Review of CMS projections

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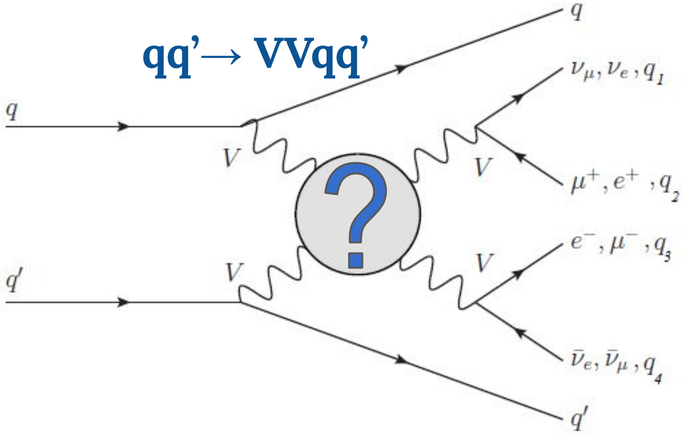
Vector Boson Scattering

- ★ Production of a pair of EWK bosons (VV) from a parton scattering process mediated by **EWK bosons** (V=W,Z,γ).
- ★ Purely **electroweak process,** VBS matrix element @LO $O(\alpha^6_{EWK}\ \alpha^0_S)$.
- ★ **QCD** induced diagrams $O(\alpha^4_{EWK}\ \alpha^2_S)$ are treated as **background.**

This talk:
$W^{\pm}W^{\pm} \rightarrow 2l\ 2\nu$
$WZ \rightarrow 3l\ 3\nu$
$ZZ \rightarrow 4l$

qq'→ VVqq'



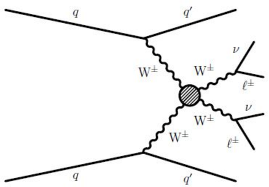
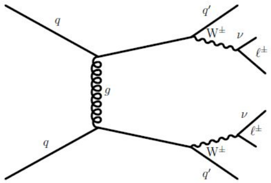
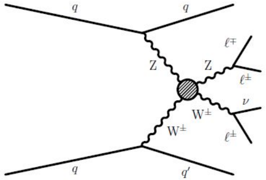
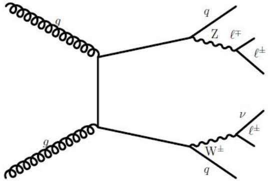
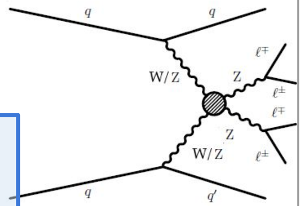
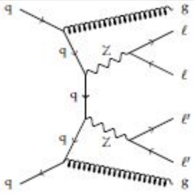
EWK sector **precise** measurements.

Sensitive to **EFT** operators, **anomalies.**

Polarization studies ⟵⟶ EWSB.

Fully leptonic analysis @ 13 TeV Run II

Statistically limited

	Signal	**Irreducible bkg**	**Other bkgs**	**Event topology**
W±W±jj Best EW/ QCD ratio			WZjj(ew/qcd) ZZ Non-prompt tVx Wγ Wrong-sign	2 same charge leptons 2 tag jets and MET
WZjj			ZZ Non-prompt tVx Wγ Wrong-sign	3 leptons with total charge -1/+1 2 tag jets and MET
ZZjj Cleanest channel, less statistics		 +ttZ, VVZ	Z+jets, tt+jets (negligible impact)	2 pair of opposite charge leptons 2 tags jets

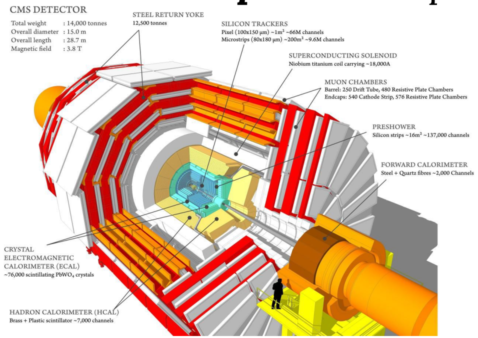
HL LHC

Instantaneous luminosity: up to L = 7.5 x 10^{34}Hz/cm^2(~ 3 times RunII)

Integrated luminosity: up to 3000 fb^{-1} → Improved statistics

Pile up: 140-200 per bunch crossing

More on this: Matteo Marchegiani's talk.



