Search for the Higgs Boson Decaying to Dark Matter at the LHC

Tsukuba Global Science Week, September 29, 2014

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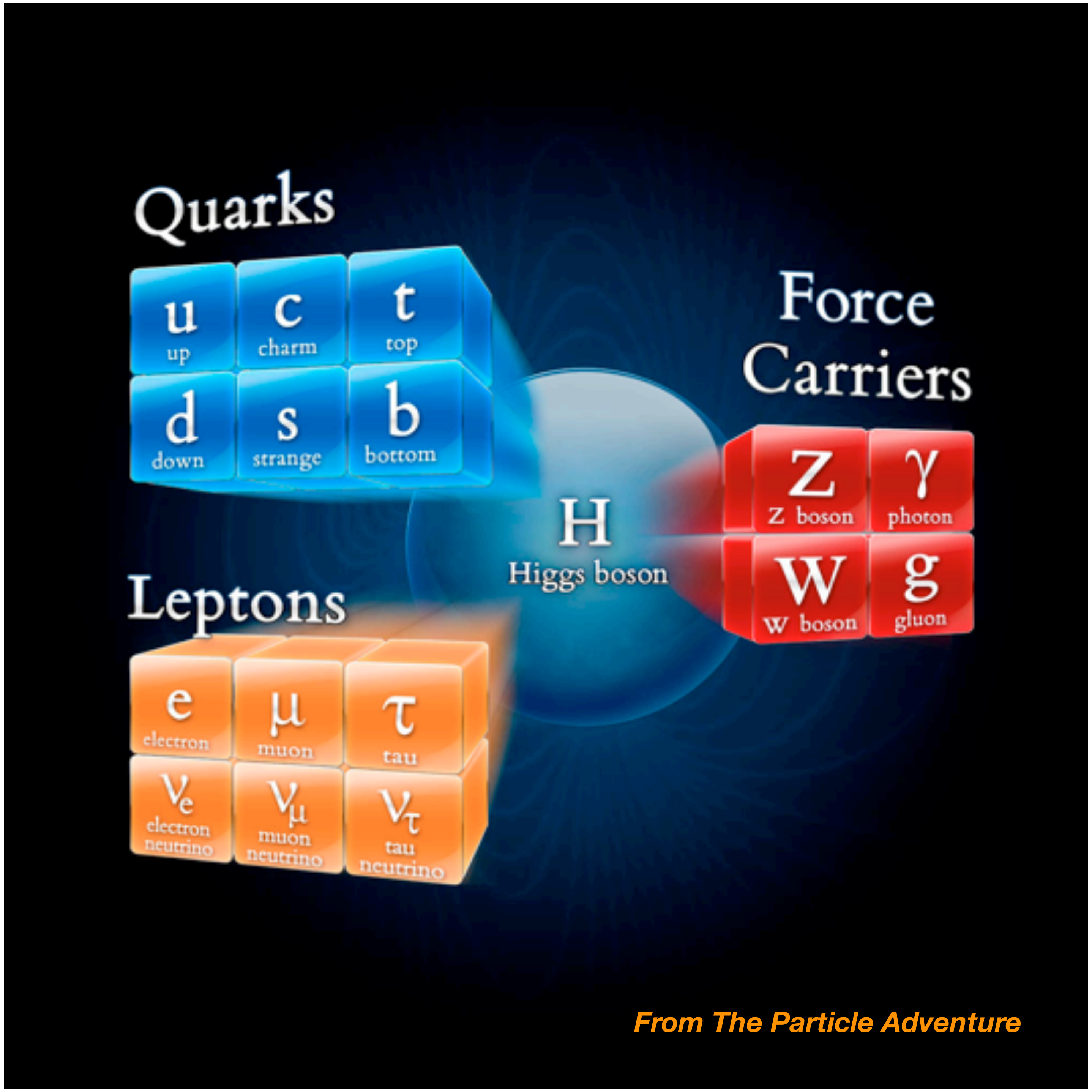
Standard Model

Elementary particles:

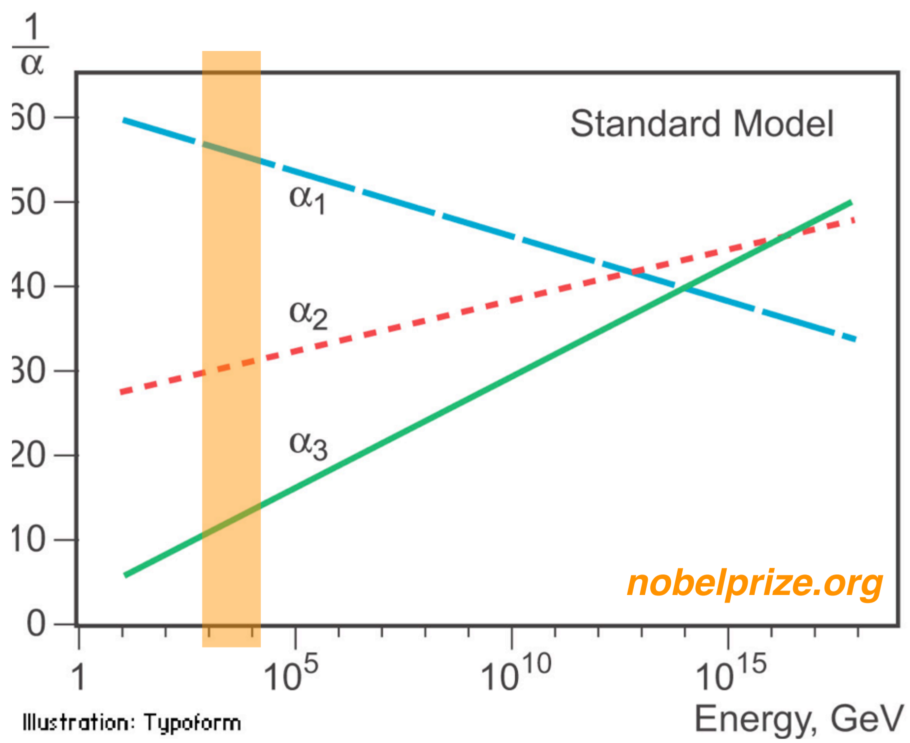
- Fermions: quarks & leptons.
- Vector Bosons (γ, W, Z, g): Force carriers.
- Scalar boson (H): Source of electroweak symmetry breaking & masses of the elementary particles.

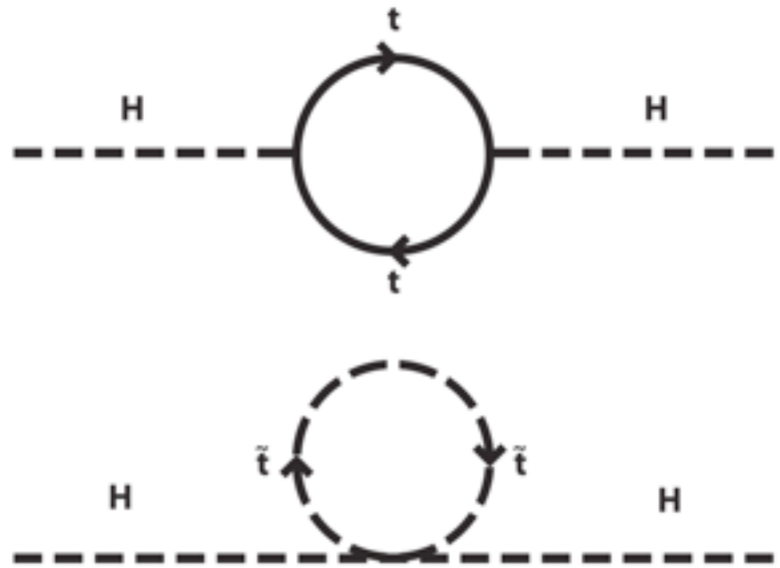
- **Higgs boson was the last missing piece in the Standard Model (SM), but was discovered in July 2012.**
- **So, Are we done?**
  Or, what's next?

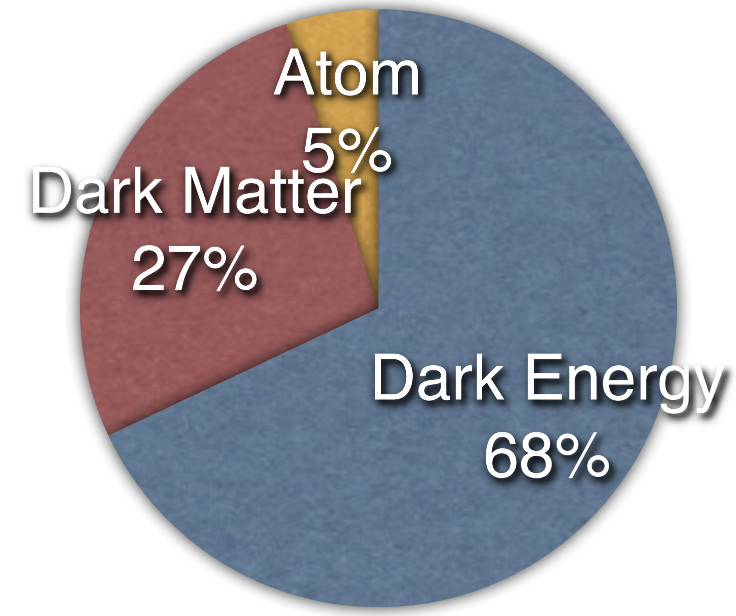


Remaining Mysteries

<u>There are many indications that the SM is not the final theory!</u>







- **With just the SM, the unification of forces would not occur.**
- **Higgs mass.** → Theoretically unstable with just the SM. Top partners?
- **Dark matter (DM)** → Expected from astrophysical observations, but DM itself has not been detected yet.

Beyond Higgs Discovery

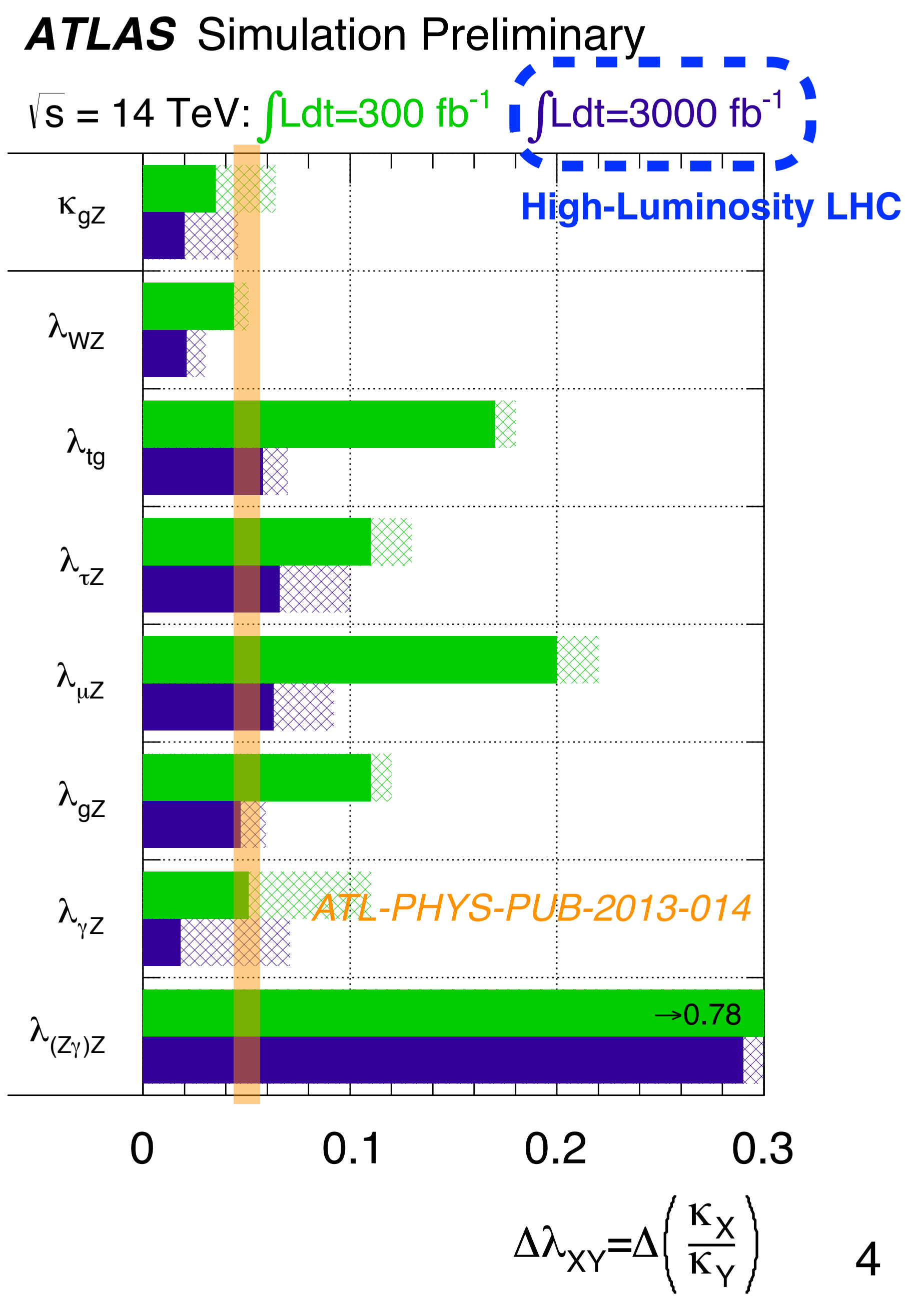
- Does the discovered Higgs boson really follow the SM?
- How can we find signs of Beyond-the-Standard-Model (BSM) physics in the Higgs sector?

