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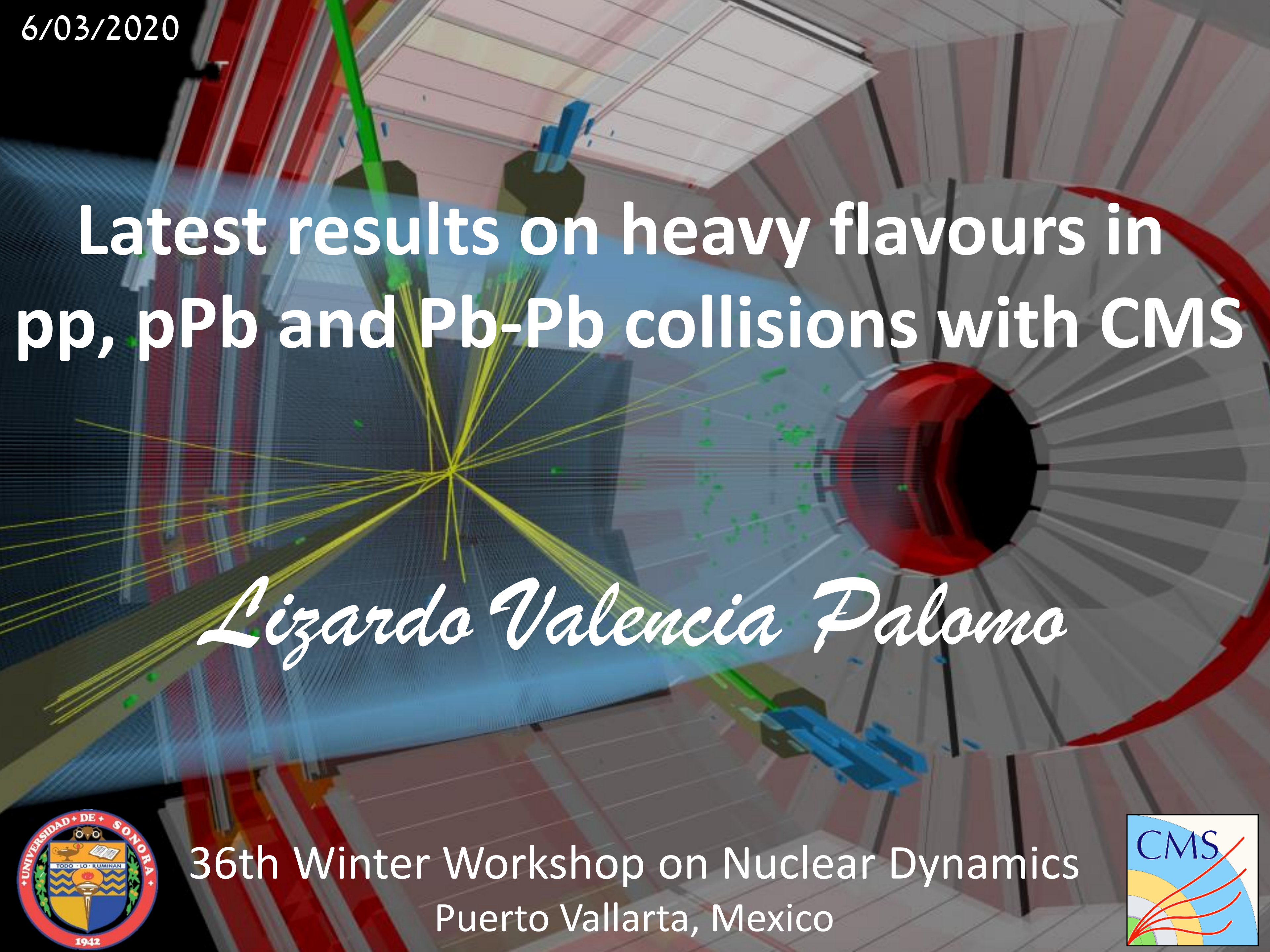

Latest results on heavy flavours in pp, pPb and Pb-Pb collisions with CMS

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36th Winter Workshop on Nuclear Dynamics

Puerto Vallarta, Mexico

Content

Physics motivation

Analysis

Quarkonium

Open Heavy Flavours

Summary

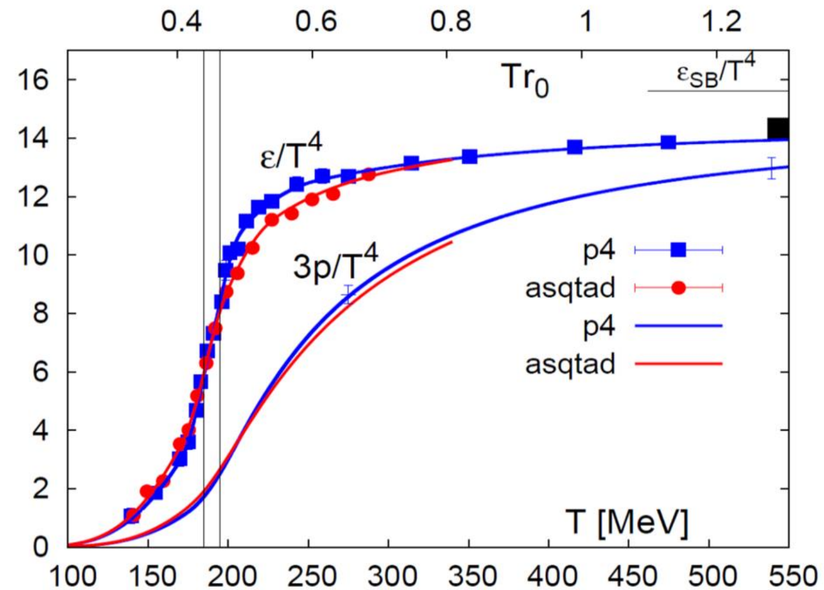
PHYSICS MOTIVATION

The Quark-Gluon Plasma

Lattice QCD predicts a phase transition of ordinary nuclear matter at a critical temperature of $T_C \approx 190$ MeV.

Energy density increases due to lattent heat of deconfinement

Quark-Gluon Plasma (QGP): deconfined state of quarks and gluons. In order to recreate the QGP in the laboratory we use high energy heavy ion collisions (A-A).



PRD 80 (2009) 014504

Different kind of probes used to study the QGP: jets, hyperons, vectorial mesons, etc.

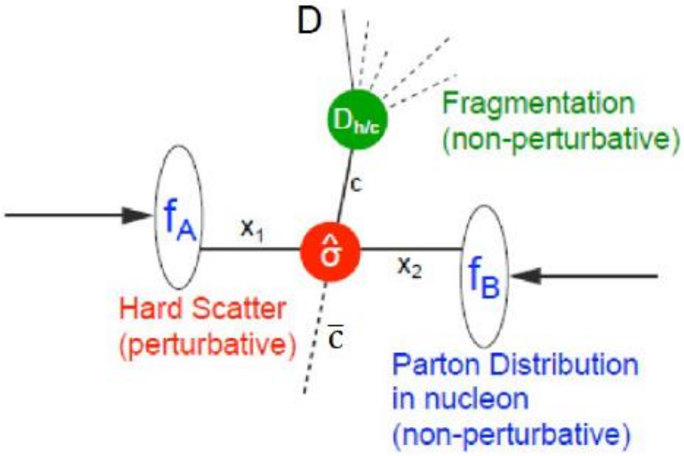
This talk will review the latest results on:

- Open Heavy Flavours (OHF): hadrons containing only one heavy quark (*c* or *b*).
- Quarkonium: pairs of heavy quark and anti-quark of the same flavour

proton-proton collisions

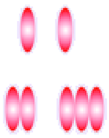
Test perturbative QCD inspired models (FONLL, GM-VFNS, NRQCD, etc): predict OHF and quarkonium production rates.

$$\sigma_{hh\to Hx} = \boxed{PDF(x_a,Q^2)PDF(x_b,Q^2)} \otimes \boxed{\sigma_{ab\to q\bar{q}}} \otimes \boxed{D_{q\to H}(z_q,Q^2)}$$



As a reference in heavy ion collisions through the Nuclear Modification Factor R_{AA}:

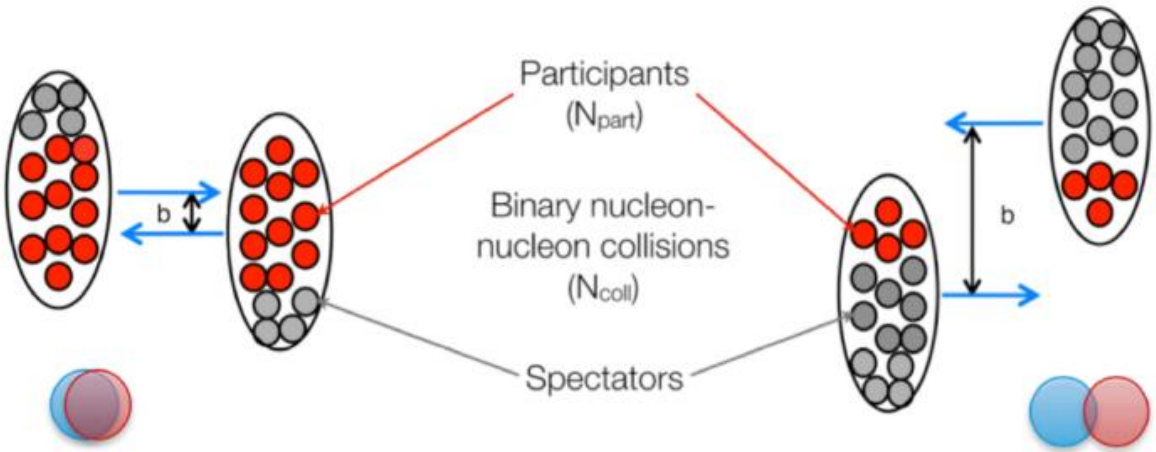
$$R_{\mathrm{AA}} = \frac{d^2N_{\mathrm{A\text{-}A}}/dp_{\mathrm{T}}d\eta}{\langle N_{\mathrm{coll}}\rangle \; d^2N_{\mathrm{pp}}/dp_{\mathrm{T}}d\eta}$$



$N_{part} = 2$ $N_{coll} = 1$

$N_{part} = 5$ $N_{coll} = 6$

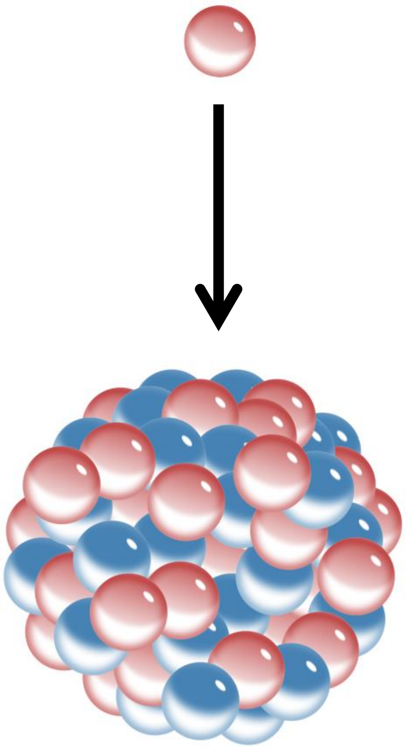
Pb-Pb cent. $N_{part} = 360$ $N_{coll} = 1500$



proton-nucleus collisions

Possibility to disentangle the Cold Nuclear Matter (CNM) effects to those related to the presence of the QGP.

CNM: initial state effects can modify the particle production. Open and hidden heavy flavour production can be affected by:



- *Shadowing/Anti-Shadowing* (JPG 32 (2006) R367): gluon PDF of nucleons in the nucleus ≠ gluon PDF of free nucleons.
- Energy loss (PRC 75 (2007) 064906): multiple scattering of partons in the nucleus before and/or after the hard scattering can lead to parton energy loss.
- Nuclear absorption (PRL 77 (1996) 1703): pre-resonance state can interact with the nuclear environment and, as a consequence, be dissociated.
- Comovers interactions (PRL 77 (1996) 1703): resonance can be destroyed by scattering on particles produced during the collision (comovers).
- Gluon saturation (NPA 920 (2013) 78): number of gluons in the wave function of a nucleus ≠ to the addition of the gluon field of the nucleons.

OHF in heavy ion collisions

Charm and beauty quarks are created in the initial hard scatterings of the collision, so they experience the whole evolution of the system.

