Going Beyond the Higgs Discovery

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Outline of the talk

- Introduction
- Summary of (our) recent activities
- (Personal) plan for the next years
- Some thoughts on CEPC (for discussions)

Introduction

When I joined ATLAL-LAL group late 2008, there were already 2 strong $H\rightarrow\gamma\gamma$, ZZ(4l) groups, so I initiated a new $H\rightarrow WW(l\nu l\nu)$ group.

Shan & I co-supervised the thesis of Xifeng Ruan (2009-2012), luckily be (small) part of the effort resulting in the Higgs discovery

Now the new challenge is to understand the newly discovered Higgs

My current research focus in ATLAS @LHC:

- property measurements (in $H\rightarrow WW^*\rightarrow l\nu l\nu$)
  - improved coupling measurement
  - spin/CP measurement

  } With Yichen Li (Joint PhD LAL-Nanjing U.)

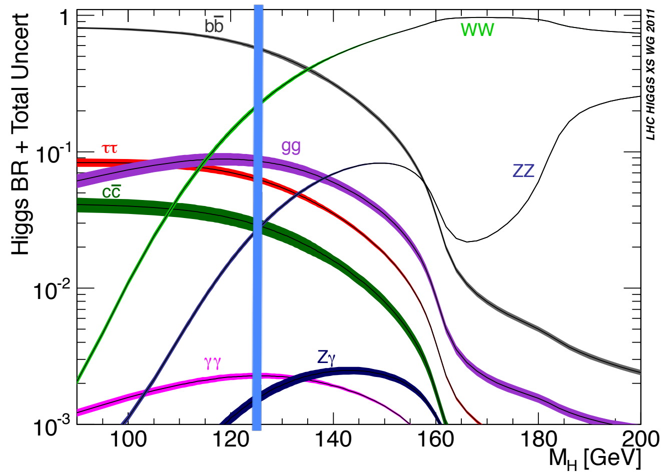
  - width constraint — With Yanping Huang (DESY fellow) and Yichen Li
- Search for additional heavy Higgs boson(s) — With Padraic Calpin (Imperial College London)