Need upgrade to cope with hardest conditions.

- Inner Tracker up to $|\eta|<4$
- Muon system coverage improved
- MTD timing layer
- High Granularity endcap calorimeter
- DAQ and trigger systems (L1 and HLT -7.5 kHz)

VBS scattering in HL LHC

VBS status @13 TeV RunII:
$W^{\pm}W^{\pm}jj$ WZjj CMS-SMP-19-012
ZZjj CMS-SMP-20-001
See Kenneth Long's Talk.

Dominated by statistics

→

VBS projections HL-LHC:
$W^{\pm}W^{\pm}jj$ CMS-PAS-FTR-18-005
WZjj CMS-PAS-FTR-18-038
ZZjj CMS-PAS-FTR-18-014

Dominated by systematics

Increased c.m. energy → ✓ Increased cross section ~15-20%

Extended tracker coverage → ✓ Better rejection of:
- pile up jets,
- additional leptons.

More statistics → better calibration → ✓ Reduction of experimental uncertainties.

$W^{\pm}W^{\pm}jj$

$W^{\pm}W^{\pm}jj$ projections

- Cross section **O(1 fb),** integrated luminosity increase
  → significant improvement

- **pile up** conditions: up to <**200** pp interactions> per bunch crossing;

- Full simulation of the **phase2 CMS** detector;

The **extended tracker** should improve the lepton identification → suppress contamination of ttbar,WZ, ZZ

The **highly granular calorimeter** should significantly enhance the capability to observe this signal.

- **Uncertainties** as Yellow Report 18:
  - **theoretical** uncertainties → **½**
  - **experimental** uncertainties → $\mathbf{1/\sqrt{L}}$ until the achievable accuracy with the upgraded detector.

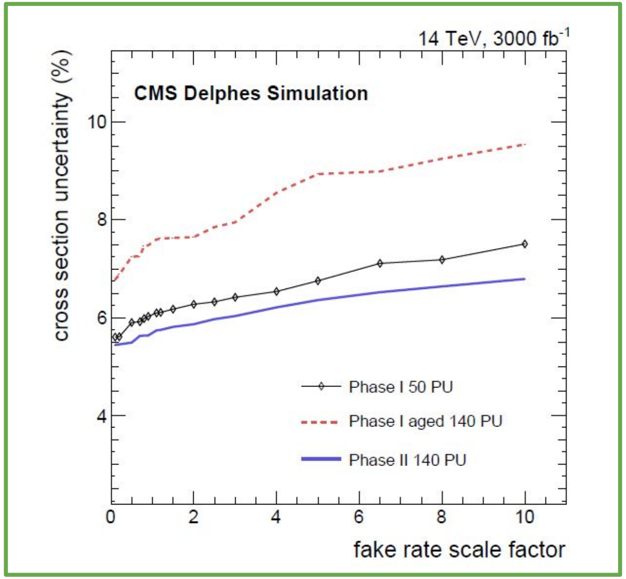
Impact of systematic uncertainties

CMS PAS FTR-18-005

Source of uncertainty	Input	300 fb^{-1} (1 year)	3000 fb^{-1} (10 years)
Statistical uncertainty		5.7%	1.8%
Trigger efficiency (electron)	1.0%	0.5%	0.2%
Trigger efficiency (muon)	1.0%	1.1%	0.6%
Electron id + iso. efficiency	1.0%	0.6%	0.3%
Muon id + iso. efficiency	0.5%	0.9%	0.6%
Jet energy scale	0.5–3.7%	1.0%	0.4%
b tag (stat. component)	1.0%	0.2%	0.3%
b tag misidentification	1–2%	1.4%	1.2%
Misidentified lepton from $t\bar{t}$	5–20%	3.5%	1.0%
Misidentified lepton from $W\gamma$	20%	0.3%	0.1%
Stat. accuracy of $W\gamma$ sample	30%	0.4%	0.1%
Total (stat + experimental syst)		7.6%	3.2%
Luminosity	1.0%	1.0%	1.0%
Theoretical/QCD scale	3.0%	3.0%	3.0%
Total (stat + syst + lumi + theory)		8.2%	4.5%

Big impact:
directly affects yields of signal events

Dependance of total cross section uncertainties on fake (misidentified) lepton scale factor @ 3000 fb^{-1}.

