B Meson relative production in LHC Run 3 PbPb Collisions

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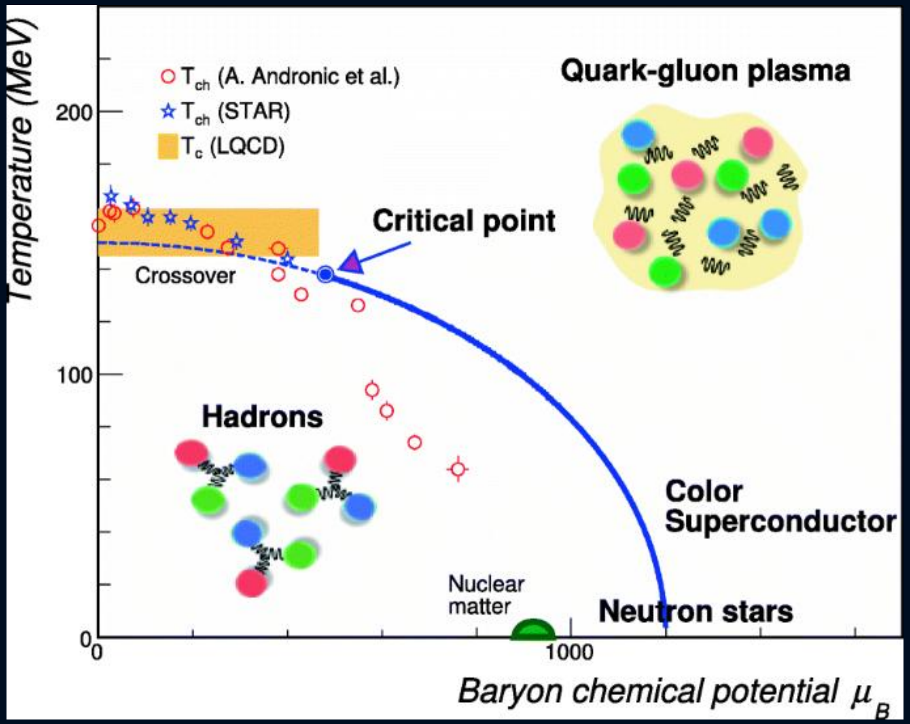
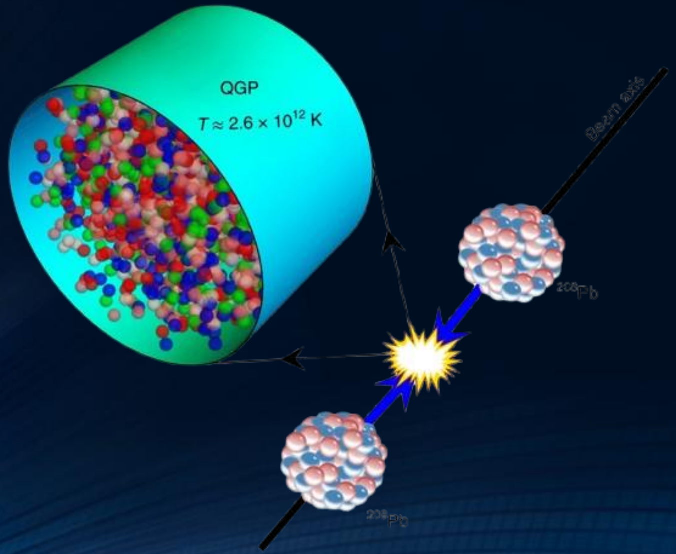
Quark-Gluon Plasma (QGP)

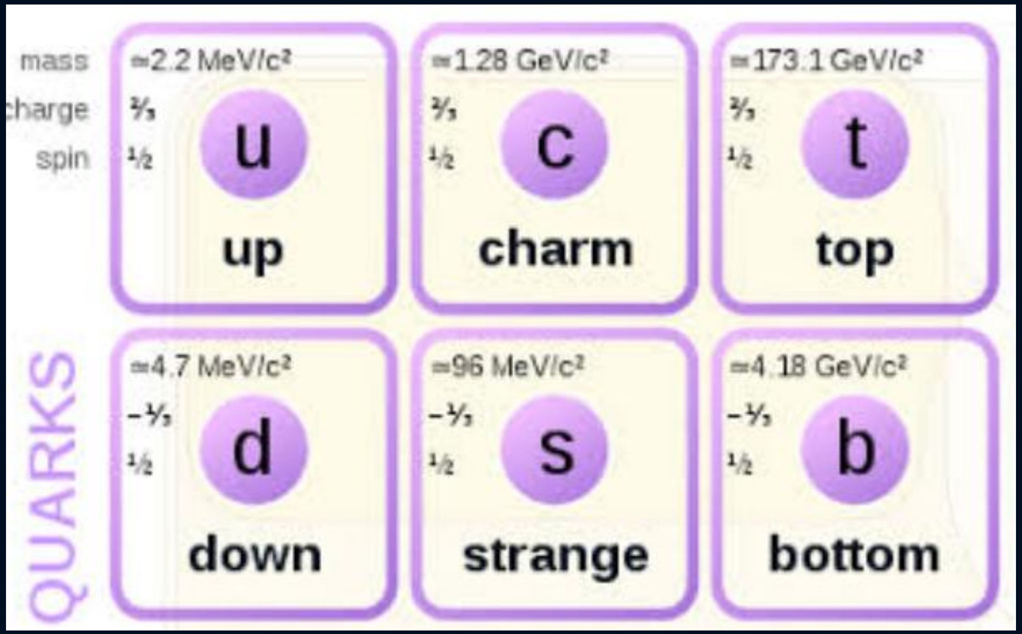
- Extreme thermodynamic state where quarks and gluons exist freely
- **Environment conditions**: High temperature and density
- It shows **perfect fluidity**, with **extreme low viscosity**
- Limitation: The life spent of a generated plasma is 10^-23 (time that takes light to cross a proton)
- QGP can be produced in heavy-ion collisions at the LHC.

