LHC EW WG3: Multi-boson Activities and Yellow Report

LHC Electroweak Working

Group General Meeting

February 17, 2022

Philip Chang

UC San Diego

Outline

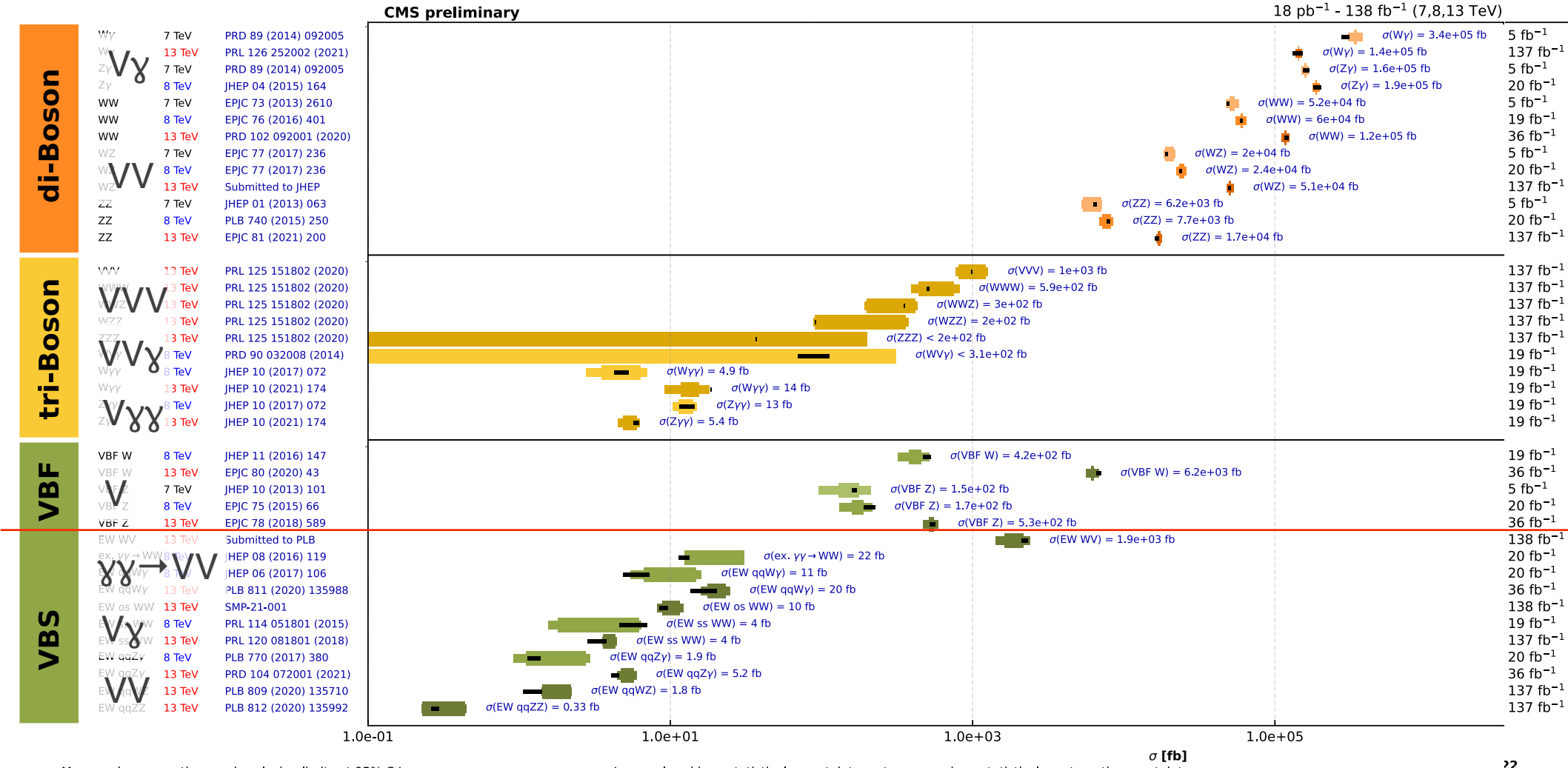
Background

Yellow Report roadmap

