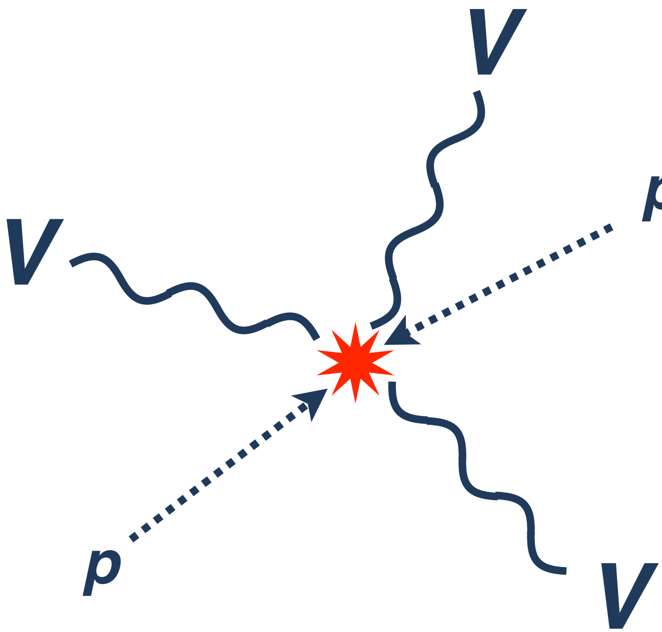
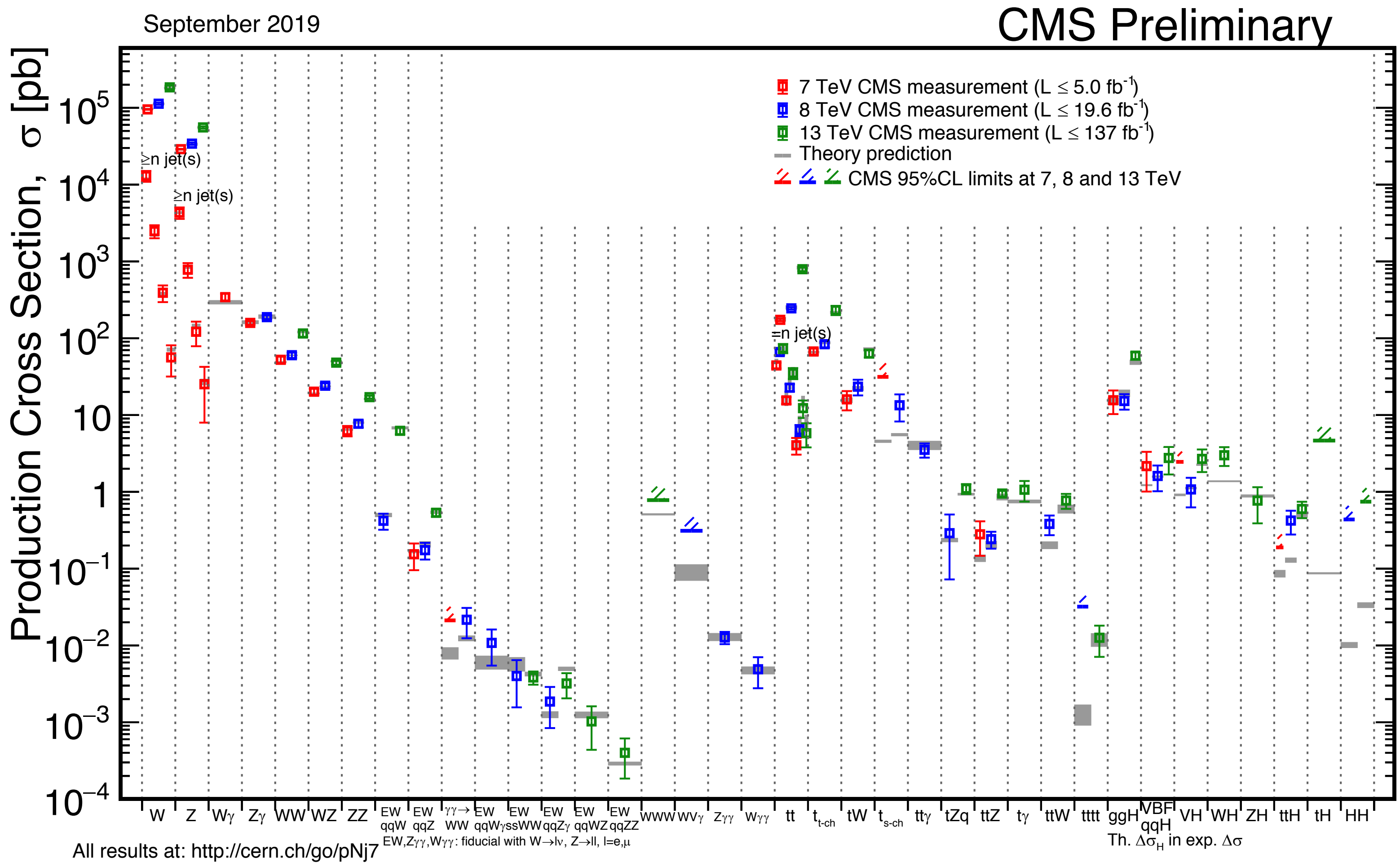
THE OBSERVATION OF TRIPLE HEAVY BOSON PRODUCTION

Hannsjörg Weber (Fermilab)



LHC for precision measurements

- The LHC is the machine that has produced the largest high energy dataset
  - ➢ A great machine to do precision measurement for rare processes.



Physics over 10 order of magnitude!

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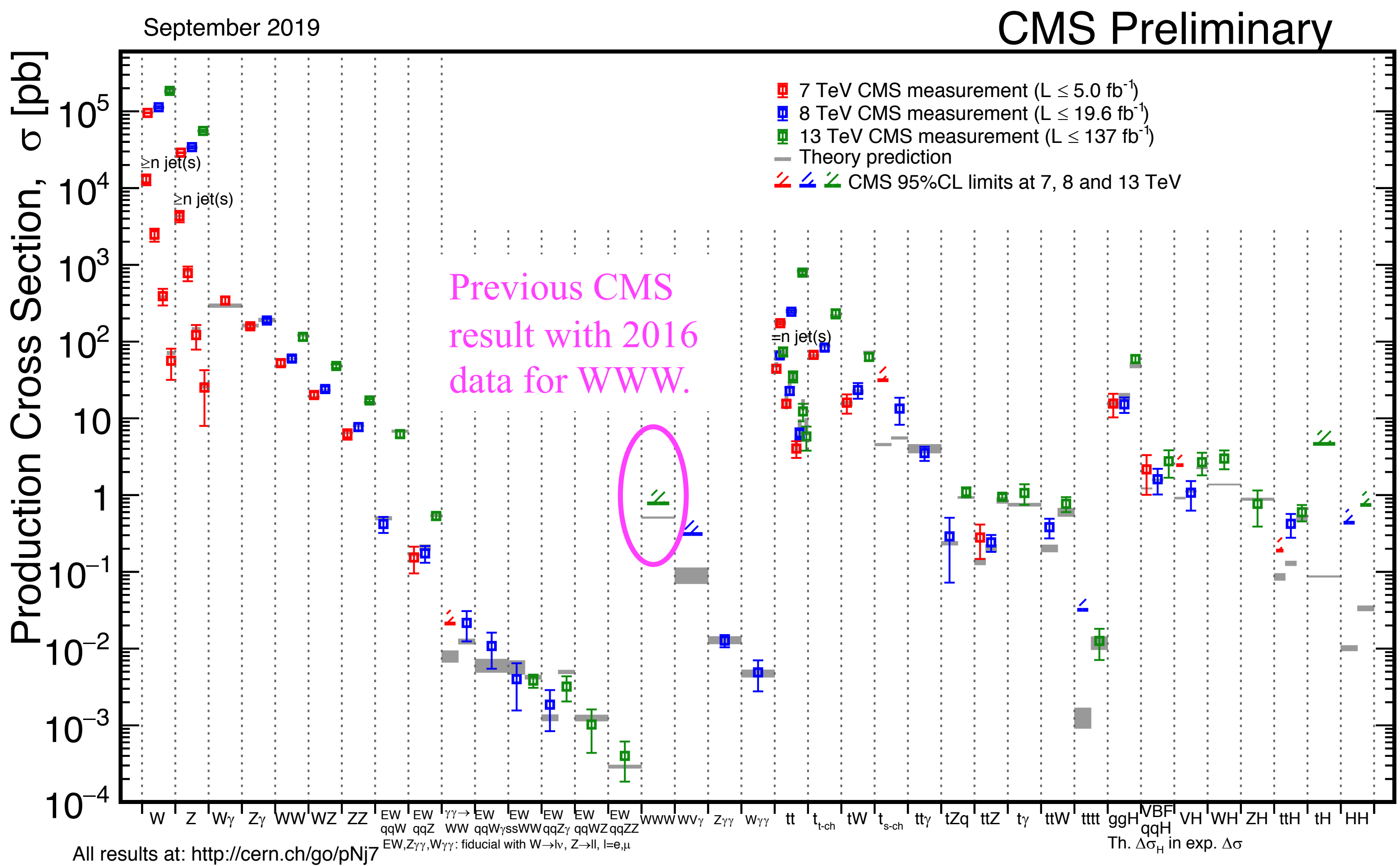
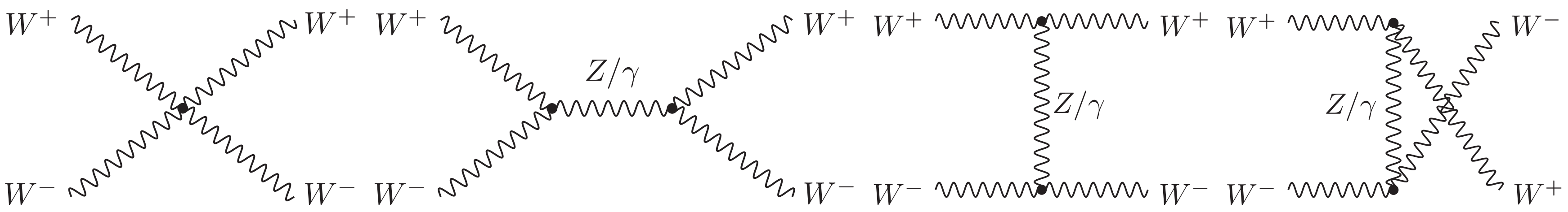


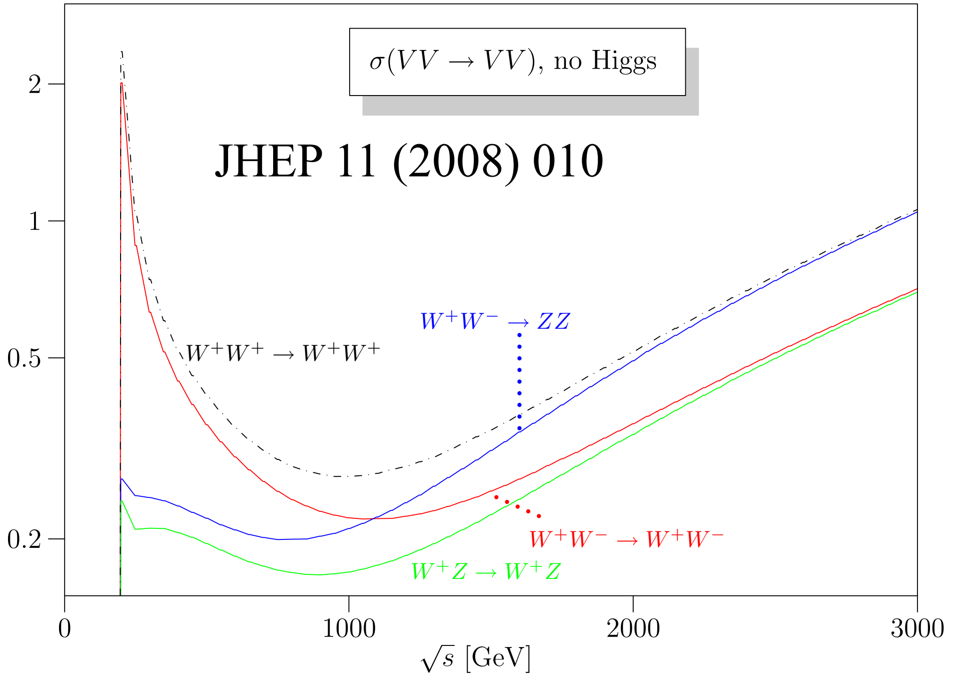
Physics over 10 order of magnitude!

A crucial player – gauge boson interactions

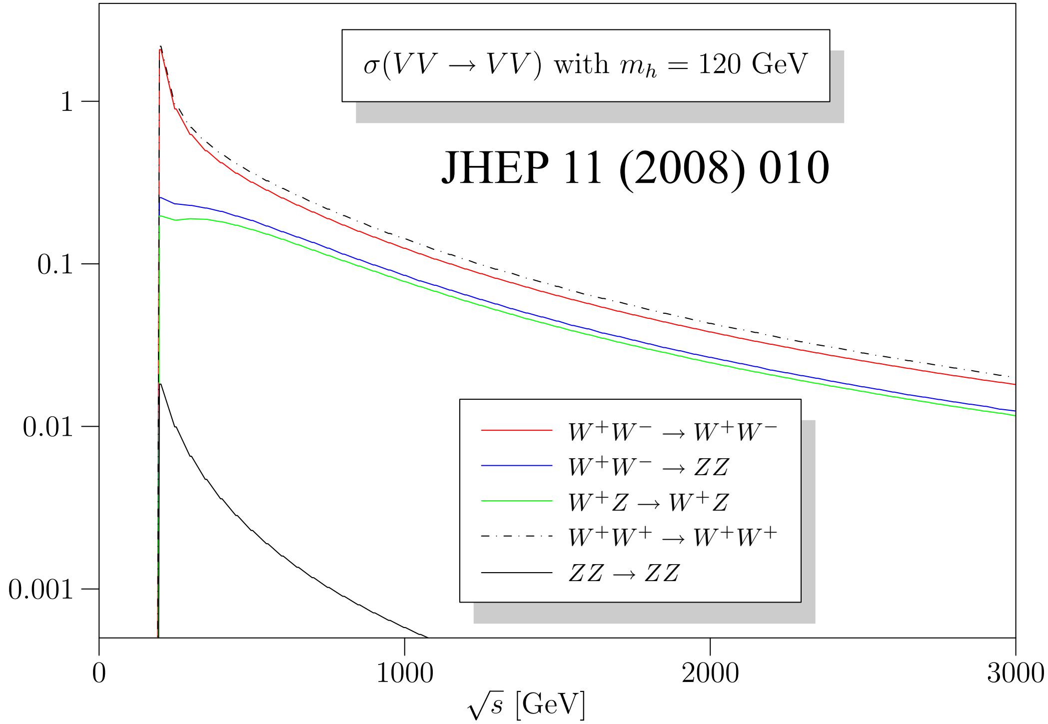
- What if there was no Higgs:



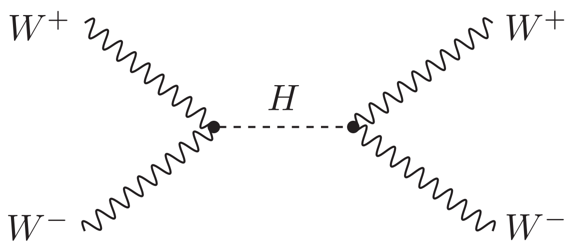
$$|\mathcal{M}(W_L^+ W_L^- \longrightarrow W_L^+ W_L^-)| \underset{E \gg M_W}{\sim} E^2$$

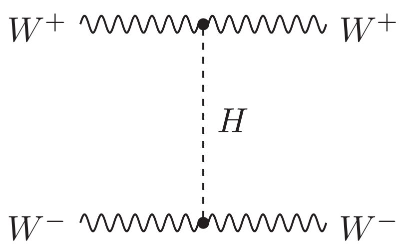


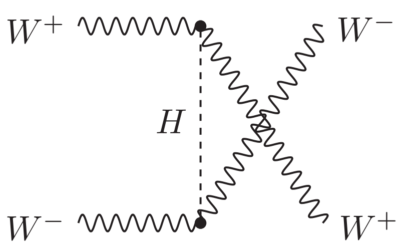
A crucial player – gauge boson interactions



- But the Higgs contribution cancels the E^2 contribution.

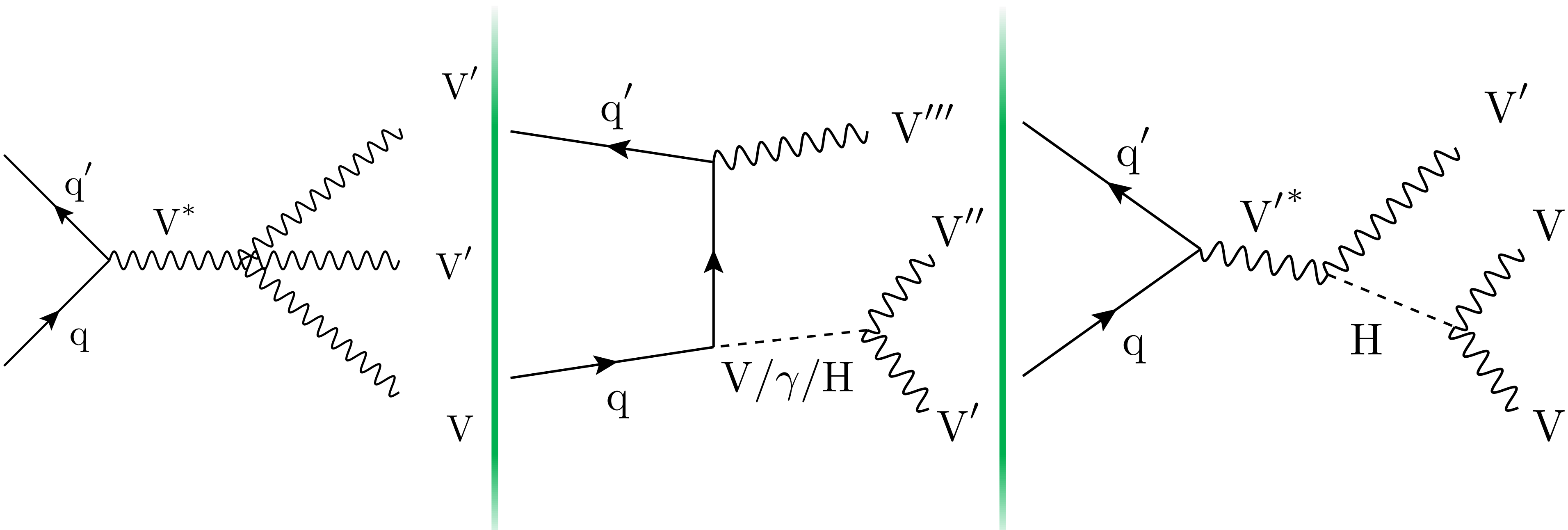






Triboson production

- Triboson process → Access to
  - quartic gauge couplings,
  - trilinear gauge couplings,
  - and Higgs couplings.



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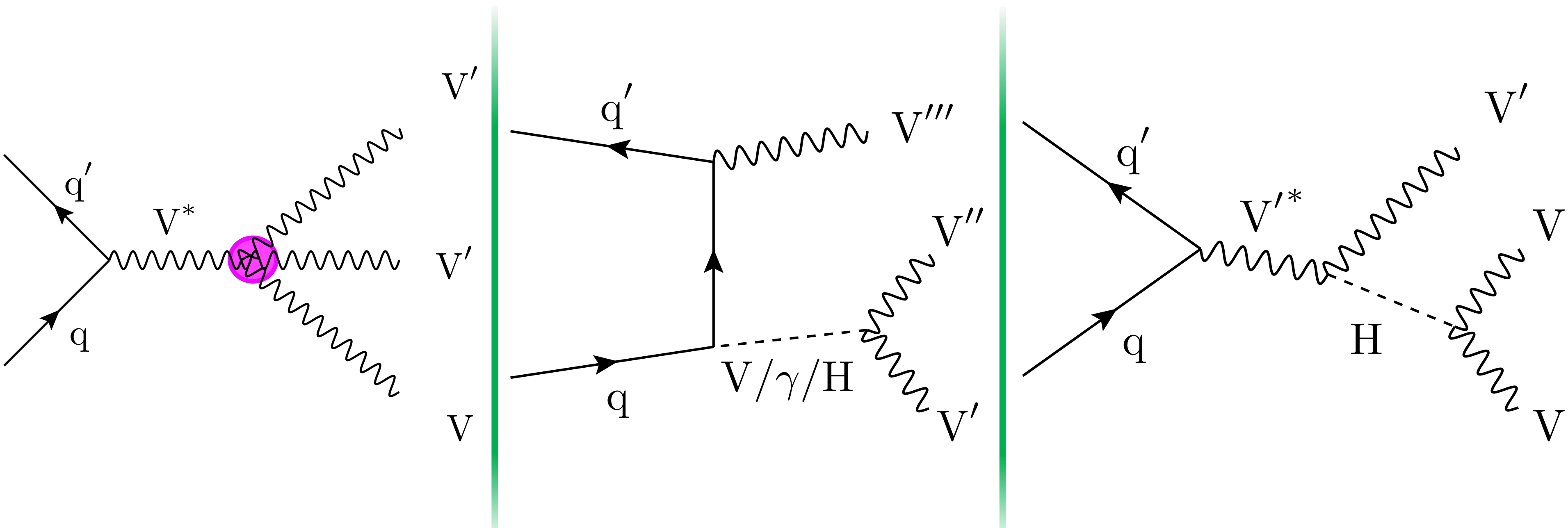

