# Investigation of Beauty Hadronization Universality from Vacuum to QGP

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Advancing the Understanding of Non-Perturbative QCD Using Energy Flow
Stony Brook University, CFNS

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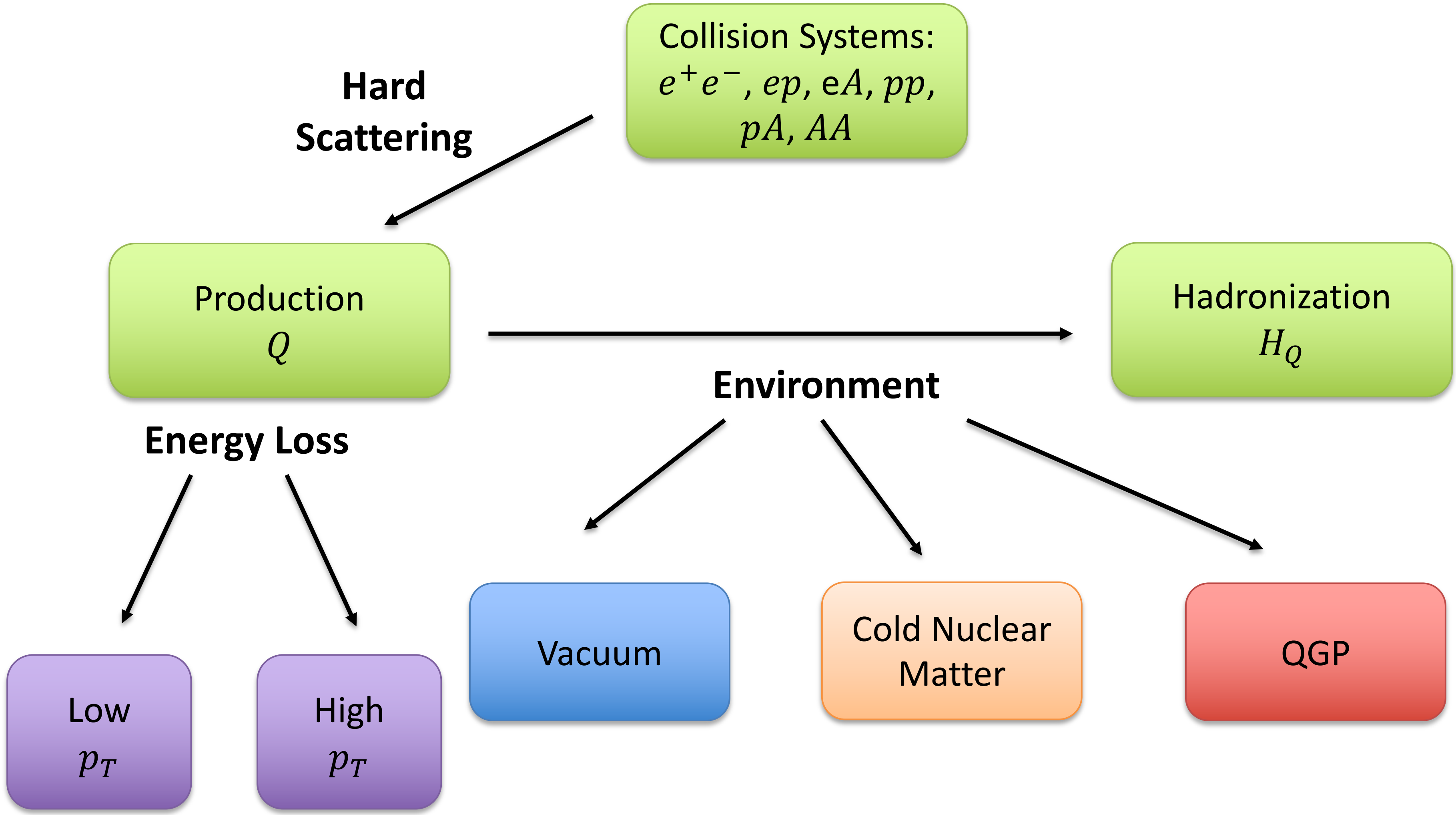
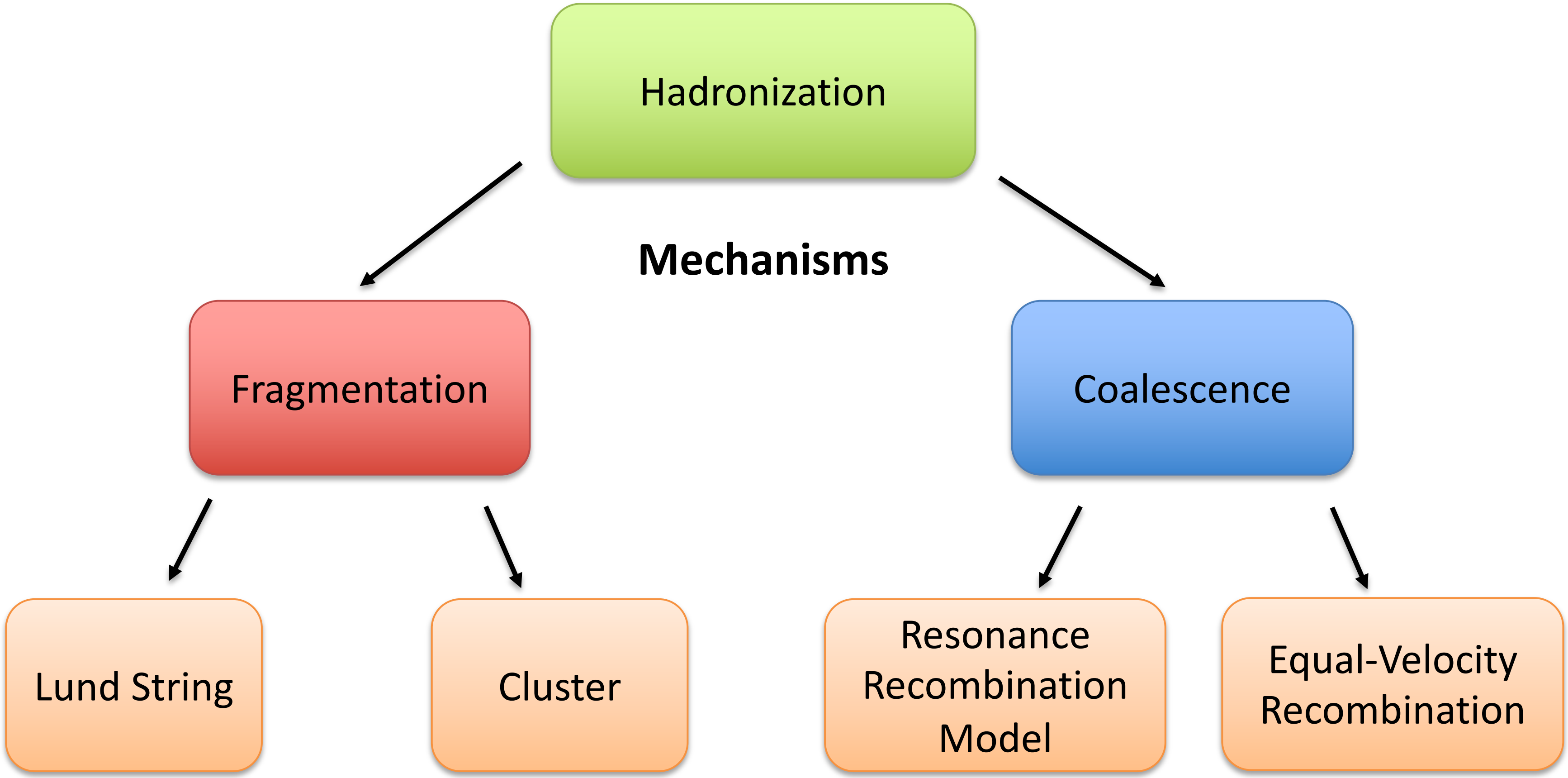
# Open Heavy Flavor Physics




