Vector-Boson-Scattering processes at 100 TeV

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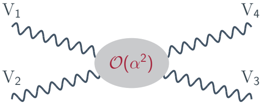
QCD, EW and tools at 100 TeV
07 - 09 Oct. 2015

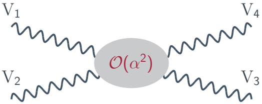
Outline

Outline

Vector-Boson-Scattering



- SM:



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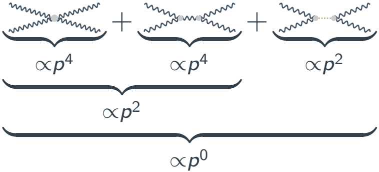
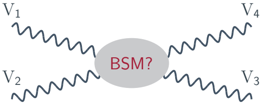


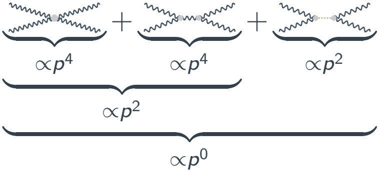
Higgs 'restores' unitarity

⇒ very sensitive to the exact realization of EWSB

Vector-Boson-Scattering



- SM:



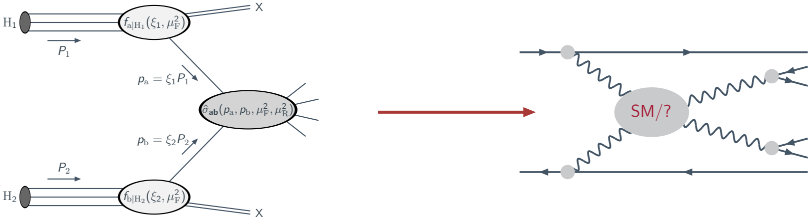
Higgs 'restores' unitarity

⇒ very sensitive to the exact realization of EWSB

- anomalous gauge couplings: aTCGs, aQGCs
- heavy Higgs-Models
- Kaluza-Klein Models
- ...

⇒ only tiny deviations from SM!?

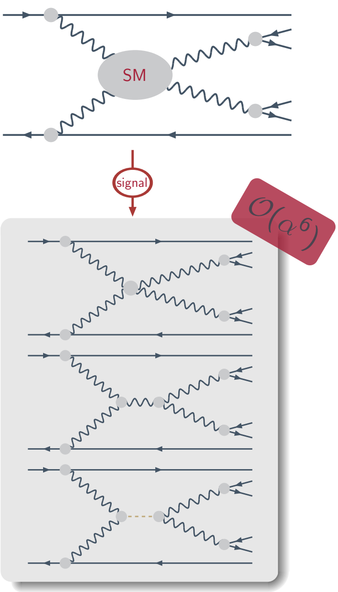
⇒ Detailed understanding of EWSB and high precision in theory and experiment is mandatory!



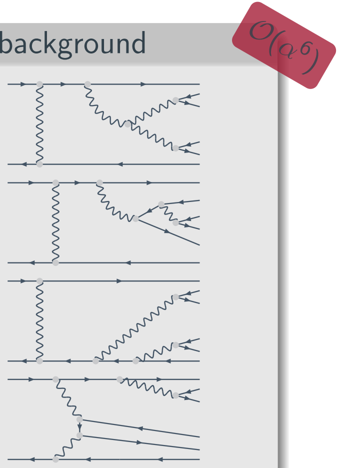
suppressed color exchange between quark lines gives rise to:

- scattered quarks ⇒ two energetic forward jets (tagging jets)
- (leptonic-) decay products typically between tagging jets
- little jet-activity in central region

VBS at hadron colliders



EW-background

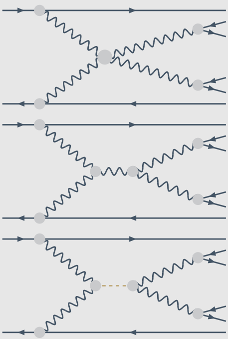


s-channel diagrams (subsequent $V \to q\bar{q}$) excluded!

VBS at hadron colliders

signal diagrams

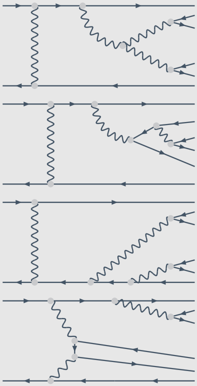
$\mathcal{O}(\alpha^6)$



process class EW_VVjj

EW-background

$\mathcal{O}(\alpha^6)$



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VBS at hadron colliders

signal diagrams

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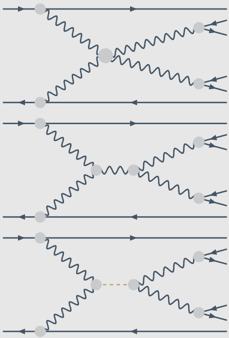
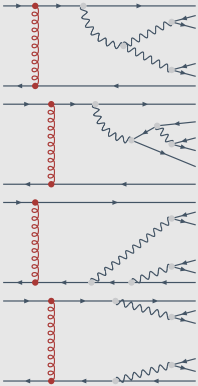