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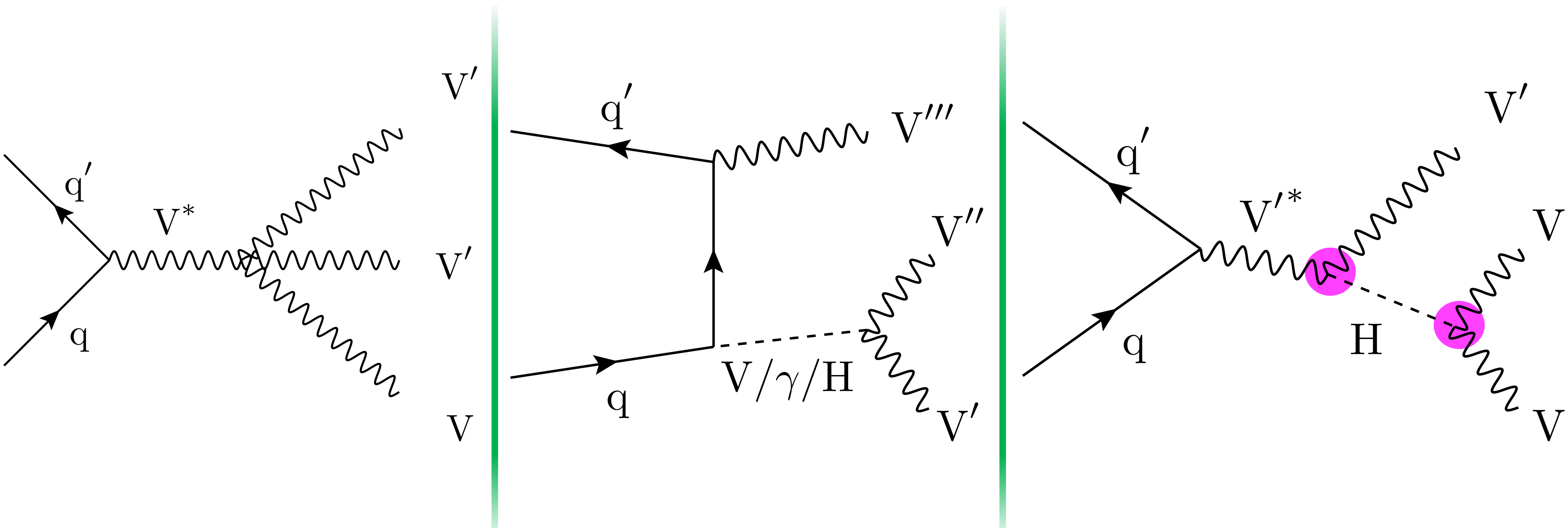
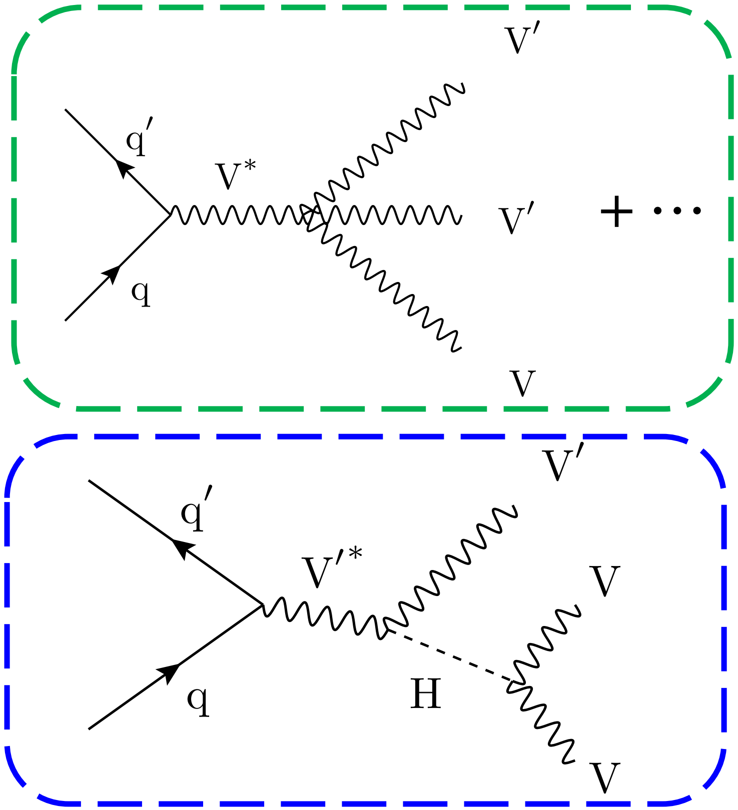
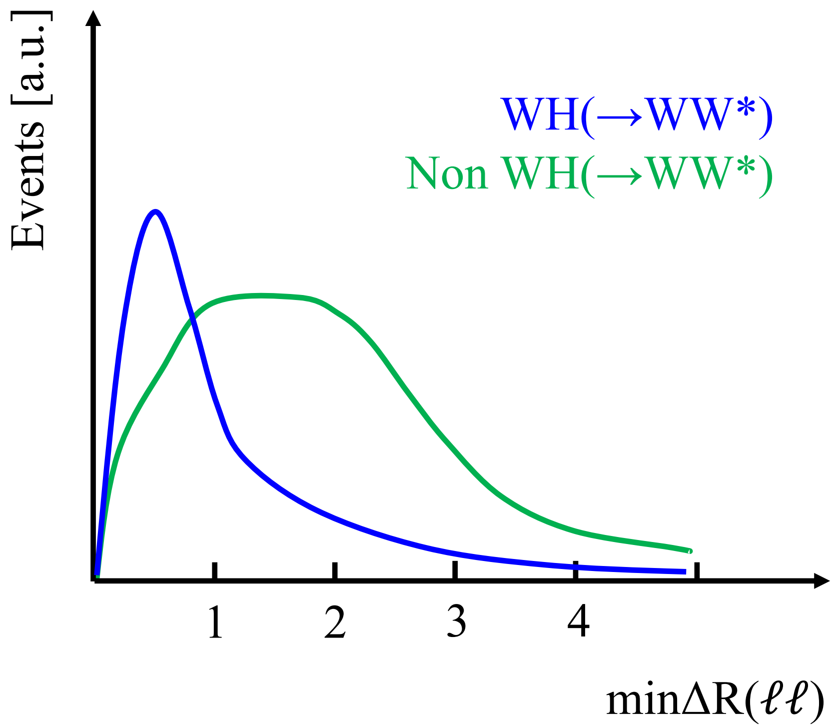


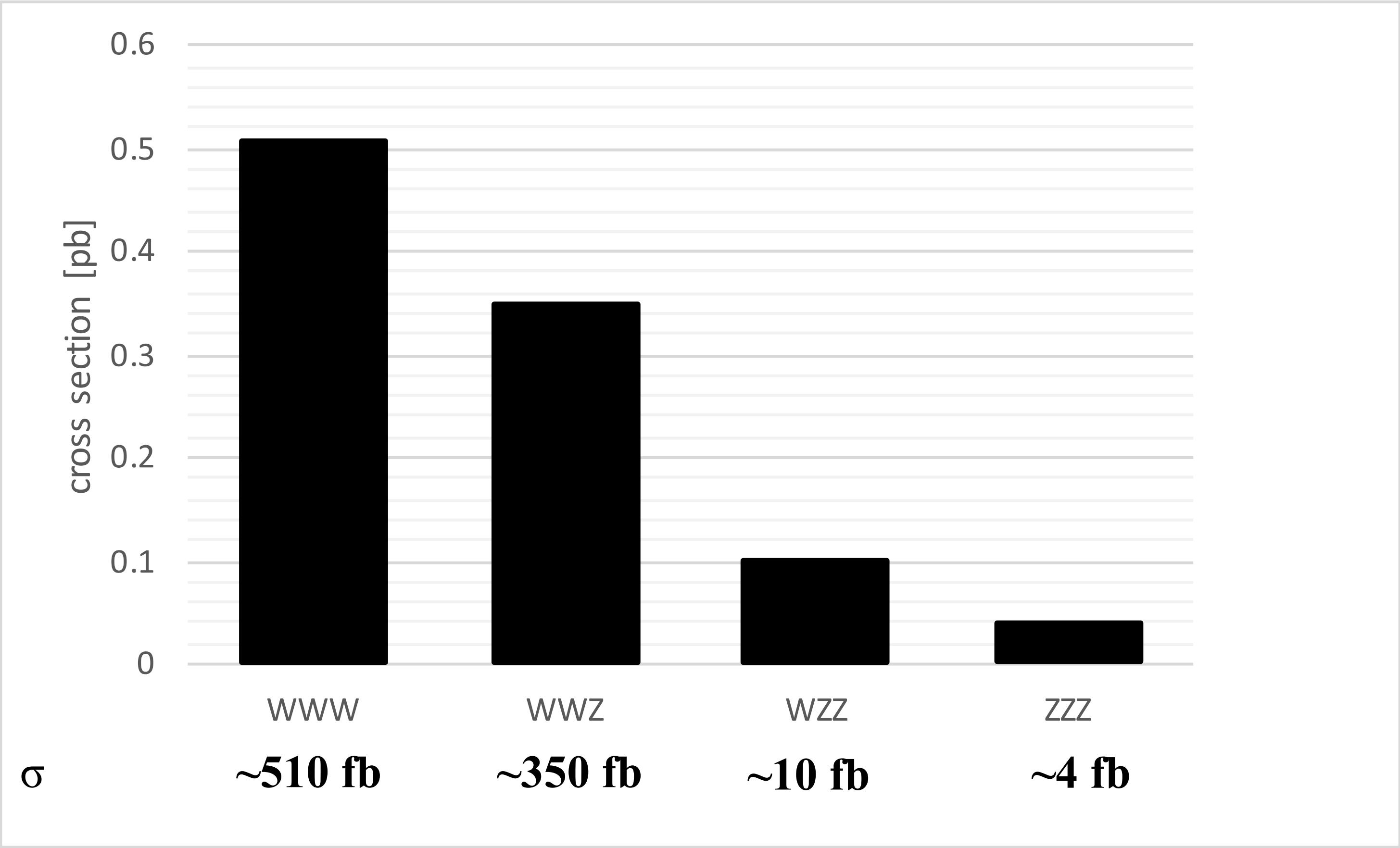
Triboson production

- Not only do we need to measure rates, but also shapes!
  - e.g. we can discriminate between Higgs and non-Higgs mediated diagrams using kinematic distributions.





Tribosons: a program



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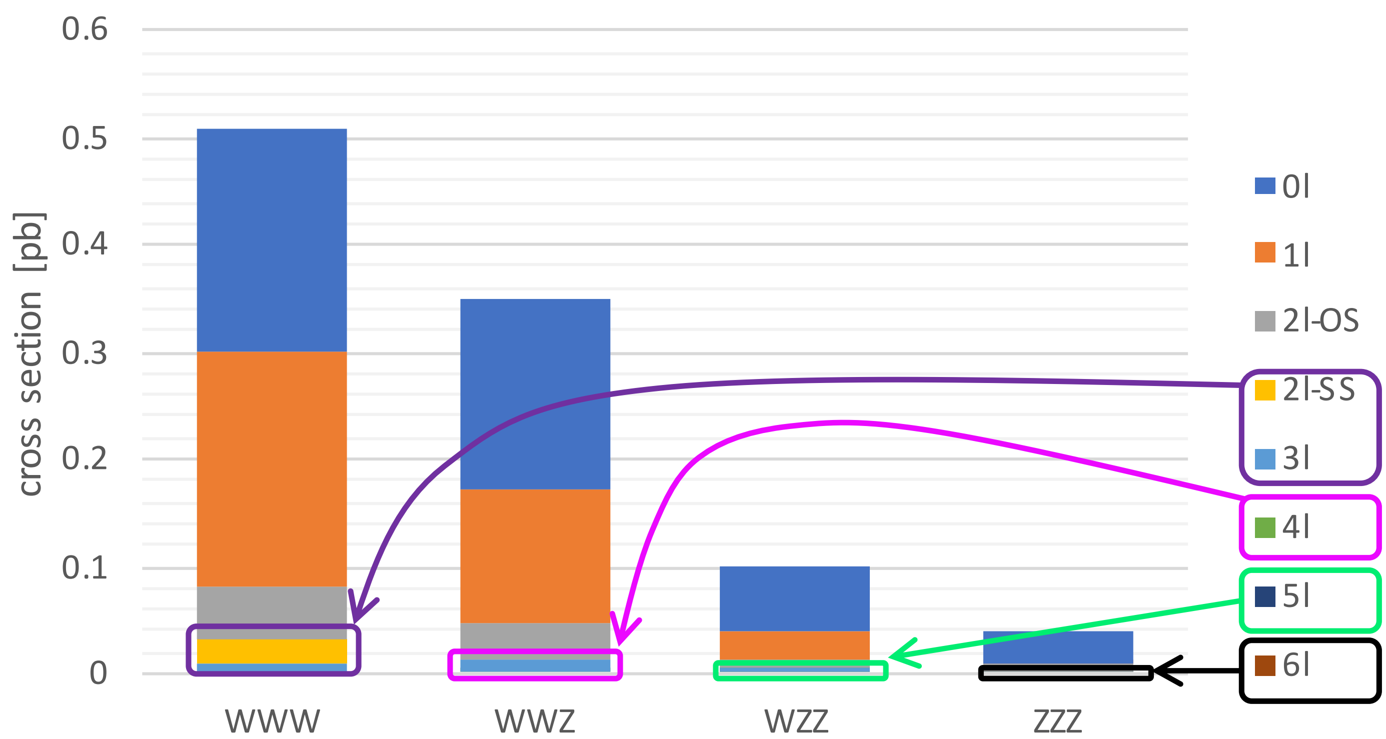

$\sigma \times$ BF	~33 fb	~2 fb	~0.1 fb	~0.01 fb

Data reconstruction with the CMS detector

- Production of three heavy gauge bosons has not yet observed so far.
  - Today I show CMS study of the **full Run-2 data** towards its observation.

Data reconstruction with the CMS detector

- Production of three heavy gauge bosons has not yet observed so far.
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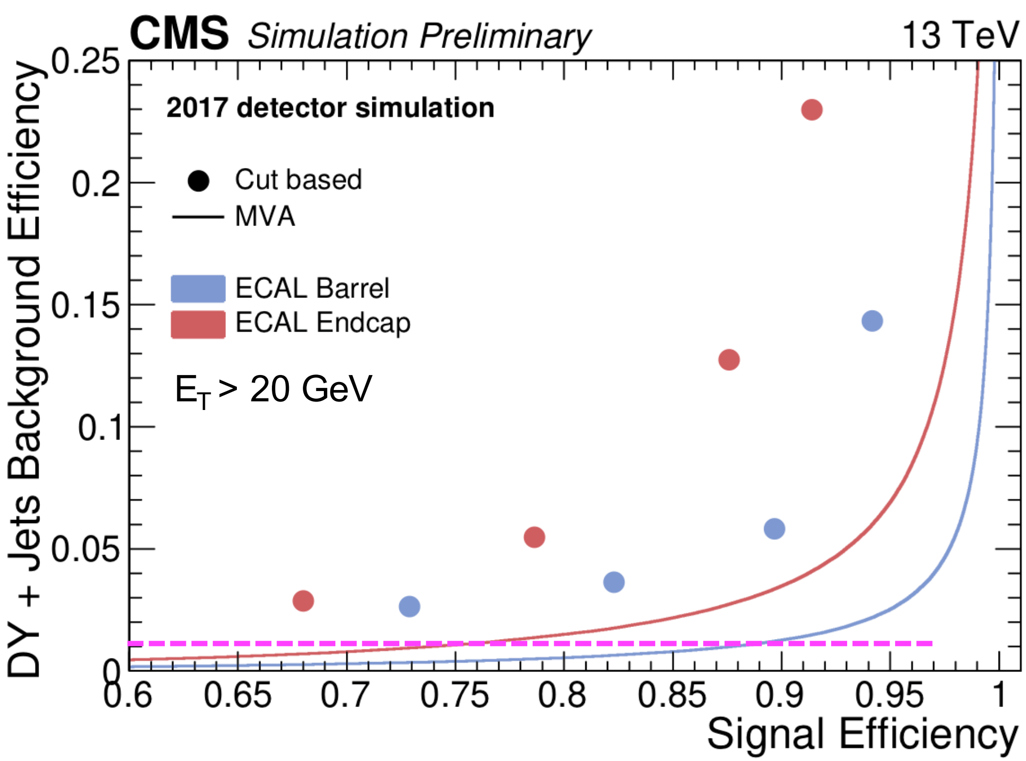
- In the next few slides, I show a few highlights of lepton reconstruction with CMS:
  - Crucial for this analysis, where we select up to six leptons (electrons or muons).

Electron reconstruction in CMS

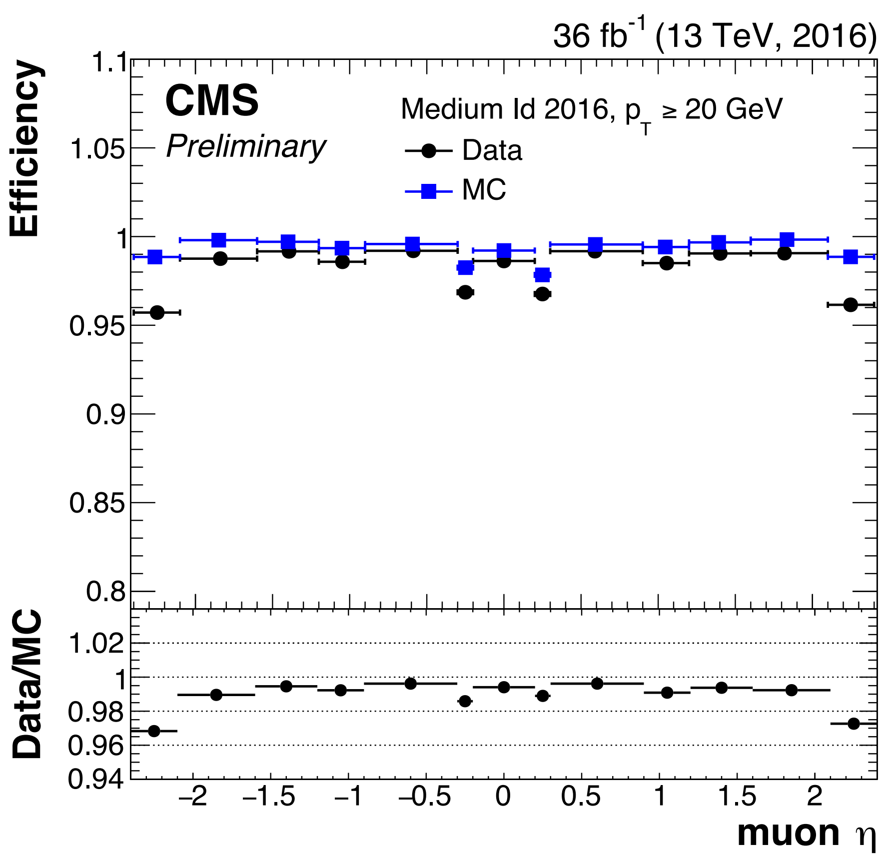
- Crucial for this analysis is the clean reconstruction of electrons:
  - We must distinguish against photons that convert into an e^+e^- pair, and against misidentified pions.
  - Use information of the shower in the electromagnetic calorimeter (ECAL) and of the associated track in the inner tracking detector to identify electrons.



- If selecting on these shower + tracking variables, lose ~30% of signal electrons.
- Train a boosted decision tree:
  - For 1% background efficiency, can reach 90% signal efficiency.

Muon reconstruction in CMS

- Muons are easier to identify: matching tracks in the inner and outer tracking detectors.
  - Fake muons only happen if hadrons punch through the calorimeter.



- Very small fake efficiency with ≥98% signal muon efficiency.
- Because of the excellent tracking, exceptional momentum/mass resolution.

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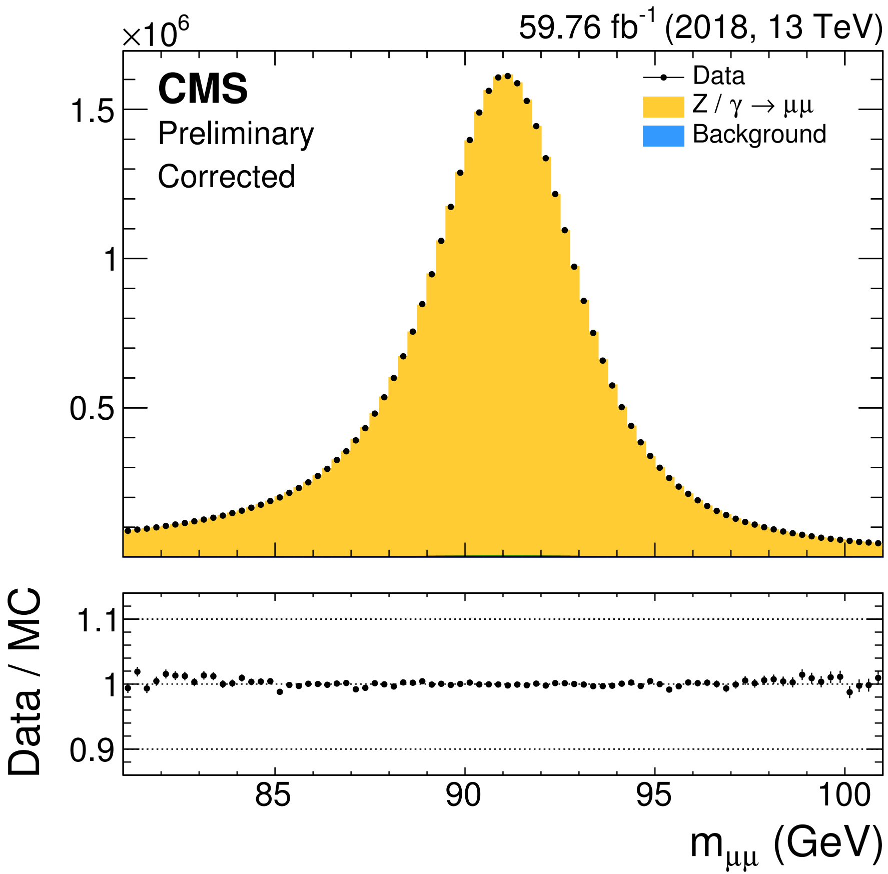


- Very small fake efficiency with ≥98% signal muon efficiency.
- Because of the excellent tracking, exceptional momentum/mass resolution.

The triple boson analyses

- The triple heavy gauge boson process has not been observed yet.

- CMS published last year a first analysis focused on the production of WWW events.
  - Published as PRD **100** (2019) 012004.
- ATLAS also published last year first evidence for WVV production with ~80 fb^{-1}:
  - Published as PLB **798** (2019) 134913

- Today I show the CMS study of the **full Run-2 data** for all triboson processes.

