Recent CMS open heavy flavor highlight(s)

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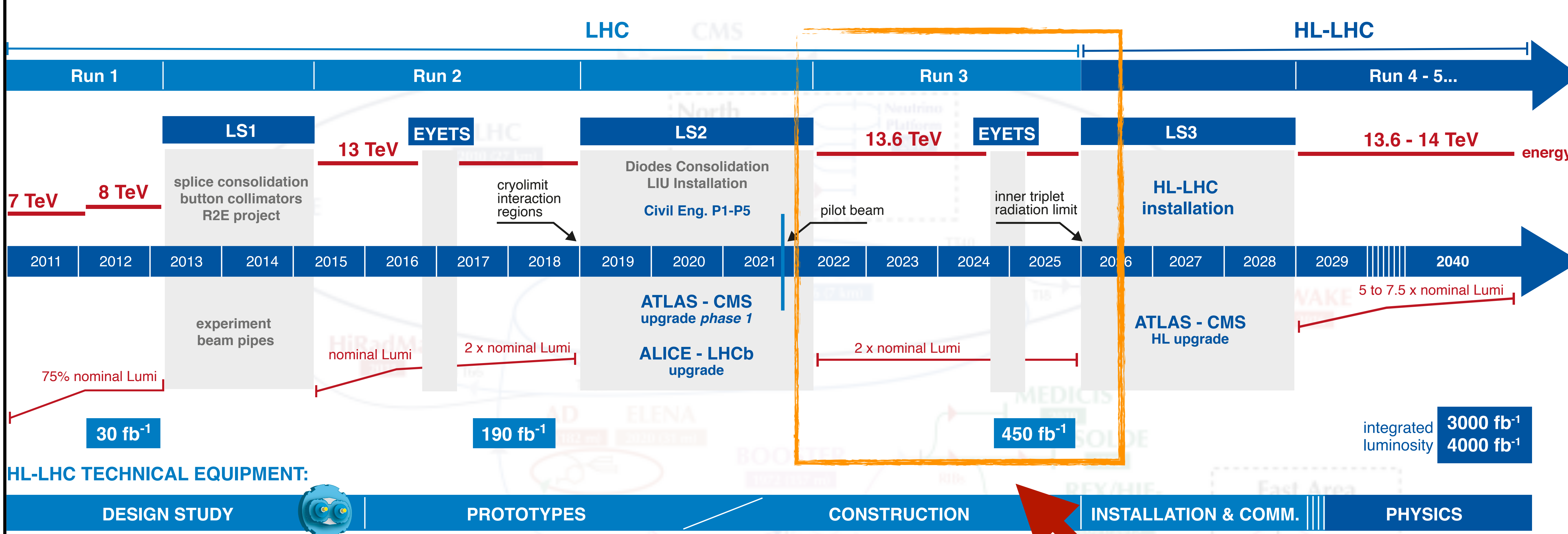
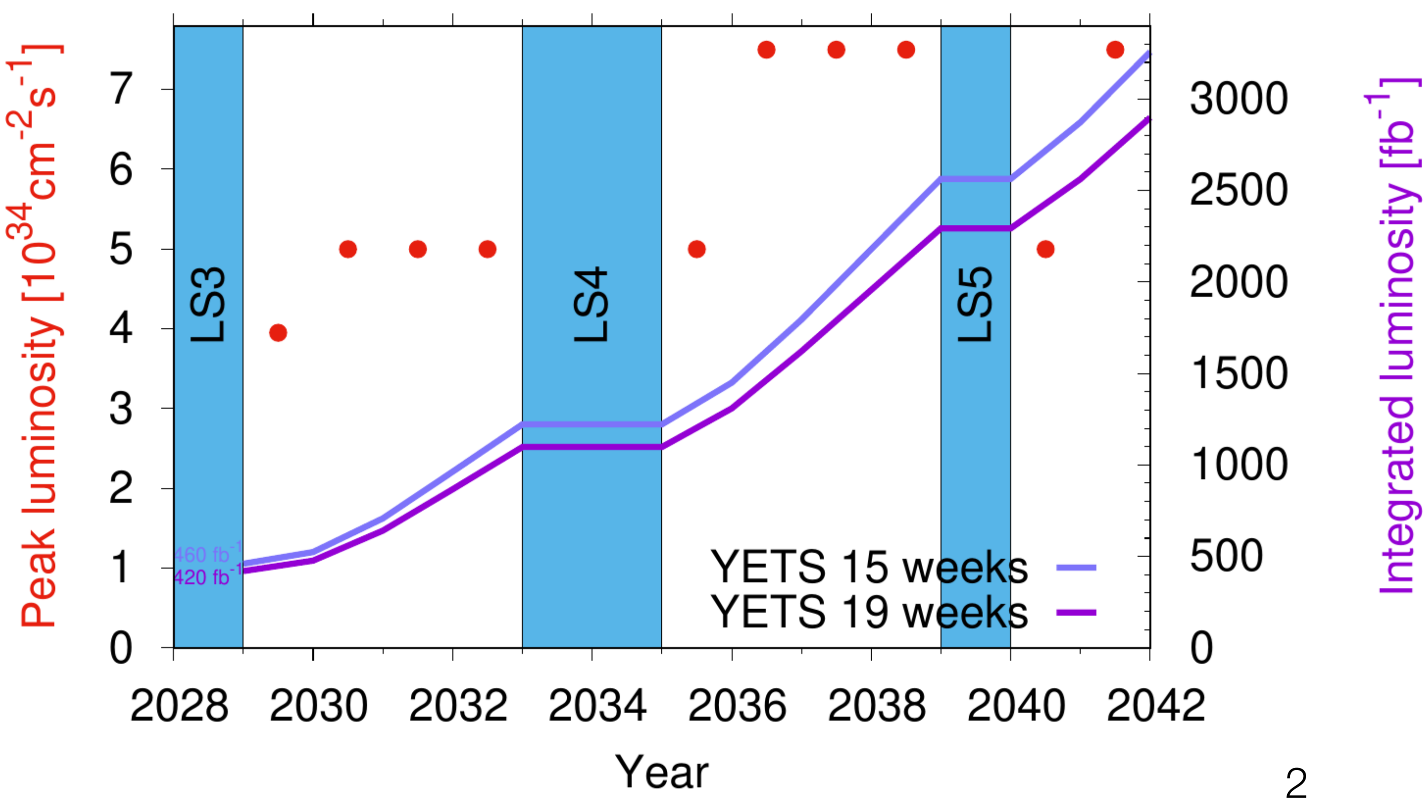
On behalf of the CMS Collaboration

2nd Workshop on advancing the understanding of
non-perturbative QCD using energy flow
November 6-9, 2023
Center for Frontiers in Nuclear Science
Sony Brook University

LHC / HL-LHC Plan

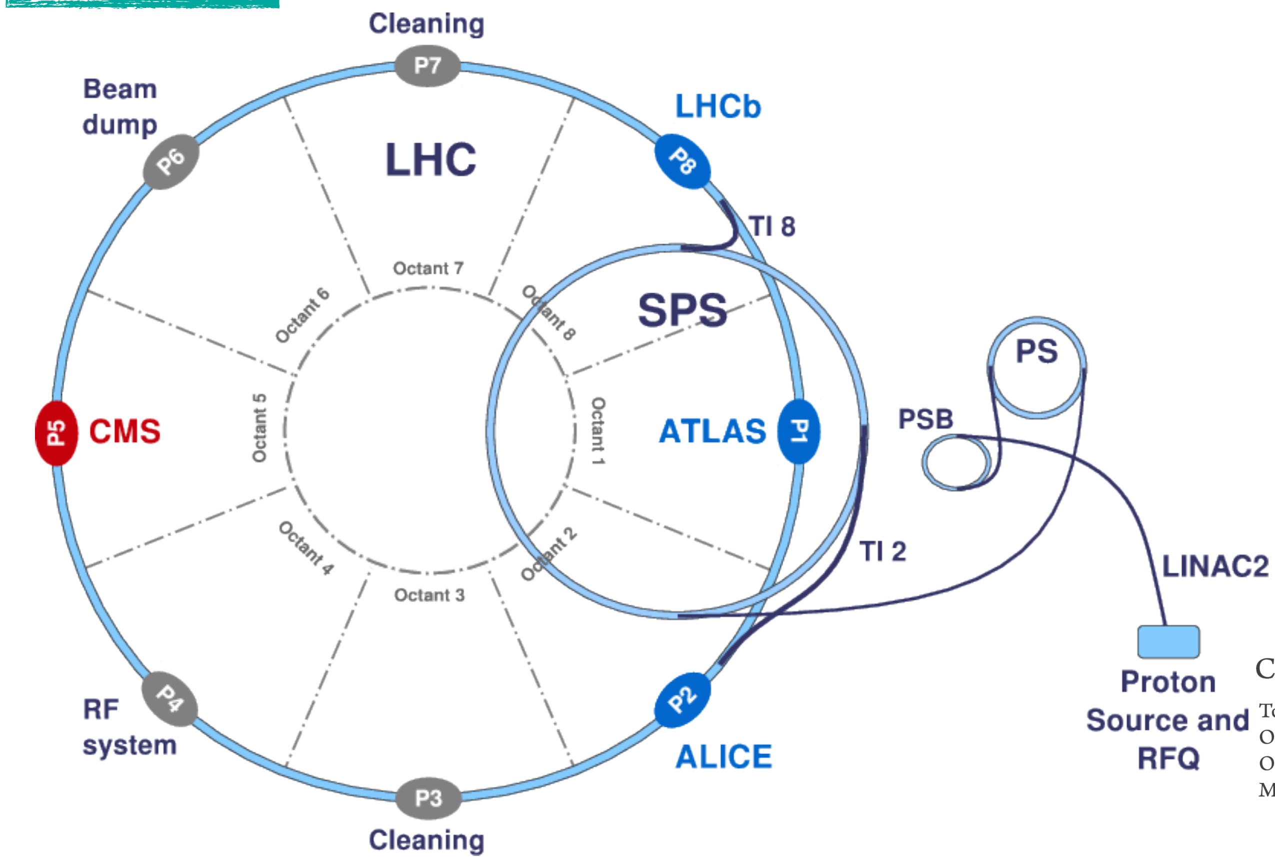


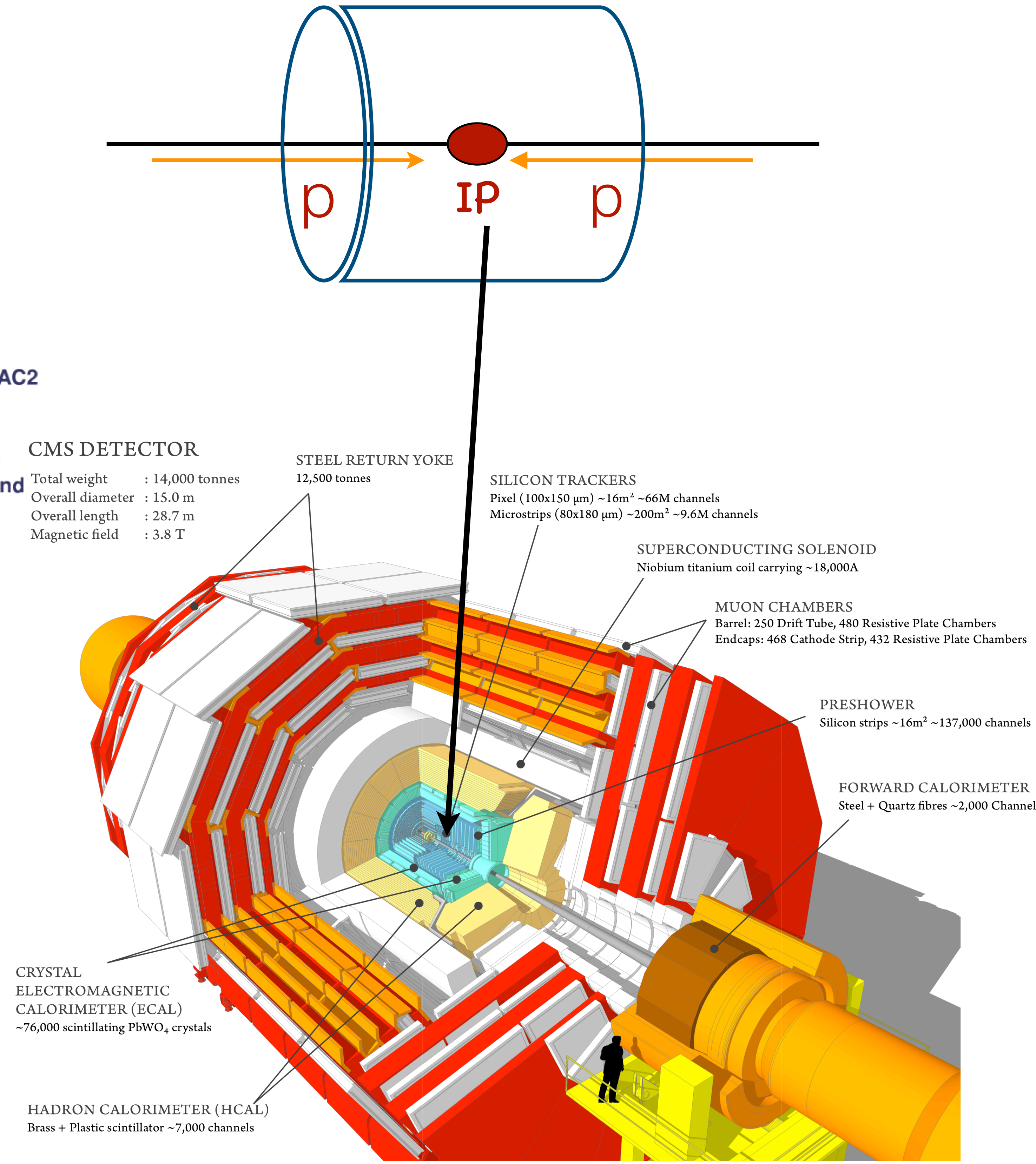


Here we are !!

Canonical idea !!

