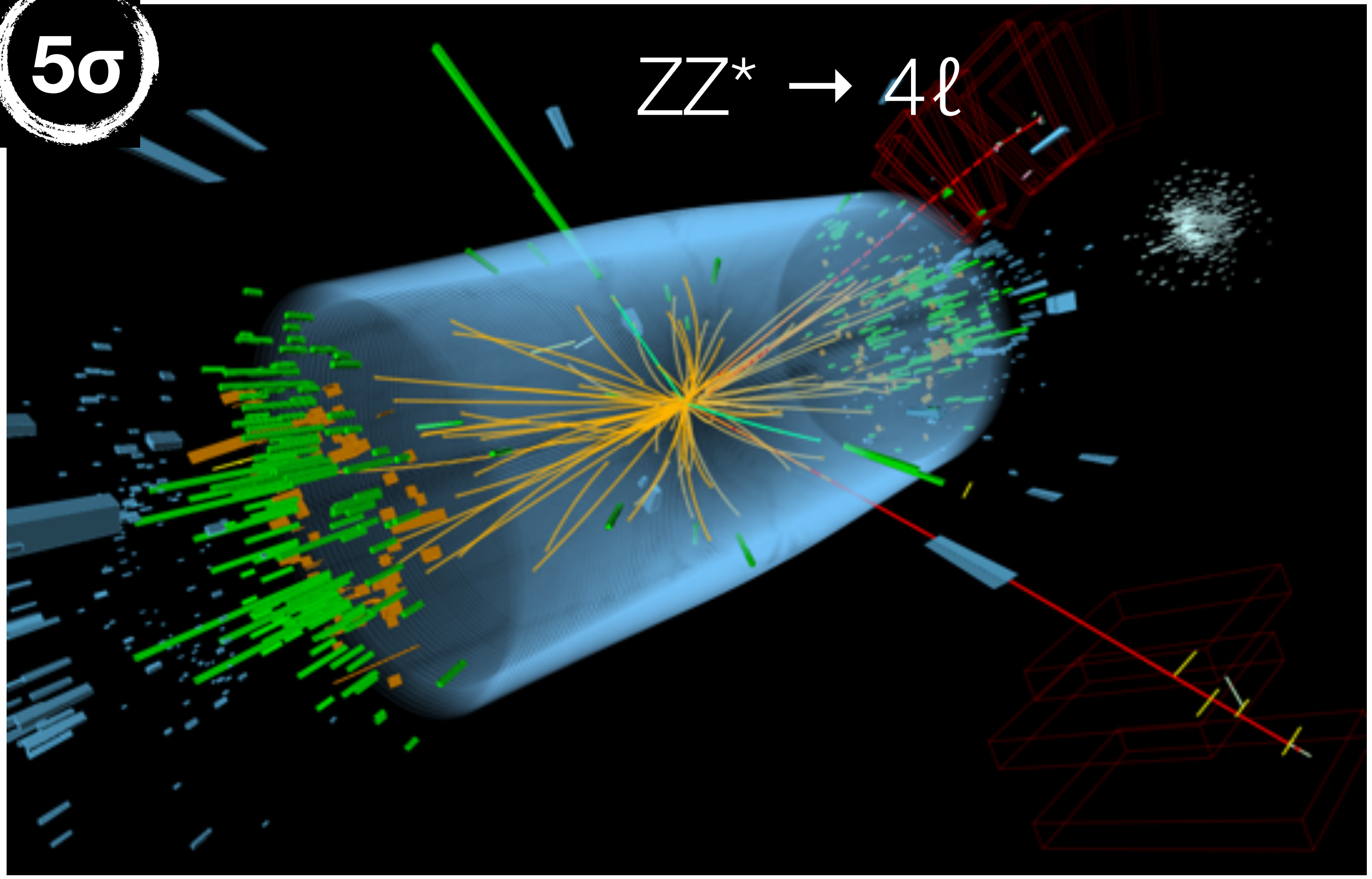
The new particle





5σ





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  - Its vacuum expectation value is responsible for EW symmetry breaking

Spin analyses

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

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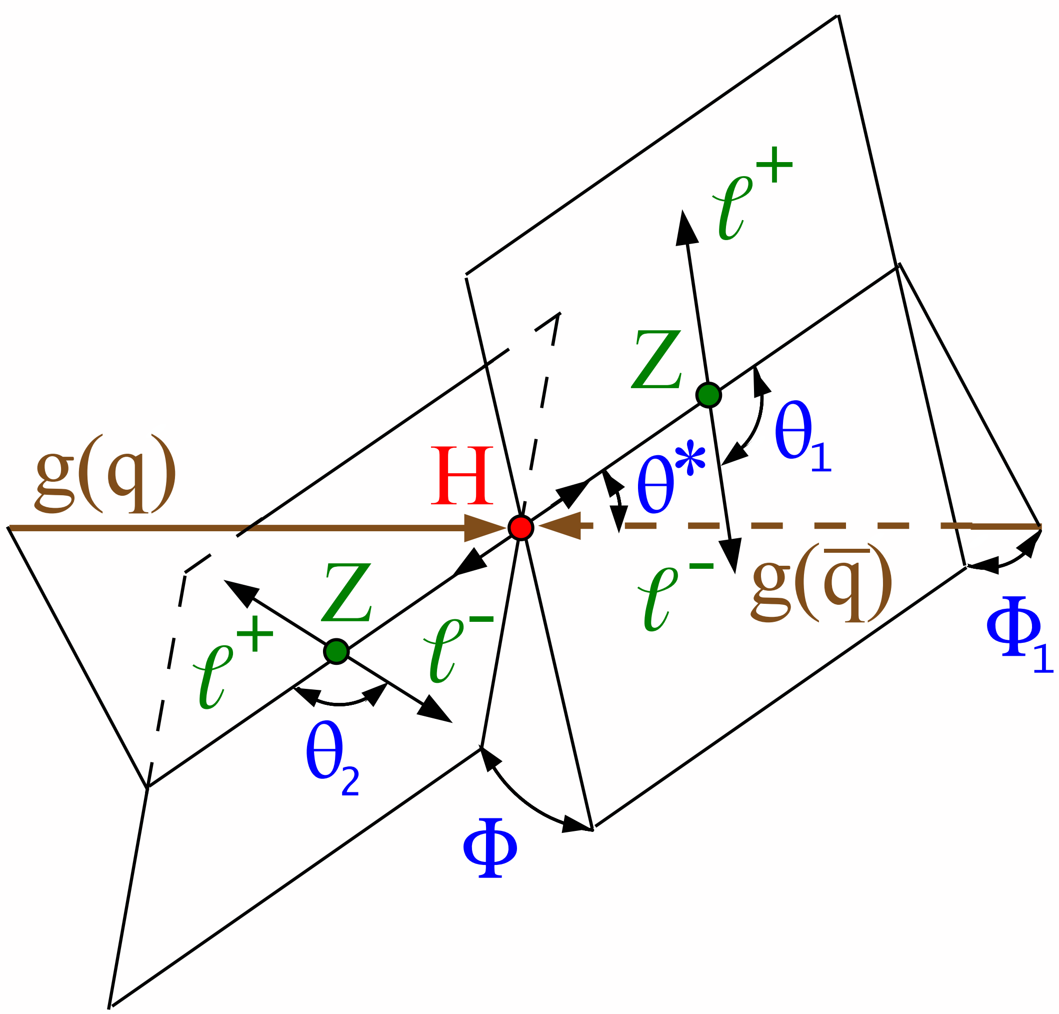
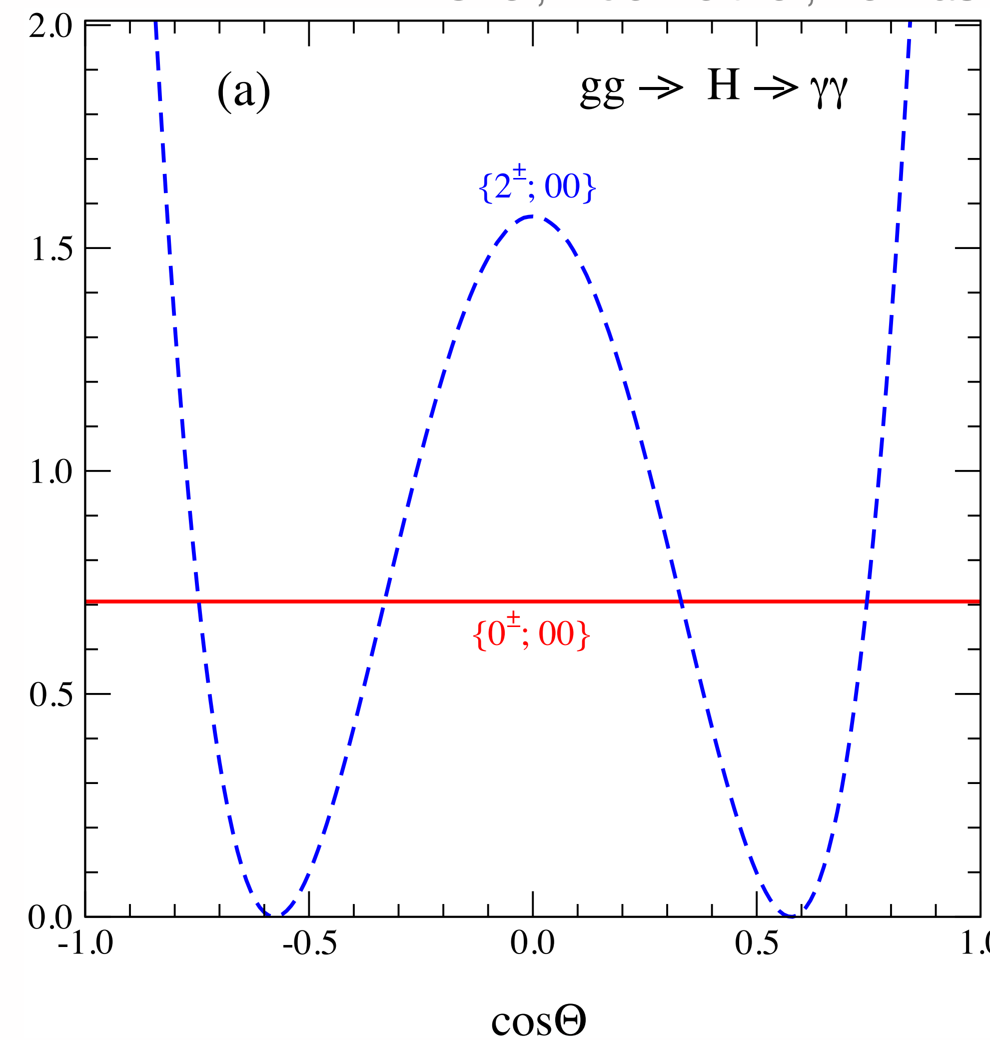
Be prepared for the unexpected!

Spin analyses

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



Choi, Muehlleitner, Zerwas



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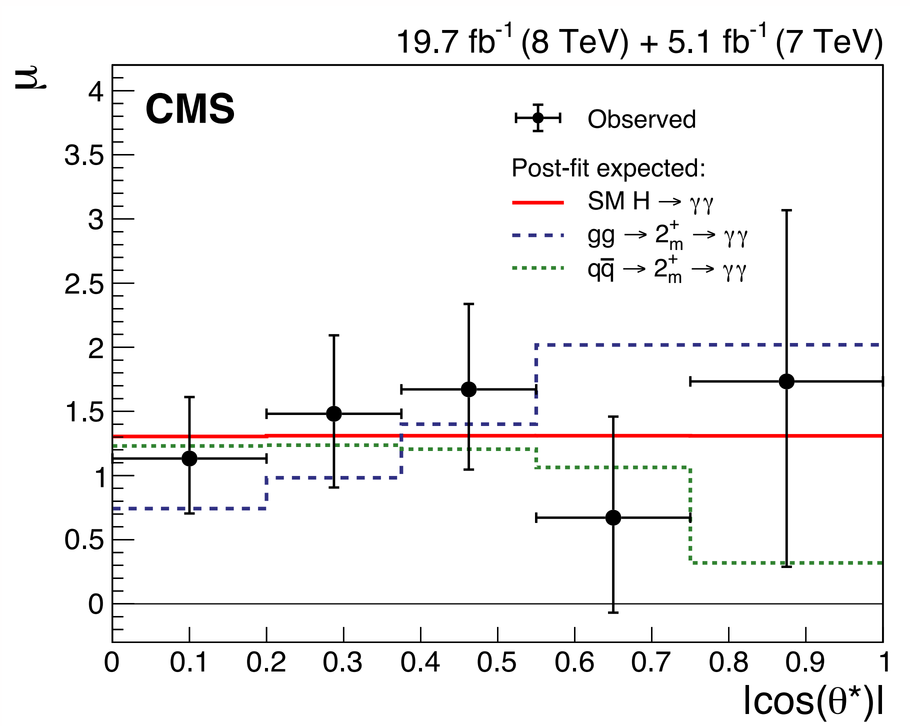
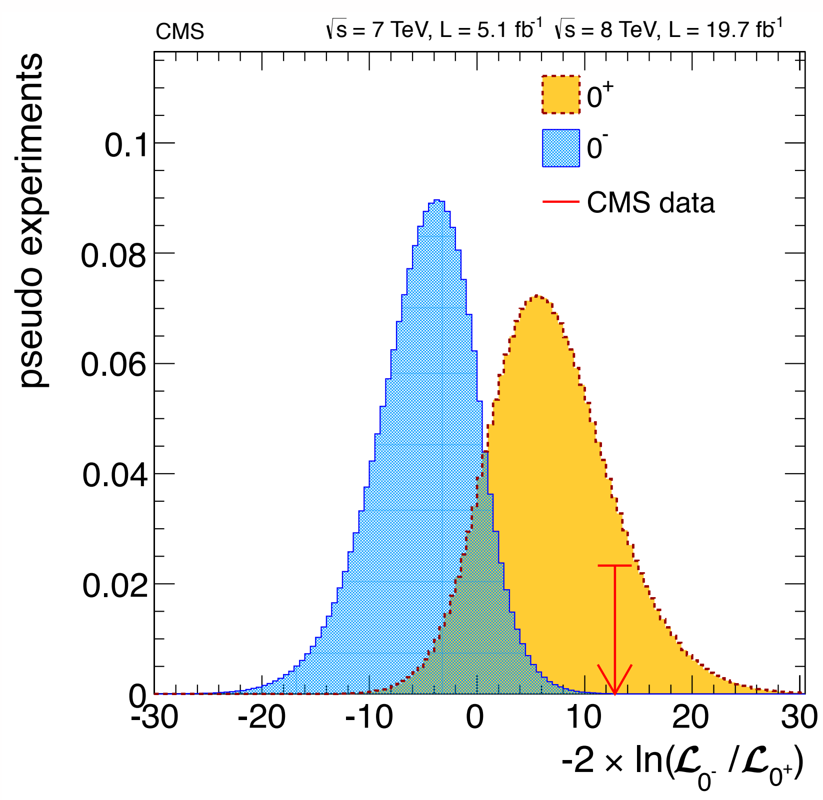
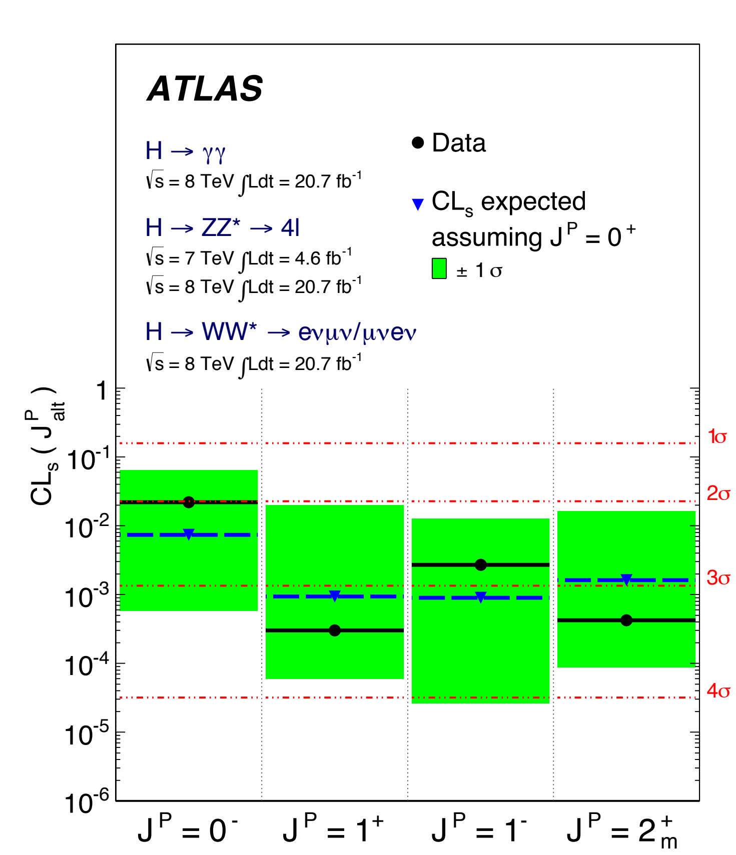






0+ strongly favored, others excluded at > 99% CL

The new particle

[Michelangelo Mangano]

- 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 γγ (and Zγ)

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

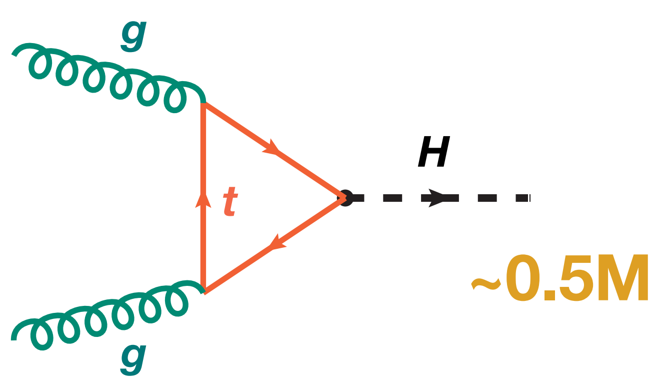
The new particle

- 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 γγ (and Zγ)
- 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

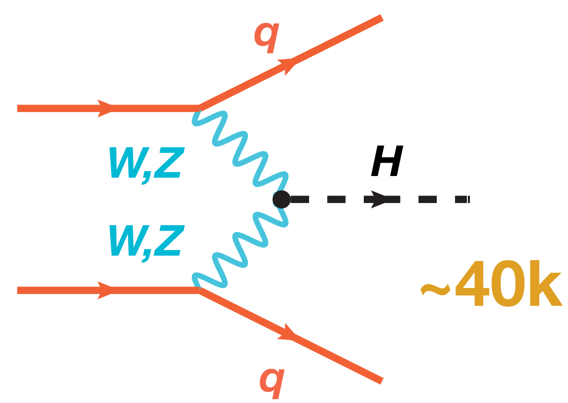
The SM Higgs boson at the LHC

Production mechanisms (events produced)

