# Probing Quark-Gluon Plasma with Heavy Quarks

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# Outline

- **Beauty Hadrochemistry in Quark-Gluon Plasma at the LHC**
- **B and D Meson Physics Simulation with sPHENIX**
- **sPHENIX EMCAL Studies and EIC EMCAL Simulations**
- **Future Outlook**



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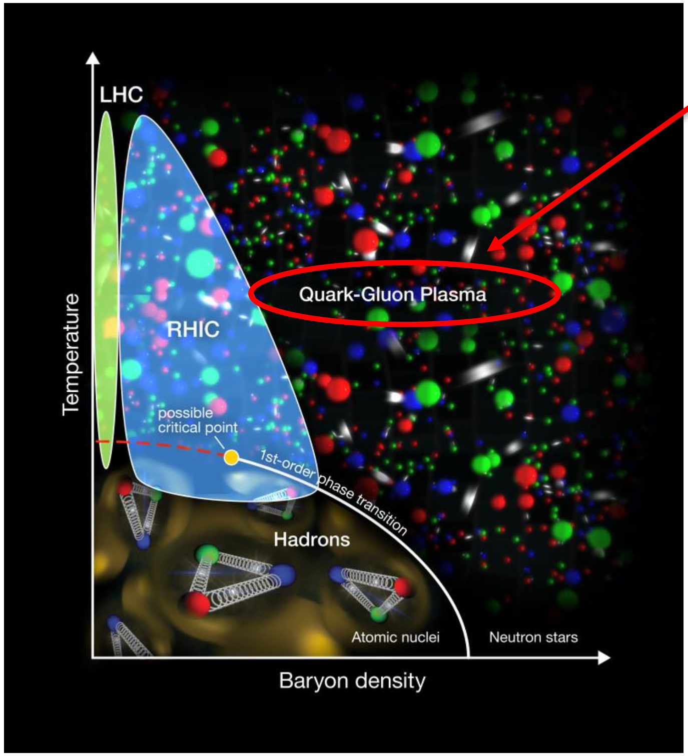
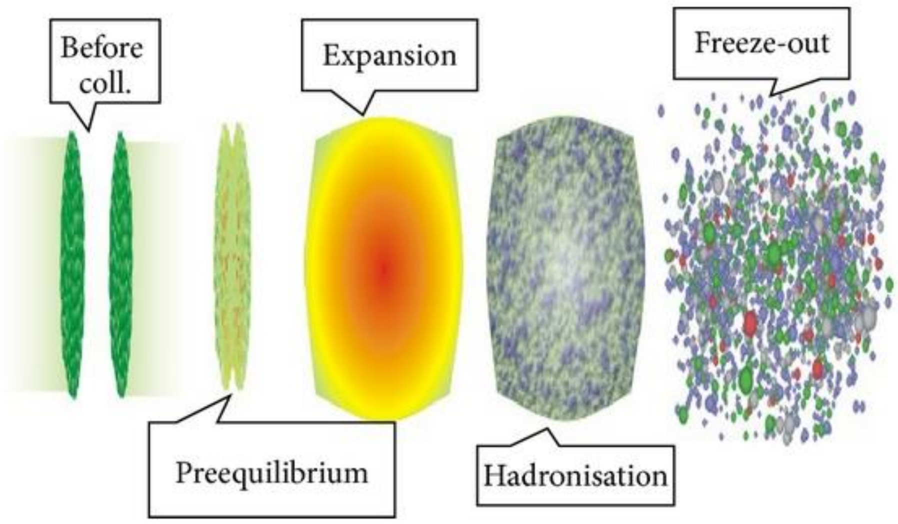
# The Quest for the Quark-Gluon Plasma




My Research

**Relativistic Heavy Ion Collision**



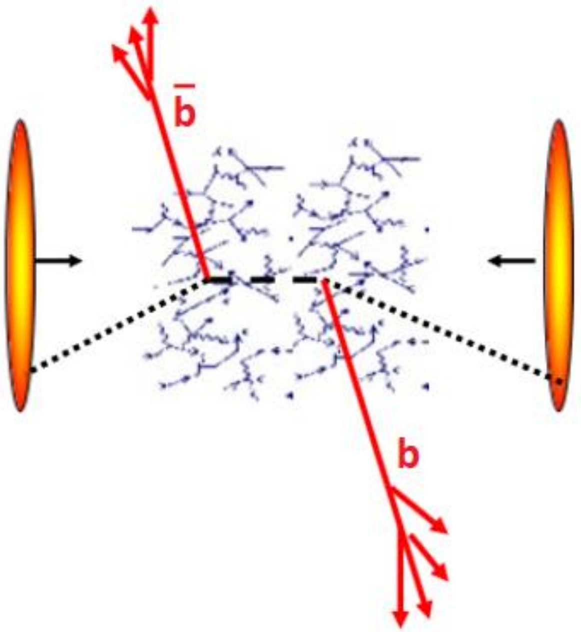

**<u>Interesting Properties of Quark-Gluon Plasma</u>**

- Deconfined phase of QCD matter in extremely high temperature
- Strongly coupled ideal liquid with very short thermalization time and lifetime
- Can be created and studied in laboratory from relativistic heavy-ion collisions
- Believed to exist in the early universe, several microseconds after the Big Bang
- The inner workings and relevant degrees of freedom still under investigation

# Heavy Quarks as Golden Hard Probes for QGP

## Properties of Heavy Quarks

- Large mass (~ GeV/c²) $m_Q \gg T_{QGP}$
- Predominantly produced in early hard scattering stage of heavy-ion collisions
- Long thermal relaxation time → Incomplete thermalization within the QGP medium
- Retain their identities and propagate through the QGP medium → Excellent probes for the microscopic structure of QGP




## Heavy Quark Low $p_T$ Dynamics in the Medium

- Undergo Brownian-Like Motion
- Diffusion by the color force in the medium
- Extraction of heavy quark diffusion coefficients from experiments to understand the fundamental properties of QGP, for instance, $\frac{\eta}{s}$

## Experimental Observables

- Detect and study final state heavy flavor hadrons spectra
- Anisotropic flow via the Fourier analysis of the azimuthal distribution
- Hadron-hadron angular correlations



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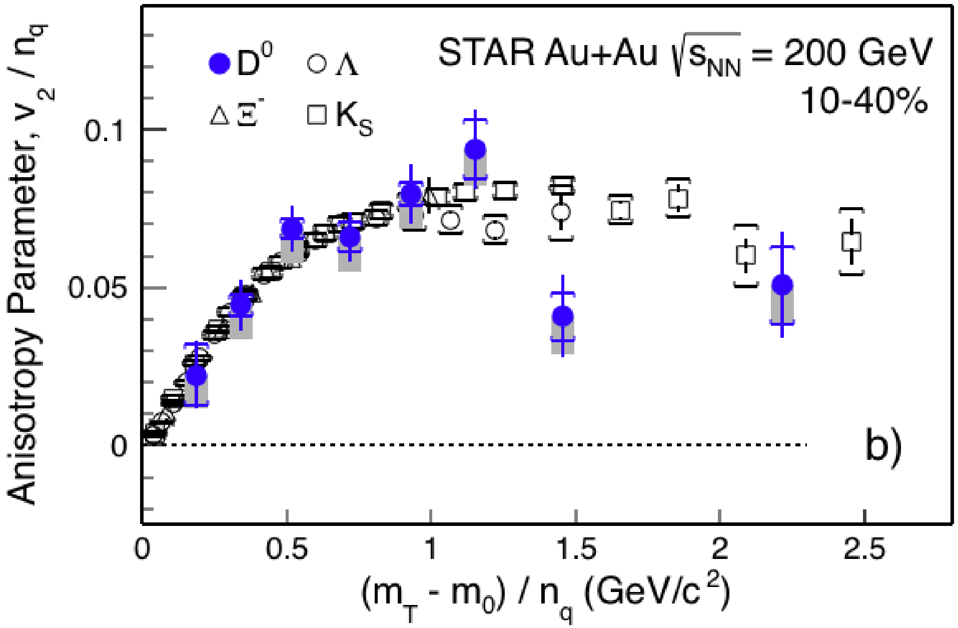
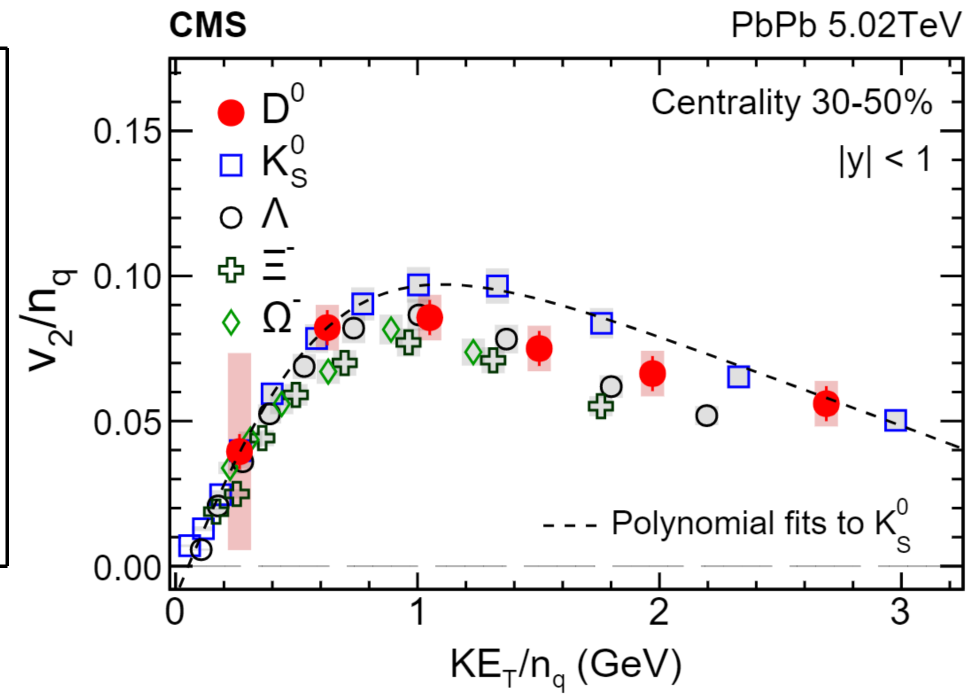
# Heavy Flavor Collectivity in QGP




- Non-zero $D^0$ meson $v_2$ are observed → charm quarks demonstrates sizable collectivity via scattering with the QGP medium
- Overall satisfying Number of Constituent Quark Scaling at RHIC and LHC
- Constrain model predictions and heavy quark diffusion coefficients along with $R_{AA}$



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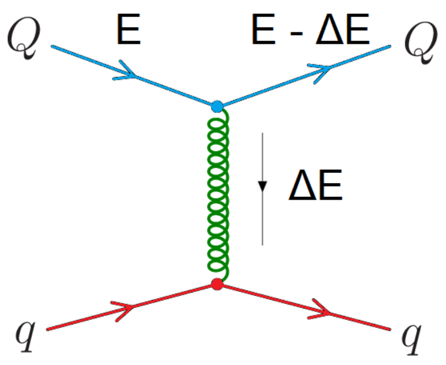
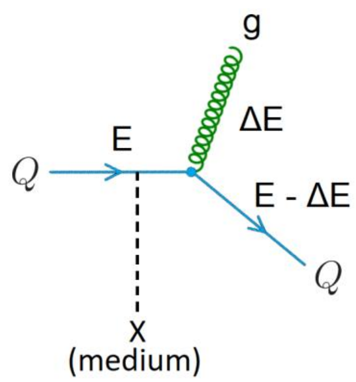
# Heavy Quark High $p_T$ Dynamics: Energy Loss

## pQCD: Weak Coupling

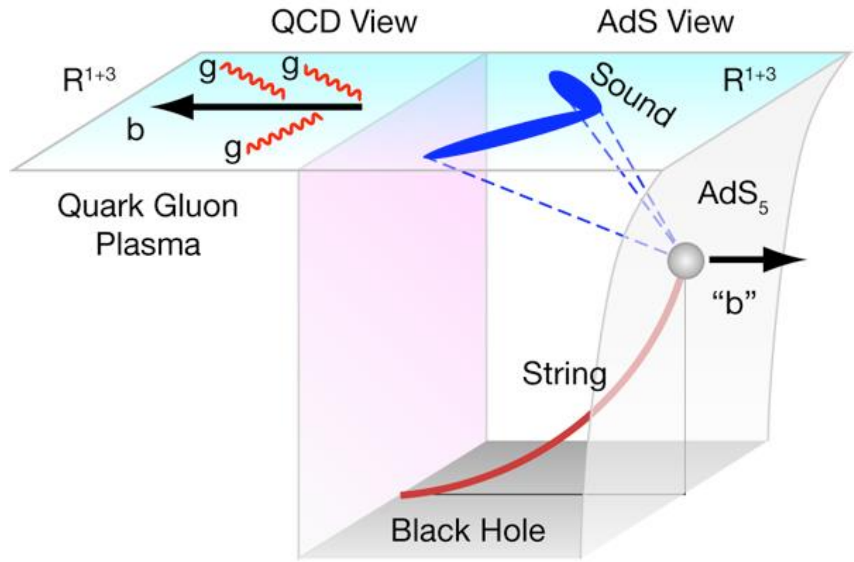
### Collisional




### Radiative




## AdS/CFT: Strong Coupling



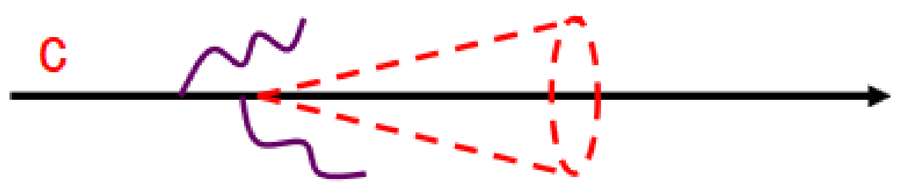

## Dead Cone Effect

- Gluon radiation spectra

$$dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 dk_\perp^2}{\left(k_\perp^2 + \omega^2 \theta_0^2\right)^2} \quad \left(\theta_0 = \frac{m}{E}\right)$$

$$\Delta E_g > \Delta E_q > \Delta E_Q$$

- Flavor dependence of energy loss




## Experimental Observables

- **Traditional:** Heavy flavor hadron nuclear modification factor
- **More differential jet substructure:** Heavy flavor jet shape and jet-hadron correlation



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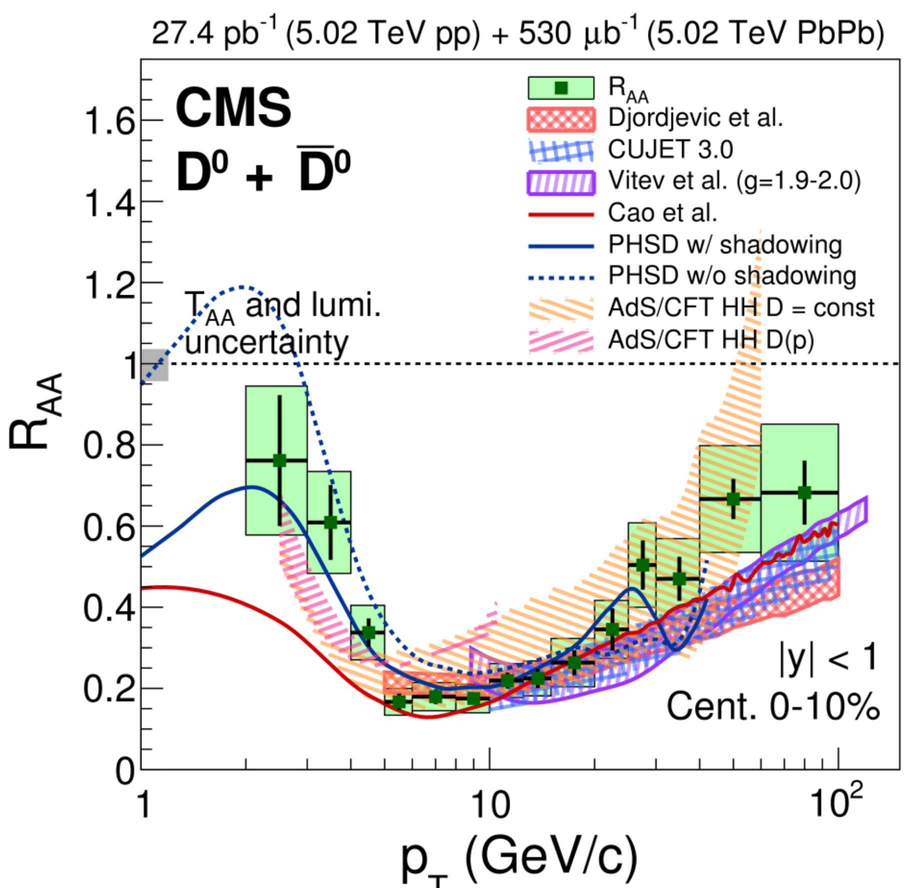
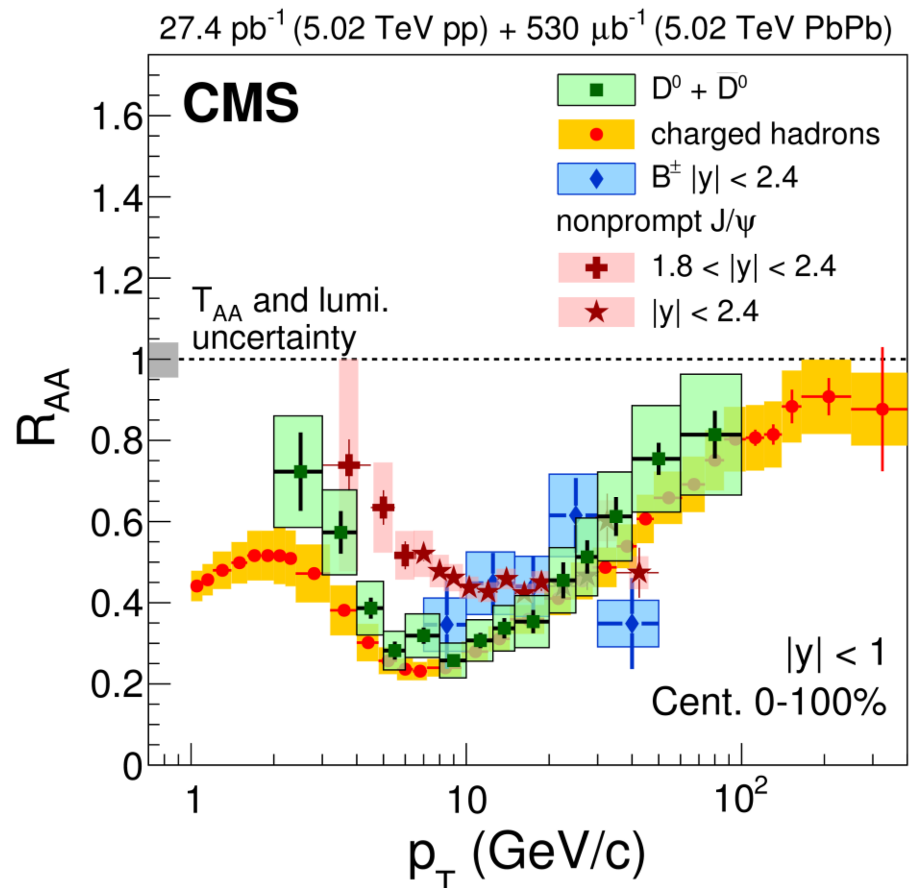
# Heavy Flavor Energy Loss Studies




- Extensive studies of both experiment and theory on heavy quark energy loss
- Lose a significant fraction of energy to the QGP medium
- Broad $p_T$ measurement → probe the QGP over a wide range of wavelengths
- $R_{AA}^{B} > R_{AA}^{D} \rightarrow \Delta E_c > \Delta E_b$

# Heavy Quark Hadronization Mechanism

## Physics Challenges

- Generally non-perturbative → first principle calculations not yet available
- Hadronization mechanisms: fragmentation and recombination
- Hadronization phenomenology models: Lund String Model, Statistical Hadronization Model, Quark Coalescence Model
- Inconsistency among hadronization models → limit our ability to interpret heavy flavor results

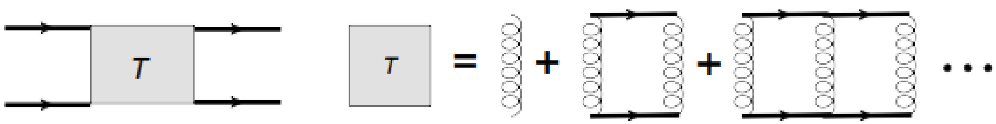
## Beauty Hadrochemistry Models in Heavy-Ion Collisions

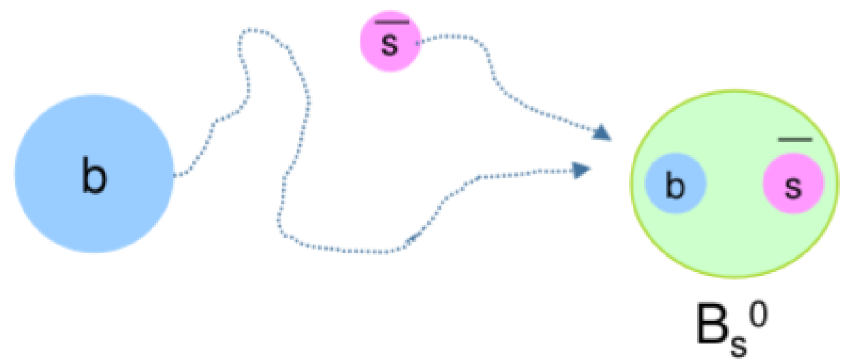
### TAMU Model

- Many-body thermodynamic T-matrix approach
- Heavy quark in-medium diffusion
- Collision energy loss only
- Recombination hadronization mechanism

### Cao, Sun, Ko Model

- Advanced Langevin hydrodynamics
- Both elastic and inelastic energy loss
- Comprehensive coalescence model + PYTHIA Peterson fragmentation model




## Experimental Observables

- Baryon-to-meson ratio
- Strange meson to non-strange meson ratio



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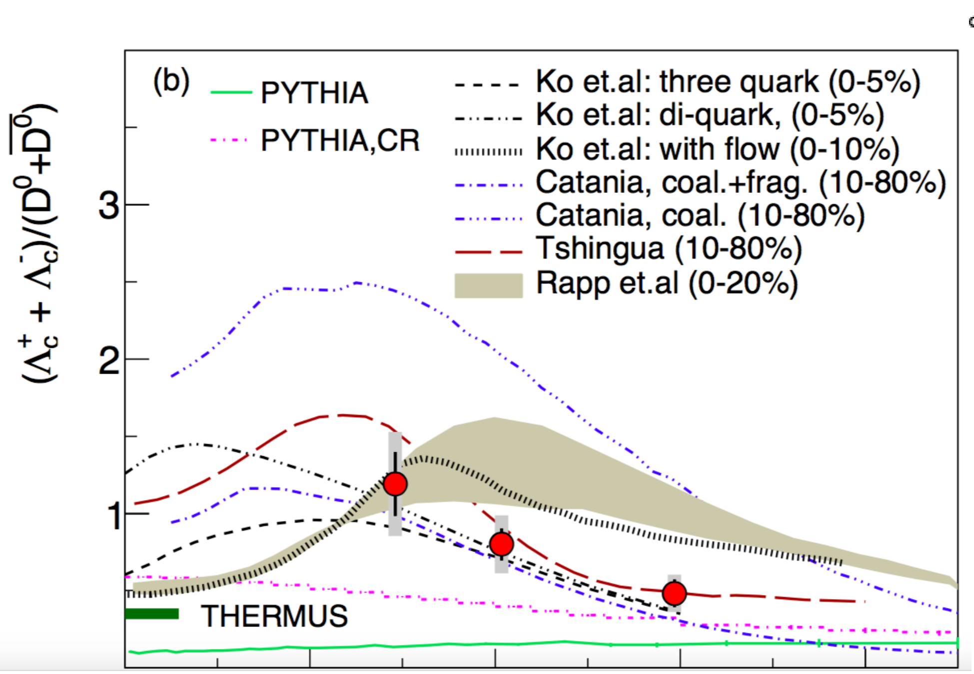
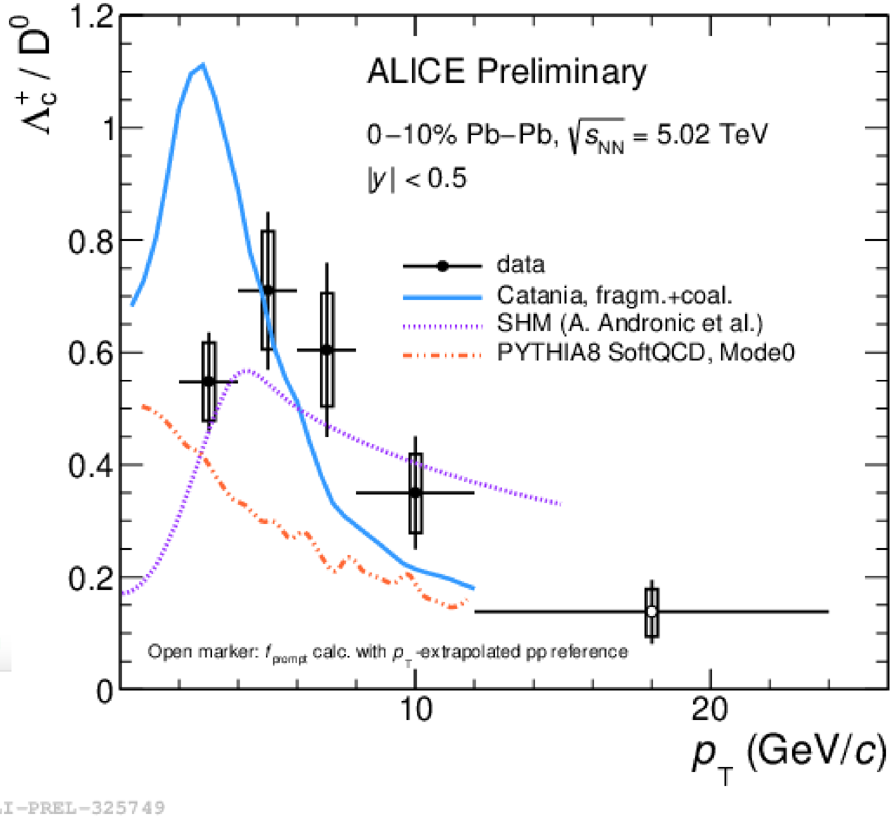
# Heavy Flavor Hadrochemistry in Heavy Ion Collisions