CMS





Tracker, ECAL, HCAL,
Superconducting Solenoid ~ 4T
& Muon Chamber

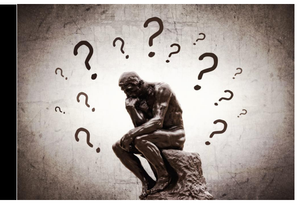
+

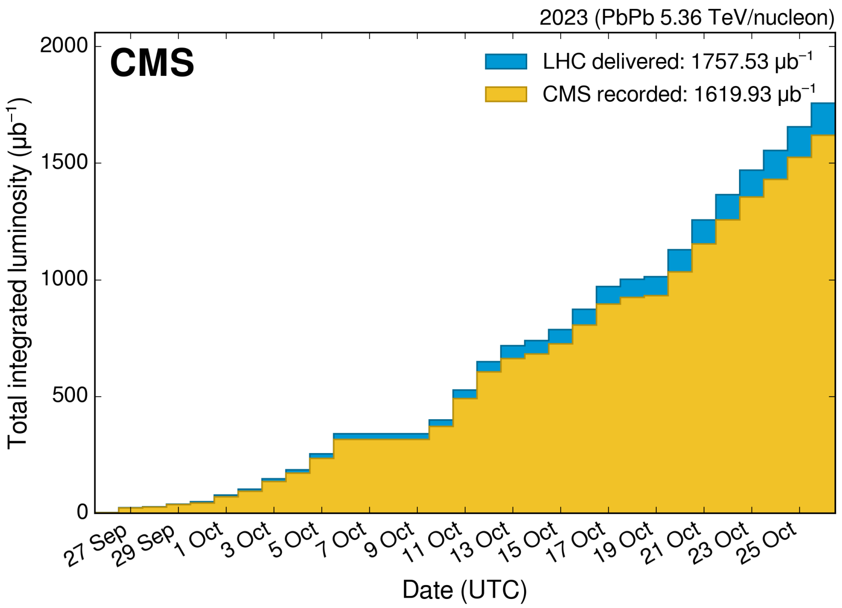
Physics Events are selected by
Level-1 & HL Trigger

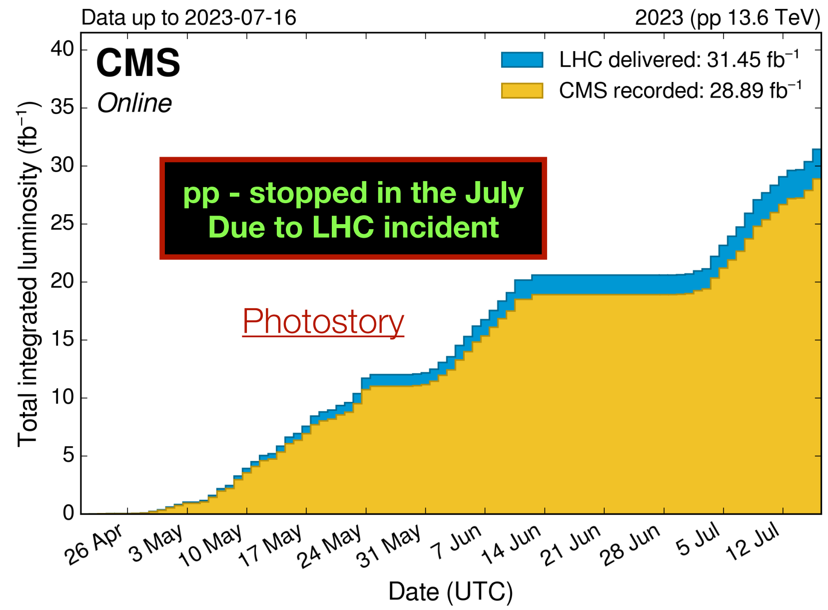
Current CMS Status

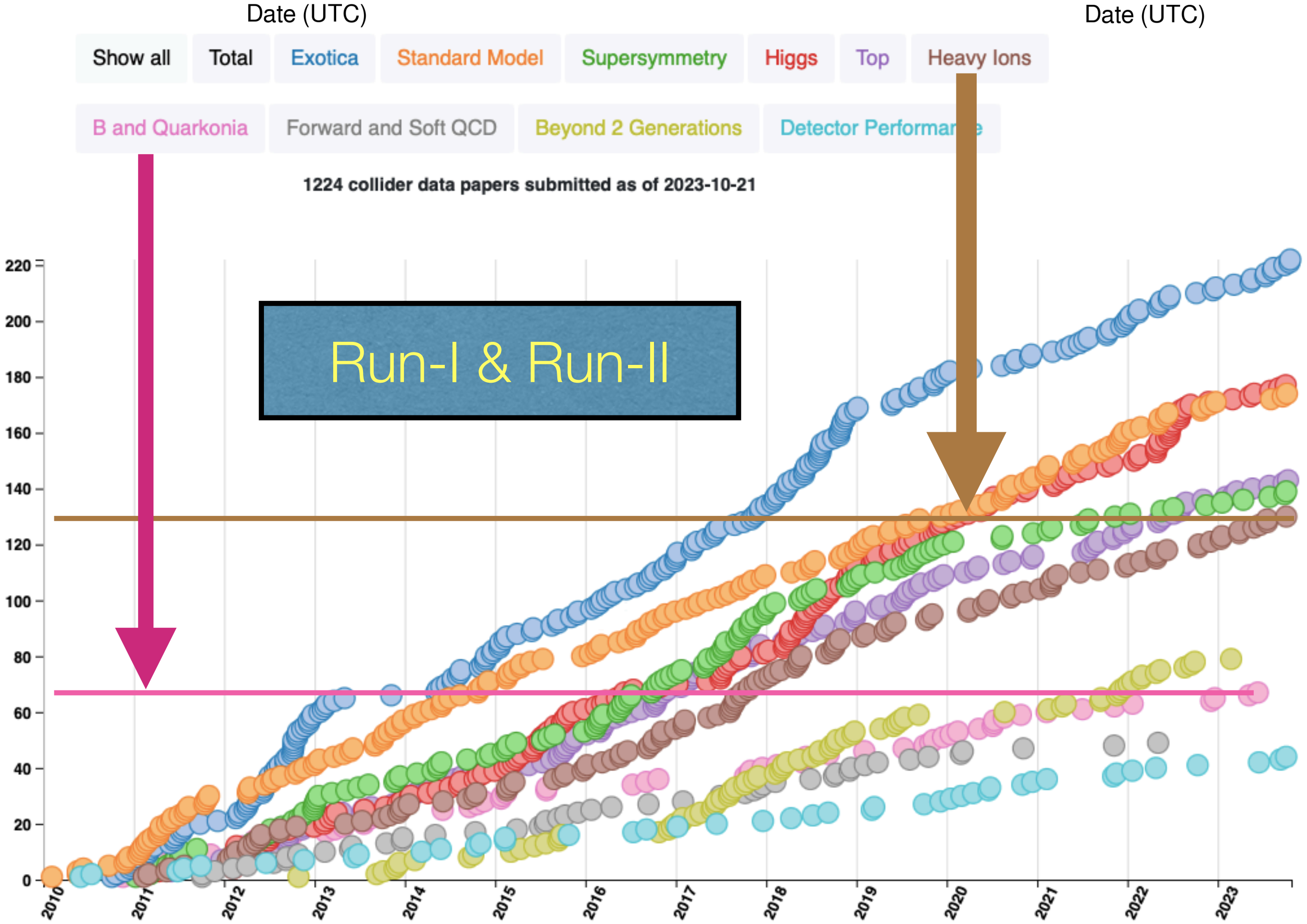
Hypothesis : that this workshop is aimed to understand the synergies between the UPCOMING EIC prospects and the ONGOING LHC prospects

Then the question is : within this larger context of collider physics where CMS stands !?









Data (2023):

pp : $29.89\ \mathrm{fb}^{-1}$

Pb-Pb : $1.6\ \mathrm{nb}^{-1}$

Publication (so far):

B-Physics : $\sim 5.5\ \%$

Heavy-Ion : $\sim 10.6\ \%$

Physics (Flagships) :

CP asymmetries , SMEFT, UPC, precision measurements

Preparation for Run-IV :

Upgrade of L1 (moving toward phase-II), ML based firmware, now ZDC is in L1

Possibility :

Days are coming when ML can help up putting many HLT in the firmware (HLT→L1)

Please find details :
CMSTDR, CMSPerformance , CMSScientific

Physics in the non-perturbative sector

-QCD : as a coherent theory, perturbative at short distances (weak coupling) and confining (strong coupling) at large distances (quark confinement → bound state →hadrons)

-Weak coupling : identification of processes where a perturbative prediction may be directly tested is far from trivial : one can obtain observables such as multiplicity or spectra of secondaries from hard process with large Q^2 transfer

-Strong coupling : this large Q^2 transfers defines the characteristics of the hard processes - down to scale $Q^2 \sim \Lambda_{QCD}$ where the hadronization takes over (*we will be talking about b, c hadrons*)

-Important properties of b, c quarks : due to the short time scale characterizing their production, heavy quarks experience the whole evolution of the system

-In Pb-Pb (p-Pb) collisions : measurement of hadrons containing heavy quarks provides crucial information on the in-medium parton energy loss

-In pp collision : measurements of open heavy-flavor hadron production are relevant tests of pQCD model calculations

-Hadrons with b and c quarks : *In this talks some of the important properties, that CMS has investigated in both heavy ion collisions and proton proton collision in the decays of the hadrons where b or c is one of the constituents, the studies of the following decay processes will be shown in this talk* :

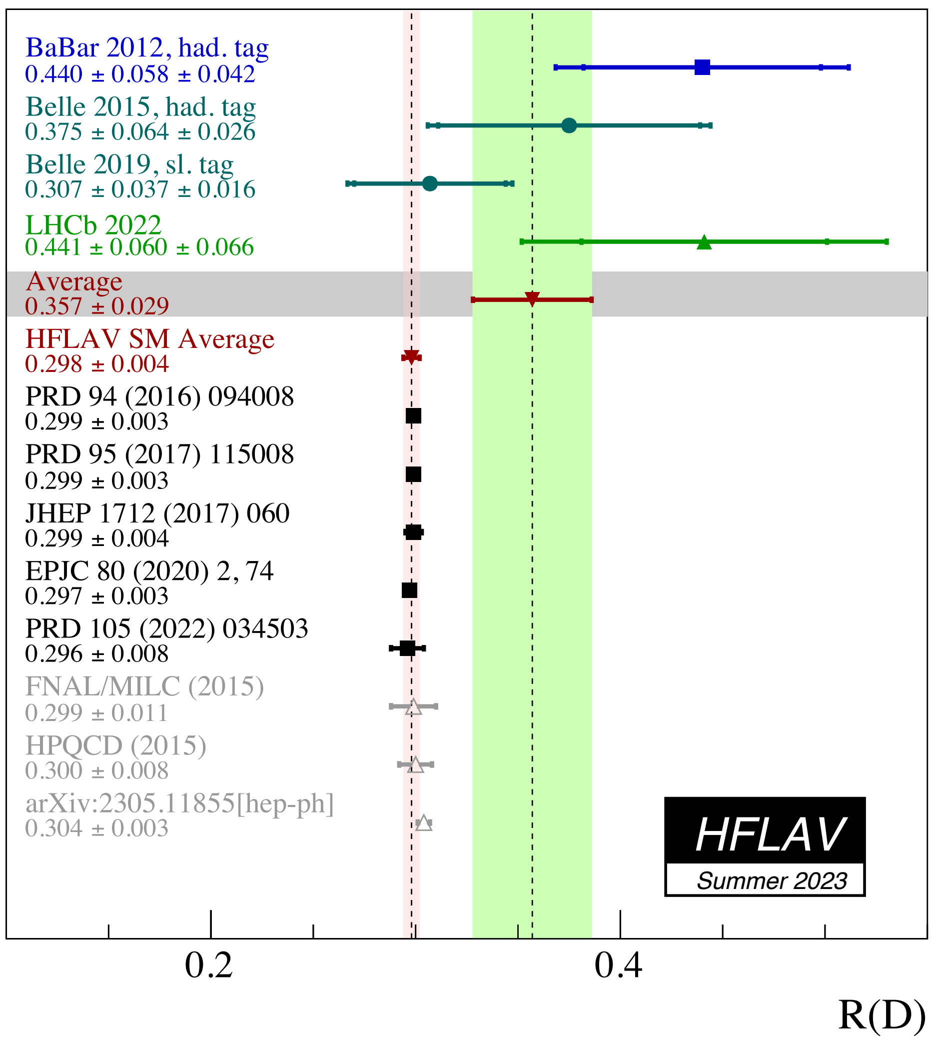
$$(pp) : B_c^+ \to J/\psi \tau^+ \nu_\tau, B^\pm \to K^\pm \ell^+ \ell^-, (\text{Pb-Pb}/p\text{-Pb}) \Lambda_c^+ \to pK^-\pi^+, B^+ \to J/\psi K^+, B_s^0 \to J/\psi \phi$$

QCD-PDG-REVIEW, 2007.13419

B-Physics Results

Lepton flavor universality violation

Origin of the deviation : indicates violation of the Lepton flavor universality, a symmetry in the gauge sector - and an accidental near-symmetry of the Yukawa sector - of the standard model by which all leptons couple with the same strength

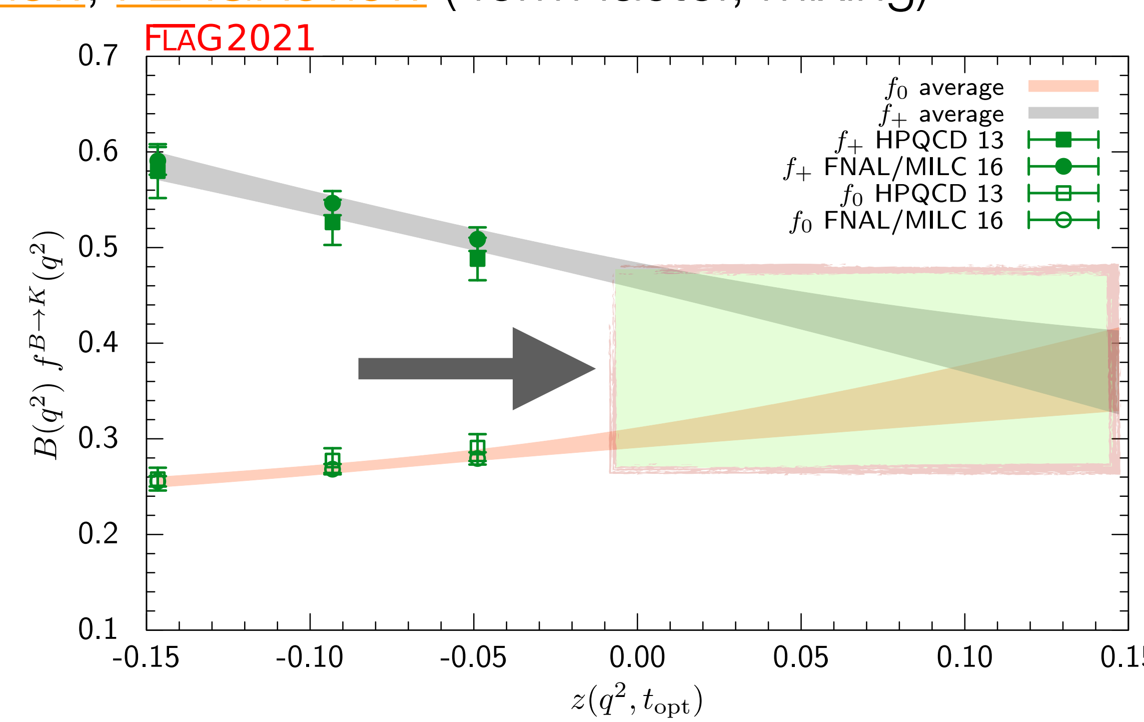


For the given decay processes :
$B_c^+ \to J/\psi \tau^+ \nu_\tau$, $B^\pm \to K^\pm \ell^+ \ell^-$ the unknown QCD corrections enters through the matrix elements of the decays in terms of the form factors
(QCD review , PDG)

Lattice, Lepto-quarks model in the non-perturbative and perturbative limits of QCD has tried to incorporate additional couplings by considering additional particle or lattice corrections

Please refer to some literature :
LVUAnnualReview, FLAGReview (form factor, mixing)

Lattice QCD results form factor ($B \to K$) extrapolation is residing far from exact $SU(3)$ symmetry : extra momentum contribution in the matrix elements through the form factors