- Basic framework of heavy flavor physics for different models

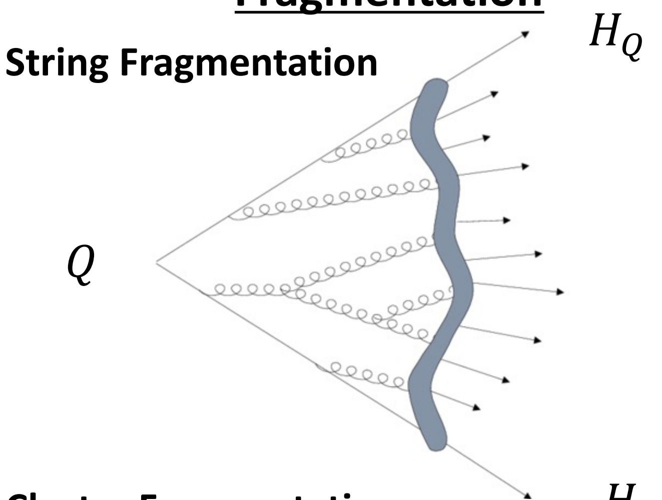
# Heavy Flavor Hadronization

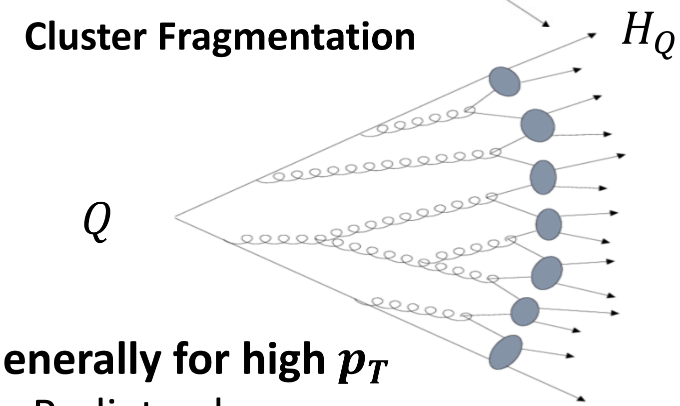



- **Generally non-perturbative** → no first principle calculations available yet
  ☛ Phenomenology: Different models made to describe hadronization
  ☛ Large discrepancies among different models → significantly limit our ability to interpret heavy flavor data

# Fragmentation vs Recombination

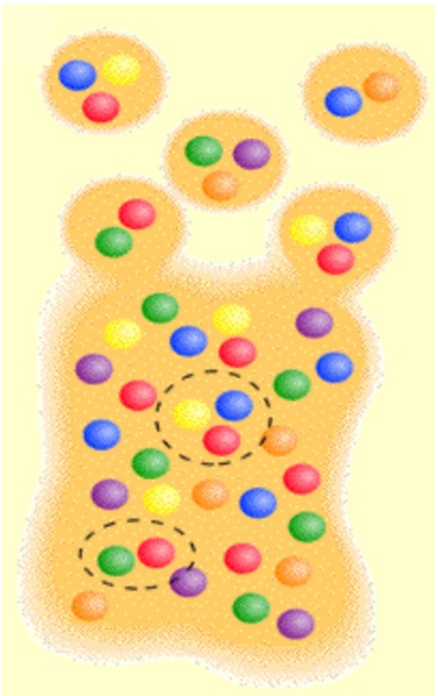
## Fragmentation




**Generally for high $p_T$**
- Radiate gluons
- Peterson fragmentation function/FONLL framework
- Applicable in vacuum

## Recombination



**Generally for low $p_T$**
- Heavy quark – comoving light quark
- Significant contribution from the light quark momentum to the hadron momentum
- Occur in dense color environment

# Hadronchemistry Models

**Examples of Hadronization Models**

- Statistical Hadronization Model
- Lund String Model
- Quark Coalescence Model

**TAMU Model**

- Fokker-Planck framework
- Heavy-light quark T-matrix interaction for transport coefficients
- Collisional energy loss only
- Hadronization recombination + FONLL fragmentation

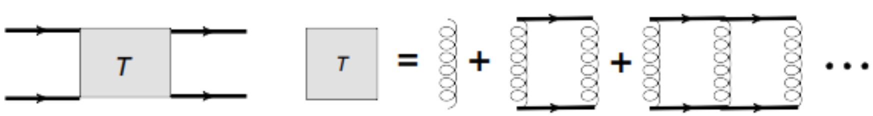
**Cao, Sun, Ko Model**

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

**Equal Velocity Combination**

- Heavy and light quarks as constituent quarks with equal velocity approximation to form color neutral hadrons
- Light quark spectra extracted from light hadron data
- Heavy quark spectra obtained from FONLL
- Applicable to low $p_T$ heavy flavor hadron in pp and PbPb collisions

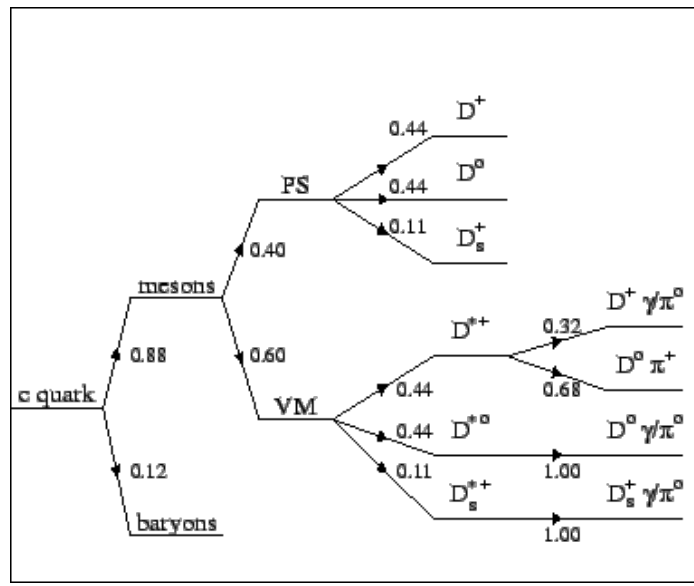
$Q - q$ T-Matrix Schematics



# Experimental Observables

**Heavy Quark Fragmentation Fraction**

- Assume only heavy quark fragment into heavy flavor hadrons: $D_{q,g\to H_Q}(z) = 0$
- Heavy quark fragmentation function: $D_{Q\to H_Q}(z) \sim f(Q \to H_Q)\delta(1-z)$
- Heavy flavor hadron spectra: $\frac{d^3\sigma^{H_Q}}{p_T dp_T dy d\phi} \sim f(Q \to H_Q)\frac{d^3\sigma^{Q}}{p_T dp_T dy d\phi}$
- Heavy quark fragmentation fraction $f(Q \to H_Q)$: the probability of a heavy quark $Q$ turning into an open heavy flavor hadron $H_Q$
  - ☛ $f(Q \to H_Q)$ is a constant
  - ☛ Unity: $\sum_{H_Q} f(Q \to H_Q) = 1$

