Standard model measurement and new physics search in CMS at LHC and at a Future Circular Collider

Meena

November 10, 2023

Physics Seminar

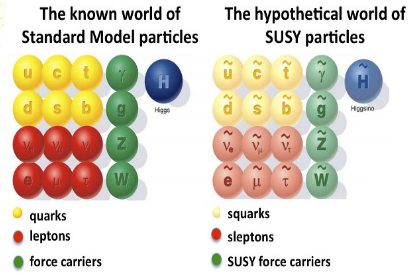
IPHC

Strasbourg (FR)

Outline

- ☆ Introduction
- ☆ LHC & CMS detector
- ☆ Future Circular Collider (FCC)
- ☆ Thesis work (Panjab University, India with Prof. Suman Bala Beri & Dr. Sunil Bansal):
  - ☆ Gas Electron Multiplier detector: Assembly & testing of GEM detector
  - ☆ Physics analysis: cross section measurement of $Z + b$-jets process
  - ☆ Summary
- ☆ Post-doctorat work (IPHC: Dr. Jeremy Andrea & Dr. Ziad El Bitar):
  - ➤ Part-1: Search for displaced top quark from a new massive particle decay in the tracker of CMS (Ongoing)
  - ➤ Part-II: Dedicated to Future Circular Collider (Next year)

- ☆ SM is most successful theory to describe fundamental particles & their interactions verified by various experiments
- ☆ SM limitation:
  - ➤ Gravitational force
  - ➤ Neutrinos are considered massless but conflict with experiment observation
  - ➤ Dark matter/energy, matter-antimatter asymmetry
  - ➤ Why 3 particle generations & much difference in masses of particles among different generations

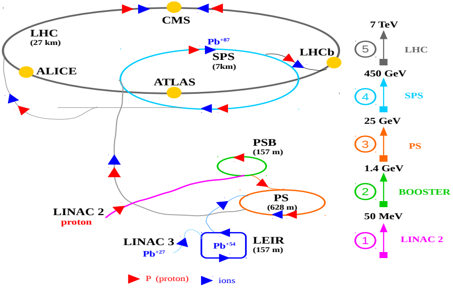


Standard Model particles

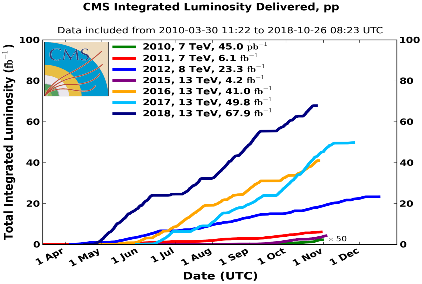
- ☆ Various beyond Standard Model (BSM) scenarios developed, like Supersymmetry, which need to be verified experimentally
- ☆ LHC experiments have been built to test predictions of SM & BSM searches
- ☆ Thesis analysis work was based on one of SM measurements using data collected by Compact Muon Solenoid (CMS) experiment at LHC

Large Hadron Collider (LHC)

- ☆ World's largest & highest energy particle accelerator ($\sim$ 50–175 m deep & 27 km circumference)
- ☆ Designed to produced pp collision at center-of-mass energy ($\sqrt{s}$) = 14 TeV & instantaneous Luminosity ($\mathcal{L}$) = $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- ☆ LHC also offer Heavy-ion collisions
- ☆ Thesis work: analysis of data collected during 2016–2018 with total 137 fb^{-1} recorded integrated luminosity at 13 TeV

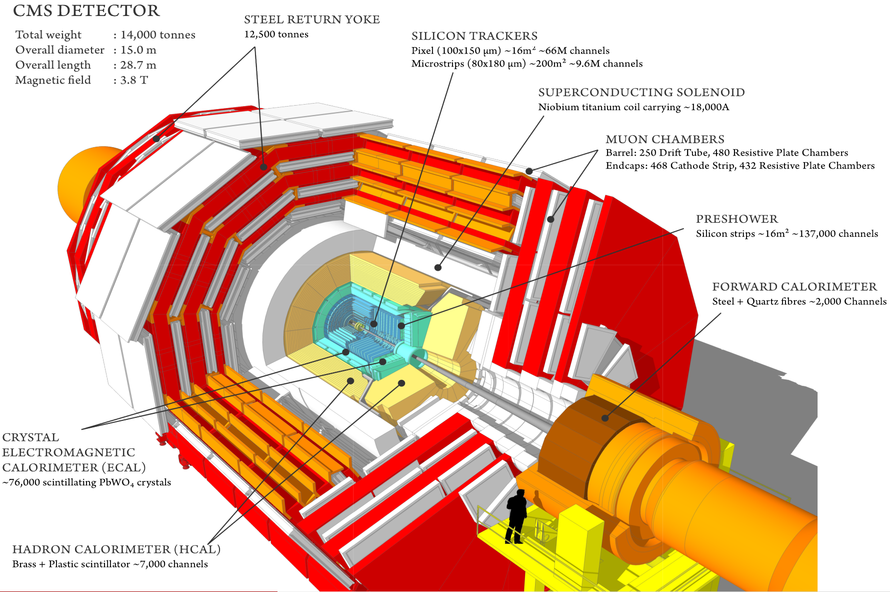


LHC injection series

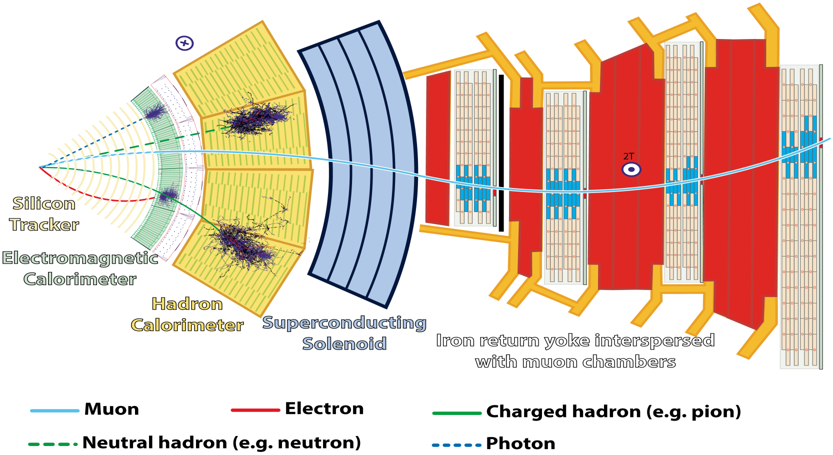


Delivered integrated luminosity

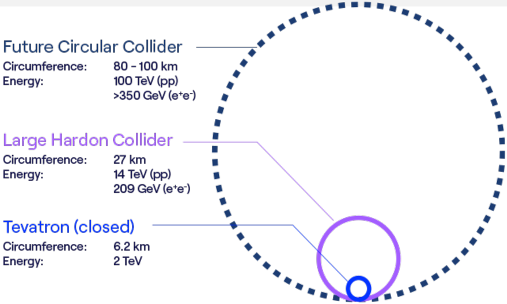
Compact Muon Solenoid (CMS) detector



- Identified by using kinematics properties & reconstructed by combining the information from all subdetector



Future Circular Collider (FCC)

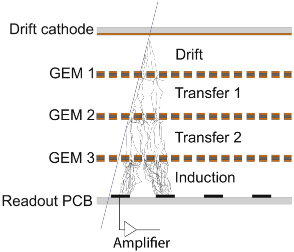


- From 2021 to 2027: feasibility study → technical & financial viability
- If all ok, next steps towards final approval of this project & start of construction after middle 2030s
- First step of operations is begnning of FCC-e^-e^+ collider around 2045
- Then FCC-hh in the same tunnel would extend research programme from the 2070s to the end of the century
- Would provide unprecedented precision measurements & potentially point the way to physics beyond the SM

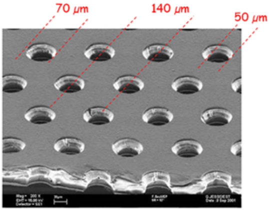
Thesis Part-I

CMS: Hardware

- GEM is a gaseous detector that makes use of electron multiplication to create a detectable analog signal
- CMS triple GEM detectors are made up of a gas volume holding a stack of 3 large-area GEM foils, embedded between a drift cathode & a Printed Circuit Board readout or anode.
- GEM foils are made by 50 μm thick Kapton coated with a copper layer of 5 μm on each side that has array of holes (140 μm pitch)
- It has gas gap configuration of 3/1/2/1 mm (drift/transfer1/transfer2/induction)
- High voltage applied across foil, avalanche of electrons created through holes & drift toward readout board where signal is registered by readout strips