- Precision measurements of the Higgs couplings.

Deviation of Higgs Couplings by BSM Physics

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Snowmass, Energy Frontier Report, 2013

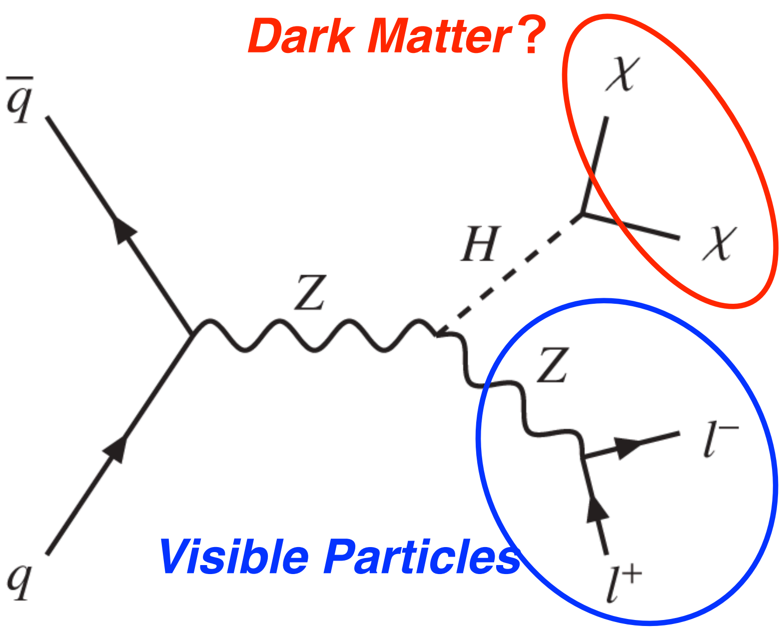


- **Search for BSM decays of Higgs.**
  → e.g. Invisible decay to dark matter.
- Search for more/heavier Higgs bosons.

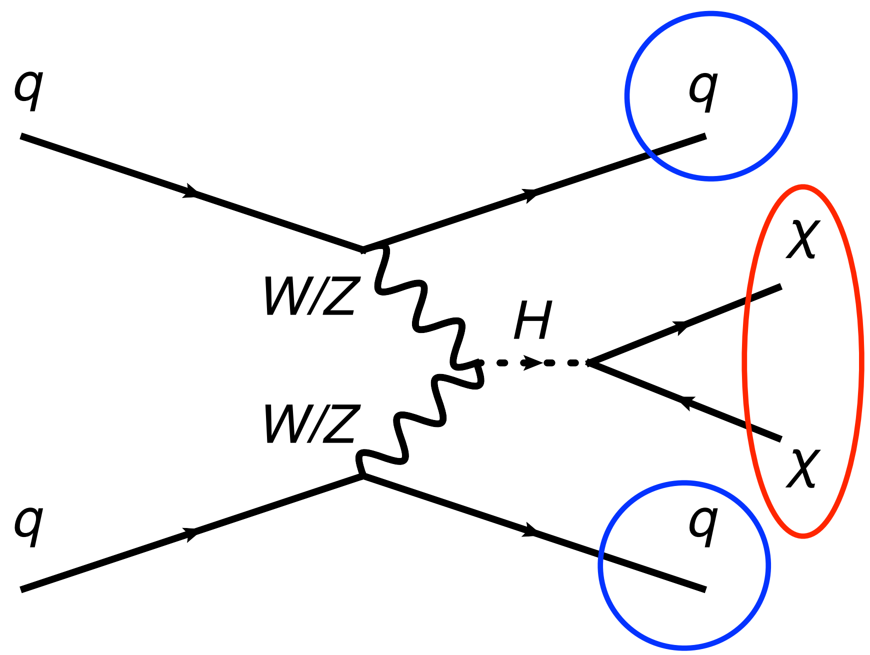
Invisible Decay of Higgs

BSM decay of Higgs boson to dark matter. Expected from Supersymmetry, etc.

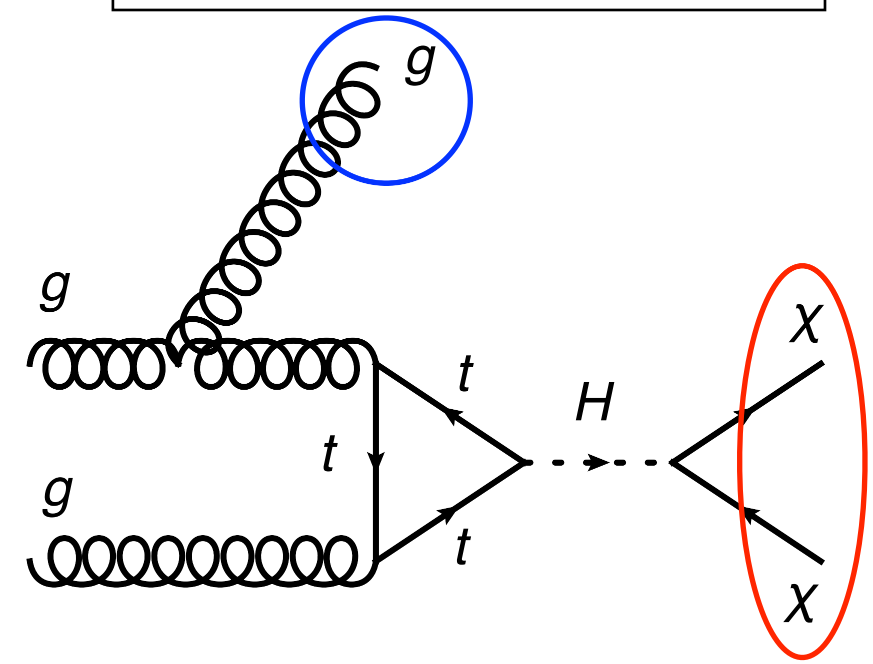
ZH Associated Production



Vector-Boson Fusion



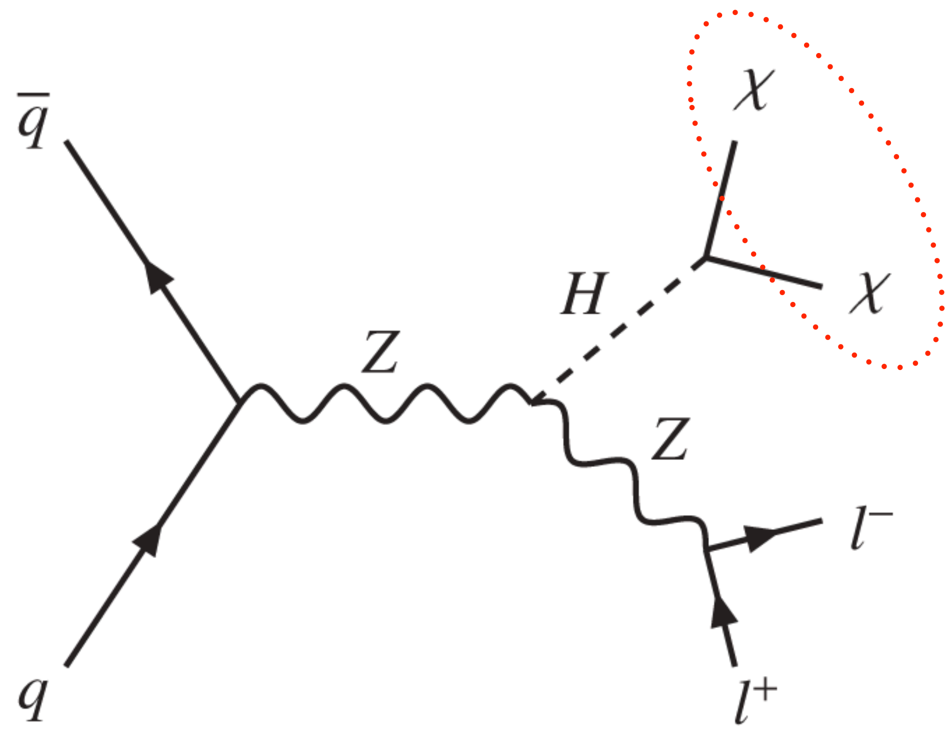
Gluon-Gluon Fusion



- To search for invisibly decaying Higgs boson, we need “visible” particles produced along with the Higgs to search for such phenomenon.
- **ZH associated & vector-boson fusion** channels are highly sensitive to the invisible Higgs decay. **ZH especially has a “clean” signature.**

