Standard Model Physics with CMS Detector

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for TIFR-CMS-A Group

Annual DHEP Meeting 7-8 April 2016

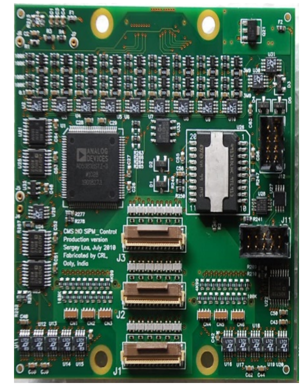
Plan of talk

- **Hardware contributions**
  - Upgrade of Outer Hadron Calorimeter
  - Embedded DAQ system for radiation monitors in HF region
  - CMS Upgrade (HGCAL and Tracker)
- **Standard Model Physics (Poster presentation tomorrow)**
  - Measurement of t-channel single top quark inclusive cross section (CMS-PAS-TOP-16-003)
  - Study of ratio of W^{+}+jets/W^{-}+jets ratio as function of p_t
  - Search for exotic Z charmonium like states

Upgrade of HO Detector with SiPM

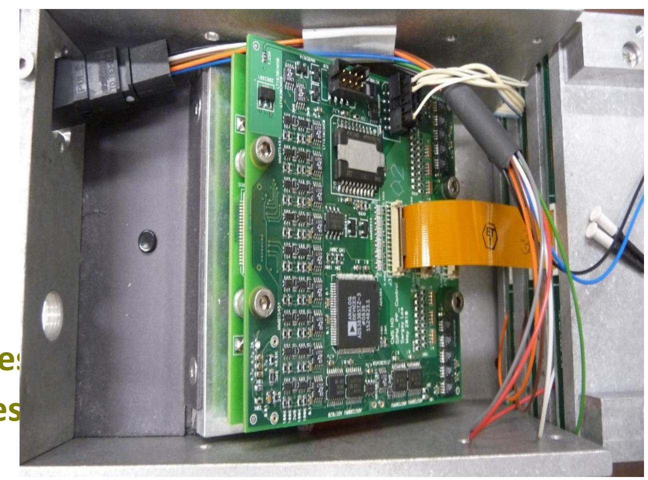
- **Validation of SiPM for CMS environment**
    - Testbeam studies, stability, radiation hardness, magnetic field immunity and saturation effects
- **Fabrication of 160 SiPM Control Boards at CRL, Ooty**
    - Each board has 18 Channels
    - Control boards provides generates bias voltage for, each channel monitors current, temperature etc.
    - Entire production and quality control of 160 boards d to be carried in India
- **Quality Control of Control Boards and SiPM Boards**
- **(160+160) at CRL, Ooty, India:**
    - Setting up stand-alone DAQ system for Control and SiPM boards
    - Development of software for QC Data Analysis
    - Generating QC report for each board
- **Installation and Commissioning:**
    - Removal of 132 Readout Modules, Assembly of Readout Modules QC and burn-in test at CERN, Installation of 132 Readout Modules
- **Project Leaders for Fabrication:**
    - Jim Freeman (FNAL) and Shashi Dugad (TIFR)
    - ***Funded by TIFR, FNAL, DESY***

HO Readout Module Assembly



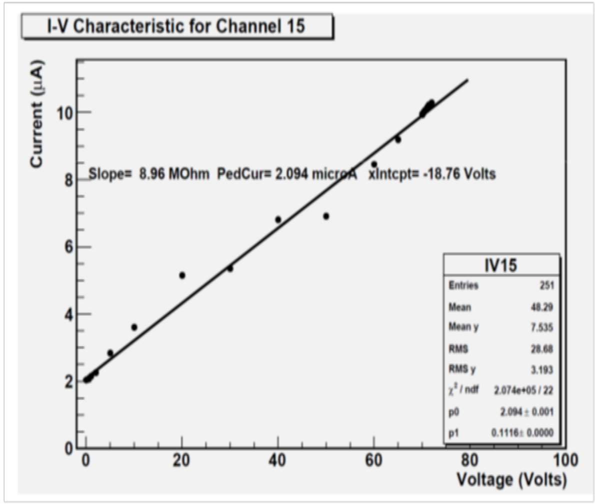
SiPM Control Board

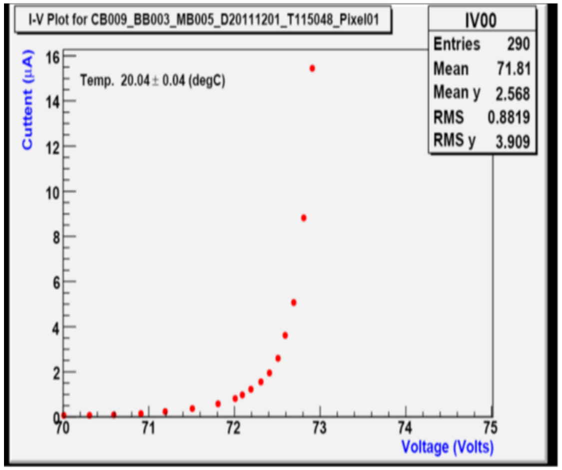
SiPM Mounting Board

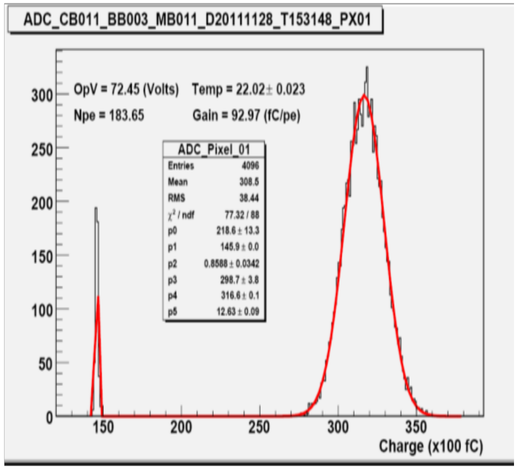


Upgrade of HO Detector with SiPM - Results

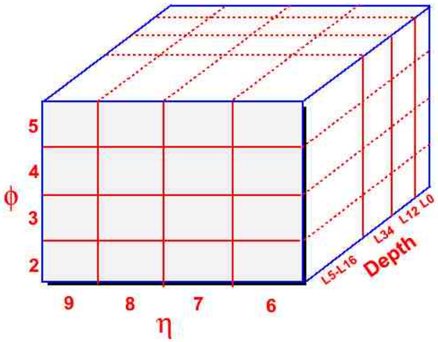
QC Results of HO Hardware

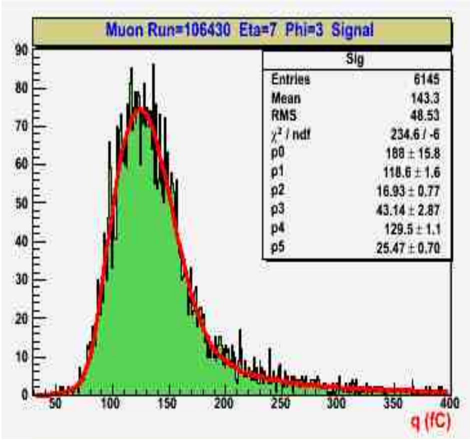


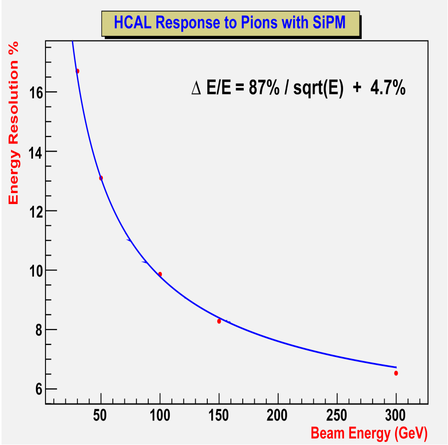


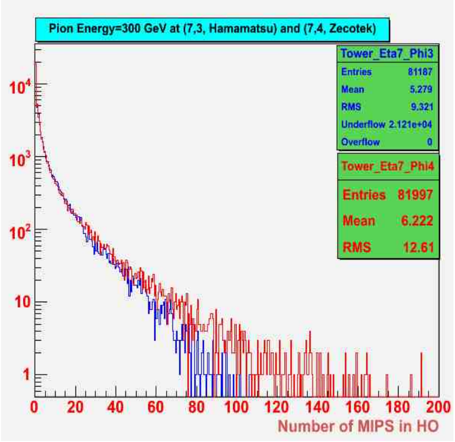


HO Response to muons, pions at Test-Beam



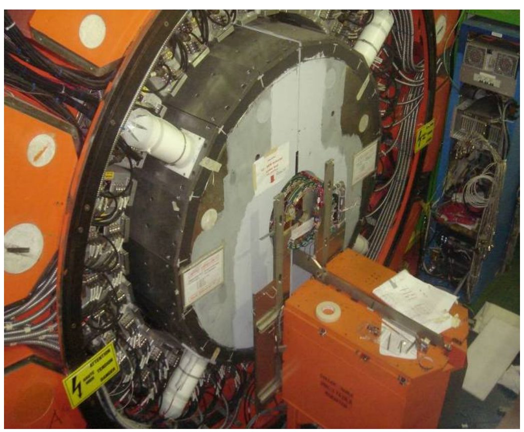




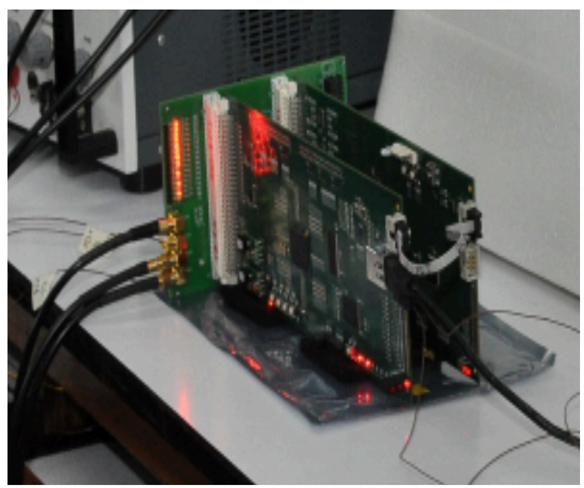


HFRADMON:
Data Acquisition System for HF Radiation Monitors at CMS

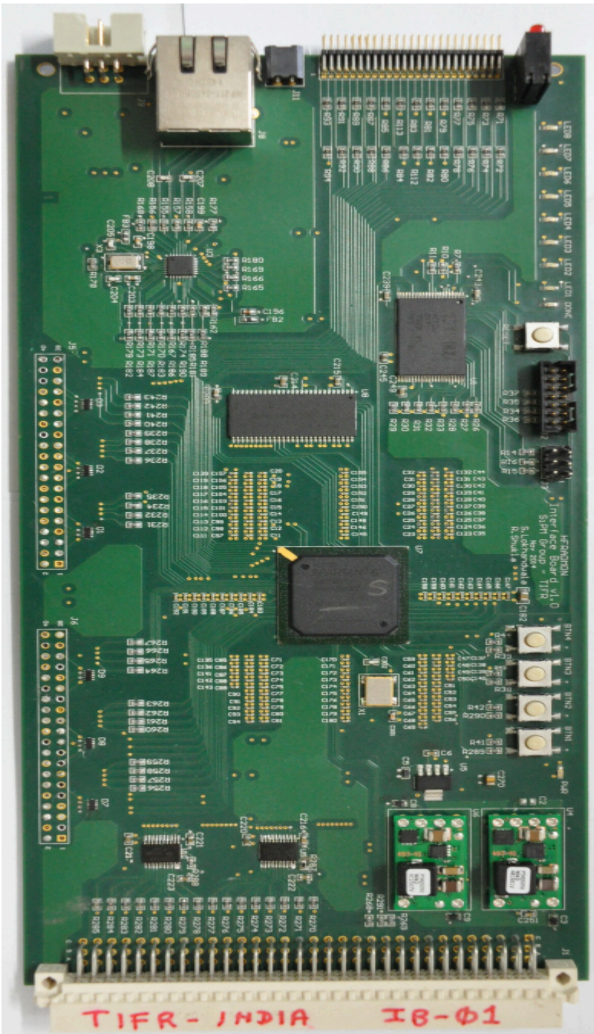
- ✓ Long term monitoring of the absorbed dose and neutron flux to estimate the expected degradation of fibers, electronics, PMTs and to measure the shielding efficiency.
- ✓ State of the art, high speed FPGA design with Ethernet communication
- ✓ Complete in-house design, fabrication and testing; complete design cycle completed in 6 months
- ✓ **Successful first prototype: Installed at CERN P5, operational 24x7**
- ✓ Highly flexible design, usability in SiPM development program and many more applications