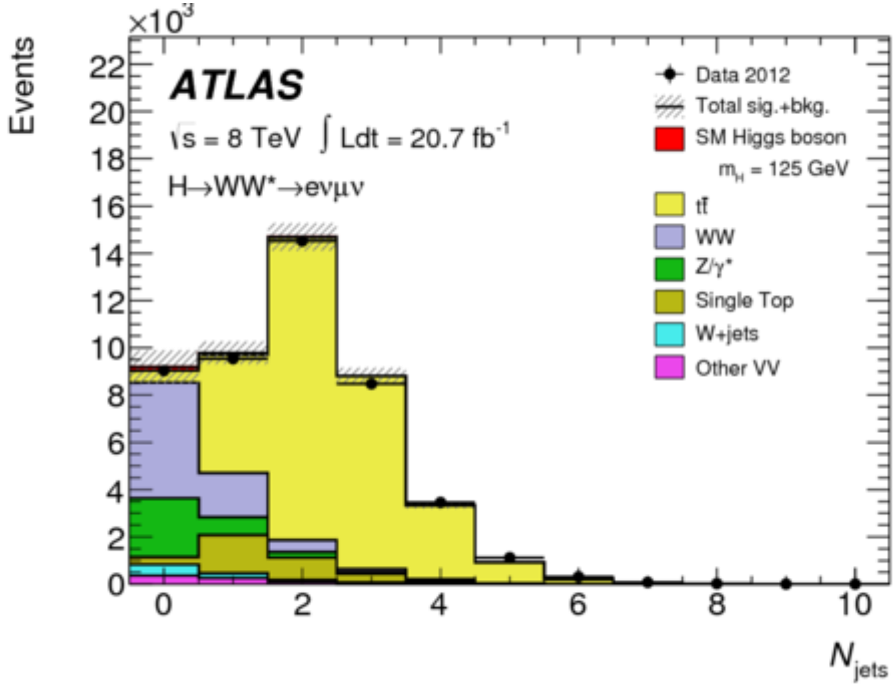
Introduction

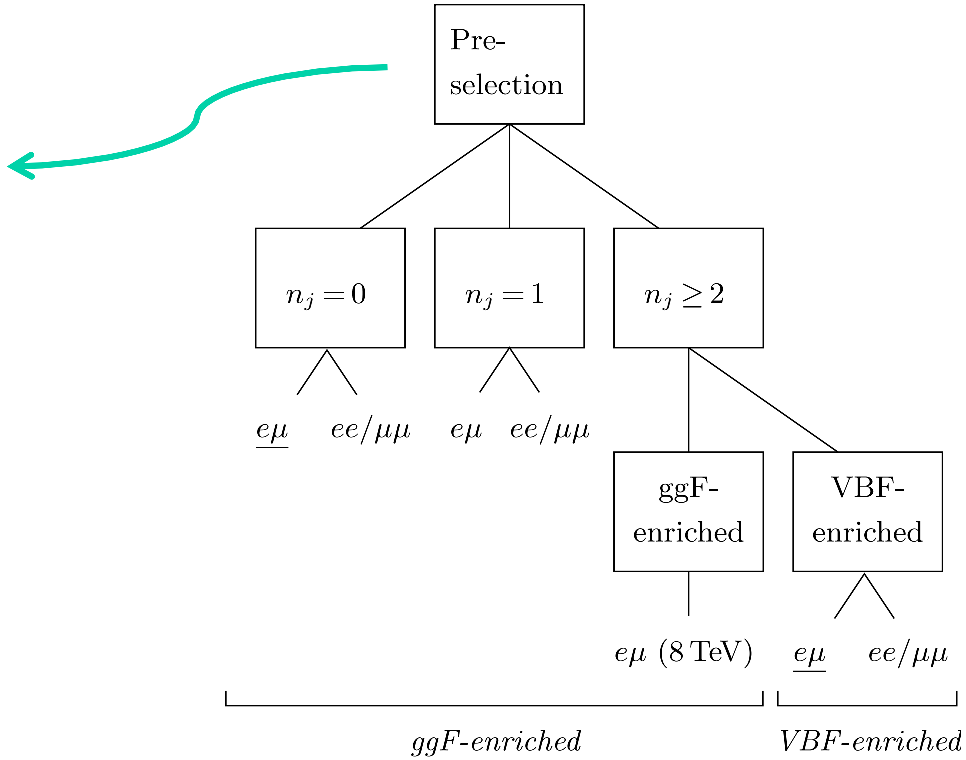
The H→WW*→lνlν channel

has the advantage that the rate is high
but is also very challenging

- no narrow resonance peak
- large (jet bin dependent) background contribution

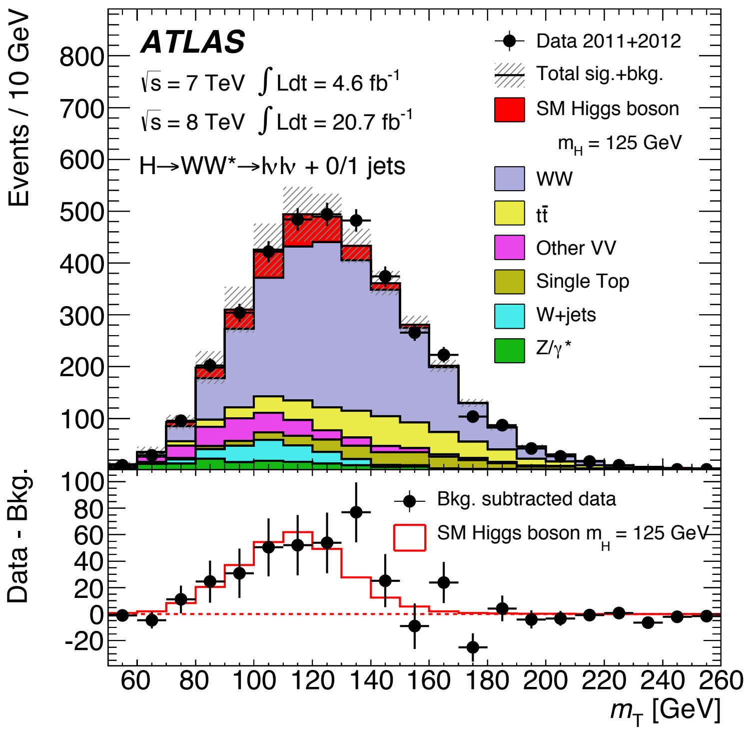




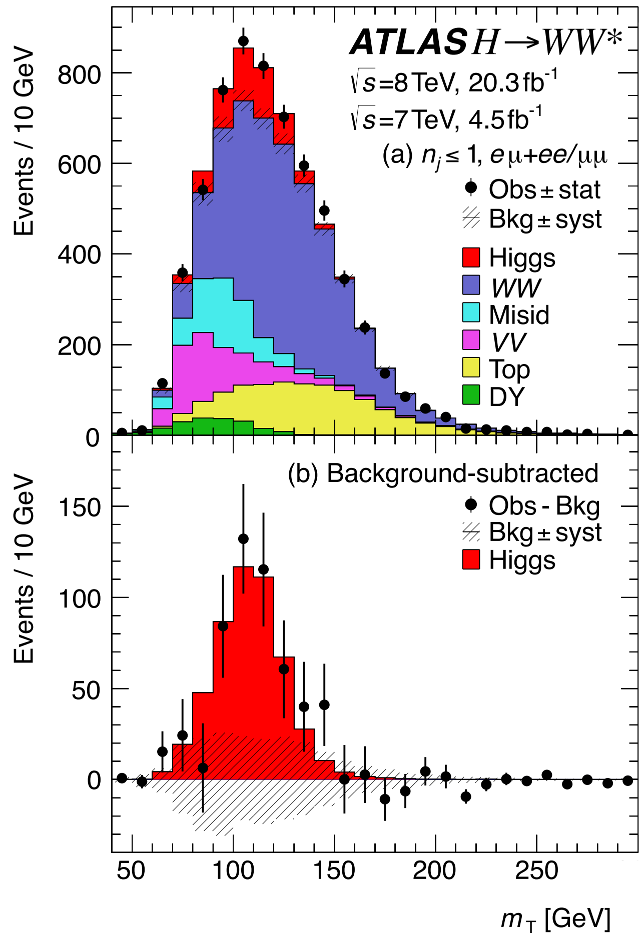


Improved Higgs Coupling Measurement (1)

2013 coupling paper



ATLAS: arXiv:1412.2641



Huge effort, long list of improvements including, e.g.

- Enhanced signal acceptance
- Reduced systematic uncertainties

(just to mention two main contributions from us)

Review Article on Top Estimation Methods

Y. Li, X. Ruan, L. Yuan & Z. Zhang, LAL preprint 13-373

Comparison of relative uncertainties (in %) for 0j channel

Method	JVSP (Eq. (3))	Temp. (Eq. (5))	Extrap. (Eq. (6))	In-situ (Eq. (11))
Stat	2.2	7.3	6.8	7.3
Exp.	4.6	17.5	13.6	9.0
Theo.	3.8	4.4	3.6	1.9
Non-top	1.5	2.3	1.8	2.0
Total	6.5	19.6	15.7	11.9