Contents

Discussion for today

Overview of CMS cross section results

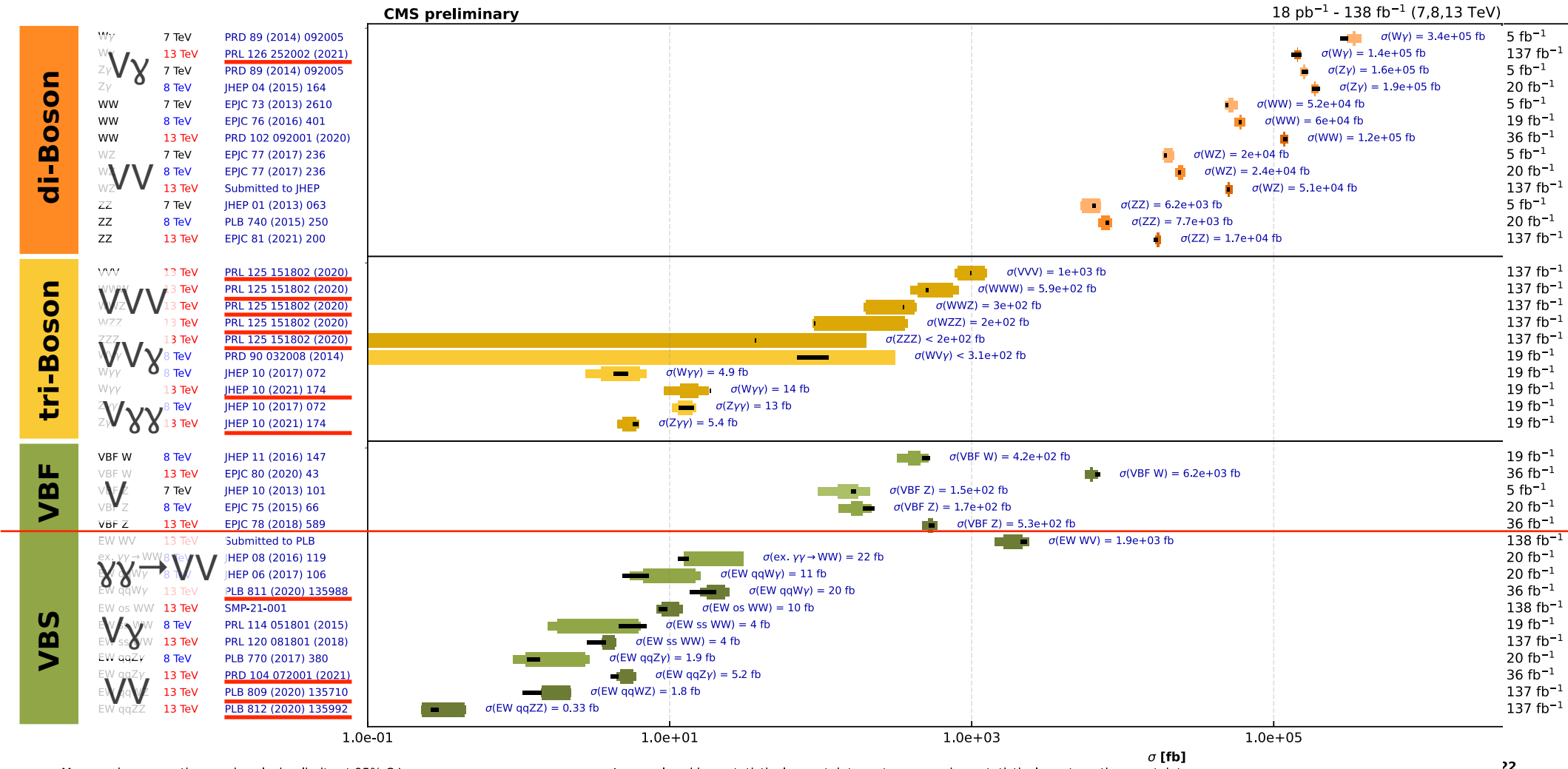


Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

Rapid expansion of final states in recent years