$\alpha(M_Z) \simeq \frac{1}{128}$

QCD-background

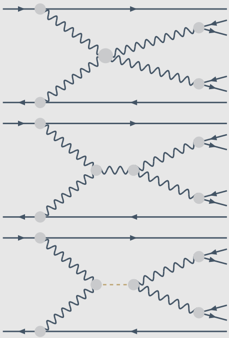
$\mathcal{O}(\alpha_s^2\alpha^4)$



$\alpha_s(M_Z) \simeq 0.14$

VBS at hadron colliders

signal diagrams

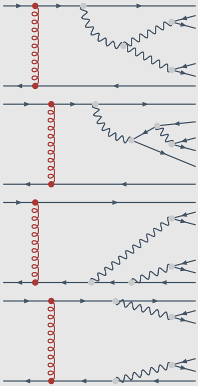


$\mathcal{O}(\alpha^6)$

$\alpha(M_Z) \simeq \frac{1}{128}$

interference $\mathcal{O}(\alpha_s^1\alpha^5)$ negligible

QCD-background

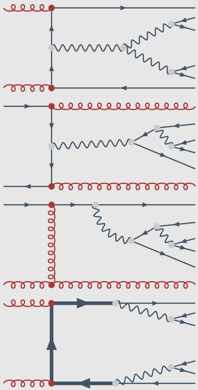


$\mathcal{O}(\alpha_s^2\alpha^4)$

$\alpha_s(M_Z) \simeq 0.14$

external gluons

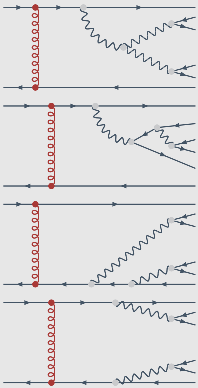
$\mathcal{O}(\alpha_s^2\alpha^4)$



process class QCD_VVjj

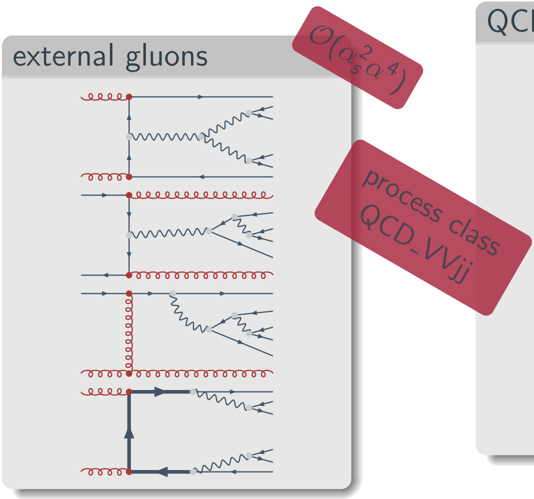
QCD-background

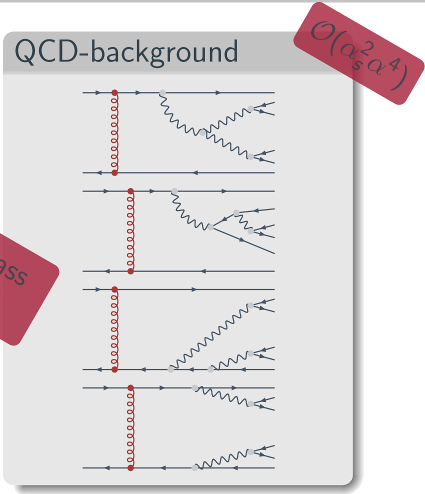
$\mathcal{O}(\alpha_s^2\alpha^4)$



- Gluon induced processes dominate (not present for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$!)

VBS at hadron colliders



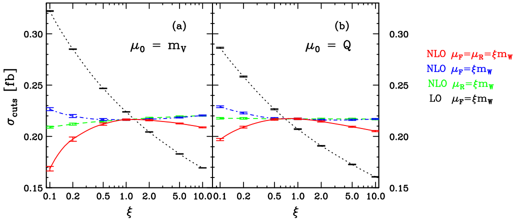


- Gluon induced processes dominate (not present for $\mathrm{W^\pm W^\pm jj}$!)
- Goal: suppress EW- & QCD-background with dedicated phasespace-cuts

VBS at next-to-leading order

NLO QCD:

- only consider leptonic decays of vector bosons
- available for EW- & QCD-induced channels
- corrections $\lesssim 5 - 10\% \rightarrow$ small! (both process classes)
- small scale dependence, especially with dynamical scale choice($\mu_0 = Q$)

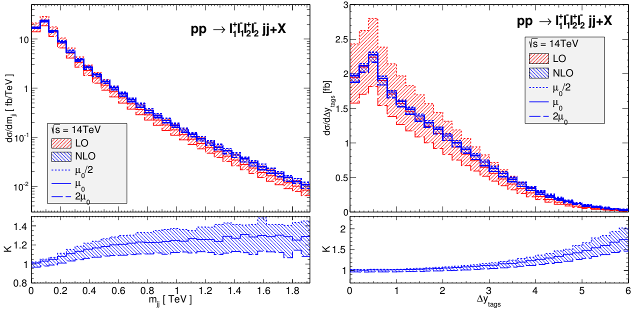


W+Zjj in VBF: [arXiv:hep-ph/0701105]