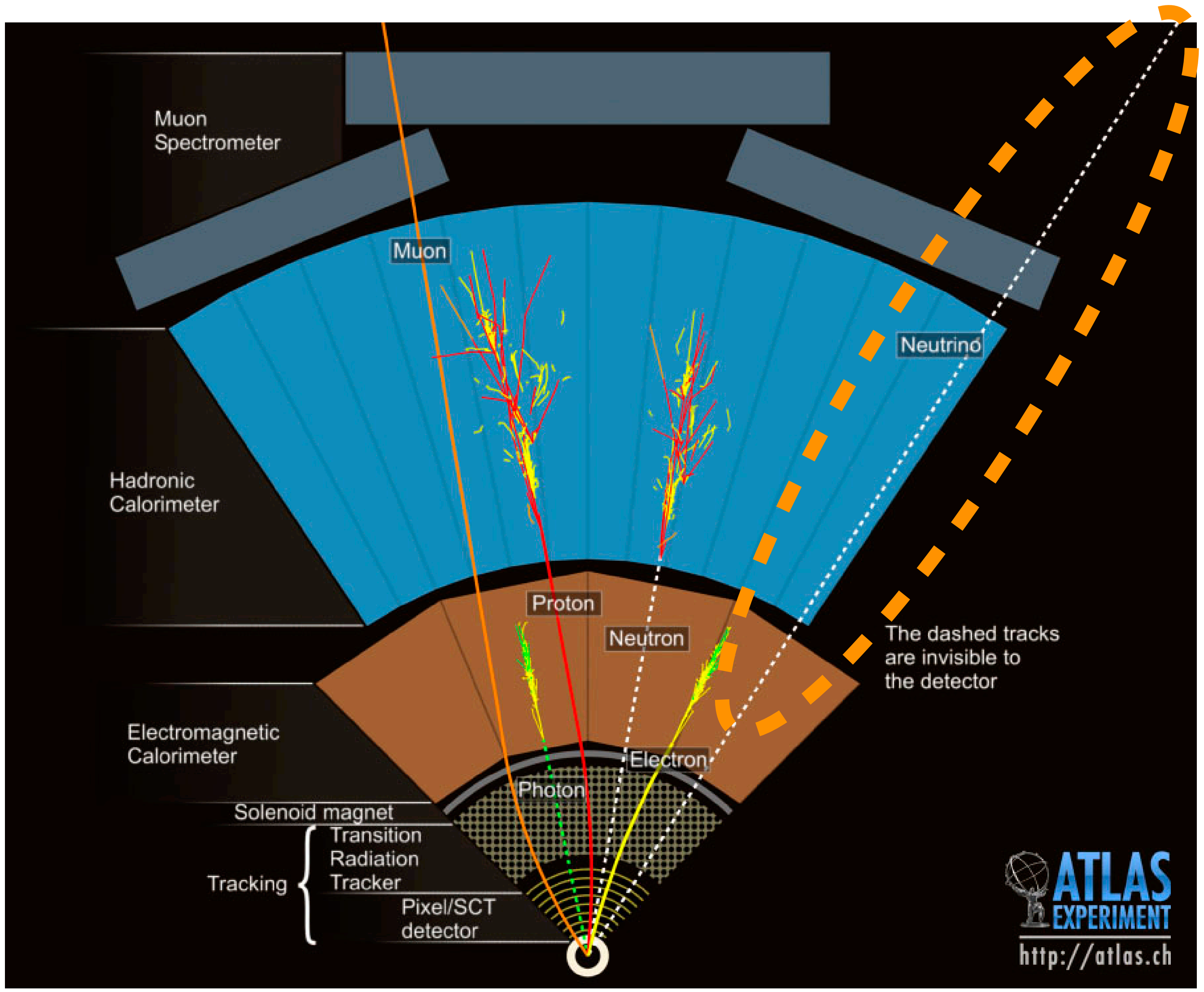
Analysis Strategy

"Z(→e^+e^-,$\mu^+\mu^-$)+Missing E_T"
Topology

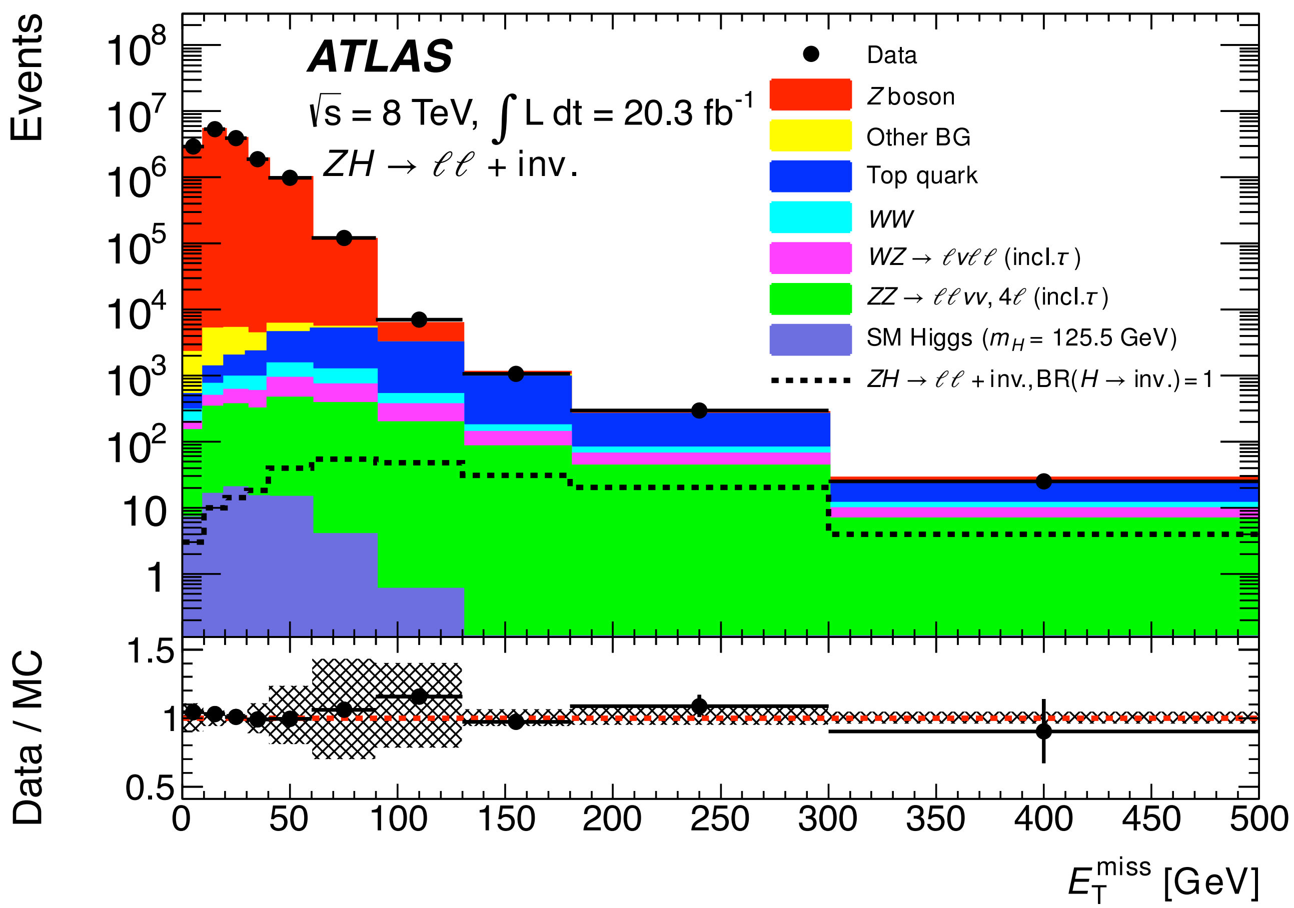


Missing E_T (E_T^{miss}): Momentum imbalance in the plane perpendicular to the beam line.

Schematic view of ATLAS detector (transverse plane)



Event Selection



- **Understanding of Missing E_T & suppression of Z BG** (cross section is $\mathcal{O}(10^4{\sim}10^5)$ higher than signals) are the key components.
- Event selection was carefully optimized to suppress the Z BG & still keep good signal acceptance.

- **e^+e^- or $\mu^+\mu^-$ w/ $76 < M_{ll} < 106$ GeV; 3rd lepton veto (p_T>7 GeV)**
- **$d\phi(l,l) < 1.7$**
- **Jet veto** (w/ p_T>25 GeV)

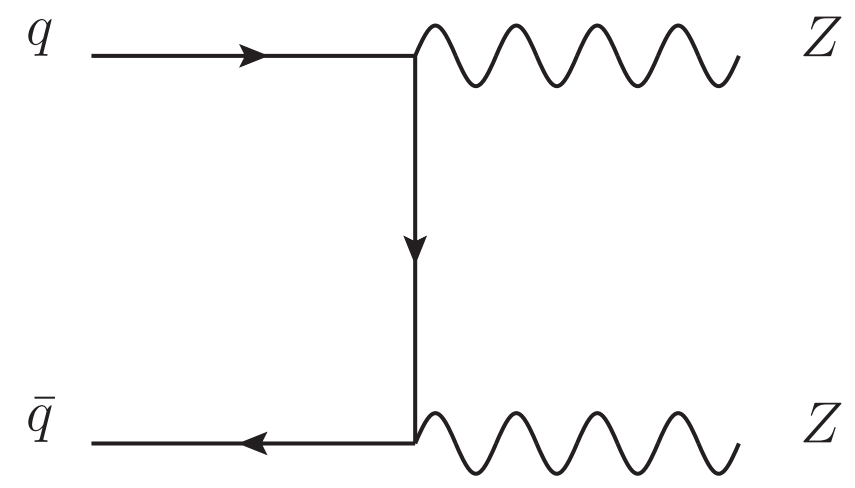
p_T^{miss}: Missing E_T reconstructed from ID tracks

- **$E_T^{miss} > 90$ GeV**
- **$d\phi(E_T^{miss}, p_T^{miss}) < 0.2$**
- **$|E_T^{miss} - p_T^{ll}| / p_T^{ll} < 0.2$**
- **$d\phi(Z, E_T^{miss}) > 2.6$**

Backgrounds

BG size

- **ZZ($\rightarrow l^+l^-\nu\nu$):** Difficult to distinguish from the signals. Estimated with Monte Carlo (MC) simulation.



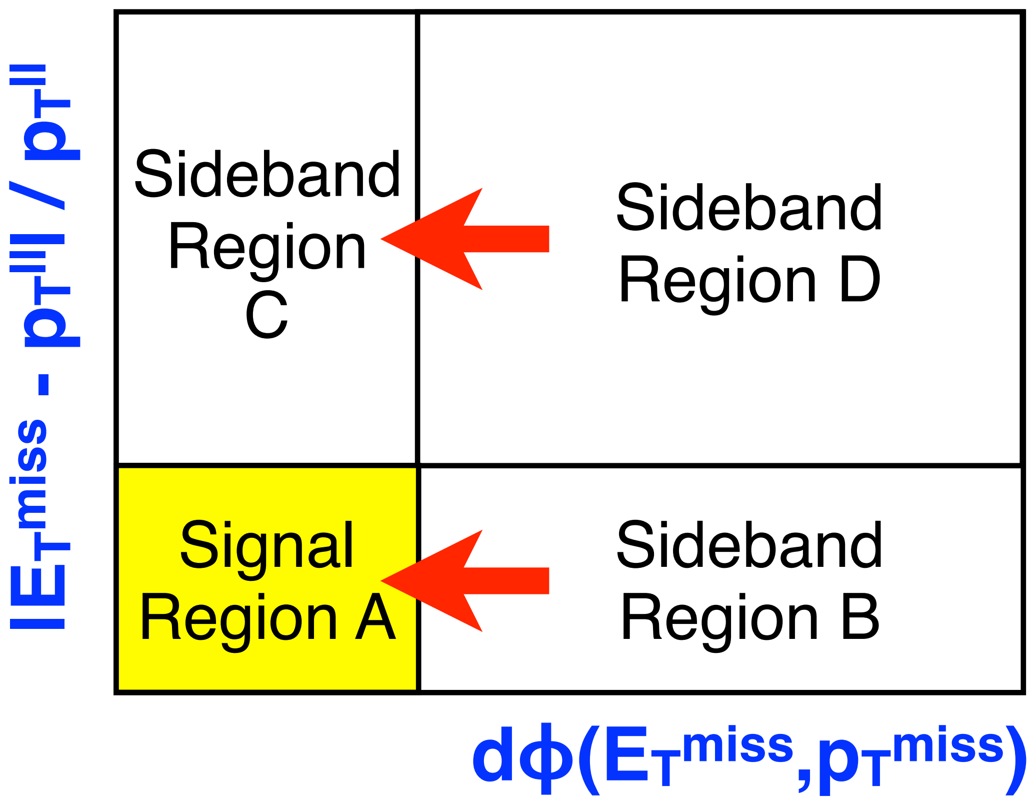
- **WZ:** Estimated with MC. Validated in a 3-lepton control region (CR).
- **$W^+W^-/t\bar{t}$&$Wt/Z(\rightarrow\tau^+\tau^-)$:** Estimated with data using e-μ CR.
- **Z+jets:** Estimated with data.

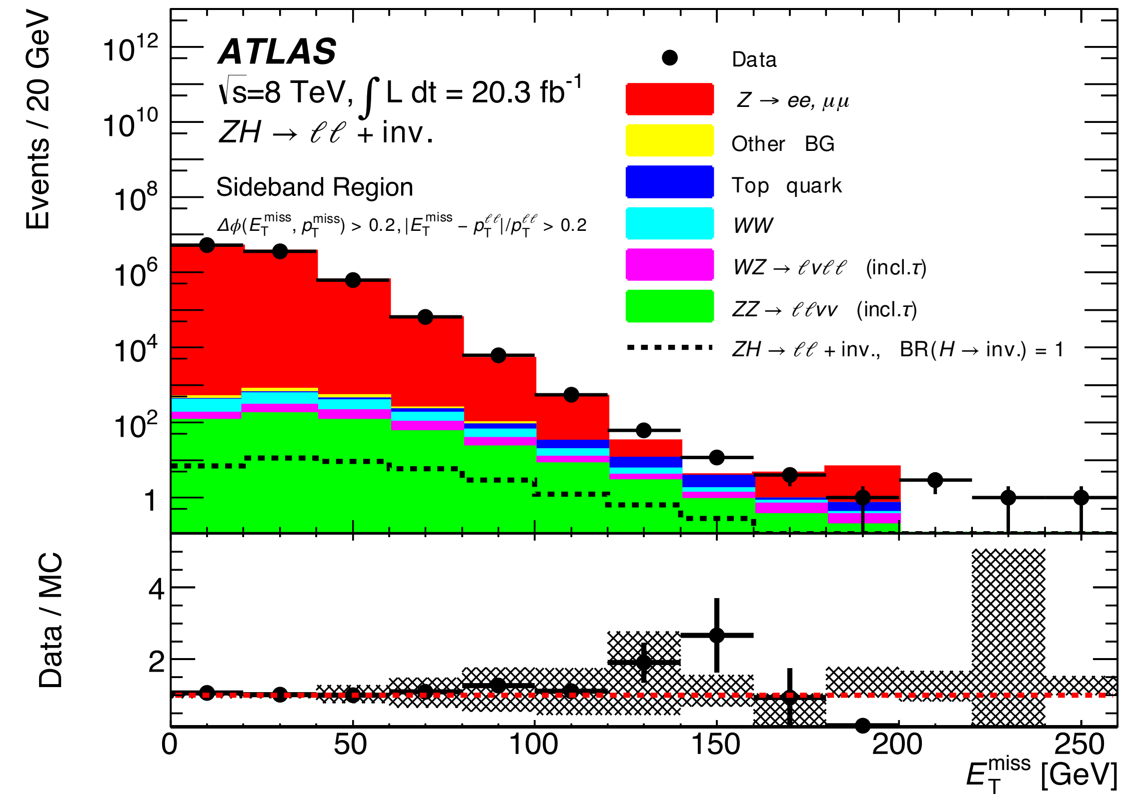
Z BG is suppressed to this level due to optimized event selection

- **W+jets/multijet:** Estimated with data. Almost negligible.

Z Background

Difficult to model with MC. Estimated with data.





Sideband regions: Z BG-enhanced.

$$N_A^{est} = N_B^{obs} \times \frac{N_C^{obs}}{N_D^{obs}} \times \alpha$$

N_C/N_D~0.1, α=1.07 (2011), 1.04 (2012)

	Z BG
2011	0.13 ± 0.12 (stat) ± 0.07 (sys)
2012	0.9 ± 0.3 (stat) ± 0.5 (sys)

Systematics uncertainties from the stability of N_A/N_B & N_C/N_D ratios, subtraction of non-Z background

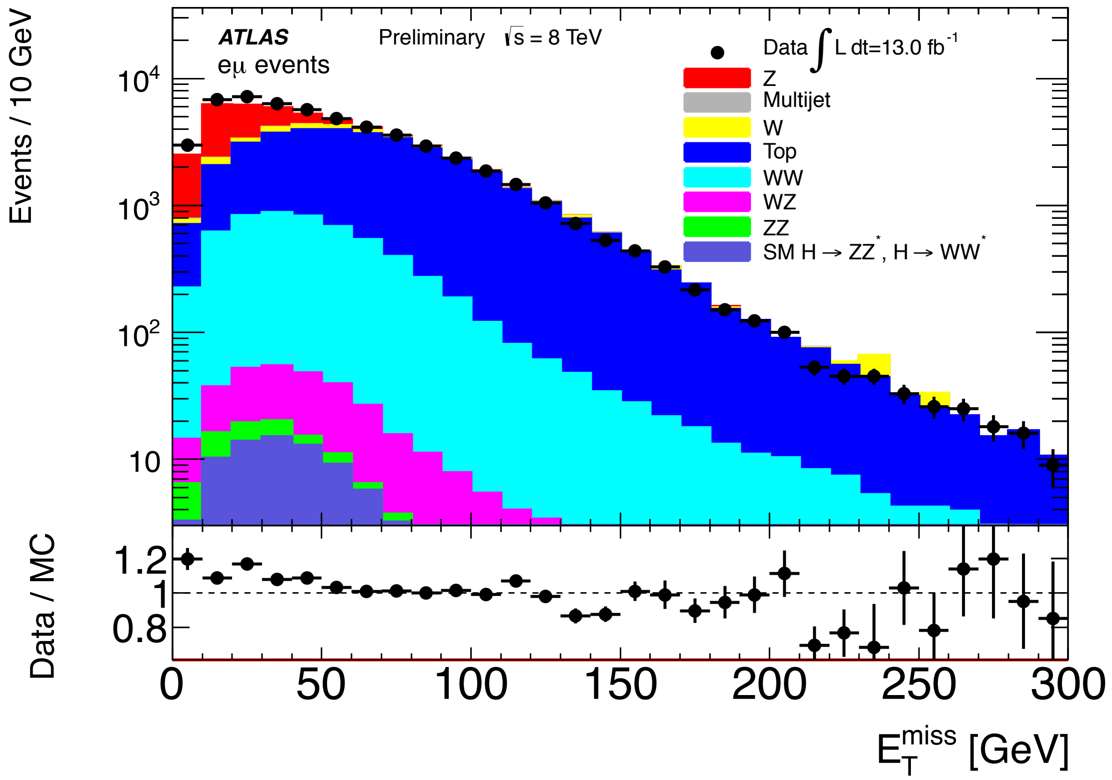
WW/Top/Zτ⁺τ⁻ Backgrounds

- **Make use of the lepton flavor symmetry ($e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$) in $W^+W^-/t\bar{t}, Wt/Z(\rightarrow\tau^+\tau^-)$ events.**

$$N_{ee}^{BG,est.} = \frac{1}{2} \times N_{e\mu}^{data,sub} \times k$$

$$N_{\mu\mu}^{BG,est.} = \frac{1}{2} \times N_{e\mu}^{data,sub} \times \frac{1}{k}$$