Overview of CMS cross section results

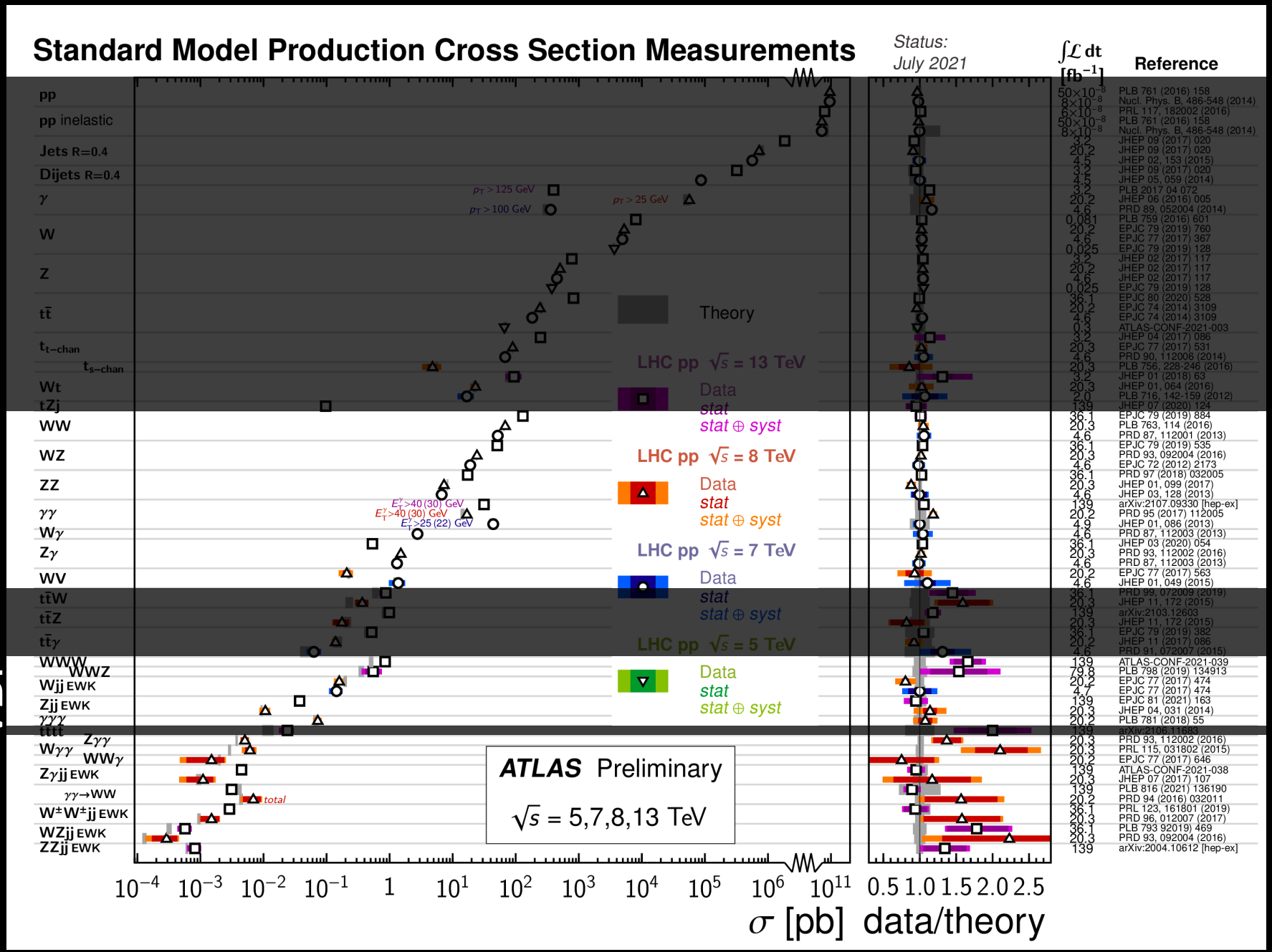


Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

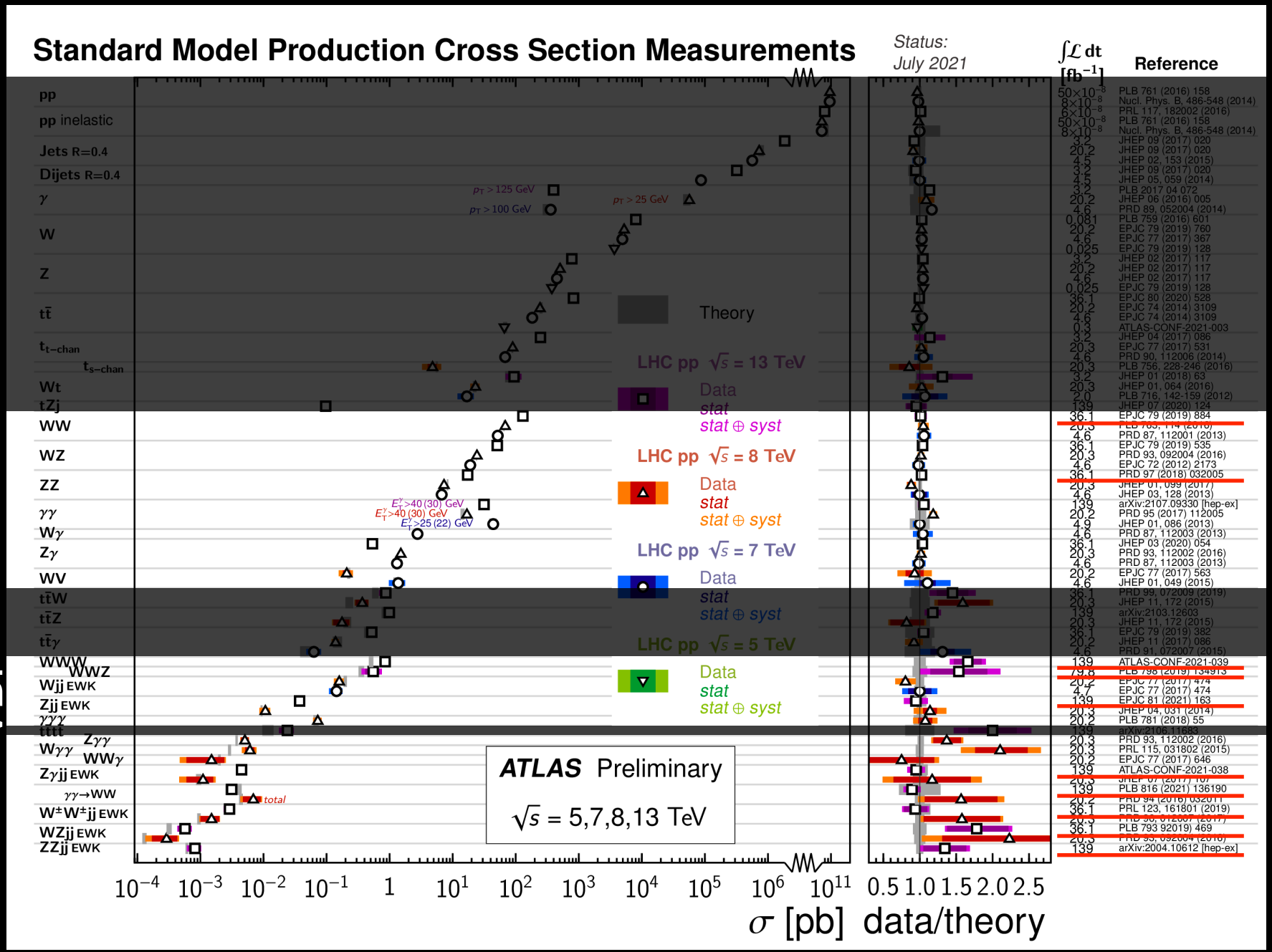
Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