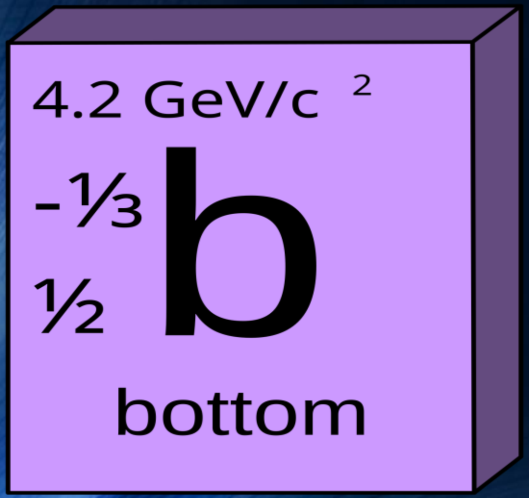




b quarks in Pb-Pb collisions

- **Early production:** produced in the early stages, before the QGP formation
- **Full medium exposure:** experience the full evolution of the QGP medium
- **"Dead cone effect":** Due to their large mass, b-quarks experience reduced medium-induced gluon radiation compared to lighter quarks or gluons

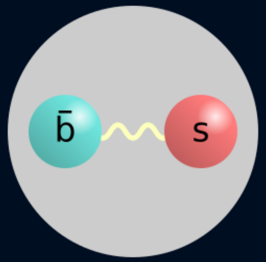




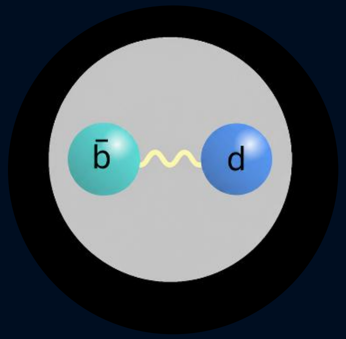
Probing medium properties with B mesons

- **Energy loss ("Jet Quenhing") :** As b-quarks pass through the QGP, they interact strongly and lose energy, causing B-meson suppression
- **Strangeness enhancement**: Measuring the ratio of strange B^0s mesons to non-strange B^+ mesons helps physicists test if b-quarks hadronize via quark-recombination inside a medium enriched with strange quarks
- **Perfect control reference:** B^o e B^+ mesons, since they contain light quarks up(u) and down(d), **do not** benefit from the strangeness enhancement of the medium.

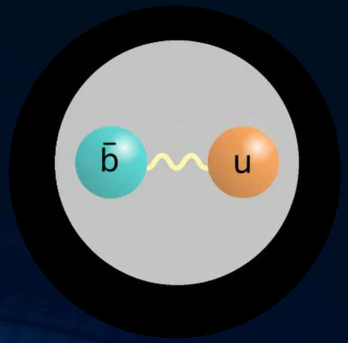
Decay Channels of interest:



$B^0s \rightarrow J/\psi\ \Phi \rightarrow \mu^+ \mu^-\ K^+ K^-$



$B^0 \rightarrow J/\psi\ K^* \rightarrow \mu^+ \mu^-\ K^+\ \pi^-$



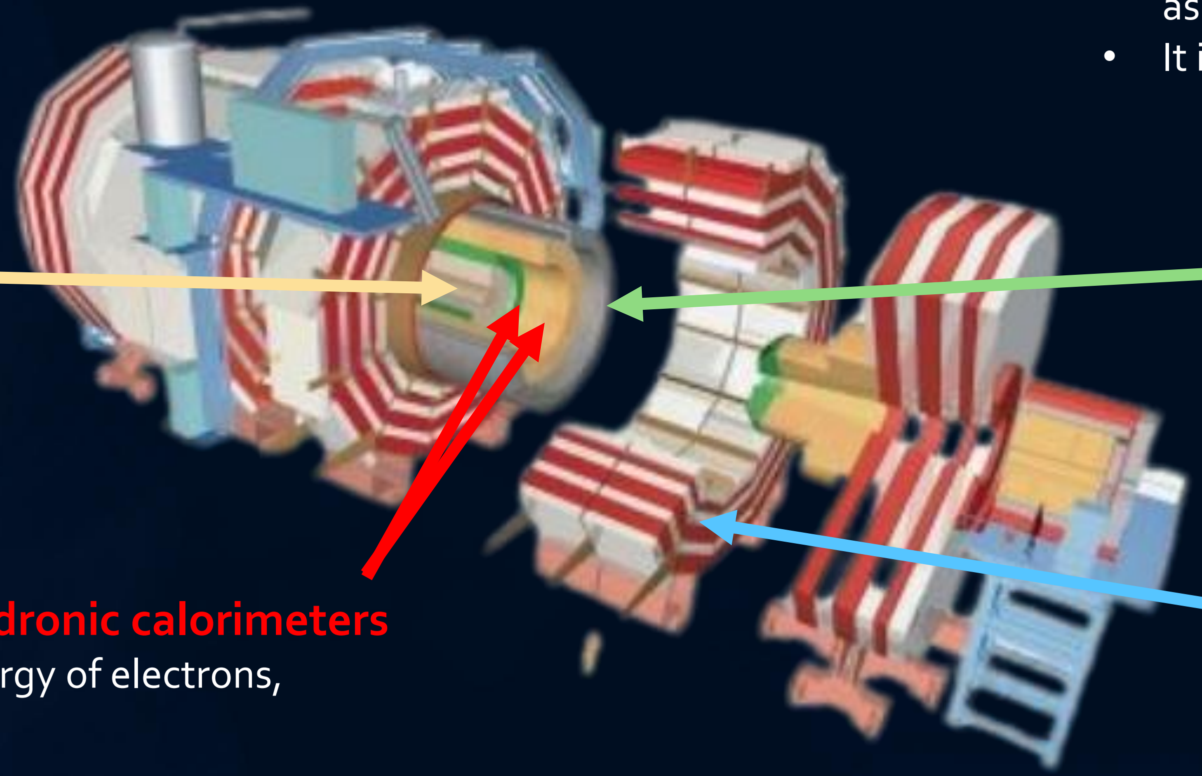
$B^+ \rightarrow J/\psi\ K^+ \rightarrow \mu^+ \mu^-\ K^+$

CMS (Compact Muon Solenoid)

- 15 meters high and 21 meters long and has the most powerful solenoid magnet ever made
- Weighs 14,000 tones and has around 75 million channels for detecting/identify assorted particles
- It is made of several layers