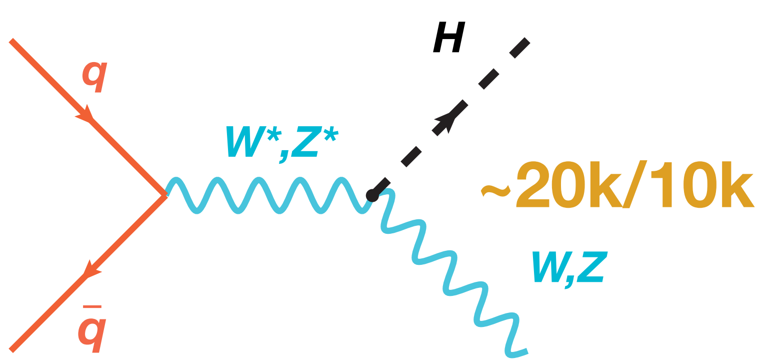
Gluon-fusion



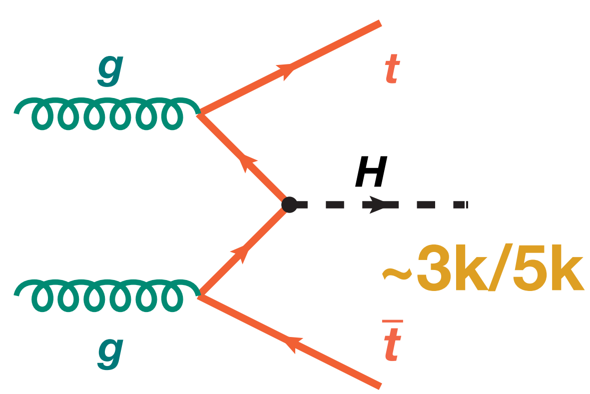
Vector boson fusion (VBF)



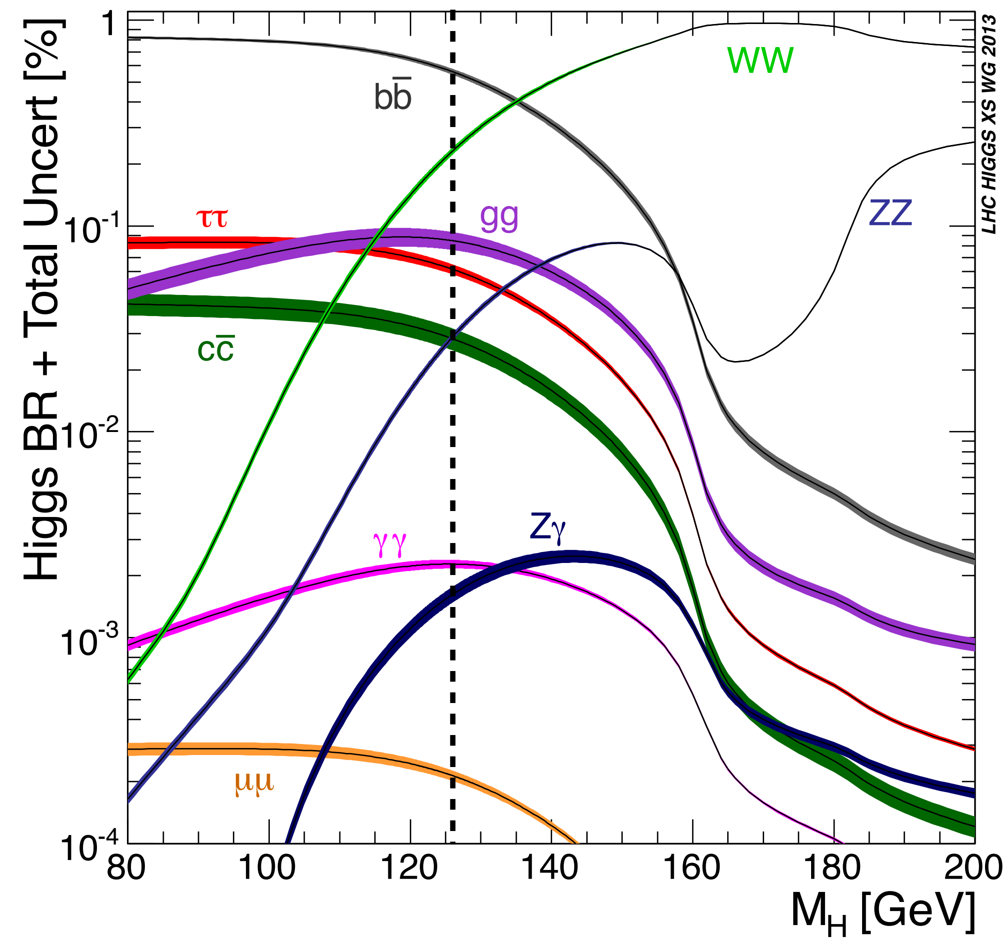
Associated with W / Z



Associated with tt (or bb)

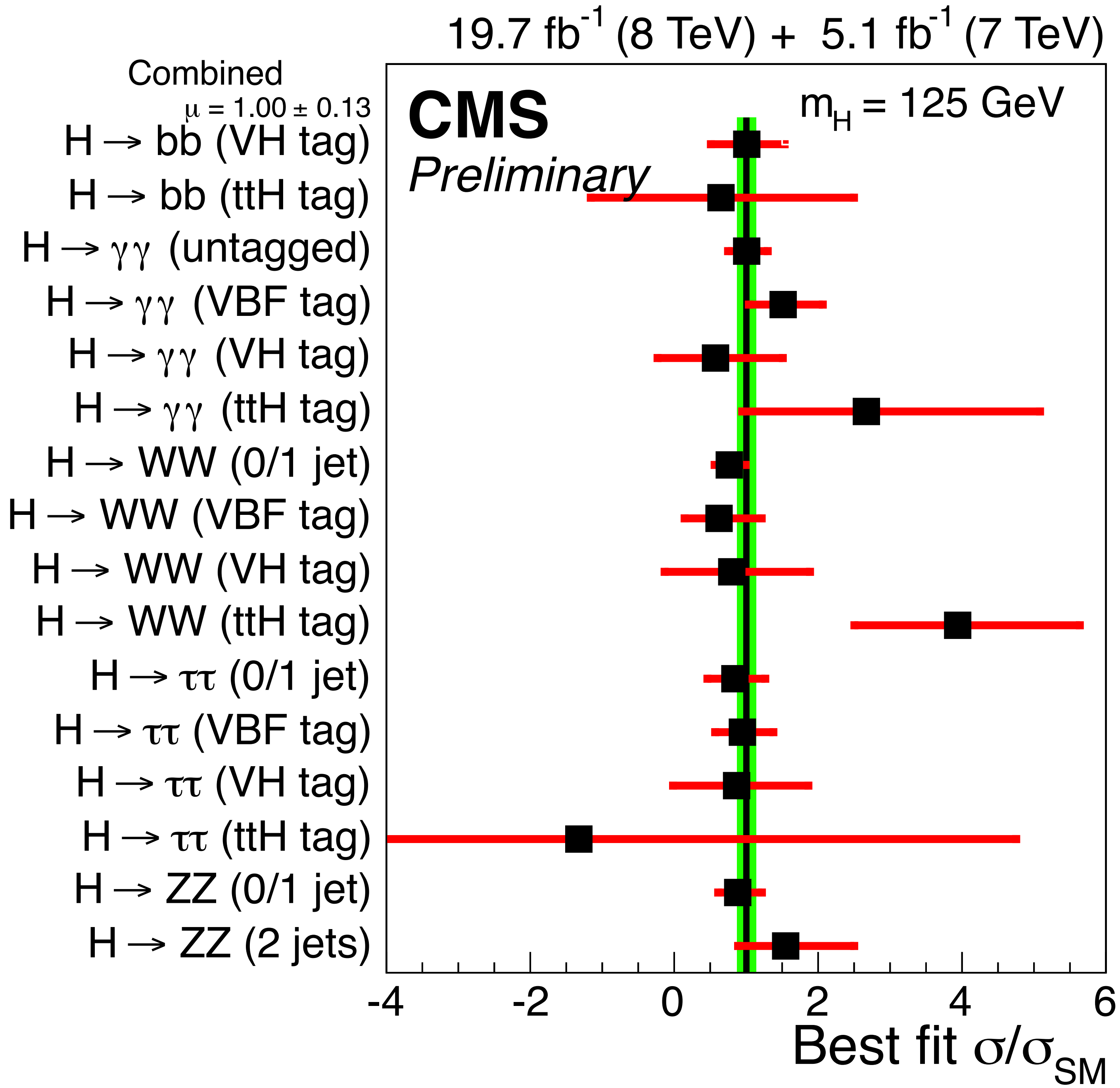


Decay modes



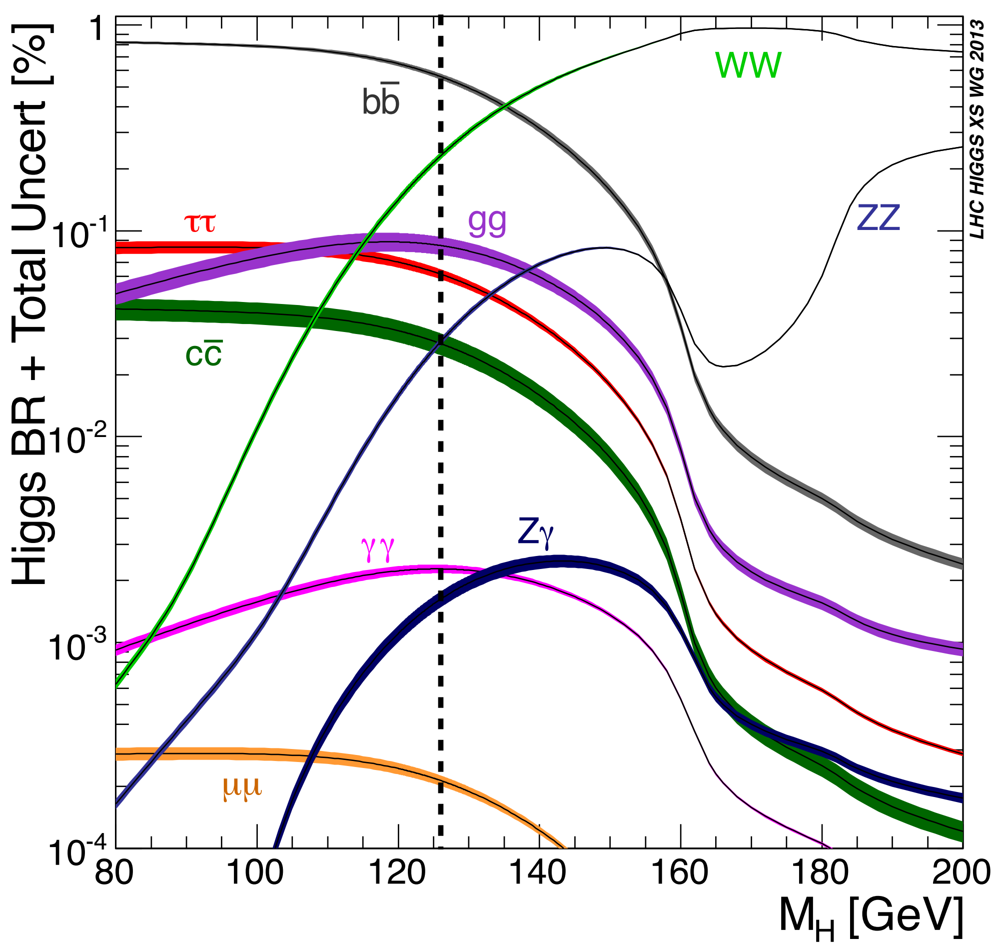
- Main channels (bosonic): H → γγ, H → ZZ* → 4ℓ, H → WW* → ℓνℓν
- Fermionic modes (associated production): (VBF) H → ττ, (W/Z) H → bb
- Rare decays: H → Zγ, H → μμ

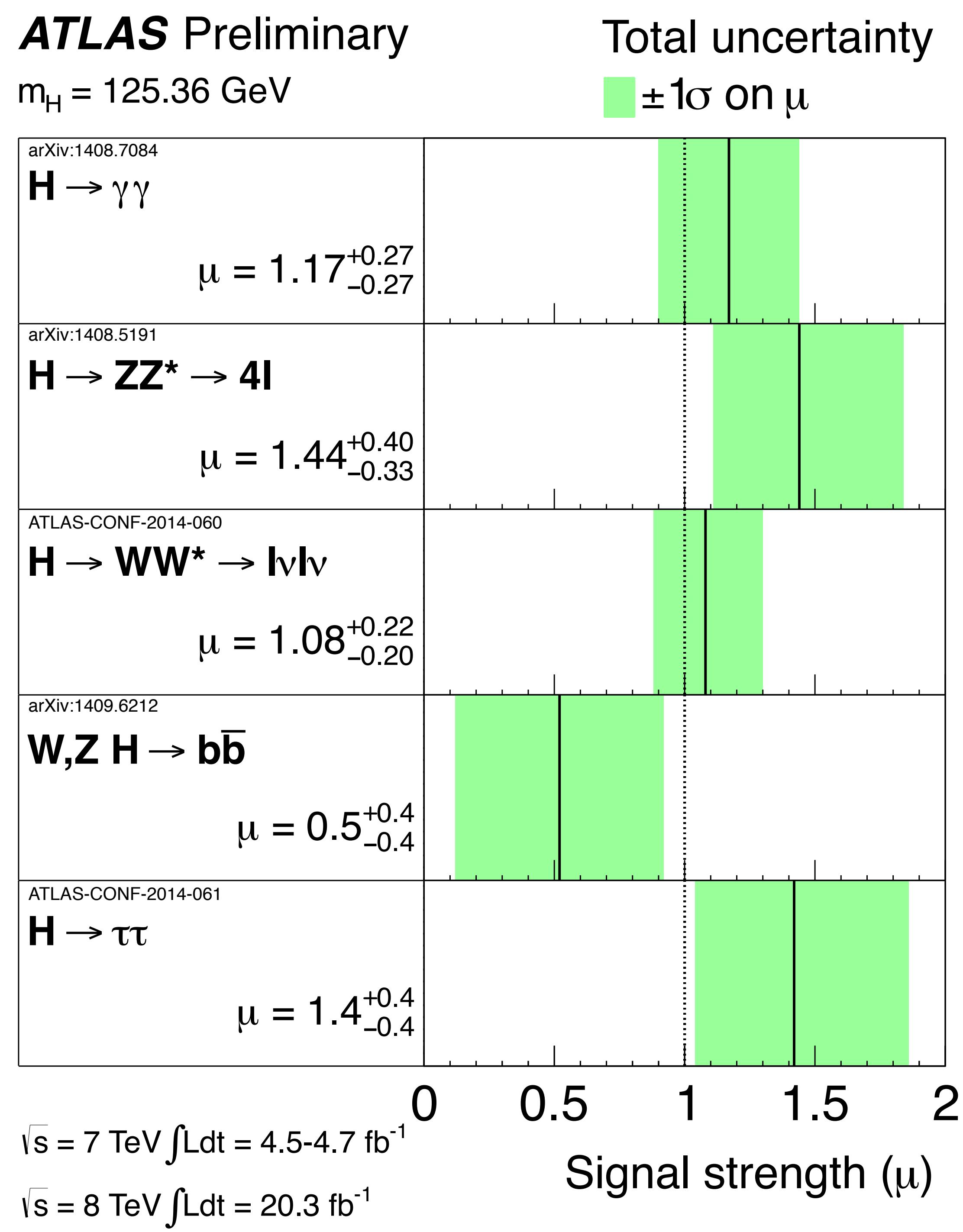
Higgs boson results: production / decays (CMS)



Higgs boson results: decays (ATLAS)

