Dilepton forward-backward asymmetry and electroweak mixing angle

SNU Nuclear and Particle Physics Workshop

2023 Mar 30

Seoul National University

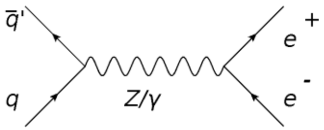
Hyon San Seo, Won Jun, Un-Ki Yang

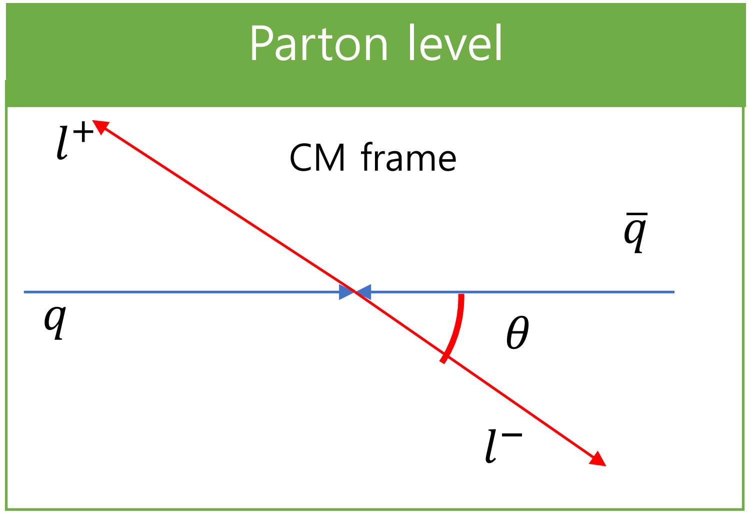
University of Rochester

Arie Bodek, Aleko Khukhunaishvili,
Rhys Taus, Evan Ranken

Forward-backward Asymmetry (AFB)

- Definition of A_{FB}





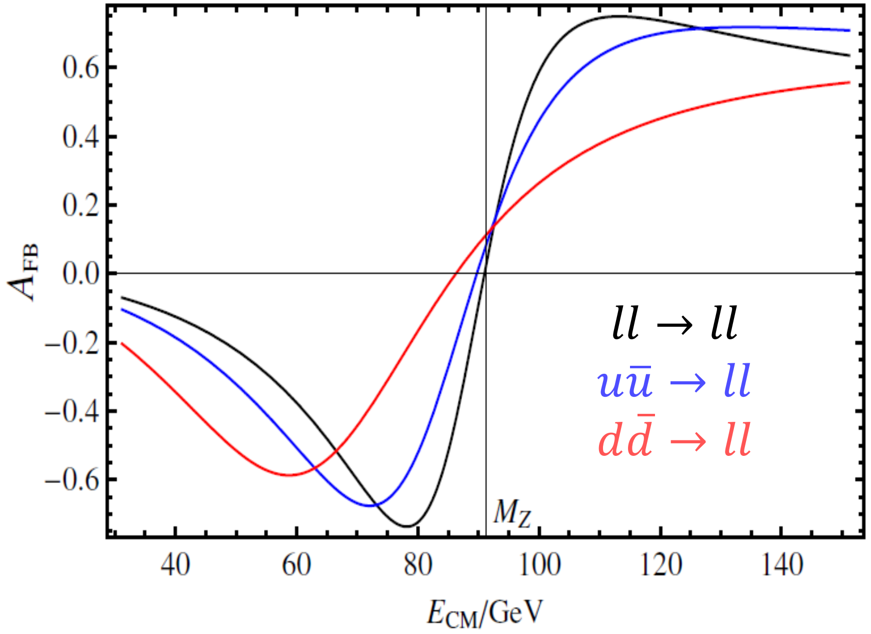
θ: Angle btw incoming and outgoing particles

$\cos\theta > 0$, forward event (F)

$\cos\theta < 0$, backward event (B)

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- A_{FB} as a function of mass

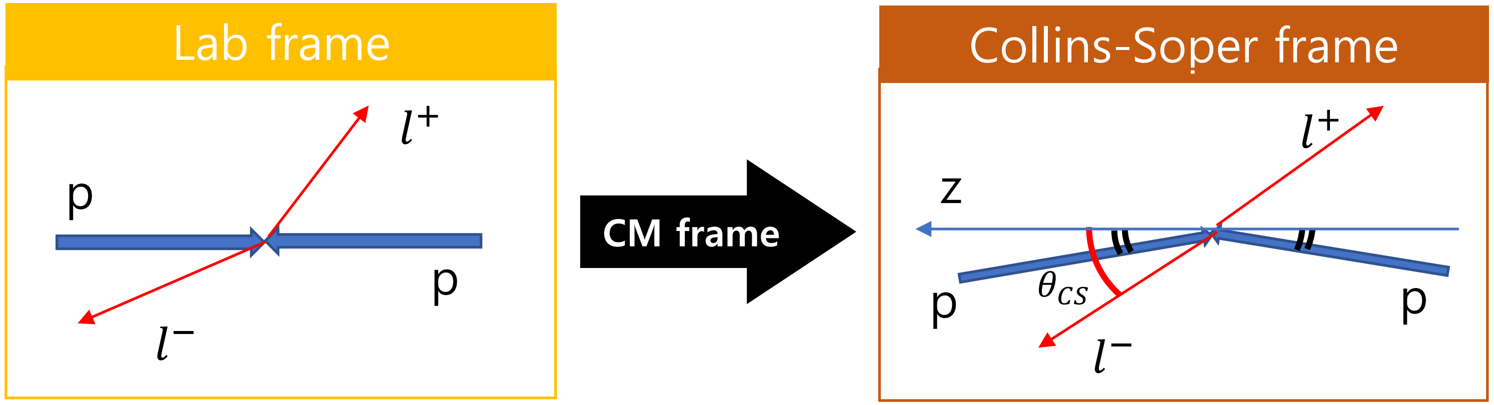


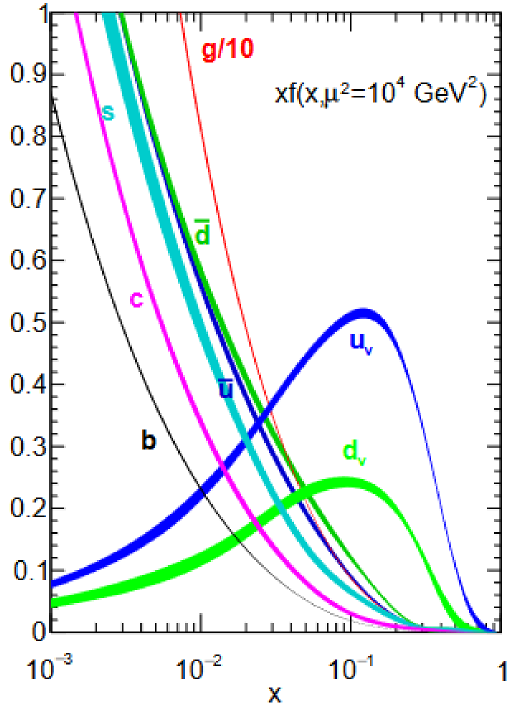
Mass dependence due to electroweak mixing

Forward-backward Asymmetry (AFB)

A_{FB} measurement in proton-proton collider

- How can we find incoming quark direction (not anti-quark) ?
  - Assume **quark** has **larger momentum** than anti-quark
  - Use **direction of Z boson**
- If there is ISR? → Use **Collins-Soper frame**



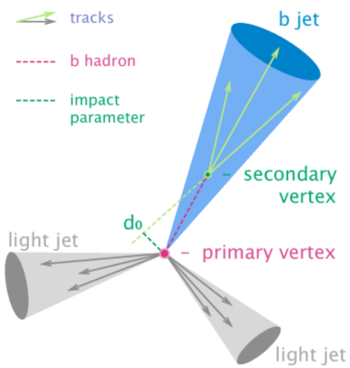


Analyses

- Differential A_{FB} with and without bjet
- $\sin^2\theta^l_{eff}$ measurement with inclusive DY events
- $\sin^2\theta^l_{eff}$ measurement with DY+bjet events

Differential A_{FB} with and without bjet

Measure A_{FB} itself for various kinematic regions
To find hint of new physics

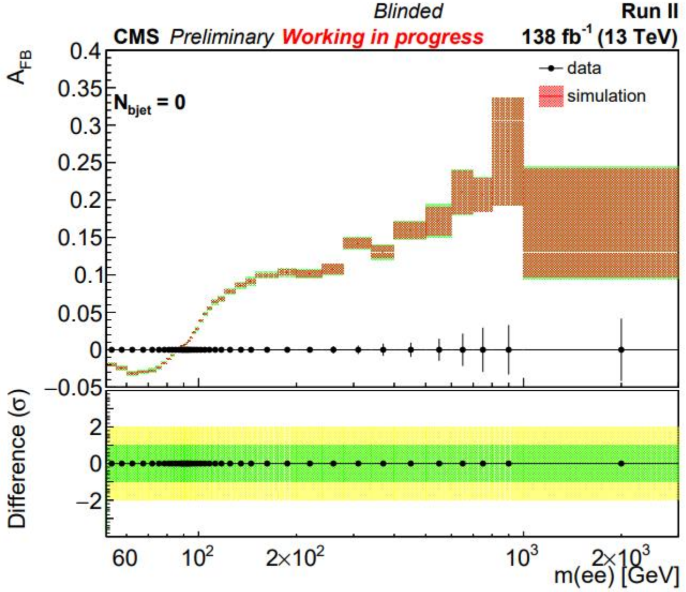


Without bjet

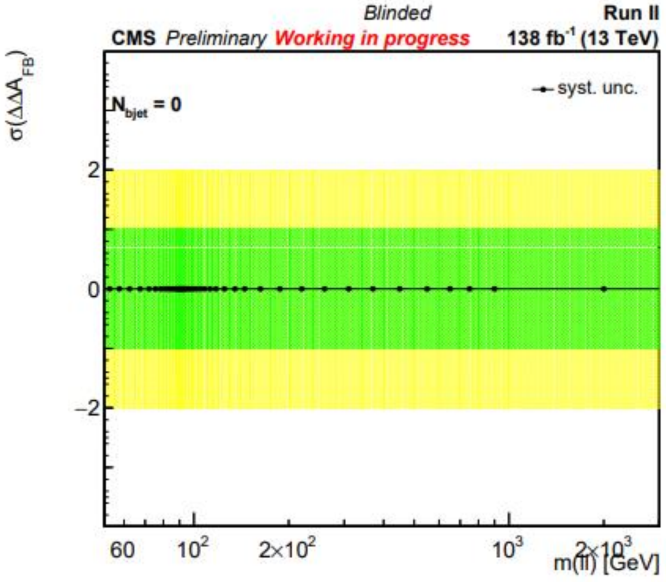
52<m<3000: $A_{FB}(m)$
52<m<77: $A_{FB}(y)$, $A_{FB}(p_T)$
77<m<106: $A_{FB}(y)$, $A_{FB}(p_T)$
106<m<280: $A_{FB}(y)$, $A_{FB}(p_T)$
280<m<3000: $A_{FB}(y)$, $A_{FB}(p_T)$

With bjet

52<m<3000: $A_{FB}(m)$
52<m<77: $A_{FB}(y)$, $A_{FB}(p_T)$
77<m<106: $A_{FB}(y)$, $A_{FB}(p_T)$
106<m<280: $A_{FB}(y)$, $A_{FB}(p_T)$
280<m<3000: $A_{FB}(y)$, $A_{FB}(p_T)$

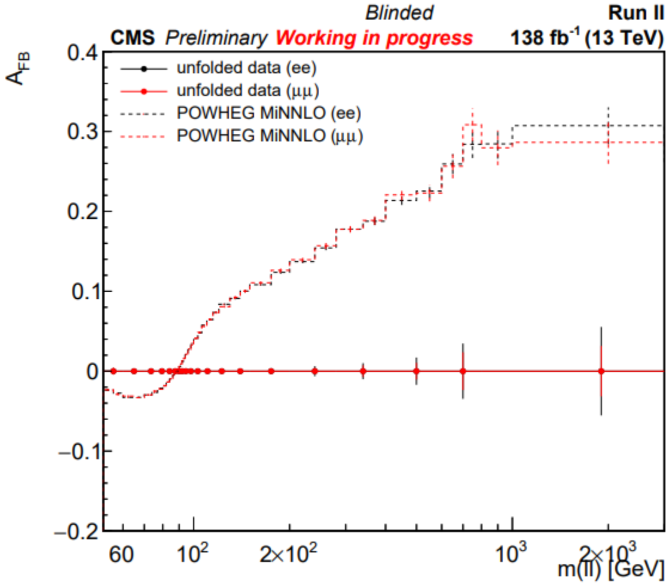


A_{FB} at detector level



Lepton universality check

$$\Delta\Delta A_{FB} = \left[A_{FB}^{data(\mu\mu)} - A_{FB}^{pred(\mu\mu)}\right] - \left[A_{FB}^{data(ee)} - A_{FB}^{pred(ee)}\right]$$