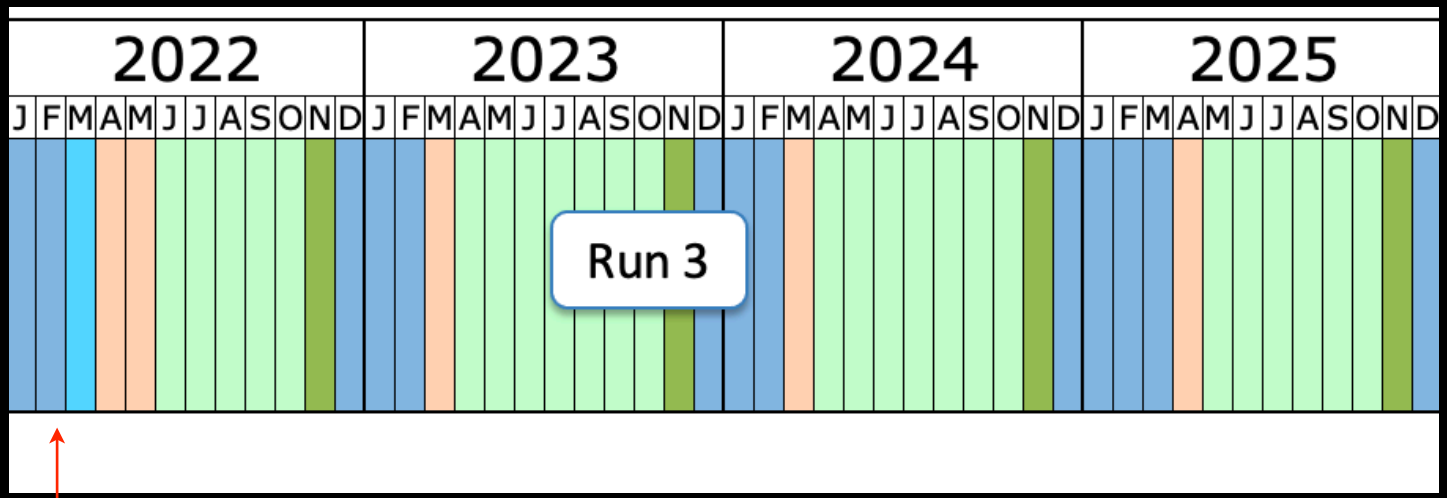
Rapid expansion of final states in recent years