- Extensive charm hadrochemistry studies at RHIC and LHC
- Fully reconstructed b hadrons via exclusive decays necessary to study beauty hadronization
- CMS and sPHENIX capable of fully reconstructing b hadrons from exclusive decays



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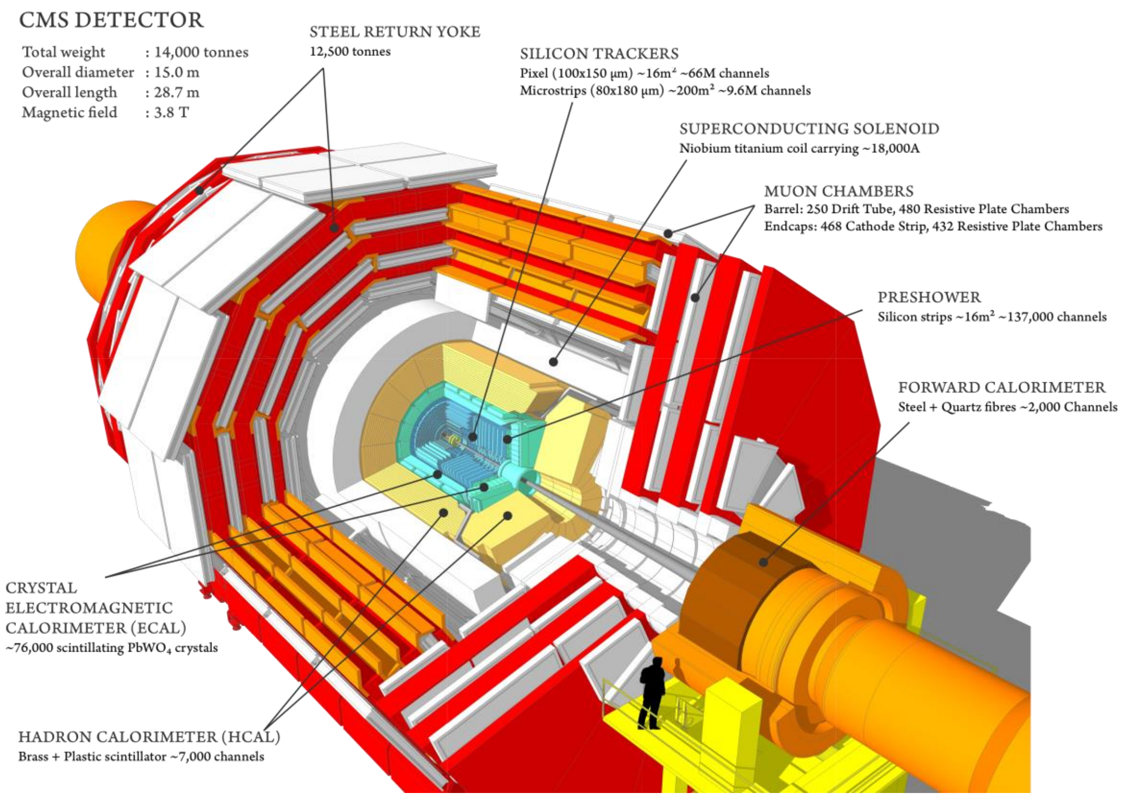
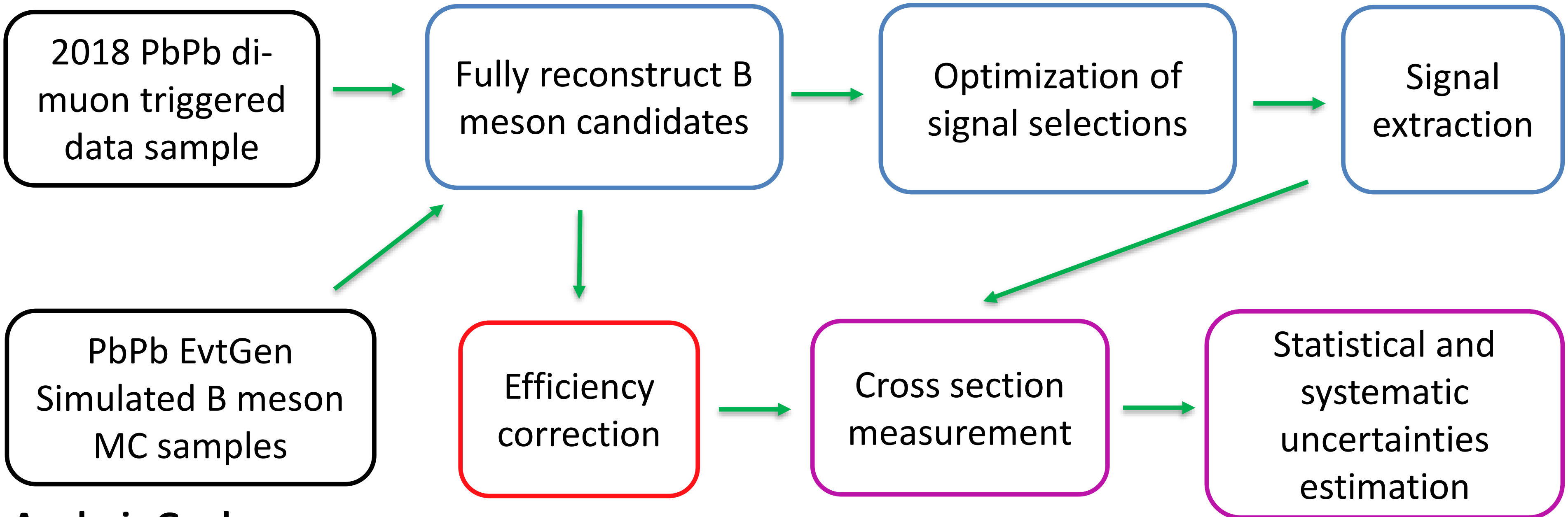
# CMS Detector




- State-of-the-art general-purpose detector with full 2π azimuthal and |η| < 2.4 coverage
- L1 hardware and HLT software triggers for efficient data acquisition
- Excellent vertexing and tracking capabilities
- Muon system with great performance for muon identification and reconstruction
- No dedicated hadronic particle identification

# B-meson Measurement with CMS

**Analysis Procedures:**




**Analysis Goals**

- Fully reconstruct $B^+$ and $B_s^0$ in a wide $p_T$ range in central and peripheral PbPb collisions
- Measure the cross section of $B_s^0$ and $B^+$ and the $B_s^0/B^+$ ratio

**Analysis Challenges**

- Small decay branching ratio in the chosen channels → low statistics of B mesons
- No hadronic PID → huge combinatorial background, particularly at low $p_T$
- Challenging for low $p_T$ due to small muon and track acceptance → Low S/B ratio



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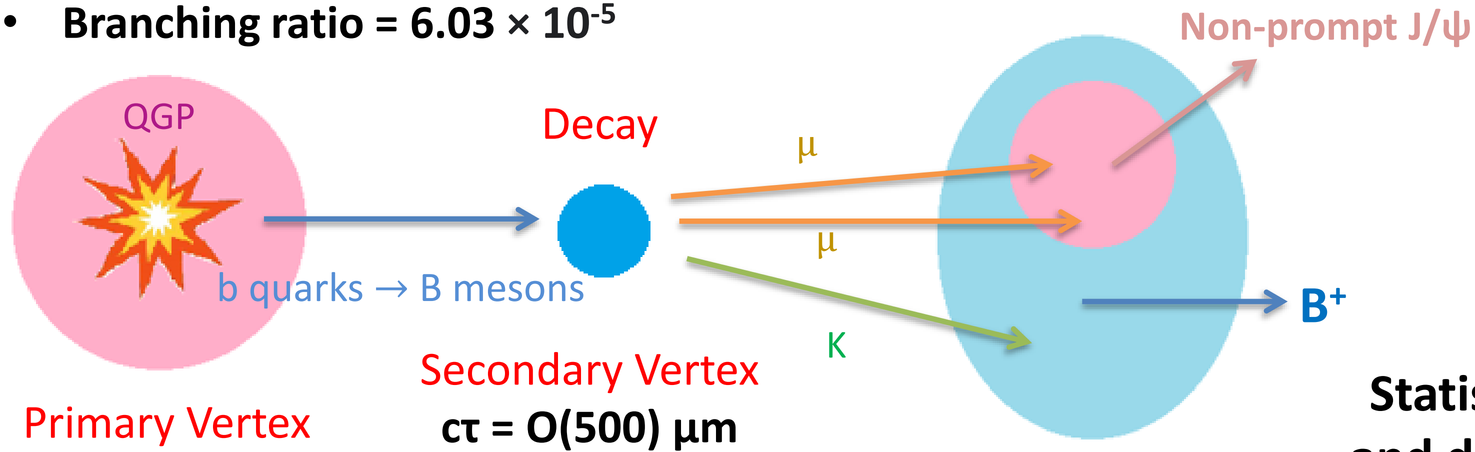
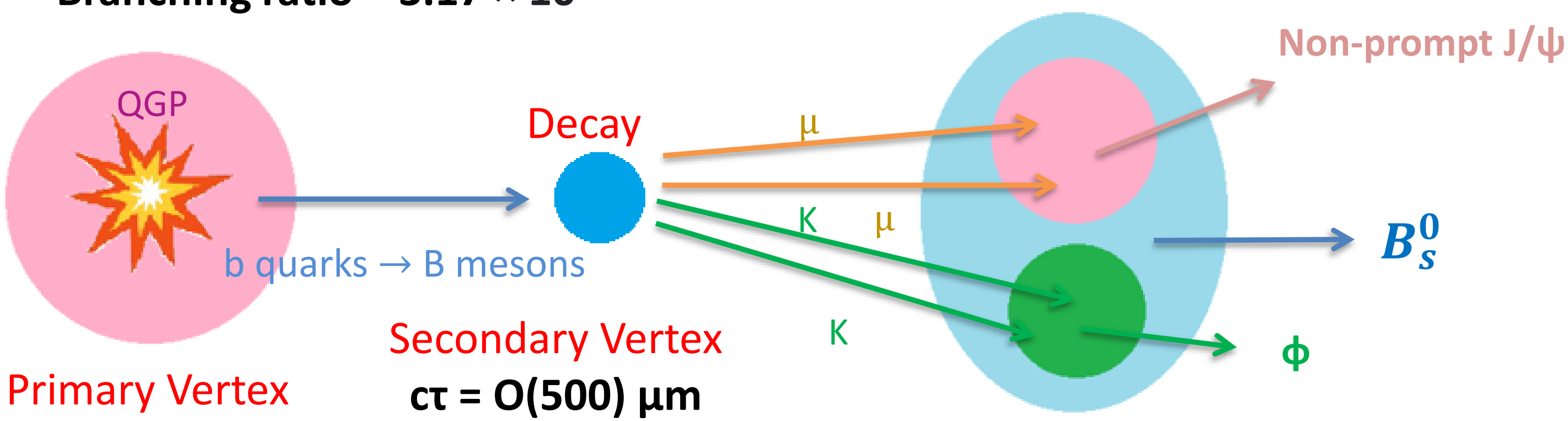
# B-mesons Full Reconstruction Strategies

- $B^+$: via the decay channel $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^- K^+$
- Branching ratio = $6.03 \times 10^{-5}$




**Statistically enriched and dedicated dimuon triggered datasets from 2018 LHC PbPb run**

- $B_s^0$: using the decay channel $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^- K^+ K^-$
- Branching ratio = $3.17 \times 10^{-5}$



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# B-meson Selections

**Topological variables in $B_s^0 \to J/\psi\phi \to \mu^+\mu^- K^+K^-$ signal selections $K^+K^-$ tracks**

$|m_{KK} - m_\phi|$

The $B_s^0$ vertex probability

DCAxy1/DCAxy1Error

DCAxy2/DCAxy1Error

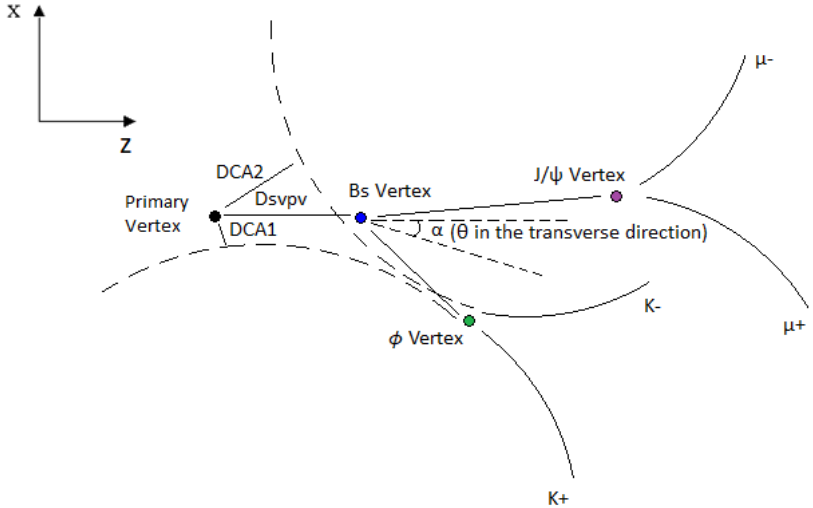
DCAz1/DCAz1Error

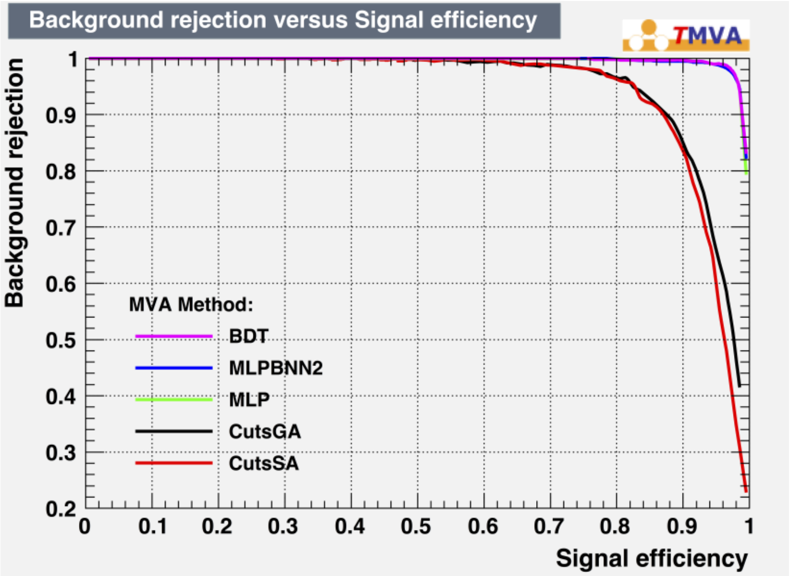
DCAz2/DCAz2Error

Dsvpv/DsvpvError

Opening angle α

Cosine of opening angle in xy: cos(θ)




**Multivariate approach with machine learning**

- MC generated B meson as signal and data B-meson mass sideband as background
- Event, track, and muon quality preselection on the input samples
- Boosted Decision Tree (**BDT**) best among other machine leaning algorithms under the optimal set of training parameters



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# Machine Learning Techniques Application

**Estimation of signal and background**

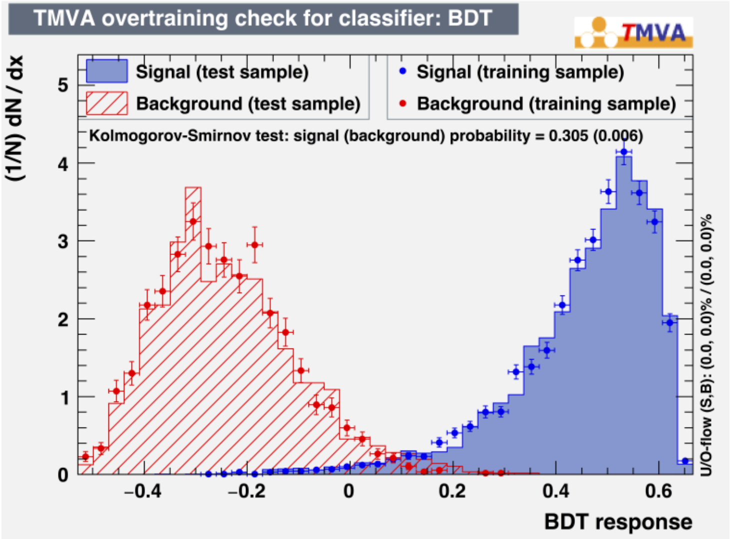
- **Data:** $B = N_{SB} w_{Sig} / w_{SB}$
- **MC:** $S = 2 R_{AA}^{2015\ Ref} L \sigma_{FONLL}^{pp \to b\bar{b}} \varepsilon_{pre} \varepsilon_S f(b \to B) BR$

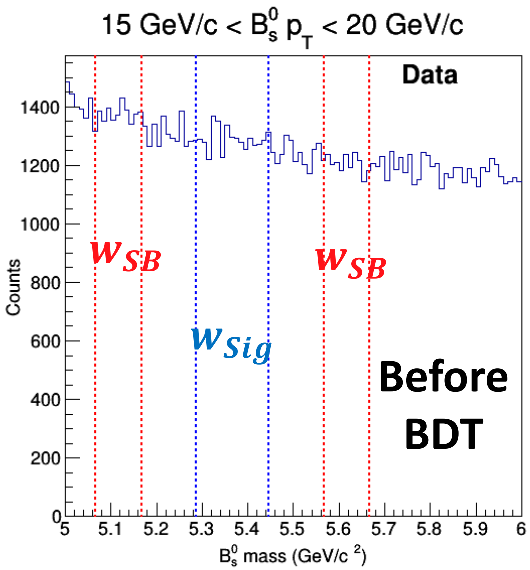
**Analysis challenges**

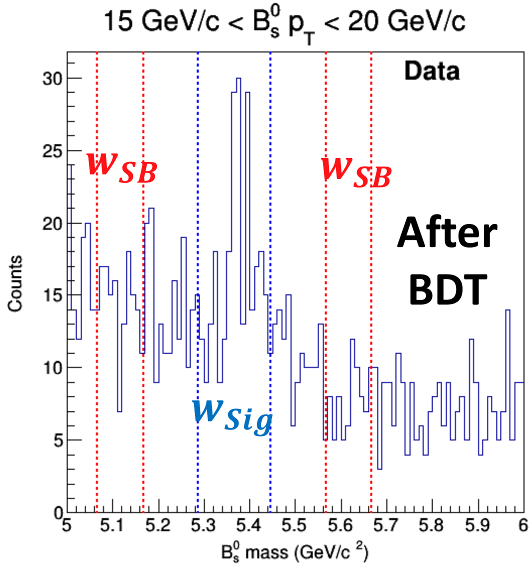
- Before selections, **B = 20672** and **S = 26**
- Need to achieve about **$10^3$** to **1** for the **B** to **S** rejection to observe $B_s^0$ signal in the PbPb data

**BDT selections**

- Excellent **Signal**/**Background** separation without overtraining
- A random BDT > 0.1 selection returns a visible signal
- Working point based on the maximum statistical significance $\frac{S}{\sqrt{S+B}}$



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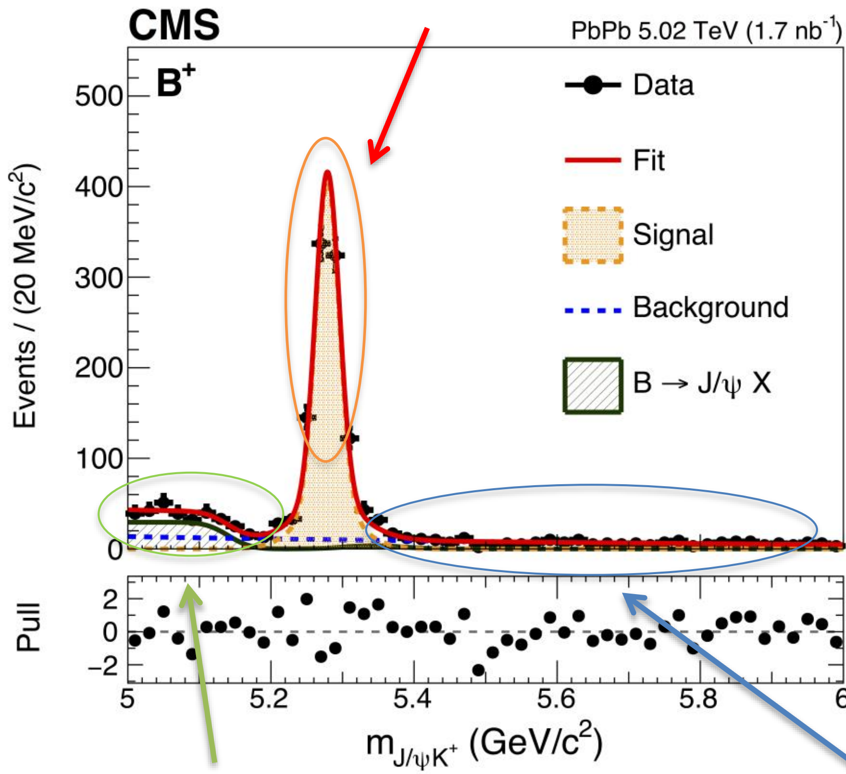
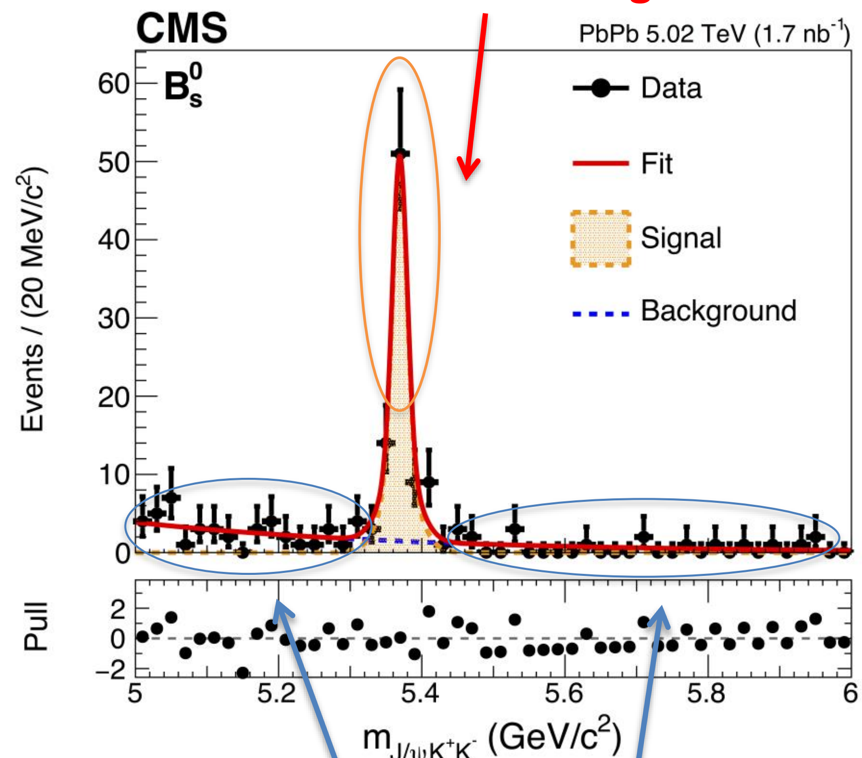
# Fully Reconstructed $B^+$ and $B_s$ in PbPb Collisions

Double Gaussian for signal




Double Gaussian for signal




Error function (shoulder) + 2 sided Gaussian (signal region) for Non-prompt background

Exponential decay for combinatorial background

Exponential decay for combinatorial background

- Clear B mesons signals after apply the BDT selections without applying hadronic PID
- Fully reconstructed $B_s$ significance > 5σ → first observation of $B_s^0$ in nuclear collisions

# Data-Driven Efficiency Correction Techniques

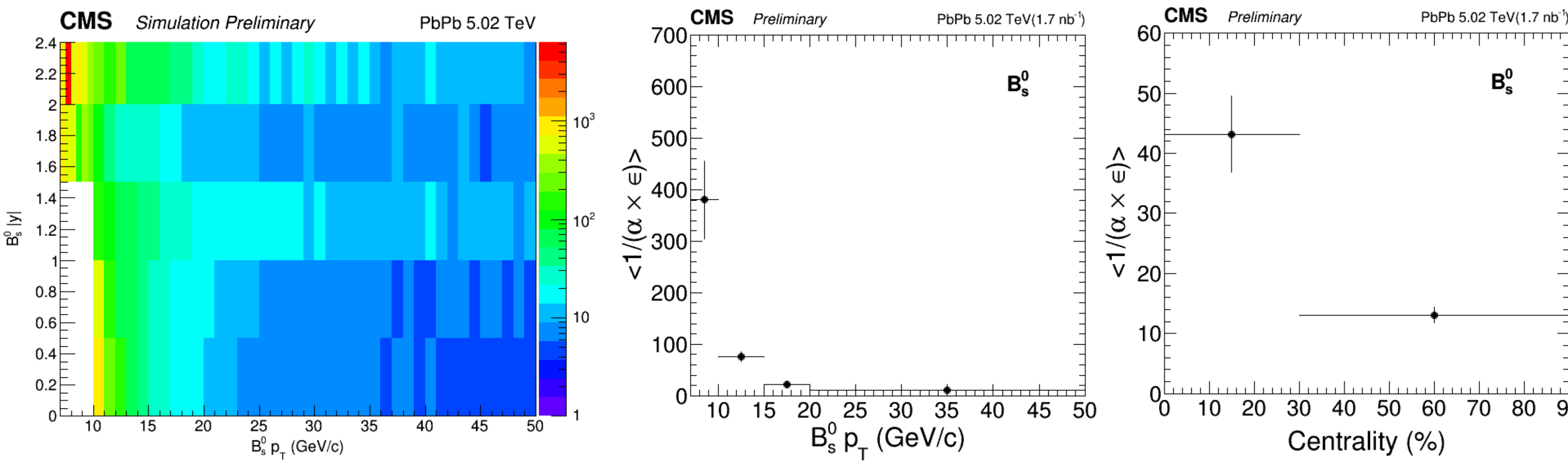
**Analysis challenges**

- Unknown B meson precise $p_T$ and $y$ distribution → huge systematics uncertainties on the efficiency correction, particularly over a large $p_T$ and $y$ range

$\boldsymbol{\alpha}$**:** acceptance
$\boldsymbol{\varepsilon}$**:** efficiency

**Data-driven way of efficiency correction**

- **Fiducial region:** $|y| > 1.5$ for $p_T < 10$ GeV/c
- Finely grained $\frac{1}{\alpha \times \varepsilon}$ 2D B mesons $p_T$ and $|y|$ efficiency maps to reduce the efficiency systematics
- **Tag-and-Probe Techniques:** Apply data-driven method for $J/\psi$ efficiency corrections according to the identification, di-muon trigger, acceptance, and tracking selections of each muon
- **Data Driven:** Compute $\left\langle \frac{1}{\alpha \times \varepsilon} \right\rangle$ of data B mesons candidates in the signal region based on their $p_T$ and $|y|$