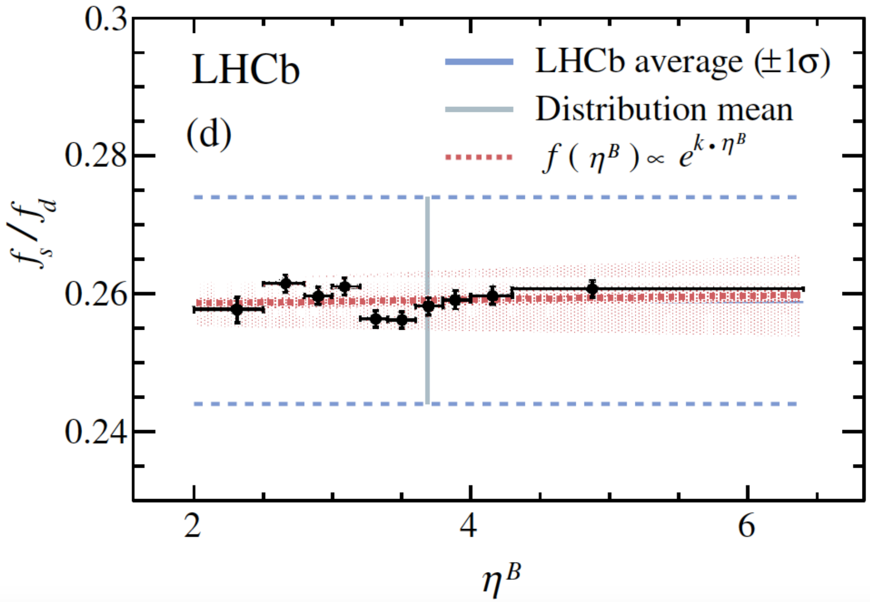


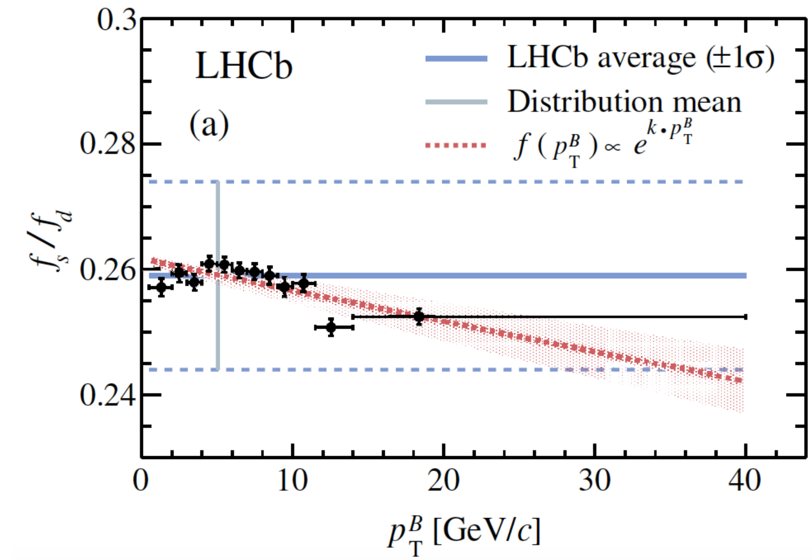

| $D^+$ | $D^0$ | $D_s^+$ |
|---|---|---|
| 0.156 | | |
| | 0.156 | |
| | | 0.040 |
| 0.076 | | |
| | 0.159 | |
| | 0.234 | |
| | | 0.061 |
| 0.232 | 0.549 | 0.101 |

**Particle Production Yield**

- Direct access to fragmentation fraction
- Relative yield measurement to cancel systematic uncertainties
- Strange to non-strange meson ratio
- Baryon-to-meson ratio
- Require fully reconstructed charm and beauty hadrons via exclusive decay channels

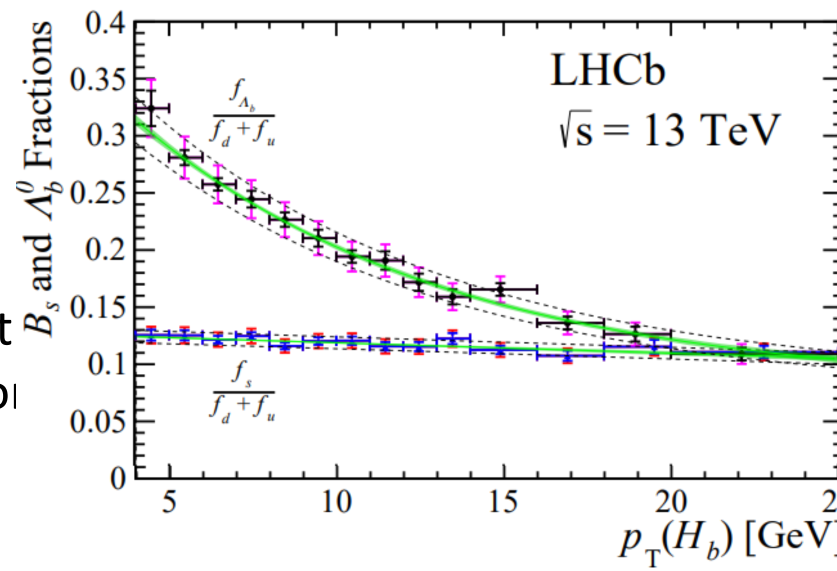
# Beauty Hadronization in pp with LHCb



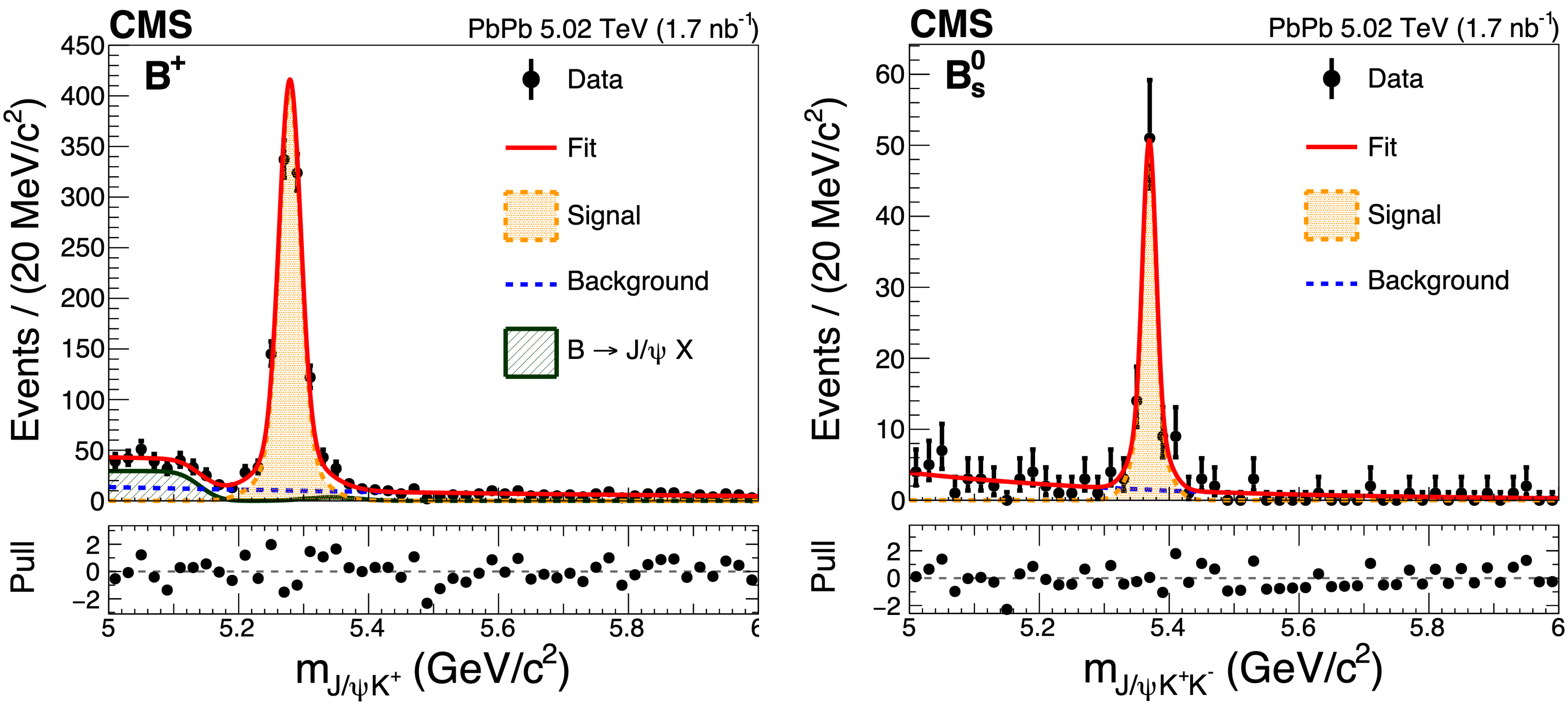




**$B^+ = u\bar{b}$, $B^0 = d\bar{b}$, $B_s^0 = s\bar{b}$, and $\Lambda_b^0 = udb$**

- Here, $f_{\Lambda_b} = f(b \to \Lambda_b^0)$, $f_s = f(b \to B_s^0)$, $f_d = f(b \to B^0)$, and $f_u = f(b \to B^+)$
- No significant $\eta$ dependence on $f_s/f_d$
- $f_s/f_d$ has sizeable $p_T$ dependence with about $> 4\sigma$ significance in the forward rapidity regio
- Strong $f_{\Lambda_b}/(f_d + f_u)$ dependence at low $p_T$
  - ☛ Fragmentation fraction is **NOT** a constant