Silicon tracker
Registers the trajectories of charged particles

Solenoid magnet



Electromagnetic and Hadronic calorimeters
Collectively measure the energy of electrons, photons and hadrons

Muon detectors

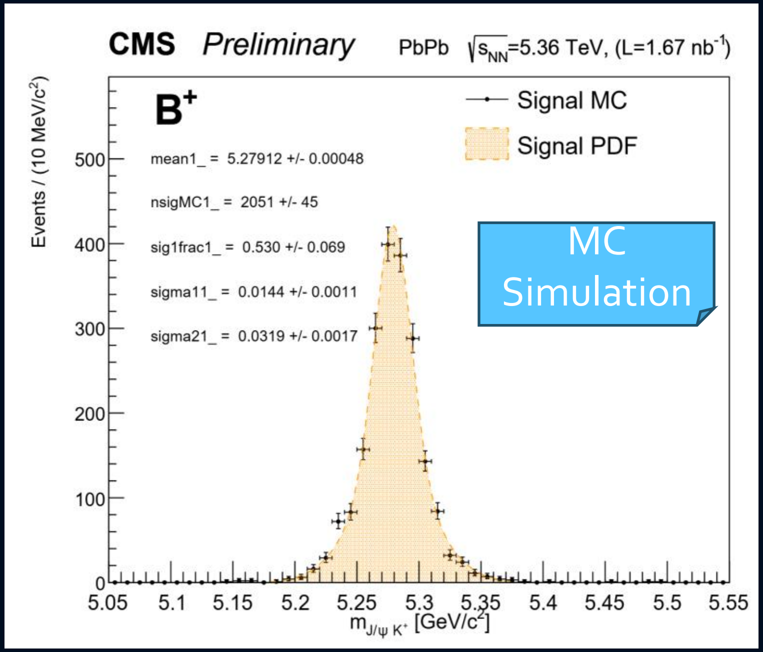
CMS **doesn't directly detect** the B mesons; it **reconstructs its decay products** and combines them into possible candidates through an algorithm combining the signals provided by the sub-detectors

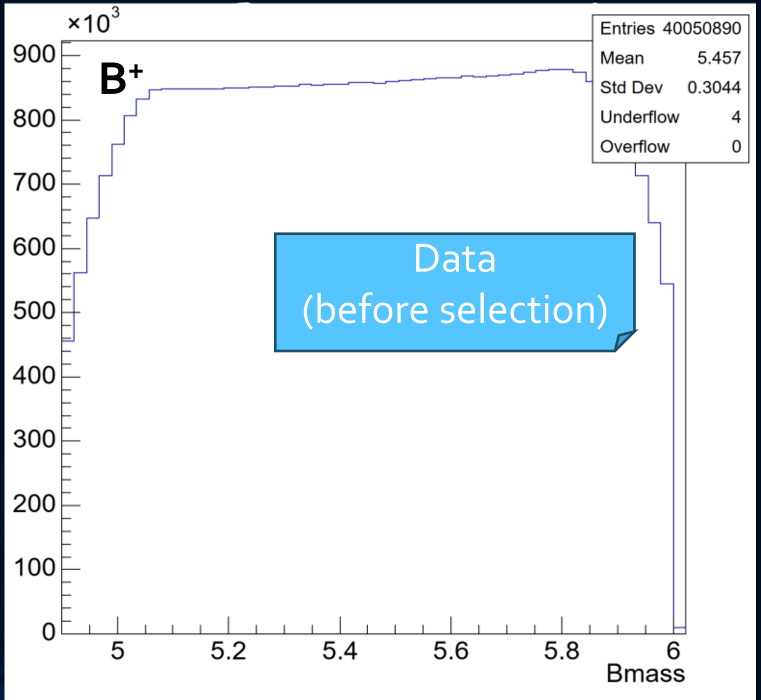
Data & MC Simulation

PbPb data collected by CMS in LHC Run 3:

- PbPb24 (L = 1.67 nb^{-1})
- 2 muon Trigger
- Detail about Pre-selection is in Back up.
- ML selection is done using discriminating variables.

Signal MC facilitates kinematic templates for detector Acceptance x selection Efficiency study (see slide 10)





B⁰ meson observation and signal extraction

- The B^0 candidate is reconstructed from the invariant mass $m(J/\psi K\pi)$.
- There are **two oppositely charged hadronic tracks**, and you have to decide which one is **the kaon** and which one is **the pion**.

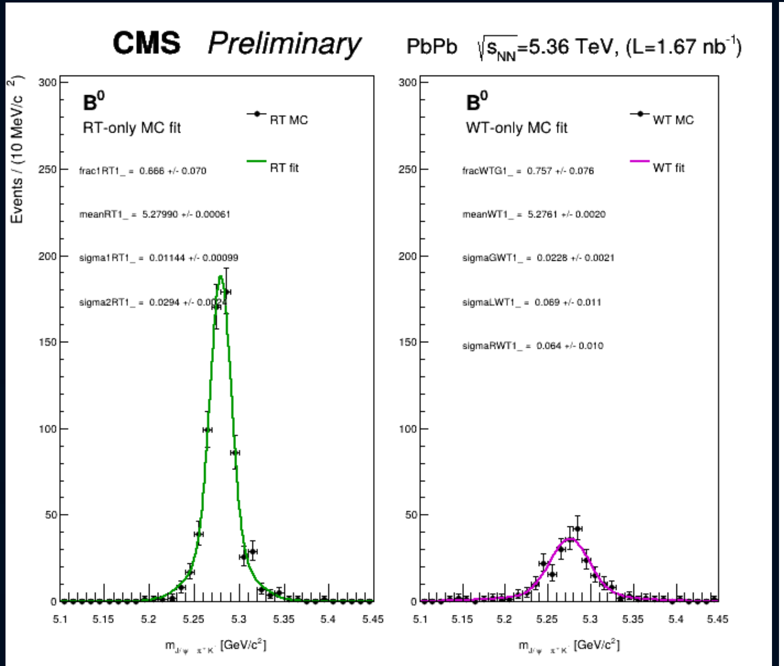
First B0 observation in PbPb

Right Tag: the K/π hypothesis assigned to the two tracks corresponds to the correct combination.
Model: Two Gaussians

