Vector-like quark T’ search and Status of CMS-HGCAL Module Assembly Center(Beijing)

Taozhe YU

SYSU-PKU Collider Physics forum For Young Scientists

July 27th, 2022

Vector-like quark T’ search

Motivation

Standard Model

Fermions：quarks, leptons

Mass: Yukawa coupling to the Higgs

Hierarchy problem

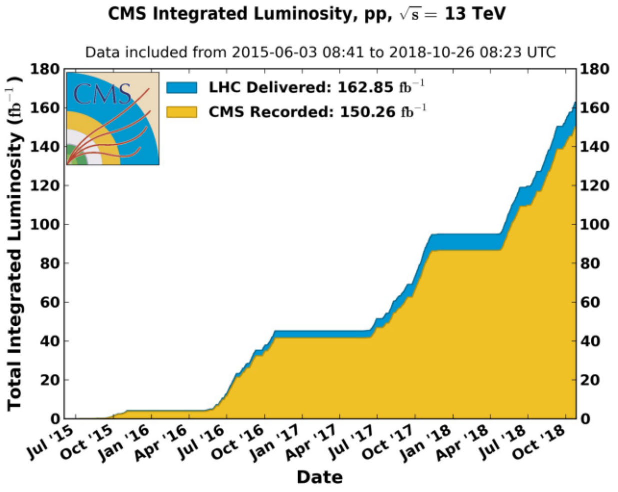
little Higgs, composite Higgs models

Fermions：Vector-like quarks

non-Yukawa coupling terms

Don’t excluded by precision SM measurements

- VLQs: hypothetical new spin -1/2 charge 2/3 particle
- VLQs offer a potential solution to the hierarchy problem of standard model
- Using all the Run2 data to search for VLQs



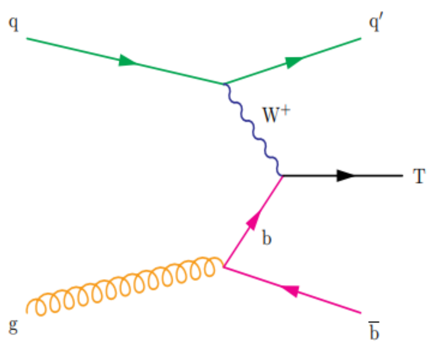
LHC

High Energy(13TeV)，

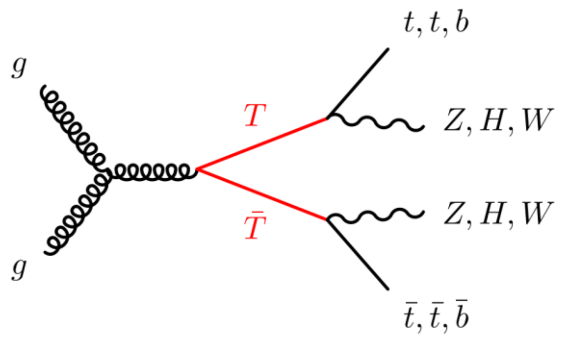
High luminosity(~150fb^{-1})

VLQs production and decay modes

Single production



Pair production



- The vector-like quarks mainly coupled to the third generation
- Three different decay channels into SM particles by the assumption of the model: bW, tH, tZ

arXiv:0907.3155

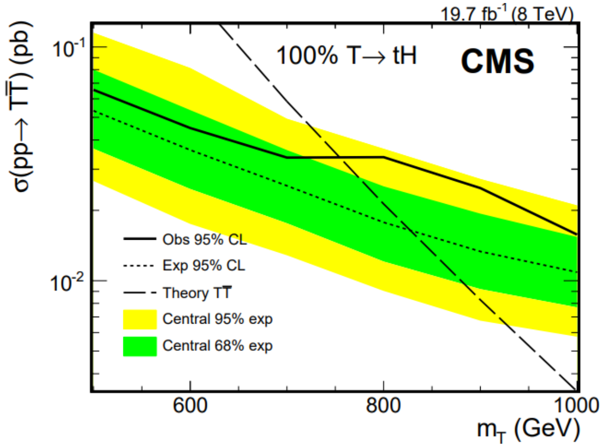
The Vector-like quark T' maybe multiplet

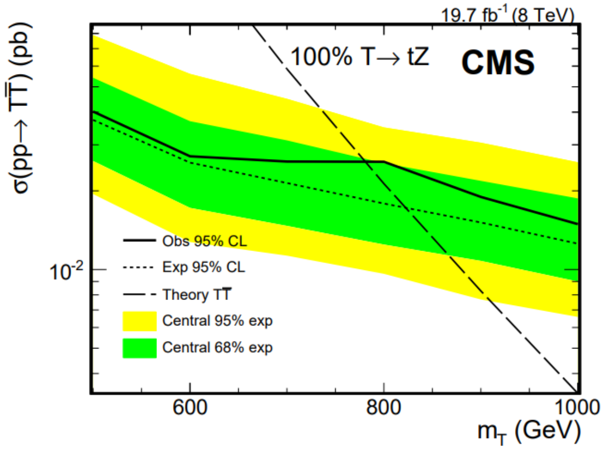
→ $SU(2)_L$ isosinglets → Branch ratio bW:tZ:tH=0.5:0.25:0.25

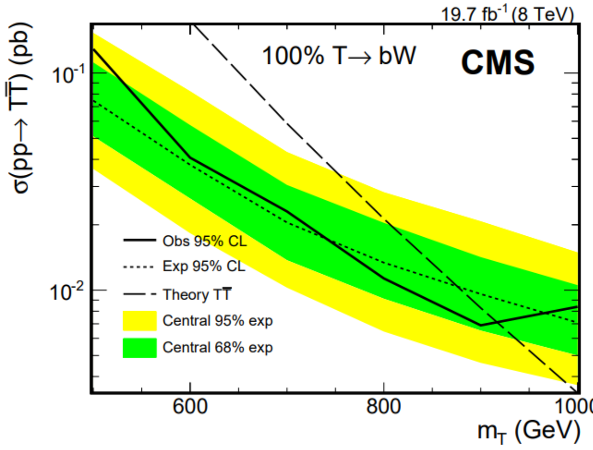
→ $SU(2)_L$ isodoublets → Branch ratio bW:tZ:tH=0:0.5:0.5

Vector-Like quarks T' @Run1

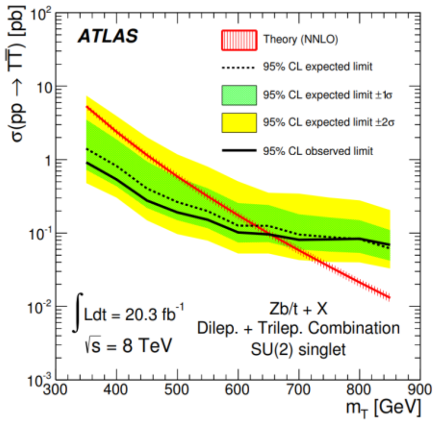
CMS@Run1: mass excluded region: below 720-920GeV @95%CL.

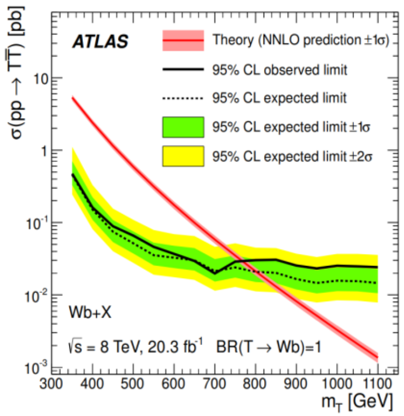


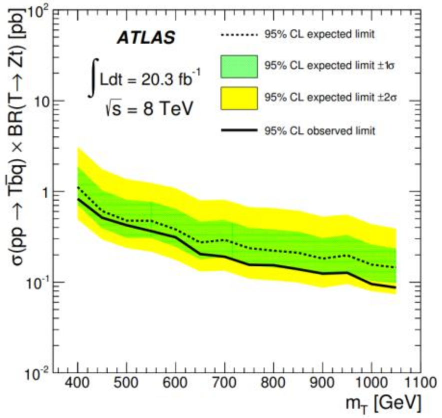


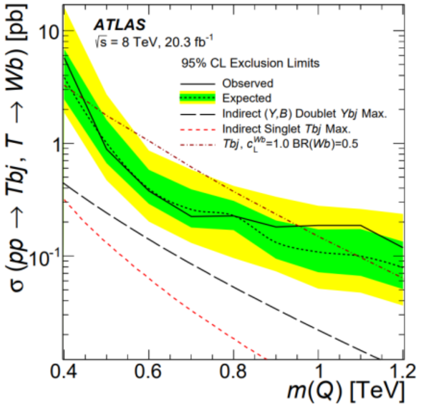


ATLAS@Run1: mass excluded region: below 650-950GeV @95%CL.



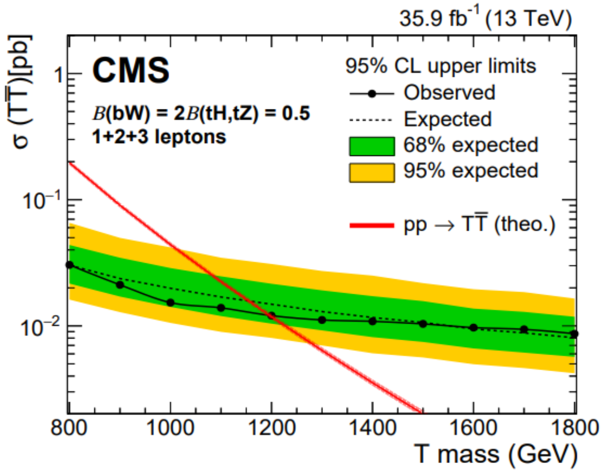


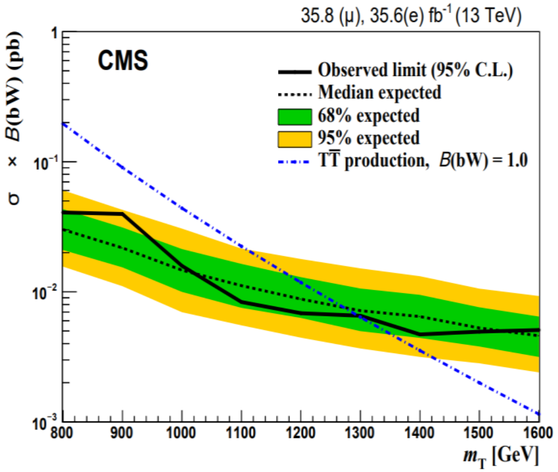


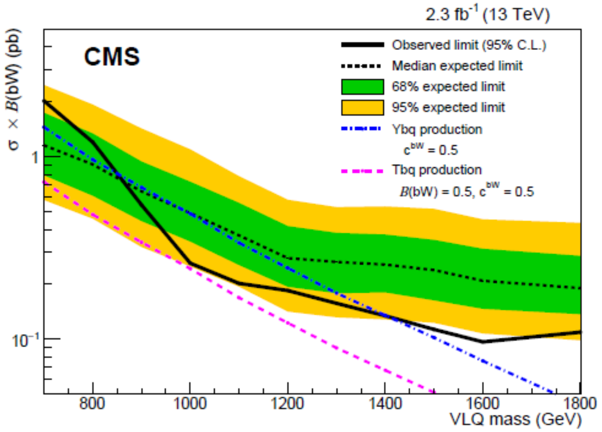


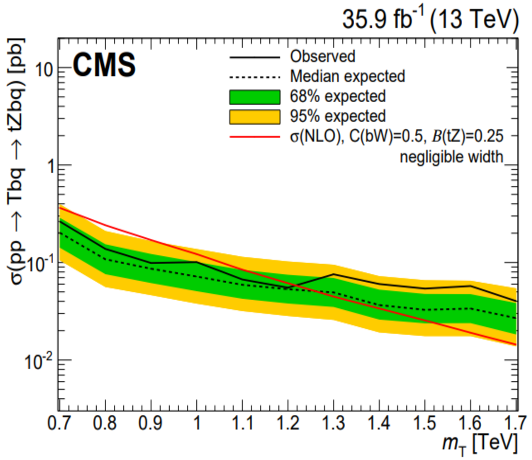
Vector-Like quarks T’ @2015 and 2016

CMS@2016 mass excluded region： below 1200-1300GeV@95%CL

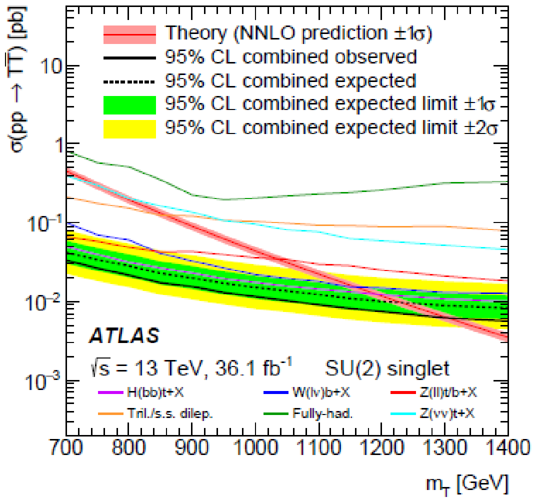


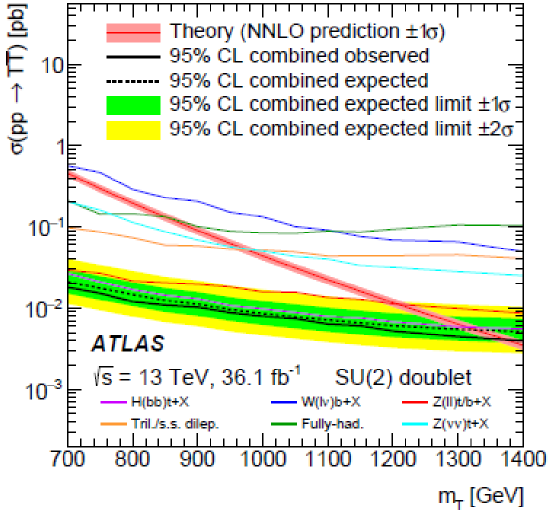


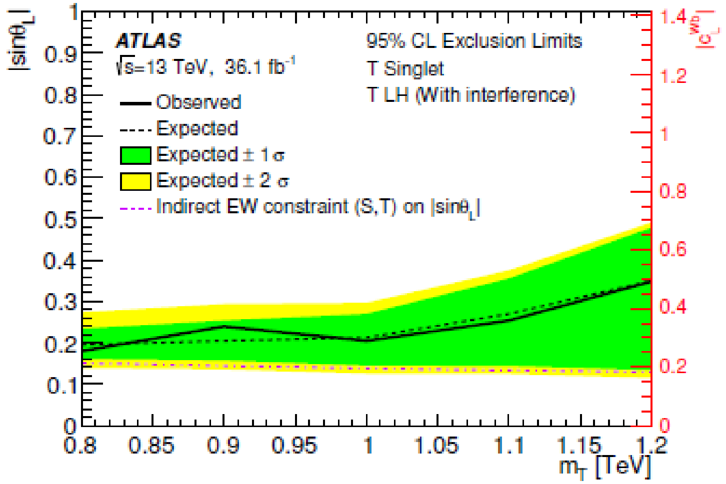




ATLAS@2016 mass excluded region： below 1300GeV以下@95%CL

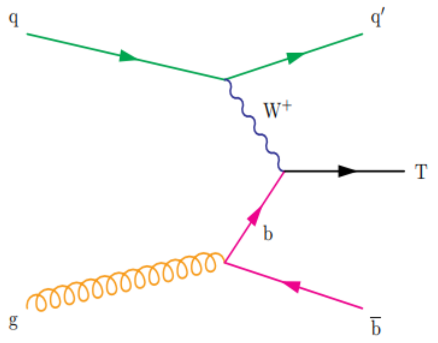






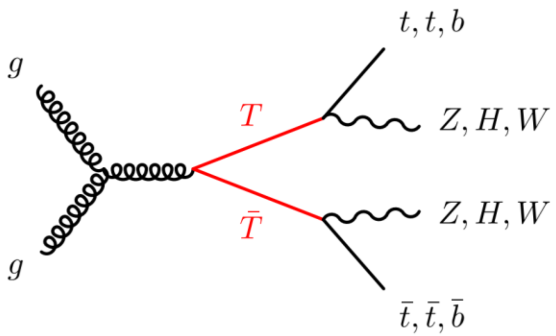
The choice of decay channel and final state