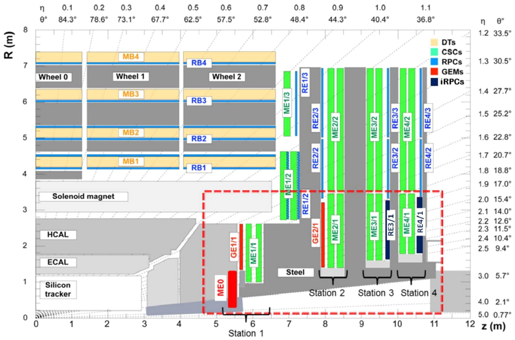
Sketch of a Triple-GEM chamber



Scanning Electron Microscope picture of a GEM foil

CMS GEM: Motivation

- ☆ Installed in 1st station/1st ring (GE1/1) of Muon Endcap covering $1.6 < |\eta| < 2.2$ to restore redundancy in muon system for robust tracking & triggering during HL-LHC (2026–2038)
- ☆ Time resolution $\sim 8\,\text{ns}$ & position resolution $\sim 260\,\mu\text{m}$ (at R=2 m) & $\sim 340\,\mu\text{m}$ (at R_{max}=2.6 m)
- ☆ Single GEM chamber efficiency > 97% (> 99.9% for Superchamber→a pair of triple-GEM)

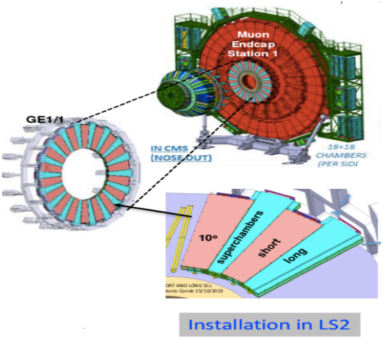


Position of GEM in CMS at CERN

- ☆ Improve L1 & HLT muon momentum resolution to reduce or maintain global muon trigger rate

Other proposed muon station upgrade in endcap: 2nd & 3rd station of GEM (GE2/1 & ME0), 3rd (RE3/1), & 4th (RE4/1) stations of improved RPC (iRPC) detectors

- ☆ Each Superchamber covers 10°
- ☆ 144 single chamber for both endcape $\rightarrow$ 36 Superchambers (72 single chamber) in one endcap
- ☆ Long ($1.55 < |\eta| < 2.18$) & short ($1.61 < |\eta| < 2.18$) version



Indian contribution:

- ☆ Assembly & characterization of 20 GE1/1 detectors (8 by Panjab University)

Workflow for GE1/1 production chamber

- **Assembly ⟶ QC tests ⟶ Installation**

Pre-assembly test on GE1/1 chambers components
↓
QC2: High voltage test on the GEM Foils/Gap before, during & after assembly
↓
QC3: Gas Leak Tightness
↓
QC4: I-V linearity+ Intrinsic Noise Rate
↓
QC5: Gain uniformity test
↓
QC6: High-voltage stability
↓
QC7: Electronics connectivity test
↓
QC8: Cosmic ray data taking

✓ **Assembled & performed quality control tests up to QC4 of 8 production chambers at Panjab university (PU) site & QC5 at Delhi University**

✓ QC7 test performed at CERN

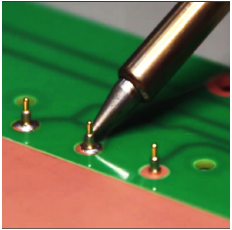
✓ Superchamber assembly at CERN

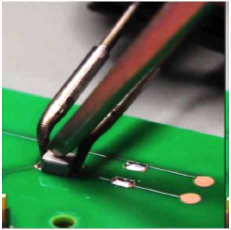
Two well established labs set-up in Department of physics,PU

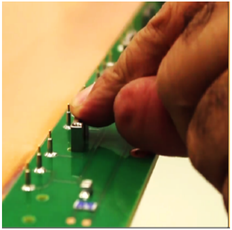
☆ One for pre-assembly & QC testing of GE1/1 detector

☆ Class 100 clean room for final assembly of GE1/1 detector

Next slides → Assembly & QC tests





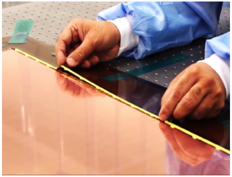
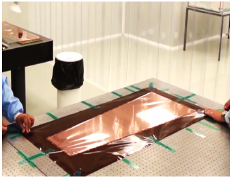


Preparing drift Board: Left: Soldering of the HV pins, Middle: Soldering of the SMD components, Right: Mounting of the pull-outs

Fixing gas connector onto readout board

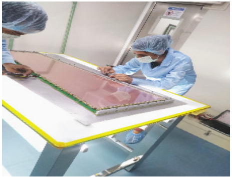
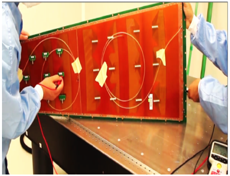
- ☆ Drift & Readout board are cleaned using a vacuum cleaner
- ☆ All screws & pull-outs are cleaned with an ultrasonic bath to remove any dust
- ☆ Drift board: include placing high voltage pins, mounting resistor & capacitor, pull-outs (top figs)
- ☆ Readout board: includes mounting of brass inserts in lateral flanges, threading of gas holes, & gluing of gas connectors (bottom fig)

Assembly GE1/1 production chamber in clean room at PU

Left: Cleaning of GEM foil, Middle: Placing internal frame after testing, Right: Assembled GEM stack

- ☆ First placed cleaned plexiglass then 3 mm cleaned spacer, then GEM1 foil, 1 mm spacer (middle fig)
- ☆ Then in similar way GEM2 foil, 2 mm spacer, GEM foil3, 1 mm spacer are placed to form GEM foil stack (right fig) → perform QC2 test at each step

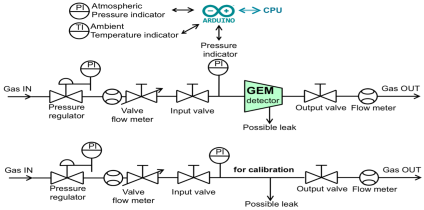



Left: Finalizing stretching of stack, Right: Final assembled detector testing induction gap

- ☆ Placed GEM foil stack on drift board (left fig) & readout board is placed on top → QC2 test again performed on GEM foils & all gaps

QC3 - Gas Leak test of GE1/1 production chamber at PU

QC3 - Gas Leak test: to check gas leak of detector by monitoring drop of internal over-pressure as a function of time

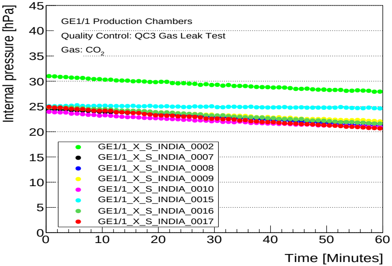


QC3 gas leak test experimental setup

Front view Back view
of QC3 Gas Leak test stand at PU

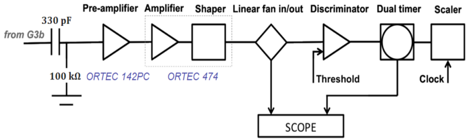
- Detector is filled with CO_2 & Internal over-pressure is set to $\approx 25\,\text{hPa}$
- Gas (Gas+Detector) system is validated if: pressure drop $< 1\ (7)\,\text{hPa/h}$

Result: all detector passed QC3 test ✌ ☛

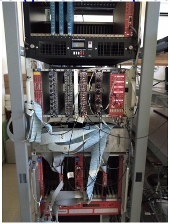


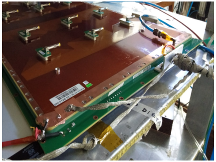
QC4 High Voltage test of GE1/1 production chamber at PU

QC4 High Voltage (HV) test: to study VI characteristic of a GE1/1 detector & to identify possible malfunctions, defects in HV circuit & intrinsic noise rate (pulses not produced by ionizing particle)