The triple boson analyses: divide and conquer

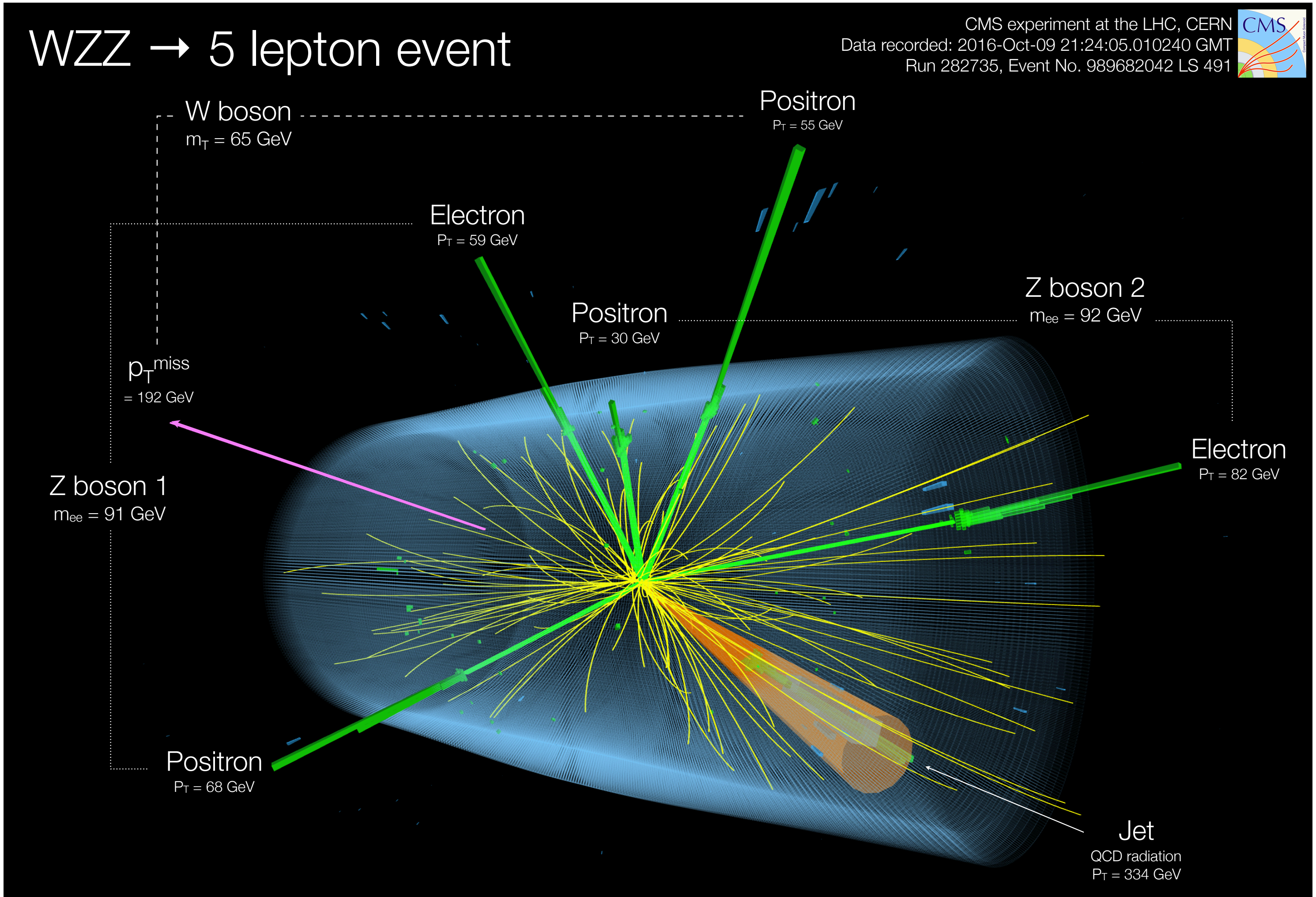
- We do **an analysis for every (sensitive) lepton (e or μ) multiplicity final state** with full Run-2 data, aiming for different processes within the triboson production.
  - Where statistics allows, **we train BDTs** to discriminate signal from the main backgrounds.

Final state	Target	Main backgrounds	Cut-based	BDT
SS-2ℓ	WWW	WZ, fakes*, ttW, $W^{\pm}W^{\pm}$	✓	✓
3ℓ	WWW	WZ, fakes*, ttW	✓	✓
4ℓ	WWZ	ZZ, ttZ	✓	✓
5ℓ	WZZ	ZZ + fakes*	✓	
6ℓ	ZZZ	ttX/ZZ + fakes*	✓	

- When we talk about fake leptons, we mean both truly misidentified leptons, as well as nonprompt leptons from parton decays, such as $B^0 \to D^{\pm}\ell^{\mp}\nu$, $D^{\pm} \to \overline{K}^0\ell^{\pm}\nu$.

5, 6ℓ analyses targeting WZZ and ZZZ

- The WZZ and ZZZ processes are targeted using the five and six lepton final state.



5 and 6ℓ analyses: WZZ and ZZZ

- In the five and six lepton final states, we expect extremely low data yields.
  - Apply minimal selections.

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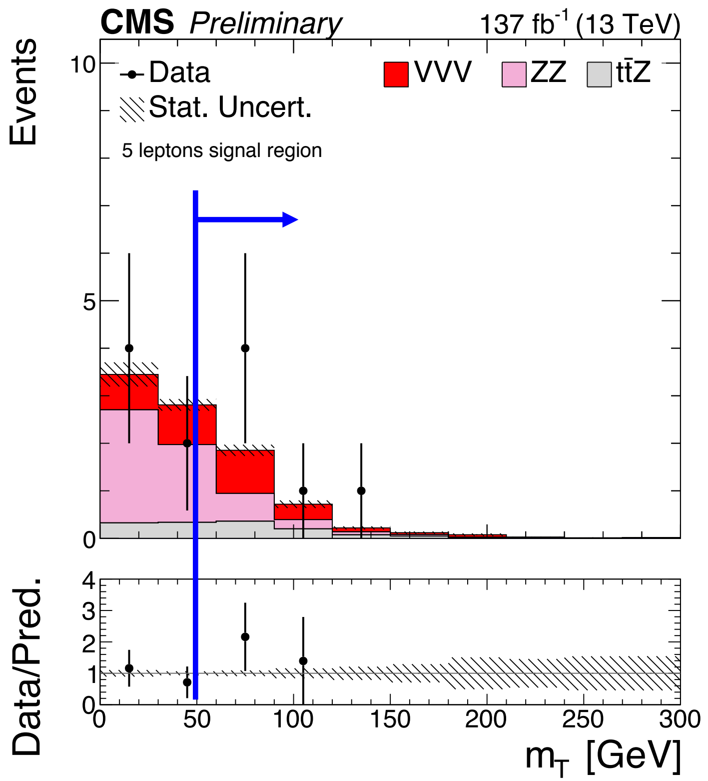
- 5ℓ analysis:
  - After **5 lepton** selection and requirement of **2 SFOS lepton pairs** consistent with a Z boson:
    - Expect in total about 7 events.



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- 5ℓ analysis:
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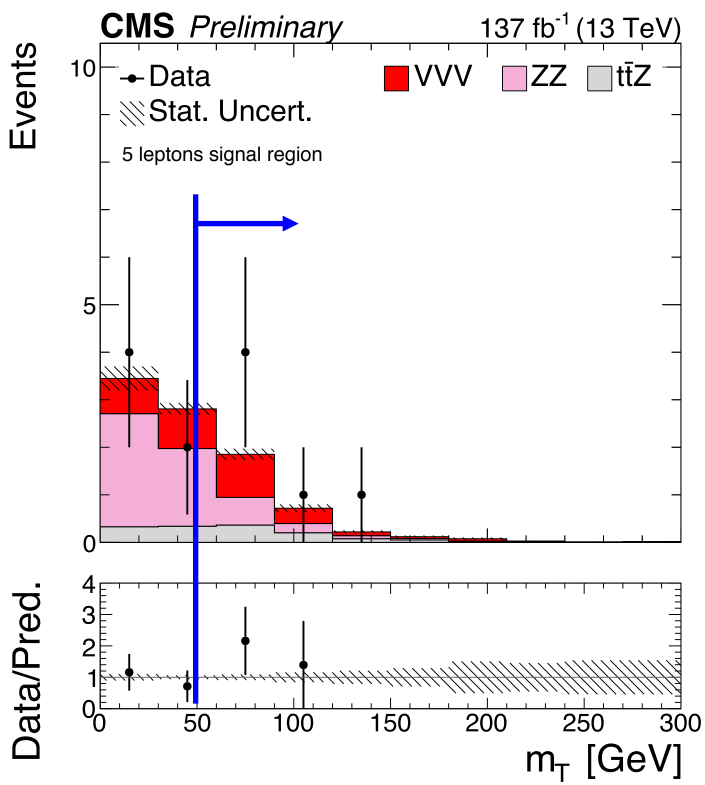
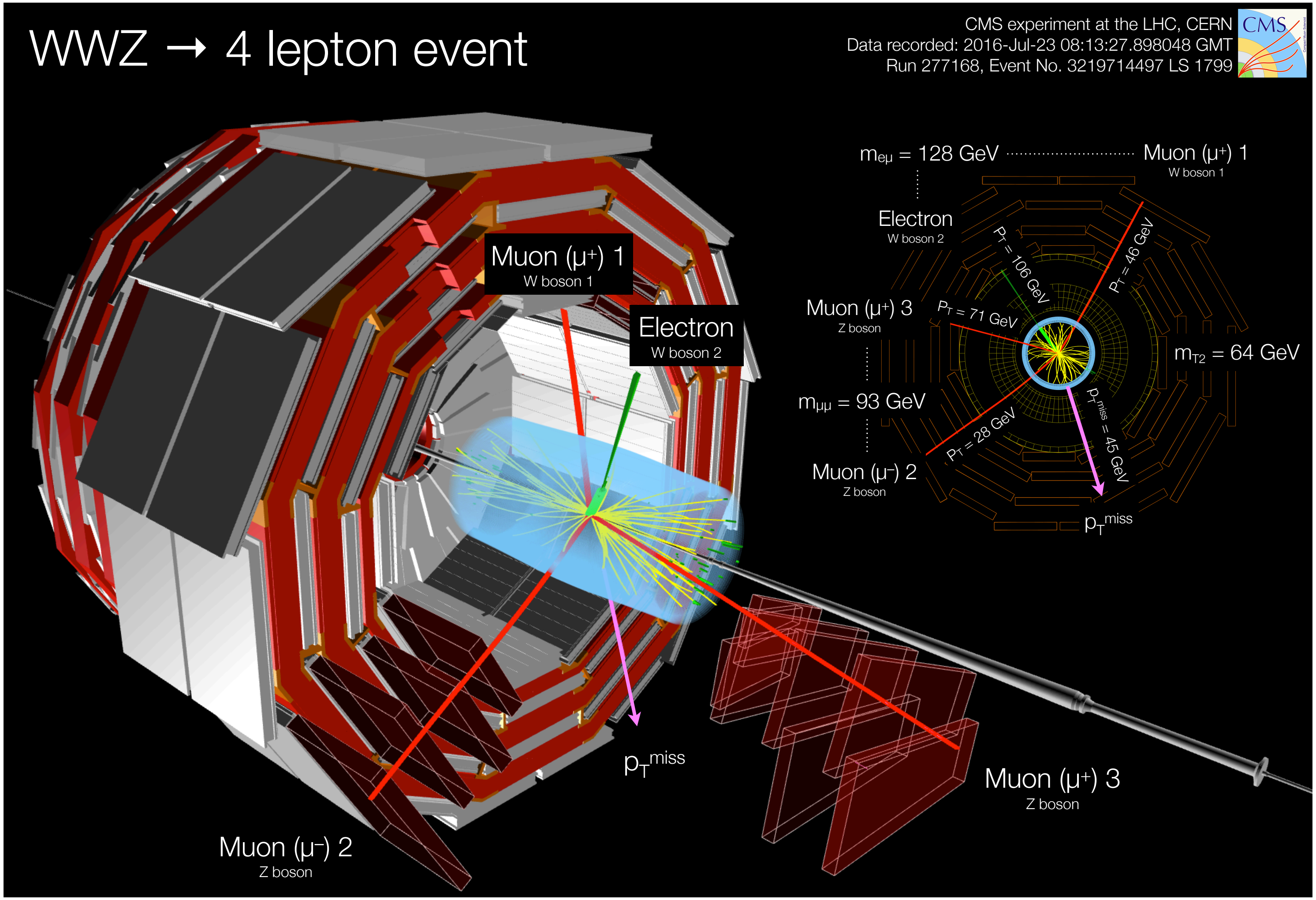
- 6ℓ analysis:
  - Select at least **6 leptons**.
    - Less than 1 event expected with 6 leptons.



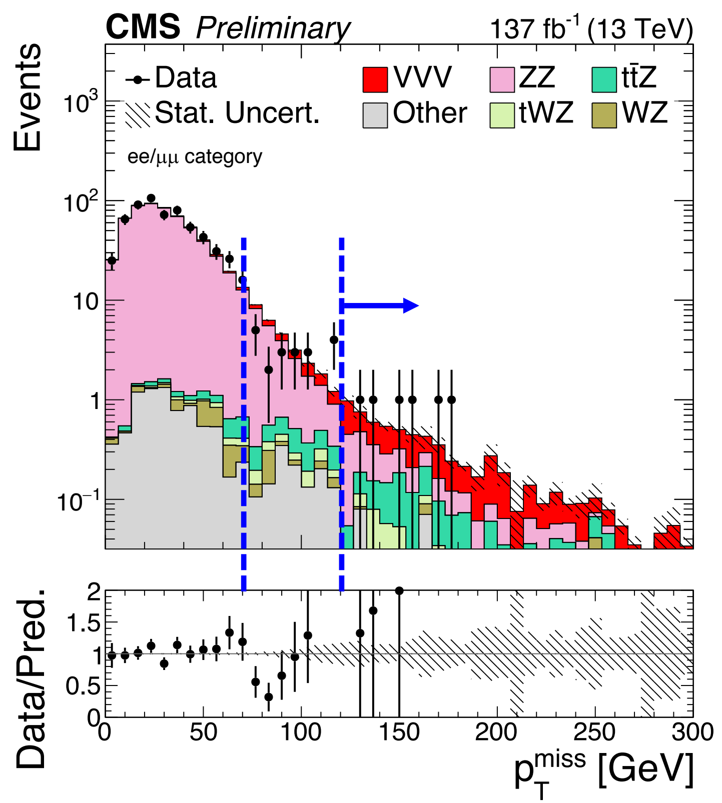
4ℓ analysis targeting WWZ

- The WWZ process is targeted using the four lepton final state.



4ℓ analysis: WWZ - strategy

- We select **exactly four leptons**, out of which **two (and only two) form an SFOS lepton pair** compatible with the Z boson.
- **Two categories** depending on flavor of the 3rd and 4th lepton: **eμ** or **ee/μμ**.
  - For ee/μμ: significant ZZ→4ℓ background. Subleading ttZ background.
    - Main discriminant: $\mathbf{p_T^{miss}}$



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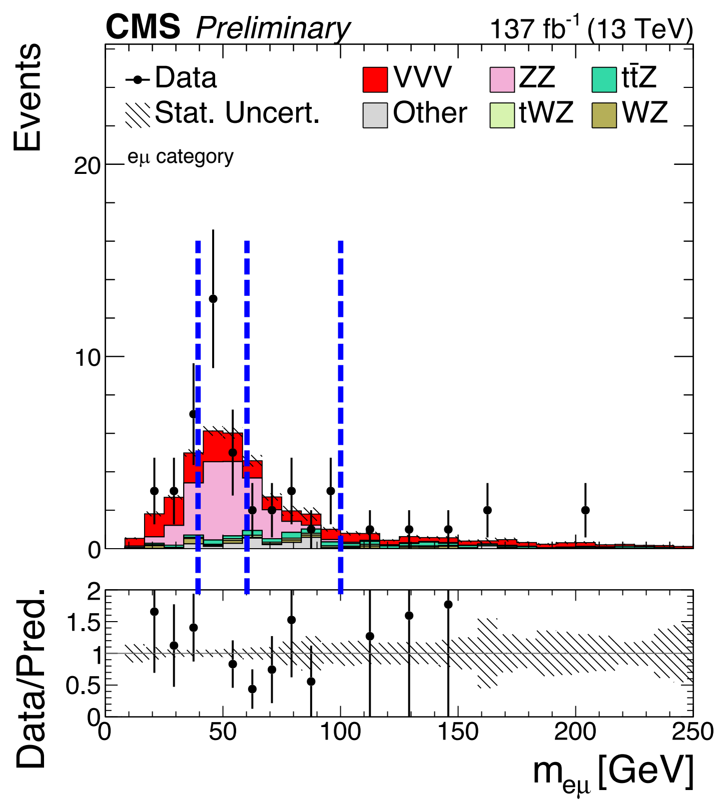
- **Two categories** depending on flavor of the 3rd and 4th lepton: **eμ** or **ee/μμ**.
  - For eμ: background mostly ZZ→ℓℓττ, ttZ subleading.
    - Main discriminant: **$m_{e\mu}$**



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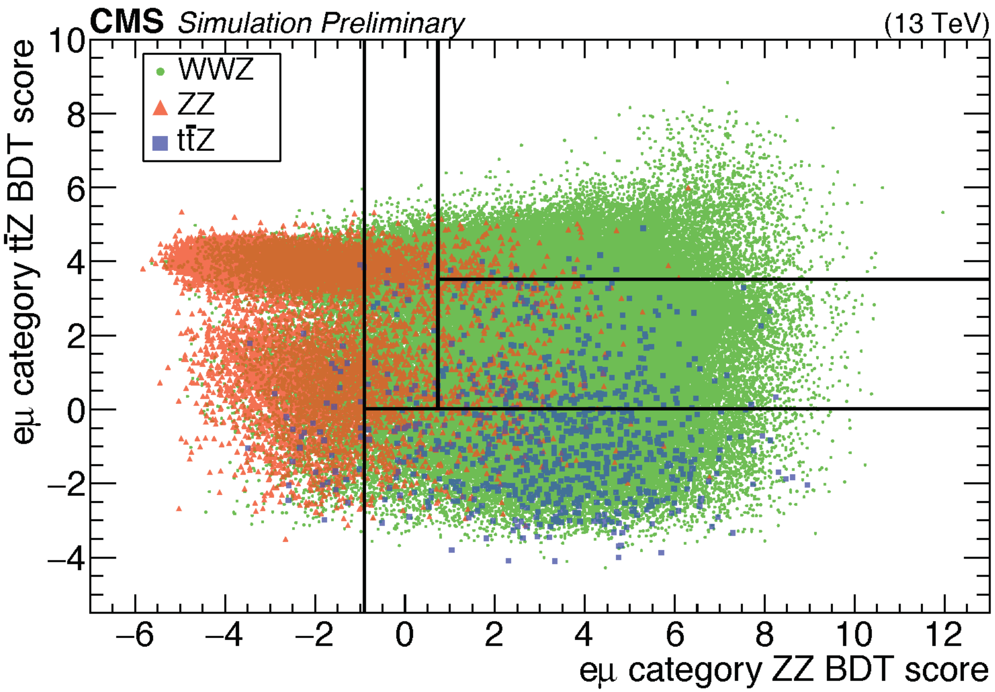
- **Two categories** depending on flavor of the 3rd and 4th lepton: **eμ** or **ee/μμ**.

- We have plenty of events:
- Besides selection-based analysis, we train two boosted decision trees:
  - Against leading background: **ZZ**.
  - Against subleading background: **ttZ**.
- Split 2D plane of decision tree discriminants, to define multiple signal regions.



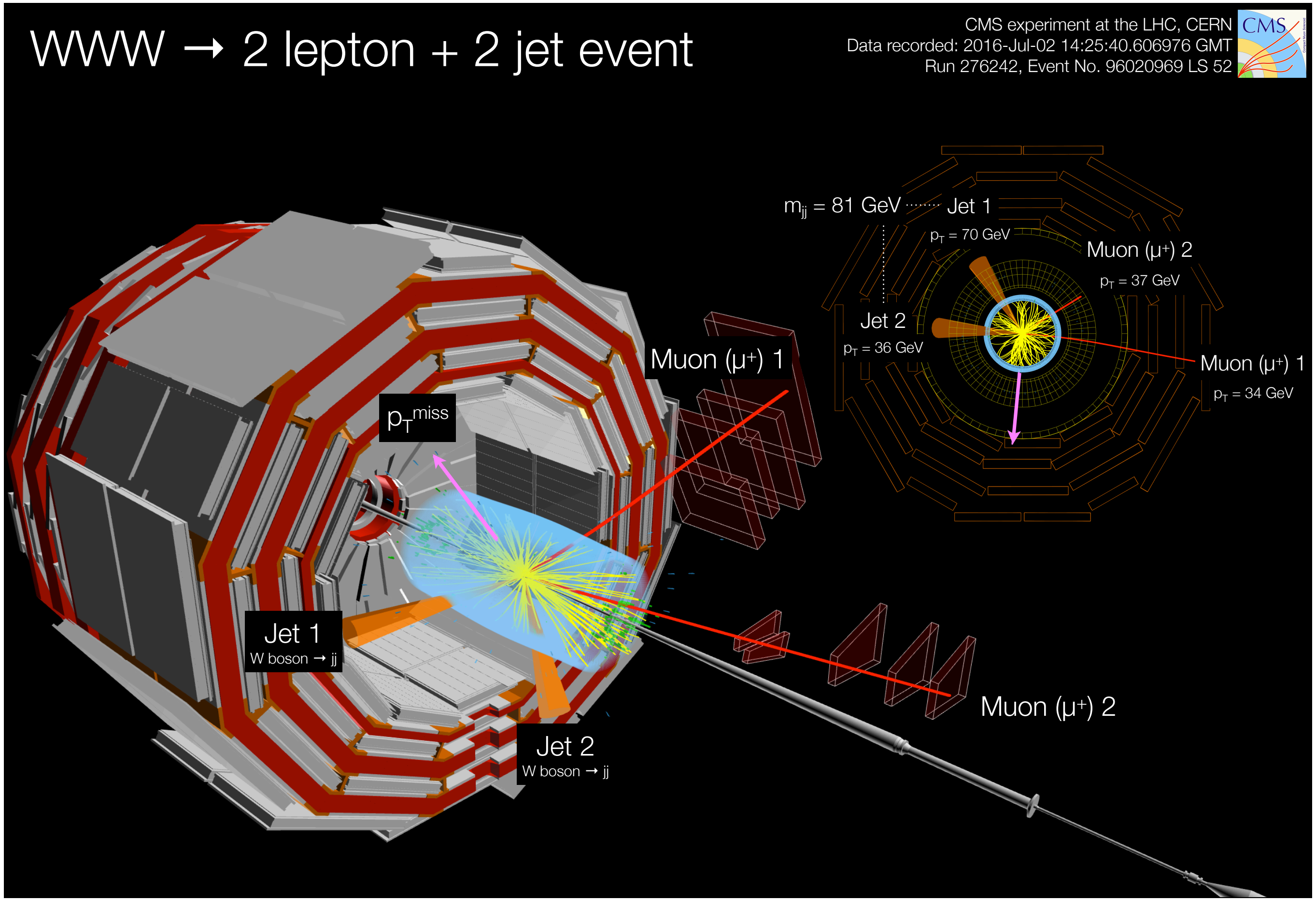
4ℓ analysis: WWZ - backgrounds

- Significant ZZ and ttZ lepton backgrounds.
- Other backgrounds such as WZ or ttH are minor

	0 b-tagged jets	≥1 b-tagged jet
4ℓ with two Z boson candidates	**ZZ dominated**	
4ℓ with one Z boson candidates	**Signal region**	**ttZ dominated**

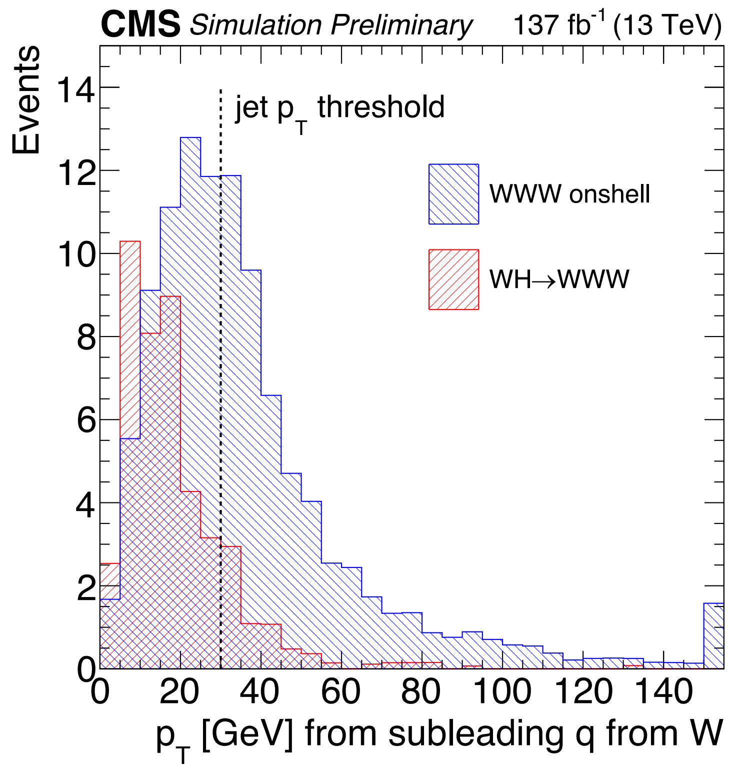
SS-2ℓ and 3ℓ analyses targeting WWW

- The WWW process is targeted using two equal charged (same-sign, SS) leptons or three leptons.