JVSP method proposed by B. Mellado, X. Ruan & Z. Zhang, PRD84 (2011) 096005
Baseline method for ATLAS H→WW analyses since beginning (also applied to SM WW)

Similar comparison for 1j and ≥2j channels

Method	$1j$		$\geq 2j$			
	Extrap.	In-situ ($1b$)	Extrap.	In-situ ($1b$)	In-situ ($\geq 1b$)	In-situ ($1b'$)
Stat.	1.3	2.4	9.4	9.5	7.7	9.5
Exp.	9.5	4.9	7.9	4.5	5.4	4.5
Theo.	3.2	2.6	18.6	16.8	19.5	17.8
Non-top	0.3	0.4	0.4	0.5	0.4	0.6
Total	10.1	6.1	22.3	19.8	21.7	20.7

In-situ b-tagging efficiency based method improved & implemented in ATLAS H→WW analysis by L. Yuan & Z. Zhang

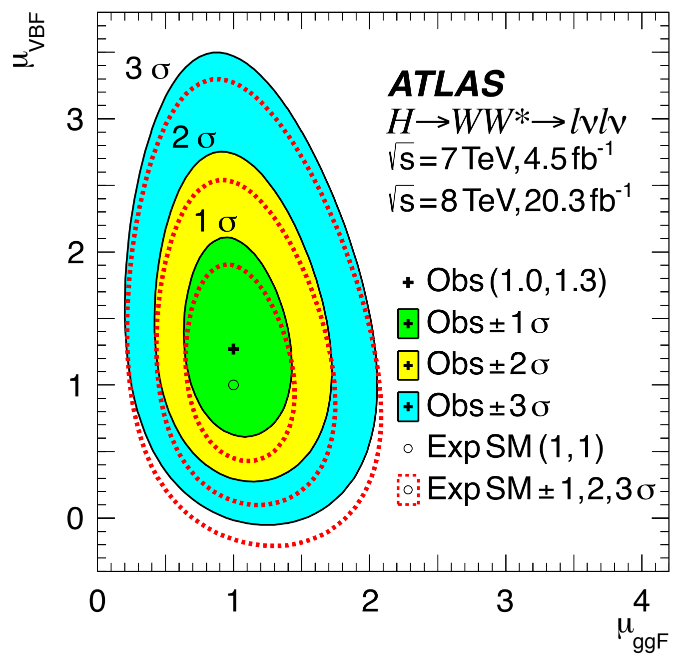
Improved Higgs Coupling Measurement (2)

	2013 coupling paper	ATLAS: arXiv:1412.2641
Observed excess	3.8σ	6.1σ 4.3σ (CMS)
Expected sensitivity	3.7σ	5.8σ 5.8σ (CMS)
Measured signal strength (μ=Measured/SM)	$1.01 \pm 21\%_{(stat)} \pm 23\%_{(syst)}$	$1.08 \pm 15\%_{(stat)} \pm 15\%_{(syst)}$ $0.72 \pm 17\%_{(stat)} \pm 22\%_{(syst)}$ (CMS)

Higgs observed in WW alone !