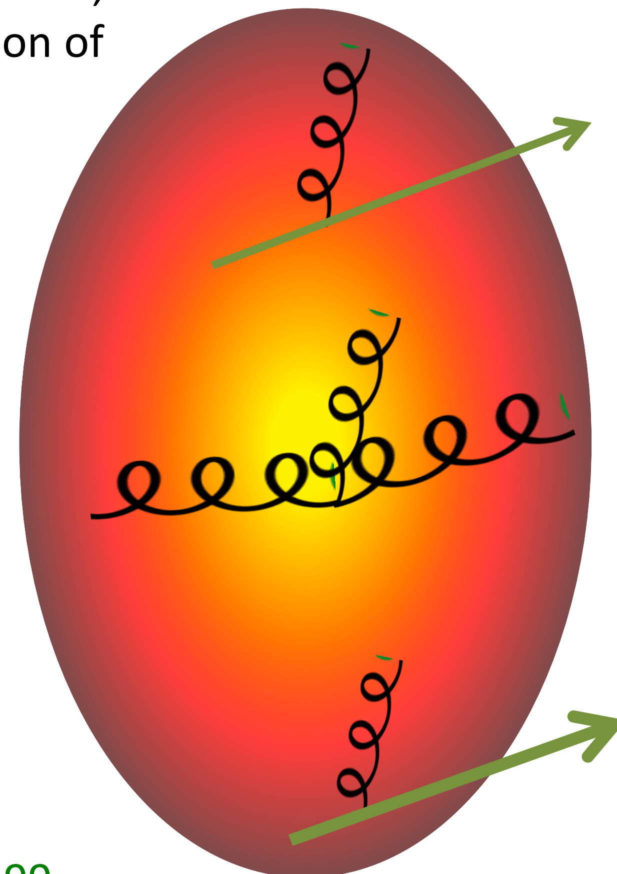
Can be used to investigate the in-medium partonic energy loss in the hot and dense QCD matter created in heavy ion collisions.

QCD and *dead cone effect* (gluon suppression radiation) say that:

$$\Delta E_g > \Delta E_c > \Delta E_b$$

$$\rightarrow \quad R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA} \;?$$

NPA 783 (2007) 493, PLB 519 (2001) 199, PRD 71 (2005) 054027



QGP

Light quarks:
$m \sim 0$, $C_R = 4/3$
Energy loss

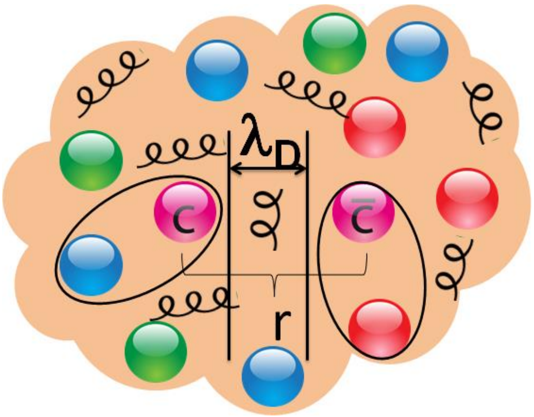
Gluons:
$m = 0$, $C_R = 3$
Larger energy loss compared to light quarks

c: $m \sim 1.5$ GeV, $C_R = 4/3$
b: $m \sim 5$ GeV, $C_R = 4/3$
dead cone effect
→ Smaller energy loss of *b* quarks

Quarkonium in heavy ion collisions

In the 1980's J/ψ was proposed as a probe of the Quark Gluon Plasma (PLB 178 (1986) 416):

- Produced in the early stages of the collisions.
- Suppressed by the Debye screening.



Suppression depends on the binding energy of quarkonium states (PRD 64 (2001) 094015):

- Excited states melt down at different temperatures ➔ sequential suppression.
- Quarkonium as a thermometer of the QGP!

At top LHC energy:

- $N_{c\bar{c}}$/central collision ≈ 120 ➔ new source of charmonium production from recombination of $c\bar{c}$ pairs?

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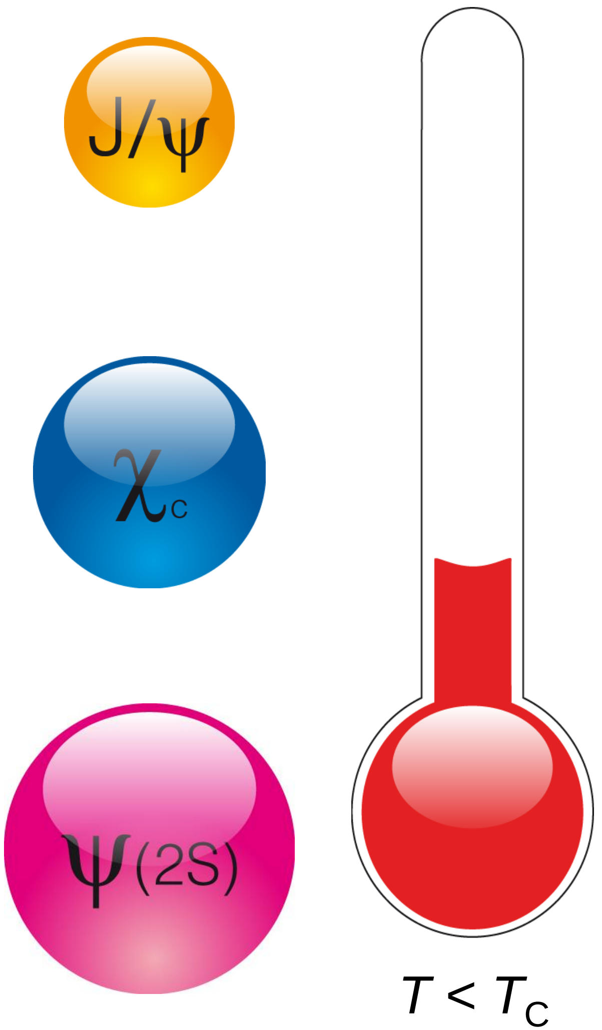

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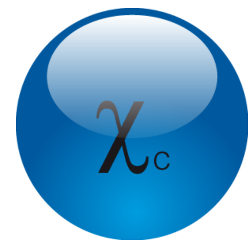

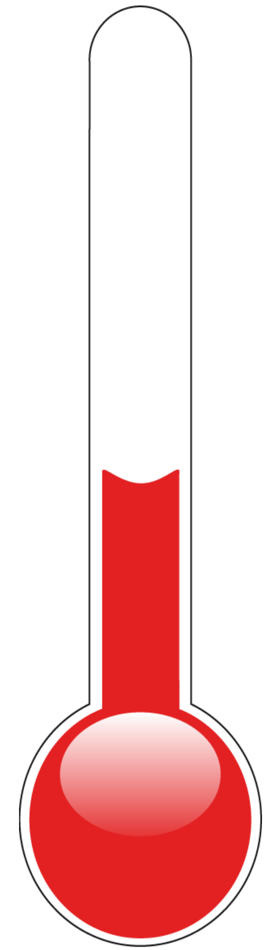

$T \approx T_C$

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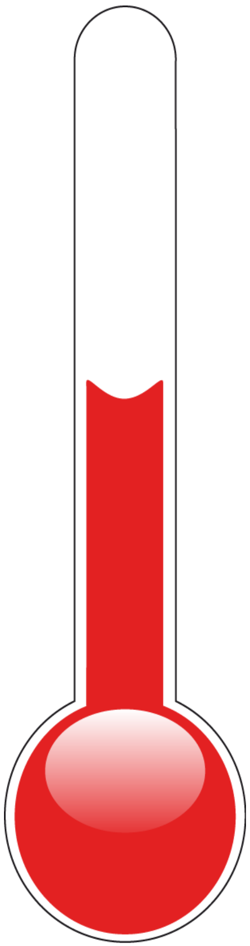

$T \approx 1.1\ T_C$

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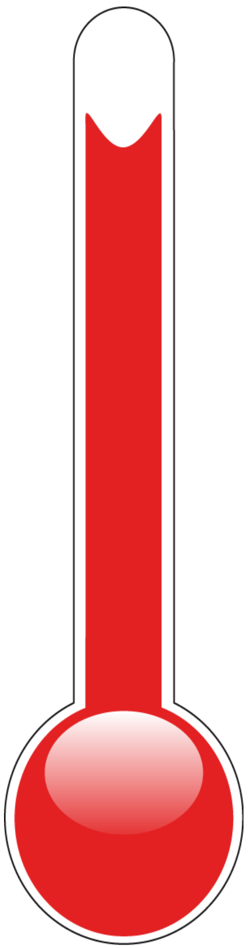
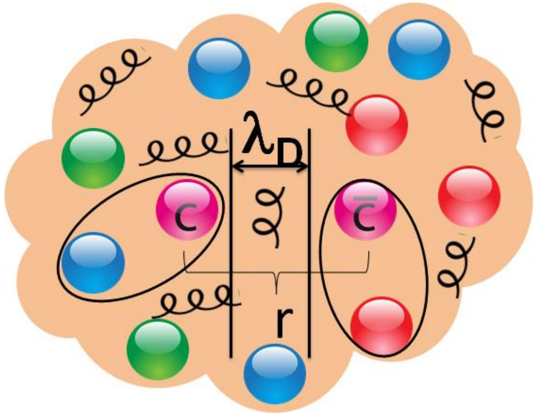


$T \approx 2.1\ T_C$

Quarkonium in heavy ion collisions



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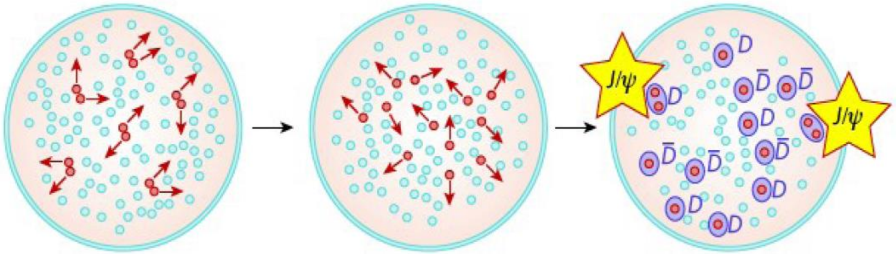


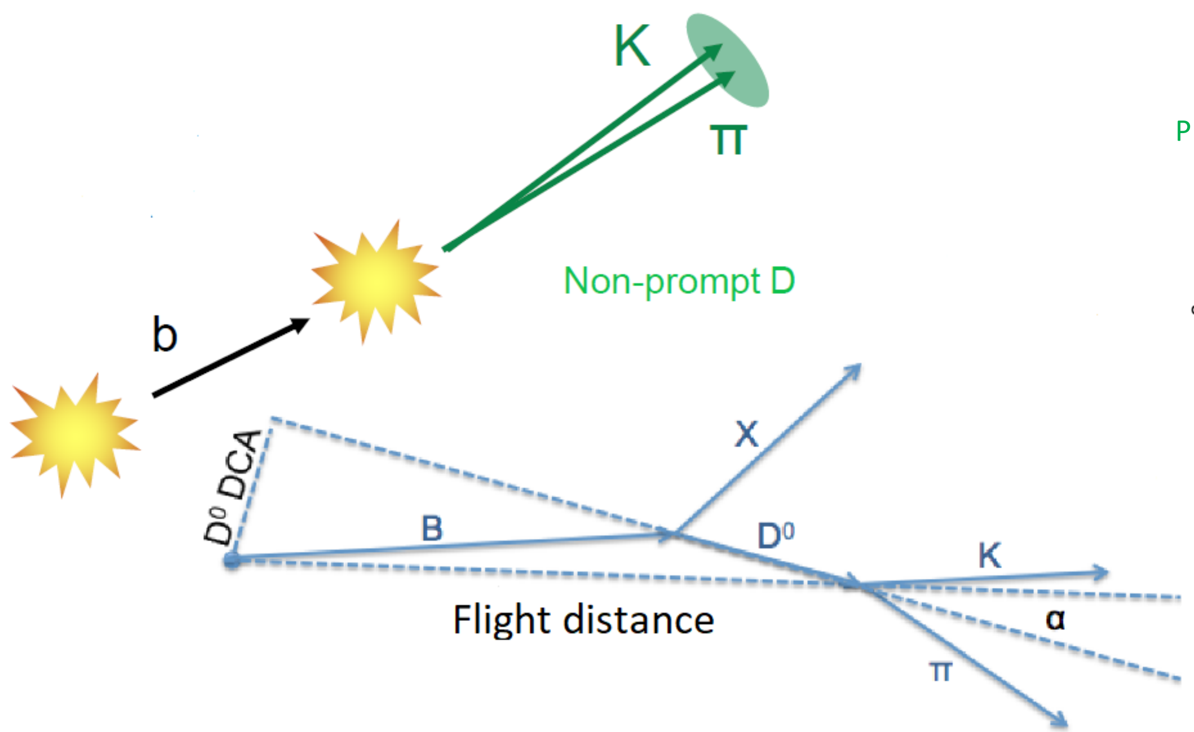
Nature 448 (2007) 302

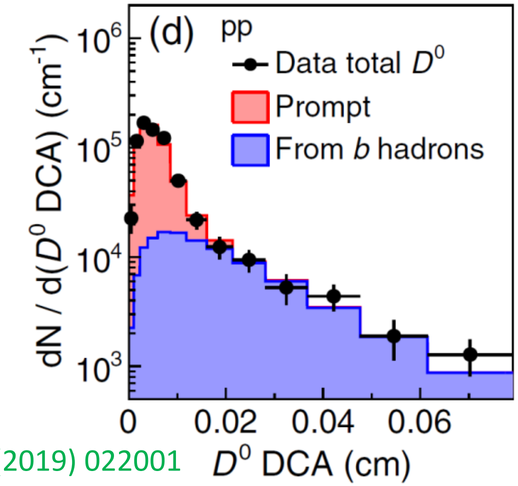
ANALYSIS

Prompt and non-prompt D mesons

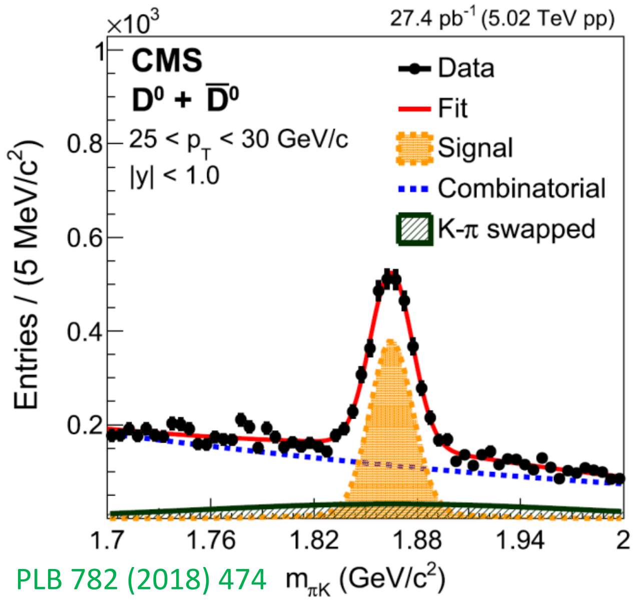
B → D: non-zero Distance of Closest Approach (DCA).
Prompt D: DCA only from track and primary vertex.