Decay modes





> 5σ

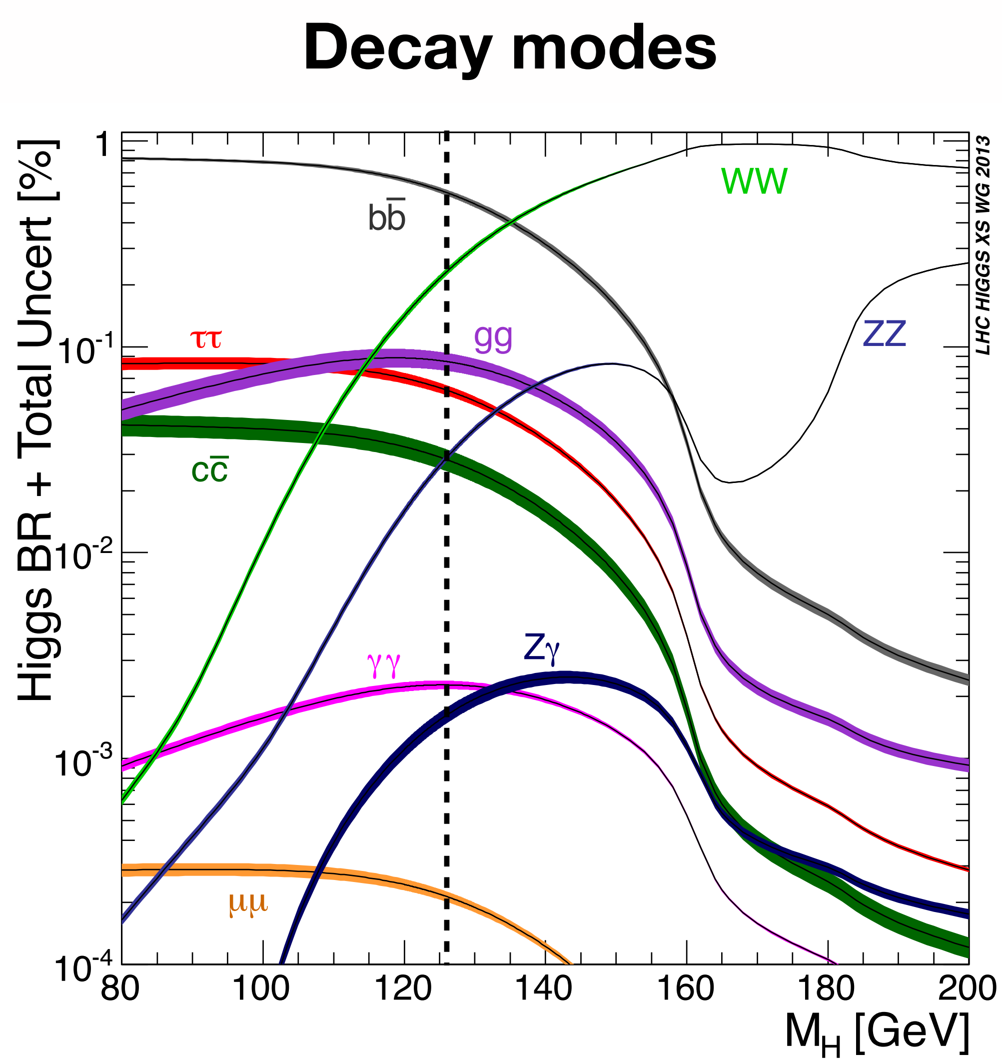
> 5σ

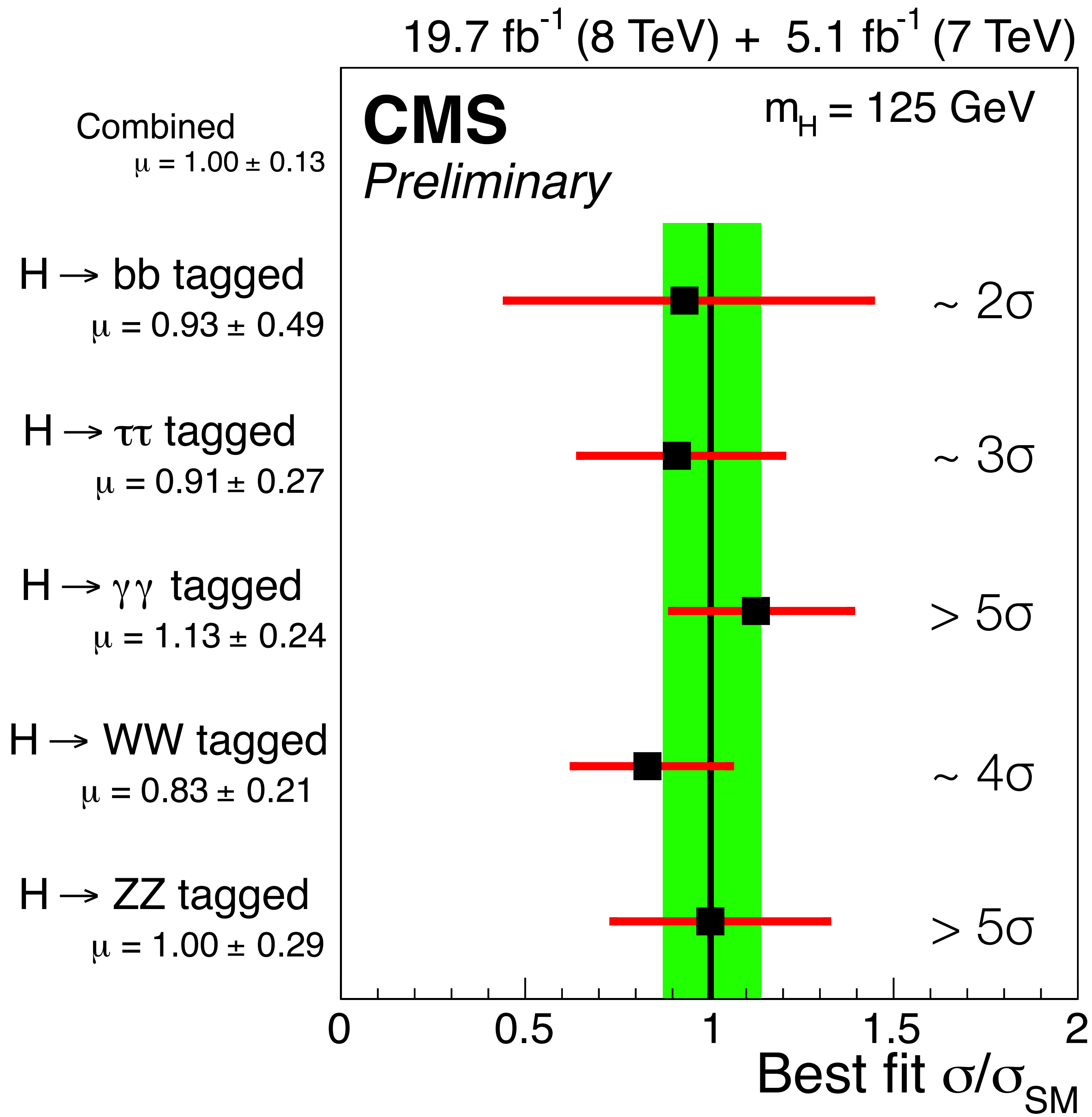
> 5σ

1.5σ

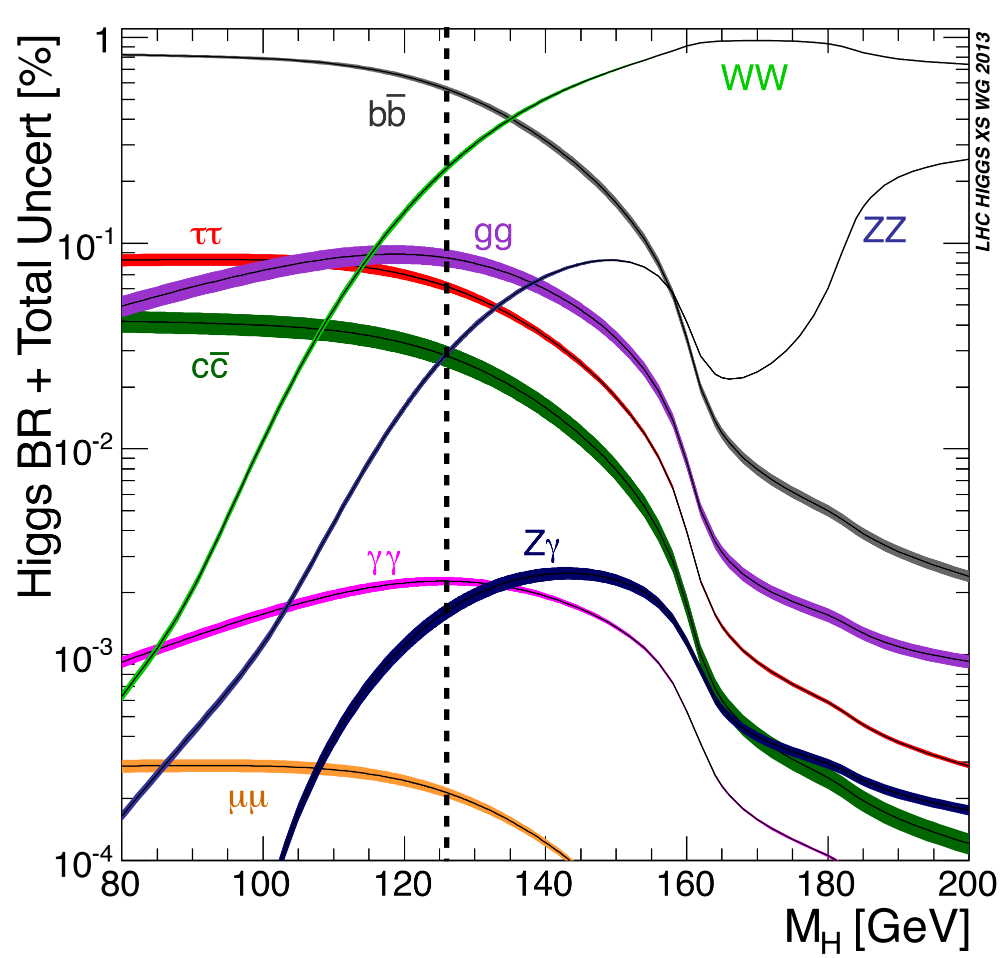
~4σ

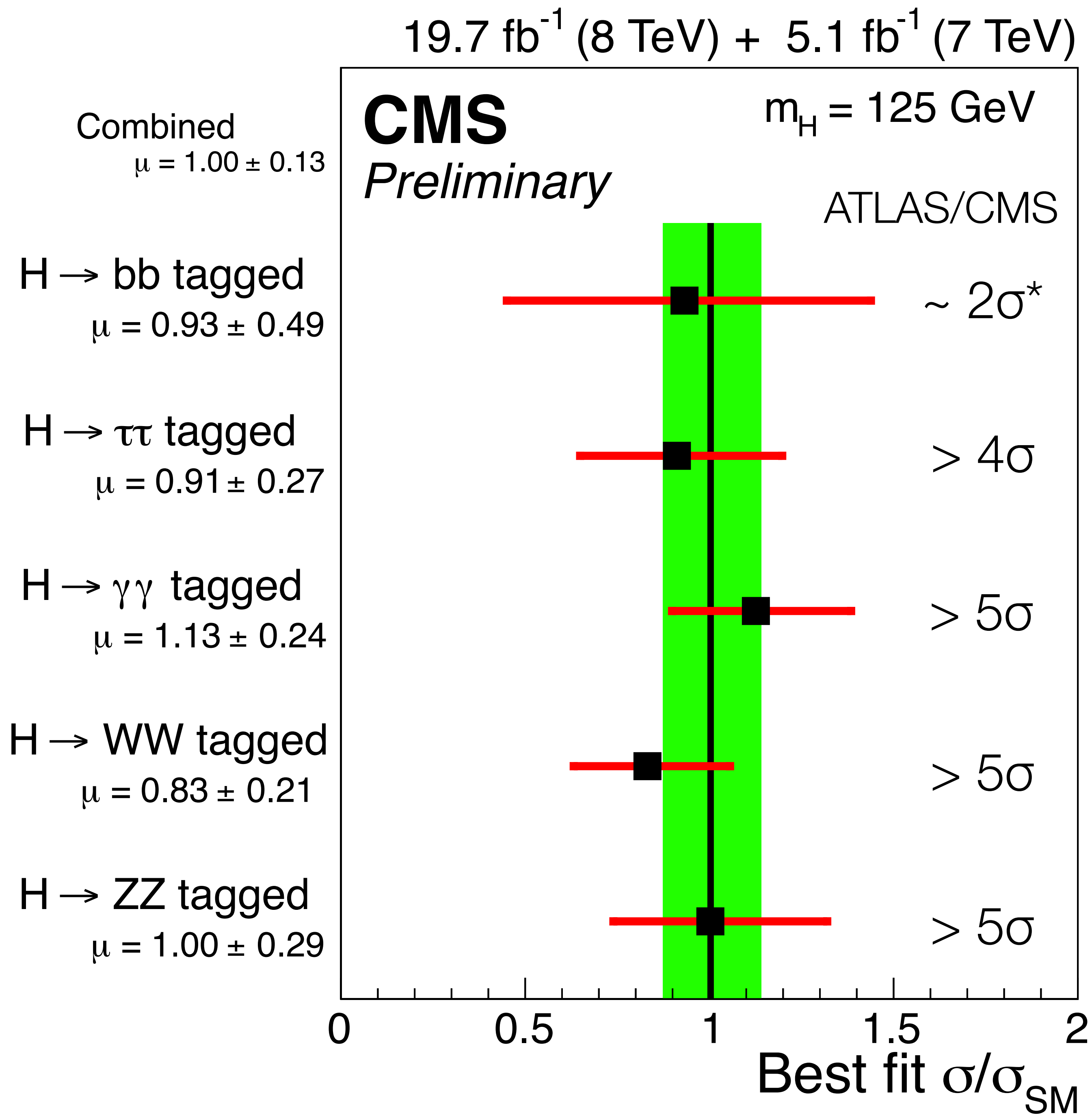
Higgs boson results: decays (CMS)





Higgs boson results: decays (ATLAS / CMS)



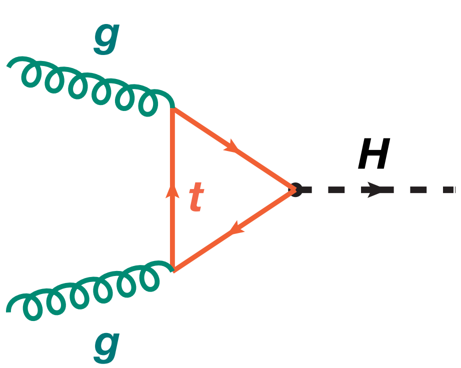


* 3σ at Tevatron

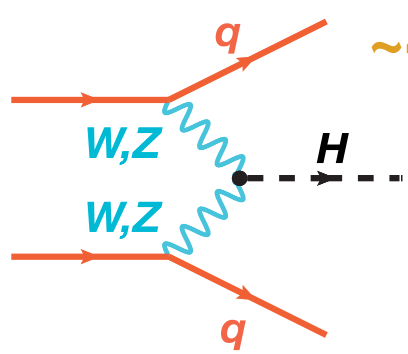
The SM Higgs boson at the LHC

Production mechanisms (events produced)

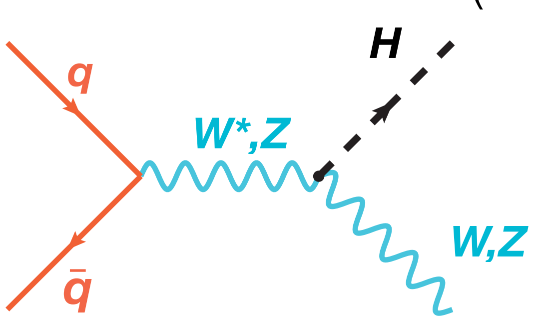
Gluon-fusion ~0.5M



Vector boson fusion (VBF) ~40k

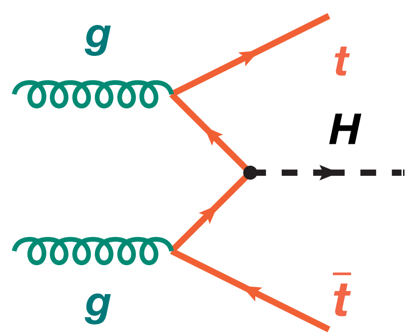


Associated with W / Z (VH)

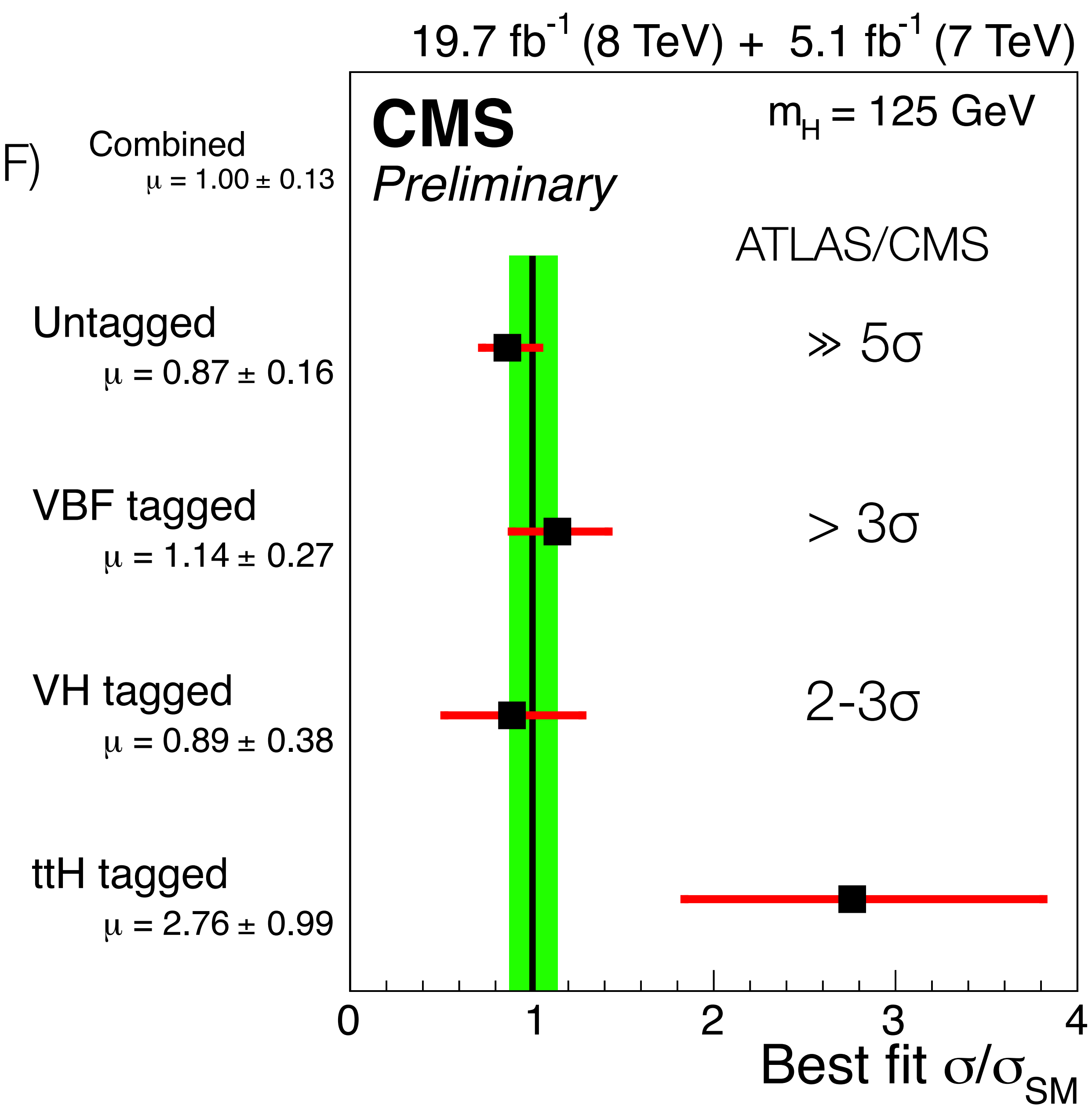


~20k/10k

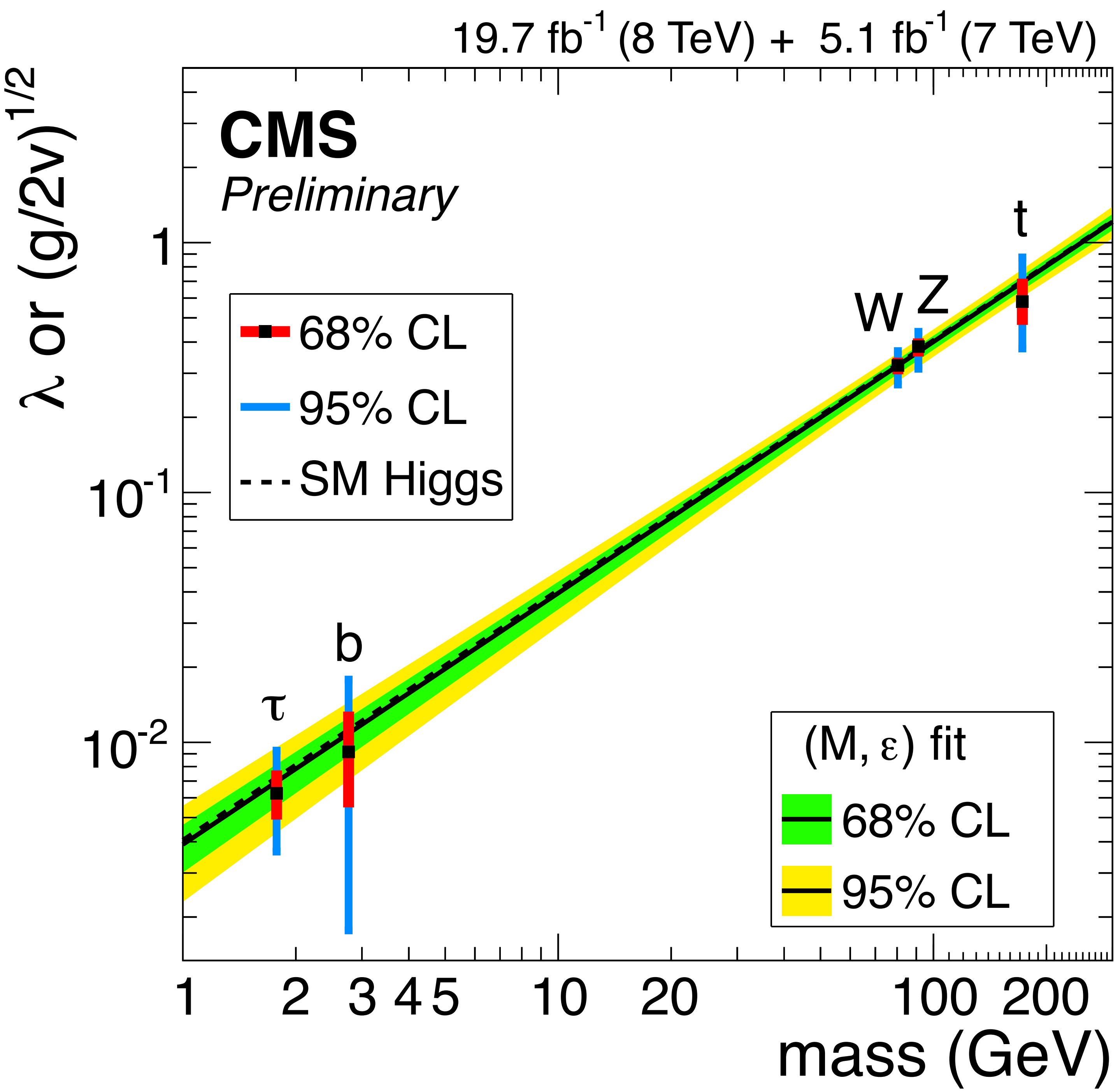
Associated with tt (or bb)