In addition, evidence (3.2σ) for VBF process

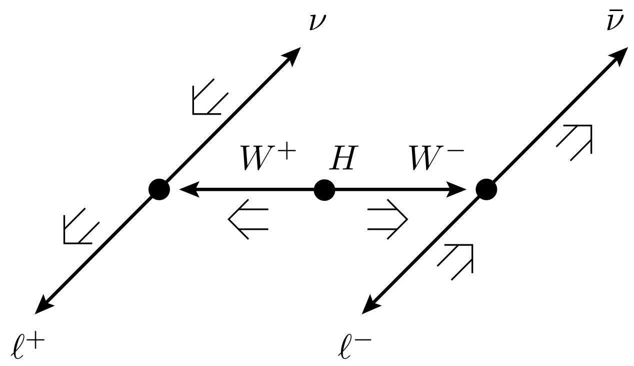
A long paper just appeared on arXiv on Tuesday submitted in PRD



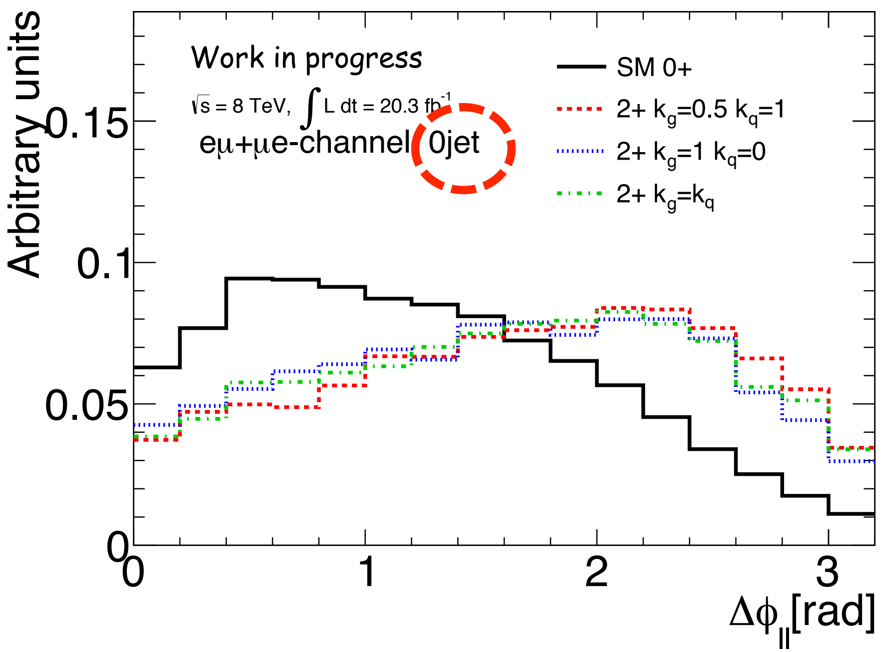
Spin/Parity Property with WW

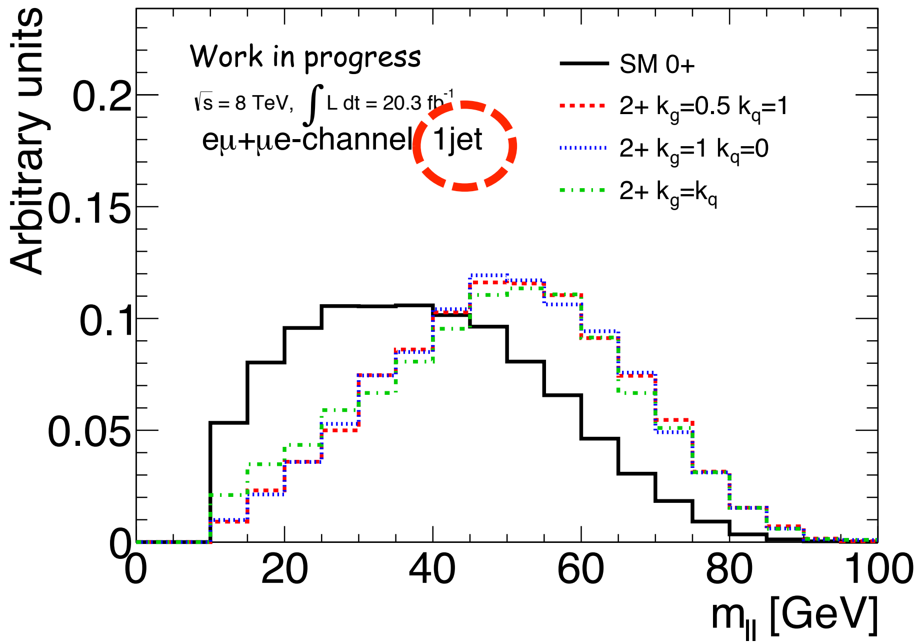
SM Higgs boson: spin 0, CP even

WW channel provides several variables in discriminating SM 0+ with other alternatives