Template fit (simulation) on DCA distribution to separate prompt and non-prompt contributions.



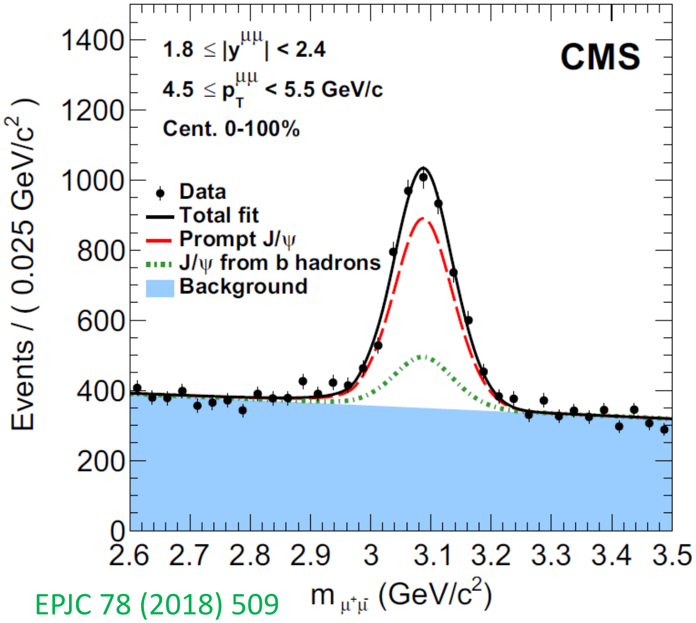


PRL 123 (2019) 022001



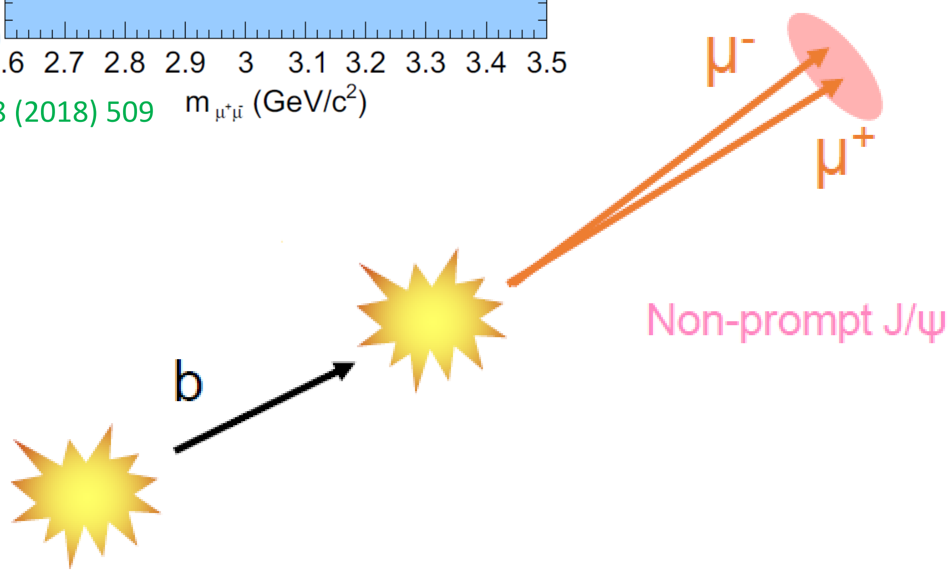
PLB 782 (2018) 474

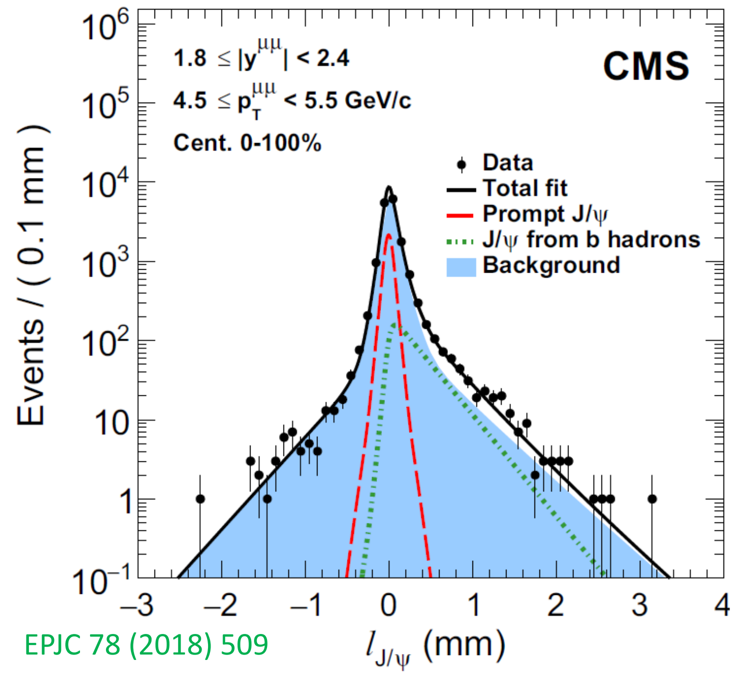
Prompt and non-prompt J/ψ



EPJC 78 (2018) 509

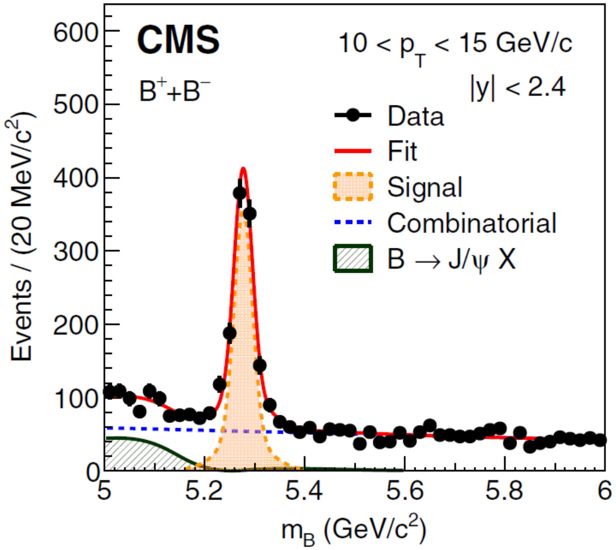
Muon pair fit to a common vertex (J/ψ candidates) and then apply a 2D fit on invariant mass decay length distributions to separate prompt and non-prompt contributions.





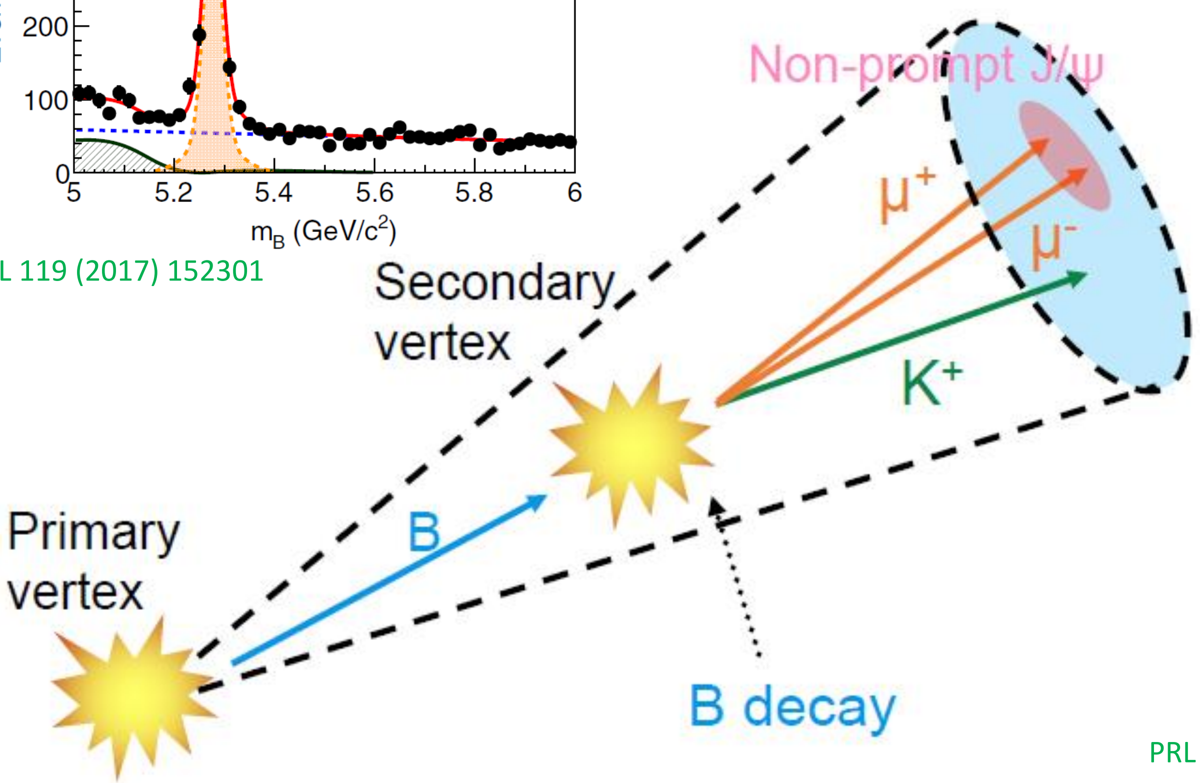
EPJC 78 (2018) 509

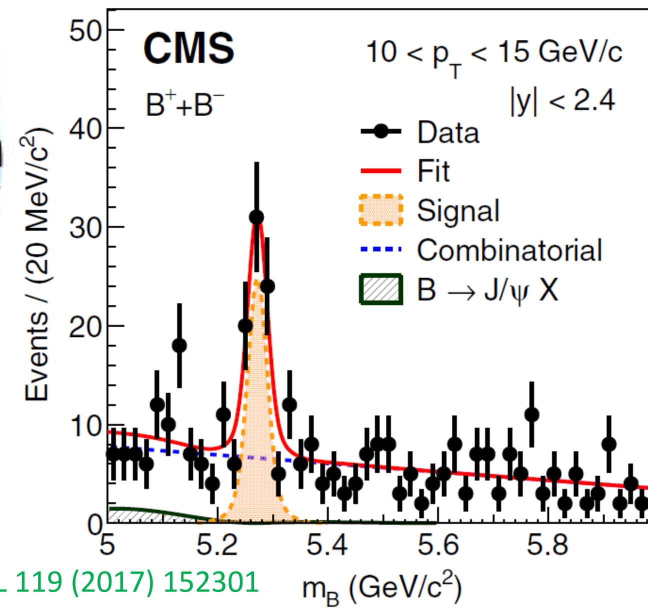
Full reconstruction of B mesons



PRL 119 (2017) 152301

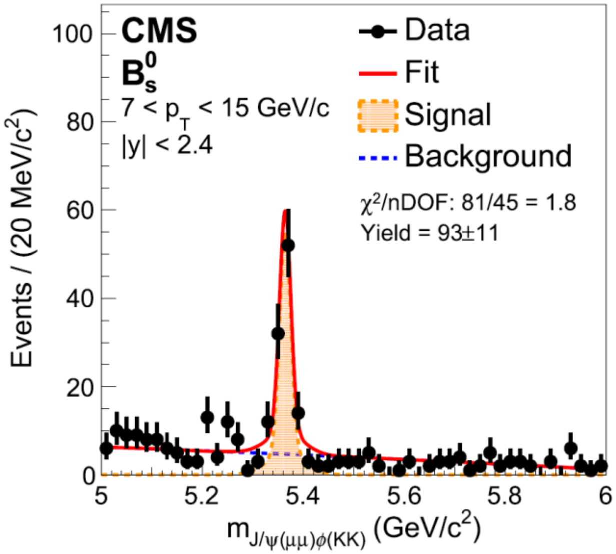
Muon pair + track (kaon mass) with common vertex. Fit on invariant mass distribution. Peaking background due to B^+ and B^0.