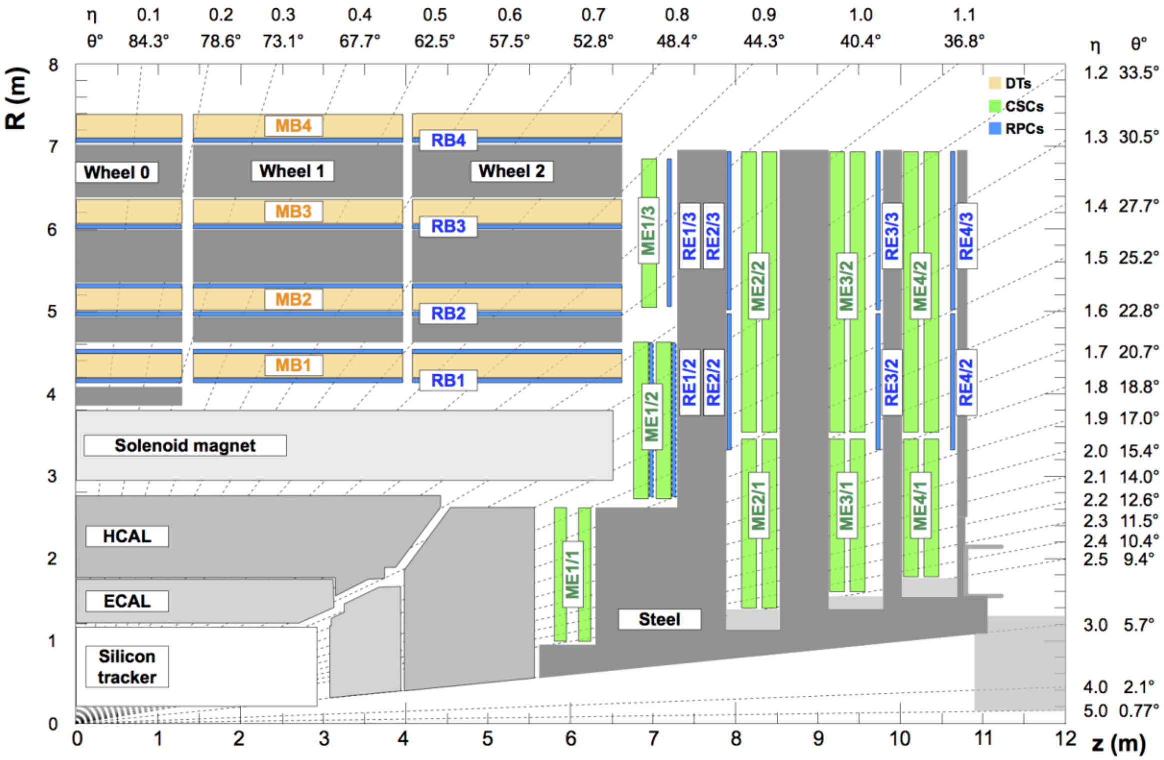


Unfolded A_{FB}

Event Selection

➢CMS full Run II data (138 fb^{-1})

	$\mu\mu$	ee
trigger	Double muon trigger (ϵ~0.87) with p_T > 17(8) GeV	Double e/γ trigger (ϵ~0.82) with p_T > 23(12) GeV
Lepton selection	Medium ID (ϵ~0.96) p_T > 20(10) GeV, |η| < 2.4	Medium ID (ϵ~0.79) p_T > 25(15) GeV, |η| < 2.5
Event selection	Opposite sign dilepton	
simulation	Drell-Yan (*POWHEG*) $t\bar{t}/tW$ (*POWHEG*) diboson (*PYTHIA8*) W (*MadGraph*) $\gamma\gamma \rightarrow ll$ (*PYTHIA8*)	
Corrections	✓ Lepton energy/momentum correction ✓ Charge-dependent ID/trigger efficiency SF ✓ Pileup reweight ✓ Trigger prefiring correction: for a trigger issue in CMS Run 2 ✓ Electron charge-flip (CF) SF ✓ Vertex Z reweight ✓ Z p_T reweight ✓ NLO weak k-factor	

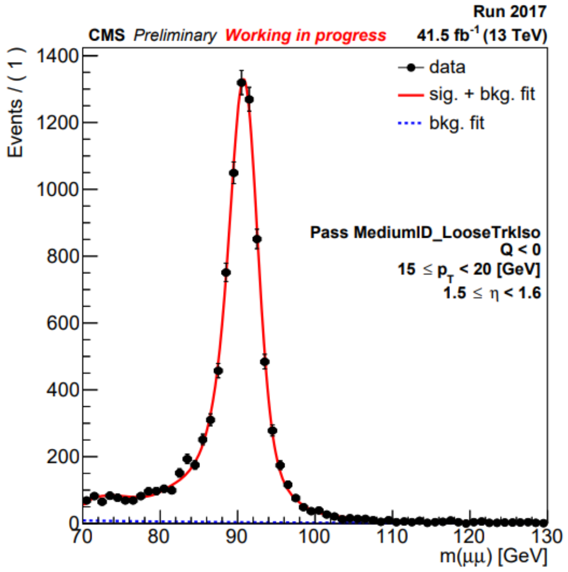


138 $fb^{-1} \times 2\ nb$ = 276M events
Acceptance = 44%

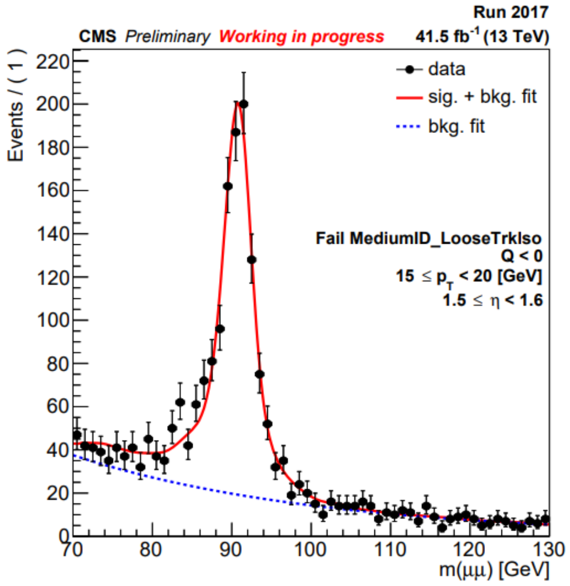
$\boldsymbol{\mu\mu}$ = 101M events
$\boldsymbol{ee}$ = 55M events

Efficiency Correction

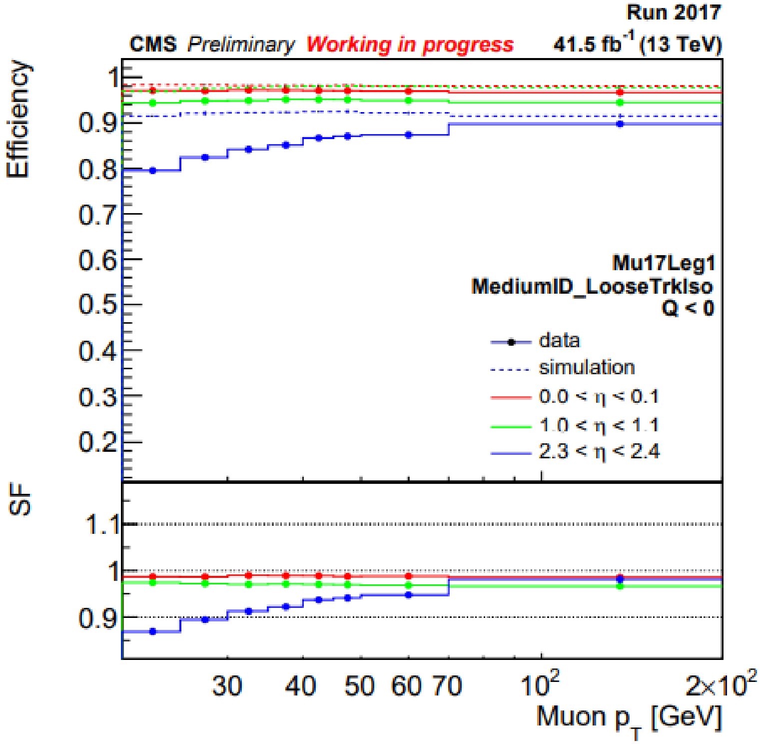
- Efficiency measurement using **the tag and probe method**
  - Low background in Z boson resonance
  - **Tag lepton**: Tight ID to be genuine lepton
  - **Probe lepton**: used to measure efficiencies
- Difference of efficiency btw data and simulation is corrected by applying **scale factor** on simulation



Events with passing probe



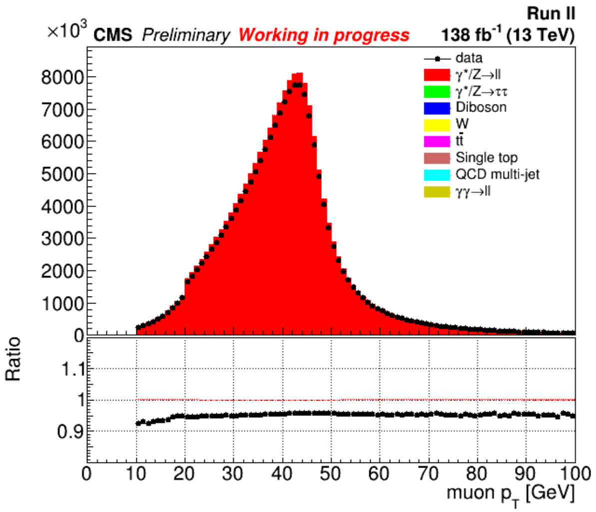
Events with failing probe

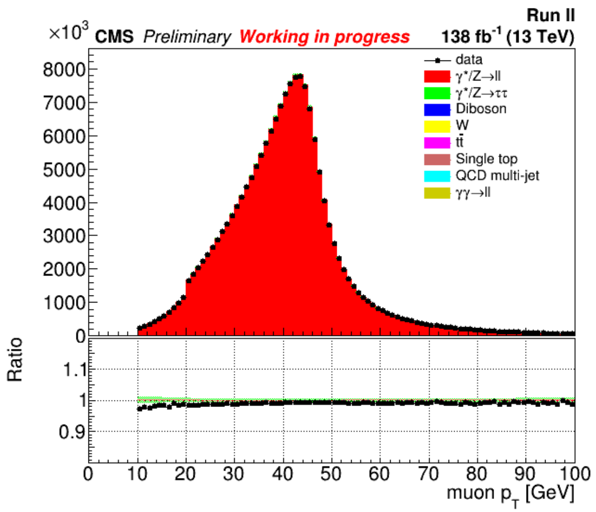


Efficiency Correction

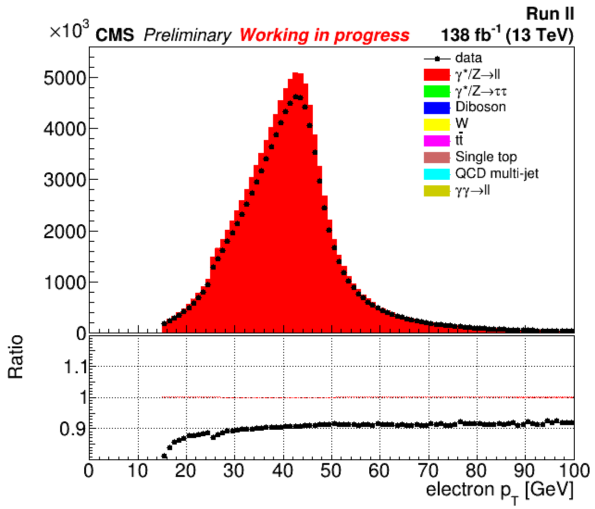
Before efficiency correction | **After efficiency correction**

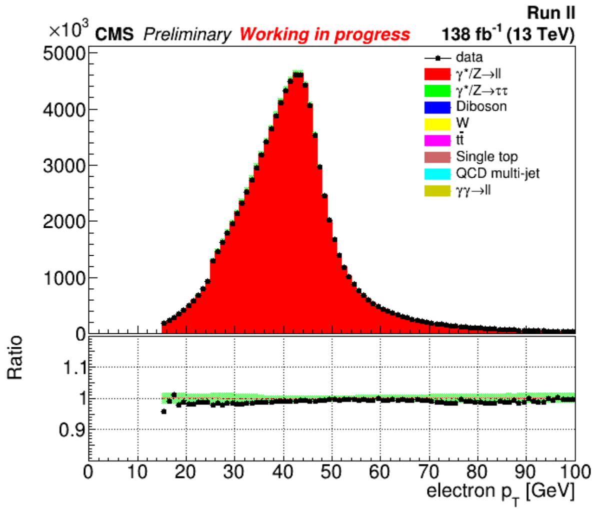
$\mu\mu$





ee



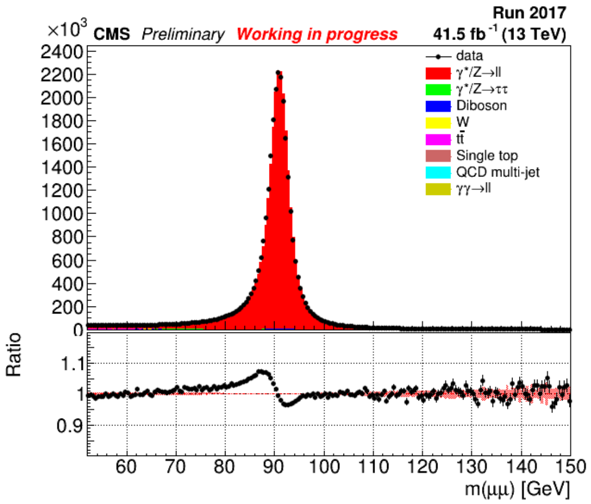


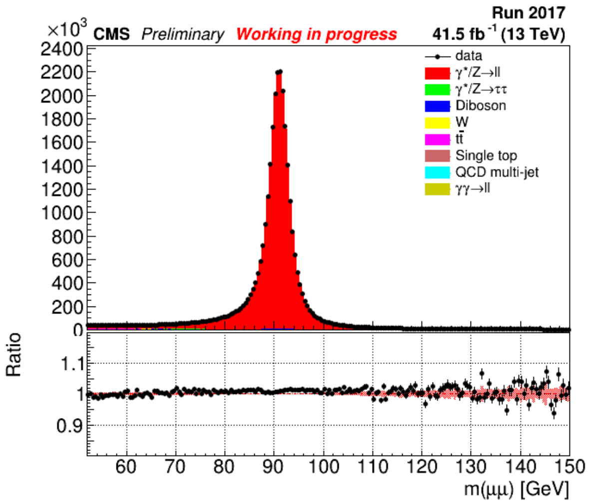
Differential AFB

Lepton energy/momentum calibration

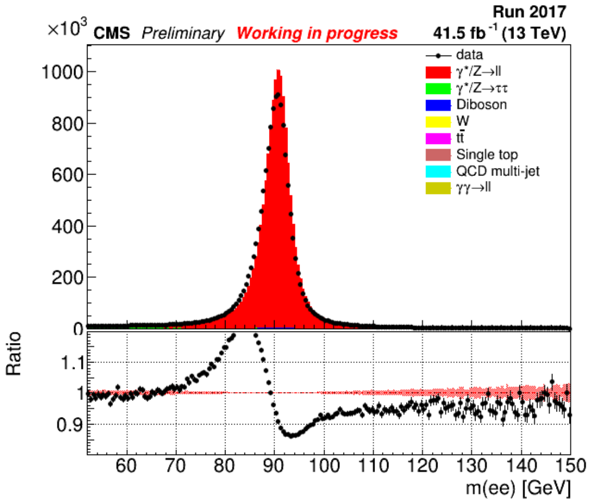
Before calibration | **After calibration**