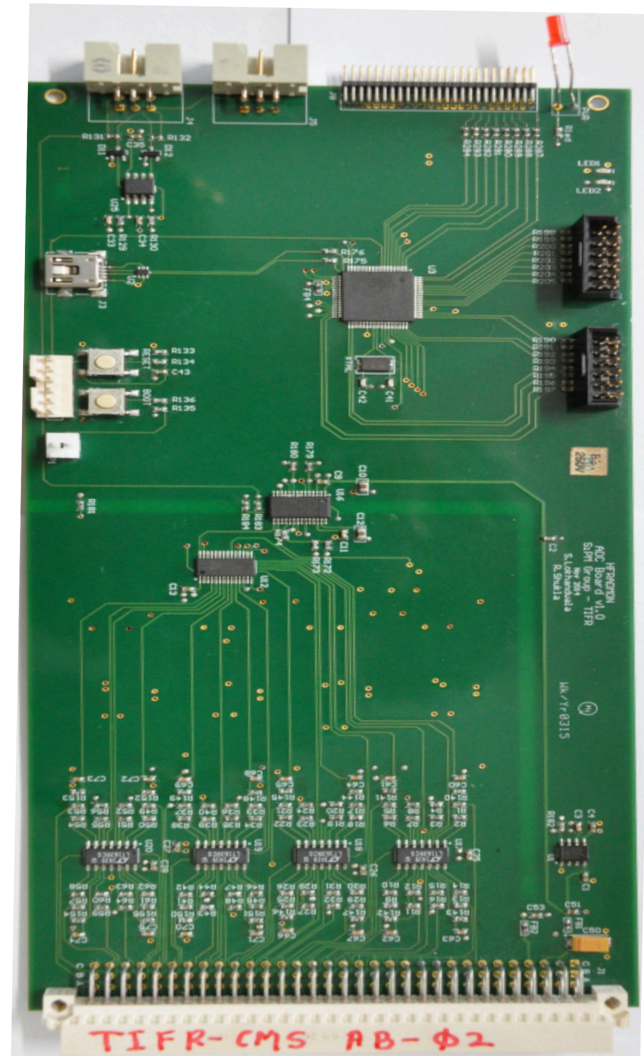


System for a radiation monitoring in the CMS HF area



Interface and ADC board





Interface and ADC board Firmware

Firmware for Spartan-6 FPGA

- ✓ Complete code written in Verilog
- ✓ In-house development of UDP soft-IP core
- ✓ 16, 32-bit high speed async counters
- ✓ Two internal counters for precise calibration of time-base
- ✓ I^2C Master controller for ADC board readout
- ✓ 32-bit checksum generation to check data integrity
- ✓ Internal and External Interlock Logic (Emergency stop)
- ✓ Detector status display with online fault monitoring logic
- ✓ Timestamp with 1ms 48-bit free running counter

Firmware for PIC Microcontroller

- ✓ Firmware has been written in embedded C
- ✓ Microcontroller acts as I^2C master as well as slave; controls on-board peripherals as a I^2C Master and responds to data read query from Interface board as I^2C slave
- ✓ The I^2C address of slave is programmed in firmware and can be any 7-bit number
- ✓ This allows for connecting many ADC boards together on common I^2C bus
- ✓ All analog channels (16 V, 16 I, temperature etc) sampled at programmable interval
- ✓ Online detector health monitoring and LED display
- ✓ 16-bit sampling event counter

CMS Endcap calorimetry

Sampling Calorimeter

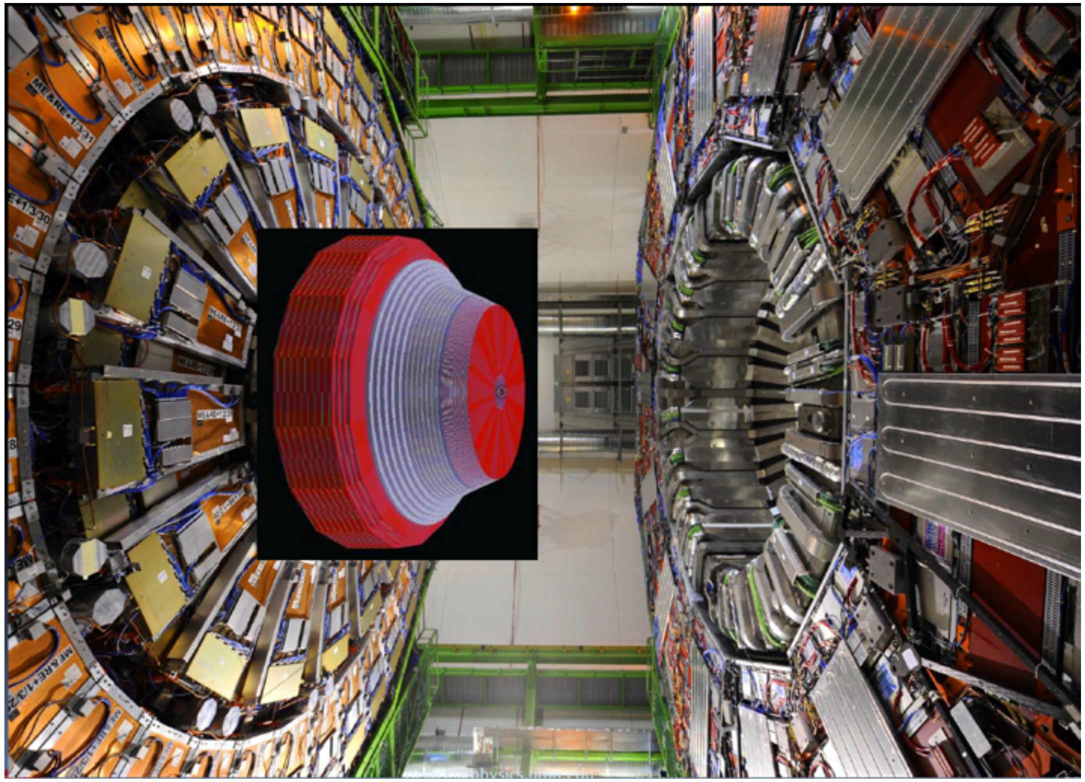
- Active Element: Scintillator
- Absorber: Brass
- Photo-readout Element: Hybrid Photo Diode
- Performance of detector degrading due to radiation damage of scintillators
- Existing Endcap scintillator based calorimeter to be replaced with silicon+scintillator based calorimeter
- Scintillators to be readout by SiPM

Next Generation Calorimeter at LHC

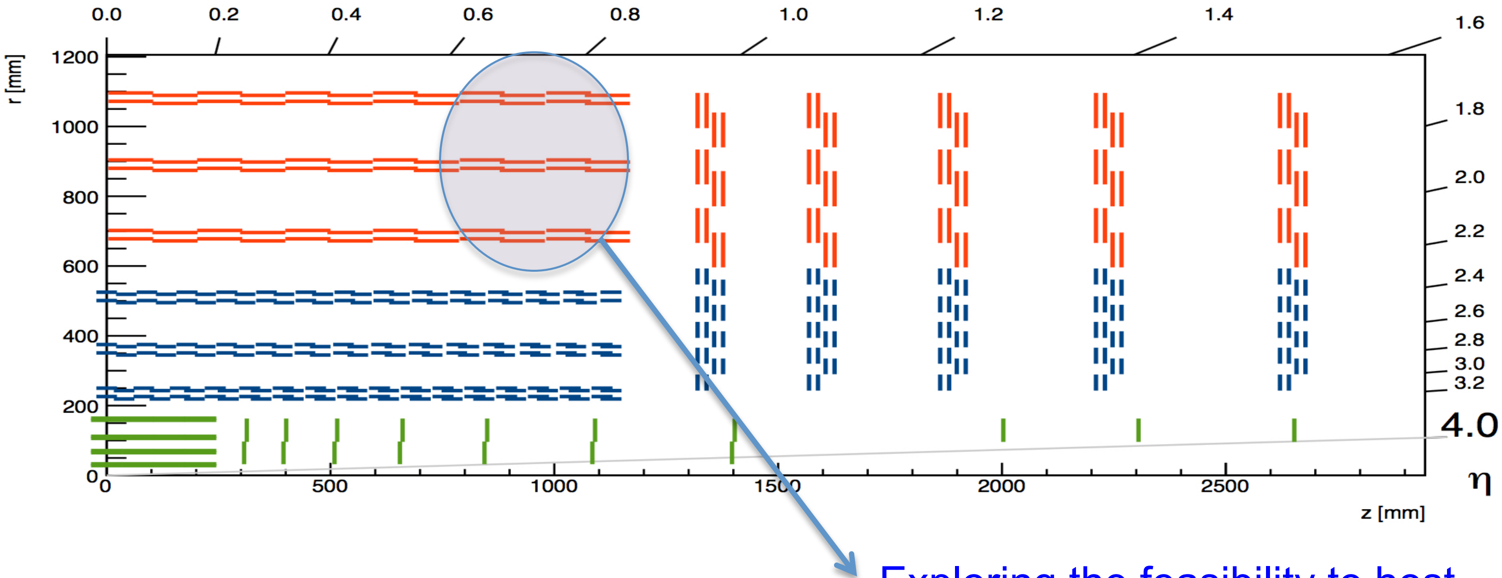
Components of HGCAL

Integrated sampling Silicon ECAL + Silicon HCAL + Backing Scintillator Calorimeters

- Sensors (Silicon/ Scintillator)
- Mechanics
- Front End Electronics
- Back End Electronics
- Trigger Generation
- Simulation



