CLHCP2024, Qingdao

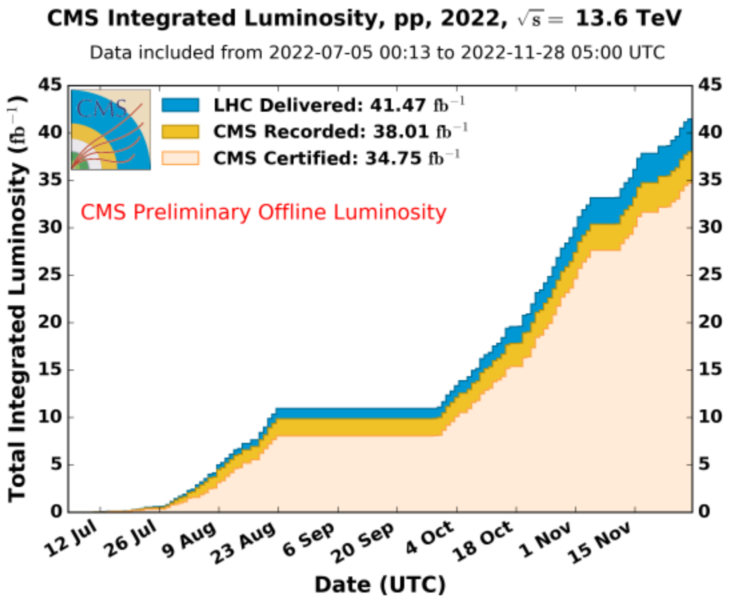
Measurements of Higgs boson production cross sections in the four-lepton final state at 13.6 TeV in CMS

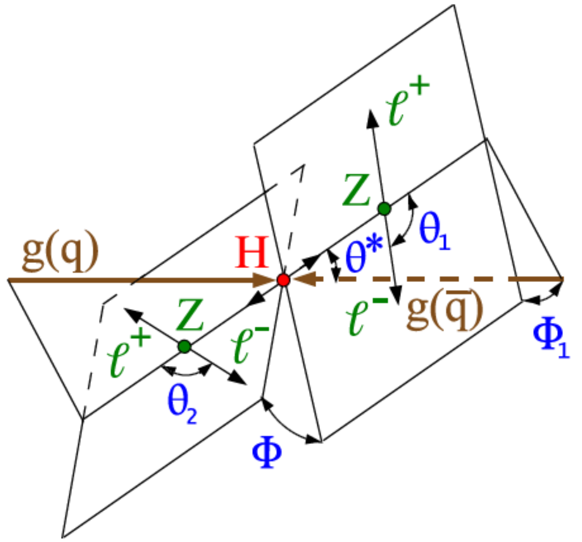
Yuji Li[1,2] for CMS Collaboration

1. Fudan University, Shanghai
2. IHEP, Beijing

Introduction

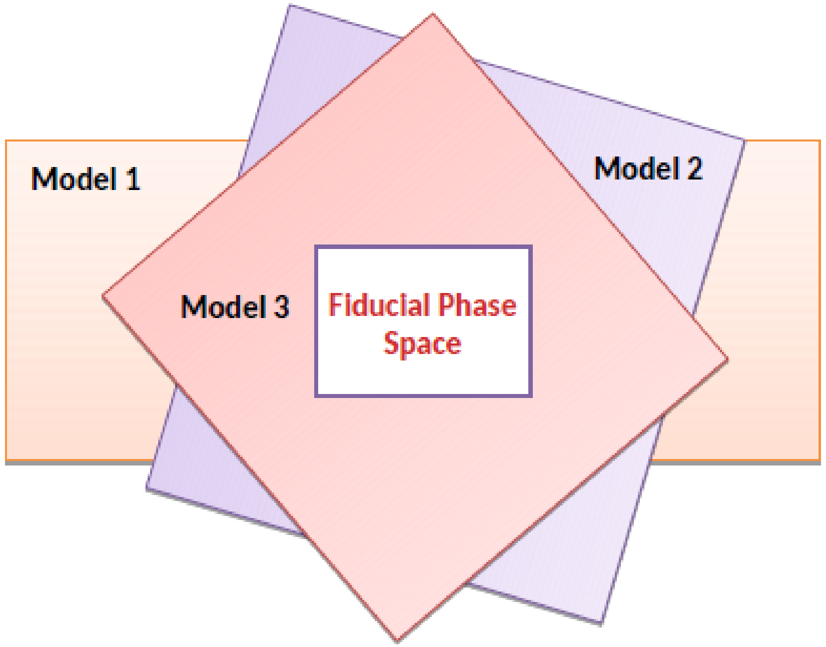
- Measure fiducial cross section of H->ZZ->4l at 13.6 TeV using the 2022 Data collected by CMS.
- The result has been open to public(ICHEP 2024), and the paper will be submitted to JHEP.
- Analysis performed on 2022preEE (ECAL leak) ReReco and 2022postEE Prompt datasets
- A total of 34.7 fb-1 has been analysed, for 7.98fb-1 in preEE era and 26.67fb-1 in postEE era.
- Cross section is measured by unfolding experimental data to the fiducial phase space at generator level.
- Differencial XS for Higgs production are also measured with several observables.





Analysis strategy

$$N^{f,i}_{obs}(m_{4\ell}) = N^{f,i}_{fid}(m_{4\ell}) + N^{f,i}_{nonfid}(m_{4\ell}) + N^{f,i}_{nonres}(m_{4\ell}) + N^{f,i}_{bkg}(m_{4\ell})$$
$$= \epsilon^{f}_{i,j} \cdot \left(1 + f^{f,i}_{nonfid}\right) \cdot \sigma^{f,j}_{fid} \cdot \mathcal{L} \cdot \mathcal{P}_{res}(m_{4\ell})$$
$$+ N^{f,i}_{nonres} \cdot \mathcal{P}_{nonres}(m_{4\ell}) + N^{f,i}_{bkg} \cdot \mathcal{P}_{bkg}(m_{4\ell})$$



$N^{f,i}_{obs}(m_{4\ell})$ is skimmed from Data.

$\epsilon^{f}_{i,j} \cdot \left(1 + f^{f,i}_{nonfid}\right)$ is measured from signal samples.

$\mathcal{P}_{res}(m_{4\ell})$ $\mathcal{P}_{nonres}(m_{4\ell})$ are described by signal shape.

$\cdot \mathcal{P}_{bkg}(m_{4\ell})$ is evaluated from backgrounds

Finally, the fiducial XS can be measured with a simutanous fitting method. Similarly, the differential XS can also be fitted with suitable observables binning.

Signal process	$\mathcal{A}_{fid}$	ϵ	f_{nonfid}	$(1 + f_{nonfid})\epsilon$
Individual Higgs boson production modes				
ggH	0.408 ± 0.001	0.625 ± 0.001	0.059 ± 0.001	0.659 ± 0.002
VBF	0.456 ± 0.001	0.645 ± 0.002	0.043 ± 0.001	0.671 ± 0.025
WH	0.353 ± 0.001	0.604 ± 0.001	0.113 ± 0.001	0.670 ± 0.009
ZH	0.346 ± 0.001	0.620 ± 0.001	0.136 ± 0.001	0.701 ± 0.008
ttH	0.355 ± 0.001	0.603 ± 0.002	0.252 ± 0.002	0.748 ± 0.009

Object Selection

- **Electrons:**

  pT > 7GeV, |eta|<2.5, dxy<0.5cm, dz<1cm

  SIP3d<4, BDT ID

- **FSR Photons:**

  pT > 2GeV, |eta|<2.5, ISO<1.8

  $\Delta R(l,\gamma)<0.5$ $\Delta R(l,\gamma)/(pT^2)<0.012$

- **Muons:**

  pT > 5GeV, |eta|<2.4, dxy<0.5cm, dz<1cm

  SIP3d<4, PF ID if pT<200,

  PF ID or HighPTID if pT>200, ISO<0.35

- **Jets:**

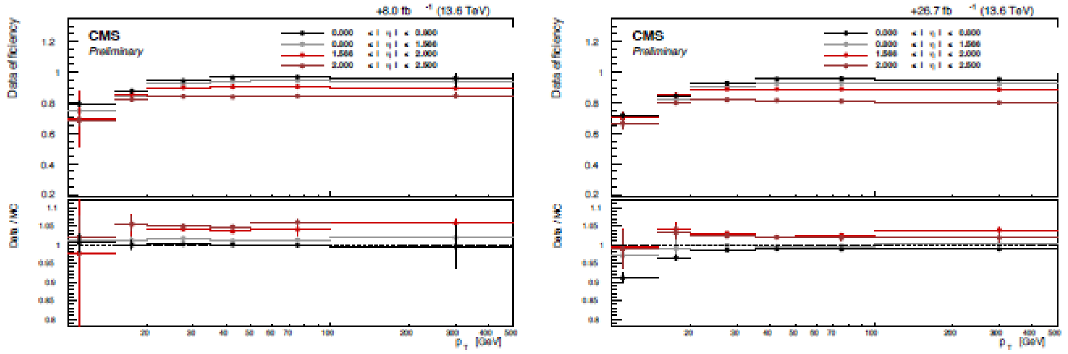
  To be updated (not used in this analysis)

Electron SFs

- Electron pT/Eta/IP selection was inherited from Run2, but the BDT ID is investigated again in 2022.

Observable type	Observable name
Cluster shape	RMS of the energy-crystal number spectrum along η and φ; $\sigma_{i\eta i\eta}$, $\sigma_{i\varphi i\varphi}$ Super cluster width along η and ϕ Ratio of the hadronic energy behind the electron supercluster to the supercluster energy, H/E Circularity $(E_{5\times5} - E_{5\times1})/E_{5\times5}$ Sum of the seed and adjacent crystal over the super cluster energy R_9 For endcap traing bins: energy fraction in pre-shower E_{PS}/E_{raw}
Track-cluster matching	Energy-momentum agreement E_{tot}/p_{in}, E_{ele}/p_{out}, $1/E_{tot} - 1/p_{in}$ Position matching $\Delta\eta_{in}$, $\Delta\varphi_{in}$, $\Delta\eta_{seed}$
tracking	Fractional momentum loss $f_{brem} = 1 - p_{out}/p_{in}$ Number of hits of the KF and GSF track N_{KF}, N_{GSF} Reduced χ^2 of the KF and GSF track χ^2_{KF}, χ^2_{GSF} Number of expected but missing inner hits Probability transform of conversion vertex fit χ^2
isolation	Particle Flow isolation from ECAL clusters Particle Flow isolation from HCAL clusters Track-based isolation with 0.3 cone
For PU-resilience	Mean energy density in the event: ρ