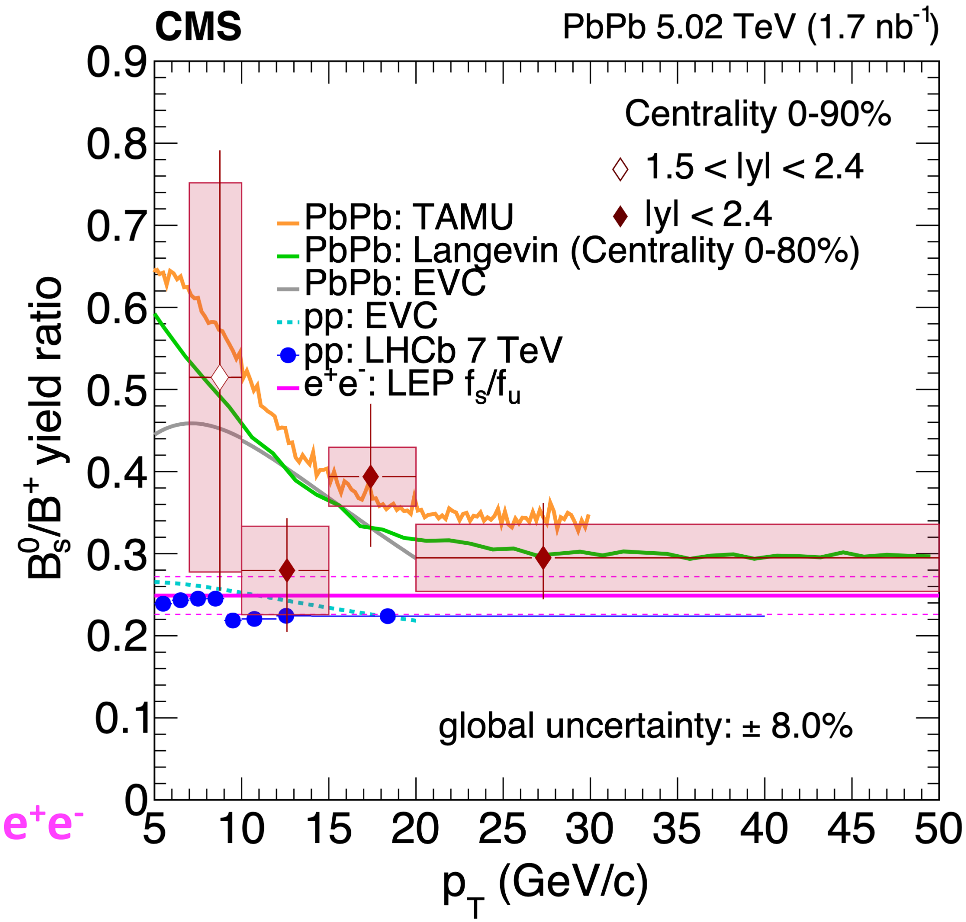
# Fully Reconstructed B mesons with CMS




- Fully reconstructed B mesons via exclusive decay processes
- Application of machine learning to optimize the cuts based on topological variables
- Excellent tracking and vertexing performance and muon capabilities
- No hadronic particle identification
- First observation of $B_s^0$ in heavy-ion collisions with a significance greater than $5\sigma$

# $B_s^0/B^+$ Ratio vs $p_T$ in PbPb Collisions

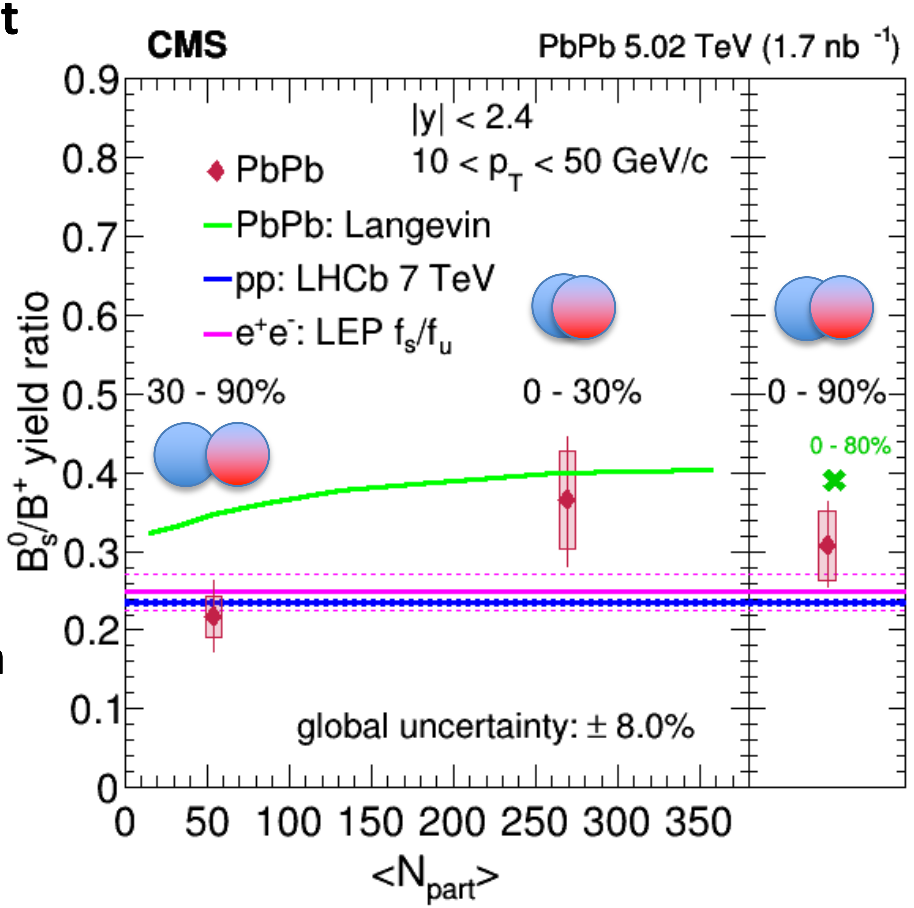
- **No significant $p_T$ dependence within uncertainties**
- **Reasonably good agreement with theoretical models**
  - ☛ Both central values and trends ($B_s^0/B^+ \downarrow$ as $p_T \uparrow$)
  - ☛ TAMU > Cao, Sun, Ko > EVC
  - ☛ Models diverge at very low $p_T$
  - ☛ Cao, Sun, Ko has the best agreement with at high $p_T$
  - ☛ EVC in pp agrees with LHCb pp




- **Systematically above LHCb pp and LEP $e^+e^-$ references but within about 1.5 $\sigma$**
  - ☛ Inconclusive about strangeness enhancement for beauty hadronization in QGP
  - ☛ Different $\sqrt{s_{NN}}$: 5.02 vs 7 TeV → Better to compare with the CMS pp (ongoing)
  - ☛ Need about 4 times more data to have an observation of > 3$\sigma$
  - ☛ Coalescence needed: fragmentation alone is insufficient to describe the data

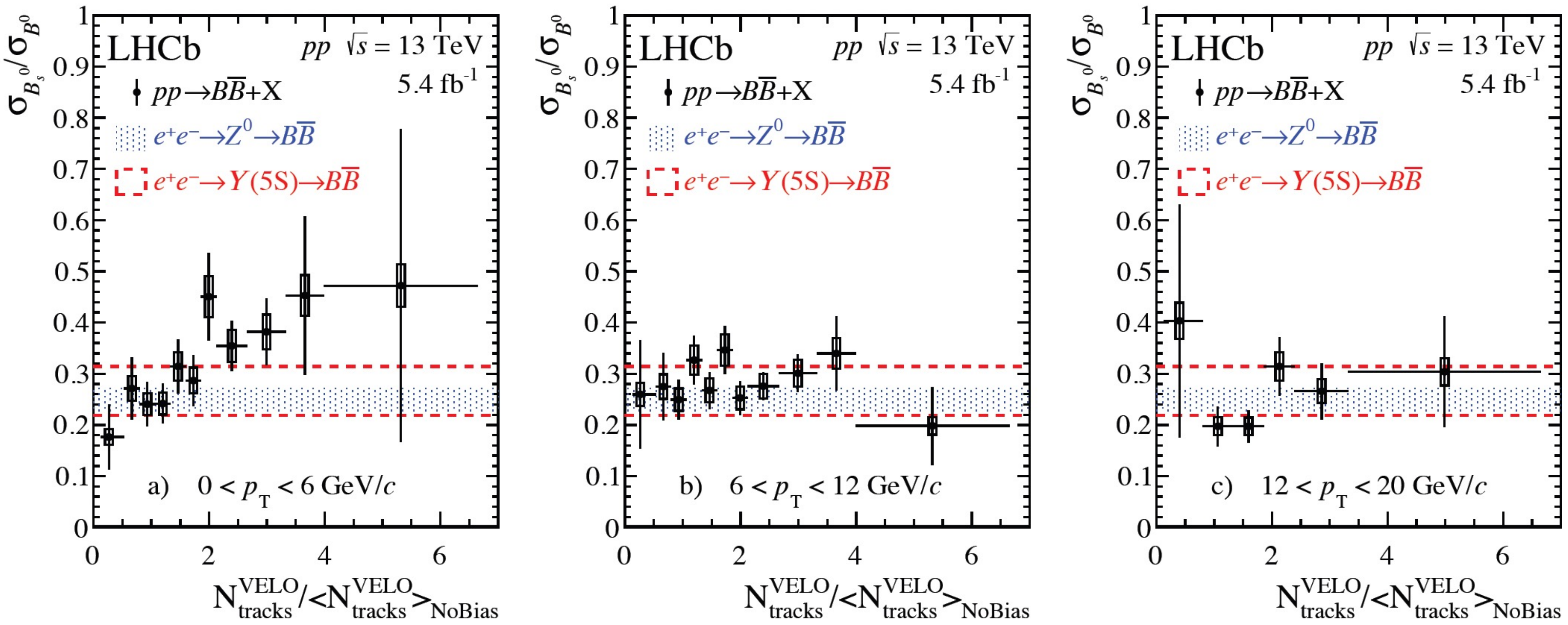
# $B_s^0/B^+$ Ratio vs Centrality in PbPb Collisions