TIFR in Phase-2 tracker upgrade

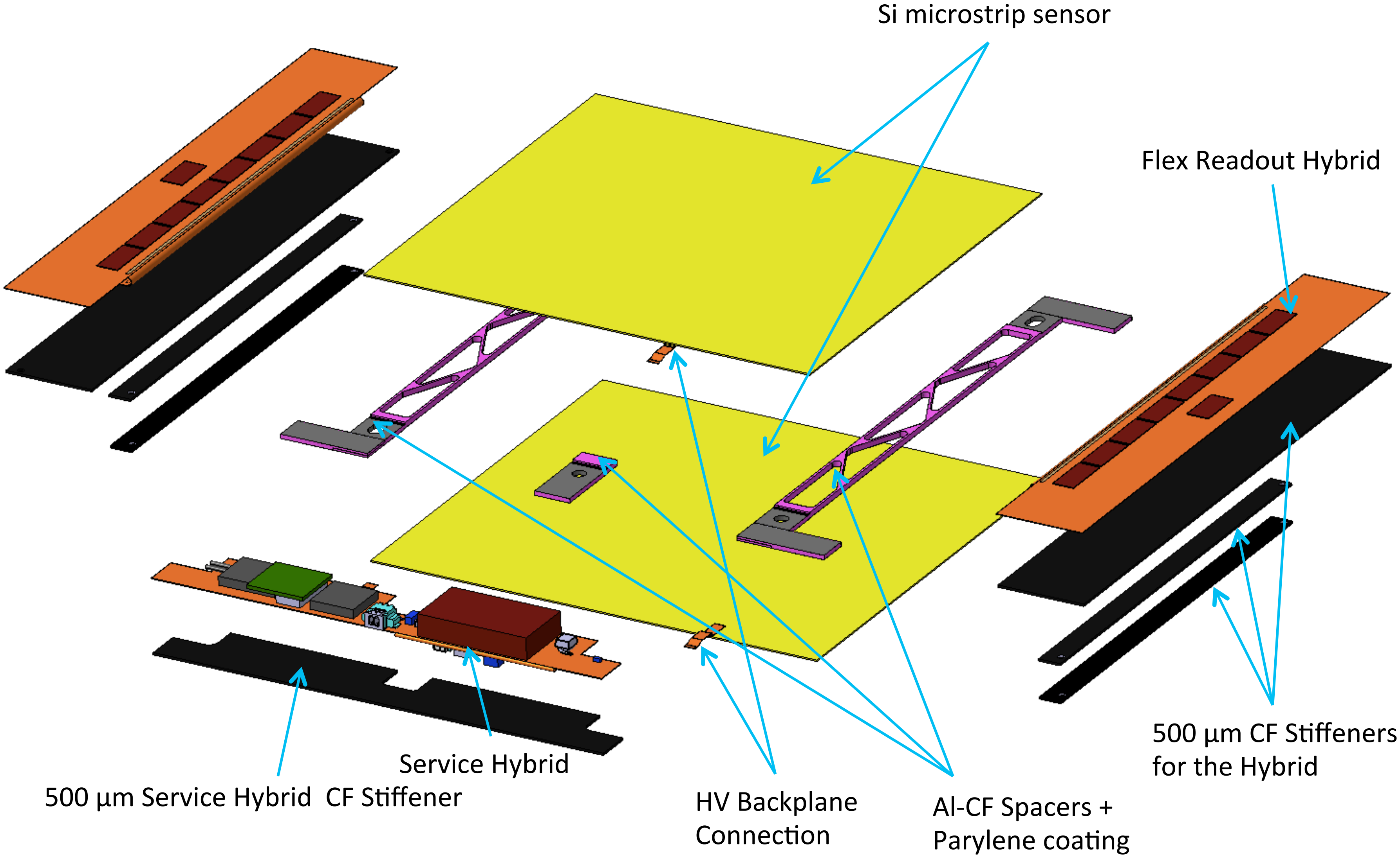


Exploring the feasibility to host one of the five assembly centers that would design, prototype and build ~2000 TB2S modules

- Phase 2: 2024-2026
- TDR expected: Jun 2017

Module assembly and testing in addition to sensor qualification and precision mechanics will be a pan-India contribution

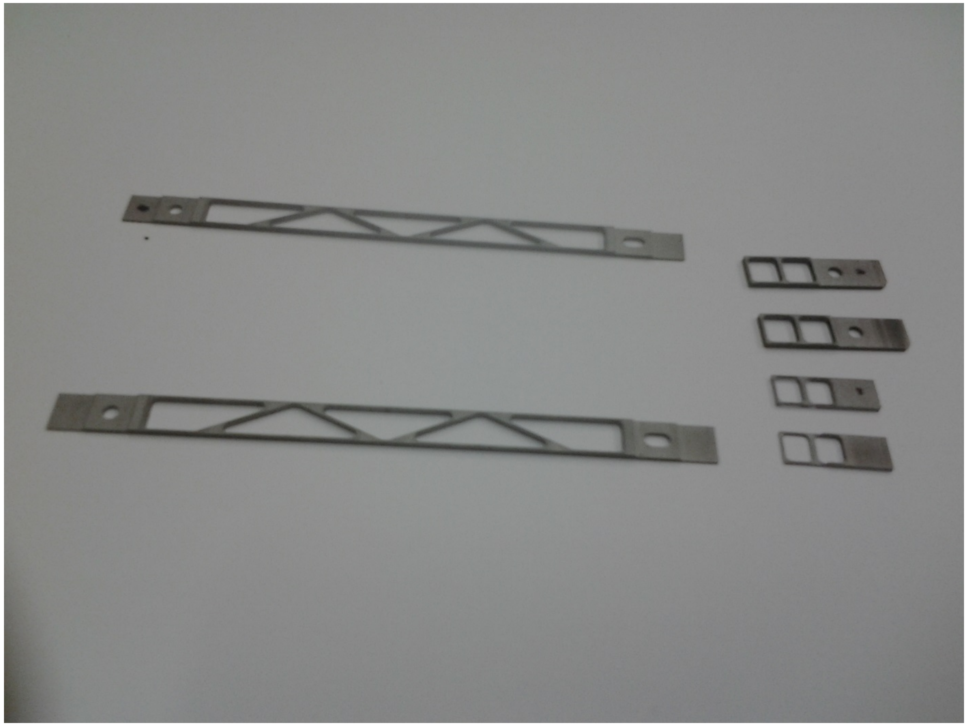
An expanded view of a TB2S module



R&D efforts on precision mechanics

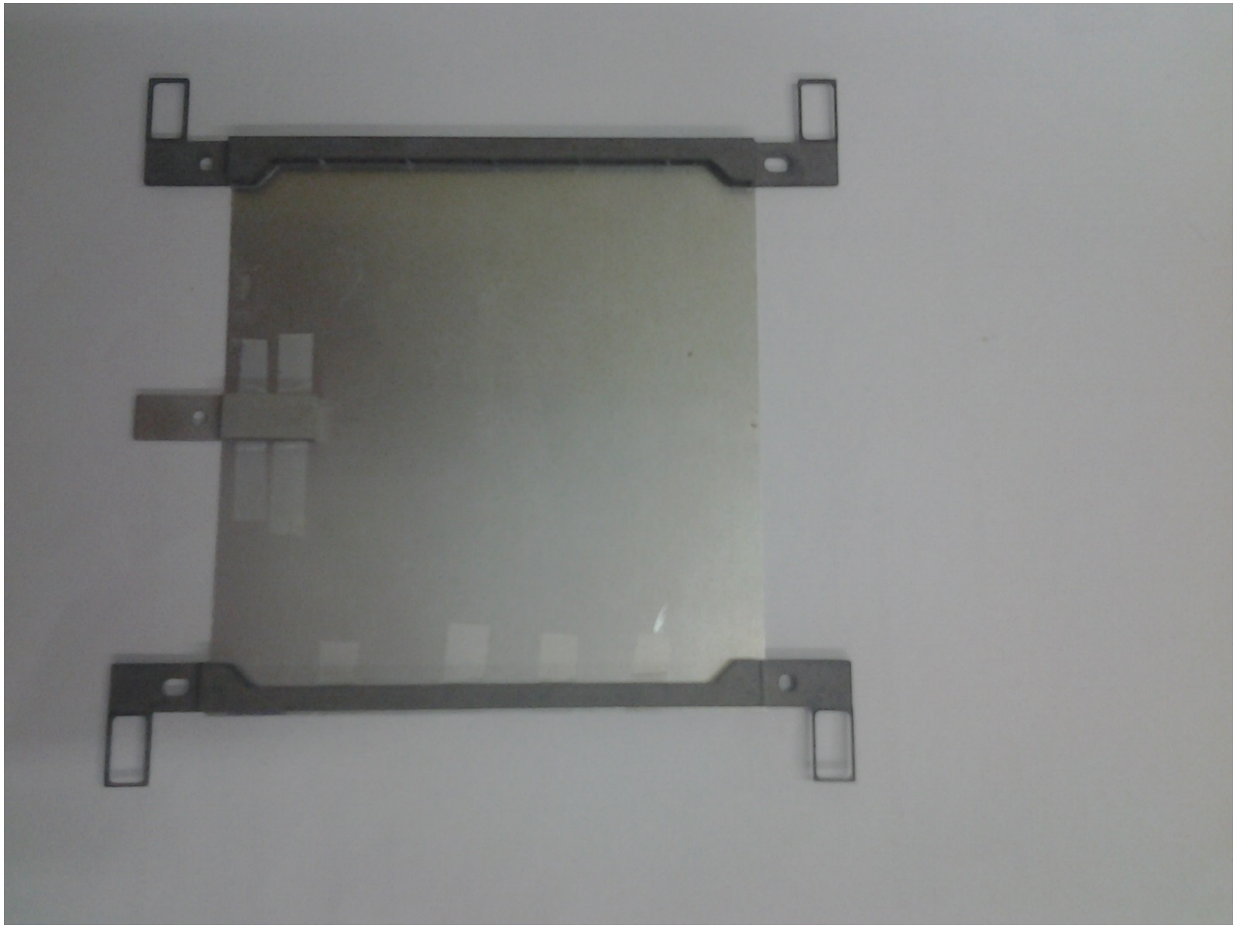
- 2S module spacers made in Mumbai:
  - Main bridge
  - Readout hybrid
  - Stump bridge
- Three spacers first made in Al3075 and later in Al-CF
- New design spacers were fabricated at ‘supertools dies’ using wire EDM
- CMM measurements done at TIFR found the spacers well within tolerances

First-trial spacers



R&D efforts on module prototyping

First manually assembled module

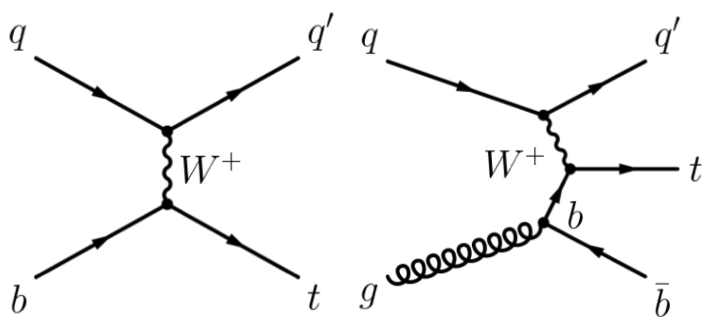


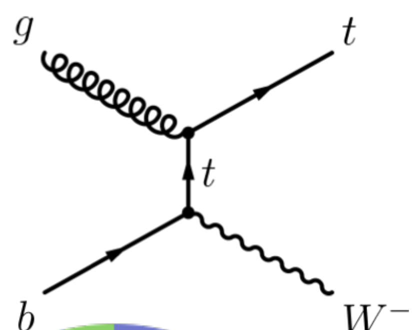
Summary on Phase-II CMS Tracker

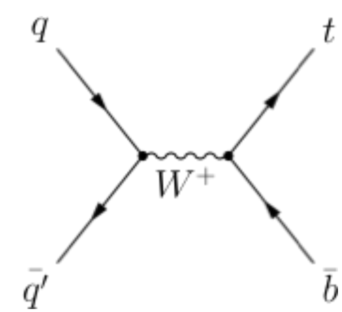
- Motivated by our experience with Belle II SVD, we are embarking another ambitious project i.e., phase-II CMS tracker
- Efforts on mechanics (various spacers) have been largely successful
- Now getting into prototype R&D

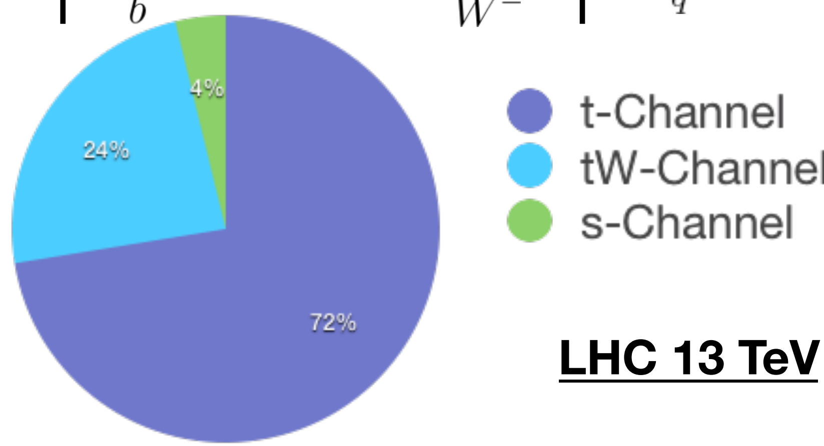
Single Top @ LHC

- Single top is produced in pp collision @ LHC via 3 modes, namely
  - ➢ t-channel (left), tW-channel (middle), s-channel (right)
- Single top quark production is one of the important electroweak processes @ LHC
  - ➢ direct probe to the charged current interaction via Wtb coupling
  - ➢ allows measurement of $|V_{tb}|$, study of top quark polarization
  - ➢ sensitive to b-quark PDF
  - ➢ sensitive to new physics like charged Higgs ($H^{\pm}$) interaction, anomalous couplings(FCNC), 4th generation etc.