This talk : $B_c^+ \to J/\psi \tau^+ \nu_\tau, B^\pm \to K^\pm \ell^+ \ell^-$

$R(J/\psi) : B_c^+ \to J/\psi\tau^+\nu_\tau$

CMS-PAS-BPH-22-012

$$R(J/\psi) = \frac{\mathscr{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

$$\boxed{J/\psi \to \mu^+\mu^-, \tau^+ \to \mu^+\nu_\mu\nu_\tau}$$

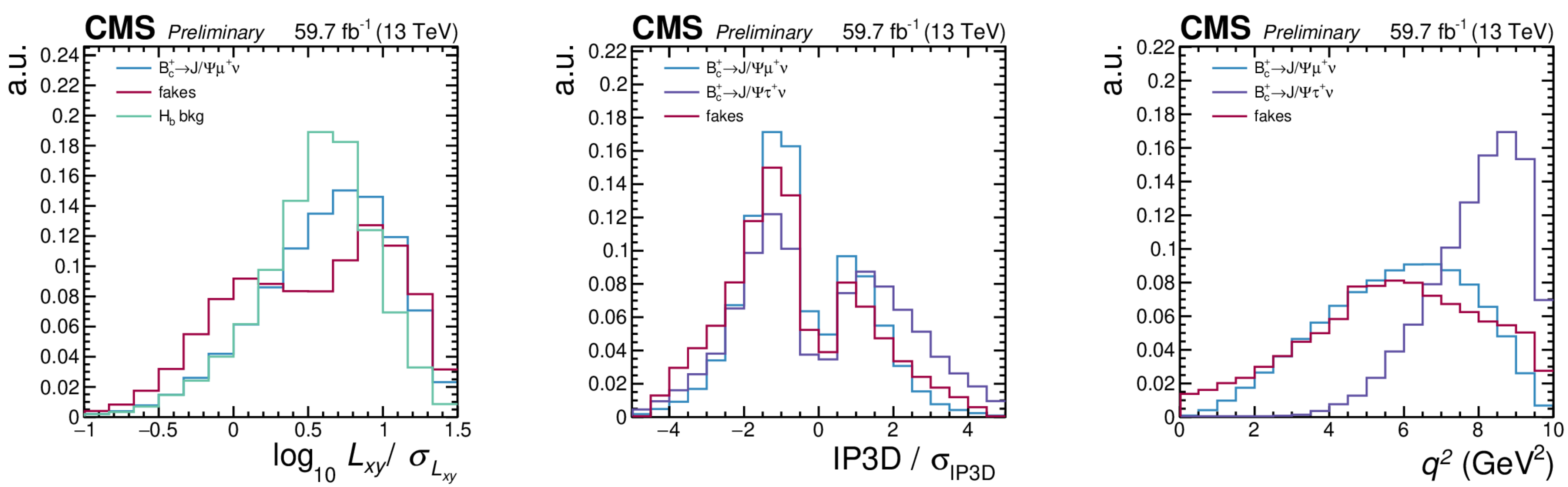
1. L1 trigger : events with 3 muons , leading $\mu : p_T > 5$ GeV, sub-leading $\mu : p_T > 3$ GeV , no p_T requirement for sub-sub-leading muon

2. 2 muons from the common vertex of J/ψ, and muon ($\mu^+\mu^-\mu^+$) not originating from J/ψ vertex referred as 3rd muon

3. Offline selections : HLT : $J/\psi + \mu$, $d_{xy} < 0.05$ cm, $d_0 < 0.2$ cm, $B_c^+(3^{rd}\ \mu)$vextex > 0.01 % ,
   $m_{B_c^+} < 10$ GeV, $p_T^{\mu 1} > 6$ GeV, $p_T^{\mu 2,\mu 3} > 4$ GeV

4. Discriminator between μ & τ channel : $q^2 = (p_{B_c^+} - p_{J/\psi})^2, p_{B_c^+} = m_{B_c^+}/m_{3\mu}^{vis} \cdot p_{3\mu}^{vis}$, $IP3D/\sigma_{IP3D}$, $L_{xy}/\sigma_{L_{xy}}$

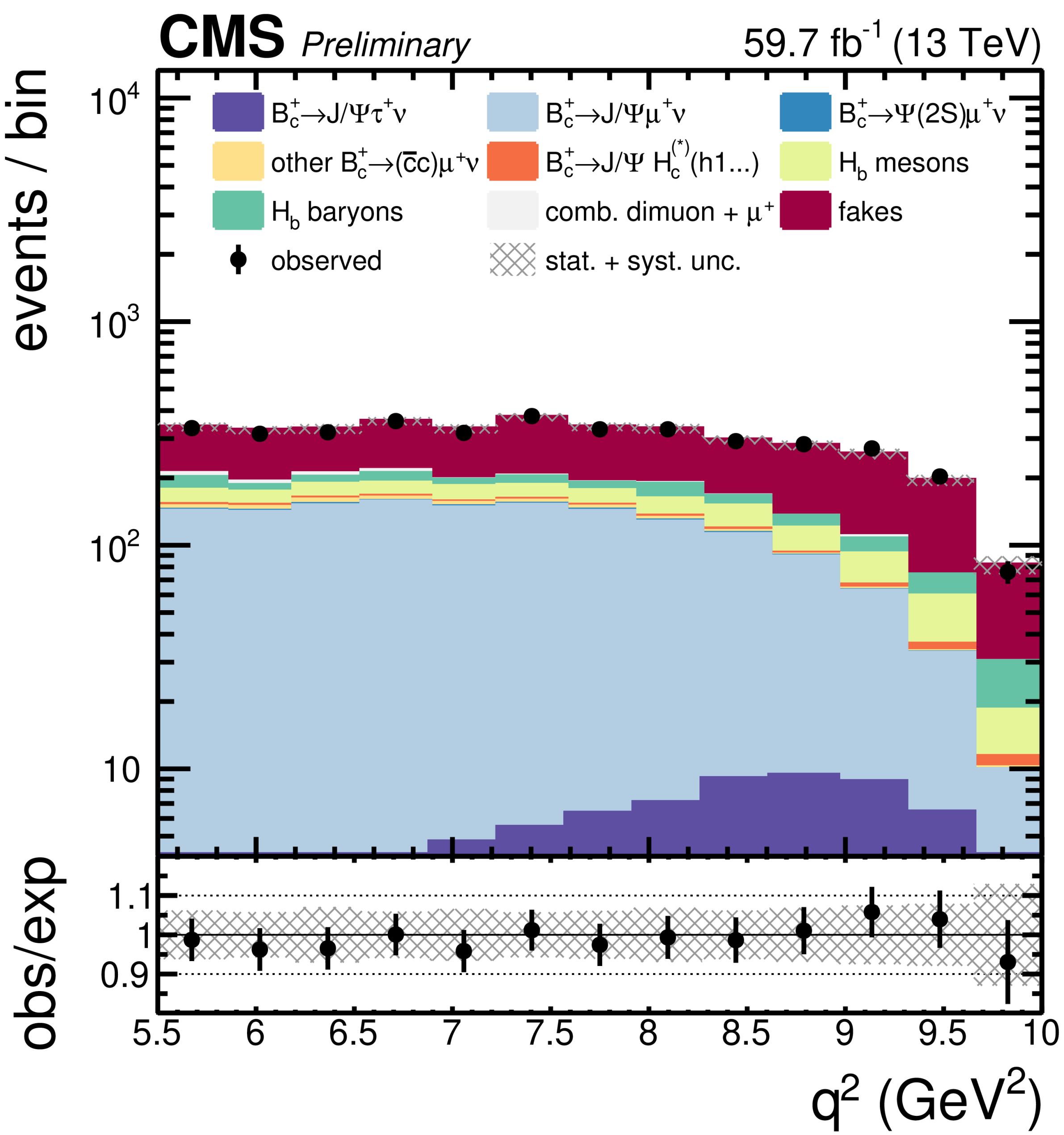
π, K : misidentified as μ : fakes, H$_b \to J/\psi(\mu^+\mu^-) + \mu^+$



$R(J/\psi) : B_c^+ \to J/\psi\tau^+\nu_\tau$

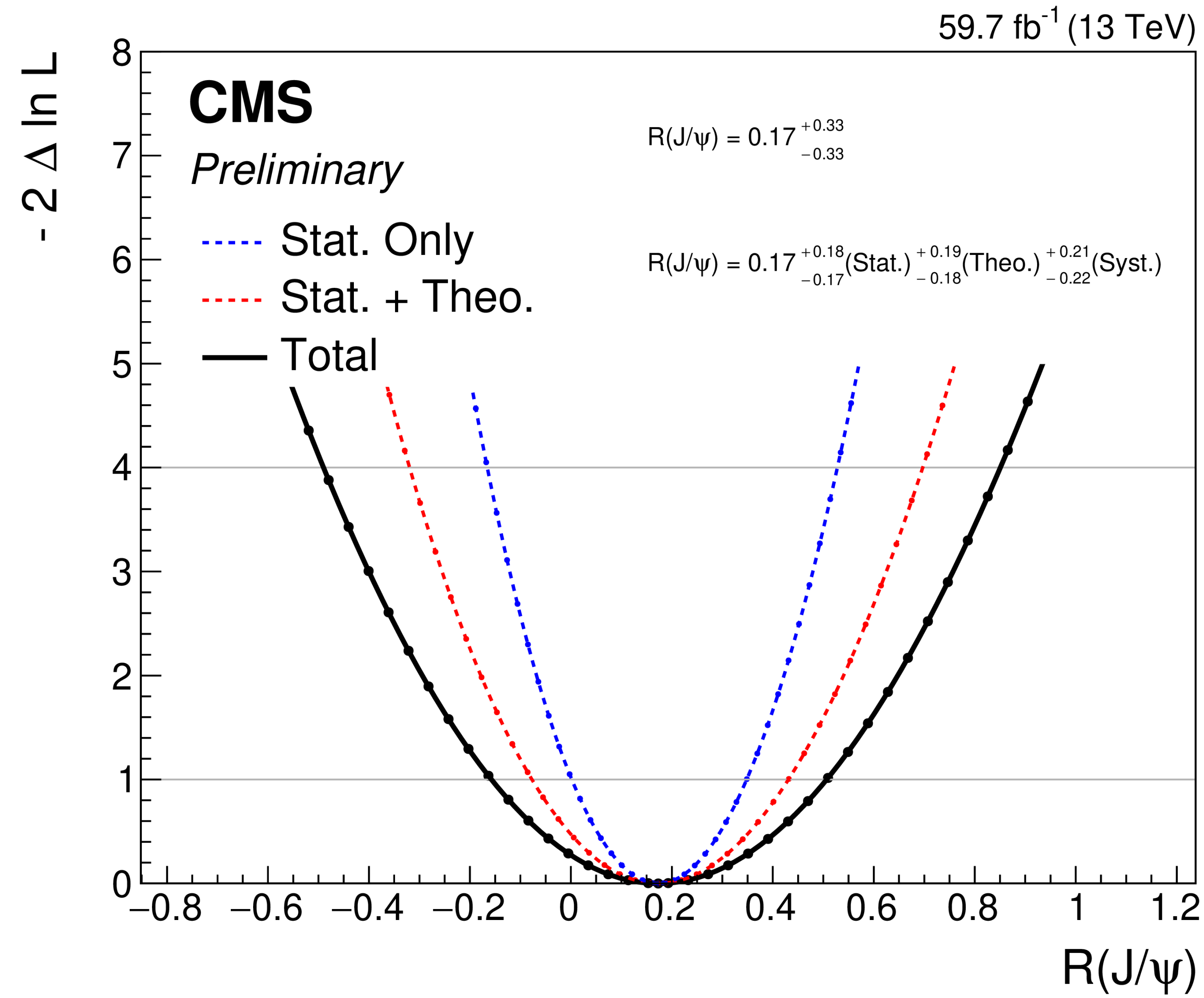
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.17^{+0.18}_{-0.17}\,(\text{stat.})^{+0.21}_{-0.22}\,(\text{syst.})^{+0.19}_{-0.18}\,(\text{theo.})$$

Physics comparison with data
in q^2 discriminator



$m(3\mu) < m_{B_c^+}, q^2 > 5.5$ GeV^2

$IP3D/\sigma_{IP3D} > 2$



Within 0.3σ with value predicted by SM and 1.3σ with the value measured by LHCb

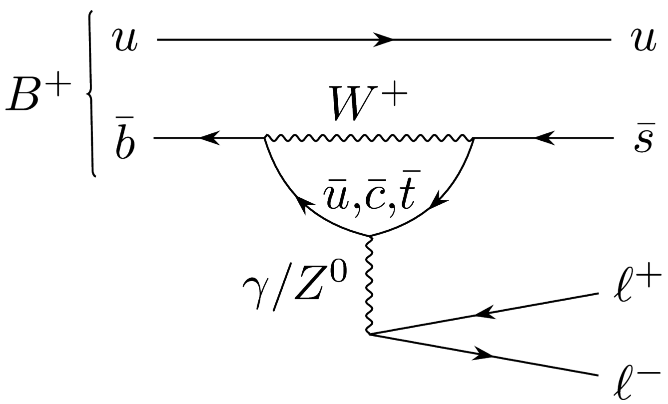
This result will certainly help the theory to be more tuned

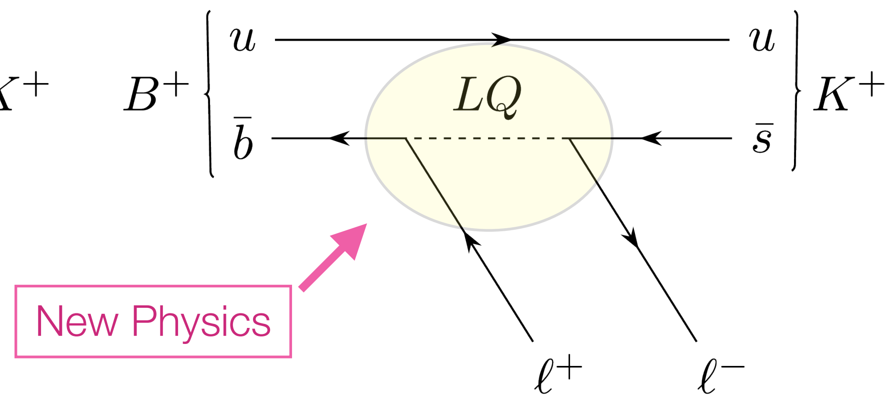
$R(K) : B^{\pm}\ell^{+}\ell^{-}$

$$R(\mathrm{K})(q^2) = \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)(q^2)}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K}^+)} \Bigg/ \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mathrm{e}^+\mathrm{e}^-)(q^2)}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mathrm{e}^+\mathrm{e}^-)\mathrm{K}^+)}$$