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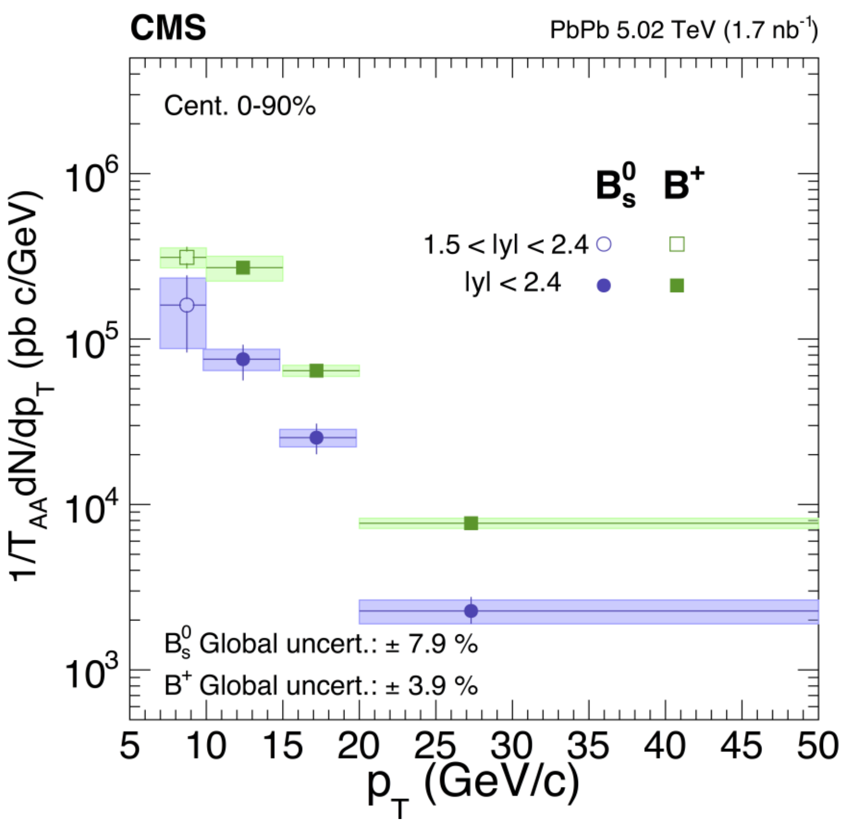
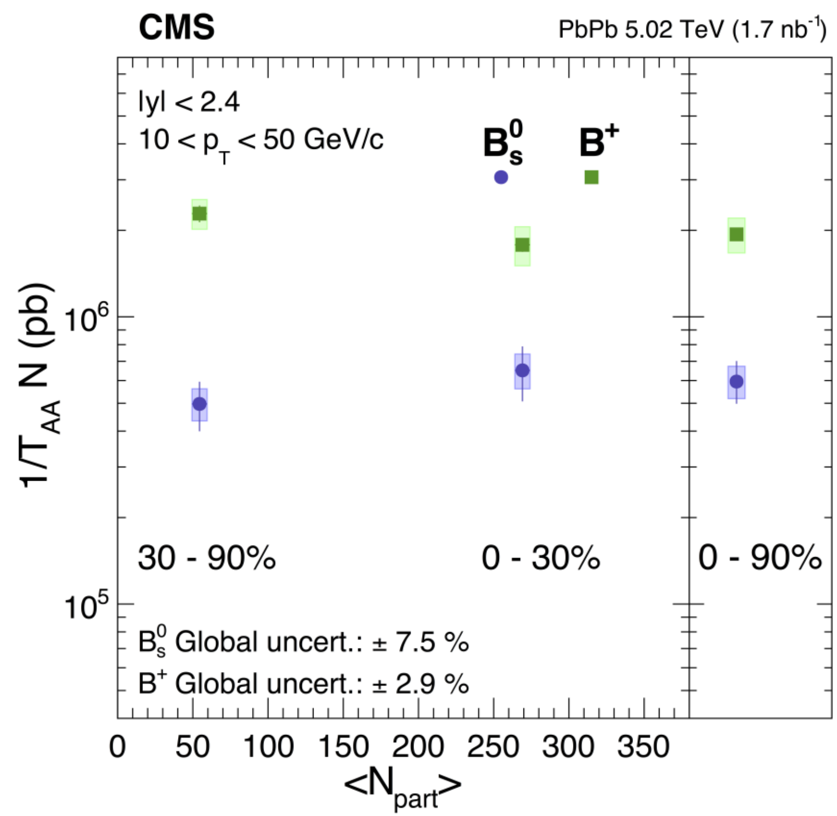
# Cross Section as a Function of $p_T$ and Centrality

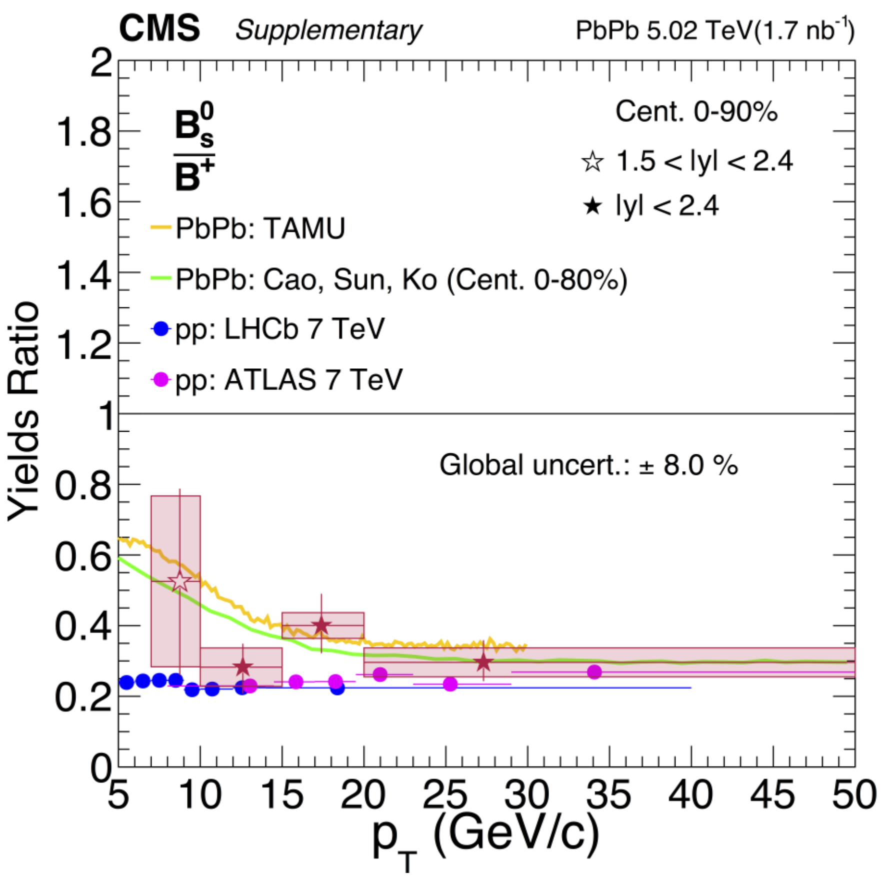


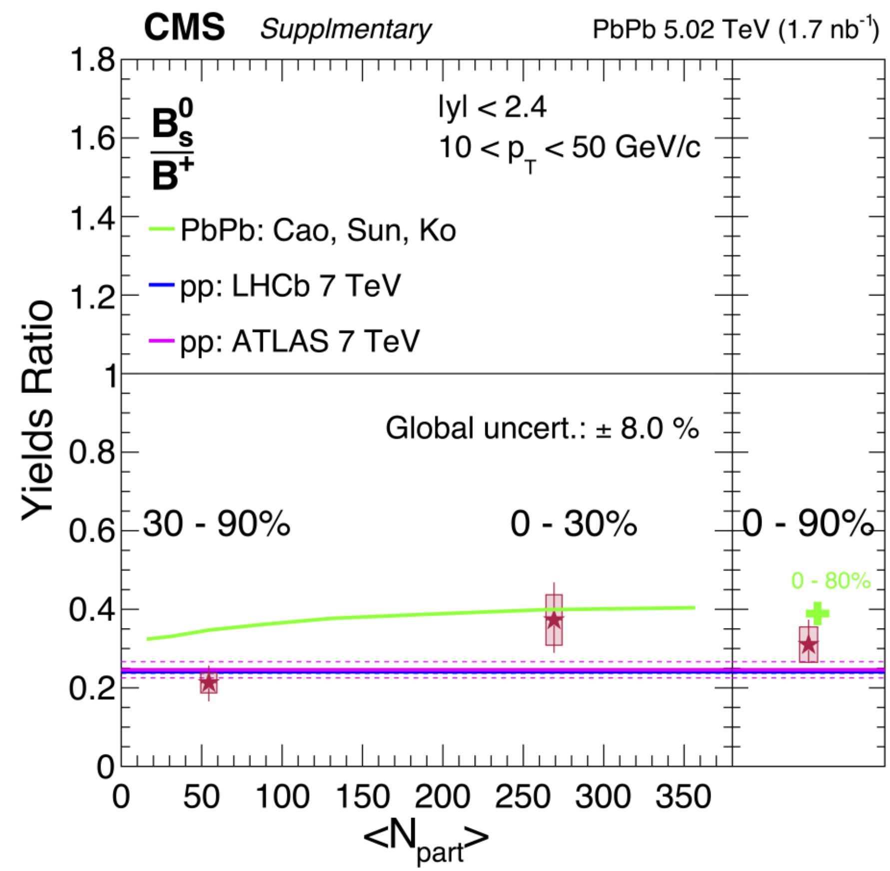




$$\frac{1}{T_{AA}}\frac{dN}{dp_T} = \frac{1}{T_{AA}}\frac{1}{2}\frac{1}{\Delta p}\frac{1}{BR \cdot N_{MB}} N^B \left\langle \frac{1}{\alpha \times \varepsilon} \right\rangle$$

- Precise $p_T$ differential cross-section measurement of $B^+$ and $B_s^0$ mesons from 7 to 50 GeV/c
- First centrality differential cross-section measurement of $B_s^0$

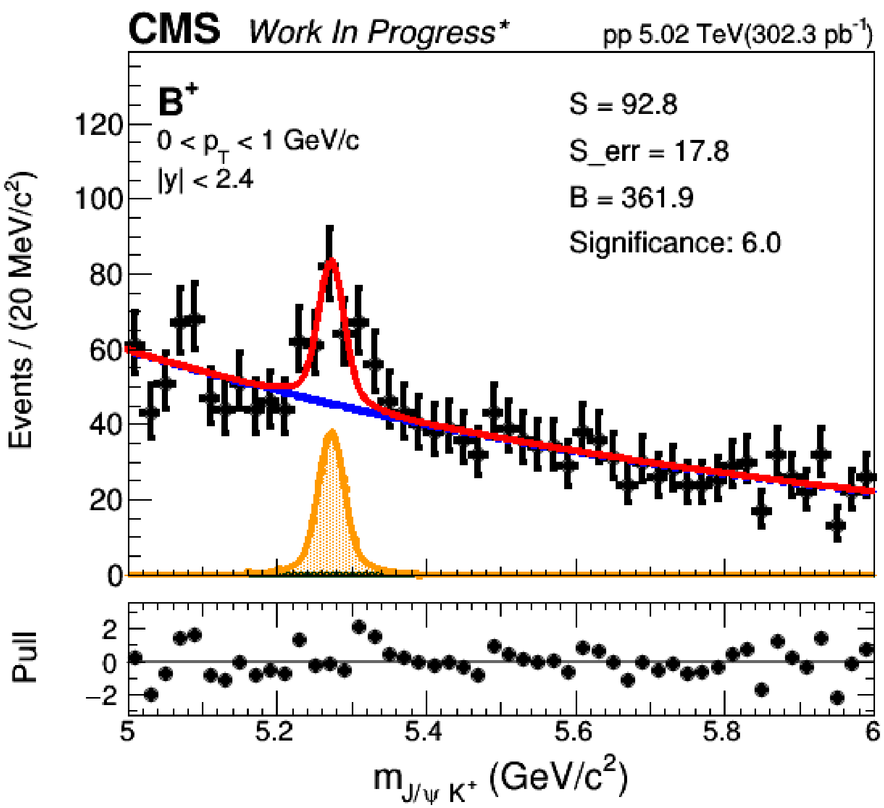
# $B_s^0/B^+$ Ratio in PbPb

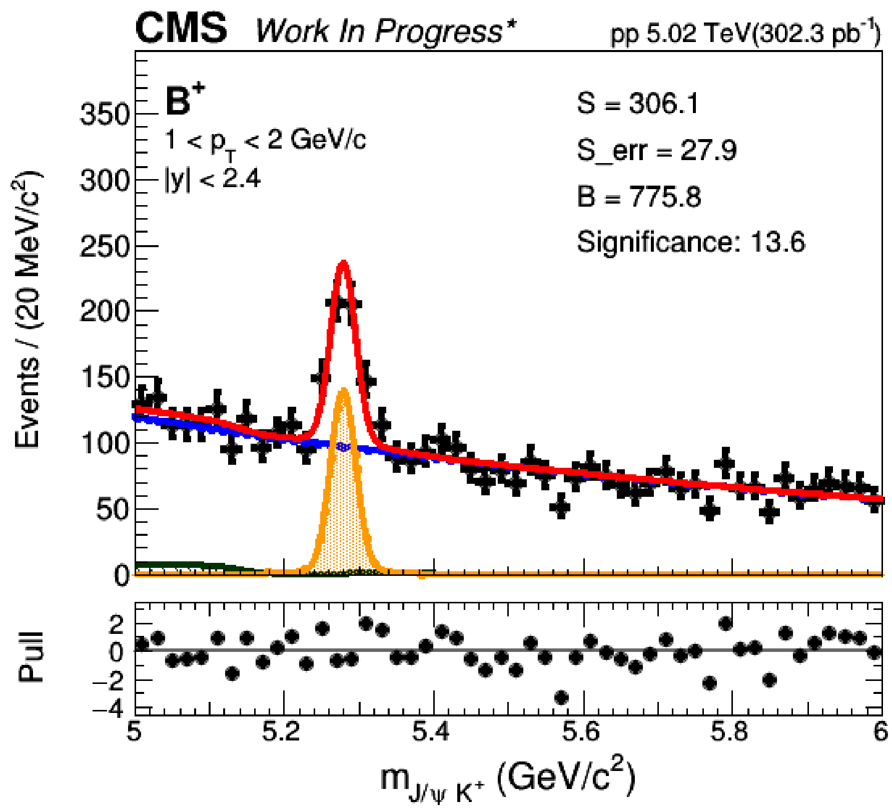



- No significant $p_T$ dependence of $B_s^0/B^+$
- $B_s^0/B^+$ agrees reasonably well with **TAMU model** and **Cao, Sun, Ko. model**
- $B_s^0/B^+$ is compatible to the **LHCb pp 7 TeV** and **ATLAS pp 7 TeV** data within about 1.5 σ

# B+ in pp Down to $p_T = 0$ with BDT




- **BDT Capabilities:** Clear $B^+$ signal down to 0 – 1 GeV/c with **> 5σ signal significance without hadronic PID.** We have also just achieved the observation of fully reconstructed $B^0$ and $B_s^0$ in pp down to 2 GeV/c
- Allow measurements of **inclusive beauty production cross section** and **B-meson fragmentation fractions**
- **LHC Run 3 & Beyond:** precise measurements of b-hadron family ($\Lambda_b^0$, $B_c^+$, $B_s^0$, $B^+$, and $B^0$) over a broad $p_T$, centrality, and multiplicity region to understand beauty hadronization and energy loss mechanisms
- **RHIC – sPHENIX:** participate in fully reconstructed $B_s^0$ and $D_s^+$ physics simulations



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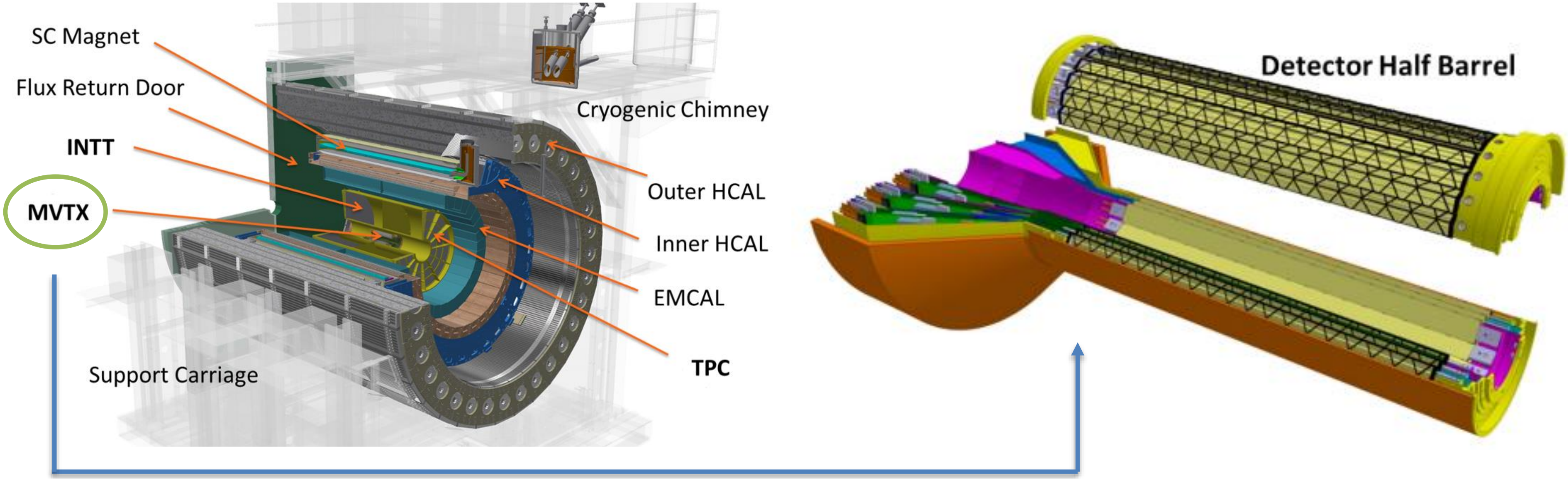
# sPHENIX Detector – MVTX




**The sPHENIX Detector**

- State-of-the-art jet detector with full 2π and |η| < 1.1 coverage upgraded from PHENIX
- Dedicated triggers to collect of large heavy-ion minimum biased datasets
- Excellent electron identification capability for heavy flavor studies
- No dedicated hadronic particle identification

**MVTX**

- A copy from ALICE ITS with the inner three layers of silicon pixel detectors
- Excellent vertexing and tracking capabilities with INTT and TPC



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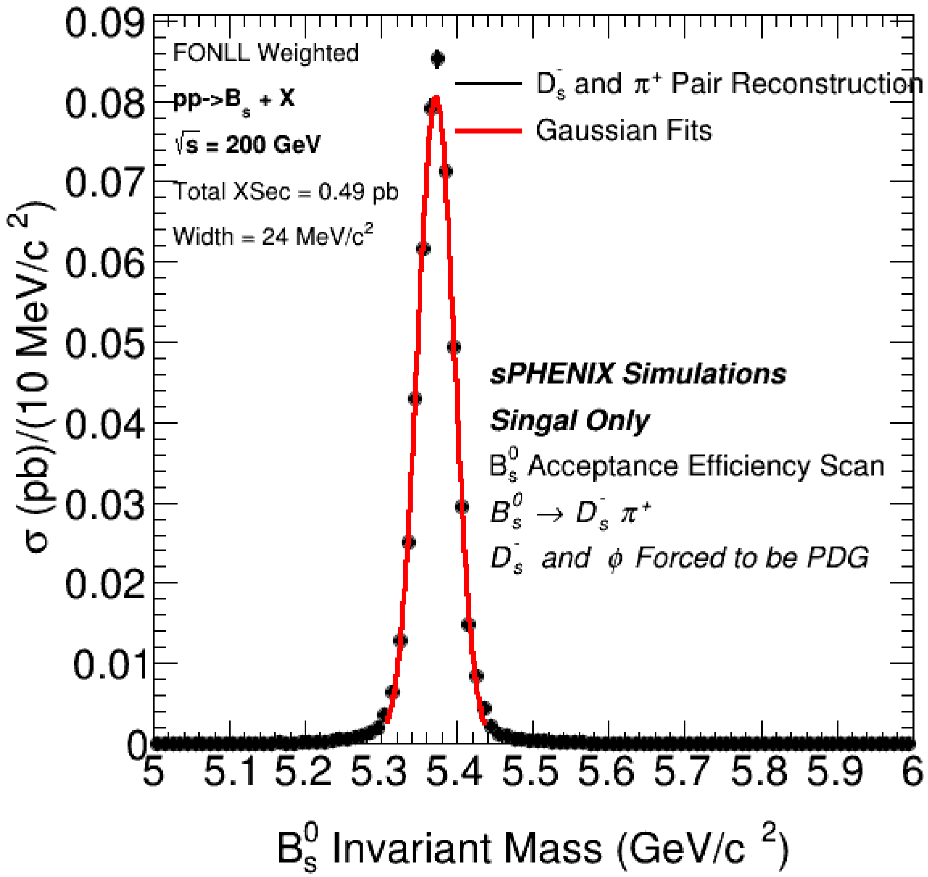
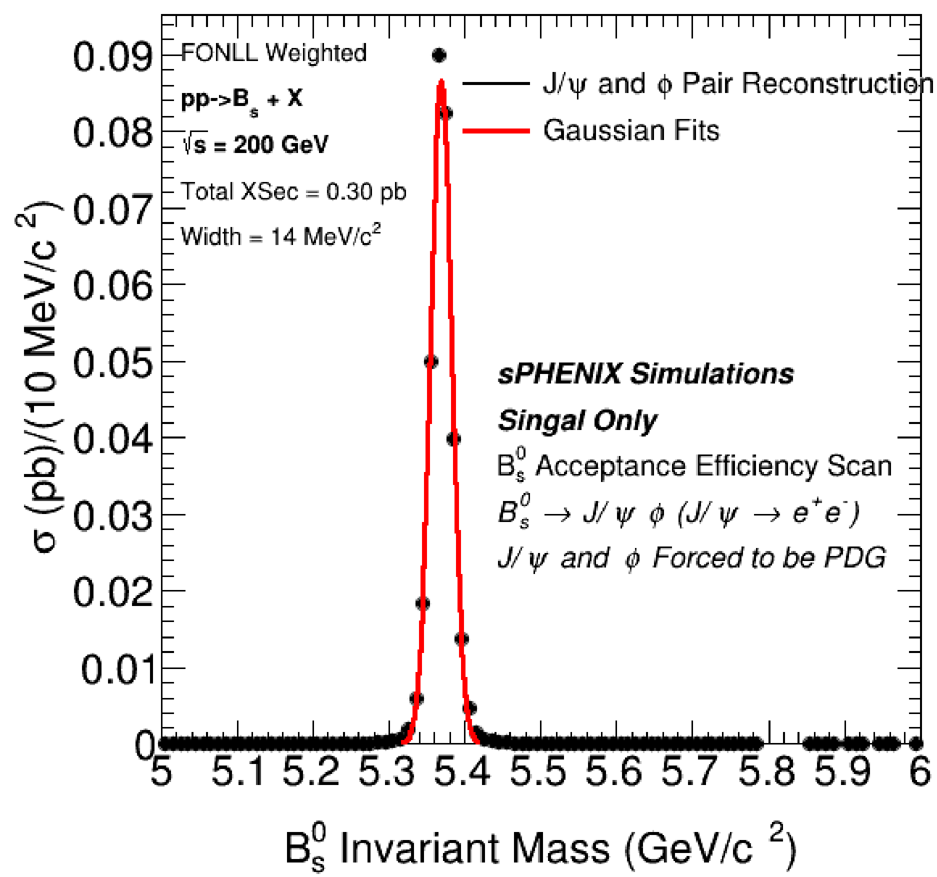
# Signal $B_s^0$ Simulations Performance




- Decay channels: $B_s^0 \rightarrow D_s^- \pi^+ \rightarrow \phi \pi^- \pi^+ \rightarrow K^+ K^- \pi^+ \pi^-$ and $B_s^0 \rightarrow J/\psi \phi \rightarrow e^+ e^- K^+ K^-$
- **Signal only simulation** considering acceptance and efficiency (weighted with FONLL)
- **Background:** Ongoing development of fast simulations with signal and background



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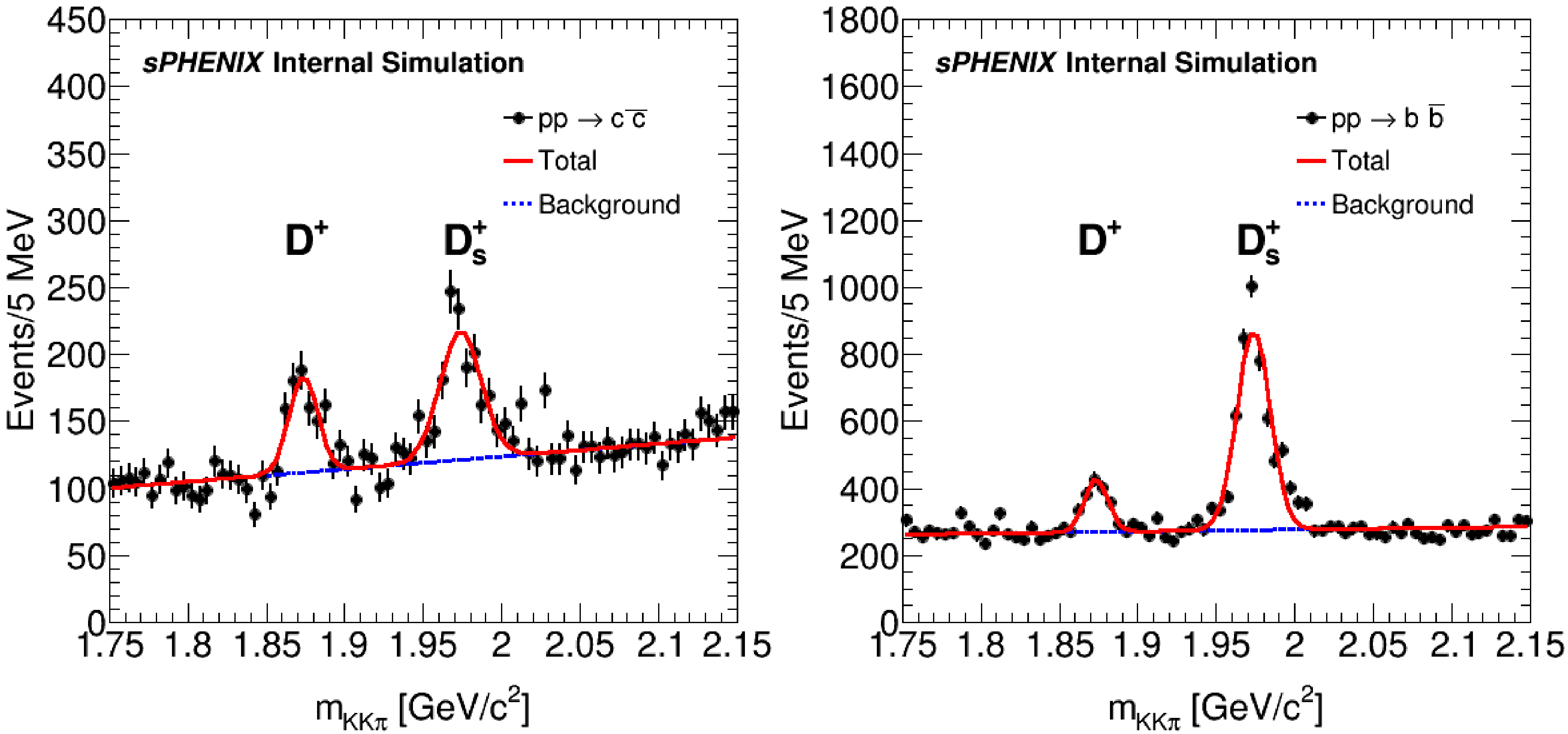
# sPHENIX Mock Data Challenging Tests