- **First centrality dependence measurement**
  - ☛ No significant centrality dependence
- **Overall good consistency between data and theoretical models**
  - ☛ Cao, Sun, Ko overall consistent to our data in 0 – 30% and 0 – 90%
  - ☛ Cao, Sun, Ko overshoots the peripheral 30 – 90% measurement
- **Compatible to LHCb pp and LEP $e^+e^-$ data within 1.3$\sigma$**
  - ☛ pp and $e^+e^-$ data are consistent
  - ☛ Excellent agreement with pp and $e^+e^-$ data with peripheral centrality 30 – 90%
  - ☛ 1.3$\sigma$ above pp reference at 0 – 30%




- **Hint of strangeness enhancement of beauty hadronization**
  - ☛ More data from Run 3 and HL-LHC to confirm the conclusion

# Ongoing Efforts at the LHC: CMS and LHCb




**Fully reconstructed $B^+$ in pp collisions down to $p_T = 0$ GeV/c**

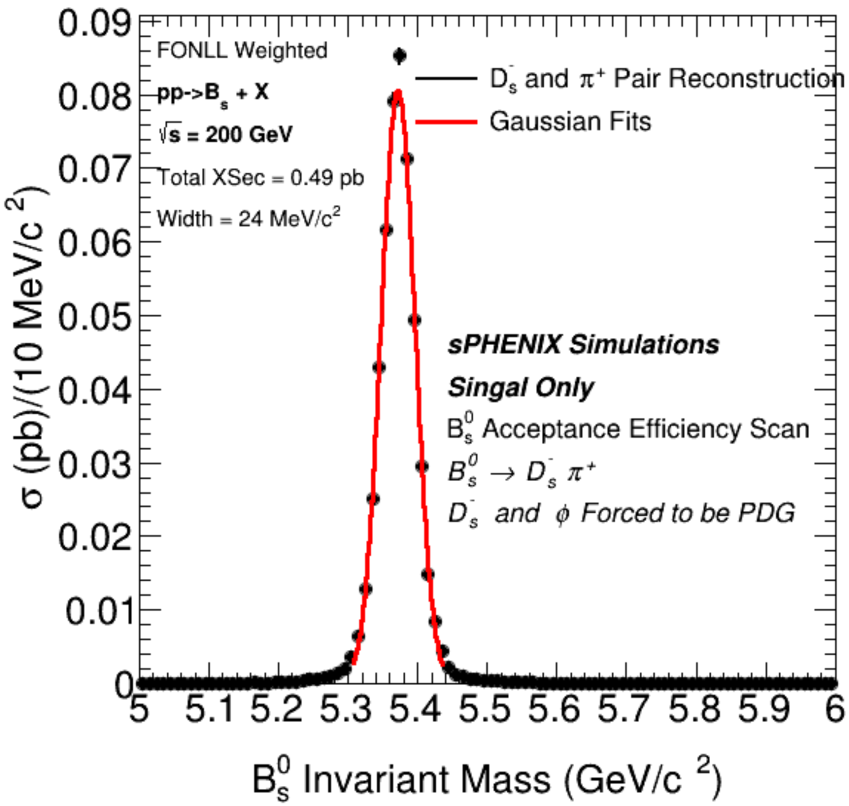
- Inclusive beauty production cross section at the LHC
- Test pQCD calculations

**$B_s^0/B^+$ or $B_s^0/B^0$ over a wide range of $p_T$ and event multiplicity with high precision**

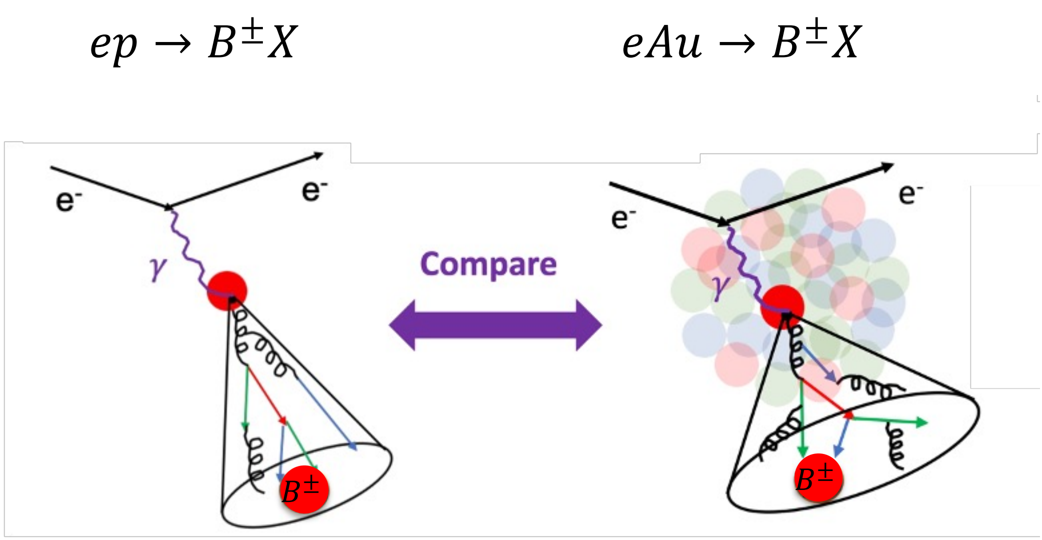
- Study beauty hadronization mechanism
- Test theoretical model calculations

# Future Opportunities: sPHENIX and EIC

**sPHENIX $B_s^0$ Signal Statistics Projection**




**b-hadron production at EIC via semi-inclusive DIS**




- Possible fully reconstructed $B_s^0$ in pp and AuAu with sPHENIX at RHIC energy
- b-hadron measurement in ep and eA at the EIC to study cold nuclear medium modification on the beauty quark fragmentation function

# Summary

**Hadronization is non-perturbative**

- No first principle calculation yet available
- Heavy quark hadronization mechanisms: fragmentation and recombination
- Different models to explain heavy quark hadronization