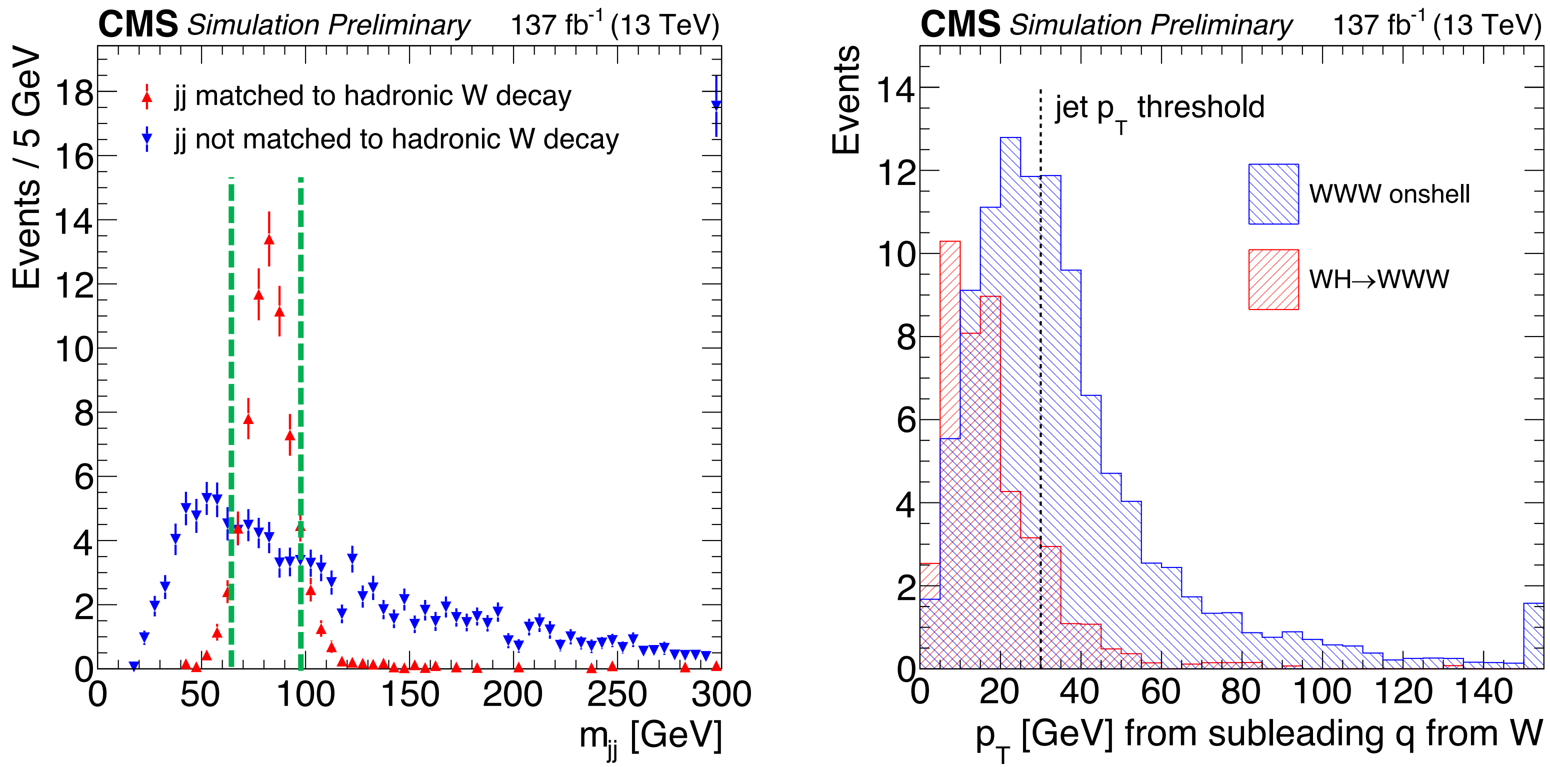
SS-2ℓ / 3ℓ analyses: WWW - strategy

- SS-2ℓ:
  - **Jet multiplicity**: ≥2 jets, **1 jet**



SS-2ℓ / 3ℓ analyses: WWW - strategy

- SS-2ℓ:
  - Jet multiplicity: ≥2 jets, 1 jet
    - For ≥2 jets: dijet invariant mass: $|\mathbf{m_{jj}} - \mathbf{m_W}| \leqslant \mathbf{15\ GeV}$ (m_{jj}-in/out)



SS-2ℓ / 3ℓ analyses: WWW - strategy

- SS-2ℓ:
  - Jet multiplicity: ≥2 jets, 1 jet
    - For ≥2 jets: dijet invariant mass: $|m_{jj} - m_W| \lessgtr 15$ GeV (m_{jj}-in/out)
- Both SS-2ℓ and 3ℓ:
  - **Lepton flavor:**
    - SS-2ℓ: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
    - 3ℓ: $e^{\pm}e^{\pm}\mu^{\mp}$, $e^{\mp}\mu^{\pm}\mu^{\pm}$ (0 SFOS)
      $e^{\pm}e^{\mp}\mu^{\pm}$, $e^{\pm}\mu^{\mp}\mu^{\pm}$ (1 SFOS)
      $e^{\pm}e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\pm}\mu^{\mp}$ (2 SFOS)

SS-2ℓ / 3ℓ analyses: WWW - strategy

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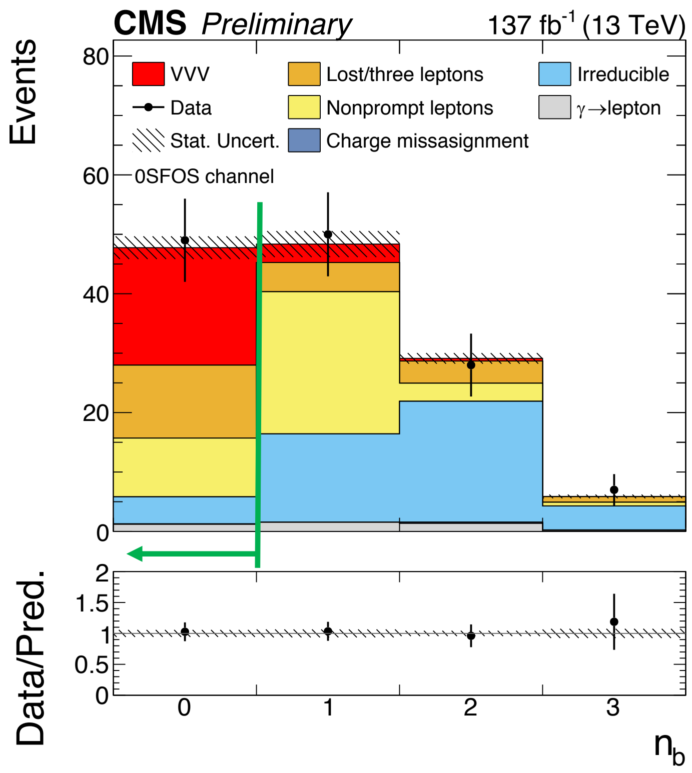
- Both SS-2ℓ and 3ℓ:
  - Lepton flavor:
    - SS-2ℓ: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
    - 3ℓ: 0, 1, 2 SFOS

- In each of these category, we optimize the event selection to reject backgrounds:
  - $W^{\pm}W^{\pm}jj/t\bar{t}W$ (prompt)
  - $WZ \rightarrow 3\ell 1\nu$ (in example $Z \rightarrow \tau\tau$)
  - $t\bar{t}$ + one nonprompt lepton

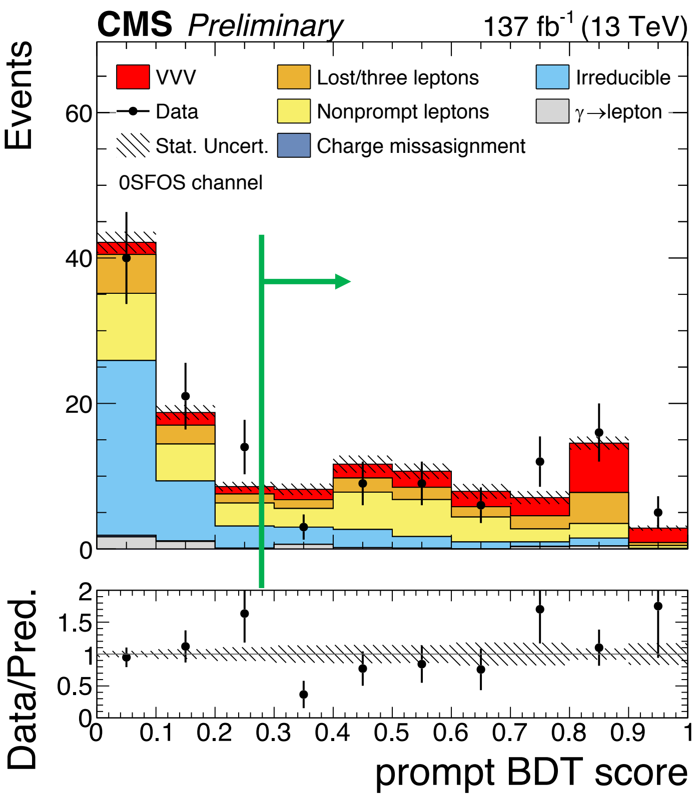


SS-2ℓ / 3ℓ analyses: WWW - strategy

- SS-2ℓ:
  - Jet multiplicity: ≥2 jets, 1 jet
    - For ≥2 jets: dijet invariant mass: $|m_{jj} - m_W| \lesssim 15$ GeV (m_{jj}-in/out)

- Both SS-2ℓ and 3ℓ:
  - Lepton flavor:
    - SS-2ℓ: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
    - 3ℓ: 0, 1, 2 SFOS

- We have plenty of events for SS-2ℓ and 3ℓ:
- In each of these category, we also train two boosted decision trees:
  - Against backgrounds with nonprompt/fake leptons.
  - Against all other backgrounds.



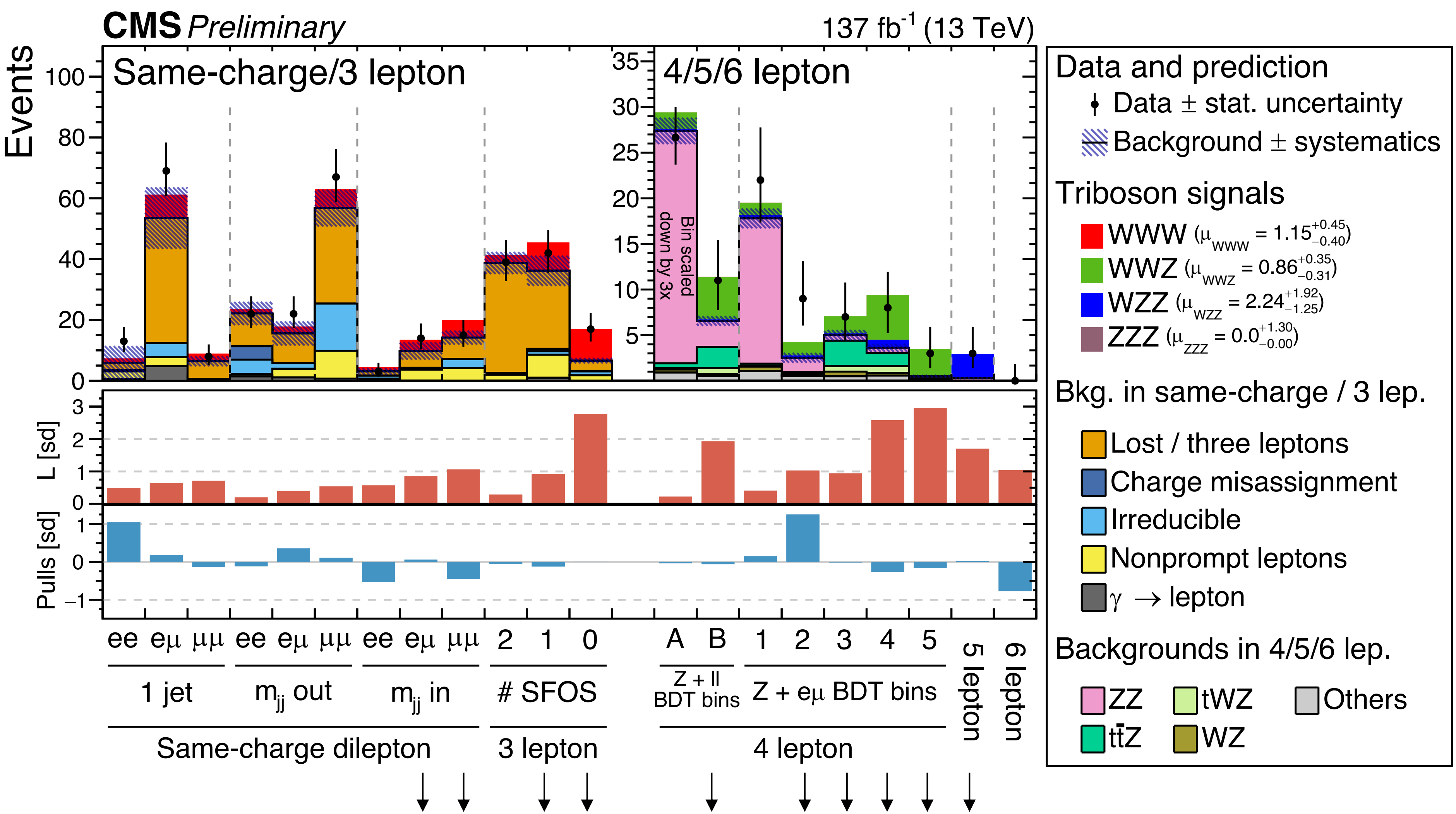
SS-2ℓ / 3ℓ analyses: WWW - backgrounds

- Significant nonprompt lepton background.
- Prompt lepton backgrounds because of WZ and $W^{\pm}W^{\pm}$.
- Other backgrounds, such as lepton-charge misidentification, are minor.

	All prompt leptons	One nonprompt lepton
3ℓ (with Z boson candidate)	**WZ dominated**	
SS-2ℓ/3ℓ (no Z boson candidate)	**Signal region**	**Nonprompt dominated**
SS-2ℓ with two forward jets (VBS)	**$W^{\pm}W^{\pm}$ dominated**	
SS-2ℓ with four jets and ≥1 b-tagged jets	**ttW dominated**	

Results

Results



- In sensitive signal regions, ratio of non-VH vs. VH signal is about $^2/_3 : ^1/_3$.

Results

Process	Significance [s.d.]
WWW	3.3 (3.1)
WWZ	3.3 (4.1)
WZZ	1.7 (0.7)
ZZZ	0.0 (0.9)
combined	**5.7 (5.9)**

observed (expected)

- **We have observed triboson production for the first time!**
- Additionally, we found evidences separately for the WWW and WWZ production.

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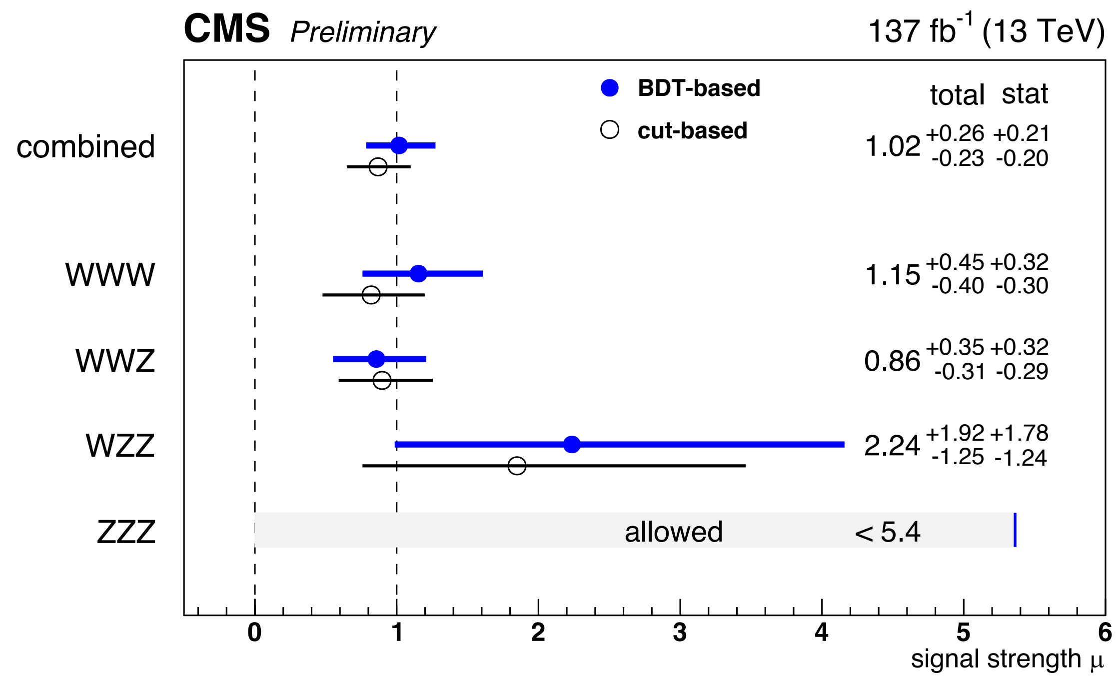

Measured over theoretical cross section [1]

- **We have observed triboson production for the first time!**
- Additionally, we found evidences separately for the WWW and WWZ production.
- The cross sections are compatible with the standard model expectation.

[1]: PRD **76** (2007) 014001, JHEP **06** (2008) 082, PLB **661** (2008) 103, PRD **78** (2008) 094012, and JHEP **09** (2017) 034

Outlook

- Having discovered the triboson production, we can use it to test the abelian structure of the standard model, and potentially even find new physics!

Outlook – using tribosons as a tool

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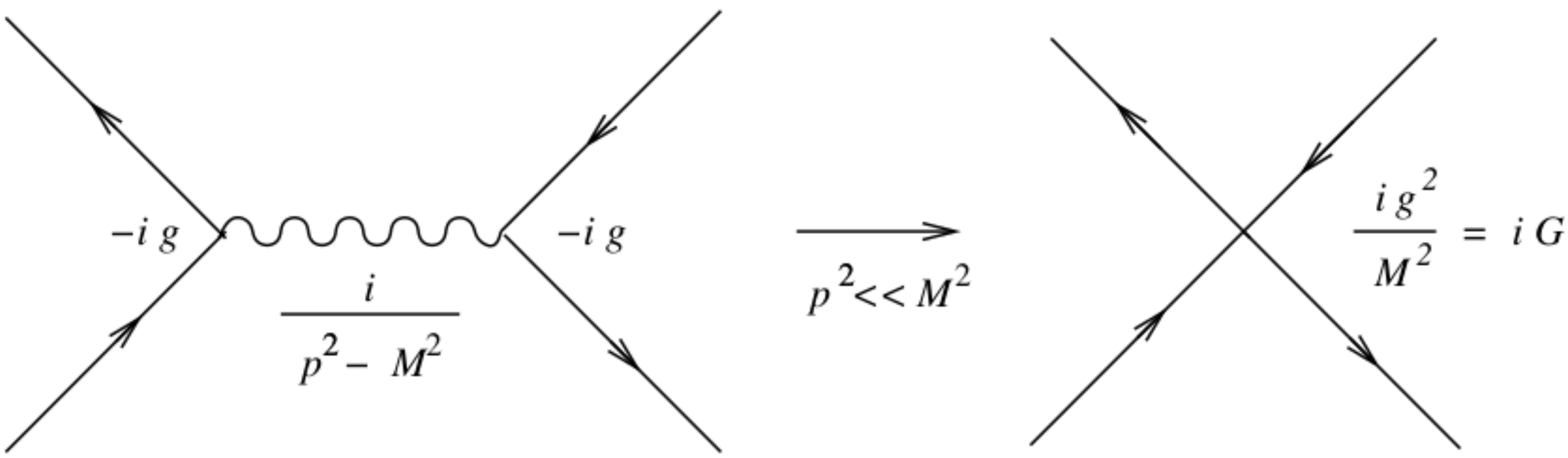
  - We have seen this in the past, such as the four-fermion interaction with the Fermi constant as effective coupling.