- sPHENIX Mock Data Challenge: simulation of about 50 million $c\bar{c}$ and $b\bar{b}$ PYTHIA pp events
- Visible prompt and non-prompt $D_s^+$ signals in $c\bar{c}$ and $b\bar{b}$ sample with some simple selections
- **First sPHENIX heavy flavor MDC results analysis notes: sPH-HF-2021-001**

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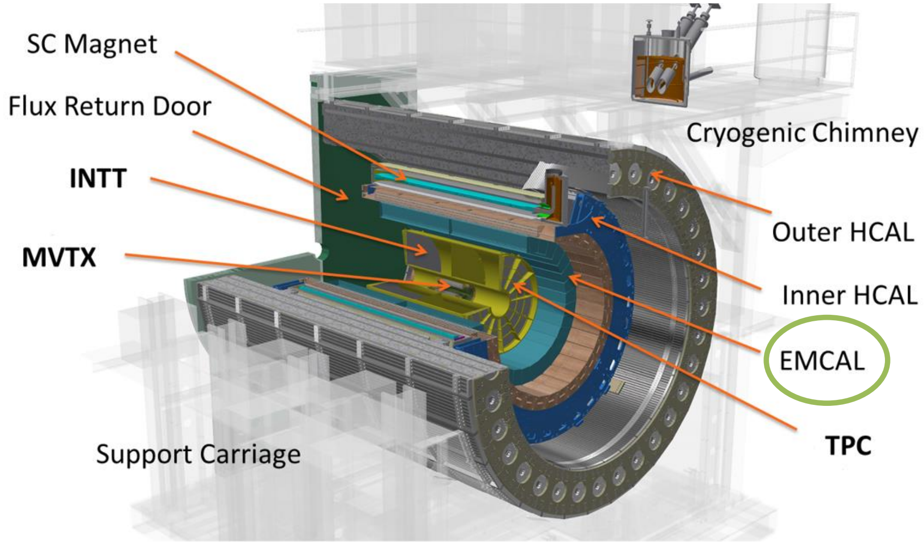
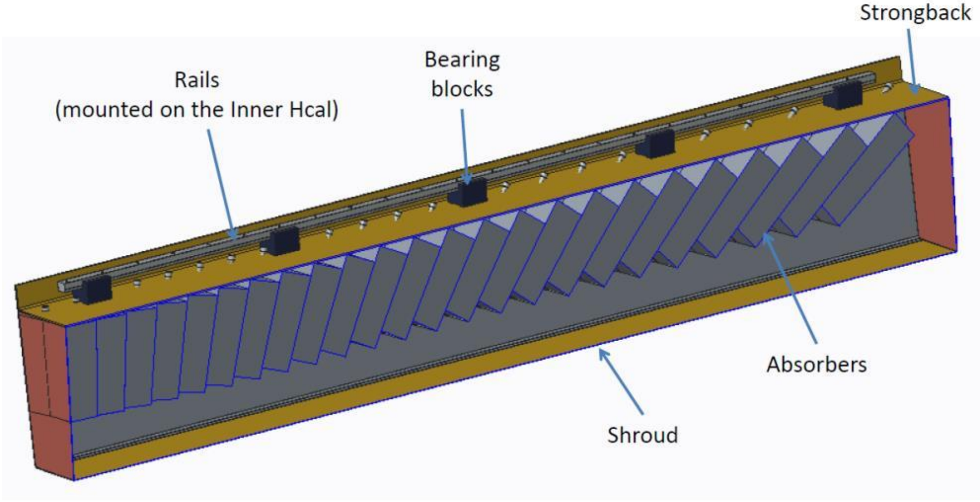
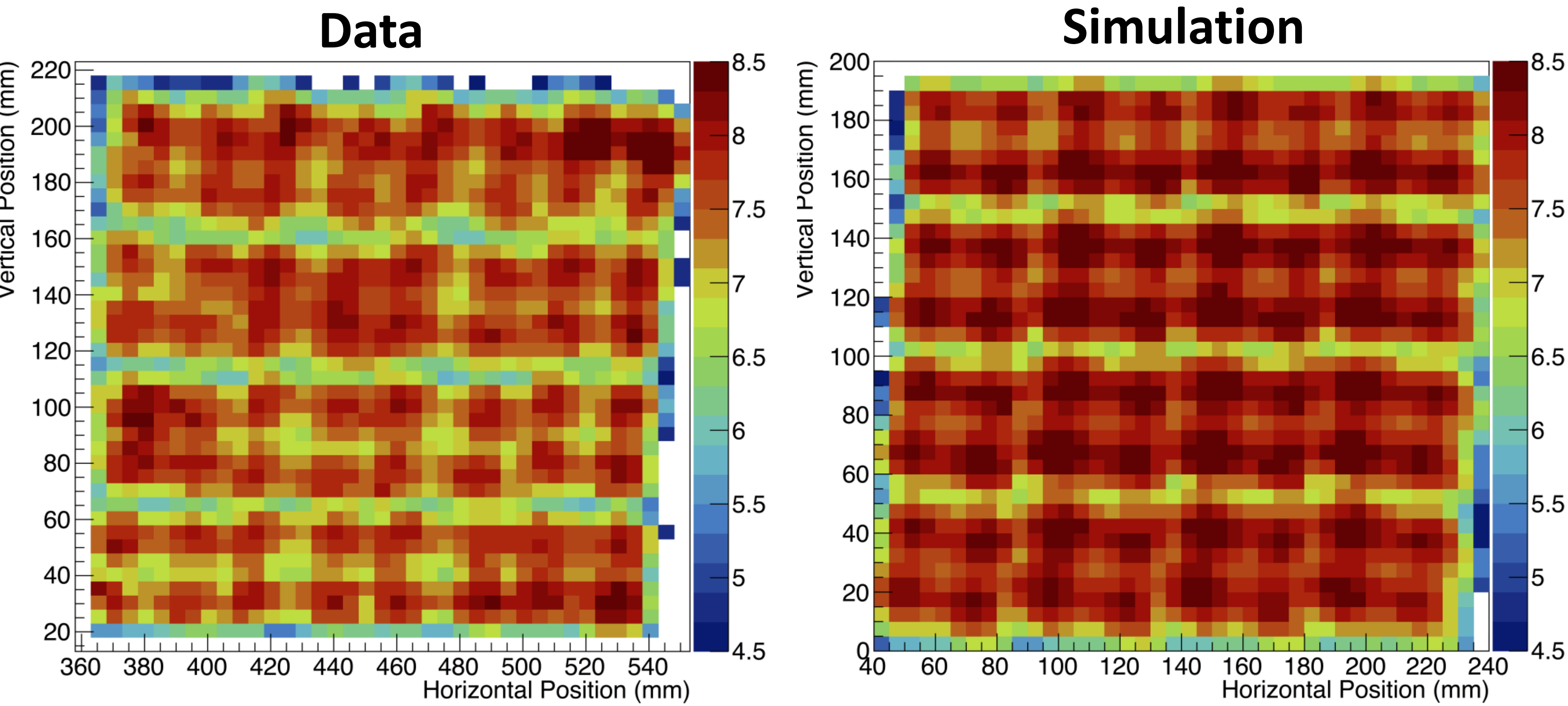
# sPHENIX Detector – EMCAL



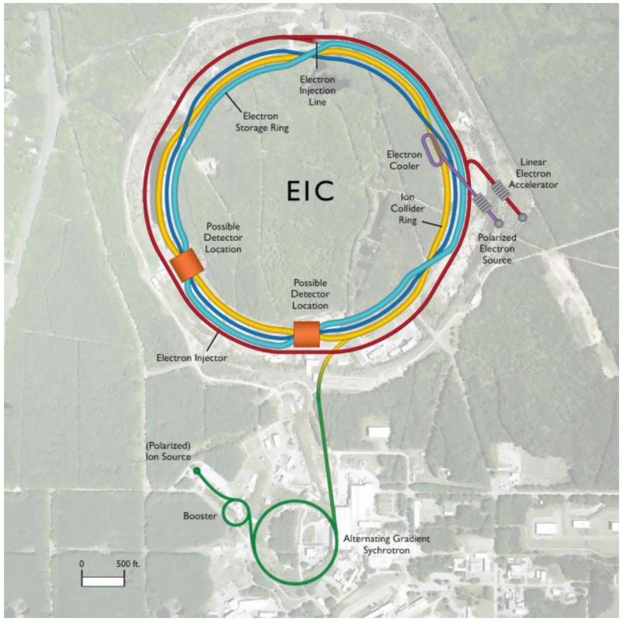

- W/scintillating fiber sampling EMCAL with 2D projective SPACAL block design
- Acceptance coverage: $2\pi$ and $|\eta| < 1.1$
- Total radiation length: 18 X0 with $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$
- Energy resolution: $\frac{\Delta E}{E} = 2.8\% \oplus \frac{15.5\%}{\sqrt{E}}$
- Good electron identification capabilities

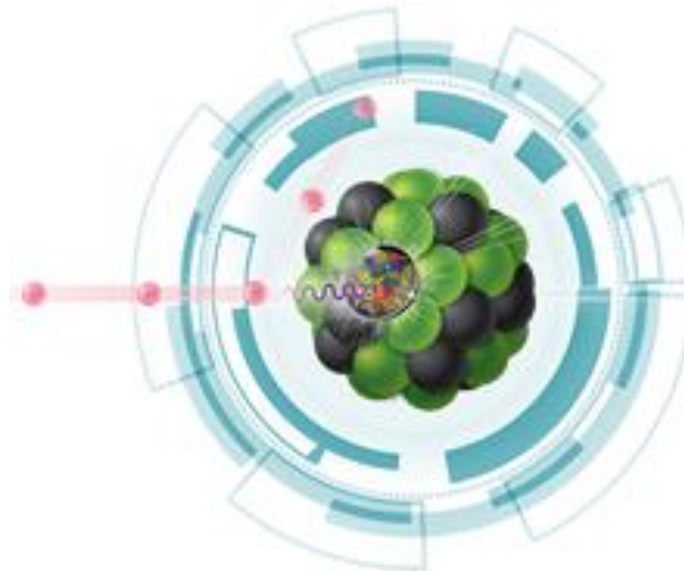
# sPHENIX EMCAL Uniformity Studies

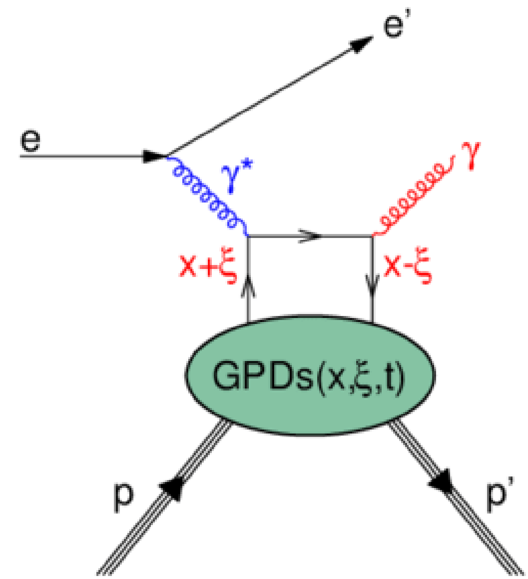



- Excellent consistency between data and simulation
- Solution to non-uniformity: position dependent correction with simulations
- **Bridge to connect with future EIC EMCAL R&D:** enhance with novel SiPM and large photocathode coverage as one of design options for EIC EMCAL

# EIC Physics and Detector R&D






DVCS

**<u>EIC Machine Capabilities</u>**

- Highly polarized beams with high luminosity
- Extensive kinematic phase space $(x, Q^2)$ coverage with a large range of ion species
- Precision 3D imaging of nuclei via Deeply Virtual Compton Scattering (DVCS) experiments

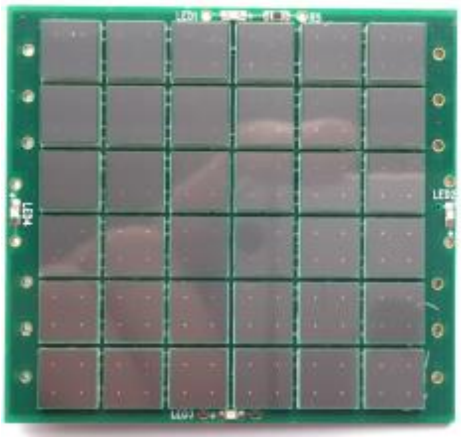
**<u>EIC Scientific Programs</u>**

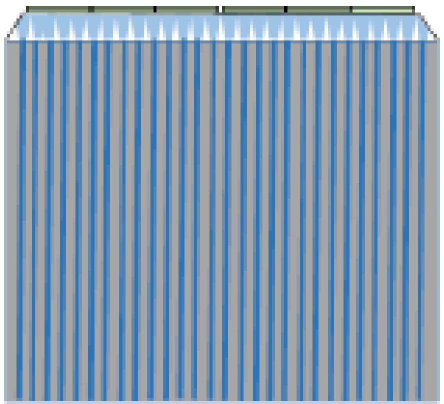
- Cold QCD physics program
- ***Detector development: apply novel technologies to develop detectors for future EIC experiments to achieve EIC Physics Goals***

# EMCAL Development for EIC Experiments

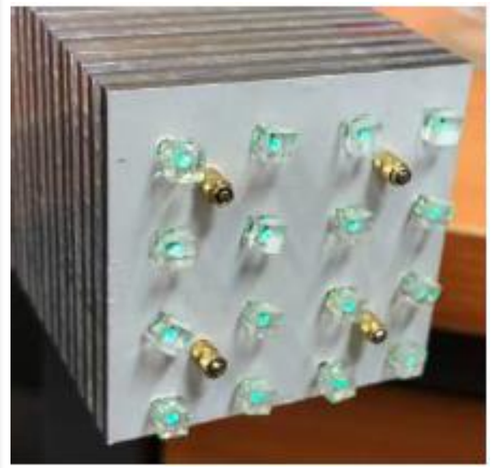
**EMCAL Design Options**

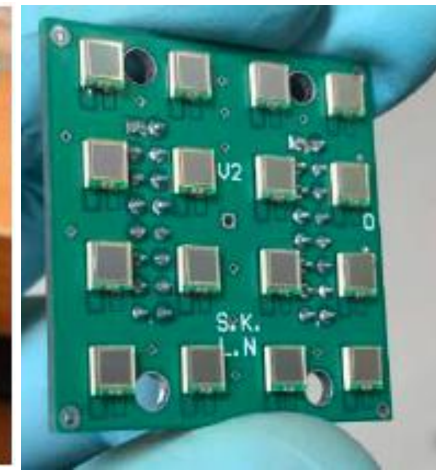
**W/SciFi SPACAL design with more SiPMs and shorter light guides to have larger photocathode coverage**





**W/Shashlik tower design with high granularity and efficient readout**

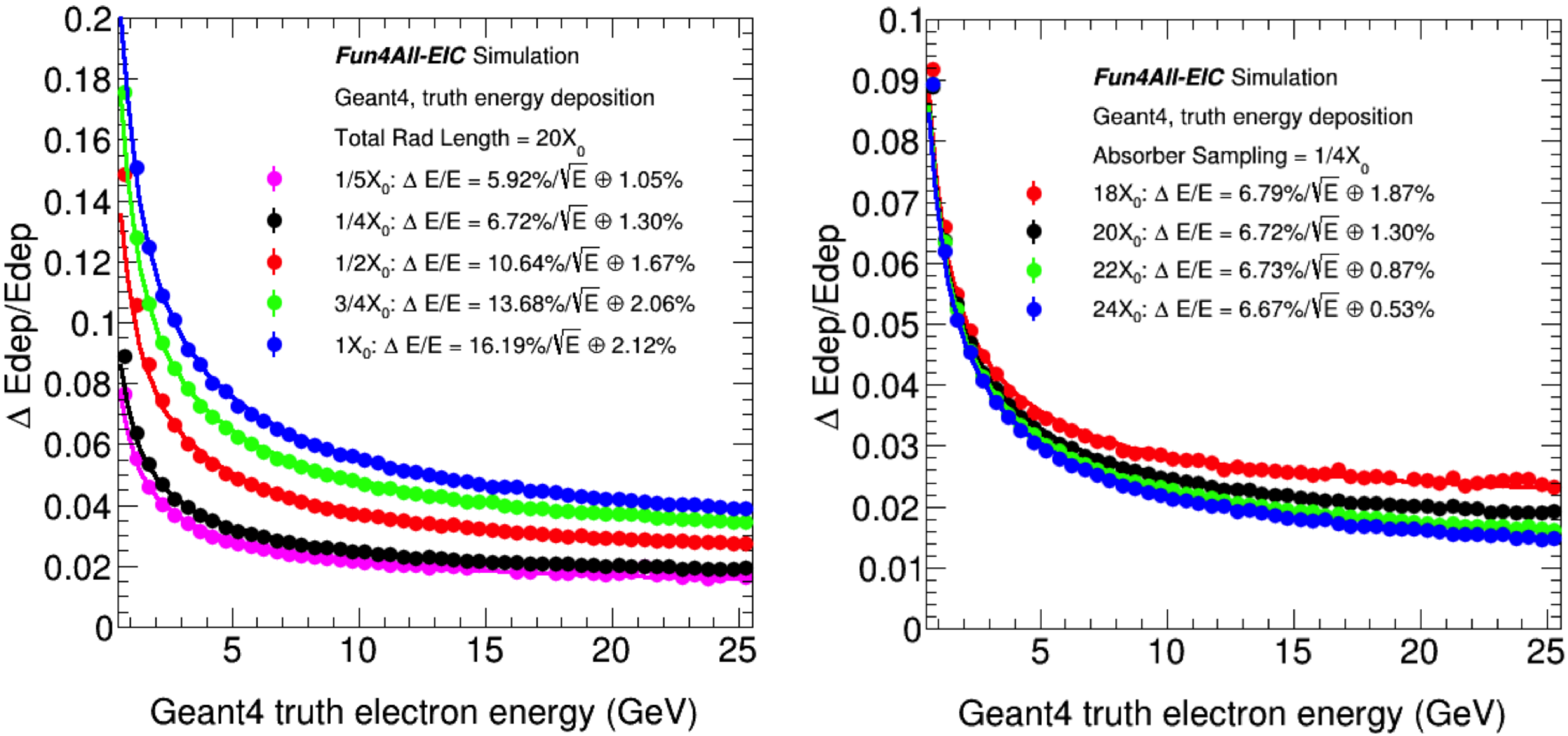




**Novel Technologies Proposed**

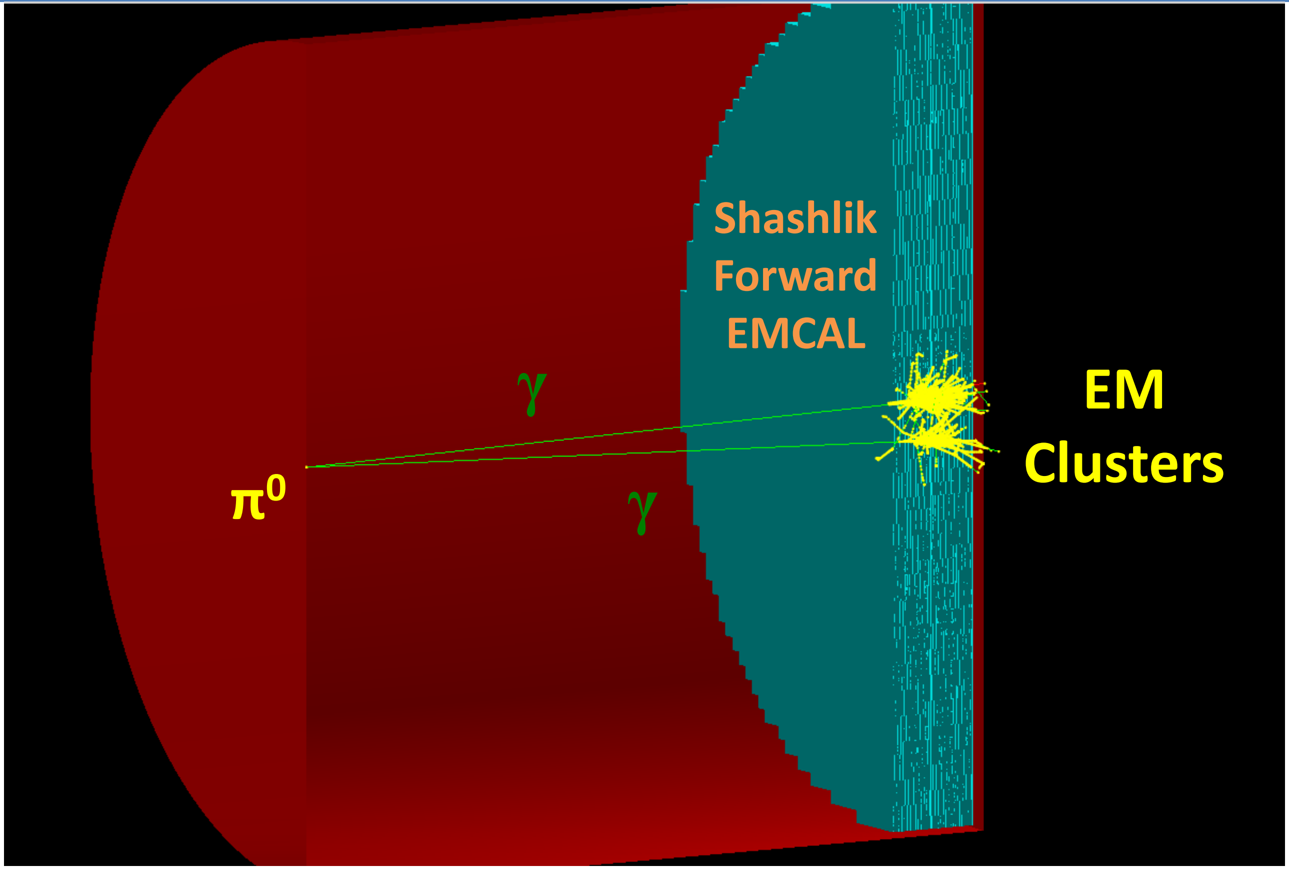
- W absorber for EMCAL to allow compact design to save space, crucial for EIC experiments
- Novel SiPMs with larger area and finer pixel size to improve light collection efficiency and uniformity
- High granularity shashlik calorimeter with SiPM readout on every fiber

# Shashlik EMCAL Energy Resolution



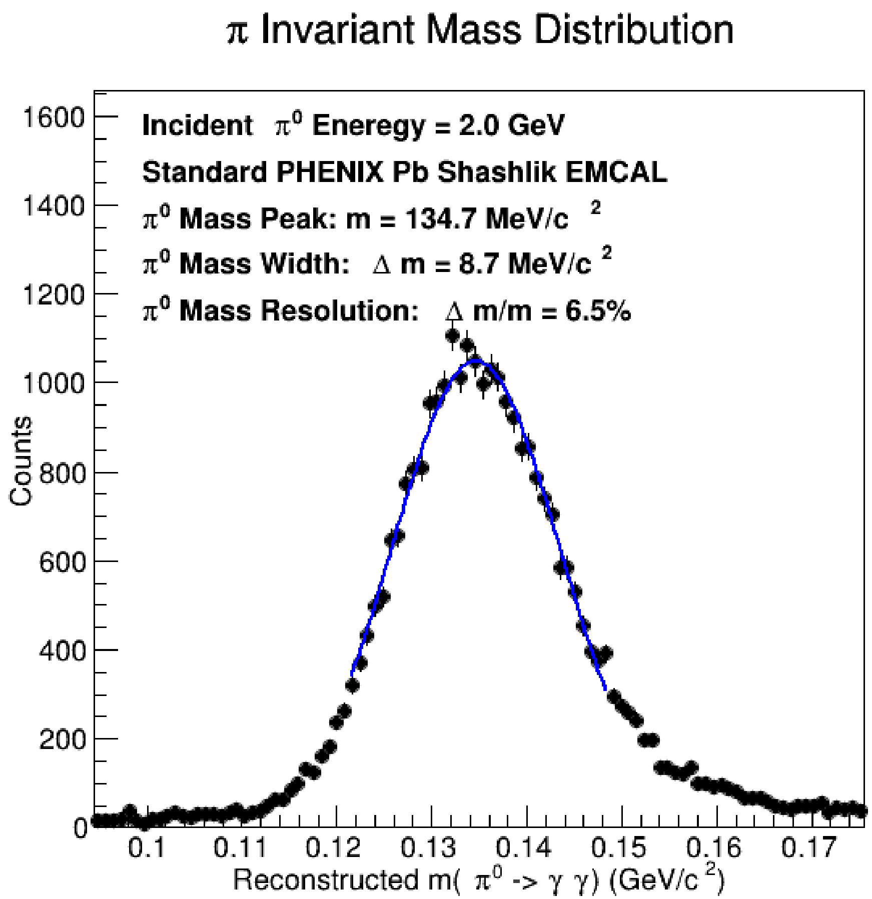

- The statistical term gets better as we go to thinner scintillators
- The constant term gets better as the number of plates increases