**Fully reconstructed b-hadron yield ratios in $e^+e^-$, pp, and AA collisions**

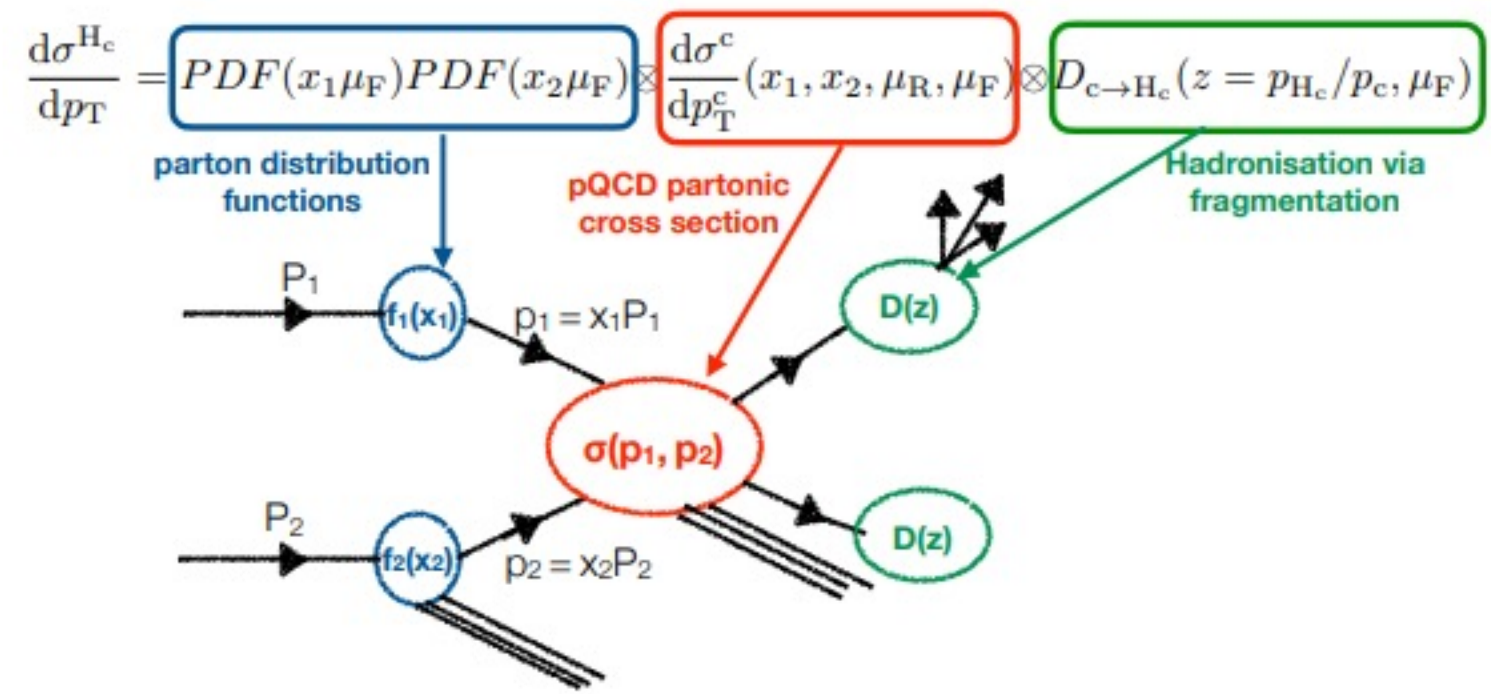
- Investigate beauty hadronization from vacuum to QGP
- Beauty fragmentation fraction vs $p_T$: significant in pp and insignificant in AA
- First observation of fully reconstructed $B_s^0$ in AA collisions with CMS
- Theoretical models all reasonably well describe experimental data
- Hint of strangeness enhancement needs to be confirmed
- Coalescence is needed to describe heavy-ion collisions

**Outlook**

- Ongoing differential and precise measurement over $B_s^0/B^+$ in pp
- High precision b-hadron measurements in PbPb with Run 3 and HL-LHC data
- b physics program with sPHENIX at RHIC energy
- EIC to study cold nuclear matter effects on beauty hadronization in eA

# Back Up

# QCD Factorization Theorem




- Foundation of perturbative QCD
- Hard processes are perturbatively described by pQCD partonic diagrams
- Soft processes are non-perturbative but can be factorized
    - Initial state dynamics described by parton distribution function (PDF)
    - Final state hadronization described by fragmentation function $D(z)$
    - PDF and $D(z)$ are assumed universal
- Applicable to $e^+e^-$, $ep$, and $pp$ colliders

# Fragmentation Fraction Derivation

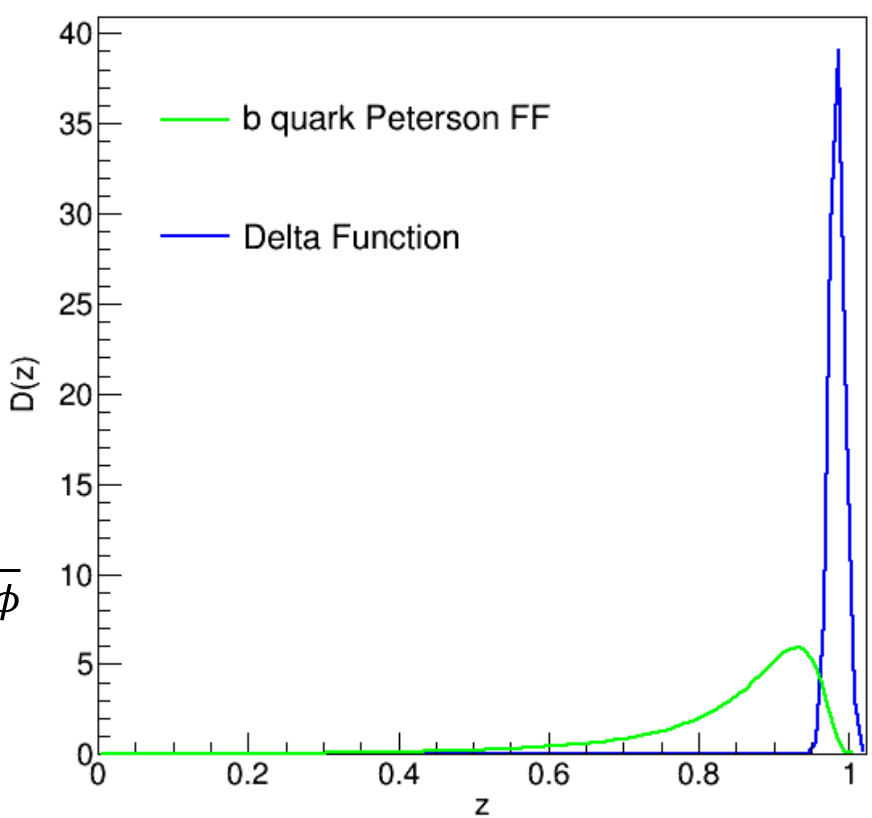
- Peterson fragmentation function takes the form:

$$D_Q^{H_Q}(z) = \frac{1}{z\left[1 - 1/z - \epsilon_Q/(1-z)\right]^2}$$

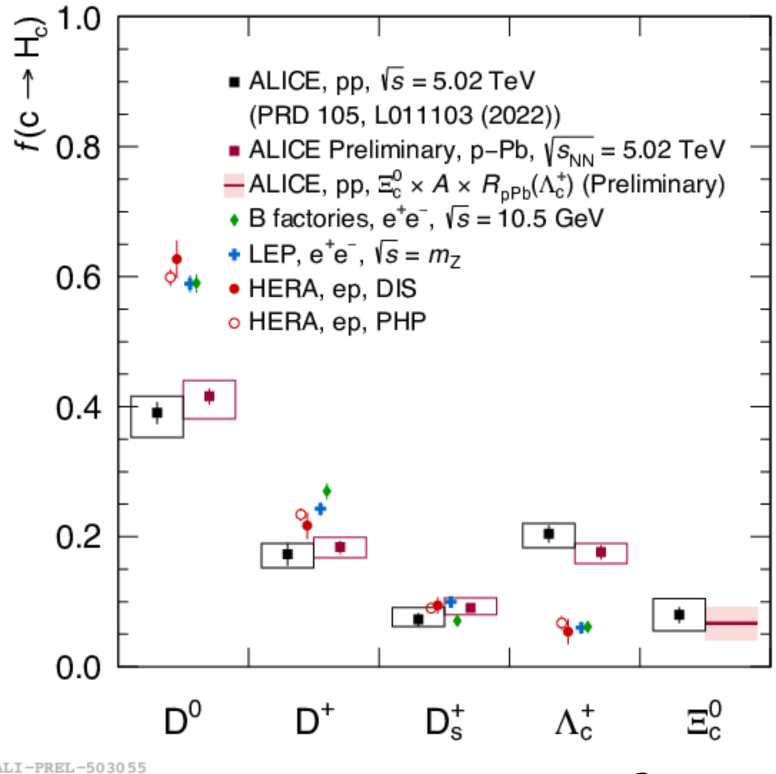
- Heavy quarks generally have a small $\epsilon_Q$
  - ☛ Charm: $\epsilon_c = 0.03$
  - ☛ Beauty: $\epsilon_b = 0.005$
- For $\epsilon_Q \to 0$, $D_Q^{H_Q}(z) \to \delta(1-z)$ and thus $\frac{d^3\sigma^{H_Q}}{p_T dp_T dy d\phi} \sim f(Q \to H_Q) \frac{d^3\sigma^Q}{p_T dp_T dy d\phi}$
- The energy sum rule