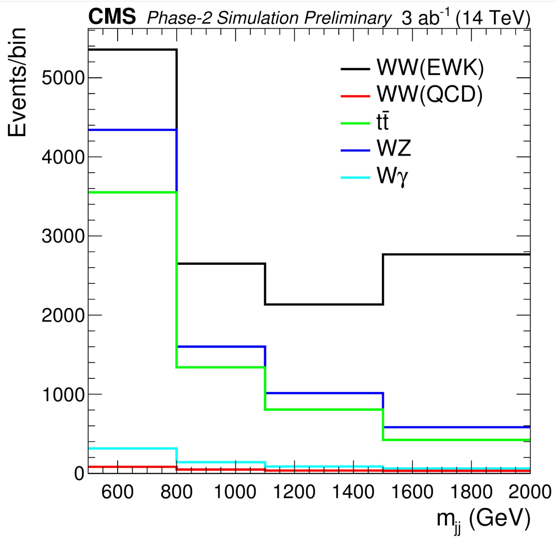


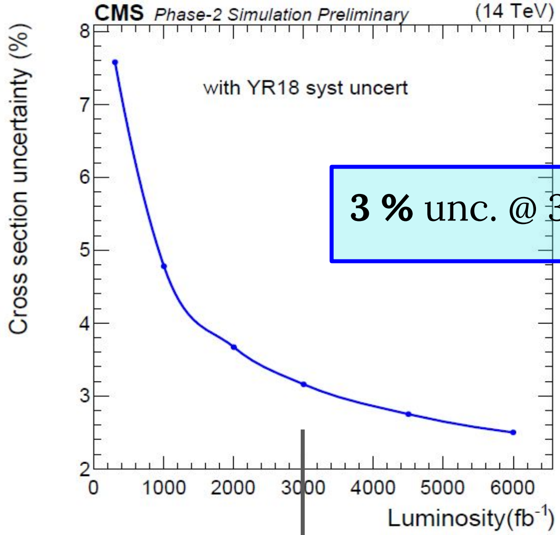
CMS-PAS-SMP-14-008

W±W±jj projections

3 final states **independent channels**: **ee, em and mm**.

mjj distribution binned maximum likelihood fit.





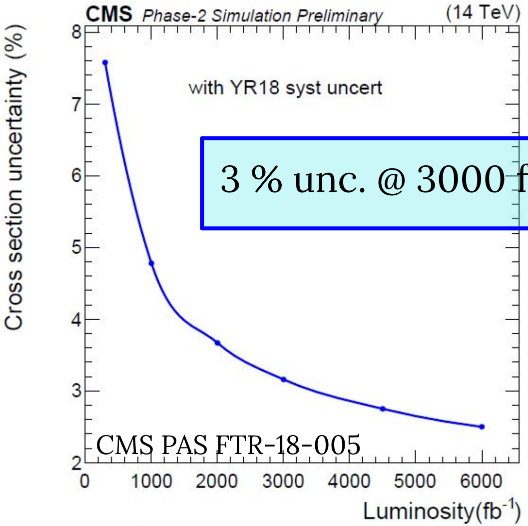
3 % unc. @ 3000 fb^{-1}

From this point, combination of ATLAS+CMS

CMS PAS FTR-18-005

$W^{\pm}W^{\pm}jj$ revised projections

What if we rescale this projection....