VBS at next-to-leading order

NLO QCD:

- only consider leptonic decays of vector bosons
- available for EW- & QCD-induced channels
- corrections $\lesssim 5 - 10\% \rightarrow$ small! (both process classes)
- small scale dependence, especially with dynamical scale choice($\mu_0 = Q$)
  - $\Rightarrow$ EW-ind.: almost constant dynamical K-factors
  - $\Rightarrow$ QCD-ind.: shapes get distorted



ZZjj_QCD-ind.: [arXiv:hep-ph/1405.3972]

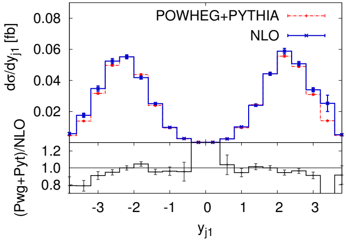
VBS at next-to-leading order

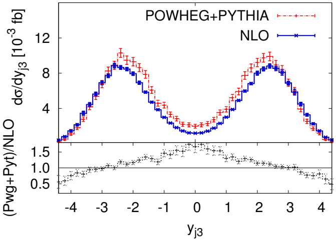
NLO QCD:

- ...

Parton-shower matching:

- influence on tagging jets small
- third jet shows more sensitivity on the parton shower





POWHEG impl. of W+W+jj in VBF: [arXiv:hep-ph/1108.0864]

VBS at next-to-leading order

NLO QCD:

- ...

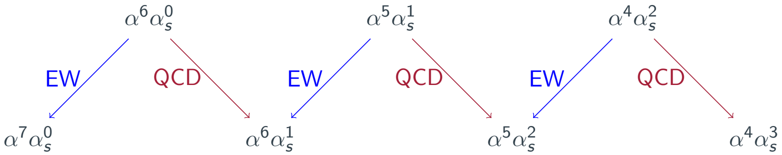
Parton-shower matching:

- ...

NLO EW:

- not yet done, but at least purely EW contributions $\mathcal{O}(\alpha^7)$ supposed to be relevant:

  $\Rightarrow$ negative corrections & shape distortions at high scales (EW-Sudakov logarithms!)



VBS - current Status

- NLO QCD Corrections to EW_VVjj
  $\rightarrow$ VBFNLO [Bozzi, Jäger, Oleari, Zeppenfeld '06 - '09]
- NLO QCD Corrections to EW_$W^{\pm}W^{\pm}$jj [Denner, Hošeková, Kallweit '12]
- NLO QCD Corrections to QCD_$W^{+}W^{\pm}$jj (on-shell W's) [Melia, Melnikov, Rontsch, Zanderighi '10, '11]
- NLO QCD Corrections to QCD_$W^{+}W^{\pm}$jj (DR contrib.) [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
- NLO QCD Corrections to QCD_VVjj (not $W^{+}W^{-}$jj)
  $\rightarrow$ VBFNLO [Campanario, Kerner, Ninh, Zeppenfeld '13, '14]
- Implementations into the POWHEG-Box (NLO QCD+PS-Effects)
  - QCD_$W^{+}W^{+}$jj [Melia, Nason, Rontsch, Zanderighi '11]
  - EW_$W^{+}W^{\pm}$jj and EW_ZZjj [Jäger, Karlberg, Zanderighi '11, '13]
- Evidence for EW_$W^{\pm}W^{\pm}$jj at 8 TeV [ATLAS & CMS collaborations '14]

Outline

1. Introduction
2. ...from 14 TeV to 100 TeV
3. Results for VBS at 100 TeV
4. Conclusion

VBS-Selectioncuts

VBFNLO-2.7.1

- MSTW2008(n)lo68cl
- $\mu_{F,R} = Q$ resp. $\frac{1}{2}H_T = \frac{1}{2}\sum_i p_{T,i} + E_T(V_1) + E_T(V_2)$
- $n_f = 5,\ V_{CKM} = \mathbb{1}$
- distinct FS lepton-flavors, exclude FS b-& t-quarks

minimal cuts

- kT-algorithm (D=0.8)
  $|y_{\mathrm{i}}| < 5,\ |y_{\mathrm{jet}}| < 4.5$
  $p_{\mathrm{T,jet}} > 20\,\mathrm{GeV}$
- $p_{\mathrm{T,l}} > 20\,\mathrm{GeV}$
  $|y_{\mathrm{l}}| < 2.5$
- $\Delta R_{\mathrm{lj}} > 0.4$
- for processes with Z's:
  $\Delta R_{\mathrm{ll}} > 0.2$
  $M_{\mathrm{ll}} > 15\,\mathrm{GeV}$