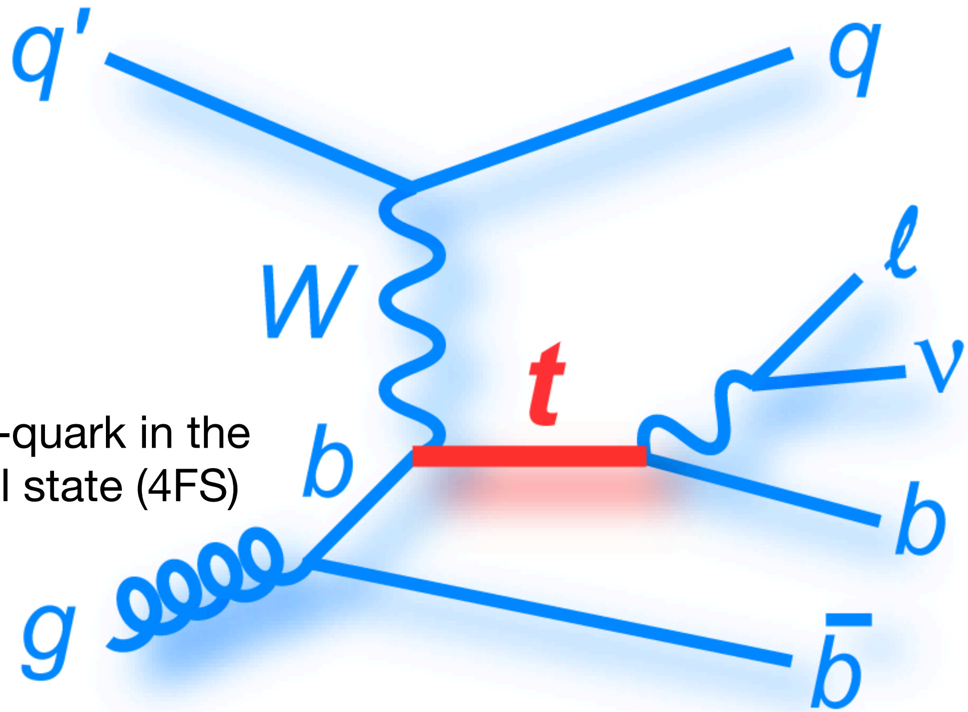




LHC 13 TeV

t-channel Single Top Topology

$t \to bW \to b\mu\nu$ decay channel



No b-quark in the initial state (4FS)

→ Light flavor jet

→ μ only in this analysis

→ Missing Energy

→ b-jet: high p_T, central

→ 2^{nd} b-jet: low p_T, broad $|\eta|$ **X**

Top reconstruction:

- Reconstruct W from *μν*

→ use m_W=80.4 GeV (PDG mass) constraint to resolve $p_{Z,\nu}$

- Add W candidate to b-jet to get top

Event Selection

Trigger:
✓ Events having at least 1 isolated muon with $p_T > 20$ GeV are selected by dedicated trigger

Muon Selection:
Require **exactly 1** muon with
✓ $p_T > 22$ GeV, $|\eta| < 2.1$
✓ passes tight ID
✓ $I_{rel} < 0.06$ within a cone of $\Delta R = 0.4$

Jet Selection:
Require **exactly 2** anti-k_T PFJets of radius=0.4 with
✓ $p_T > 40$ GeV, $|\eta| < 4.7$
✓ passes loose ID
✓ $\Delta R(\mu, \text{jets}) > 0.3$
✓ JER smearing is applied for MC

Additional LeptonVeto:
veto events having another muon (electron) with
✓ $p_T > 10$ (20) GeV , $|\eta| < 2.5$
✓ passes loose (veto) ID
✓ $I_{rel} < 0.2$ within a cone of $\Delta R = 0.4$ (for muon only)

2J1T

Exactly 1 b-tagged jet out of 2 within $|\eta| < 2.4$ passing
→ Combined secondary vertex tight working point (discriminator > 0.935)

QCD Rejection:
→ $m_T^W > 50$ GeV

- Events are categorized as N-jet-M-tag (NjMt)
- Analysis performed on 2.3 fb^{-1} data collected by CMS in 2015 with 25ns bunch spacing

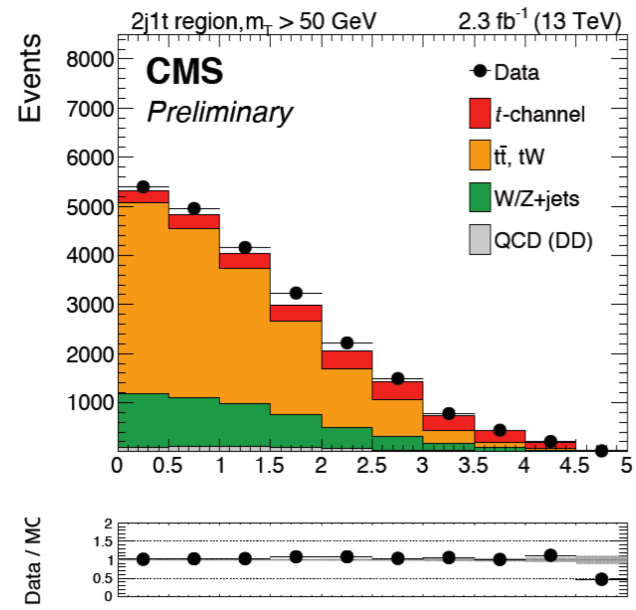
Event yield after all selection

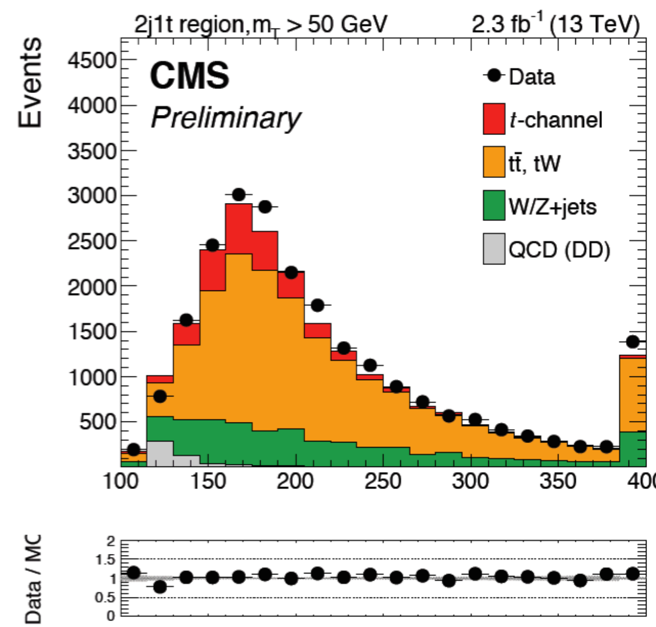
Pre - Fit Plots

07/04/16

Process	μ^+	μ^-
Top ($t\bar{t}$ & tW)	7048±13	7056±13
W/Z + Jets	3039±102	2399±90
QCD	241±12	219±11
Single top t-Channel	1539±13	977±10
Total Expected	11867±159	10651±143
Data	11877	11017

- Event yields in 2J1T after all selection and correction factors
- QCD yield is estimated from data
- Yields of all other process are taken from simulation

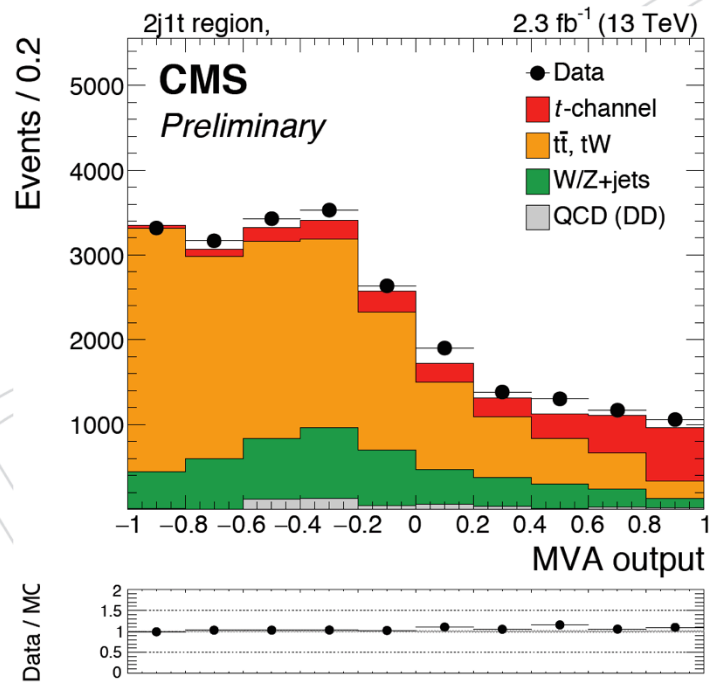


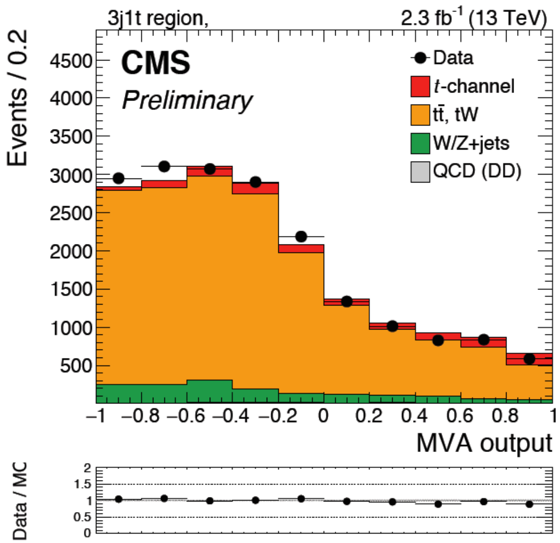


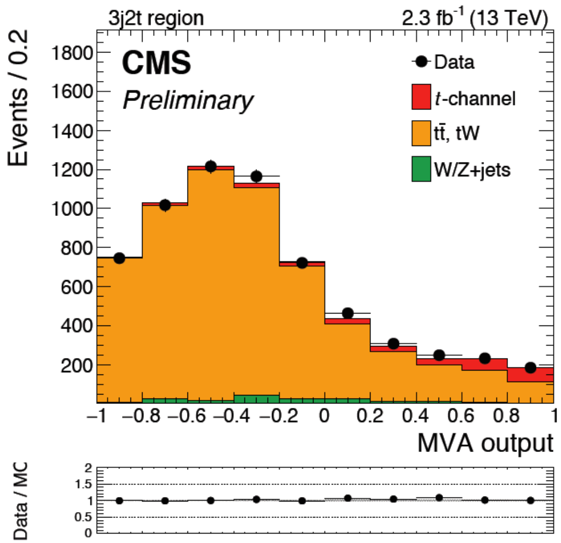
MultiVariate Analysis

Pre - Fit Plots

Rank	Variable	Description
1	light quark $\|\eta\|$	Absolute value of the pseudorapidity of the light-quark jet
2	top quark mass	Invariant mass of the top quark reconstructed from muon, neutrino, and b-tagged jet
3	dijet mass	Invariant mass of the two selected jets
4	transverse W boson mass	Transverse mass of the W boson, calculated from the muon momentum and the $\vec{p}\!\!\!/_T$
5	jet-p_T sum	Scalar sum of the transverse momenta of the two jets
6	$\cos\theta^*$	Cosine of the angle between the muon and the light-quark jet in the rest frame of the top quark
7	hardest jet mass	Invariant mass of the jet with the largest transverse momentum
8	ΔR (light quark, b quark)	Difference in R between the light-quark jet and the b-tagged jet.
9	light quark p_T	Transverse momentum of the light-quark jet
10	light quark mass	Invariant mass of the light-quark jet
11	W boson $\|\eta\|$	Absolute value of the pseudorapidity of the reconstructed W boson







