Hadron Production and Suppression

in hadron collisions @ LHC

N. Leonardo, nuno@cern.ch

AFIF - Associação de Física de Interações Fortes, Coimbra, 14/7/2017

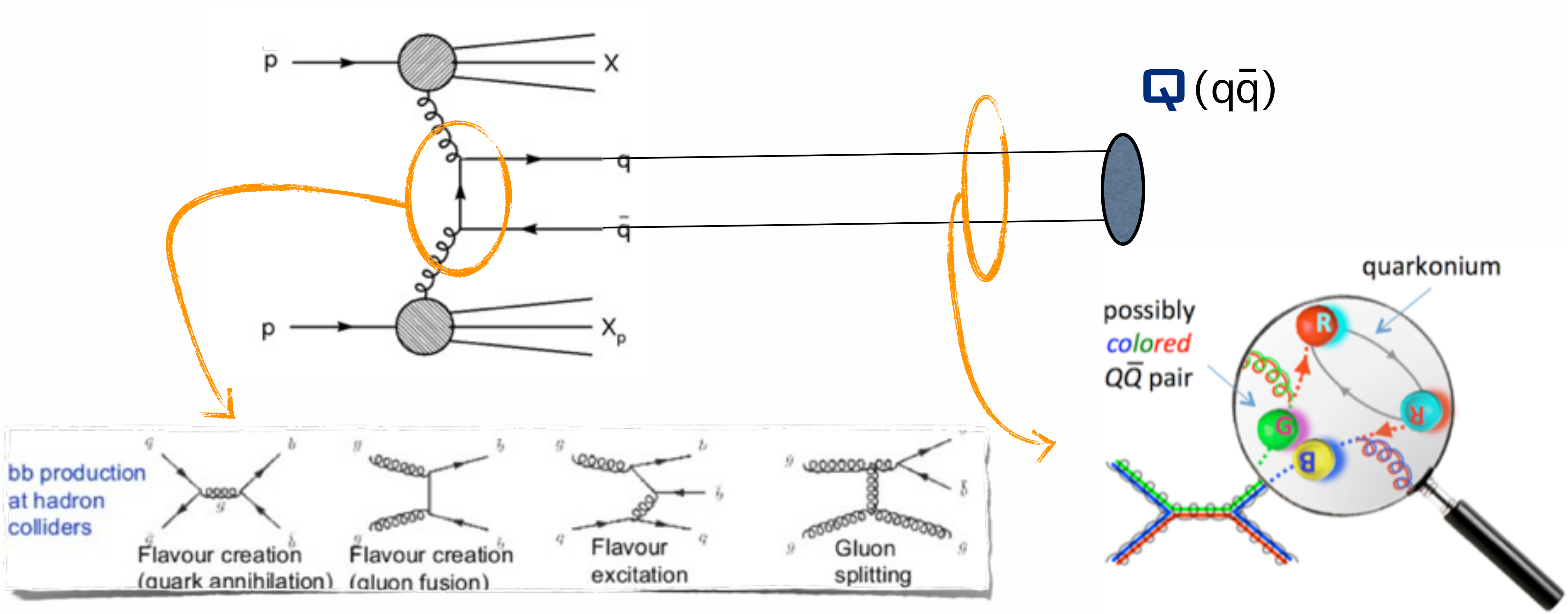
LIP
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

Personal Introduction

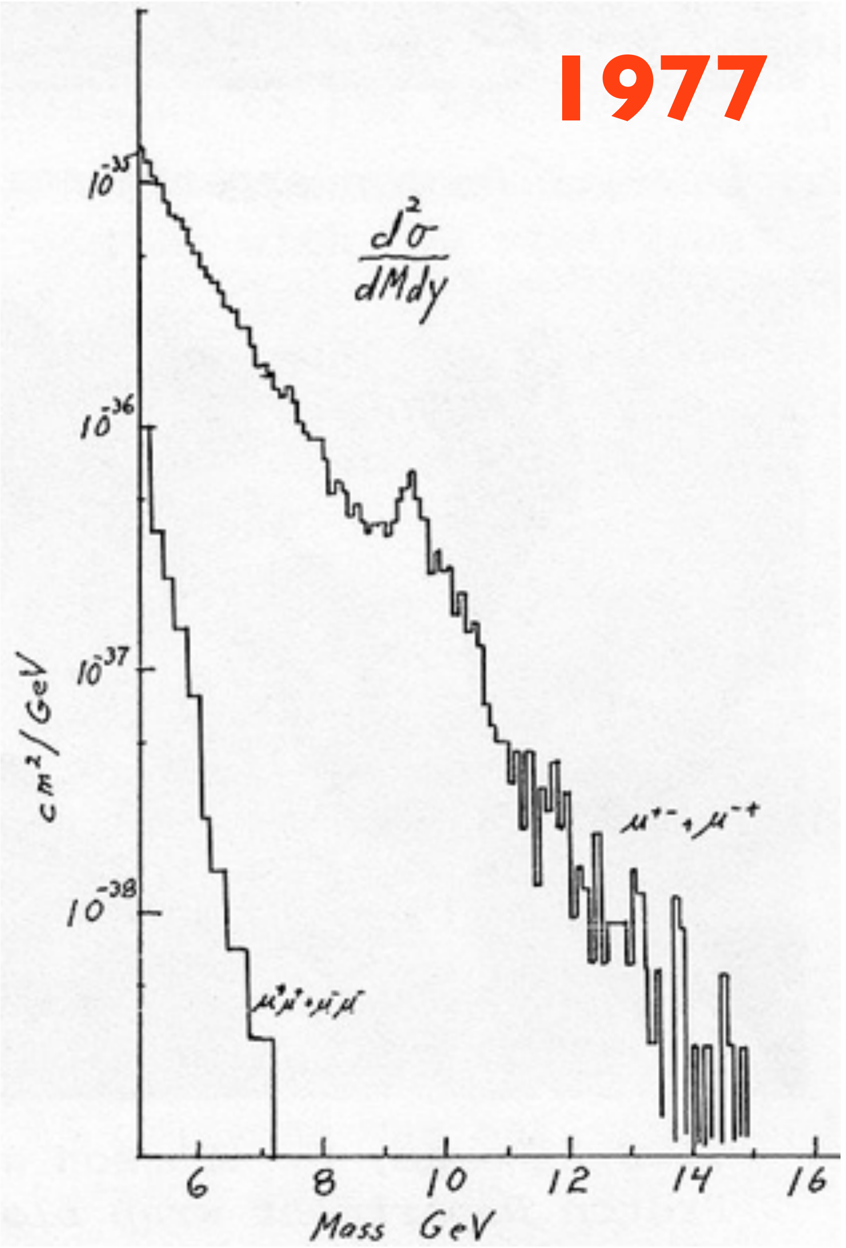
- Licenciatura in Physics, LEFT IST
- MSc in Math, Cambridge
- PhD in Physics, MIT
  - CDF experiment @ Fermilab's Tevatron
    ➠ the most powerful collider then
  - commissioning and operation of EVB & L3 farm
  - discovery of B_s particle-antiparticle oscillations (thesis)
- post-doctoral research at CERN, Purdue
  - CMS experiment @ CERN's LHC
    ➠ the most powerful collider now (and next decades')
  - commissioning of the hardware & Software trigger systems
  - discovery of sequential meson melting in QGP
  - discovery of $B_s \to \mu\mu$ rare decay
  - precision measurements, direct searches for BSM particles
- Researcher at LIP Lisbon
  - coordinator: CMS Hadronic physics (HF & Quarkonia) group
  - PI, Exploring heavy flavors and rare decays with CMS@LHC

heavy flavor = a great QCD lab



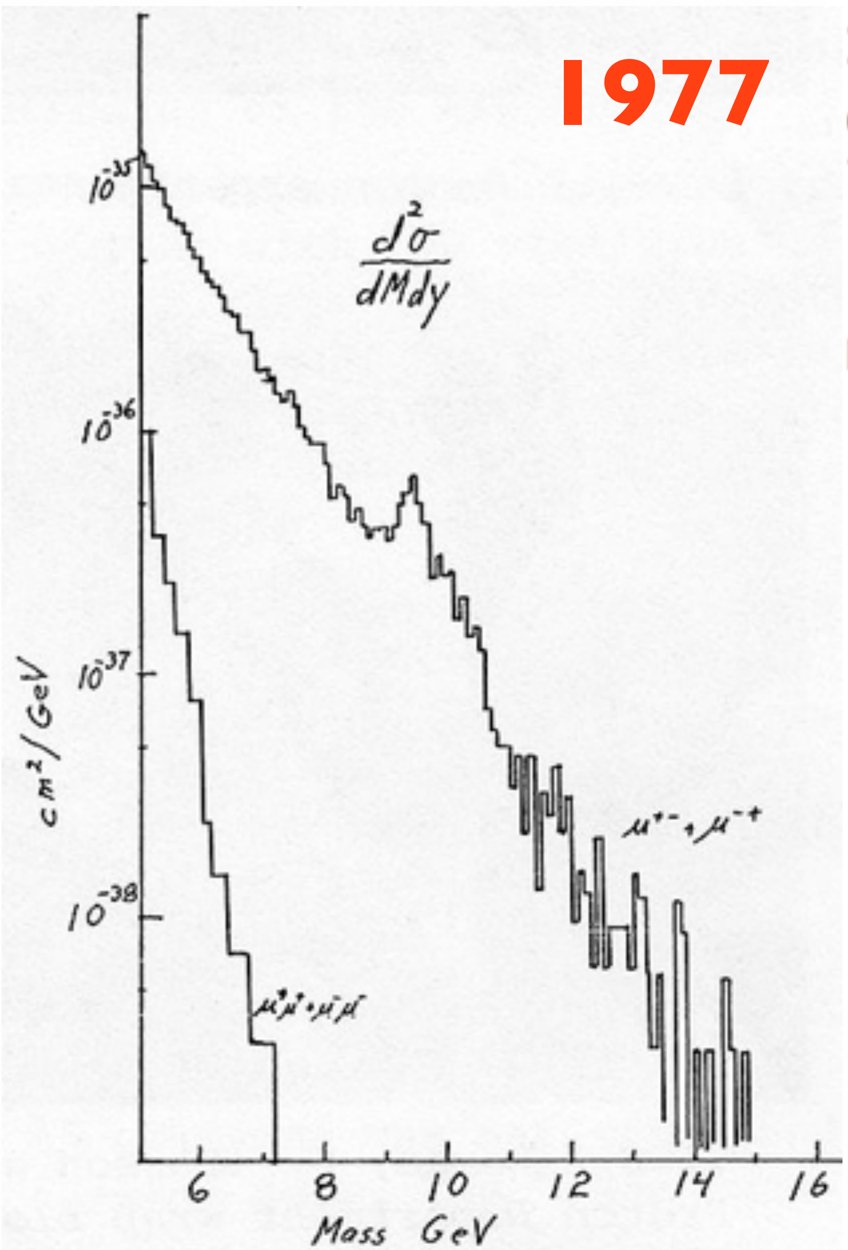
- **in vacuum**
  - understand the mechanisms of hadroproduction
  - address the "quarkonium puzzle" (inherited from the Tevatron)
- **in medium**
  - hard probes of the QCD hot matter created in heavy-ion collisions
  - understand the mechanisms of hadron suppression and energy loss