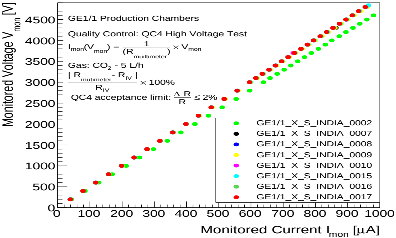


QC4 HV test experimental setup

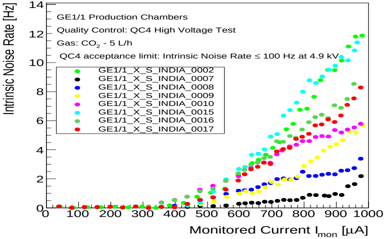




Data acquisition setup & assembled chamber for QC4 HV test at PU



I-V characteristics

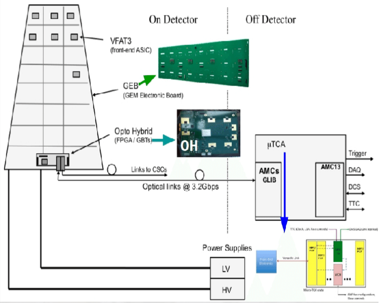


Intrinsic Noise Rate

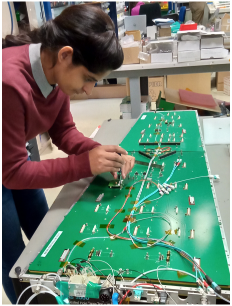
Result: all detectors passed QC4 test

QC7 and Superchamber assembly at CERN

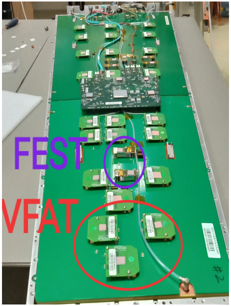
- QC7 $\longrightarrow$ test of electronics equipment's if they are working fine or not. GEM equipped with electronic components: i) VFAT3 Chip ii) FEST iii) Opto-Hybrid (OH)



GEM electronics readout system



GEM with Electronics Board (GEB)



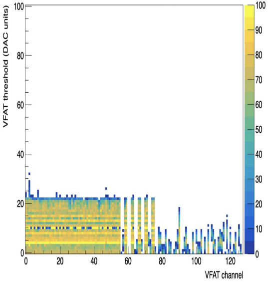
GEB + Electronics component

- ☆ VFAT3 Chip: one VFAT has 128 input channels in 24 different sections, give us information about response of channels, splits data into two paths: i) triggering ii) tracking
- ☆ OH: communicate with VFATs $\rightarrow$ i)3 VTXs transmit tracking data out of detector to off-detector electronics ii) transmit trigger data, one to GEMs & 2nd to CSCs electronics
- ☆ FEST: supply voltage to VFAT & Opto-Hybrid

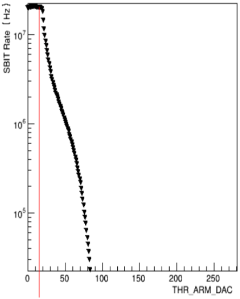
QC7 tests

QC7 tests:

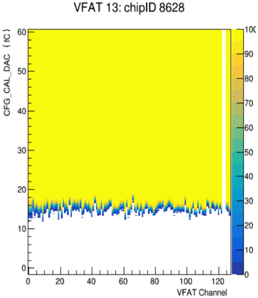
1. **Visibly & DAC threshold scan connectivity test:** absence of hits in channels indicates a disconnection of VFATs from readout strips
2. **Sbit scan:** check no issue in trigger path by looking output from trigger link i.e number of event from noise & threshold must < 50
3. **Scurve scan:** represent overall response of a channel to amount of injected charge. & If dead channel (0 eff) < 3, figure out how to fix it & run test again. In figure, y-axis: injected charge, z-axis: no. of hits out of 100



Partially unplugged VFAT



Bad Sbit scan

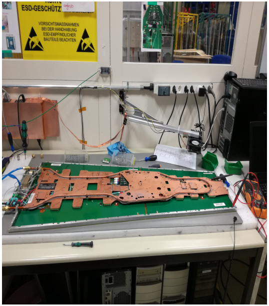


Bad Scruve

QC7 tests continue... & Superchamber assembly

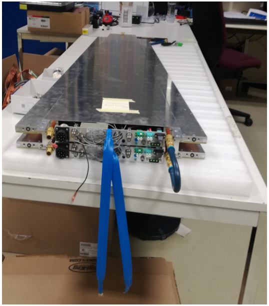
- Again performed all QC7 tests with:

1. Cooling plate
2. Thermal screen



Chamber with cooling plate

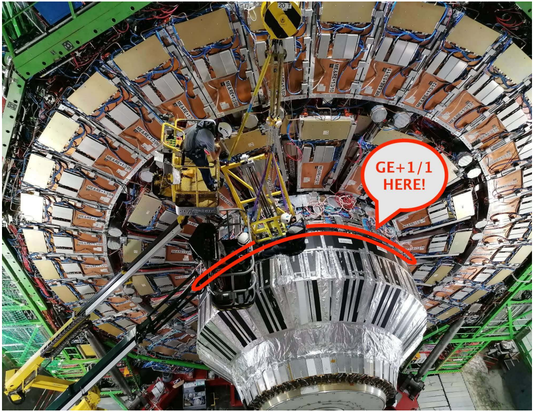
Chamber with thermal screen



Assembled Superchamber

GE1/1:

- Eight production chambers have been assembled & qualified quality control test at PU site & later on at CERN
- All chamber successfully have already been installed in CMS detector during Long shutdown 2 & are currently taking data
- Performed QC7 test of 15 chamber for full time at CERN

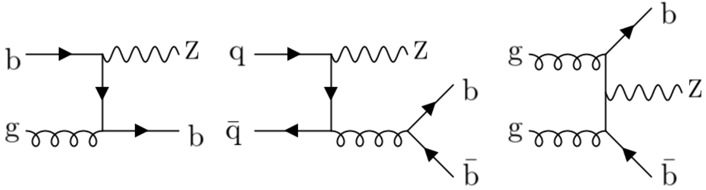


Thesis Part-II

Physics data analysis

Motivation: Z + b-jets analysis

- ☆ Measurements of Z + HF production provides important test of electroweak & pQCD predictions
- ☆ Provides information on b quark PDFs & help to improve modeling of b quarks production
- ☆ Provide valuable inputs for tuning & constraining model parameters of advanced MC
- ☆ Important background in many SM measurements & BSM searches
- ☆ Previous measurements showed substantial mismodeling of b quark



Z + 1 b-jet   Z + 2 b-jets

- To measure integrated & differential cross sections for $Z(\rightarrow ll{=}ee/\mu\mu) + \geq 1$ b-jet & $Z(\rightarrow ll{=}ee/\mu\mu) + \geq 2$ b-jets

☆ Observables in differential cross section measurements

$Z + \geq 1$ b-jet:

- $p_{\mathrm{T}}^{\mathrm{Z}}$
- $p_{\mathrm{T}}^{\text{b-jet}}$
- $|\eta^{\text{b-jet}}|$
- $\Delta\phi^{(\mathrm{Z},\,\text{b-jet})}$
- $\Delta y^{(\mathrm{Z},\,\text{b-jet})}$
- $\Delta R^{(\mathrm{Z},\,\text{b-jet})}$

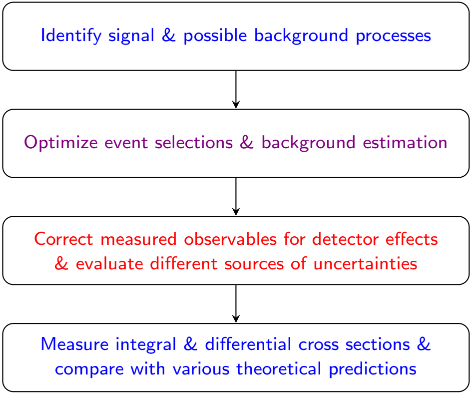
$Z + \geq 2$ b-jets:

- $p_{\mathrm{T}}^{\mathrm{Z}}$, $p_{\mathrm{T}}^{\text{b-jet}_1}$, $p_{\mathrm{T}}^{\text{b-jet}_2}$
- $m^{(\text{b-jet}_1,\,\text{b-jet}_2)}$, $m^{(\mathrm{Z},\text{b-jet}_1,\,\text{b-jet}_2)}$
- $\Delta R^{(\text{b-jet}_1,\,\text{b-jet}_2)}$, $\Delta R^{(\mathrm{Z},\,\text{b-jet}_1,\,\text{b-jet}_2)}$
- $\min[\Delta R^{(\mathrm{Z},\,\text{b-jet}_1)}, \Delta R^{(\mathrm{Z},\,\text{b-jet}_2)}]$
- $A^{(\mathrm{Z},\text{b-jet}_1,\,\text{b-jet}_2)} = \frac{\max\Delta\mathrm{R_{Zb}} - \min\Delta\mathrm{R_{Zb}}}{\max\Delta\mathrm{R_{Zb}} + \min\Delta\mathrm{R_{Zb}}}$

➤ These are sensitive to PDF, initial-state radiation, final-state radiation, gluon splitting, & multiparton interactions