VBS-cuts

<u>14 TeV</u>

$M_{\mathrm{j1j2}} > 600\,\mathrm{GeV}$
$\Delta y_{\mathrm{j1j2}} > 4$
$y_{\mathrm{j}_1} \times y_{\mathrm{j}_2} < 0$

<u>100 TeV</u>

$M_{\mathrm{j1j2}} > ?$
$\Delta y_{\mathrm{j1j2}} > ?$
$y_{\mathrm{j}_1} \times y_{\mathrm{j}_2} < 0$

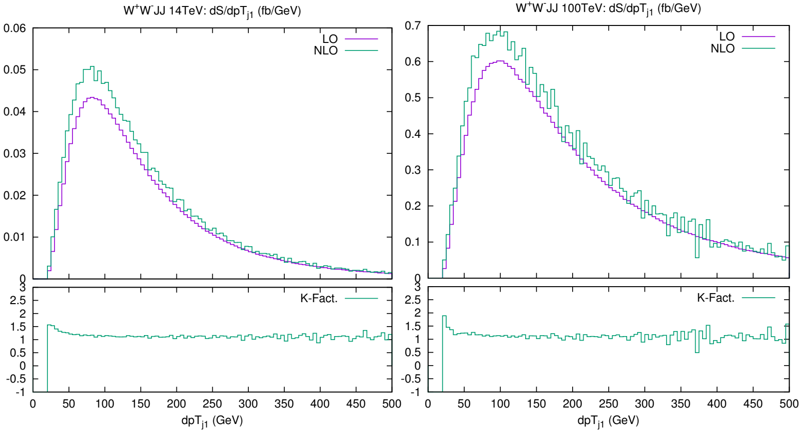
VBS at 100 TeV with minimal cuts

LO-XS	14 TeV			100 TeV		
	EW	QCD	S/B	EW	QCD	S/B
W^+W^-jj [fb]	7.272(4)	-	-	142.40(9)	-	-
W^+W^+jj [fb]	2.6577(3)	2.0969(4)	$5/4$	52.589(8)	17.225(6)	$3/1$
W^+Zjj [fb]	0.47311(6)	14.942(2)	$1/31$	9.650(1)	273.06(5)	$1/28$
$ZZjj$ [fb]	0.12513(3)	2.4666(3)	$1/20$	2.9198(8)	50.95(1)	$3/50$

- QCD_W^+W^-jj not implemented in VBFNLO
- 100 TeV-XS of EW-induced enhanced by $\approx \times 20$ wrt. 14 TeV
- 100 TeV-XS of QCD_W^+W^+jj enhanced by $\approx \times 8$ wrt. 14 TeV
- S/B-ratio slightly improved wrt. 14 TeV

EW_W^+W^-jj with minimal cuts

W^+W^-jj	14 TeV			100 TeV		
	EW	QCD	S/B	EW	QCD	S/B
LO [fb]	7.272(4)	-	-	142.40(9)	-	-
NLO [fb]	8.30(1)	-	-	158.9(2)	-	-
K	1.14	-	-	1.12	-	-



EW_W^+W^-jj with minimal cuts

W^+W^-jj	14 TeV EW	14 TeV QCD	14 TeV S/B	100 TeV EW	100 TeV QCD	100 TeV S/B
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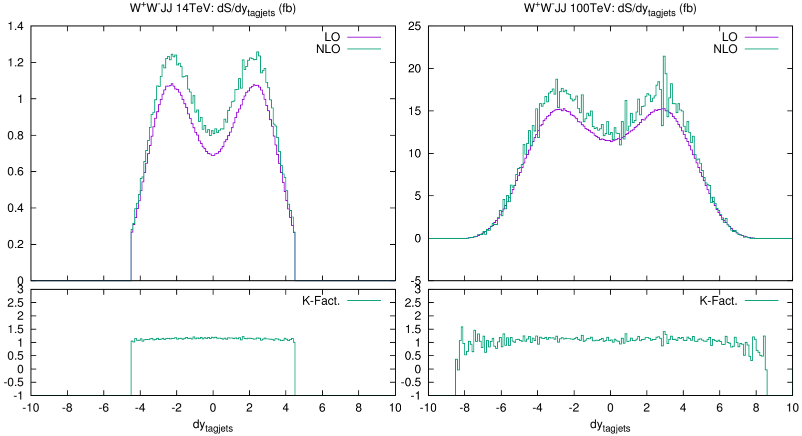

VBS-Selectioncuts

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  $p_{\mathrm{T},\mathrm{jet}} > 20\,\mathrm{GeV}$
- $p_{\mathrm{T},\mathrm{l}} > 20\,\mathrm{GeV}$
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- $\Delta R_\mathrm{lj} > 0.4$
- for processes with Z's:
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  $M_\mathrm{ll} > 15\,\mathrm{GeV}$

VBS-cuts

<u>14 TeV</u>

$M_{\mathrm{j1j2}} > 600\,\mathrm{GeV}$
$\Delta y_{\mathrm{j1j2}} > 4$
$y_{\mathrm{j}_1} \times y_{\mathrm{j}_2} < 0$

<u>100 TeV</u>

$M_{\mathrm{j1j2}} > ?$
$\Delta y_{\mathrm{j1j2}} > ?$
$y_{\mathrm{j}_1} \times y_{\mathrm{j}_2} < 0$

$\Rightarrow$ compare diff. distributions of EW_VVjj & QCD_VVjj at leading order within the addapted minimal-cut szenario for the 100 TeV FCC...