Systematic uncertainties

- Experimental uncertainties are of 2 categories:
  - ☛ JES, JER, b-tagging, lepton reconstruction and trigger etc. ± 5.5%
  - ☛ pile-up (-0.2 / +0.1 %), MC statistics (± 2.8%)

- **Total experimental uncertainty : ± 6.2%**

- Theoretical uncertainties are evaluated using pseudo-experiments
  - ☛ Generator modelling: ± 9.2%
  - ☛ Q^2 scale: -6.9 / +8.7%
  - ☛ PDF: re-weighted templates derived from 102 sets of NNPDF (-3.0 / +2.6 %)
  - ☛ top p_T re-weighting : ± 0.1%

- **Total theoretical uncertainty: - 12.1/ +12.6 %**

- **Luminosity uncertainty: ±2.7 %**

Result

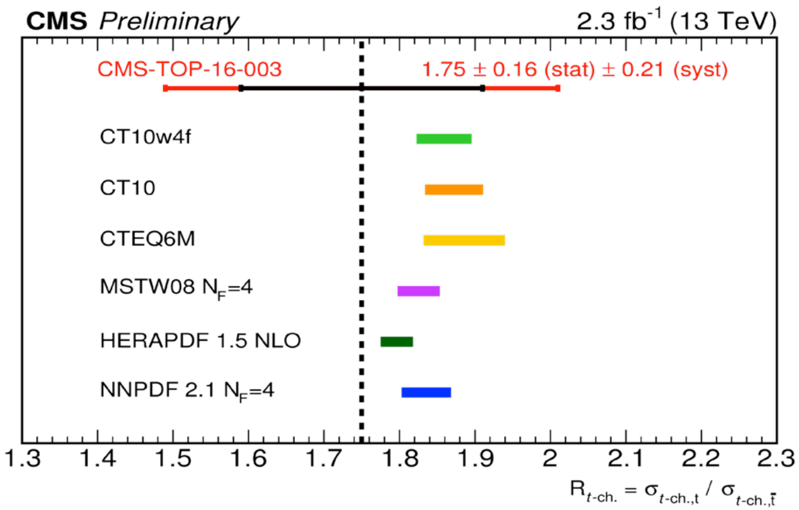
$$\sigma_{t\text{-ch}} = N_s / \{\varepsilon . \mathscr{B}(t \to bl\nu) . L_{Int}\}$$

$$\sigma_{t\text{-ch.},t} = 141.5 \pm 6.7\,(\text{stat.}) \pm 9.4\,(\text{exp.})\,^{+19.3}_{-19.6}\,(\text{theo.}) \pm 3.8\,(\text{lumi.})\,\text{pb} = 141.5\,^{+22.8}_{-23.0}\,\text{pb},$$

$$\sigma_{t\text{-ch.},\bar{t}} = 81.0 \pm 6.2\,(\text{stat.}) \pm 8.1\,(\text{exp.})\,^{+10.9}_{-10.9}\,(\text{theo.}) \pm 2.2\,(\text{lumi.})\,\text{pb} = 81.0\,^{+15.1}_{-15.1}\,\text{pb}.$$

$$\sigma_{t\text{-ch.}} = 227.8 \pm 9.1\,(\text{stat.}) \pm 14.0\,(\text{exp.})\,^{+28.7}_{-27.7}\,(\text{theo.}) \pm 6.2\,(\text{lumi.})\,\text{pb} = 227.8\,^{+33.7}_{-33.0}\,\text{pb}$$

$$R_{t-\text{ch.}} = 1.75 \pm 0.16\,(\text{stat.}) \pm 0.21\,(\text{syst.}).$$



Result

$$\sigma_{t\text{-ch.}} = 227.8 \pm 9.1\,(\text{stat.}) \pm 14.0\,(\text{exp.})\,^{+28.7}_{-27.7}\,(\text{theo.}) \pm 6.2\,(\text{lumi.})\text{ pb} = 227.8\,^{+33.7}_{-33.0}\text{ pb}$$

$$|V_{tb}| >> |V_{td}|, |V_{ts}|$$

$$\sigma_{t-ch.} = 216.99^{+6.62}_{-4.64}(scale) \pm 6.16(PDF)pb$$

$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma^{meas}_{t-ch}}{\sigma^{th}_{t-ch}}}$$

$$|f_{LV}V_{tb}| = 1.02 \pm 0.07(exp.) \pm 0.02(theo.)$$

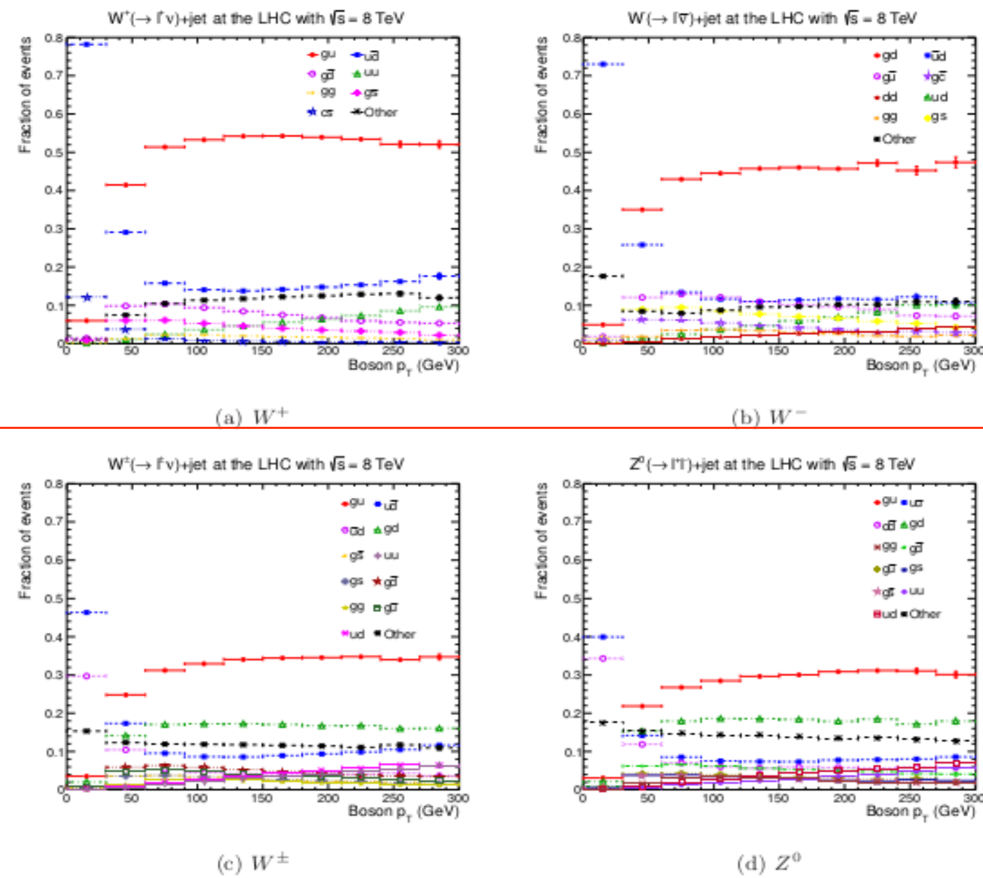
Study of Ratio of W^++jets/W^-+jets to probe Parton Distribution Functions

The low pT bosons are mainly produced by the quark contents of the protons

W^+	W^-	Z^0	$W^{\{\pm\}}$
$u\bar{d}$	$\bar{u}d$	$u\bar{u}$	$u\bar{d}$

Whereas for high pT bosons, the gluons determine the Initial state, contributing to roughly 50% of the total W production

W^+	W^-	Z^0	$W^{\{\pm\}}$
ug	dg	ug	ug



(a) W^+ (b) W^- (c) $W^{\pm}$ (d) Z^0

arXiv:1304.2424v1 Malik and Watt

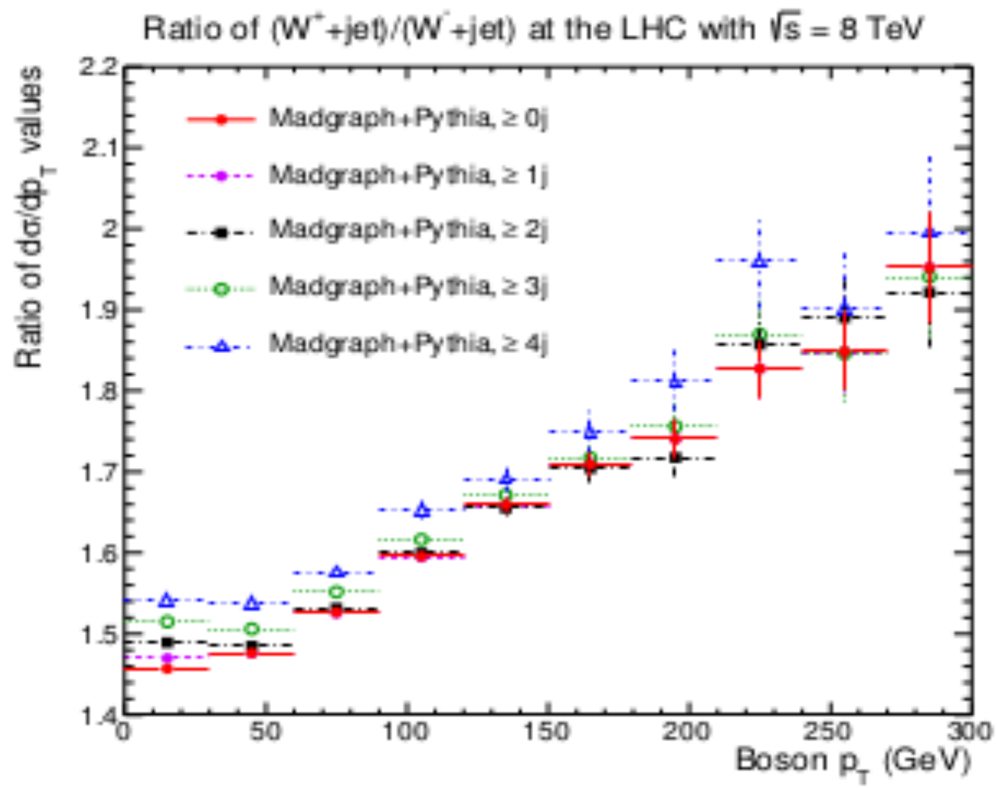
Four interesting high pT boson ratios

- When we take the ratios of
- the differential cross-sections
- as a function of pT
- distributions of the bosons,
- we get these four distributions

$\frac{W^{+}}{W^{-}}$	$\frac{W^{+}}{Z^{0}}$	$\frac{W^{-}}{Z^{0}}$	$\frac{W^{(\pm)}}{Z^{0}}$
$\frac{u}{d}$ Must Increase	Moderate Change	$\frac{d}{u}$ Must Decrease	Moderate Change

- This ratio varies approximately
- by 30-40%
- Furthermore, this pT dependent
- ratio can be used as a
- comlementary distribution
- alongside with the η deptendent
- W-charge asymmetry to constrain
- the PDFs

arXiv:1304.2424v1 Malik and Watt



(a) W^{+}/W^{-}

Event Selection and Backgrounds

- SignalMC : W(->μν)+Njets where N>=0,1,2,3 etc
- Background :