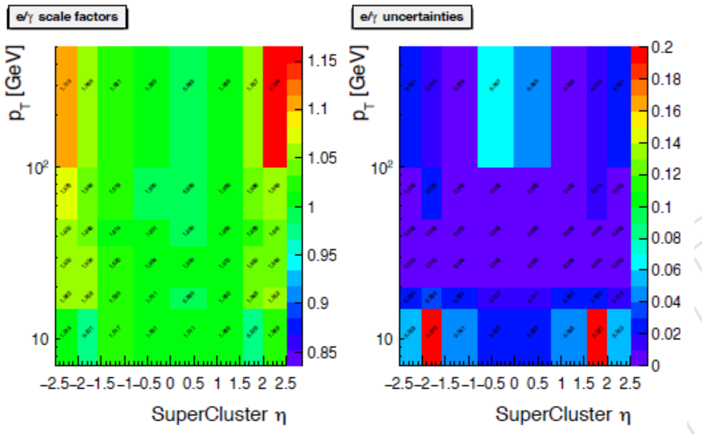
BDT input Features



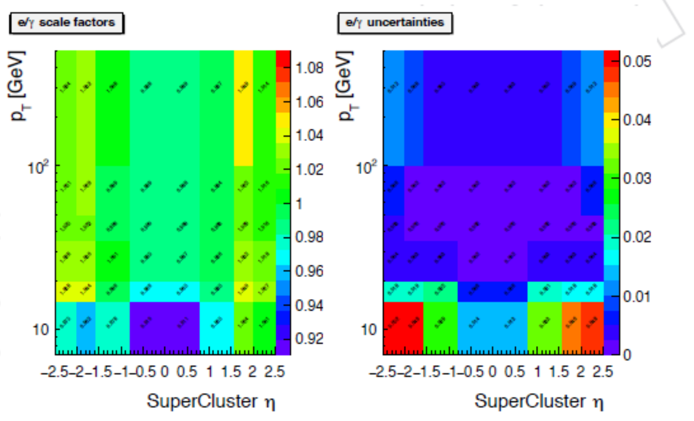
Corresponding Effs with tag-and-probe methods

	$\|\eta\| < 0.8$		
	Cut on BDT score	Signal eff.	Background eff.
$5 < p_T < 10$ GeV	1.6339	81.64%	4.2%
$p_T > 10$ GeV	0.3685	97.45%	2.27%
	$0.8 < \|\eta\| < 1.479$		
	Cut on BDT score	Signal eff.	Background eff.
$5 < p_T < 10$ GeV	1.5499	80.31%	4.11%
$p_T > 10$ GeV	0.2662	96.68%	2.83%
	$\|\eta\| > 1.479$		
	Cut on BDT score	Signal eff.	Background eff.
$5 < p_T < 10$ GeV	2.0629	74.37%	2.97%
$p_T > 10$ GeV	-0.5444	96.62%	7.46%

BDT WPs for tight electron selection



preEE SFs



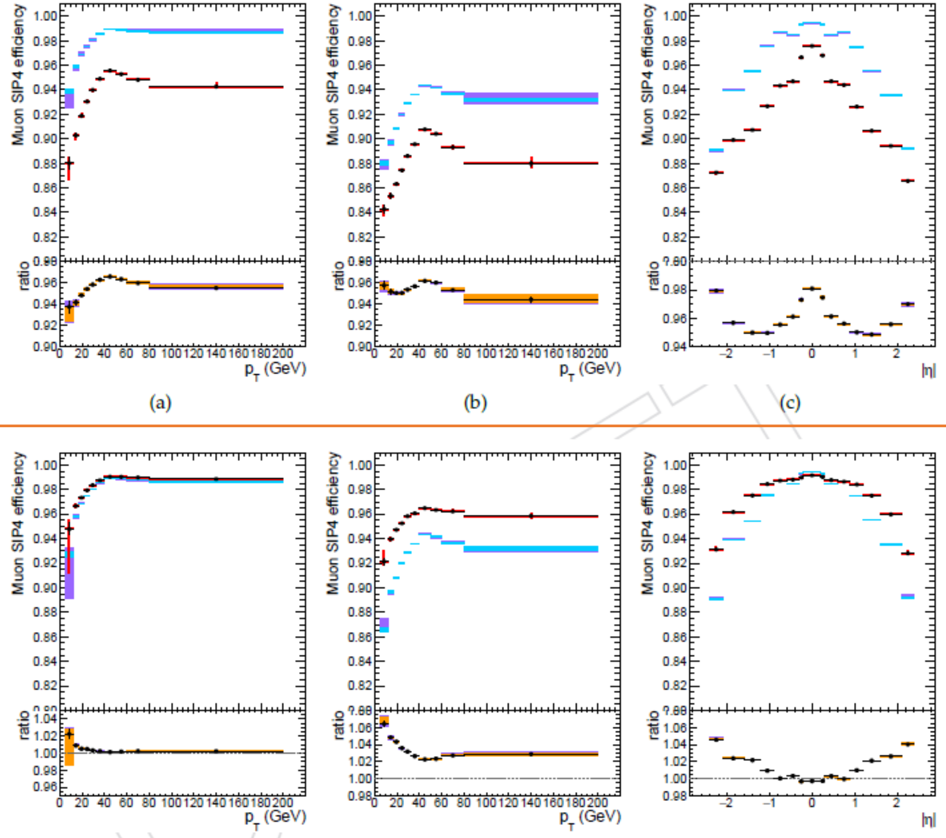
postEE SFs

Muon SFs

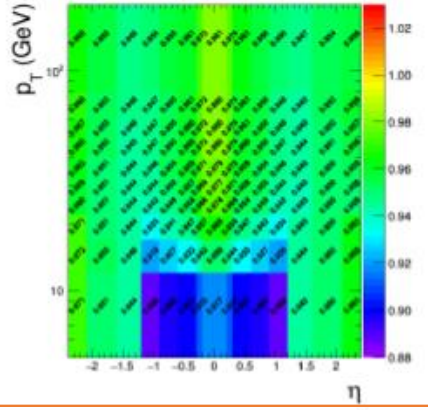
Muon Efficiencies are measured under LooseID, SIP, ISO cuts with tag-and-probe method, and finally combined as the SFs.

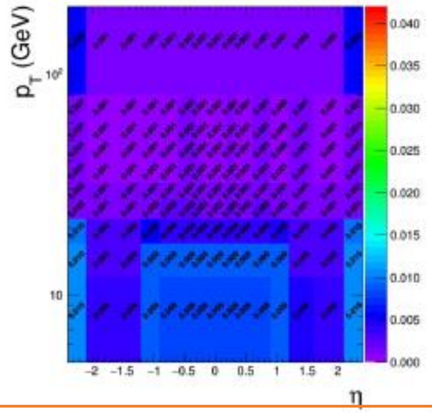
PreEE

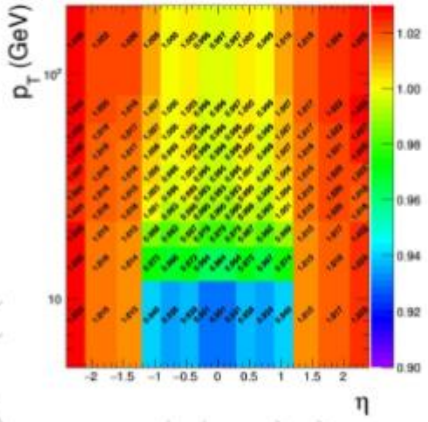
PostEE

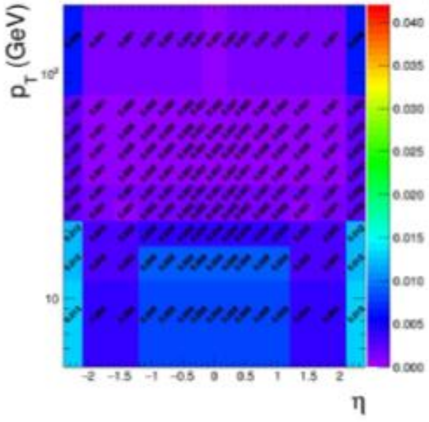


(a) (b) (c)
(d) (e) (f)









Event Selection

- Z Candidates:

  any OS-SF lepton pairs with 12 GeV<m_ll<120GeV

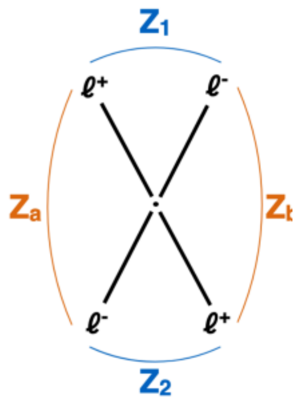
- ZZ Candidates:

  a) Build all possible ZZ pair

  b)m_Z1>40GeV, leading Lep_pT>20GeV, sub leading Lep_pT>10GeV, ΔR(l,l)>0.02

  c)For each OS pair, m_ll>4GeV(QCD rejection)

  d)For 4e/4mu events, reject |mZa – mZ| <|mZ1 mZ| AND mZb < 12GeV).



Unfolding

Fiducial Space

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_T	$p_T > 20$ GeV
next-to-leading lepton p_T	$p_T > 10$ GeV
additional electrons (muons) p_T	$p_T > 7(5)$ GeV
pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$
p_T sum of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_T$
Event topology	
existence of at least two same flavour opposite sign lepton pairs, where the leptons satisfy criteria above	
inv. mass of the Z_1 candidate	$40\,\text{GeV} < m(Z_1) < 120\,\text{GeV}$
inv. mass of the Z_2 candidate	$12\,\text{GeV} < m(Z_2) < 120\,\text{GeV}$
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$m(\ell^+ \ell'^-) > 4\,\text{GeV}$
inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 160\,\text{GeV}$
the selected four leptons must originate from the $H \to 4\ell$ decay	

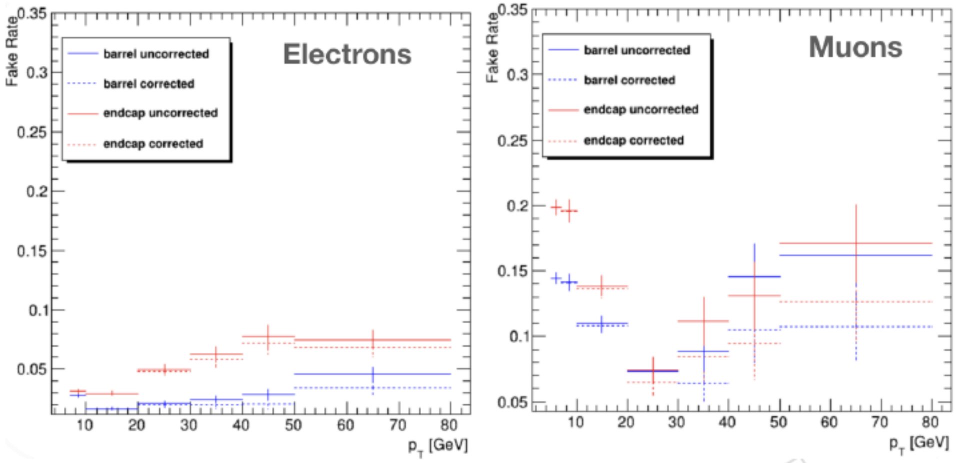
Fiducial phase space defined at gen-level to match closely the experimental selections at reco-level to ensure model-independency of the measurement and easy re-interpretability.

BKG estimation

In our selection, two main kinds of bkg process should be taken into account.

1) Irreducible bkg with 4 prompt lepton: qqZZ4l, ggZZ4l, MC well simulated
2) Reducible bkg by the misidentification of non-prompt leptons: Z+X, using Data Driven method.