the dimuon spectrum

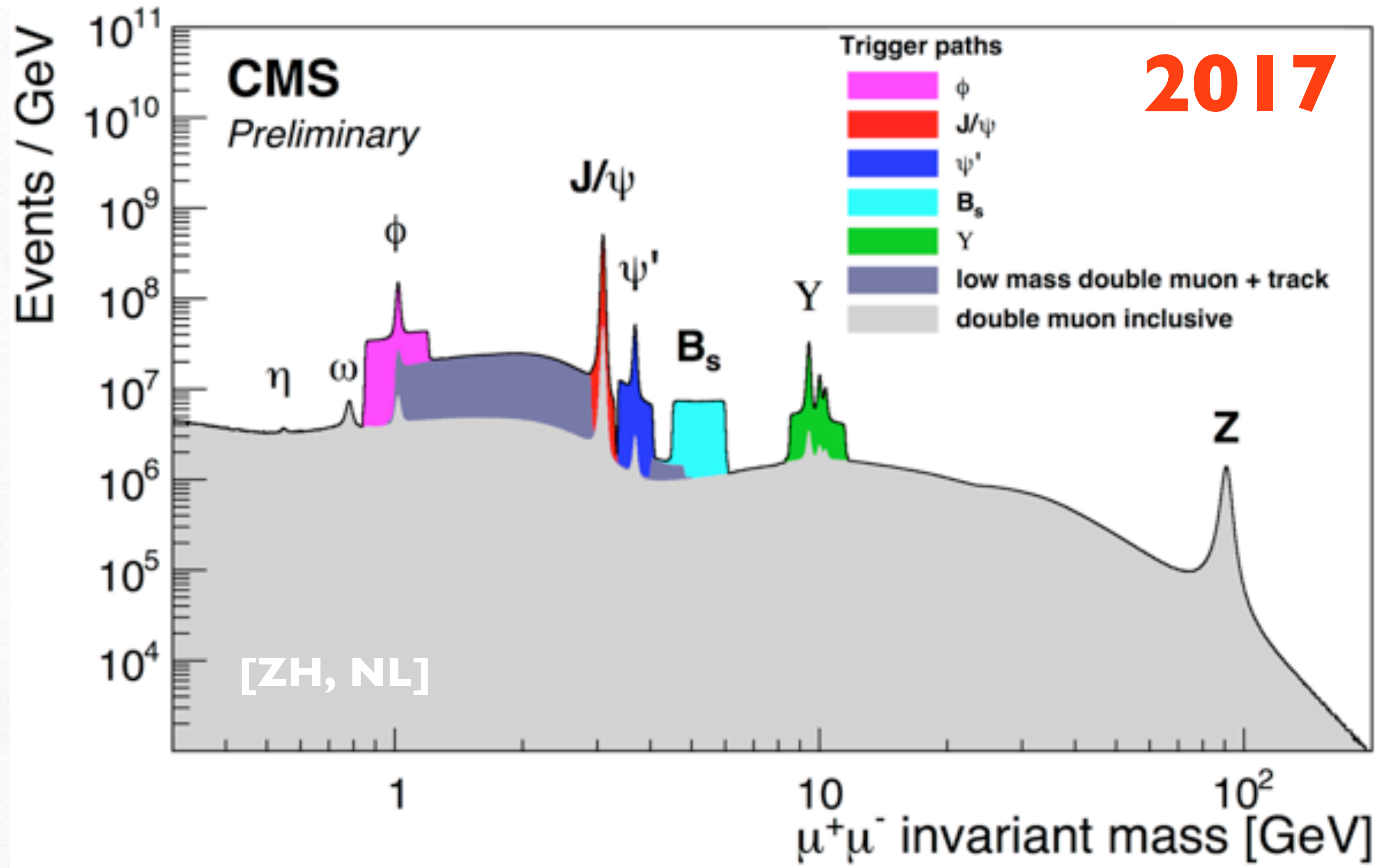


the discovery of the
b quark

the dimuon spectrum

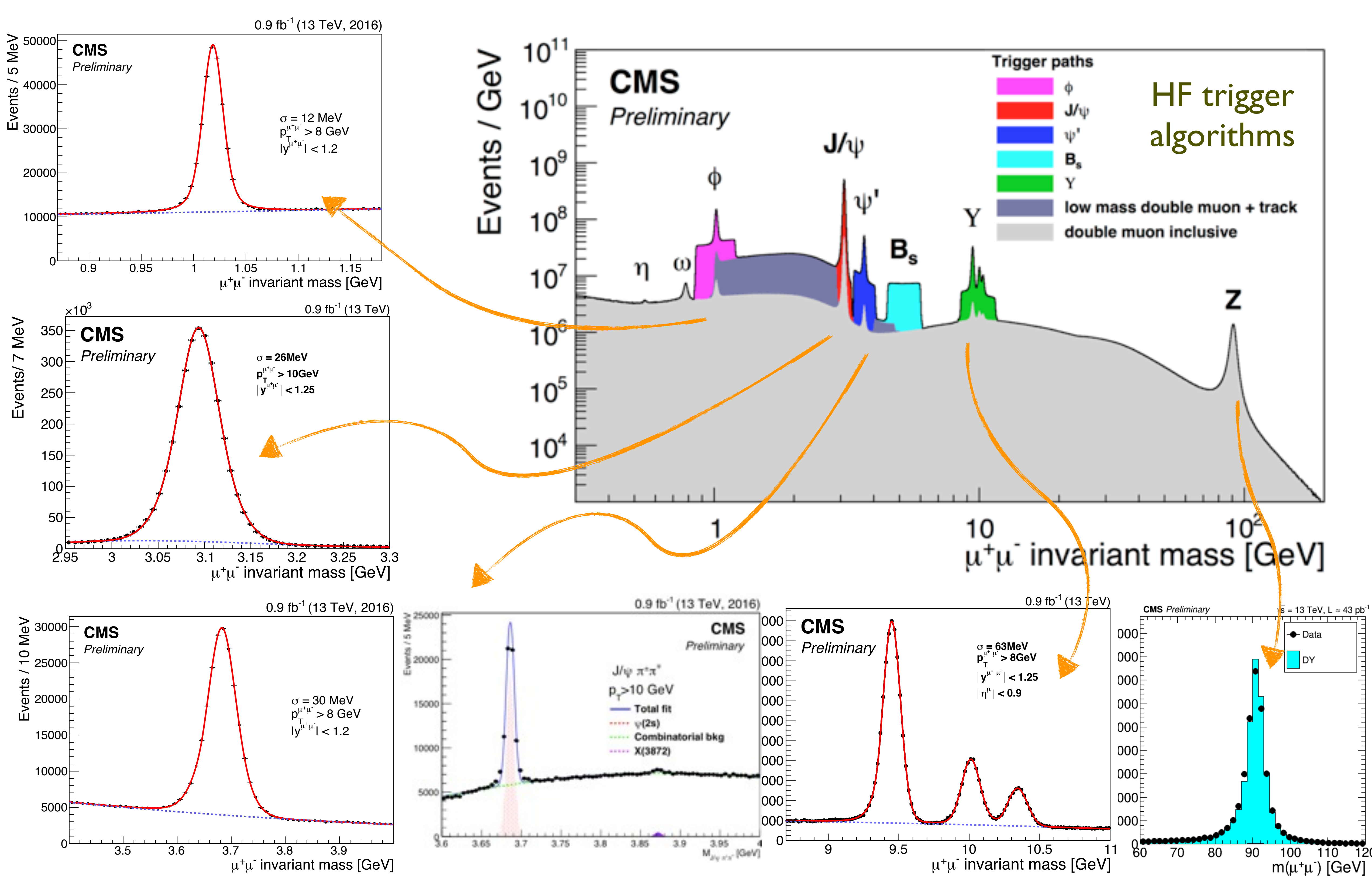


the discovery of the
b quark



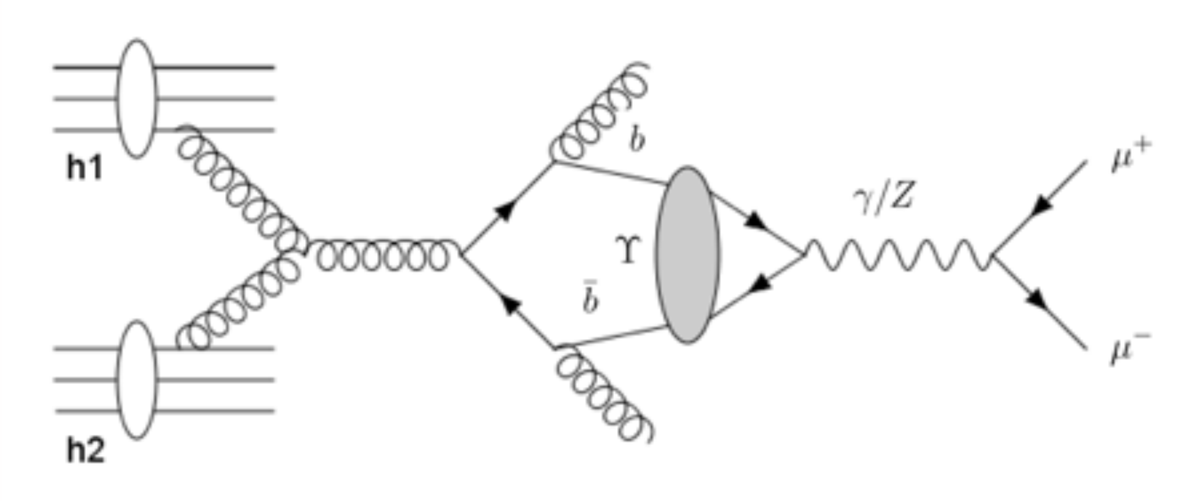
the higher resolution version of the spectrum
with latest LHC datasets
illustrating precision across the extended spectrum

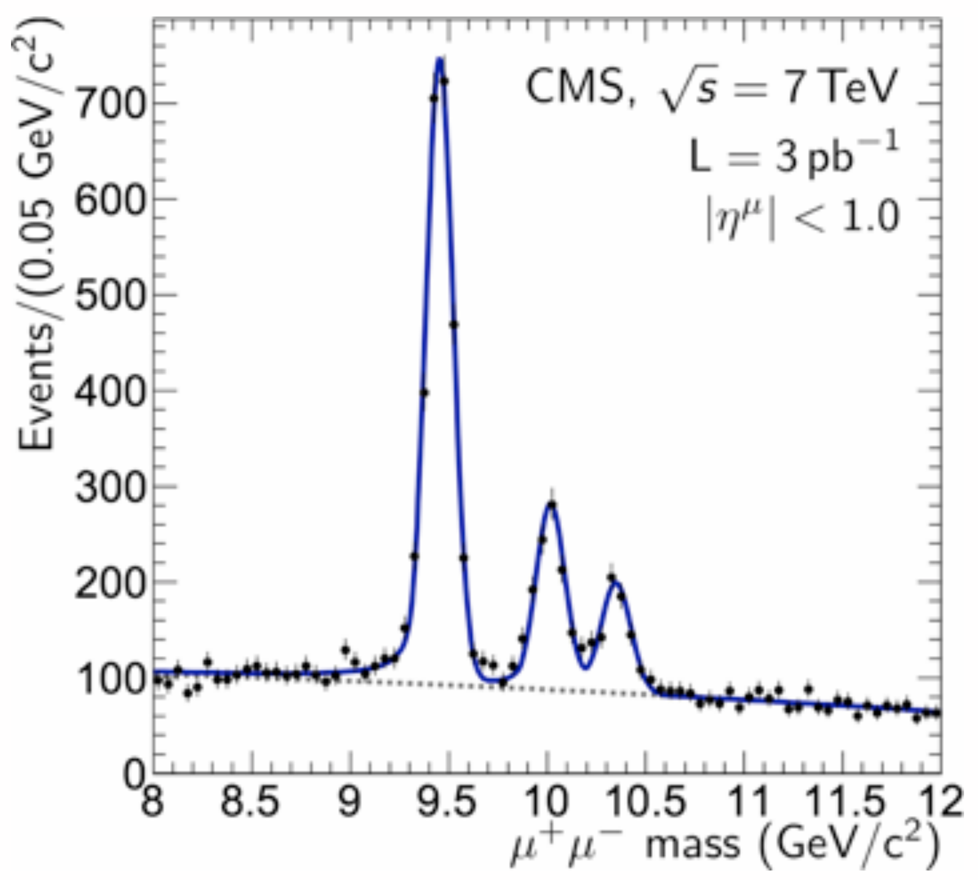
the dimuon spectrum



Upsilon, Υ

- {$b\bar{b}$} bound state
- extensively explored in Run1
  - first measurements with LHC data
- CMS capability to separate the 3 lowest lying states
  - allows robust measurements
- no feed-down from light b-hadrons
- the system satisfies best the non-relativistic approximation (NRQCD)
  - sensitive probe to test and discriminate effective models of QCD

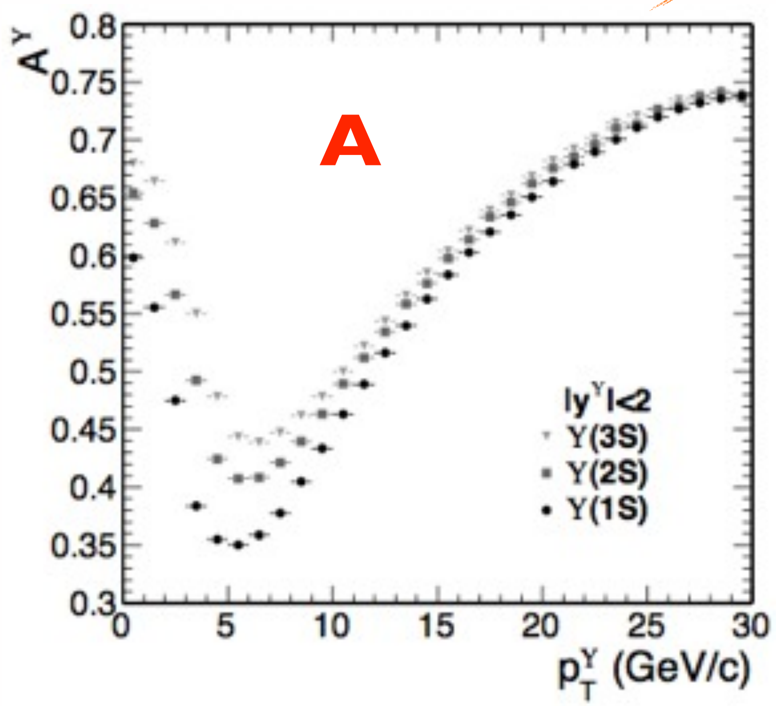




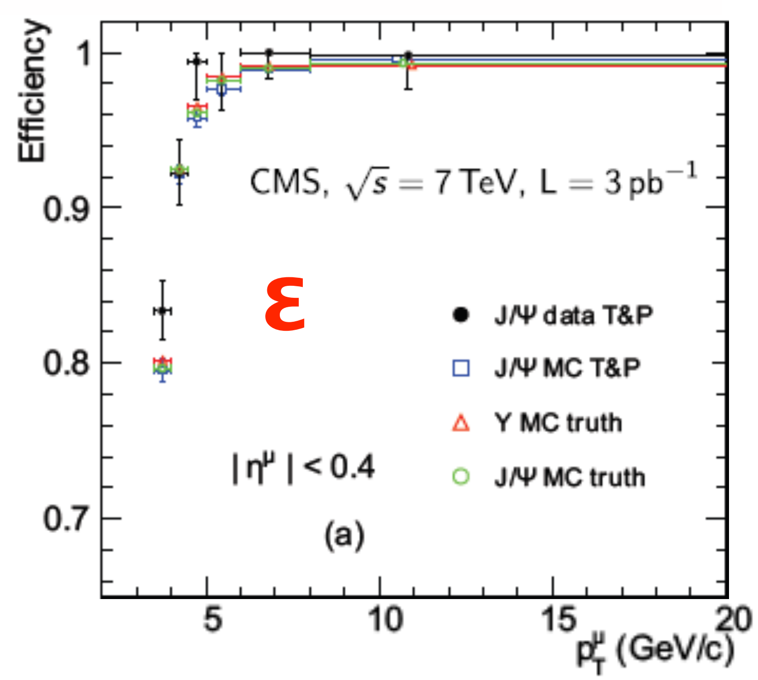
production measurement

- cross section ("N=L.σ")