Wrong Tag: The mass hypotheses are swapped, that is, the track that should be treated as K is treated as π and vice versa.
Model: A simple Gaussian + a bifurcated Gaussian

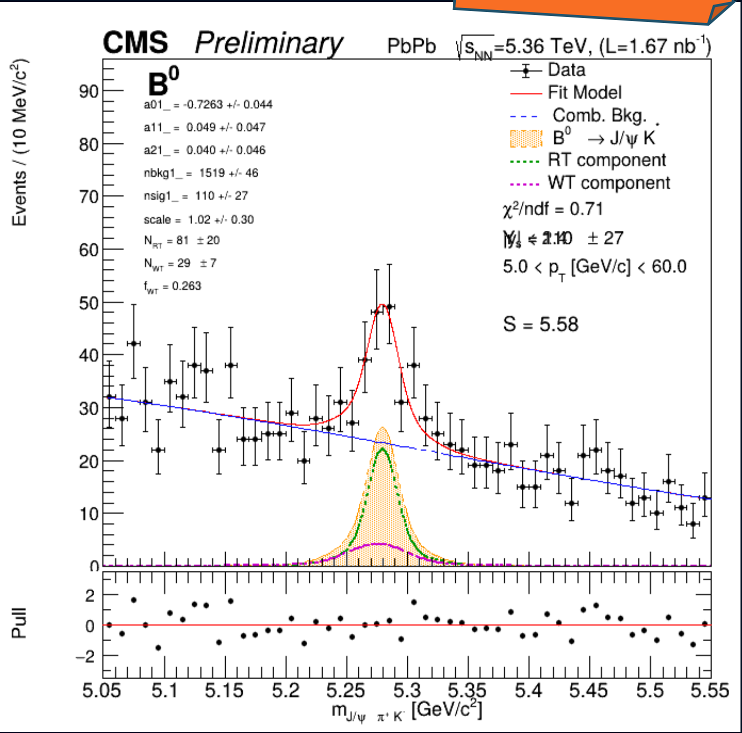
$$P_{B^0}(m) = (1 - f_{WT})P_{RT}(m) + f_{WT}(m)P_{WT}(m)$$
$$N_{B^0}(m) = N_{RT} + N_{WT}$$

Fitted through the maximum likelihood method (RooFit)



MC Simulation

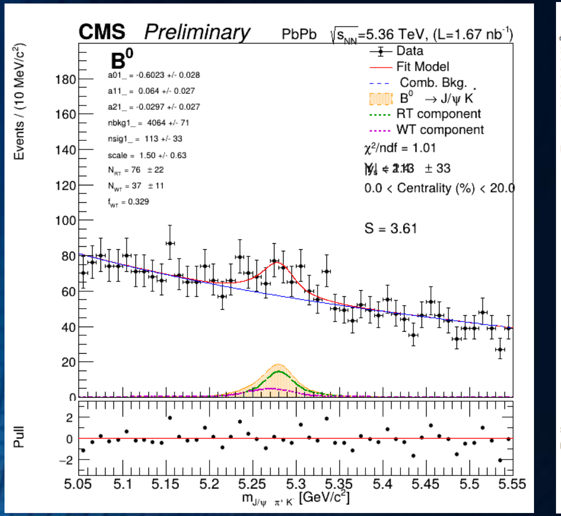
The signal shapes are determined separately from MC.

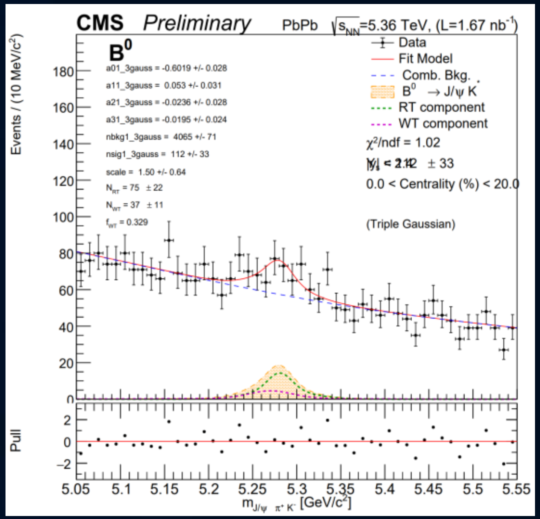


These shapes are then combined in the data fit using the Wrong-Tag fraction (f_{WT})

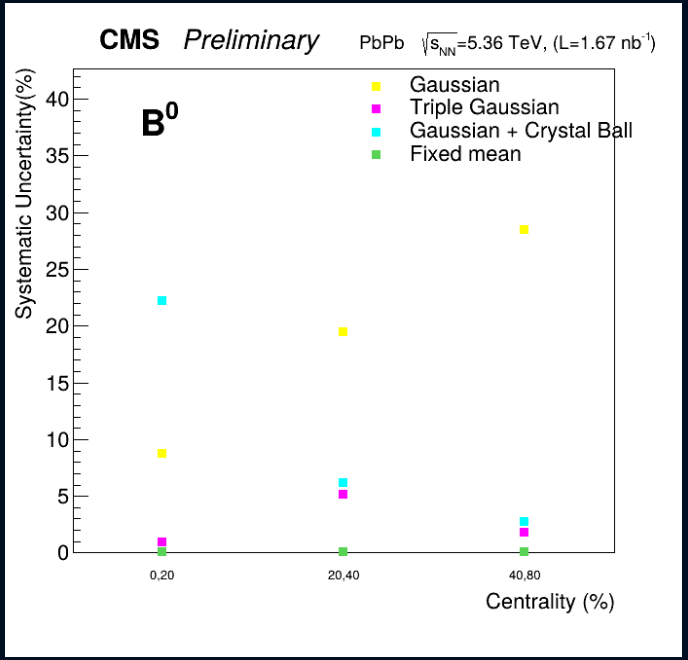
Systematic Uncertainties

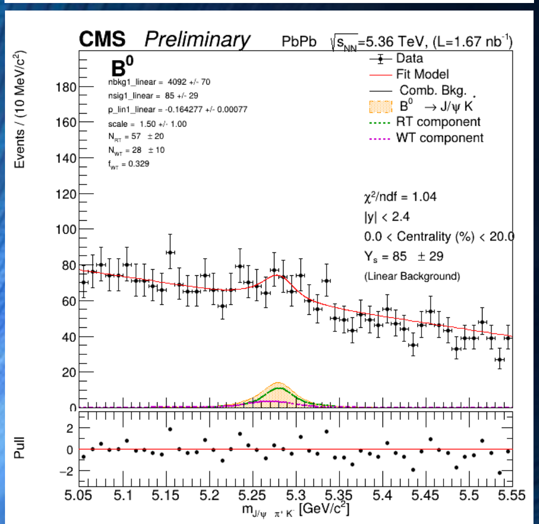
Centrality quantifies the degree of overlap between the two colliding nuclei in PbPb collisions.