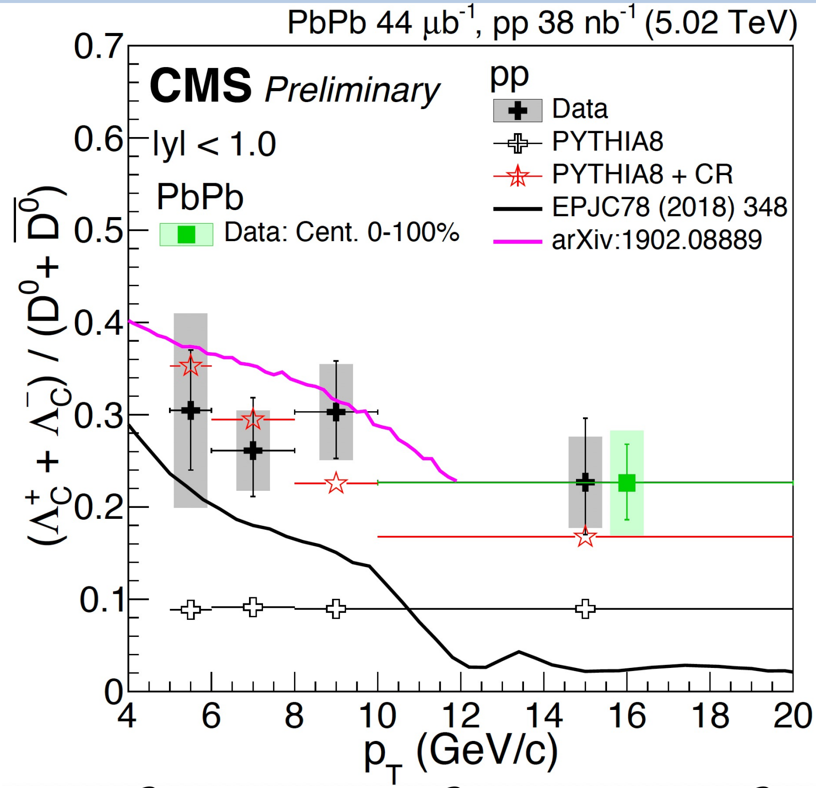
$\sum_{H_Q} \int_0^1 D_Q^{H_Q}(z)dz = 1$ leads to

$$\sum_{H_Q} f(Q \to H_Q) = 1$$



# QCD Factorization Breaking for Charm Sector




- Hadronization universality: $D(z,Q^2) = D_{e^+e^-}(z,Q^2) = D_{ep}(z,Q^2) = D_{pp}(z,Q^2)$
- Significant enhancement and suppression in pp by ALICE at the LHC
- Broken due to quark coalescence mechanism? Additional dependence on color charge density: $D_{pp}(z,Q^2) \rightarrow D_{pp}(z,Q^2,n_c)$?
- Significant enhancement of $\Lambda_c^+/D^0$ and $D_s^+/D^0$ also observed by STAR at RHIC and ALICE at the LHC in AA collisionsx

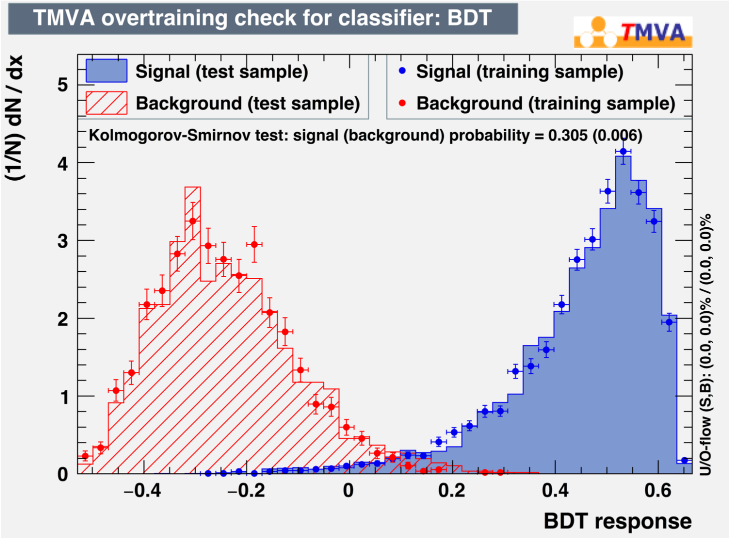
# CMS Detector

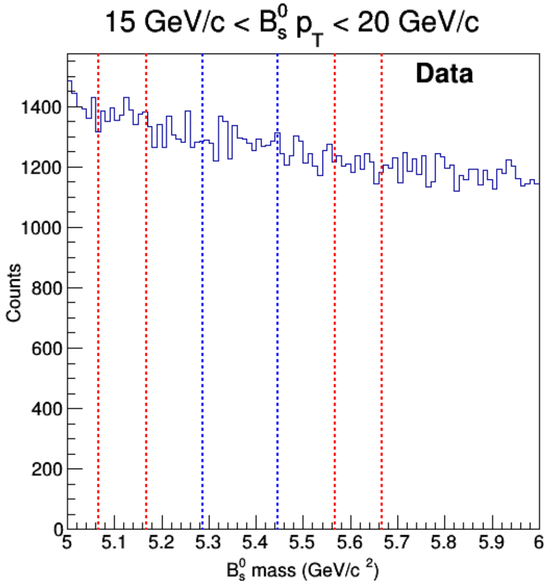
**Analysis challenges**

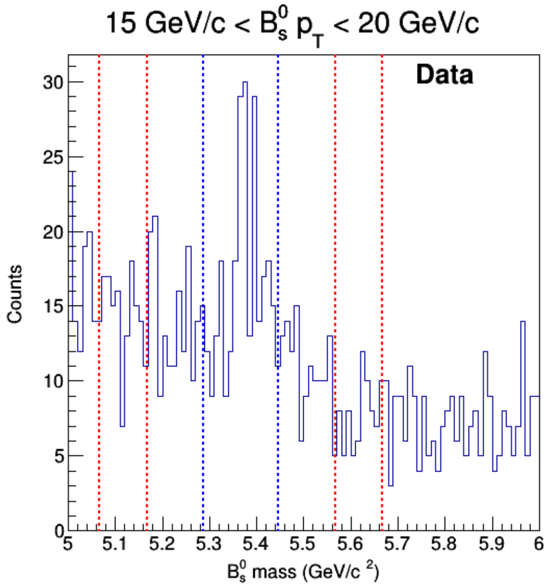
- Before selections, **B = 20672** and **S = 26**
- Require to obtain significant **B** to **S** rejection in order to observe $B_s^0$ signal in the PbPb data

**Boosted Decision Tree Machine Learning Algorithm**

- Excellent **Signal**/**Background** separation without overtraining
- A random BDT > 0.1 selection returns a visible signal
- Achieve better than **$10^3$** to **1** for the **B** to **S** rejection



# Machine Learning Performance

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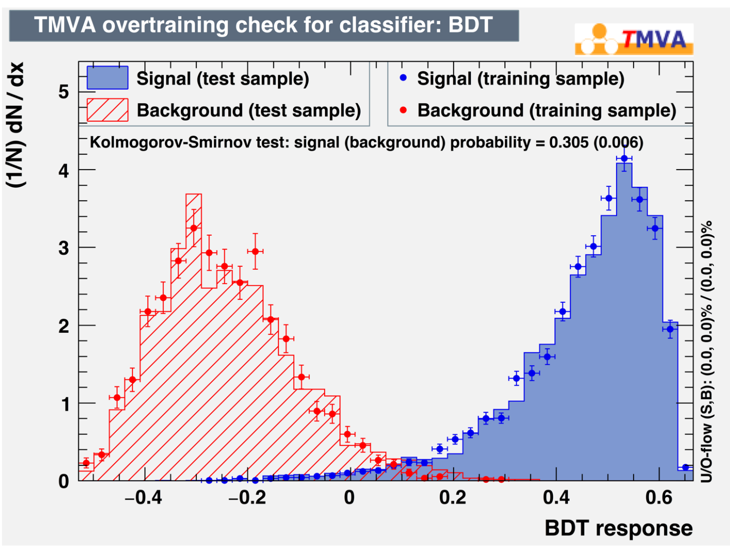