VBS Triboson Diboson VBF

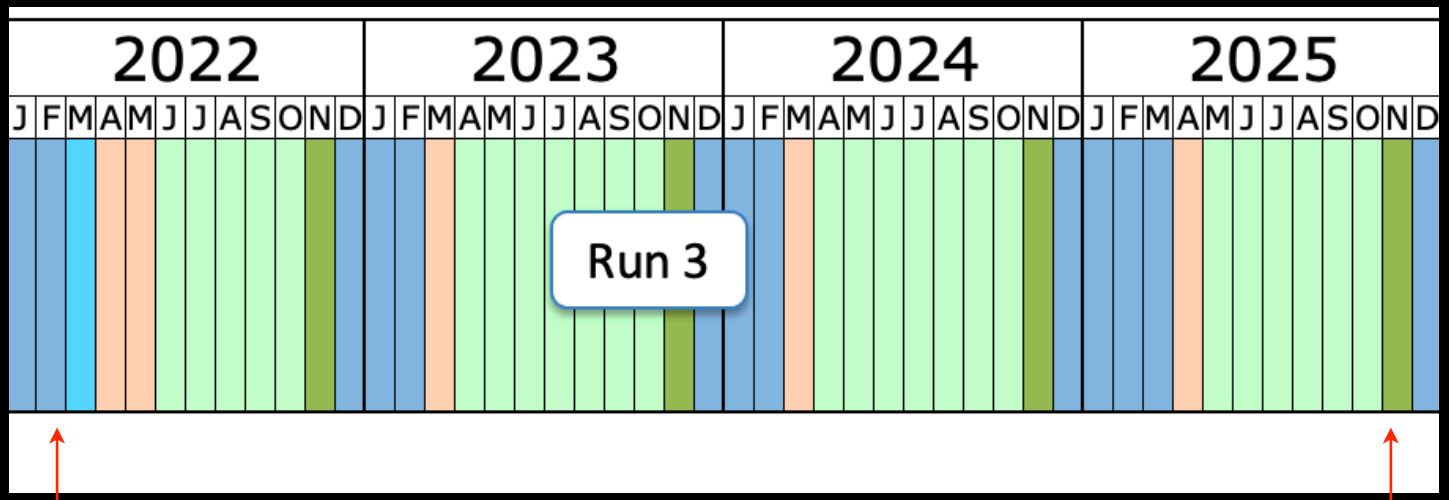


VBS Triboson Diboson VBF




2022
2023
2024
2025
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Run 3

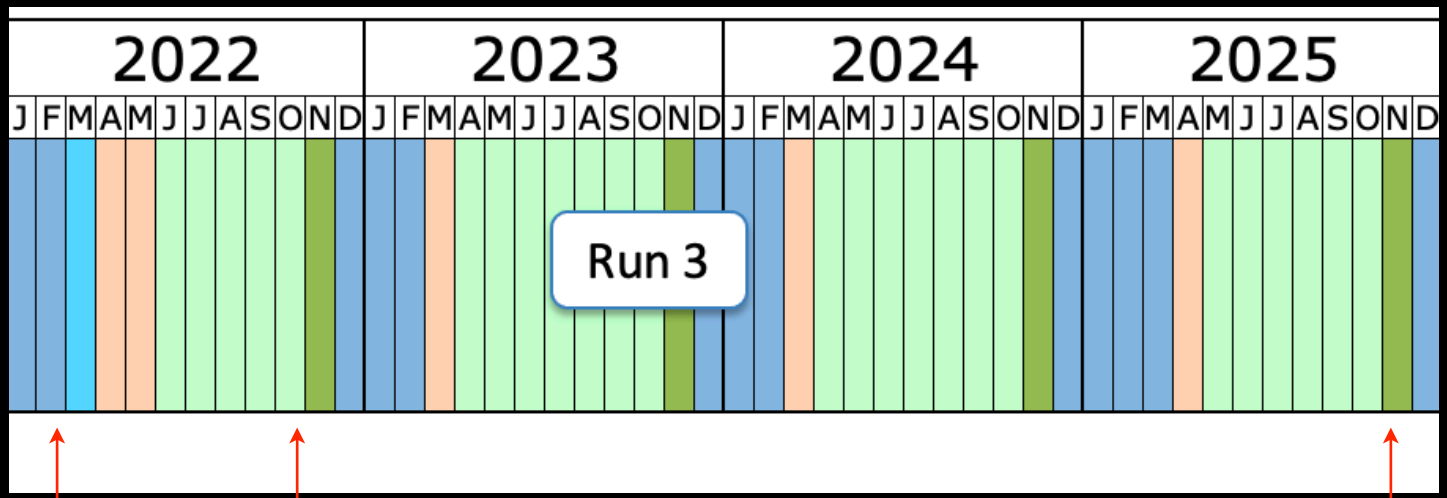
Today



Today

Future

Precision VV
VV Diff-XS / Polarization
VVV Observations
Interplay w/ Higgs
Longitudinal VBS
$\gamma\gamma \rightarrow VV$
...
...



Today

Future

Yellow Report
Survey existing results and provide recommendations / guidelines

Precision VV
VV Diff-XS / Polarization
VVV Observations
Interplay w/ Higgs
Longitudinal VBS
$\gamma\gamma \rightarrow VV$
...
...

Milestones

Chang
UC San Diego

- 1st quarter (Now - Jan): First survey existing results (ATLAS/CMS/Theory) and write texts
- 2nd quarter (Jan - April): Expand by writing important lessons, suggestions, consensus between experiments for Run 3 (and beyond)
- 3rd quarter (April - July): Finalize the texts
- 4th quarter (July - Oct): Work towards publishing YR

Contents

1 Diboson production **1**
1.1 Introduction . . . 1
1.2 Theory predictions (S. Kallweit, M. Wiesemann) . . . 1
1.2.1 Relevant processes . . . 1
1.2.2 Perturbative higher-order corrections . . . 2
1.2.3 State of the art . . . 2
1.2.4 QCD/EW combination and cross section predictions . . . 2
1.3 Experimental review . . . 5

2 Vector boson fusion **7**
2.1 Introduction . . . 7
2.1.1 VBF and QCD $V + 2$j production . . . 7
2.2 Theory predictions (J. Lindert) . . . 7
2.2.1 State of the art . . . 8
2.2.2 Best practise . . . 8
2.3 Experimental review . . . 8
2.3.1 Total cross sections . . . 8
2.3.2 Differential measurements . . . 10
2.3.3 TGC/EFT measurements . . . 10
2.4 Challenges . . . 11
2.4.1 Background modelling . . . 11
2.4.2 Gap activity studies . . . 11
2.5 Monte Carlo comparison . . . 11
2.6 Future directions . . . 11
2.7 Recommendations . . . 13

3 Vector boson scattering **15**
3.1 Introduction . . . 15
3.2 Theory predictions (M. Pellen, M. Zaro) . . . 15
3.3 Experimental review . . . 17
3.3.1 VBS measurements in a glance . . . 19
3.3.2 Same-sign $\mathrm{W}^{\pm}\mathrm{W}^{\pm} \to \ell^{\pm}\nu\ell'^{\pm}\nu$ production . . . 19
3.3.3 Opposite-sign $\mathrm{W}^{\pm}\mathrm{W}^{\mp} \to \ell^{\pm}\nu\ell'^{\mp}\nu$ production . . . 23
3.3.4 $W^{\pm}Z \to \ell^{\pm}\nu\ell'^{\pm}\ell'^{\mp}$ production . . . 25
3.3.5 ZZ production in fully leptonic decays . . . 26
3.3.6 $\mathrm{WV} \to \ell\nu jj$ production . . . 27
3.3.7 VV production in semileptonic final states . . . 29
3.3.8 Wγ production . . . 32
3.3.9 Zγ production . . . 33
3.3.10 Future prospects . . . 38

4 Tribosons **43**
4.1 Theory predictions (M. Schönherr) . . . 43
4.2 Experimental review . . . 43
4.2.1 $\gamma\gamma\gamma$ . . . 44
4.2.2 $W\gamma\gamma$ . . . 45
4.2.3 $Z\gamma\gamma$ . . . 45
4.2.4 $WW\gamma$ and $WZ\gamma$ . . . 46
4.2.5 WWW . . . 46
4.2.6 WWZ and WZZ . . . 46

VV

VBF

VBS

VVV

Contents

1 Diboson production **1**
1.1 Introduction . . . 1
1.2 Theory predictions (S. Kallweit, M. Wiesemann) . . . 1
1.2.1 Relevant processes . . . 1
1.2.2 Perturbative higher-order corrections . . . 2
1.2.3 State of the art . . . 2
1.2.4 QCD/EW combination and cross section predictions . . . 2
1.3 Experimental review . . . 5