The resulting yield variations are converted into systematic uncertainties.





The stability of the extracted signal yield is tested by varying the signal and background models.

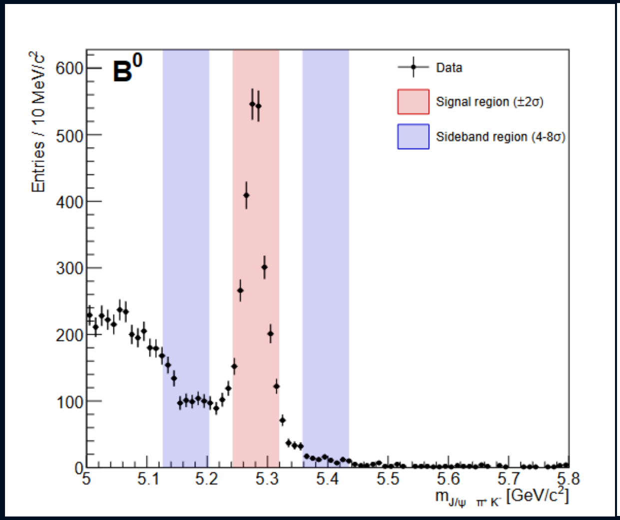
- **Nominal fit → Two Gaussians(RT), a Gaussian + a bifurcated Gaussian(WT)** (signal)
  → 3rd order Chebyshev polynomial (background)
- Alternative signal model → **Gaussian + Crystal Ball**
- Alternative background model → **Linear background**

MC Validation: Data VS Simulation

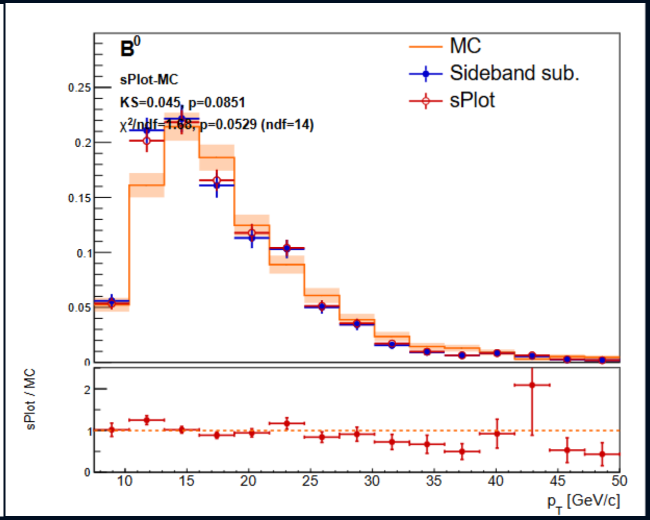
- Check whether the simulation reproduces the kinematic and topological distributions observed in data, supporting its use for efficiency corrections and signal modeling.
- Before comparing data with simulation, we first need to isolate the signal contribution in data. For this, two MC validation methods are used:

1. **sPlot**: Signal and background are statistically separated using candidate weights derived from the invariant-mass fit.
2. **Sideband subtraction**: The background contribution is estimated from invariant-mass sidebands (4-8 σ) and subtracted from the signal region (μ ± 2σeff)

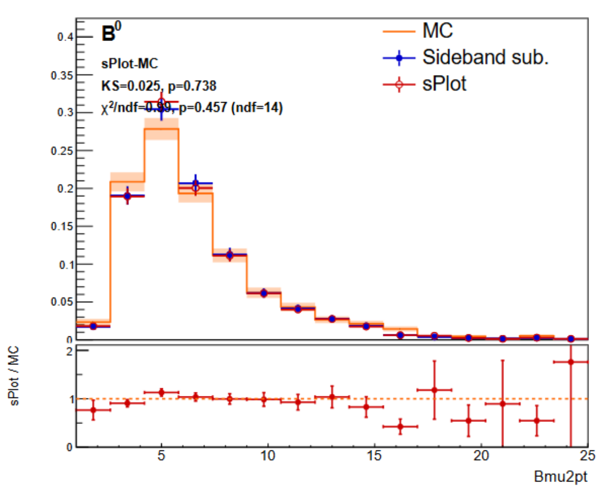
- We conclude that MC can be used for efficiency study.



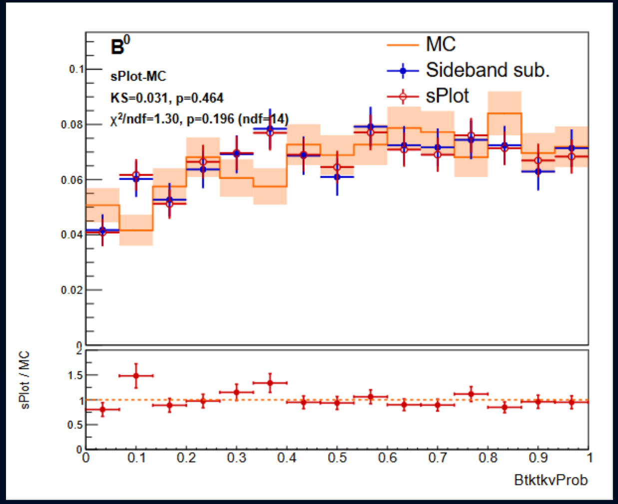
mass window



Bpt



Bmu2pt (muon transverse momentum)