Fake rate measurement:
Z+1L CR requires 2 tight OSSF lepton, and an additional loose lepton. We can count how many prompt in this CR to get Fake Rates.



Fake rate in 2022 preEE

Estimation:
For 2P2F and 3P1F CR in Z+X, once we know the probability for a “fake” lepton identified as a prompt lepton, we can evaluate how many Z+X evts in SR according to CR yields and fake rates.

$$N_{SR} = (fr_2/(1-fr_2))N_{3P1F} - (fr_1/(1-fr_1))*(fr_2/(1-fr_2))N_{2P2F}$$

Channel	4μ	$4e$	$2e2\mu$	$2\mu 2e$
OS	10.88 ± 3.96	3.89 ± 1.31	7.38 ± 2.88	4.66 ± 1.53
SS	$8.41^{+2.75}_{-2.77}$	$3.01^{+1.36}_{-1.52}$	$6.32^{+2.06}_{-2.08}$	$3.57^{+1.62}_{-1.82}$
Combination	9.19	3.47	6.67	4.15
OS/SS	1.165 ± 0.071	1.030 ± 0.028	0.966 ± 0.079	1.041 ± 0.026

2022 preEE Z+X yield in SR

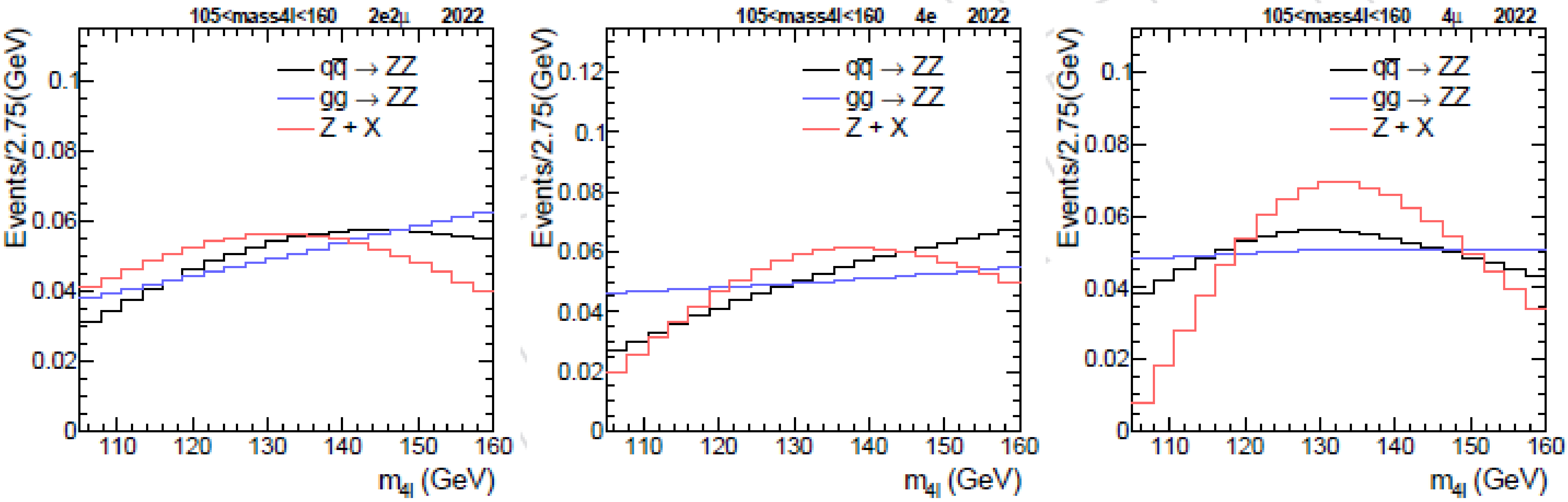
Channel	4μ	$4e$	$2e2\mu$	$2\mu 2e$
OS	22.23 ± 7.42	10.40 ± 3.24	19.80 ± 6.57	9.97 ± 3.11
SS	$21.49^{+6.66}_{-6.67}$	$9.29^{+3.70}_{-3.95}$	$17.69^{+5.48}_{-5.49}$	$11.57^{+4.60}_{-4.91}$
Combination	21.82	9.92	18.56	10.47
OS/SS	0.997 ± 0.039	0.990 ± 0.017	1.039 ± 0.043	1.016 ± 0.016

2022 postEE Z+X yield in SR

BKG Modeling

Both kind of Bkg can be fitted with the histogram template of reconstructed mass4l.

1) **Irreducible bkg qqZZ4l, ggZZ4l extracted this shape from MC simulation**
2) **Reducible bkg Z+X is filled from the reweighted distribution from CR**



qqZZ was generated in NLO, but the diff. XS was computed as NNLO. (Consider for both EW & QCD)
The NNLO/NLO k-factors are applied for qqZZ as a part of the event weight.

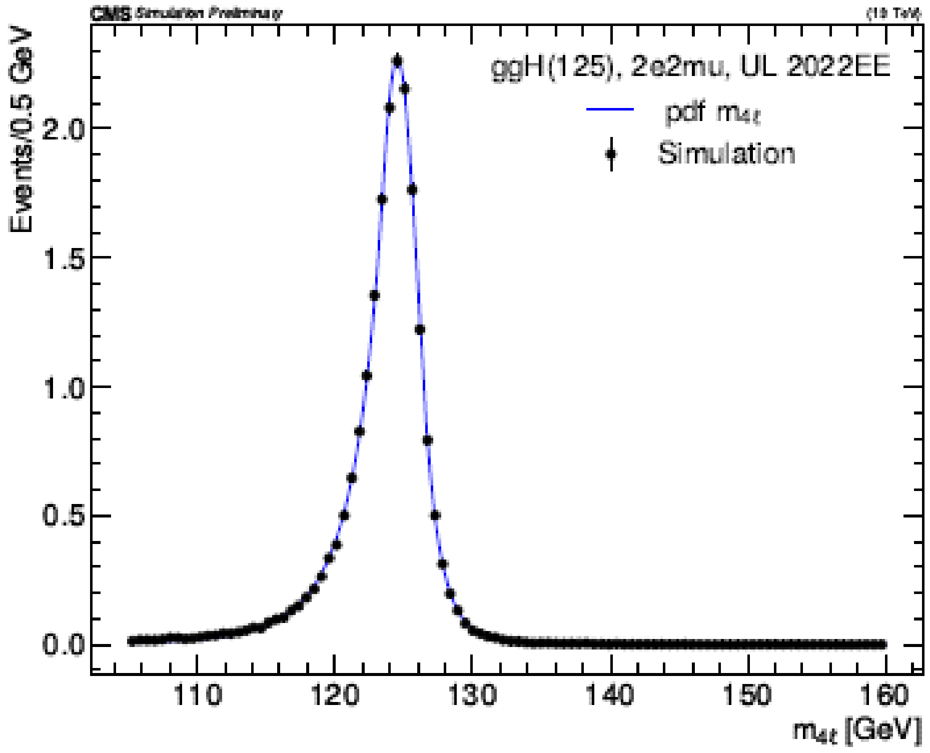
Similarly, ggZZ can only be generated in LO, so the NNLO/LO or NNLO/LO k-factors should applied for ggZZ as a part of the event weight.

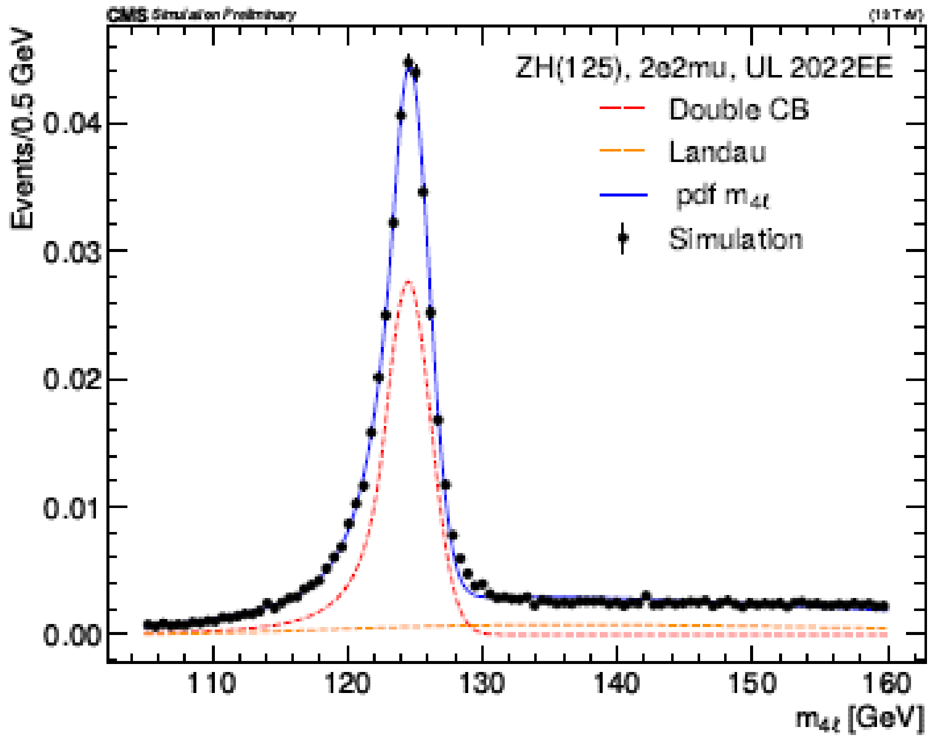
Signal Modeling

Signal of resonance 4l can be fitted with Double CB functions, where a set of parameters can be determined. Meanwhile, the non-resonance (VH, ttH) 4l will be described by Landau shape.