~3k/5k



Higgs couplings scale with mass



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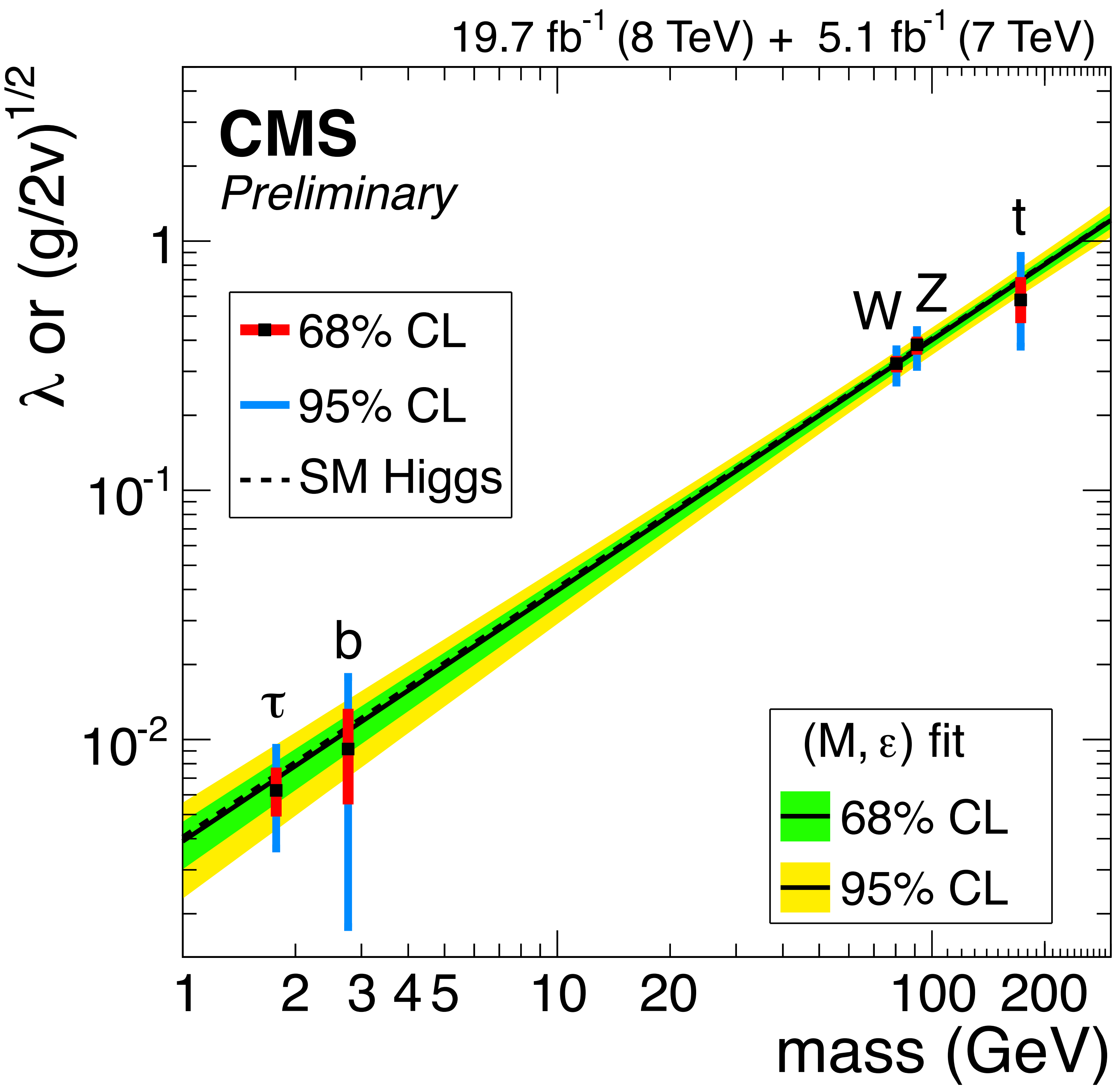
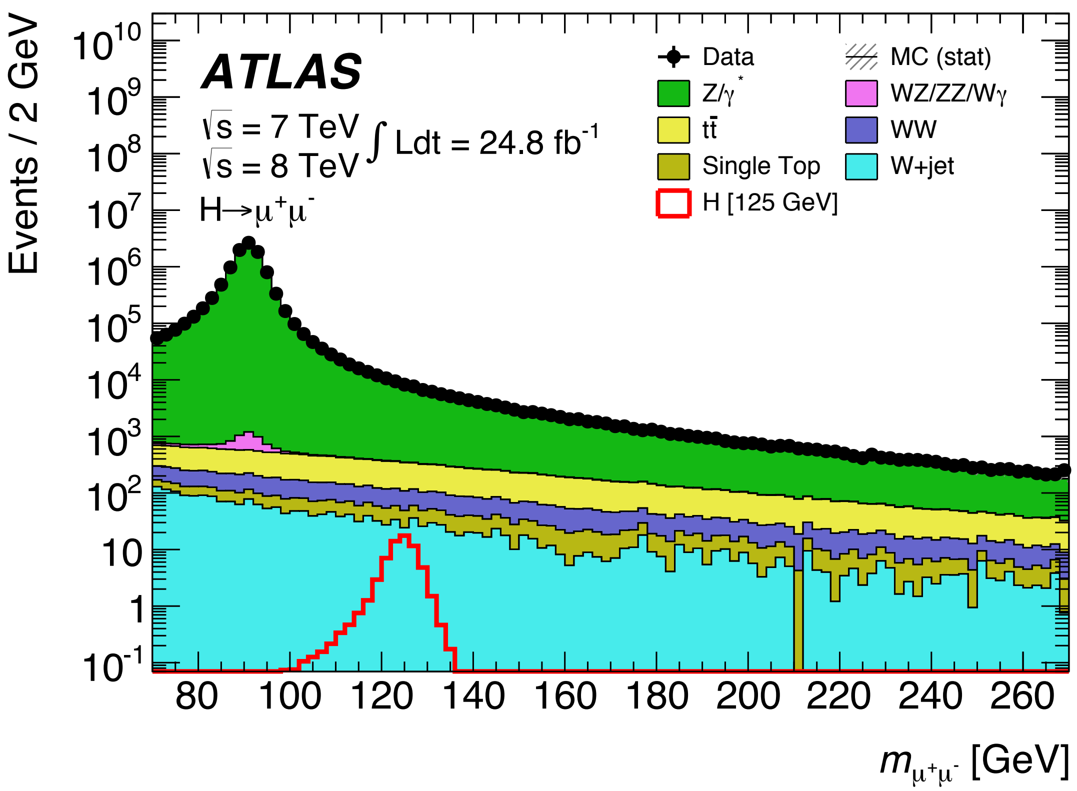


Evidence for $H \rightarrow \tau^+\tau^-$

no sign of $H \rightarrow \mu^+\mu^-$ (or e^+e^-)

(no lepton universality)



Higgs width

- SM: Γ_H(125 GeV) ~ 4 MeV. Detector resolution ~ 1 GeV
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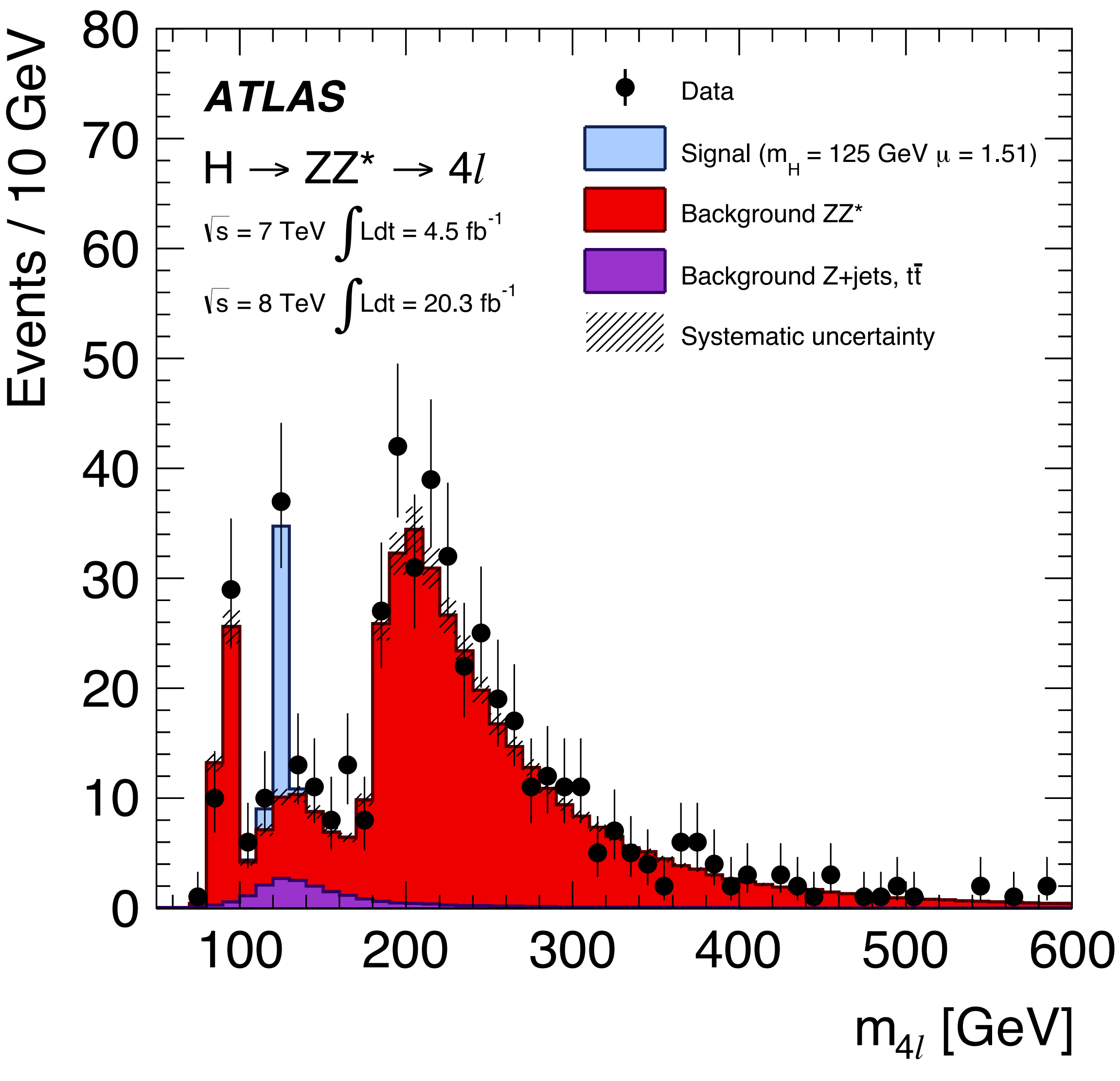
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

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



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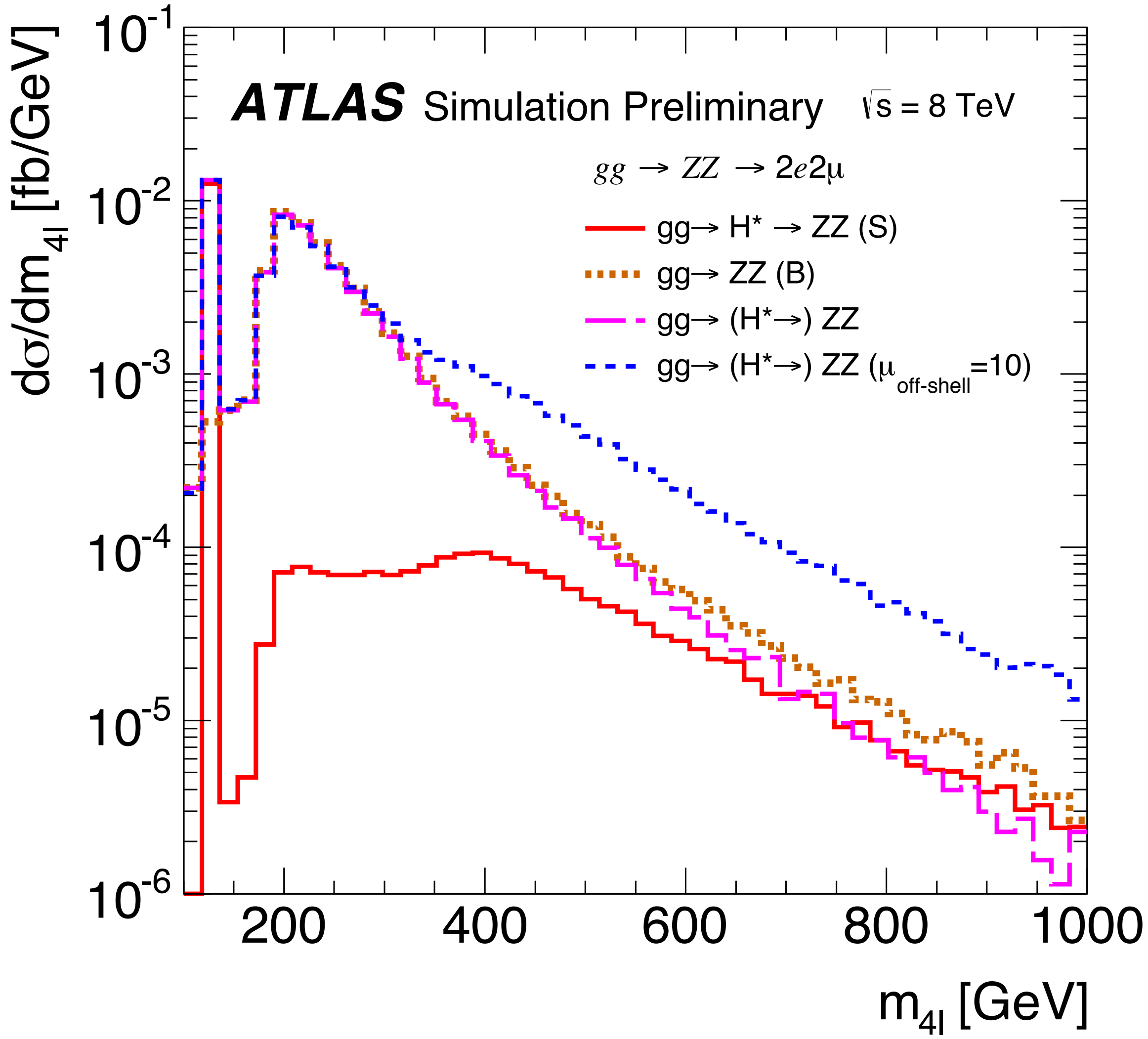
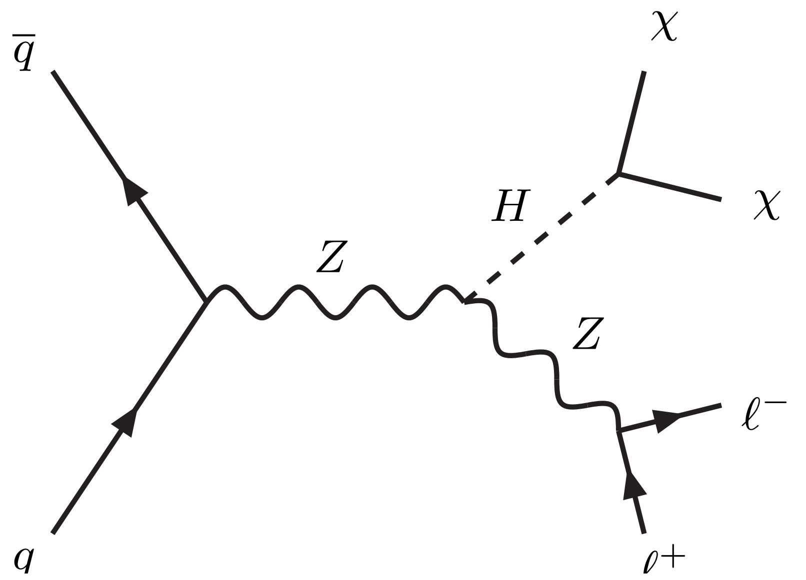
- Interference with with gg → ZZ, assumes no new physics there