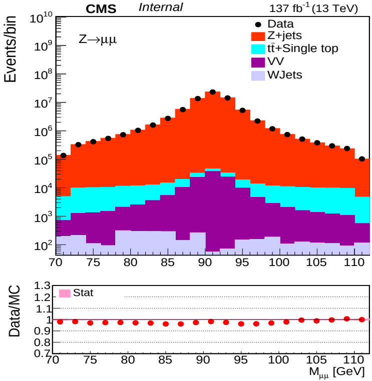
Analysis workflow

- Signal: $Z(\rightarrow ll{=}ee/\mu\mu) + \geq 1$ b-jet: Madgraph & Sherpa event generators are used to simulate Z + jets process which is inclusive in jet flavors (b, c, & light)
  - Classification Z + jets events into Z + b-jet, Z + c-jet, and Z + light-jet based on flavors of reconstructed jets
- Background: Z + jets, $t\bar{t}$, WW, WZ, ZZ, W + jets



- ☆ Run 2 (2016–2018) collision data with integrated luminosity of 137 fb^{-1}
- ☆ Single lepton triggers with p_T threshold of 27, 32, & 32 GeV (24, 27, & 24 GeV) for electron (muon) for 2016, 2017, and 2018
- ☆ Tight lepton ID and relative isolation criteria
- ☆ Z($\mu\mu$ or ee) boson: pair of oppositely charged leading & subleading lepton with p_T > 35 & 25 GeV & $|\eta_{ll}| < 2.4$, Z mass window (71 GeV $< M_{\mu\mu/ee} <$ 111 GeV)

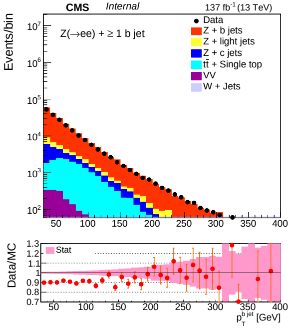
- Good agreement between data & MC for dilepton mass distributions

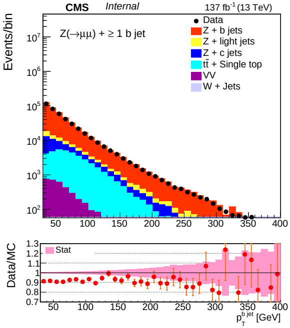


- ☆ MET < 50 GeV $\rightarrow$ to reduce $t\bar{t}$ background
- ☆ Jet: jets reconstructed with anti-k_T algorithm with a distance parameter of 0.4
  Tight Jet ID, $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R(\text{jet, lepton}) > 0.4$, PU MVA ID
- ☆ b-jets: tight WP of deepCSV btagger with 50–60% b-tagging efficiencies Click here
- ▶ Various scale factors applied related to lepton & jets selection

- $Z + \geq 1$ b-jet: leading b-tagged jet in p_T
- $Z + \geq 2$ b-jets: leading & subleading b-tagged jets in p_T

❖ $Z + \text{b-jet}$: MC overestimates data by 10–15%





Event yields in $Z + \geq 1$ b-jet final states

Process	2016		2017		2018		Run2	
	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$
Data	49481	107030	57578	118892	87377	189049	194436	414972
$Z +$ b-jets	47214	105082	48594	99639	77670	163498	173478	368221
$Z +$ light-jets	2114	4220	1888	3368	5774	10280	13700	29254
$Z +$ c-jets	3907	9240	3438	7136	6354	12877	9777	17868
Total simulation	127430	57309	59306	121263	98112	204371	214727	453142
Data/Total simulation	0.84	0.86	0.97	0.98	0.89	0.92	0.90	0.91

- Signal ($Z + \geq 1$ b-jet) is $\sim$ 81–84%
- Backgrounds: $t\bar{t}$ $\sim$3–7 %, $Z +$ light-jets $\sim$3–5%, $Z +$ c-jets $\sim$6–7%
  - $t\bar{t}$ validated using $e\mu + \geq 1$ b-jet
  - $Z +$ light-jets & $Z +$ c-jets validated with different tagger condition

Process: $e\mu + \geq 1$ b-jet, $t\bar{t}$-CR $\rightarrow e\mu$ + btag(T)

- $e\mu + \geq 1$ b-jet is very much clean process
- $t\bar{t}$ considered from data driven estimation

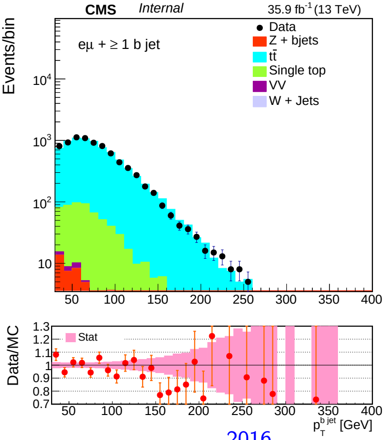
	2016	2017	2018
Data/Total MC	0.98	0.88	0.88
Purity (%)	92	92	92
Scale Factor	0.98	0.87	0.87

$$\text{Scale factor} = \frac{N_{e\mu}^{data} - N_{e\mu}^{non-t\bar{t}\,bkg}}{N^{t\bar{t}} MC_{e\mu}}$$

Purity = [data − (non-$t\bar{t}$ bkg)]/data,

non-$t\bar{t}$ bkg = DY+single top+WJets+VV

- Scale factor applied to $t\bar{t}$ $MC_{\mu\mu/ee}$ in $\mu\mu$ & ee channel

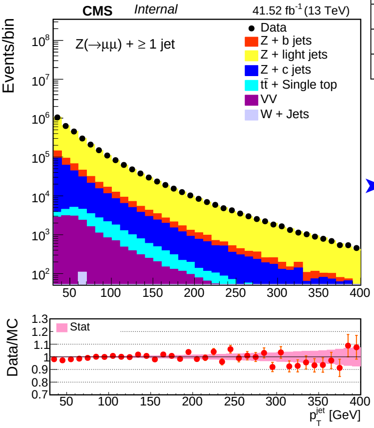


2016

Process: $Z + \geq 1$ jet

- L-CR1: $\rightarrow$ inclusive jets (Without b/c discriminator cut)
- Purity = [data − (non-light-jet bkg)]/data
- Scale factor applied in signal region ($Z + \geq 1$ b-jet) to $Z +$ light-jet MC

	2016		2017		2018	
	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee
Data/Total MC	0.94	0.96	0.98	0.98	0.92	0.90
Purity (%)	83	83	85	85	84	84
Scale Factors	0.93	0.95	0.98	0.98	0.91	0.89

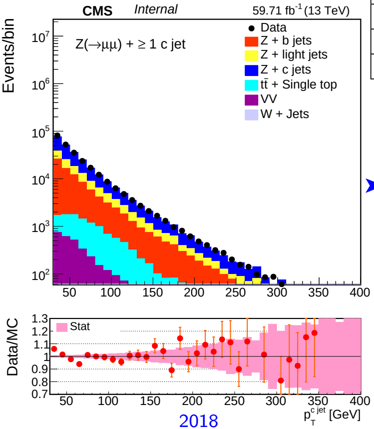


- Cross-check:
  - $Z +$ light-jet control region (CR2) $\rightarrow$ Inclusive jets (With anti-b & anti-c tag discriminator cut) to reject $Z +$ b-jet & $Z +$ c-jet events
  - Scale factors in CR1 & CR2 are consistent within 1–2%

Process: $Z + \geq 1$ c-jet

- C-CR3 $\rightarrow$ ctag(T)= CsvL& CsvB
- Purity = [data − (non-c-jet bkg)]/data
- Scale factor applied in signal region ($Z + \geq 1$ b-jet) to $Z +$ c-jet MC

	2016		2017		2018	
	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee
Data/Total MC	0.88	0.90	1.04	1.04	1.01	0.98
Purity (%)	41	41	55	53	49	47
Scale Factor	0.74	0.79	1.08	1.08	1.02	0.96



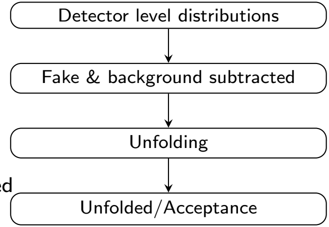
2018

- Cross-check:
  - Z + c-jet control region (C-CR4) $\rightarrow$ c tag & anti-b tag discriminator (to reject $Z +$ b-jet events)
  - Scale factors in CR3 & CR4 are consistent within 1–2%