2 Vector boson fusion **7**
2.1 Introduction . . . 7
2.1.1 VBF and QCD $V + 2j$ production . . . 7
2.2 Theory predictions (J. Lindert) . . . 7
2.2.1 State of the art . . . 8
2.2.2 Best practise . . . 8
2.3 Experimental review . . . 8
2.3.1 Total cross sections . . . 8
2.3.2 Differential measurements . . . 10
2.3.3 TGC/EFT measurements . . . 10
2.4 Challenges . . . 11
2.4.1 Background modelling . . . 11
2.4.2 Gap activity studies . . . 11
2.5 Monte Carlo comparison . . . 11
2.6 Future directions . . . 11
2.7 Recommendations . . . 13

3 Vector boson scattering **15**
3.1 Introduction . . . 15
3.2 Theory predictions (M. Pellen, M. Zaro) . . . 15
3.3 Experimental review . . . 17
3.3.1 VBS measurements in a glance . . . 19
3.3.2 Same-sign $W^{\pm}W^{\pm} \to \ell^{\pm}\nu\ell'^{\pm}\nu$ production . . . 19
3.3.3 Opposite-sign $W^{\pm}W^{\mp} \to \ell^{\pm}\nu\ell'^{\mp}\nu$ production . . . 23
3.3.4 $W^{\pm}Z \to \ell^{\pm}\nu\ell'^{\pm}\ell'^{\mp}$ production . . . 25
3.3.5 ZZ production in fully leptonic decays . . . 26
3.3.6 $WV \to \ell\nu jj$ production . . . 27
3.3.7 VV production in semileptonic final states . . . 29
3.3.8 $W\gamma$ production . . . 32
3.3.9 $Z\gamma$ production . . . 33
3.3.10 Future prospects . . . 38

4 Tribosons **43**
4.1 Theory predictions (M. Schönherr) . . . 43
4.2 Experimental review . . . 43
4.2.1 $\gamma\gamma\gamma$ . . . 44
4.2.2 $W\gamma\gamma$ . . . 45
4.2.3 $Z\gamma\gamma$ . . . 45
4.2.4 $WW\gamma$ and $WZ\gamma$ . . . 46
4.2.5 WWW . . . 46
4.2.6 WWZ and WZZ . . . 46

Chang
UC San Diego

VV

VBF

VBS

VVV

Contents

1 Diboson production **1**
1.1 Introduction . . . 1
1.2 Theory predictions (S. Kallweit, M. Wiesemann) . . . 1
1.2.1 Relevant processes . . . 1
1.2.2 Perturbative higher-order corrections . . . 2
1.2.3 State of the art . . . 2
1.2.4 QCD/EW combination and cross section predictions . . . 2
1.3 Experimental review . . . 5

2 Vector boson fusion **7**
2.1 Introduction . . . 7
2.1.1 VBF and QCD $V + 2j$ production . . . 7
2.2 Theory predictions (J. Lindert) . . . 7
2.2.1 State of the art . . . 8
2.2.2 Best practise . . . 8
2.3 Experimental review . . . 8
2.3.1 Total cross sections . . . 8
2.3.2 Differential measurements . . . 10
2.3.3 TGC/EFT measurements . . . 10
2.4 Challenges . . . 11
2.4.1 Background modelling . . . 11
2.4.2 Gap activity studies . . . 11
2.5 Monte Carlo comparison . . . 11
2.6 Future directions . . . 11
2.7 Recommendations . . . 13

3 Vector boson scattering **15**
3.1 Introduction . . . 15
3.2 Theory predictions (M. Pellen, M. Zaro) . . . 15
3.3 Experimental review . . . 17
3.3.1 VBS measurements in a glance . . . 19
3.3.2 Same-sign $W^{\pm}W^{\pm} \to \ell^{\pm}\nu\ell'^{\pm}\nu$ production . . . 19
3.3.3 Opposite-sign $W^{\pm}W^{\mp} \to \ell^{\pm}\nu\ell'^{\mp}\nu$ production . . . 23
3.3.4 $W^{\pm}Z \to \ell^{\pm}\nu\ell'^{\pm}\ell'^{\mp}$ production . . . 25
3.3.5 ZZ production in fully leptonic decays . . . 26
3.3.6 $WV \to \ell\nu jj$ production . . . 27
3.3.7 VV production in semileptonic final states . . . 29
3.3.8 $W\gamma$ production . . . 32
3.3.9 $Z\gamma$ production . . . 33
3.3.10 Future prospects . . . 38

4 Tribosons **43**
4.1 Theory predictions (M. Schönherr) . . . 43
4.2 Experimental review . . . 43
4.2.1 $\gamma\gamma\gamma$ . . . 44
4.2.2 $W\gamma\gamma$ . . . 45
4.2.3 $Z\gamma\gamma$ . . . 45
4.2.4 $WW\gamma$ and $WZ\gamma$ . . . 46
4.2.5 WWW . . . 46
4.2.6 WWZ and WZZ . . . 46

Intro
Theory
Expt. overview
Challenges
MC comparisons (if available)
Future guidelines / Recommendations

LHC Electroweak Working Group Multiboson Conveners

- Theory:
  - Jonas Lindert, Celine Degrande
- CMS:
  - Philip Chang, Roberto Covarelli
- ATLAS:
  - Heather Russell, Joany Manjarres Ramos, Shu Li, Kristin Lohwasser