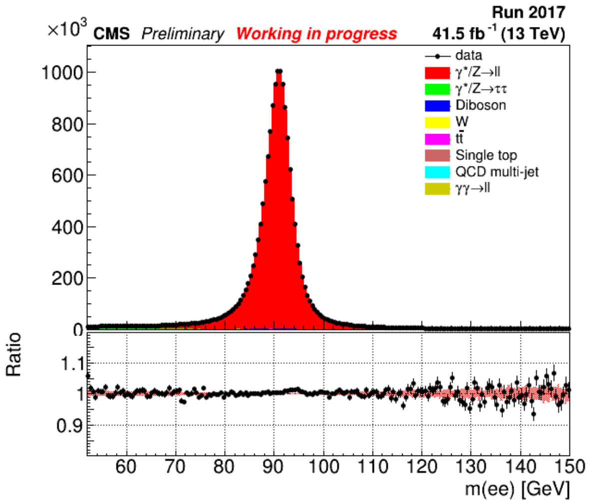
μμ





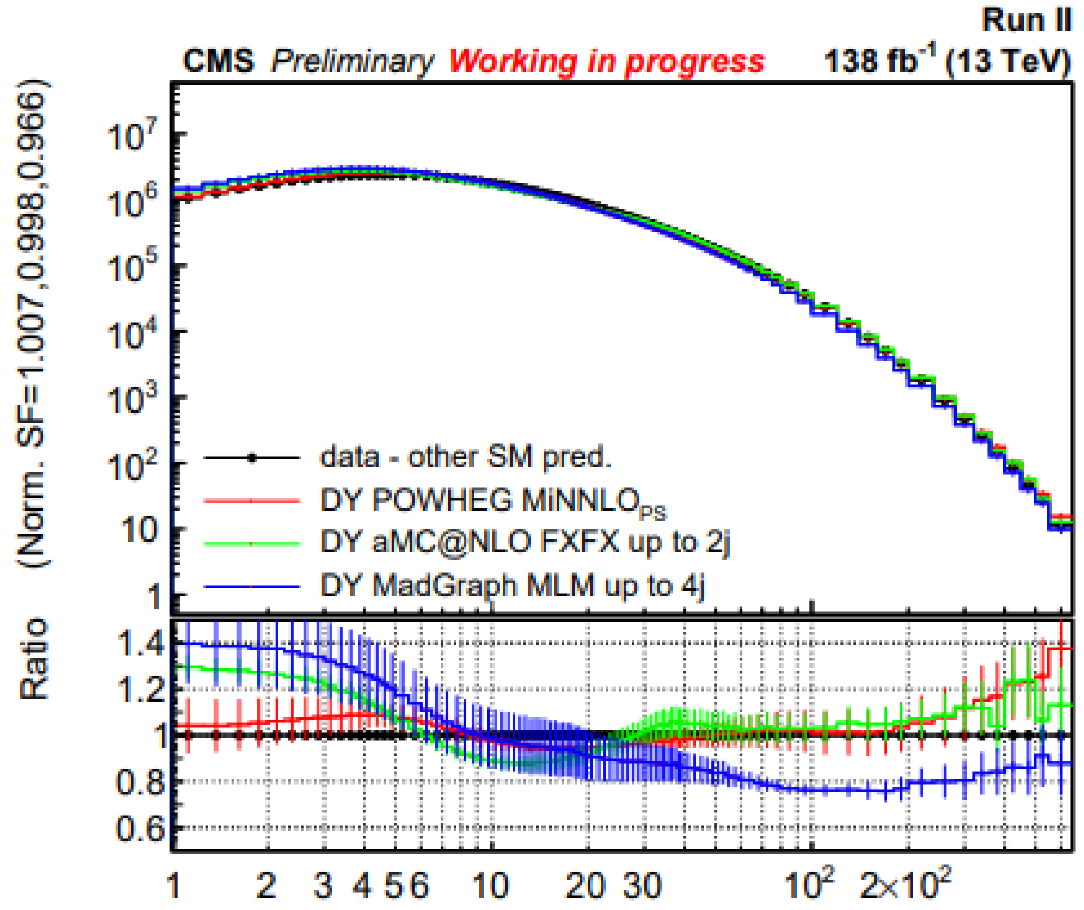
ee





Differential AFB
Z p_T reweight

- Higher order contribution on Z p_T distribution is not negligible
- Not easy to predict



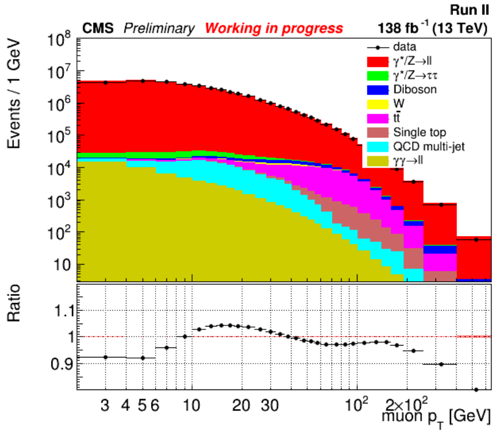
Differential AFB
Z p_T reweight

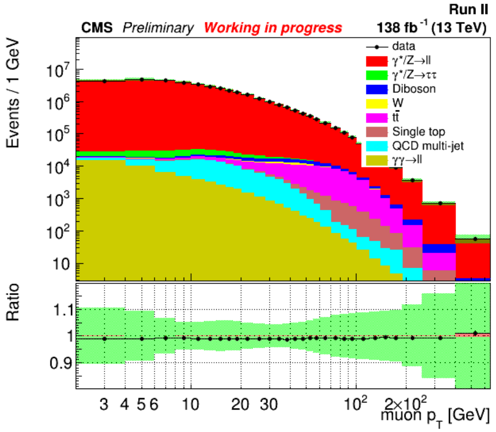
- DY simulation is reweighted to match with data
  - reweight at generator level
  - era-independent correction
  - channel-independent correction

Before

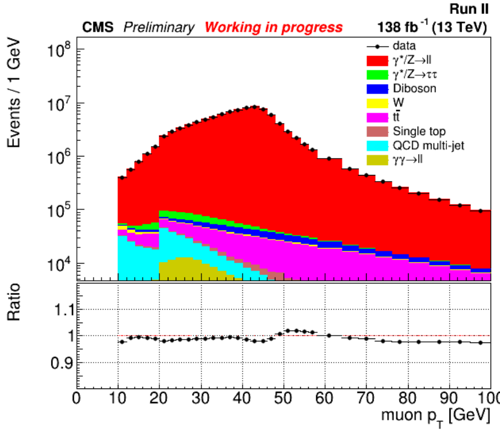
After

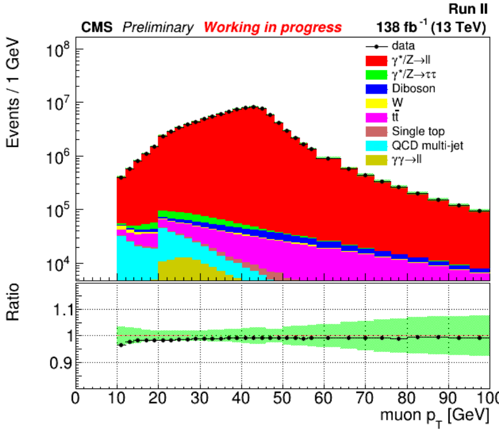
$p_T(\mu\mu)$



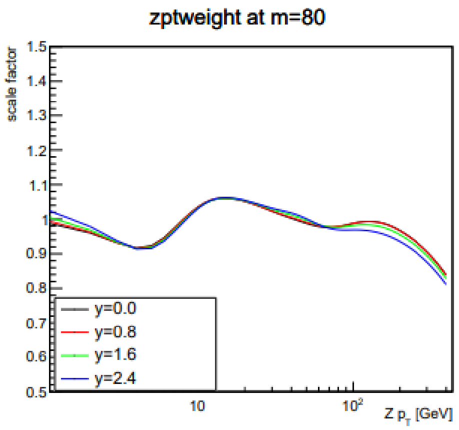


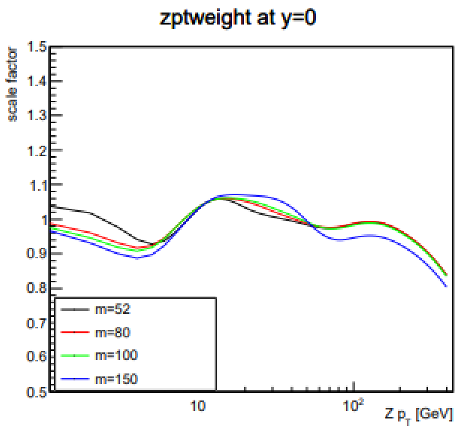
$p_T(\mu)$





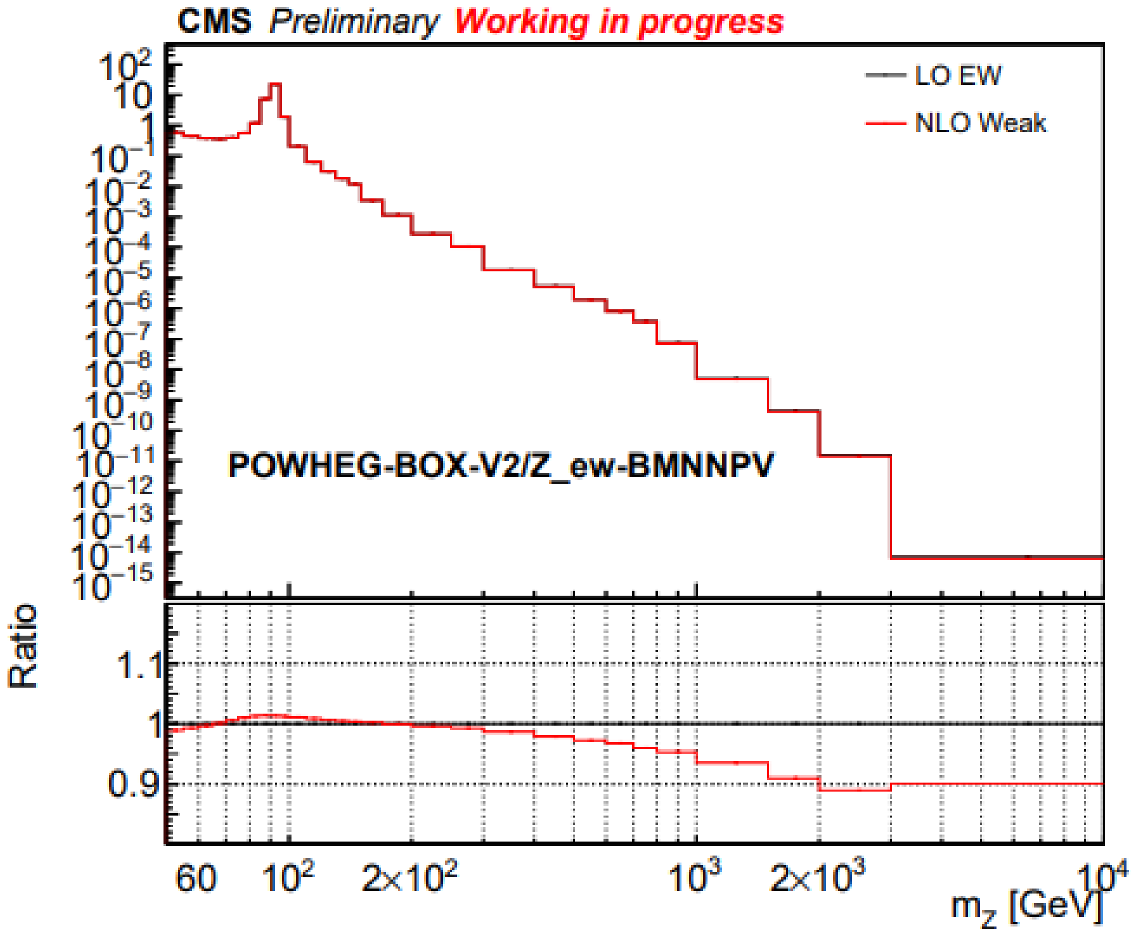
Reweight factor





Differential AFB
NLO weak virtual correction

- DY simulation:
  - QCD NNLO
  - \+ Parton shower
  - \+ QED NLO
- No weak higher order correction
- NLO/LO k-factor for weak interaction is applied
  - non-negligible effect at high mass