BtktkvProb (vertex variable)

Acceptance X Efficiency

- Acceptance (A) → Fraction of generated B mesons that fall within the detector and analysis kinematic region

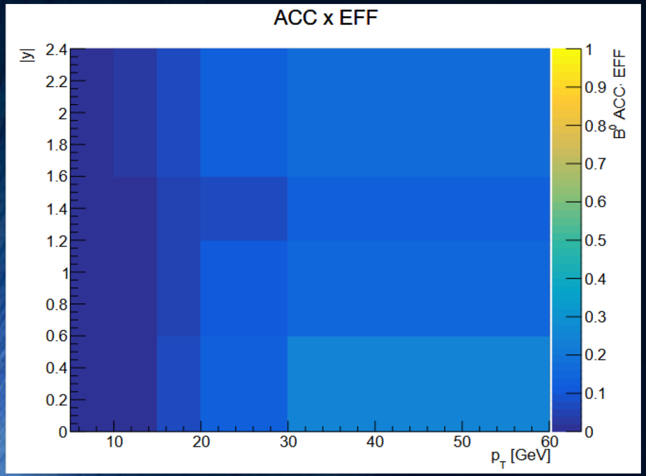
$$A_i = \frac{N_i^{\text{gen, acc}}}{N_i^{\text{gen}}}$$

- Efficiency (ε) → Fraction of generated signal candidates that are reconstructed and selected

$$\varepsilon_i = \frac{N_i^{\text{reco, sel}}}{N_i^{\text{gen, acc}}}$$

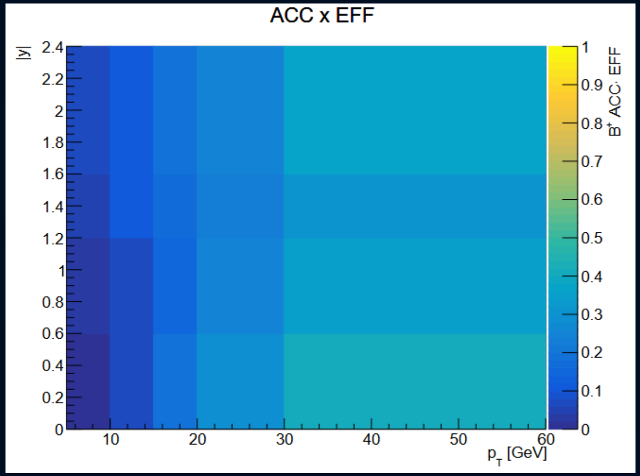
- The $A \times \varepsilon$ correction is determined from simulated events and converts the reconstructed yield into the corresponding produced yield

$$N_{\text{corr}} = \frac{N_{\text{raw}}}{A\,\varepsilon}$$



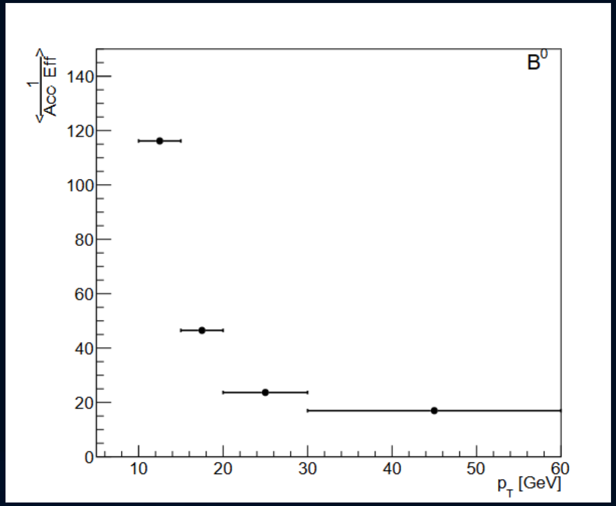
Raw $A \times \varepsilon$ map

Directly obtained from simulated events in $(p_T, |y|)$ bins.



Self-weighted $A \times \varepsilon$ map

reduces the dependence of the efficiency estimate on the generated kinematic spectrum.



Self weighted correction factor

The resulting p_T-dependent correction is applied to the measured B^0 yield.

Relative B-meson production ratios in PbPb

- $B^0/B+$ shows a relatively stable central value between the two extraction methods
- A larger variation is observed for B_s/B^+ between the 1D and sPlot approaches
- The total uncertainty is dominated by the **yield** uncertainty, while the branching-fraction (BF) contribution is small.

Production Ratio	Central Value	Yield Unc.	BF Unc.	Effic. Unc.	Total Unc.
B0/B+ B^0/B^+	2.34	± 0.71	± 0.10	±0.47	± 0.86
Bs/B+ B_s/B^+	0.57	± 0.13	± 0.025	±0.29	± 0.32

$$R_{i/+} = \frac{N_i}{N_+}\frac{A_+}{A_i}\frac{\varepsilon_+}{\varepsilon_i}\frac{\mathcal{B}_+}{\mathcal{B}_i}$$

N: signal yield
A: acceptance
ε: reconstruction & selection efficiency
$\boldsymbol{\mathcal{B}}$: branching fraction
$\boldsymbol{i} = B^0, B_s$; reference channel: B+

1D: signal-region yield correction in p_T bins
sPlot: candidate-by-candidate signal weighting from the mass fit
selfW: p_T-reweighted MC used to derive A×ε

Summary

- Studied B meson signals in LHC Run3 PbPb collision CMS data
- First observation of the B^0 meson in nuclear collisions
- Preliminary B meson production results

Future goals

- Measure Fragmentation Fractions.
- Measure Cross Sections for studied B mesons.