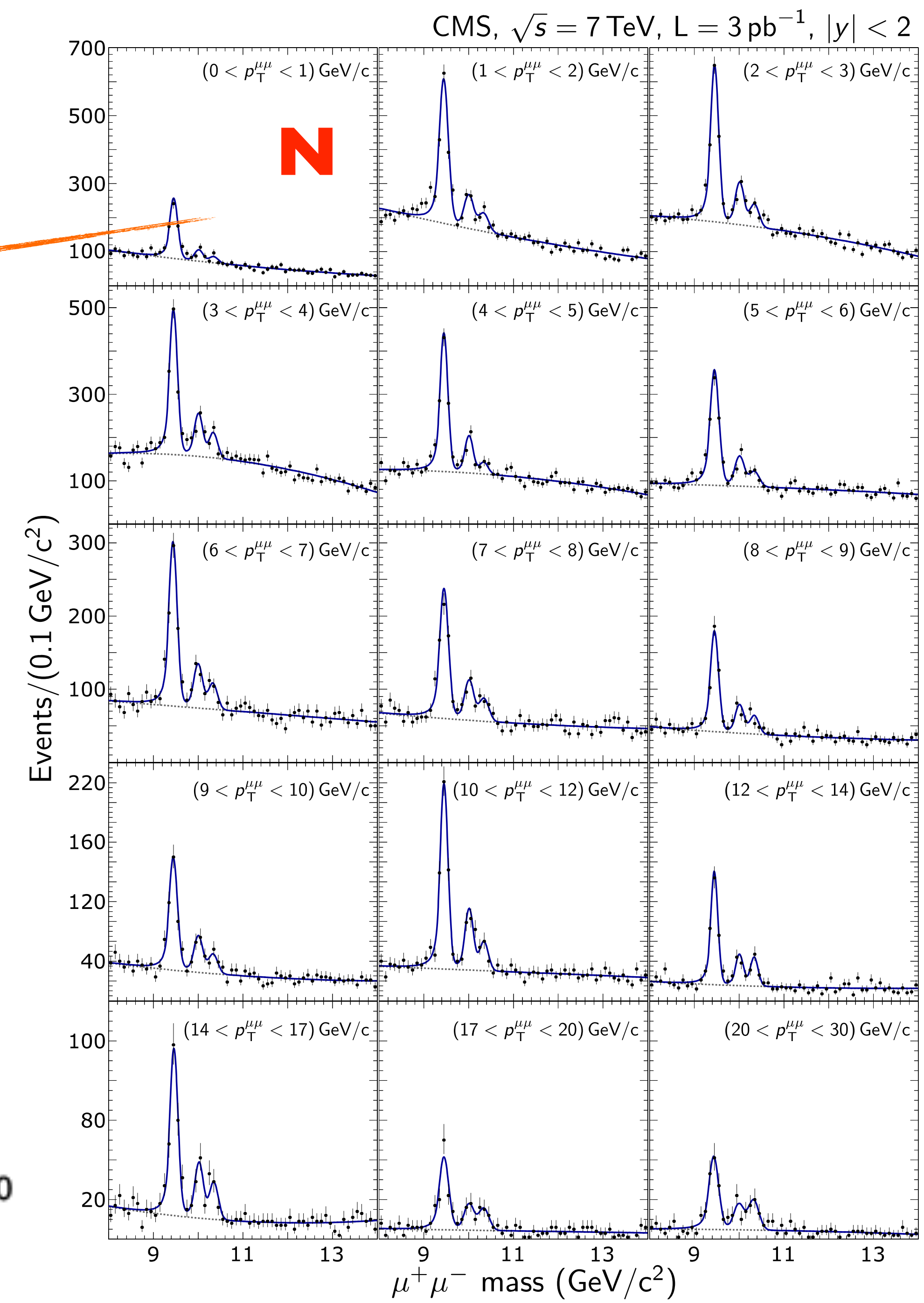
$$\frac{d^2\sigma(Q\overline{Q})}{dp_T dy}\mathcal{B}\left(Q\overline{Q}\rightarrow\mu^+\mu^-\right)=\frac{N_{fit}(Q\overline{Q})}{\mathcal{L}\cdot\mathcal{A}\cdot\epsilon\cdot\Delta p_T\cdot\Delta y}$$



detector geometry, acceptance, calculated from simulation



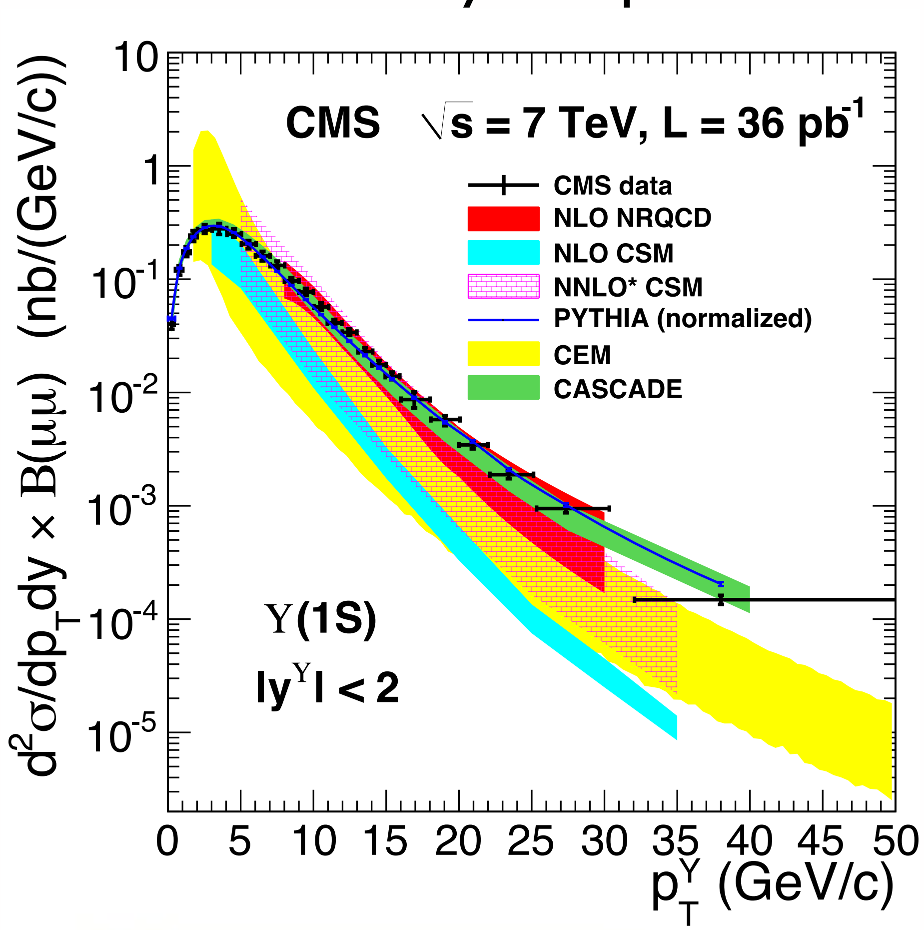
reconstruction efficiency, determined from data



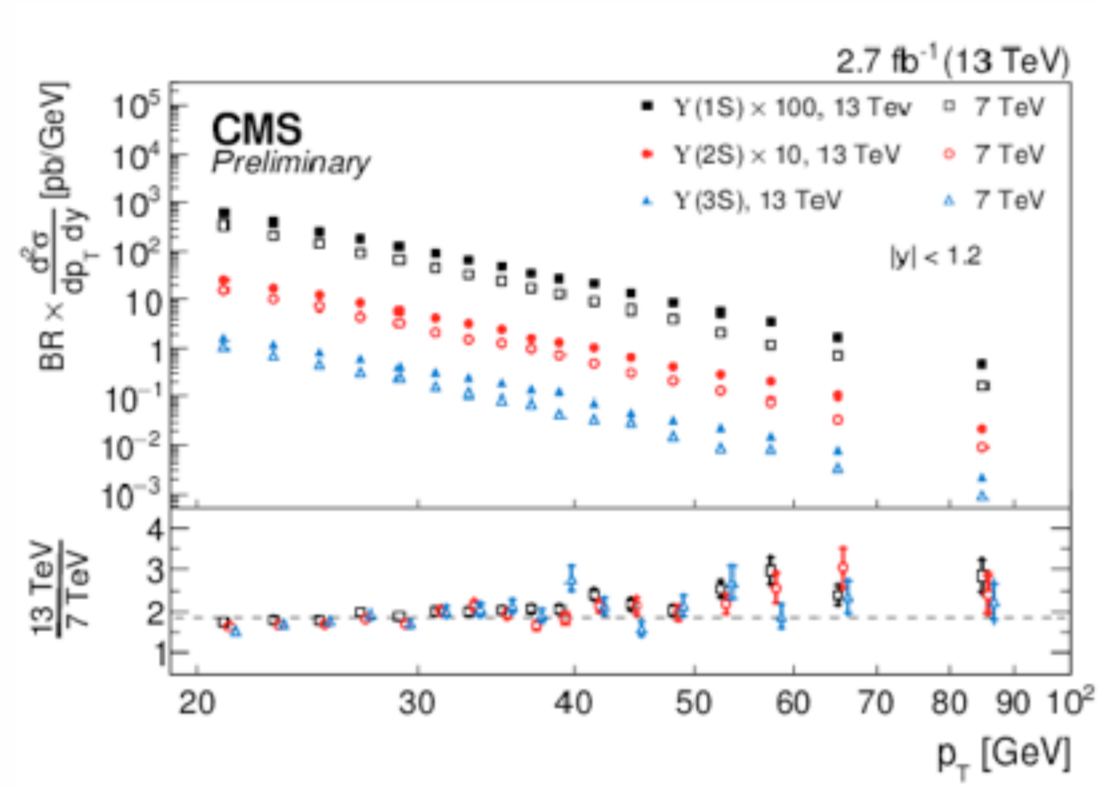
signal yield, extracted from fits to the data

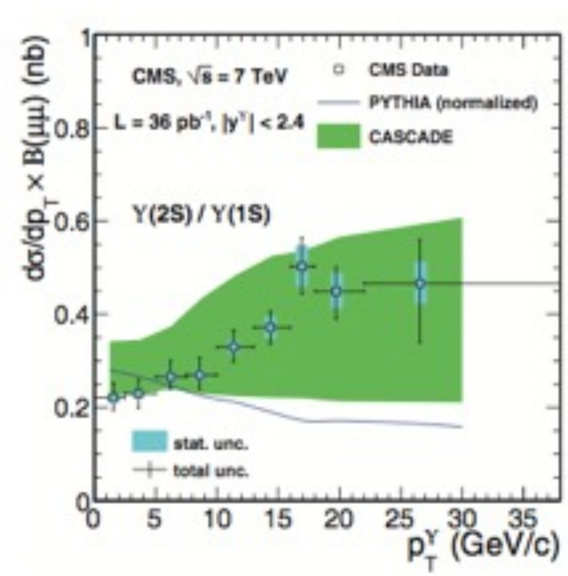
production cross sections

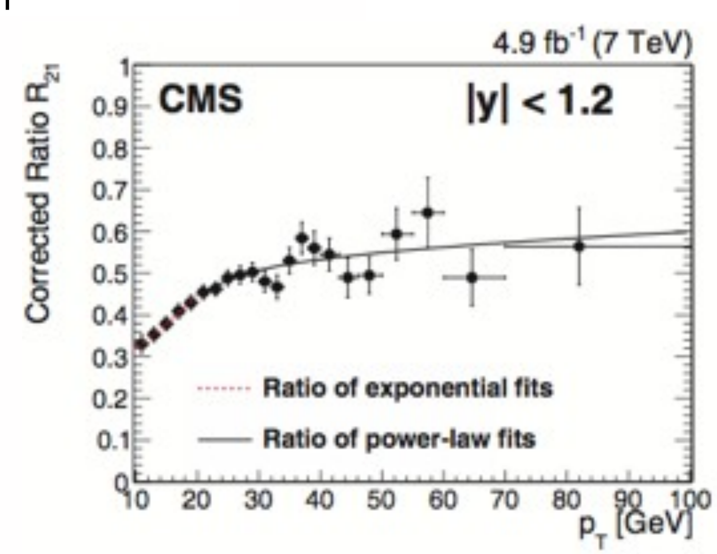
data-theory comparison



larger data sets allow to probe higher p_T region: 100GeV and above !