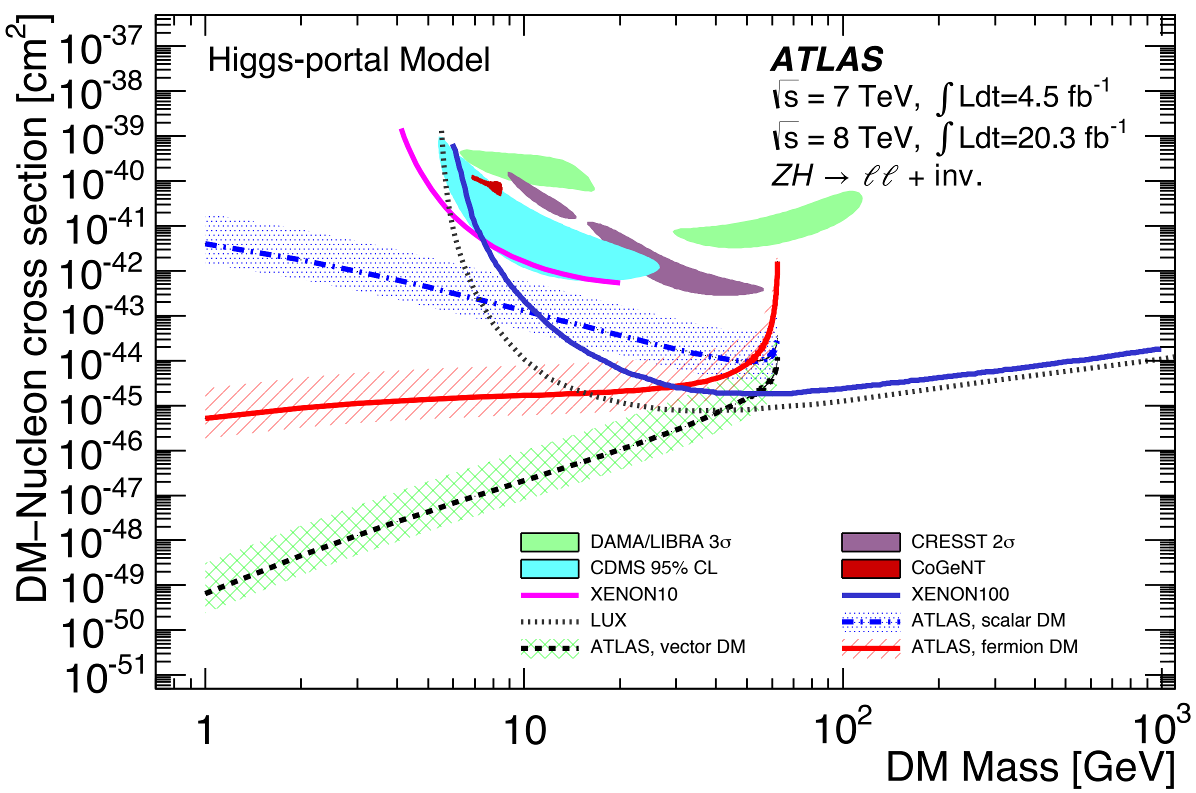


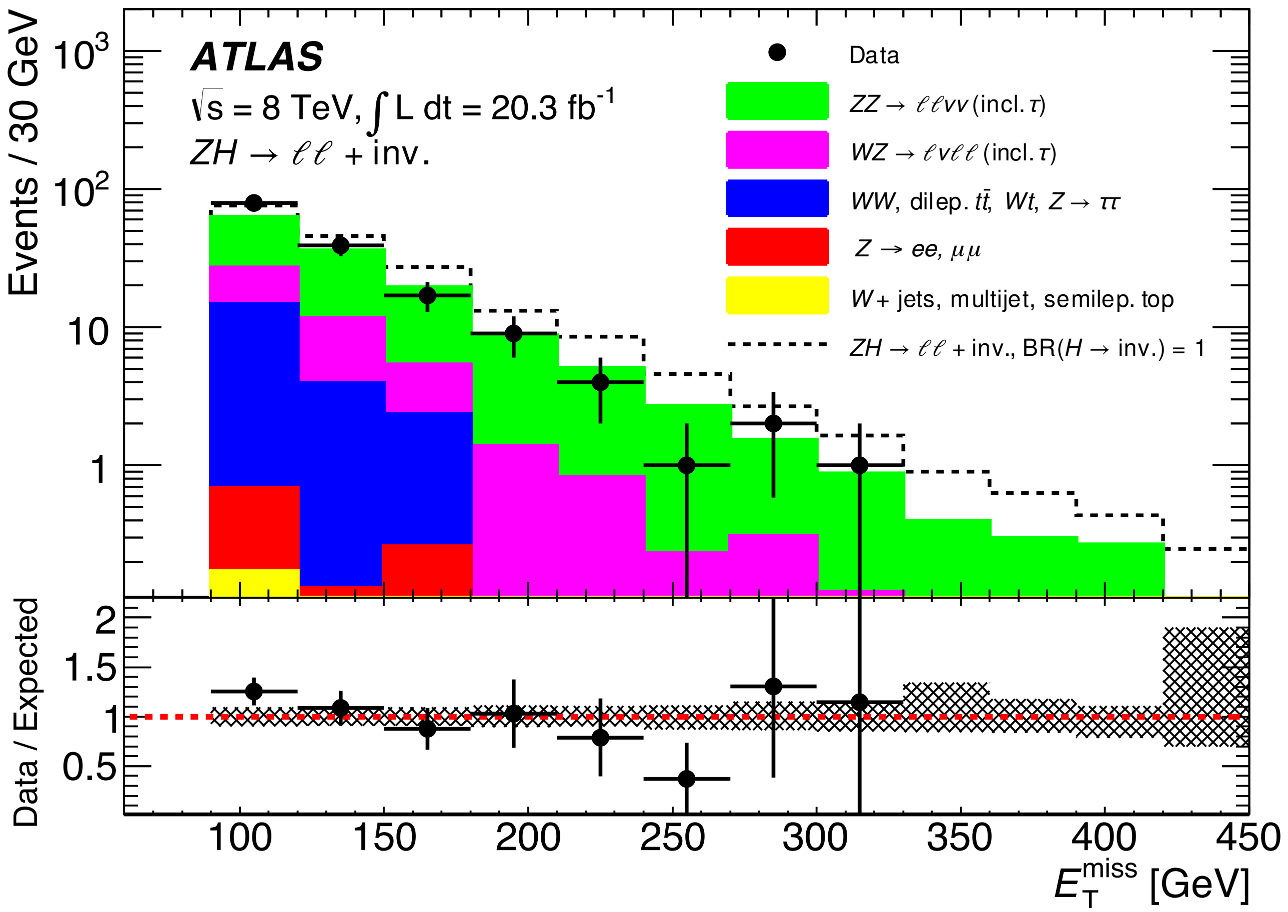
ATLAS/CMS: $\Gamma/\Gamma_{SM} \lesssim 5$ @ 95% CL

Higgs decays to invisible particles

Look for H → missing energy







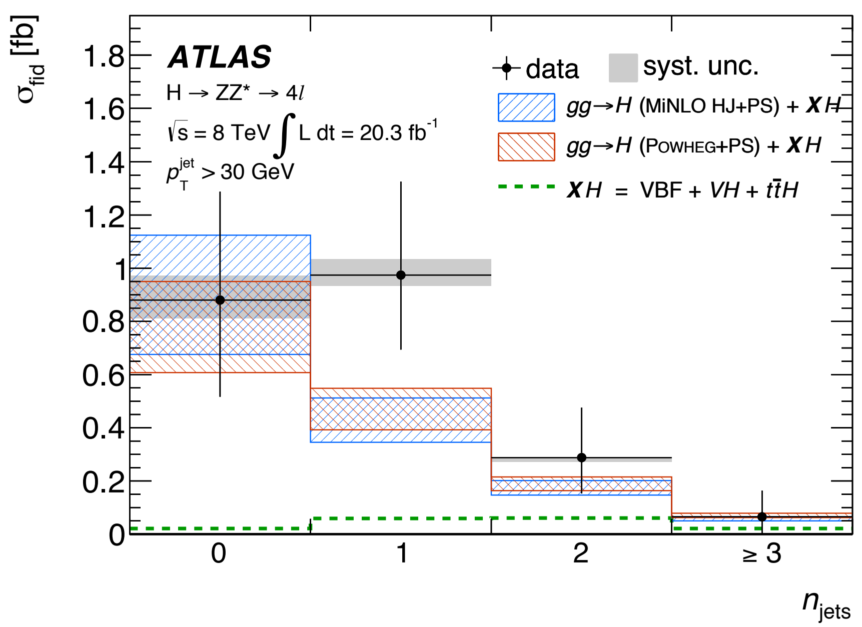
ATLAS: BR(inv) < 0.75 (0.62) @ 95% C.L.

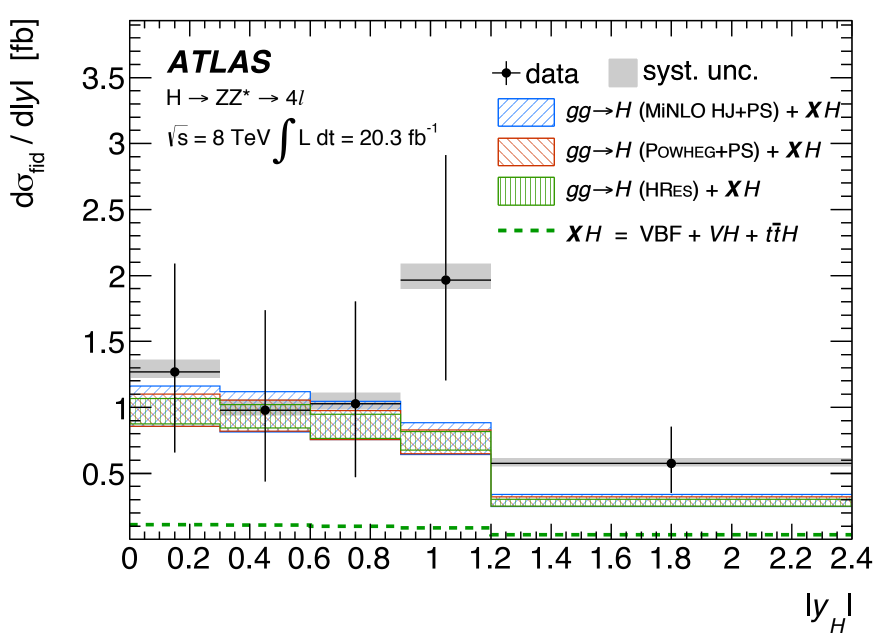
CMS: BR(inv) < 0.58 (0.44) @ 95% C.L.

Differential distributions

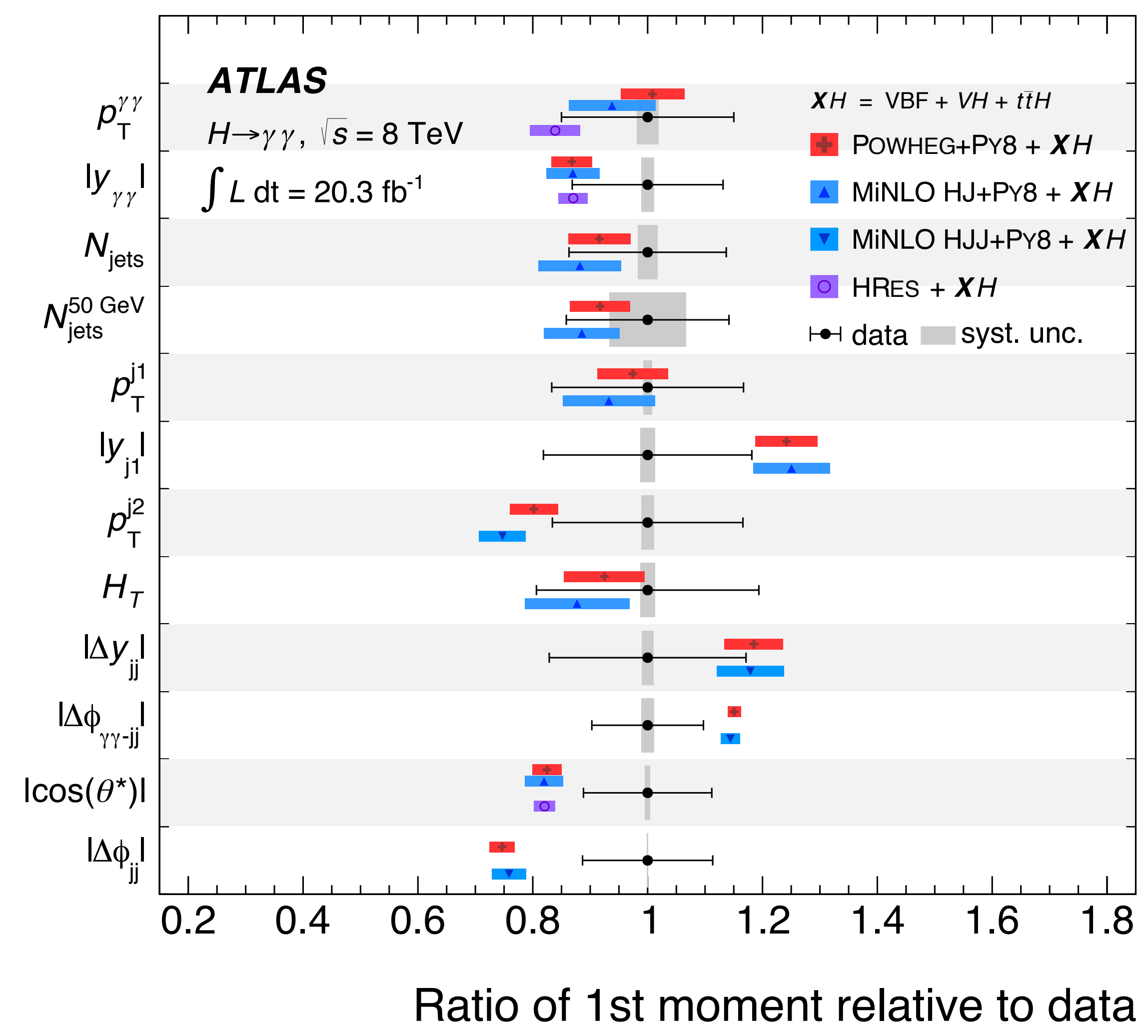
Kinematics of Higgs production / decay corrected for detector effects
(validate theoretical calculations)

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



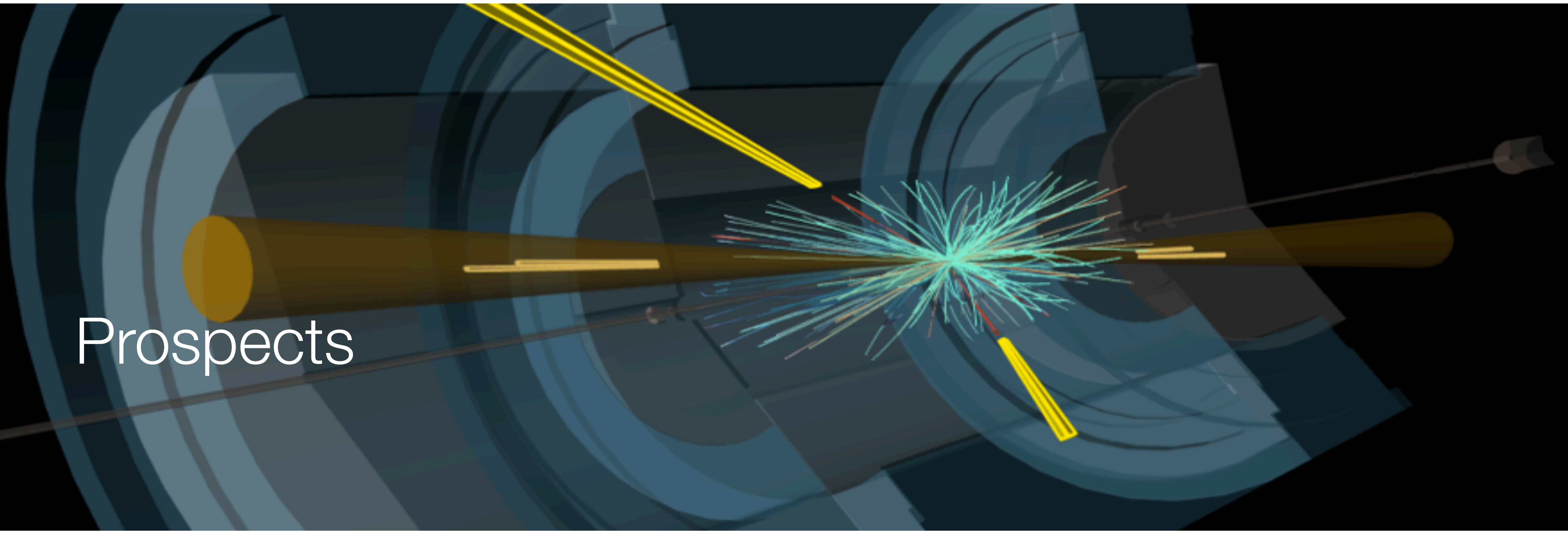


$H \rightarrow \gamma\gamma$ (summary)



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 ~30% precision
  - Deviations in the most attractive scenarios of physics beyond the SM $\lesssim$ 10%

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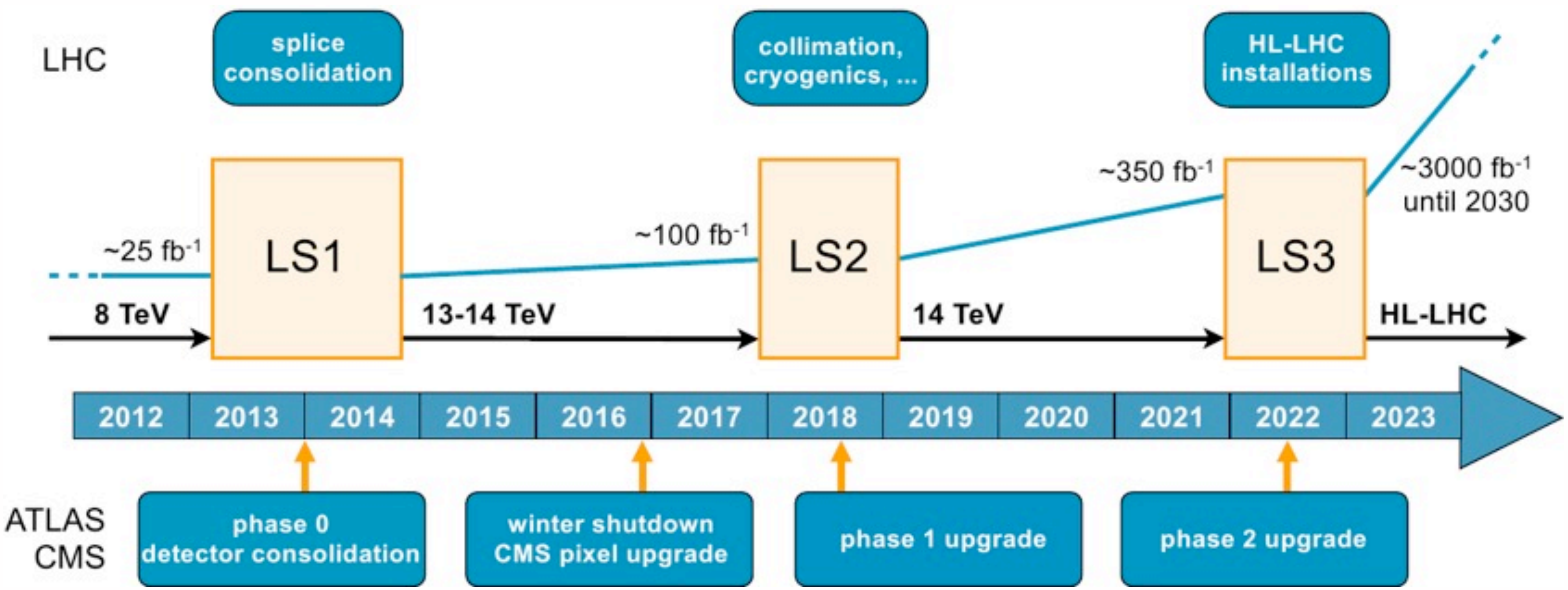
  - Couplings measured to ~30% precision
  - Deviations in the most attractive scenarios of physics beyond the SM $\lesssim$ 10%
- How to go beyond ?
  - Better experimentalists (and theorists) ?
  - More data (luminosity) ?
  - More energy ?
  - Collide different particles ?