Back up

Muon & Track Pre-selection pp

Muons

- **Soft muons:**
  - **normalized χ^2** $<= 1.8$
  - **Hits:**
    - tracker layers ≥ 6
    - pixel Layers ≥ 1
  - **Displacement from vertex:**
    - $dz < 35$
    - $dxy < 4$
- **Acceptance region:**
  - $\boldsymbol{pT} \geq 3.5$ GeV/c & $|\boldsymbol{\eta}| < 1.2$
  - $\boldsymbol{pT} \geq (5.47 - 1.89 \times |\boldsymbol{\eta}|)$GeV/c & $1.2 \leq |\boldsymbol{\eta}| < 2.1$
  - $\boldsymbol{pT} \geq 1.5$ GeV/c & $2.1 \leq |\boldsymbol{\eta}| < 2.4$
- **HLT matching:**
  - **Path:** *"HLT_PPRefL1DoubleMu0_v6"*
  - **Filter:** *"hltL1fL1sDoubleMu0L1Filtered0PPRef"*

Tracks

- **Quality:**
  - High purity tracks
  - $\sigma_{pT}/pT < 0.1$
  - N_{hits} (pixel + tracker hits) ≥ 11
  - $\frac{\chi^2/ndf}{N_{hits}} < 0.18$
- **Acceptance:**
  - $pT > 0.5$
  - $|\eta| < 2.4$

Di-muon system

- Opposite muon charges
- Common vertex probability **> 1%**
- System's mass within $\mathbf{0.15}$ **GeV** from $\boldsymbol{J/\Psi}$ **mass**

B Candidate

- χ^2_{cl}> 0.005
- Bnorm_svpvDistance>2

Di-Track system

- K^{*0}:
  - $m_{\pi K} \sim K^{*0}$ Tagged
  - $|m_{KK} - m_{\Phi}|$<15 MeV
- Φ:
  - $|m_{KK} - m_{\Phi}|$<15 MeV

Candidate Selection and Machine Learning Strategy

1. **Pre-selection** removes clearly incompatible candidates and reduces the sample before the ML classifier (before XGBoost)

Muons				
Trigger matching	Muon ID	Muon acceptance	J/ψ mass window	J/ψ vertex probability
-	Hybrid SoftMu ID	Yes	±150 MeV	> 0.01

Hadronic track			
Track transverse momentum	Relative pT uncertainty	Number of pixel + strip layers	High-purity track flag
pTtrk >0.9 GeV	σ(pT)/pT <0.1	> 10	Required

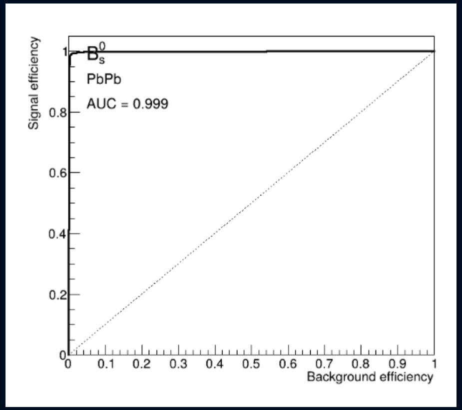
Intermidiate state
$|m_{KK} - m_{\phi}| < 0.015$ GeV
$|m_{K\pi} - m_{\phi}| < 0.150$ GeV
$P(X^2_B) \geq 0.005$

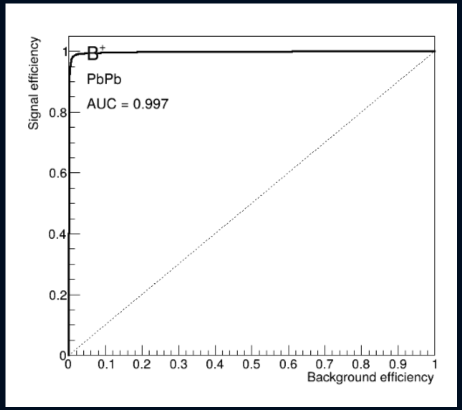
2. **Baseline selection** is more restricted to define the physical region where the analysis will be performed

Channels	Baseline Cuts
B+, Bs, Bo	pT>7.5 GeV, |y(B)|<2.4

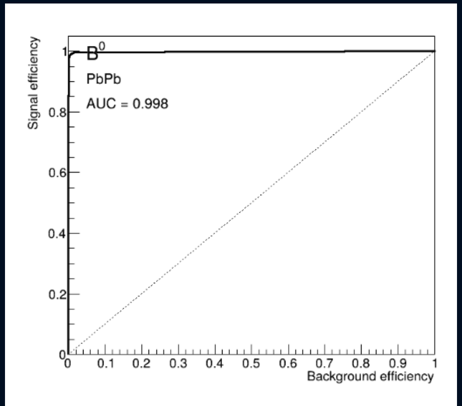
3. **XGBoost** input variables : the purpose is to separate signal-like from background-like candidates using kinematic, vertex and decay-topology variables (Ex: vertex displacement, pointing angle, vertex probability, track p_T, muon p_T, angular variables.)

Signal	Simulated B-meson candidates (MC)
Background	Candidates from data mass sidebands
Output	Prediction score between 0 and 1





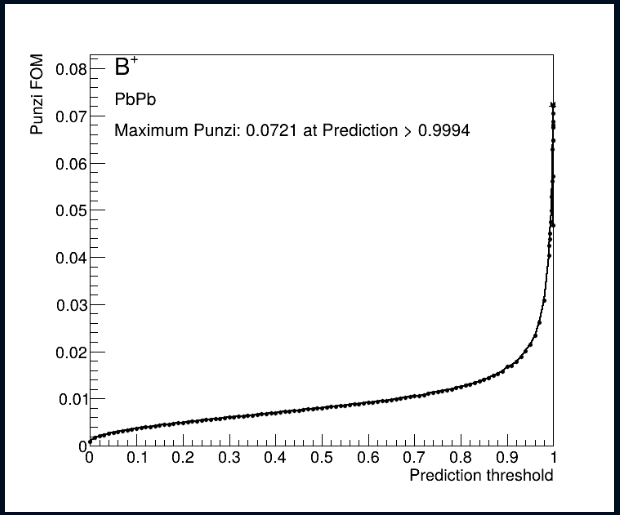
4. **ROC Curves**: evaluates if the classifier is truly able to separate the signal from the background