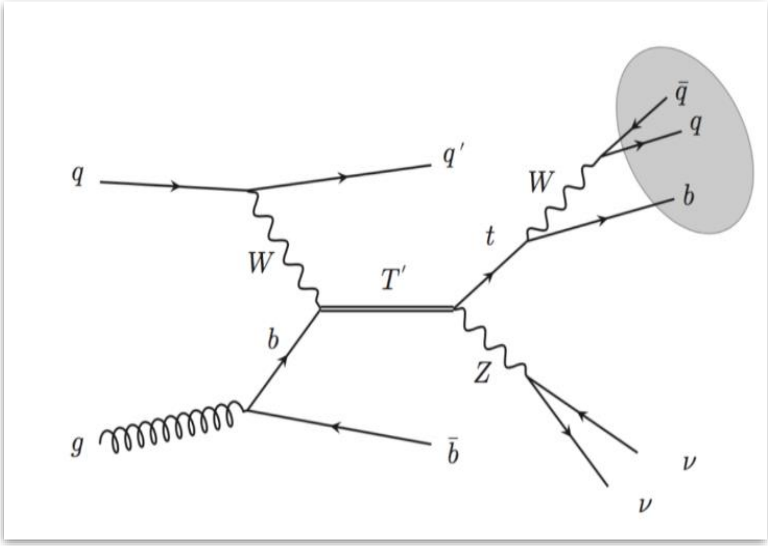
Single production



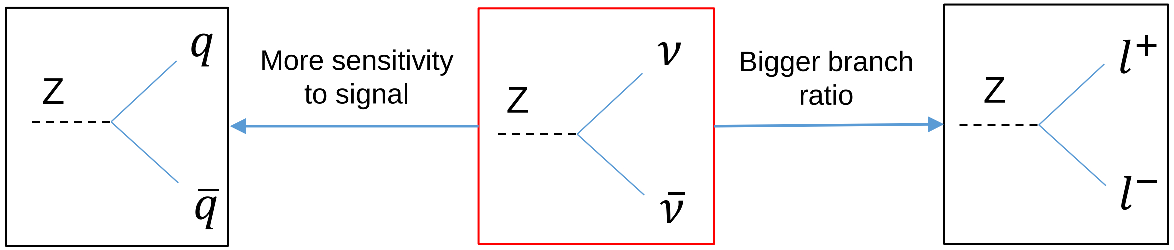
Single production of VLQs have larger phase space above 1TeV

Pair production





- Final state: MET + Jets
- CMS first use this final state to search T’



Analysis strategy

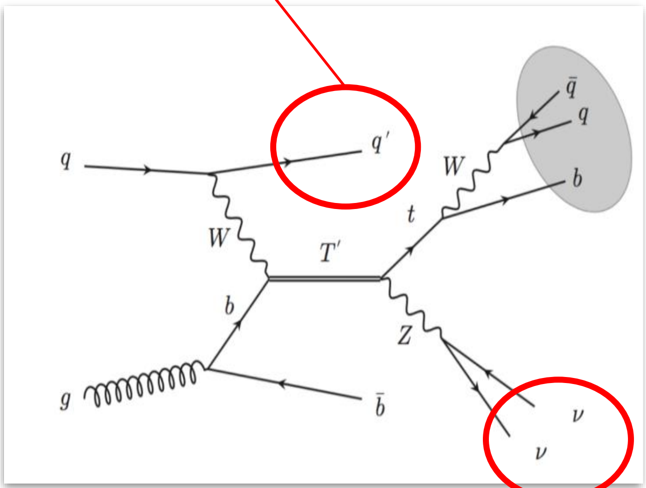
➢Forward jets: define two categories with enhanced sensitivity
- ✓No forward jets
- ✓At least 1 forward jet

- The top quark identified in three different scenarios：

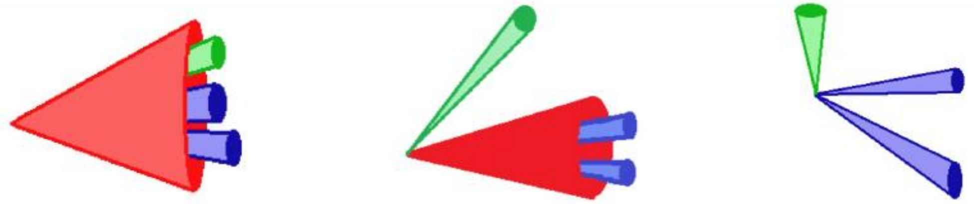
AK4 jet: anti-kt jet with radius = 0.4

AK8 jet: anti-kt jet with radius = 0.8

So We have six categories in each year



- **Three reconstruction algorithms** to have good sensitivity in all mass range
  - ✓ **Fully merged topology**: top candidate is a top-jet
  - ✓ **Partially merged topology**: top candidate given by one W-jet and one ak4 jet
  - ✓ **Resolved topology**: top candidate given by three ak4 jets



Fully merged topology | **Partially merged topology** | **Resolved topology**

Boosted top category | **Resolved top category**

- Neutrinos are not detected in the experimental apparatus.
- T quark four-momentum cannot be reconstruction

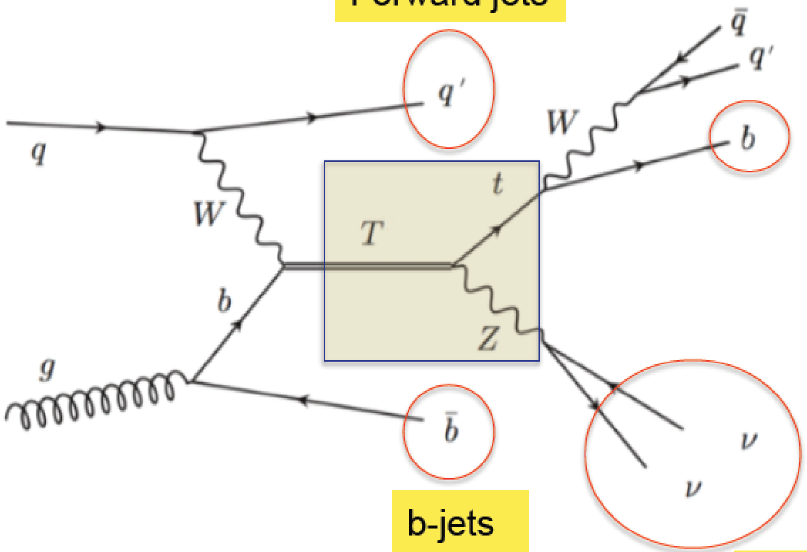
Final discriminating variable: transverse mass M_T between top and MET

$$M_T = \sqrt{2p_T^{top} \cdot p_T^{MET}\,(1 - cos\Delta\phi)}$$

Events reconstruction and Selection

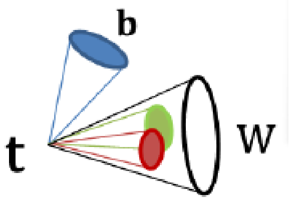
In order to improve the sensitivity of the analysis, the following selection is applied:

Forward jets

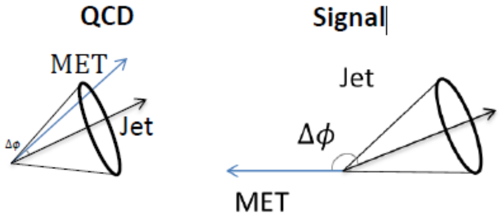


b-jets

b-jets → **Boosted category**: 1 merged W jet + 1 b-jet; 1 merged top jet. **Resolved category**: 2 AK4 jets + 1 b-jet

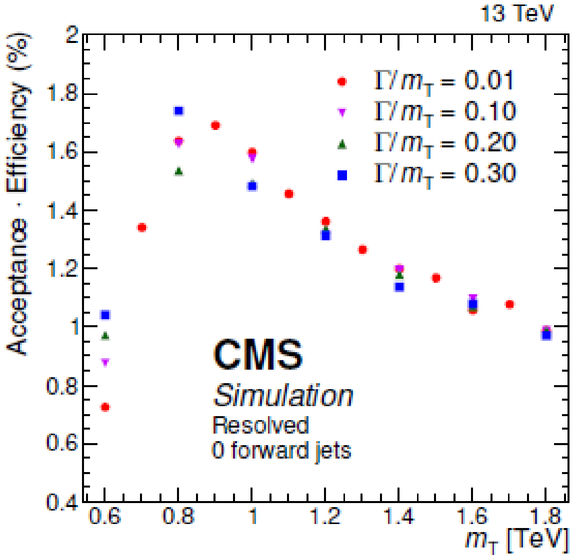


Angular separation between MET and jets min[$\Delta\phi$(MET, jets)] → $\Delta\Phi$(Jet,MET)>0.6



No final state leptons → Veto leptons

Large event MET → MET pt>200GeV



b-tagger	W-tagger	Top-tagger
CHS ak4 Jet pt>30GeV DeepCSV medium WP	PUPPI AK8 Jet pt > 200GeV 65 < SD mass < 105 GeV tau21DDT < 0.43	PUPPI AK8 Jet pt > 200GeV 105 < SD mass < 220 GeV tau32 < 0.65

Background Estimation

- Main Background: Z+jets, W+jets, ttbar
- Using Data-driven method to get correction factors from control region in data
- Control regions for the main backgrounds are defined as:

➢ Resolved category

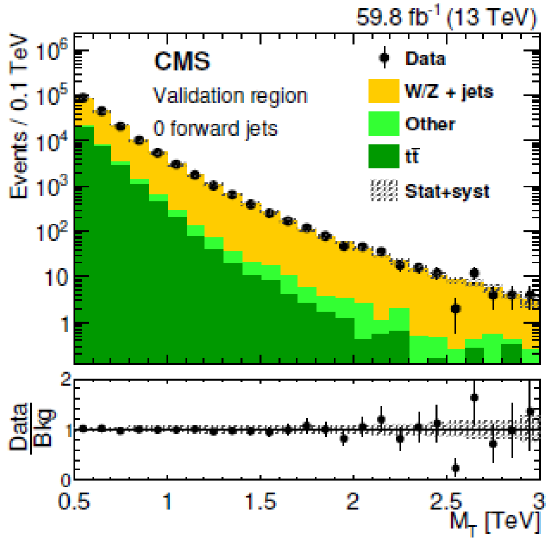
Variable	SR	Z+jets CR	W+jets CR	ttbar CR
lepton	veto	veto	>=1	>=1
Number of midum b jet	>=1	=0	=0	>=1

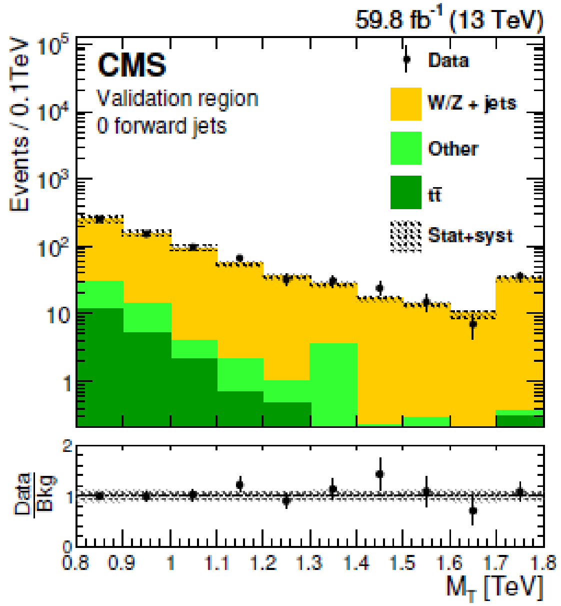
➢ Partially merged category

Variable	SR	ttbar CR
minΦ(MET,jet)	> 0.6	< 0.6

➢ Fully merged category

Variable	SR	W/Z+jets CR	ttbar CR
Leotpn	veto	veto	1 loose muon or electron
minΦ(MET,jet)	> 0.6	> 0.6	No cut
Top jet	1 b-subjet	0 b-subjet	1 b-subjet





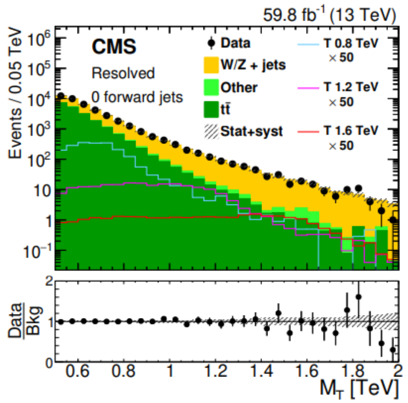
Systematics

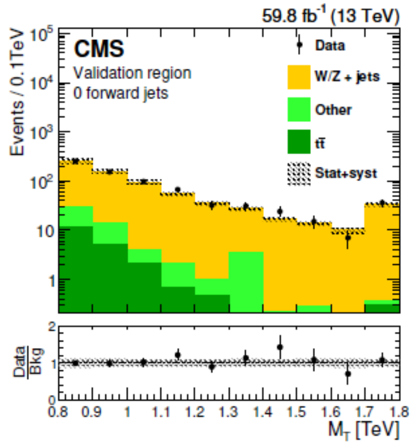
Source	Effect(%)	Type
Luminosity	1.8	rate
Pileup	0.2-3	rate
b-tagging	0.5-1.2	rate
Top tagging	9-10	rate, shape
W tagging	7-8	rate, shape
Trigger efficiency	1-3	rate, shape
Prefiring	0.2-3	rate, shape
JES	2-18	rate, shape
JER	2-5	rate, shape
PDF	1-5	rate
μ_F和μ_R	8-13	rate, shape
Background scale factors	5-30	rate, shape

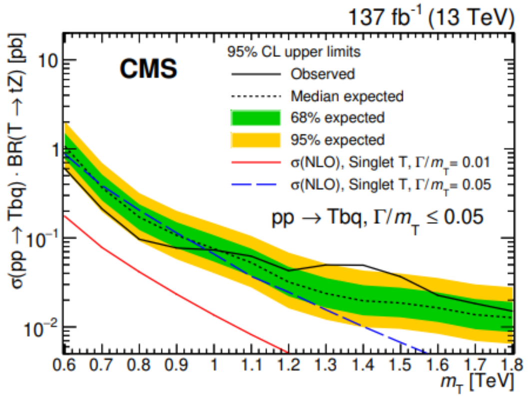
The dominant systematics are: top tagging, W tagging, μ_R, μ_F, background SF

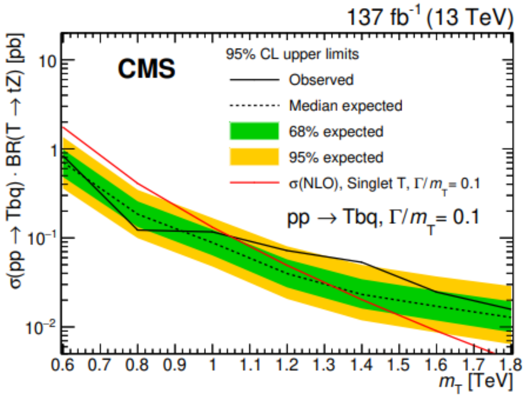
Results

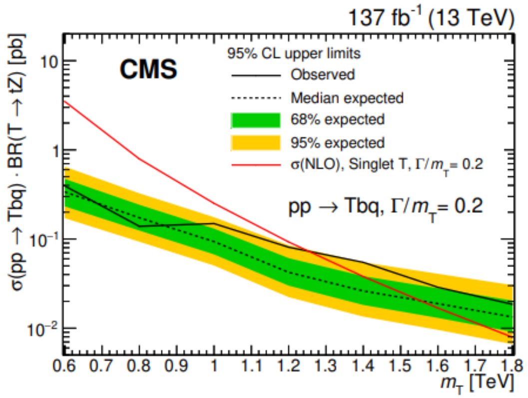
95% confidence level(CL) exclusion limits on the production cross section of T’ times BR