Spin 2+ minimal coupling scenarios:
- at LO, ggF (k_g=1) and VBF (k_q=1) independent
- Beyond LO, both k_g,k_q contribute with k_g=k_q being a special universal coupling case





Our Contribution to the Spin Analysis

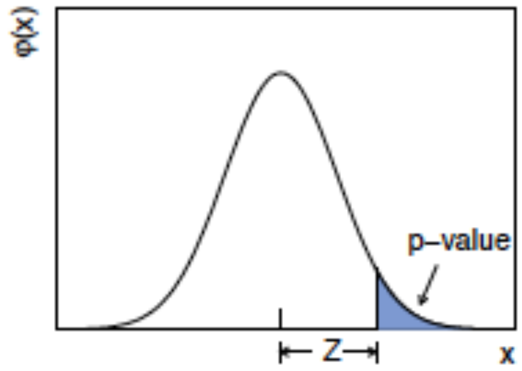
For previous spin property results, only 0-jet channel was used

We have helped in adding 1-jet channel with all associated studies, e.g.
- signal and background separation with an MVA technique
- systematic uncertainty evaluation

➔ 1-jet channel is necessary as it's sensitive to higher-order effects
➔ Signal significance substantially improved, e.g. for one spin-2 model:

(k_g=0.5, k_q=1)

Channel	Z^0_{exp}	Z^2_{exp}
0-jet	1.35 ± 0.02	1.94 ± 0.03
1-jet	1.30 ± 0.02	1.23 ± 0.02
0+1-jet	1.89 ± 0.02	2.29 ± 0.04



A publication is in preparation

Constraint on the Higgs Width

SM Higgs boson width ~4MeV much smaller than detector resolution
→ Very difficult to measure at LHC, see indeed the direct width limits

Obs (exp) upper limits [GeV] @95%CL	$H\to\gamma\gamma$	$H\to ZZ(4l)$
ATLAS	5.0 (6.2)	2.6 (6.2)
CMS	2.4 (3.1)	3.4 (2.8)

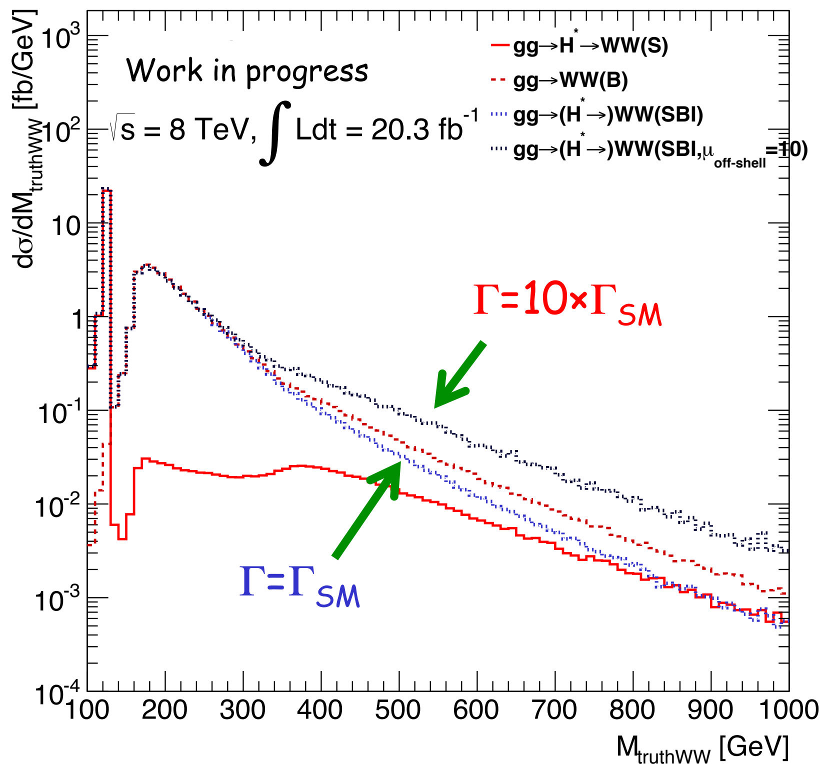
In narrow width approximation:

$$\sigma_{i\to H\to j} \propto \frac{g_i^2 g_f^2}{\Gamma_h}$$

→ Without knowing Γ_h, g cannot be precisely determined from σ at LHC

Several groups (1206.4803, 1307.4935, 1311.3589, 1312.1628) point out the off-shell Higgs production is sizable

→ Measured off-shell production can be used to constrain the off-shell signal strength, Higgs width



Expected Results

Campbell & Ellis estimated in arXiv:1312.1628 the Higgs width upper limit

- $\Gamma < (100\text{-}500)\ \Gamma_{SM}$ based on ATLAS' 125GeV coupling analysis cuts
- $\Gamma < (25\text{-}50)\ \Gamma_{SM}$ best potential limits

We designed a powerful and optimum off-shell selection which allowed

- minimize the contamination of the on-shell resonance
- efficient background rejection
- maximize the off-shell contribution
- keep the analysis as inclusive as possible for NNLO k-factor correction

Upper limits @95%CL	Stat	Stat + Exp	Stat + Exp + Theo
Expected ($\times\Gamma_{SM}$)	18.3	18.5	20.3

A publication with combined WW($l\nu l\nu$)+ZZ($4l$+$ll\nu\nu$) is being finalized

Search for Heavy Higgs Boson

Is an alternative and efficient way for answering the question $H = H^{SM}$?