VBS at 100 TeV with minimal cuts

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	EW	QCD	S/B	EW	QCD	S/B
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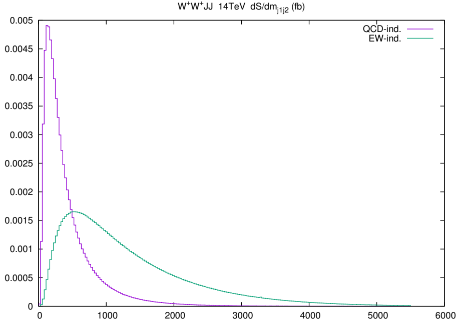

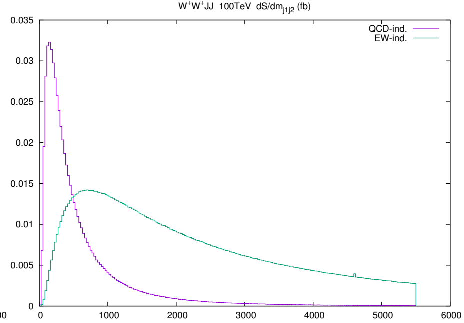

crossing at $\approx 500\,\mathrm{GeV}$
EW-peak at $\approx 500\,\mathrm{GeV}$

crossing at $\approx 500\,\mathrm{GeV}$
EW-peak at $\approx 700\,\mathrm{GeV}$

VBS at 100 TeV with minimal cuts

LO-XS	14 TeV EW	14 TeV QCD	14 TeV S/B	100 TeV EW	100 TeV QCD	100 TeV S/B
W^+W^-jj [fb]	7.272(4)	-	-	142.40(9)	-	-
W^+W^+jj [fb]	2.6577(3)	2.0969(4)	5/4	52.589(8)	17.225(6)	3/1
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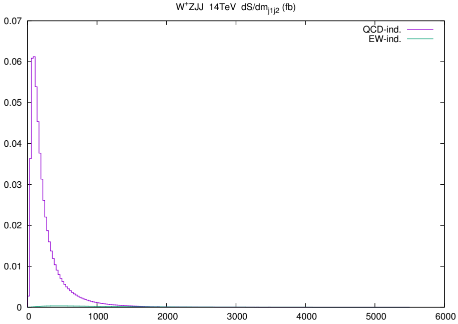

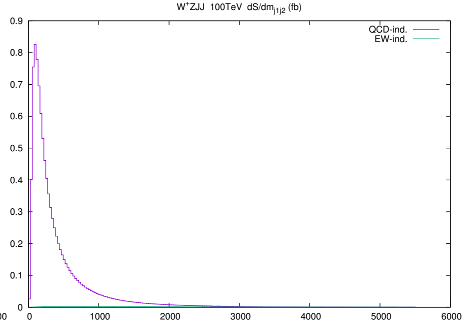

VBS at 100 TeV with minimal cuts

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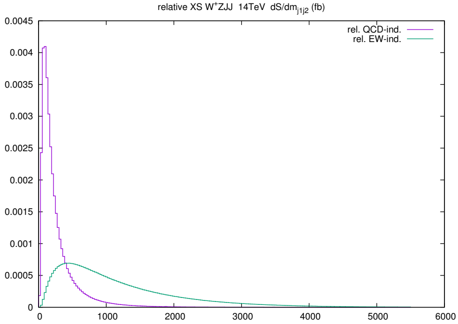

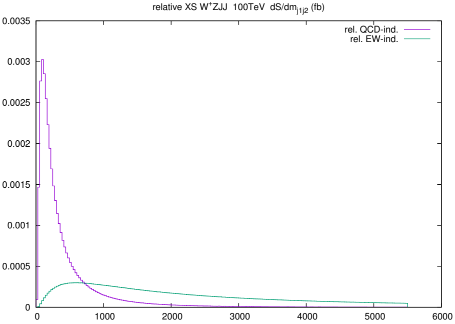

crossing at $\approx 500\,\mathrm{GeV}$ crossing at $\approx 700\,\mathrm{GeV}$

VBS at 100 TeV with minimal cuts

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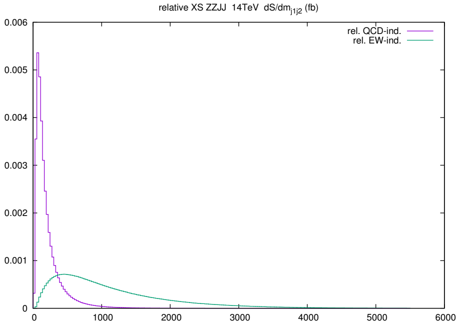