Higgs prospects: LHC / HL-LHC

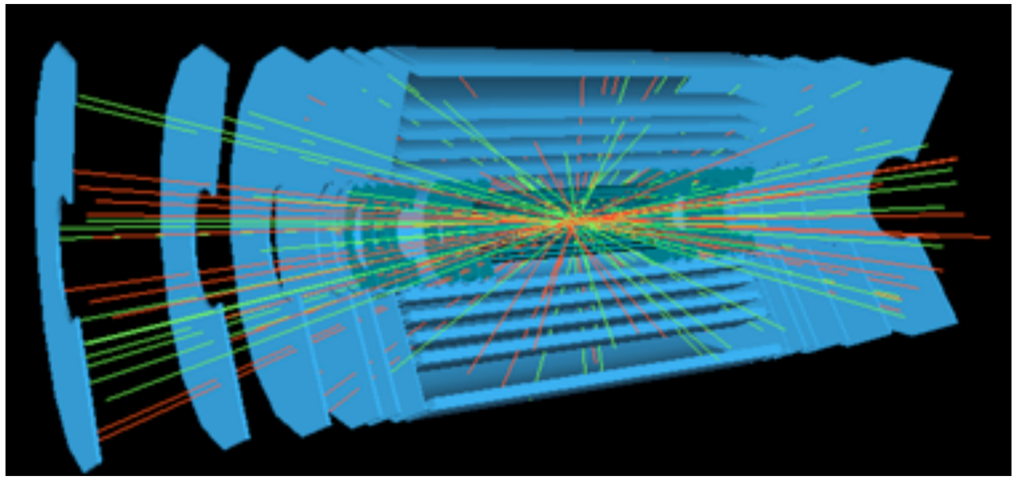
- LHC is expected to operate for another ~15y and produce ~100x more data



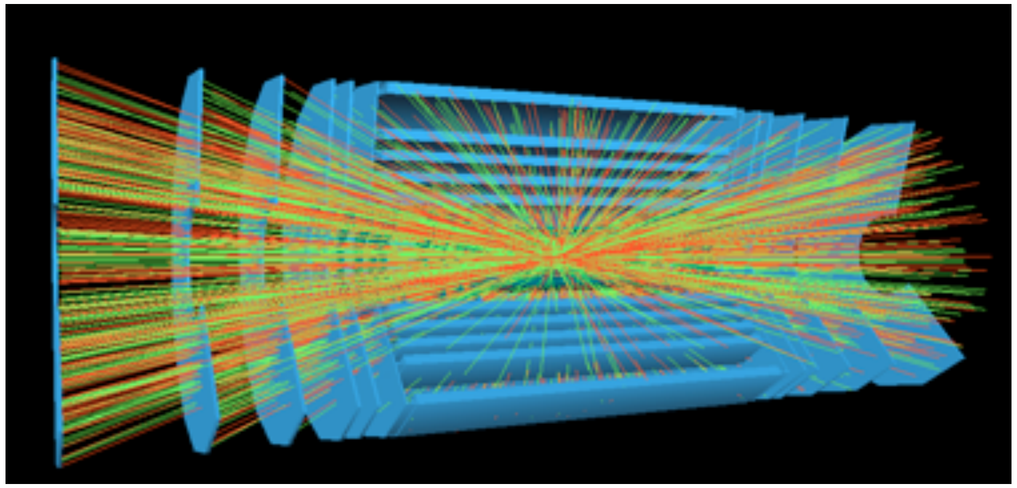
Higgs prospects: LHC / HL-LHC

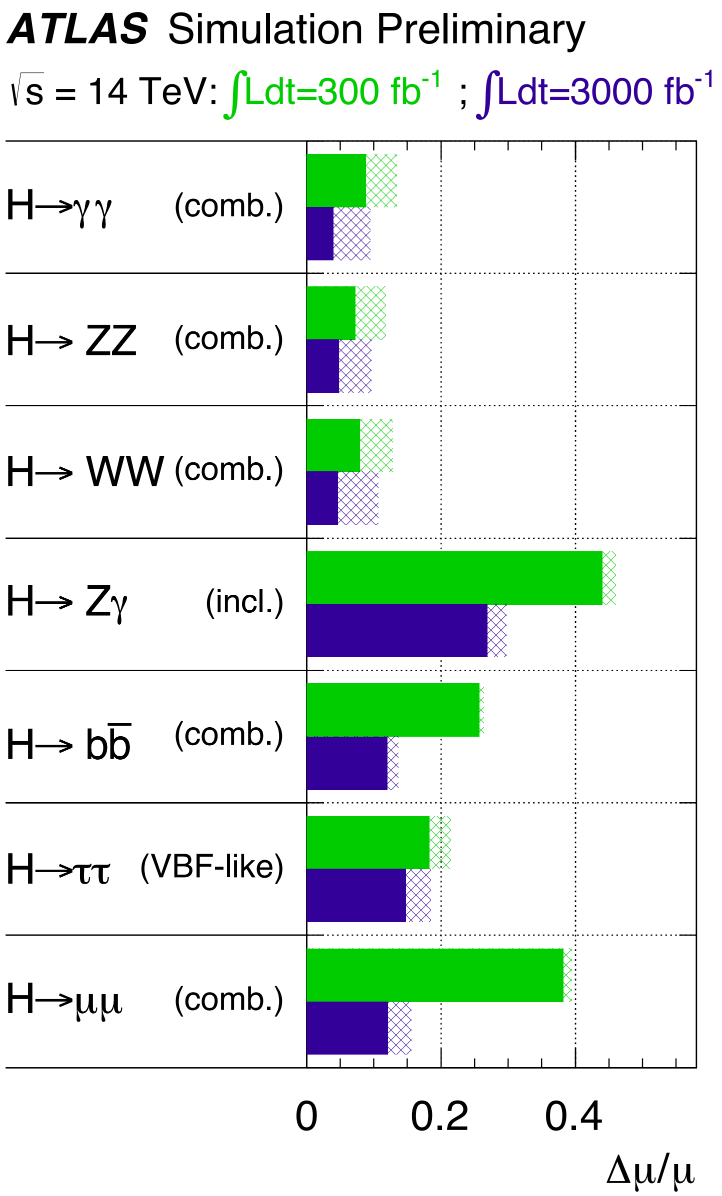
- LHC is expected to operate for another ~15y and produce ~100x more data
  - Naively would lead to 10x better coupling determinations but with higher luminosities comes higher pileup → challenging for the detectors

23 additional interactions



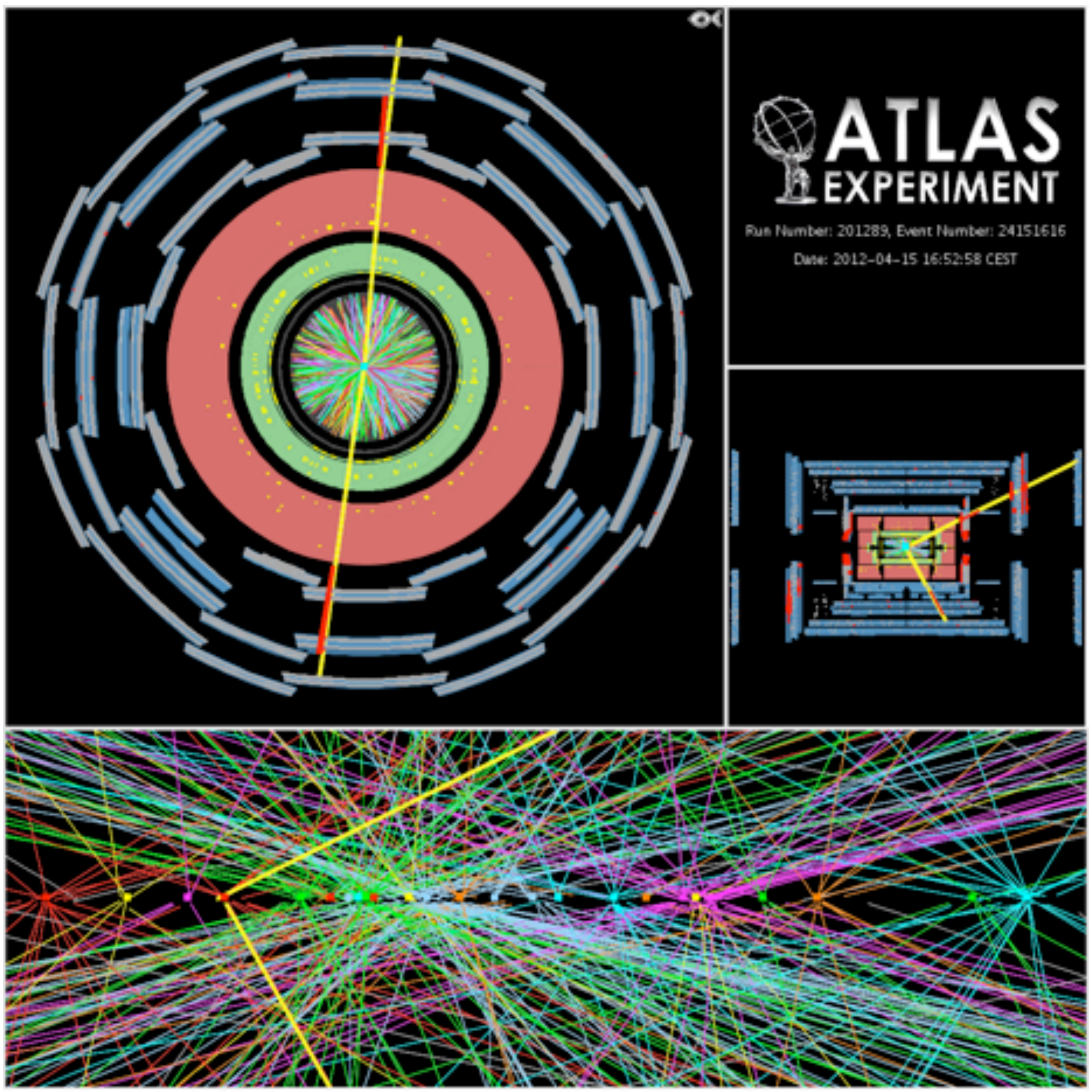
230 additional interactions



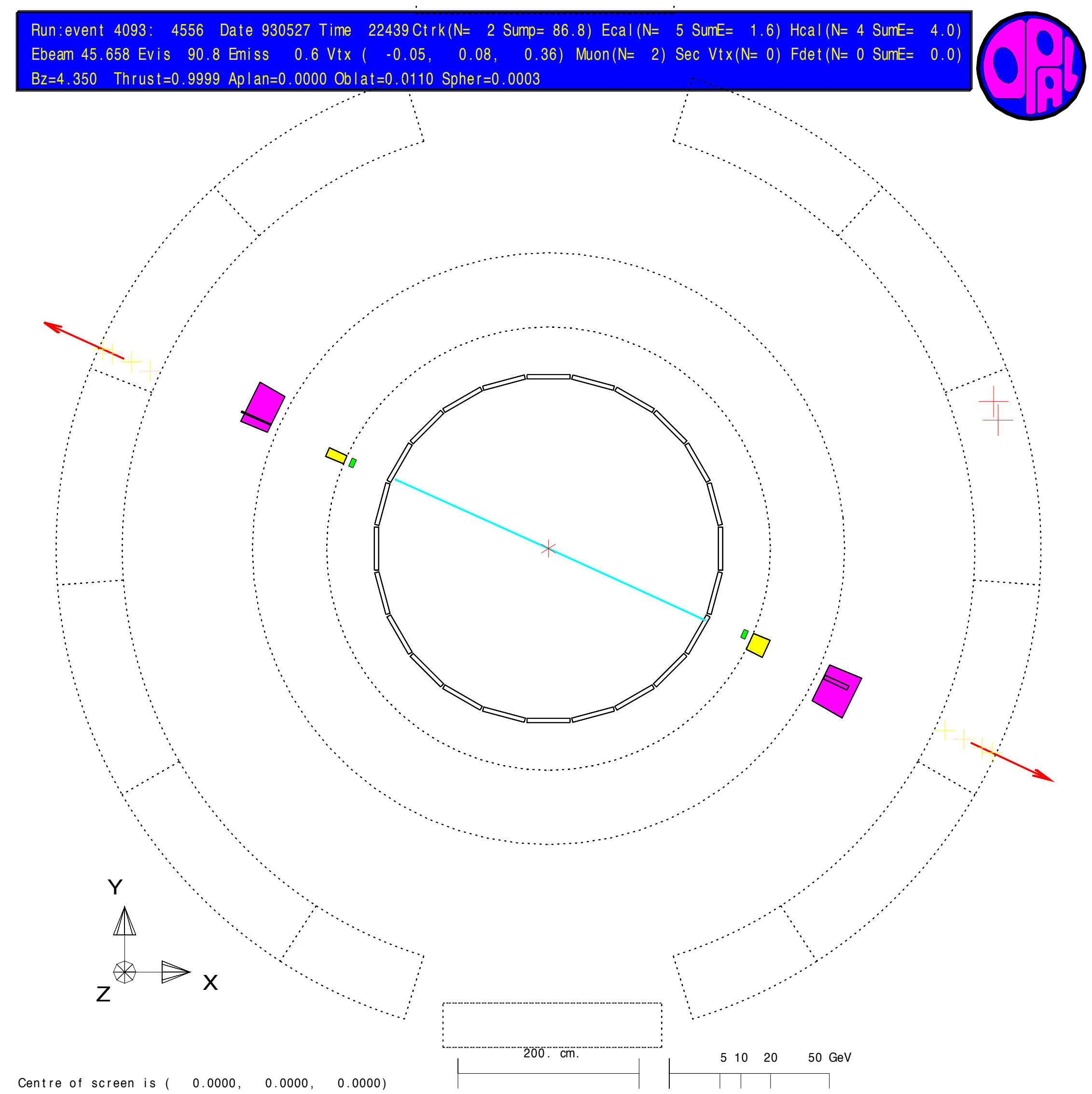


pp vs. e^+e^- colliders

pp → Z → μμ + ~25 interactions

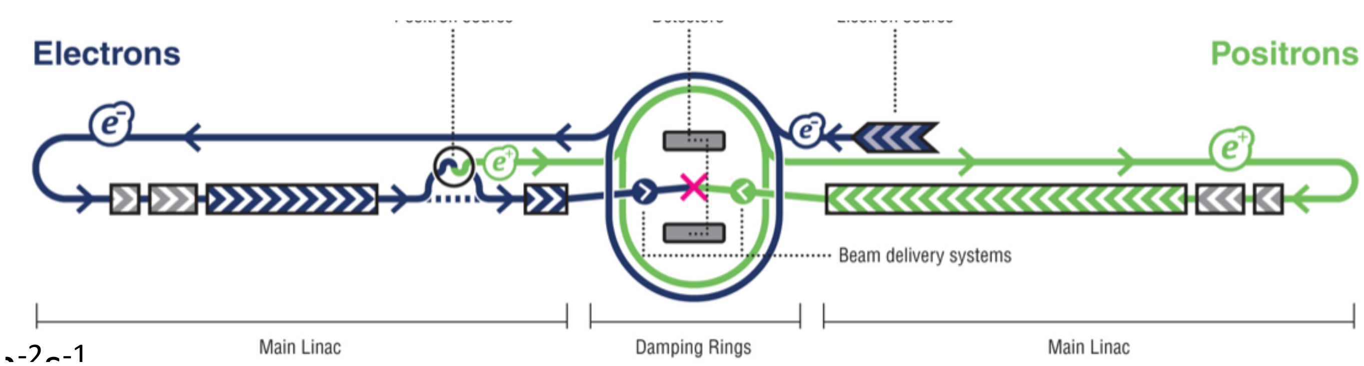


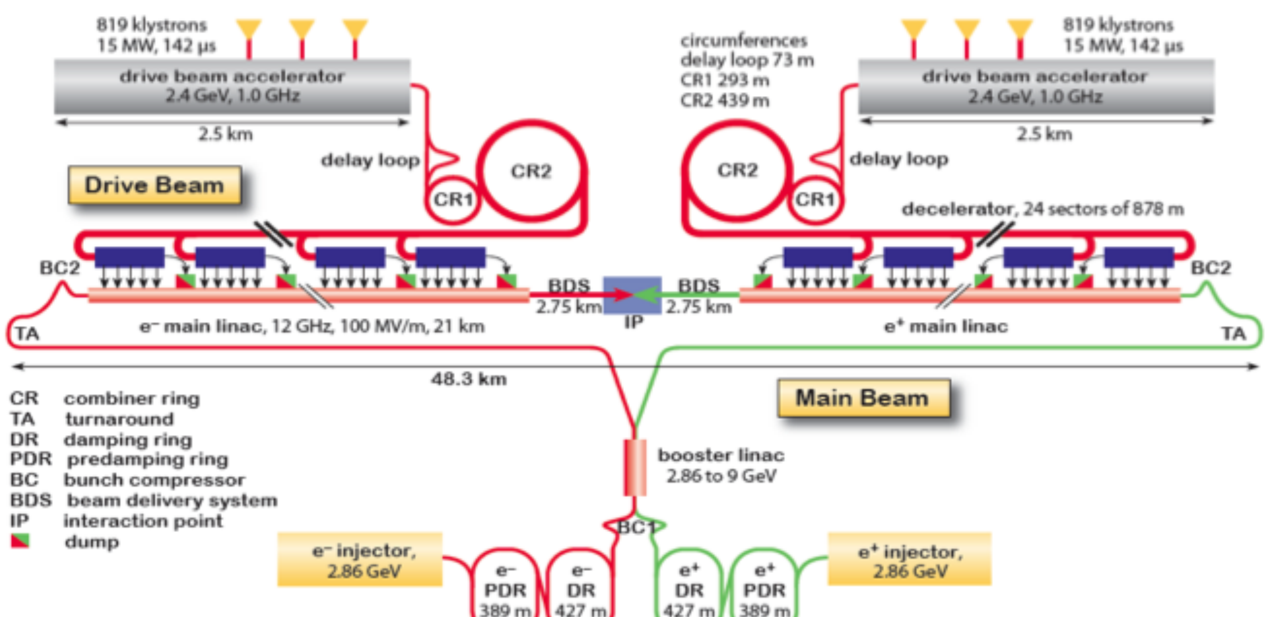
e^+e^- → Z → μμ



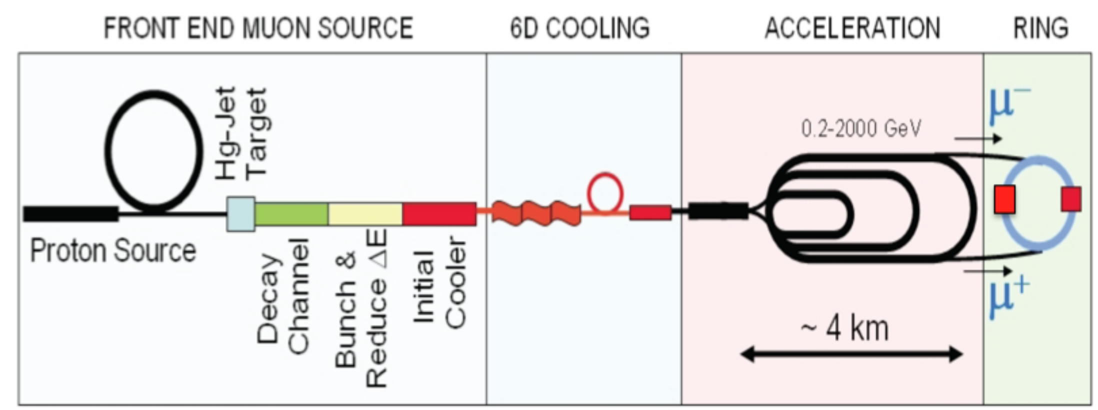
Future projects: lepton or photon colliders