CMS-PAS-BPH-22-005

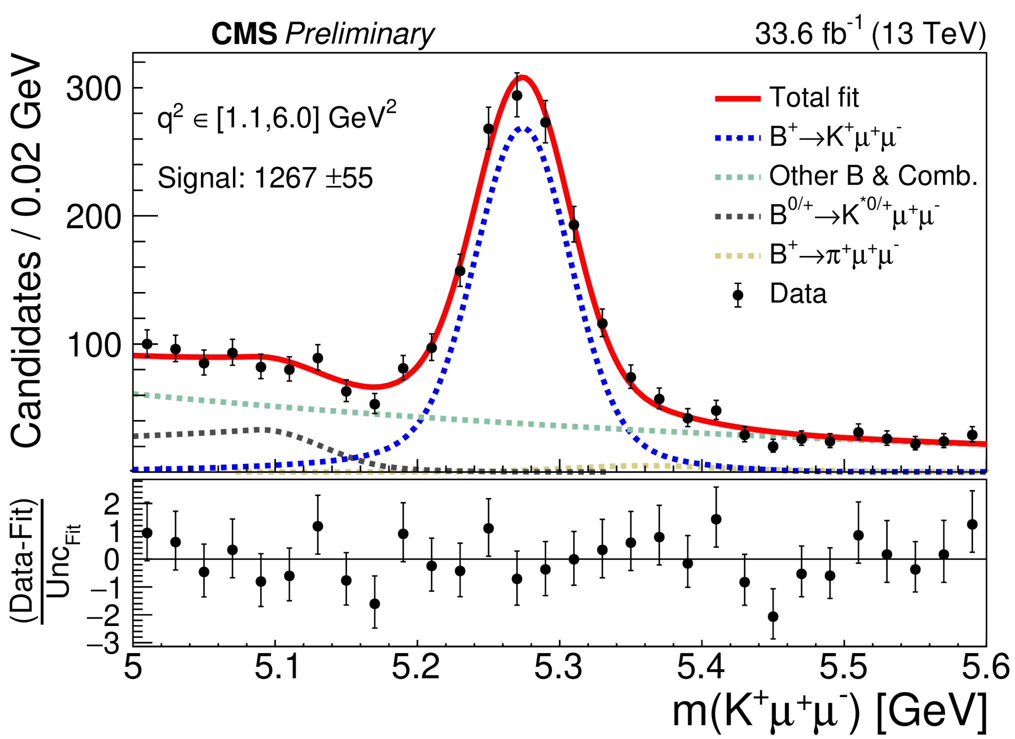
$1.1 < q^2 < 6.0$ GeV^2

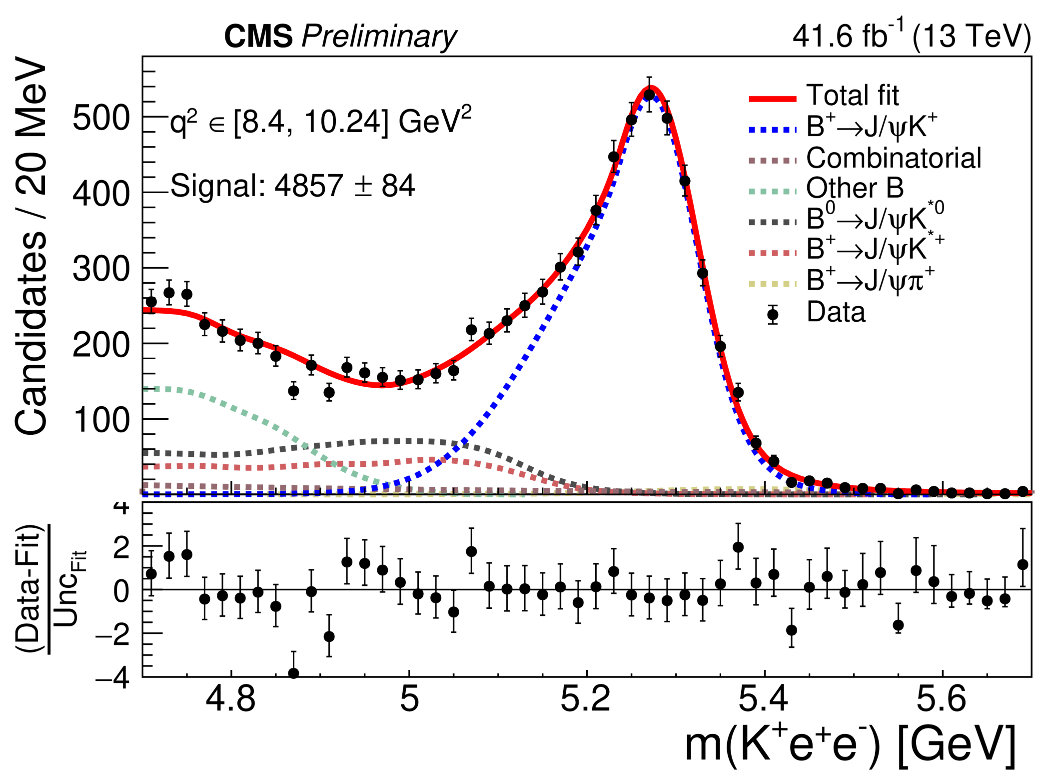




The analysis exploits the usage of B-Parking data collected with a delayed trigger

1. HLT : $\mu_{trig} : p_t > 9$ GeV, $IP_{xy}/\sigma_{xy} > 6, \mu_2 : p_t > 2$ GeV, $\Delta z(\mu_{trig}, K^+) < 1$ cm, $\Delta z(\mu_{trig}, mu_2) < 1$ cm
2. Offline selections : HLT : $p_T(K^+) > 1$ GeV, $p_T(B^+) > 3$ GeV, $L_{xy}/\sigma_{L_{xy}} > 1, P_{B^+\text{vextex}} > 10^{-5}$,
   $\cos\alpha_{3D}(B^+) > 0.9,\ 5.0 < m_{B^+} < 5.6$ GeV





Double ratio method : to avoid systematics

Final results

$$R(K) = 0.78^{+0.47}_{-0.23}$$

$$\mathscr{B}(K^{\pm}\mu^+\mu^-) = (12.42 \pm 0.68) \times 10^{-8}$$

Heavy Ion Results

QGP, Nuclear modification factor and all that …

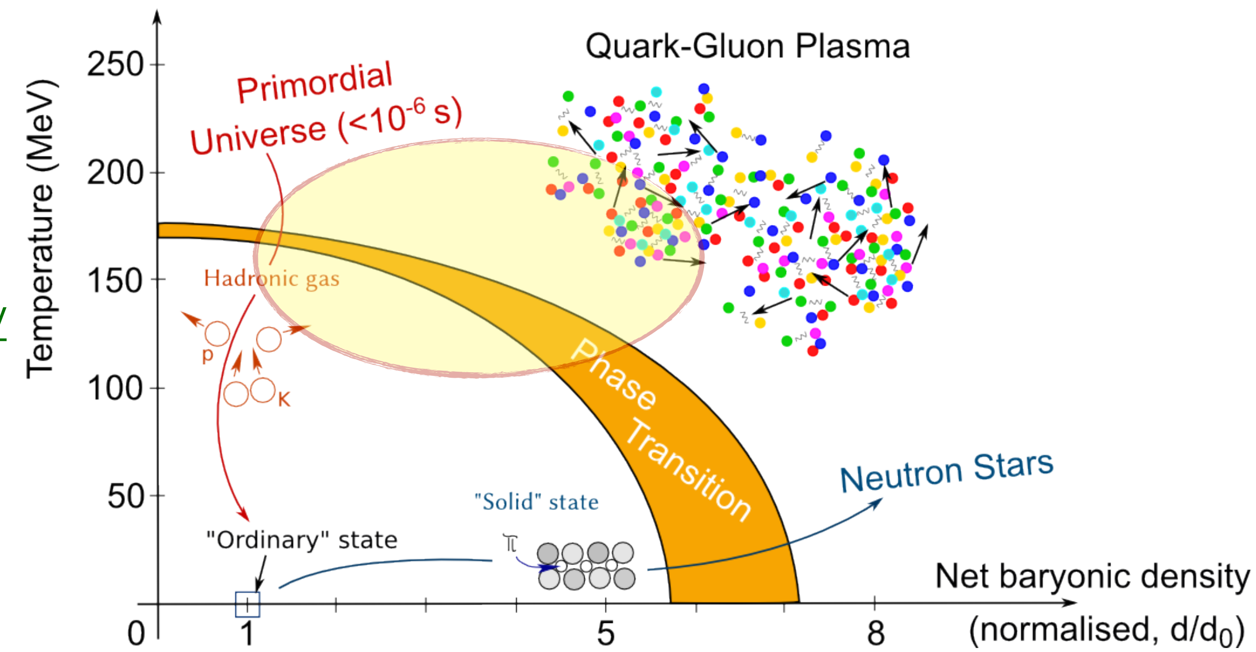
-Quark epoch :
$10^{-12} \sim 10^{-5}$ sec, 10^{15} K – 10^{15} K, 150 GeV – 150 MeV, possibility of the existence of the quark-gluon plasma in this epoch

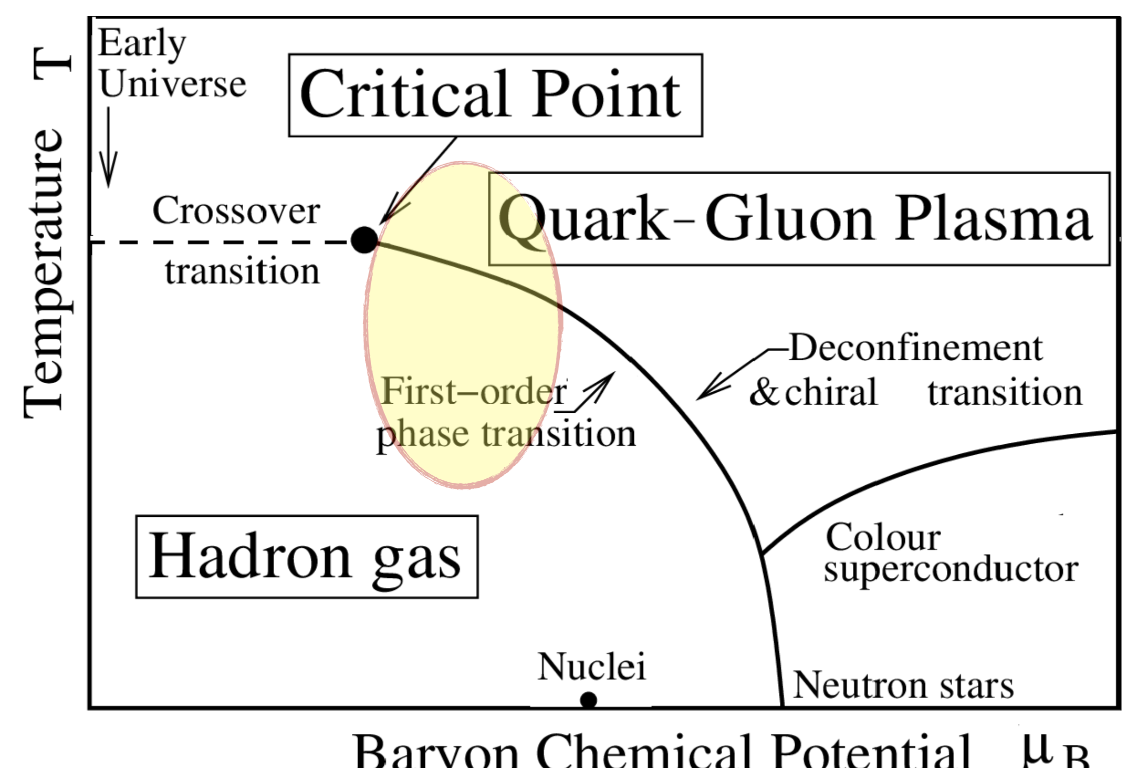
-QGP formed in the heavy ion collision could unfold some early universe properties

-Indeed gravity was **already decoupled during the quark epoch**, still we do not know what was the ***aftermath of the decoupling of*** $R_{\mu\nu\delta\gamma}$, on the other hand the QFT in high temperature could study the properties of the hot QGP soup, ***thermal behaviors of the QGP soup can be linked to the thermal properties of the massive gravitating bodies in terms of entropies*** ?

- interesting properties such as : nuclear modification factor (R_{AA}) (the ratio of the yield in Pb-Pb to the corresponding yield in pp collisions scaled by the number of binary nucleon-nucleon collisions), mean nuclear overlap function (T_{AA}) (average number nucleon-nucleon binary collisions normalized by pp inelastic cross section) are the indicating factors of how hot medium modifies the particle production compared to the simple superposition nucleon-nucleon collisions

CERN-THESIS-2011-263

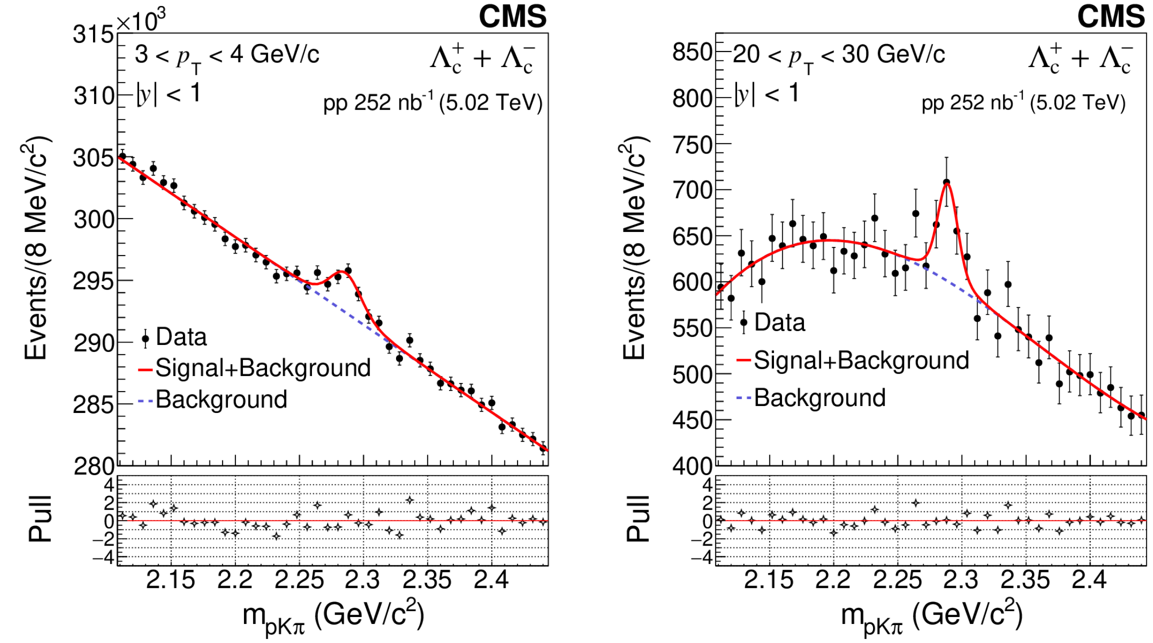




This talk : Pb-Pb/p-Pb : $\Lambda_c^+ \to pK^-\pi^+, B^+ \to J/\psi K^+, B_s^0 \to J/\psi\phi$

$\Lambda_c^+ \to pK^-\pi^+$

CMS-HIN-21-004



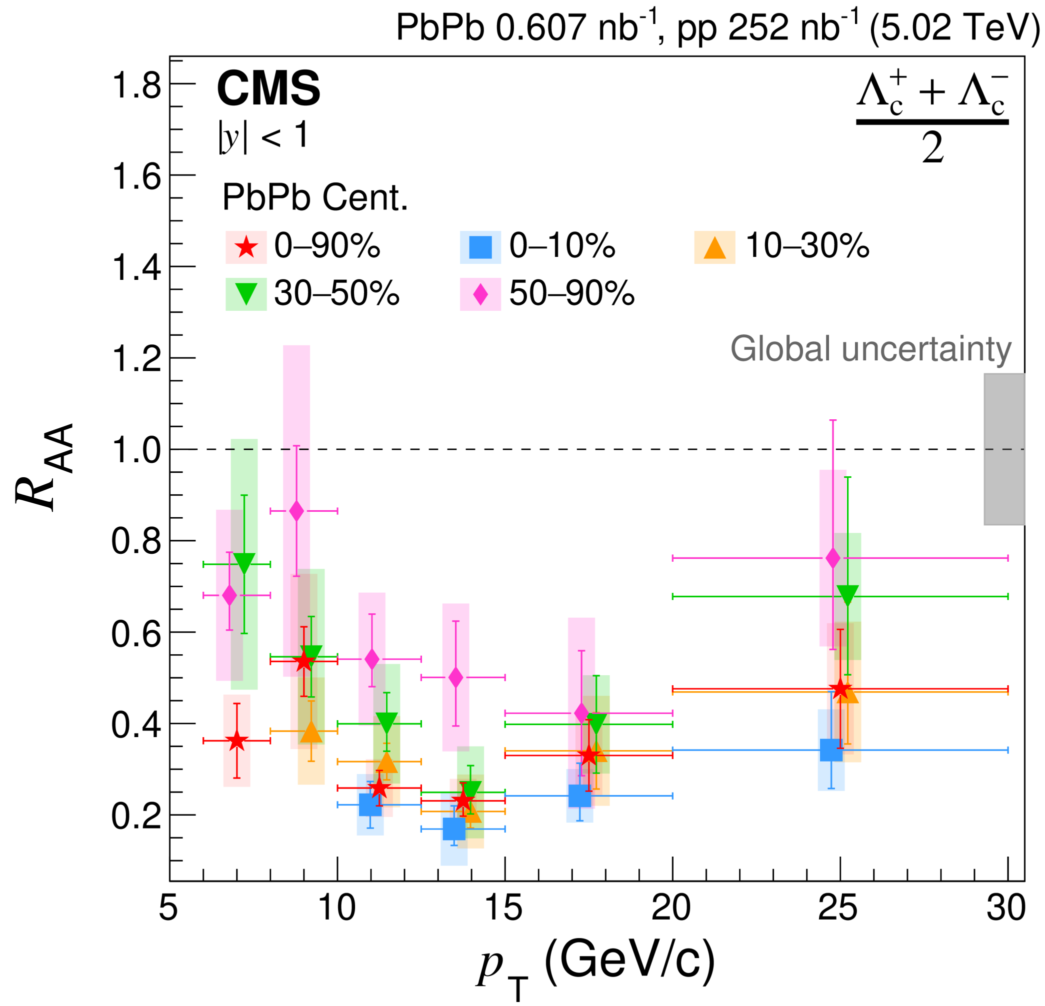
Selection:

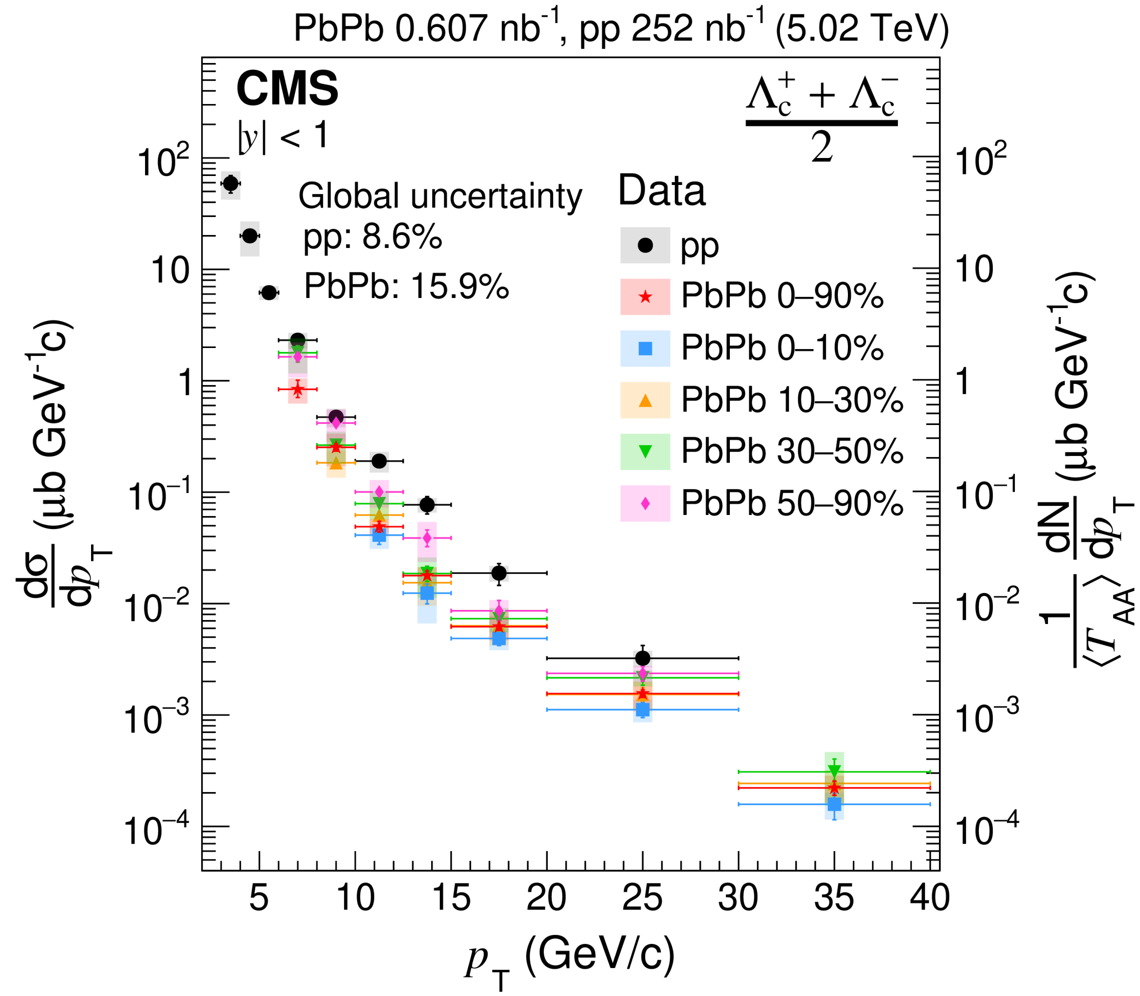
$|\eta| < 1.2$, $p_T > 0.5$ GeV(pp), > 1 GeV(Pb-Pb), $2.11 < m(\Lambda_c^+) < 2.45$GeV, boosted tree is used to optimized the physics selection for pp and lead-lead collisions, the total charge of the signal $\Lambda_c^+ \to pK^-\pi^+$ (charged conjugate) is assigned +1(-1)

Fit :

Unbinned maximum likelihood fit : signal : triple Gaussian , combinatorial background : Chevyshev polynomial

global uncertainty for R_{AA} is 16.5%

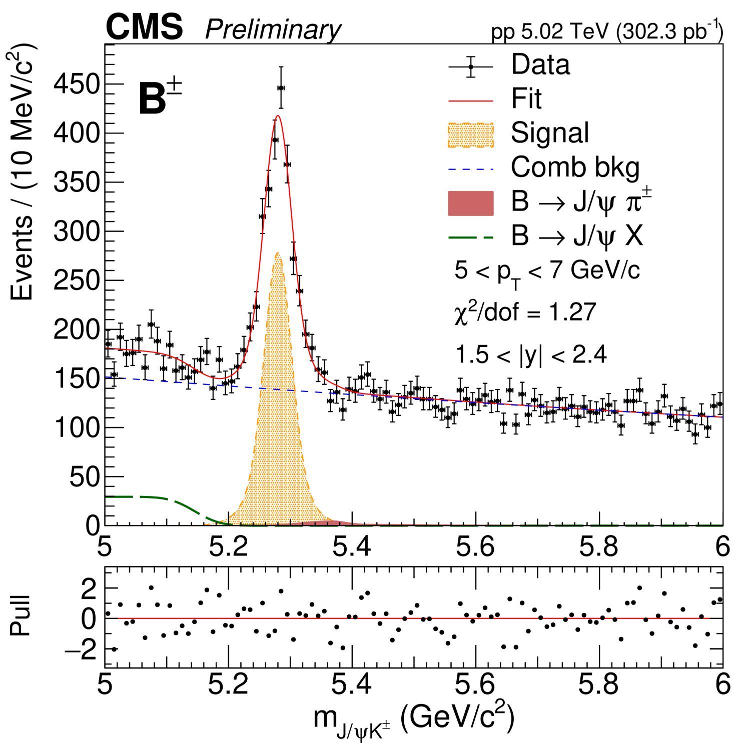


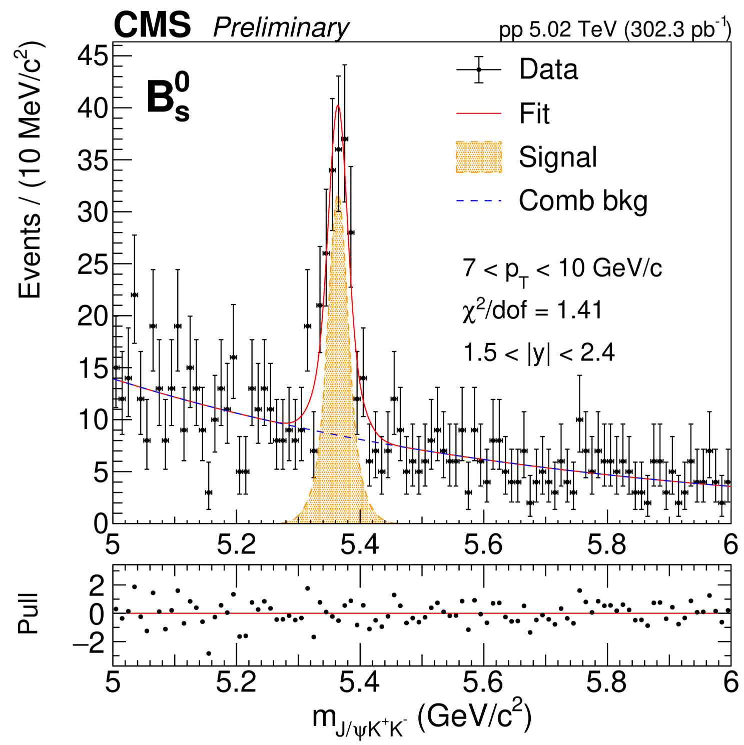


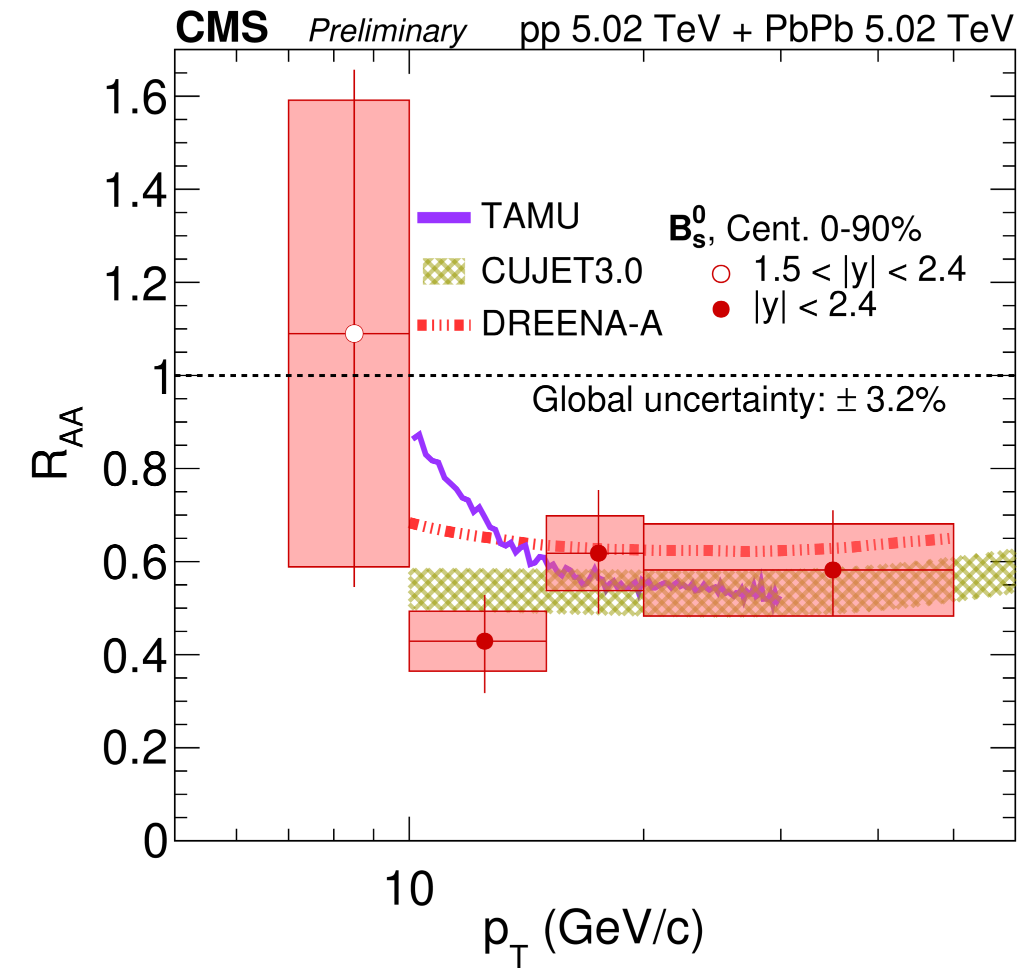
The Λ_c^+ baryon yields for pp collisions are much higher than predicted by calculations with the general-mass variable-flavor-number scheme that use fragmentation functions obtained by fit-ting results from the OPAL and Belle collaborations, indicating a breakdown of the universality of charm quark fragmentation functions

$B^+ \to J/\psi K^+$ & $B_s^0 \to J/\psi \phi$

CMS-PAS-HIN-21-014







1. Common vertex requirement for the resonance vertex, with $J/\psi(B^+, B_s^0), \phi(B_s^0)$ resonances

2. Fiducial region for the B meson candidate reconstruction :

$1.5 < |y| < 2.4 : p_T < 10$ GeV

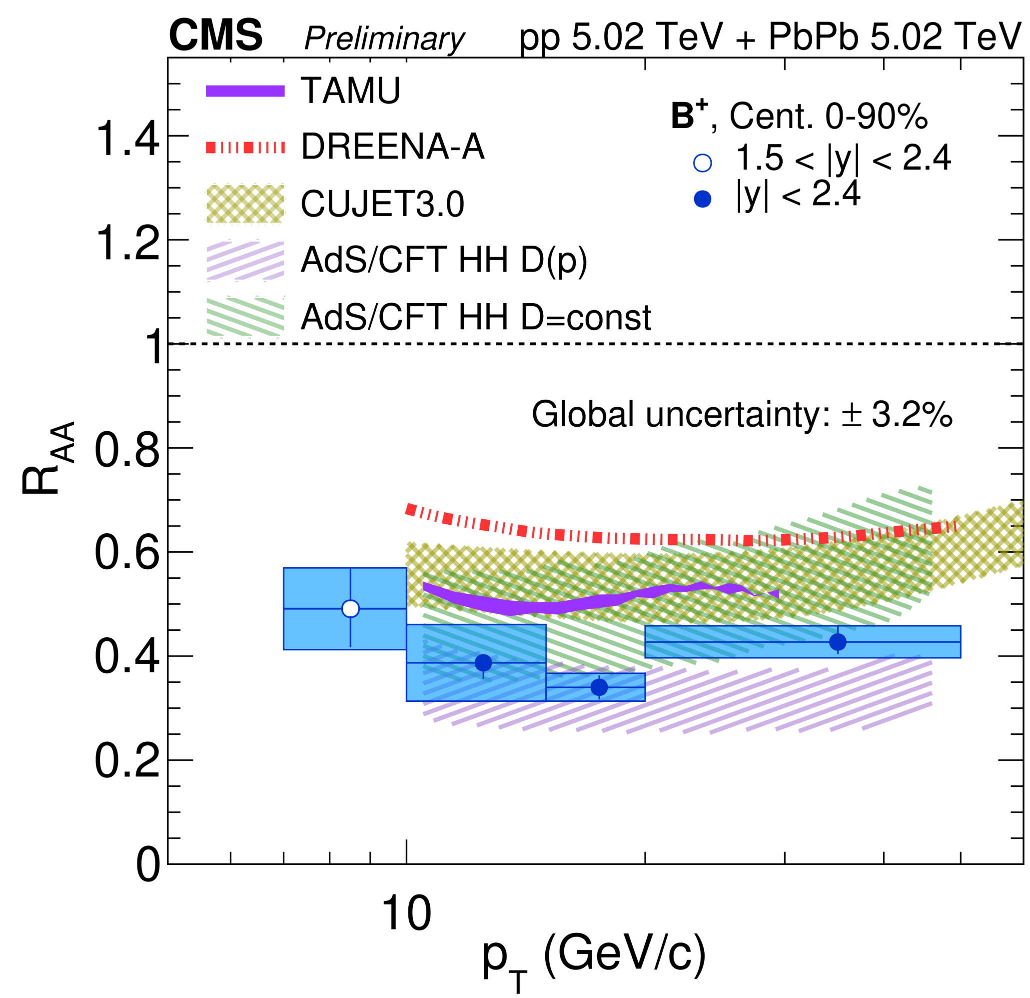
$|y| < 2.4 : p_T > 10$ GeV

3. R_{AA}:

B^+ : all comparison with diffusion coefficient either dependent or independent of the quark momentum;

B_s^0 : the theory line contains the total b quark coalescence probability

The nuclear modification factors, R_{AA}, of B^+ are significantly lower than unity at $p_T > 10$ GeV, while at low p_T, the B_s^0 hints at a larger R_{AA} than that of B^+. The R_{AA} data from B^+ and B_s^0 are also compared to theoretical calculations, providing constraining power on the mechanism of beauty quark energy loss and hadronization in the quark-gluon plasma.