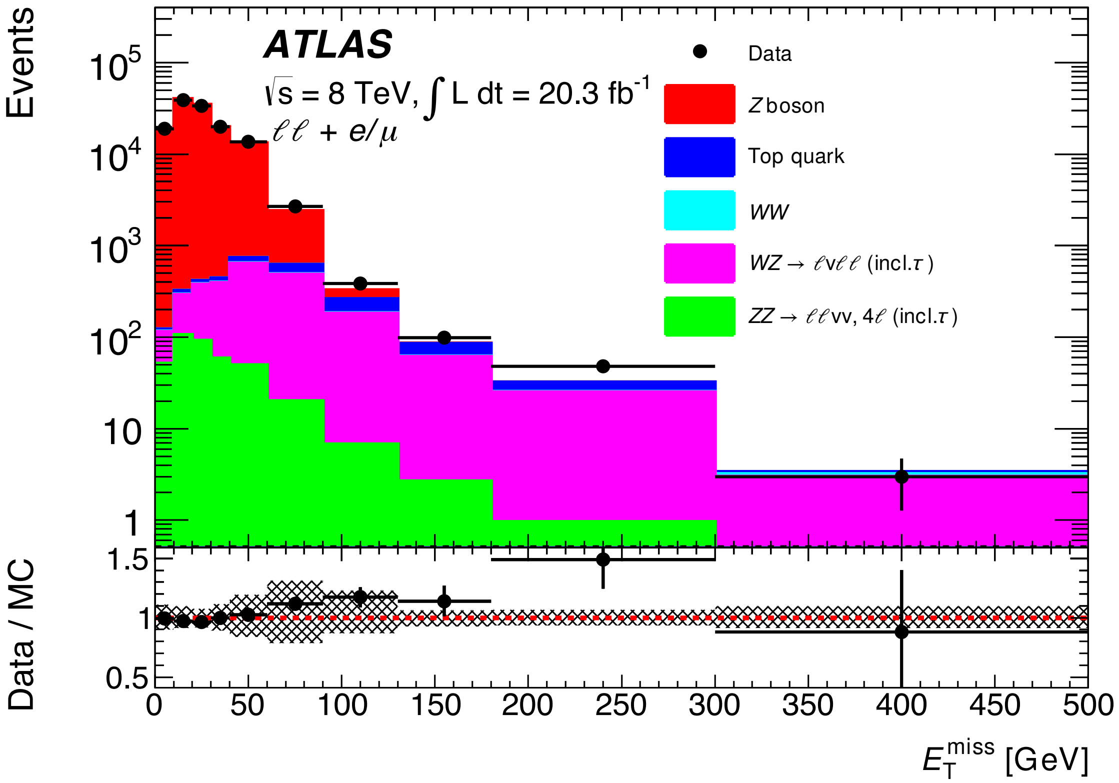
$$k = \sqrt{\frac{N_{ee}^{data}}{N_{\mu\mu}^{data}}}$$



- $N_{e\mu}^{BG,est}$: estimated background yields.
- $N_{e\mu}^{data,sub}$: events in the CR, but contributions from non-WW/Top/Z ($\rightarrow\tau\tau$) BG are subtracted with MC.
- k-efficiency factor & MC subtraction are the main source of systematics.

	2011	2012
WW/Top/Z($\rightarrow\tau^+\tau^-$)	0.5 ± 0.4 (stat) ± 0.1 (sys)	20 ± 3 (stat) ± 5 (sys)

WZ/ZZ Backgrounds

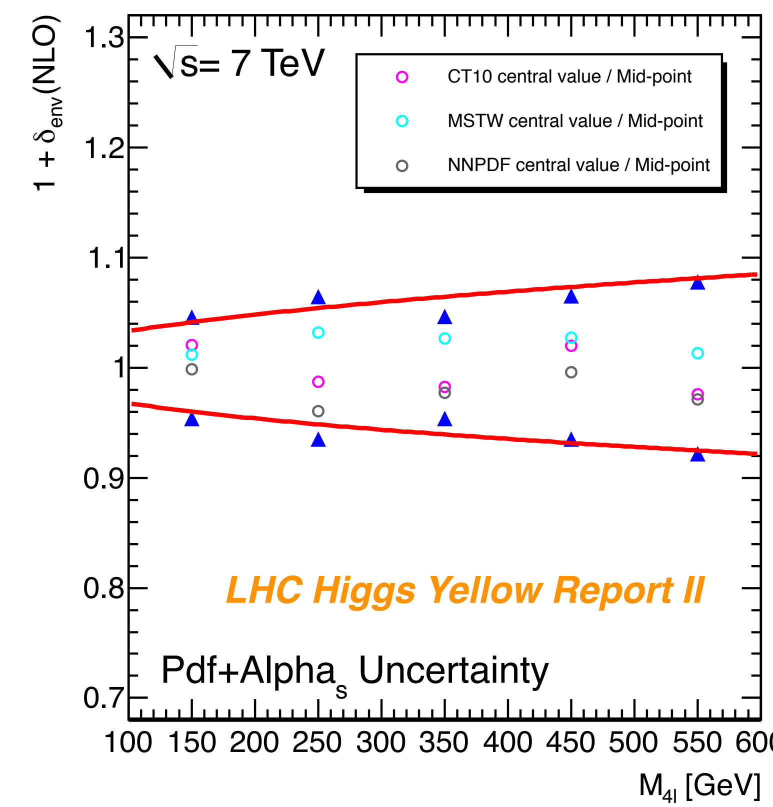


- WZ/ZZ are both estimated with MC. WZ MC is validated in the 3-lepton CR.
- NLO theory & ATLAS measurement agree well for the ZZ cross section.

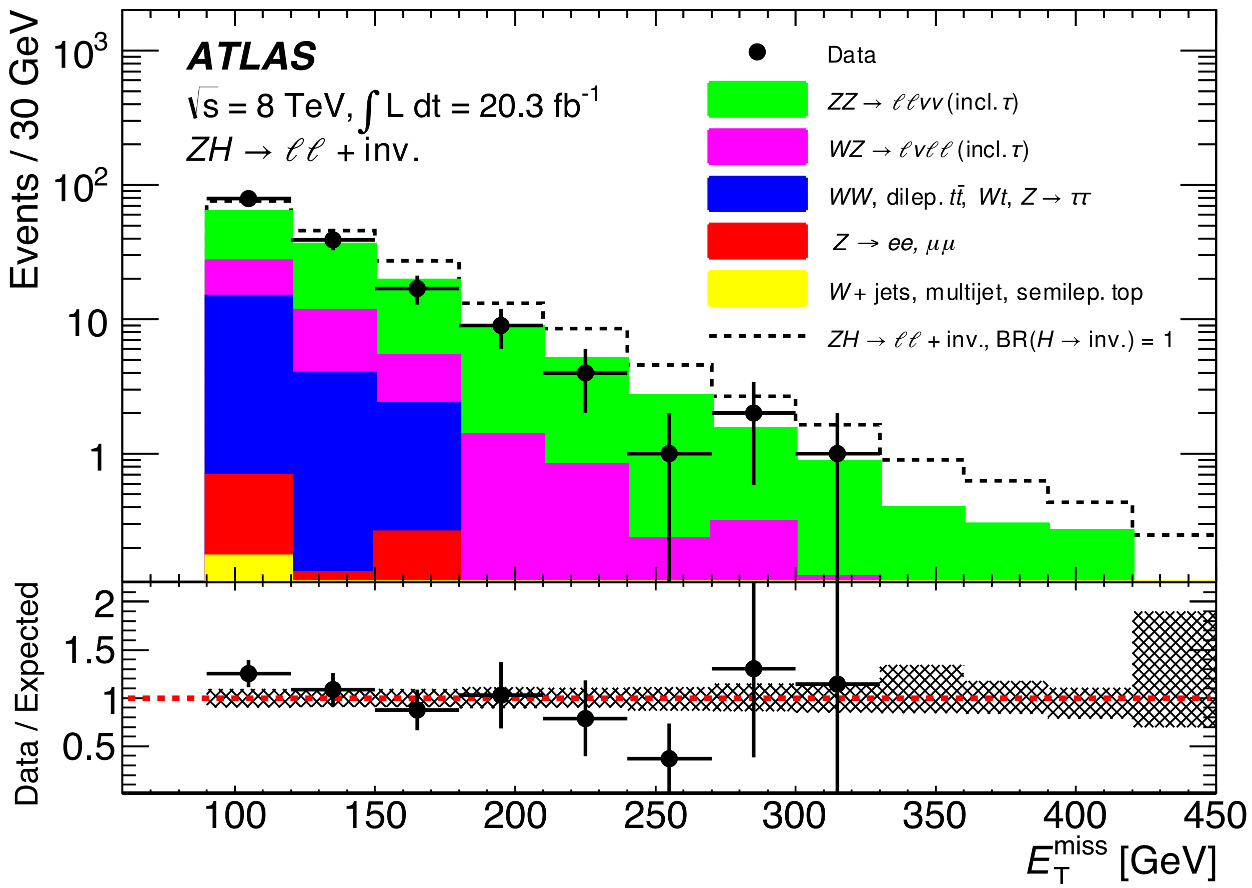
$$\sigma^{\text{measured}}(ZZ) = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst}) \pm 0.2(\text{lumi.})\text{pb}$$
$$\sigma^{\text{NLO}}(ZZ) = 7.2^{+0.3}_{-0.2}\text{pb}$$

ATLAS-CONF-2013-020

- Lepton scale & resolution: 1.0-1.5%.
  Jet energy scale & resolution: 3-6%.
- PDF & scale uncertainty: ~5%.
- gg→WW/ZZ→l⁺l⁻νν diagram is also considered (~3% of qq→ZZ)。



Results



<u>No significant excess from the Standard Model expectation</u>

- **Obtained limits on the invisible branching fraction BR(H→inv) < <u>75% observed (63% expected) @ 95% confidence level</u>.**

~20% better expected limit than CMS

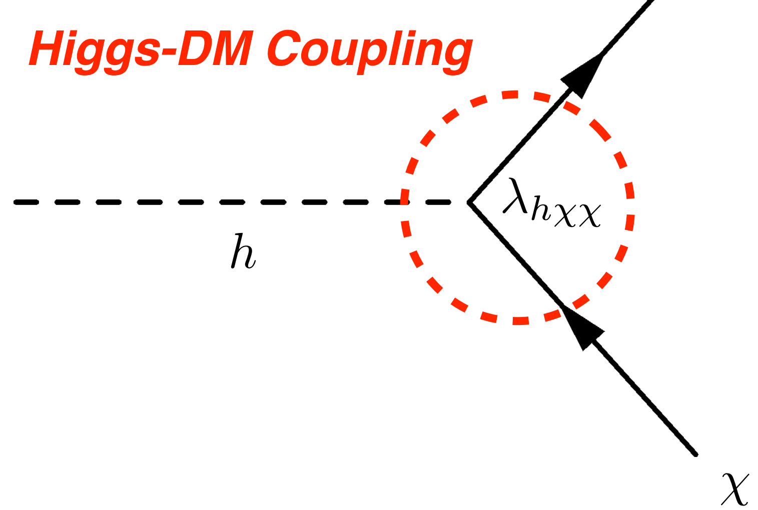
- First results at the LHC on the invisible decay of the Higgs boson!