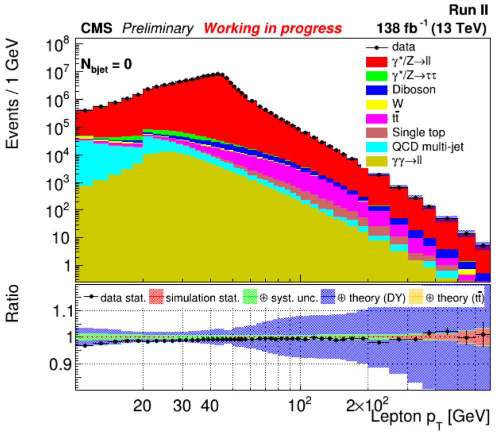


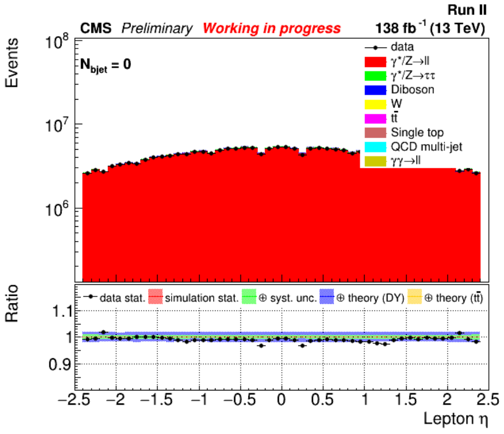
Differential AFB

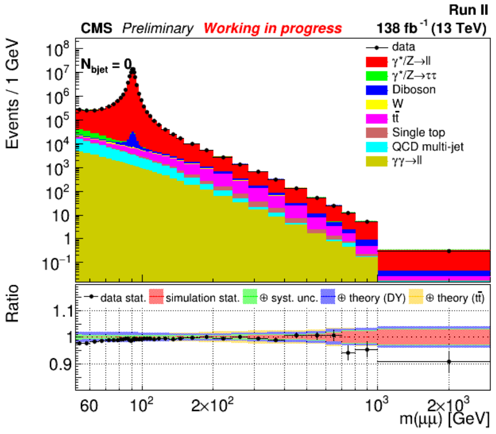
Kinematic distribution

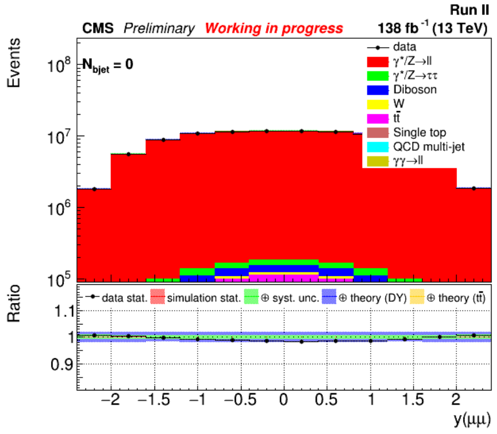
Lepton p_T | **Lepton η** | **Dilepton mass** | **Dilepton y**

$N_b = 0$

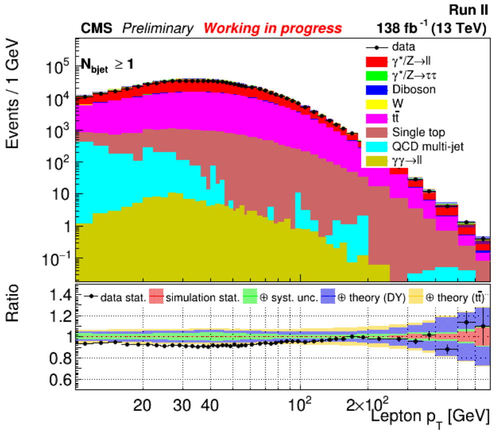


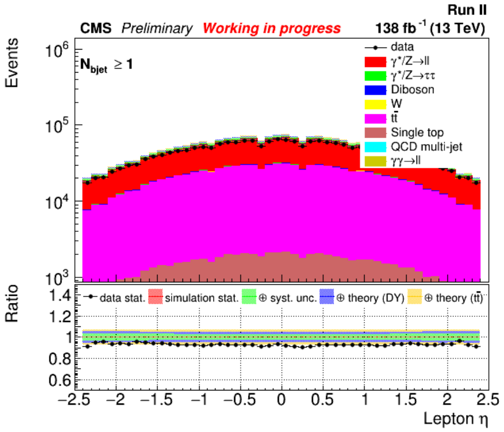


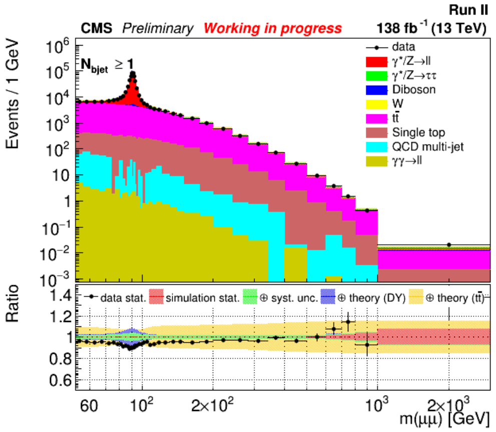


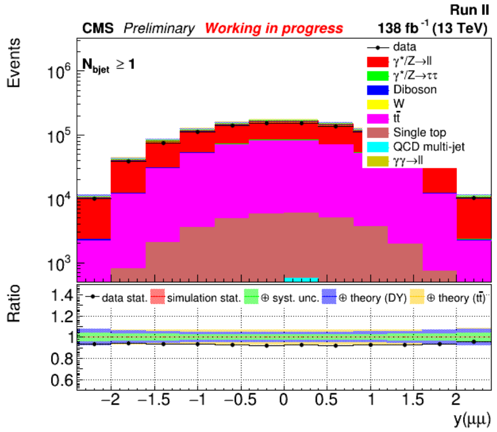


$N_b > 0$









- Currently working on understanding disagreement at N_b>0 region

$\sin^2\theta^l_{eff}$ measurement with inclusive DY events

➢ A_{FB} **near Z pole is sensitive to** $\sin^2\theta^l_{eff}$

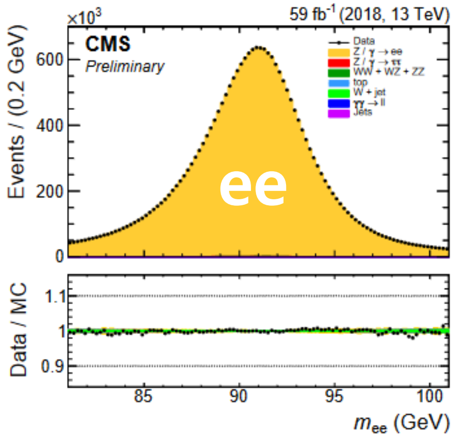
→ **Measure** $\sin^2\theta^l_{eff}$ **using** A_{FB}

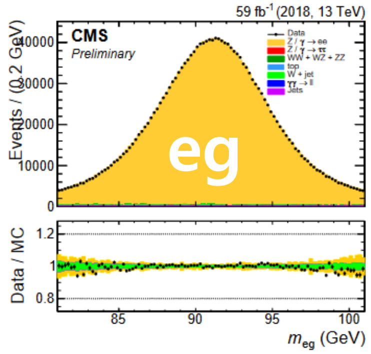
➢ Using Run1 (8TeV, 19 fb^{-1}) + Run2 (13TeV, 138 fb^{-1})

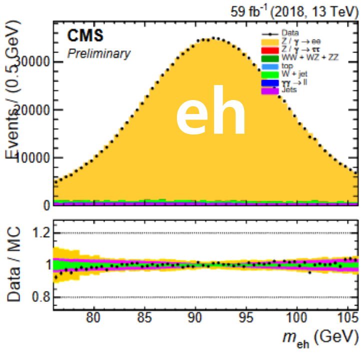
➢ Exploit forward detectors
  - **e**: ECAL+tracker ($|\eta| < 2.5$)
  - **g**: ECAL ($2.5 < |\eta| < 2.87$)
  - **h**: forward HCAL ($3.14 < |\eta| < 4.36$)

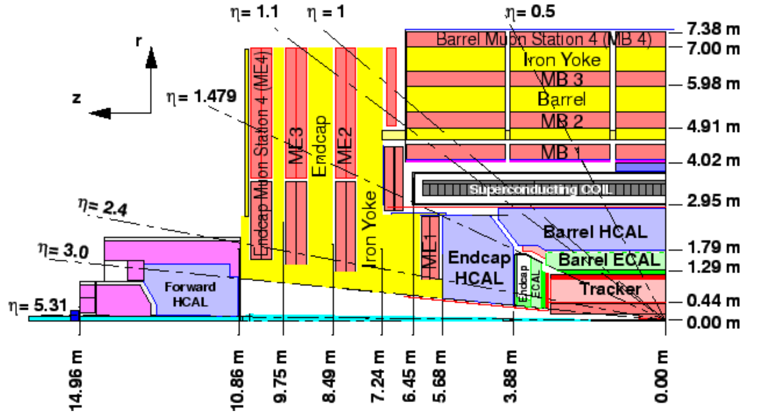
→ more high rapidity and high $\cos\theta_{CS}$ events

which are more sensitive to mixing angle







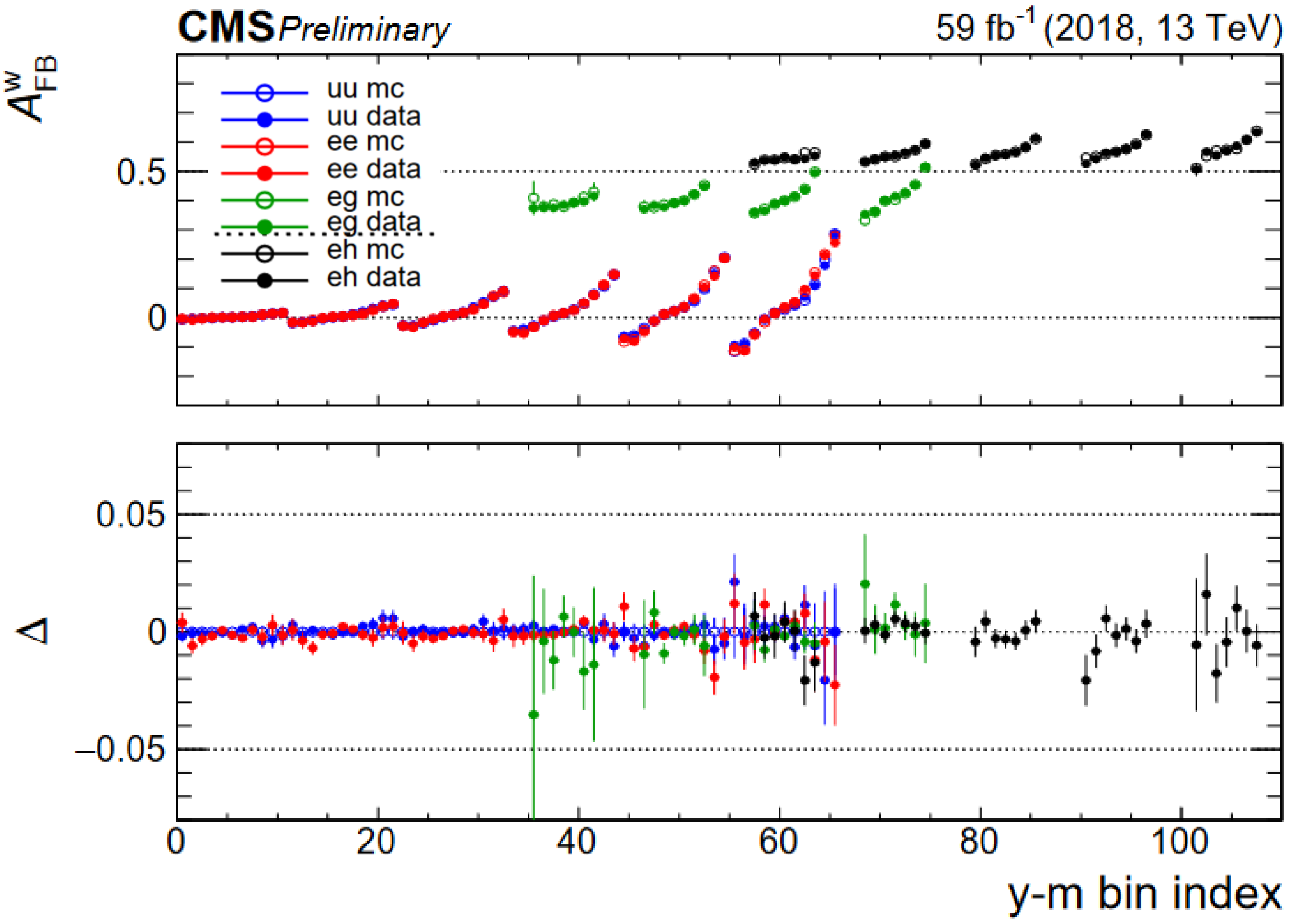


Channel	$\lvert\eta\rvert$	min p_T^{lead} (GeV)	min p_T^{trail} (GeV)
$\mu\mu$	[0.00 – 2.40]	20	10
ee	[0.00 – 2.50]	25	15