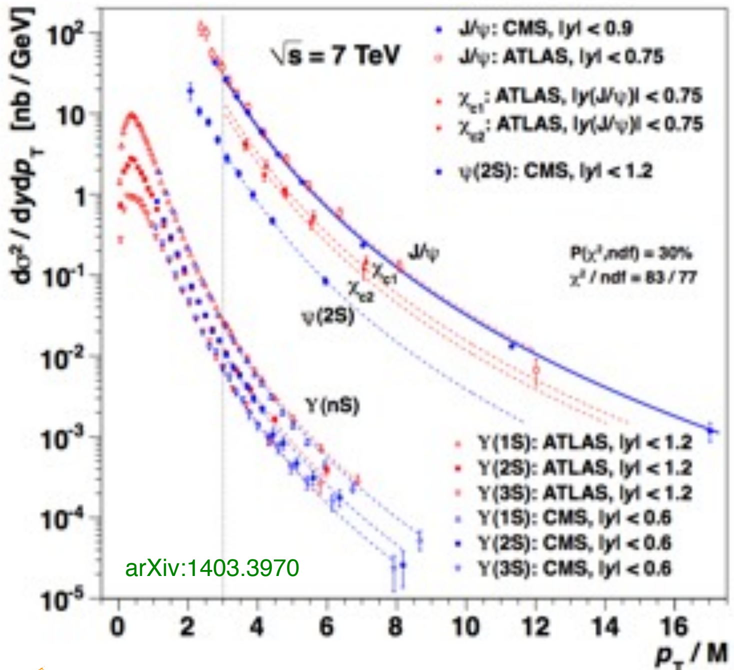


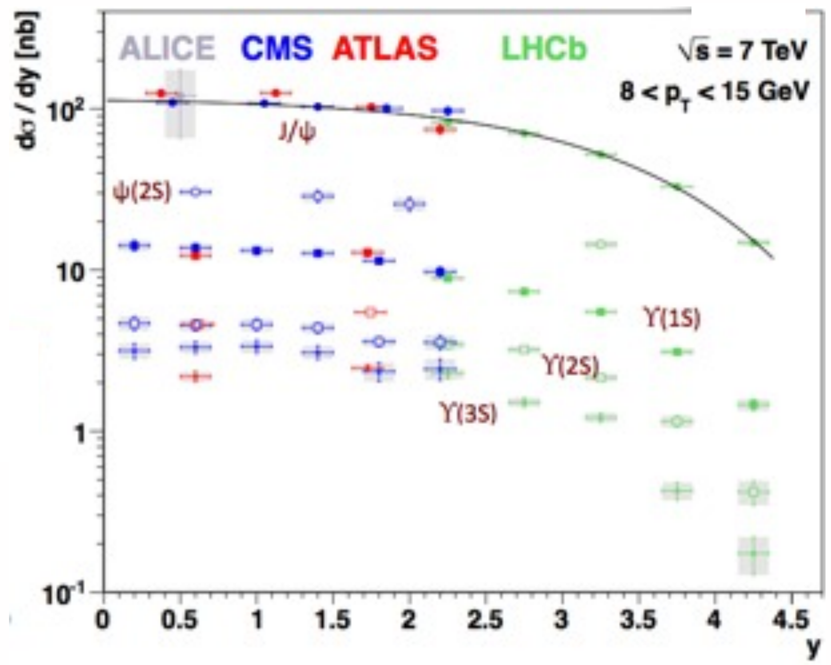


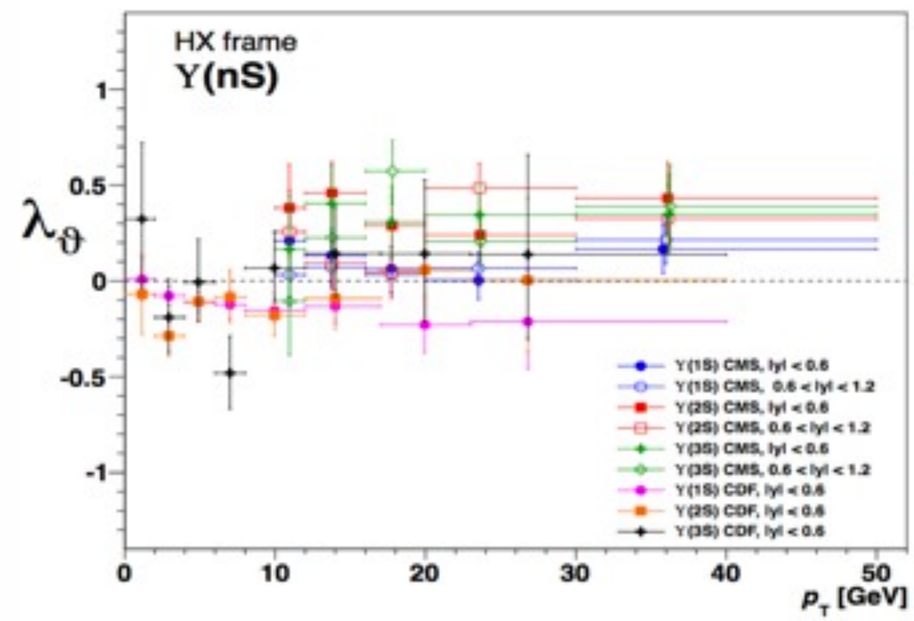
Υ(nS) production ratios provide additional, robust observables

- a non-anticipated dependence at low p_T is clearly observed

onia production, global view



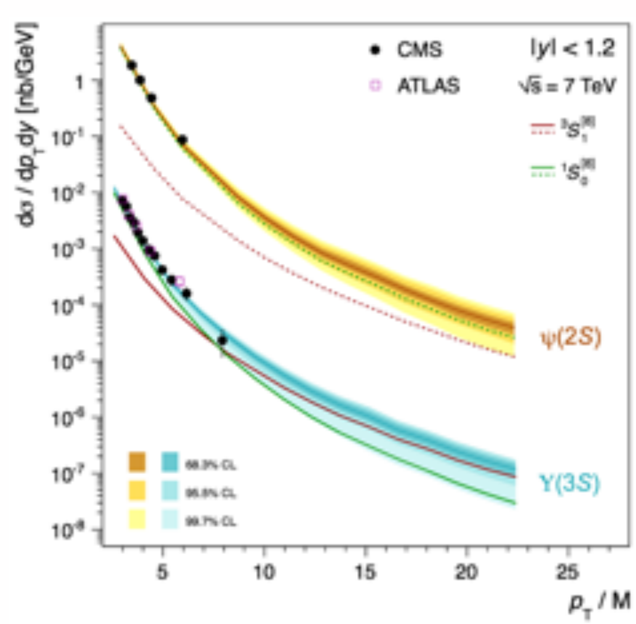


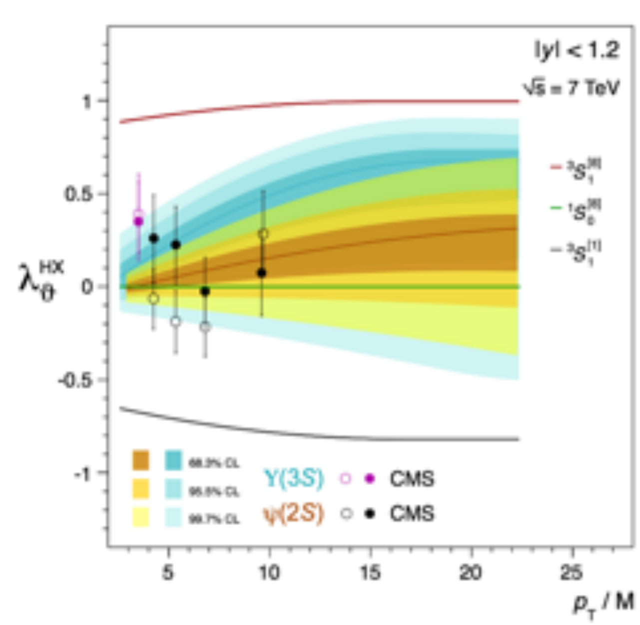


- LHC has provided detailed measurements of cross sections and polarizations
- which are the crucial input to carry out global fits to production mechanisms

GLOBAL FITS TO EXPERIMENTAL MEASUREMENTS

example:
Seixas, Faccioli et al,
eg: PLB 736 (2014) 98

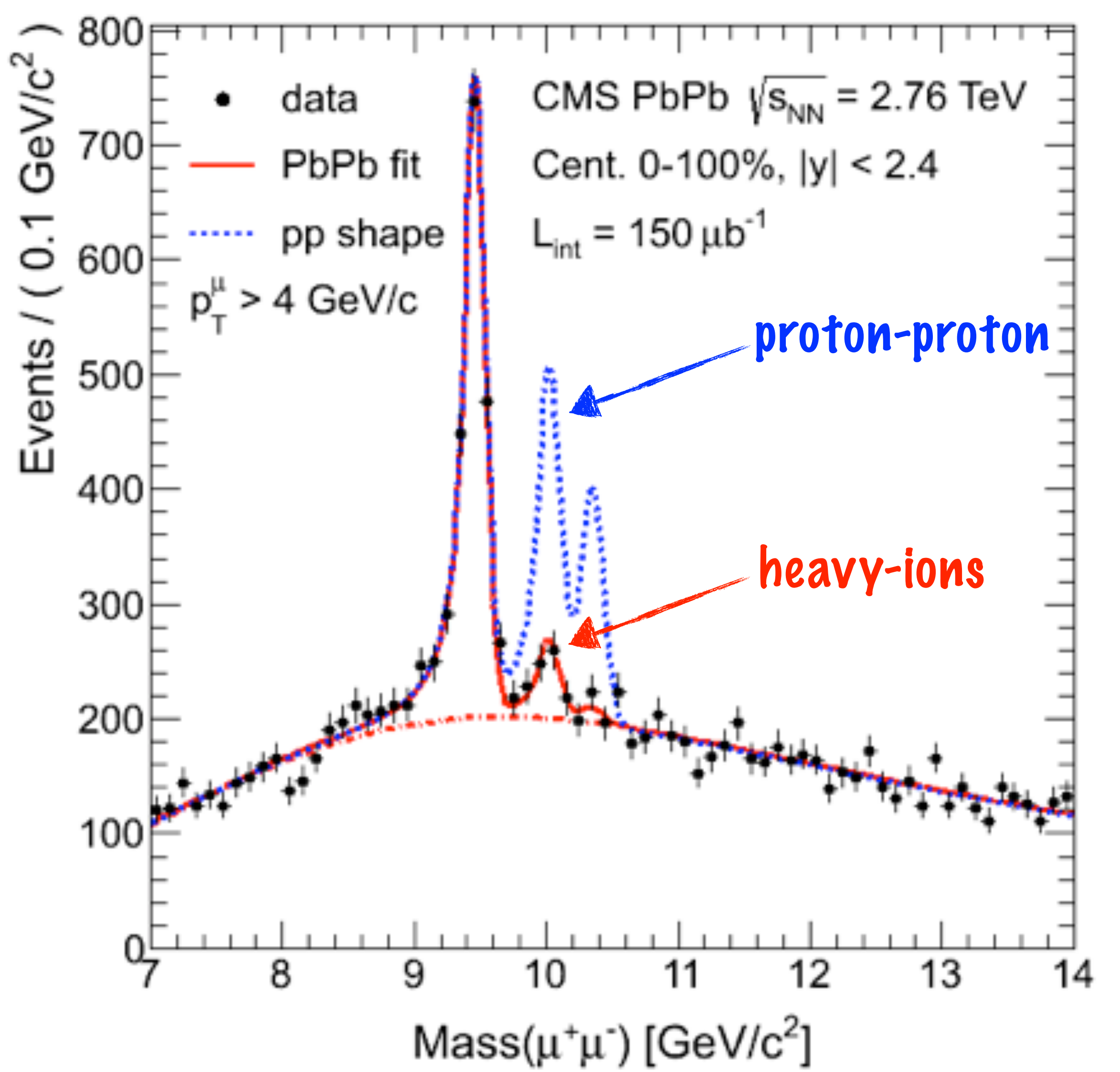




further LHC data will allow to explore the higher p_T regime, and access direct production

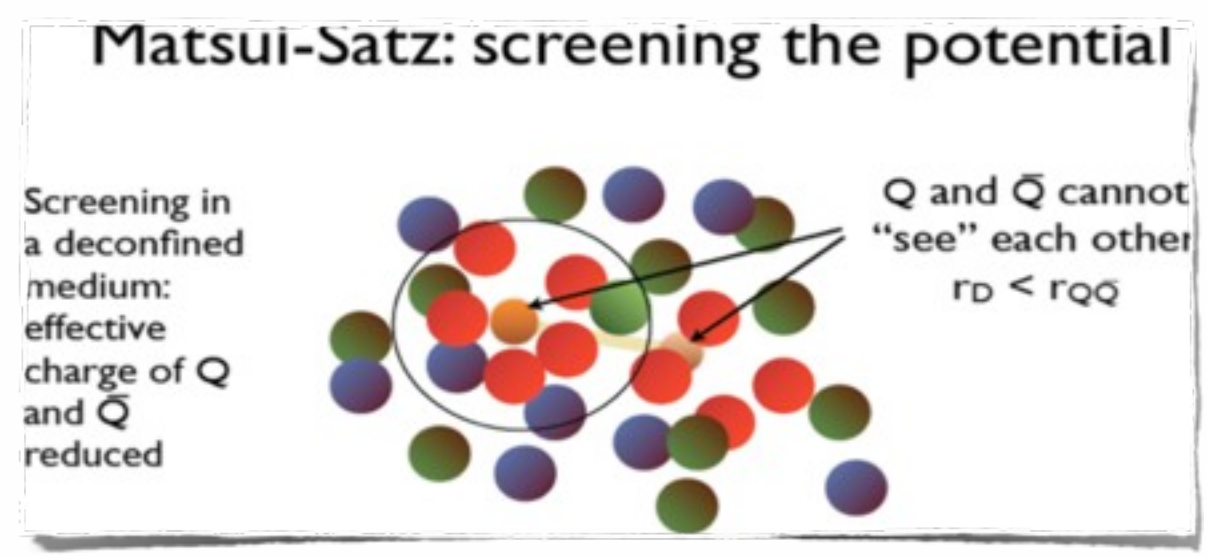
towards a more complete resolution of the "quarkonium puzzle"

Υ in heavy–ion collisions



- first (quantitative) measurements of the Υ(nS) states in HI collisions
- unprecedented resolutions, allowing to separate the three states
  - experimentally and theoretically robust
- excited states observed (>5σ) to be more suppressed than ground state
- spectacular indication of formation of **Q**uark **G**luon **P**lasma in heavy ion coll.

"the LHC heavy-ion **text book** result"



A flagship result of the LHC Heavy-ion physics program

Featured in Physics | Editors' Suggestion | Open Access

Observation of Sequential Υ Suppression in PbPb Collisions

S. Chatrchyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **109**, 222301 – Published 26 November 2012

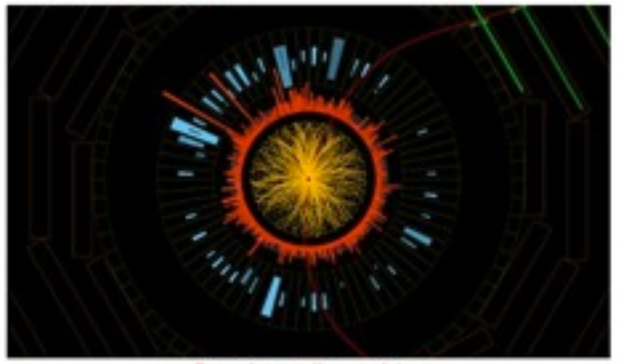
Physics See Viewpoint: New Temperature Probe for Quark-Gluon Plasma

Physics VIEWPOINT

New Temperature Probe for Quark-Gluon Plasma

Mesons measure collision temperatures

Dec 13, 2012 8 comments



Decaying upsilon particles

A new method to accurately work out the temperature of a quark–gluon plasma has been developed by researchers at the Compact Muon Solenoid (CMS) collaboration at the Large Hadron Collider (LHC) at CERN. The technique involves looking at the behaviour of certain mesons in lead–lead collisions. While a similar result was reported last year, this latest effort is claimed to be much stronger and more statistically significant.