Data Period	2011 (7 TeV)	2012 (8 TeV)
$ZZ \to \ell\ell\nu\nu$	$20.0 \pm 0.7 \pm 1.6$	$91 \pm 1 \pm 7$
$WZ \to \ell\nu\ell\ell$	$4.8 \pm 0.3 \pm 0.5$	$26 \pm 1 \pm 3$
Dileptonic $t\bar{t}$, Wt, WW, $Z \to \tau\tau$	$0.5 \pm 0.4 \pm 0.1$	$20 \pm 3 \pm 5$
$Z \to ee$, $Z \to \mu\mu$	$0.13 \pm 0.12 \pm 0.07$	$0.9 \pm 0.3 \pm 0.5$
W + jets, multijet, semileptonic top	$0.020 \pm 0.005 \pm 0.008$	$0.29 \pm 0.02 \pm 0.06$
Total background	$25.4 \pm 0.8 \pm 1.7$	$138 \pm 4 \pm 9$
Signal ($m_H = 125.5$ GeV, $\sigma_{SM}(ZH)$, BR($H \to$ inv.) = 100%)	$8.9 \pm 0.1 \pm 0.5$	$44 \pm 1 \pm 3$
Observed	28	152

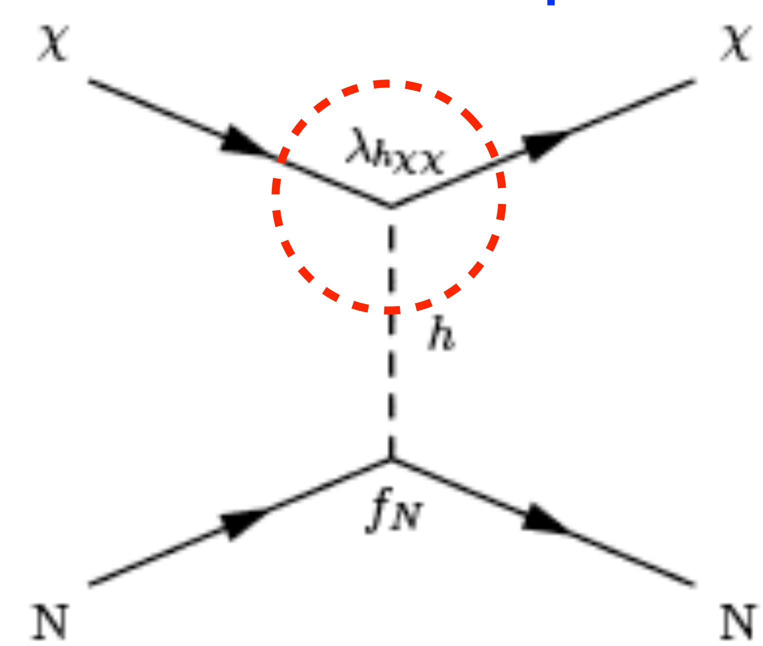
Dark Matter Interpretation

Higgs-portal model: Assume that the DM only interacts with the Higgs boson.
Predicts very small DM-nucleon cross section & matches with various experimental results.

Seach at the LHC



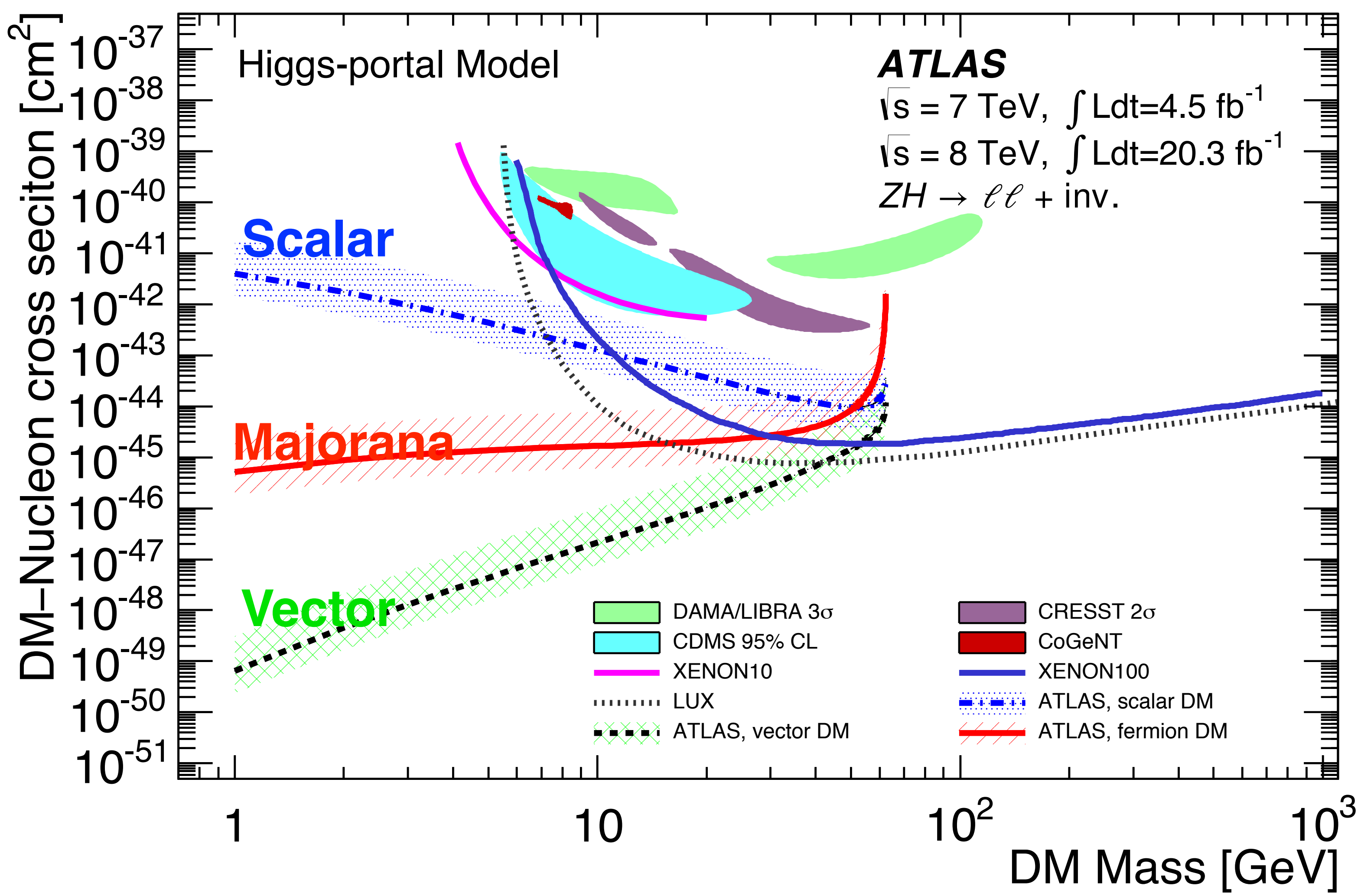
Direct detection experiments



Higgs Invisible Decay		Higgs-DM Coupling		DM-Nucleon Cross Section
$\Gamma(h \to \chi\chi)$	$\Leftrightarrow$	$\lambda^2_{h\chi\chi}$	$\Leftrightarrow$	$\sigma_{N\chi}$

$$BR(h \to \chi\chi) = \frac{\Gamma(h \to \chi\chi)}{\Gamma(h \to \chi\chi) + \Gamma(h \to SM)}$$

Higgs-Portal Model



The ATLAS bands show the uncertainties on the Higgs-nucleon form factor

- Mapped the BR(H→inv) limit to Higgs-portal DM interpretation.
- LHC has very good sensitivity in $m_{DM} < m_H/2$ region & provides complementary results to the direct detection experiments.

Summary

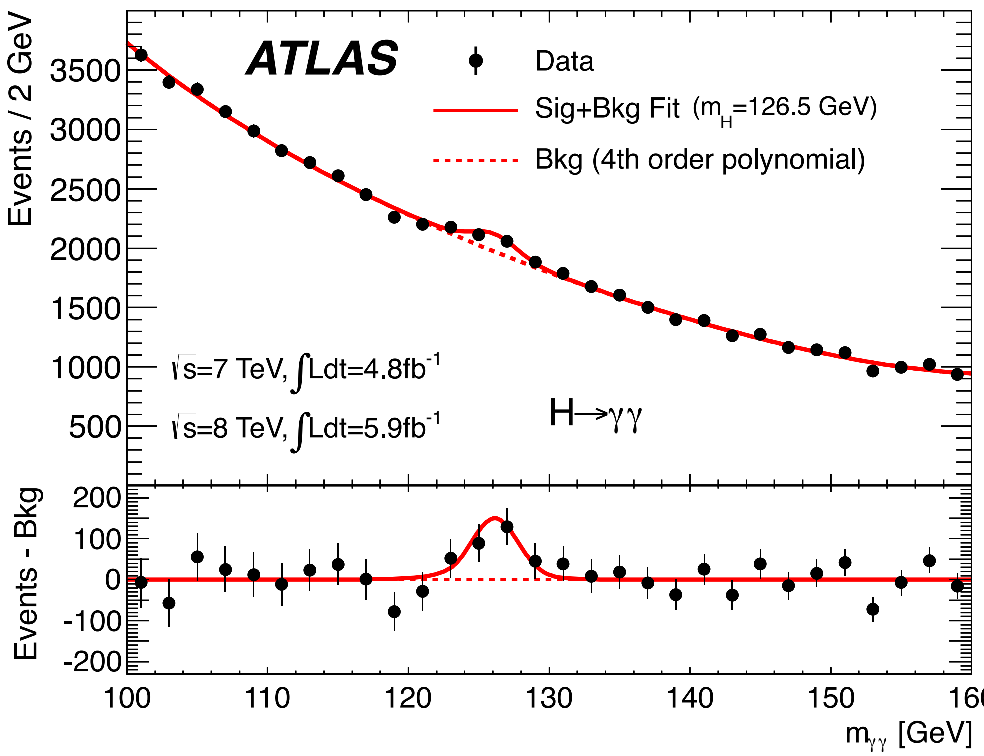
- Searched for the Higgs boson decaying to dark matter with the ATLAS detector at the LHC using the full $\sqrt{s}$=7 & 8 TeV datasets.
- No significant excess is observed for both years. Obtained limits of BR(H→inv.)<75% (observed), 63% (expected) with 95% confidence level.
- BR(H→inv.) limit was interpreted with Higgs-portal dark matter scenarios. We have a very good sensitivity in $m_{DM}<m_H/2$ region & exceeds the limits from the direct detection experiments.
- Prospects:
  - With 300 (3000) fb^{-1} of the 14 TeV LHC data, the ZH channel will have sensitivity of BR(H→inv.)~10, 20%. Combining with other channels would even enhance the sensitivity & will reach the interesting region for the supersymmetry.

backups

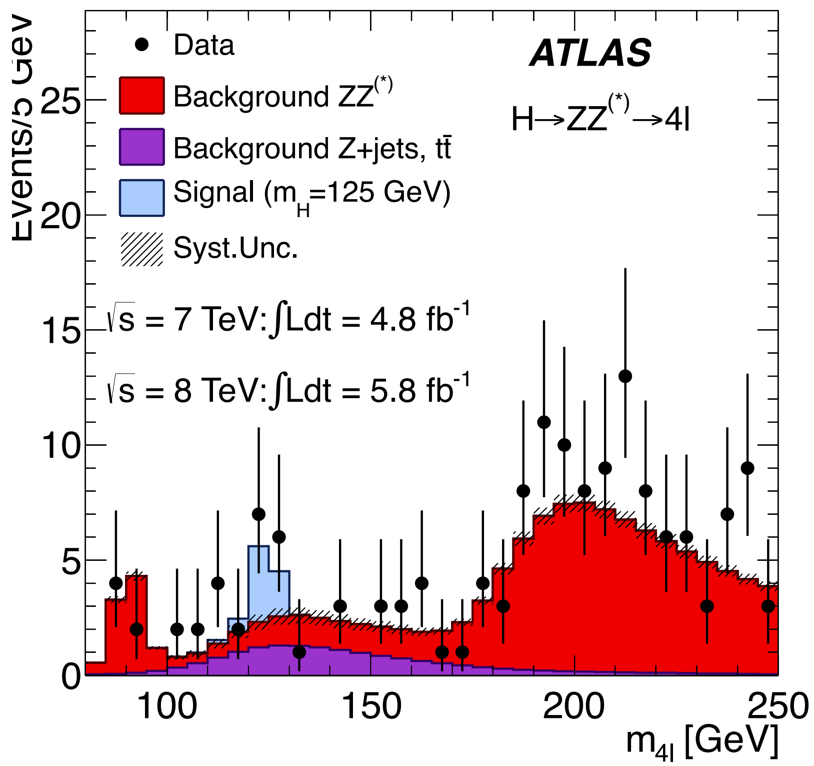
Discovery of Higgs Boson (2012)