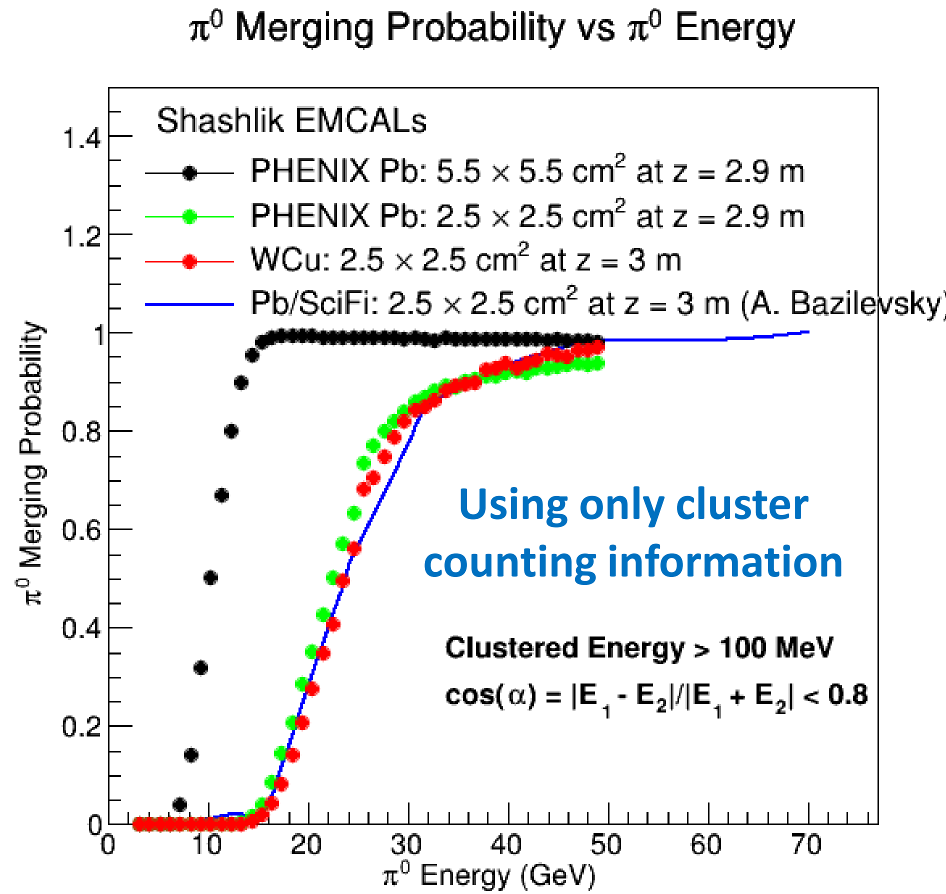
# EIC Forward EMCAL: $\pi^0$ Merging Probability




- Forward EMCAL: hadron going direction
- $\pi^0$ beam at normal incidence used to reconstruct $\pi^0$ and study the merging probability of the two photon clusters into one
- Study $\pi^0$ merging probability of two clusters into one with various EMCAL granularities

# $\pi^0$ Merging Probability Studies




- $\pi^0$ merging probability decreases with finer granularity → reconstruct $\pi^0$ up to higher energy
- Strong dependence on granularity while weak dependence on Moliere radius
- Presented in EIC eRD1 Report and EIC Calorimetry workshops

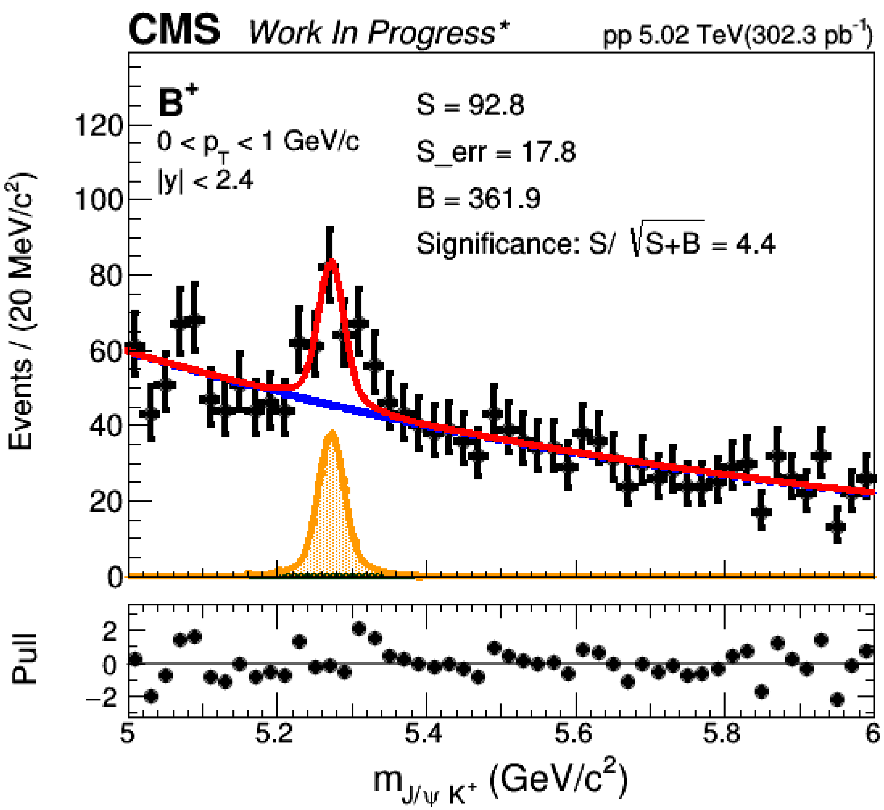
# Outline

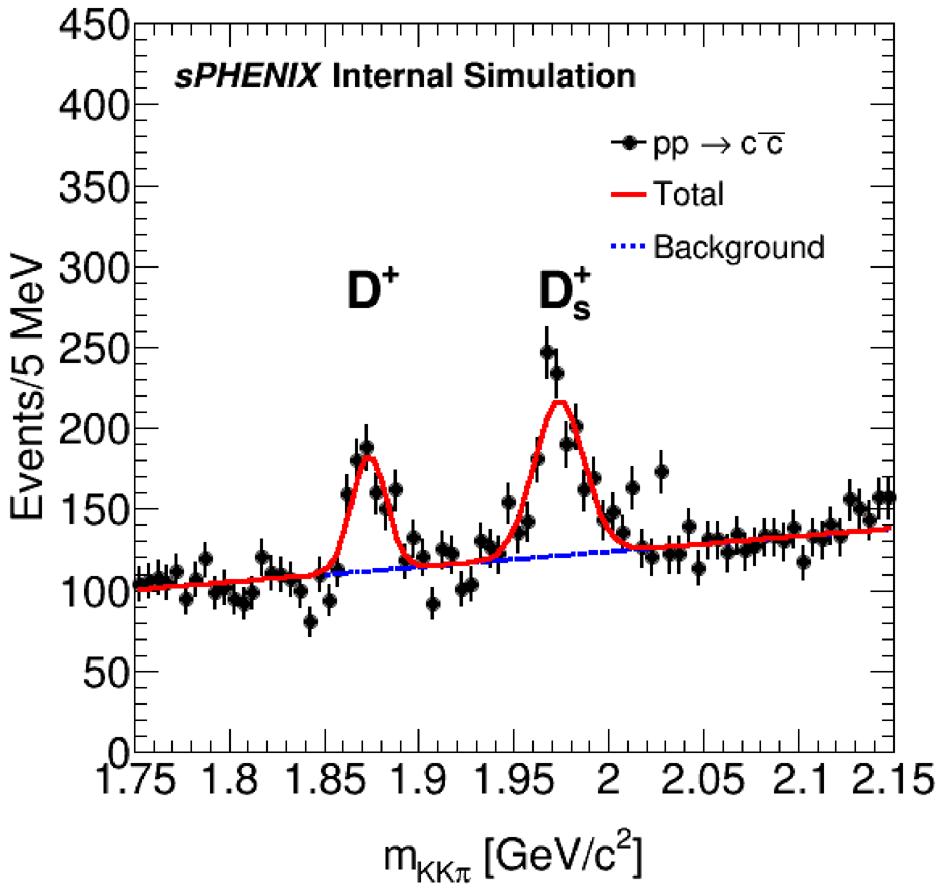
- **Beauty Hadrochemistry in Quark-Gluon Plasma at the LHC**
- **B and D meson Physics Simulation with sPHENIX**
- **sPHENIX EMCAL Studies and EIC EMCAL Simulations**
- **Future Outlook**



Physics

# Heavy Flavor Physics with Machine Learning

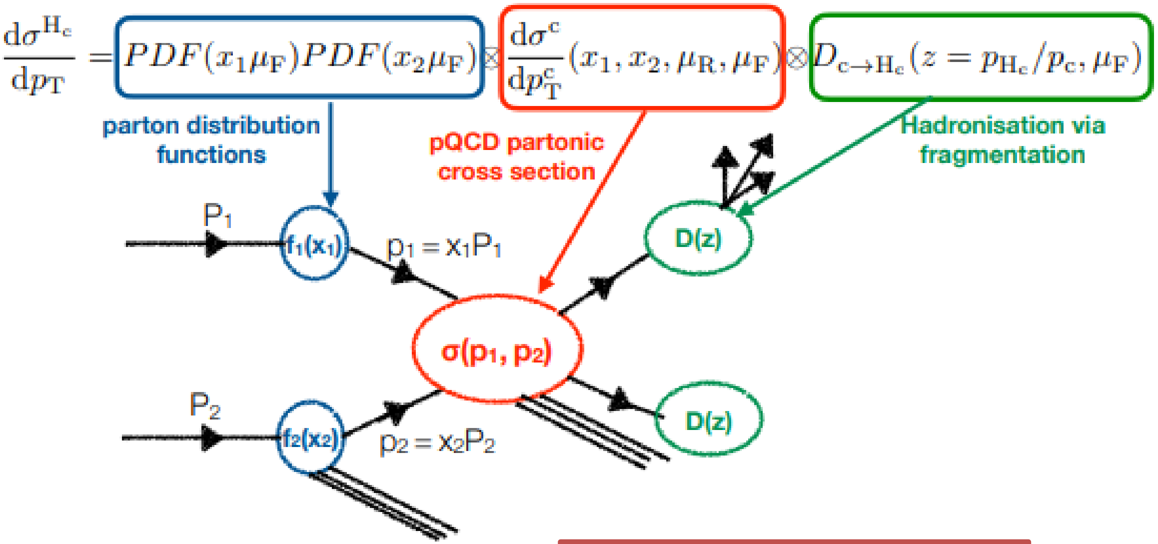


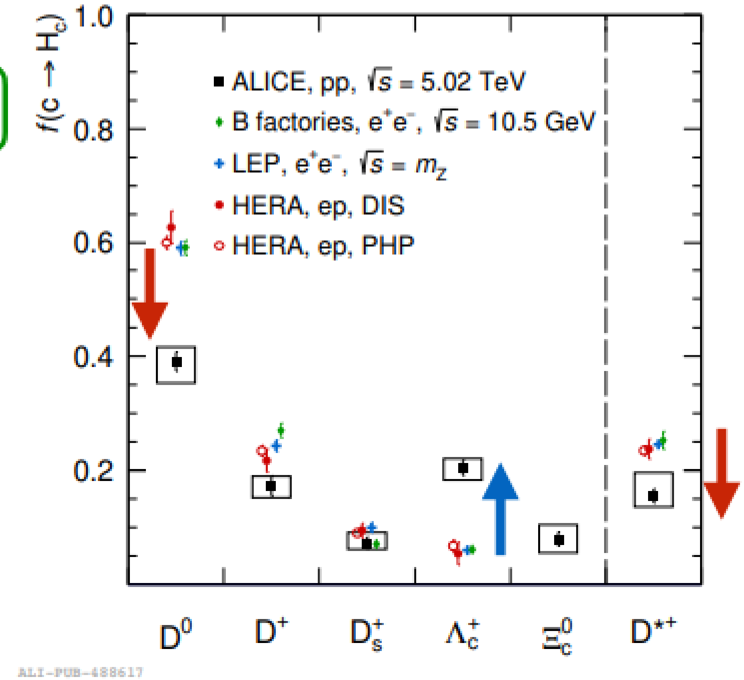




**Opportunities with machine learning**

- Applied in the full reconstruction of STAR and ALICE $D_s^{\pm}$, CMS $B^+$, $B_s^0$ and $\Lambda_c^+$
- Applicable as well for sPHENIX $D_s^+$ and $B_s^0$ and potentially in $\Lambda_c^+$ and $\Lambda_b^+$ studies
- Extend to low $p_T$ and high multiplicity measurements thanks to machine learning and MVTX

# Hadronization Universality Breaking




**Innocenti: SQM 2021**

- QCD Factorization Theorem: PDF ⊗ pQCD Diagrams ⊗ Fragmentation Function $D(z, Q^2)$
- Hadronization Universality: $D(z, Q^2) = D_{e^+e^-}(z, Q^2) = D_{ep}(z, Q^2) = D_{pp}(z, Q^2)$
- Broken due to quark coalescence mechanism? Additional dependence on color charge density: $D_{pp}(z, Q^2) \rightarrow D_{pp}(z, Q^2, n_c)$?
- Future opportunities: RHIC energy? EIC energy and collision systems? Beauty sector at RHIC and the LHC? Differential studies on Hadronization Universality Breaking?

# Summary

- **Application of Machine Learning in Heavy Flavor Physics Studies**
- Full reconstructions of $B^+$, $B^0$, and $B_s^0$ down to very low $p_T$ in pp and PbPb
- First observation of $B_s^0$ signal in nuclear collisions with > 5σ significance

- **Beauty Production and Hadronization Studies with CMS at the LHC**
- $B_s^0/B^+$ in pp and PbPb collisions
- Precise measurement of $B^+$ $R_{AA}$ over a wide range of $p_T$
- Inclusive beauty production cross measurement in pp collisions
- Beauty fragmentation fraction measurement vs $p_T$ and multiplicity

- **sPHENIX Heavy Flavor Physics Studies**
- sPHENIX heavy flavor physics simulations and MDC 1 data analysis
- Complementary measurements to the LHC experiments at different energies

- **EMCAL Detector Studies**
- sPHENIX EMCAL characterization studies at test beam
- EIC shashlik EMCAL simulations

# Thank You

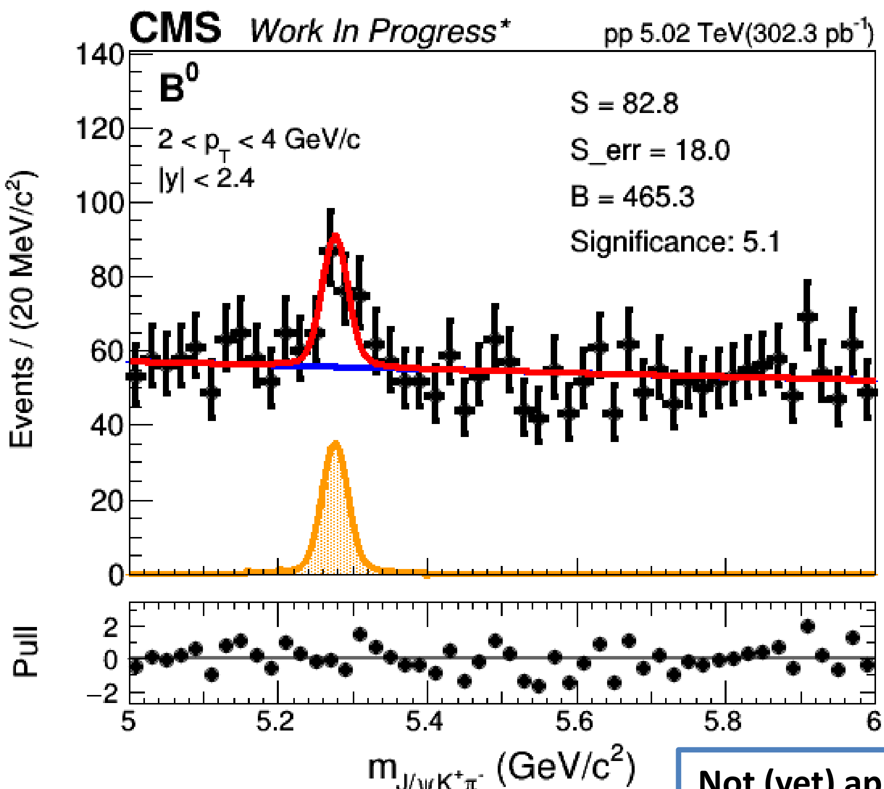
# Back Up

# Future Plans

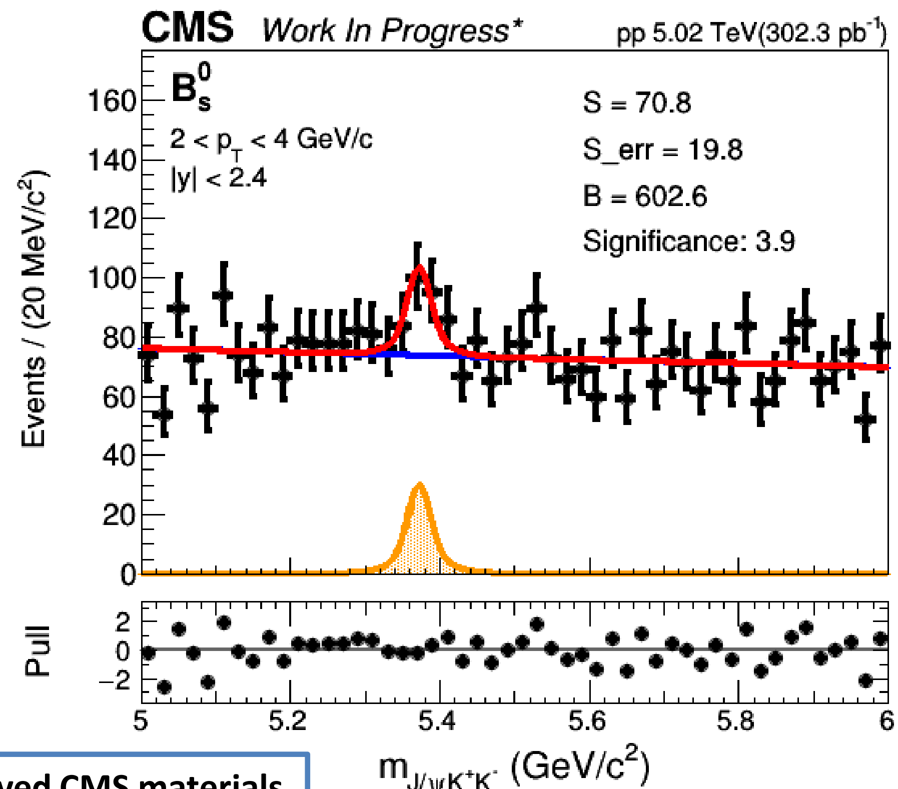
- **RHIC – sPHENIX Experiment**
- Physics simulations for B and D mesons
- sPHENIX EMCAL commissioning
- EIC EMCAL detector hardware and readout electronics studies
- sPHENIX EMCAL and heavy flavor analysis software development
- B and D mesons data analysis with sPHENIX pp, pAu, and AuAu datasets

- **LHC – ATLAS Experiment**
- ATLAS heavy flavor physics data analysis with the application of multivariate analysis and machine learning
- Study hadronization universality in the beauty sector at LHC energy

# $B^0$ and $B_s^0$ Performance with BDT

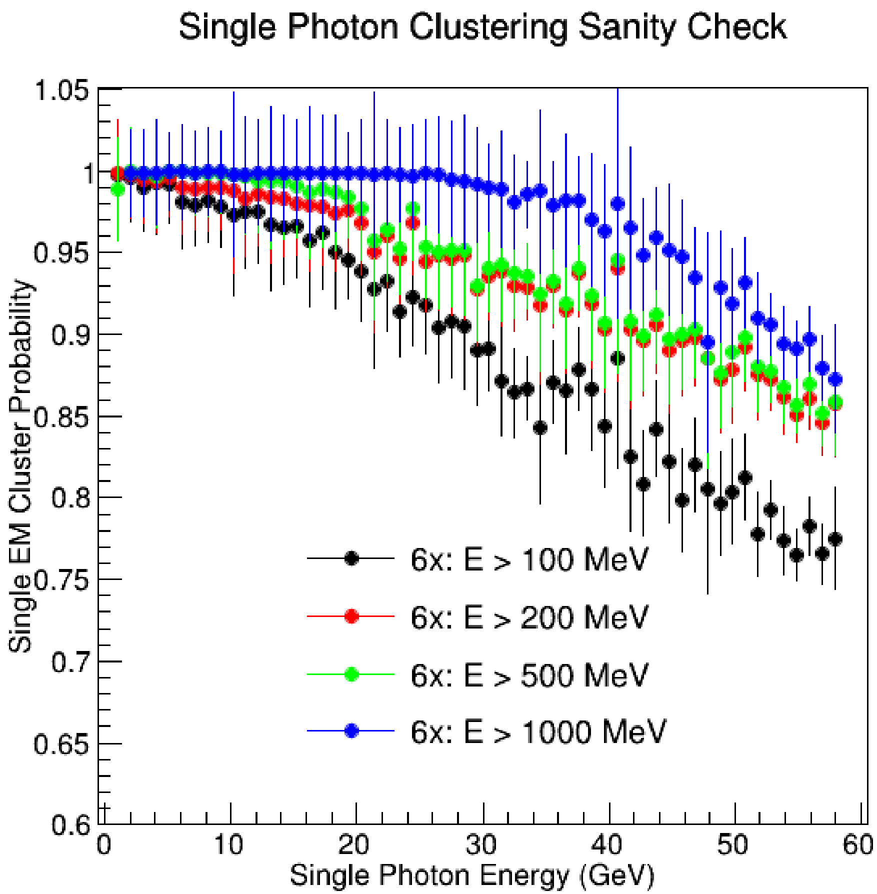


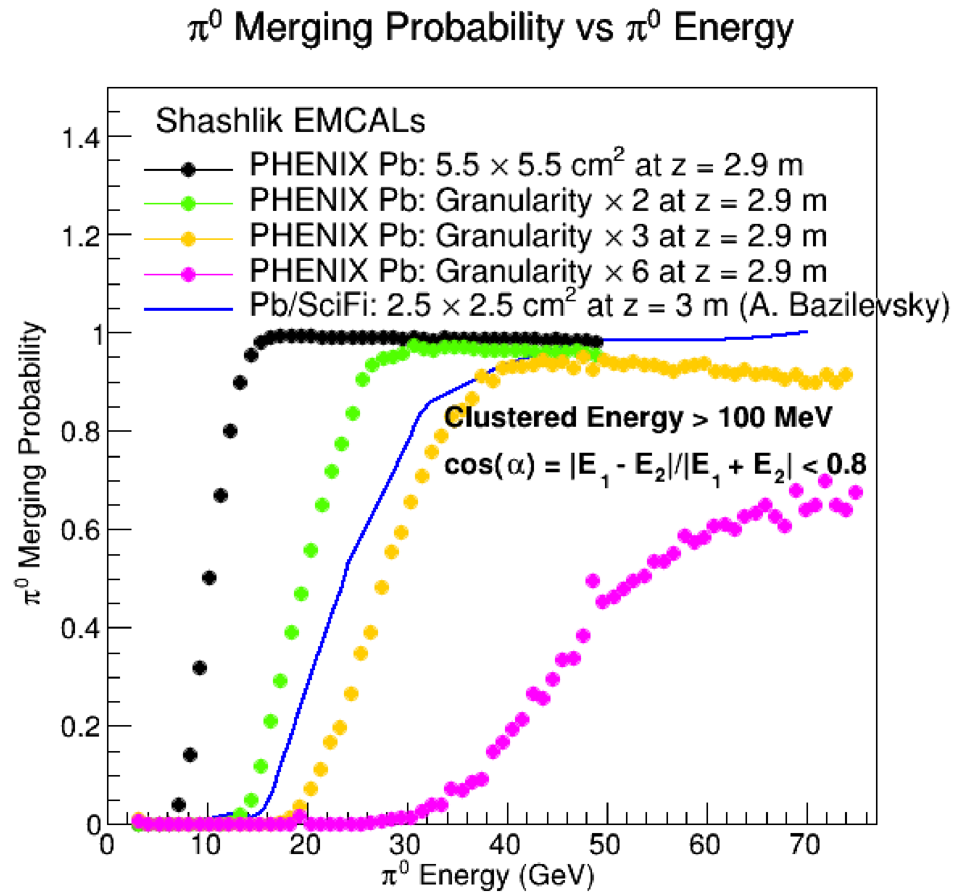

**Not (yet) approved CMS materials**




- **BDT capabilities:** Clear $B^0$ and $B_s^0$ signals **without hadronic PID down to $p_T =$ 2 GeV/c**
- **Beauty hadrochemistry:** $b \to B$ fragmentation fraction measurement vs $p_T$ and multiplicity

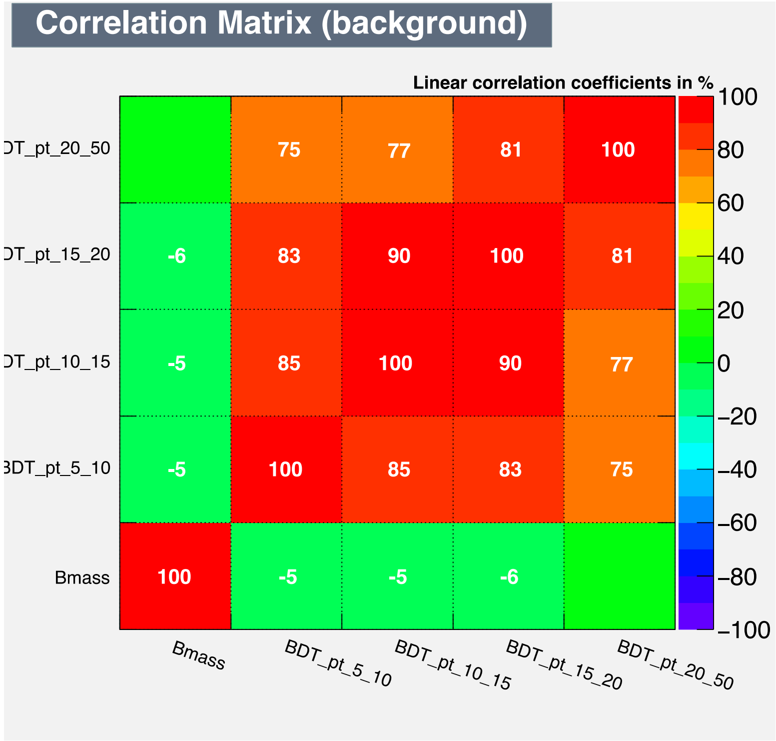
# $\pi^0$ Merging Probability: High Granularity Limit