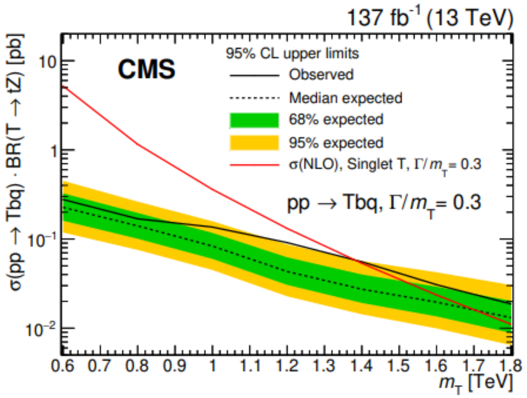


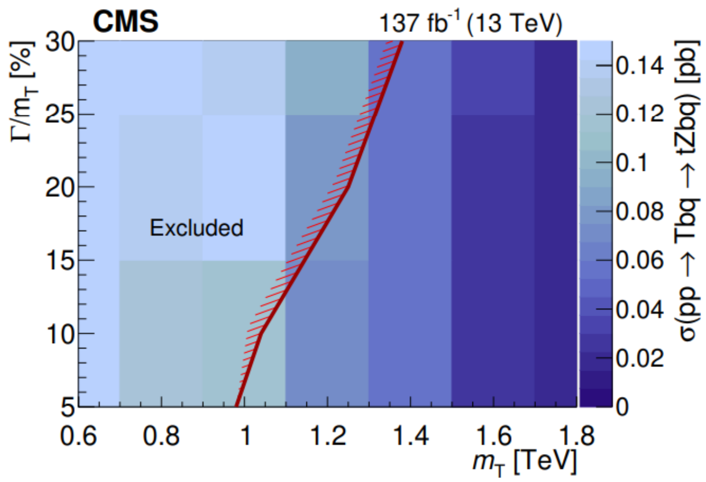










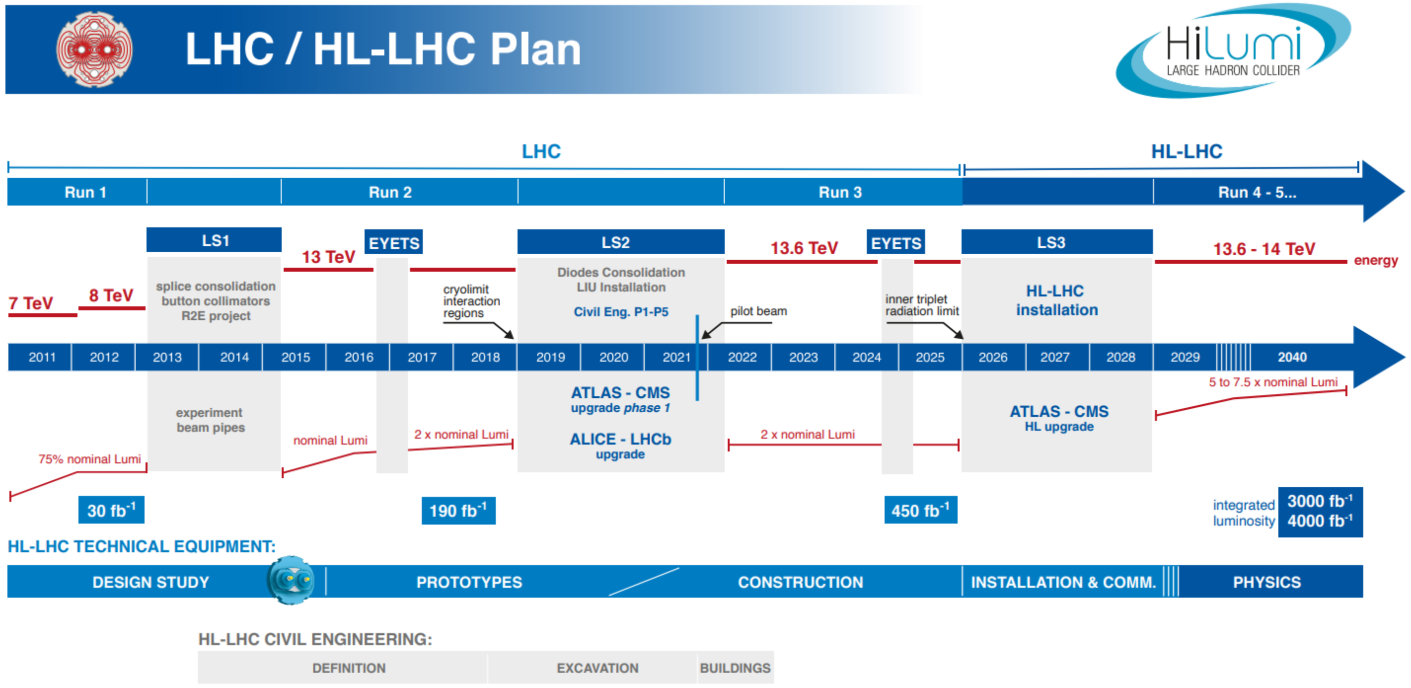


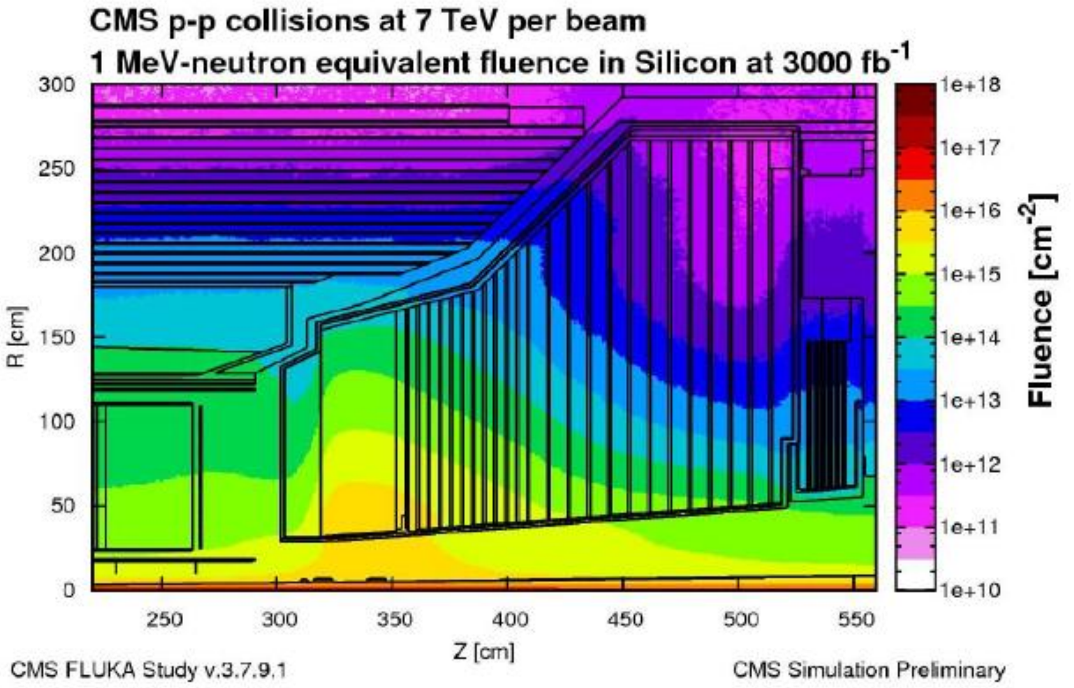
- Narrow width resonance: cross section : greater than 602–15 fb.   Masses: below 0.98TeV
- 10-30% width resonance : cross section : greater than 836–16 fb Masses: below 1.4TeV
- 2D limit: The hashed red line indicates the boundary of the excluded region

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Status of CMS-HGCAL Module Assembly Center(Beijing)

CMS-HGCAL project: motivations



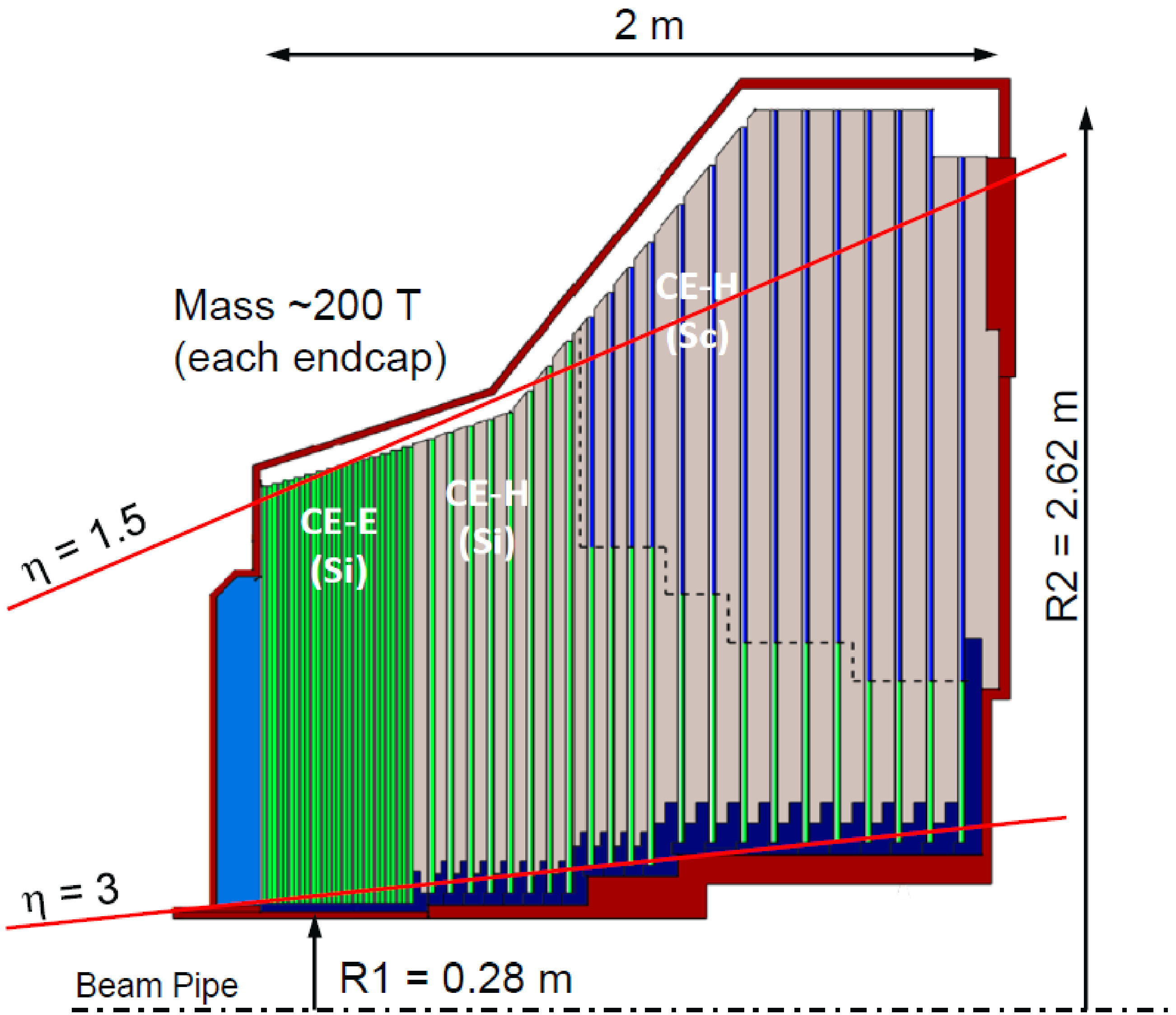


➢CMS endcap calorimeters: Phase-2 upgrade

- Harsh environment at HL-LHC: high pile-up, high radiation level
- Required to replace the existing endcap calorimeters
- Construct a High Granularity Calorimeter: HGCAL project

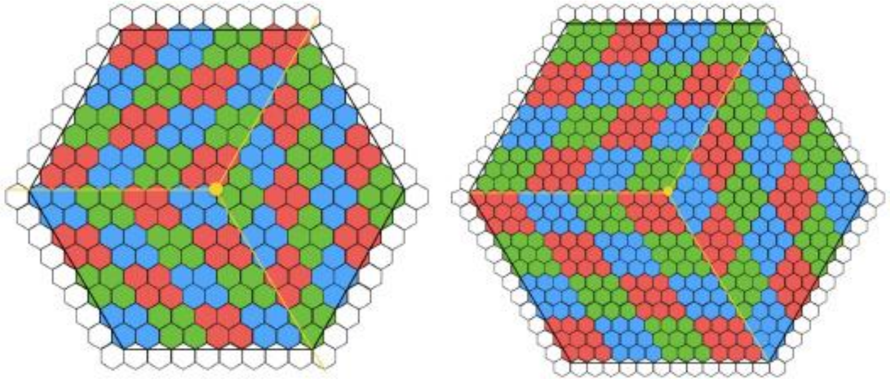
CMS HGCAL project overview

- Key Parameter(update from the TDR):
  - HGCAL covers 1.5<|η|<3.0
  - Full system maintained at -30℃
  - ~640 m^2 of silicon sensors
  - ~370 m^2 of scintillators
  - 6.1M silicon channels: 0.5 or 1.1cm2 cell size
  - 240k scintillator-tile-SiPM channels
  - Data readout from all layers
  - ~31k Si-modules: including spares
- Active layers and elements
  - Si-sensors (full and partial hexagons) in CE-E and high-radiation region of CE-H
  - SiPM-on-Tile in low-radiation region of CE-H
- Electromagnetic calorimeter(CE-E):
  - 28 layers, $25.5X_0$(1.7λ)
  - Si, Cu/CuW/Pb absorbers
- Hadronic calorimeter(CE-H):
  - 22 layers, ~9.5 λ(including CE-E)
  - Si & scintillator, steel absorbers