Phys. Lett. B 716 (2012) 1

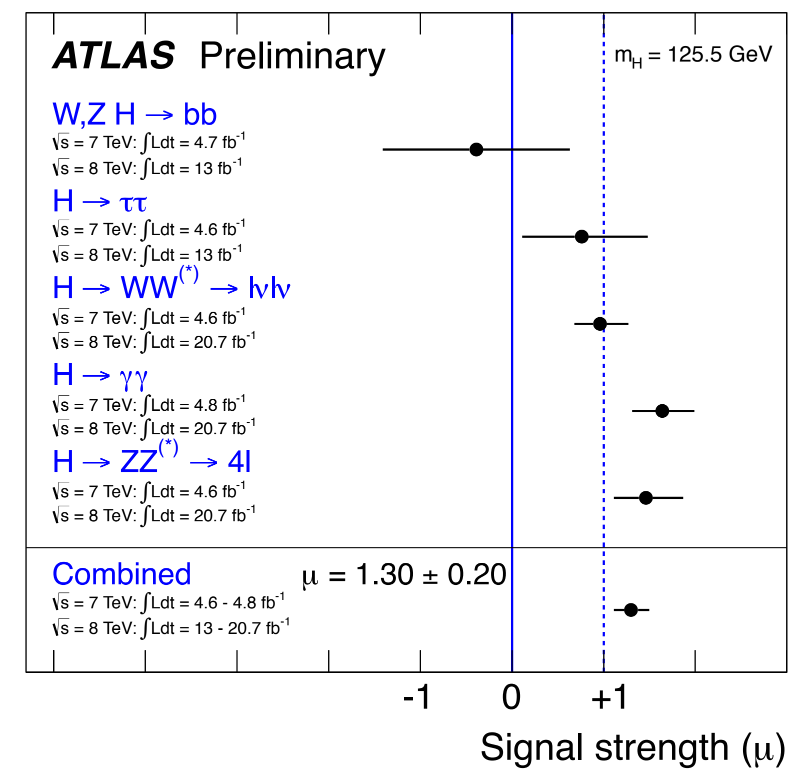
Diphoton Invariant Mass



4-lepton Invariant Mass

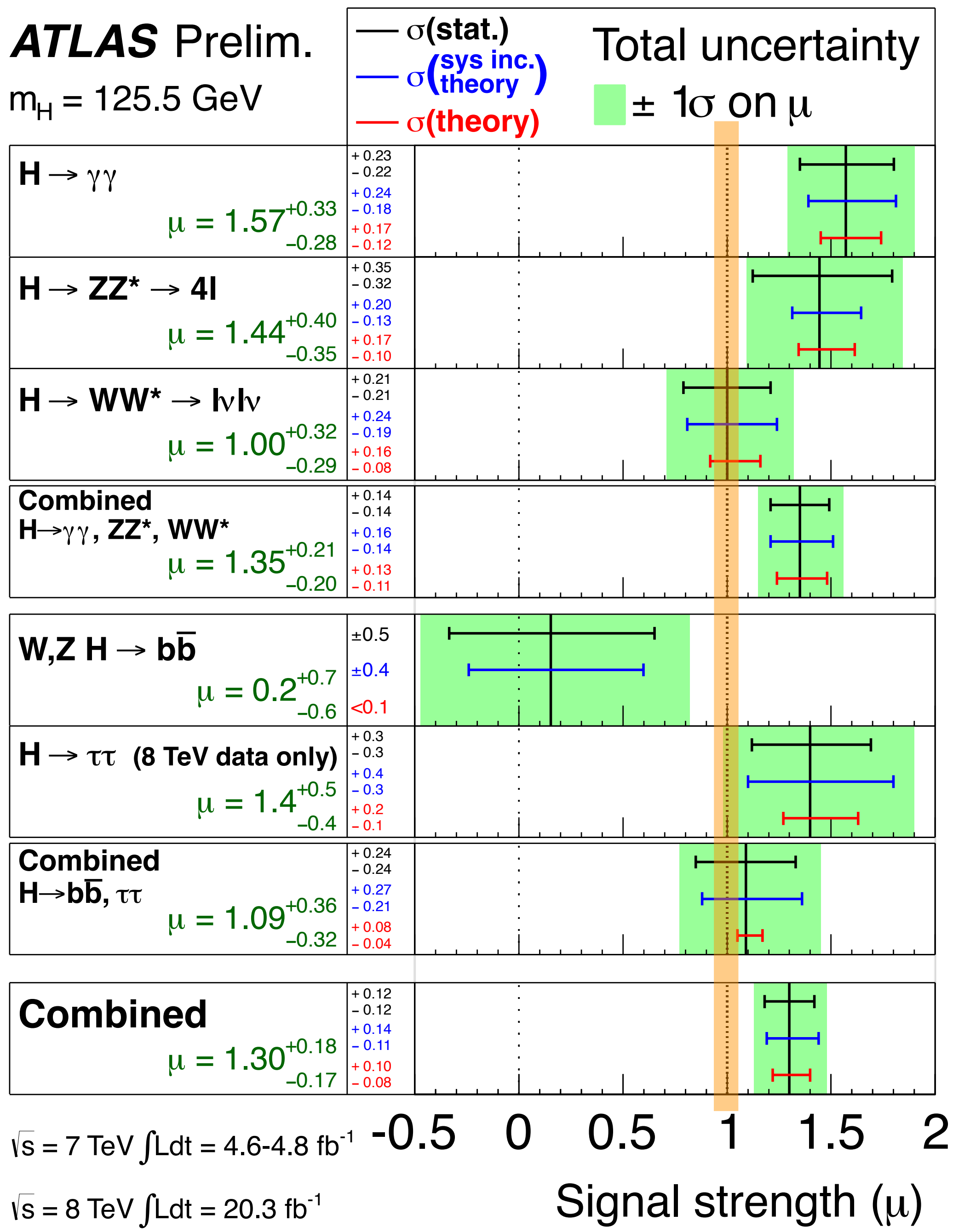


Signal Strength



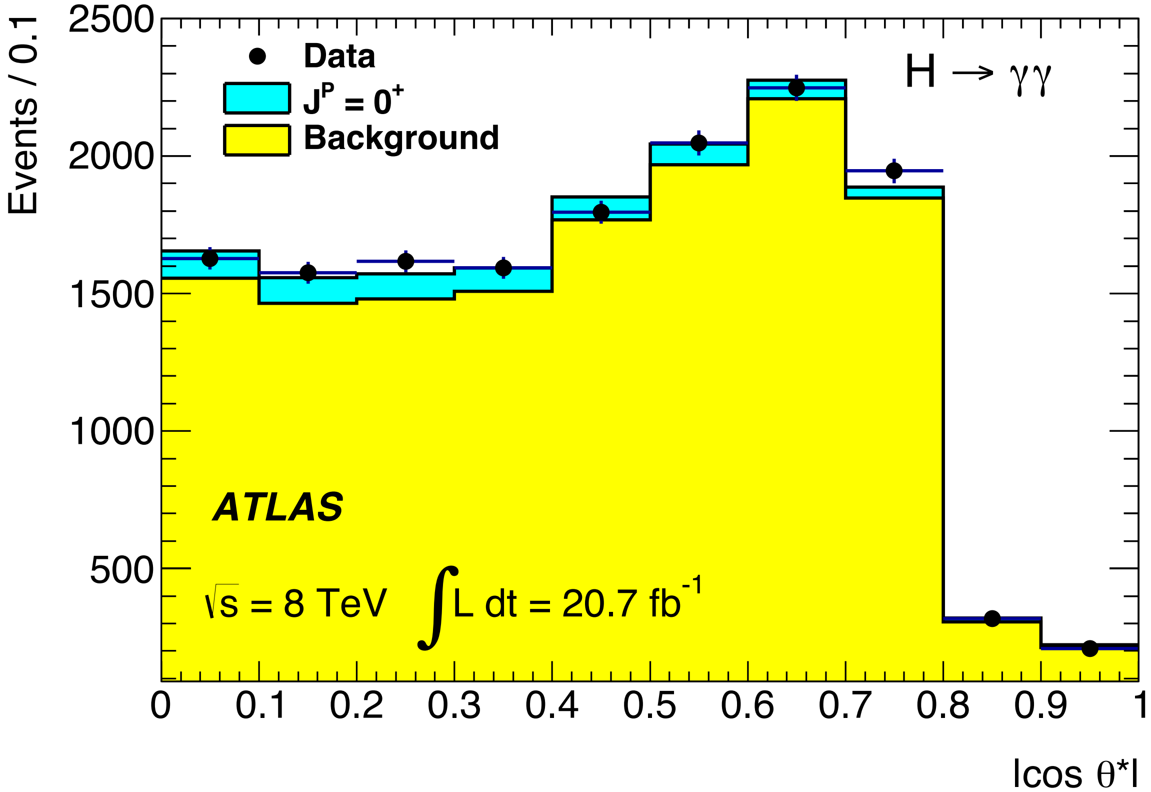
- In July 2012, we discovered a particle at ~125 GeV, **consistent with a Standard Model Higgs boson**.
  → signal strengths in H→γγ,ZZ,WW,ττ,bb & spin/parity results later in 2013.
- Further investigations are needed to confirm whether there is a sign of physics beyond the Standard Model (BSM) in the Higgs sector.

Standard Model Higgs?



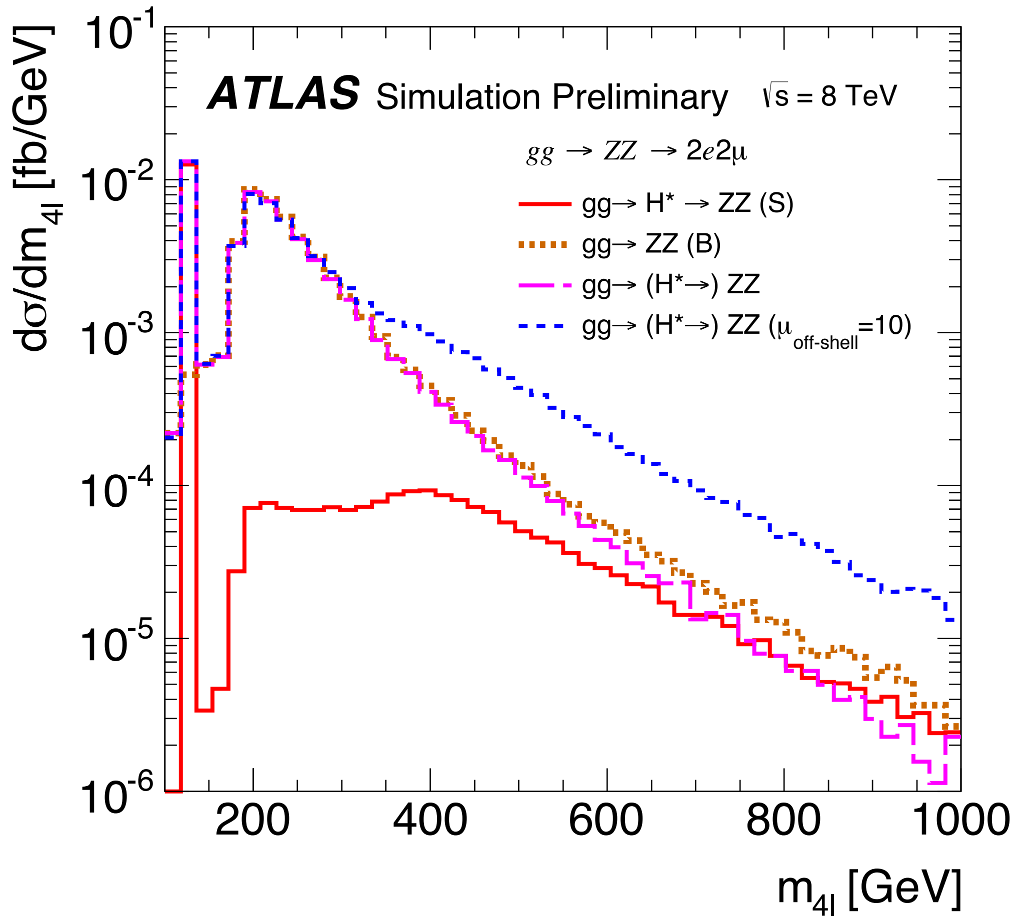
ATLAS-CONF-2014-009 (2014)

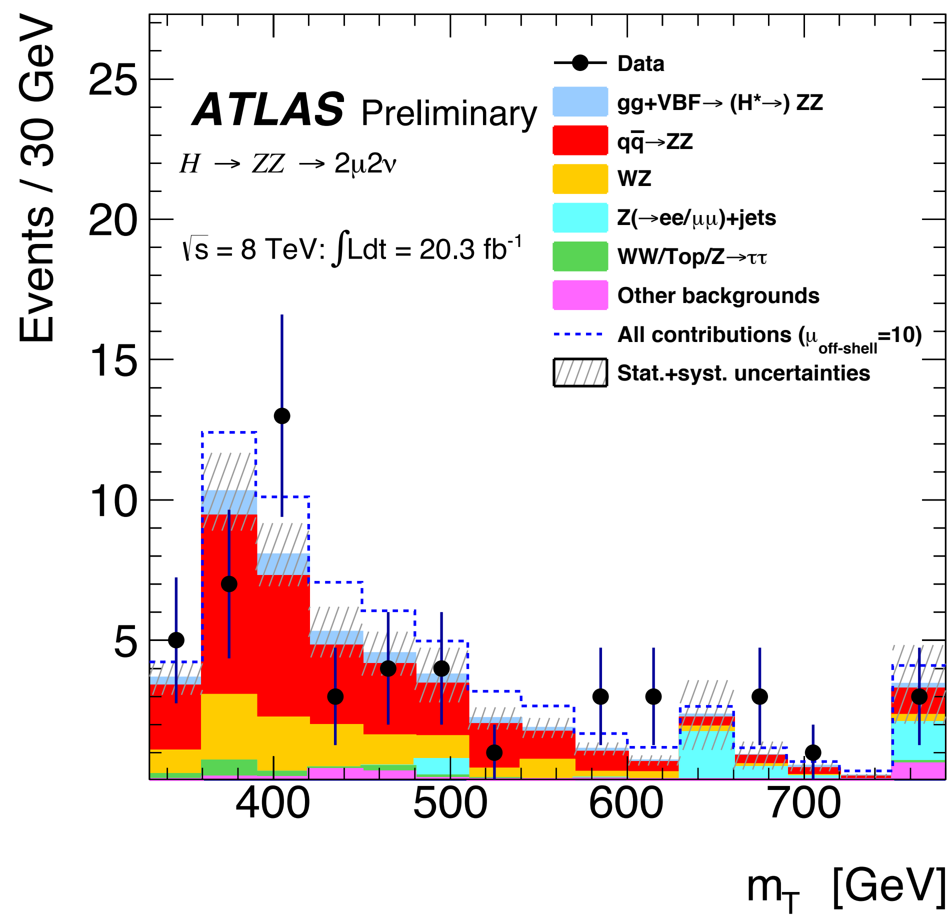
Phys. Lett. B 726 (2013), 120



Higgs Width Measurement

ATLAS-CONF-2014-042





	Observed			Median expected			Alternative hypothesis
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0	
$\mu_{\text{off-shell}}$	5.6	**6.7**	9.0	6.6	**7.9**	10.7	$R^B_{H^*} = 1, \mu_{\text{off-shell}} = 1$
$\Gamma_H/\Gamma_H^{\text{SM}}$	4.1	**4.8**	6.0	5.0	**5.8**	7.2	$R^B_{H^*} = 1, \Gamma_H/\Gamma_H^{\text{SM}} = 1, \mu_{\text{on-shell}} = 1.51$
$\Gamma_H/\Gamma_H^{\text{SM}}$	4.8	**5.7**	7.7	7.0	**8.5**	12.0	$R^B_{H^*} = 1, \Gamma_H/\Gamma_H^{\text{SM}} = 1, \mu_{\text{on-shell}} = 1$