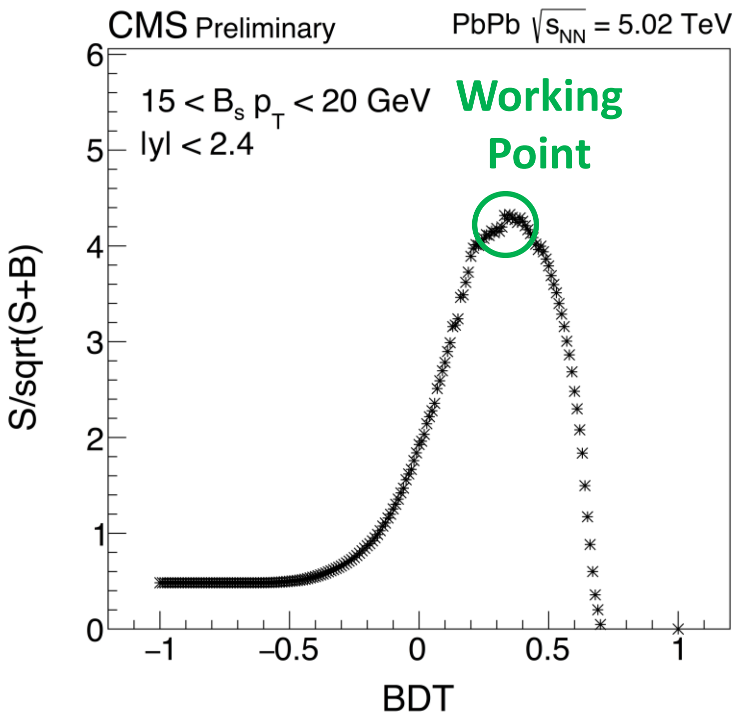



- The clustering algorithm breaks down in the limit of very high granularity for shashlik EMCAL towers
- The merging probability does not saturate at unity due to mismatch between clusters to the number of shower particles → potentially improved with machine learning

# BDT Training Performance and Working Points




- Perform BDT training for each $p_T$ bin
- No significant correlation between the BDT scores and the $B_s^0$ invariant mass → BDT cut valid to use in our analysis
- Maximize the statistical significance = $\frac{S}{\sqrt{S+B}}$ for BDT working point determination of each $p_T$ bin in our analysis



Physics

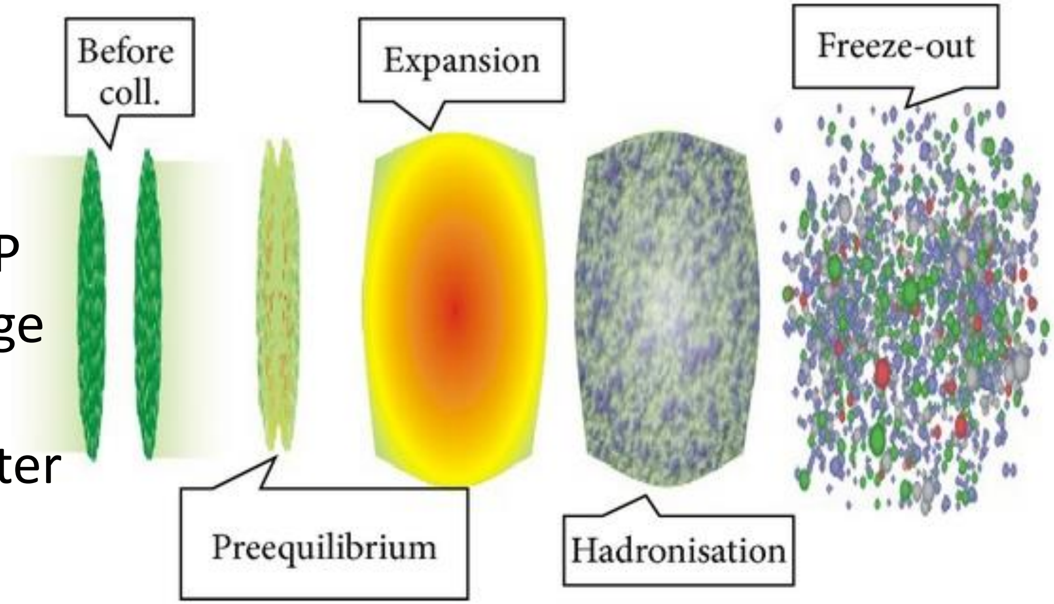
# Laboratory for Relativistic Heavy-Ion Physics

**Relativistic Heavy Ion Collisions:**

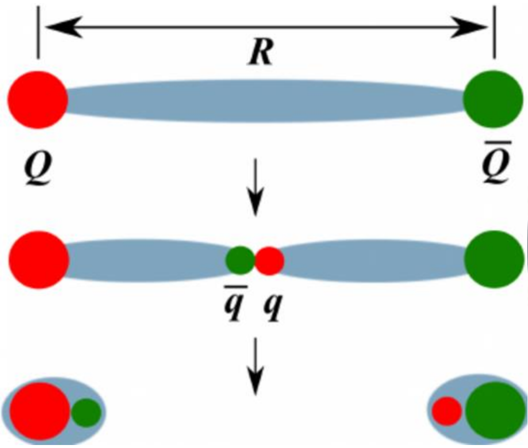
- Use accelerators to collide heavy nuclei at high energy to create an extreme hot and dense environment (170 MeV -> Trillion degrees Kelvin)
- Experimental variables to control (knobs to turn):
  - Collision energy
  - Nuclei species
  - Impact parameter
  - Nuclei spin polarization

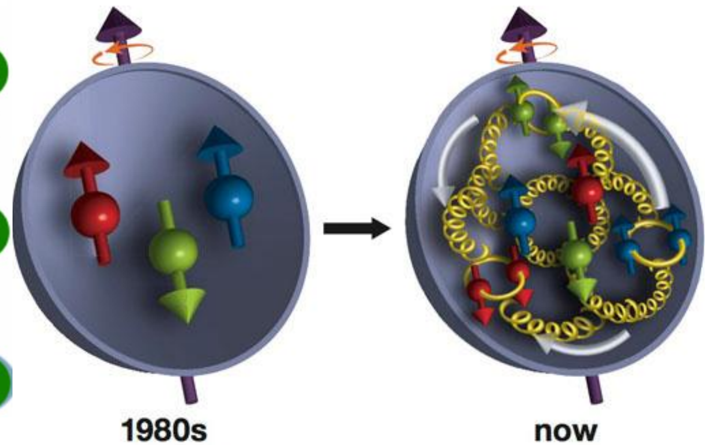
**Stages in Heavy Ion Collisions:**

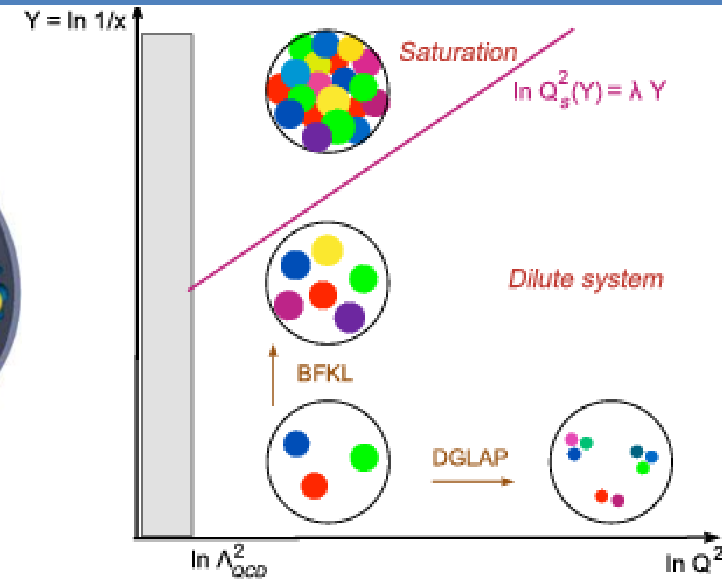
- Hot and dense QCD matter QGP exists during the expansion stage (lifetime ~ 10 fm/c ~ $10^{-23}$ s)
- Final state hadrons detected after the freeze-out stage



# Cold QCD Physics



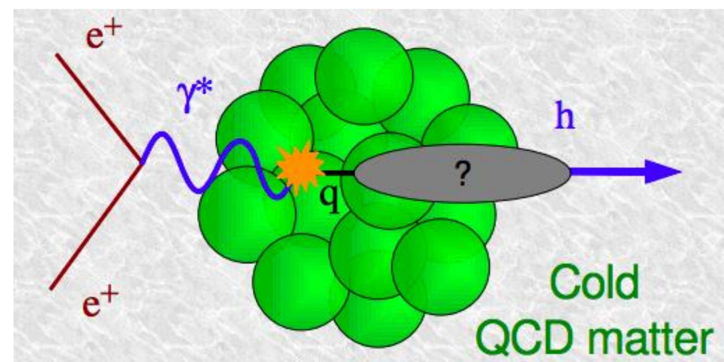




**Color Confinement:**

- Feature of non-abelian gauge theory
- Quarks and gluons are confined and form QCD bound states

**Partonic Structure of Hadrons:**

- Non-perturbative QCD at low temperature
- The spin structure of proton: angular momentum carried quarks and gluons in proton
- Gluon Saturation at small x: nuclear shadowing effect




**Parton - Hadron Interaction and Hadronization Mechanism:**

- Parton propagation in cold nuclear matter: modification of parton energy loss
- Parton hadronize in color environment: cold nuclear matter effects on hadronization

# Physics Motivations

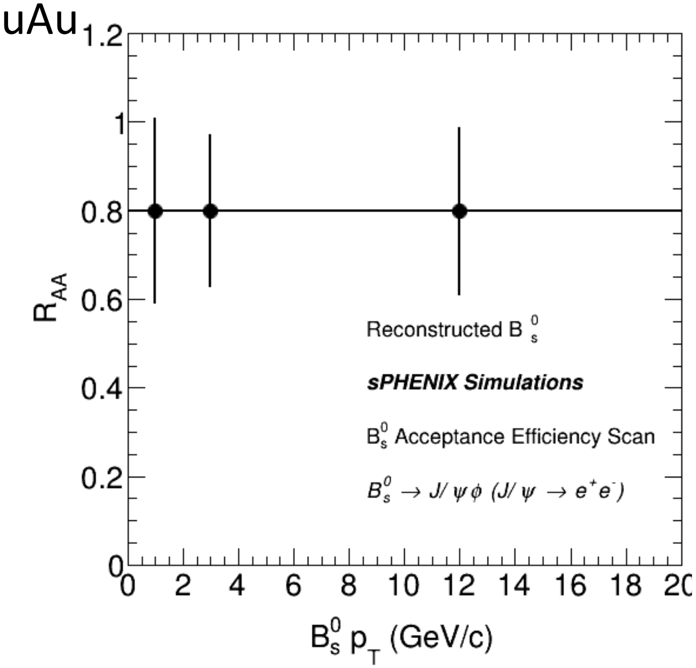
**Physics Motivations**

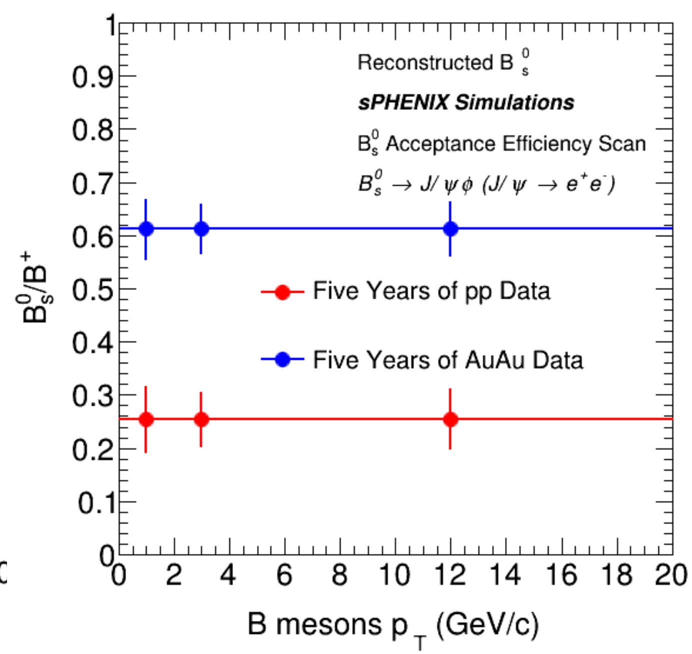
- Complementary heavy flavor measurements to LHC experiments
- Probing QGP at different temperatures and baryon chemical potentials
- More comprehensive understanding beauty hadronization mechanism
- Measurement of inclusive beauty cross section in pp and AuAu at RHIC energy

**Experimental Observables:**

- $B_s$ and $B^+$ nuclear modification factor
- $B_s/B^+$ Ratio in pp and AuAu

**Lumi = 1.4 fb$^{-1}$**



# Event and Track Selections

**Event Selections**

- Event noise filters
- Centrality selections (0 – 90%)
- Longitudinal component of the primary vertex $|PV_z| < 15$cm

**Muon selections**

| $|\eta|$ | 0 – 1.2 | 1.2 – 2.1 | 2.1 – 2.4 |
|---|---|---|---|
| $p_T$ (GeV/c) | > 3.5 | > 5.47 – 1.89 $|\eta|$ | > 1.5 |

- Pixel Layer > 0 and Pixel Layer + Strip Layer > 5
- 2D DCA to PV < 0.3, z-component DCA to PV < 20
- Both global and tracker muons are required

**$J/\psi$ and $\phi$ mesons selections**

$|m[J/\psi(\mu\mu)] - m[J/\psi(PDG)]| < 0.15$ GeV/c$^2$

$|m[\phi(KK)] - m[\phi(PDG)]| < 0.015$ GeV/c$^2$ (For $B_s$ only)

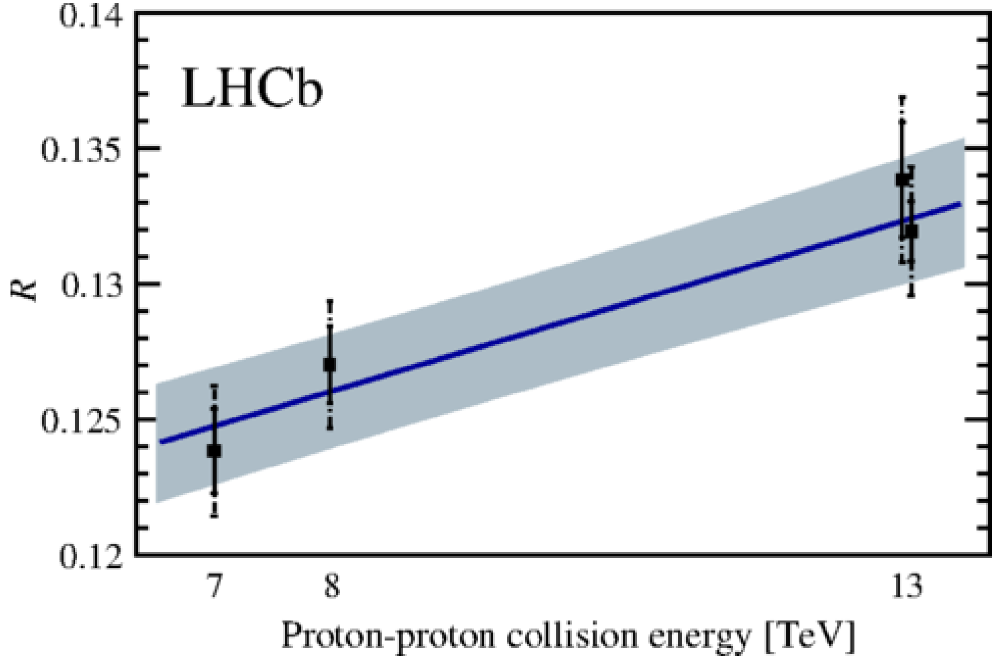
**Hadronic Track Selections**

| | |
|---|---|
| High Purity Track | Pixel + Strip Hits > 10 |
| $|\eta| < 2.4$ | Track $p_T$ error/track $p_T$ < 0.1 |
| $p_T > 1.0$ GeV/c | Track $\chi^2$/ndf /Track nHits < 0.18 |



MIT Physics

# Collision Energy Dependence of $B_s^0/B^+$ Ratio in pp




**Phys. Rev. Lett. 124, 122002**

- **LHCb measurement of $B_s^0/B^+$ ratio at different $\sqrt{s}$**

☛ $R = \frac{1}{2} f_s/f_u$

☛ Same decay channels

☛ No branching fraction

☛ Observation of dependence on $\sqrt{s}$ with 4.8σ significance



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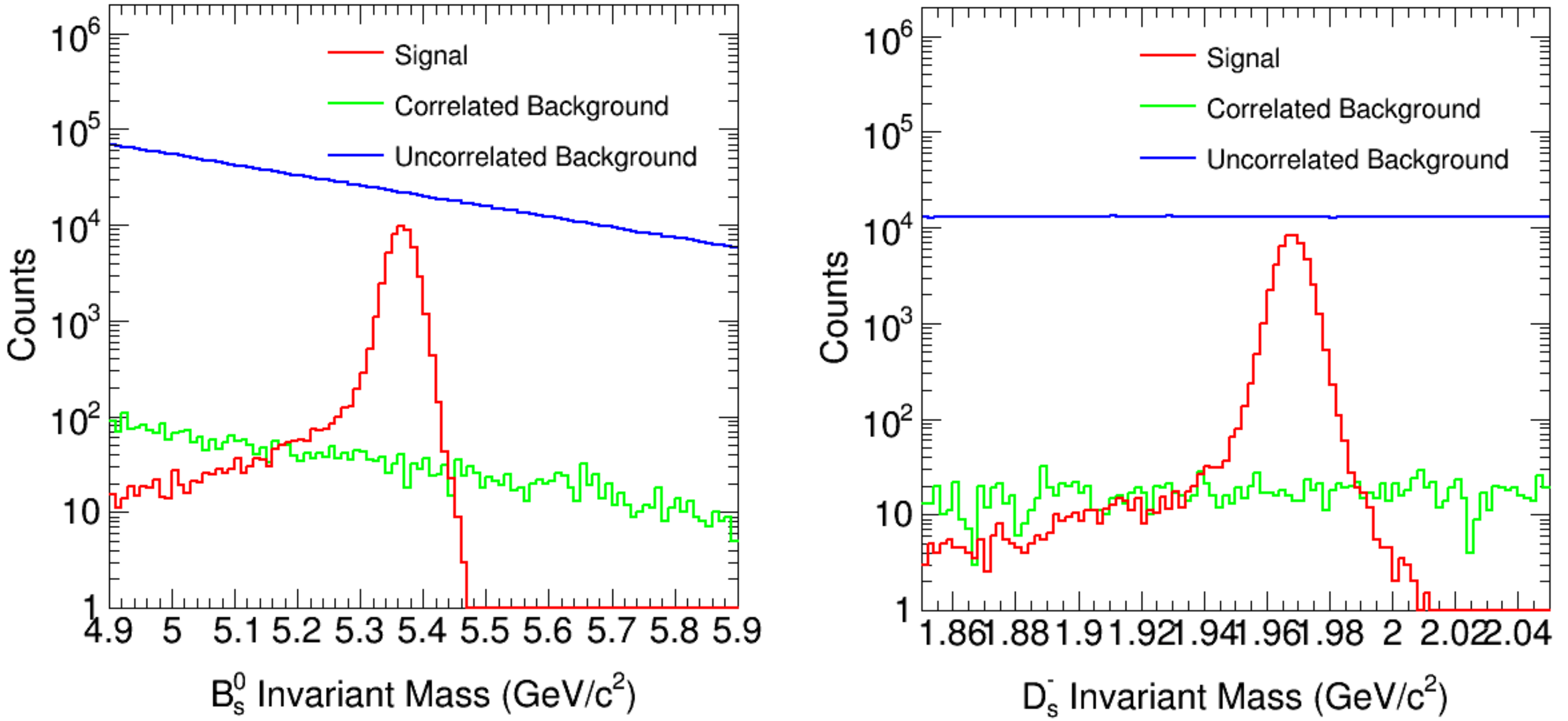
# sPHENIX Fast Simulations (Ongoing)




**Fast simulation Machinery:**

- Simulation sample: total 480000 events filtered with some event and track quality selections
- Signal: EvtGen package to force $B_s$ -> $D_s$ decay channel
- Correlated background: $pp \rightarrow b\bar{b}$ with PYTHIA 8
- Uncorrelated background: randomly sample identified p, K, π spectra from primary vertex

Everything is still in the beginning!!! More validations and improvements still ongoing!



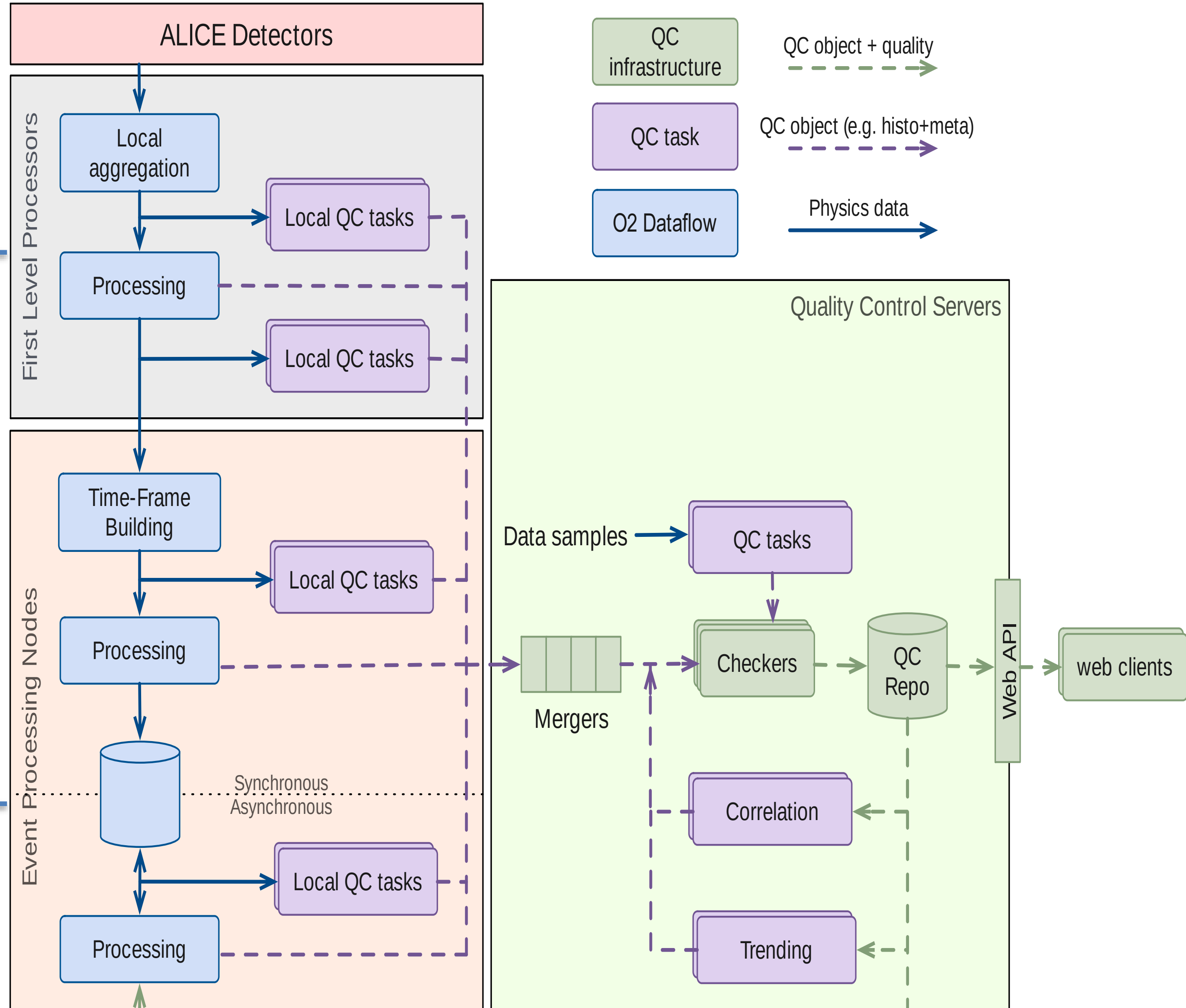
Physics

# Quality Control Software System for ALICE ITS Upgrade

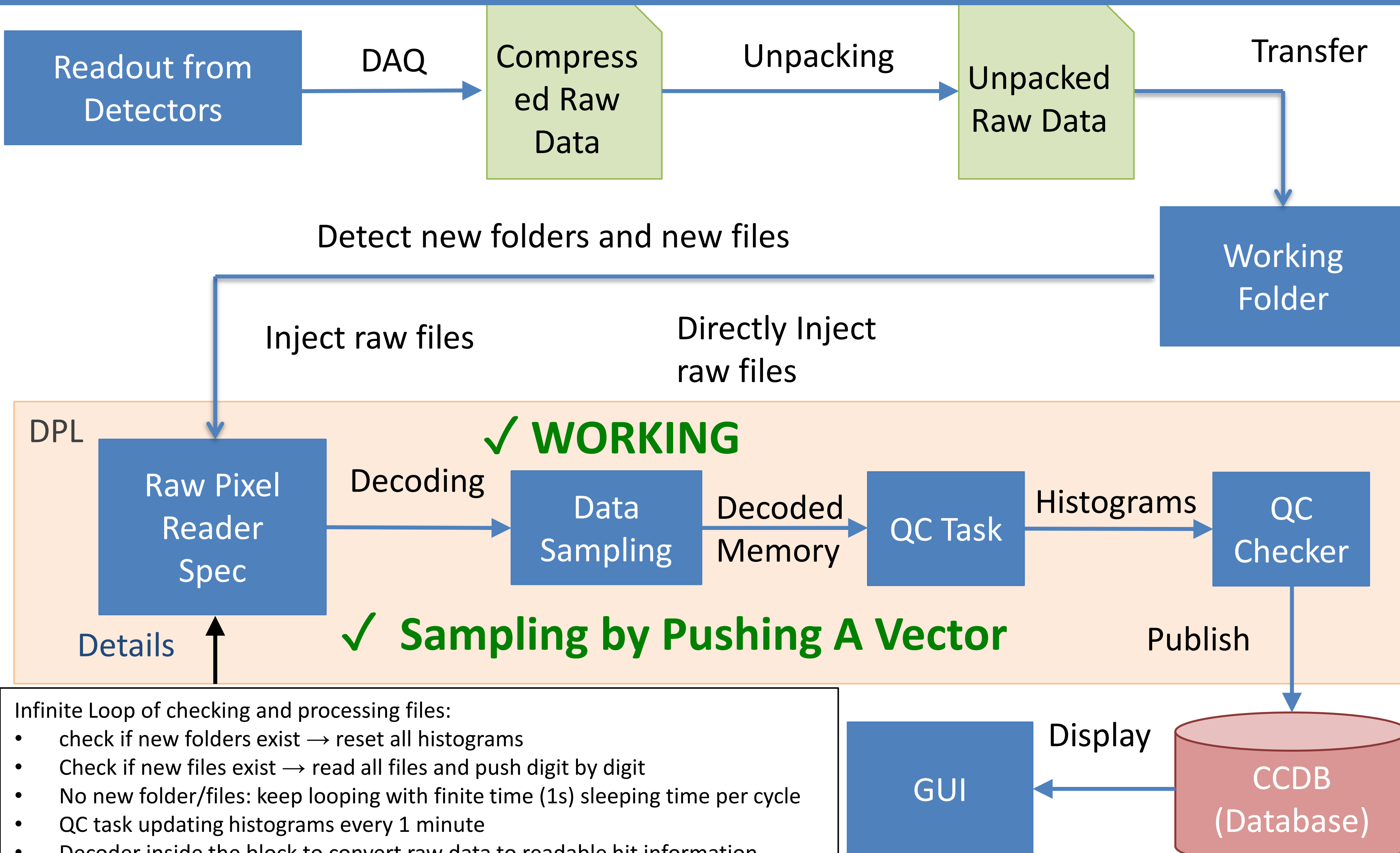
# General ALICE QC Framework

**Currently, in ALICE ITS commissioning, the QC are all installed in the FLP machines**

**In principle, QC can also be installed at EPN if needed**



# QC Workflow




Infinite Loop of checking and processing files:

- check if new folders exist → reset all histograms
- Check if new files exist → read all files and push digit by digit
- No new folder/files: keep looping with finite time (1s) sleeping time per cycle
- QC task updating histograms every 1 minute
- Decoder inside the block to convert raw data to readable hit information

# CCDB Database

- **System**

- CCDB is a database that stores the histograms of the analysis results
- CCDB will only clean up every hour and keep the one histogram in a hour
- CCDB has a total storage of about 700 GB
- CCDB for ALICE ITS commissioning website: http://ccdb-test.cern.ch:8080/browse/ITSRAWDS

- **Features**

- Tree structure of the analysis results
- Metadata (RunID + FileID) has been implemented along with the tree structure on CCDB

| ID | Valid from | Valid until | Initial validity limit | Created at | Last modified | MD5 | File name | Content type | Size | Path | Metadata | Replicas |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| d75ed4d0-be9d-11e9-a7a5-808d5c675566 | 1565792074393<br>14 Aug 2019 16:14 | 1881152074393<br>11 Aug 2029 16:14 | 1881152074393<br>11 Aug 2029 16:14 | 1565792074397<br>14 Aug 2019 16:14 | 1565792074397<br>14 Aug 2019 16:14 | 91bfe25031a229cf0e31b7bae37afebf | ITSQC/General/ErrorPlots_1565792074393.root | application/octet-stream | 833 | ITSRAWDS/ITSQC/General/ErrorPlots | partName<br>send<br>Run<br>1621<br>File<br>0<br>quality<br>10 | • 0 |
| 77de5380-bdff-11e9-a7a4-808d5c675566 | 1565724053684<br>13 Aug 2019 21:20 | 1565792074392<br>14 Aug 2019 16:14 | 1881084053684<br>10 Aug 2029 21:20 | 1565724053688<br>13 Aug 2019 21:20 | 1565724053688<br>13 Aug 2019 21:20 | 322875321099bf55611c76b417b65537 | ITSQC/General/ErrorPlots_1565724053684.root | application/octet-stream | 833 | ITSRAWDS/ITSQC/General/ErrorPlots | UpdatedFrom<br>2001:1458:202:28:0:0:100:35<br>partName<br>send<br>Run<br>1610<br>File<br>3<br>quality<br>10 | • 0 |

- Retrieving old data based on the metadata is available from metadata for further analysis



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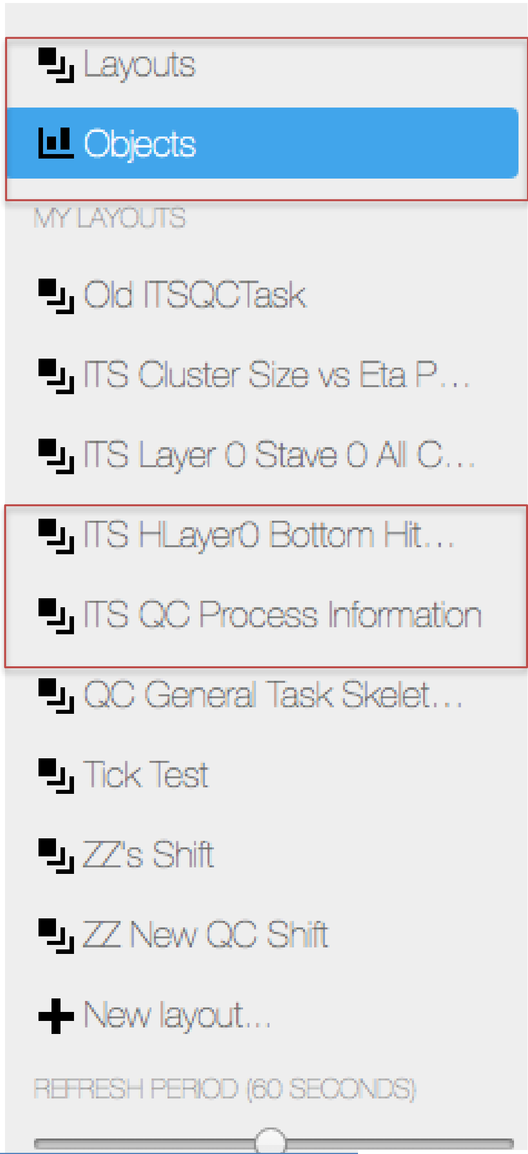
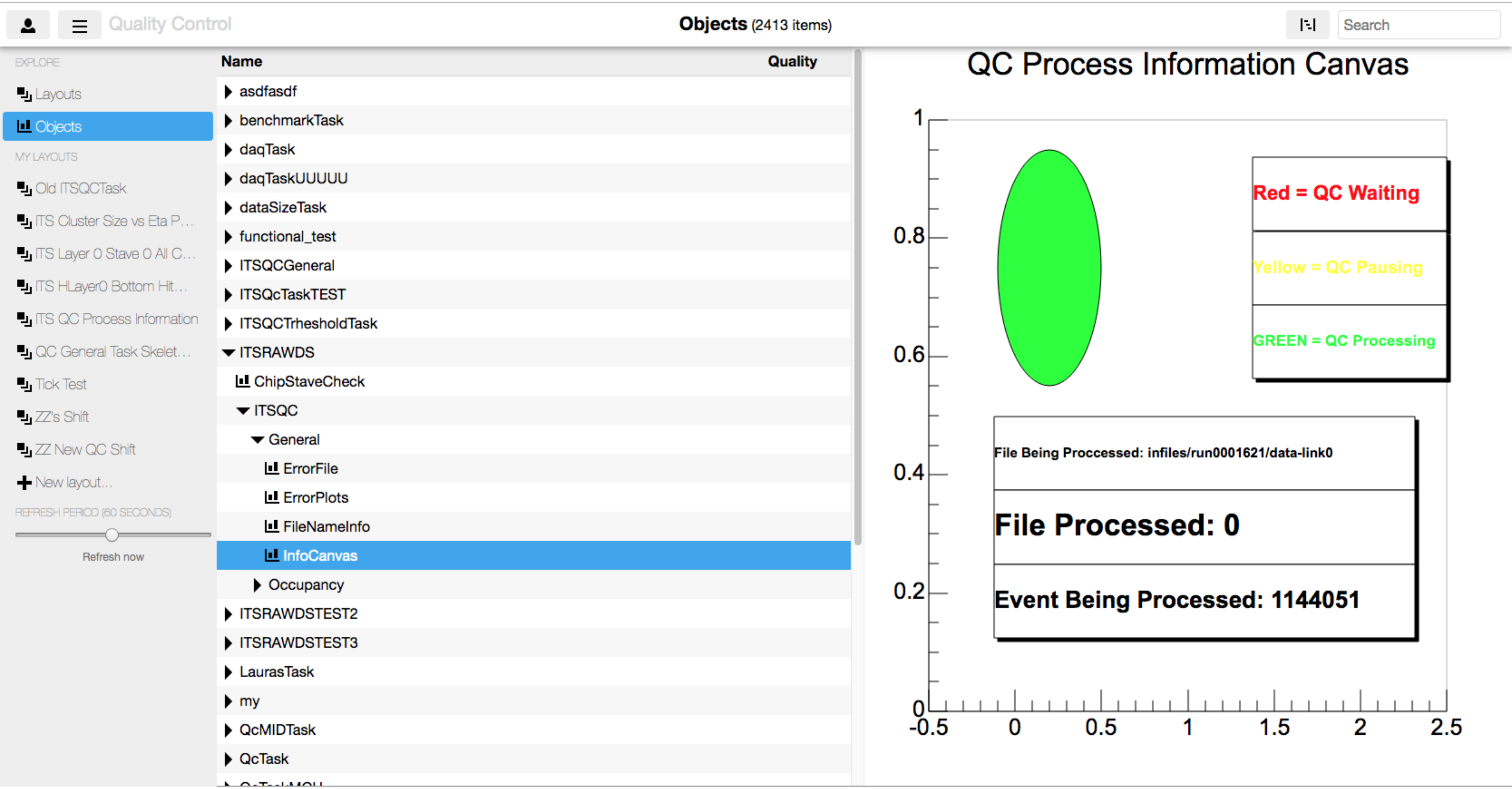
# GUI

- **System**
- GUI for ALICE ITS commissioning website (ALICE Access Required): https://qcg-test.cern.ch/?page=layoutList
- GUI will automatically refresh every 60 second
- GUI has objects and layouts
- Histogram plots are stored at the objects under the Task name folder. The GUI also has a tree structure similar to the CCDB

- **Features**
- User can create (and name), modify (and rename) and delete a layout and selection plots from the objects to put in the layout
- The plots size on the layout can be adjusted to $1 \times 1$, $1 \times 2$, $2 \times 2$, $3 \times 3$, ect. The layout page size is $4 \times 4$
- The draw options such as "COLZ" and log x and y options are also available
- Currently, we have two layout for the ALICE ITS commissioning shift: ITS QC Process information and ITS HLayer0 Bottom Hit

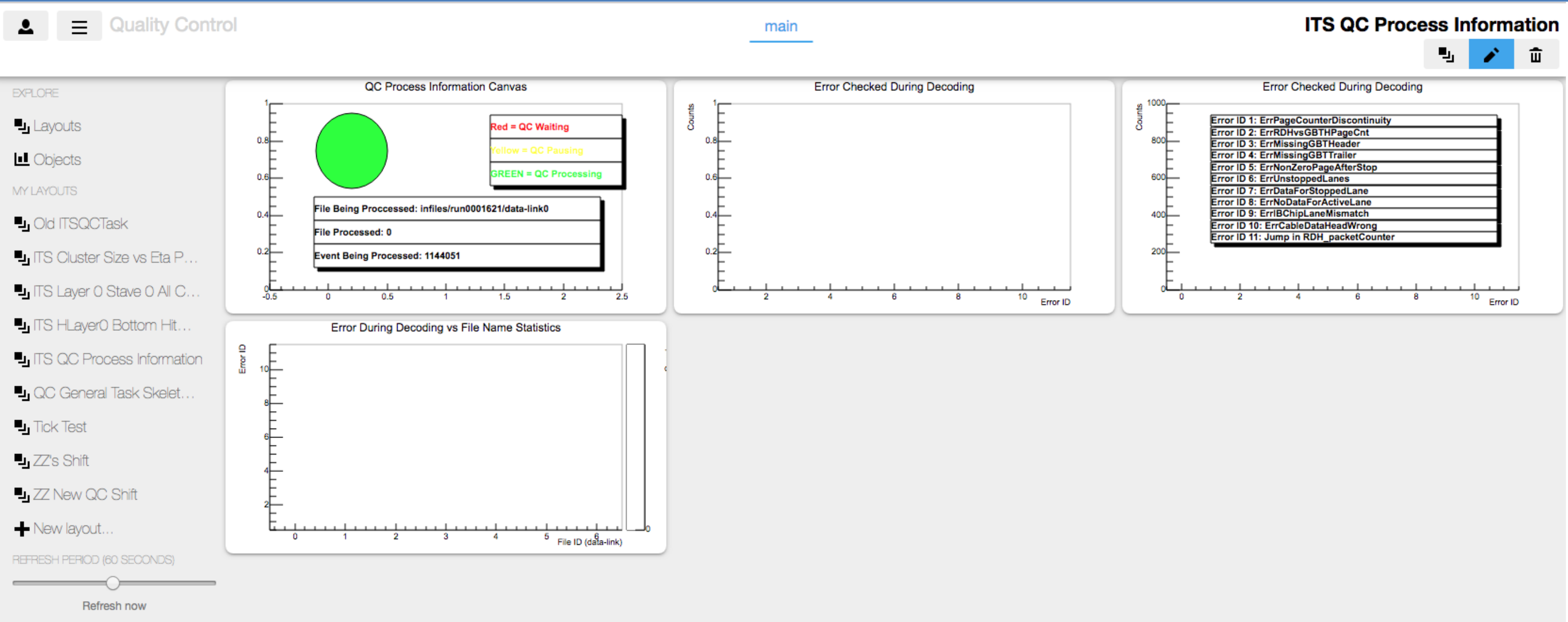


# Object Examples on the GUI




- Tree structure for ALICE ITS commissioning QC
- Many other ALICE QC tasks are also saved in the GUI

# General QC Information Canvas




- The shifters will perform a screenshot on this page and save it to the log book when the green light turns red
- **Will develop similar quality control software system for sPHENIX MVTX**



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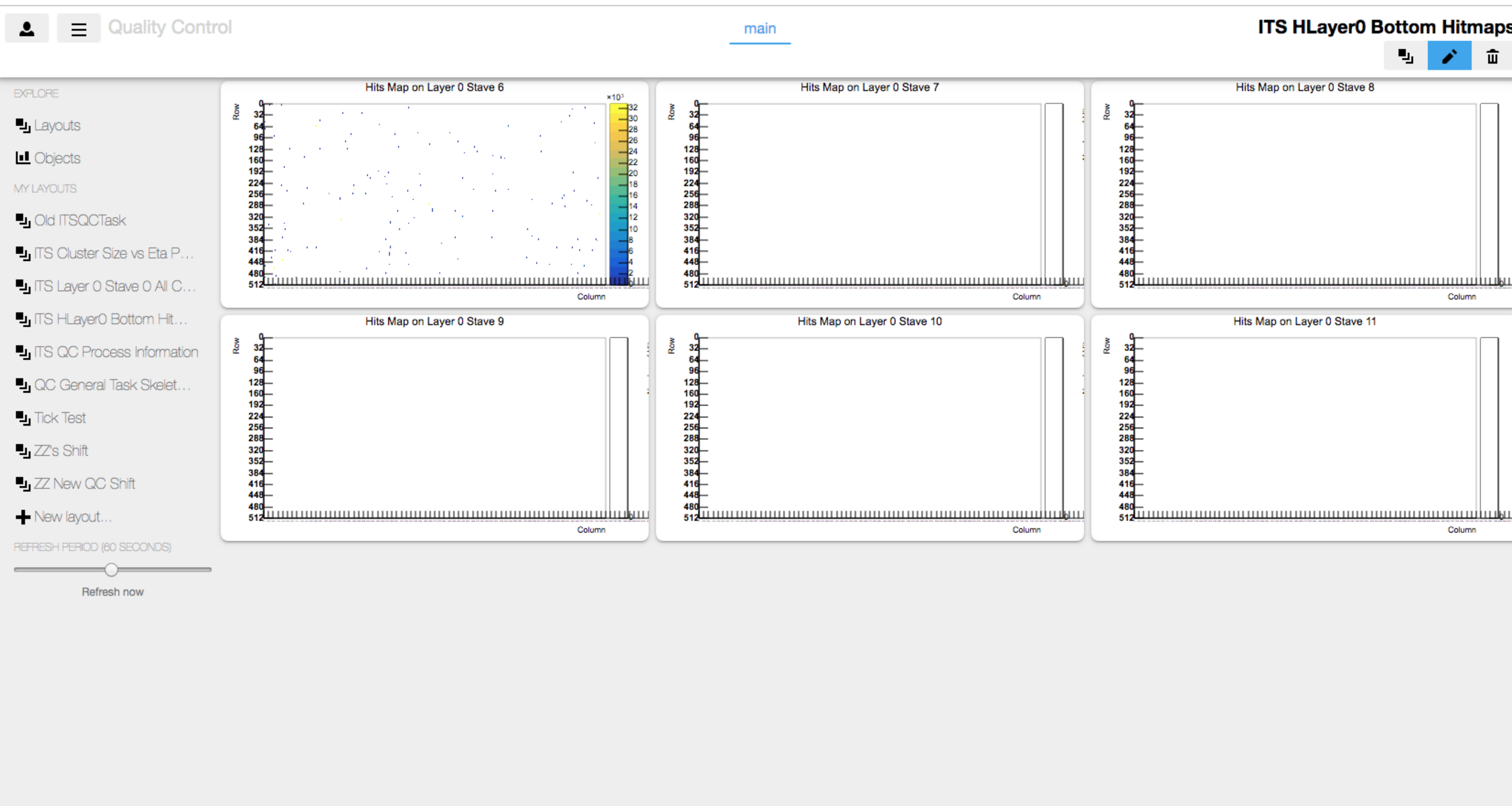
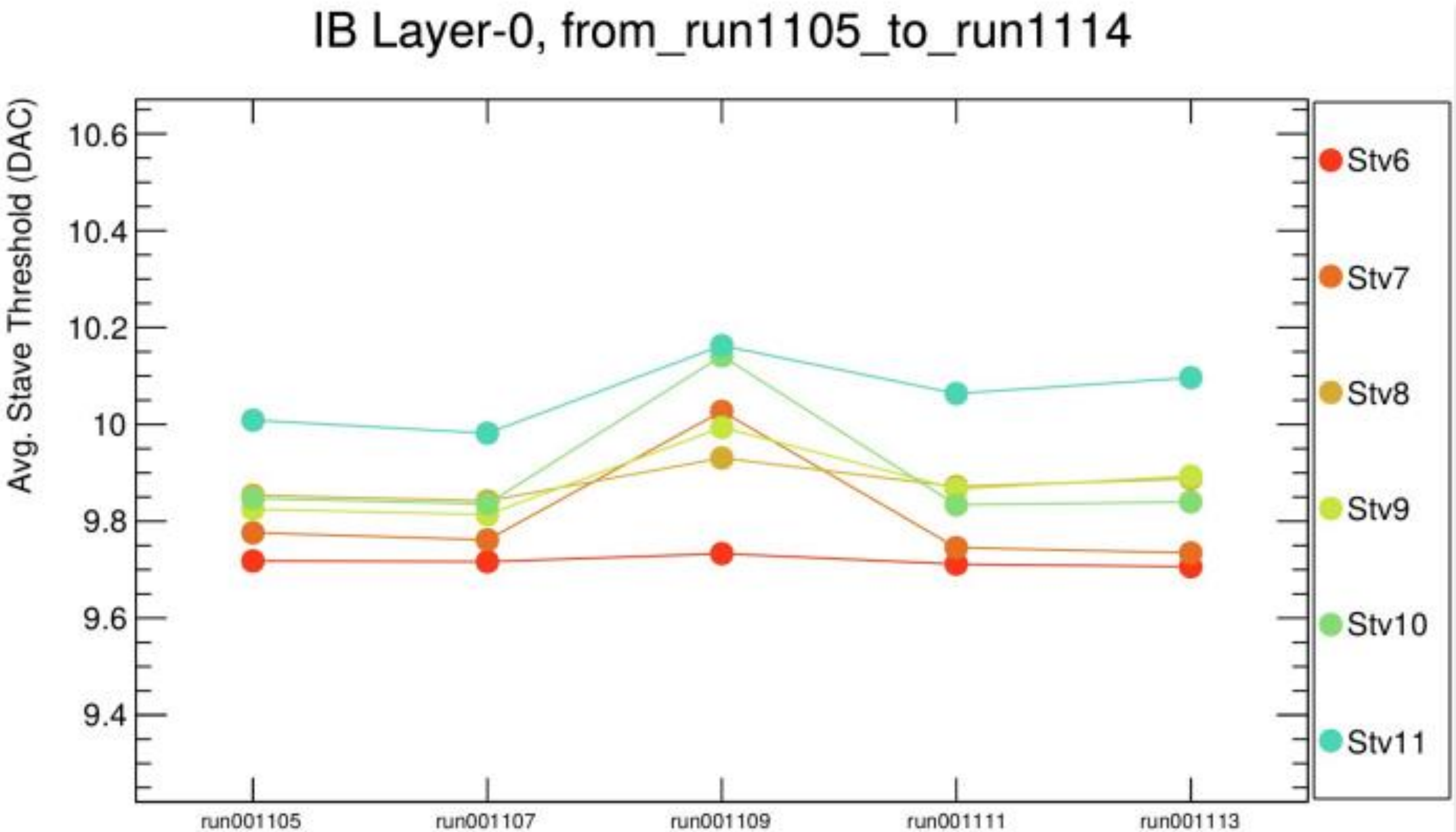
# 2D Hit Maps for ITS Layer 0




- The shifters will perform a screenshot on also this page and save it to the log book when the green light turns red

# QC Shift Results

- We also create a weekly QC shift to perform the analysis on the ITS performance on larger time scale based on the QC output retrieved from CCDB
- We can visualize the ITS performance over a week for different runs

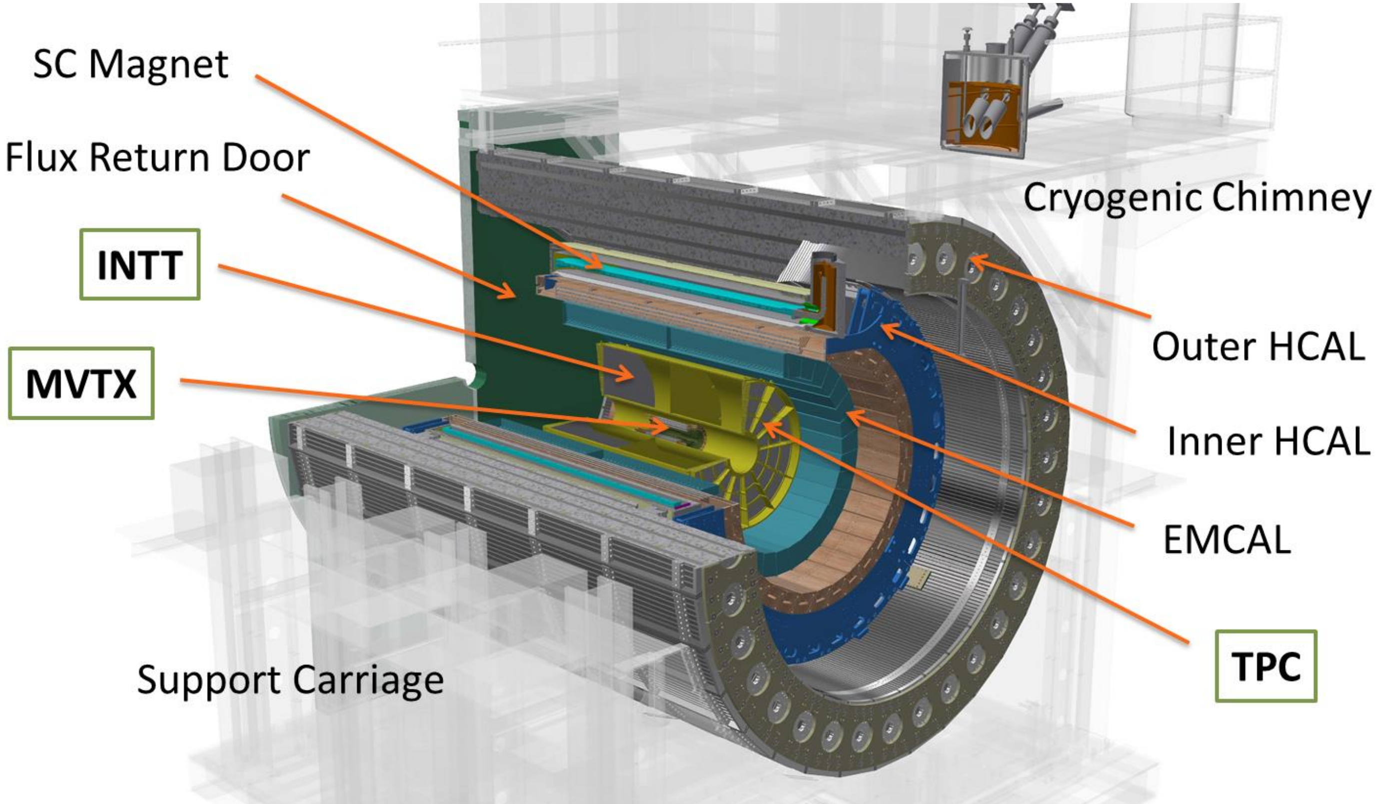


# QC for sPHENIX MVTX

- We have developed the QC system for ALICE ITS Commissioning. It has been stable and currently still in use for not only ITS but also other parts of the ALICE detector
- The general workflow of the QC can be ported from ITS to MVTX
- The systems codes and performance plots can be just directly copied from ITS. Many other functions will need to adjust and integrated to the Fun4All software framework
- We need to have some other parts of the components ready for the QC such as the decoder, data sampling, database, and GUI
- Currently, I start to get actively involved in the sPHENIX MVTX team and get familiar with the test beam online monitoring and offline analysis codes to get some first results