3 % unc. @ 3000 fb^{-1}

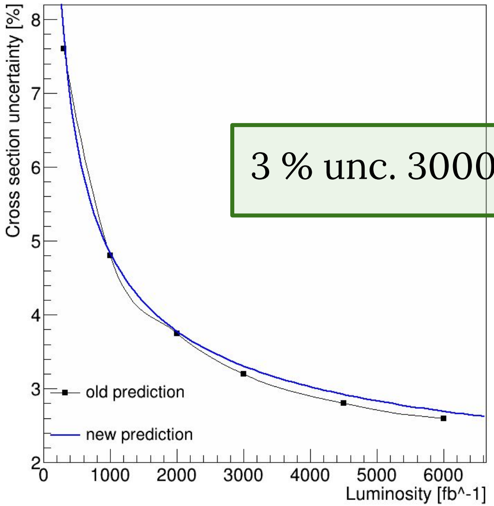
CMS PAS FTR-18-005

... to the latest published result with Full Run 2 datasets?

11% unc. @13 TeV RunII

From SMP-19-012

(Arxiv:2005.01173)



3 % unc. 3000 fb^{-1}

Latest published results looks compatible with projections.

WZjj

WZjj projections

- The **cross sections** @ $\sqrt{s}$ = 14 TeV increase in general increase by 8 – 20% wrt 13 TeV:
  - **EW WZjj → 16%**
  - **QCD WZ → 8%.**
- The **increase in the pseudorapidity** coverage increases the **yield** for different decay channels by **5–8%**.
- Lepton efficiency, PDF uncertainties, and other measurable and theoretical uncertainties → **1% level.**

Systematic Source	Type	Amount, %
Integrated luminosity	Norm.	1
Nonprompt norm.	Norm.	10
b-tagging	Norm.	1-3
Electron scale and res.	Shape	1
Muon efficiency and res.	Shape	0.5
MET	Shape	1-4
Other background theory	Shape	1-5
QCD-WZjj PDF	Shape	1
QCD-WZjj Scale	Shape	3-4
EW-WZjj PDF	Shape	1
EW-WZjj Scale	Shape	2-3
Jet energy scale	Shape	1-3
Jet energy resolution	Shape	1-4

Cross check the Delphes, generated for 14 TeV and PhaseII geometry, VS the FullSim used in Run2 and Phase1 geometry.

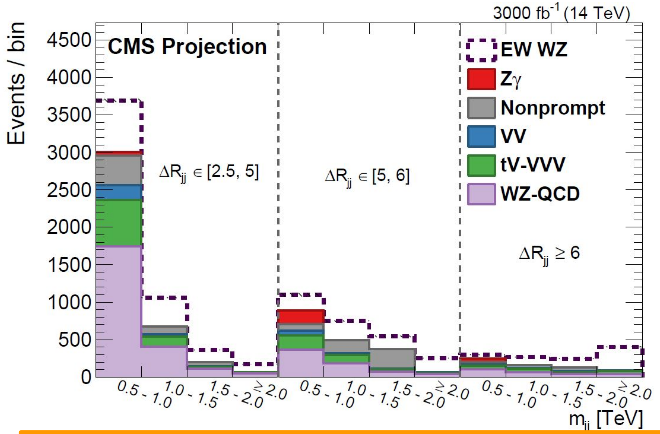
Use the MC 13 TeV samples, scaled for cross section, acceptance and luminosity increase.

WZjj projections

Relative fraction of EW process in WZjj production increases with increasing:

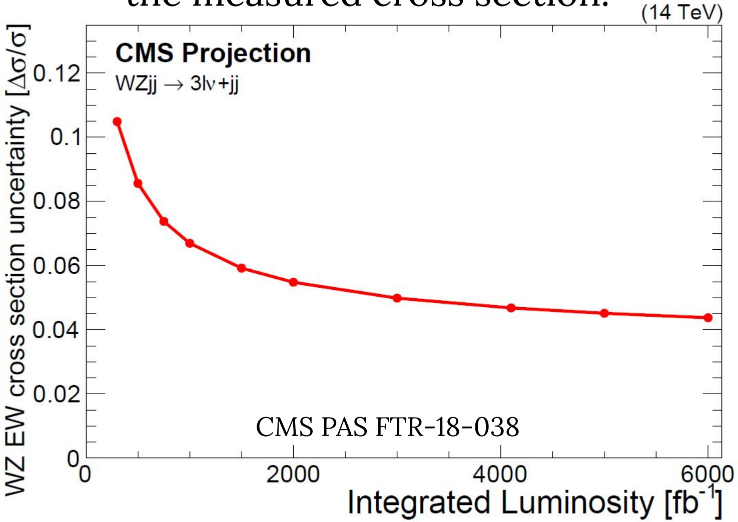
1. dijet mass
2. angular separation of the leading jets.