Higgs Width & Cross Section

$$\sigma_{i \longrightarrow H \longrightarrow f} \sim \frac{\kappa_i^2 \kappa_f^2}{\Gamma_H}$$

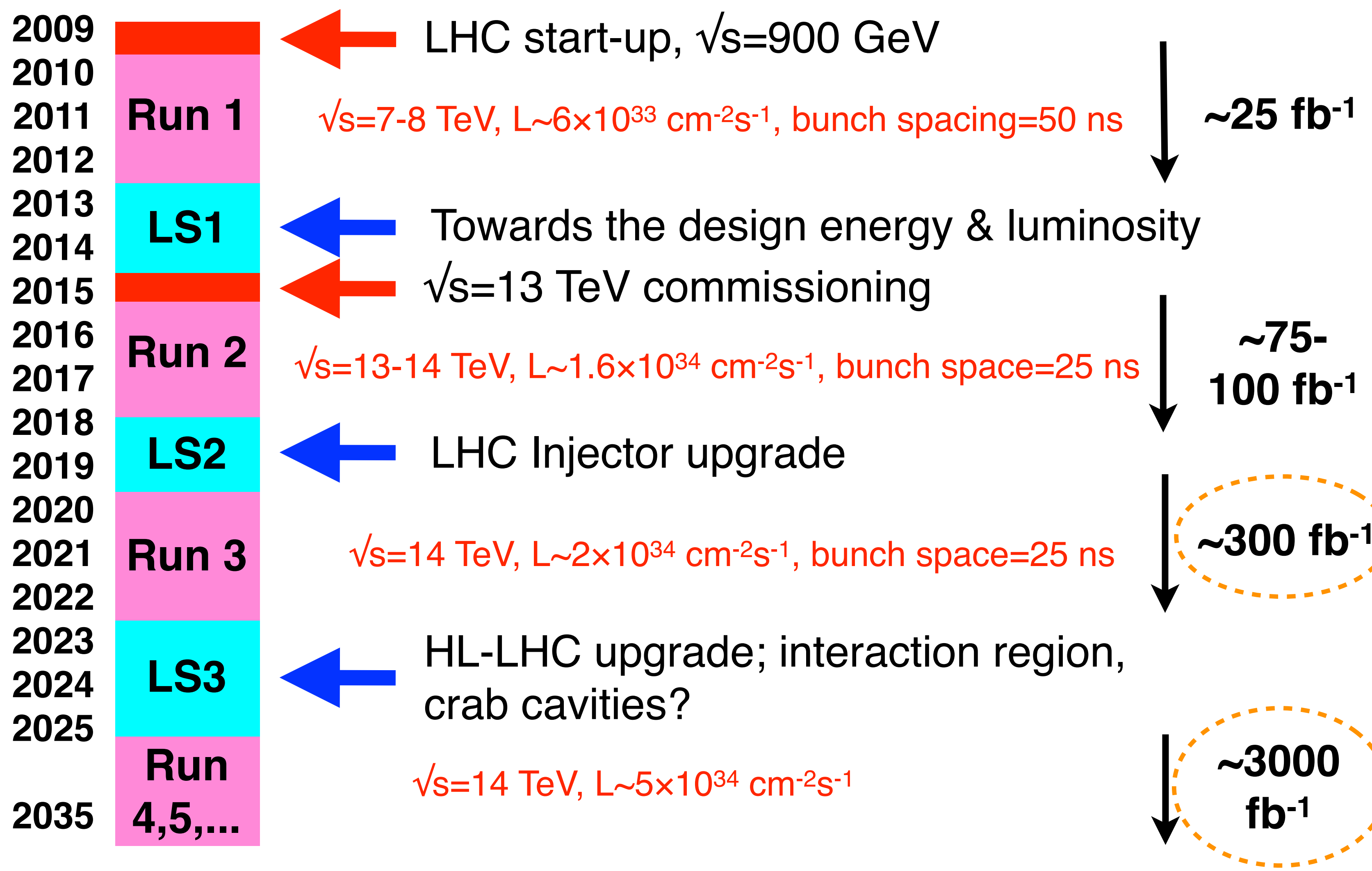
- $\sigma_{i \to H \to f}$: Cross section of Higgs produced with production process i & decays process f.
- κ_i: Higgs coupling to particle i
- κ_f: Higgs coupling to particle f
- Γ_H: Higgs width

LHC Program

LHC 13-14 TeV (2015-2022)

- $\sqrt{s}$=13-14 TeV.
- Will surpass the design luminosity in Run 2. Twice the design lumi. in Run 3.
- Expected integ. lumi. ~300 fb^{-1}

LHCC open meeting, Dec. 2013



HL-LHC 14 TeV (2025-2030s)

- $\sqrt{s}$=14 TeV.

σ(Higgs@LHC) > 50 pb w/ $\sqrt{s}$=14 TeV,
cf. σ(Higgs@e^+e^-)~ 0.2-0.3 pb w/ $\sqrt{s}$=250-500 GeV

- The luminosity will increase by a factor 5 from the initial design. Expected integ. lumi.~250-300 fb^{-1}/year & ~3000 fb^{-1} after a decade of operation.

LHC

Luminosity

$$L = \frac{f \cdot N^2}{4 \cdot \epsilon \cdot \beta^*}$$

f: Bunch crossing frequency, N: number of protons in a bunch,
ϵ: emittance, β*: amplitude function

CERN Courier, Aug. 2013

Parameter	2010	2011	2012	design value
Beam energy	3.5	3.5	4	7
β* in IP 1 and 5 (m)	2.0/3.5	1.5/1.0	0.6	0.55
Bunch spacing (ns)	150	75/50	50	25
Max. number of bunches	368	1380	1380	2808
Max. bunch intensity (protons per bunch)	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized emittance at start of fill (mm mrad)	≈2.0	≈2.4	≈2.5	3.75
Peak luminosity ($cm^{-2}s^{-1}$)	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1×10^{34}
Max. mean number of events per bunch crossing	4	17	37	19
Stored beam energy (MJ)	≈28	≈110	≈140	362

F.Bordry, LHCC Open Meeting, Dec. 2013

	Number of bunches	Intensity per bunch	Transverse emittance	Peak luminosity	Pile up	Int. yearly luminosity
25 ns BCMS	2508	1.15×10^{11}	1.9 μm	1.6×10^{34} $cm^{-2}s^{-1}$	~43	~42 fb^{-1}

and $\beta^* \leq 0.5$ m

Detector Upgrades

To cope with the radiation damage of detector components, limitation of bandwidth, improve granularity & coverage

Phase-0 upgrade (2013-2014)

- ATLAS: Insertable B-layer (IBL), Level-1 topological trigger, Fast Track Trigger (FTK)
- CMS: 4th muon end-cap station, new detector consolidation

Phase-1 upgrade (2018-2019)

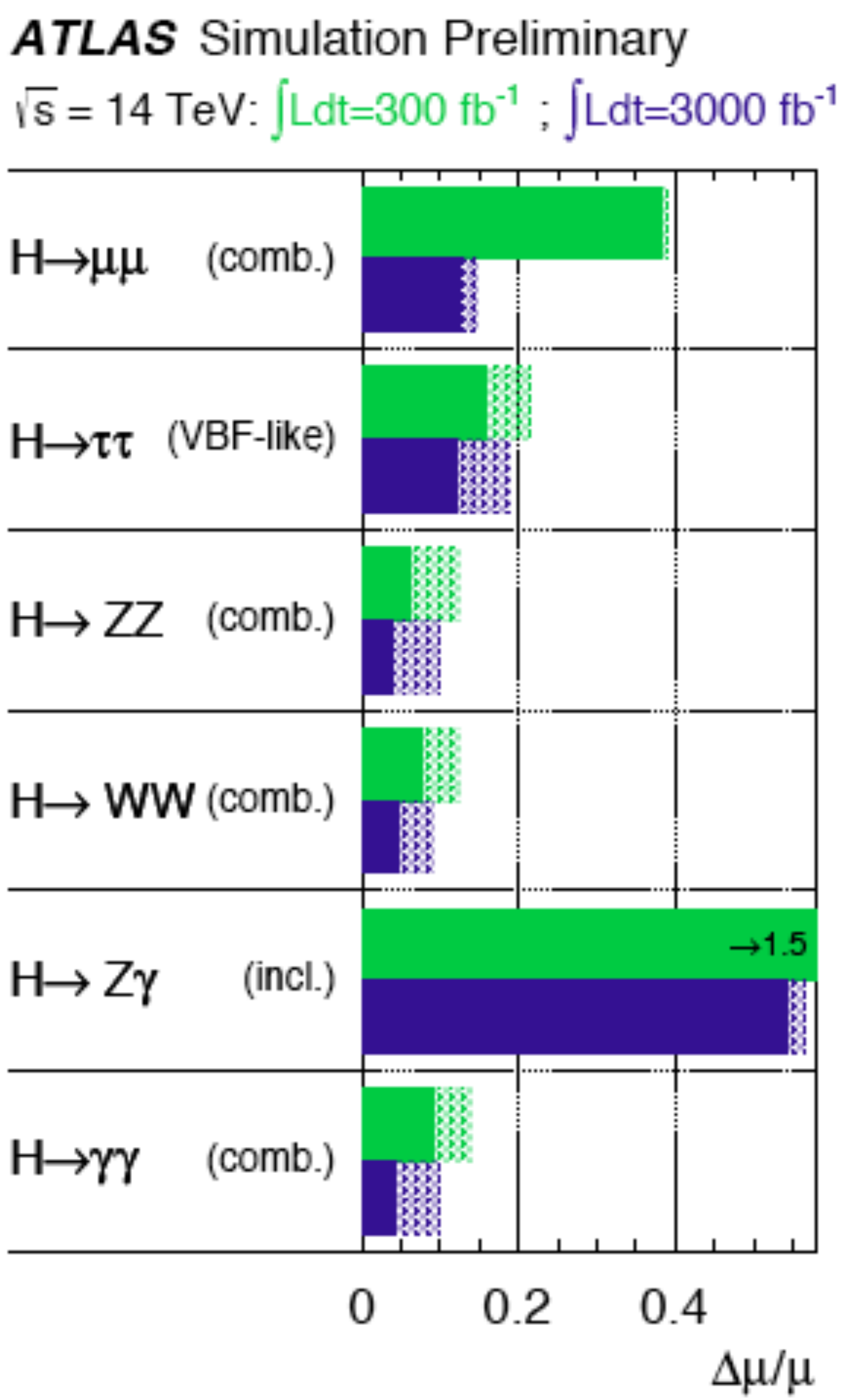
- ATLAS: High granularity Level-1 calorimeter trigger, New small wheel for Level-1 muon trigger
- CMS: New Level-1 trigger system, new pixel detector, new photo-detector & electronics for HCAL