Yellow Report is a community effort

Contact conveners <lhc-ewwg-multiboson-admin@cern.ch>

if you have inputs / comments / start a discussion

Yellow Report Topical Group Editors

- Dibosons (WW / WZ / ZZ / Wg / Zg)
  - Theory: Stefan Kallweit, Marius Wiesemann
  - CMS: Kenneth Long
  - ATLAS: Yee Chinn Yap
- VBF (W / Z / (g))
  - Theory: Jonas Lindert
  - CMS: Paolo Azzurri
  - ATLAS: Dag Gillberg
- VBS (WW / WZ / ZZ / Wg / Zg)
  - Theory: Mathieu Pellen, Marco Zaro
  - CMS: Guillelmo Gomez Ceballos Retuerto
  - ATLAS: Narei Lorenzo Martinez
- Tribosons (WWW / WWZ / WZZ / ZZZ / WWg / WZg / (ZZg / Wgg / Zgg)
  - Theory: Marek Schönherr
  - CMS: Saptaparna Bhattacharya
  - ATLAS: Andrea Sciandra

LHCEWWG-MB: VBS OS WW / Yellow Report Discussion

Shu Li (Tsung-Dao Lee Institute (CN) & Shanghai Jiao Tong Univ. (CN)), Roberto Covarelli (University/INFN Torino (IT)), et al.
20 January 2022 07:00
Home » Projects » LHC Physics Centre at CERN » LHC Working Groups » Electroweak precision measurements

LHCEWWG-MB: VBS Vgamma session

Shu Li (Tsung-Dao Lee Institute (CN) & Shanghai Jiao Tong Univ. (CN)), Roberto Covarelli (University/INFN Torino (IT)), et al.
18 November 2021 07:00
Home » Projects » LHC Physics Centre at CERN » LHC Working Groups » Electroweak precision measurements

LHCEWWG-MB: Tribosons

Shu Li (Tsung-Dao Lee Institute (CN) & Shanghai Jiao Tong Univ. (CN)), Roberto Covarelli (University/INFN Torino (IT)), et al.
21 October 2021 07:00
Home » Projects » LHC Physics Centre at CERN » LHC Working Groups » Electroweak precision measurements

LHCEWWG-MB: Polarized Multibosons

04 June 2021 06:00
Home » Projects » LHC Physics Centre at CERN » LHC Working Groups » Electroweak precision measurements

LHCEWWG-MB: Dibosons

28 May 2021 06:00
Home » Projects » LHC Physics Centre at CERN » LHC Working Groups » Electroweak precision measurements

LHCEWWG-MB: Precision studies

07 June 2019 05:00
Home » Projects » LHC Physics Centre at CERN » LHC Working Groups » Electroweak precision measurements

Third week of Thursday of each month at 16h00 CERN time

https://indico.cern.ch/category/3290/

Yellow Report discussion can take place here
Contact conveners <lhc-ewwg-multiboson-admin@cern.ch> if you have inputs / comments / start a discussion

VBF

2 Vector boson fusion **7**
2.1 Introduction . . . 7
2.1.1 VBF and QCD $V + 2j$ production . . . 7
2.2 Theory predictions (J. Lindert) . . . 7
2.2.1 State of the art . . . 8
2.2.2 Best practise . . . 8
2.3 Experimental review . . . 8
2.3.1 Total cross sections . . . 8
2.3.2 Differential measurements . . . 10
2.3.3 TGC/EFT measurements . . . 10
2.4 Challenges . . . 11
2.4.1 Background modelling . . . 11
2.4.2 Gap activity studies . . . 11
2.5 Monte Carlo comparison . . . 11
2.6 Future directions . . . 11
2.7 Recommendations . . . 13

Intro

Theory

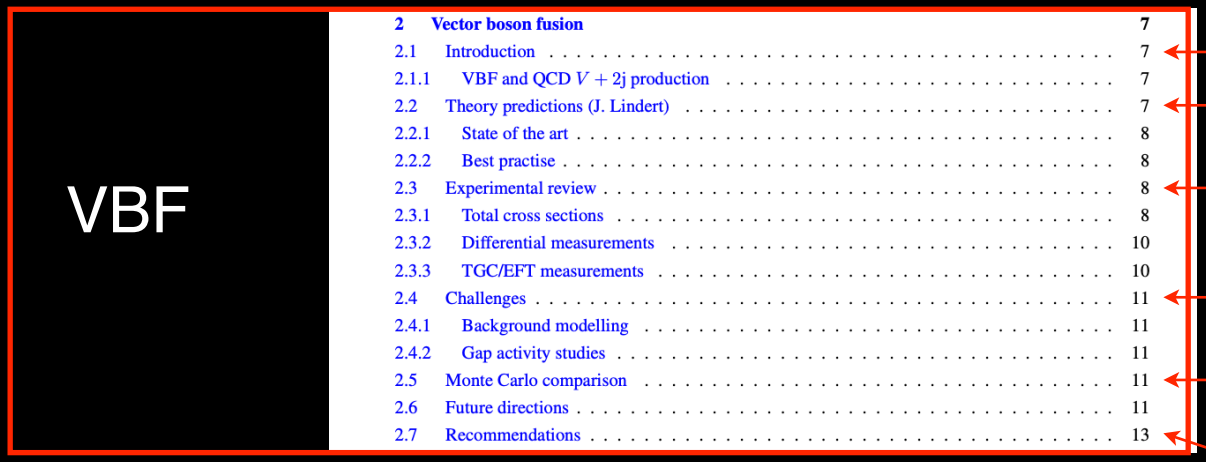
Expt. overview

Challenges

MC comparisons (if available)

Future guidelines / Recommendations

VBF



2 Vector boson fusion 7
2.1 Introduction . . . 7
2.1.1 VBF and QCD $V + 2j$ production . . . 7
2.2 Theory predictions (J. Lindert) . . . 7
2.2.1 State of the art . . . 8
2.2.2 Best practise . . . 8
2.3 Experimental review . . . 8
2.3.1 Total cross sections . . . 8
2.3.2 Differential measurements . . . 10
2.3.3 TGC/EFT measurements . . . 10
2.4 Challenges . . . 11
2.4.1 Background modelling . . . 11
2.4.2 Gap activity studies . . . 11
2.5 Monte Carlo comparison . . . 11
2.6 Future directions . . . 11
2.7 Recommendations . . . 13