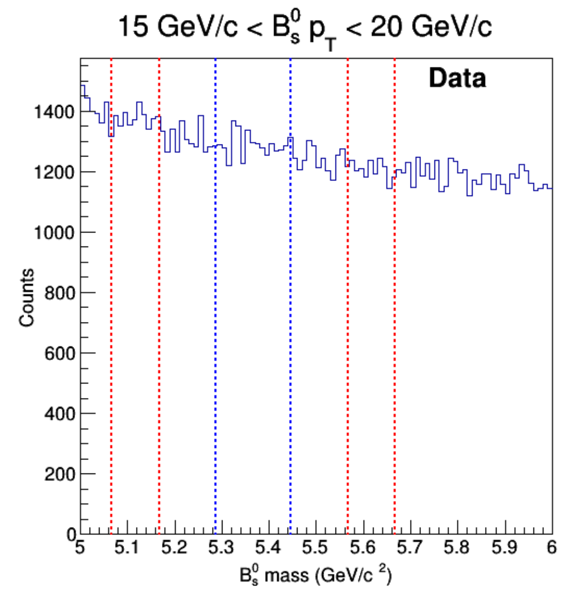


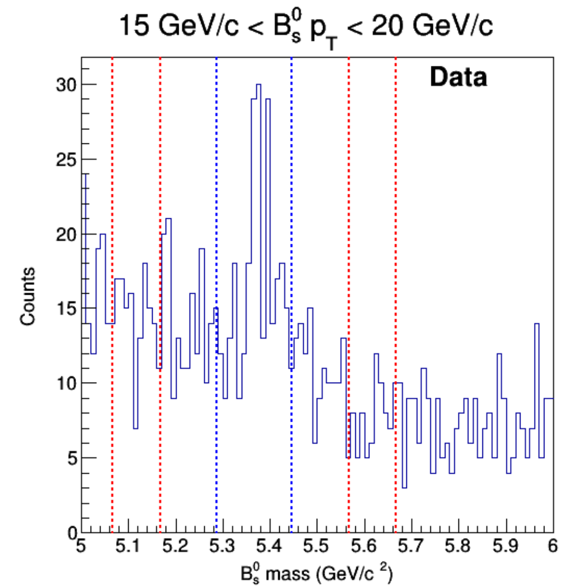


sPHENIX



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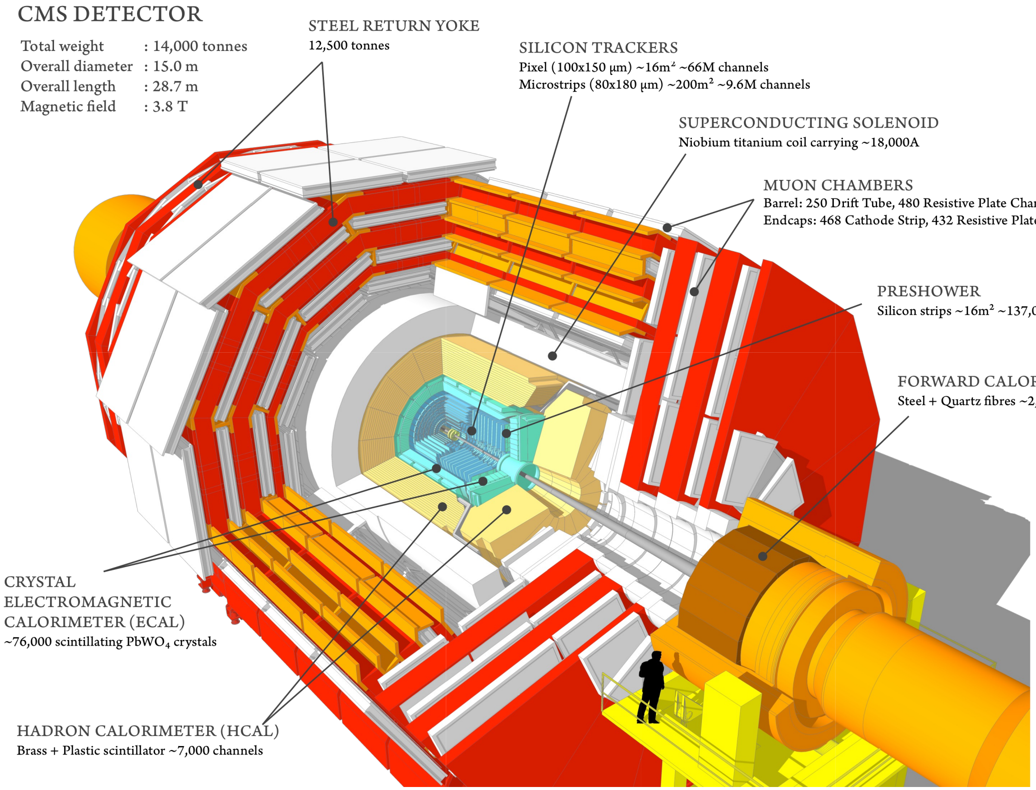
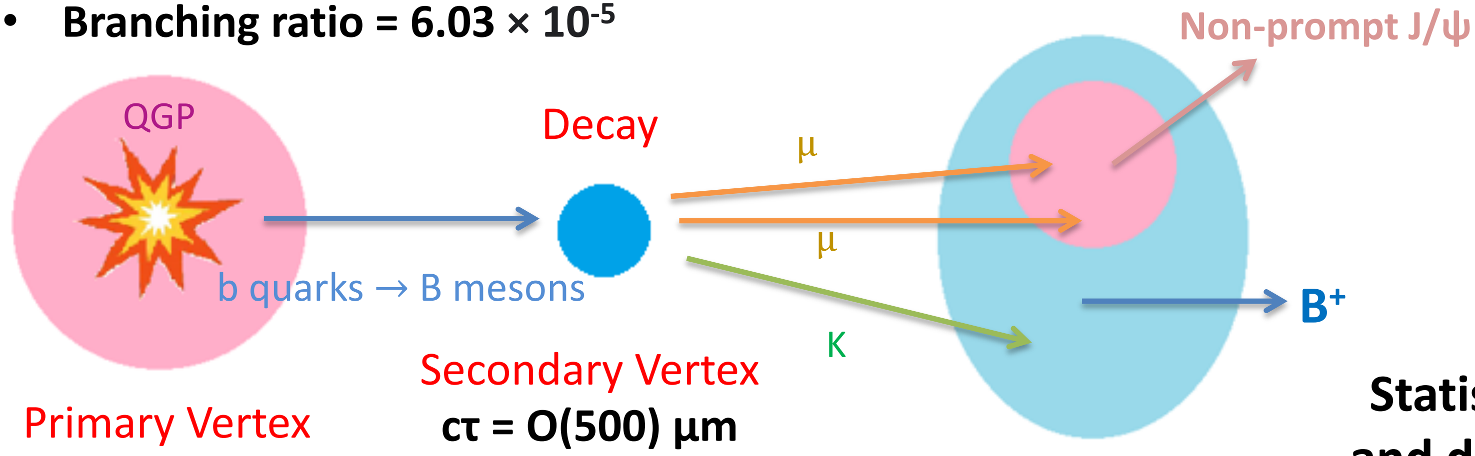
# Fully Reconstructed $B_s^0$ with CMS at the LHC




- Fully reconstructed B mesons from decay chain involve $J/\psi$
- Take advantage of excellent muon and tracking capabilities
- Not using hadronic particle identification or calorimeter information
- Constrain intermediate state resonances to improve the results
- Apply multivariate approach with machine learning techniques

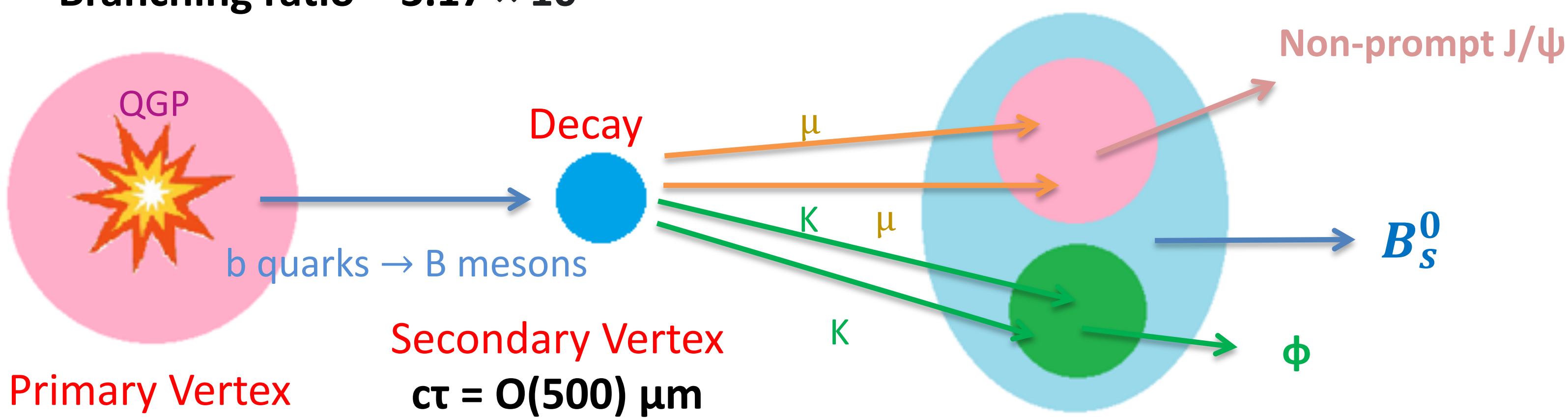
# Analysis Strategies

- $B^+$: 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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