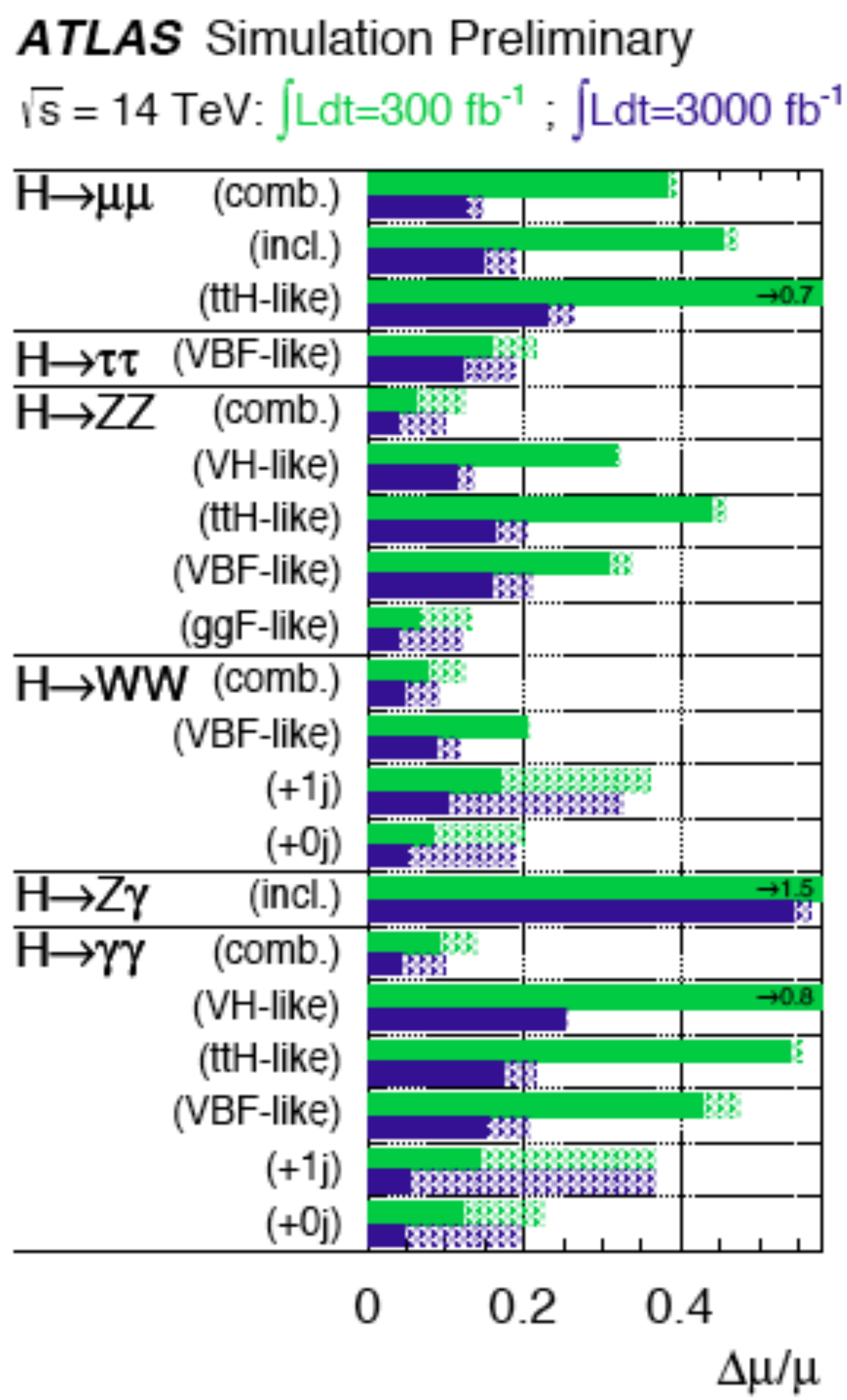
Phase-2 upgrade (2023-2025)

- ATLAS: New silicon tracker & forward calorimeter & electronics, level-1 track trigger
- CMS: New tracker with Level-1 capability, DAQ/HLT upgrade, replace end-cap & forward calo; possibly extension of muon coverage & EM preshower system

Signal Strengths

ATL-PHYS-PUB-2013-014





Coupling Scale Factors

CMS

ATL-PHYS-PUB-2013-014, CMS NOTE-13-002

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

ATLAS

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	3.2%	2.7%	2.5%	2.5%	1.9%	1.6%
2	$\kappa_V = \kappa_Z = \kappa_W$	3.3%	2.8%	2.7%	2.6%	1.9%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.6%	7.5%	7.1%	4.1%	3.5%	3.2%
3	κ_Z	8.4%	7.3%	6.8%	6.3%	5.0%	4.6%
	κ_W	8.0%	6.7%	6.2%	6.1%	4.8%	4.3%
	κ_t	11%	9.0%	8.3%	7.0%	5.6%	5.1%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	14%	13%	14%	11%	10%
	κ_μ	22%	20%	20%	10%	8.1%	7.5%
4	κ_Z	8.0%	7.0%	6.6%	5.2%	4.3%	4.0%
	κ_W	7.7%	6.8%	6.5%	4.9%	4.2%	3.9%
	κ_t	19%	18%	18%	7.7%	6.7%	6.3%
	$\kappa_d = \kappa_\tau = \kappa_\mu = \kappa_b$	16%	13%	12%	11%	8.2%	7.2%
	κ_g	8.9%	7.9%	7.5%	4.3%	3.8%	3.6%
	κ_γ	13%	9.3%	7.8%	9.3%	5.9%	4.2%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%
5	κ_Z	8.1%	7.1%	6.7%	6.2%	4.9%	4.4%
	κ_W	7.9%	6.9%	6.5%	5.9%	4.8%	4.4%
	κ_t	22%	20%	20%	10%	8.4%	7.8%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	15%	13%	15%	11%	9.7%
	κ_μ	23%	21%	21%	11%	8.5%	7.6%
	κ_g	11%	9.1%	8.5%	6.9%	5.5%	4.9%
	κ_γ	13%	9.3%	7.8%	9.4%	6.1%	4.6%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%

Yukawa Coupling

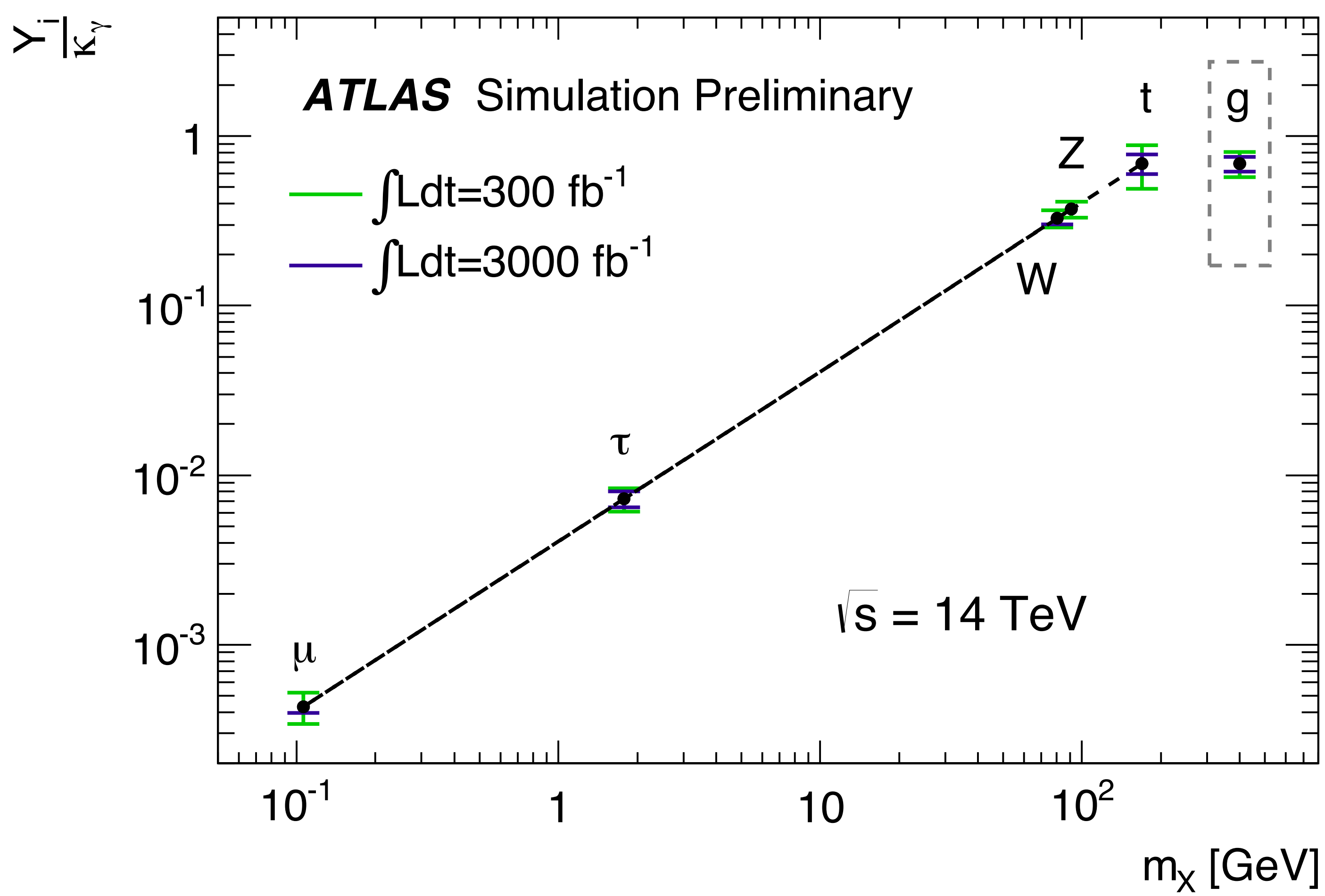
ATL-PHYS-PUB-2013-014

Yukawa Coupling

$$Y_f = \kappa_f \frac{m_f}{v}$$

$$Y_V = \kappa_V \frac{m_V}{v}$$

Y: Yukawa coupling, f: fermion, V: weak boson,
m: mass



Coupling Scale Ratios

CMS

L (fb^{-1})	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ / κ_Z	κ_W / κ_Z	κ_b / κ_Z	κ_τ / κ_Z	κ_Z / κ_g	κ_t / κ_g	κ_μ / κ_Z	$\kappa_{Z\gamma} / \kappa_Z$
300	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

ATLAS

Nr.	Coupling ratio	300 fb^{-1} Theory unc.:			3000 fb^{-1} Theory unc.:		
		All	Half	None	All	Half	None
1	κ_{VV}	7.6%	7.1%	6.9%	4.1%	3.3%	3.0%
	λ_{FV}	8.5%	7.7%	7.5%	3.7%	3.2%	3.0%
2	κ_{ZZ}	10%	9.3%	8.9%	6.1%	4.7%	4.1%
	λ_{WZ}	4.7%	4.0%	3.7%	2.8%	2.0%	1.6%
	λ_{FZ}	9.4%	8.6%	8.4%	4.5%	3.9%	3.6%
3	κ_{uu}	13%	11%	10%	6.3%	5.0%	4.5%
	λ_{Vu}	10%	8.9%	8.5%	4.6%	3.8%	3.5%
	λ_{du}	11%	9.1%	8.2%	7.1%	5.6%	4.9%
4	$\kappa_{\tau\tau}$	22%	18%	16%	17%	14%	12%
	$\lambda_{V\tau}$	12%	11%	9.8%	9.3%	7.2%	6.4%
	$\lambda_{q\tau}$	12%	9.6%	8.7%	9.1%	7.0%	6.1%
	$\lambda_{\mu\tau}$	24%	22%	21%	12%	9.6%	8.8%
5	κ_{gZ}	6.4%	4.4%	3.5%	4.6%	2.9%	2.0%
	λ_{WZ}	5.1%	4.6%	4.4%	3.0%	2.3%	2.1%
	λ_{tg}	18%	18%	17%	7.0%	6.1%	5.8%
	$\lambda_{\tau Z}$	13%	11%	11%	10%	7.6%	6.6%
	$\lambda_{\mu Z}$	22%	21%	20%	9.2%	7.2%	6.3%
	λ_{gZ}	12%	11%	11%	5.9%	5.0%	4.7%
	$\lambda_{\gamma Z}$	11%	6.9%	5.1%	7.1%	3.9%	1.8%
	$\lambda_{(Z\gamma)Z}$	78%	78%	78%	30%	29%	29%
6	$\kappa_{\gamma\gamma}$	22%	16%	13%	14%	8.3%	5.4%
	$\lambda_{Z\gamma}$	11%	6.9%	5.1%	7.1%	3.9%	1.8%
	$\lambda_{W\gamma}$	11%	7.3%	5.6%	7.4%	4.2%	2.2%
	$\lambda_{t\gamma}$	27%	23%	21%	14%	9.7%	7.7%
	$\lambda_{\tau\gamma}$	15%	12%	11%	10%	7.7%	6.7%
	$\lambda_{\mu\gamma}$	21%	20%	20%	7.2%	6.6%	6.3%
	$\lambda_{g\gamma}$	18%	13%	11%	11%	6.8%	5.0%
	$\lambda_{(Z\gamma)\gamma}$	77%	76%	76%	29%	29%	29%

ATL-PHYS-PUB-2013-014,
CMS NOTE-13-002

Mapping & DM-types

Higgs invisible decay — *Higgs-DM coupling* — *DM-nucleon xsec*

$$\Gamma(h \to \chi\chi) \Leftrightarrow \lambda^2_{h\chi\chi} \Leftrightarrow \sigma_{N\chi}$$

$$BR(h \to \chi\chi) = \frac{\Gamma(h \to \chi\chi)}{\Gamma(h \to \chi\chi) + \Gamma(h \to SM)}$$

We consider three DM types: scalar, vector, majorana fermion

$$\Gamma^{\rm Scalar}(h \to \chi\chi) = \frac{\lambda^{2\,\rm Scalar}_{h\chi\chi} v^2}{64\pi m_h}\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

$$\Gamma^{\rm Vector}(h \to \chi\chi) = \frac{\lambda^{2\,\rm Vector}_{h\chi\chi} v^2}{256\pi m^4_\chi m_h}\left[m^4_h - 4m^2_\chi m^2_h + 12 m^4_\chi\right]\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

$$\Gamma^{\rm Majorana}(h \to \chi\chi) = \frac{\lambda^{2\,\rm Majorana}_{h\chi\chi} v^2 m_h}{32\pi\Lambda^2}\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{3/2}$$

$$\sigma^{\rm Scalar}_{\chi N} = \frac{\lambda^{2\,\rm Scalar}_{h\chi\chi}}{16\pi m^4_h}\frac{m^4_N f^2_N}{(m_\chi + m_N)^2}$$

$$\sigma^{\rm Vector}_{\chi N} = \frac{\lambda^{2\,\rm Vector}_{h\chi\chi}}{16\pi m^4_h}\frac{m^4_N f^2_N}{(m_\chi + m_N)^2}$$

$$\sigma^{\rm Majorana}_{\chi N} = \frac{\lambda^{2\,\rm Majorana}_{h\chi\chi}}{4\pi\Lambda^2 m^4_h}\frac{m^2_\chi m^4_N f^2_N}{(m_\chi + m_N)^2}$$

LHC & Other Colliders

Snowmass, Higgs Working Group Report, 2013

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

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%