ZZ
WZ
Top
QCD
TTjets
WW
TTjets

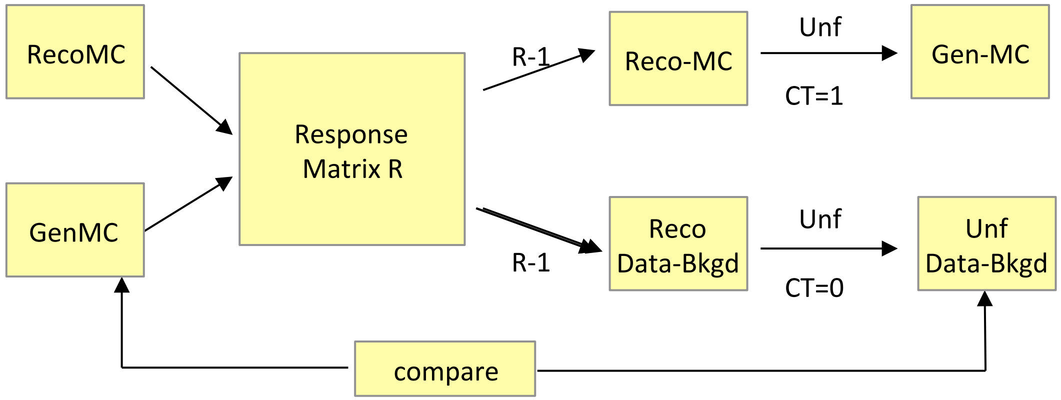
Event Selection

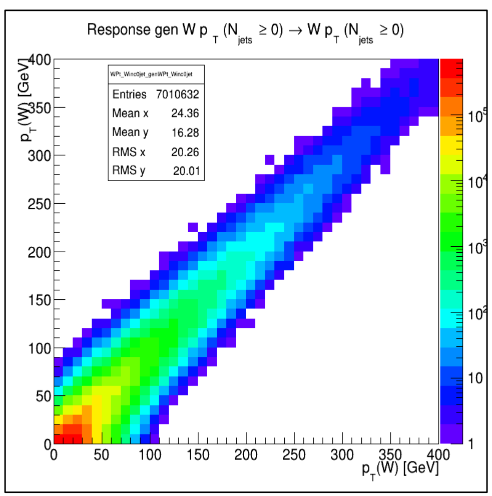
μpt>25GeV
|μη|<2.1
MET>25GeV
Jetpt>30GeV
|Jetη|<2.4
MT>50GeV

Madgraph + Pythia with cteq6l1 as a PDF
is used to evaluate SignalMC and backgrounds
except the QCD background
(only LO level calculations are considered)

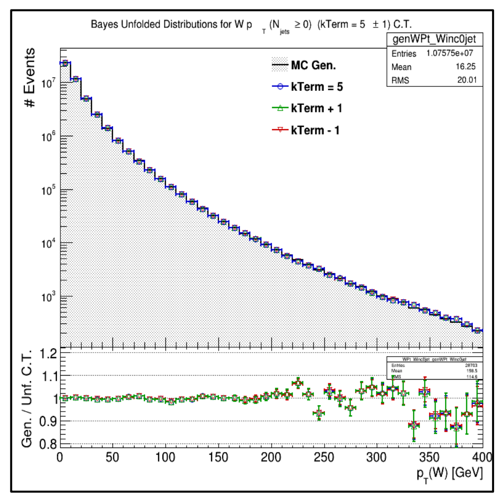
Unfolding Distributions

- Unfolding techniques are used to eliminate systamatics effects due to
- Imperfection in detector and obtain unfolded distribution at True level





Response Matrix

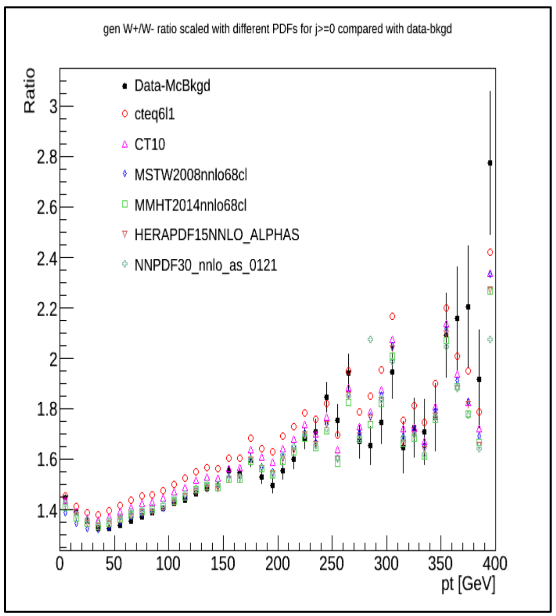


Unfolded Wpt distribution

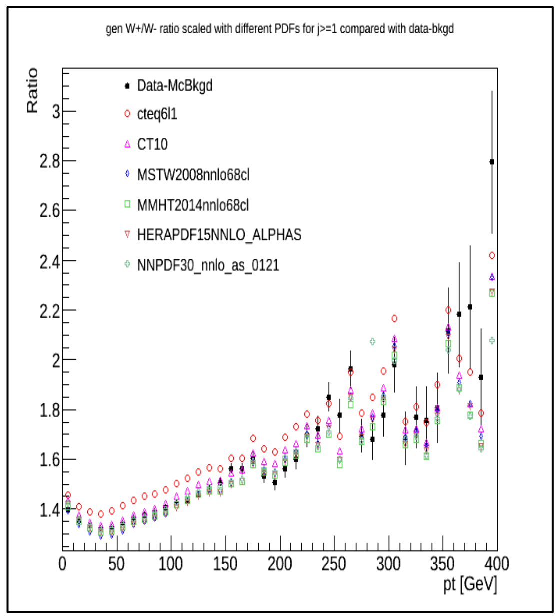
Ratios

The gen level (W^+/W^-)pt plot scaled with different PDFsets for inclusive 0, 1 and 2 jets

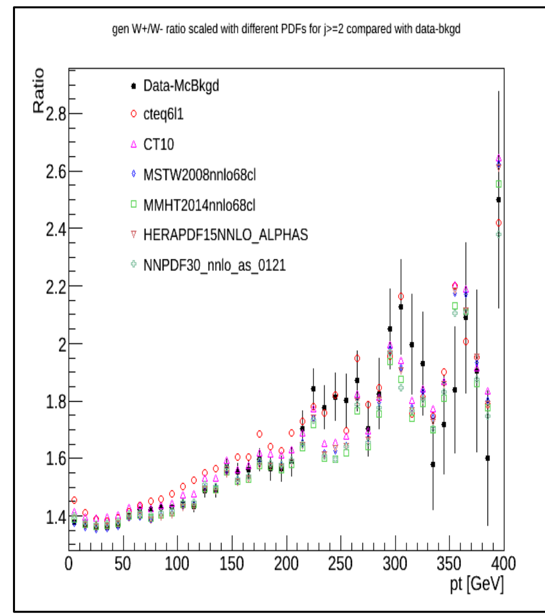
Inclusive 0 jet



Inclusive 1 jet



Inclusive 2 jets



Search for exotic Z charmonium like states at CMS

- Charged Z charmonium-like states $|c\bar{c}d\bar{u}\rangle$ are particularly interesting as candidates for tetra-quark states with an exotic quark content :

- Discovery of the **Z(4430)$^{\pm}$** in the **ψ'π** spectrum in the decay **$B^0 \rightarrow$ ψ' Kπ** by Belle (2007)

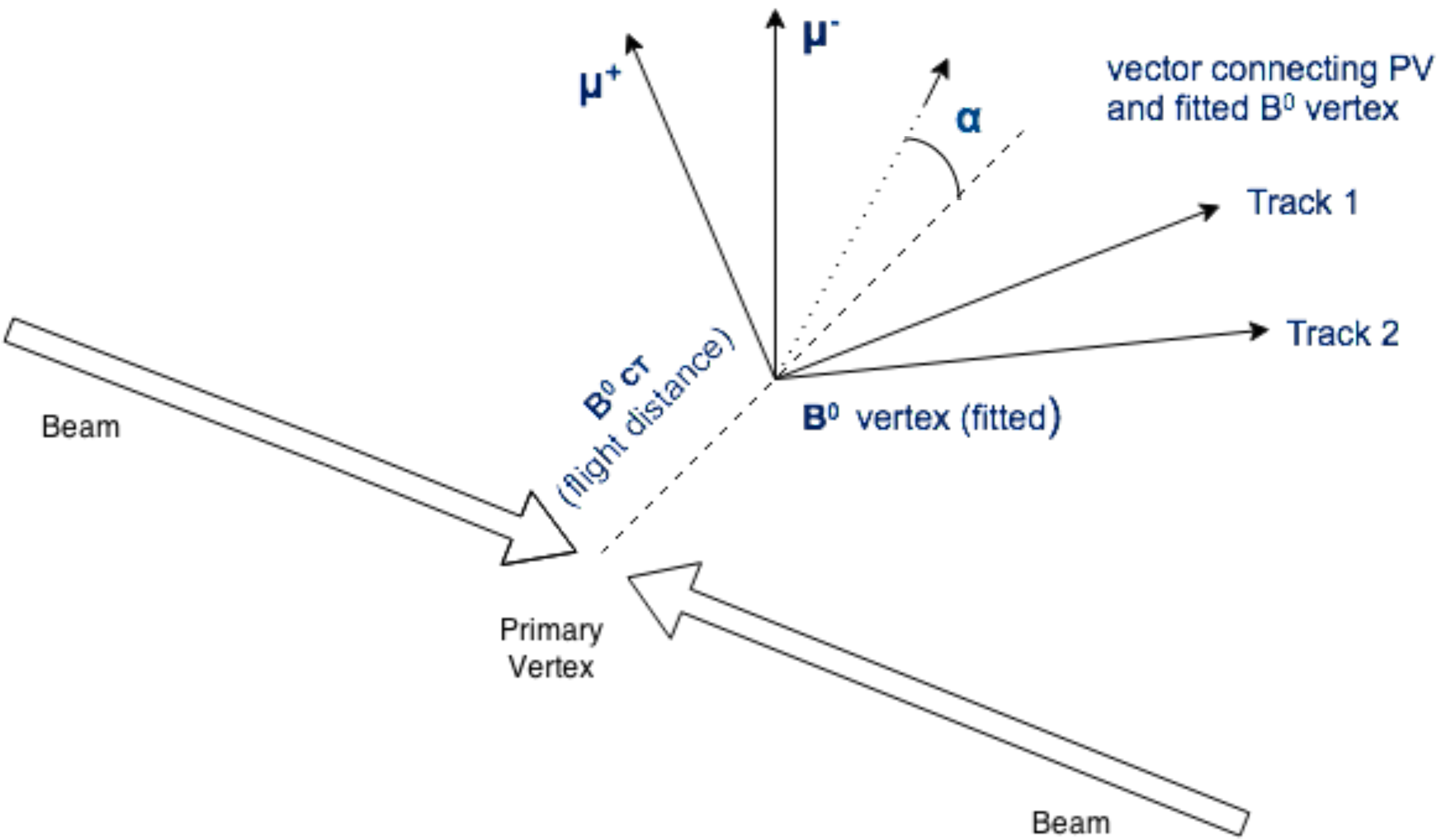
- LHCb confirmed this state recently (2014)

- Belle have observed this and other similar exotic resonances in **J/ψπ** invariant mass spectrum like the **Z(4200)$^{\pm}$**

- BESIII has observed some other related resonances

- CMS has the potentialities to look within it's data for the presence of such states by searching exclusively in the **$B^0 \rightarrow$ J/ψ** (or **ψ')** **Kπ** with **J/ψ $\rightarrow \mu^+\mu^-$**