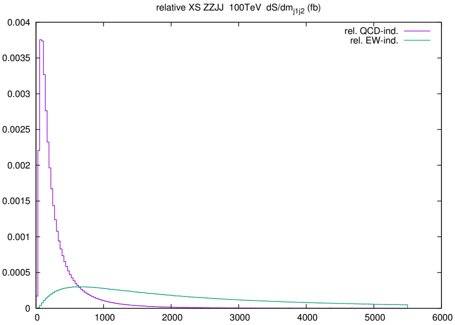

$\Rightarrow$ raise M_{j1j2} cut from 600 GeV to 800 GeV

VBS at 100 TeV with minimal cuts

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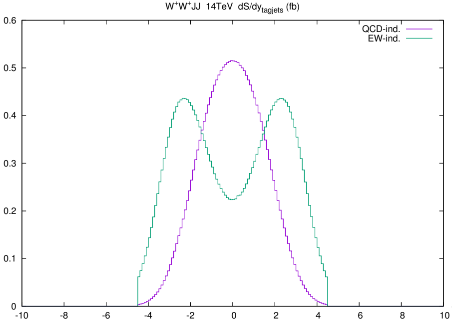

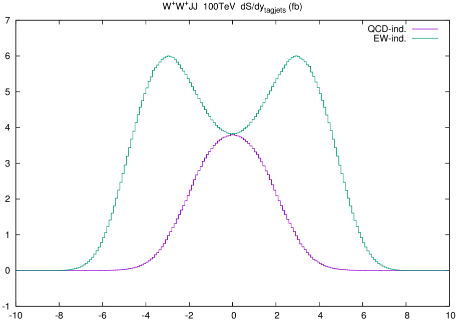

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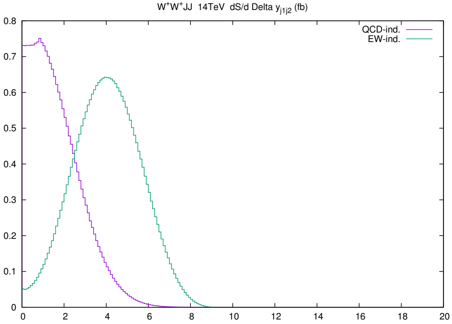
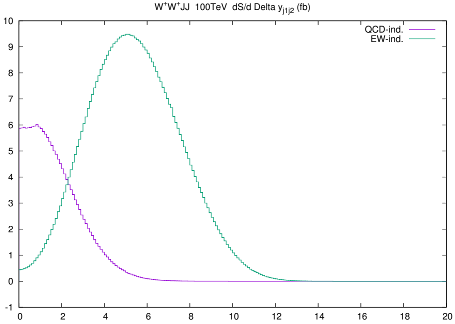


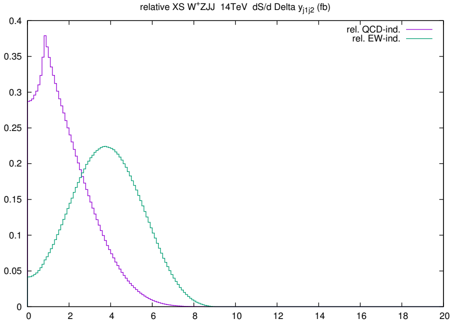


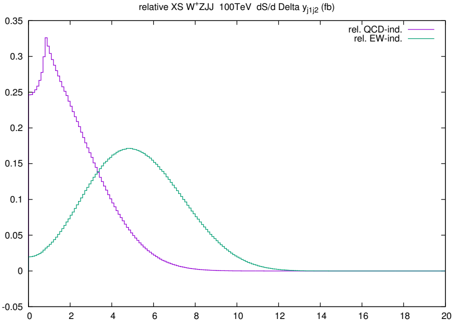
EW-peak at ≈ 4

EW-peak at ≈ 5

VBS at 100 TeV with minimal cuts

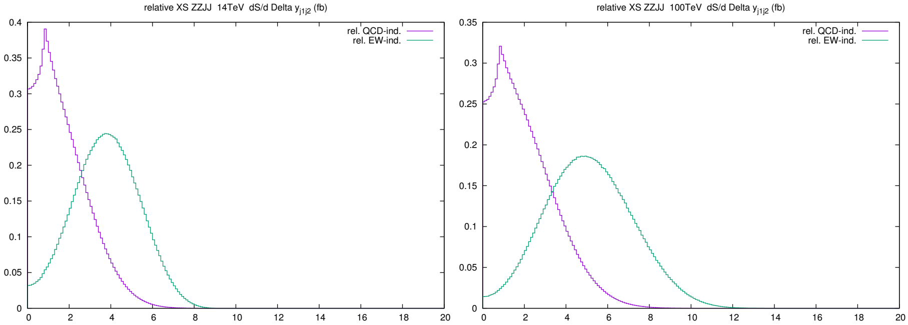
LO-XS	14 TeV			100 TeV		
	EW	QCD	S/B	EW	QCD	S/B
W^+W^-jj [fb]	7.272(4)	-	-	142.40(9)	-	-
W^+W^+jj [fb]	2.6577(3)	2.0969(4)	$5/4$	52.589(8)	17.225(6)	$3/1$
W^+Zjj [fb]	0.47311(6)	14.942(2)	$1/31$	9.650(1)	273.06(5)	$1/28$
$ZZjj$ [fb]	0.12513(3)	2.4666(3)	$1/20$	2.9198(8)	50.95(1)	$3/50$