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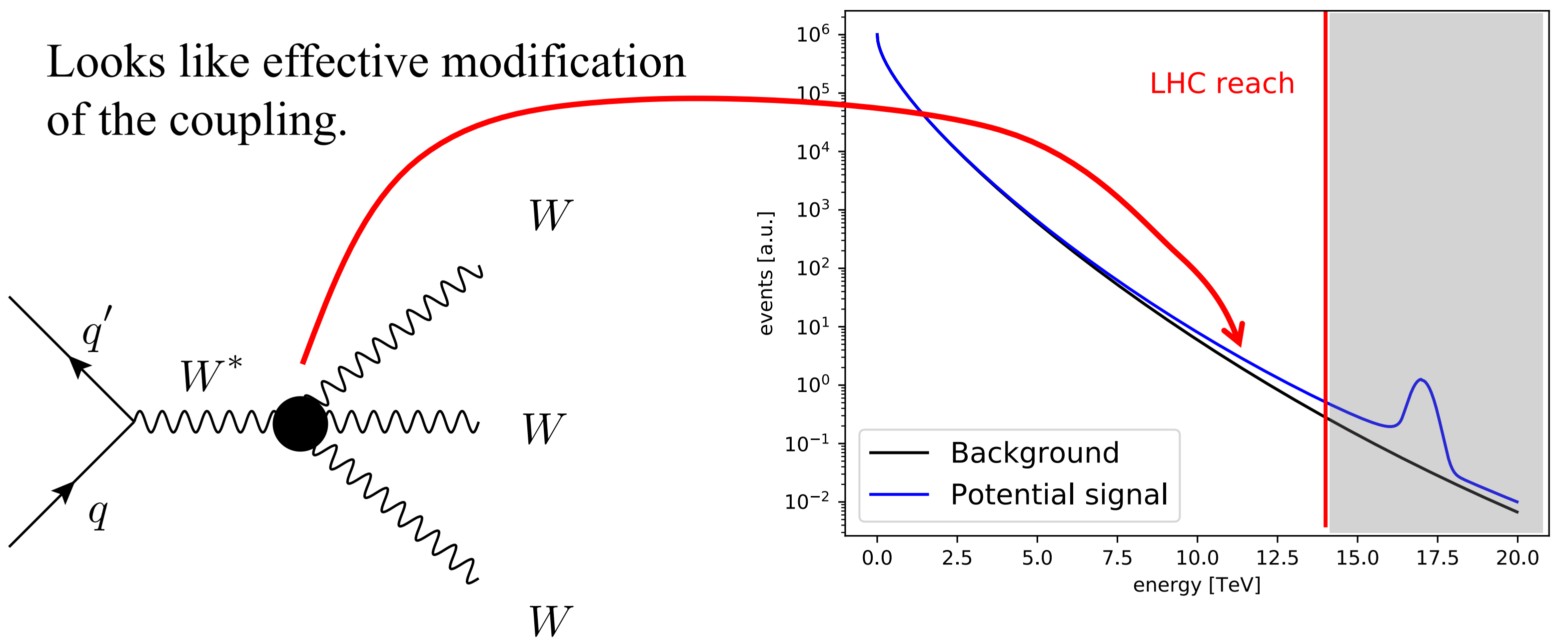
- This could happen also for **four-gauge boson couplings**.

Looks like effective modification of the coupling.



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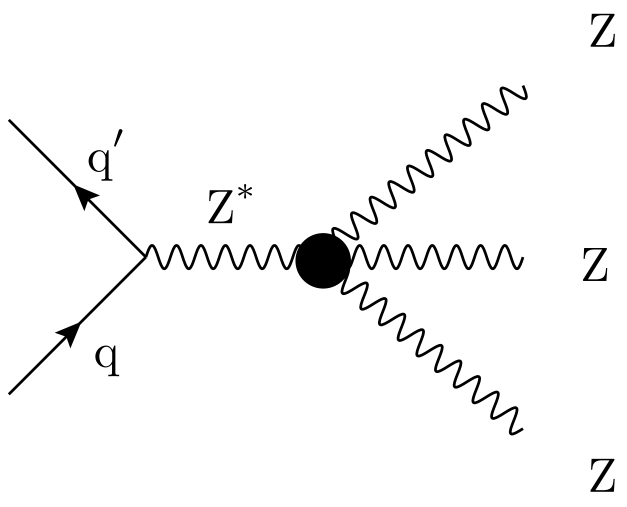
- This could happen also for **four-gauge boson couplings**.

- There are even vertices that do not appear in the SM!



Summary

- The CMS collaboration has **observed**, for the first time, **the production of events with three heavy gauge bosons.**

- We have found two evidences: for WWW and WWZ production.
- We see first hints for WZZ production, no hints for ZZZ production yet.

- The measured signal strength for triboson production is $\mu = 1.02^{+0.26}_{-0.23}$, translating to a **cross section of $\mathbf{1.01^{+0.21}_{-0.20}}$ (stat)$\mathbf{^{+0.15}_{-0.12}}$(syst) pb.**

- The observation of tribosons open a door to uniquely study the standard model, and potentially is sensitive to new physics.
  - This result has only been the first step of great physics ahead.

- Further documentation can be found at CMS-PAS-SMP-19-014 and
  - https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-19-014/index.html

Backup

Selections: SS-2ℓ, 3ℓ

- SS-2ℓ:

Variable	m_{jj}-in and m_{jj}-out	1j
Signal leptons	Exactly 2 tight SS leptons with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$	
Additional leptons	No additional lepton or isolated track	
Jets	≥ 2 jets	1 jet
b-tagging	no b-tagged jets and soft b-tag objects	
$m_{\ell\ell}$	$>20\,\mathrm{GeV}$	
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_{\mathrm{Z}}\rvert > 20\,\mathrm{GeV}$ if $\mathrm{e}^{\pm}\mathrm{e}^{\pm}$	
$p_{\mathrm{T}}^{\mathrm{miss}}$	$>45\,\mathrm{GeV}$	
m_{JJ} (leading jets)	$<500\,\mathrm{GeV}$	–
$\Delta\eta_{\mathrm{JJ}}$ (leading jets)	<2.5	–
m_{jj} (closest ΔR)	$65 < m_{\mathrm{jj}} < 95\,\mathrm{GeV}$ or $\lvert m_{\mathrm{jj}} - 80\,\mathrm{GeV}\rvert \geq 15\,\mathrm{GeV}$	–
$\Delta R_{\ell\mathrm{j}}^{\mathrm{min}}$	–	<1.5
$m_{\mathrm{T}}^{\mathrm{max}}$	$>90\,\mathrm{GeV}$ if not $\mu^{\pm}\mu^{\pm}$	$>90\,\mathrm{GeV}$

- 3ℓ:

Variable	0 SFOS	1 and 2 SFOS
Signal leptons	3 tight leptons with charge sum $= \pm 1\mathrm{e}$	
	$p_{\mathrm{T}} > 25/25/25\,\mathrm{GeV}$	$p_{\mathrm{T}} > 25/20/20\,\mathrm{GeV}$
Additional leptons	No additional lepton	
m_{SFOS}	$m_{\mathrm{SFOS}} > 20\,\mathrm{GeV}$ and $\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}}\rvert > 20\,\mathrm{GeV}$	
$m_{\ell\ell\ell}$	$\lvert m_{\ell\ell\ell} - m_{\mathrm{Z}}\rvert > 10\,\mathrm{GeV}$	
SF lepton mass	$>20\,\mathrm{GeV}$	–
Dielectron mass	$\lvert m_{\mathrm{ee}} - m_{\mathrm{Z}}\rvert > 20\,\mathrm{GeV}$	–
Jets	0 jets	≤ 1 jet
b-tagging	No b-tagged jets and soft b-tag objects	
$\Delta\phi\left(\vec{p}_{\mathrm{T}}(\ell\ell\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$	–	>2.5
$p_{\mathrm{T}}(\ell\ell\ell)$	–	$>50\,\mathrm{GeV}$
$m_{\mathrm{T}}^{\mathrm{third}}$ (1 SFOS) or $m_{\mathrm{T}}^{\mathrm{max}}$ (2 SFOS)	–	$>90\,\mathrm{GeV}$

Selections: 4ℓ, 5ℓ and 6ℓ

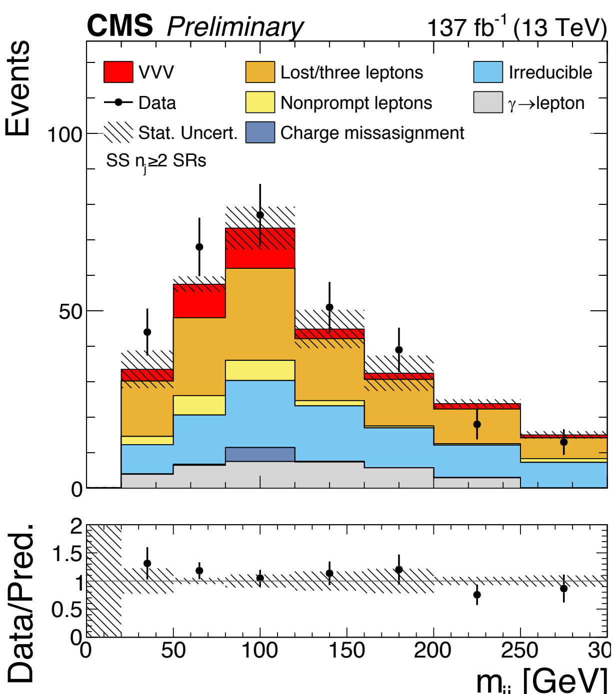
- 4ℓ analysis:
  - 0 b-tagged jets
  - 1 SFOS lepton pairs consistent with a Z boson.
  - ee/μμ:
    - BDT-based: 2 bins in ZZ BDT
    - Sequential-cut based:
      - $70 < p_T^{miss} \leq 120$ GeV && $p_T^{4\ell} = (40,70)$ or $(70,\infty)$ GeV
      - $p_T^{miss} > 120$ GeV
  - eμ:
    - BDT-based: 7 bins in ttZ / ZZ BDT
    - Sequential-cut based:
      - $m_{e\mu} = (0,40), (40,60), (60,100), (100,\infty)$ GeV
      - $m_{T2} > 25$ GeV if $m_{e\mu} < 100$ GeV

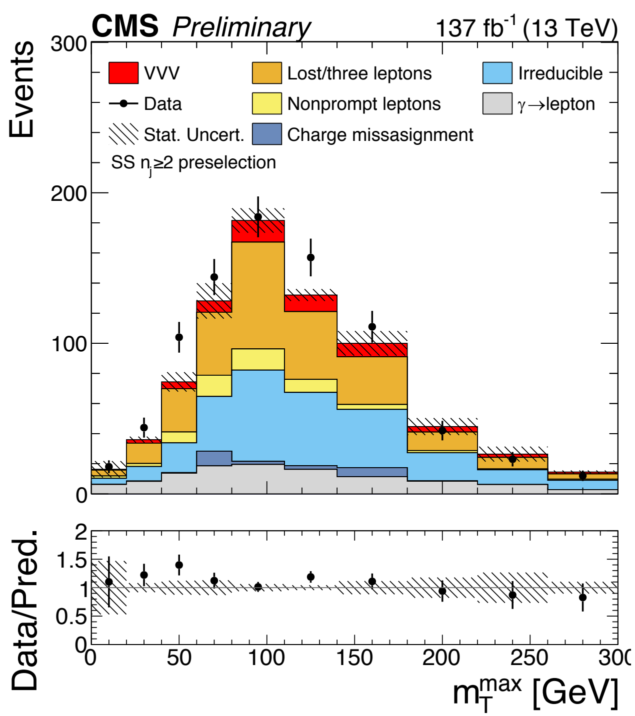
- 5ℓ analysis:
  - 2 SFOS lepton pairs consistent with a Z boson.
  - If 5th lepton is an electron, require $m_T(e, p_T^{miss}) > 50$ GeV.

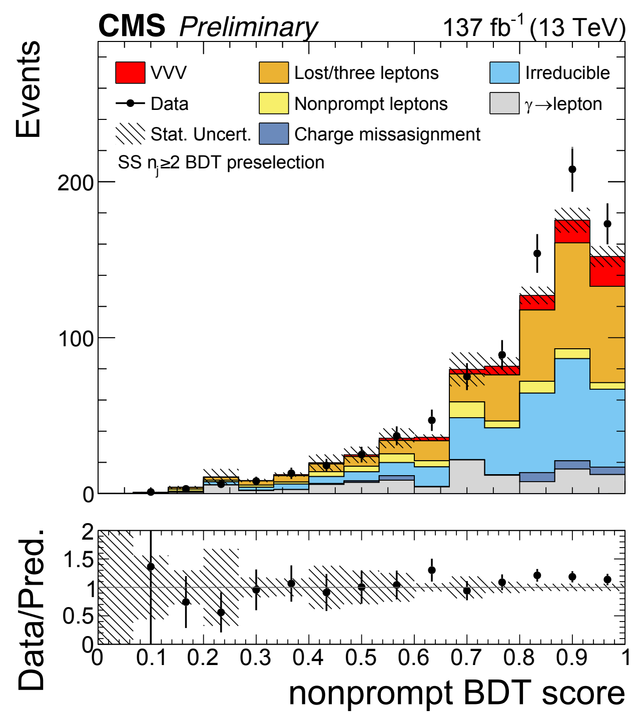
- 6ℓ analysis:
  - Require $\sum(p_T(\ell)) > 250$ GeV

Selections: SS-2ℓ, 3ℓ – discriminating variables

- Discriminating variables (that are not in the main body of the slides):
  - Examples for SS-2ℓ with ≥2 jets







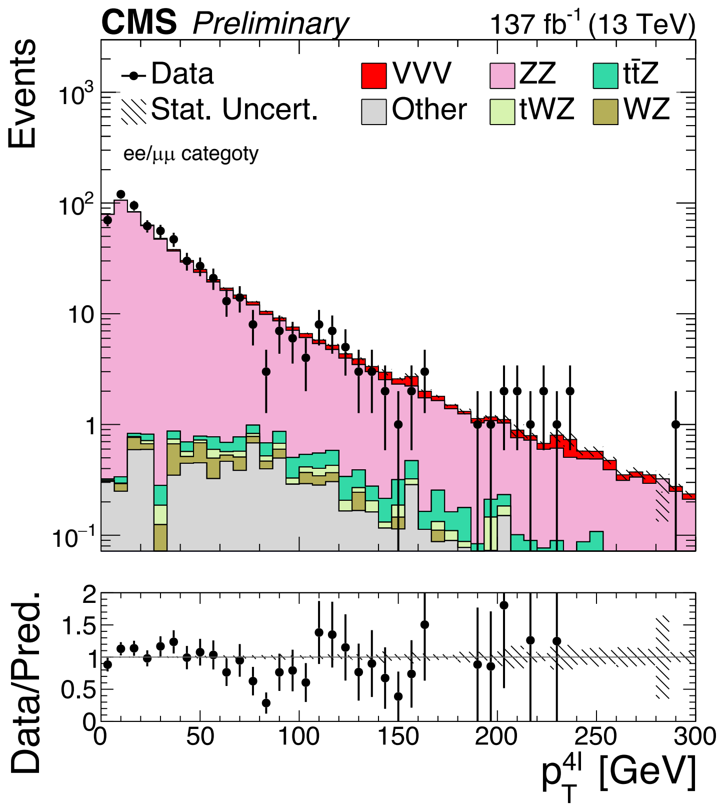
W→qq’ peak for signal

$m_T \leq m_W$ for WZ

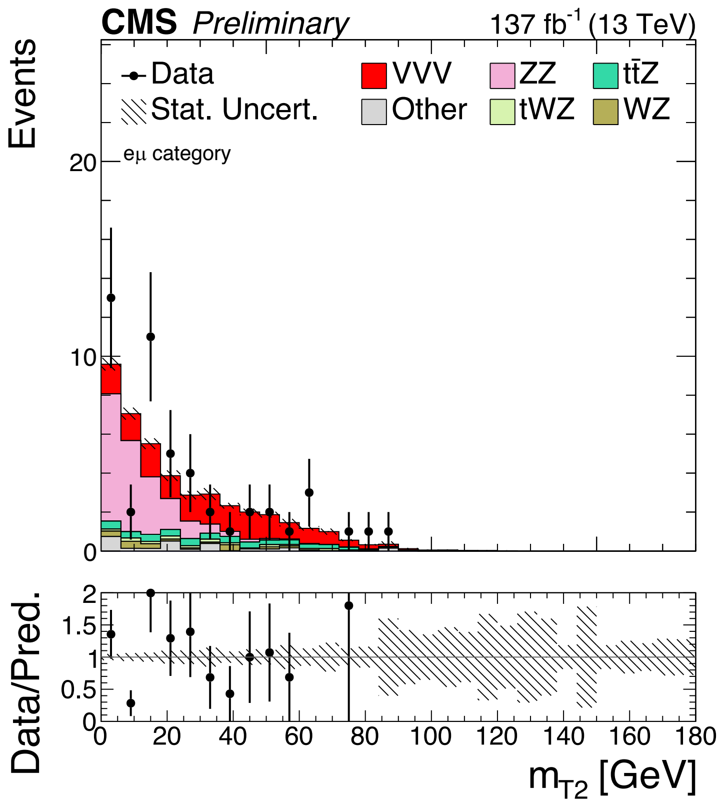
Nonprompt BDT score

Selections: 4ℓ – discriminating variables

- Discriminating variables (that are not in the main body of the slides):



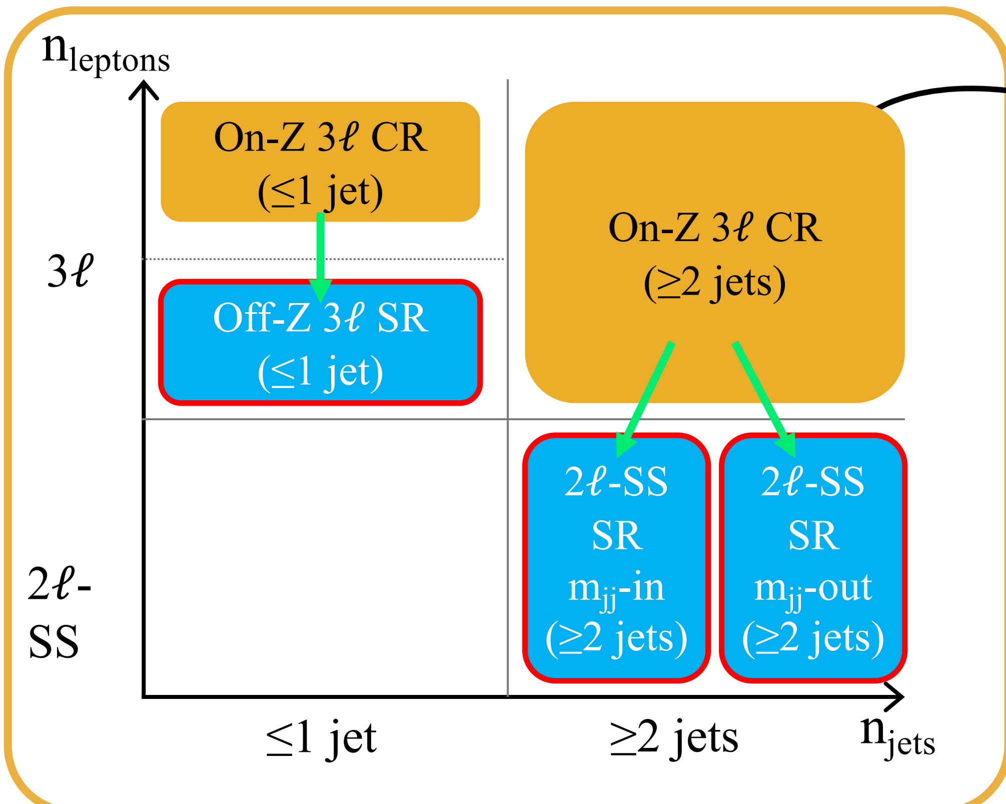
$p_T^{4\ell}$ for ee/μμ category

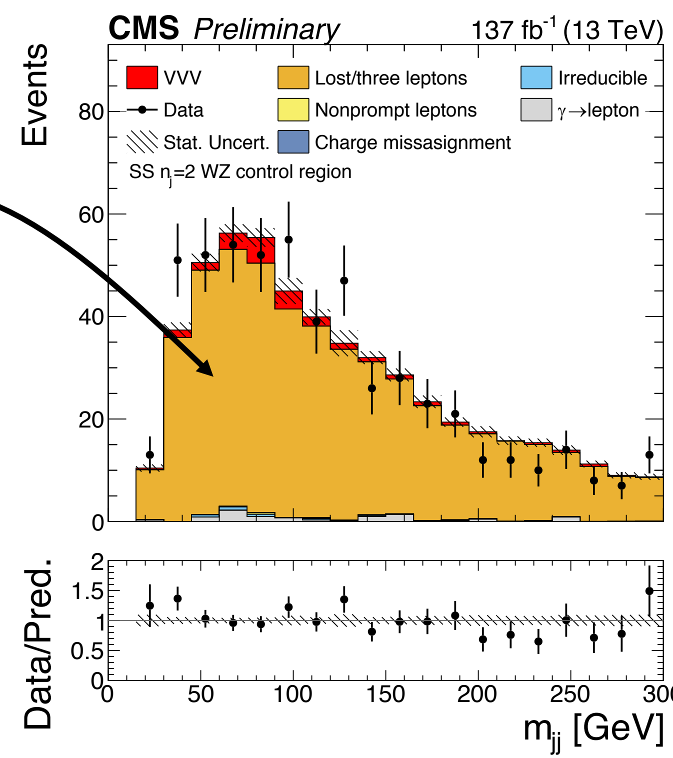


m_{T2} for eμ category

Backgrounds: SS-2ℓ, 3ℓ: WZ

- We need to discriminate the SM WWW signal against three backgrounds:
  - $W^{\pm}W^{\pm}jj/t\bar{t}W$ (prompt)
  - $WZ \rightarrow 3\ell 1\nu$
  - $t\bar{t}$ + one nonprompt lepton