Cosmologists and particle physicists have long been keen to understand in what state matter existed in the primordial universe.

Related stories

Curious correlations seen by CMS

Quark–gluon mania returns to CERN

Unexpected 'ridge' seen in CMS collision data

Quarks break free at two trillion degrees

Related links

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Phys. Rev. Lett. **109** 222301

CMS homepage

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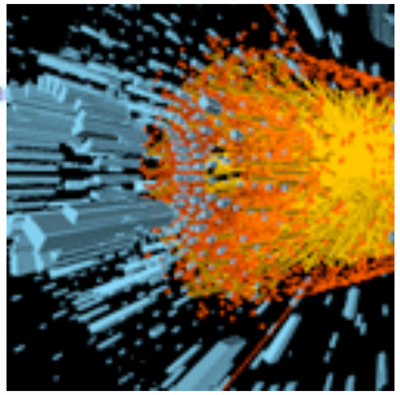
Indications of Suppression of Excited Υ States in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

S. Chatrchyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **107**, 052302 – Published 28 July 2011

Physics See Synopsis: Bringing nuclei together breaks quarks apa



Fermilab *Today*

Physics ABOUT BROWSE PRESS COLLECTIONS

Synopsis: Bringing nuclei together breaks quarks apart

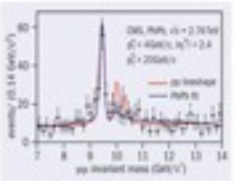
July 28, 2011

The hot, dense particle soup created by colliding lead nuclei breaks up pairs of weakly bound bottom quarks, as expected if the collision creates a plasma of unbound quarks and gluons.

CERN COURIER

Jul 19, 2011

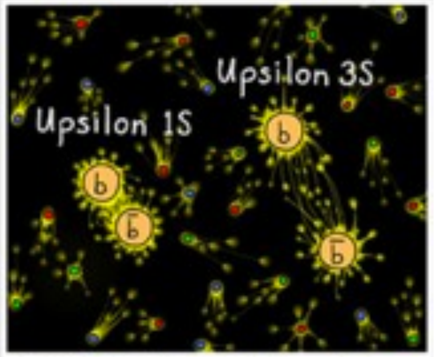
CMS observes Υ suppression in lead–lead collisions



Υ suppression

The heavy-ion collision data collected in November 2010 at the LHC continue to provide exciting new physics results. Recently, at the time of the Quark Matter 2011 conference, the CMS collaboration released the first results on the observation of a suppression of the excited Υ resonances in the lead–lead collisions at 2.76 TeV per nucleon pair. The suppression of heavy quarkonia is considered to be one of the "candle" signatures for the possible formation of a quark gluon plasma (QGP).

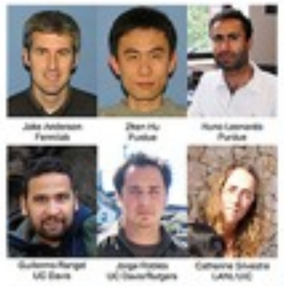
Melting mesons



Since the bottom quarks (b and $\bar{b}$) inside the Upsilon 1S (left) are held together more tightly than in the Upsilon 3S (right), the Upsilon 1S is less

Investigating exotic plasma

There are few places as complicated as the debris formed from a high-energy collision of two nuclei of atoms, and there is no facility that can muster as much energy as the LHC. For about a month each year, the LHC slams together two beams of nuclei from lead atoms. If the collision is head on, the 416 protons and neutrons involved in the collision melt, freeing the quarks and gluons. The resulting state of affairs is often called quark-gluon plasma (QGP). This mix hasn't been commonly seen in the universe since about a millionth of a second after the Big Bang.



Proton-proton collisions can result in a meson, while collisions involving lead nuclei can make it more difficult for the meson to form.

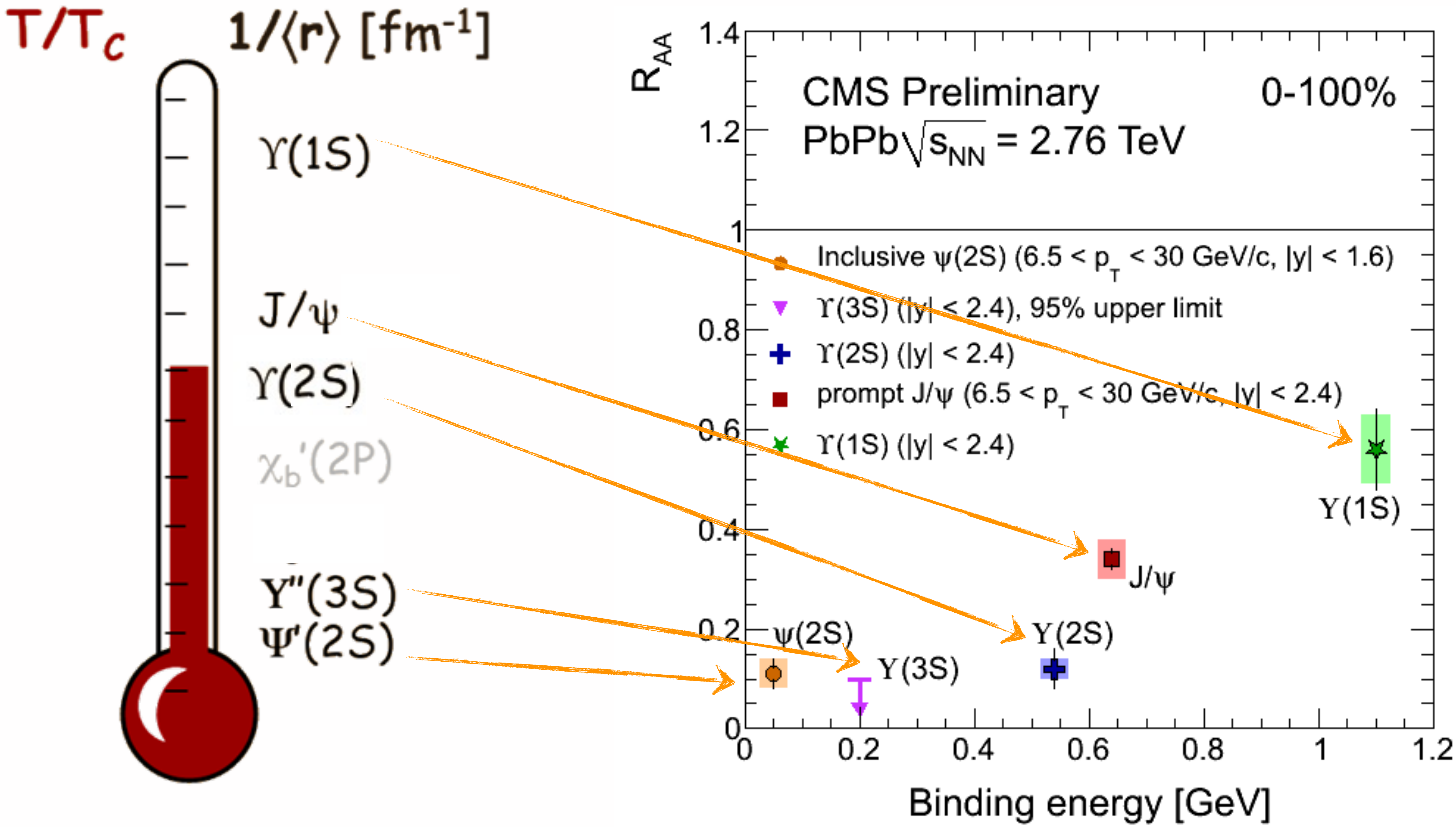
In order to study the behavior of matter under these conditions, we turn to bottom and charm quarks. These particles decay into muons that do not experience the strong nuclear force, which lets them escape the plasma unscathed. By observing muons, we can understand the behavior of the parent quarks that are affected by the QGP.

In a collision, charm quarks can be produced in a meson called the J/ψ, (consisting of a charm quark and charm antimatter quark) while the bottom quarks can be produced in a meson called the Υ, (which consists of a bottom quark/antiquark pair). In ordinary LHC collisions between pairs of protons, these quark/antiquark pairs see each other and bind together into the mesons. However, in collisions between lead

This effect introduces a new way to study quark-gluon plasmas—a new state of matter so hot and so short-lived that subatomic particles are the only thermometer.