$$\mathcal{P}_{res}(m_{4\ell}|m_H) = N \cdot \begin{cases} A \cdot (B + \mid \xi \mid)^{-n_L} & \text{if } \xi < \alpha_L \\ \exp(-\xi^2/2) & \text{if } \alpha_L \leq \xi \alpha_R \\ A \cdot (B + \mid \xi \mid)^{-n_R} & \text{if } \xi > \alpha_R \end{cases}$$

$$\xi = (m_{4\ell} - m_H - \Delta m_H)/\sigma_m$$



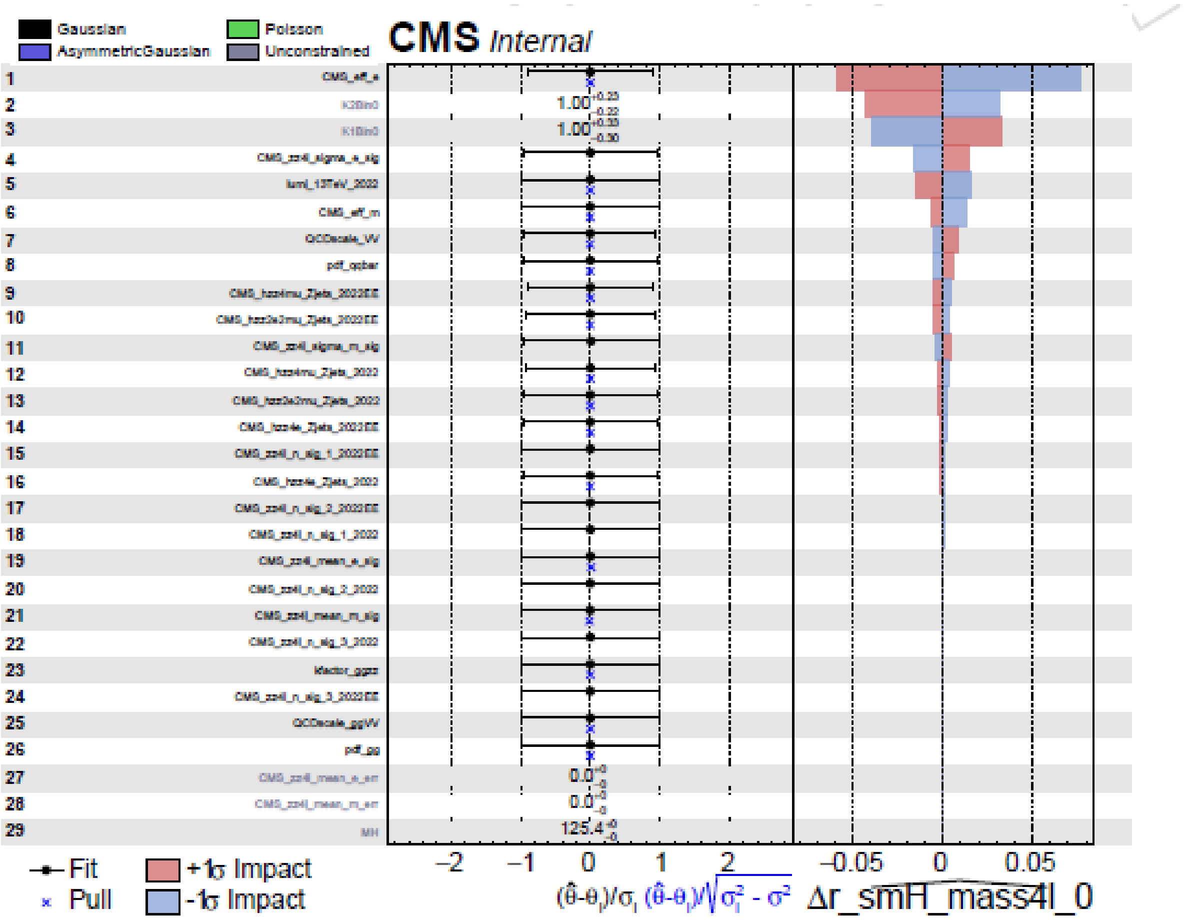


Systematic Uncertainties

Systematic Uncertainties can be traced from experimental source and theoretical source.

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	1.4 %
Lepton id/reco efficiencies	0.8 – 16.8 %
Background related uncertainties	
Reducible background (Z+X)	25 – 45 %
Signal related uncertainties	
Lepton energy scale	0.05 %(μ) - 0.2 %(e)
Lepton energy resolution	5 %(μ) - 12 %(e)

Summary of inclusive theory uncertainties	
QCD scale (gg)	$\pm$ 3.9 %
PDF set (gg)	$\pm$ 3.2 %
$gg \to ZZ$ k-factor (gg)	$\pm$ 10 %
QCD scale ($q\bar{q} \to ZZ$)	+3.2/-4.2 % %
PDF set ($q\bar{q} \to ZZ$)	+3.1/-3.4 %
Electroweak corrections ($q\bar{q} \to ZZ$)	$\pm$ 0.1 %

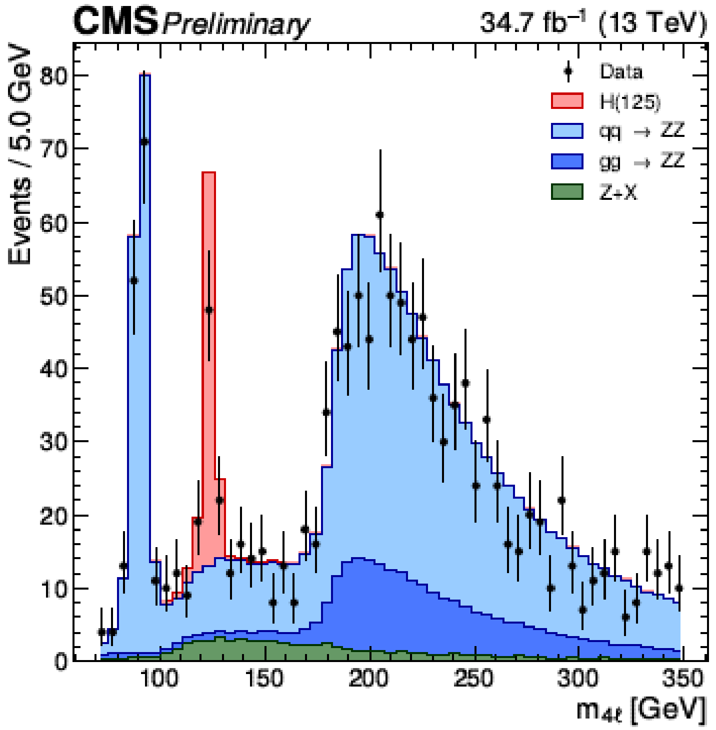


Electron Efficiency is the most relevant!

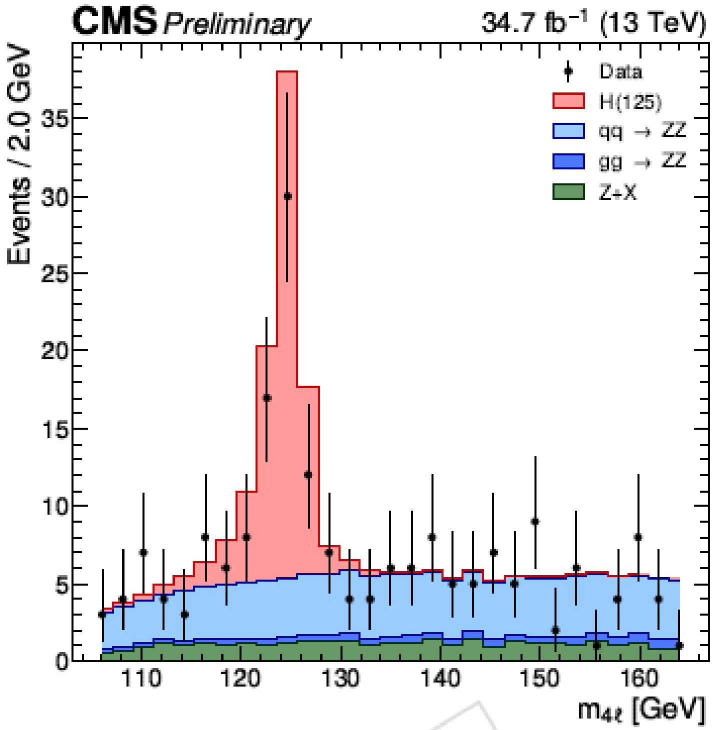
Yields in SR(Pre-fit)

Channel	4μ	$4e$	$2e2\mu$	$4l$
qqZZ	379.62	209.12	504.43	1093.18
ggZZ	71.93	46.47	110.33	228.72
ZX	33.97	13.77	42.31	90.04
Sum backgrounds	485.52	269.36	657.07	1412
Signal (m_H =125 GeV)	27.05	12.91	33.56	73.52
Total expected	512.57	282.26	690.63	1485
Data	506	277	674	1457

Channel	4μ	$4e$	$2e2\mu$	$4l$
qqZZ	33.28	13.1	38.49	84.86
ggZZ	3.92	1.86	3.92	9.7
ZX	15.77	4.25	16.74	36.76
Sum backgrounds	52.97	19.22	59.15	131
Signal (m_H =125 GeV)	25.28	11.69	30.87	67.84
Total expected	78.25	30.9	90.02	199
Data	59	32	93	184