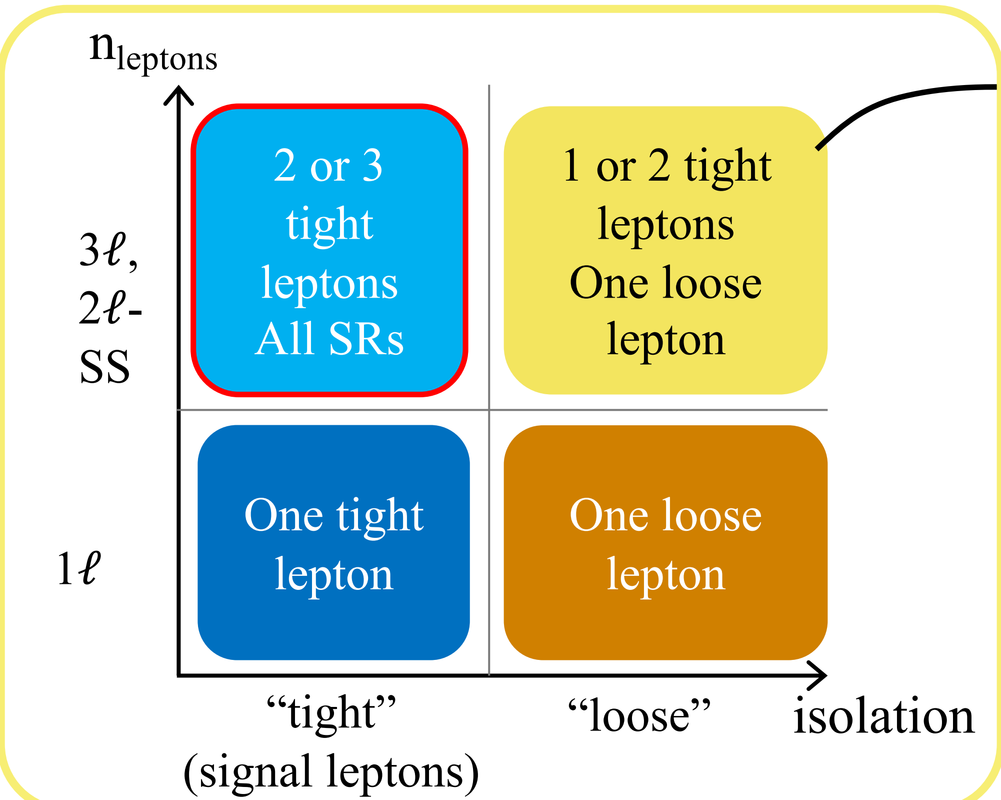


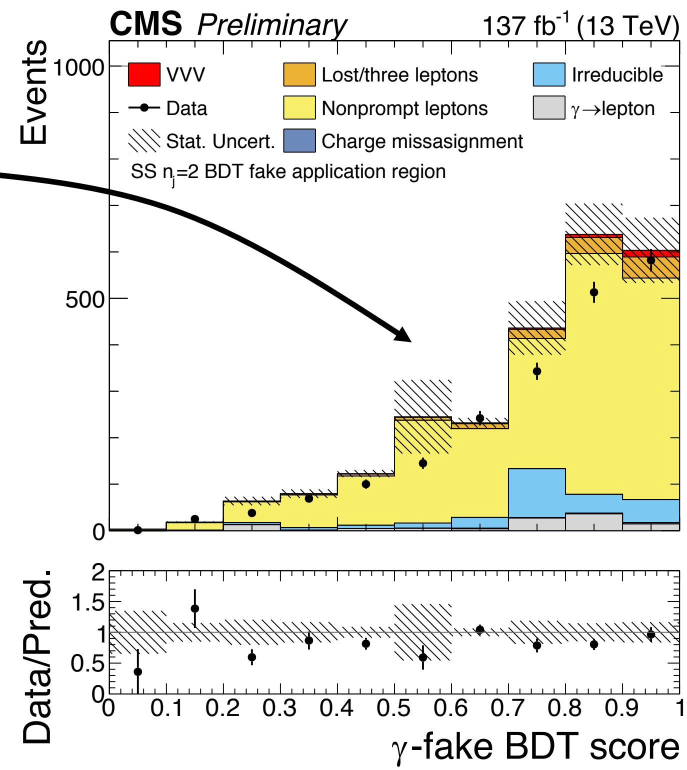


m_{jj} in WZ CR (cutbased)

Backgrounds: SS-2ℓ, 3ℓ: nonprompt

- We need to discriminate the SM WWW signal against three backgrounds:
  - $W^{\pm}W^{\pm}jj/t\bar{t}W$ (prompt)
  - $WZ \to 3\ell 1\nu$
  - $t\bar{t}$ + one nonprompt lepton

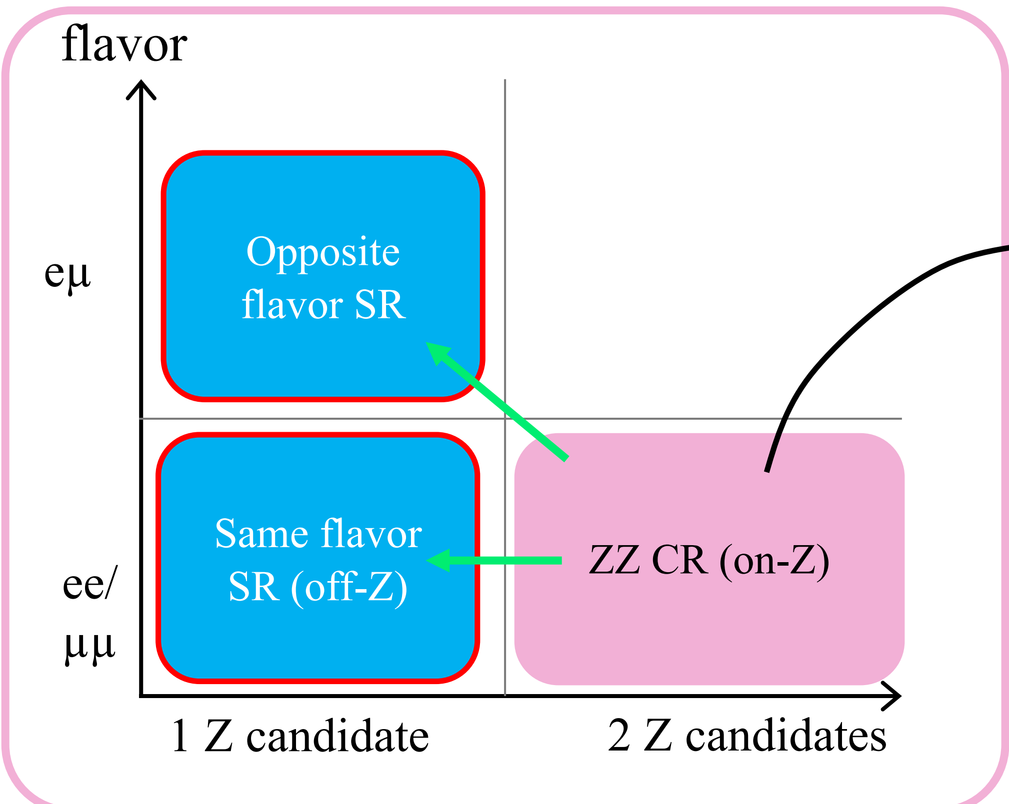


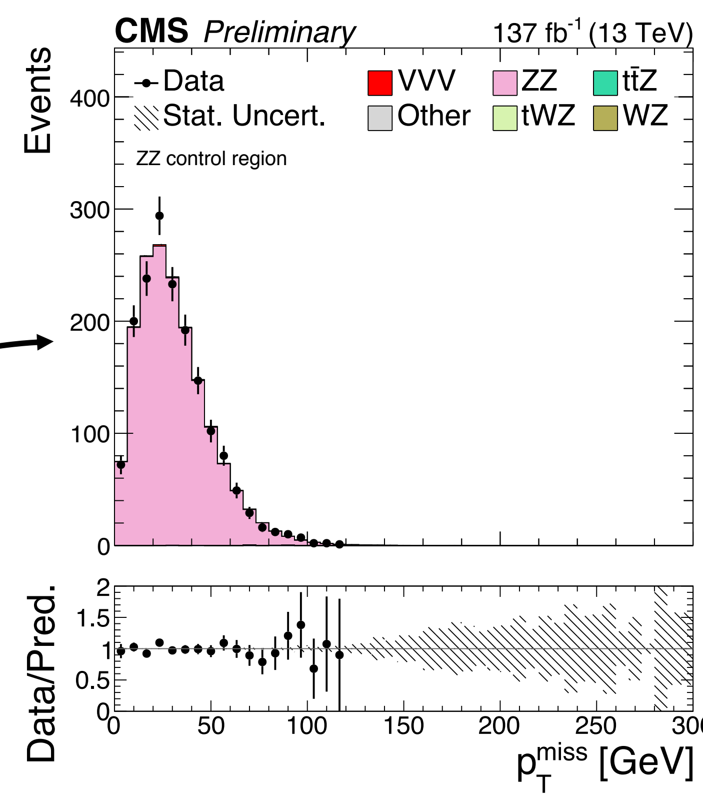


Fake BDT score – fake CR

Backgrounds: 4ℓ: ZZ

- We need to discriminate the SM WWZ signal against three backgrounds:
  - ZZ
  - ttZ
  - Others (incl. WZ + fake)

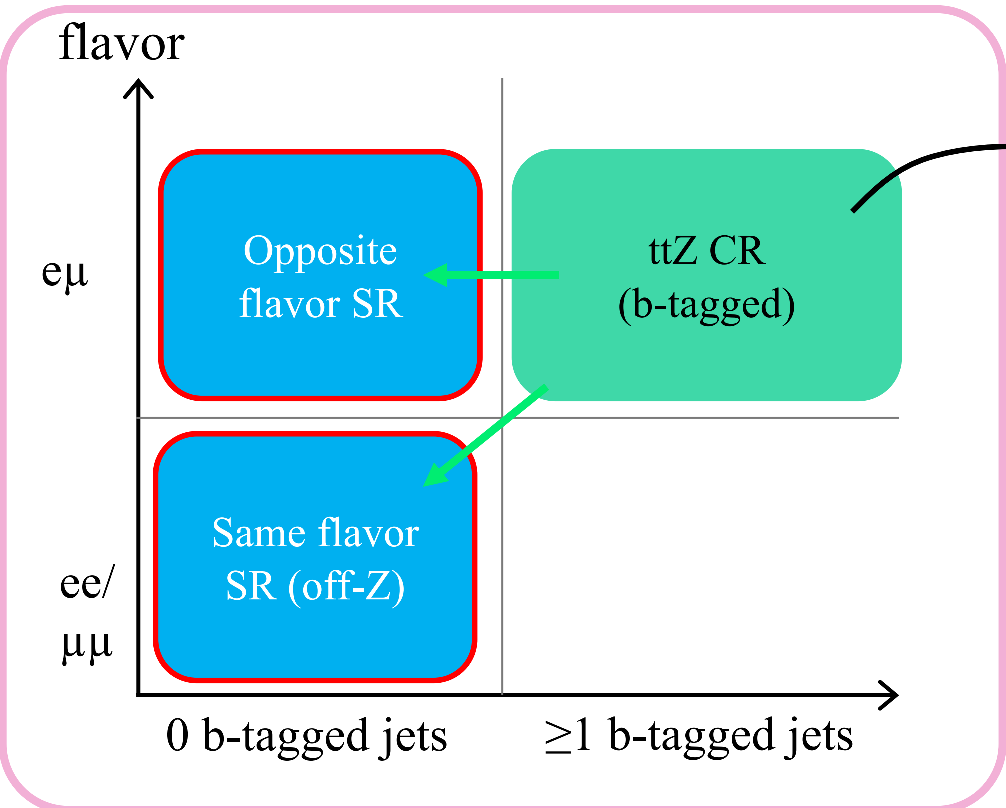


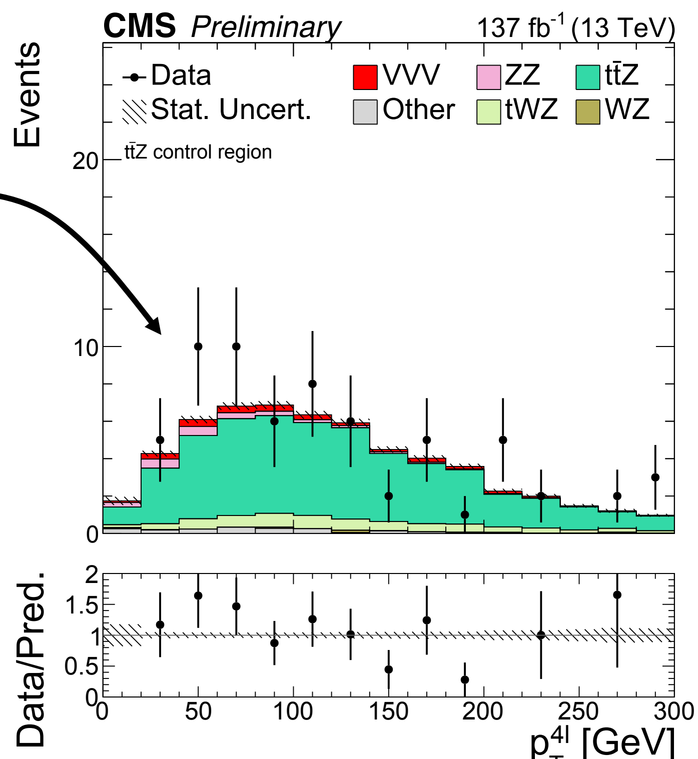


p_T^{miss} in ZZ CR (cutbased)

Backgrounds: 4ℓ: ttZ

- We need to discriminate the SM WWZ signal against three backgrounds:
  - ZZ
  - ttZ
  - Others (incl. WZ + fake)





$p_T^{4\ell}$ in ttZ CR (cutbased)

Results – in table form: SS-2ℓ, 3ℓ

Signal	SS m_{jj}-in			SS m_{jj}-out			SS 1j			3ℓ		
region	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	0 SFOS	1 SFOS	2 SFOS
Lost/three ℓ	1.4±0.9	5.5±1.6	7.0±1.7	10.7±2.6	9.7±3.6	31.4±3.8	2.5±1.1	41.0±6.1	5.8±1.6	3.5±0.7	25.6±4.2	36.1±3.1
Irreducible	1.0±0.1	0.6±0.1	2.9±0.2	4.7±0.4	1.9±0.2	15.5±1.2	0.4±0.0	4.6±0.2	0.5±0.1	1.3±0.1	1.2±0.1	0.3±0.0
Nonprompt ℓ	0.6±0.6	3.6±2.4	4.2±1.5	0.8±1.0	2.8±1.5	9.1±4.5	2.5±5.2	2.9±1.4	0.2±0.1	1.8±0.5	7.5±2.3	1.8±1.1
Charge flips	<0.1	<0.1	<0.1	4.5±2.5	<0.1	<0.1	<0.1	0.1±0.1	<0.1	<0.1	0.8±1.2	0.3±0.1
$\gamma \to$ nonprompt ℓ	0.1±0.2	0.1±0.4	<0.1	1.4±0.5	1.1±0.4	0.7±0.4	0.6±1.2	4.8±8.0	<0.1	<0.1	1.0±0.4	0.1±1.5
Background sum	3.1±1.1	9.8±2.9	14.2±2.3	22.1±3.8	15.6±4.0	56.8±6.0	6.0±5.4	53.5±10.1	6.4±1.6	6.6±0.9	36.2±5.0	38.7±3.6
WWW onshell	0.9±0.4	2.3±0.9	4.6±1.7	0.9±0.4	1.0±0.6	3.3±1.3	0.3±0.2	1.2±0.4	0.4±0.2	6.7±2.4	4.3±1.6	1.8±0.7
WH $\to$ WWW	0.4±0.3	1.3±0.9	1.2±0.5	0.5±0.3	1.3±1.3	2.7±1.2	1.1±0.8	6.5±3.1	2.2±1.1	3.4±1.6	5.0±2.1	0.6±0.6
WWW total	1.3±0.5	3.7±1.3	5.8±1.7	1.5±0.5	2.3±1.4	6.0±1.7	1.4±0.8	7.7±3.1	2.5±1.1	10.1±2.9	9.3±2.6	2.4±0.9
WWZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2±0.1	<0.1	<0.1
ZH $\to$ WWZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1±0.1	0.1±0.1	<0.1
WWZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3±0.1	0.1±0.1	<0.1
WZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
WH $\to$ WZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
WZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
ZZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
ZH $\to$ ZZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
ZZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
VVV onshell	0.9±0.4	2.3±0.9	4.6±1.7	0.9±0.4	1.0±0.6	3.3±1.3	0.3±0.2	1.2±0.4	0.4±0.2	6.9±2.4	4.3±1.6	1.8±0.7
VH $\to$ VVV	0.4±0.3	1.3±0.9	1.2±0.5	0.5±0.3	1.3±1.3	2.7±1.2	1.1±0.8	6.5±3.1	2.2±1.1	3.6±1.6	5.1±2.1	0.6±0.6
VVV total	1.3±0.5	3.7±1.3	5.8±1.7	1.5±0.5	2.3±1.4	6.0±1.7	1.4±0.8	7.7±3.1	2.5±1.1	10.4±2.9	9.3±2.6	2.4±0.9
Total	4.4±1.2	13.5±3.2	20.0±2.9	23.6±3.8	17.8±4.2	62.7±6.3	7.4±5.5	61.2±10.6	9.0±2.0	17.0±3.0	45.5±5.6	41.1±3.7
Observed	3	14	15	22	22	67	13	69	8	17	42	39

Results – in table form: 4ℓ, 5ℓ, 6ℓ

Signal region	4ℓ $e\mu$ bin 1	4ℓ $e\mu$ bin 2	4ℓ $e\mu$ bin 3	4ℓ $e\mu$ bin 4	4ℓ $e\mu$ bin 5	4ℓ ee/$\mu\mu$ bin A	4ℓ ee/$\mu\mu$ bin B	5ℓ	6ℓ
ZZ	15.9±1.0	1.6±0.1	0.6±0.1	0.6±0.1	0.2±0.0	76.4±4.3	2.9±0.3	0.30±0.09	0.01±0.01
$t\bar{t}Z$	0.2±0.1	0.1±0.1	2.8±0.5	1.4±0.2	0.1±0.1	1.5±0.3	2.3±0.3	<0.01	<0.01
tWZ	0.1±0.1	0.1±0.1	0.6±0.1	0.7±0.1	0.1±0.1	0.5±0.1	0.7±0.1	<0.01	<0.01
WZ	0.5±0.2	0.2±0.2	0.5±0.2	0.3±0.3	0.1±0.1	1.0±0.4	0.2±0.1	<0.01	<0.01
Other	1.1±0.4	0.5±0.5	0.5±0.2	0.6±0.2	<0.1	2.7±0.6	0.5±0.2	<0.01	<0.01
Background sum	17.8±1.1	2.5±0.5	5.0±0.6	3.6±0.4	0.5±0.1	82.2±4.3	6.6±0.5	0.30±0.09	0.01±0.01
WWW onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WH → WWW	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WWW total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
WWZ onshell	0.3±0.1	0.4±0.2	1.4±0.7	3.6±1.5	1.0±0.5	2.7±1.2	3.2±1.4	<0.01	<0.01
ZH → WWZ	1.1±0.5	1.1±0.5	0.5±0.2	1.3±0.5	1.8±0.8	2.9±1.2	1.5±0.6	<0.01	<0.01
WWZ total	1.3±0.5	1.5±0.5	1.9±0.8	4.9±1.6	2.9±0.9	5.6±1.7	4.7±1.5	<0.01	<0.01
WZZ onshell	0.2±0.2	0.1±0.1	0.2±0.2	0.4±0.4	0.1±0.1	0.5±0.4	0.2±0.2	2.62±1.82	0.03±0.05
WH → WZZ	0.2±0.3	0.2±0.3	<0.1	0.5±0.5	<0.1	<0.1	<0.1	<0.01	<0.01
WZZ total	0.4±0.3	0.3±0.3	0.2±0.2	0.9±0.7	0.1±0.1	0.5±0.4	0.2±0.2	2.62±1.82	0.03±0.05
ZZZ onshell	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
ZH → ZZZ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
ZZZ total	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01
VVV onshell	0.5±0.2	0.4±0.2	1.6±0.8	4.0±1.5	1.1±0.5	3.2±1.3	3.4±1.4	2.62±1.82	0.03±0.05
VH → VVV	1.2±0.5	1.3±0.6	0.5±0.2	1.7±0.8	1.8±0.8	2.9±1.2	1.5±0.6	<0.01	<0.01
VVV total	1.7±0.6	1.7±0.6	2.1±0.8	5.8±1.7	3.0±0.9	6.1±1.8	4.8±1.5	2.62±1.82	0.03±0.05
Total	19.5±1.2	4.2±0.8	7.1±1.0	9.4±1.8	3.5±0.9	88.2±4.7	11.4±1.6	2.92±1.82	0.04±0.05
Observed	22	9	7	8	3	80	11	3	0