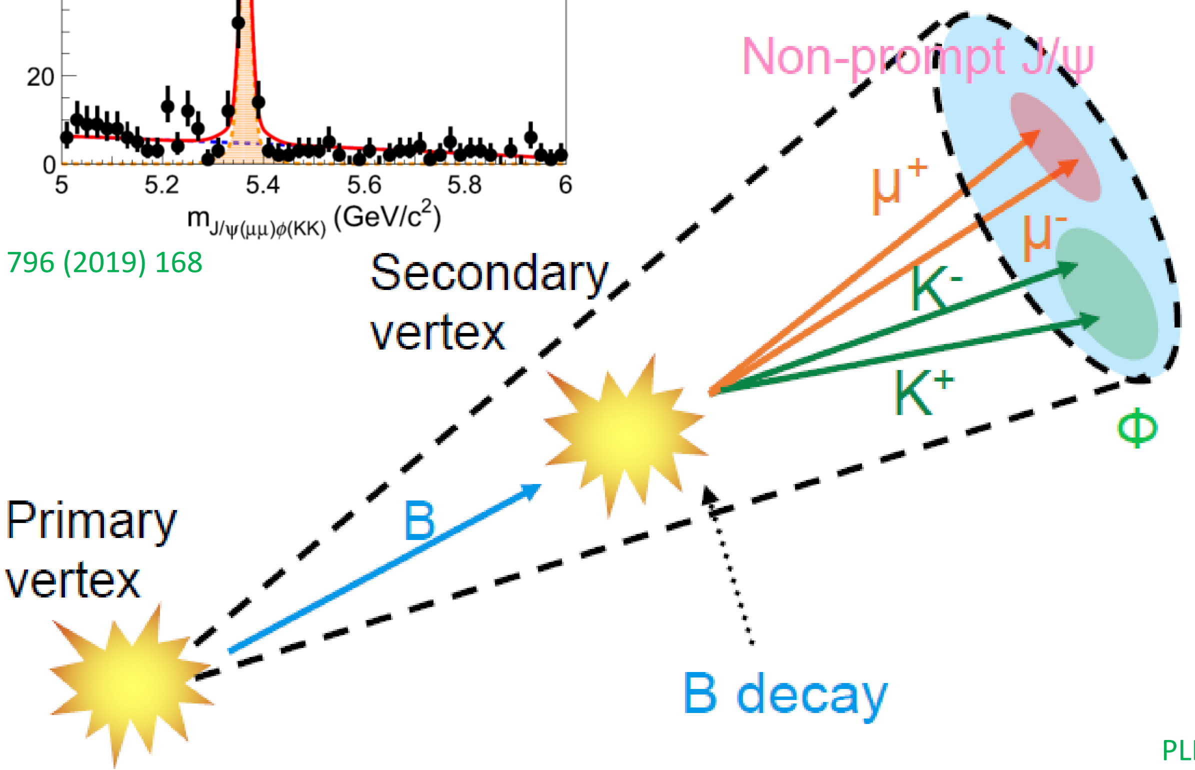
PRL 119 (2017) 152301

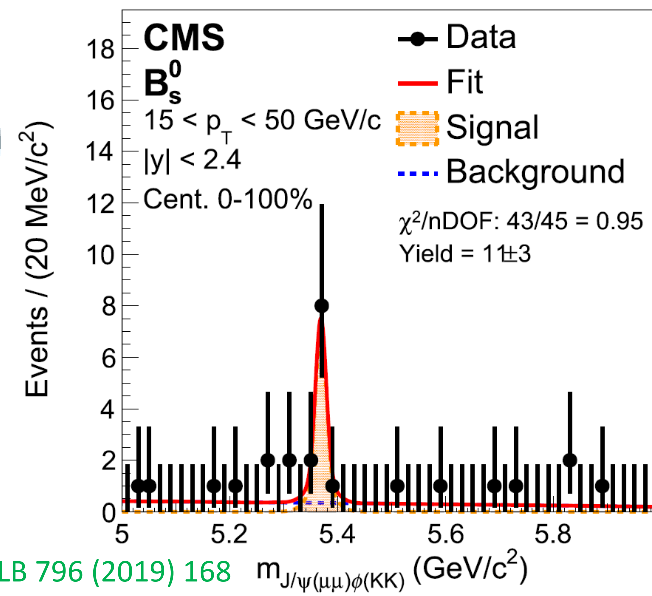
Full reconstruction of Bs mesons



PLB 796 (2019) 168

Muon pair + track (kaon mass) with common vertex. Fit on invariant mass distribution. No peaking background, narrow width due to Φ meson.

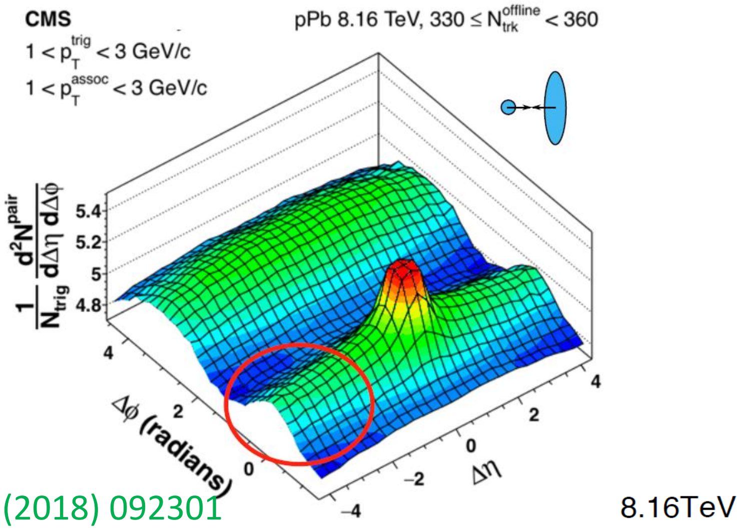




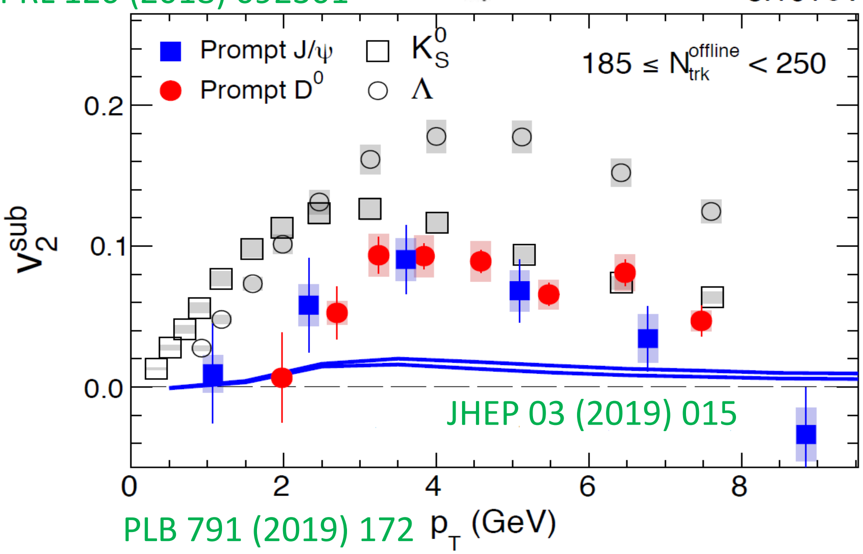
PLB 796 (2019) 168

QUARKONIUM

Elliptic Flow in pPb



PRL 120 (2018) 092301



JHEP 03 (2019) 015

PLB 791 (2019) 172

Strong collective behavior found in azimuthal correlations of light particles emitted in high multiplicity p-Pb collisions.

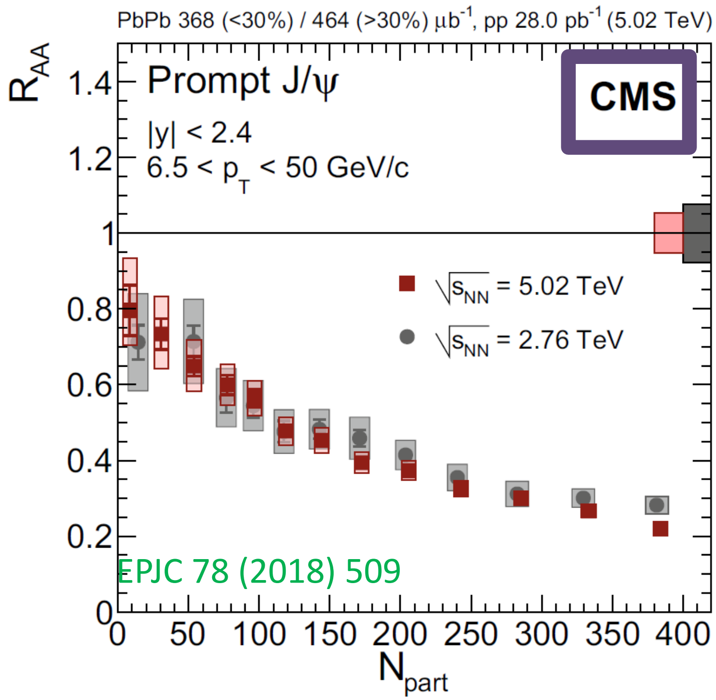
Correlation of single-particles assessed via Fourier decomposition: elliptic flow (v_2).

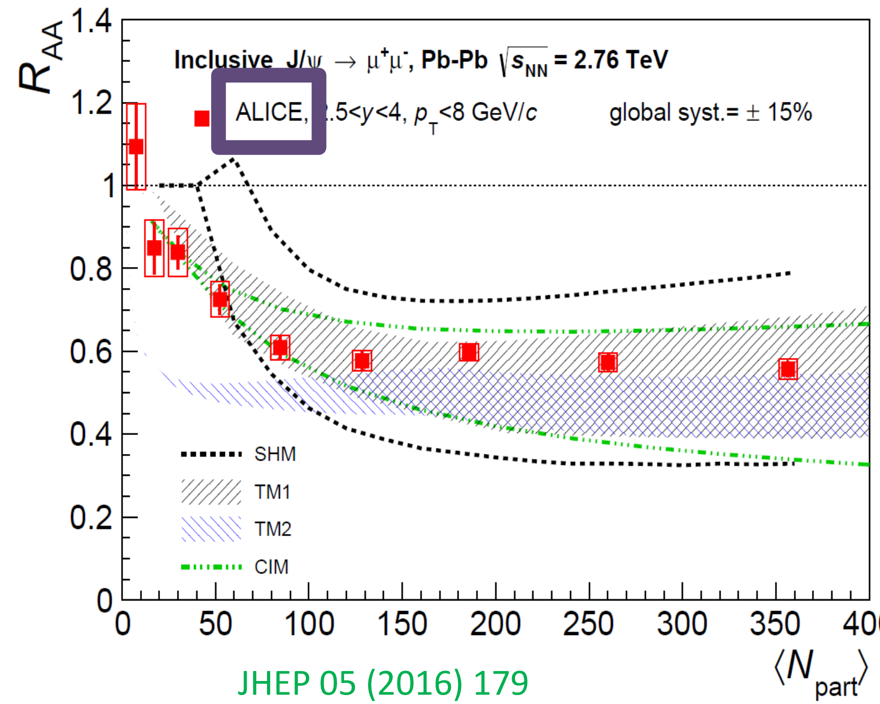
Sub v_2 = v_2 – residual jet correlations.

v_2 prompt J/ψ ≈ v_2 prompt D^0 < v_2 light flavors ➔ charm quarks develop a weaker collective dynamics than light quarks in small systems.

Model based on FS interactions (QGP-*c* quark) significantly underestimates the data ➔ Additional contributions (IS?) needed.