—*Jim Pivarski*

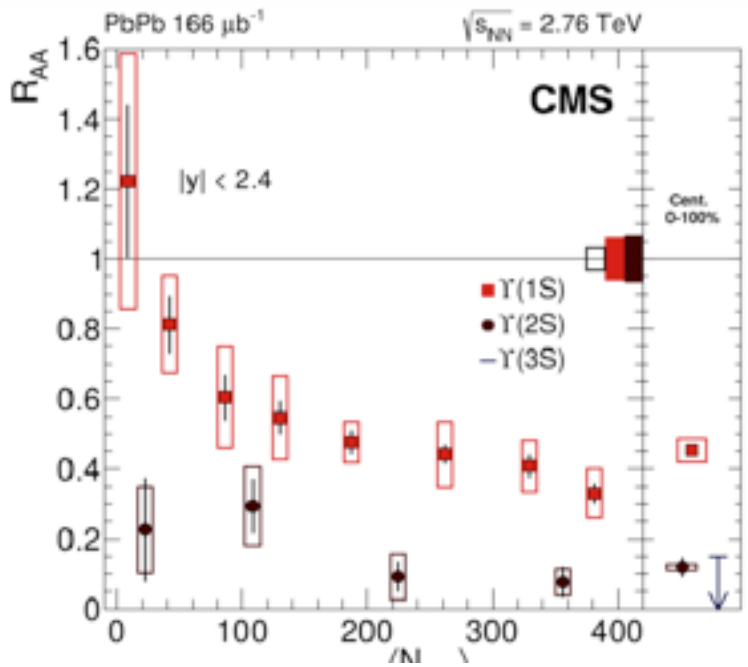
sequential suppression

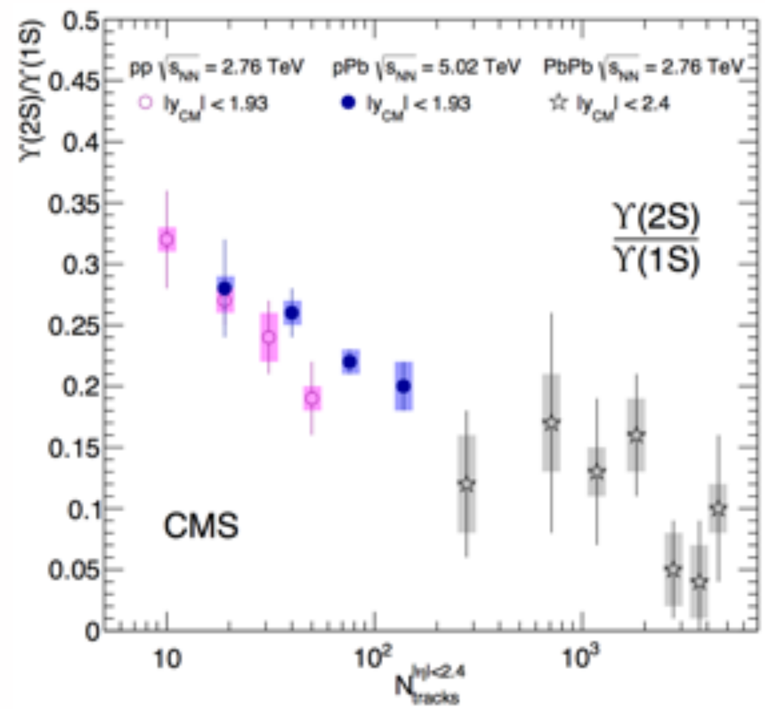


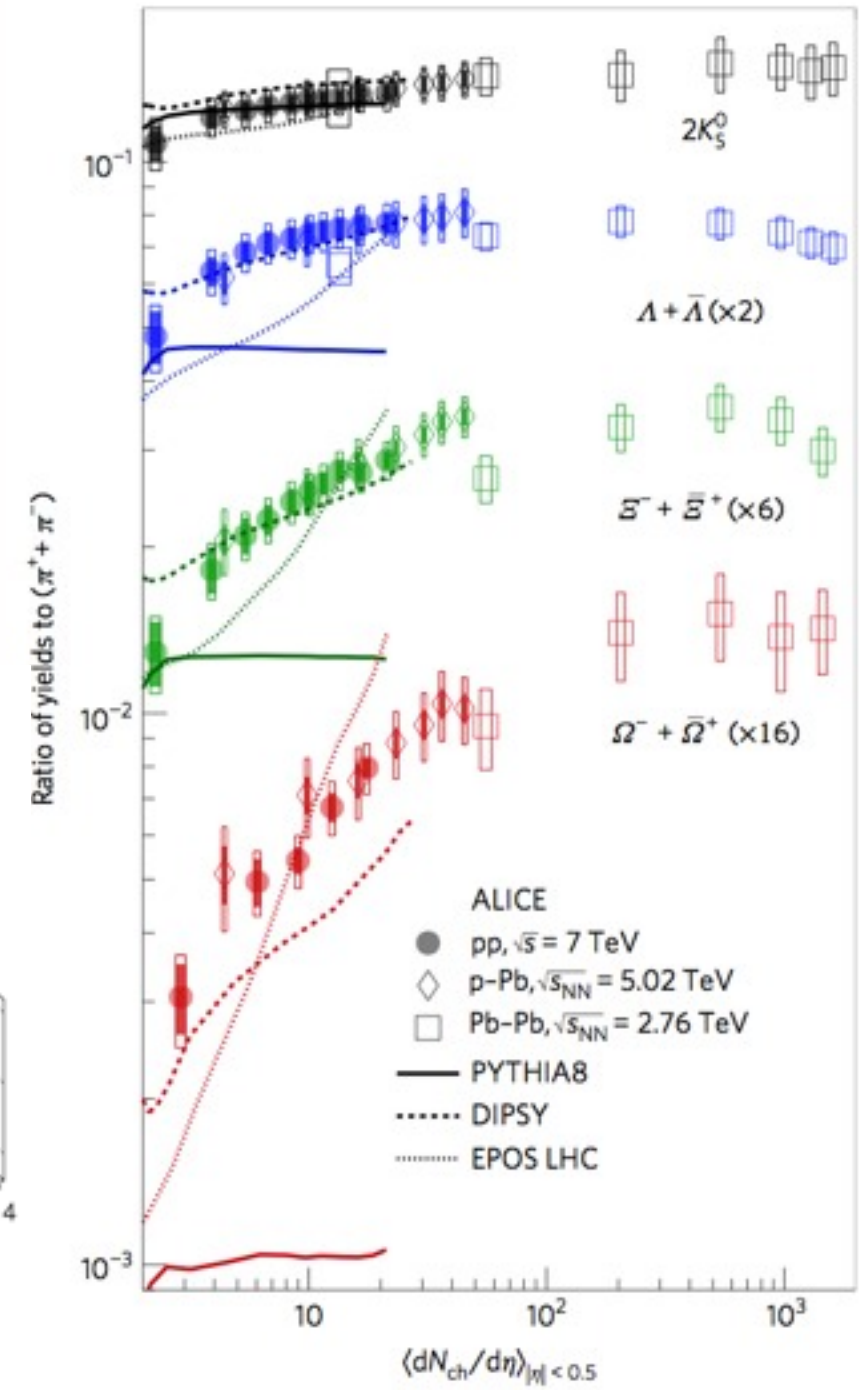
QUARKONIUM SUPPRESSION PATTERN EXPERIMENTALLY ESTABLISHED:

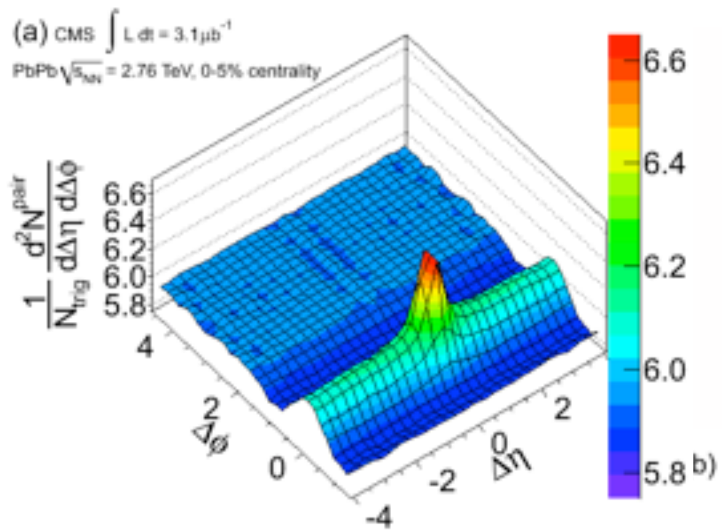
LESS TIGHTLY BOUND STATES ARE MORE SUPPRESSED IN THE MEDIUM

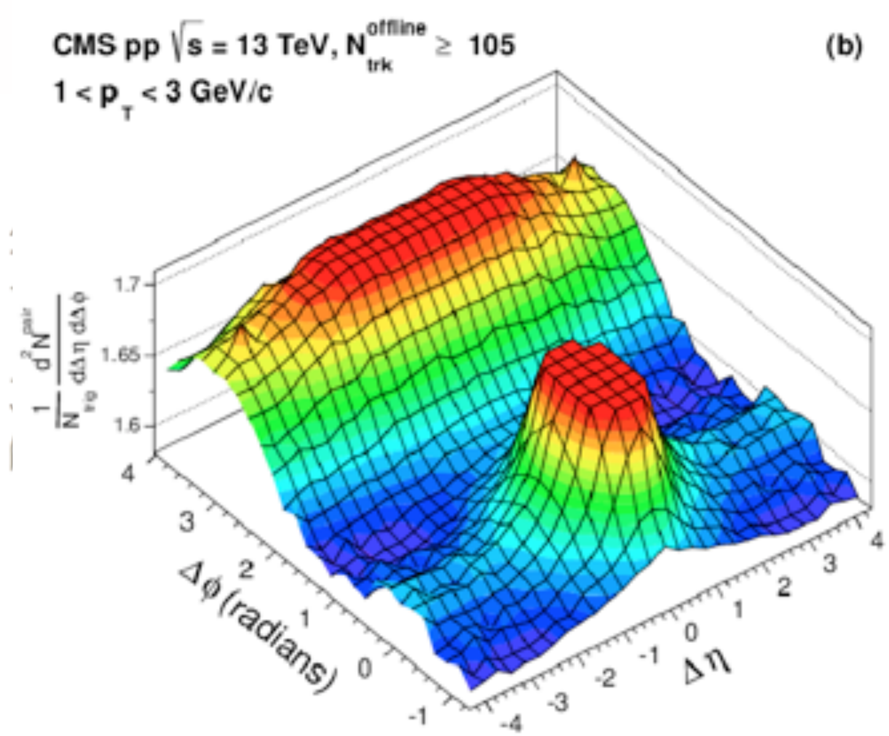
QGP-like hints in pp ?!

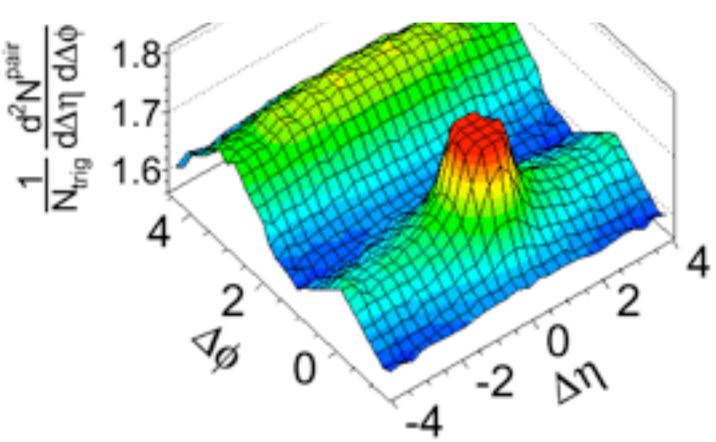












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World Scientific
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Review of bottomonium measurements from CMS

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We review the results on the bottomonium system from the CMS experiment at the Large Hadron Collider. Measurements have been carried out at different center-of-mass energies in proton collisions and in collisions involving heavy ions. These include precision measurements of cross sections and polarizations, shedding light on hadroproduction mechanisms, and the observation of quarkonium sequential suppression, a notable indication of quark–gluon plasma formation. The observation of the production of bottomonium pairs is also reported along with searches for new states. We close with a brief outlook of the future physics program.

Υ summary

NL led and carried out thorough exploration of the Υ family

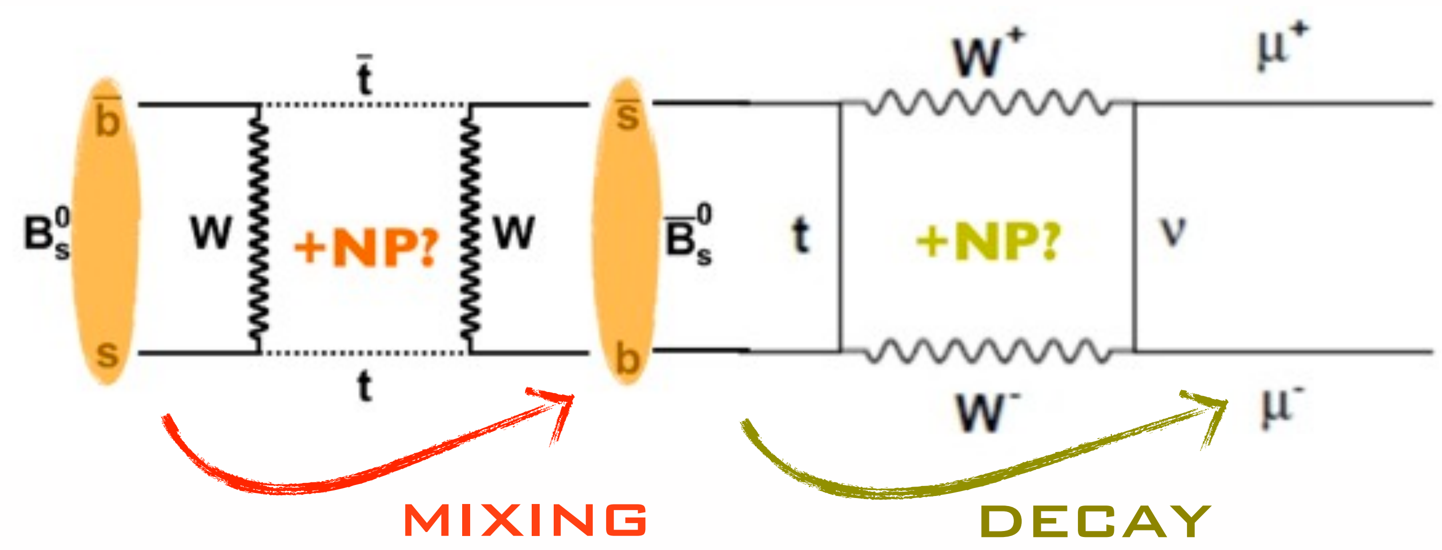
in different collision types and energies at LHC Run1 with CMS

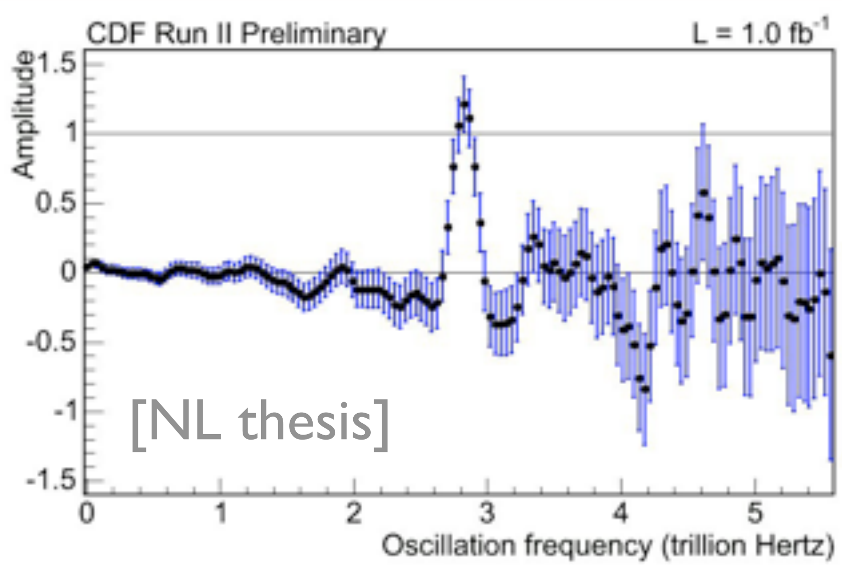
involving precision measurements and discovery

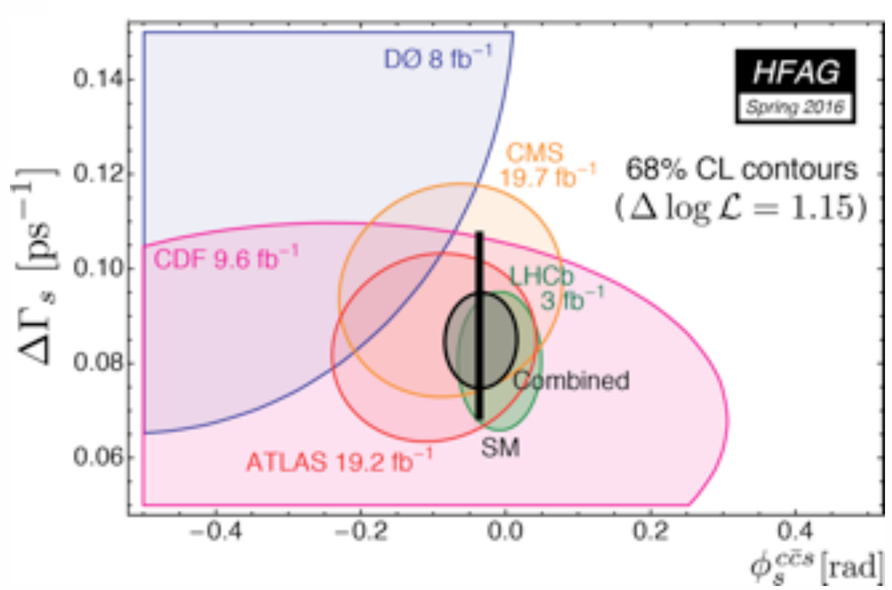
wrote a comprehensive **review**, with my former PhD student, just published