Extended Higgs sector predicted by several BSM models, e.g.:

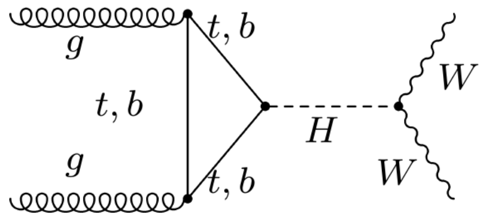
- 2HDMs (Two Higgs Doublet Models)
- EWS (ElectroWeak Singlet) Models

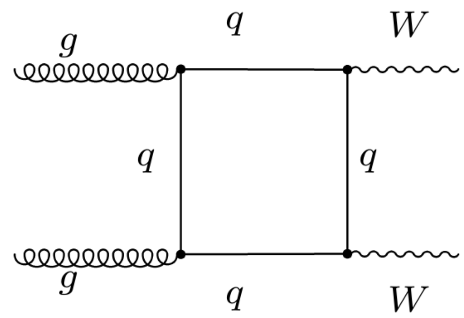
ATLAS analysis performed for 4 interpretations:

- Heavy Higgs boson with SM-like width
  (performed in mass range [200, 1000]GeV)
- Heavy Higgs boson with narrow width
  (performed in mass range [300, 2000]GeV)
- Heavy Higgs boson in the EWS model
  (performed m_H=[200,1000]GeV, Γ_H=[0.1,1]×Γ_{SM})
- Heavy Higgs boson in Type-I & -II 2DHMs

Our Contribution to the Heavy Higgs Search

- Checked the contribution of other Higgs decay modes ttbar, ZZ, $\tau\tau$
- Studied the Higgs lineshape (i.e. Higgs invariant mass distribution), found/confirmed
  - Breit-Winger distribution provides a good approximation for m_H<~400GeV
  - Need Complex Pole Scheme (CPS) at higher m_H and/or larger Γ_H
- Investigated signal & background interference effects: missing in our current MC samples, important when the width is SM-like (very broad @ high mass)
- Compared difference between dynamic scale ($m_{WW}/2$) vs. fixed scale ($m_H/2$)





(SM continuum WW is known at LO as well as the interference, ➔ need theoretical improvement)

Results not yet fully approved, but we expect a big improvement over what's published based on 7TeV data (133GeV < mH < 261GeV at 95%CL for SM-like)

A publication in combination with other channels (e.g. WW→lνqq) expected early next year

(Personal) Plan for the Next Years

- LHC is the unique energy frontier machine in the world in the next 10-20 years
  Fully exploit physics potential at LHC is the top priority

- Search for new physics
  Searching for additional Higgs bosons will continue with Run-2 data
  (Joint PhD thesis for Yongke Zhao with Shandong University)