Summary

1. We have a smooth detector operation now and looking forward to more challenging aspect : both detector development and physics

2. Results Presented :

B-Physics : $R(J/\psi) : B_c^+ \to J/\psi \tau^+ \nu_\tau$, $R(K) : B^\pm \ell^+ \ell^-$

Heavy Ion : R_{AA} : $\Lambda_c^+ \to pK^- \pi^+, B^+ \to J/\psi K^+$ & $B_s^0 \to J/\psi \phi$

3. There are more analysis (due to time constrain I would invite you look at the CMS public results)

B-Physics : Observation of $\Lambda_b^0 \to J/\psi \Xi^- K^+$ (CMS-PAS-BPH-22-002)

Heavy ion : a. Multiplicity dependence of charm baryon and meson production in pPb collisions at 8.16 TeV (Λ_c^+, D^0) (CMS-PAS-HIN-21-016)

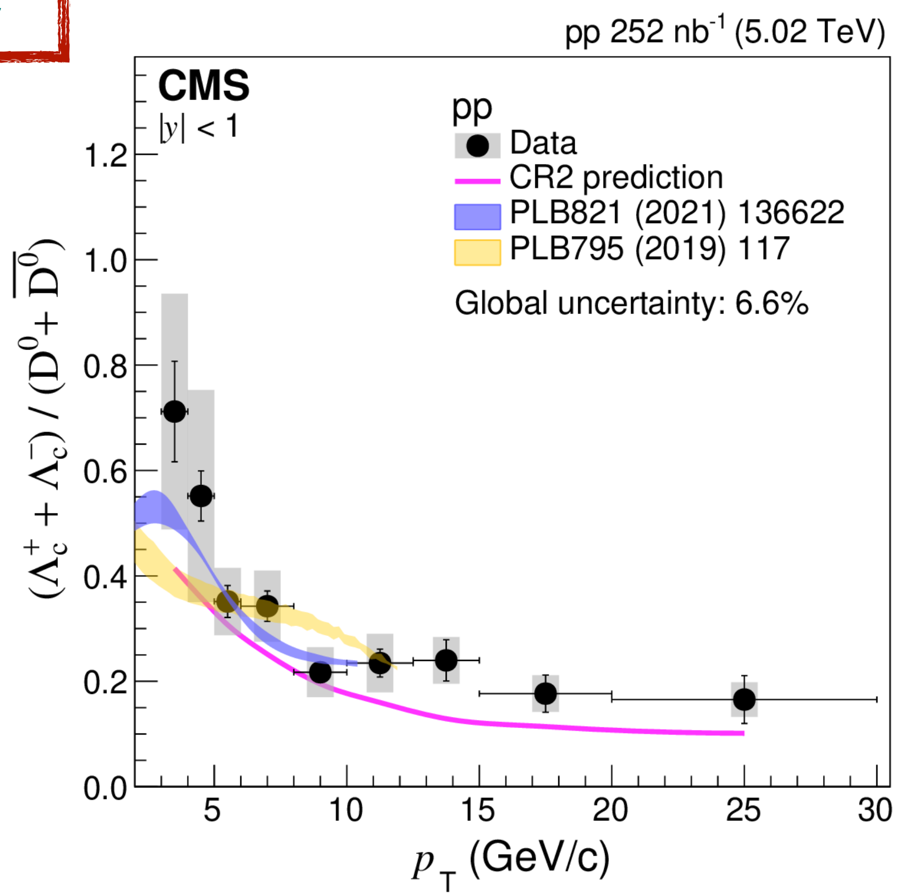
b. Measurement of the B^+ differential cross section as a function of P_T (pPb) (CMS-PAS-HIN-22-001)

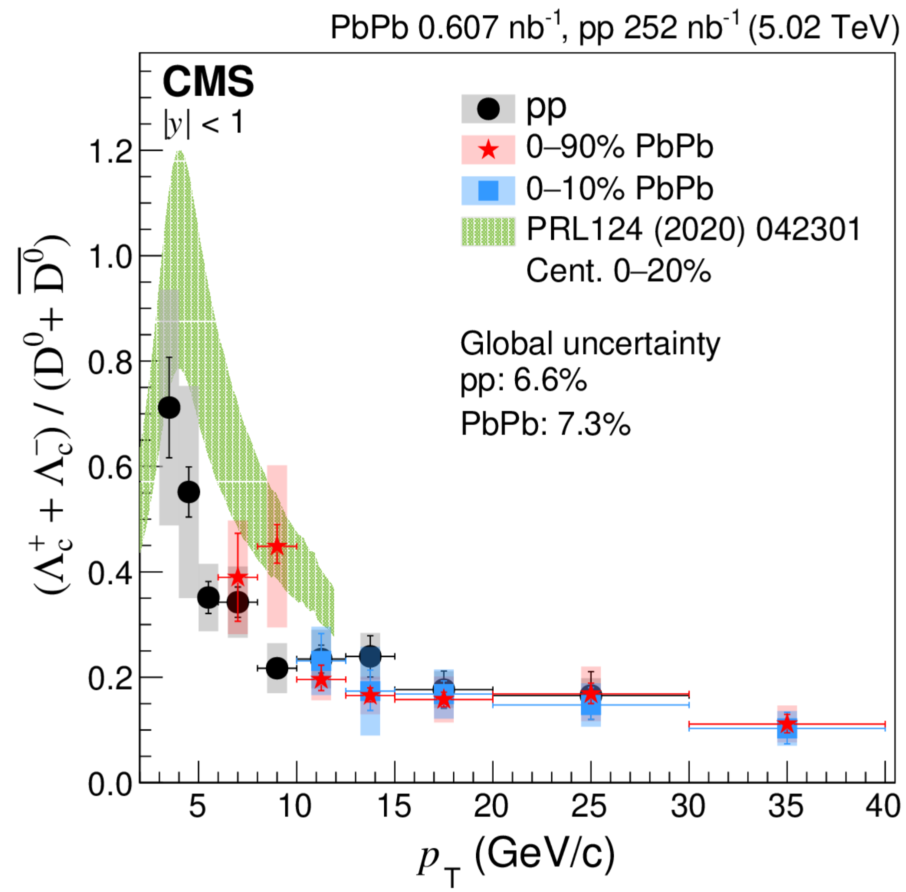
4. We are also looking forward to see the results of the Run-III data.

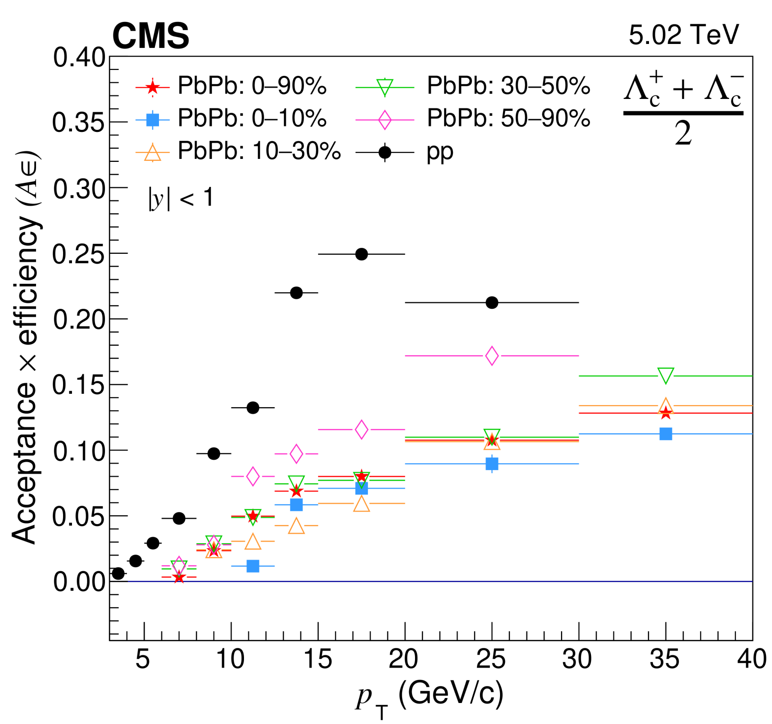
Thank you!!