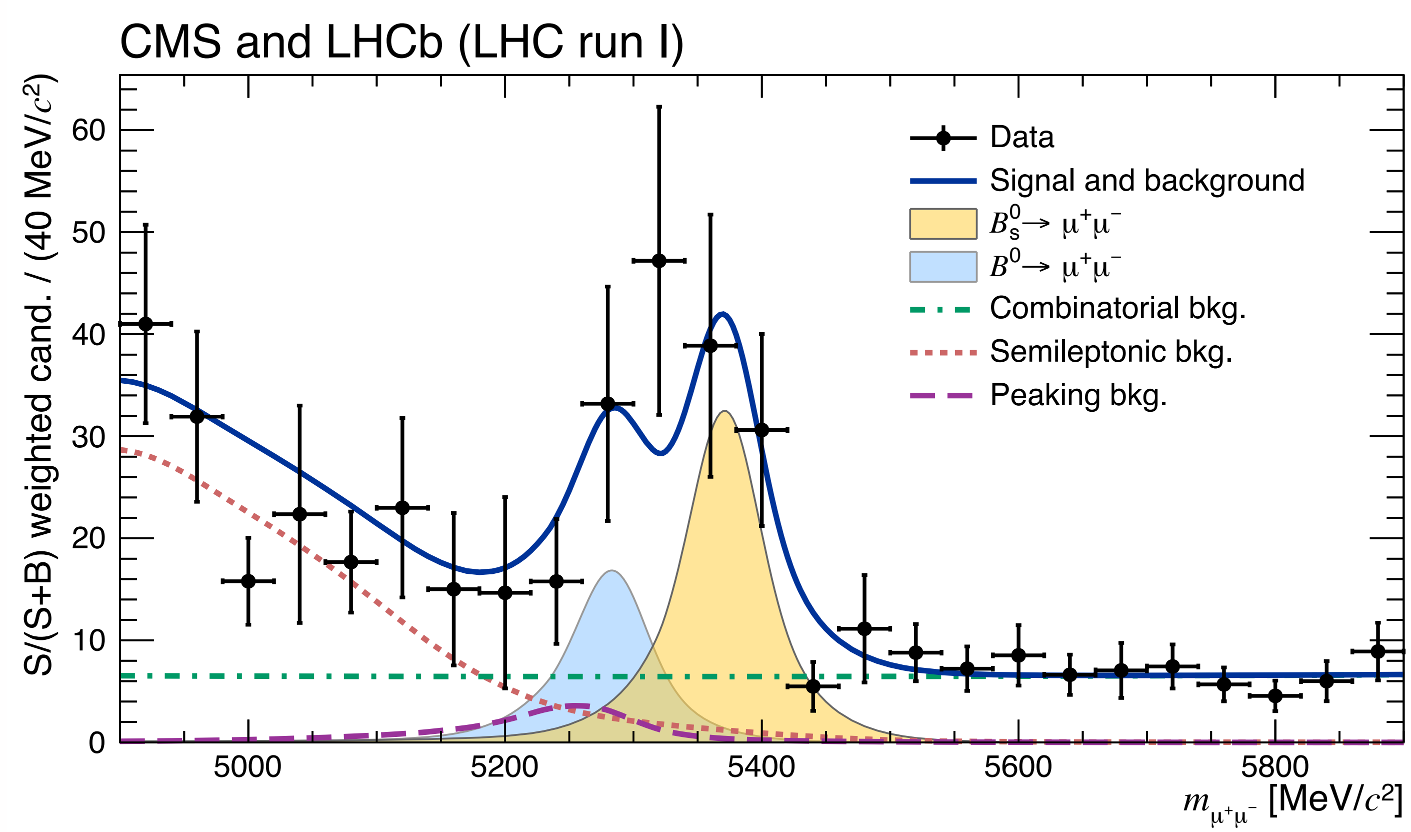
B_s

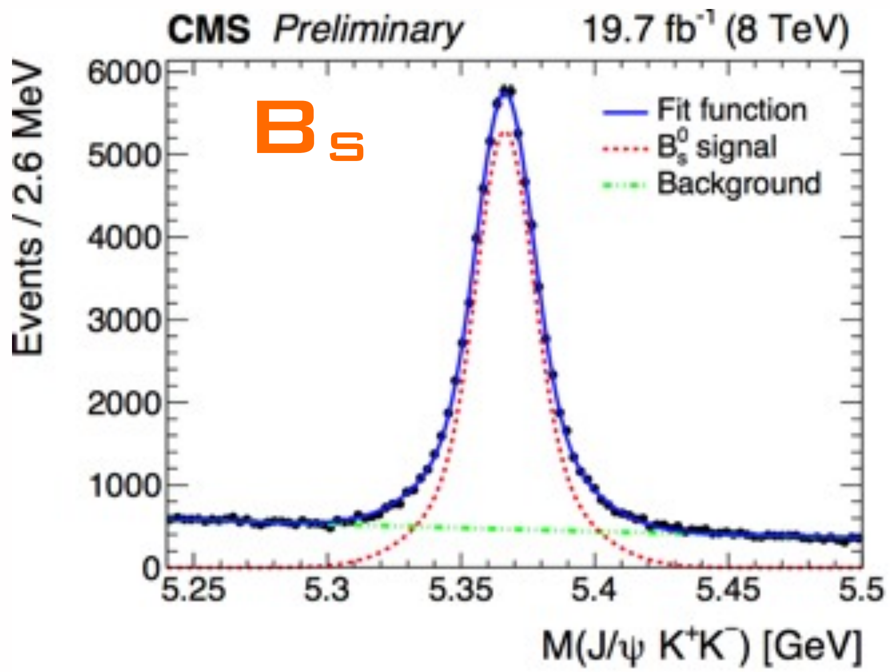
- highly interesting meson system



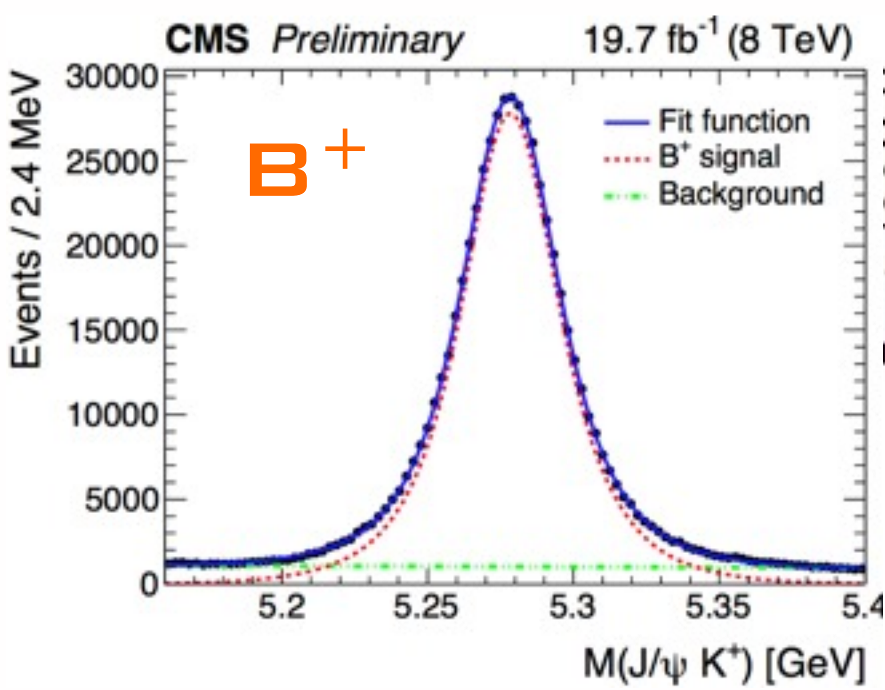


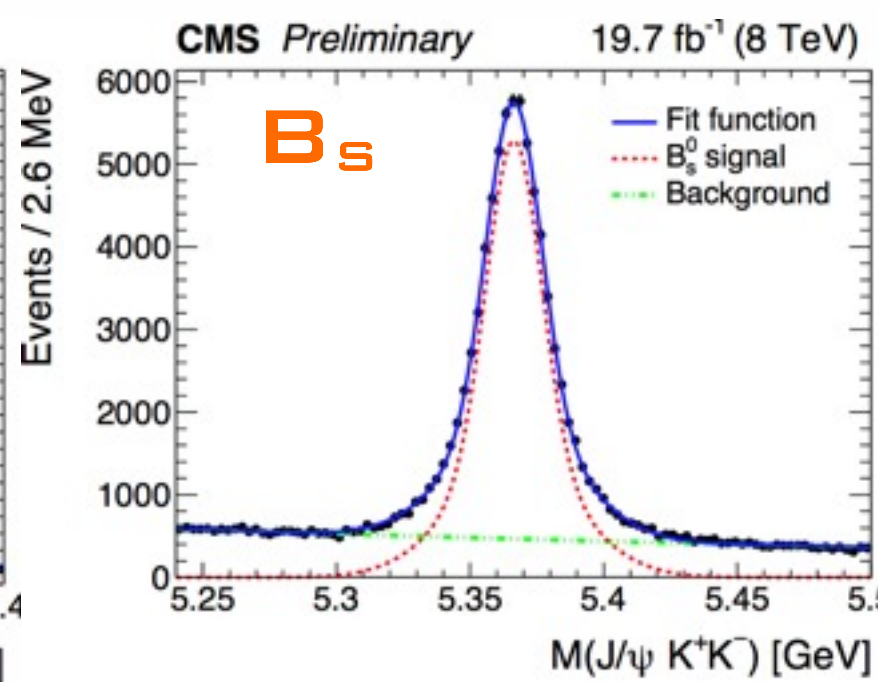


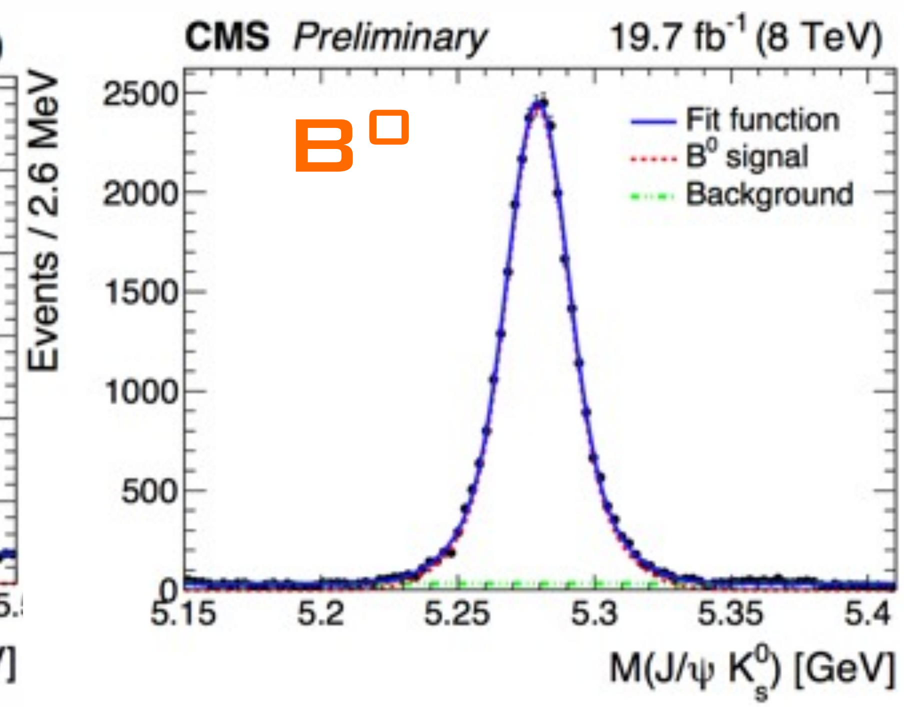


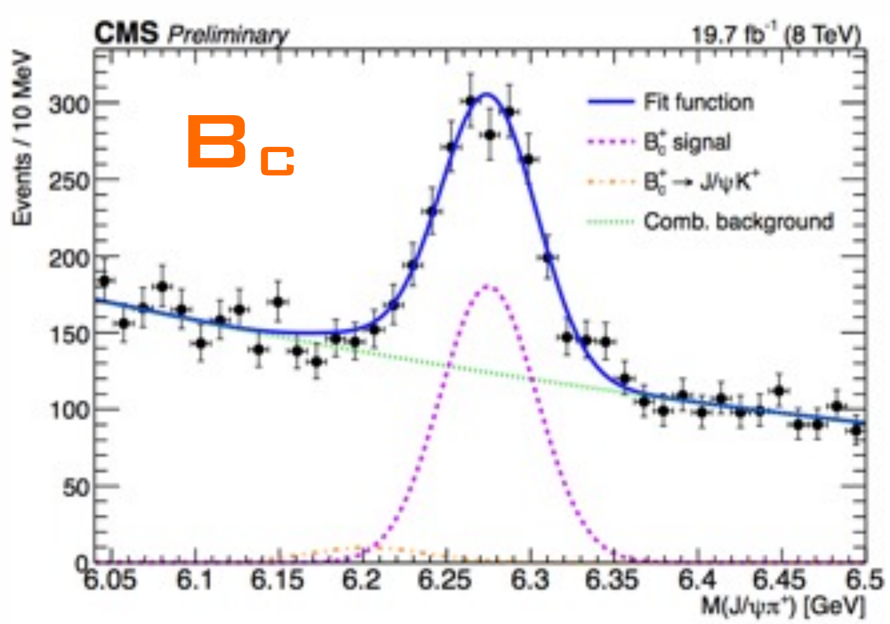

CMS Preliminary
19.7 fb⁻¹ (8 TeV)
Bs
Fit function
B_s^0 signal
Background
Events / 2.6 MeV
6000
5000
4000
3000
2000
1000
0
5.25
5.3
5.35
5.4
5.45
5.5
M(J/ψ K⁺K⁻) [GeV]