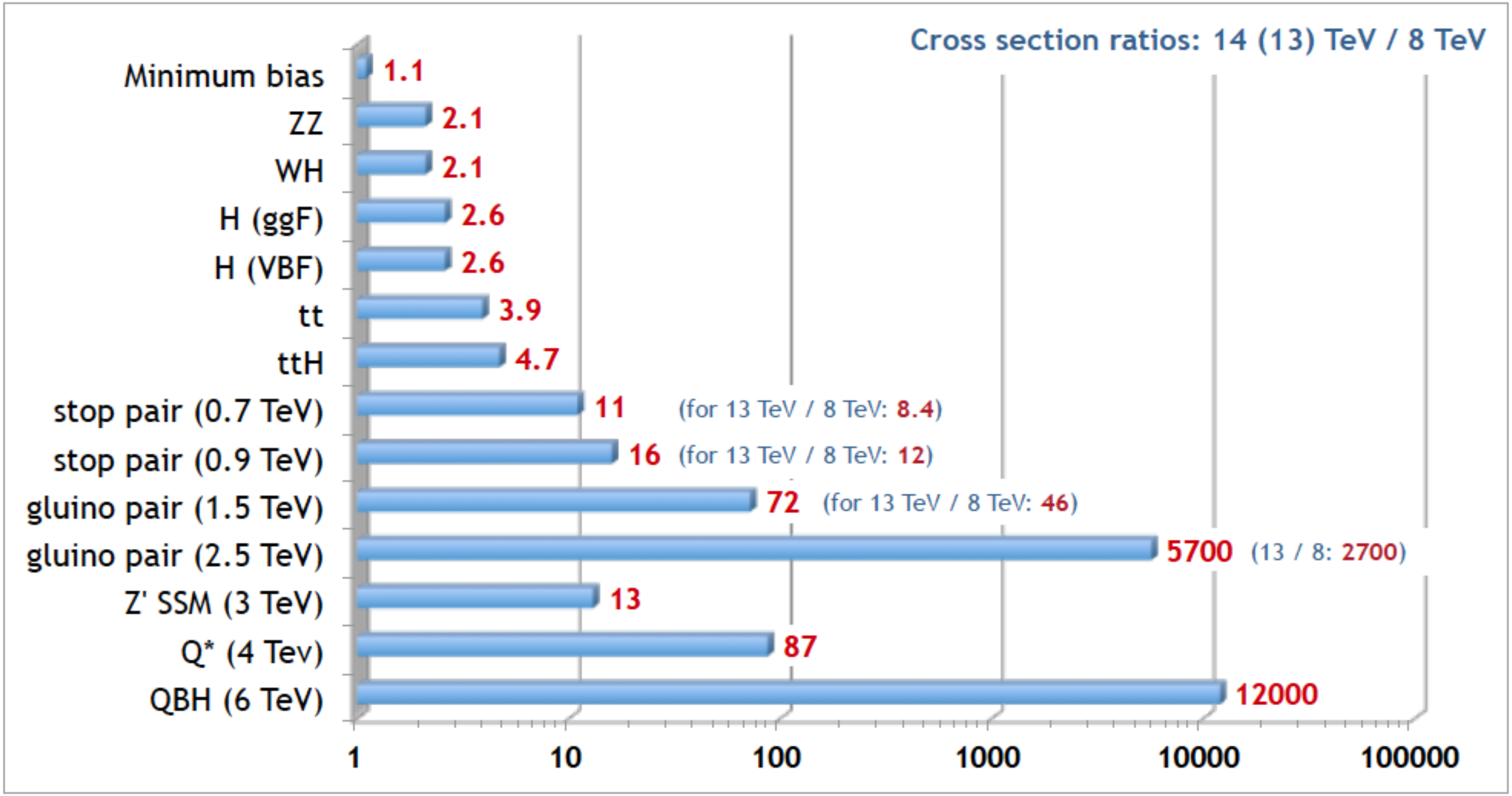
- Precision measurements/predictions
  - Higgs property measurements would be a long term project
  - Understanding 20% (>2σ) excess in the SM WW cross section measurement
    (ongoing projects with USTC, China and KTH, Sweden)
  - Continue phenomenology activity on muon g-2 (in view of forthcoming Fermilab and J-PARC measurements), invitation for a chapter for a book for CERN'60

- Try to contribute to IHEP/China's initiative for CEPC/SppC
  - Close contact with Manqi Ruan (a former joint PhD student with Yanning)
  - subscribed to CEPC mailing list
  - trying to follow some of the weekly meetings
  - invited to review the pre-CDR report

Expected Gain in Cross Sections at LHC

for selected processes

Hugely increased potential for discovery of heavy particles at 13~14 TeV



Some (Naïve) Thoughts on CEPC for discussion

- Unique time window to build CEPC in China
  - Europe has the LHC to explore and upgrade
  - US does not seem in a position to host a big high energy project
  - Japan keen to host ILC but insufficient world-wide financial support

- Then which energy/luminosity option to have?

  Do we want CEPC to be a LEP-like machine?

  Do we want to have a "cheap" machine/detector but "expensive" running cost? (to achieve a given precision)