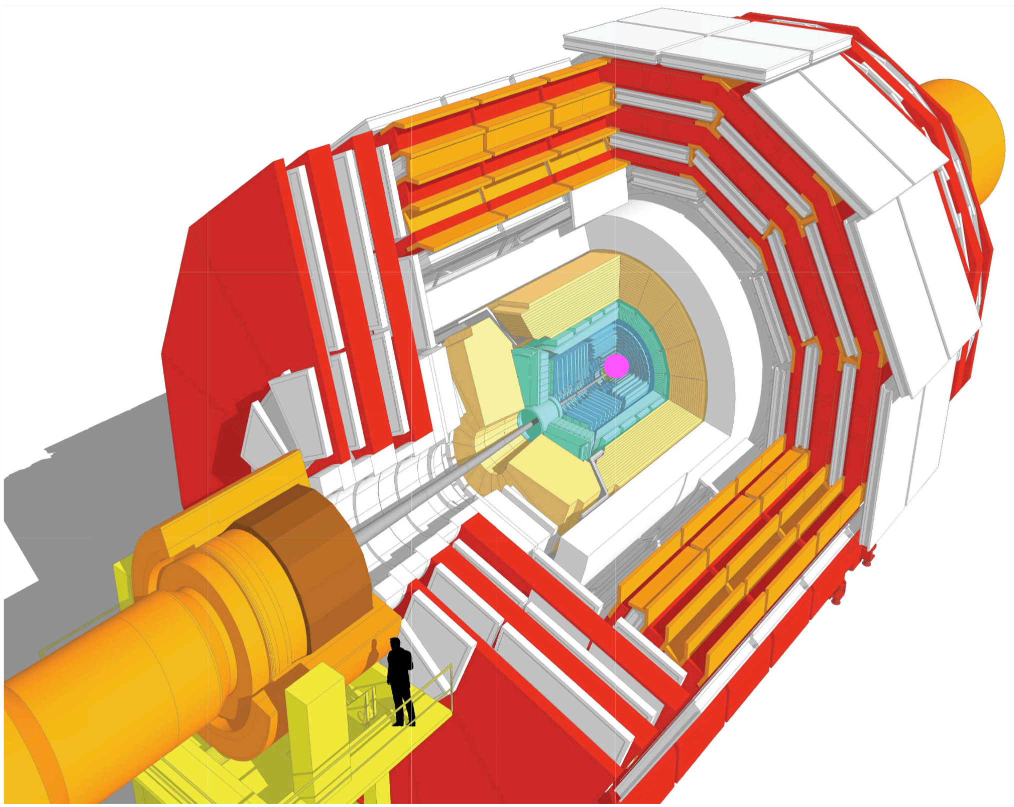
Results – detailed significances

Process	Higgs boson contributions as signal		Higgs boson contributions as background	
	sequential-cut	BDT-based	sequential-cut	BDT-based
WWW	2.5 (2.9)	3.3 (3.1)	1.0 (1.8)	1.6 (1.9)
WWZ	3.5 (3.6)	3.3 (4.1)	0.9 (2.2)	1.3 (2.1)
WZZ	1.6 (0.7)	1.7 (0.7)	1.7 (0.8)	1.7 (0.8)
ZZZ	0.0 (0.9)	0.0 (0.9)	0.0 (0.9)	0.0 (0.9)
VVV	5.1 (5.4)	5.7 (5.9)	2.3 (3.5)	2.9 (3.5)

Results – measured cross sections

Channel	Cross section (fb)
Higgs boson contributions as signal	
VVV	$1010^{+210}_{-200}{}^{+150}_{-120}$
WWW	$590^{+160}_{-150}{}^{+160}_{-130}$
WWZ	$300^{+120}_{-100}{}^{+50}_{-40}$
WZZ	$200^{+160}_{-110}{}^{+70}_{-20}$
ZZZ	<200
Higgs boson contributions as background	
VVV	$370^{+140}_{-130}{}^{+80}_{-60}$
WWW	$190^{+110}_{-100}{}^{+80}_{-70}$
WWZ	$100^{+80}_{-70}{}^{+30}_{-30}$
WZZ	$110^{+100}_{-70}{}^{+30}_{-10}$
ZZZ	<80

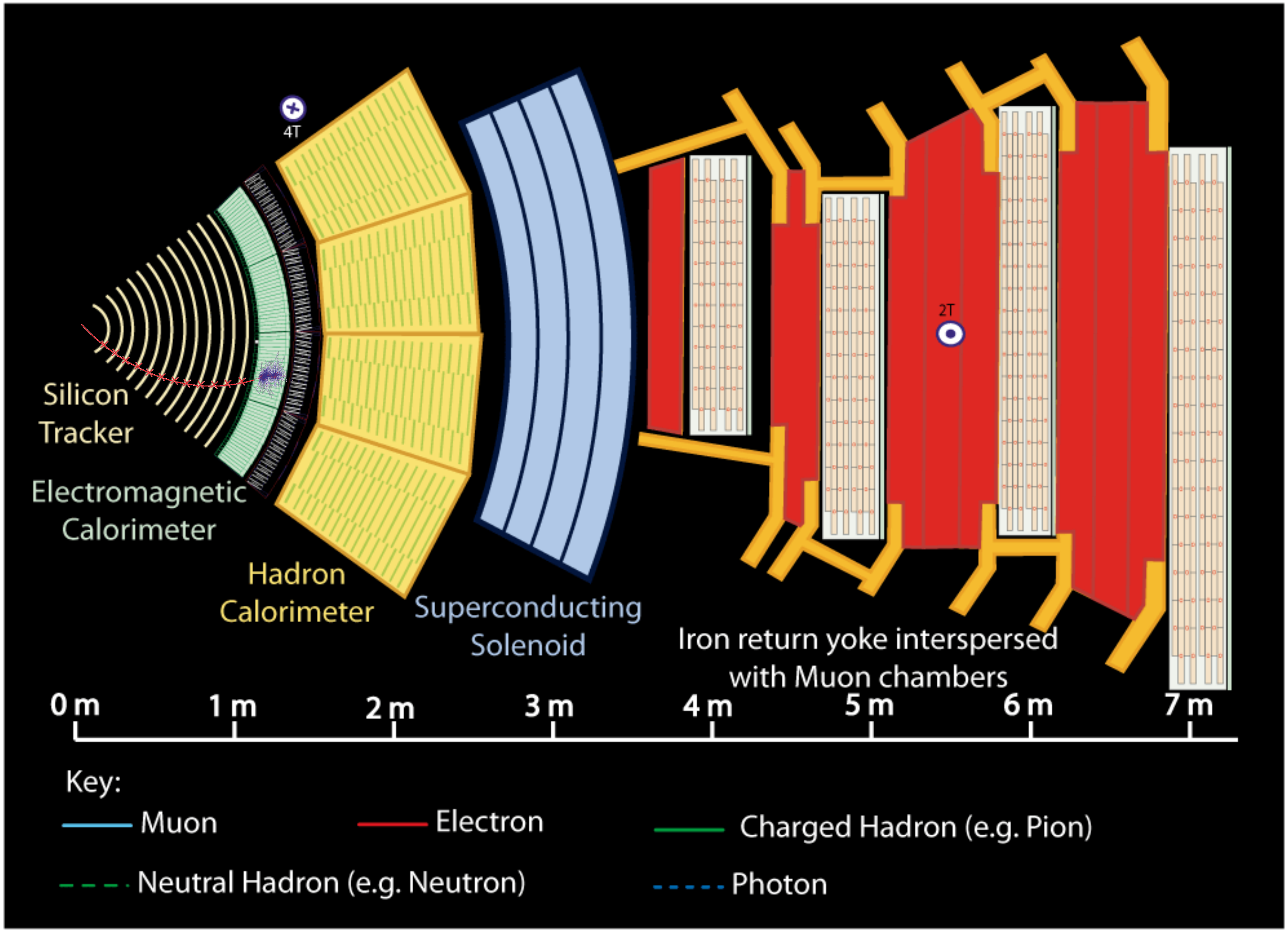
The CMS experiment at the LHC



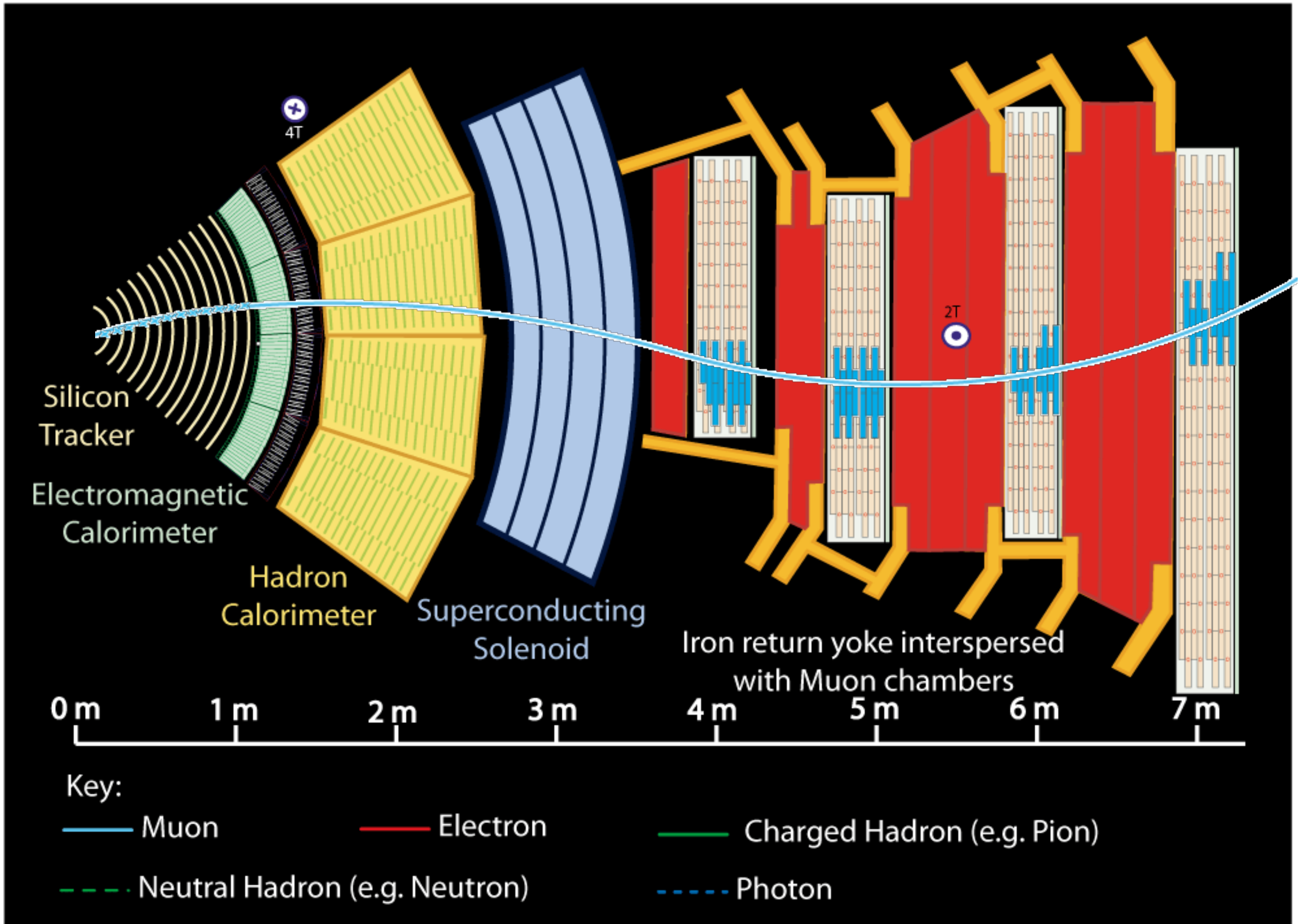
The CMS experiment at the LHC:

- Multipurpose experiment.
- Consists of several detectors surrounding the collision point:
  - Two inner tracking detectors,
  - Two calorimeters,
  - One outer tracking detector.
- Allows to measure full momentum of (almost) all particles coming out of the collision.
  - Known exception: neutrinos

Lepton reconstruction in CMS: electrons

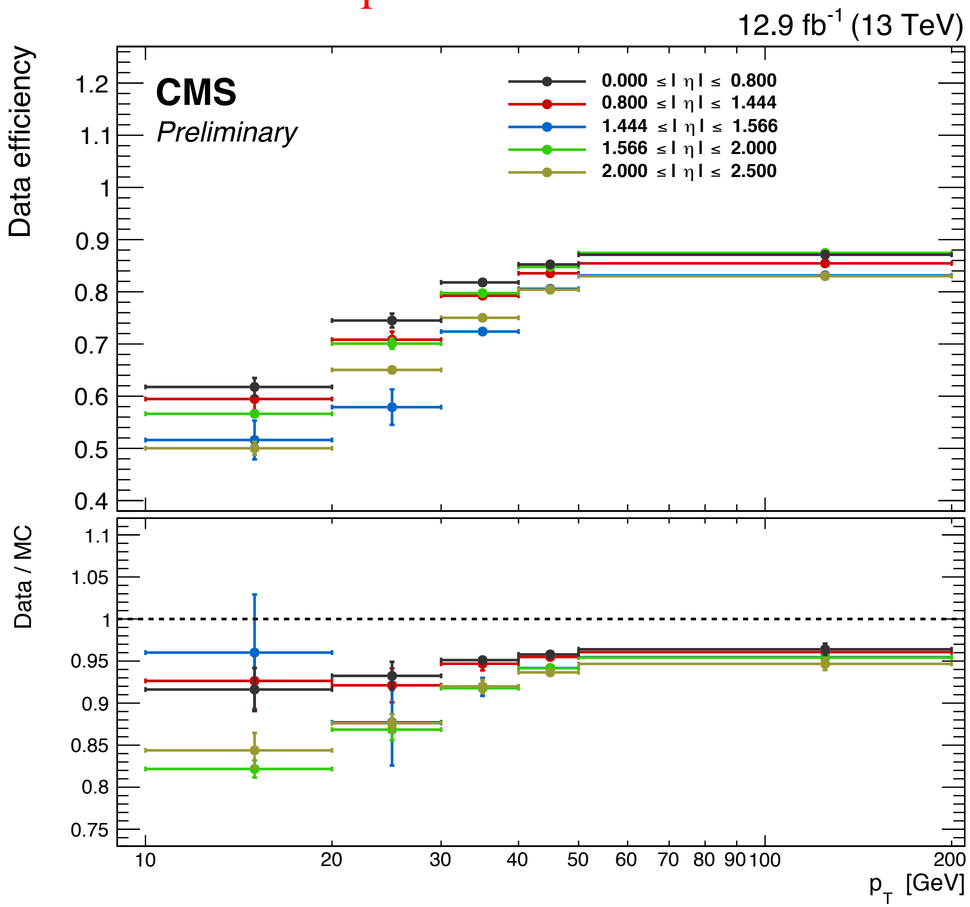


Lepton reconstruction in CMS: muons



Lepton reconstruction in CMS: electrons

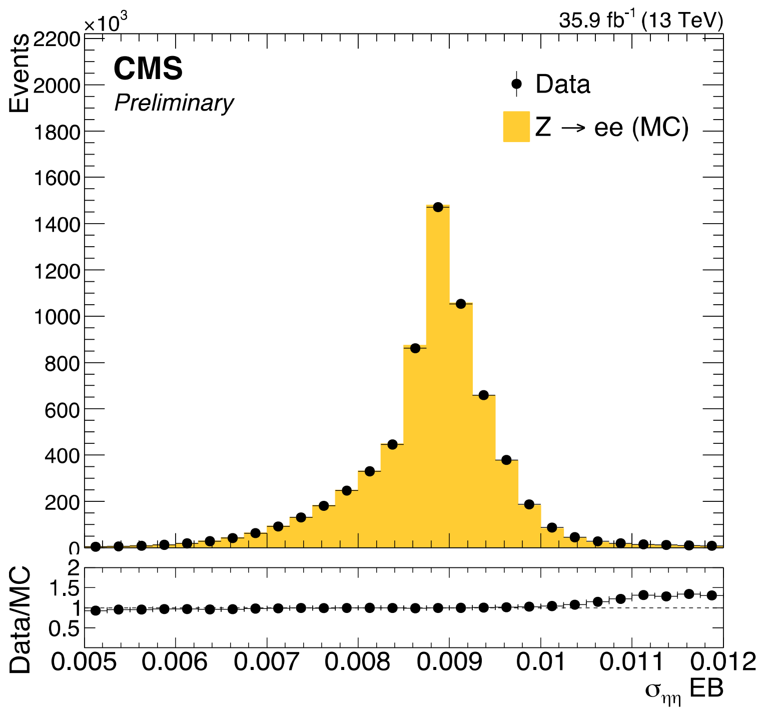
- Crucial for this analysis is the clean reconstruction of electrons:
  - We must distinguish against photons that convert into an e^+e^- pair, and against misidentified pions.

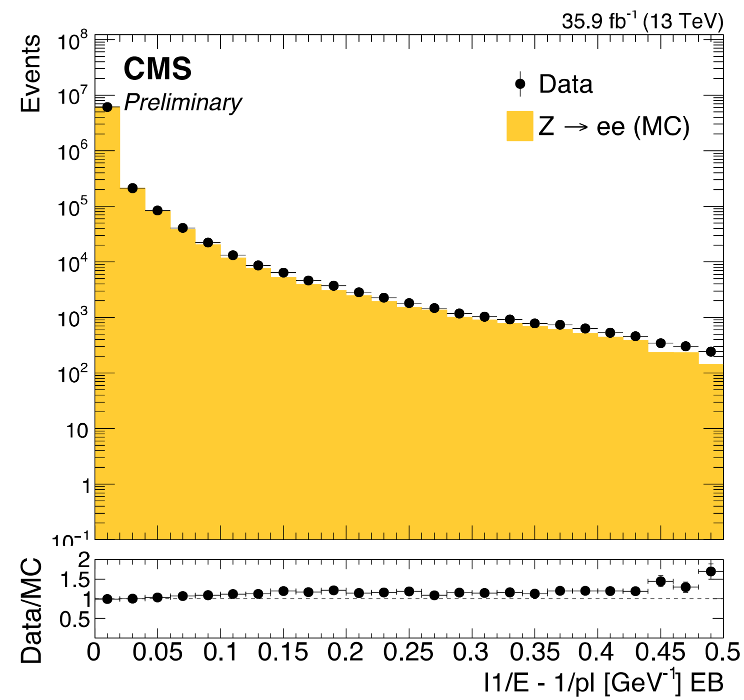


- If selecting on these shower + tracking variables, lose ~30% of electrons.
- Train a boosted decision tree:
  - For 1% background efficiency, can reach 90% signal efficiency.
  - Low/High signal efficiency for low/high p_T.

Lepton reconstruction in CMS: electrons

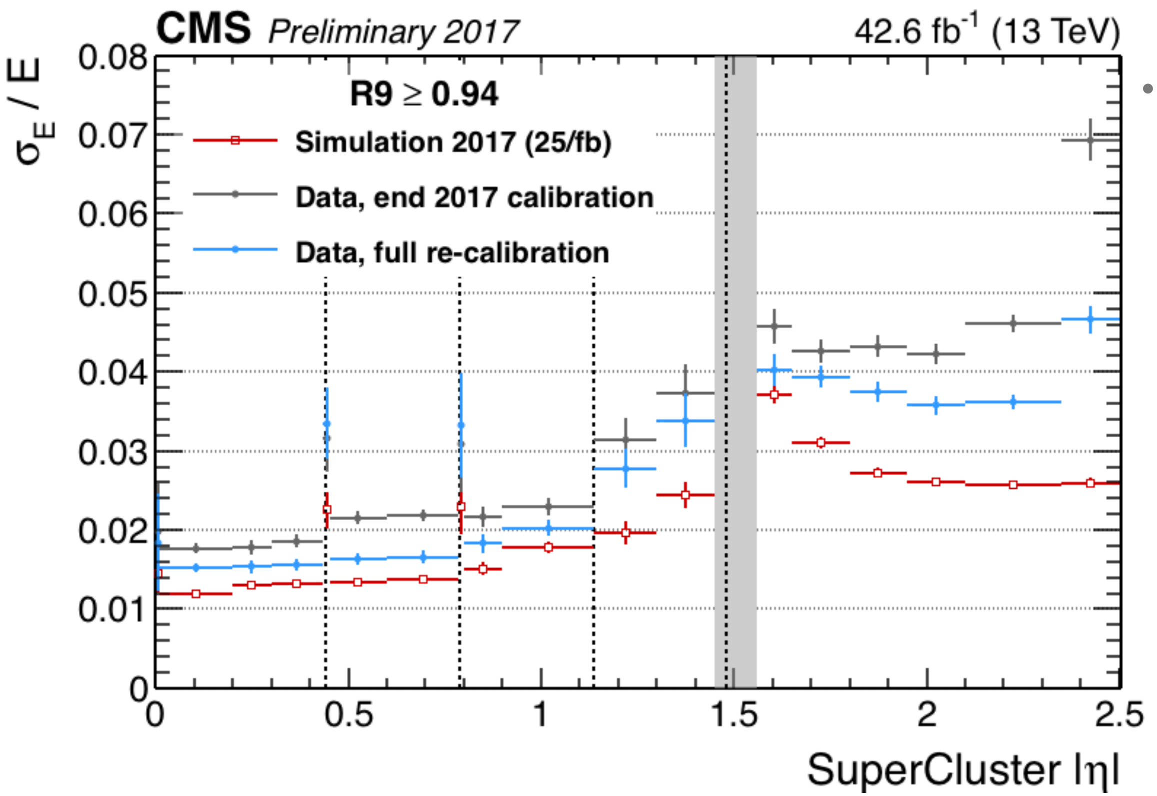
- Modeling of distribution for electron identification variables in run-2 data and simulation:





Lepton reconstruction in CMS: electrons

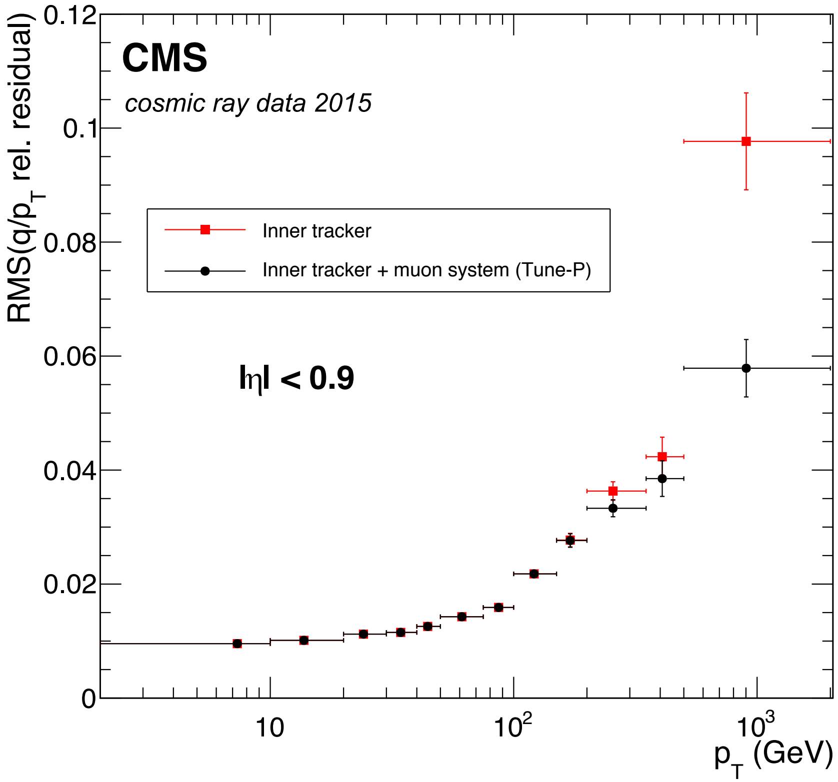
- Energy resolution in run-2 data and simulation.



- Combining tracker and calorimeter information yields good resolution.
  - ~1-3% × $p_T(e)$ in barrel.
  - ~4-5% × $p_T(e)$ in endcap.