$$\Delta R_{jj} = \sqrt{(\Delta\eta_{jj})^2 + (\Delta\phi_{jj})^2}$$



4 final states **independent channels**: **eee, eeμ, μμe, μμμ.**
Maximum likelihood fit of **m_{jj}-ΔR**.

~4-5% @ 3000-6000 /fb **systematic uncertainties** will dominate the accuracy of the measured cross section.



zzjj

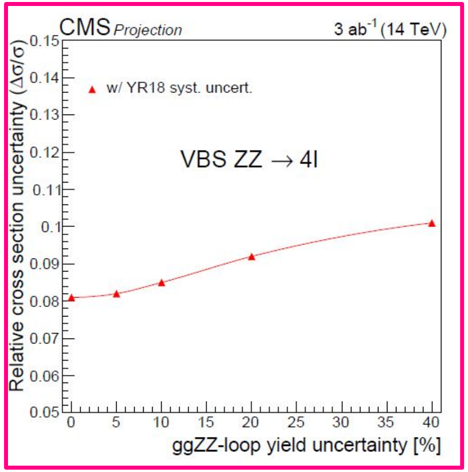
ZZjj projections

Scaling the expected yields for the signal and the background processes @ 13 TeV phase 1, accounting for:

- Luminosity increase;
- Cross section increase;
- Detector acceptance → **Signal yield** increase up to 20%.
  QCD qqZZ → 10% higher than for the signal.
  ggZZ → less because more central.
- Uncertainties as Yellow Report 18:
  - **theoretical** uncertainties → ½
  - **experimental** uncertainties → $1/\sqrt{L}$ until the achievable accuracy with the upgraded detector.

	EW ZZ	QCD qqZZ	QCD ggZZ
$\sigma_{14\,\text{TeV}} / \sigma_{13\,\text{TeV}}$	1.15	1.17	1.13

	EW ZZ	QCD qqZZ	QCD ggZZ
$\lvert\eta\rvert < 3.0(2.8) / \lvert\eta\rvert < 2.5(2.4)$	1.13	1.18	1.12
$\lvert\eta\rvert < 4.0(2.8) / \lvert\eta\rvert < 2.5(2.4)$	1.21	1.33	1.15

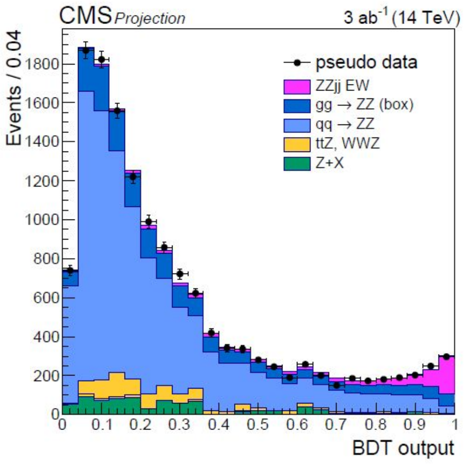


Most relevant: theory uncertainty on **QCD ZZjj**

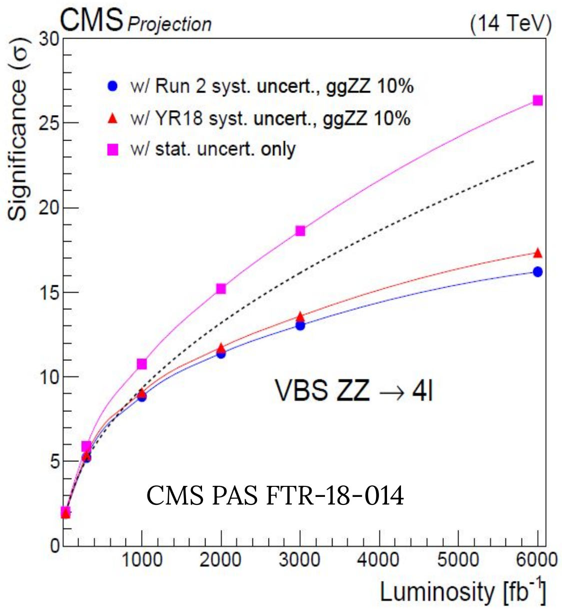
ZZjj projections

BDT to disentangle the EW ZZjj component from the QCD one.