Channel	$\lvert\eta_e\rvert$	$\lvert\eta_{g,h}\rvert$	min p_T^{e} (GeV)	min $p_T^{g,h}$ (GeV)
eg	[0.00 – 2.50]	2.50 – 2.87	30 (35 in 2018)	20
eh	[1.57 – 2.50]	3.14 – 4.36	30 (35 in 2018)	20

$\sin^2 \theta^l_{eff}$ measurement

A_{FB}

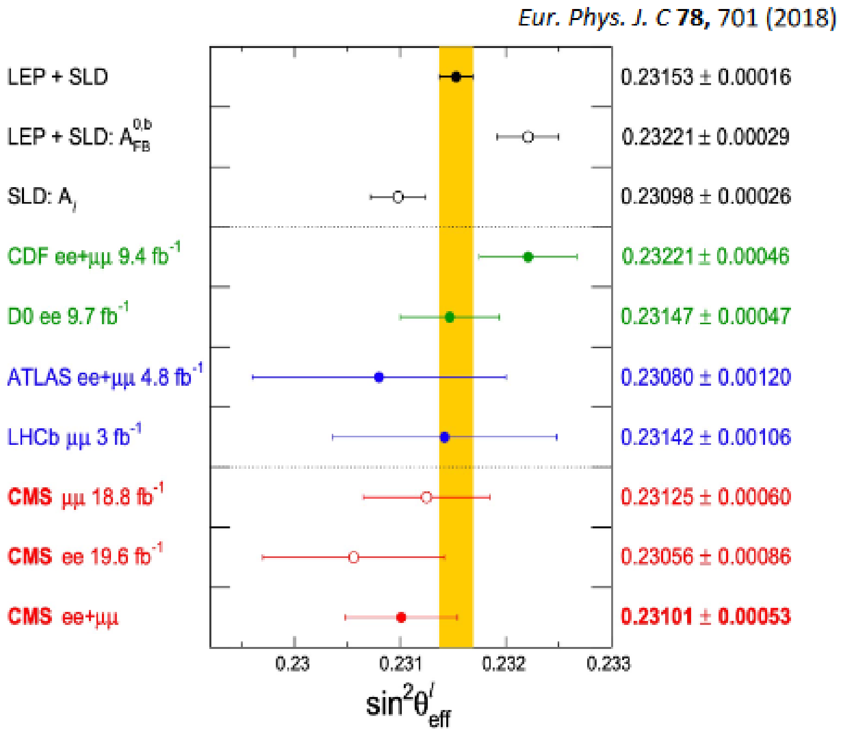


values are shifted for blinding

$\sin^2\theta^l_{eff}$ measurement

Expected result

Previous measurements



This study

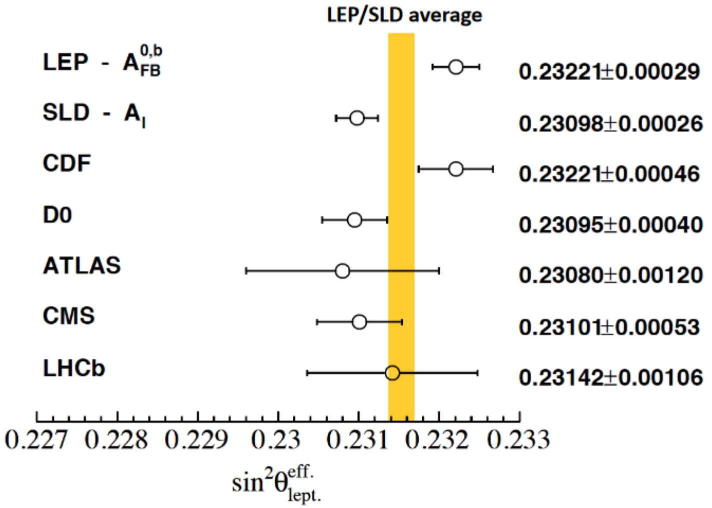
Run	ch	χ^2	nb	$\sin^2\theta^\ell_{\rm eff} \pm \sigma$	stat	exp	theo	pdf
R1	uu	52.0	66	103045 ± 58	41	29	4	28
R1	ee	55.2	66	103143 ± 73	53	40	5	30
16a	uu	66.2	66	665690 ± 67	46	32	9	35
16a	ee	67.5	66	665747 ± 82	61	40	8	37
16b	uu	59.4	66	665560 ± 72	49	39	9	35
16b	ee	53.3	66	665719 ± 90	65	48	7	39
17	uu	63.5	66	665708 ± 51	31	26	9	30
17	ee	69.2	66	665644 ± 60	41	28	8	32
18	uu	51.6	66	665672 ± 46	26	22	9	29
18	ee	73.5	66	665718 ± 50	33	23	8	30

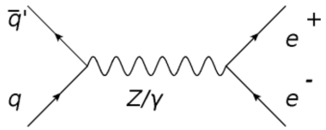
Run	ch	χ^2	nb	$\sin^2\theta^\ell_{\rm eff} \pm \sigma$	stat	exp	theo	pdf
16a	eg	27.7	28	762081 ± 154	116	93	6	42
16b	eg	17.1	28	761981 ± 164	122	101	7	45
17	eg	19.7	28	762022 ± 94	62	58	8	39
18	eg	19.9	28	761838 ± 81	47	52	9	39
16a	eh	20.8	35	895456 ± 81	52	57	6	25
16b	eh	29.1	35	895397 ± 95	63	66	6	25
17	eh	35.5	35	895536 ± 67	35	50	7	27
18	eh	24.6	35	895430 ± 60	31	44	8	26

$$\sin^2\theta^\ell_{\rm eff} = 0.2???? \pm 0.00024.$$

$\sin^2\theta^l_{eff}$ measurement with DY+bjet events

- Two most significant measurements
  - LEP $ee \to bb$
  - SLD $ee \to ll$
  - 3 sigma deviation



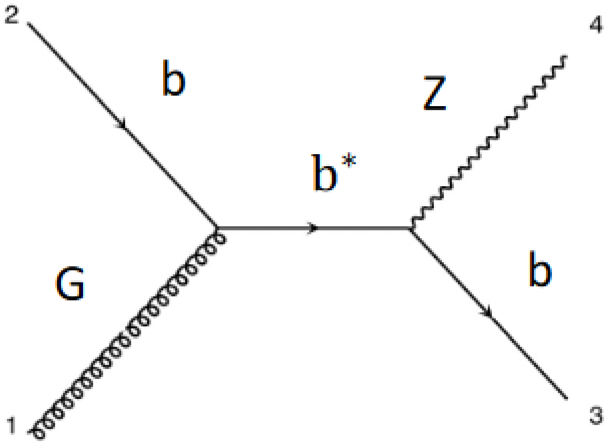


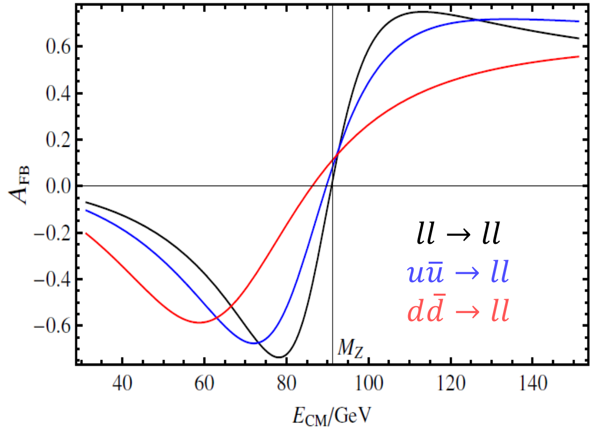
$$A^0_{FB} = \frac{3}{4} A_f A_{f'}$$

	A_f	$\frac{\partial A_f}{\partial \sin^2\theta}$
u	0.67	-3.5
d	0.94	-0.6
l	0.14	-7.9
ν	1.00	0.0

A_{FB} with b at CMS?

- Challenges
  - DY+bjet event selection
  - AFB dilution due to high Z pT
  - bjet charge determination



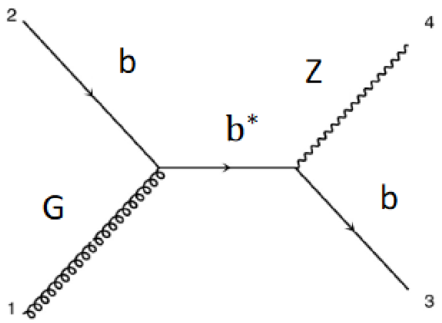


$\sin^2\theta^l_{eff}$ measurement with DY+bjet events

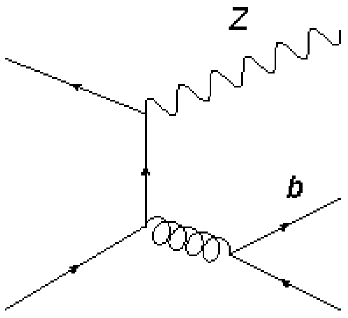
DY+bjet event selection

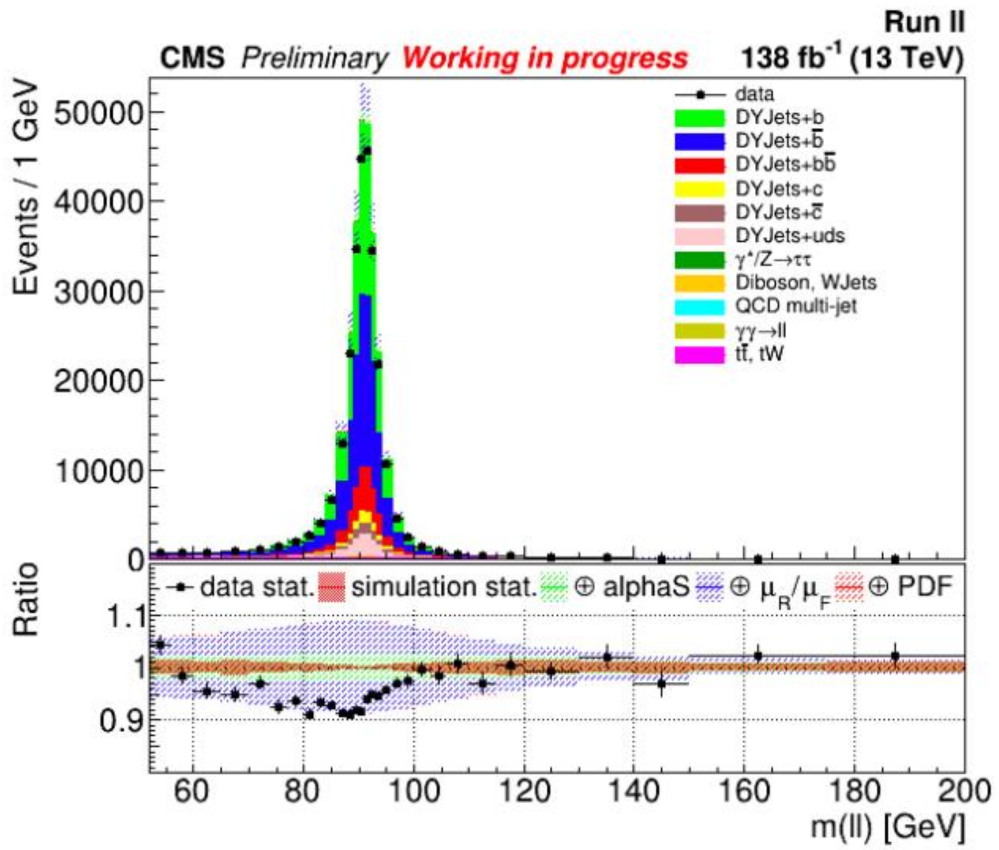
- 1 tight bjet with p_T>30 GeV
- Veto additional loose bjet or cjet with pT>20 GeV
- Veto additional jet with pT>30 GeV
- $|\Delta\phi(Z,b)| > 1.6$
- $p_T(Z)$>15 GeV
- $p_T(Z+b)$<60 GeV
- Missing E_T<75 GeV