Lepton reconstruction in CMS: muons

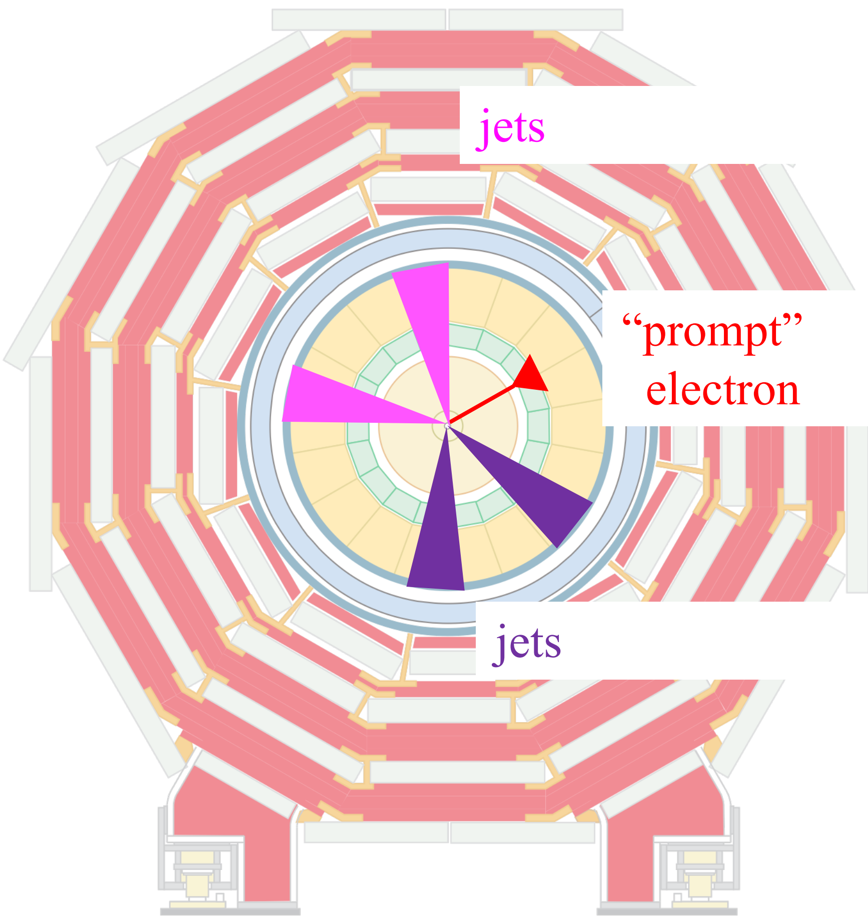
- Energy resolution in data using cosmic rays.

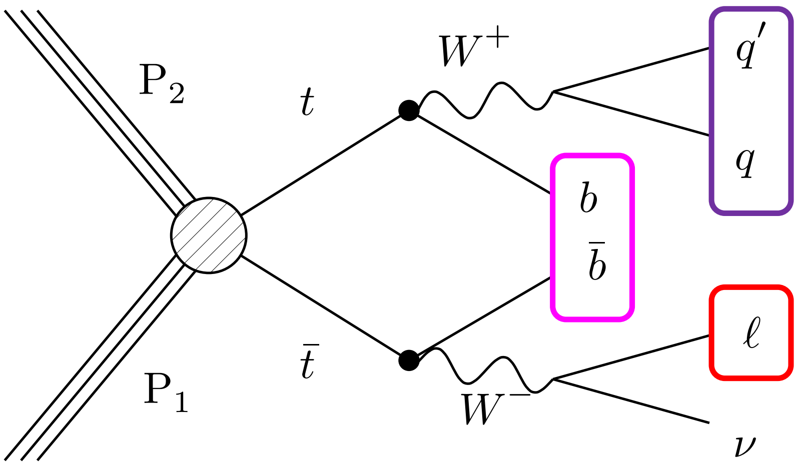


- The tracking capabilities of both inner and muon tracker are very good.
  - The resolution is ~1% × $p_T(\mu)$ in region of interest (muons from non-boosted W bosons).

Nonprompt lepton background

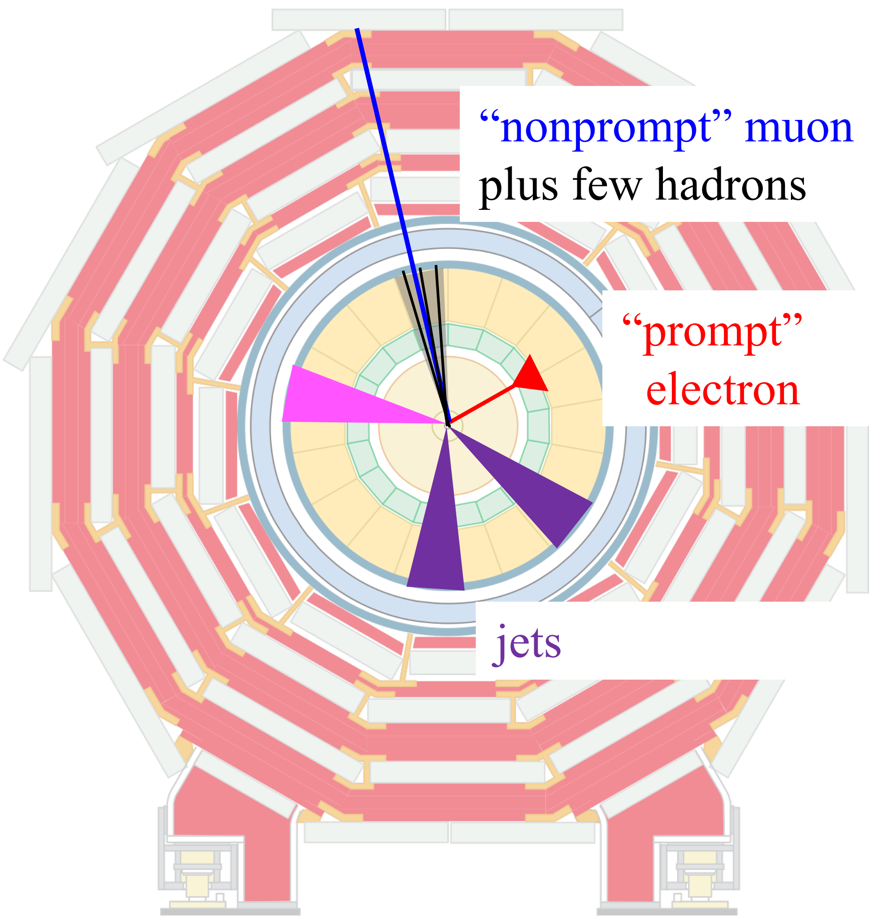
- We need to discriminate against nonprompt leptons: e.g. top quark production





Nonprompt lepton background

- We need to discriminate against nonprompt leptons: e.g. top quark production
  - a jet might contain a lepton from hadron decay: $B^0 \rightarrow D^{\pm}\mu^{\mp}\nu$



- Generally, we require them to be isolated from any hadronic activity in CMS.

Nonprompt lepton background

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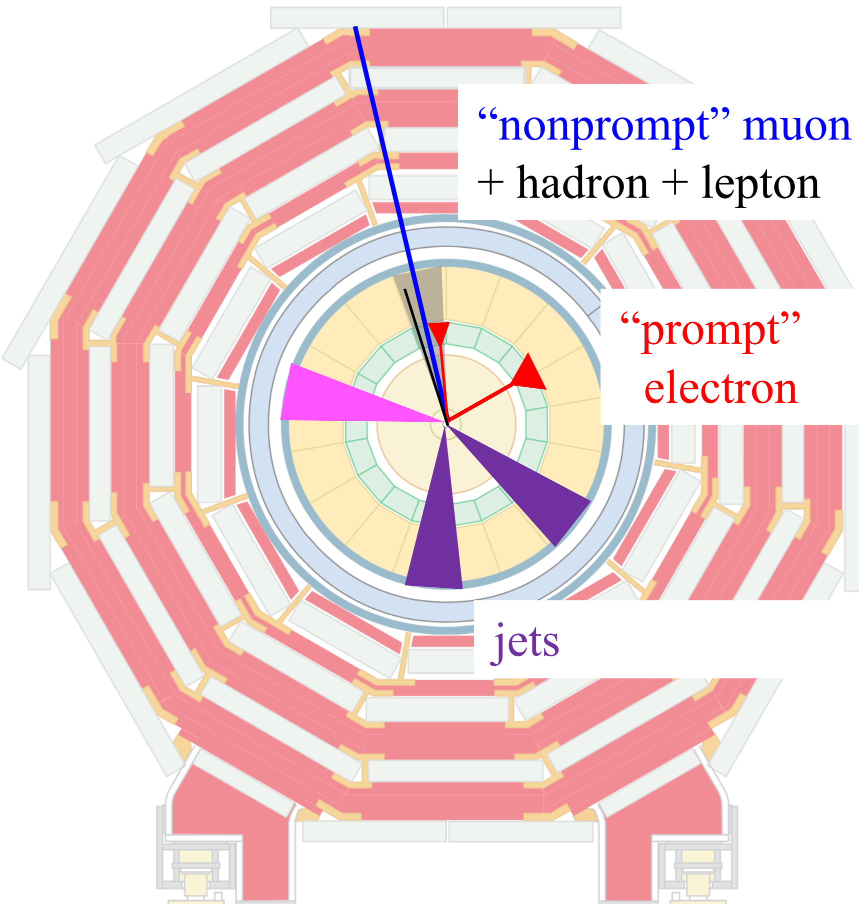
  - a jet might contain a lepton from hadron decay: $B^0 \rightarrow D^{\pm}\mu^{\mp}\nu$



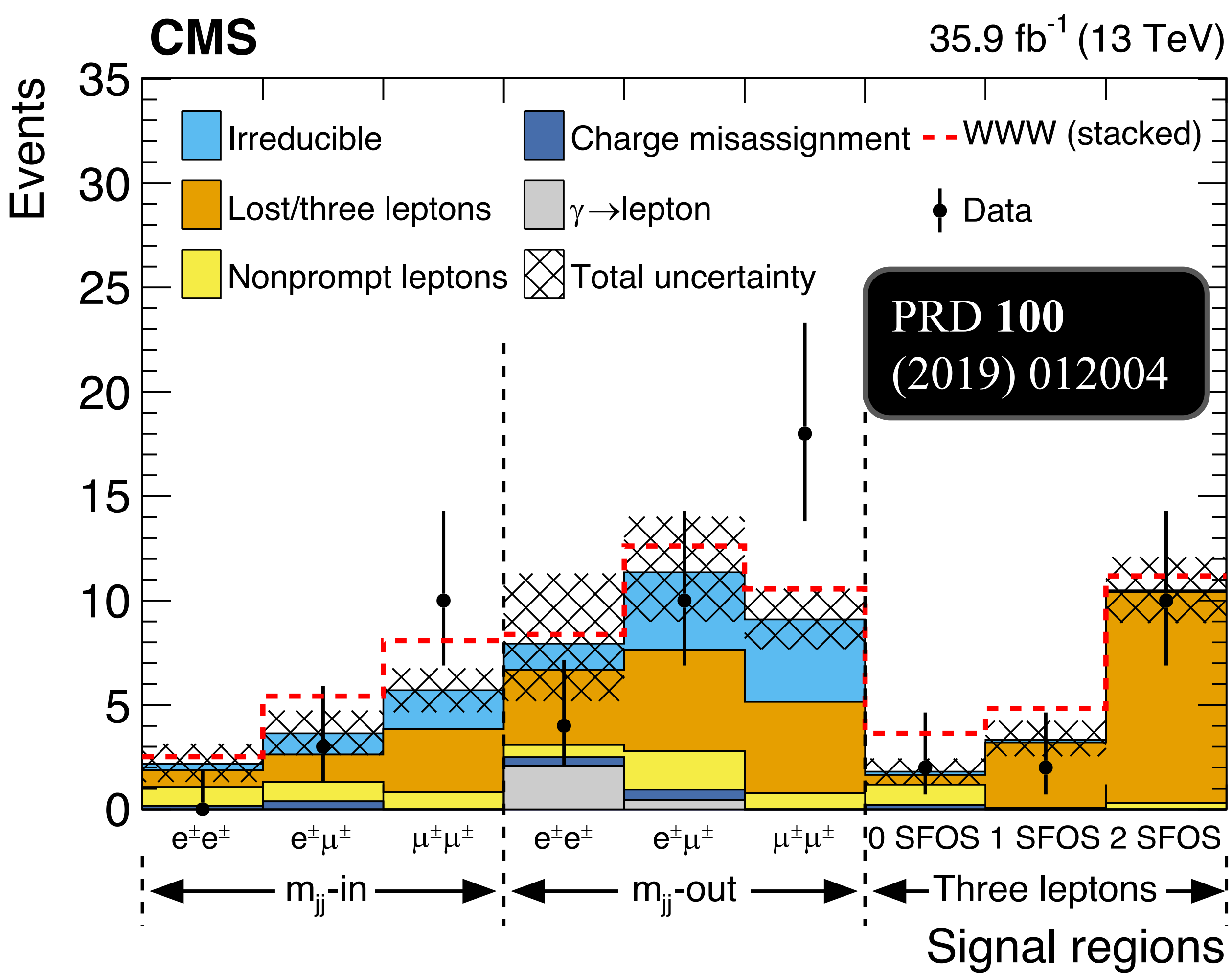
- Generally, we require leptons to be isolated from any hadronic activity in CMS.
- For few decays, we see, e.g. $B^0 \rightarrow D^{\pm}\mu^{\mp}\nu$, $D^{\pm} \rightarrow \overline{K}^0 \ell^{\pm}\nu$.
  - Those are events, CMS might not reject.

➢ Reject leptons that are not isolated against secondary leptons (**custom development for this analysis**).

Results of 2016 WWW analysis

- Expected significance: 1.8 s.d.
- Observed significance: 0.6 s.d.

- This corresponds to a cross section of $0.17^{+0.32}_{-0.17}$ pb.



Comparison to ATLAS

- ATLAS published an analysis based on 80 fb^{-1}: PLB 798 (2019) 134913

CMS:

Process	Significance [s.d.]
WWW	3.3 (3.1)
WWZ	3.3 (4.1)
WZZ	1.7 (0.7)
ZZZ	0.0 (0.9)
combined	**5.7 (5.9)**

ATLAS:

Decay channel	Significance Observed	Significance Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ

Comparison to ATLAS

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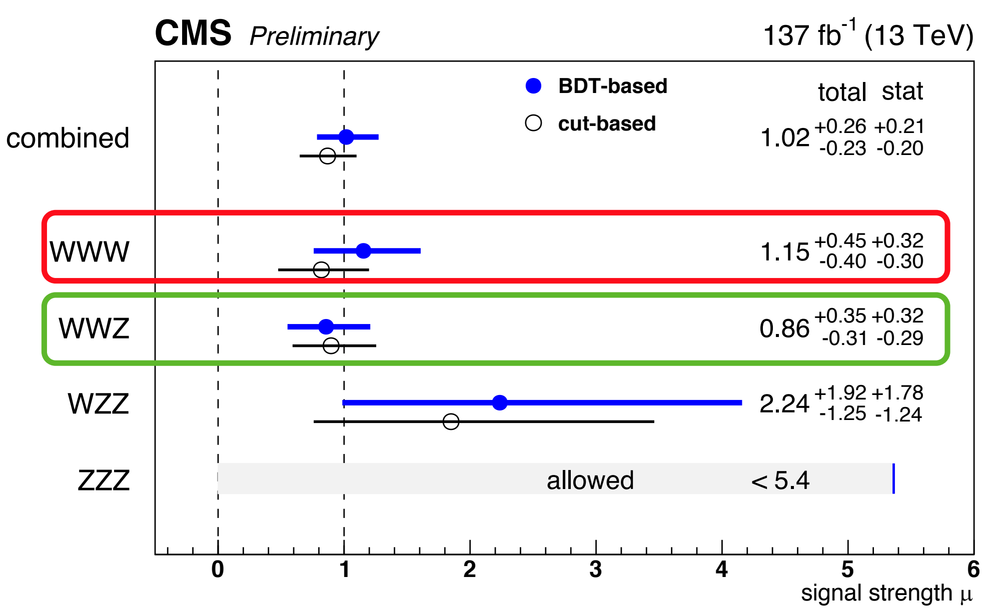
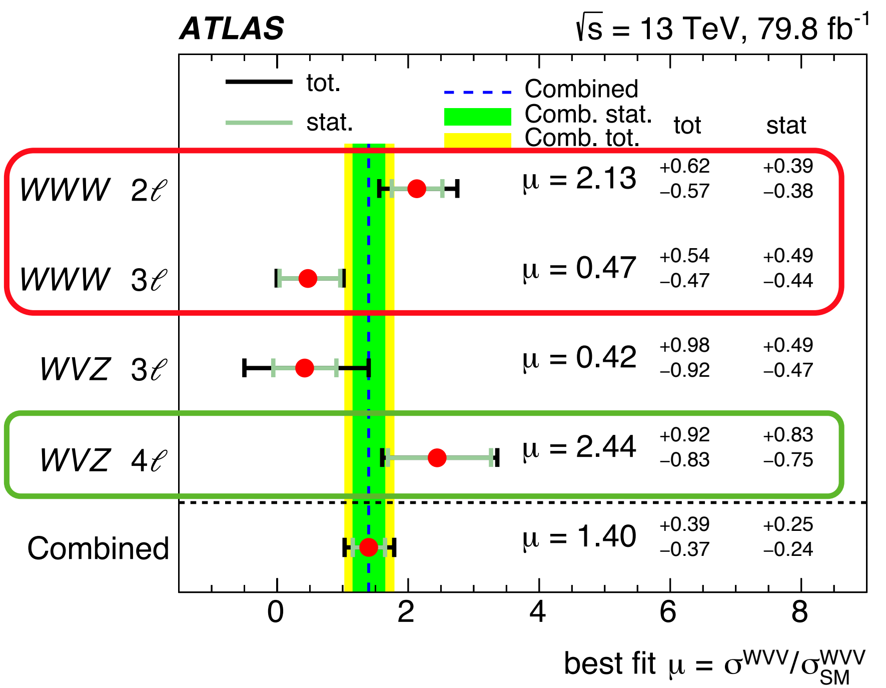
CMS:



ATLAS:



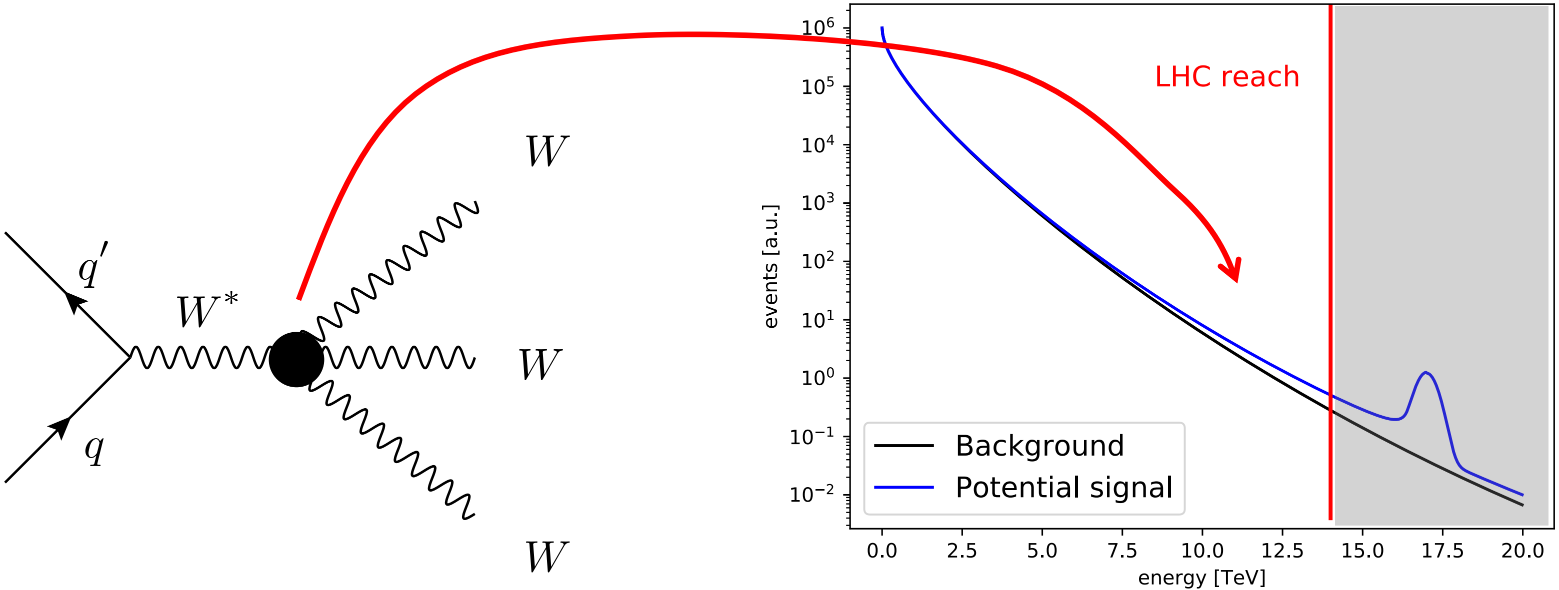
The future for tribosons

Boson decay	WWW
All leptonic, no hadronic	$\mathcal{O}$(0.1-1%)
Two leptonic, one hadronic	$\mathcal{O}$(1-10%)
One leptonic, two hadronic	$\mathcal{O}$(10-30%)
No leptonic, all hadronic	$\mathcal{O}$(30-35%)

↑ Higher purity: Good for measurement

Higher acceptance: Good for searches ↓

At high energies, we might explore signatures with boosted hadronically decaying bosons.



The future for tribosons

- We will be able to measure these processes with hundreds of multilepton events expected from simulation.
- The (HL-)LHC dataset will allow us to test the electroweak theory, especially towards quartic couplings.

Boson decay	WWW	WWZ	WZZ	ZZZ
All leptonic, no hadronic	1.7%	0.5%	0.1%	<0.1%
Two leptonic, one hadronic	13.2%	4.7%	2.9%	1.0%
One leptonic, two hadronic	23.2%	27.3%	19.3%	10.5%
No leptonic, all hadronic	30.6%	31.8%	32.9%	34.1%

- If anomalous quartic couplings happen at high energies, we might be able to explore events with boosted hadronic vector bosons.
- The (HL-)LHC will either set strong constraints on or be able to observe on modification of those couplings.