BDT distribution binned maximum likelihood fit.



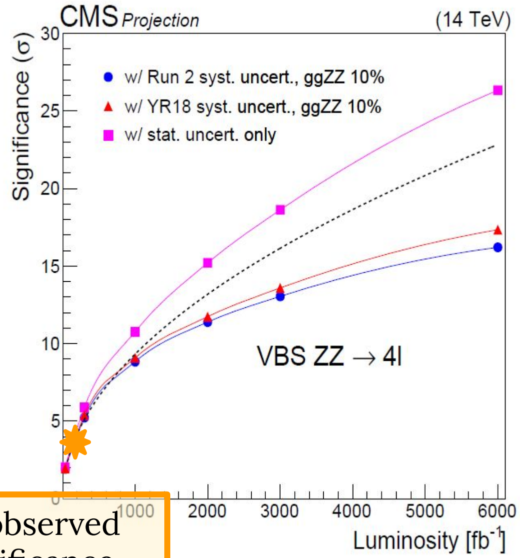
The expected significance for the YR18 scenario* **13.6** @ 3000 fb^{-1}.



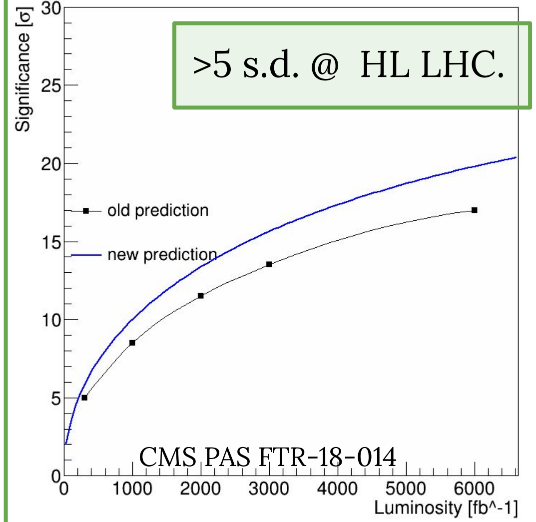
*10% uncertainty in the QCD ggZZ background yield

ZZjj revised projections

The current analysis use a **matrix element discriminant** (K_D) (instead of a BDT) to separate the **signal** and the **QCD** background. This could explain the **gain** observed.



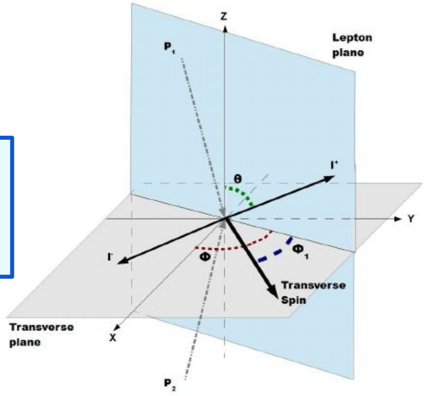
4.0 observed significance
SMP-20-001
(2008.07013v2)



>5 s.d. @ HL LHC.