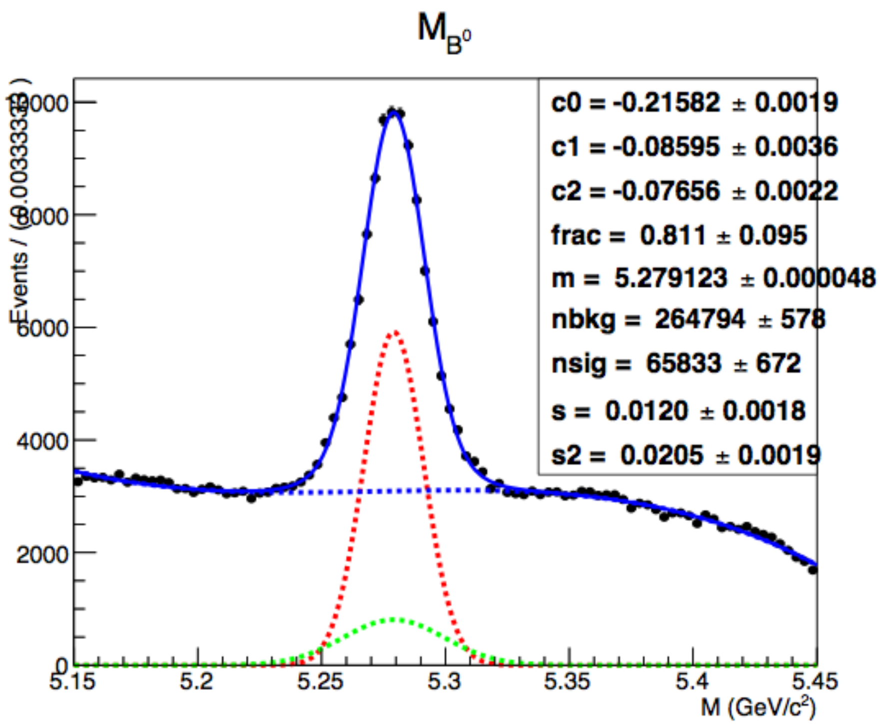
Event Topology



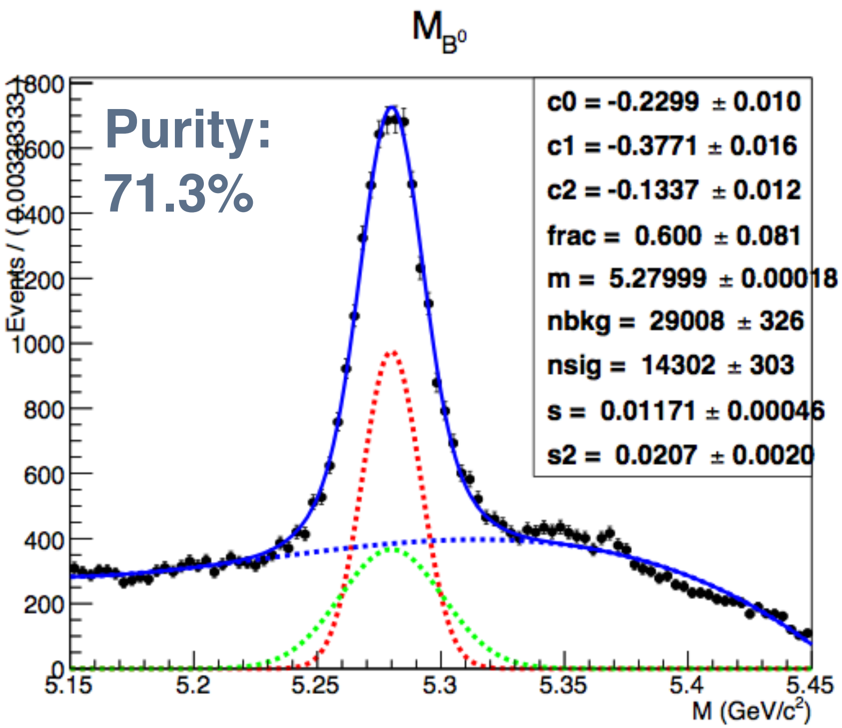
Cut based Signal Optimization for Muonia2012ABCD

- MuChi2/NDF <3
- Mu Strip hits > 5
- Mu Pixel hits >0
- Mu Dz <20 cm
- Mu Dxy <0.3 cm
- B0Vtx_CL > 0.09
- B0CosAlphaPV > 0.9985
- B0CTauPV/B0CTauPVE > 9.0
- MuMuVtx_CL > 0.02
- jpsip4.DeltaR(track) < 1.0
- trackChi2/NDF < 7.0
- track Strip hits > 10
- track Pixel hits >0
- B0 Pt > 8 GeV
- track pt > 0.45 GeV
- Jpsi reconstructed mass - PDG mass < 0.12 GeV

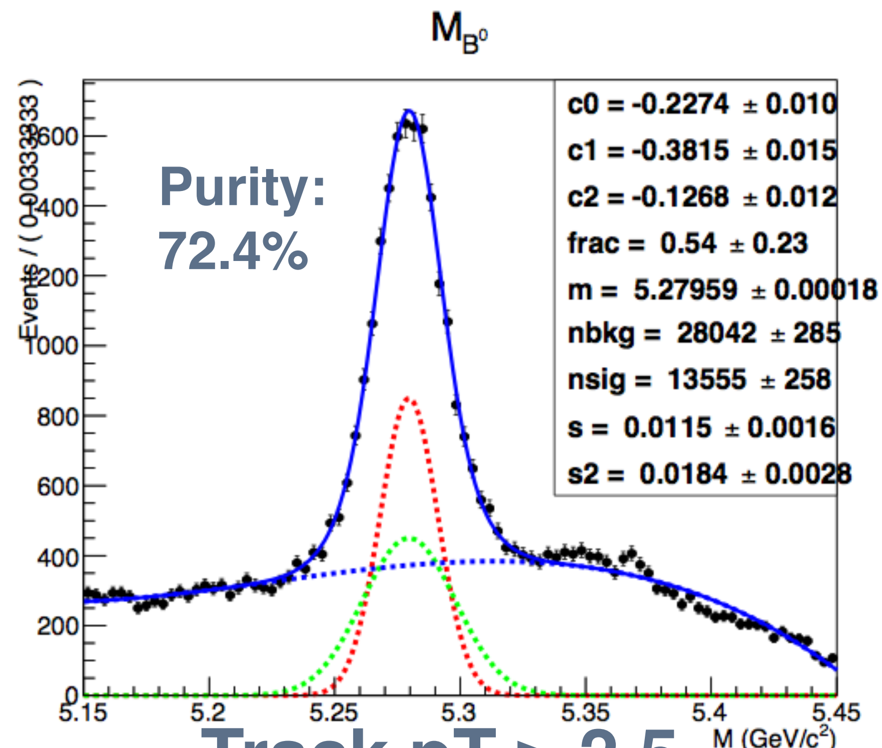
Purity: S/(S+B) = 60.0%



A Bit more Fine-tuning

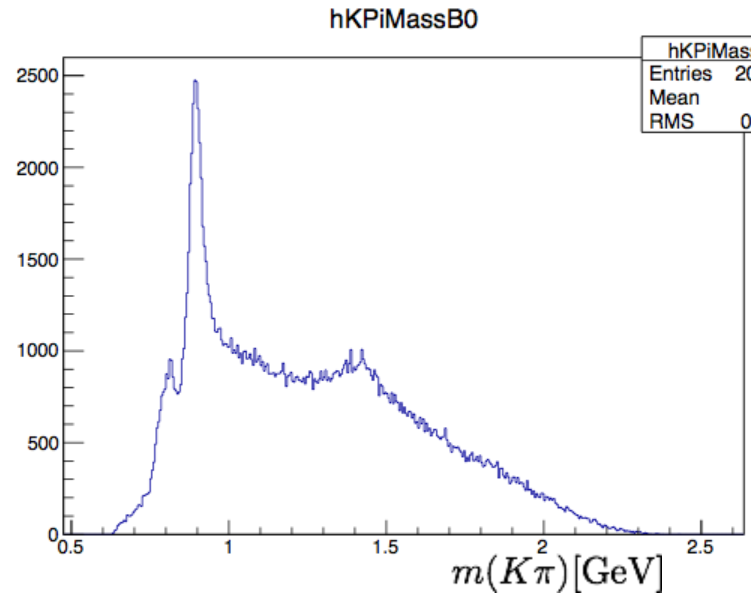


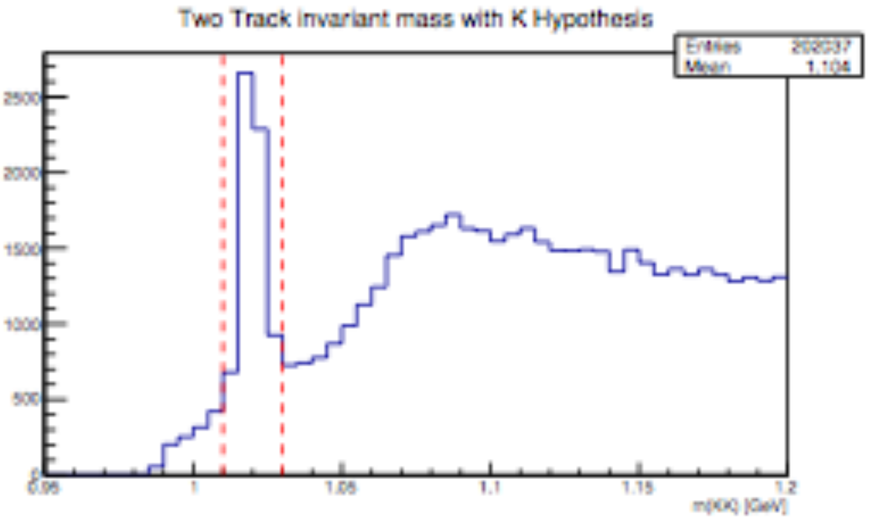
Track pT > 2.5 GeV,
nB0 = 1

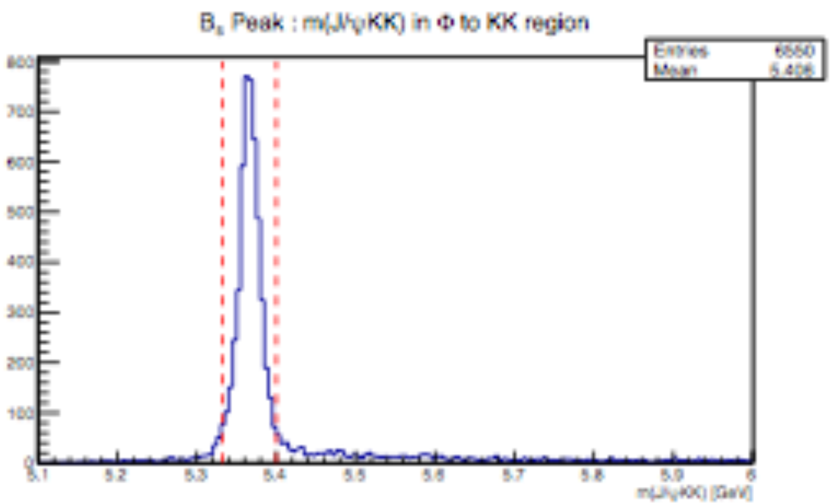


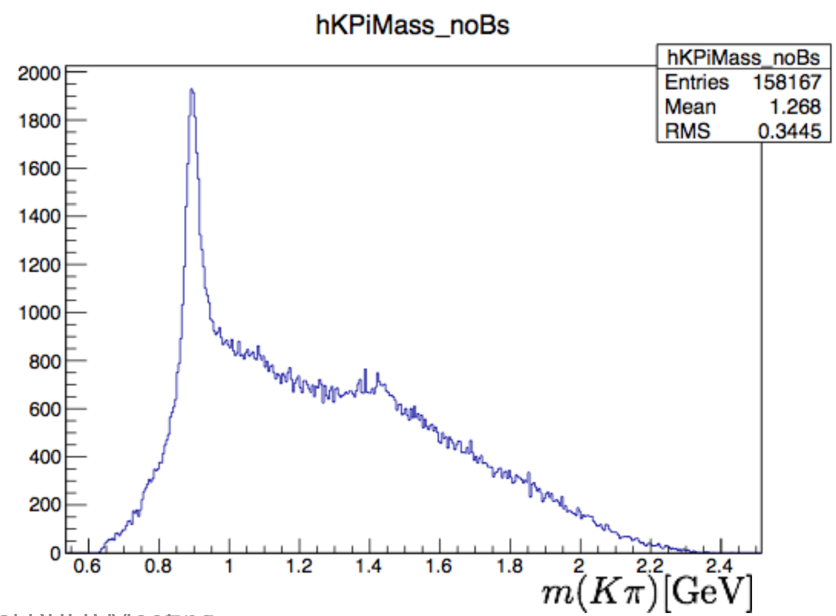
Track pT > 2.5 GeV,
B0 pT > 18 GeV,
nB0 = 1