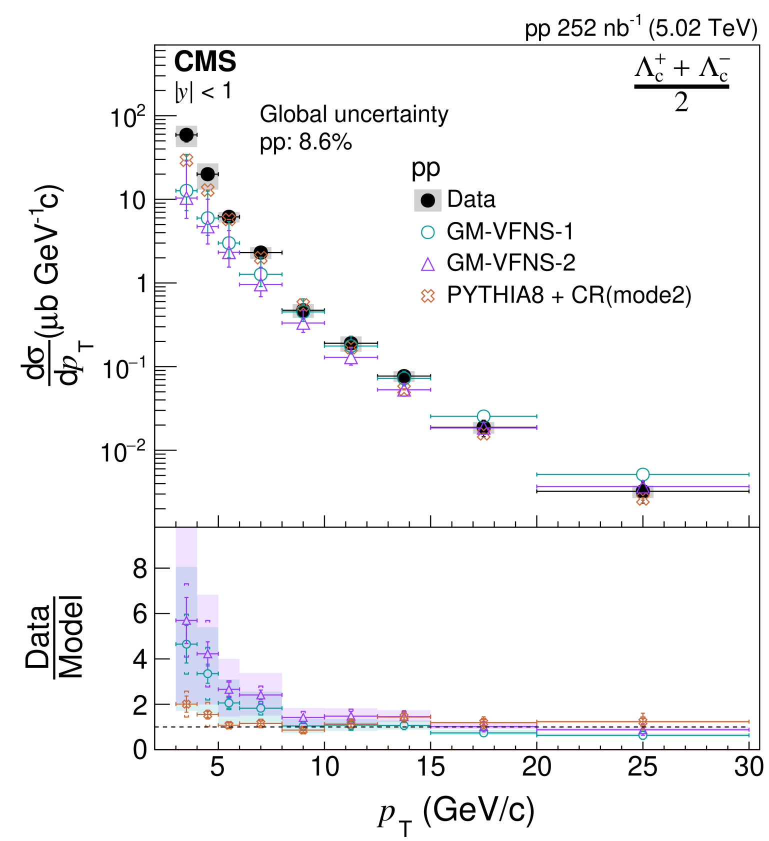
Bonus Slides

$\Lambda_c^+ \to pK^-\pi^+$

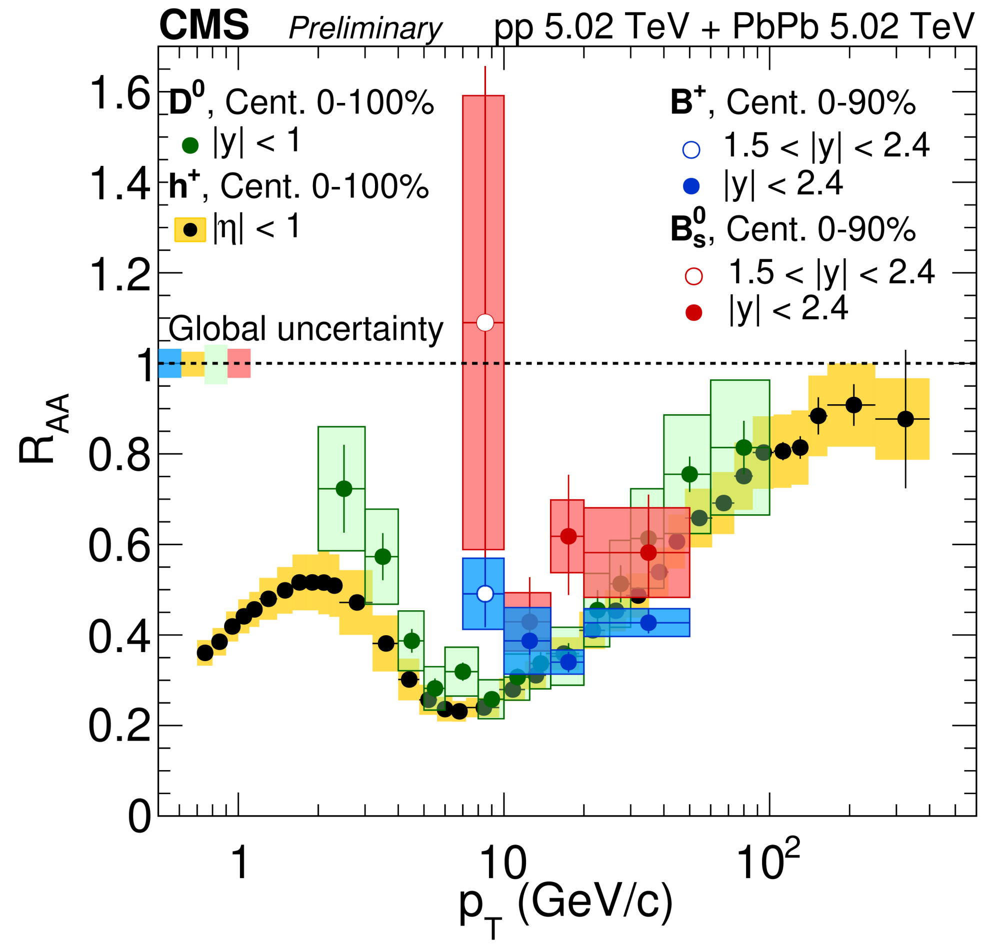




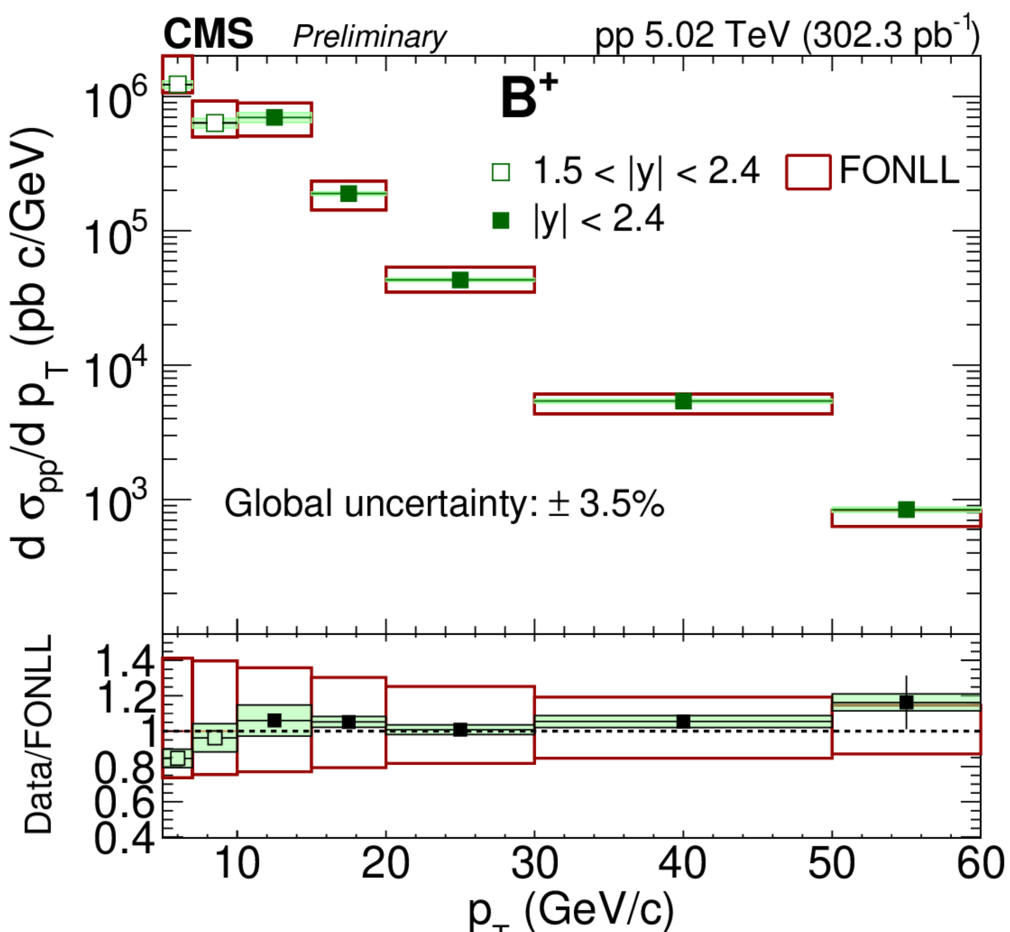


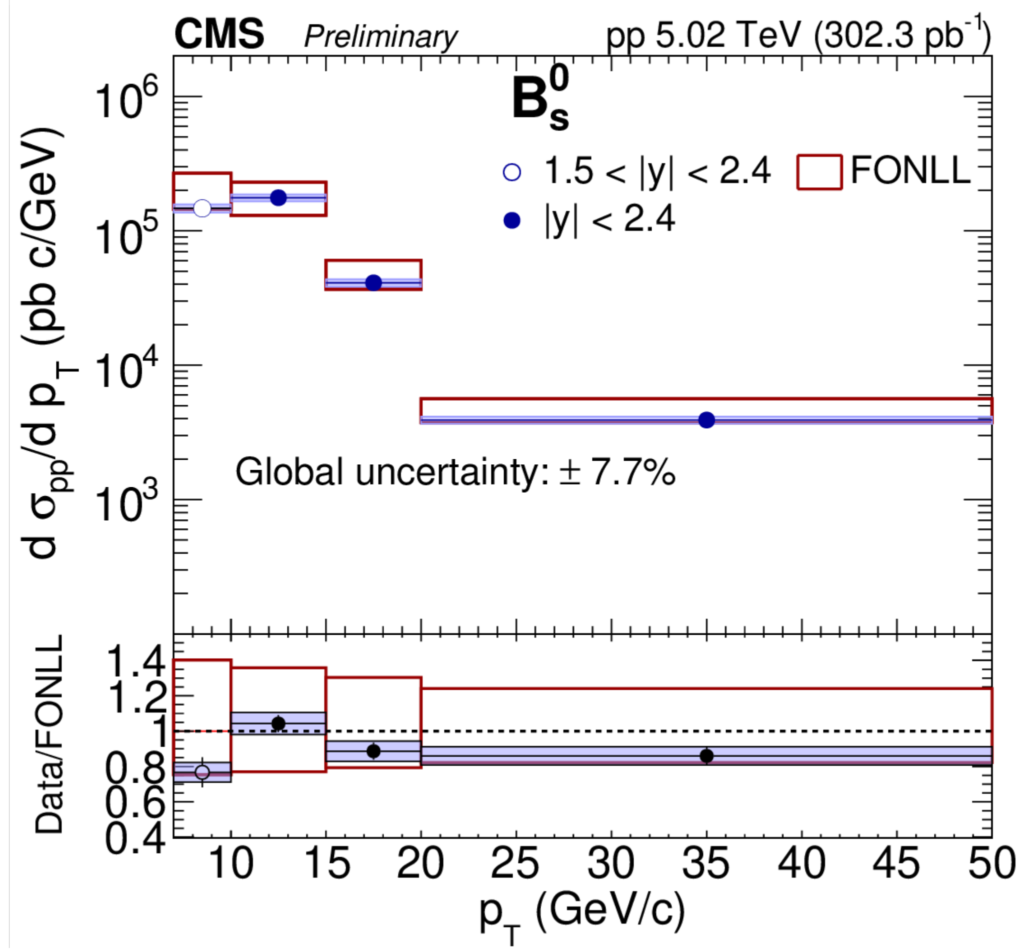


$B^+ \to J/\psi K^+$ & $B_s^0 \to J/\psi \phi$



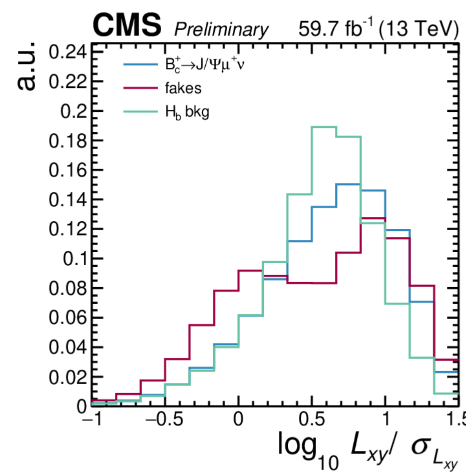
X-section and comparison with D^0

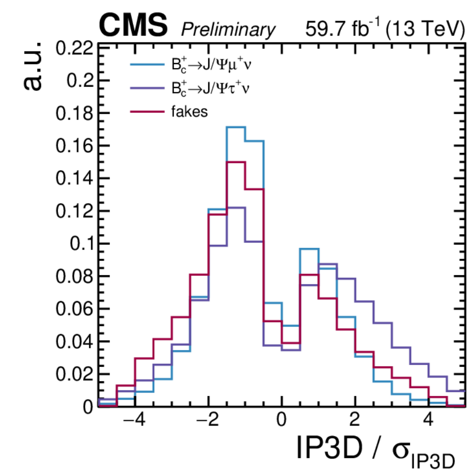


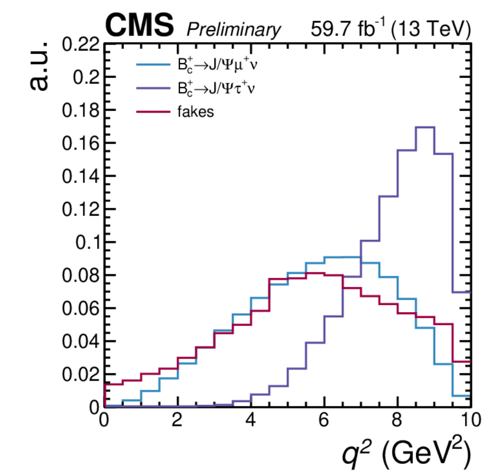


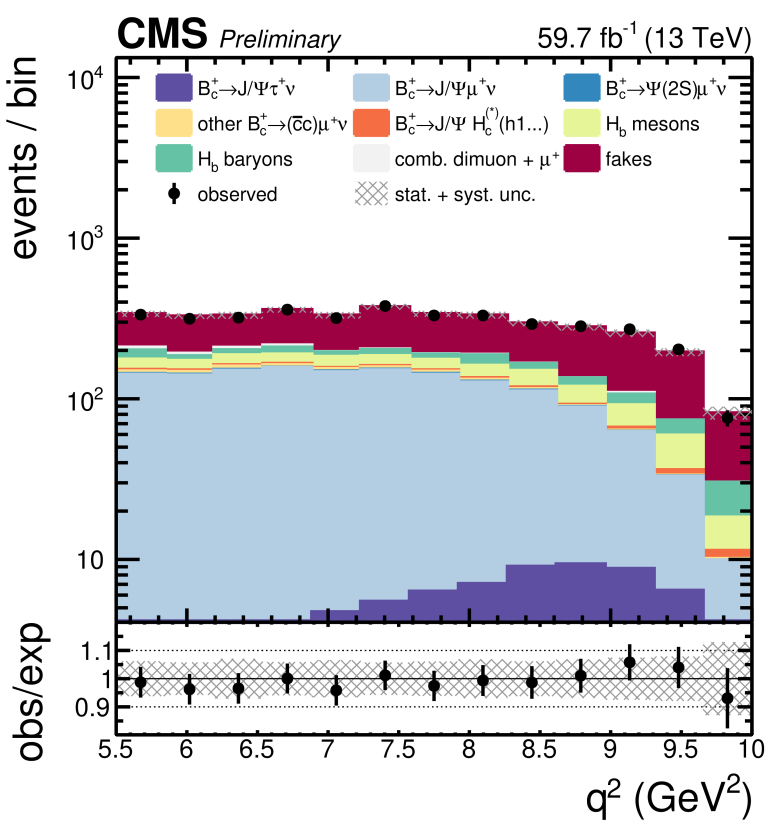
$R(J/\psi) : B_c^+ \to J/\psi \tau^+ \nu_\tau$

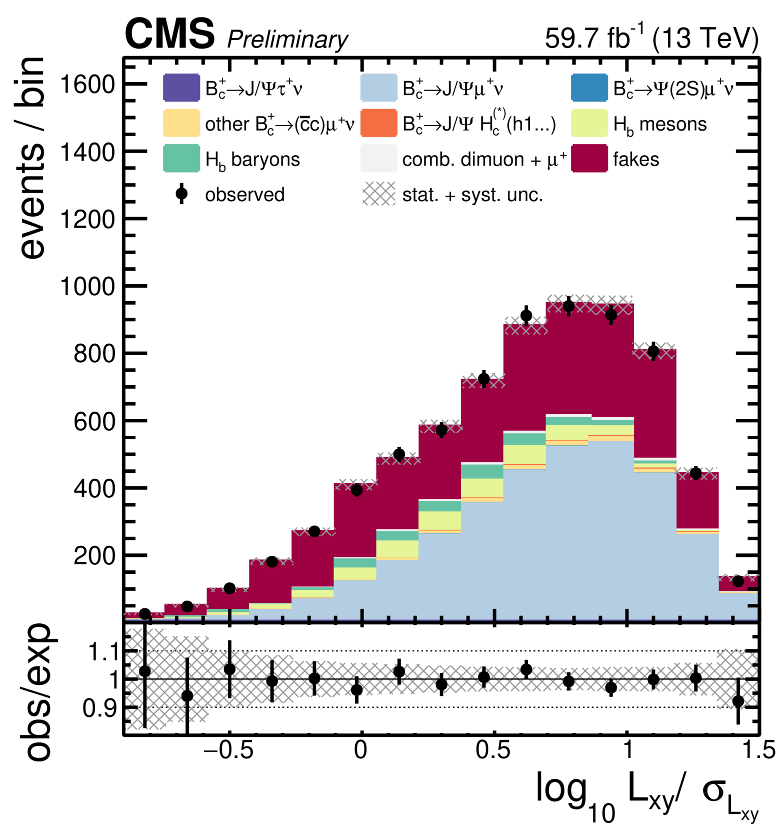
π, K : misidentified
as μ : fakes,
$H_b \to J/\psi(\mu^+\mu^-) + \mu^+$