# sPHENIX EMCAL Characterization at Test Beam

# sPHENIX Detector



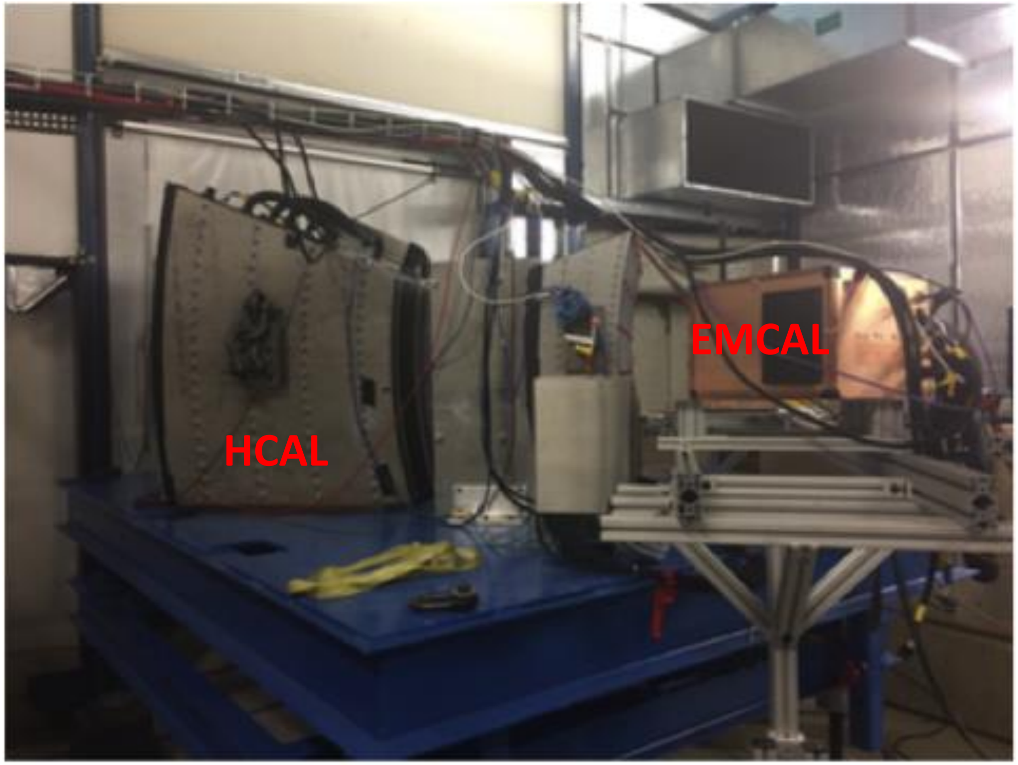

**The Super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) at RHIC**

- State-of-the-arts jet detector with full $2\pi$ and $|\eta| < 1.1$ coverage upgraded from PHENIX
- Dedicated triggers to collect of large heavy-ion minimum biased datasets
- Excellent vertexing and tracking capabilities with MVTX and TPC
- Excellent electron identification capability for heavy flavor studies
- No dedicated hadronic particle identification

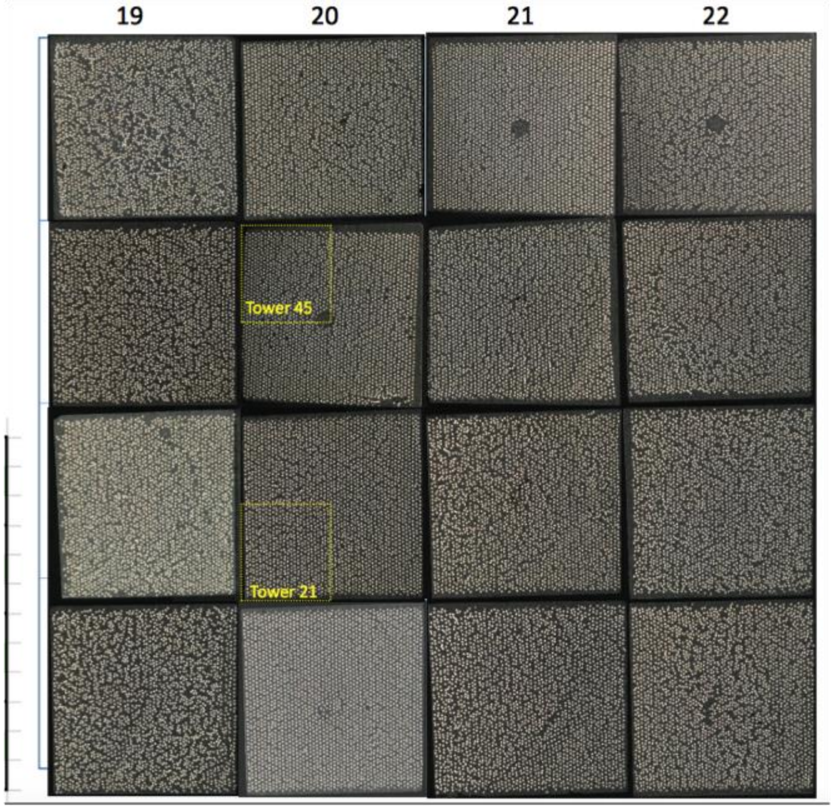
# sPHENIX Calorimeter Test Beam at Fermilab

- High rapidity ($\eta = 1$)
- 2D projective EMCAL towers
- Orientations: 0, 5°, and 10° tilted in the $\phi$ direction

**Test Beam Experiment Setup**




**EMCAL Block Configuration**



# sPHENIX EMCAL

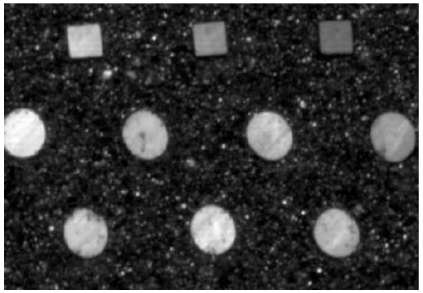
**sPHENIX EMCAL Technical Information:**

- W/scintillating fiber sampling EMCAL
- Acceptance coverage: 2π and |η| < 1.1
- Total radiation length: 18 X0
- 2D project SPACAL block design
- Tower size: 2.5 cm × 2.5 cm
- Energy resolution: $\frac{\Delta E}{E} = 2.8\% \oplus \frac{15.5\%}{\sqrt{E}}$

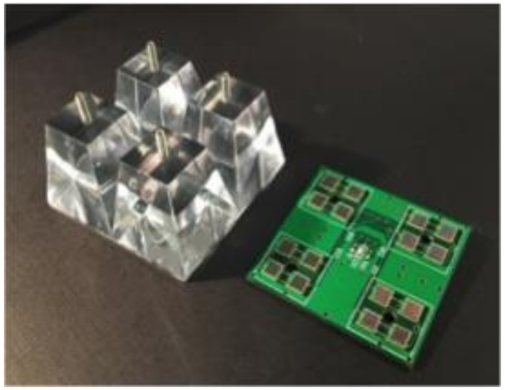
Constant Term

Statistical Term

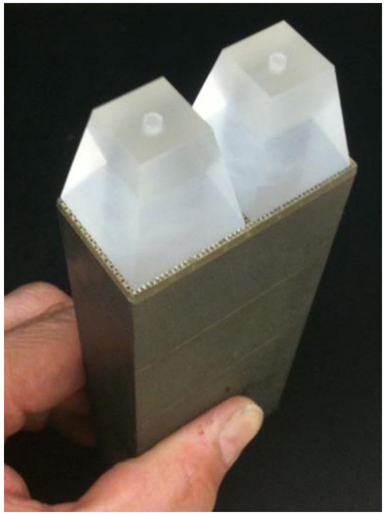
**W/Scintillating Fiber**



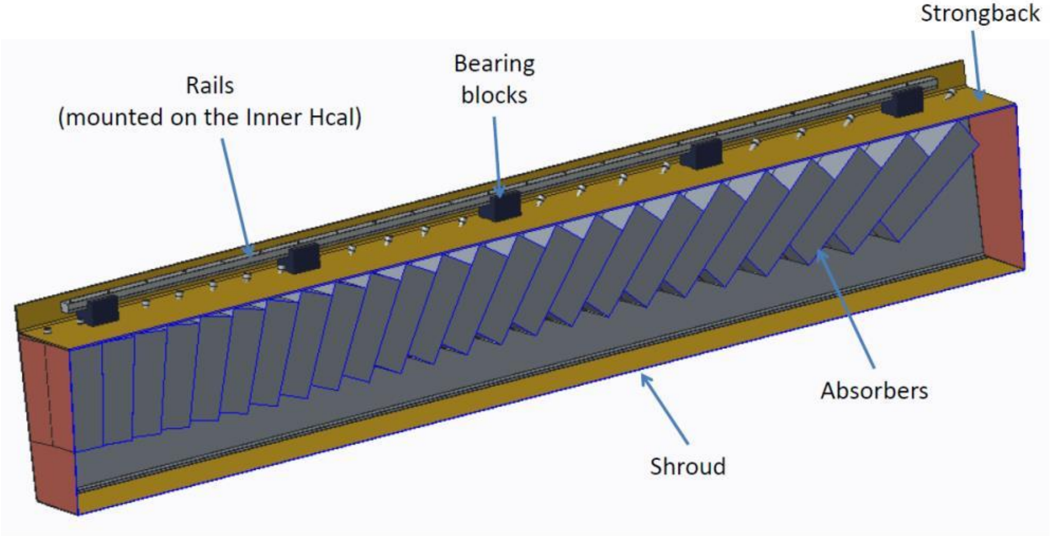
**Light Guides and SiPMs**



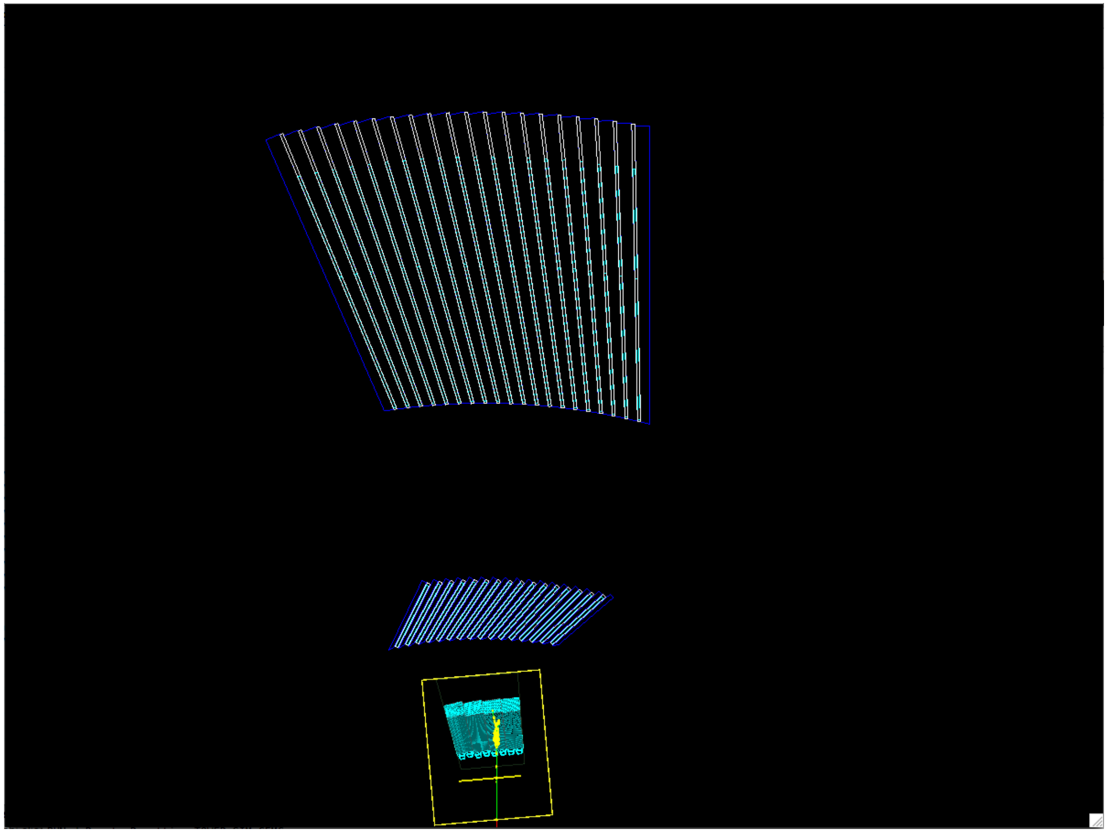
**EMCAL Tower**



**2D project SPACAL Blocks Design**

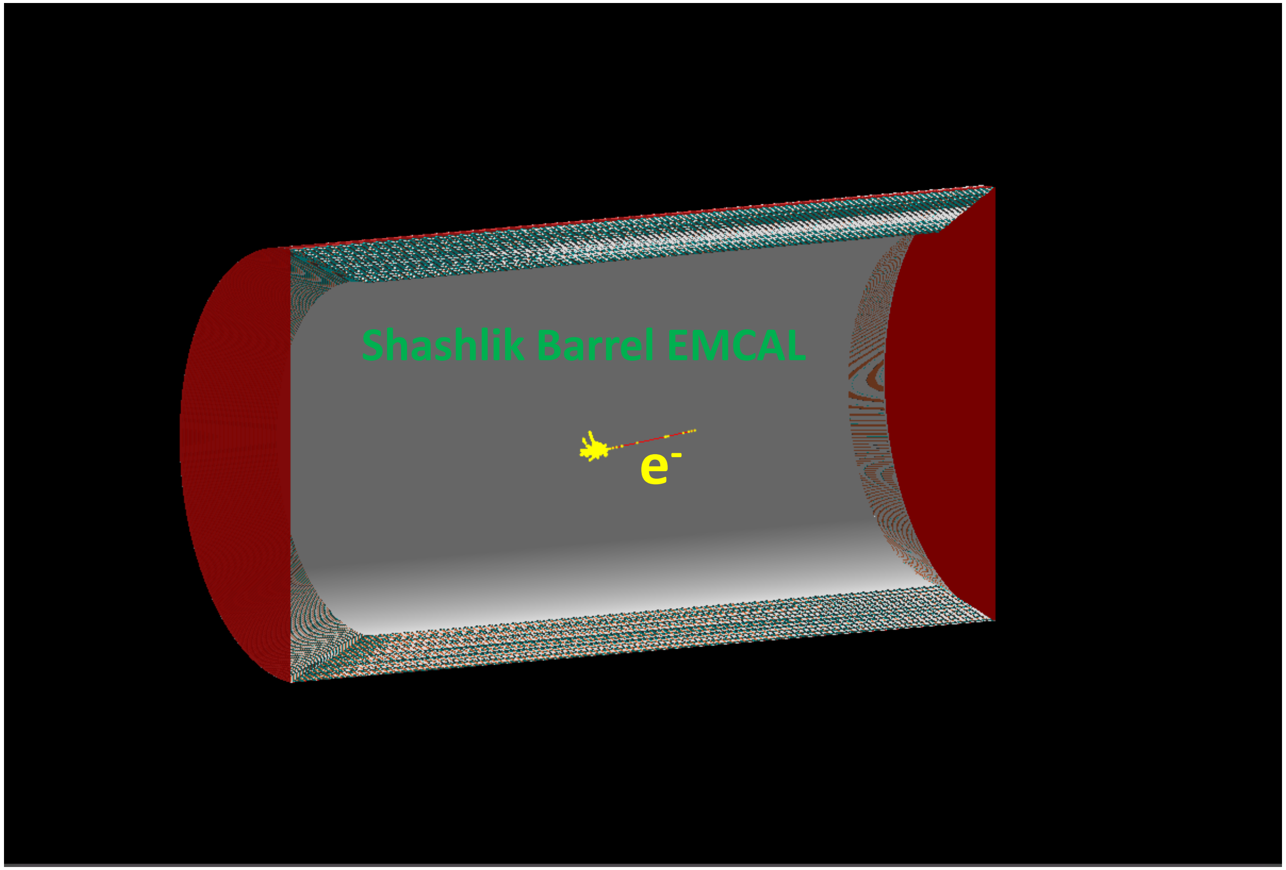


# GEANT 4 Simulations



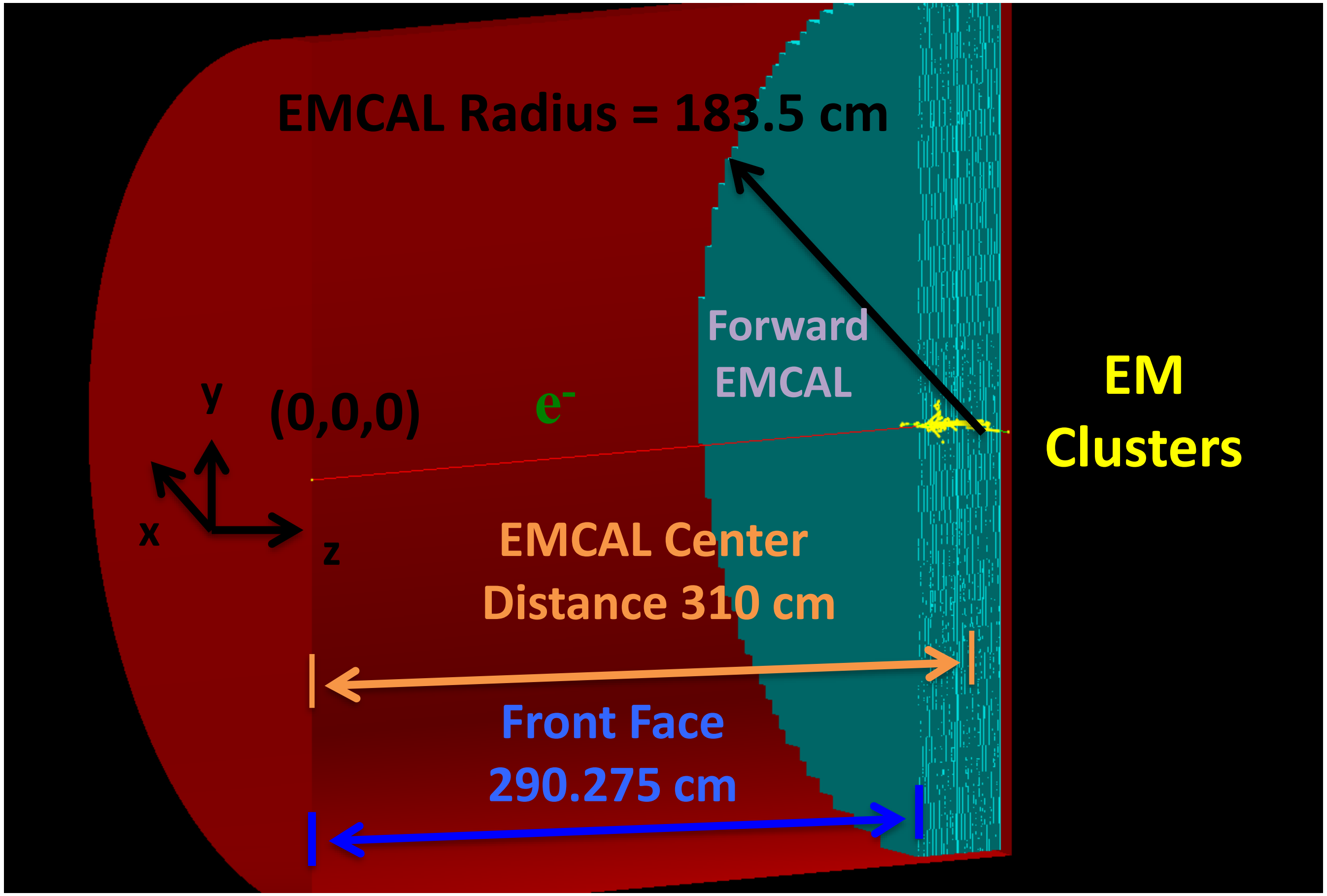
- GEANT 4: a software toolkit for the simulation of the passage of particles through matter
- Up-to-date EMCAL detector geometry and light collection efficiency maps as the inputs for the simulations to model the EMCAL prototype used in the test beam experiment
- 8 GeV electron beam with Gaussian beam profile scanning through the EMCAL

# EIC EMCAL Simulations Setup




- GEANT 4 simulation of W/Cu (80/20 alloy) shashlik barrel EMCAL (r ~ 1 m)
- Event above: 1 GeV electron at η = 0 producing an electromagnetic shower
- Vary scintillator thickness and number of plates to study the effects of sampling frequency and total radiation length on EMCAL energy resolution

# EIC Forward Endcap EMCAL Simulations Setup

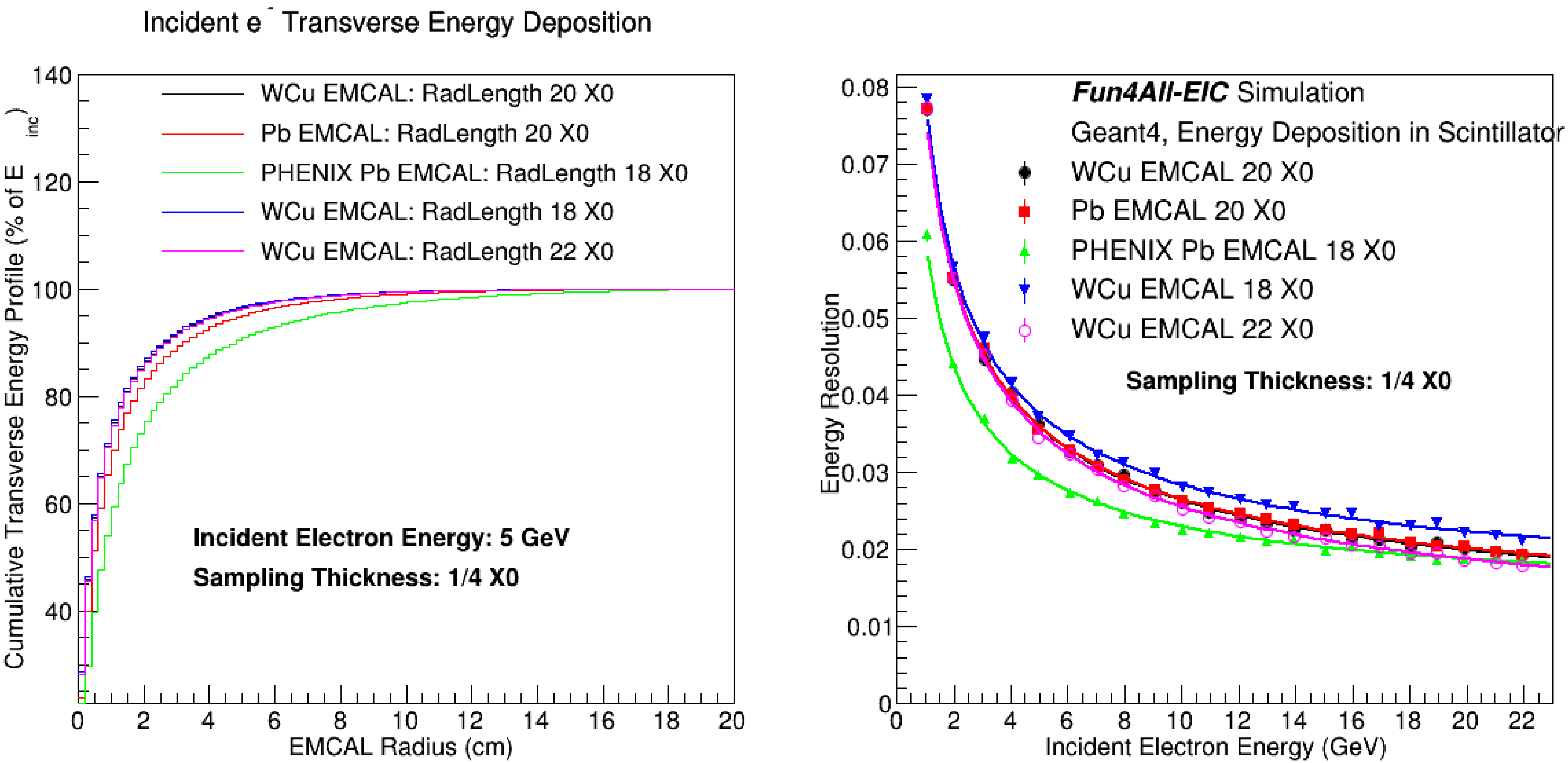



- A 1 GeV electron beam created at (0,0,0) entering the EMCAL in the +z direction
- Will use these setup to compare the performance of W/Cu and Pb EMCALs



Physics

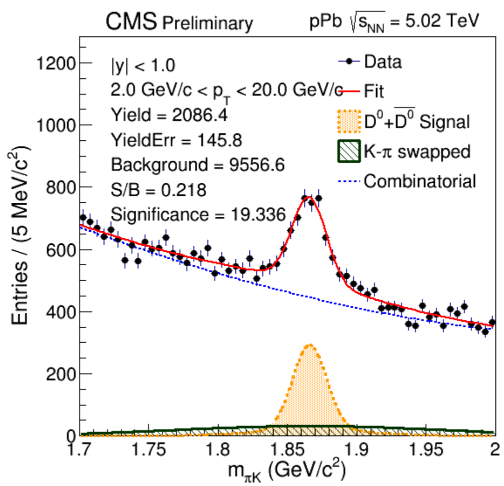
# Transverse Shower Profile and Energy Resolution



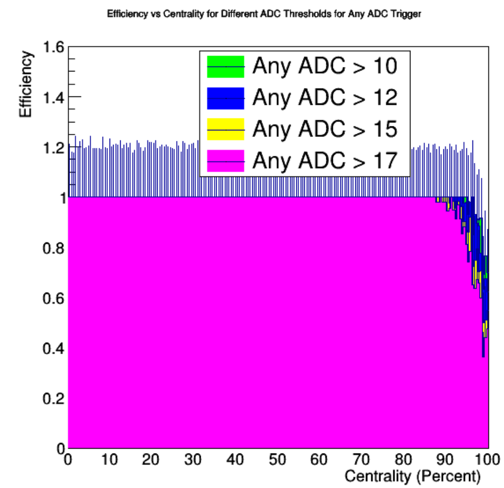

- Moliere Radius: WCu = 2.5 cm, Pb = 3.3 cm, sPHENIX = 4.5 cm, consistent with the left figure
- Sampling fraction: PHENIX > Pb > WCu
- The energy resolution: PHENIX configuration EMCAL is overall slightly better than the published results because we ignore actual detector electronics effects

# Other PhD Research Trainings and Service Work

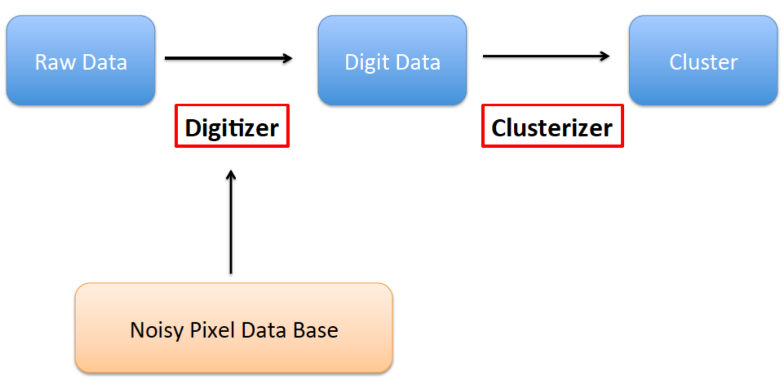
## $D^0$ $R_{pA}$ in pp and pPb at 5.02 TeV with CMS




## CMS 2018 PbPb MB Trigger Development




## Noisy Pixel Calibration for ALICE ITS Upgrade

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