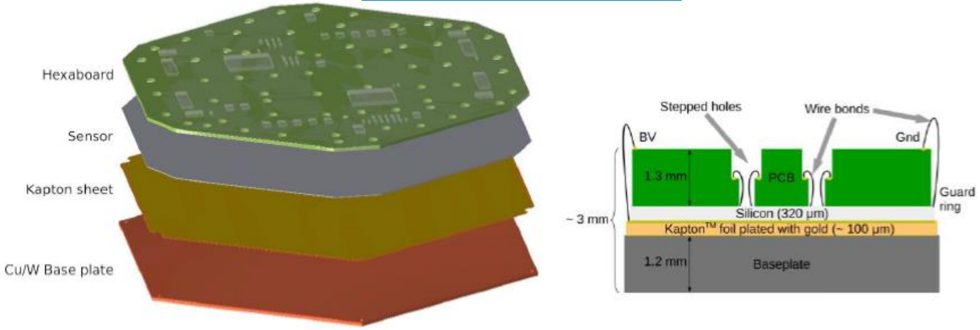


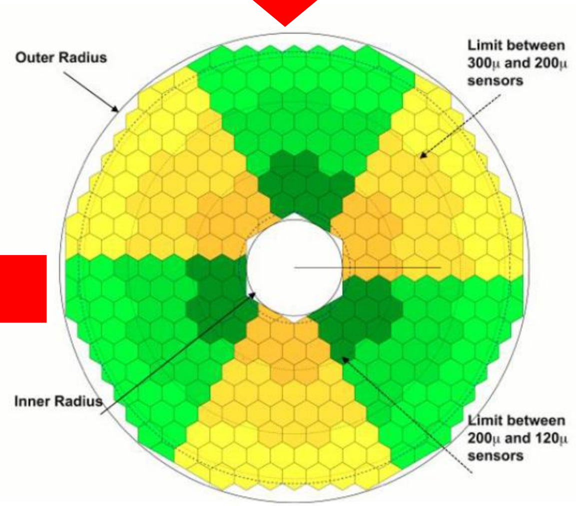
Structure of CMS endcap calorimeter

8 inch sensor

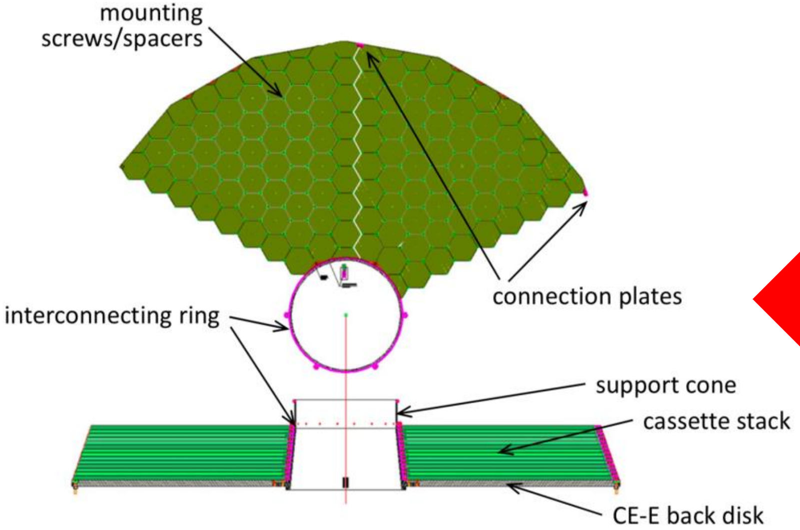


Silicon modules

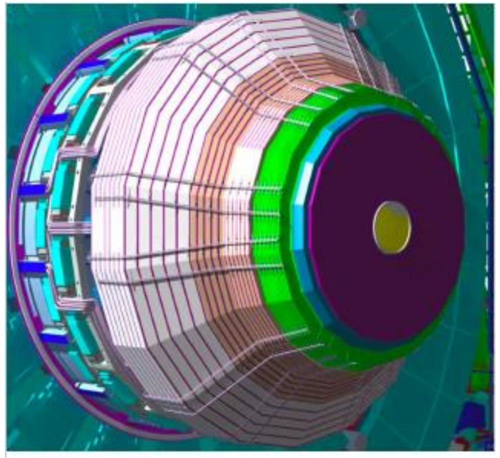




Tiling



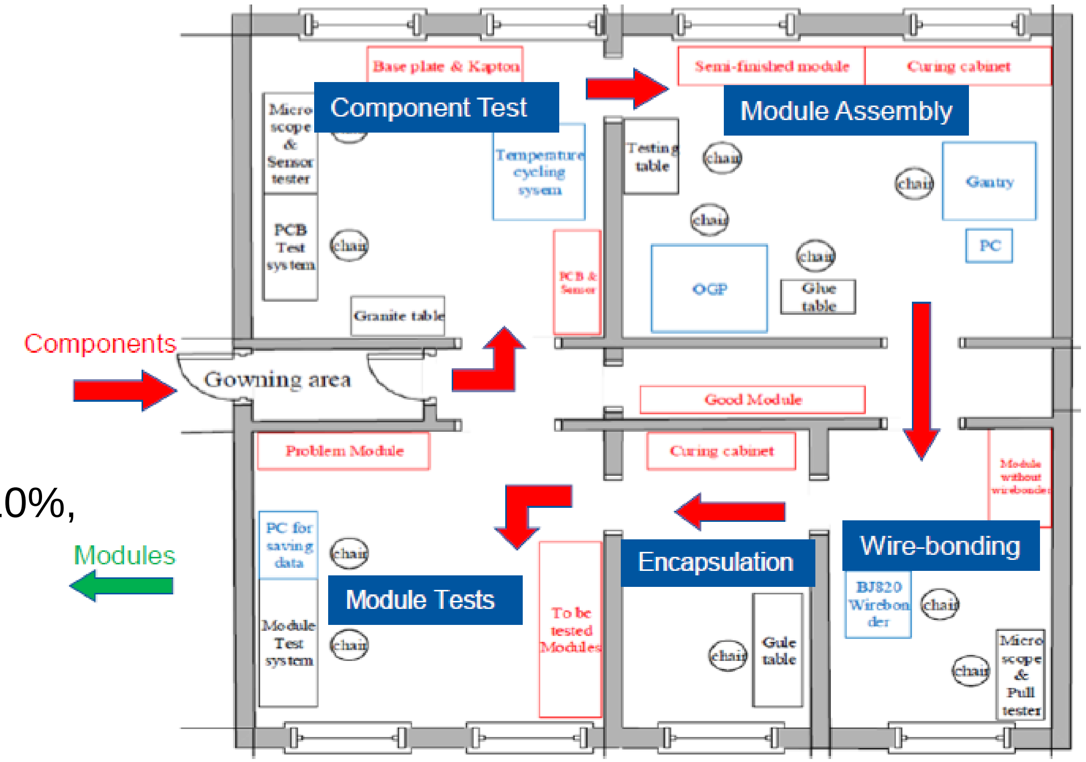
Stacking

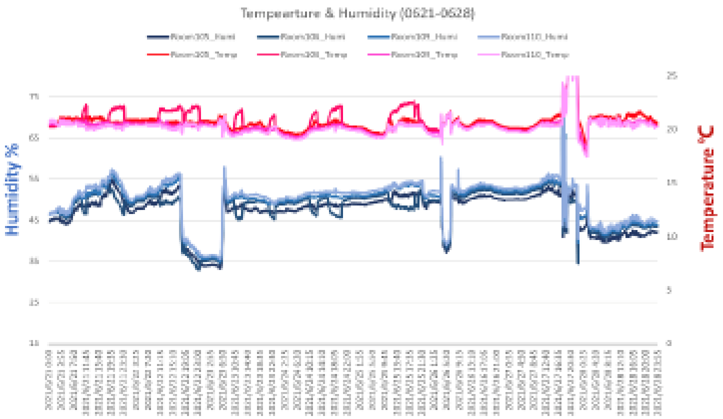


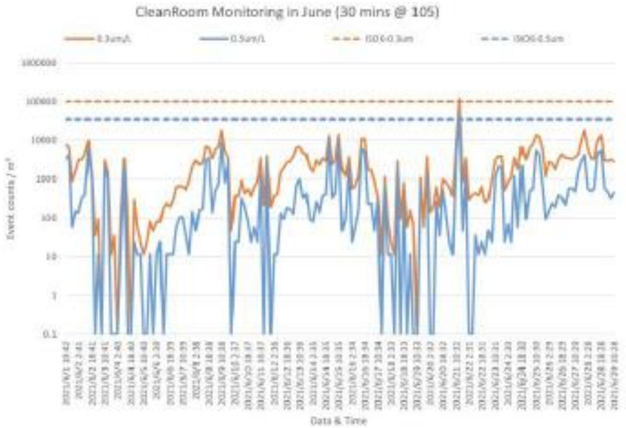
Endcap calorimeter

Module Assembly Center(MAC)

- HGCAL: ~31000 silicon modules
  - Module assembly chain established
- Module Assembly Center(MAC)
  - 6 MACs world wide: 3 in Asia, 3 in US
  - Each MAC expected to assembly ~5000 silicon module
  - MAC-Beijing: a dedicated silicon lab on IHEP campus
- MAC at IHEP
  - 140m^2 Clean room: temperature 21±1℃，humidity: 45±10%, Monitoring of particle level: better than Class 1000





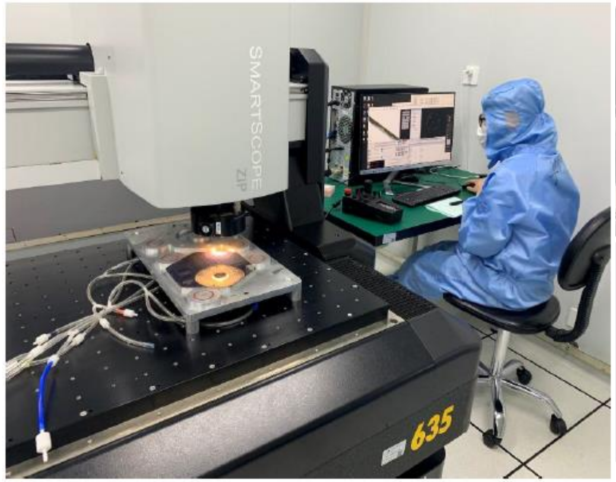


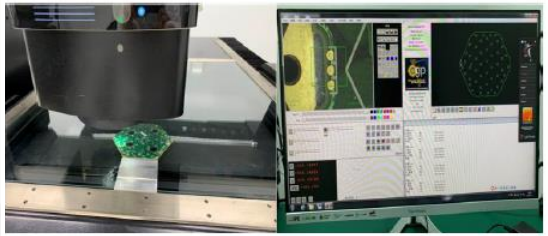
Key procedure in module assembly: component Testing

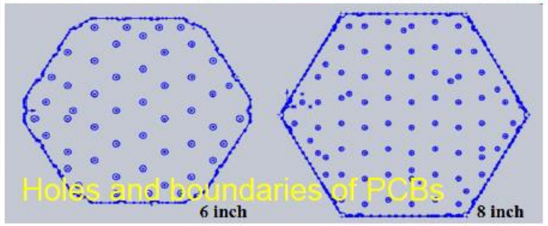
Component testing → Module Assembly by Gentry → Wire-bonding → Module Encapsulation → Module testing

➢PCB testing: Optical gauging product(OGP)

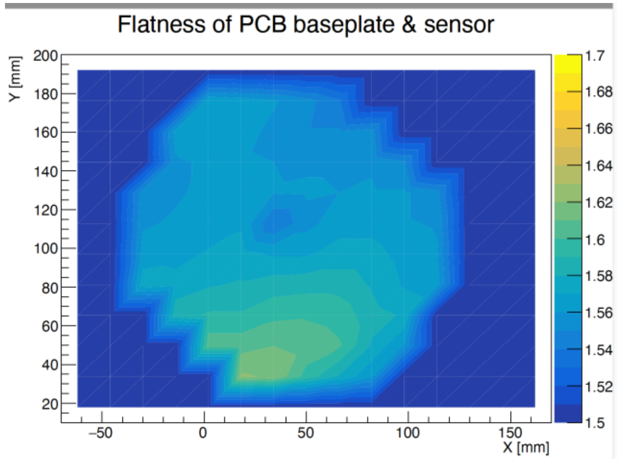
- Extensive measurements performed for baseplates, PCBs: size, boundaries, thickness, flatness
- Visual inspection boosted by machine learning: identify and categorize scratches on silicon sensors

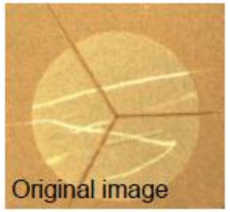






- Thickness tolerance of sensor on PCB < 40μm
- Thickness tolerance of module < 125μm
- Standard tolerance: 250μm
- Flatness meeting the requirement





Hex-sensor

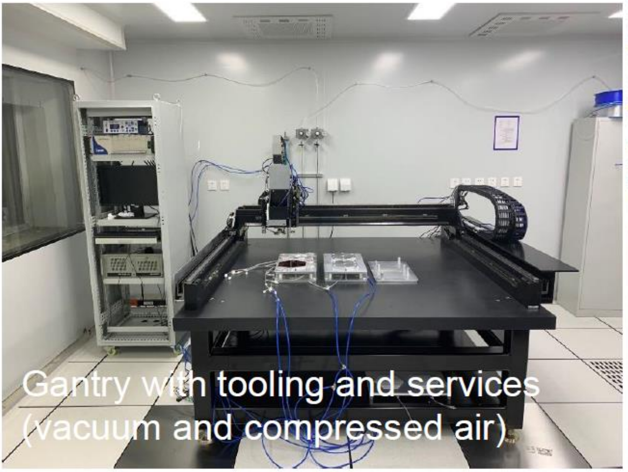
- Delta_x ~ 24 μm
- Delta_y ~ 45 μm
- Center-to-center tolerance： 50μm

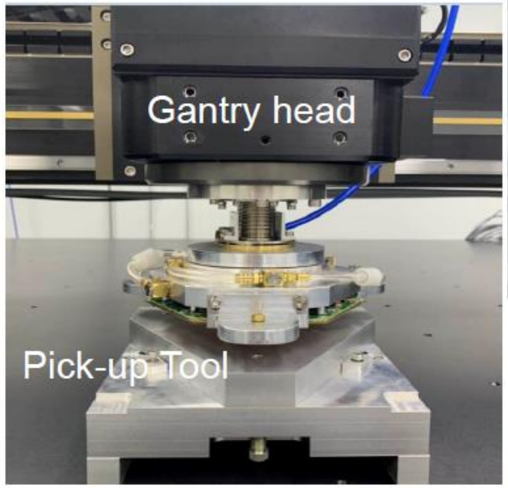
	X(mm)	Y(mm)
Baseplate	40.34447	104.39552
	40.35422	104.41038
Sensor	40.35995	104.36856
	40.36047	104.37022
Hexaboard	40.33810	104.41023
	40.33637	104.41361

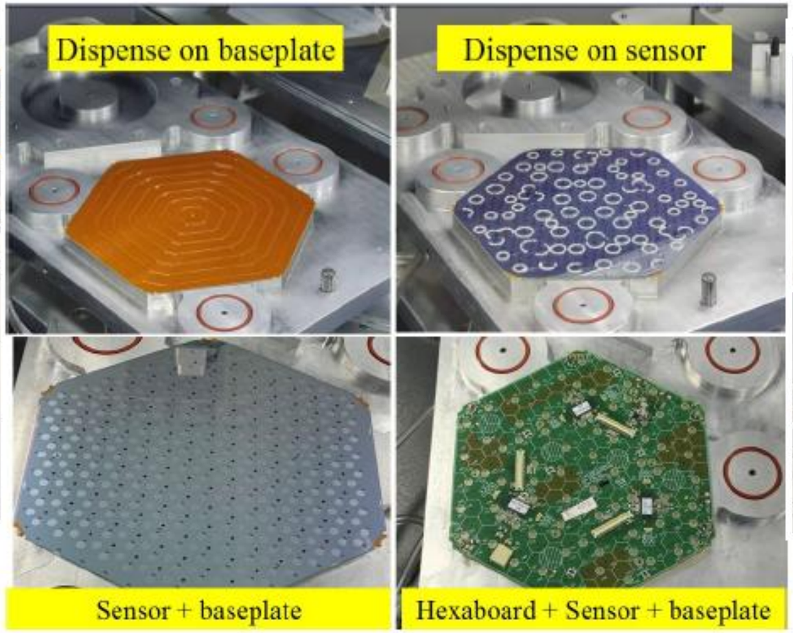
Key procedure in module assembly: gantry operations

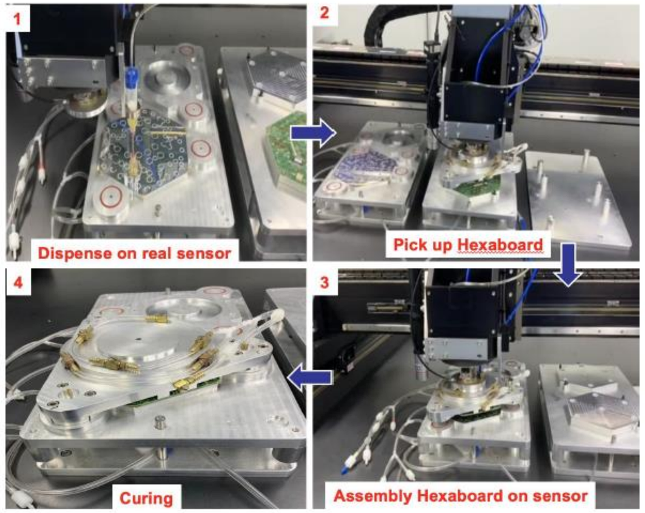
Component testing → **Module Assembly by Gentry** → Wire-bonding → Module Encapsulation → Module testing

- Module assembly: with the main gantry and tooling (camera, gantry head, fixtures, etc.)
  - Precision pick-and-place movements with components, fine glue dispensing
  - Automated operations with dedicated software





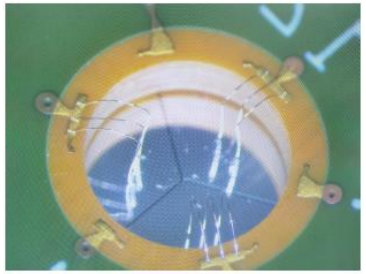




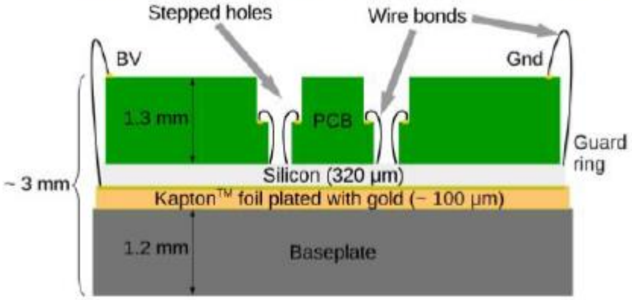
Key procedure in module assembly: Wiring bonding

Component testing → Module Assembly by Gentry → Wire-bonding → Module Encapsulation → Module testing

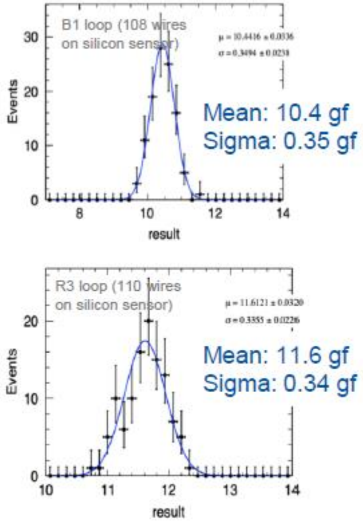
- Wire-bonding: to build electrical connections between silicon sensors and PCB
  - Exercises with dummy sensors and PCBs and optimize bonding parameters
  - Applied optimized parameters for the assembly 8-inch real modules



Schematics of wire-bondings of silicon modules (side view)



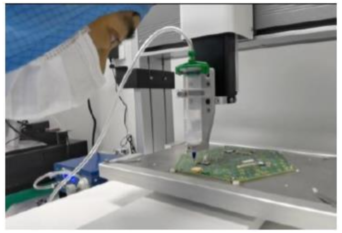
- Wire-bonding quality (by pull tester): wire-bonds can fulfill the strength requirement
  - Destructive pull test: measure the strength of bonding wires and feet
  - Non-destructive test: to extract the correction factor to be applied for destructive pull tests
  - Wire-bond in a triangle form (max. 5gf strength set)

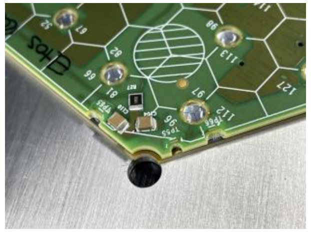


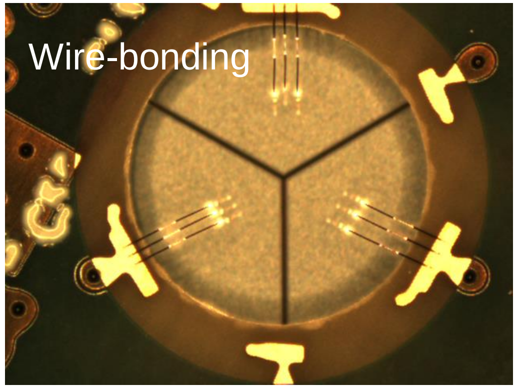
Key procedure in module assembly: Encapsulation