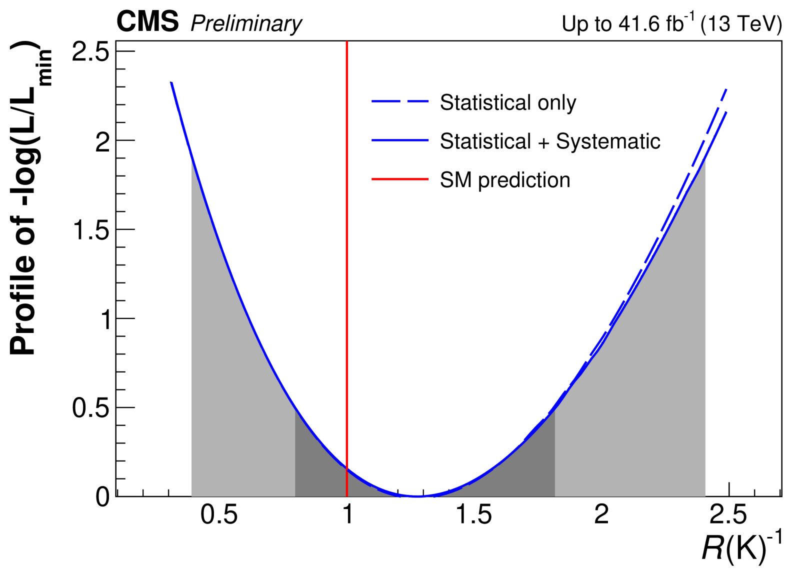


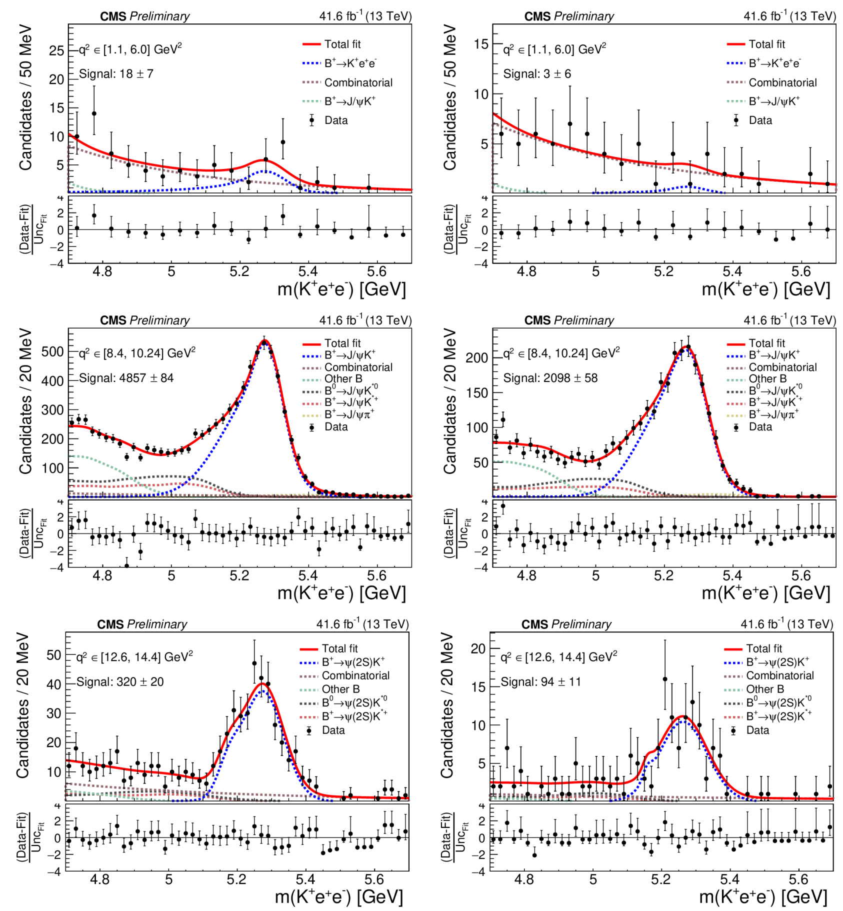


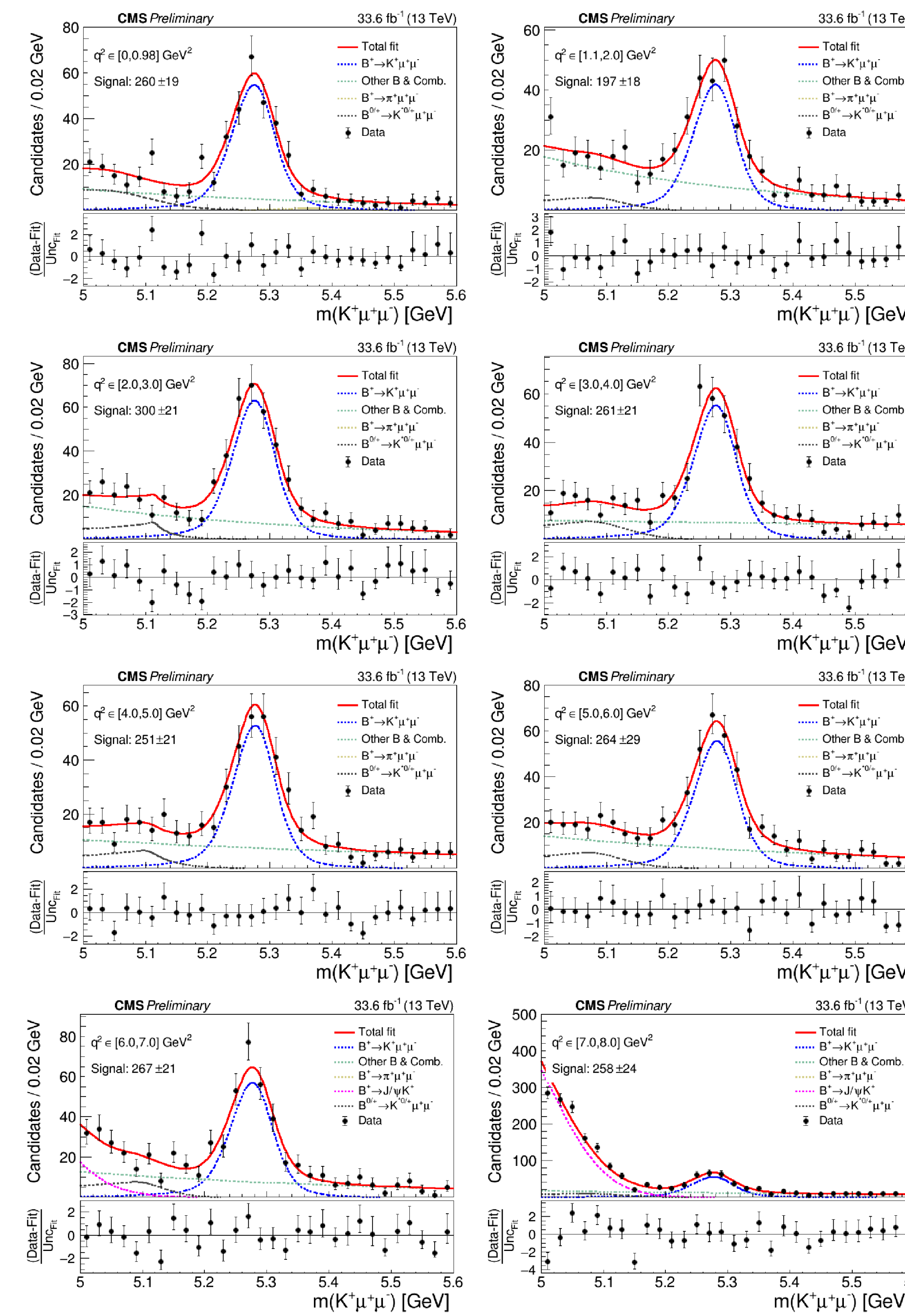
$m(3\mu) < m_{B_c^+}, q^2 > 5.5$ GeV^2
$IP3D/\sigma_{IP3D} > 2$

$m(3\mu) < m_{B_c^+}, q^2 > 4.5$ GeV^2
$IP3D/\sigma_{IP3D} > 0$

$R(K) : B^{\pm}\ell^{+}\ell^{-}$







Channel	q^2 range	Yield
$B^+ \to K^+\mu^+\mu^-$	1.1–6.0 GeV^2	1267 ± 55
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	8.41–10.24 GeV^2	$728\,000 \pm 1100$
$B^+ \to \psi(2S)(\mu^+\mu^-)K^+$	12.60–14.44 GeV^2	$68\,300 \pm 500$

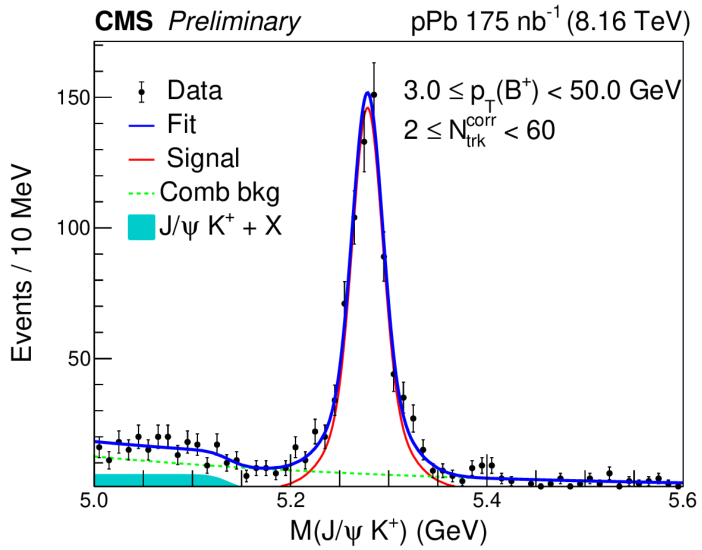
Channel	q^2 range	PF-PF yield	PF-LP yield
$B^+ \to K^+e^+e^-$ (low-q^2)	1.1–6.0 GeV^2	17.9 ± 7.2	3.0 ± 5.9
$B^+ \to J/\psi(e^+e^-)K^+$	8.41–10.24 GeV^2	4857 ± 84	2098 ± 58
$B^+ \to \psi(2S)(e^+e^-)K^+$	12.60–14.44 GeV^2	320 ± 20	94 ± 11

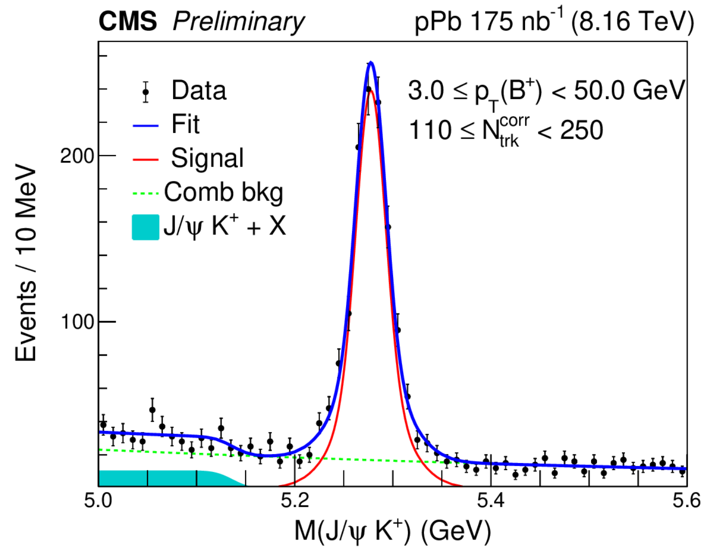
$B^+ \to J/\psi K^+$

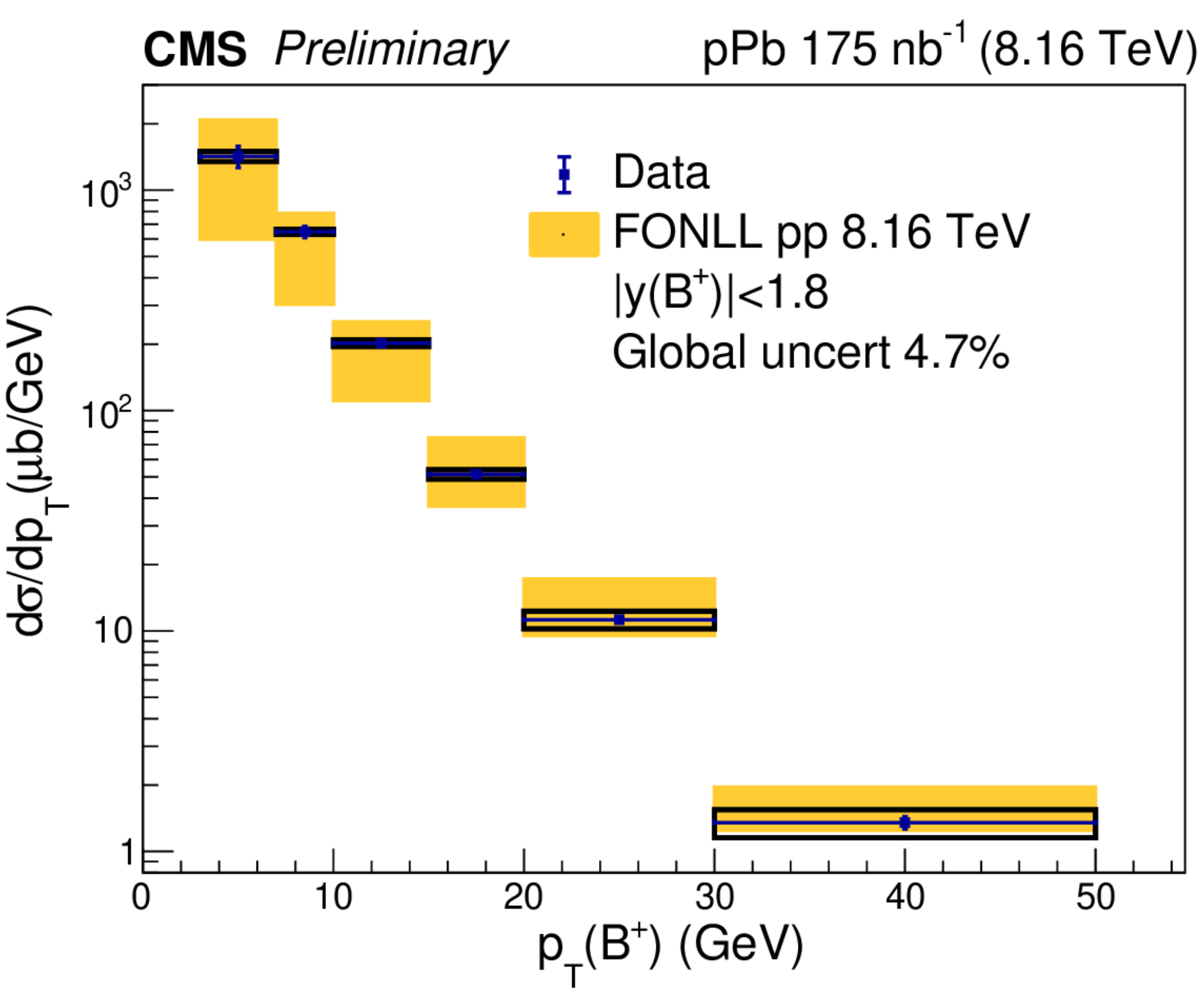
CMS-PAS-HIN-2

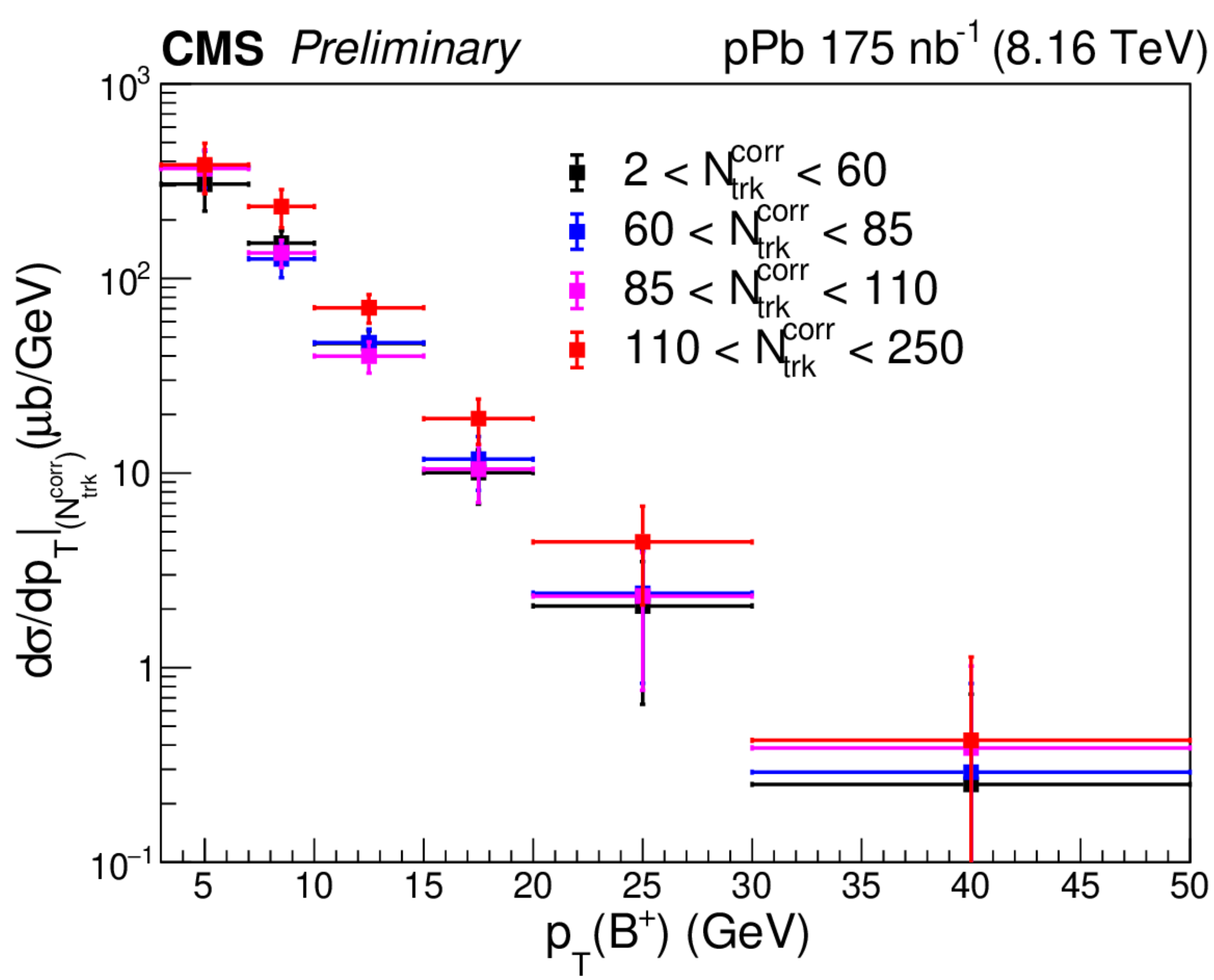
1. B^+ : production cross section with respect to the transverse momentum inclusively

2. B^+ : for the first time, in different charged particle multiplicities, in proton-lead collisions









Mention of the two more analysis in the summary