Signal



Background

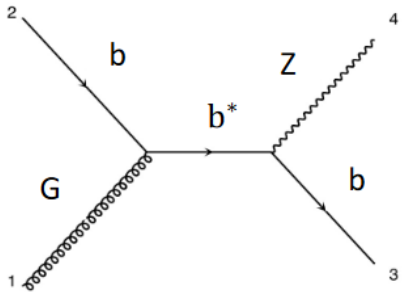


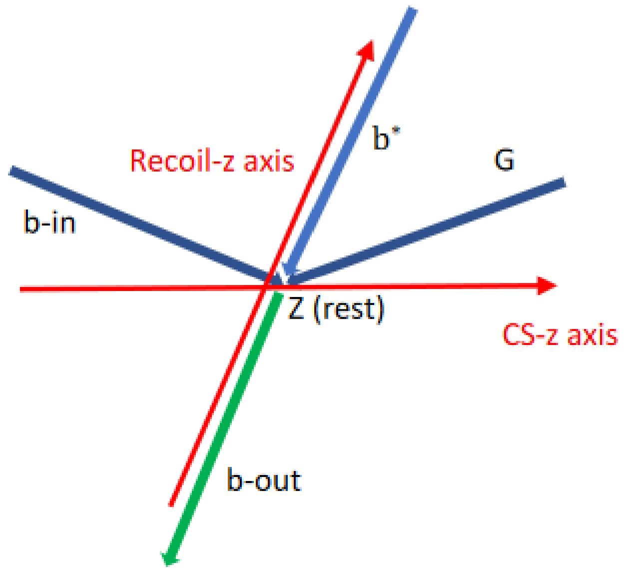


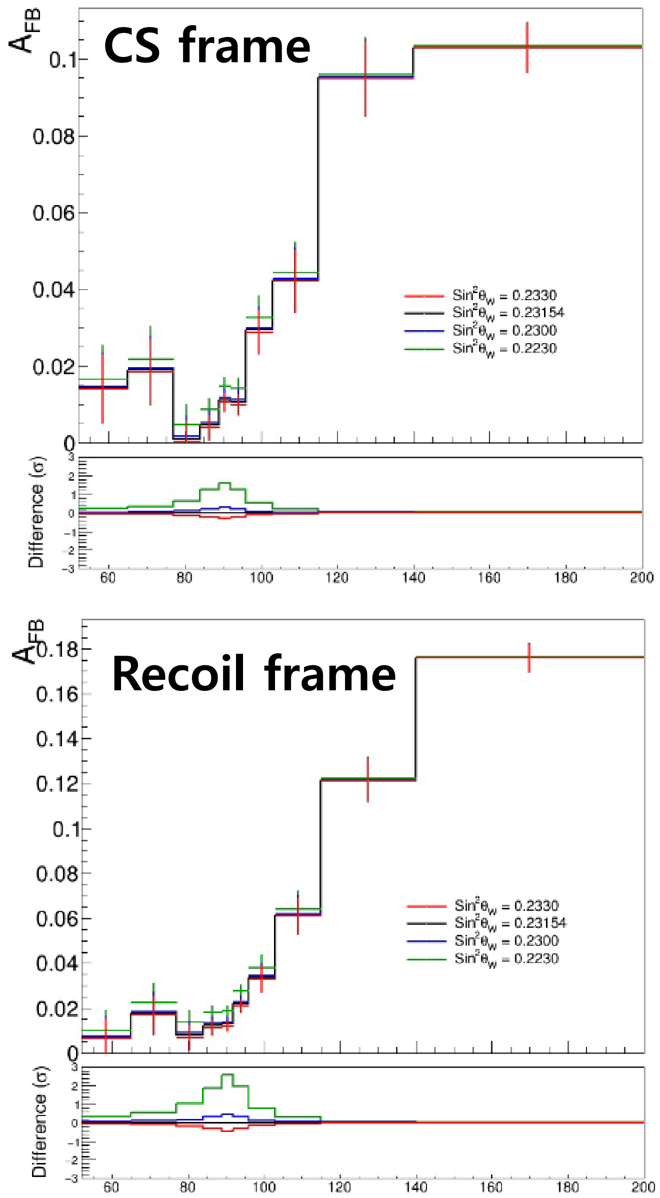
Purity~74%

$\sin^2\theta^l_{eff}$ measurement with DY+bjet events
Recoil frame

- CS frame: use bisector of proton axes
  - usual frame for AFB
  - dilution at high Z p_T region
- Recoil frame: use bjet axis
  - exploit bjet information
  - Needs good bjet charge determination

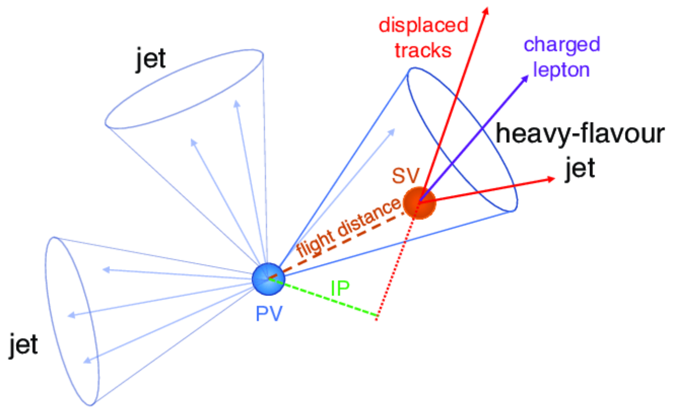






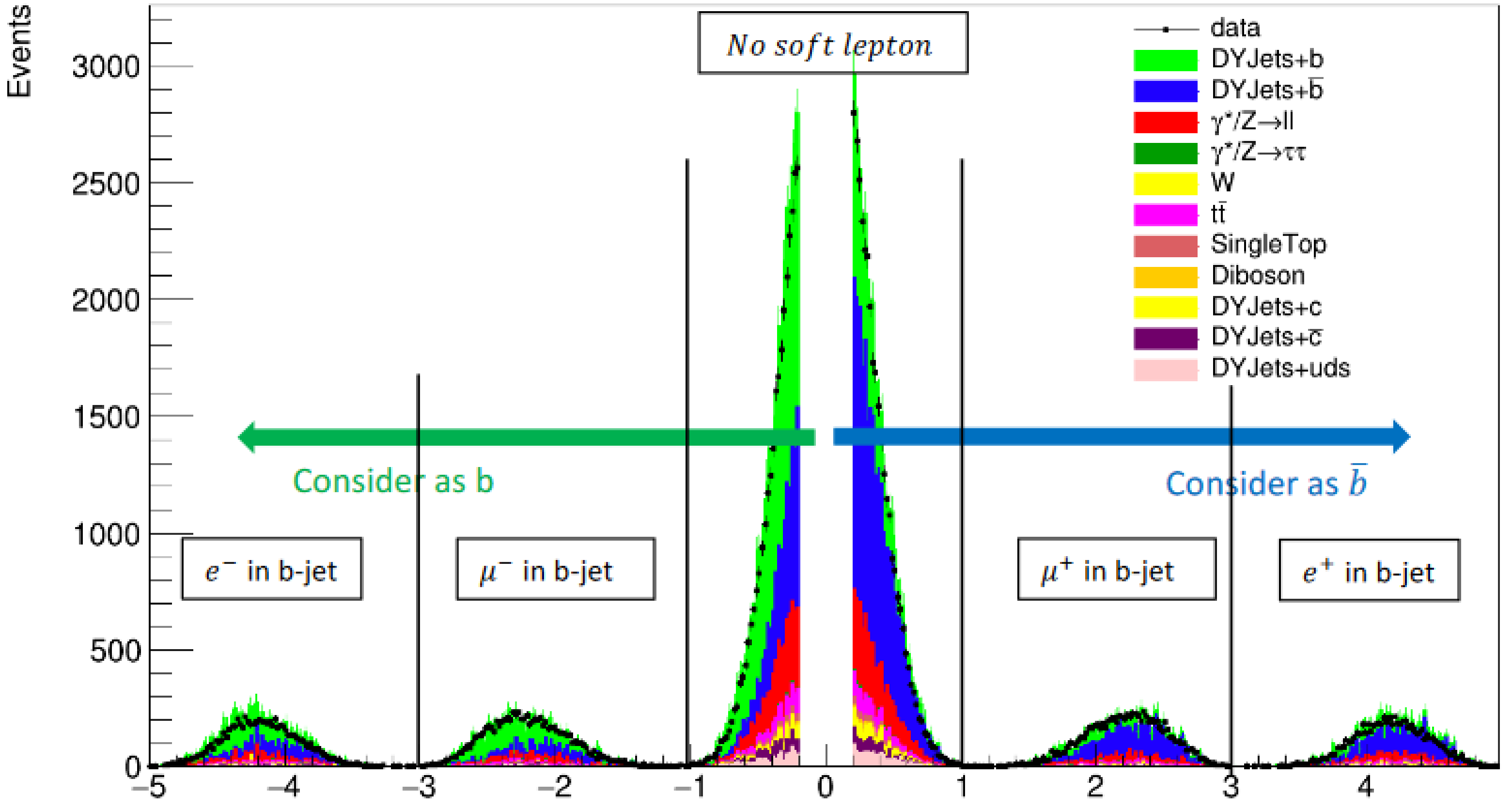
Recoil frame shows better sensitivity in this analysis

$\sin^2\theta^l_{eff}$ measurement with DY+bjet events
bjet charge determination



- Soft lepton charge
  - Use soft lepton from b hadron decay

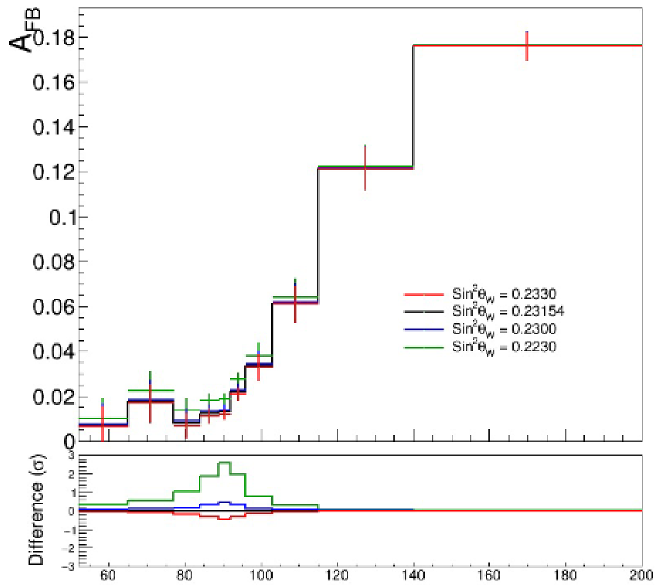
- p_T weighted jet charge

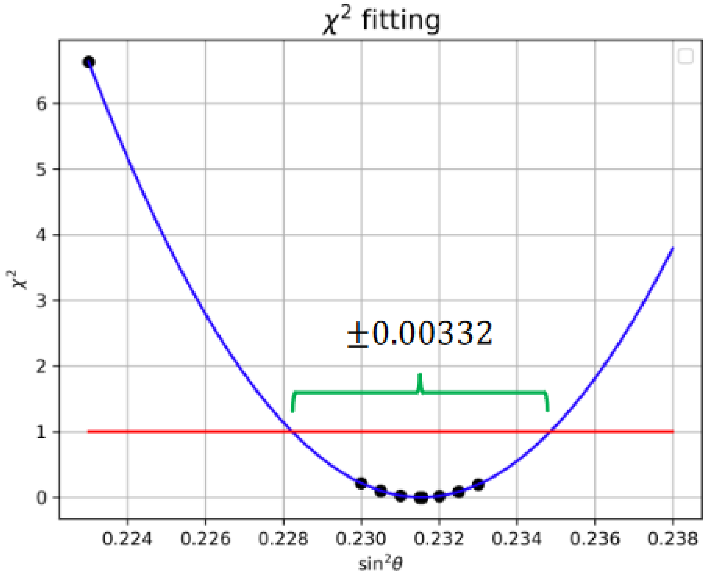


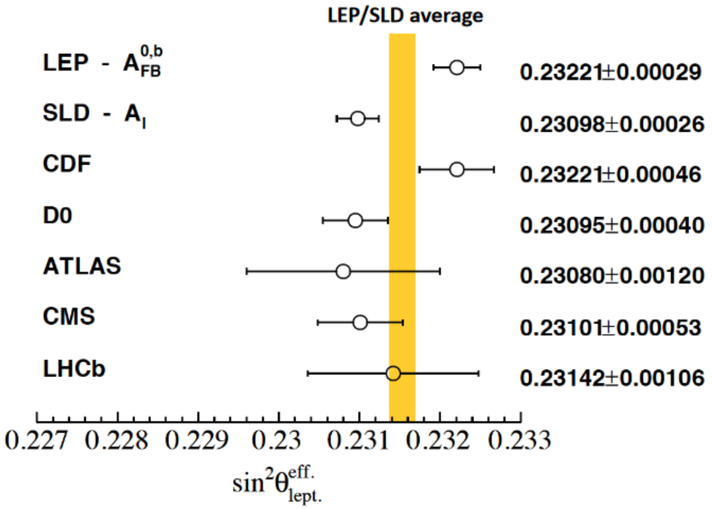
efficiency: 61%
charge-misID: 30%

$\sin^2\theta^l_{eff}$ measurement with DY+bjet events
Sensitivity

- Very rough estimation
  - $\sin^2\theta^l_{eff} \sim 0.2????\pm0.00332$ (Run2)







Its sensitivity is much less than previous measurements, but
- First A_{FB} measurement with Zbb vertex at hadron collider
- First A_{FB} measurement using the recoil frame

Summary

- Differential AFB with and without bjet

- $\sin^2\theta^l_{eff}$ measurement with inclusive DY events
  - $\sin^2\theta^l_{eff} = 0.2????\pm0.00024$