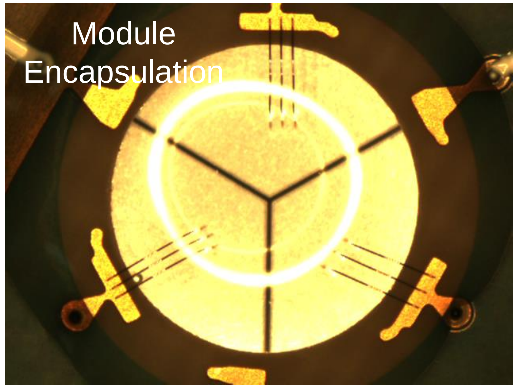
Component testing → Module Assembly by Gentry → Wire-bonding → Module Encapsulation → Module testing

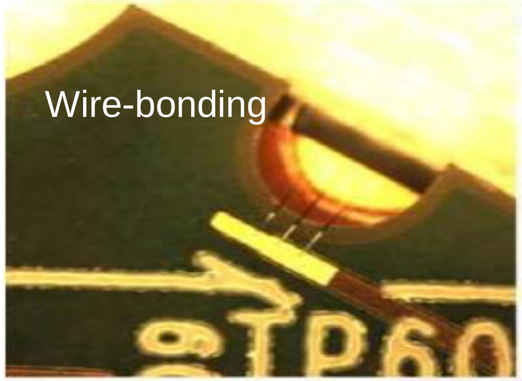
- Mini-gantry system: dispense glue to encapsulate the wire-bonds for better mechanical stability
  - Mini-gantry: to dispense glue points into the stepped holes of PCBs, exercises with mock-ups
  - Centrifuge: to remove bubbles in 2-component glue mixture

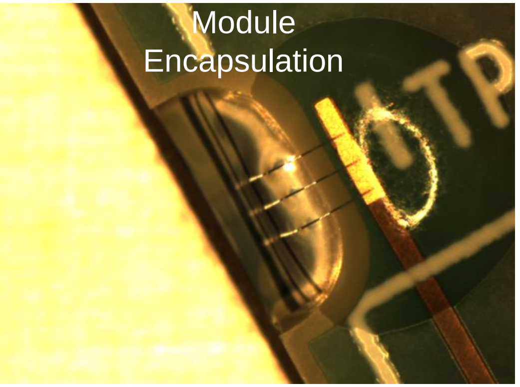








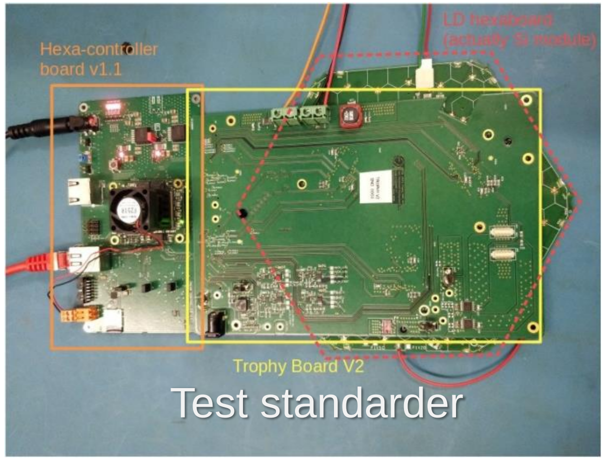


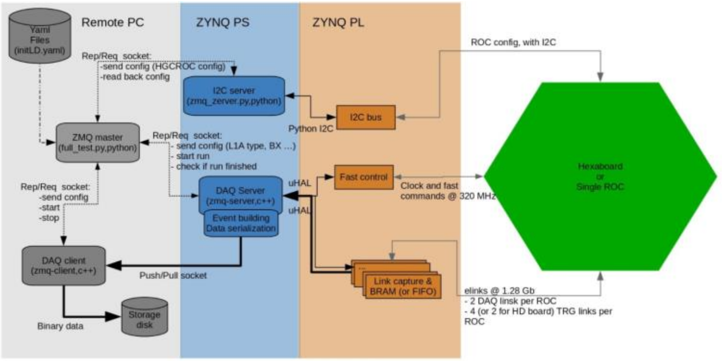


Hex-aboard Electronics testing

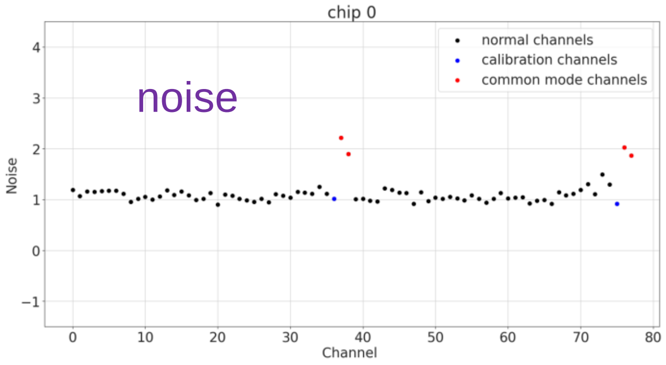
Component testing → Module Assembly by Gentry → Wire-bonding → Module Encapsulation → Module testing

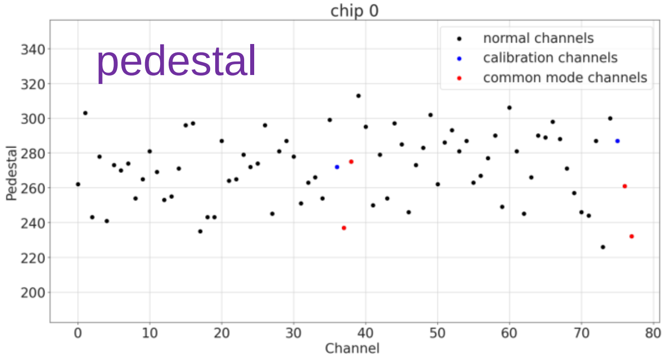
Hex-aboard Electronics testing

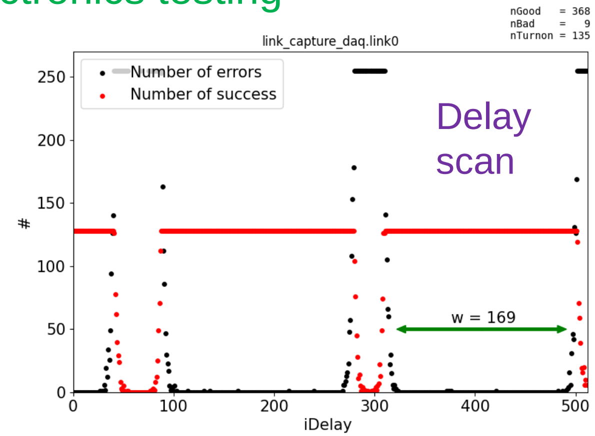




DAQ system diagram





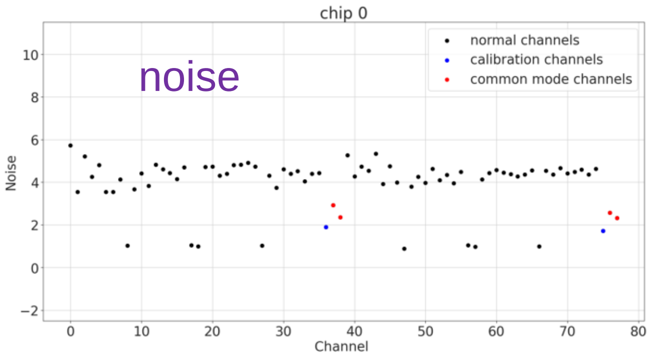


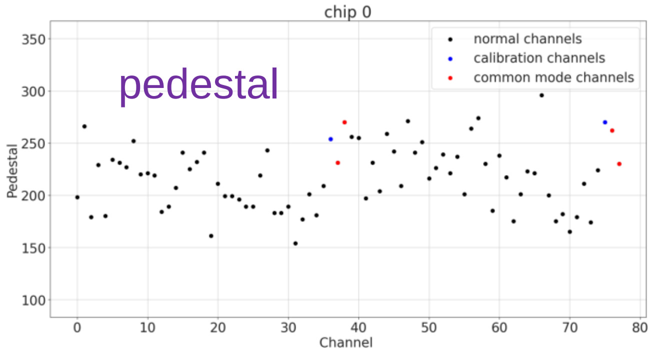
- Low noise for hex-aboard
- Good pedestal for hex-aboard

Si-Module Electronics testing

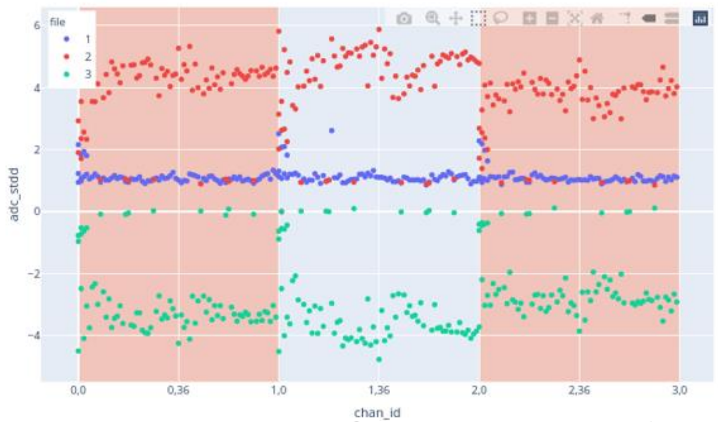
Component testing → Module Assembly by Gentry → Wire-bonding → Module Encapsulation → Module testing

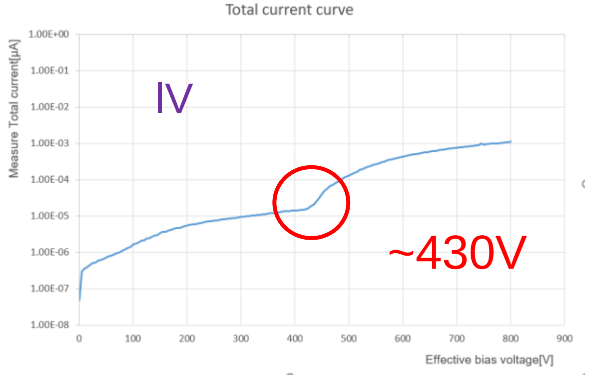
Module Electronics testing





Noise before/after assembly



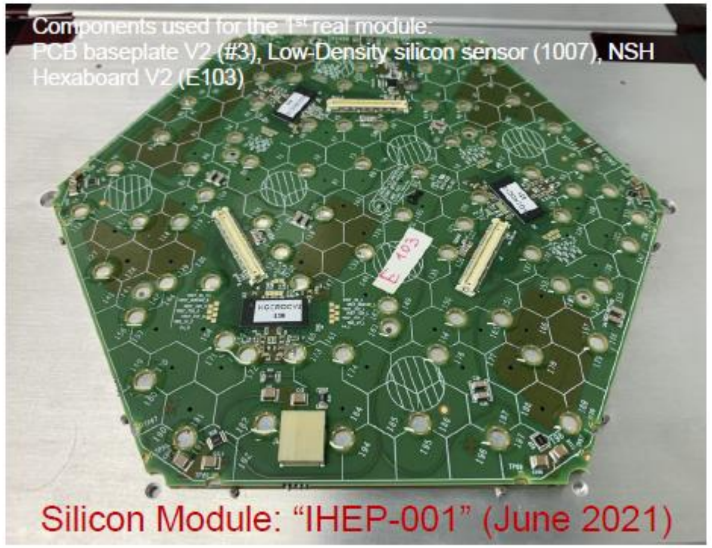


Pedestal before/after assembly

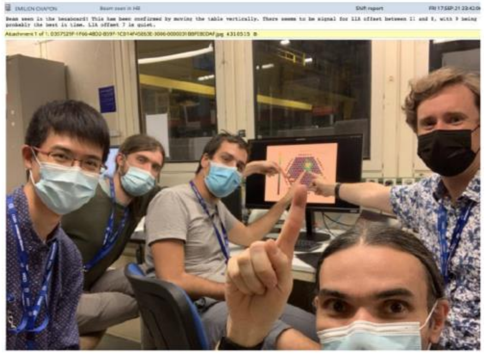
- Low noise before/after assembly
- Good pedestal before/after assembly
- Good IV for the Module

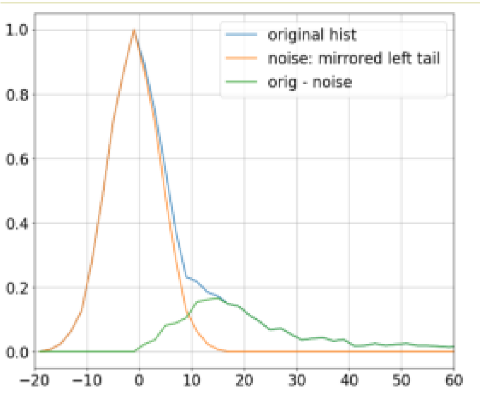
Module assembly at IHEP(1)

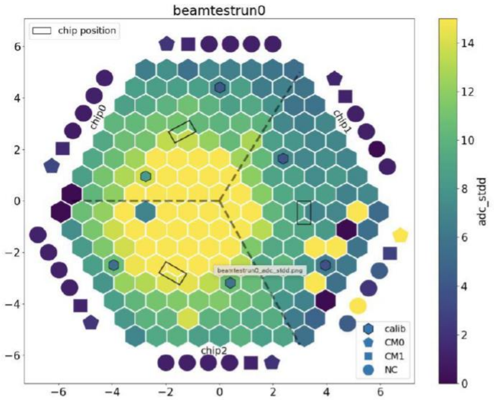
- Successfully assembled the first 8-inch silicon module: **the first MAC to achieve this goal**
  - Applied optimized parameters from extensive exercises of dummy module assembly
  - Full functionality demonstrated in lab tests →validated the 8” silicon module design



- Beam testing at CERN SPS in Sep.-Oct. 2021
  - Two silicon modules(HGCROC v2, v3) assembled by IHEP was tested in CERN
  - Successfully seen hexa-board response to beam: MIP signals

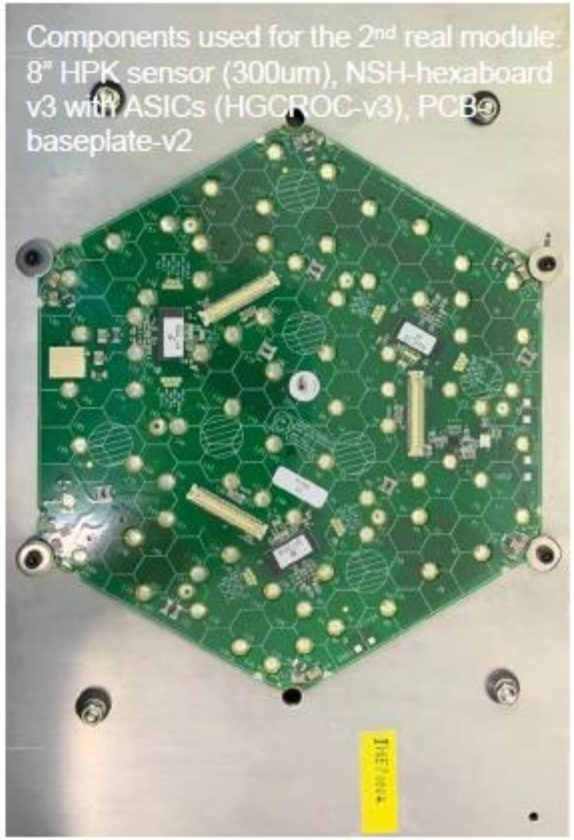






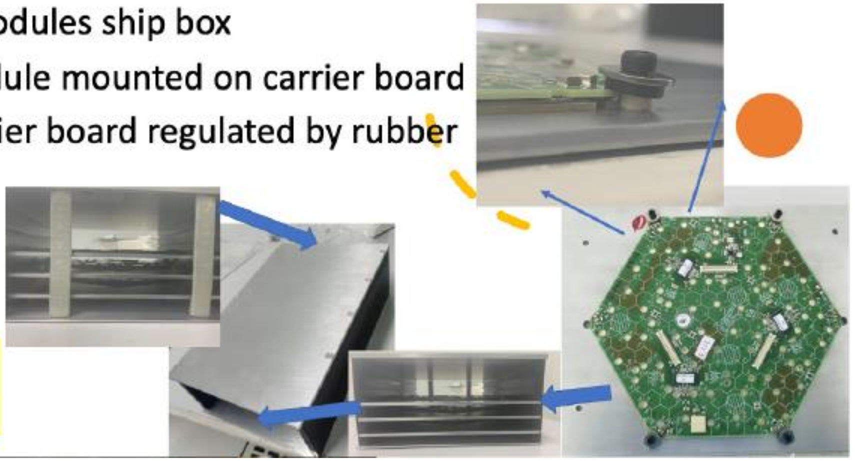
Module assembly at IHEP(2)

- Successful assembly of the second 8-inch LD module

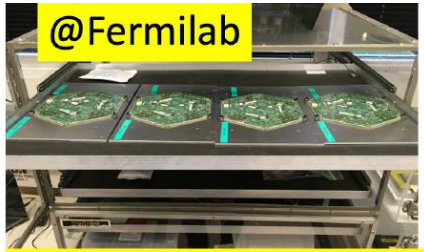


- A successed small "mass" pre-production

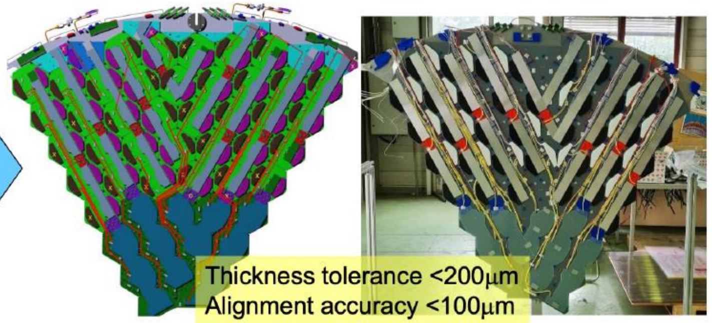
- 5 modules ship box
- Module mounted on carrier board
- Carrier board regulated by rubber



@IHEP



4 Modules were accepted by Fermilab on 13 Apr. for cassette test



MAC Beijing Certify

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
COMPACT MUON SOLENOID COLLABORATION
URL : http://cms.cern

Dr. Karl Gill
CMS HGCAL Project Manager
Principal Applied Physicist
CERN - EP Department
CH - 1211 GENEVA 23
Switzerland

Tel. +41 75 411 4712
E-mail Karl.Aaron.Gill@cern.ch

December 15, 2021

Subject: ***Certification of qualification the HGCAL Module Assembly Centre at IHEP, Beijing***

To whom it may concern,

I am writing as Project Manager for the CMS endcap calorimeter upgrade project (HGCAL) to certify that the silicon module assembly center (MAC) at IHEP Beijing, led by Prof. Huaqiao Zhang, has been qualified for the HGCAL project as ready to move into the Pre-Series phase of construction.