VBS at 100 TeV with minimal cuts

LO-XS	14 TeV EW	14 TeV QCD	14 TeV S/B	100 TeV EW	100 TeV QCD	100 TeV S/B
W^+W^-jj [fb]	7.272(4)	-	-	142.40(9)	-	-
W^+W^+jj [fb]	2.6577(3)	2.0969(4)	$5/4$	52.589(8)	17.225(6)	$3/1$
W^+Zjj [fb]	0.47311(6)	14.942(2)	$1/31$	9.650(1)	273.06(5)	$1/28$
$ZZjj$ [fb]	0.12513(3)	2.4666(3)	$1/20$	2.9198(8)	50.95(1)	$3/50$



$\Rightarrow$ raise Δy_{j1j2} cut from 4 to 5

VBS-Selectioncuts

minimal cuts

- kT-algorithm (D=0.8)
  $p_{\mathrm{T,jet}} > 20\,\mathrm{GeV}$
- $p_{\mathrm{T,l}} > 20\,\mathrm{GeV}$
  $|y_{\mathrm{l}}| < 2.5$
- $\Delta R_{\mathrm{lj}} > 0.4$
- for processes with Z's:
  $\Delta R_{\mathrm{ll}} > 0.2$
  $M_{\mathrm{ll}} > 15\,\mathrm{GeV}$

VBS-cuts

14 TeV

$M_{\mathrm{j1j2}} > 600\,\mathrm{GeV}$
$\Delta y_{\mathrm{j1j2}} > 4$
$y_{\mathrm{j_1}} \times y_{\mathrm{j_2}} < 0$

100 TeV

$M_{\mathrm{j1j2}} > 800\,\mathrm{GeV}$
$\Delta y_{\mathrm{j1j2}} > 5$
$y_{\mathrm{j_1}} \times y_{\mathrm{j_2}} < 0$

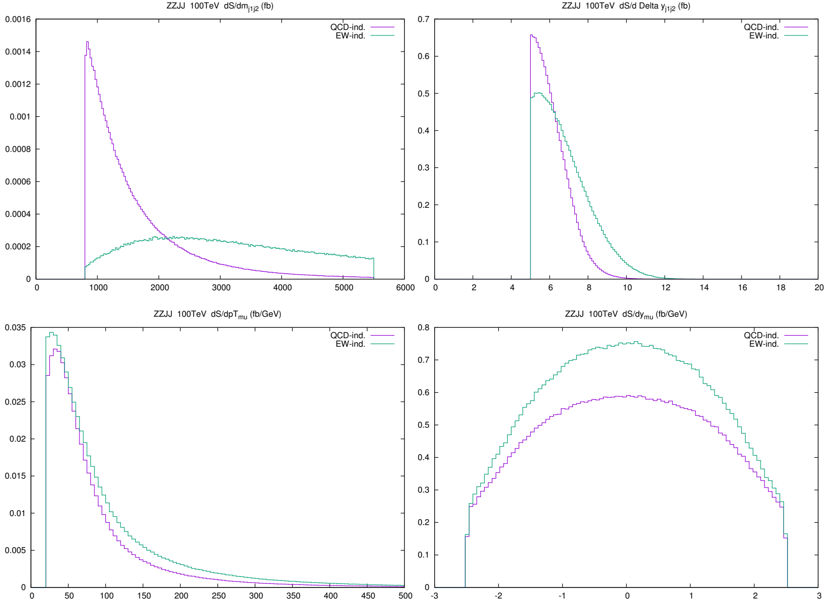
Outline

Results for VBS at 100 TeV

LO-XS		no VBS-cuts			with VBS-cuts		
		EW	QCD	S/B	EW	QCD	S/B
14 TeV	W^+W^-jj [fb]	7.272(4)	-	-	3.109(2)	-	-
	W^+W^+jj [fb]	2.6577(3)	2.0969(4)	$5/4$	1.2851(4)	0.06088(6)	$21/1$
	W^+Zjj [fb]	0.47311(6)	14.942(2)	$1/31$	0.1970(4)	0.5892(4)	$1/3$
	$ZZjj$ [fb]	0.12513(3)	2.4666(3)	$1/20$	0.0523(3)	0.0453(3)5	$7/6$
100 TeV	W^+W^-jj [fb]	142.40(9)	-	-	71.34(5)	-	-
	W^+W^+jj [fb]	52.589(8)	17.225(6)	$3/1$	28.63(1)	0.221(5)	$130/1$
	W^+Zjj [fb]	9.650(1)	273.06(5)	$1/28$	4.7812(2)	10.961(6)	$4/9$
	$ZZjj$ [fb]	2.9198(8)	50.95(1)	$3/50$	1.454(1)	1.185(1)	$5/4$