CMS PAS FTR-18-014

Polarization studies

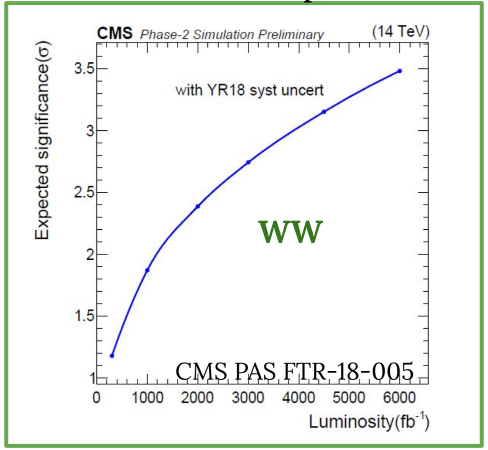


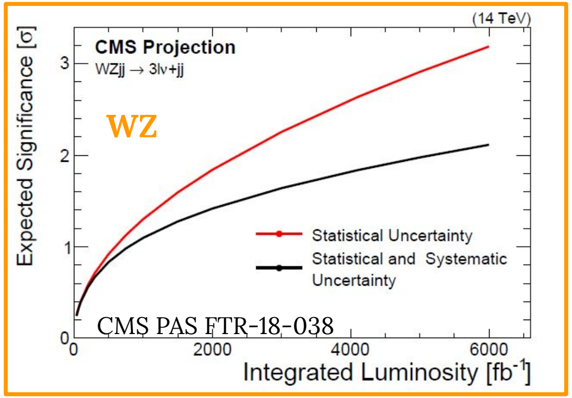
- ★ **Massive V bosons**: 1 longitudinal (L) + 2 transverse (T) polarization mode.

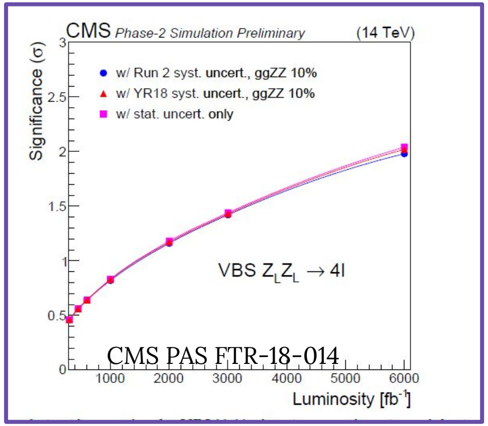
- ★ **Longitudinal component**: directly related to
  - the Electroweak Spontaneous Symmetry Breaking
  - and to Higgs boson → cancellation of divergences @ high energy.

< 10 % of the inclusive cross section

- ★ **ZZ channel** particularly suitable: **complete reconstructions** of the final state particle.







Other effects

HL-LHC would be a great place to study **VBS**.

- The **more signal** yield could allow:
  - division in more **categories** → enhance final sensitivity
  - more raffinate **Machine Learning** techniques → to disentangle from the intrinsic QCD background.

- Better **detector performance** could suppress reducible backgrounds e.g.:
  - in W+W- (not observed yet) could help reducing the limiting top background.
  - Helps further the study semi-leptonic final state, which guarantees an higher statistics than the leptonic ones.

Summary

- ★ **Vector Boson Scattering** production of a pair of EWK bosons (VV) are **rare** process that allow **precision** measurements of the **EW** sector.

- ★ The VBS processes, **statistically limited** analysis at 13 TeV **RunII**, would benefit from the HL-LHC operation condition (14 TeV, 3000 fb^{-1}):

  - **Better** constraint of **known** process (WW, WZ)

  - **Measure** of **not yet observed** processes e.g.
    - W+W-, ZZ ... ;
    - polarization cross section;
    - study different final state (semi-leptonic-hadronic);
    - EFT studies...

- ★ In this scenario, the **limiting** factor would be the **systematic uncertainties**:
  - A work toward the reduction of systematic, theoretical and experimental, would be of primary interest.

Backups

Signature of VVjj

The two bosons may decay hadronically or leptonically, leading to **3** possible final states:

+statistics

1. **leptonic** VV→ lν lν
2. **semi-leptonic** VV → lν q'q"
3. **hadronic** VV → qq' q"q'"

+purity

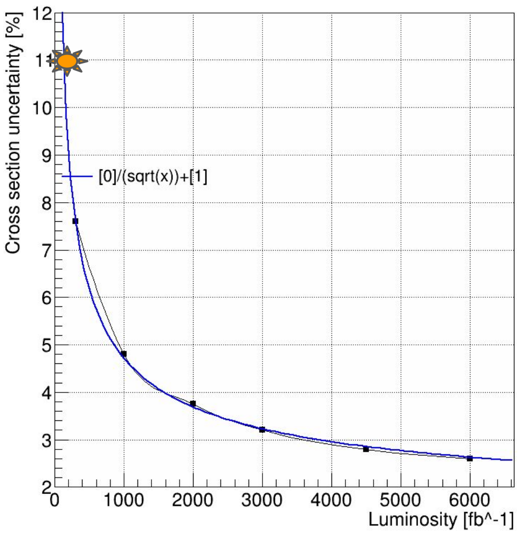
6 fermions in the final state.