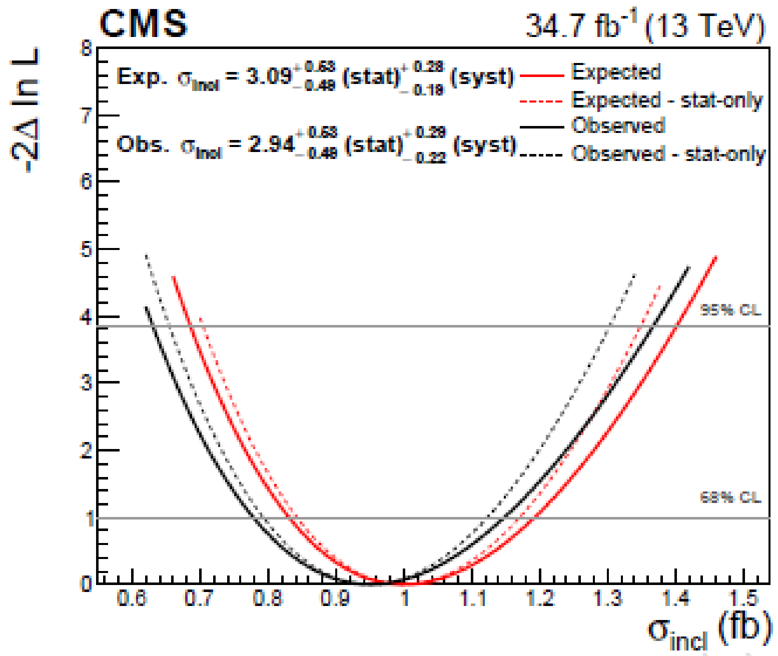


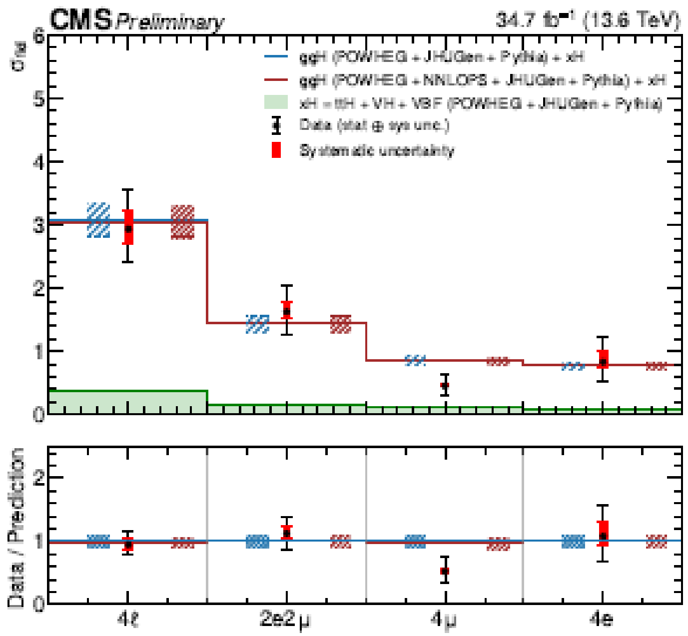
m_4l>70GeV

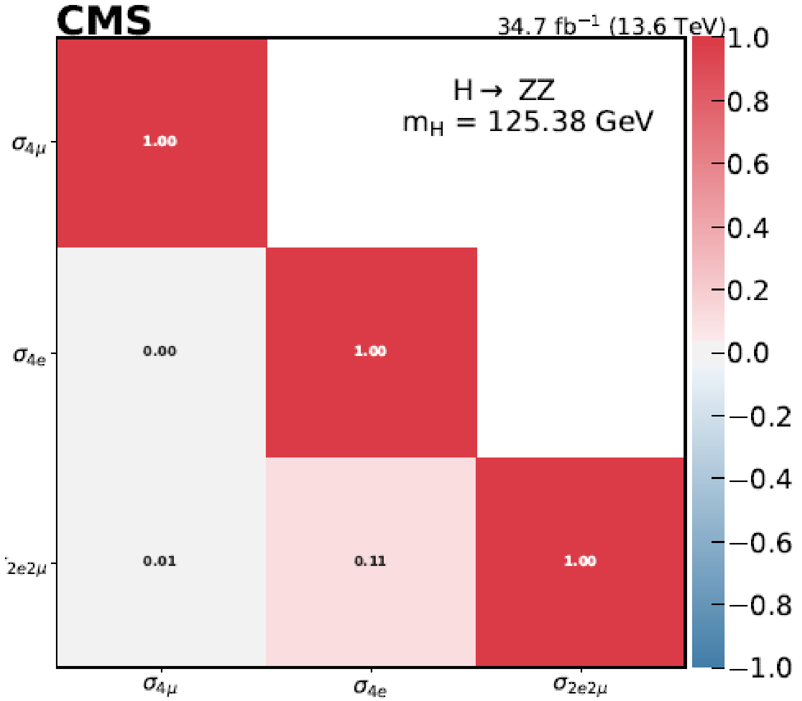


105GeV<m_4l<160GeV

Final Results



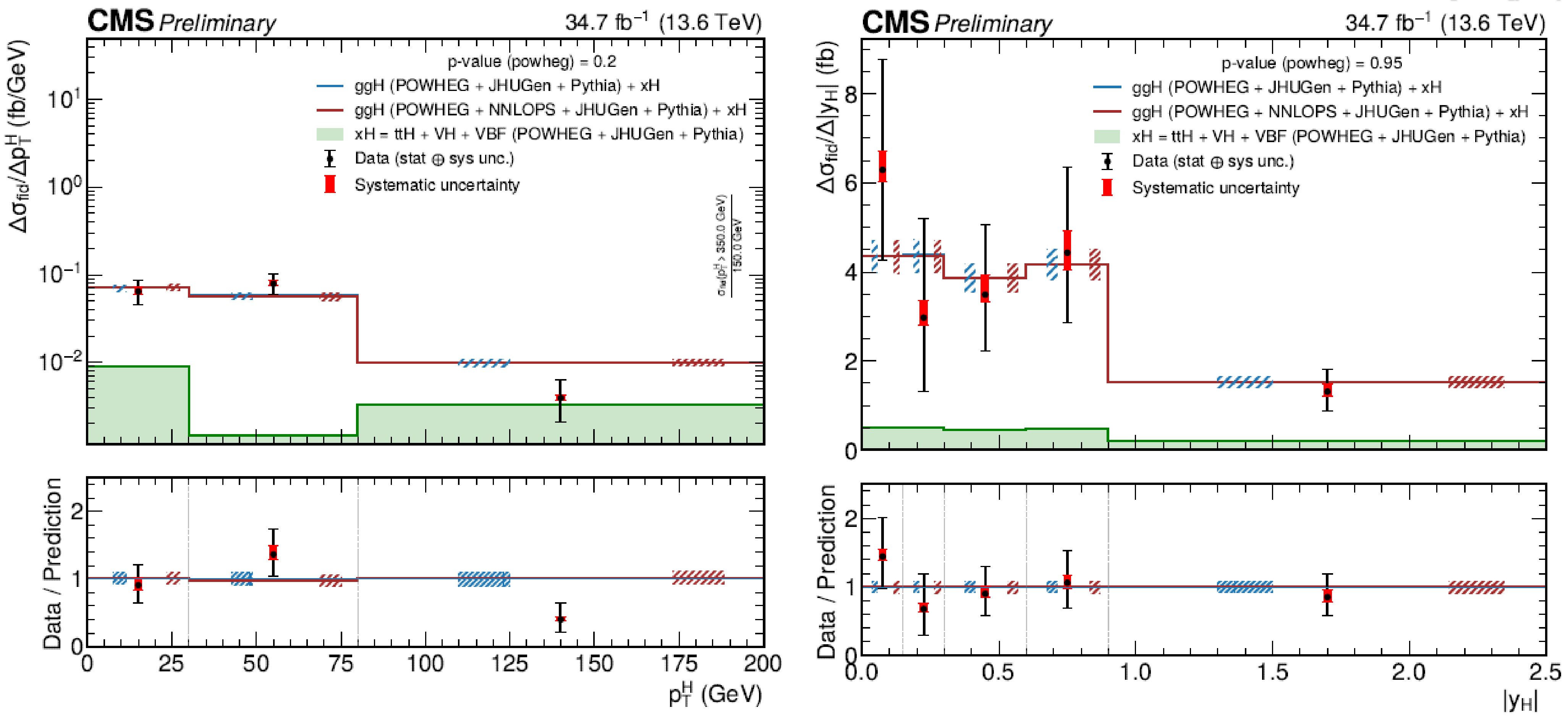




Inclusive fiducial XS fitting result, and the x-axis of the left plots is represented by signal strength. The uncertainy of XS can be extracted by 1-d likehood scanning.

Correlation of different final states.

Final Results



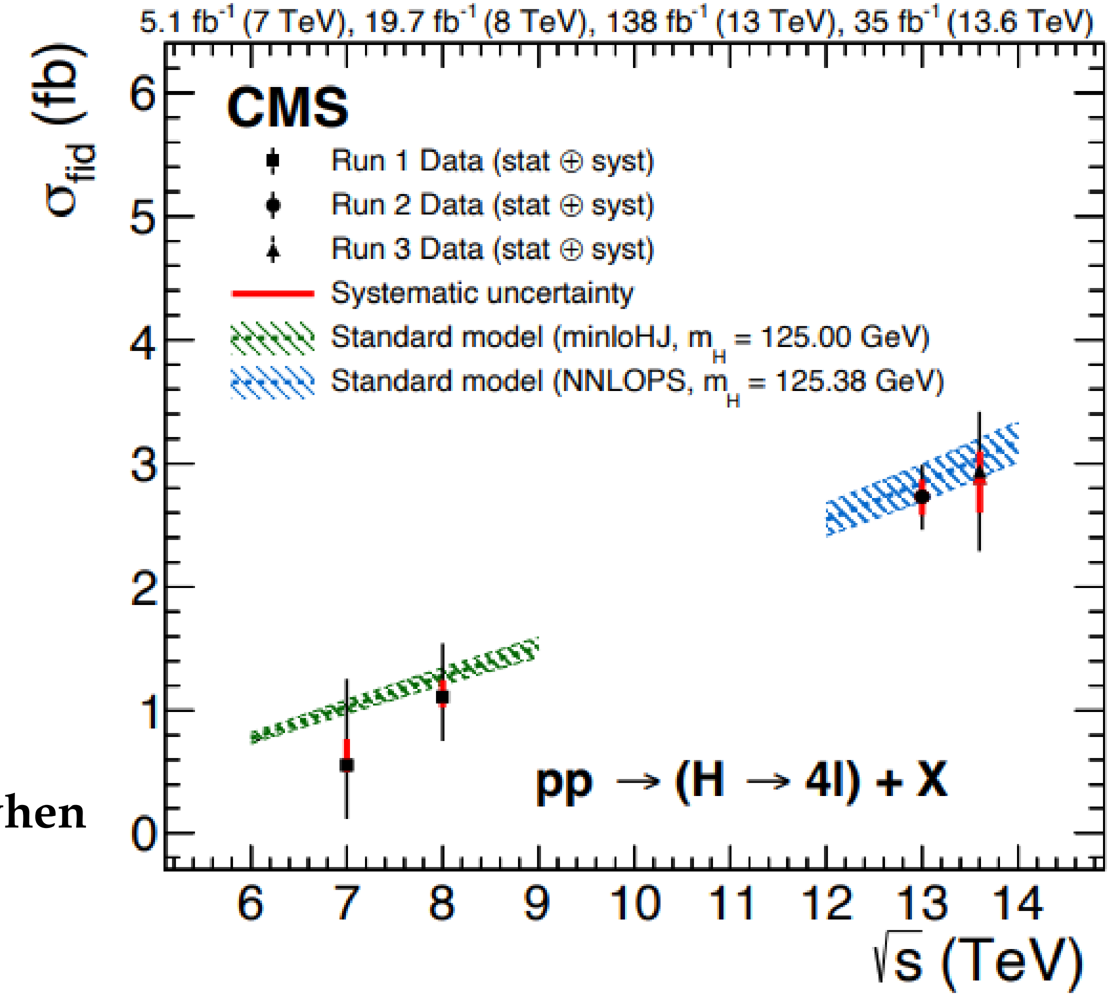
Different XS for Higgs Production could be measured as a function of transverse momentum and rapidity.

Summary

- Same analysis strategy as Run2 is performed.
- The performace of electron and muon are well measured in Run3 2022 data.
- Fiducial XS are measured with unbinned max-likelihood method, and the result is:

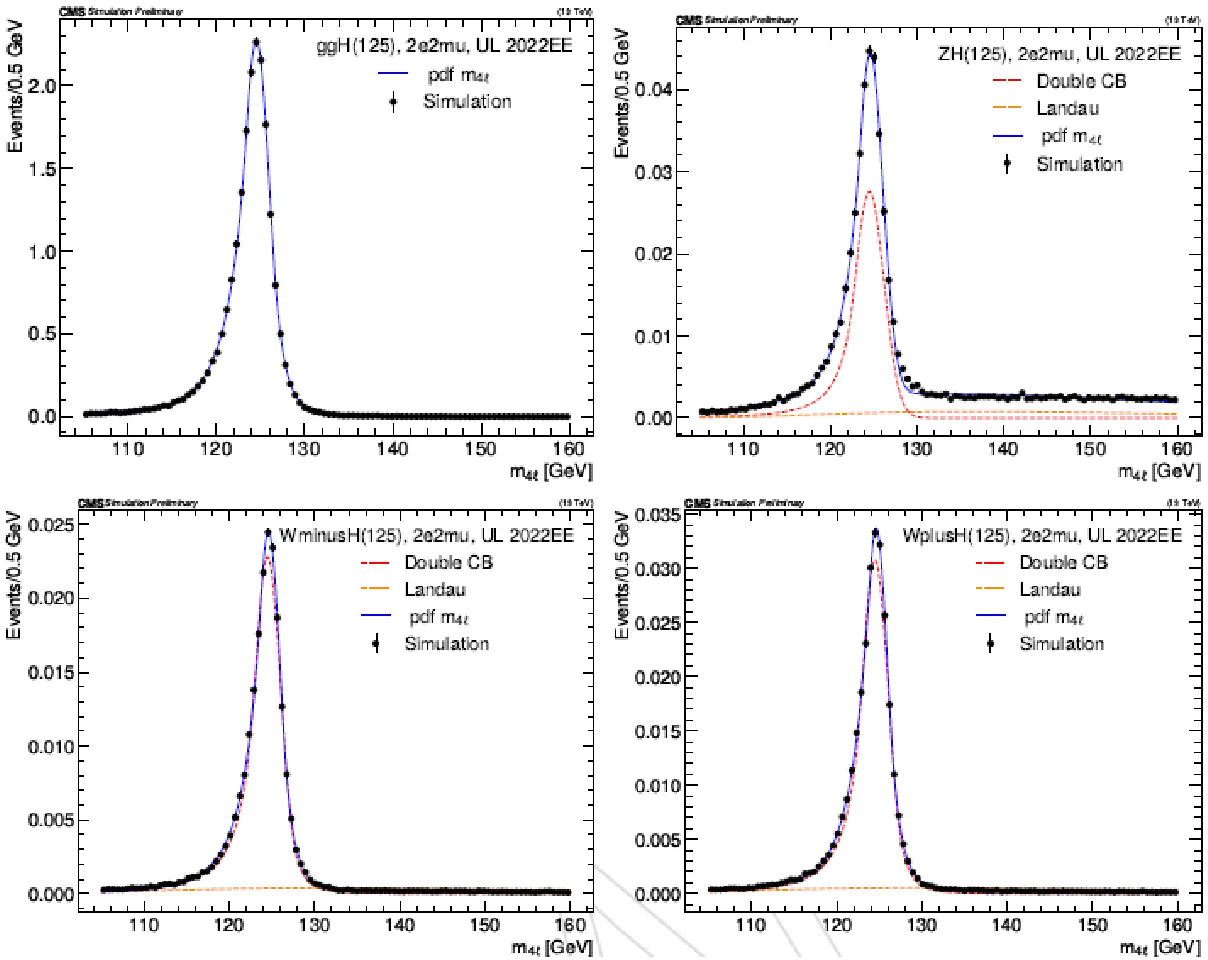
$$\sigma_{\text{fid}} = 2.94^{+0.53}_{-0.49}\ (\text{stat.})^{+0.29}_{-0.22}\ (\text{syst.})\ \text{fb}$$

- Comparing with Run1 and Run2 results, they are corresponding with SM predictions.
- Differential XS can also be measured with this framework, whichwill bring more information when we have more statistics in Run3.(2022-2025)



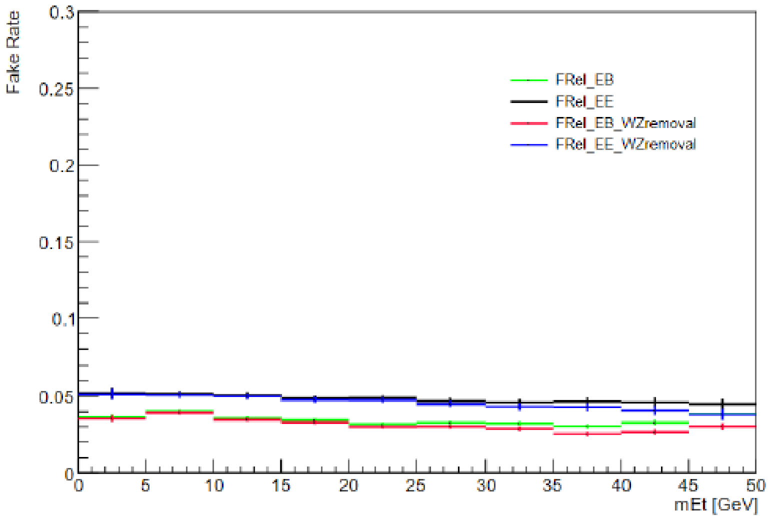
Thanks!

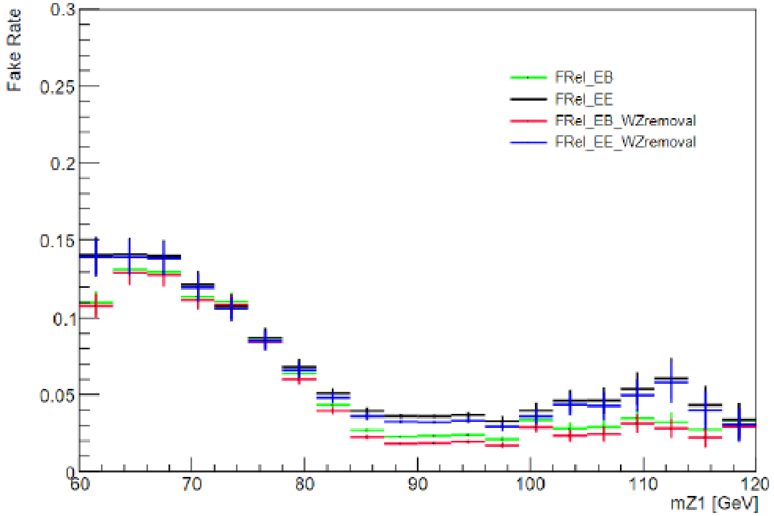
Backup

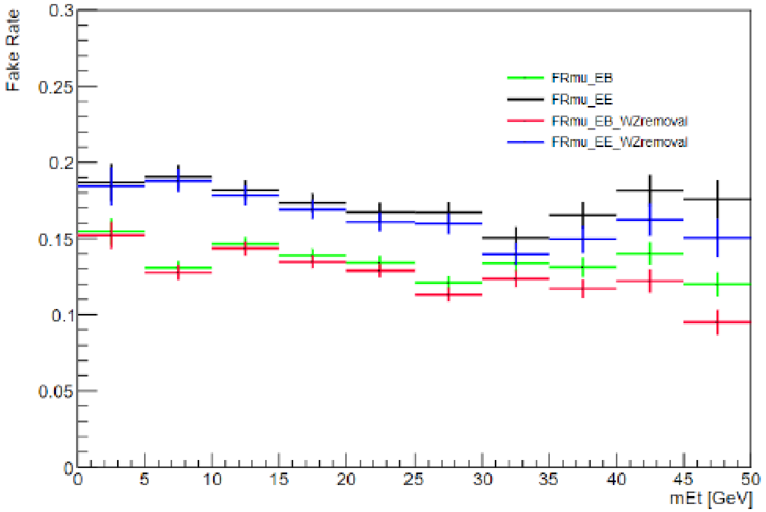


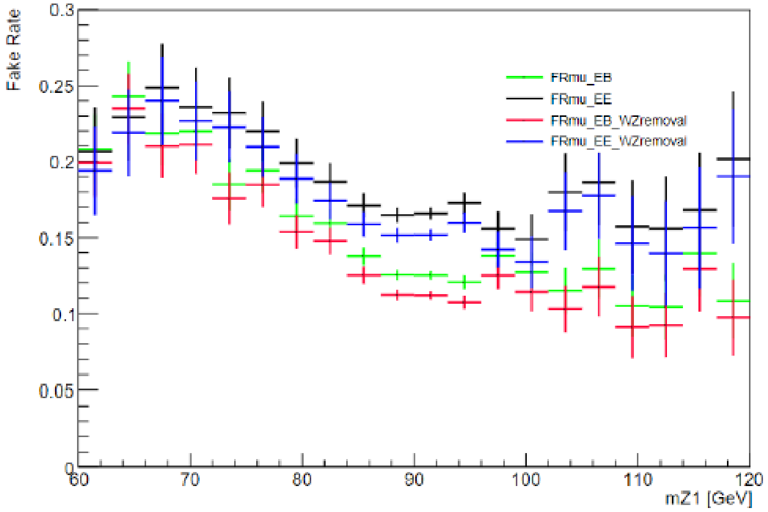
CMS Simulation Preliminary
ggH(125), 2e2mu, UL 2022EE
pdf m4ℓ
Simulation
Events/0.5 GeV
m4ℓ [GeV]
ZH(125), 2e2mu, UL 2022EE
Double CB
Landau
pdf m4ℓ
Simulation
WminusH(125), 2e2mu, UL 2022EE
Double CB
Landau
pdf m4ℓ
Simulation
WplusH(125), 2e2mu, UL 2022EE
Double CB
Landau
pdf m4ℓ
Simulation

Fake rates

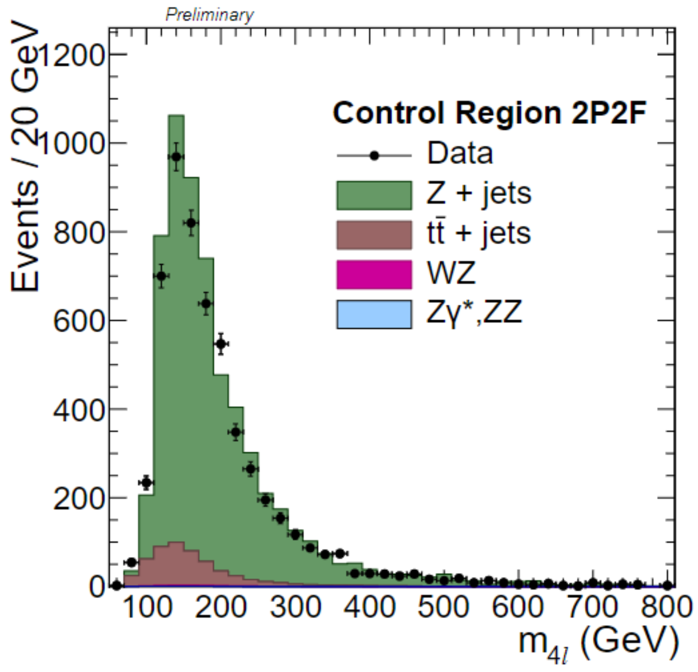

Fake Rate
FRel_EB
FRel_EE
FRel_EB_WZremoval
FRel_EE_WZremoval
mEt [GeV]


Fake Rate
FRel_EB
FRel_EE
FRel_EB_WZremoval
FRel_EE_WZremoval
mZ1 [GeV]

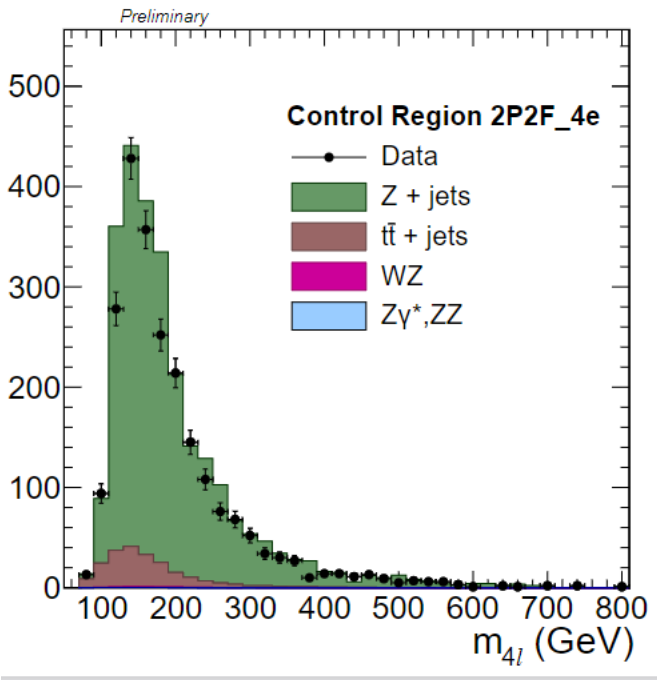

Fake Rate
FRmu_EB
FRmu_EE
FRmu_EB_WZremoval
FRmu_EE_WZremoval
mEt [GeV]