- ☆ Event properties such as energy or scattering angle are measured only with finite precision & limited efficiency. Events may be reconstructed in wrong bin or may get lost
- ☆ Solution is $\rightarrow$ Unfold: that correct for detector effect
  - Unfolded results are useful for theoretical community & can be used for comparing measurements from different experiments

Unfolding Procedure:

- ➤ **Background/Fake:** subtracted from detector level distribution before unfolding
- ➤ **Response Matrix:** detector level events matched at gen level $\rightarrow$ unfold background subtracted distribution
- ➤ **Acceptance/Efficiency:** unfolded distribution is corrected with it to obtain final results



Uncertainties on integrated cross sections

Uncertainty (%)	ee	$\mu\mu$	ll
Statistical	1.0	0.7	0.6
JES, JER	2.7	3.0	2.9
b tagging/mistagging	3.0	2.9	2.9
Unclustered energy of $p_{\mathrm{T}}^{\mathrm{miss}}$	2.8	2.8	2.8
Background estimation	2.2	2.0	2.1
Pileup reweighting	2.4	1.7	1.9
Electron selection	4.6	—	1.5
Luminosity	1.6	1.6	1.6
Muon selection	—	0.6	0.4
Pileup jet identification	0.3	0.3	0.3
L1 prefiring	0.3	0.2	0.2
μ_{R} and μ_{F} scales	2.6	2.9	2.1
PDF	0.4	0.3	0.3
α_{s}	0.3	0.2	0.2
Total experimental	7.6	5.9	6.1
Total theoretical	2.6	2.9	2.1

PRD 105 (2022) 092014

Production cross section within fiducial region (b-jet $p_T > 30$ GeV, $|\eta| < 2.4$)

PRD 105 (2022) 092014

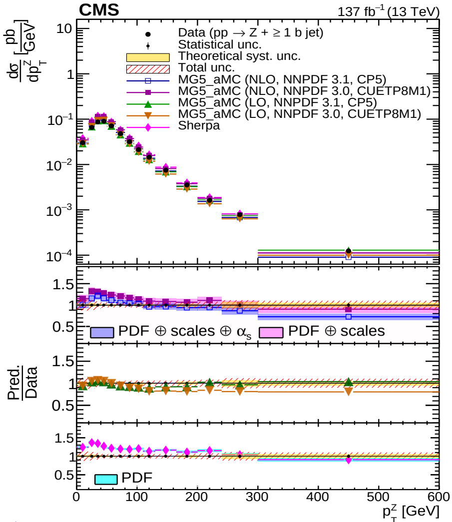
Channel		Measured	MG5_aMC LO NNPDF 3.0 CUETP8M1	MG5_aMC LO NNPDF 3.1 CP5	MG5_aMC NLO NNPDF 3.0 CUETP8M1	MG5_aMC NLO NNPDF 3.1 CP5	SHERPA
$Z + \geq 1$ b-jet	ee	6.45 ± 0.06 (stat) ± 0.49 (syst) ± 0.17 (theo)	6.25	6.33	7.86 ± 0.52 (theo)	7.05 ± 0.48 (theo)	8.05
	$\mu\mu$	6.55 ± 0.05 (stat) ± 0.39 (syst) ± 0.19 (theo)	6.26	6.34	7.86 ± 0.51 (theo)	7.02 ± 0.47 (theo)	7.98
	ll	6.52 ± 0.04 (stat) ± 0.40 (syst) ± 0.14 (theo)	6.25	6.34	7.86 ± 0.51 (theo)	7.03 ± 0.47 (theo)	8.02
$Z + \geq 2$ b-jets	ee	0.66 ± 0.05 (stat) ± 0.07 (syst) ± 0.02 (theo)	0.62	0.72	0.89 ± 0.08 (theo)	0.77 ± 0.07 (theo)	0.84
	$\mu\mu$	0.65 ± 0.04 (stat) ± 0.06 (syst) ± 0.02 (theo)	0.64	0.71	0.91 ± 0.09 (theo)	0.77 ± 0.07 (theo)	0.84
	ll	0.65 ± 0.03 (stat) ± 0.07 (syst) ± 0.02 (theo)	0.63	0.71	0.90 ± 0.09 (theo)	0.77 ± 0.07 (theo)	0.84

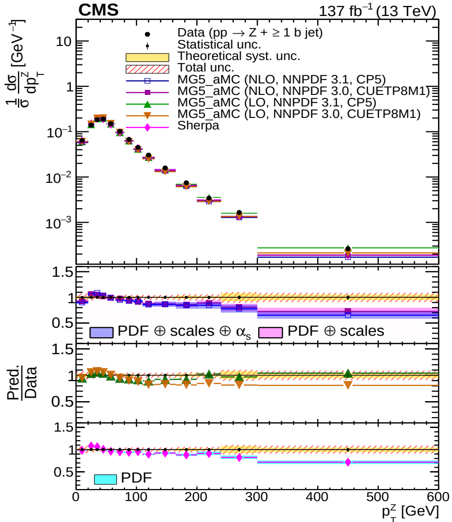
- ☆ $Z + \geq 1$ b-jet: MG5_aMC (LO) describe well data, MG5_aMC (NLO, NNPDF 3.1, CP5), MG5_aMC (NLO, NNPDF 3.0, CUETP8M1), & SHERPA overestimate up to 10%, 18%, & 24%, respectively
- ☆ $Z + \geq 2$ b-jets: MG5_aMC (NLO) & SHERPA generators overestimate data by 23% & 29%, respectively

MC predictions from MG5_aMC (NLO), MG5_aMC (LO), & SHERPA are normalized to an NNLO cross section

Unfolded differential & normalized differential cross section distributions

$Z + \geq 1$ b-jet (I/VI)

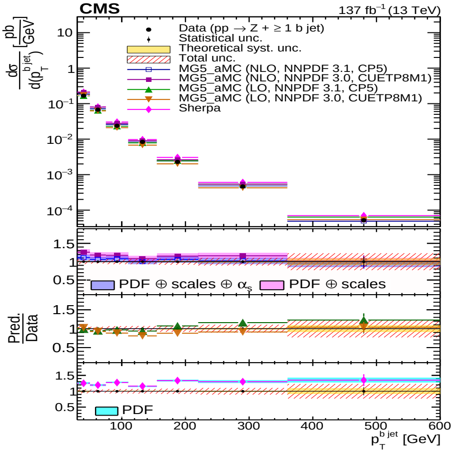


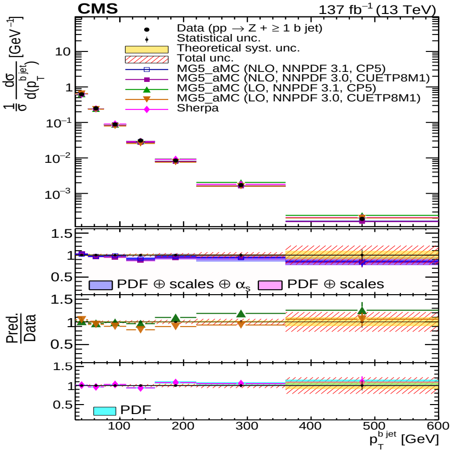


- Shapes of these distributions are described best by MG5_aMC (LO), while MG5_aMC (NLO) & SHERPA predictions vary up to 30% depending on Z p_T

PRD 105 (2022) 092014

Unfolded differential & normalized differential cross section distributions
$Z + \geq 1$ b-jet (II/VI)



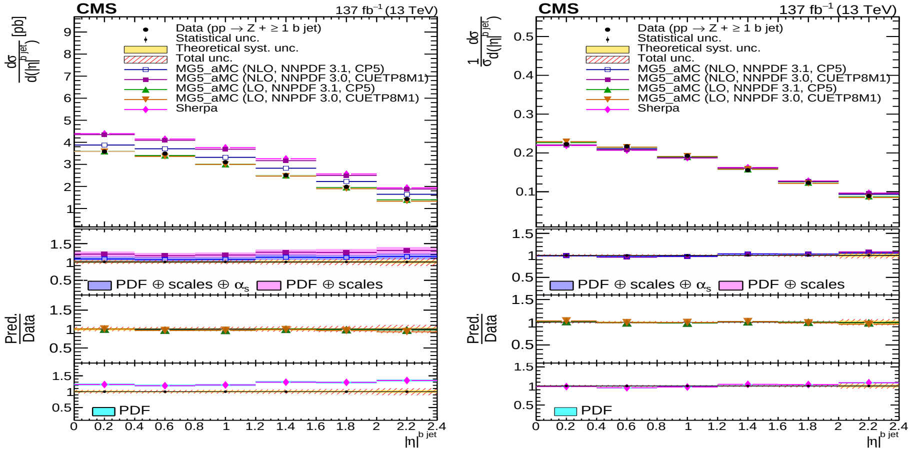


- Shapes of distributions are well described by all simulations, except for MG5_aMC (LO) that deviates up to 30% in higher p_T region.