e^+e^- colliders

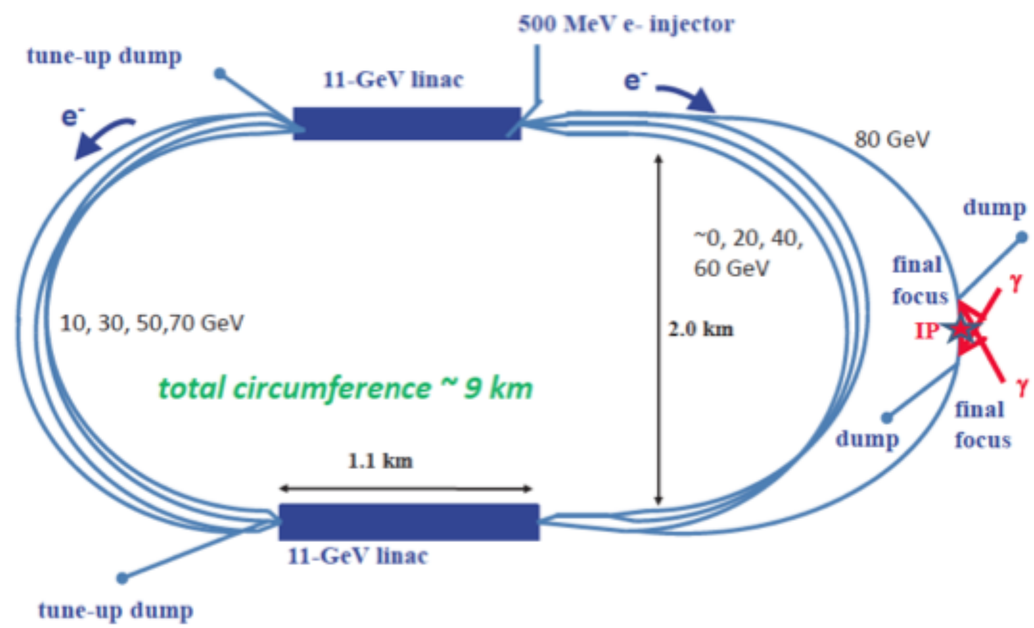




μμ collider



γγ collider



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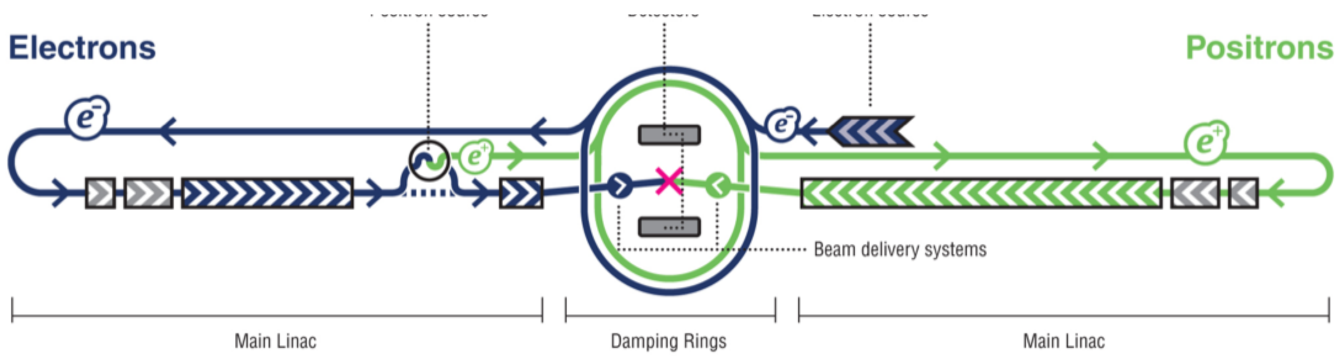
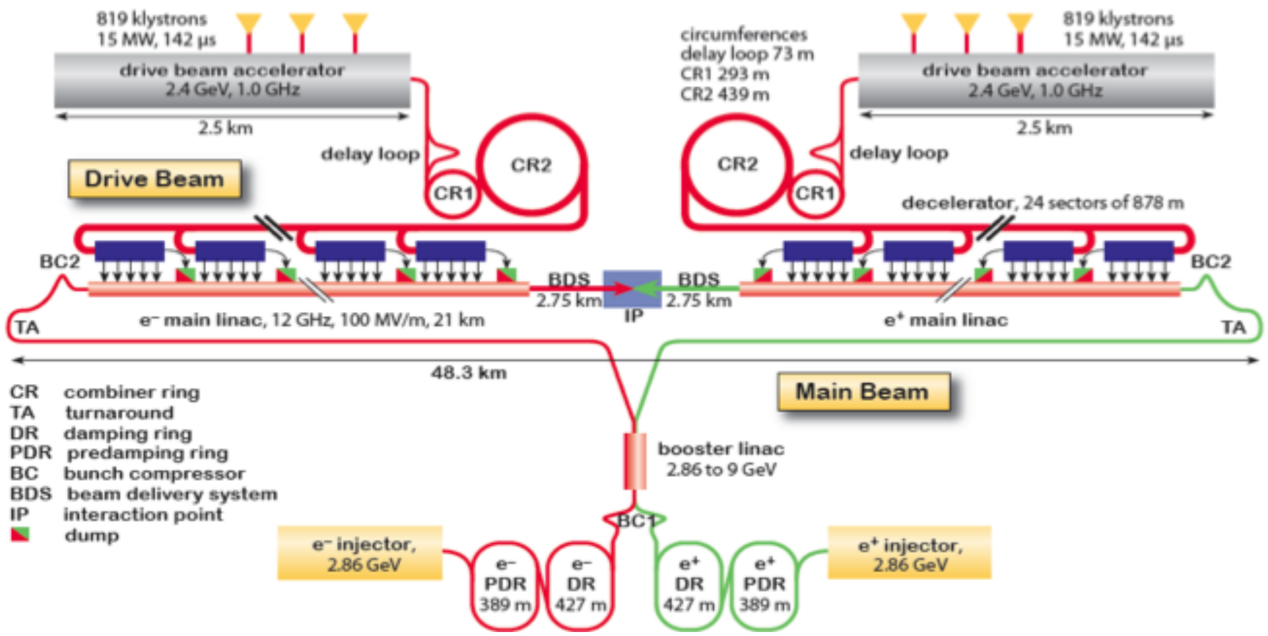
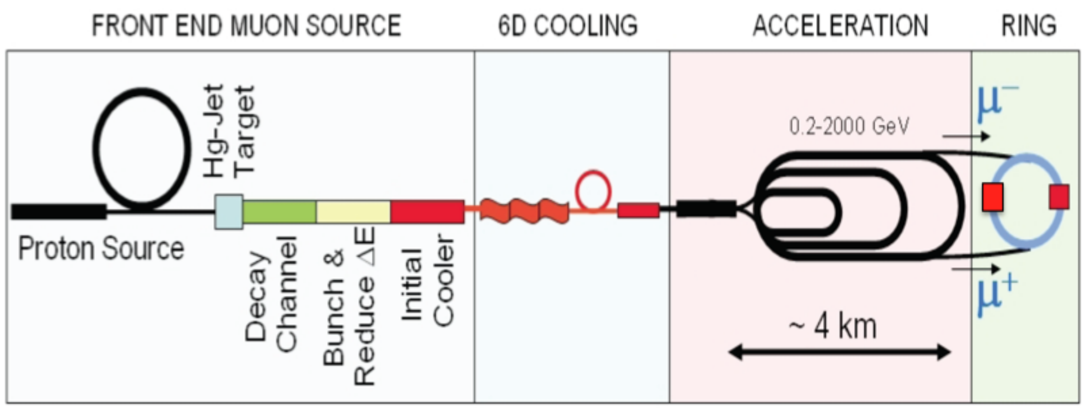
e^+e^- colliders

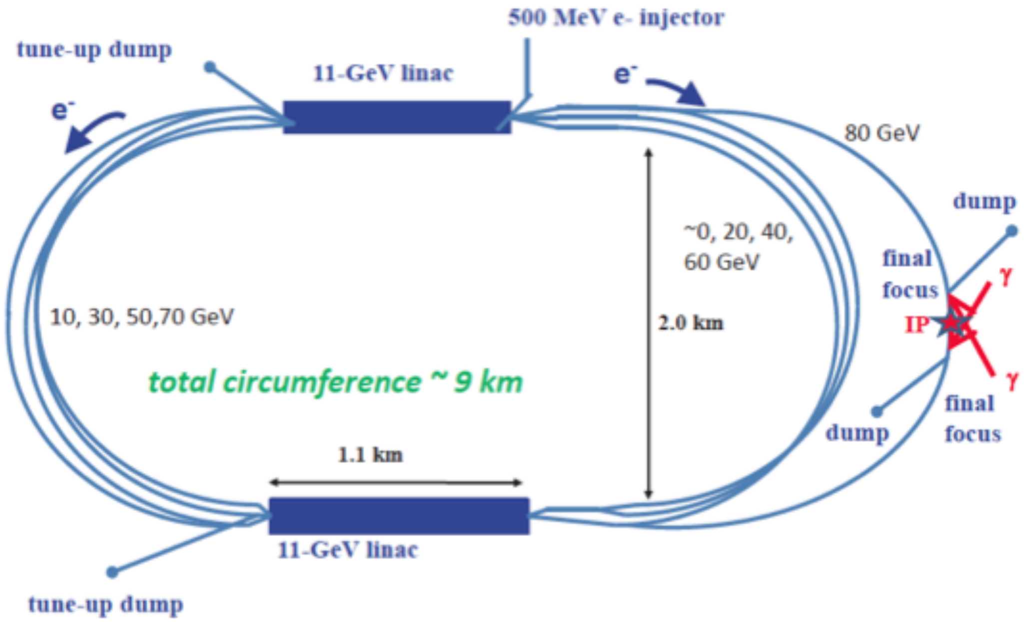




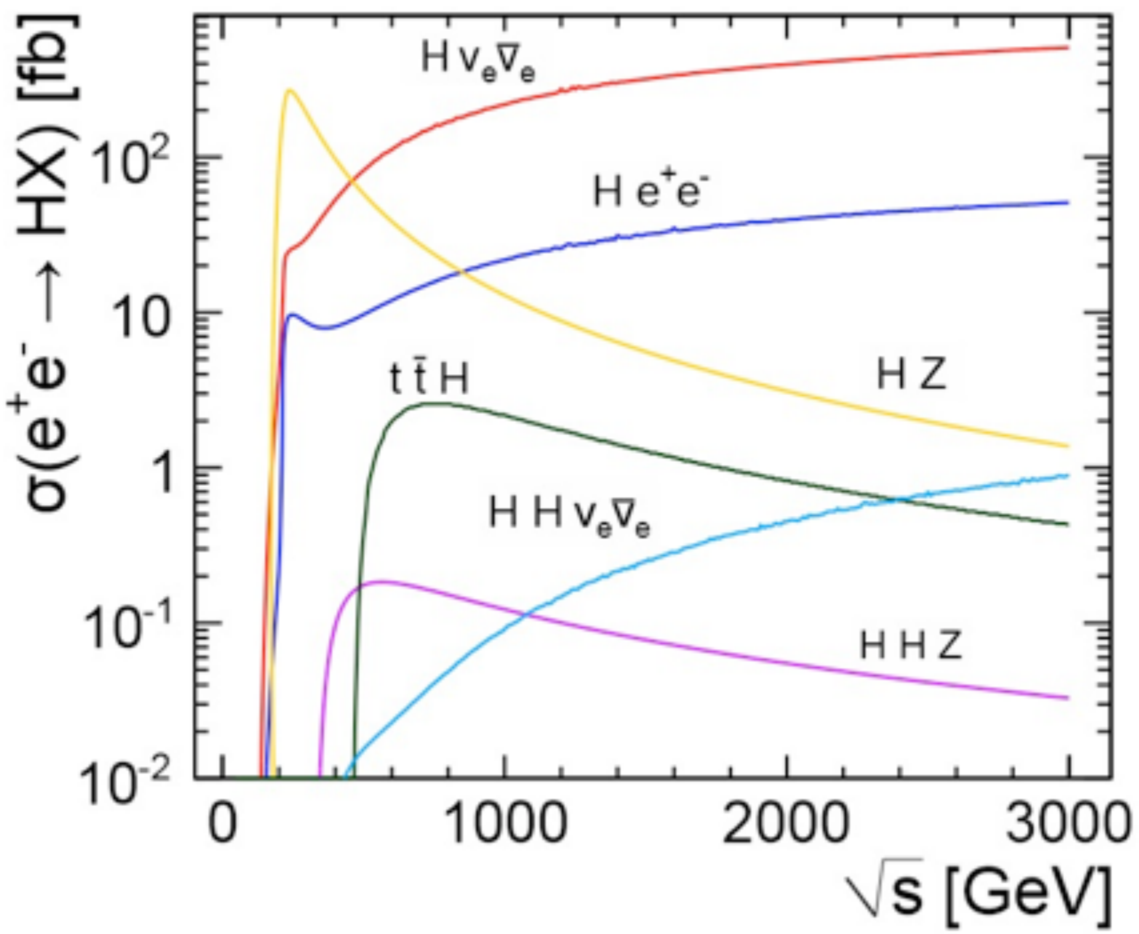
μμ collider



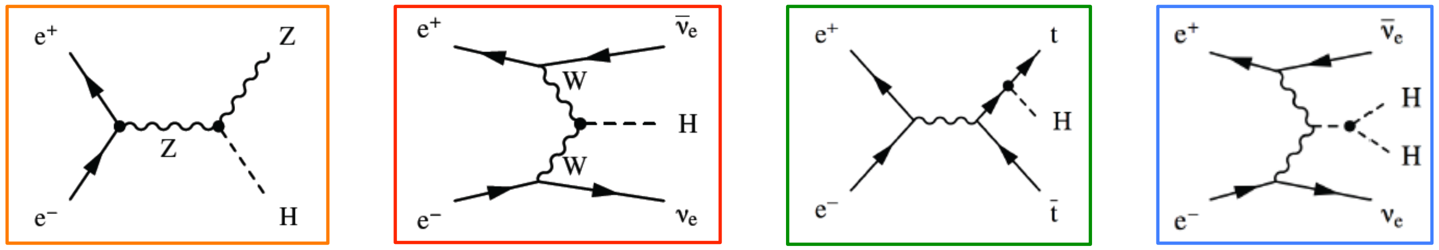
γγ collider

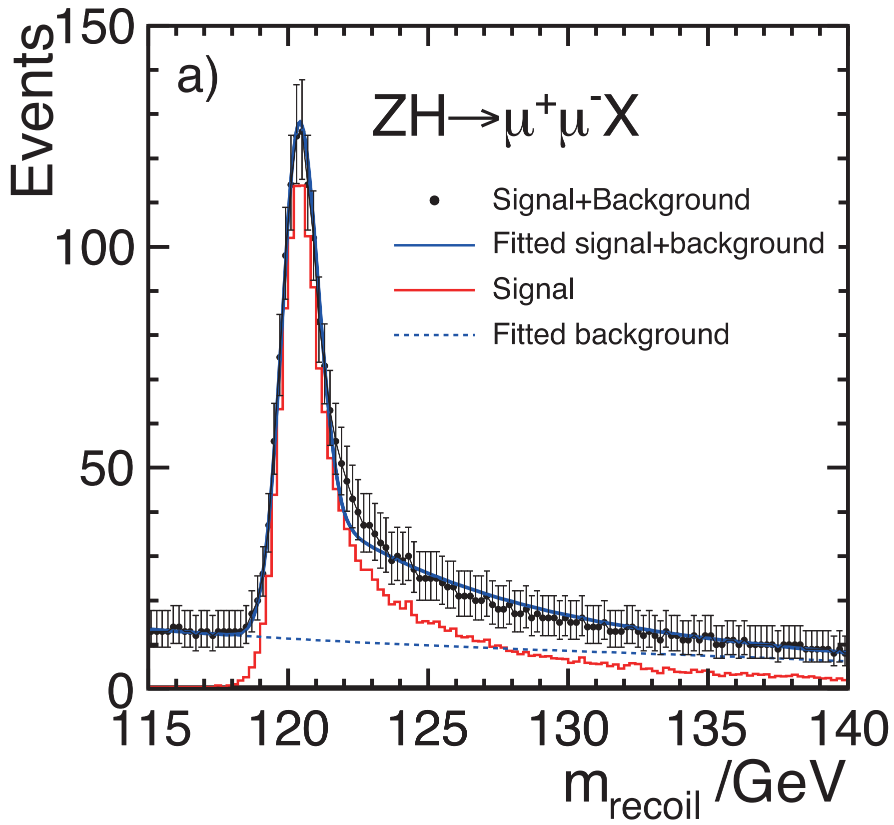


Higgs at e+e- colliders

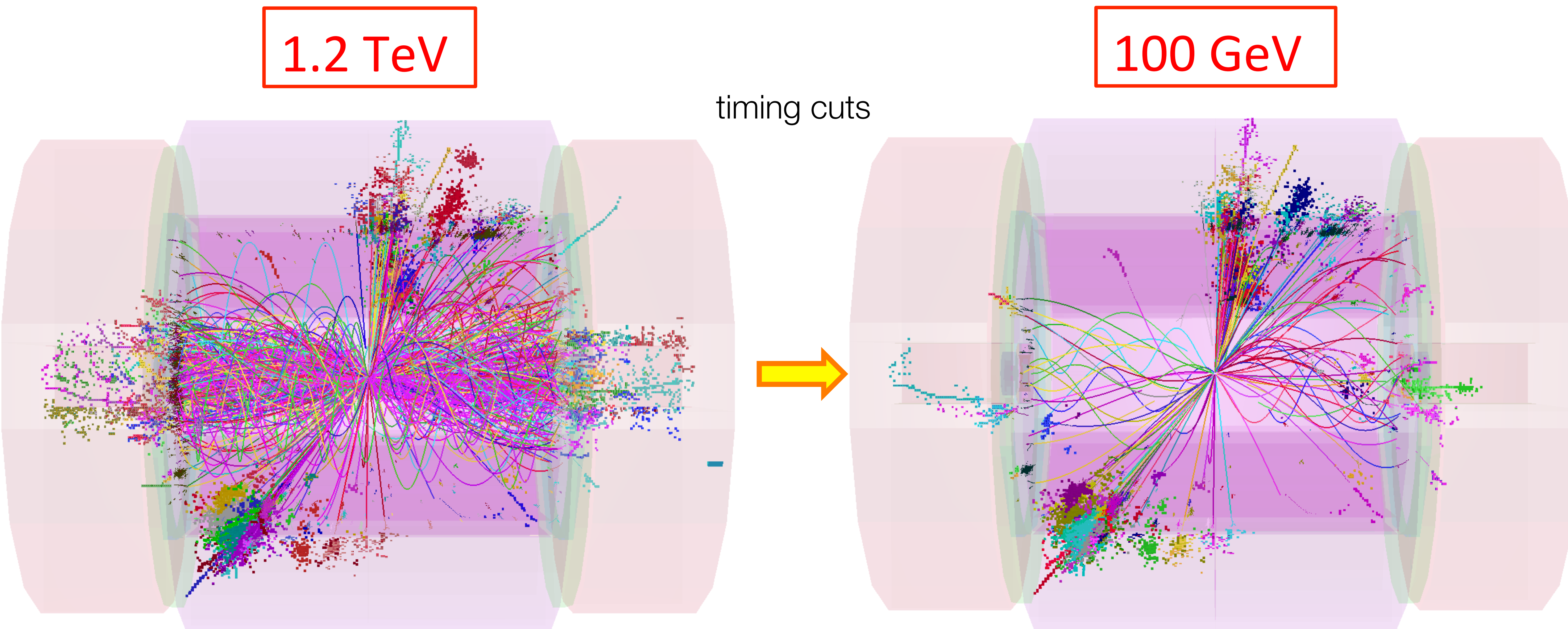


- Hadronic final states (bb, cc, gg)
- Mass measurement (40 MeV)
- Width
- ...