$B_s \to J/\psi(\to \mu^+\mu^-)\Phi(\to K^+K^-)$ contamination

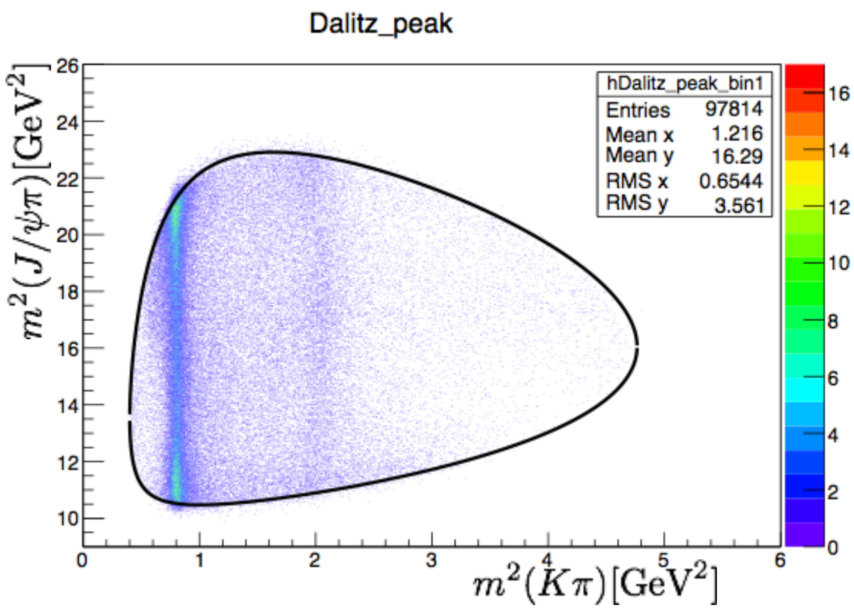


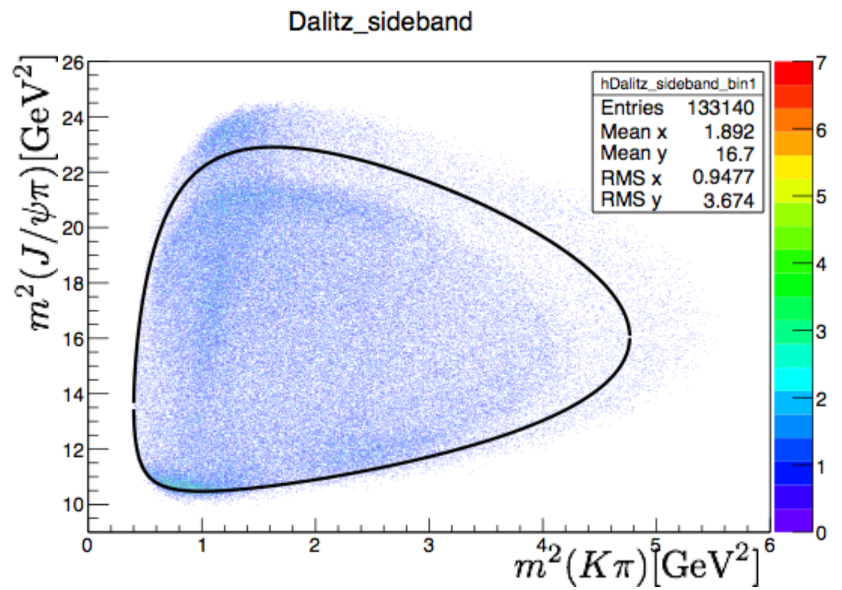


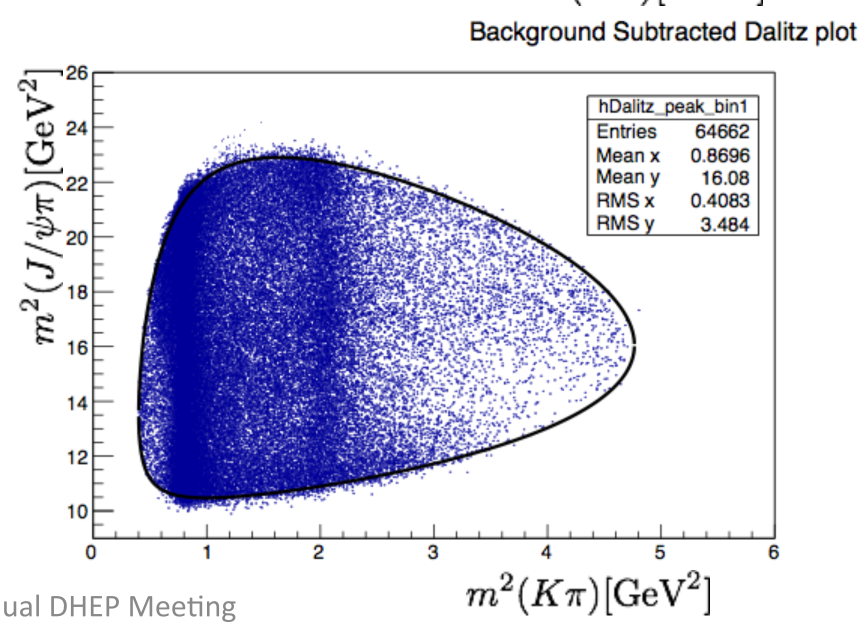




Dalitz Plots







peak = +/-2sigma(core)
sideband = +/-5 to 7 sigma (core)
no of background events in peak = 34901.8
no of background events in sidebands = 37701.9
Scale factor = 0.9257

Summary

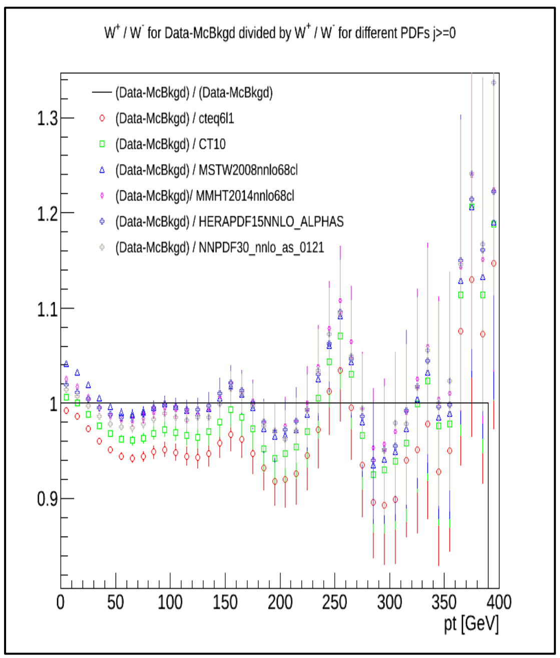
- **Hardware Activities**
  - **Expertise developed with HO upgrade, HFRADMON, BELLE-II Silicon upgrade will be very useful in taking bigger challenging activities in HGCAL/Tracker upgrade**

- **Standard Model Physics (Poster presentation tomorrow)**
  - **Three analysis are being pursued and progressing well**
  - **For details on each of these analysis; visit poster gallary today**

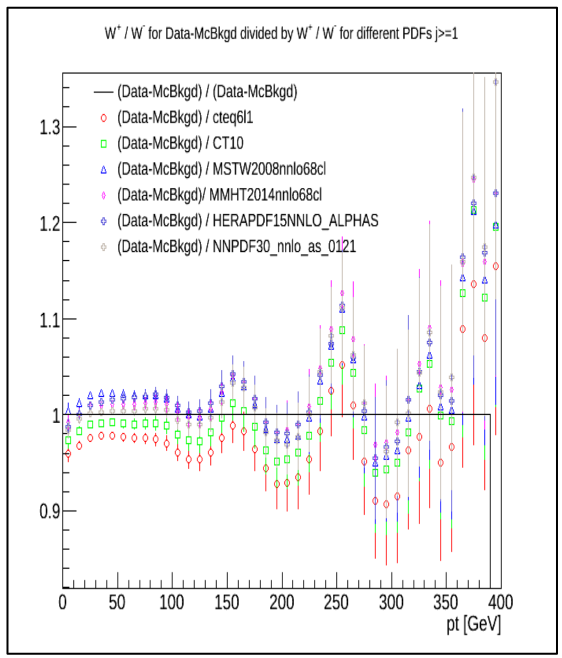
Sensitivity of different PDFsets

It can be seen that MSTW, MMHT and NNPDF perform well compared to cteq6l, CT10 and HERAPDF

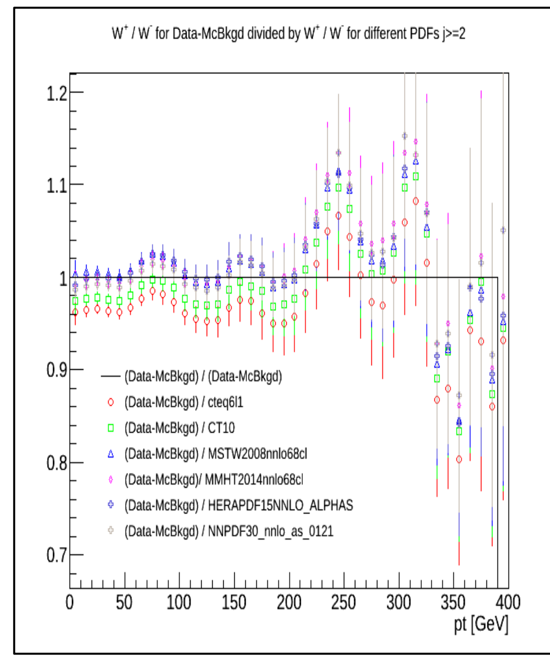
Inclusive 0 jet



Inclusive 1 jet



Inclusive 2 jets



Variables for Calculation of Amplitudes for each K* resonance

1. Measured B0 mass from event
2. Measured KPi mass from event
3. Measured J/Psi (MuMu) mass from event
4. Measured J/PsiPi mass from event
5. B0 3-momentum (modulus)
6. KPi 3-momentum
7. Jpsi 3-momentum
8. K 3-momentum
9. Pi 3-momentum
10. Theta K* (K* helicity angle)
11. Theta J/psi
12. Phi (angle between K* and J/ψ decay planes)

Amplitude Analysis Formalism

- The amplitude of the decay $B^0 \rightarrow J/\psi K\pi$ is represented by the sum of Breit-Wigner contributions for several intermediate two-body states

- $K_*0(800)$, $K_*(892)$, $K_*(1410)$, $K_*0(1430)$, $K_*2(1430)$, $K_*(1680)$, $K_*3(1780)$, $K_*0(1950)$, $K_*2(1980)$, $K_*4(2045)$

- The idea is to show that the fit to data where amplitudes of all these resonances add up and interfere is not good enough, a new intermediate resonance $B^0 \rightarrow Z(4430)K$, $(Z(4430) \rightarrow J/\psi\pi)$ is needed

Parameter space = $\Phi = (M^2_{K\pi}, M^2_{J/\psi\pi}, \theta_{J/\psi}, \varphi).$

Signal Density Function = $S(\Phi) = \sum_{\xi=1,-1} \left| \sum_{K^*} \sum_{\lambda=-1,0,1} A^{K^*}_{\lambda\xi} + \sum_{\lambda'=-1,0,1} A^{Z^-}_{\lambda'\xi} \right|^2$

$$A^{K^*}_{\lambda\xi}(\Phi) = H^{K^*}_{\lambda} A^{K^*}(M^2_{K^-\pi^+}) d^{J(K^*)}_{\lambda 0}(\theta_{K^*}) e^{i\lambda\varphi} d^1_{\lambda\xi}(\theta_{\psi'})$$