PRD 105 (2022) 092014

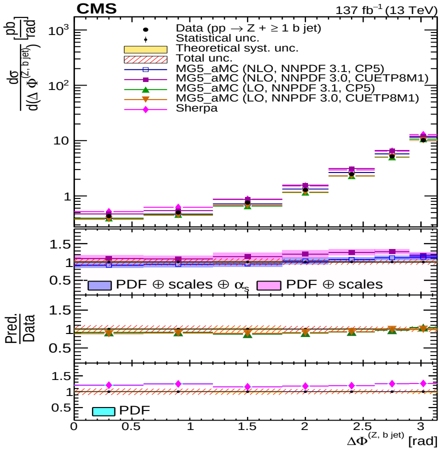
Unfolded differential & normalized differential cross section distributions

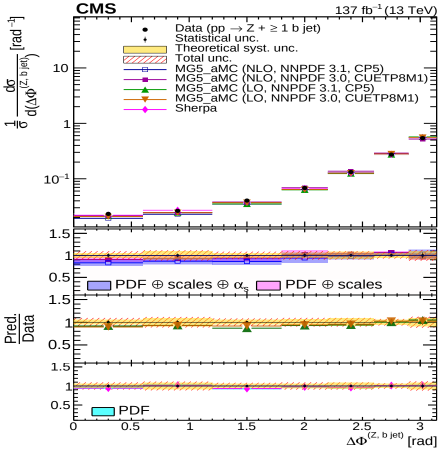
$Z + \geq 1$ b-jet (III/VI)



➤ Shapes of these distributions are well described by all simulations

PRD 105 (2022) 092014



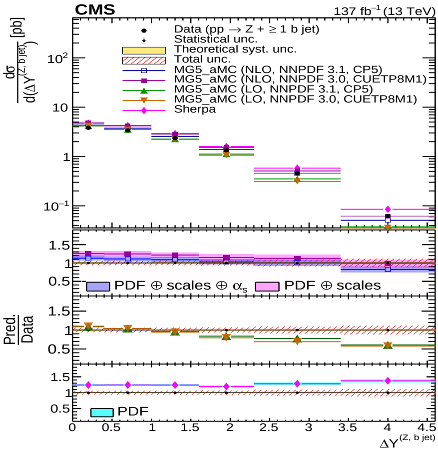


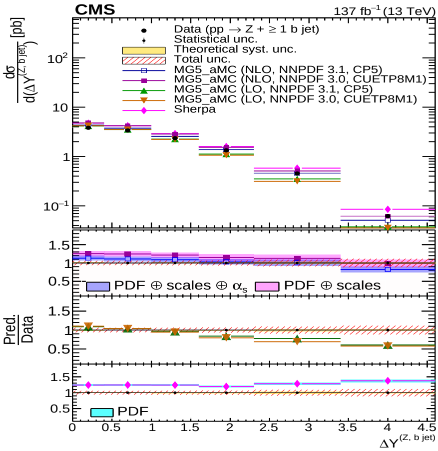
- Shapes of distributions are well described by SHERPA
- MG5_aMC NLO & LO both provide similar agreement for shape, although agreement is somewhat better for higher $\Delta\phi$ values than lower values

PRD 105 (2022) 092014

Unfolded differential & normalized differential cross section distributions

$Z + \geq 1$ b-jet (V/VI)



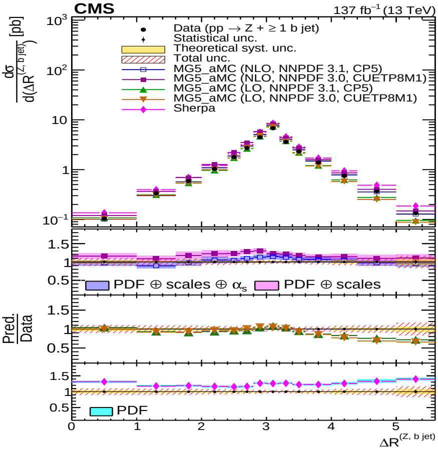


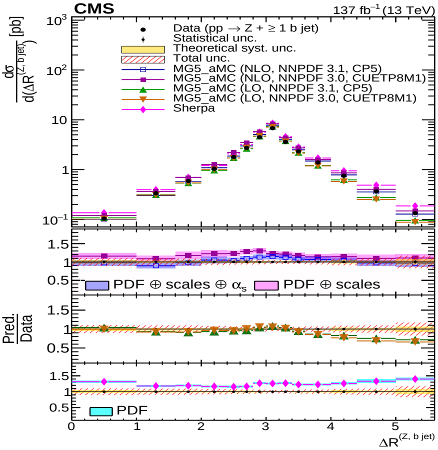
- Shape of SHERPA prediction agrees with data
- MG5_aMC LO shows largest deviation from data in high $\Delta y^{(\mathrm{Z,\, b\text{-}jet})}$ region, which is significantly improved with NLO prediction by MG5_aMC

PRD 105 (2022) 092014

Unfolded differential & normalized differential cross section distributions

$Z + \geq 1$ b-jet (VI/VI)





- Shapes of these distributions are well described by SHERPA
- MG5_aMC LO shows largest deviation from data in high $\Delta R^{(Z,\,\text{b-jet})}$ region, which is significantly improved with NLO prediction by MG5_aMC

PRD 105 (2022) 092014

Cross section ratio measurement

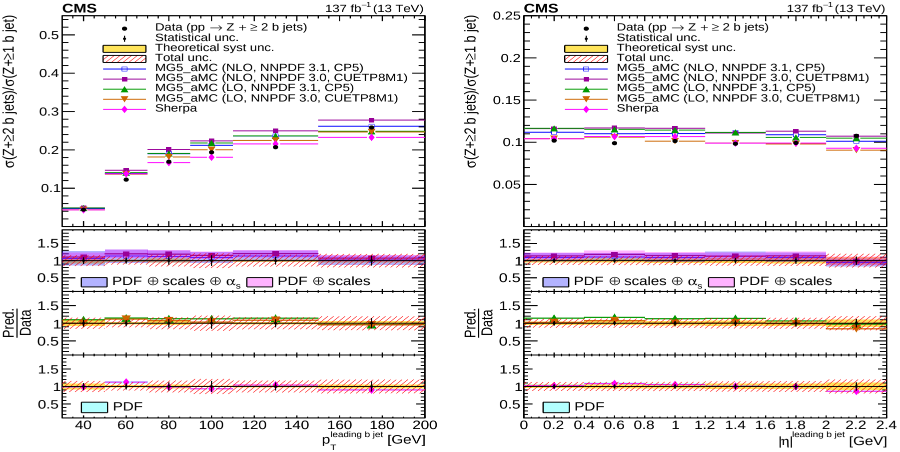
- ☆ Measure cross section ratios $\sigma(\mathrm{Z} + \geq 2\,\text{b-jets})/\sigma(\mathrm{Z} + \geq 1\,\text{b-jet})$
- ☆ Systematic uncertainties:
  - ➤ For correlated uncertainties (JES+JER, $p_{\mathrm{T}}^{\mathrm{miss}}$, b tagging, lepton selection, PU, L1 prefiring): vary uncertainties up & down simultaneously for $\mathrm{Z} + \geq 2\,\text{b-jets}$ & $\mathrm{Z} + \geq 1$ b-jet cross sections to obtain uncertainty on ratio
  - ➤ Background estimation uncertainty: summed in quadrature
  - ➤ Theoretical uncertainty (PDF, renormalization & factorization scales): summed in quadrature

PRD 105 (2022) 092014

	Channel	Measured	MG5_aMC LO NNPDF 3.0 CUETP8M1	MG5_aMC LO NNPDF 3.1 CP5	MG5_aMC NLO NNPDF 3.0 CUETP8M1	MG5_aMC NLO NNPDF 3.1 CP5	SHERPA
Ratio	ee	0.102 ± 0.008 (stat) ± 0.008 (syst) ± 0.004 (theo)	0.100	0.113	0.113 ± 0.016 (theo)	0.110 ± 0.013 (theo)	0.104
	$\mu\mu$	0.100 ± 0.006 (stat) ± 0.006 (syst) ± 0.004 (theo)	0.103	0.112	0.116 ± 0.016 (theo)	0.110 ± 0.013 (theo)	0.105
	ll	0.100 ± 0.005 (stat) ± 0.007 (syst) ± 0.003 (theo)	0.102	0.112	0.114 ± 0.016 (theo)	0.110 ± 0.013 (theo)	0.105