J/ψ in Pb-Pb

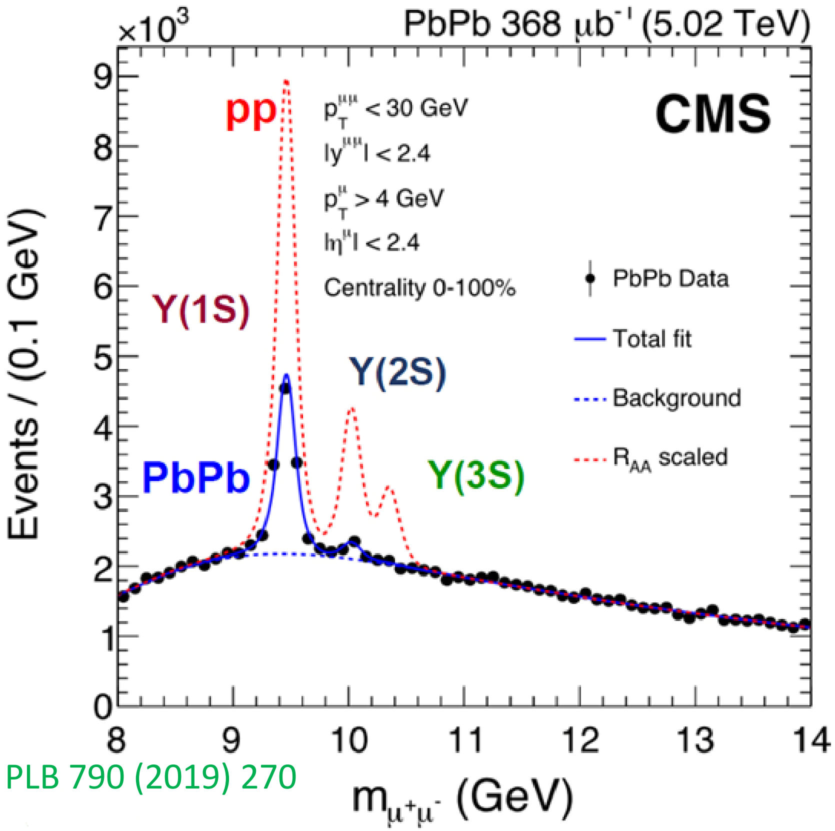




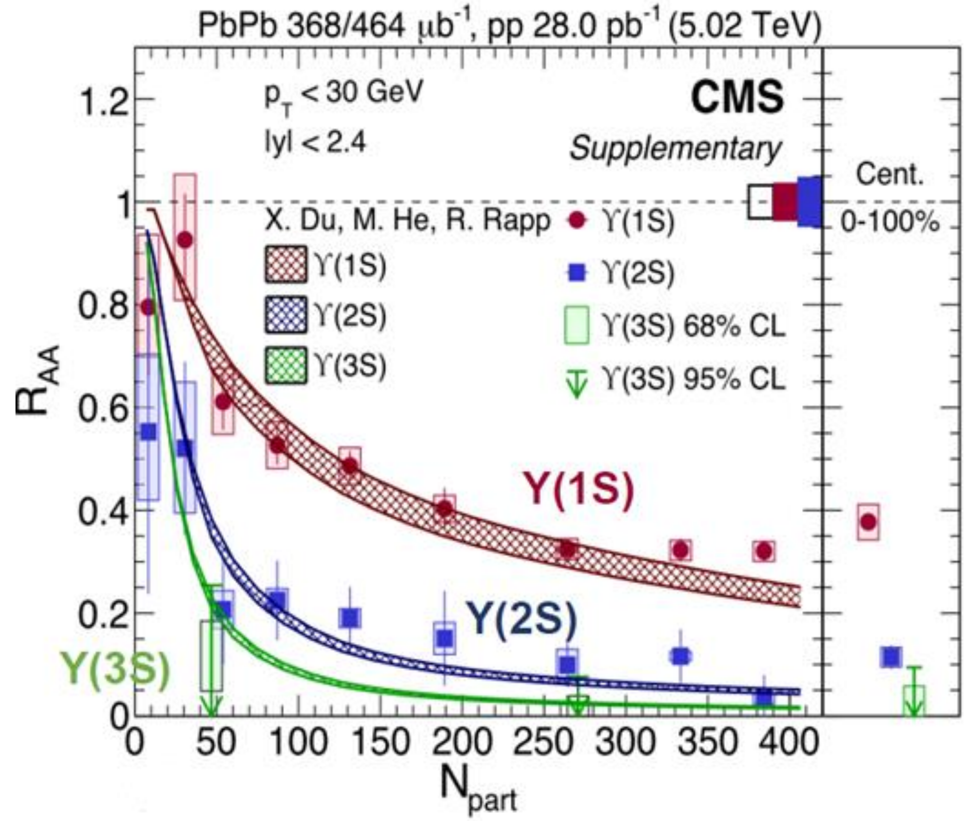
CMS (high-p_T): Clear suppression of prompt J/Ψ that depends on the centrality of the event, as expected in a sequential melting scenario.

ALICE (low-p_T): inclusive J/Ψ suppression at forward rapidity is independent of centrality for N_{part} > 80. Models including J/Ψ from $c\bar{c}$ recombination can reproduce the data.

Upsilon in Pb-Pb



PLB 790 (2019) 270



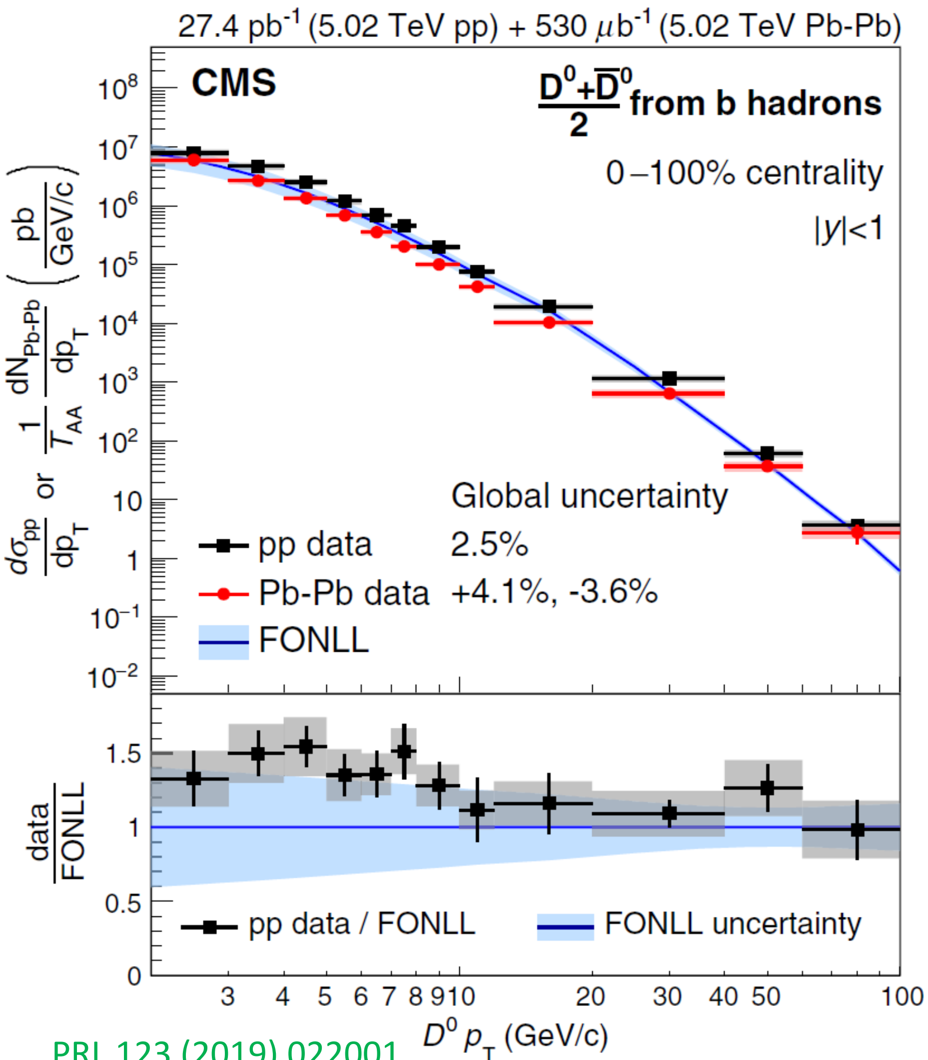
Production rate 200 x smaller than charmonium ➔ small contribution from regeneration.

Larger binding energies than charmonium ➔ probe a wider temperature range.

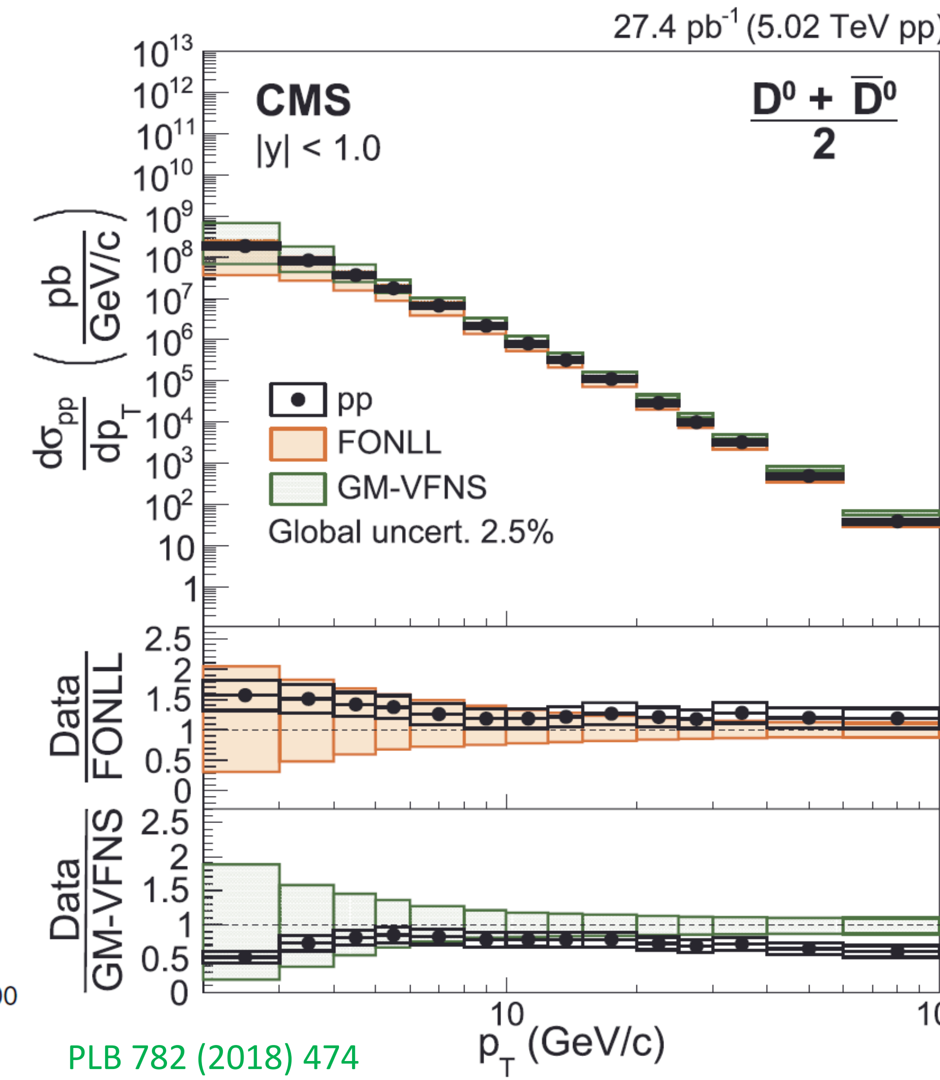
R_{AA} indicates a clear ordering suppression with binding energies, as expected in a sequential melting scenario.