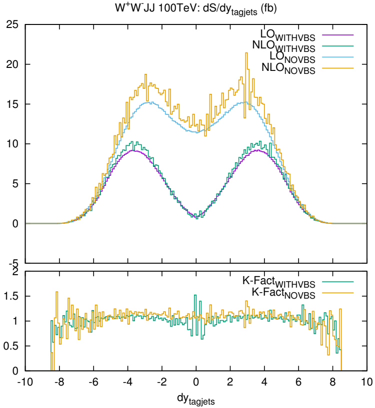
- VBS-cuts reduce XS of EW-ind. to $\approx 50\%$
- much stronger reduction of QCD-ind. XS
- slight improvement wrt. VBS-cuts at 14 TeV
- even more stingent cuts possible due to high XS
- W^+W^+jj-measurement at 8 TeV:
  EW-XS$= 0.88\text{fb}$ (all channels), $S/B \approx 9/1$, 14 EW-events (34 total)

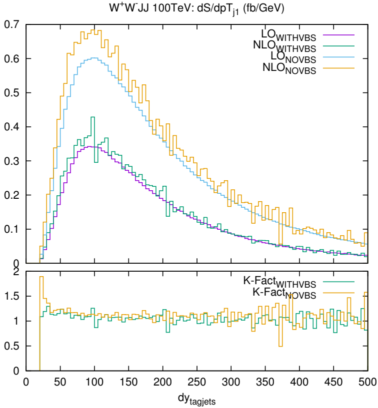
ZZJJ at 100 TeV with VBS-cuts



K-factors for EW_VVjj with VBS-cuts

NLO-XS	14 TeV NLO[fb]	14 TeV K	100 TeV NLO[fb]	100 TeV K
EW_W^+W^-jj	3.332(4)	1.071	75.5(1)	1.059
EW_W^+W^+jj	1.3770(9)	1.071	30.52(3)	1.066
EW_W^+Zjj	0.2109(2)	1.071	5.060(6)	1.058
EW_ZZjj	0.0569(1)	1.088	1.574(4)	1.082





Outline

Conclusion and Outlook

- QCD-correction remain small at 100 TeV (at least for EW-ind.)
- 100 TeV XS $\sim 20\times$ larger than 14 TeV XS
- VBS-cuts clearly improve S/B-ratio
- more stringent/dedicated cuts possible due to hugh XS

- NLO for QCD-ind. at 100 TeV
- scale variations at 100 TeV
- predictions for QCD_W^+W^-jj
- impact of BSM-physics?
- EW-PDFs?
- role of EW-corrections?

comments & further suggestions are very welcome!

ATLAS: arXiv:1405.6241v2 [hep-ex]

$M_{\mathrm{j1j2}} > 500\,\mathrm{GeV}$
$\Delta y_{\mathrm{j1j2}} > 2.4$

is strongly suppressed [16]. The cross section for the electroweak $W^{\pm}W^{\pm}jj$ process is predicted to be 1.00 ± 0.06 fb in the inclusive region and 0.88 ± 0.05 fb in the VBS region. The cross section for the strong $W^{\pm}W^{\pm}jj$ process is 0.35 ± 0.05 fb in the inclusive region and 0.098 ± 0.018 fb for the VBS region. The uncertainty on these predictions include 68% confidence level PDF uncertainties [20], parton shower and hadronization mod-

	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

TABLE II: Estimated background yields, observed number of data events, and predicted signal yields for the three channels are shown with their systematic uncertainty. Contributions due to interference are included in the $W^{\pm}W^{\pm}jj$ electroweak prediction.

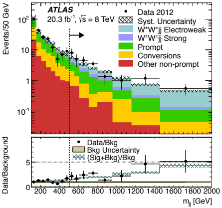


FIG. 1: The m_{jj} distribution for events passing the inclusive region selections except for the m_{jj} selection indicated by the dashed line. The black hatched band in the upper plot represents the systematic uncertainty on the total prediction. On the lower plot the shaded band represents the fractional uncertainty of the total background while the solid line and hatched band represents the ratio of the total prediction to background only and its uncertainty. The $W^{\pm}W^{\pm}jj$ prediction is normalized to the SM expectation.

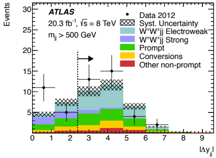


FIG. 2: The $|\Delta y_{jj}|$ distribution for events passing all inclusive region selections. The $|\Delta y_{jj}|$ selection is indicated by a dashed line. The $W^{\pm}W^{\pm}jj$ prediction is normalized to the SM expectation.

$\mu^{\pm}\mu^{\pm}$ channels respectively. The efficiency also accounts for the contribution of leptonic τ decays, which are not included in the fiducial cross-section definition: 10% of signal candidates are expected to originate from leptonic τ decays. The uncertainty on the signal efficiency is dominated by the jet reconstruction uncertainty of 6%.

The measured fiducial cross section for strong and elec-