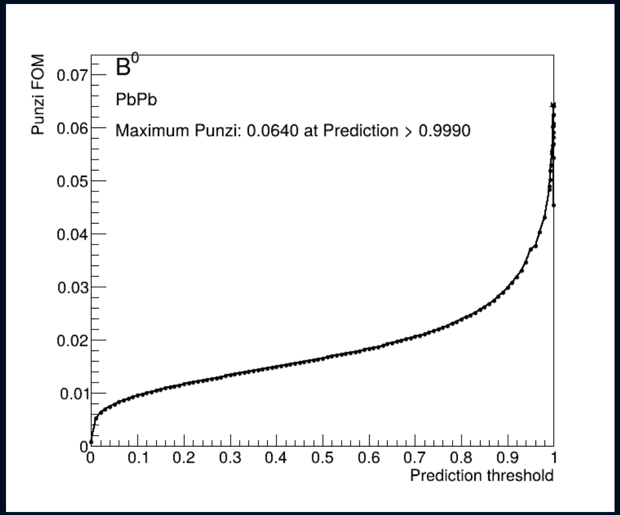


Curve close to the diagonal → weak separation
Curve well above the diagonal → good separation
AUC close to 1 → very good classifier
AUC close to 0.5 → performance similar to random guessing

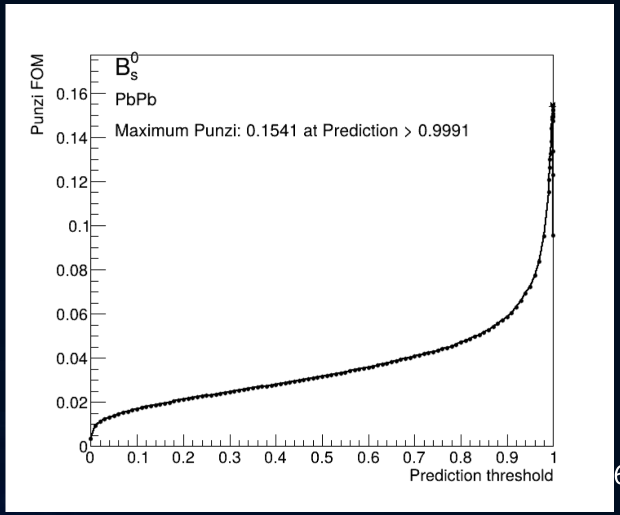
Selection Optimisation – Punzi Figure of Merit (FOM)

- The FOM quantifies the quality of a selection; a higher value corresponds to a better signal-efficiency/background trade-off.
- signal efficiency (ϵ_S)is evaluated from MC
- The background is obtained from the
- fit to data in the signal region
- a sets the **target significance level**, in units of Gaussian standard deviations.





$$\text{Punzi FOM} = \frac{\epsilon_S}{a/2 + \sqrt{B}}, \qquad a = 3$$



Variables for B mesons selection

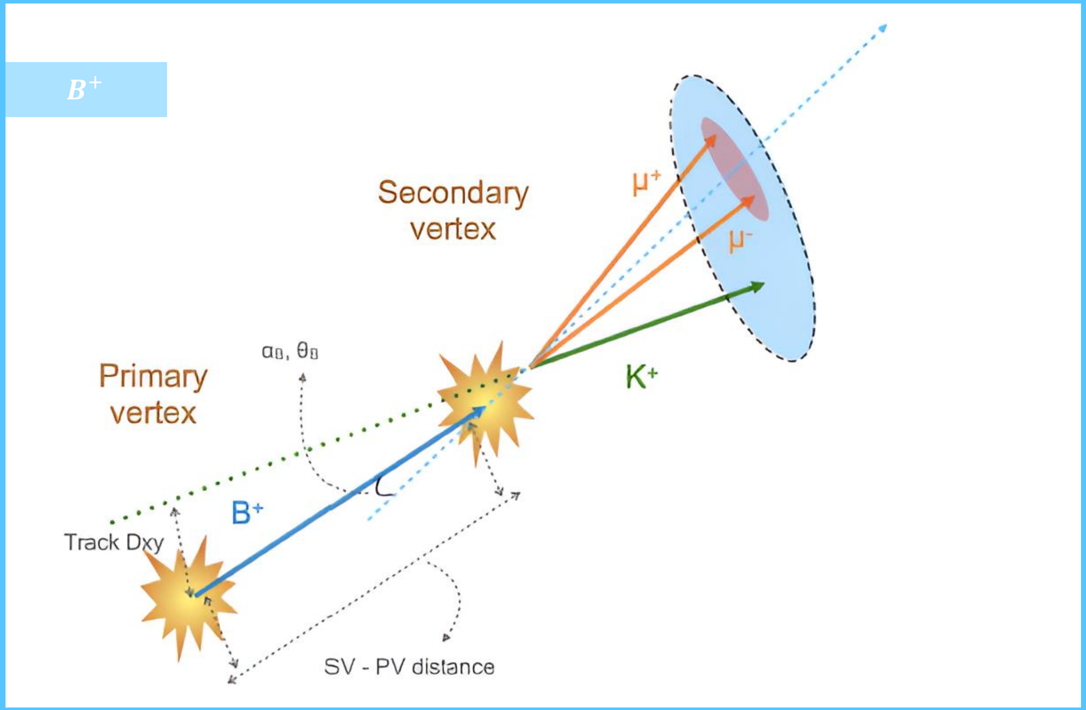
Normalized Flight length: 3D distance between the beam spot and the vertex where B decays, normalized by its uncertainty

Normalized Flight length in the transverse plane: 2D distance between the beam spot and the vertex where B decays, normalized by its uncertainty

Pointing angle(alpha): pointing angle between the flight direction and the reconstructed B meson momentum (3D)

θ(theta): pointing angle between the flight direction and the reconstructed B meson momentum (in the xy traversal plane, 2D)

dR: Angle between J/ψ and Hadron Track (for B_s^0 and B^0 there are two hadron tracks and for B^+ there is only one)



Method	Production Ratio	Central Value	Yield Uncertainty	BF Uncertainty	Total Uncertainty
1D + selfW	B0/B+B^0/B^+	2.3412	± 0.7058	± 0.1020	± 0.7131
1D + selfW	Bs/B+B_s/B^+	0.5736	± 0.1254	± 0.0254	± 0.1279
sPlot + selfW	B0/B+B^0/B^+	1.8689	± 0.7136	± 0.0814	± 0.7183
sPlot + selfW	Bs/B+B_s/B^+	0.2799	± 0.1452	± 0.0124	± 0.1457