OPEN HEAVY FLAVOURS

Prompt and non-prompt D° in pp

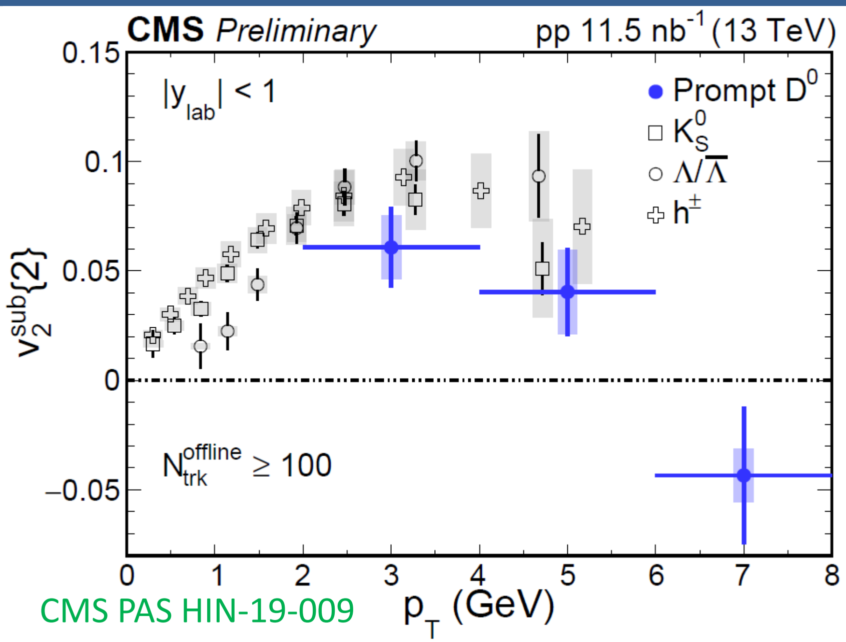


PRL 123 (2019) 022001

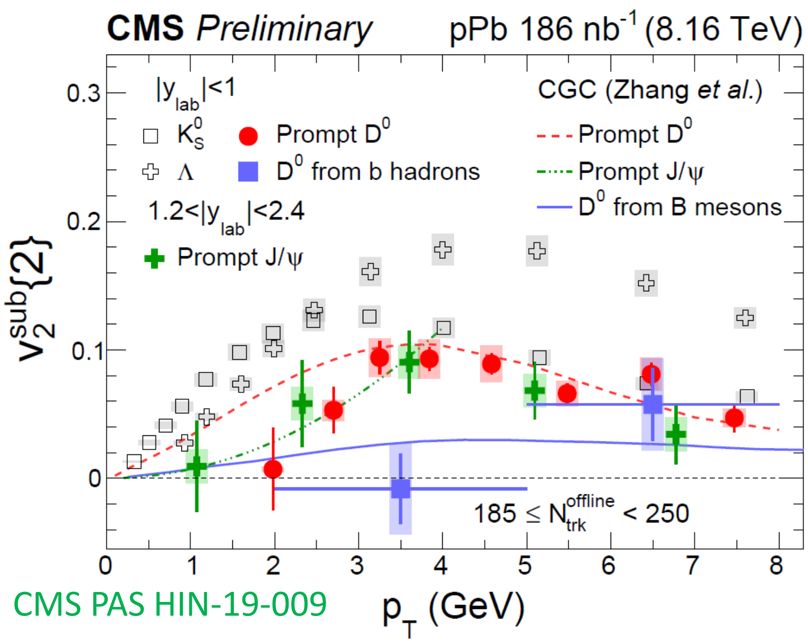


PLB 782 (2018) 474

Prompt and non-prompt D⁰ in pp & pPb



CMS PAS HIN-19-009



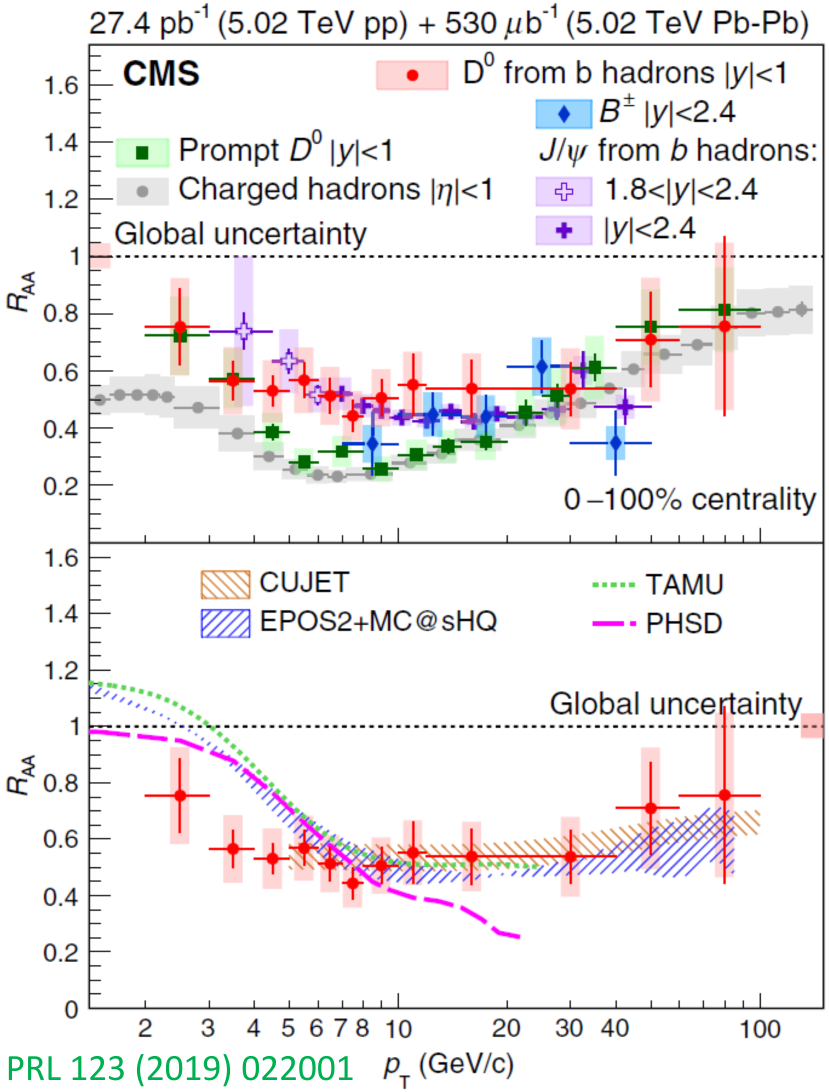
CMS PAS HIN-19-009

Positive v_2 for $2 < p_T < 4$ GeV/c: strong collectivity developed by c hadrons in high multiplicity pp collisions. Comparable to light-flavours.

In pPb collisions non-prompt D^0 v_2 is consistent with zero at low- p_T, while at high- p_T there is a hint of positive value.

Qualitatively consistent with the scenario of v_2 being generated via final-state rescatterings, where heavier quarks develop a weaker collectivity.

Prompt and non-prompt D⁰ in Pb-Pb



PRL 123 (2019) 022001

R_{AA} of prompt D^0 = R_{AA} of non-prompt D^0 at low- and high-p_T. Larger suppression of prompt D^0 at mid-p_T, consistent with energy los dependence on quark mass.

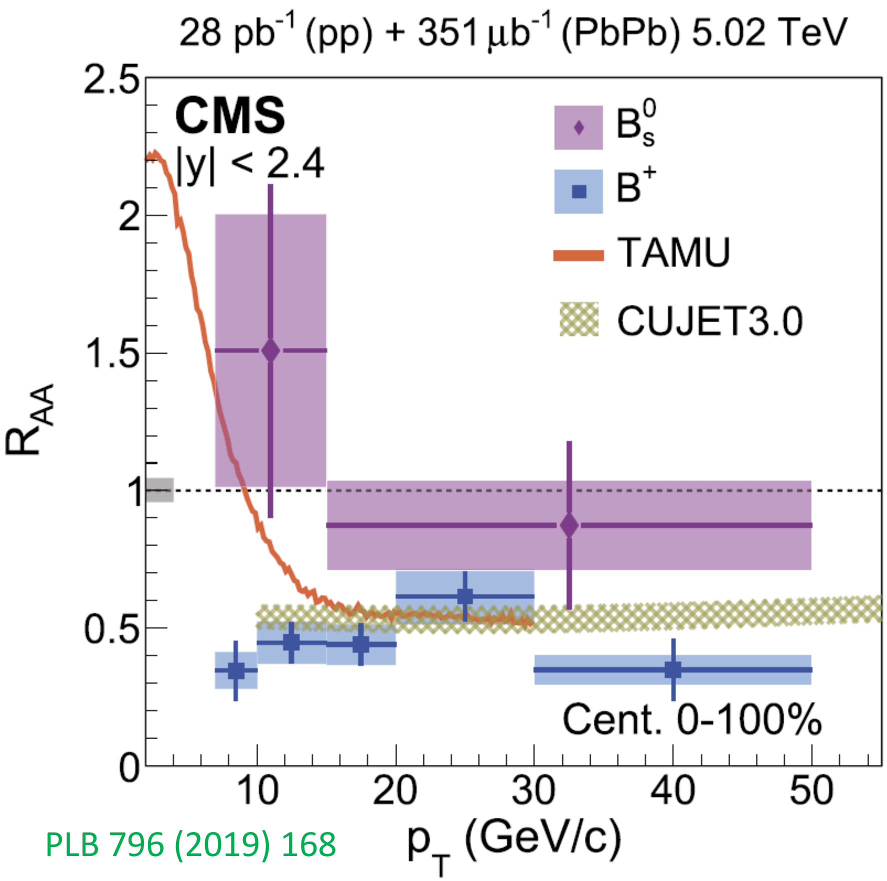
R_{AA} of non-prompt J/ψ ≈ R_{AA} of non-prompt D^0 ≈ R_{AA} of B mesons.

CUJET and EPOS2 include both collisional and radiative energy los, while transport models (TAMU and PHSD) only collisional.

Models underestimate suppression at low-p_T, indicating stronger energy los of *b* quark.

All models can describe the data at mid- and high-p_T.

Bs in Pb-Pb



PLB 796 (2019) 168

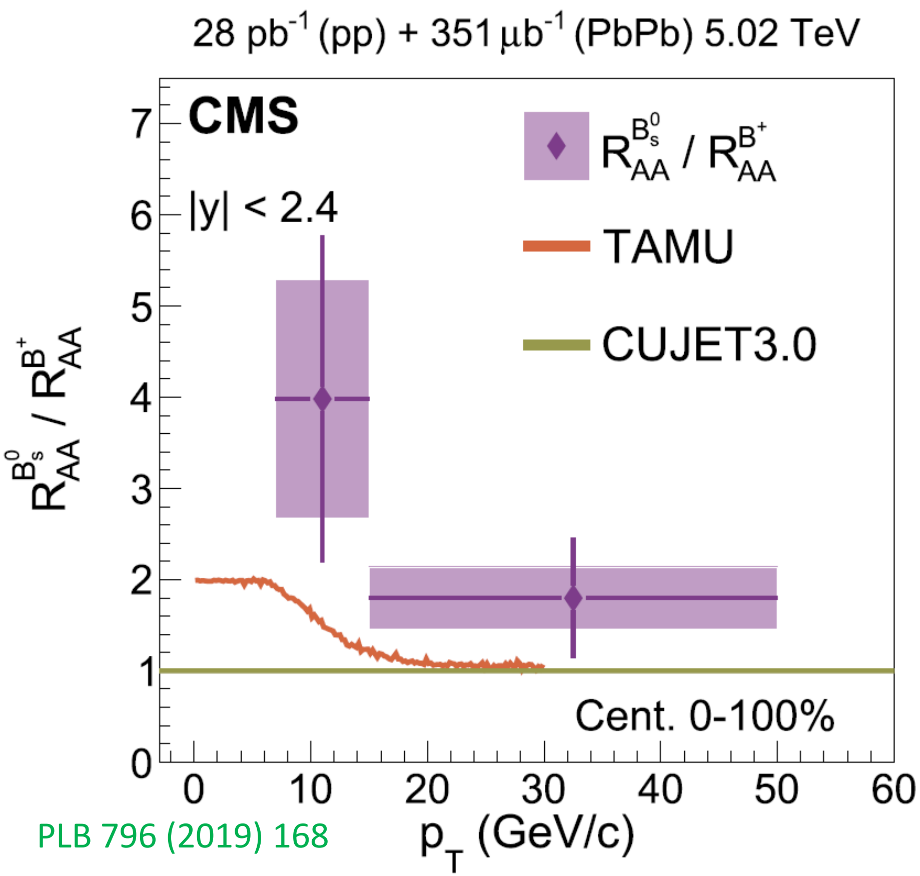
First measurement of exclusive B_s ever performed in nucleus-nucleus collisions!

Expected strangeness enhancement in thermally and chemically equilibrated QGP if temperatura > m_s.

Indication of enhancement of B_s relative to B mesons (large stat. and syst. uncertainties).

Relative yield of Bs wrt nonstrange B mesons can be enhanced in A-A compared to pp if recombination is a significant factor of beauty hadronization in the QGP.

Bs in Pb-Pb



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SUMMARY

Summary

Heavy quarks are useful tools to test pQCD inspired models but also to probe the QGP.

In pp collisions:

- pQCD inspired models can correctly describe the cross sections in a broad p_{T} range.

In pPb collisions:

- Charm quarks develop a weaker collective dynamics than light quarks in small systems

In Pb-Pb collisions:

- Recombination of $c\bar{c}$ pairs at low-p_{T}, while sequential suppression escenario at high-p_{T}.
- Larger suppression of prompt D^{0} at mid-p_{T}, consistent with energy los dependence on quark mass.