Fake Rate
FRmu_EB
FRmu_EE
FRmu_EB_WZremoval
FRmu_EE_WZremoval
mZ1 [GeV]

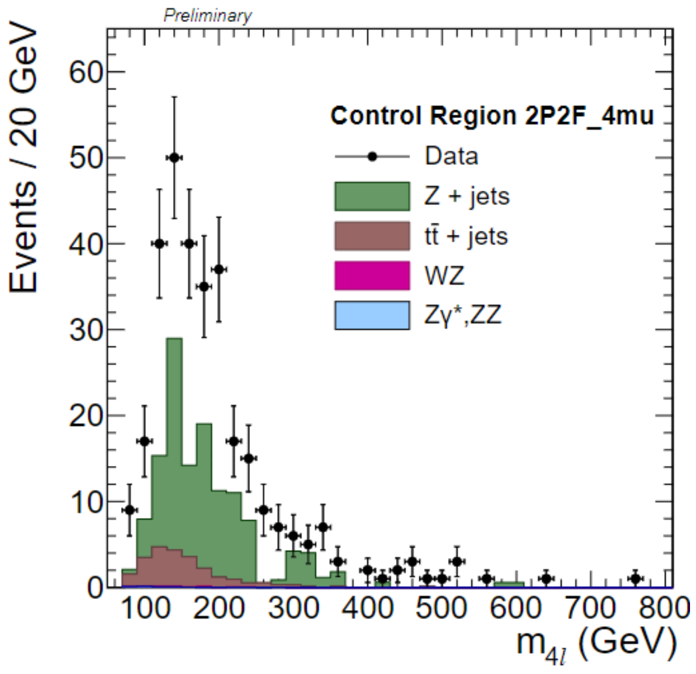
ZXCR plots



Preliminary
Control Region 2P2F
Data
Z + jets
$t\bar{t}$ + jets
WZ
Zγ*,ZZ
Events / 20 GeV
0
200
400
600
800
1000
1200
100 200 300 400 500 600 700 800
m_{4l} (GeV)



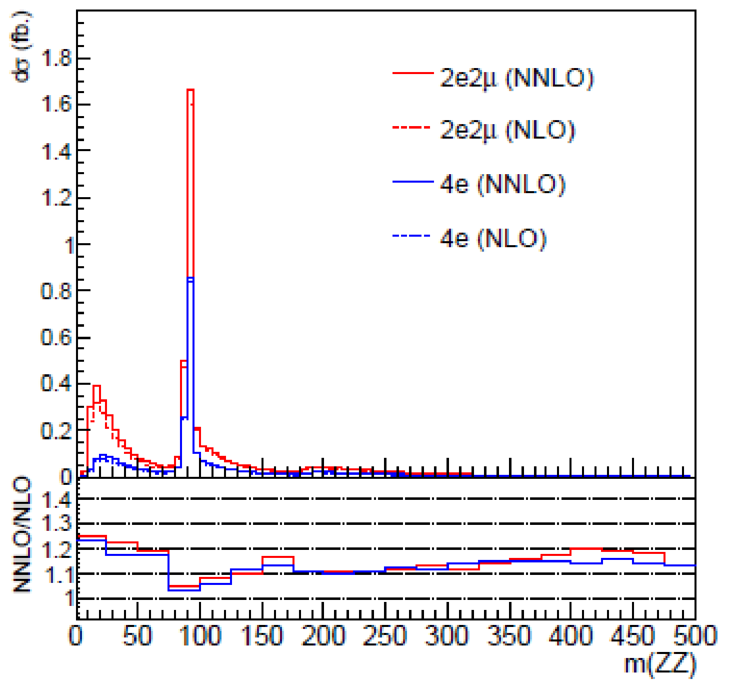
Preliminary
Control Region 2P2F_4e
Data
Z + jets
$t\bar{t}$ + jets
WZ
Zγ*,ZZ
0
100
200
300
400
500
100 200 300 400 500 600 700 800
m_{4l} (GeV)

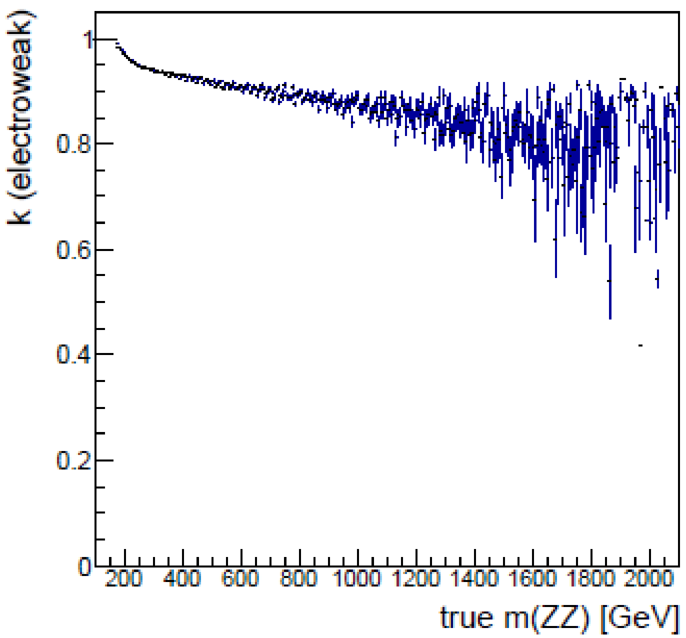


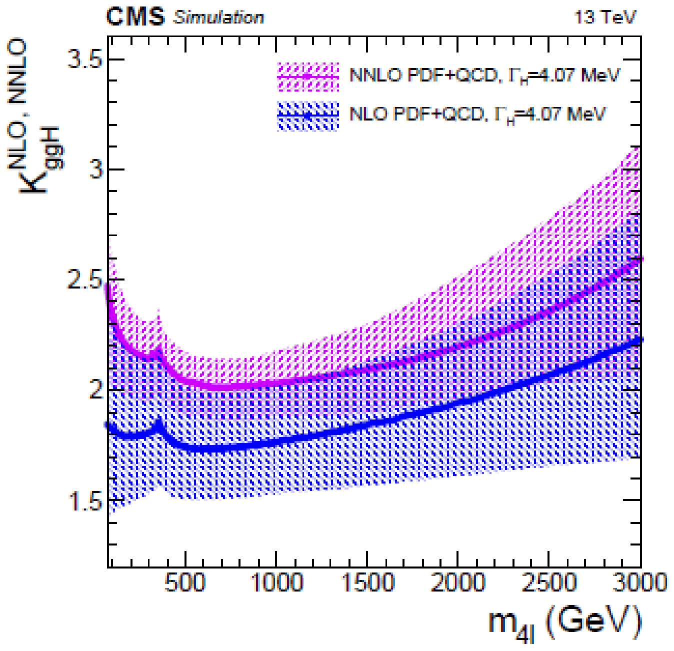
Preliminary
Control Region 2P2F_4mu
Data
Z + jets
$t\bar{t}$ + jets
WZ
Zγ*,ZZ
Events / 20 GeV
0
10
20
30
40
50
60
100 200 300 400 500 600 700 800
m_{4l} (GeV)

BKG estimation

qqZZ was generated in NLO, but the diff. XS was computed as NNLO. (Consider for both EW & QCD)
The NNLO/NLO k-factors are applied for qqZZ as a part of the event weight.