Intro

Theory

Expt. overview

Challenges

MC comparisons (if available)

Future guidelines / Recommendations

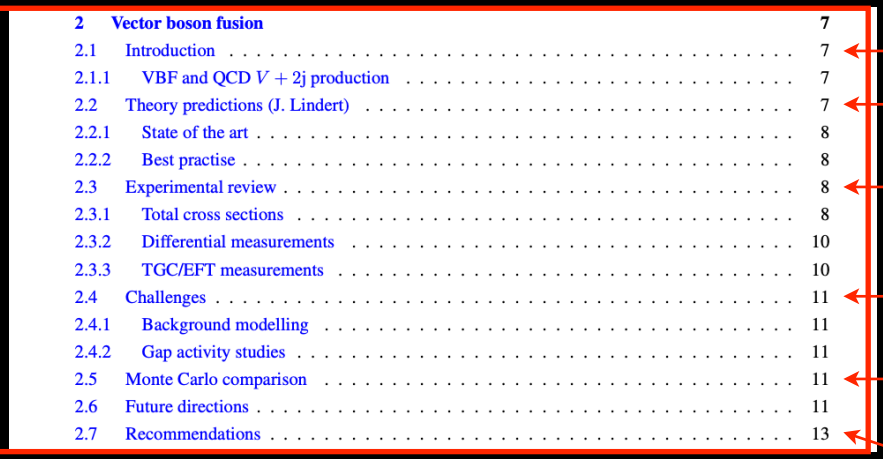
We welcome discussions about new theory

Interesting challenges

Studies of MC comparisons

Suggestions for future guidlines and recommendations

VBF



2 Vector boson fusion 7
2.1 Introduction . . . 7
2.1.1 VBF and QCD $V + 2j$ production . . . 7
2.2 Theory predictions (J. Lindert) . . . 7
2.2.1 State of the art . . . 8
2.2.2 Best practise . . . 8
2.3 Experimental review . . . 8
2.3.1 Total cross sections . . . 8
2.3.2 Differential measurements . . . 10
2.3.3 TGC/EFT measurements . . . 10
2.4 Challenges . . . 11
2.4.1 Background modelling . . . 11
2.4.2 Gap activity studies . . . 11
2.5 Monte Carlo comparison . . . 11
2.6 Future directions . . . 11
2.7 Recommendations . . . 13

Intro

Theory

Expt. overview

Challenges

MC comparisons (if available)

Future guidelines / Recommendations

We welcome discussions about new theory

Interesting challenges

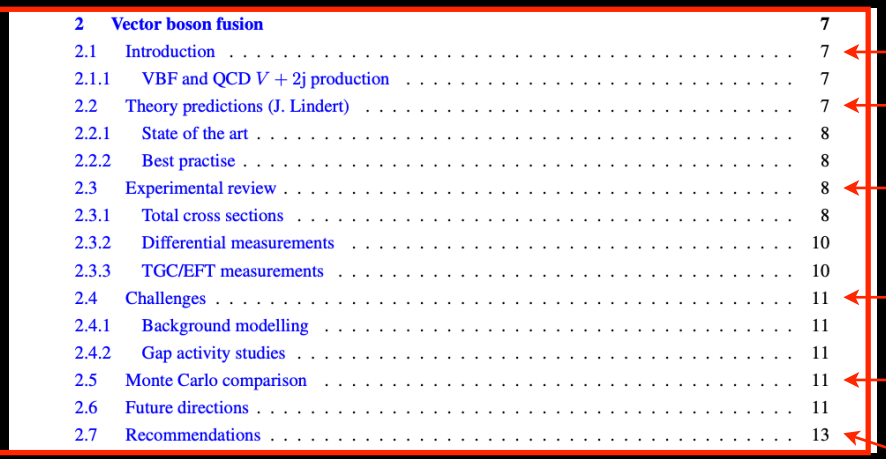
Studies of MC comparisons

Suggestions for future guidlines and recommendations

Yellow Report discussion can take place here

Contact conveners <lhc-ewwg-multiboson-admin@cern.ch> if you have inputs / comments / start a discussion

VBF



2 Vector boson fusion 7
2.1 Introduction . . . 7
2.1.1 VBF and QCD $V + 2j$ production . . . 7
2.2 Theory predictions (J. Lindert) . . . 7
2.2.1 State of the art . . . 8
2.2.2 Best practise . . . 8
2.3 Experimental review . . . 8
2.3.1 Total cross sections . . . 8
2.3.2 Differential measurements . . . 10
2.3.3 TGC/EFT measurements . . . 10
2.4 Challenges . . . 11
2.4.1 Background modelling . . . 11
2.4.2 Gap activity studies . . . 11
2.5 Monte Carlo comparison . . . 11
2.6 Future directions . . . 11
2.7 Recommendations . . . 13

Intro

Theory

Expt. overview

Challenges

MC comparisons (if available)

Future guidelines / Recommendations

Today

We welcome discussions about new theory

Interesting challenges

Studies of MC comparisons

Suggestions for future guidlines and recommendations

Yellow Report discussion can take place here

Contact conveners <lhc-ewwg-multiboson-admin@cern.ch> if you have inputs / comments / start a discussion