HGCAL will replace several of the present CMS sub-detectors: the silicon/lead endcap pre-shower detector, the lead-tungstate crystal electromagnetic endcap calorimeter, and the plastic/brass endcap hadron calorimeter. HGCAL is a novel sampling calorimeter, based on a large-scale deployment of silicon modules (a grand total of approximately 26000 installed, plus 5% spares), positioned between dense layers of absorber. The silicon modules will be complemented with plastic scintillator tiles instrumented by silicon photomultipliers (SiPMs) in regions of the detector where particles arrive with lower intensity.

The qualification of the IHEP Beijing MAC has been completed on time to meet the corresponding project milestone. The MAC is set up in a Class 1000 clean room that is dedicated to this facility and all of the equipment for mass production of silicon modules for HGCAL has been installed in the clean room and commissioned. This equipment includes a gantry machine for automated module assembly, a wire-bonding machine, an optical inspection and coordination measurement machine, and a silicon module test-stand. The IHEP Beijing team has been trained in how to use the MAC equipment, and they have practiced extensively on dummy module components before moving onto using live components.

which will be used for the integration of larger prototype assemblies ('cassettes') of the HGCAL detector. The pre-series phase will exercise all the handling, the tooling, and the QA/QC procedures associated with large scale module assembly and testing. It will also permit a deep study and characterization of the robustness of the pre-series modules with large statistics.

We plan to start the pre-series assembly in 2022, once the component parts are all available, and beyond the pre-series, we look forward to ramping up the IHEP Beijing MAC for full-scale mass production.

Yours faithfully,

K. Gill

Karl A. Gill
CMS HGCAL Project Manager

站点认证证明信

Summary

➢Vector-Like quark T' search

- Study of single production of VLQ in tZ (top hadronic, Z to neutrinos) has been shown all Run2 data
- This is first result of MET + jets final state in CMS
- This is the current best published result on single-VLQ T' in the tZ(vv) decay channel.

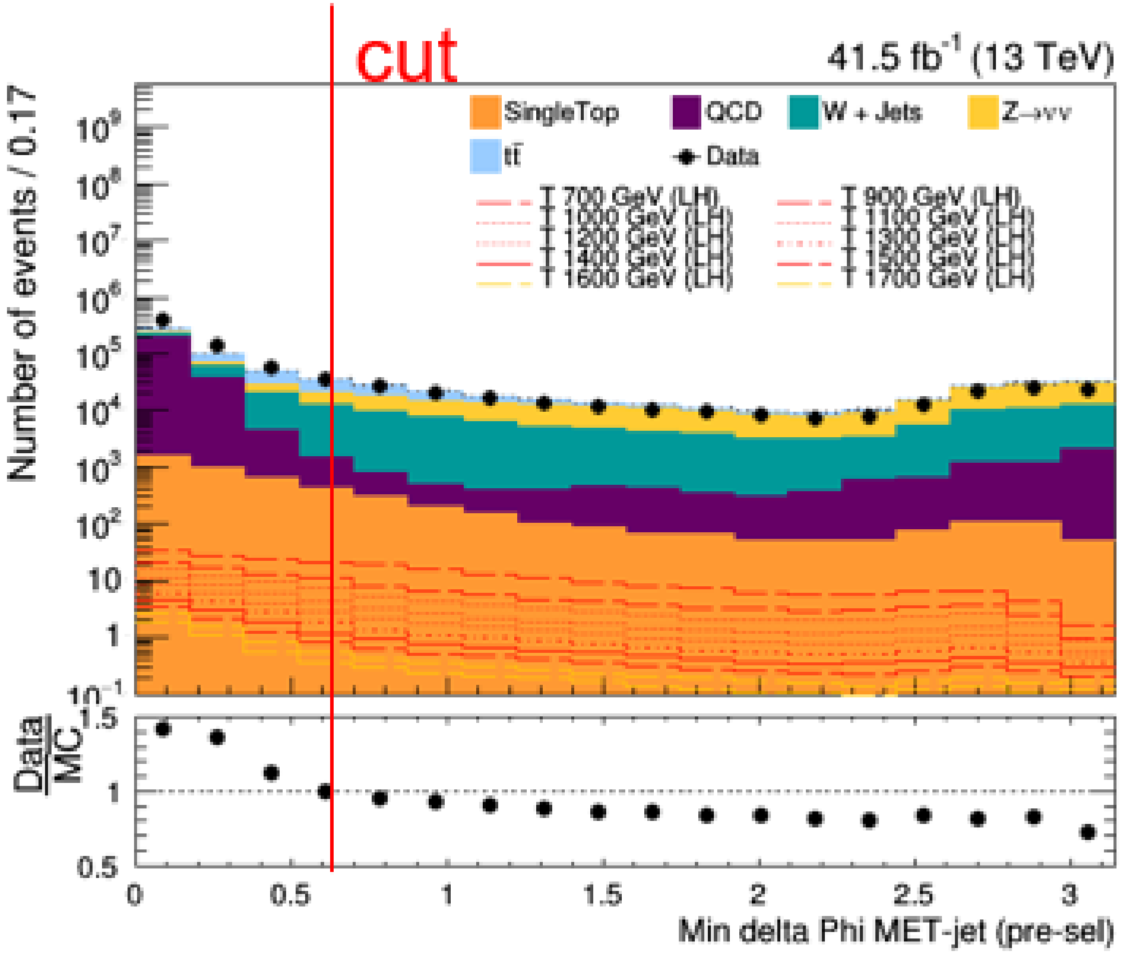
	Cross section@95%CL	Mass@95%CL
Narrow width resonance	>602-15fb	<0.98TeV(5%)
10-30% width resonance	>836–16 fb	<1.4TeV(30%)

➢Status of CMS-HGCAL Module Assembly Center(Beijing)

- Infrastructure established: 140m² clean room, key equipment, test stands, services
- Have the ability to do full chain Module assembly
- MAC-Beijing qualified : Successfully built the first 8-inch silicon module and have built 7 modules, full functionality demonstrated in lab tests
- Complete the MAC certificate

Back up

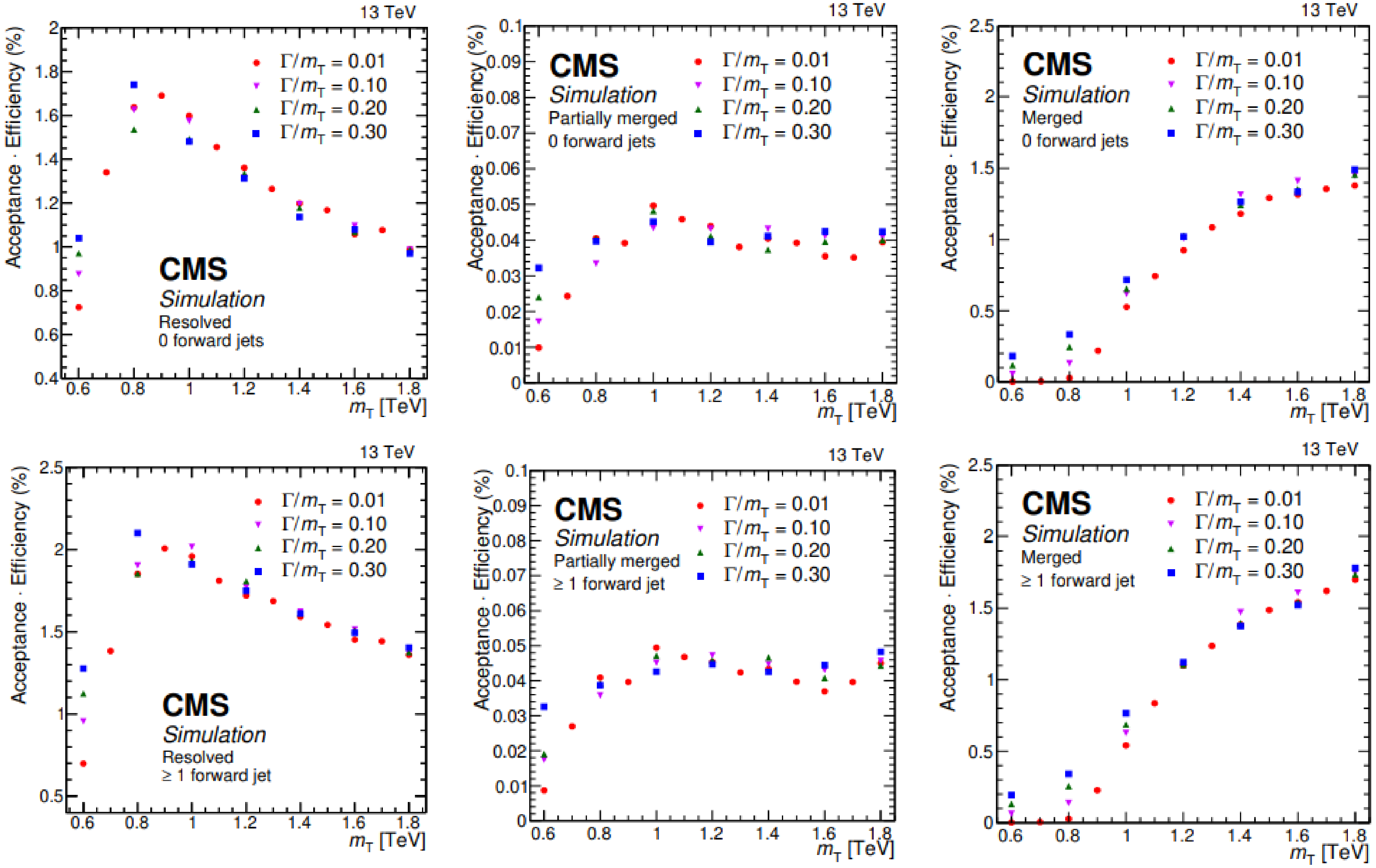
DelatPhi



cut
41.5 fb^{-1} (13 TeV)
SingleTop
QCD
W + Jets
Z→νν
$t\bar{t}$
Data
T 700 GeV (LH)
T 900 GeV (LH)
T 1000 GeV (LH)
T 1100 GeV (LH)
T 1200 GeV (LH)
T 1300 GeV (LH)
T 1400 GeV (LH)
T 1500 GeV (LH)
T 1600 GeV (LH)
T 1700 GeV (LH)
Number of events / 0.17
Data/MC
Min delta Phi MET-jet (pre-sel)

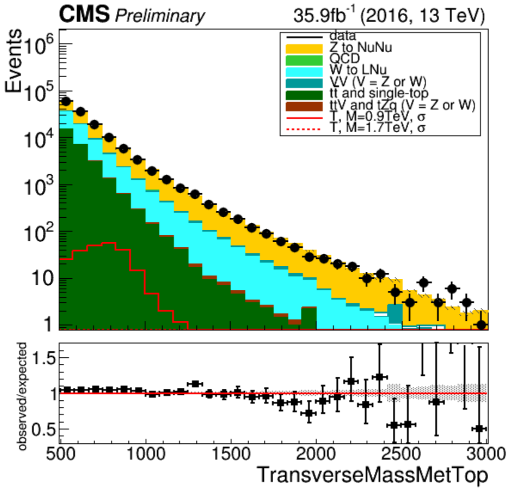
signal selection efficiency

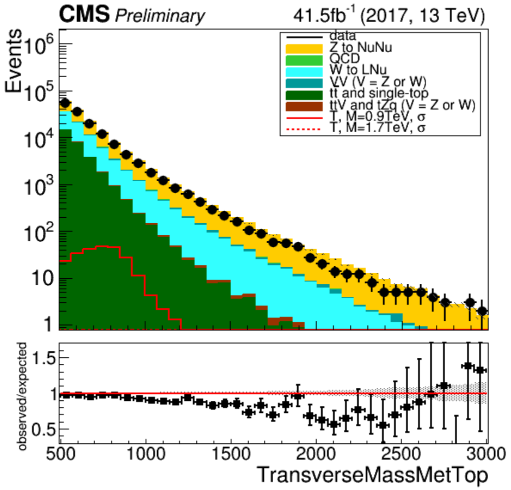
- The signal selection efficiency for different categories list here:

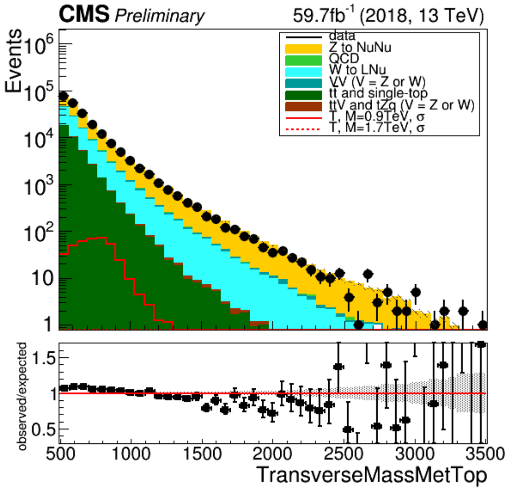


Scale factor test in preselection

without 2D SF

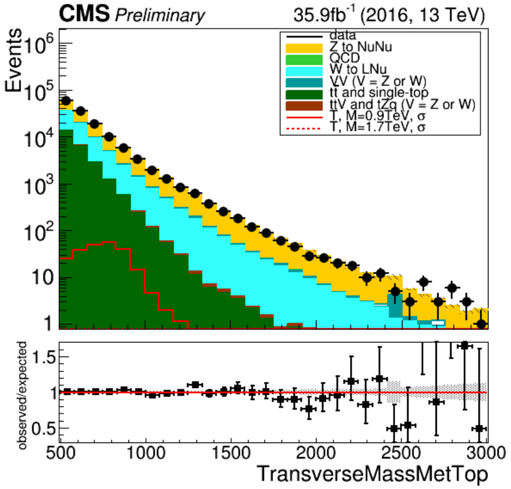


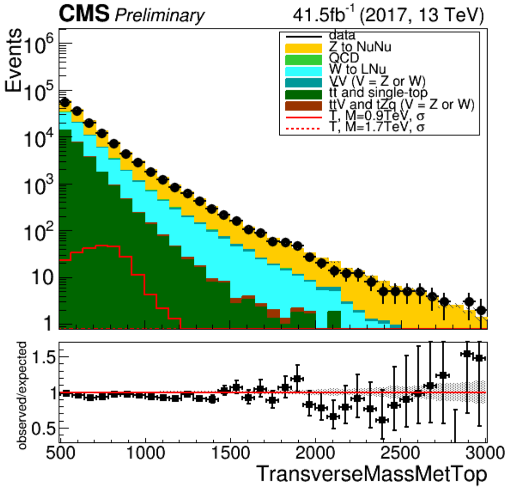


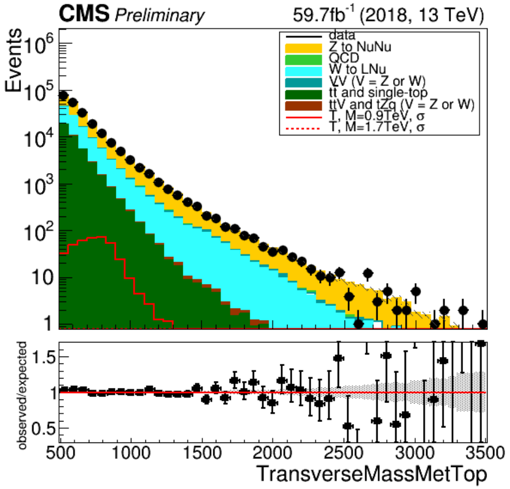


add the 2D SF

Apply 2D SF



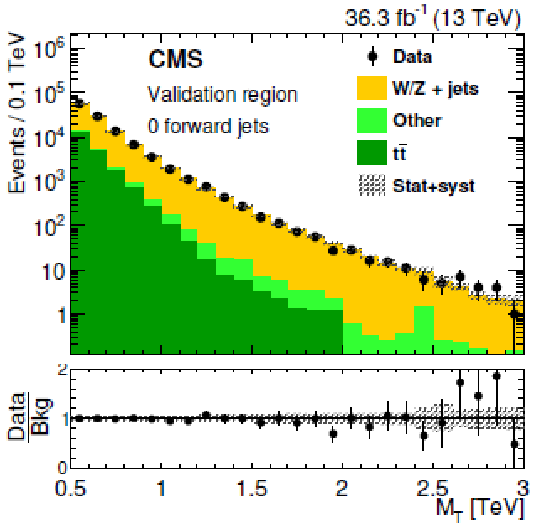


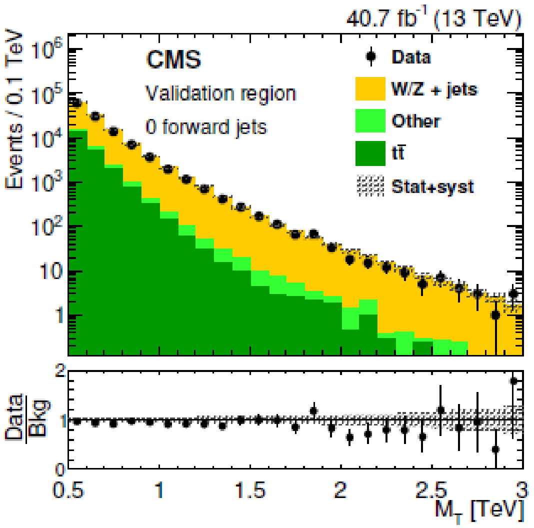


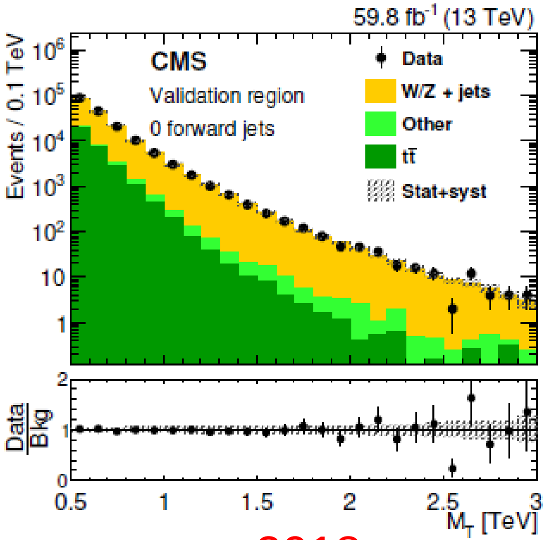
2016 2017 2018

Background estimation test

FWD0

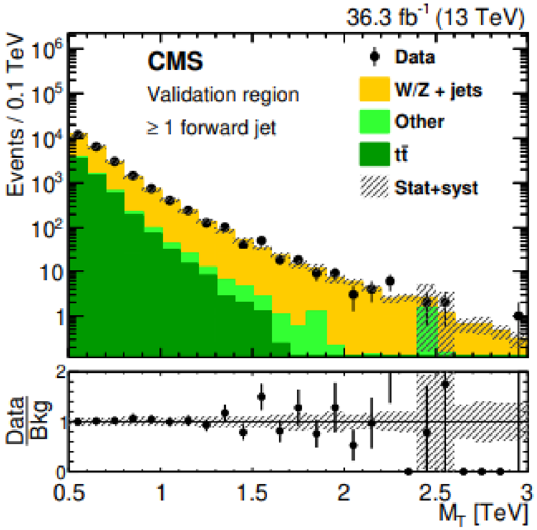


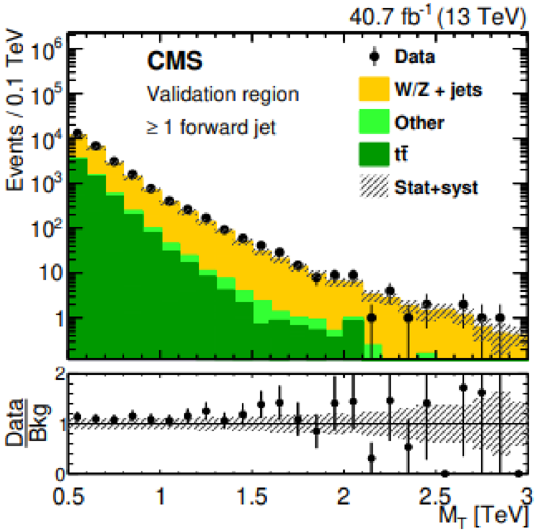


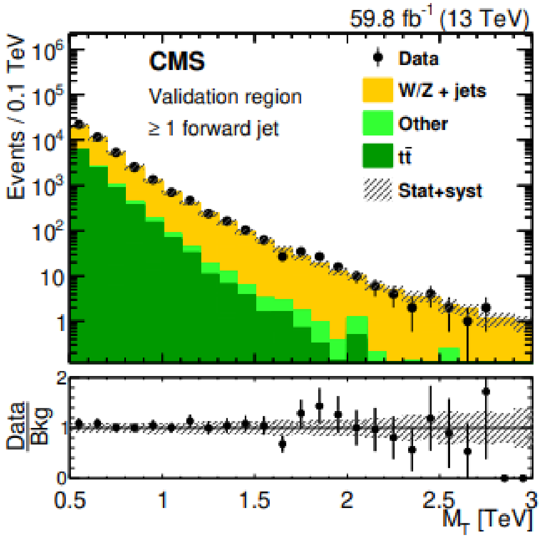


2016 2017 2018

FWD1



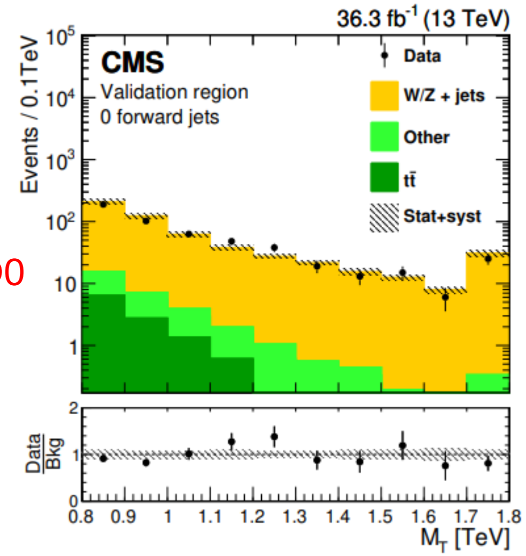


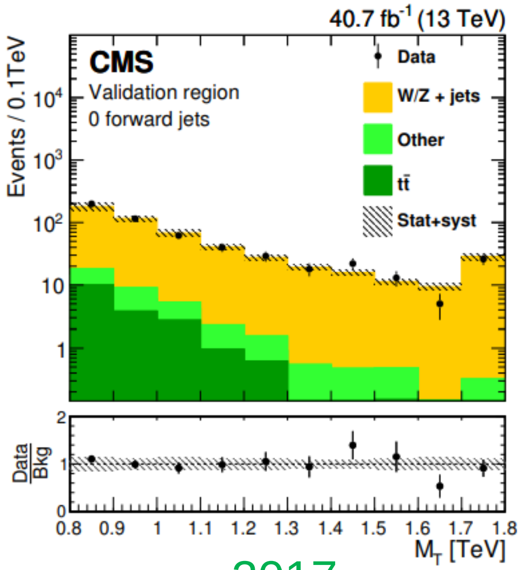


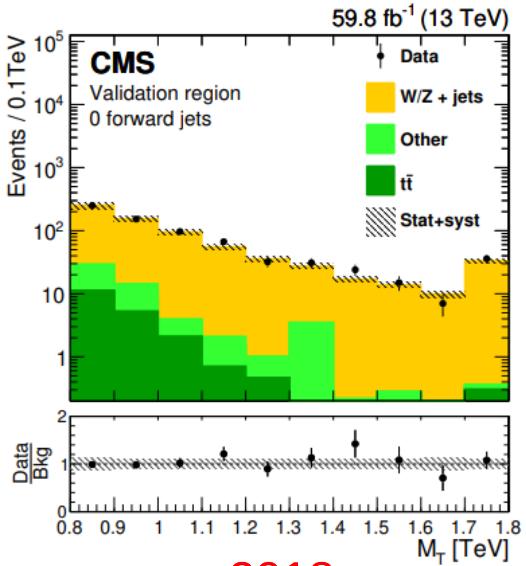
Comparison of data and the predicted background(resolved)

Background estimation test

FWD0

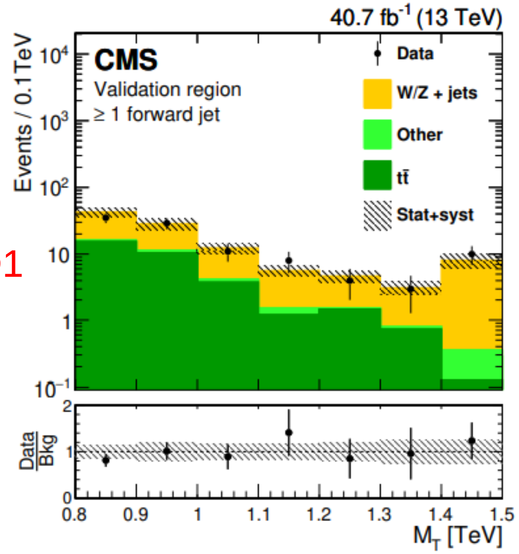


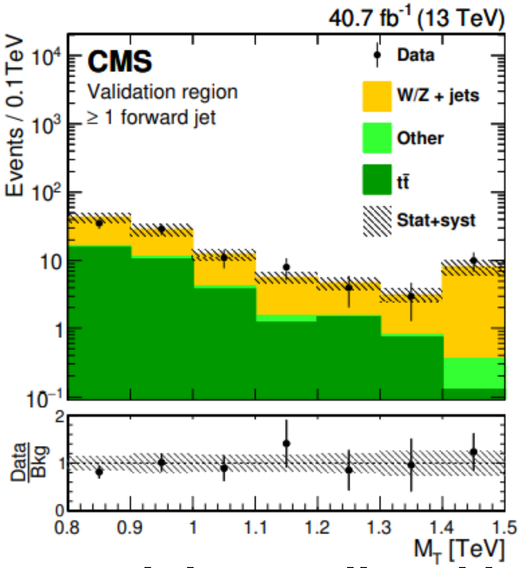


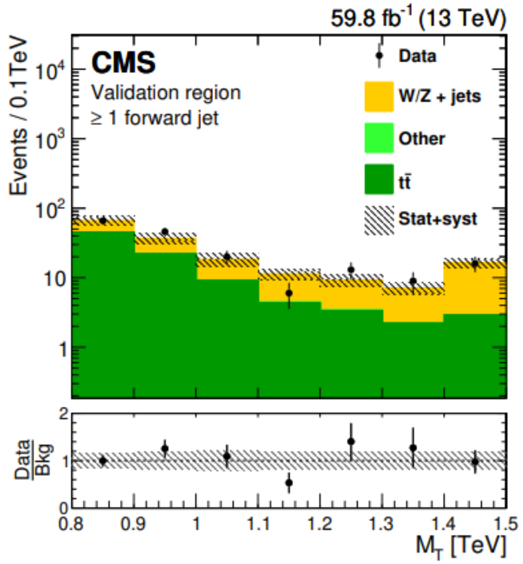


2016 2017 2018

FWD1



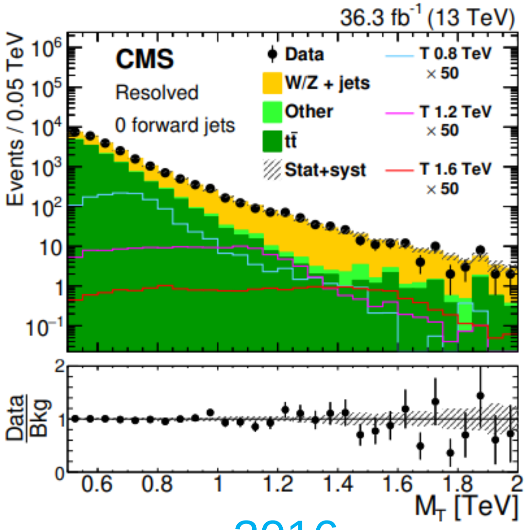


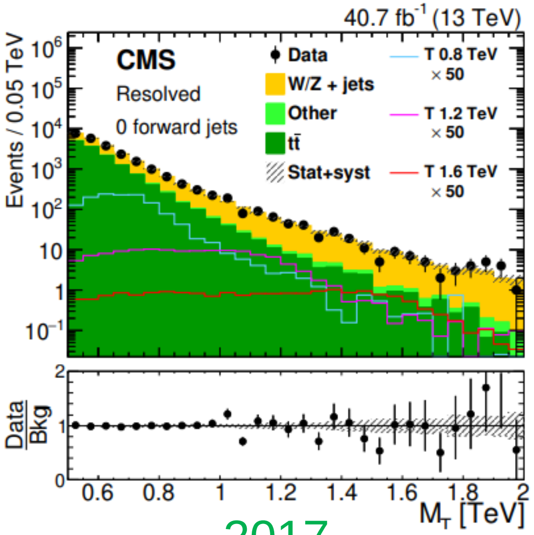


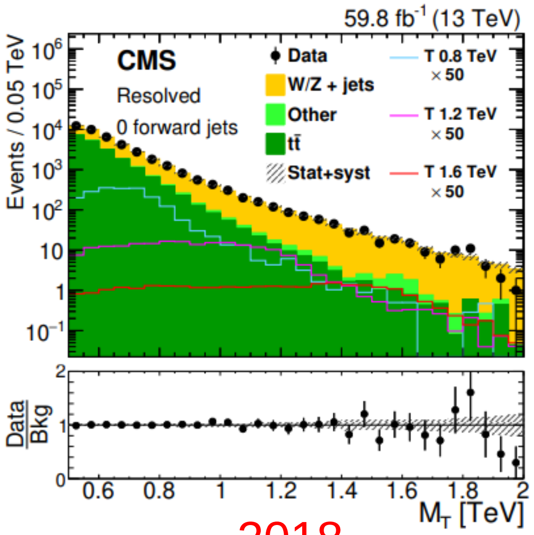
Comparison of data and the predicted background(merged)