Thanks

for

your

attention

BACKUP

High energy heavy ion collisions

Space-time evolution of high energy heavy ion collisions:

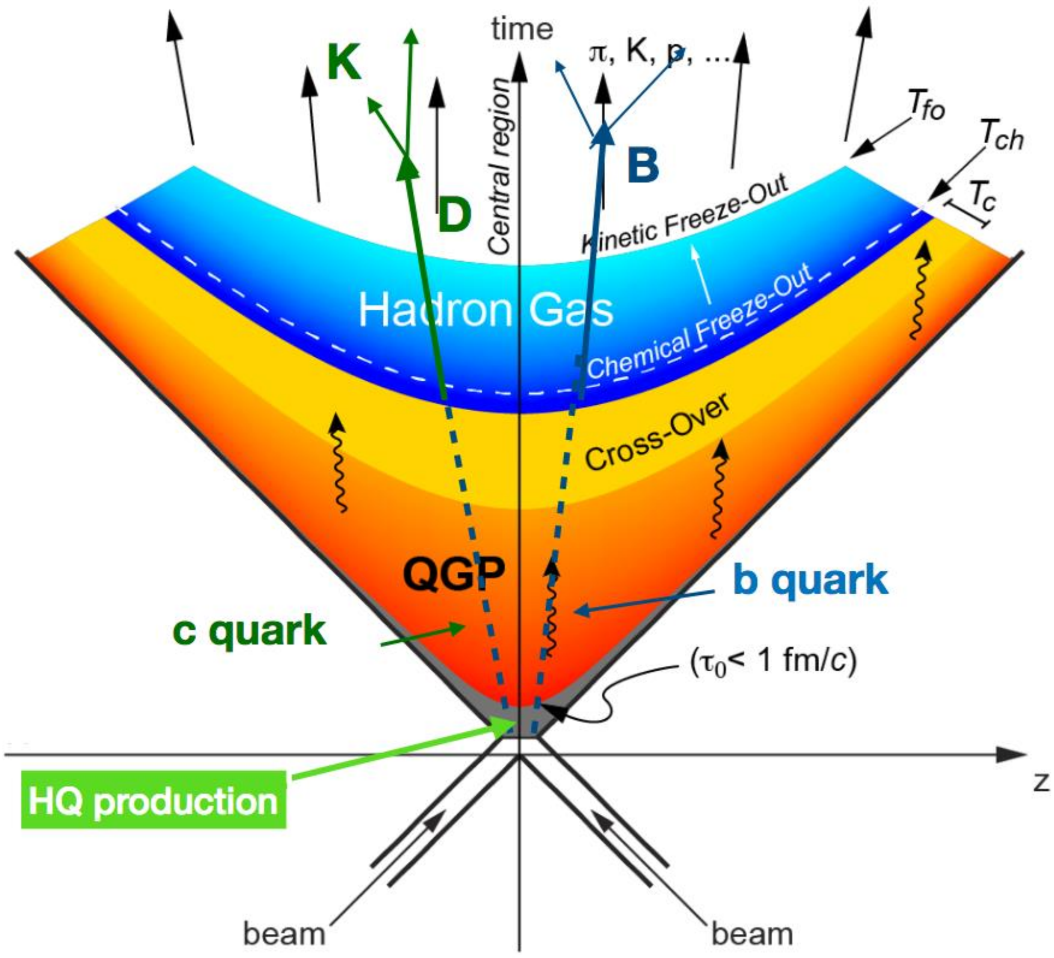
$t \approx 0$ fm/c: first parton-parton inelastic scatterings.

$t \approx 1$ - 2 fm/c: fast increase of entropy.

$t \approx 10$ - 15 fm/c: deconfinement takes places (QGP).

$t \approx 20$ fm/c: system expands and cools down.

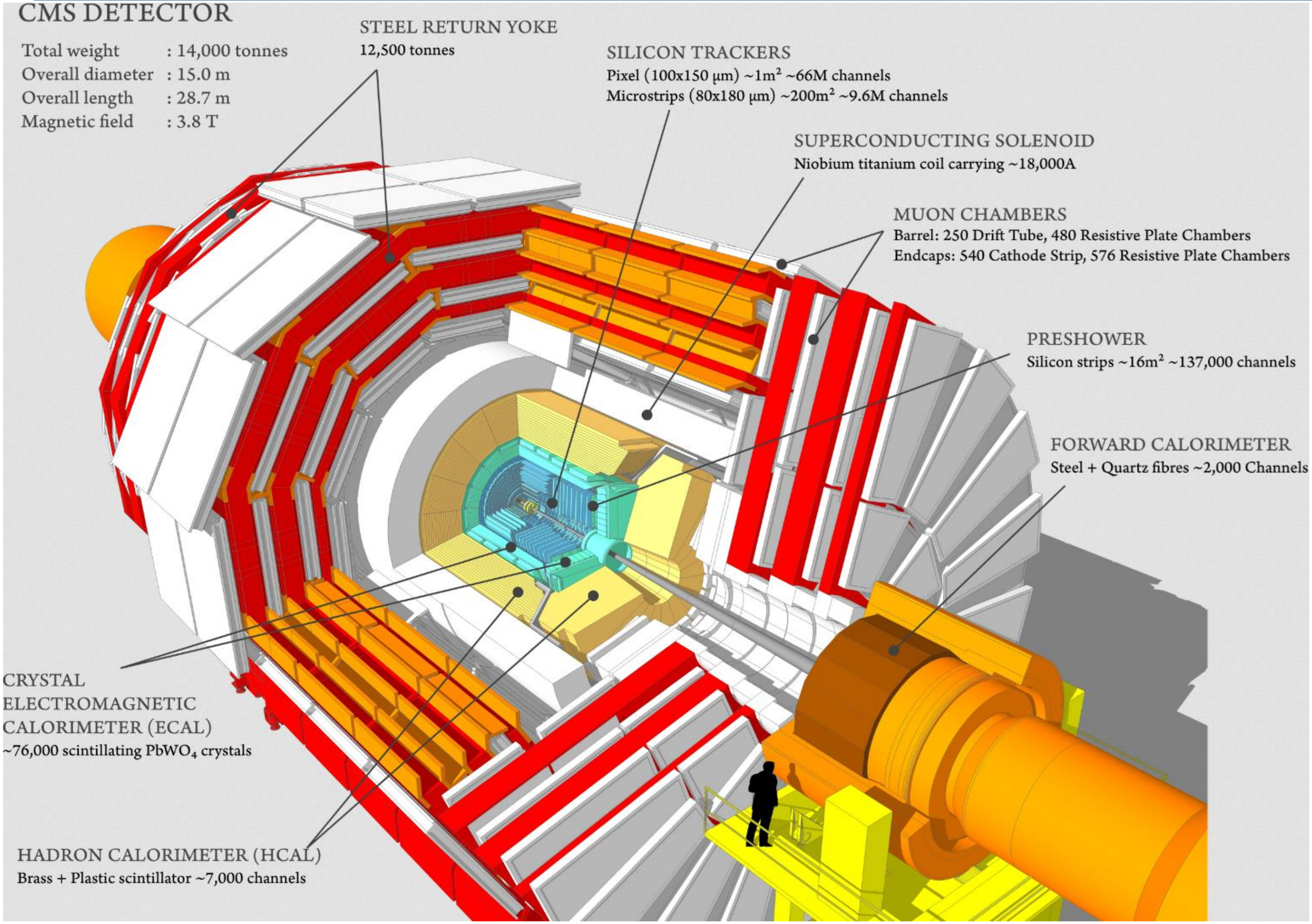
Imposible to study, directly, the Quark Gluon Plasma. Indirect measurements are needed.



HIN physics at CMS

System	Years	$\sqrt{s_{NN}}$, [TeV]	$L^{ATLAS}_{int} \approx L^{CMS}_{int}$
Pb-Pb	2010-2011 2015 2018	2.76 5.02 5.02	~0.14 nb^{-1} ~0.49 nb^{-1} ~1.7 nb^{-1}
Xe-Xe	2017	5.44	~3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~29 nb^{-1} ~0.5 nb^{-1}, ~0.16 pb^{-1}
pp	2011-2013 2015, 2017	2.76, 8 5.02	~4 pb^{-1}, ~19.4 fb^{-1} ~270 pb^{-1}

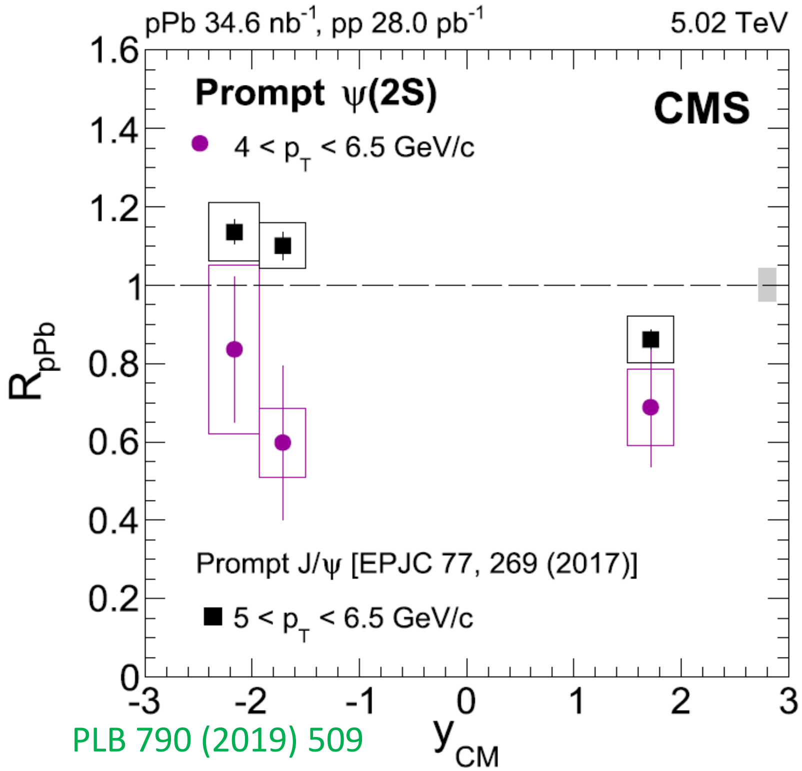
CMS detector



Silicon Tracker
$|\eta| < 2.4$
EM & Hadron Calorimeters
$|\eta| < 3.0$
with HF calo up to
$|\eta| < 5.2$
Muon Chambers
$|\eta| < 2.4$
CASTOR
$5.2 < |\eta| < 6.6$
ZDC
$z = \pm 140$ m

Magnetic field: 3.8 Tesla

Psi(2S) vs J/ψ in pPb



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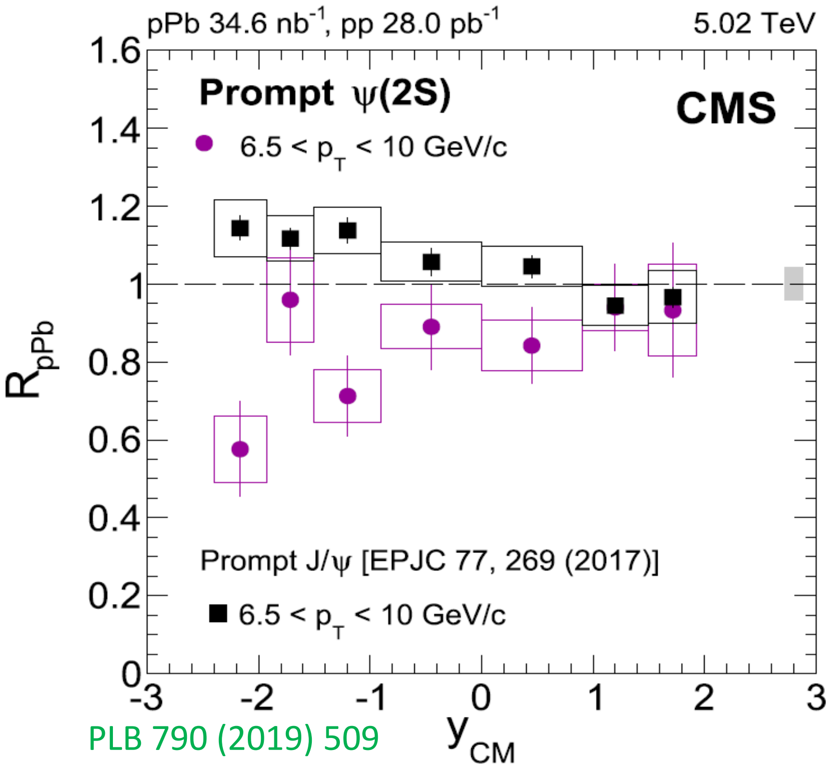