- ➤ Measurement is in agreement only with MG5_aMC (LO, NNPDF 3.0, CUETP8M1) & SHERPA

Unfolded differential cross section ratio distributions of $Z + \geq 2$ b-jets & $Z + \geq 1$ b-jet



- ➤ Ratios increase as a function of leading jet p_T. They are independent of leading jet $|\eta|$
- ➤ MC predictions are consistent with data within uncertainties

PRD 105 (2022) 092014

☆ Z + b-jets analysis

- Cross sections measurement of Z + b-jets processes performed using 2016–2018 pp collisions data at $\sqrt{s} = 13$ TeV
- $\sigma(Z + \geq 1$ b-jet$) = 6.52 \pm 0.04$ (stat) ± 0.40 (syst) ± 0.14 (theo) pb
  - Well described by both MG5_aMC (LO, NNPDF 3.0, CUETP8M1) & MG5_aMC (LO, NNPDF 3.1, CP5) simulations
  - MG5_aMC (NLO, NNPDF 3.1, CP5), MG5_aMC (NLO, NNPDF 3.0, CUETP8M1), & SHERPA overestimate data by ≈10%, ≈18% & ≈24%, respectively
- $\sigma(Z + \geq 2$ b-jets$)/\sigma(Z + \geq 1$ b-jet$) = 0.100 \pm 0.005$ (stat) ± 0.007 (syst) ± 0.003 (theo)
  - Well described by MG5_aMC (LO, NNPDF 3.0, CUETP8M1) & SHERPA calculations but overestimated by MG5_aMC (NLO) predictions
- Shapes of various kinematic observables are well described by SHERPA prediction but are not completely described by MG5_aMC (LO) and MG5_aMC (NLO) predictions
  - This differences between MG5_aMC (NLO) & MG5_aMC (LO) results could be attributable to variations in shapes of observables & settings (parton distribution functions, MC tunes, matching schemes) used in those simulations
- Present measurements can be used as an input for further optimization of simulation parameters & b quark PDF to improve MC
- This work has been published in PRD 105 (2022) 092014 & presented in various international conferences

Ongoing work

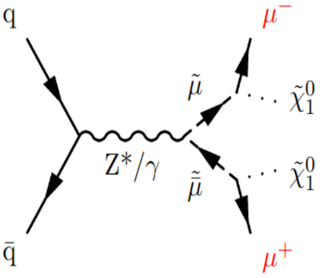
Physics data analysis: Search for massive long-lived particle (LLP) decaying to a top quark in pp collisions at 13 TeV

Group: Daniel Bloch & Jérémy Andrea & Paul Vaucelle

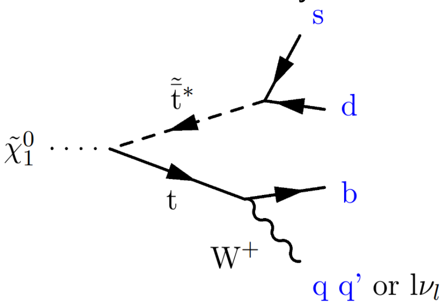
Based on *a phenomenological study*[1] to look for displaced top quarks, we focus on the RPV process with a Bino-like neutralino production from slepton decay

[1] : J.Andrea, D.Bloch, É.Conte, D.Darej, R.Ducrocq, E.Nibigira, arXiv:2212.06678 (2023)

smuon pair production



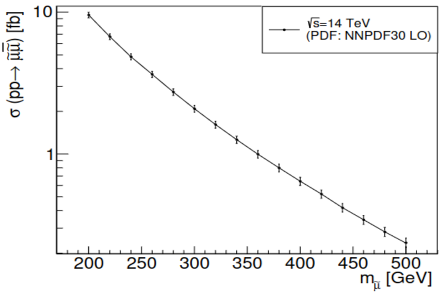
Neutralino decay

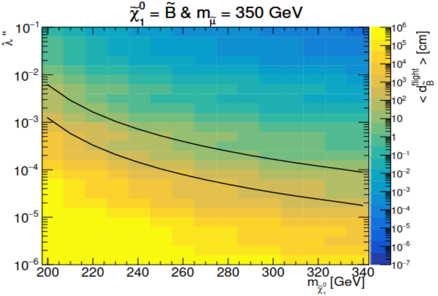


- $Br(\tilde{\mu} \to \mu\tilde{\chi}_1^0) = 1$
- 2 long-lived neutralinos
  - Two prompt muons
  - Trigger on muons

- λ''_{312} RPV Coupling
- Displaced top and stop → 6 to 10 jets

Phase Space





- smuon pair-production has a cross section of the order of few fb
- Lower limit on Mass $\tilde{\mu}$ due to previous experimental results
- Upper limit for the signal to be observable or to put limits on it

- λ''_{312} vs Mass $\tilde{\chi}^0_1$ for a given Mass $\tilde{\mu}$
- Constraint our search to the tracker volume (black lines)

- 2018 collision data (later 2016 & 2017...)
- Double || Single lepton triggers with p_{T} threshold of 17 || 24 GeV
- **Offline selection of dimuons**: Two muons with Tight ID + TkIsoTight are required $p_{T1} > 25 GeV$, $\eta < 2.4$, & $p_{T2} > 10 GeV$ $|d_{xy}| < 0.1$ cm & $|d_z| < 0.2$ cm (prompt), $M_{\mu\mu} > 10$ GeV (remove low-resonances)

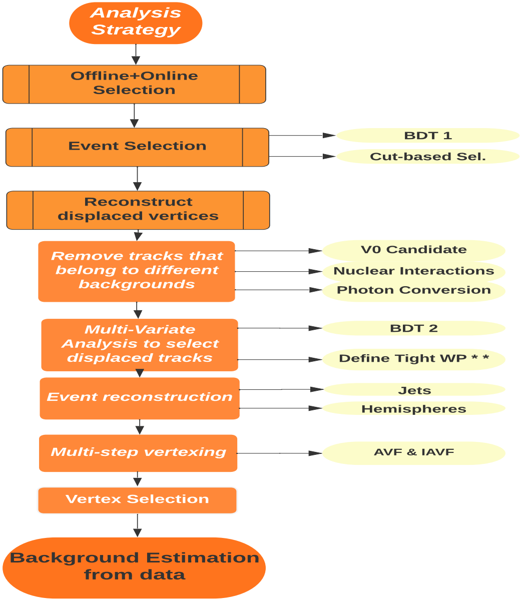
☆ $\sim$ 75% of signal ($\sim$ 12% of $t\bar{t} \rightarrow ll$+jets) events pass through triggers + offline selection

- AK4PF jets: Tight Jet ID with lepton veto, $p_T > 20 GeV$, η <2.4

☆ In signal region dominant background is $t\bar{t}$ estimated in eμ channel (WIP)

  - One muon: Tight ID + TkIsoTight, $p_T^\mu > 25 GeV$, $\eta < 2.4$, $|D_{xy}^\mu| < 0.1$ cm & $|d_z^\mu| < 0.2$ cm (prompt)
  - One electron: Tight ID, $p_{T2}^e > 10 GeV$, $\eta^e < 2.4$, excluded 1.442< $|\eta| < 1.566$, Barrel→ d0 (dz) 0.05 (0.10) cm, Endcap→ d0 (dz) 0.10 (0.20) cm
  - $M_{\mu e} > 10$ GeV (remove low-resonances)

Analysis Strategy



Track pre-selections

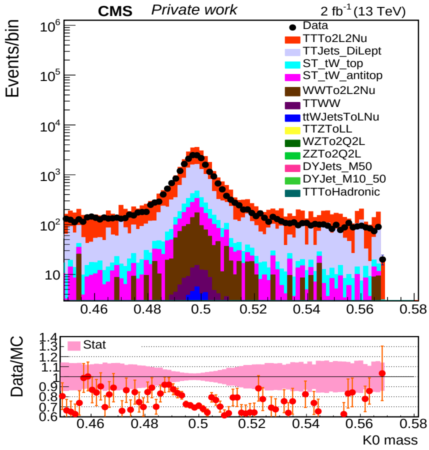
- First tracks are removed coming from different sources such as $V^0(K_s^0 \to (\pi^+\pi^-)$, $\Lambda \to (p\pi^-)$ or $(\bar{p}\pi^+))$ candidates, photon conversions & other nuclear interactions
- Preselection cut: Tracks with $p_t > 1\,\mathrm{GeV}$ & $\chi^2/dof < 5$ & $|\frac{d_{xy}}{\sigma_{xy}}| > 5$