Results-Resolved topology

FWD0

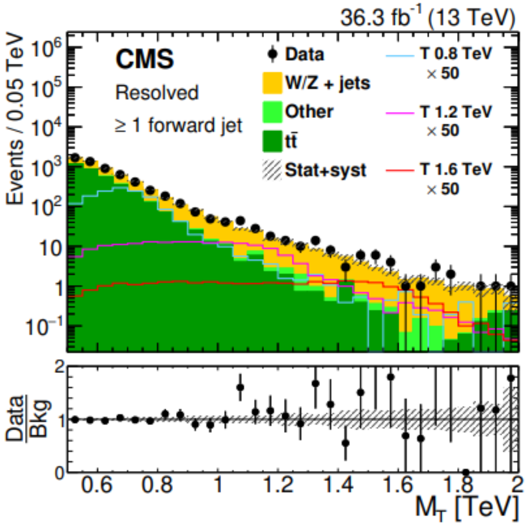


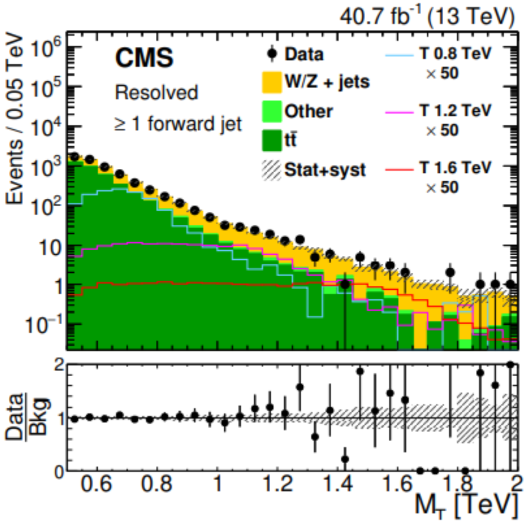


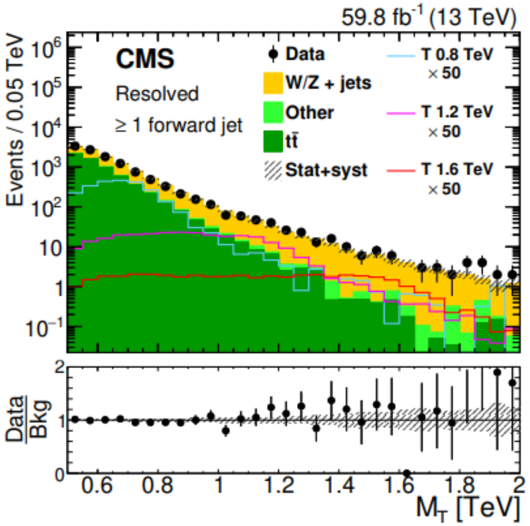


2016 2017 2018

FWD1



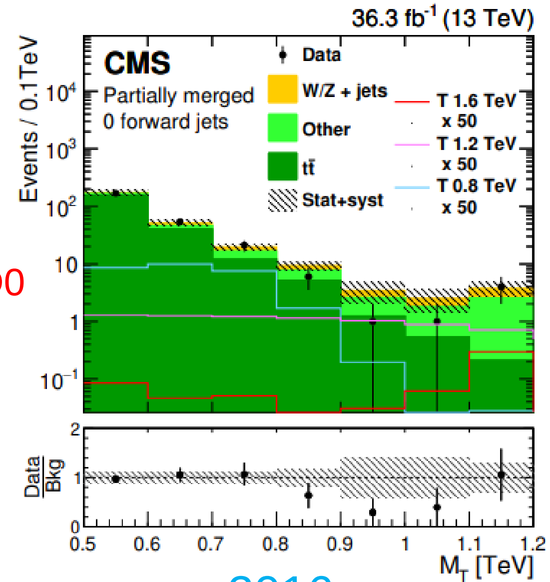


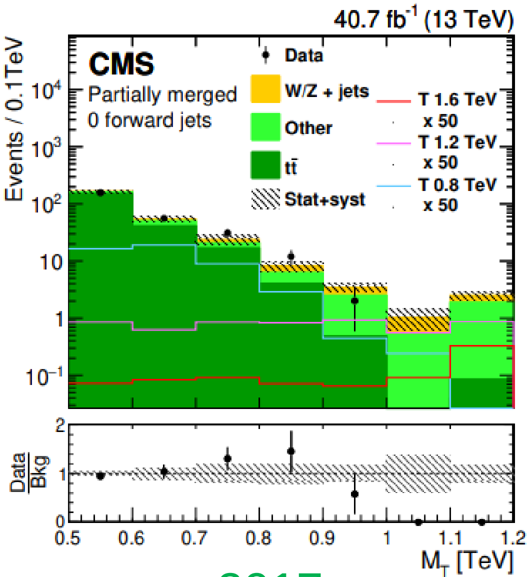


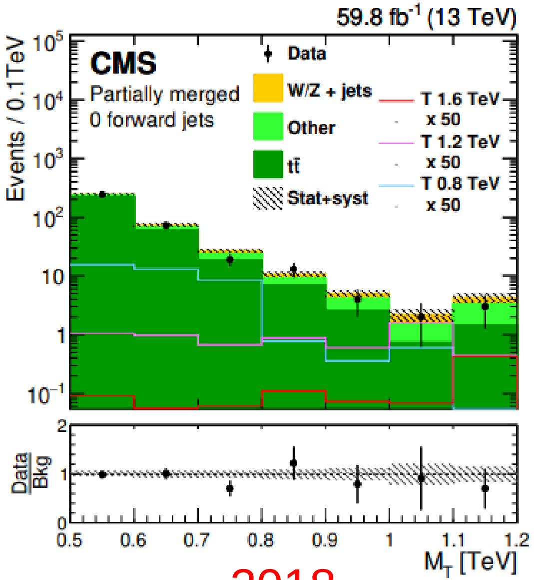
- Distribution of the transverse mass in the signal region
- All background processes are derived from the fit to data

Results – Partially merged topology

FWD0

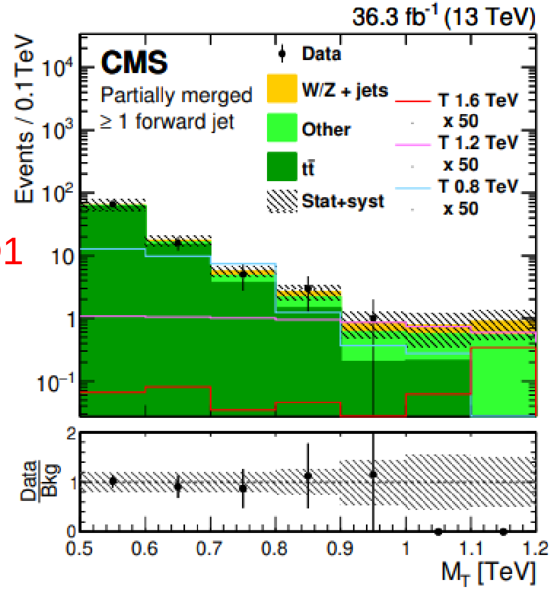


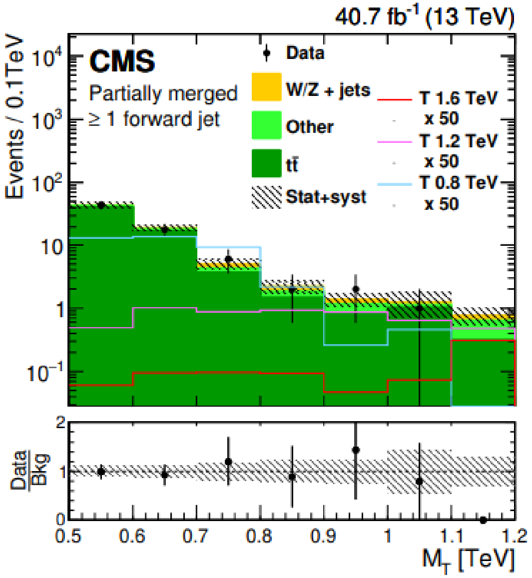


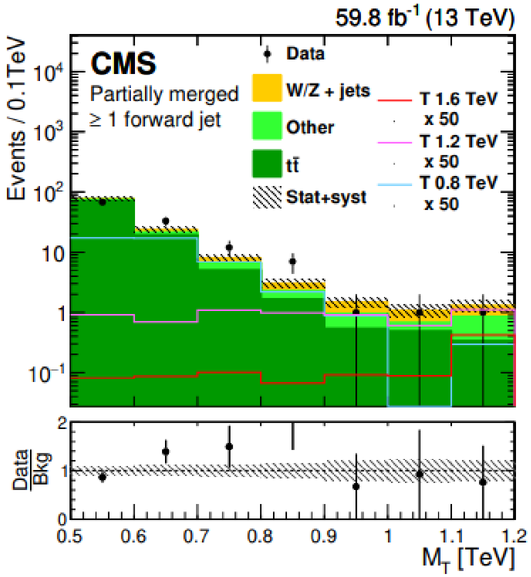


2016 2017 2018

FWD1

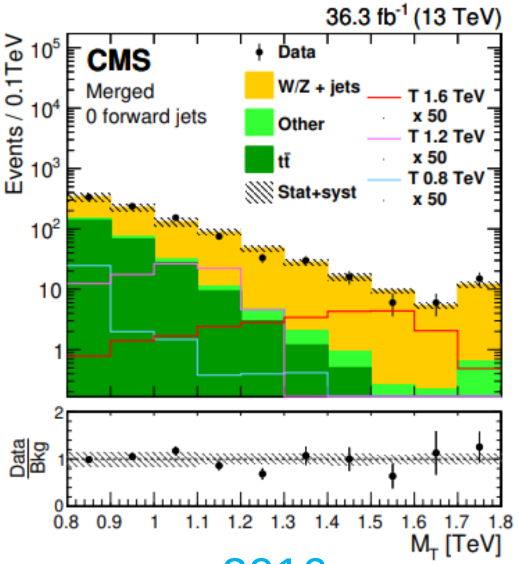


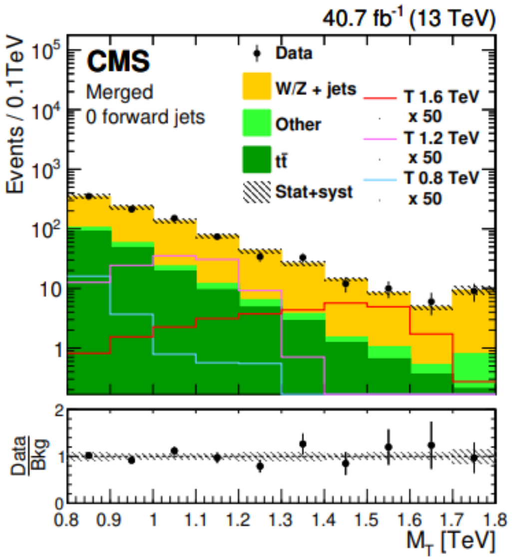


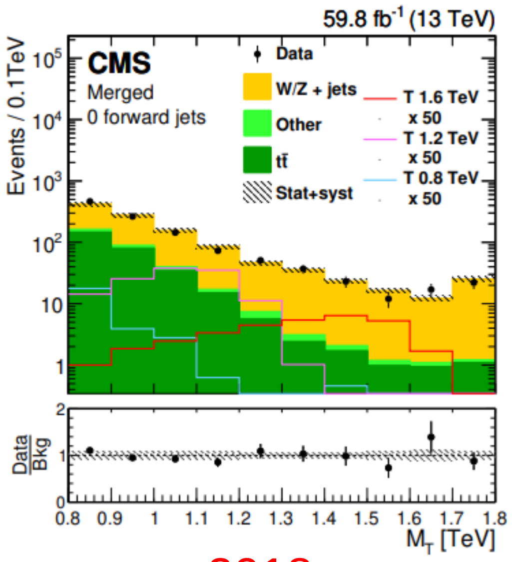


Results – Fully merged topology

FWD0

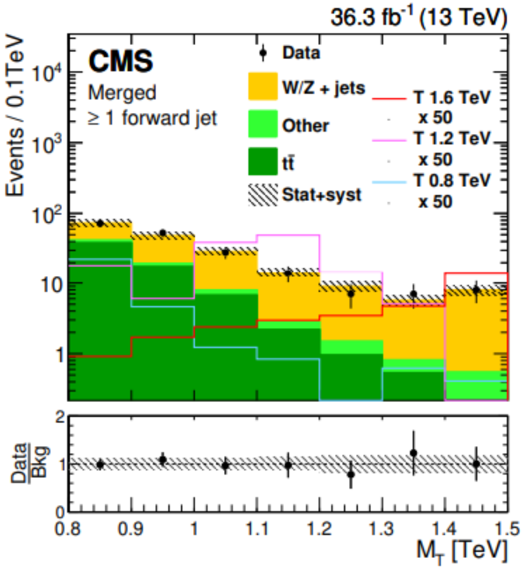


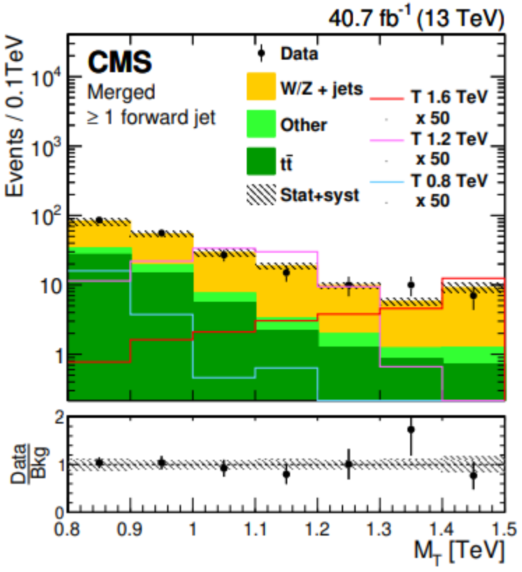


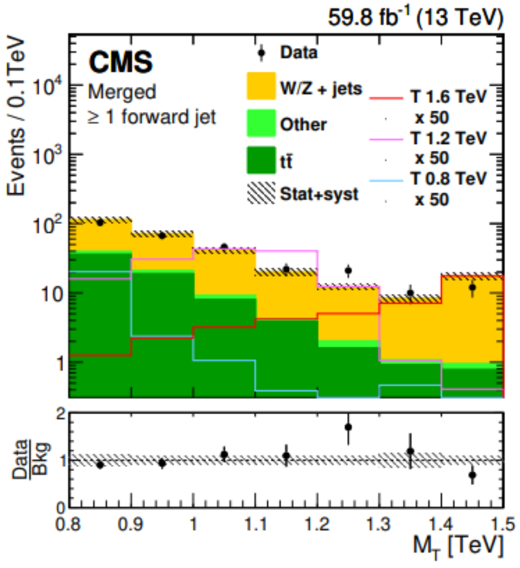


2016 2017 2018

FWD1







系统误差 (III)

LHC上的硬散射过程的截面可以写成：

$$\sigma_{h_1h_2} \to x = \sum_{a,b}\int_0^1 dx_1\, dx_2 f_{h_1/a}(x_1,\mu_F^2) f_{h_2/b}(x_2,\mu_F^2)\cdot\hat{\sigma}_{a,b\to x}(x_1,x_2,\alpha_s(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

➢部分子分布函数误差

其中$f_{h_1/a}(x_1,\mu_F^2)f_{h_2/b}(x_2,\mu_F^2)$是部分子分布函数(PDF)，从实验中测量得到其误差

→本底信号产额或横质量形状

➢因子化参数和重整化参数误差

可以看到式子中因子化参数和重整化参数μ_F和μ_R会影响硬散射过程的截面，通过把μ_F和μ_R的值加倍或者减半来估计其造成的误差

→本底信号产额或横质量形状

产生截面限制的计算方法

零假设H$_0$：仅用标准模型理论可以描述观测数据

备择假设H$_1$: 需用标准模型理论+类矢量顶夸克理论描述观测数据

使用本底的分布概率密度构造的似然函数$L(b)$

使用本底+信号的分布概率密度构造的似然函数$L(s+b)$

拟合

拟合

观测数据

极大似然值$L_m(b)$

极大似然值$L_m(s+b)$

构造变量$\lambda = L_m(b)/L_m(s+b)$，$u = -2ln\lambda = 2(\ln L_m(s+b) - lnL_m(b))$

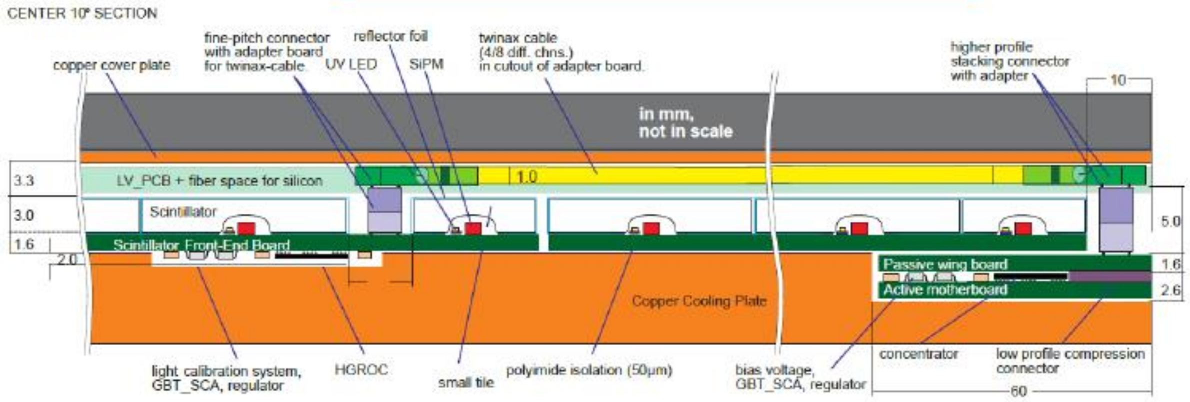
p值$p_b = \int_{u \geq u_{obs}} f(u|H_0)du$

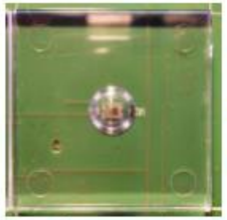
p值$p_\mu = \int_{u \geq u_{obs}} f(u|H_1)du$

$CL_s = p_\mu/(1-p_b)$是限制值(limit)的渐进近似

SiPM-on-Tile Module

"SiPM-on-Tile" Modules





"SiPM-on-Tile" design: scintillator tile directly coupled with SMD-SiPM