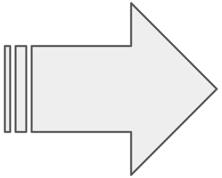
★ 2 high energy jet (tag jets) from the scattering partons:
- high $\mathbf{m_{jj}}$
- great gap in **η**;
- **no QCD** activity between them (leptonic final state).

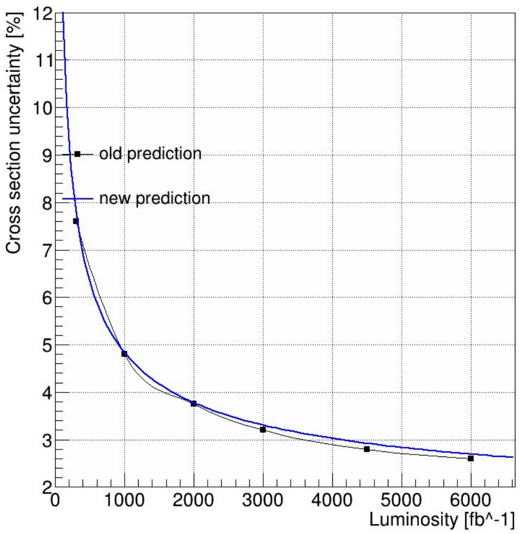
“Revision method”

Simple method to **have a feeling** of the way of recent results impacts the projections.

1. Fit the old distribution with a suited function.
2. Extrapolate to run 2 luminosity.
3. Scale the function to the ratio err(actual res. run2)/err(extr. 137fb-1)







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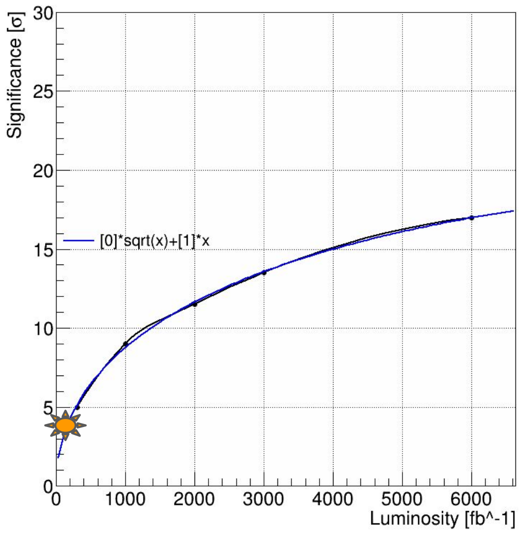

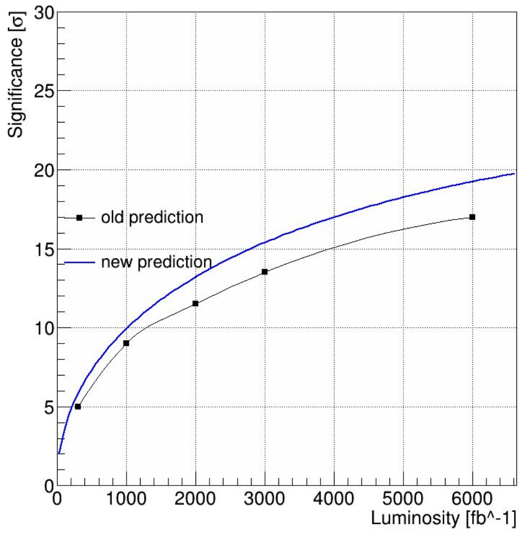

WZ projections

CMS-PAS-SMP-14-008