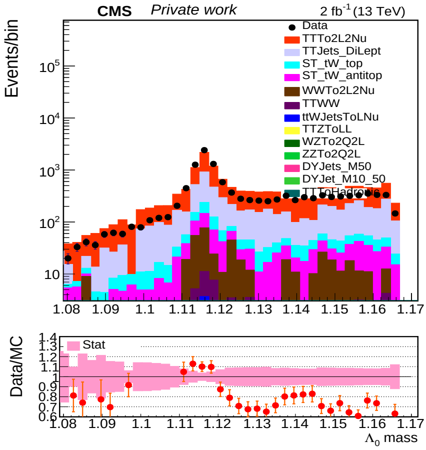
➤ $\sim$95% of the tracks from generated neutralinos are kept

➤ $\sim$90% of the bkg tracks are removed (from primary vertex or pileup or fake tracks)

➤ $\sim$94% of the tracks from $t\bar{t}$ are rejected

Data vs MC Validation in $t\bar{t}$ control region





Summary

WIP:

1. Data/MC agreement with Run2 data & estimating dominant background from data

Future:

1. Started an Analysis Note
2. Hopefully officially register in Cms Analysis Database Interface (CADI) line before the end of the year for internal review in CMS

List of Publications (AN/PAS/Paper)

1. "Measurement of Z+b jets cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV", CMS PAS-20-015 (2021).
2. "Measurement of distributions sensitive to double parton scattering using Z bosons produced in association with jets at 13 TeV", CMS PAS-SMP-20-009 (2021).
3. "Level-jets and energy sums trigger performance with full 2017 dataset", CMS-DP-2018/004 (2018).
4. "Measurement of the production cross section for Z + b jets in proton-proton collisions at $\sqrt{s} = 13$ TeV", **PRD 105 (2022) 092014**.
5. "Benchmarking LHC background particle simulation with the CMS triple-GEM detector", **JINST 16, P12026 (2021)**.
6. "Measurements of Z bosons plus jets using variables sensitive to double parton scattering in pp collisions at 13 TeV" **JHEP 10 (2021) 176**.
7. "Interstrip capacitances of the readout board used in large triple-GEM detectors for the CMS Muon Upgrade", **JINST 15 (2020) P12019.**
8. "Performance of the CMS Level-1 Trigger in proton-proton collisions at 13 TeV", **JINST 15 (2020) P10017.**

Conference proceedings

1. "Study for vector bosons production in association with heavy-flavor jets in proton-proton collisions", **Springer Proc. Phys. 277 (2022) 161**.
2. "Recent jet and jet substructure measurements at the LHC, and ML based tagging", **SciPost. Phys. Proc. (2021)**.
3. "Experimental measurement of Heavy Flavors and jets", **PoS LHCP 2021 (2021) 087.**
4. "Fabrication and Characterization of Gaseous Detector for the identification of High Energy Particles", **IOP Conference Series: Materials Science and Engineering (1033) 012055 (2021)**.
5. Quality Control Testing of GEM Detector, **Proceedings of the DAE Symp. on Nucl. Phys. (62) 2017.**
6. "Production of vector bosons in association with jets in CMS", **submitted in Zenodo, in April 2022.**

Presentations at Conferences and Workshops

1. "Azimuthal correlation measurements from Z+jets and dijets", in *REF22: Resummation, Evolution, Factorization 2022*, 31$^{\mathrm{st}}$ October-4$^{\mathrm{th}}$ November 2022, University of Montenegro, Montenegro.
2. "Vector boson associated with jets in CMS", in 30$^{\mathrm{th}}$ *International Symposium on Lepton Photon Interactions at High Energies*, was held on 10$^{\mathrm{th}}$-14$^{\mathrm{th}}$ January, 2022 at the University of Manchester.
3. Poster presented on "Recent measurement of heavy flavors jets with CMS detector" in *Posters@LHCC* on 18th November, 2021.
4. "Recent jet and jet substructure measurements at the LHC, and ML based tagging", in *50*$^{\mathrm{th}}$ *International Symposium on Multiparticle Dynamics (ISMD2021)*, held on 12$^{\mathrm{th}}$-16$^{\mathrm{th}}$ July, 2021.
5. "Experimental measurement of Heavy Flavors and jets", in *The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021*, held on 7$^{\mathrm{th}}$-12$^{\mathrm{th}}$ June, 2021.
6. "Vector boson plus heavy-flavor jets measurements at CMS", in *Pheno2021: Phenomenology 2021 Symposium*, University of Pittsburgh, Pennsylvania, held on 24$^{\mathrm{th}}$-26$^{\mathrm{th}}$ May, 2021.
7. "Study for vector bosons production in association with heavy-flavor jets" in 24$^{\mathrm{th}}$ *DAE-BRNS High Energy Physics Symposium 2020, Bhubaneswar, India* held on 14$^{\mathrm{th}}$-20$^{\mathrm{th}}$ December, 2020.
8. "Study Of Z+ Heavy Flavor Jets In Proton Proton Collision" in 14$^{\mathrm{th}}$ *Chandigarh Science Congress (CHASCON)*, held at Panjab University, Chandigarh, India on 17$^{\mathrm{th}}$-19$^{\mathrm{th}}$ December, 2020.

9. "Fabrication and Characterization of Gaseous Detector for the identification of High Energy Particles" in *International Conference on Integrated Interdisciplinary Innovations in Engineering* held at UIET, Panjab University, Chandigarh, India held on 28^{th}-30^{th} August, 2020.
10. "Study for Z boson production in association with b-jets in proton-proton collision at 13 TeV" in 23^{rd} *DAE-BRNS High Energy Physics Symposium* held at IIT Madras, India on 10^{th} - 14^{th} December, 2018.


Thank
You
Merci
Danke
Grazas
Arigato
Dank Je
Biyan
Maake
Dhanyavadagalu
Juspaxar
ありがとう
谢谢

Jets:

- Due to color confinement of parton (quark & gluon), hadronization takes place & produces colorless hadrons in cones of outgoing particles called jets

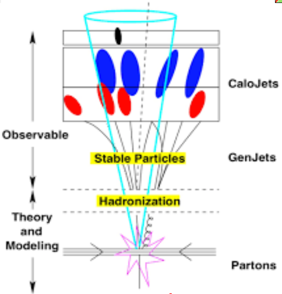
b-jets:

- Initiated by b quark with characteristic lifetime (1.5 ps) of b hadron, will travel ∼1 cm (at energy in lab frame ∼10–100 GeV) before decaying to several particles form new vertex (secondary vertex)

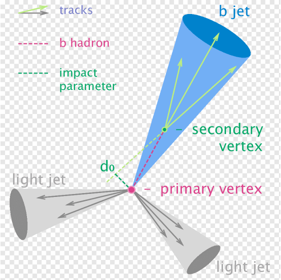
Identification of b-jets:

- Reconstructable secondary vertex, time of flight
- Displaced tracks with respect to primary interaction vertex (PV)
- Sign of impact parameter (positive if track minimal approach to jet axis is downstream PV along jet direction)
- Soft lepton information

Go back



Jets

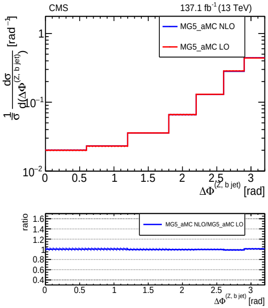


b-jets

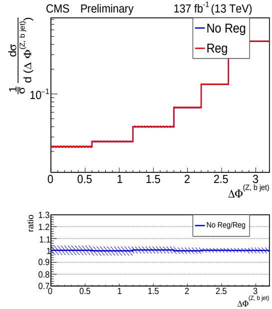
Unfolding method (TUnfold package)

☆ Unfolding of full Run 2 data:

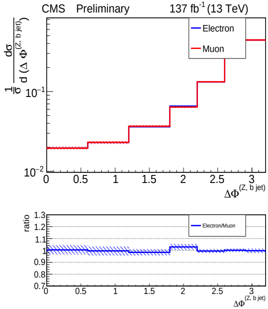
- ➤ Unfolding of full data is done with a single response matrix
- ➤ Background/Fake subtracted for each channel & year before combined unfolding
- ➤ Acceptance estimated from a combination of channels & years
- ➤ Binning chosen on basis of resolution, purity, fake rate, & stability
- ➤ Detector-level binning are about twice that of particle-level distributions bins
- ➤ Performed MC truth validations (statistically independent tests), checked effect of regularization, & studied feasibility to combine muon & electron channels



Statistical independent test



With & without regularization



Feasibility to combine μ & electron channels