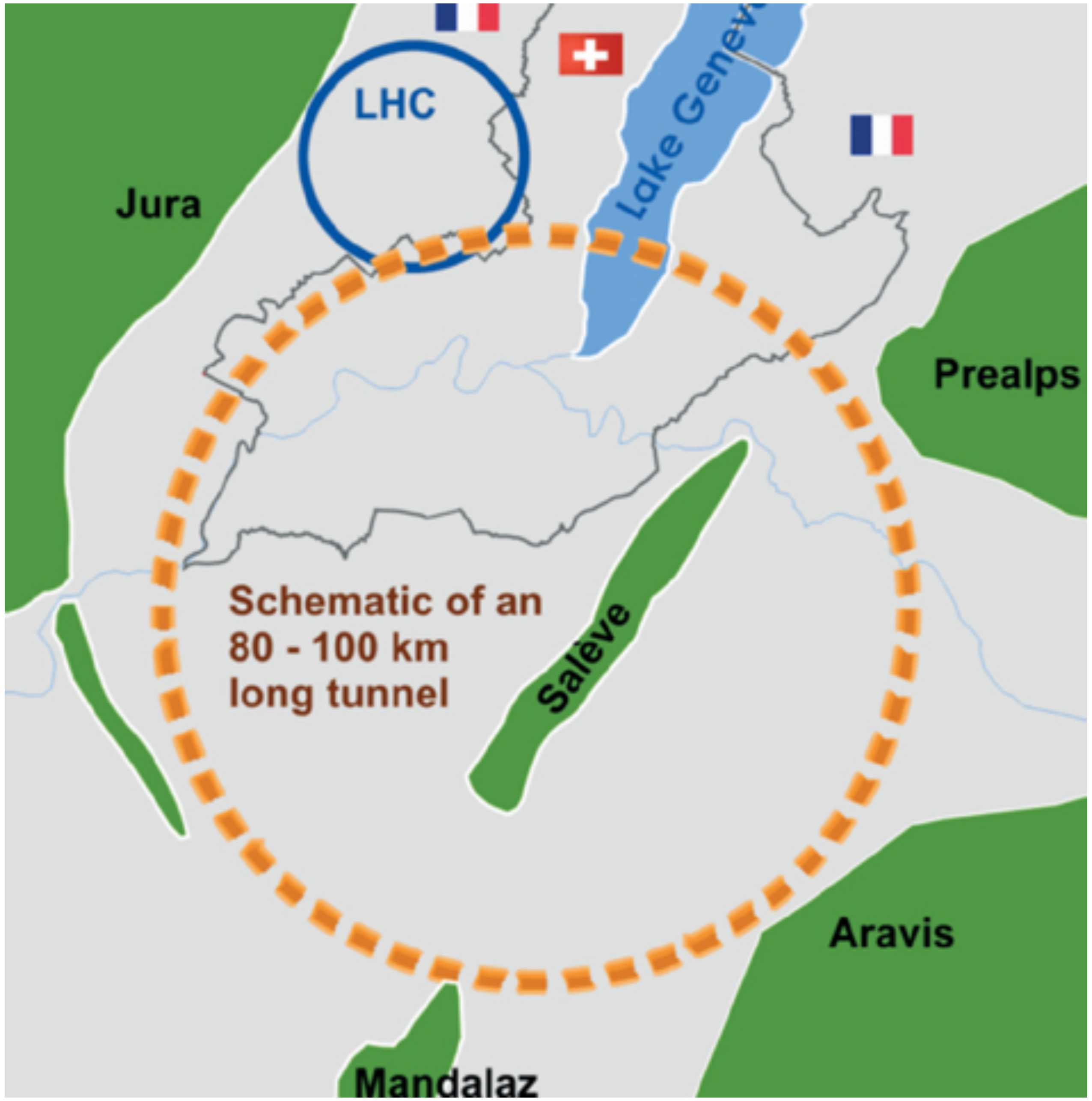
Background energy in the detector:



Not so clean anymore but manageable with fast detectors

Future circular colliders (FCC, previously TLEP, VLHC)

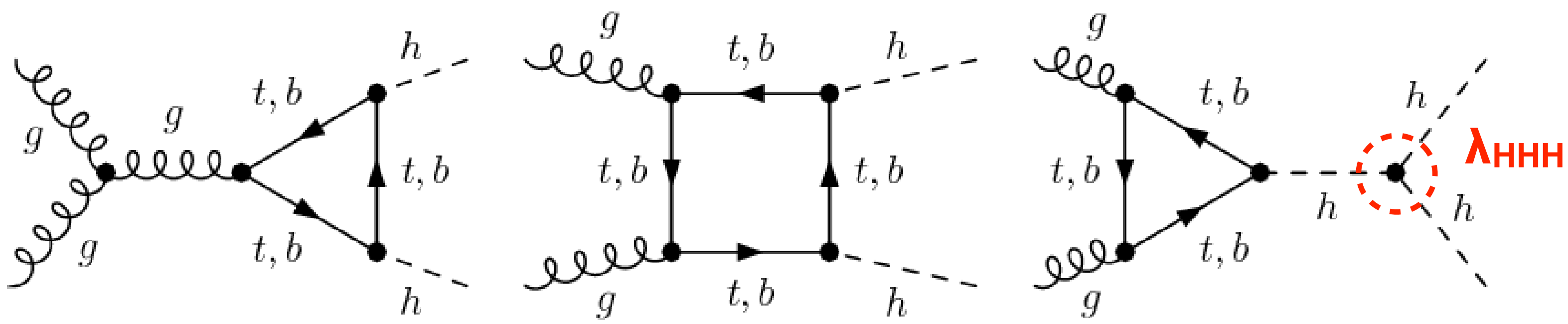
- 80 - 100 km tunnel
- 4 interaction points
- e^+e^-: $\sqrt{s}$ ~ 240 and 350 GeV
  - Need top-up injection
- pp: $\sqrt{s}$ up to 100 TeV
  - 20T magnets
- Higgs factory and increased reach for new physics
- Detailed studies of physics case starting



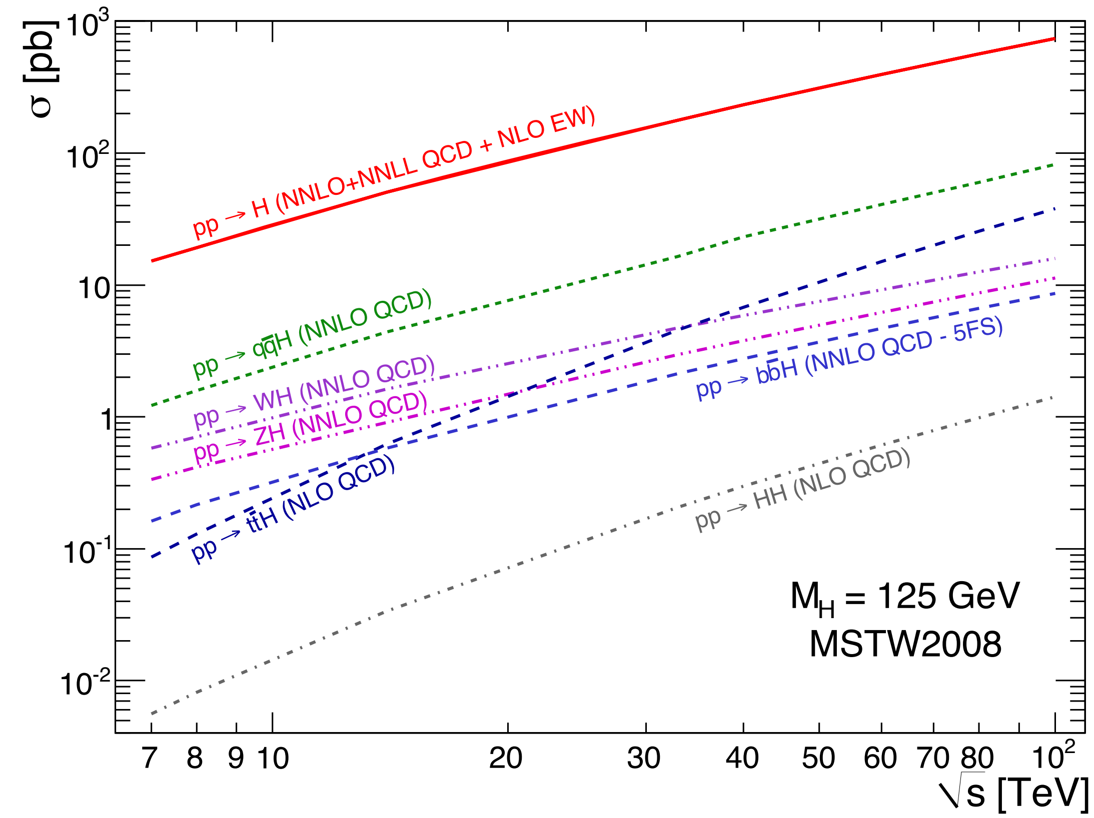
Higgs prospects at LHC and e+e- colliders

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

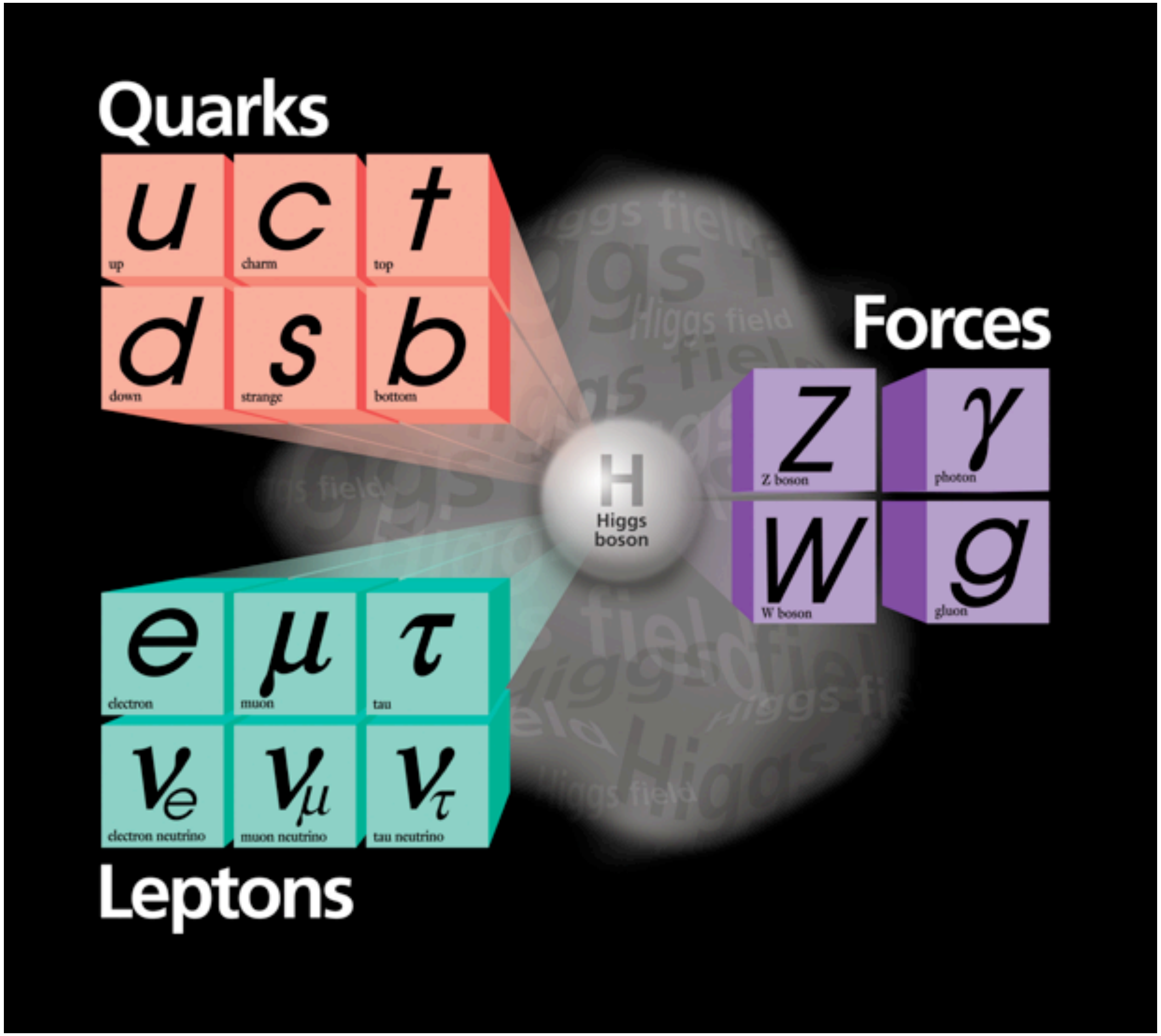


- Cross sections increase with √s
  - Important for HH production
    - Destructive interference between diagrams
    - Need to explore many final states: bbγγ, bbττ, bbWW, ...



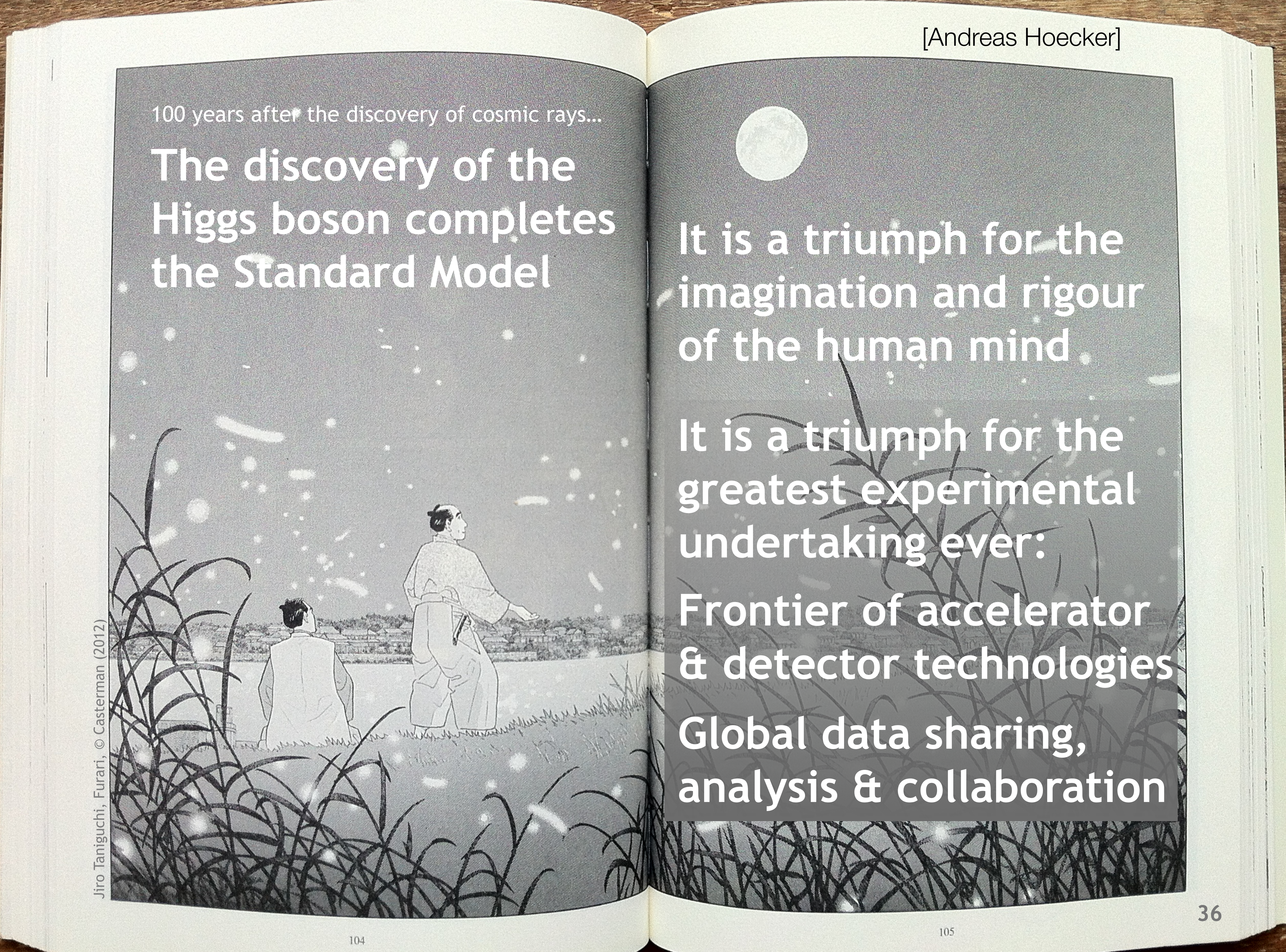
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

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

[Andreas Hoecker]



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

Jiro Taniguchi, Furari, © Casterman (2012)