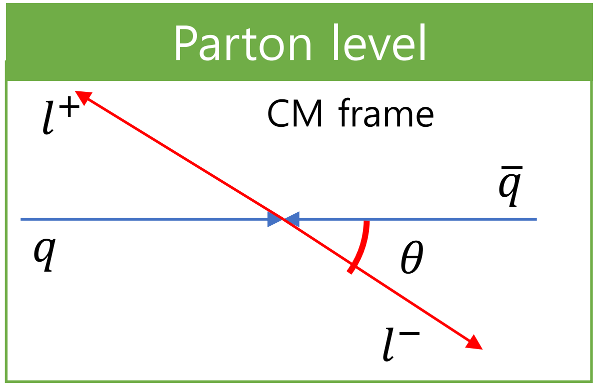
- $\sin^2\theta^l_{eff}$ measurement with DY+bjet events
  - $\sin^2\theta^l_{eff} \sim 0.2????\pm0.00332$

Backup

- backup

Forward-backward Asymmetry (AFB)

- Definition of A_{FB}



$\boldsymbol{\theta}$: Angle btw incoming and outgoing particles
$\cos\theta > 0$, forward event (F)
$\cos\theta < 0$, backward event (B)

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- If incoming and outgoing particles have

same helicity → forward event is preferred

$$\sigma_{LL}, \sigma_{RR} \propto (1+\cos\theta)^2$$

opposite helicity → backward event is preferred

$$\sigma_{LR}, \sigma_{RL} \propto (1-\cos\theta)^2$$

due to angular momentum conservation

- Couplings of Z/γ^* to fermions

$\mathcal{L} = \bar{f}_L\gamma^\mu\left(T_3 g W_\mu^3 + g' Y_L B_\mu\right) f_L + g' Y_e \bar{f}_R \gamma^\mu B_\mu f_R$ [Before symmetry breaking]

$= \bar{f}_L\gamma^\mu\left(T_3 g\left(Z_\mu \cos\theta_w + A_\mu \sin\theta_w\right) + g' Y_L\left(A_\mu\cos\theta_w - Z_\mu \sin\theta_w\right)\right) f_L +$

$g' Y_R \bar{f}_R\gamma^\mu\left(A_\mu\cos\theta_w - Z_\mu\sin\theta_w\right) f_R$ [After symmetry breaking]

$= \left(T_3 g\cos\theta_w - Y_L g'\sin\theta_w\right)\bar{f}_L\gamma^\mu Z_\mu f_L - Y_R g'\sin\theta_w \bar{f}_R\gamma^\mu Z_\mu f_R$

$+\left(T_3 g\sin\theta_w + Y_L g'\cos\theta_w\right)\bar{f}_L\gamma^\mu A_\mu f_L + Y_R g'\cos\theta_w \bar{f}_R\gamma^\mu A_\mu f_R$

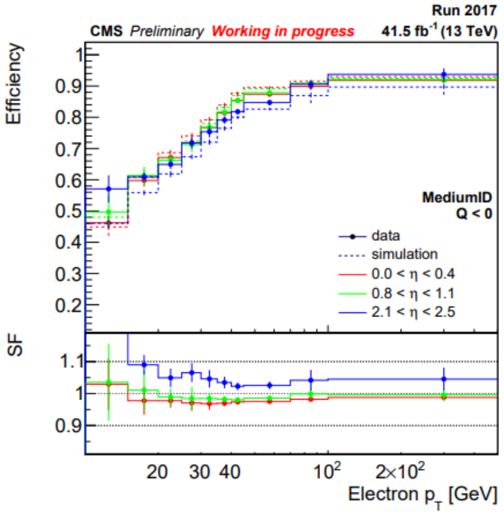
Coupling	Z_μ		A_μ	
	Left-handed	Right-handed	Left-handed	Right-handed
l	$-\frac{1}{2}\left(\frac{g}{g'}-\frac{g'}{g}\right)e$ $\approx -0.64e$	$\frac{g'}{g}e$ $\approx 0.55e$	$-e$	$-e$
ν	$\frac{1}{2}\left(\frac{g}{g'}+\frac{g'}{g}\right)e$ $\approx 1.19e$	0	0	0
u	$\left(\frac{g}{2g'}-\frac{g'}{6g}\right)e$ $\approx 0.82e$	$-\frac{2g'}{3g}e$ $\approx -0.36e$	$\frac{2}{3}e$	$\frac{2}{3}e$
d	$\left(-\frac{g}{2g'}-\frac{g'}{6g}\right)e$ $\approx -1.01e$	$\frac{g'}{3g}e$ $\approx 0.18e$	$-\frac{1}{3}e$	$-\frac{1}{3}e$

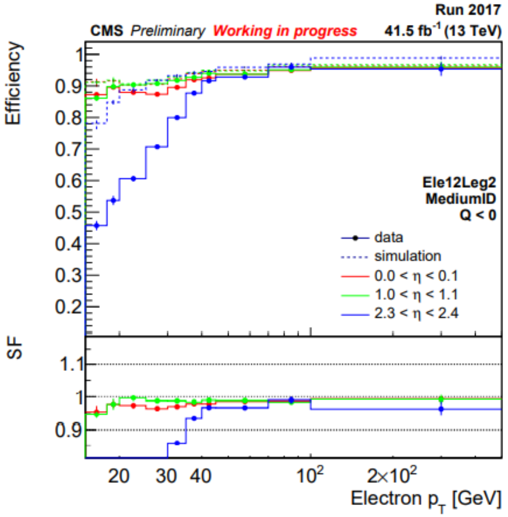
Efficiency scale factor

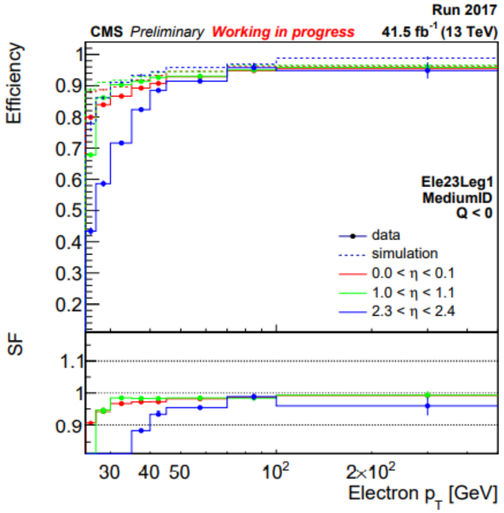
- Charge dependent efficiency
- Fine eta binning ($\Delta\eta$=0.1)
- Method
  - ID efficiency: TnP fitting
  - HLT Leg efficiency: TnP counting
  - HLT DZ efficiency: dedicated method

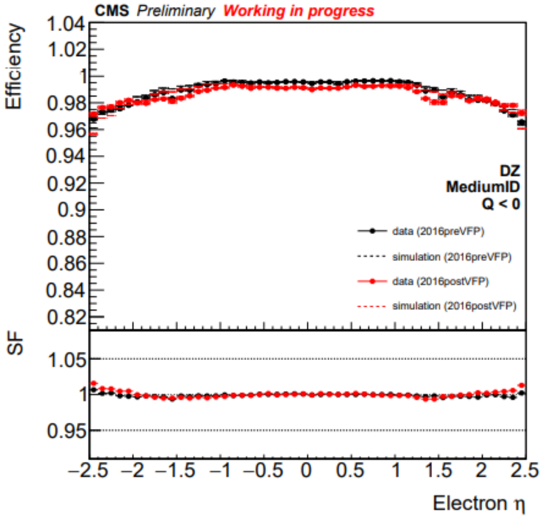
Differential AFB
Efficiency scale factor

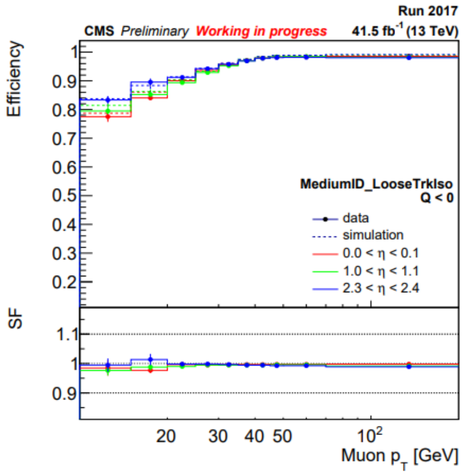
- ○ ○ ○

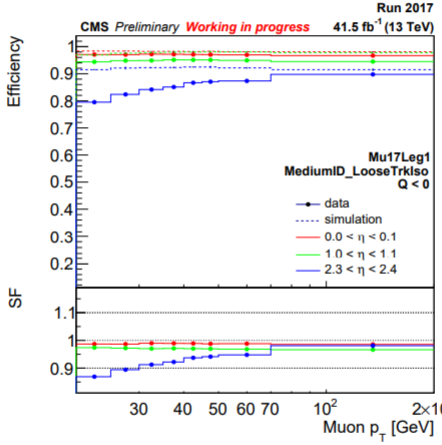


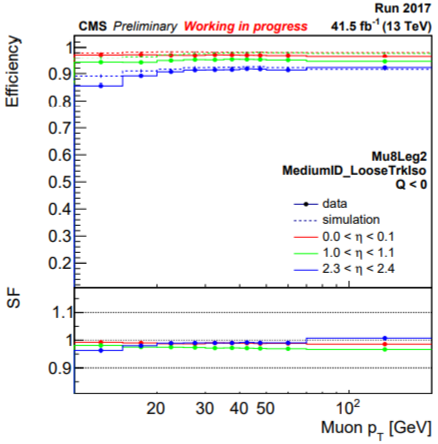


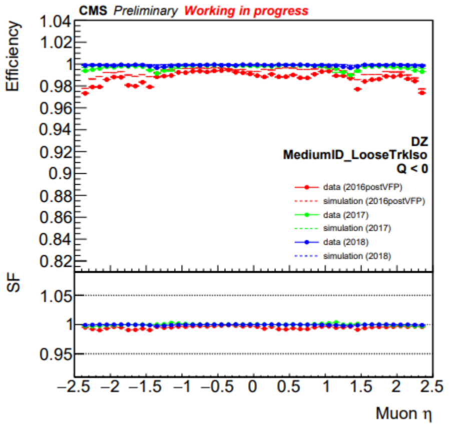




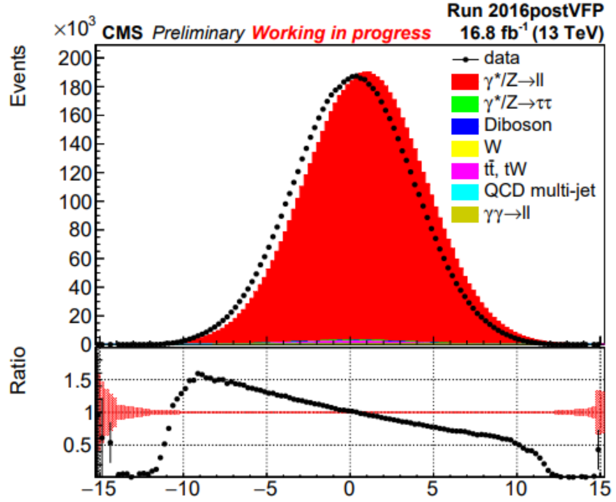
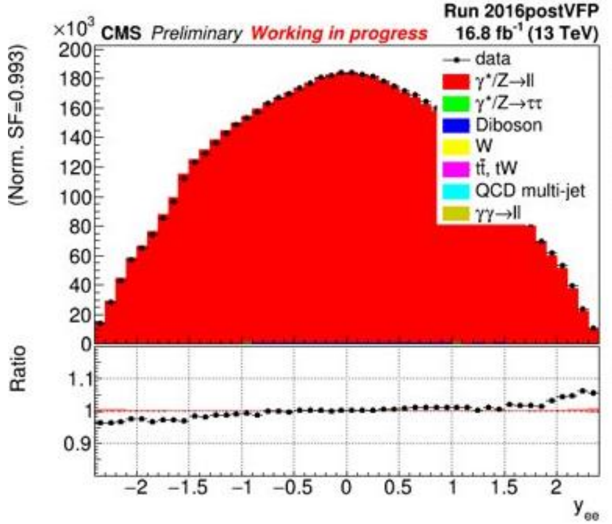
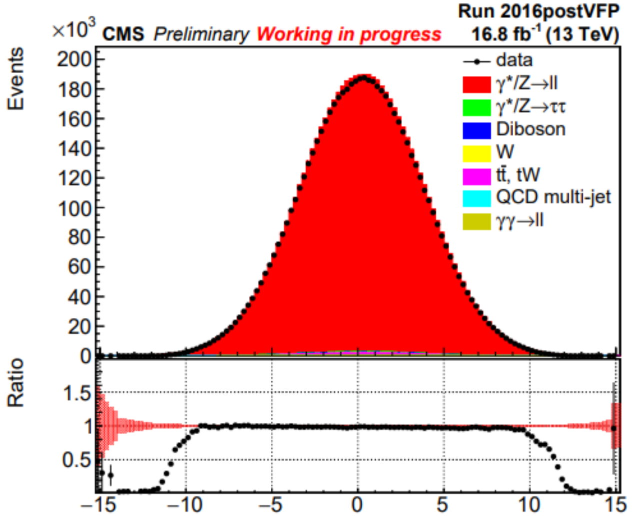
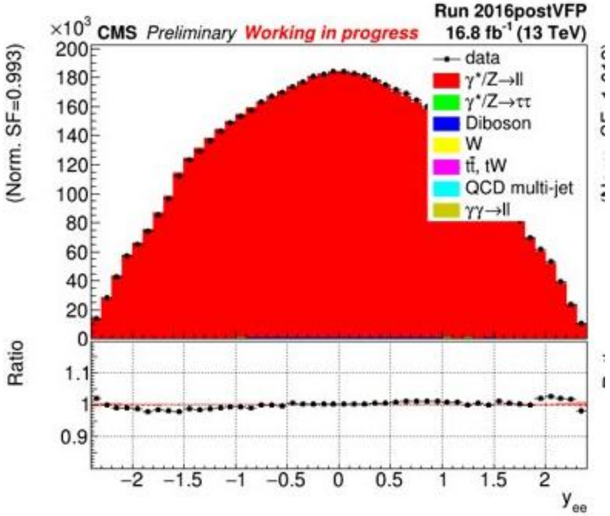