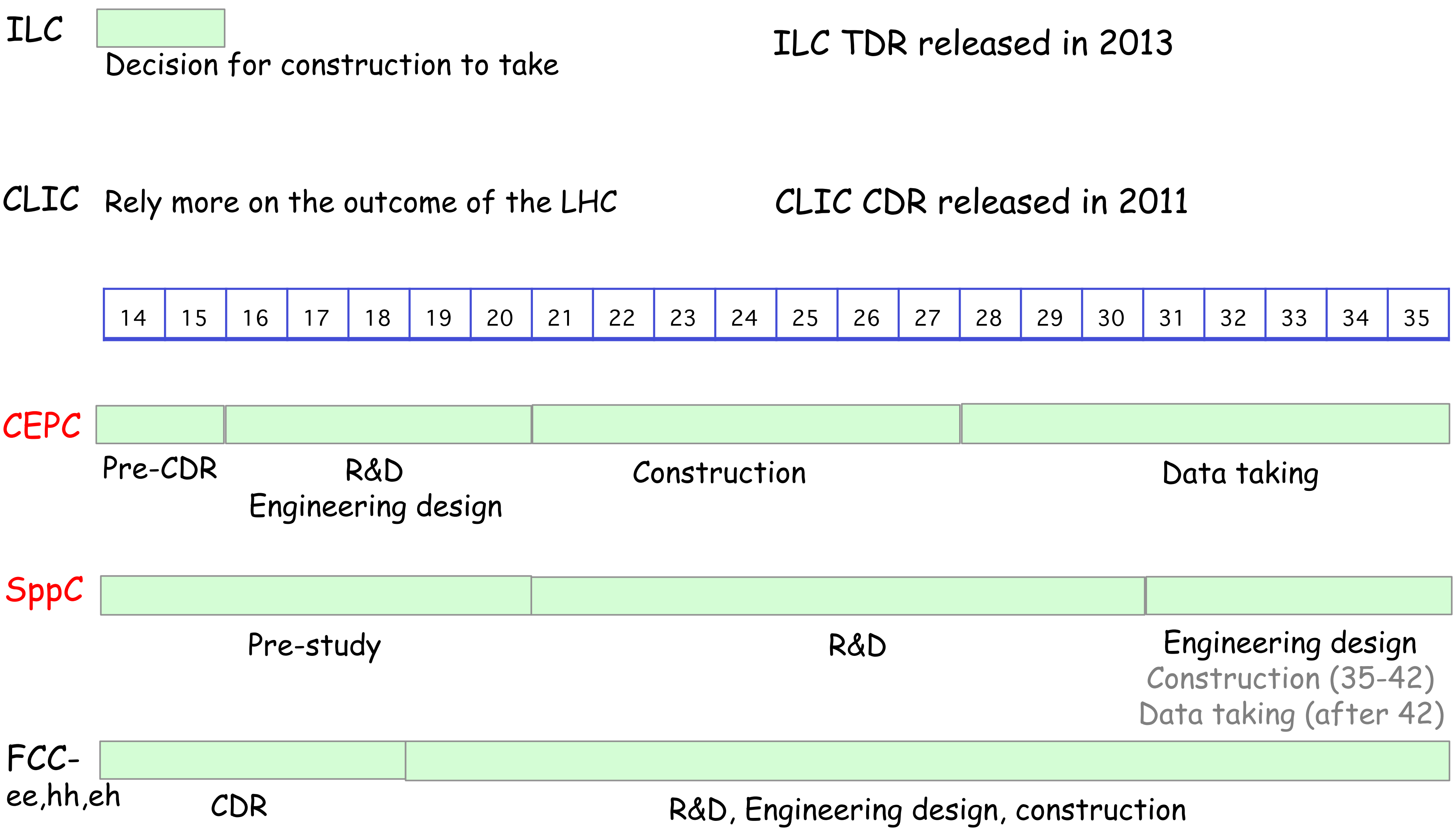
  Do we want to leave the top precision study for SppC?

- If not too late, is it possible to consider the following scenarios?
  - define the minimum and cheapest option (Higgs precision physics)
  - ambitious option both in energy and physics coverage (though more expensive)
  - intermediate ones

  and leave the decision to political/funding body?

Additional Slides

Unique Opportunity for CEPC/SppC



Possible Scenarios In Next Years/Decade

- LHC and/or HL-LHC find new physics:
  the heavier part of the spectrum may not be fully accessible at $\sqrt{s}$ ~ 14 TeV
  → strong case for a 100 TeV pp collider:
  complete the spectrum and measure it in some detail

- LHC and/or HL-LHC find indications for the scale of new physics being in the 10-50 TeV region (e.g. from dijet angular distributions → Λ Compositeness)
  → strong case for a 100 TeV pp collider:
  directly probe the scale of new physics

- LHC and HL-LHC find no new physics nor indications of next energy scale
  → Missed due to small cross sections or difficult experimental signatures?
  → A precision e+e- machine may be a good choice to find new guidance for future direction

Hadron Collider vs. e+e-(lepton)

Hadron Collider:

SppC (Super proton-proton Collider), China ←
FCC-hh (Future Circular Collider), CERN ←

e+e- Collider:

ILC (International Linear Collider), Japan?
CLIC (Compact LInear Collider), CERN
CEPC (Circular Electron Positron Collider), China
FCC-ee (TLEP), CERN
Muon collider (μC), Fermilab?

+ Energy frontier
  → large direct discovery potential

- Precision measurement challenging
  - Pile-up
  - UE, MPI*
  - Composite proton → PDF uncertainty
  - large theoretical (QCD) corrections

+ Precision frontier
  - Clean experimental environment
  - Known $\sqrt{s}$
  - Beam polarization (linear collider)
  - Precise theoretical predictions

- Lower $\sqrt{s}$
  → still large indirect scale reach

*UE: Underlying Event; MPI: Multi-Parton Interaction

Physics Goal vs. √s at a e+e- Collider

ILC TDR

Circular

CEPC

FCC-ee

Multi-detector

pp → ee

Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

Linear

ILC

CLIC

Single detector or Push-pull

Energy upgradability

3TeV