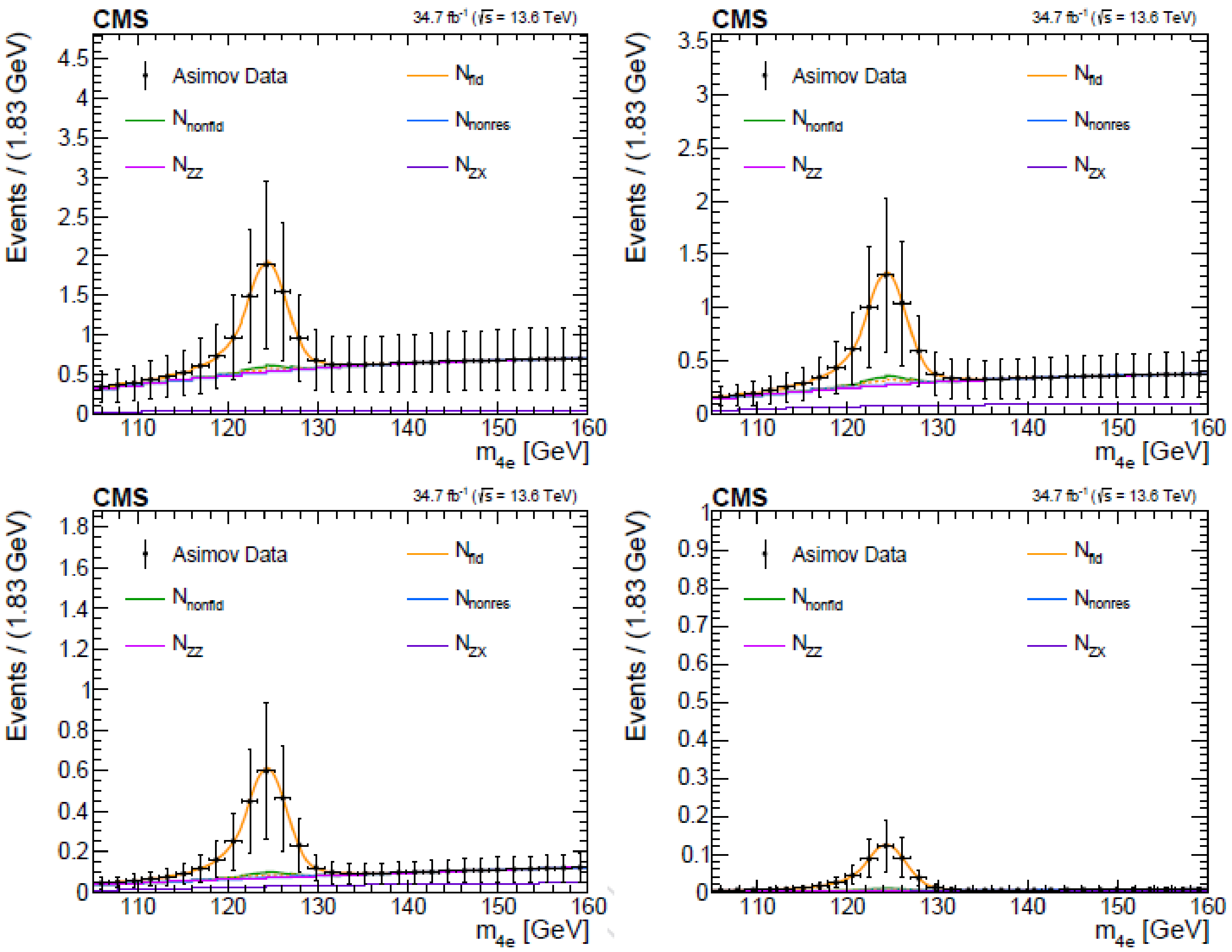




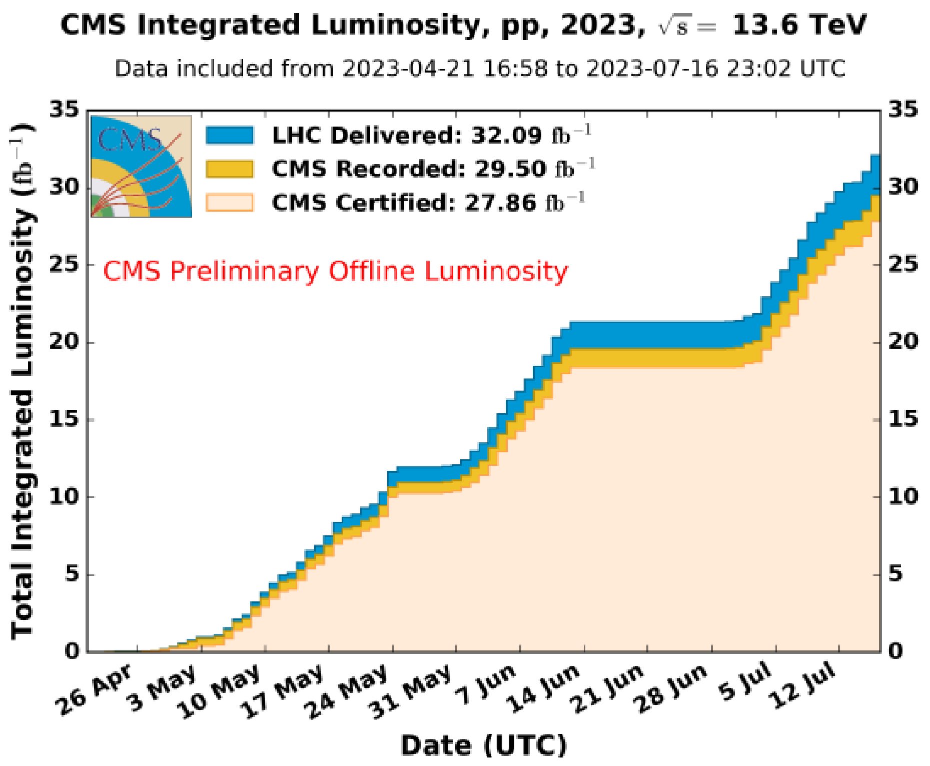


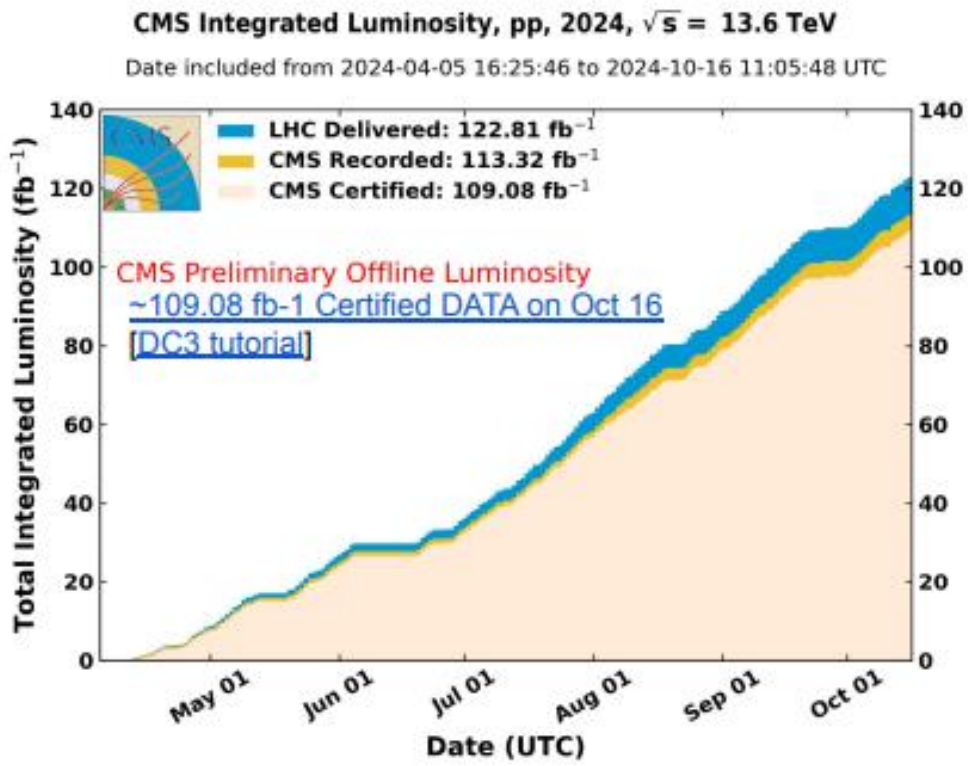
Similarly, ggZZ can only be generated in LO, so the NNLO/LO or NNLO/LO k-factors should applied for ggZZ as a part of the event weight.

Simutanous fits



CMS Lumi


CMS Integrated Luminosity, pp, 2023, √s = 13.6 TeV
Data included from 2023-04-21 16:58 to 2023-07-16 23:02 UTC
LHC Delivered: 32.09 fb⁻¹
CMS Recorded: 29.50 fb⁻¹
CMS Certified: 27.86 fb⁻¹
CMS Preliminary Offline Luminosity
Total Integrated Luminosity (fb⁻¹)
Date (UTC)
26 Apr
3 May
10 May
17 May
24 May
31 May
7 Jun
14 Jun
21 Jun
28 Jun
5 Jul
12 Jul


CMS Integrated Luminosity, pp, 2024, √s = 13.6 TeV
Date included from 2024-04-05 16:25:46 to 2024-10-16 11:05:48 UTC
LHC Delivered: 122.81 fb⁻¹
CMS Recorded: 113.32 fb⁻¹
CMS Certified: 109.08 fb⁻¹
CMS Preliminary Offline Luminosity
~109.08 fb-1 Certified DATA on Oct 16
[DC3 tutorial]
Total Integrated Luminosity (fb⁻¹)
Date (UTC)
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Oct 01

Dataset and MC Samples

Primary Dataset	DAS Path	Runs	Luminosity
SingleMu2022C	/SingleMuon/Run2022C-22Sep2023-v1/NANOAOD		
DoubleMu2022C	/DoubleMuon/Run2022C-22Sep2023-v1/NANOAOD		
Muon2022C	/Muon/Run2022C-22Sep2023-v1/NANOAOD	355862 - 357482	6.3 fb^{-1}
MuonEG2022C	/MuonEG/Run2022C-22Sep2023-v1/NANOAOD		
EGamma2022C	/EGamma/Run2022C-22Sep2023-v1/NANOAOD		
Muon2022D	/Muon/Run2022D-22Sep2023-v1/NANOAOD		
MuonEG2022D	/MuonEG/Run2022D-22Sep2023-v1/NANOAOD	357538 - 357900	3.3 fb^{-1}
EGamma2022D	/EGamma/Run2022D-22Sep2023-v1/NANOAOD		
Muon2022E	/Muon/Run2022E-22Sep2023-v1/NANOAOD		
MuonEG2022E	/MuonEG/Run2022E-22Sep2023-v1/NANOAOD	359356 - 360327	6.1 fb^{-1}
EGamma2022E	/EGamma/Run2022E-22Sep2023-v1/NANOAOD		
Muon2022F	/Muon/Run2022F-22Sep2023-v2/NANOAOD		
MuonEG2022F	/MuonEG/Run2022F-22Sep2023-v1/NANOAOD	360335 - 362167	18.4 fb^{-1}
EGamma2022F	/EGamma/Run2022F-22Sep2023-v1/NANOAOD		
Muon2022G	/Muon/Run2022G-22Sep2023-v1/NANOAOD		
MuonEG2022G	/MuonEG/Run2022G-22Sep2023-v1/NANOAOD	362353 - 362760	3.2 fb^{-1}
EGamma2022G	/EGamma/Run2022G-22Sep2023-v2/NANOAOD		

Flag	HLT Paths
passSingleEle	HLT_Ele30_WPTight_Gsf
passSingleMu	HLT_IsoMu24
passDiEle	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL HLT_DoubleEle25_CaloIdL_MW
passDiMu	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8
passMuEle	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ HLT_DiMu9_Ele9_CaloIdL_TrackIdL_DZ HLT_Mu8_DiEle12_CaloIdL_TrackIdL_DZ
passTriMu	HLT_TripleMu_10_5_5_DZ HLT_TripleMu_12_10_5

Process	MC Generator(s)	$\sigma \times$ BR ($\times \epsilon_{filter}$)
$gg \to H \to ZZ \to 4\ell$	Standard	14.34 fb
$qq \to Hqq \to ZZqq \to 4\ell qq$	Standard	1.12 fb
$q\bar{q} \to ZH \to ZZZ \to 4\ell + X$	POWHEG 2.0 (minlo HZJ)	0.775 fb
$q\bar{q} \to W^+H \to W^+ZZ \to 4\ell + X$	POWHEG 2.0 (minlo HWJ)	0.244 fb
$q\bar{q} \to W^-H \to W^-ZZ \to 4\ell + X$	POWHEG 2.0 (minlo HWJ)	0.156 fb
$gg \to ttH \to ttZZ \to 4\ell + X$	Standard	3.12 fb

Process	Dataset Name	$\sigma \cdot BR$
$qq \to ZZ \to 4\ell$	/ZZTo4L_TuneCP5_13p6TeV_powheg_pythia8/	1.39 pb
$gg \to ZZ \to 4e$	/GluGlutoContinto2Zto4E_TuneCP5_13p6TeV_mcfm-pythia8	0.003 pb
$gg \to ZZ \to 4\mu$	/GluGlutoContinto2Zto4Mu_TuneCP5_13p6TeV_mcfm-pythia8	0.003 pb
$gg \to ZZ \to 4\tau$	/GluGlutoContinto2Zto4Tau_TuneCP5_13p6TeV_mcfm-pythia8	0.003 pb
$gg \to ZZ \to 2e2^{-}$	/GluGlutoContinto2Zto2E2X_TuneCP5_13p6TeV_mcfm-pythia8	0.006 pb
$gg \to ZZ \to 2e2ø$	/GluGlutoContinto2Zto2E2X_TuneCP5_13p6TeV_mcfm-pythia8	0.006 pb
$Z \to \ell\ell$ + jets	DYJetsToLL_M-50_TuneCP5_13p6TeV-madgraphMLM-pythia8	5558.0 pb
$t\bar{t} \to 2\ell 2\nu$	TTto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8	762.1 pb
$WZ \to 3\ell\nu$	WZto3LNu_TuneCP5_13p6TeV_powheg-pythia8	4.924 pb