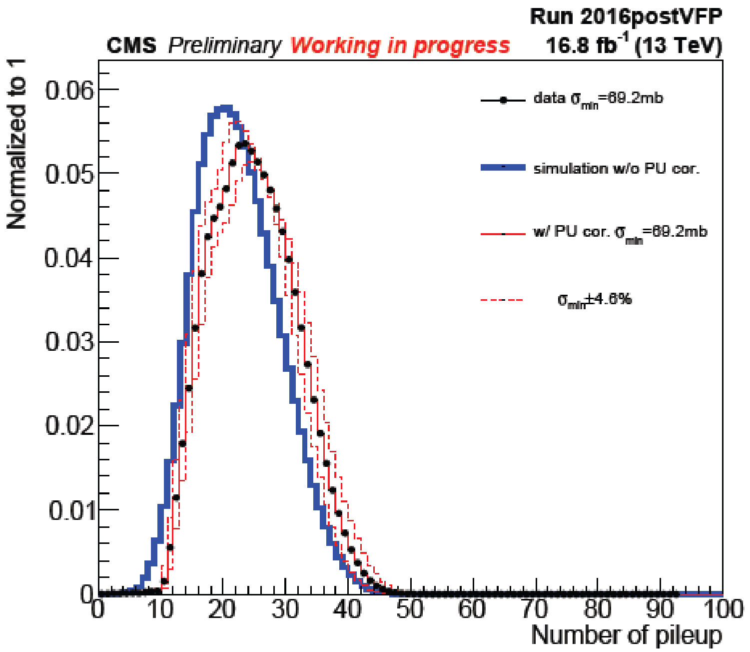


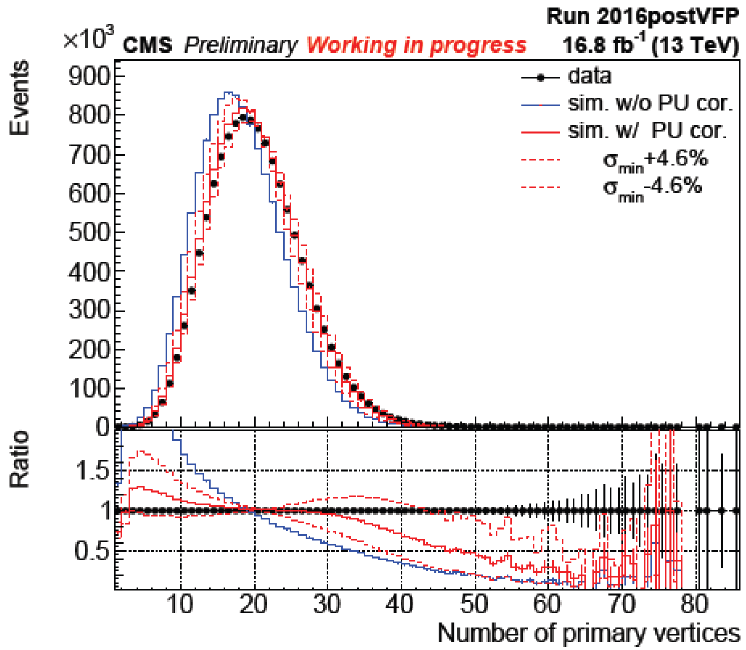
Vertex Z reweight

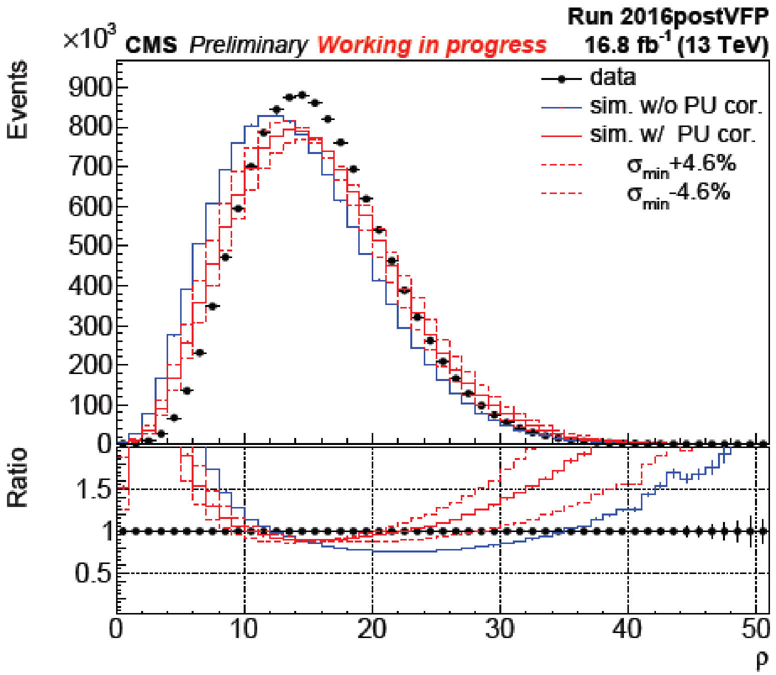
	Vertex Z distribution	Dielectron rapidity (y) distribution
Before reweight		
After reweight		

Differential AFB

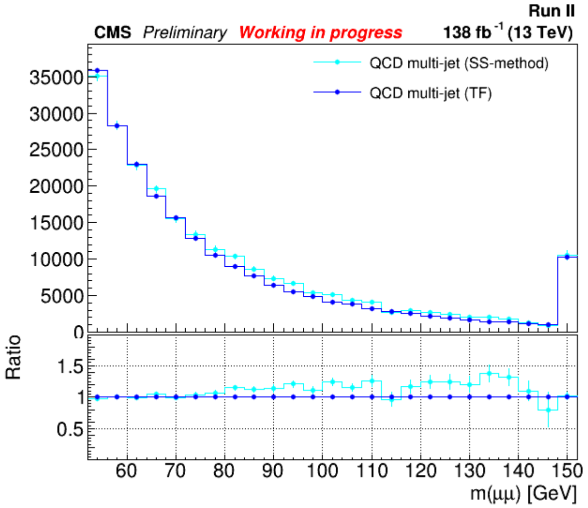
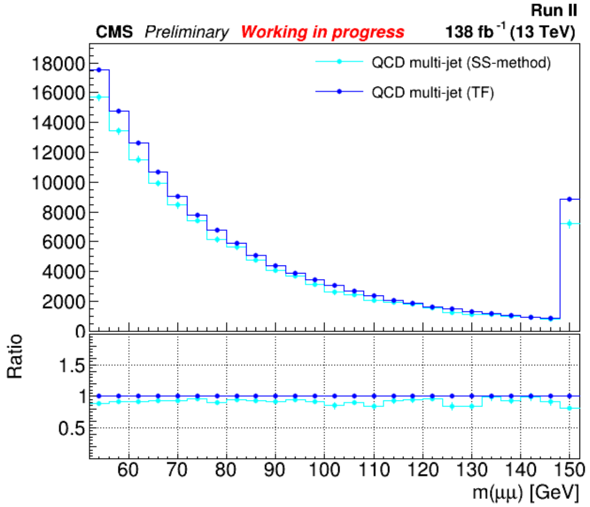
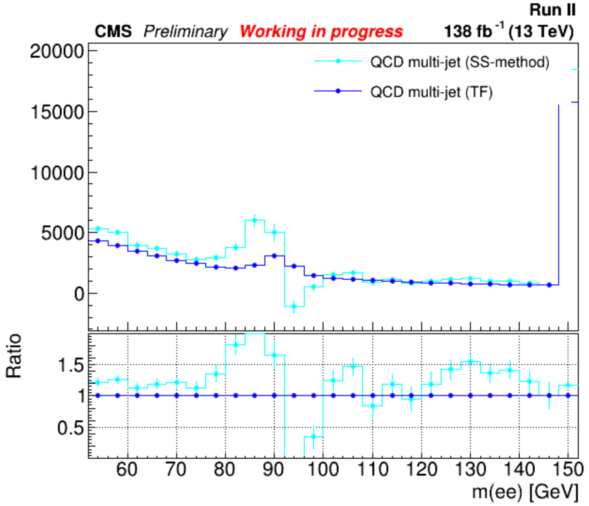
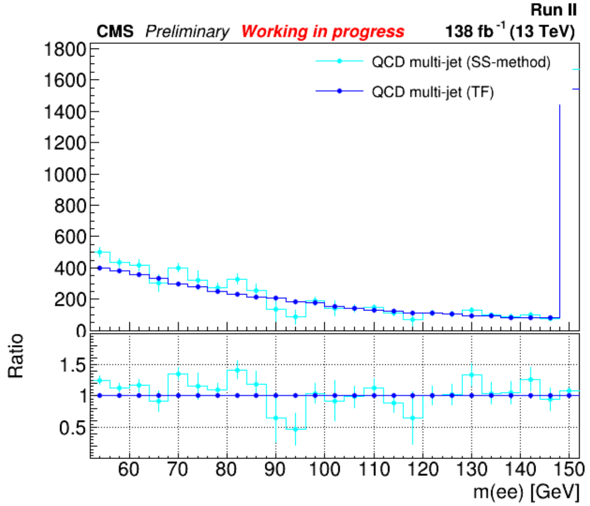
Pileup correction



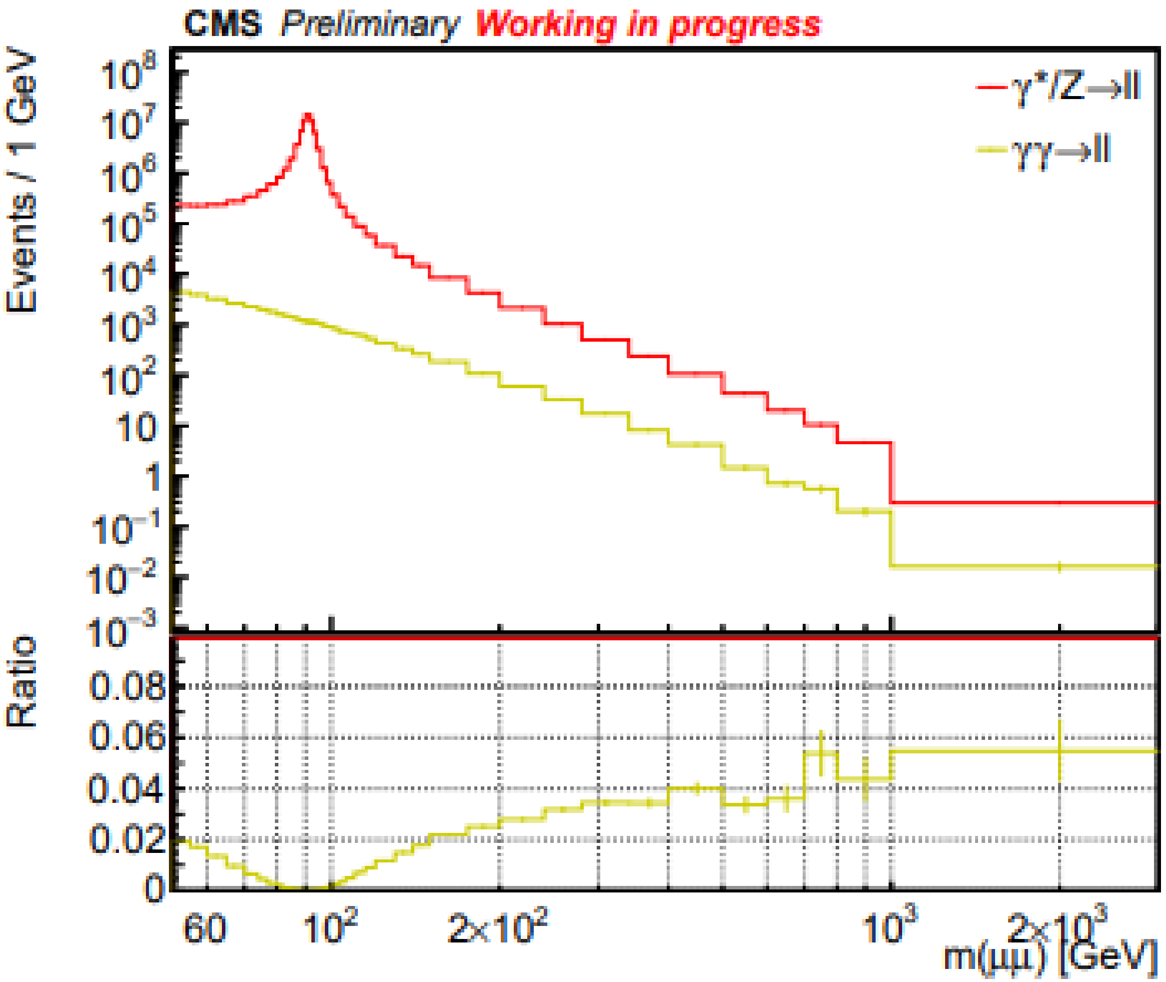




Differential AFB
QCD estimation

	0bjet	nbjet
$\mu\mu$		
ee		

Photon-induced process



Differential AFB
Kinematic distribution