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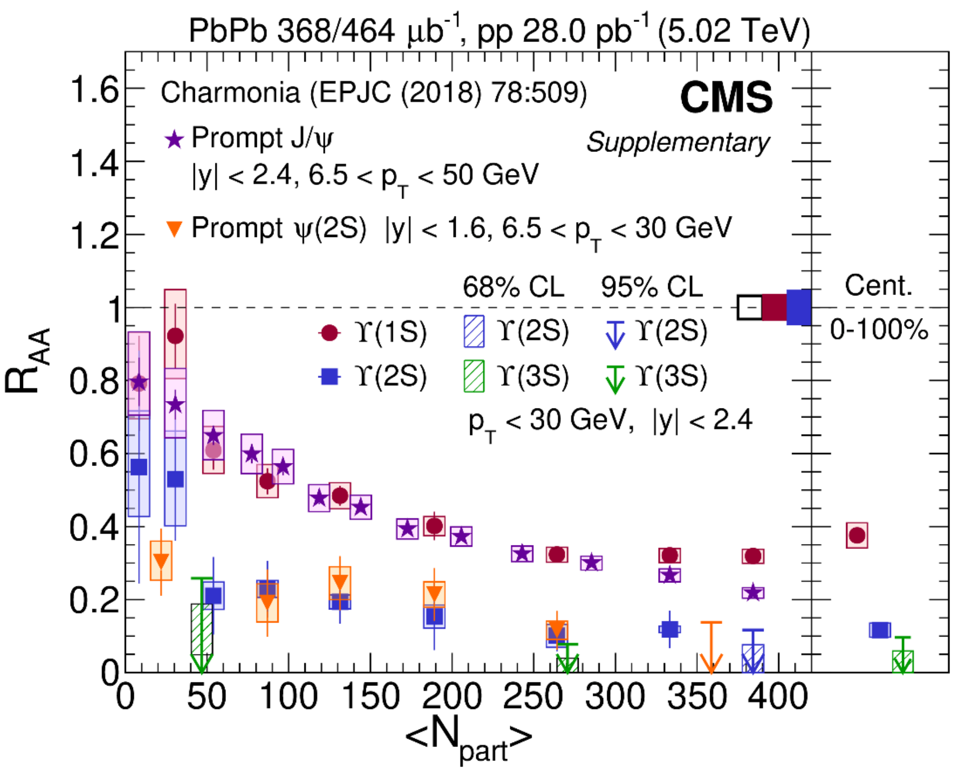
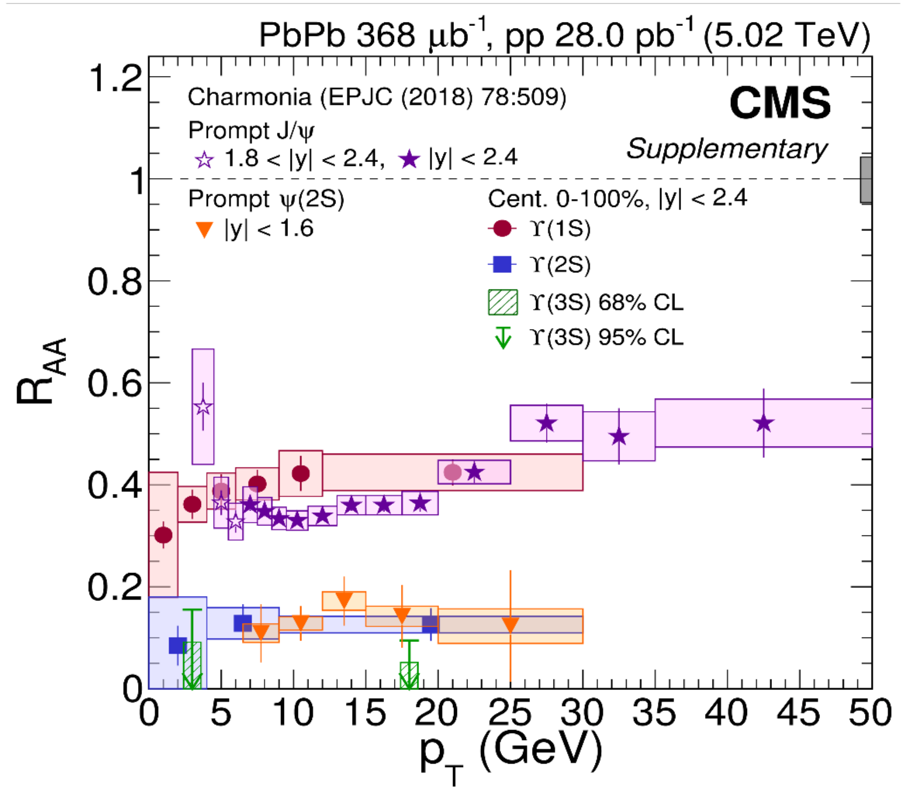
Backward rapidity: Psi(2S) systematically more suppressed than prompt J/ψ.

Suggests different (final) nuclear effects at play in the production of excited charmonium state compared to the ground state.

Upsilon vs J/ψ in Pb-Pb

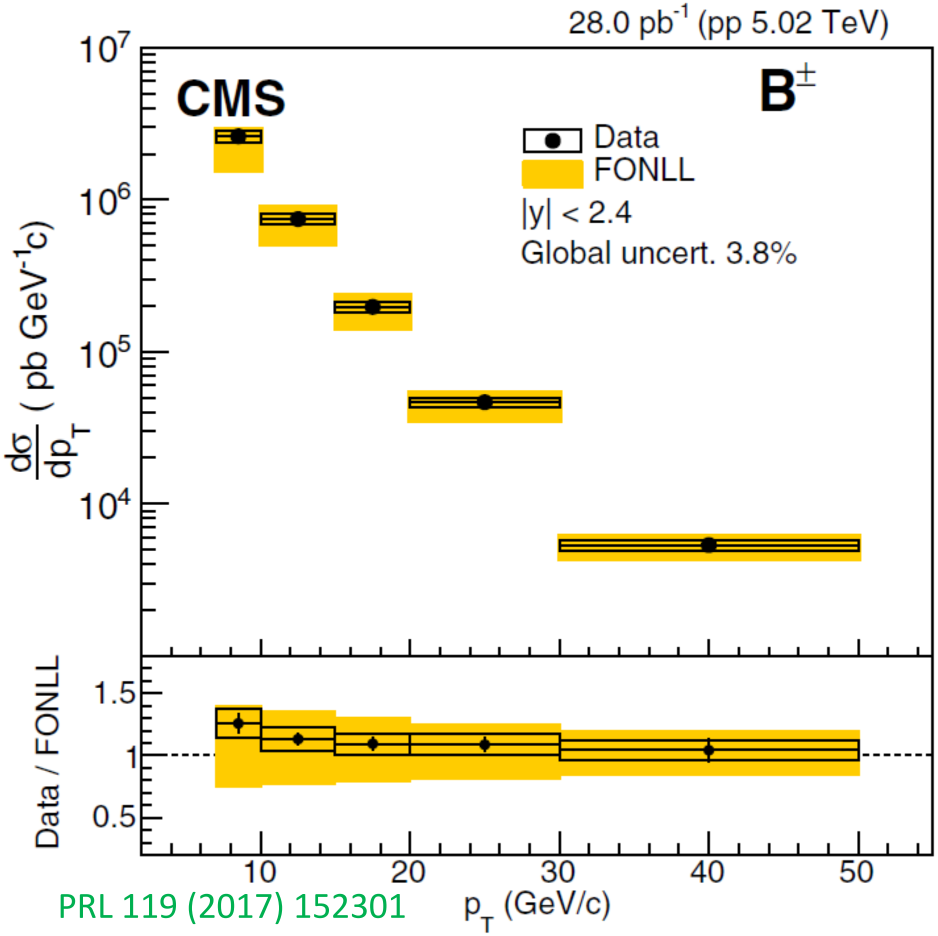




Prompt Ψ(2S) vs ϒ(2S): same suppression as a function of centrality and p_T.

Prompt J/Ψ vs ϒ: same suppression as a function of centrality and p_T.

B mesons in pp



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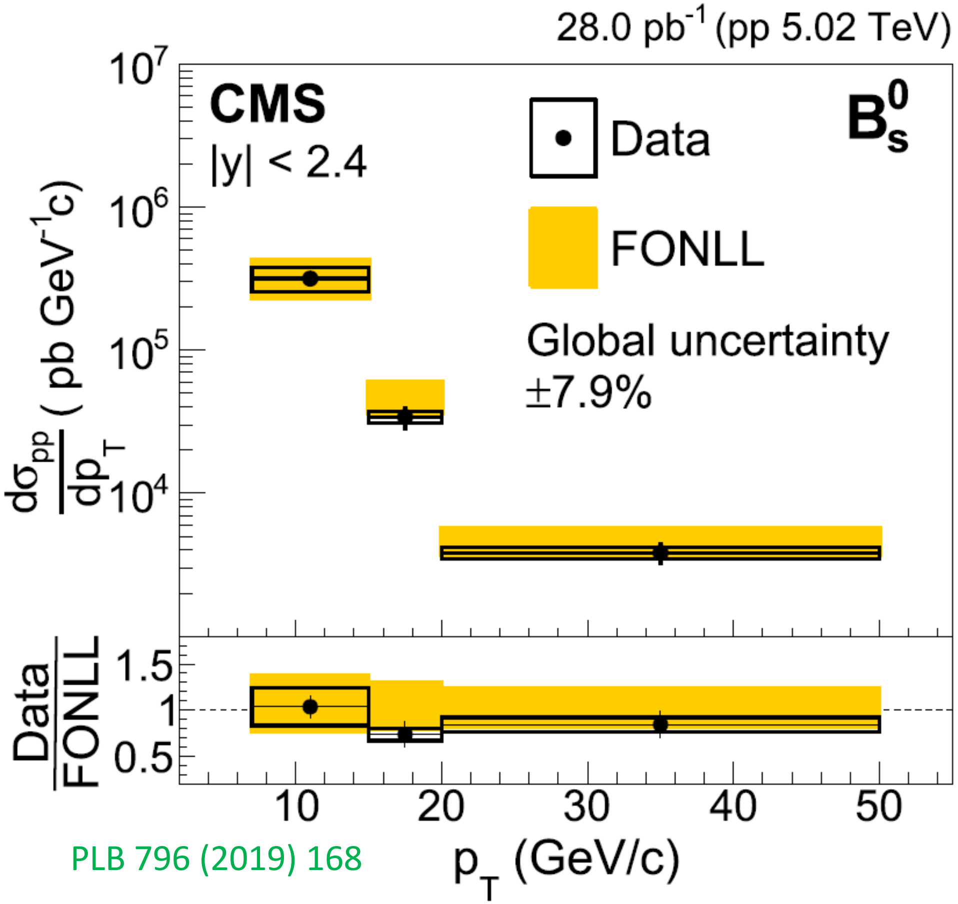

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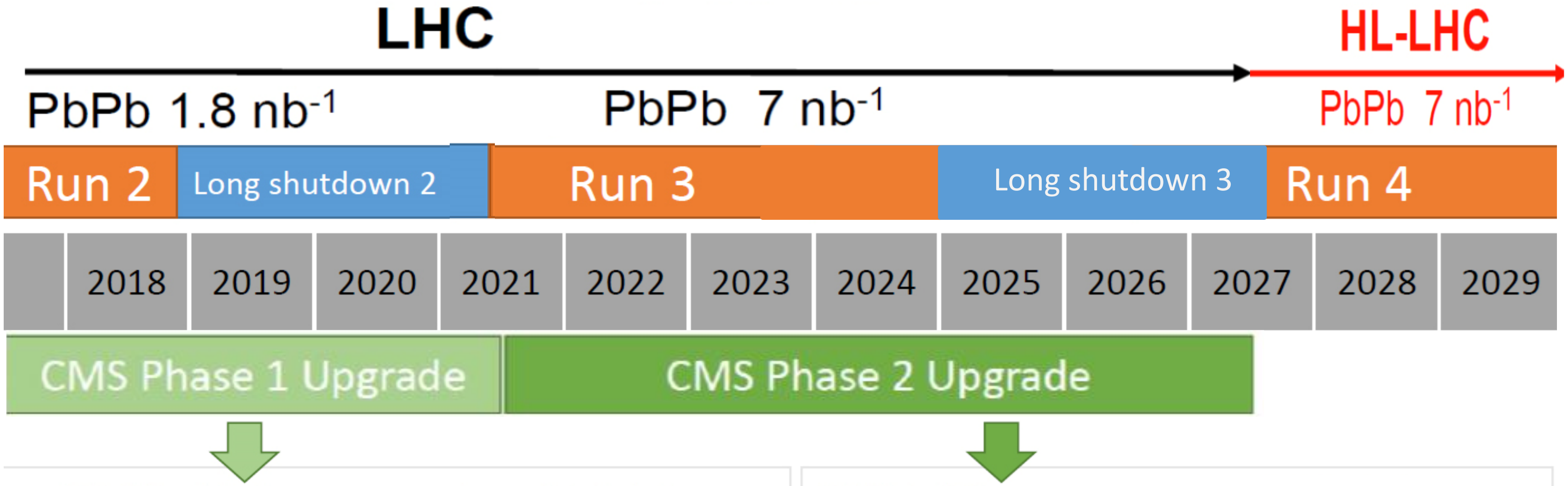
Measurements located in the upper region of the predictions from FONLL

The future of HI at CMS



- 2016: Major upgrade of L1 trigger
- 2017: 4-Layer Pixel Detector
- 2018 Performance:
  - pp L1 100kHz
  - PbPb L1 **30kHz** (3x of 2015)
  - DAQ: 6 GB/s
    - Up to **6.5 kHz** MinBias events to tape (20x of 2015)

2024-26

- Tracker **|η|<4**
- Muon ID up to **|η|<3**
- High Granularity Calo **1.6<|η|<3.0**
- **MIP timing detector**
  - 4D vertexing
  - **Possible p/K/π PID !!!**
- pp L1: 750 kHz
- DAQ: 60 GB/s