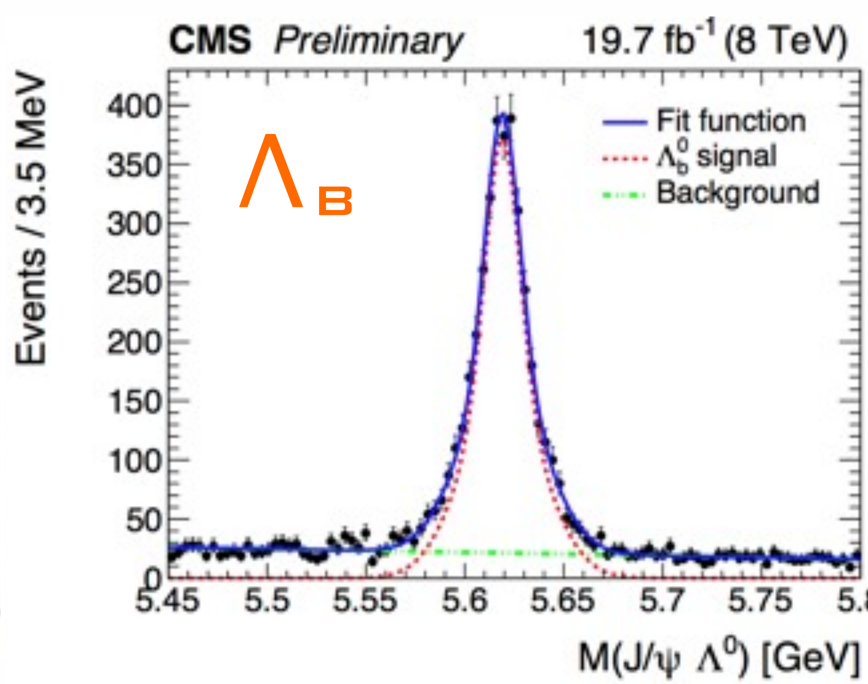
b hadrons

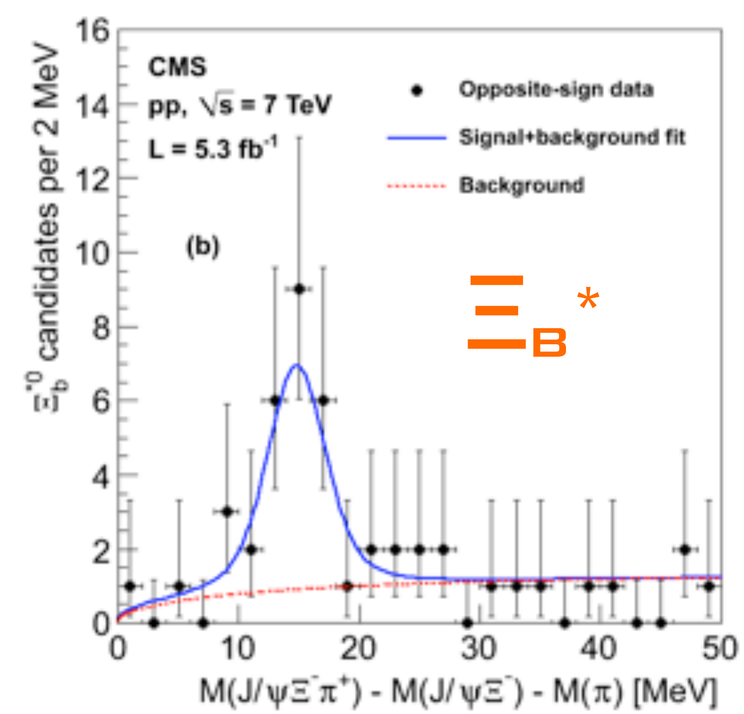

CMS Preliminary 19.7 fb-1 (8 TeV)
B+
Fit function
B+ signal
Background
Events / 2.4 MeV
M(J/ψ K+) [GeV]


CMS Preliminary 19.7 fb-1 (8 TeV)
Bs
Fit function
B0s signal
Background
Events / 2.6 MeV
M(J/ψ K+K−) [GeV]

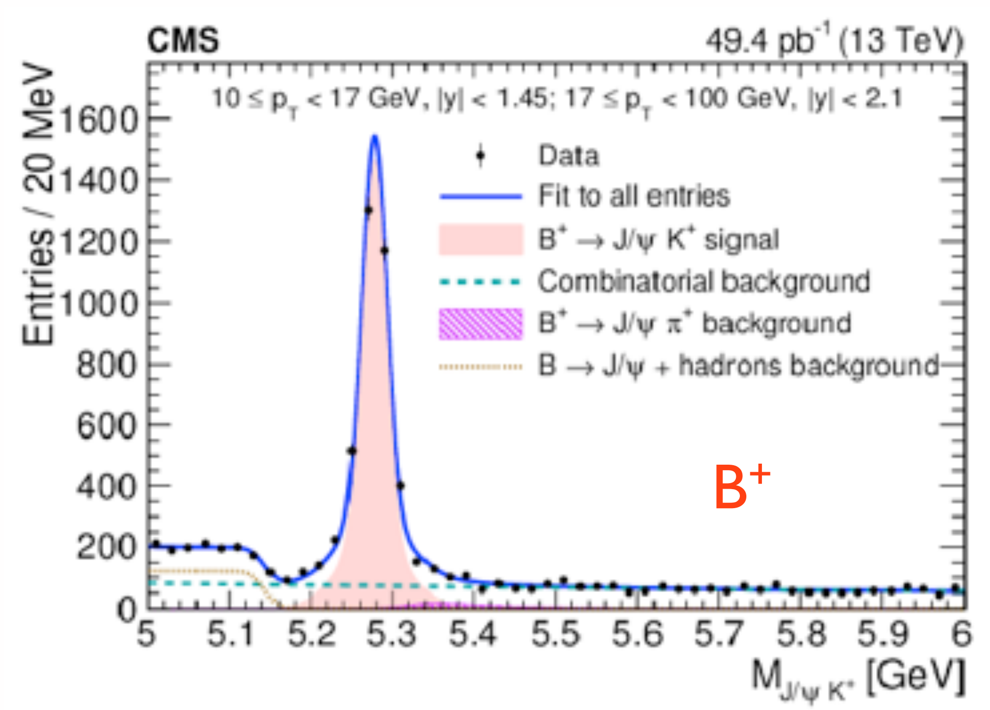

CMS Preliminary 19.7 fb-1 (8 TeV)
B0
Fit function
B0 signal
Background
Events / 2.6 MeV
M(J/ψ K0s) [GeV]

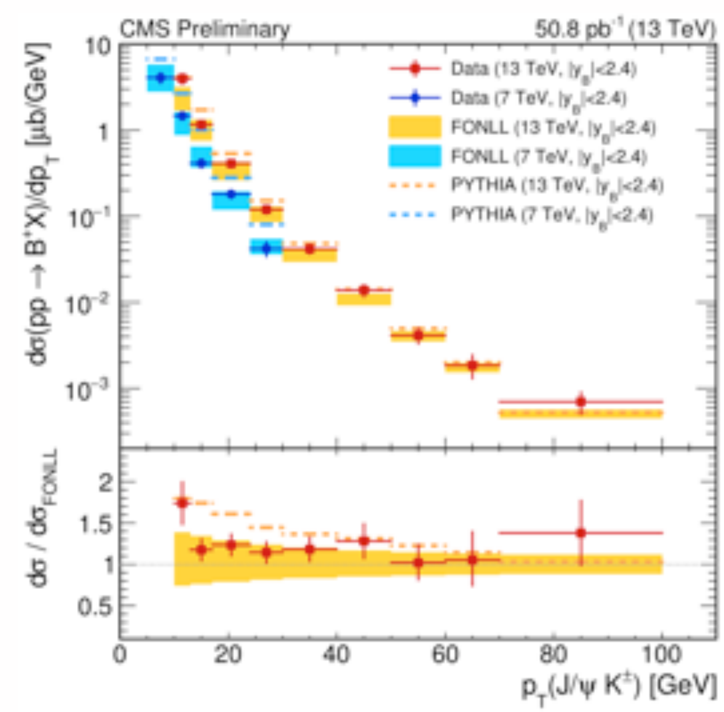

CMS Preliminary 19.7 fb-1 (8 TeV)
Bc
Fit function
B+c signal
B+c → J/ψK+
Comb. background
Events / 10 MeV
M(J/ψπ+) [GeV]

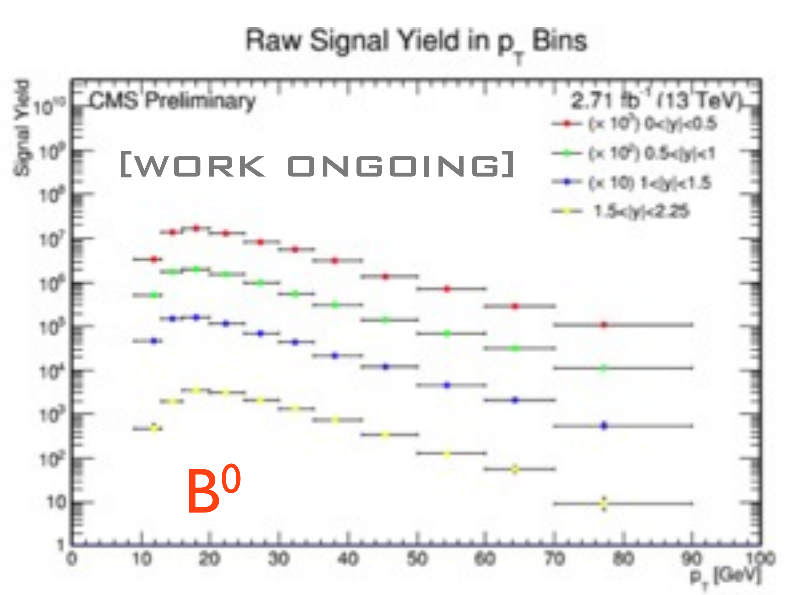

CMS Preliminary 19.7 fb-1 (8 TeV)
ΛB
Fit function
Λ0b signal
Background
Events / 3.5 MeV
M(J/ψ Λ0) [GeV]

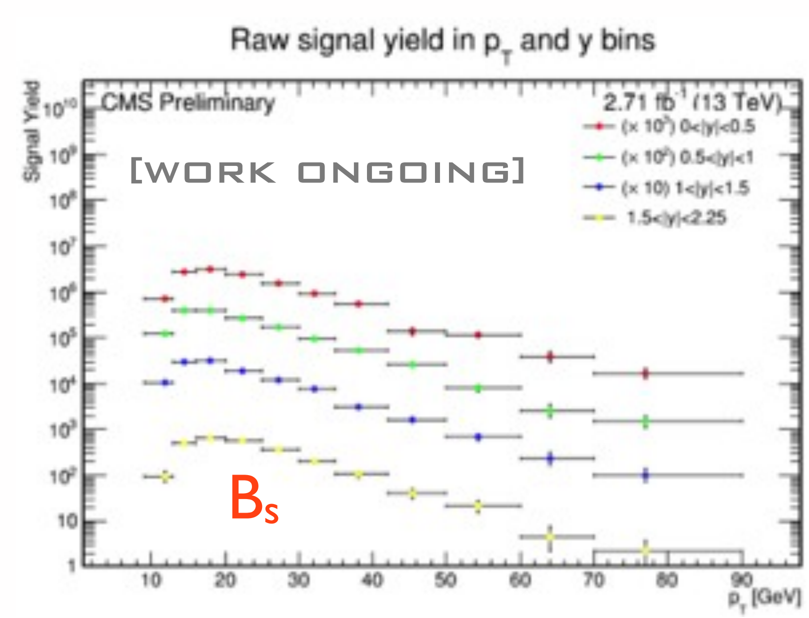

CMS
pp, √s = 7 TeV
L = 5.3 fb-1
(b)
Opposite-sign data
Signal+background fit
Background
ΞB*
Ξb*0 candidates per 2 MeV
M(J/ψΞ−π+) - M(J/ψΞ−) - M(π) [MeV]

cross section







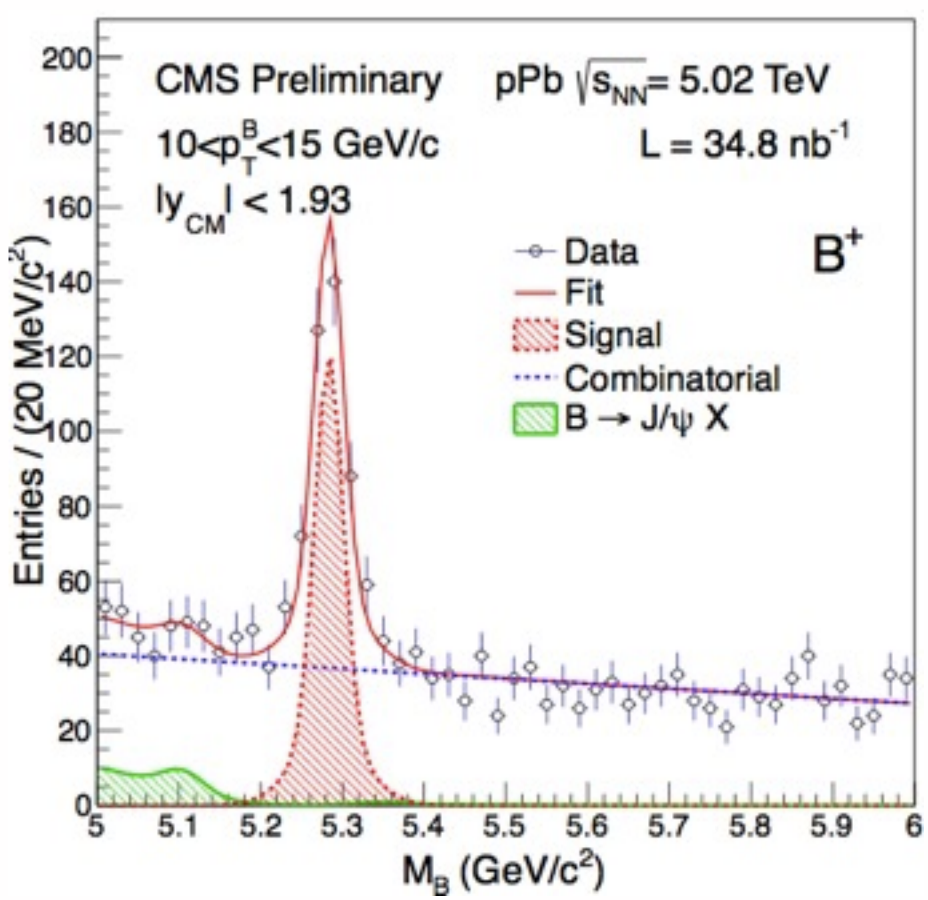


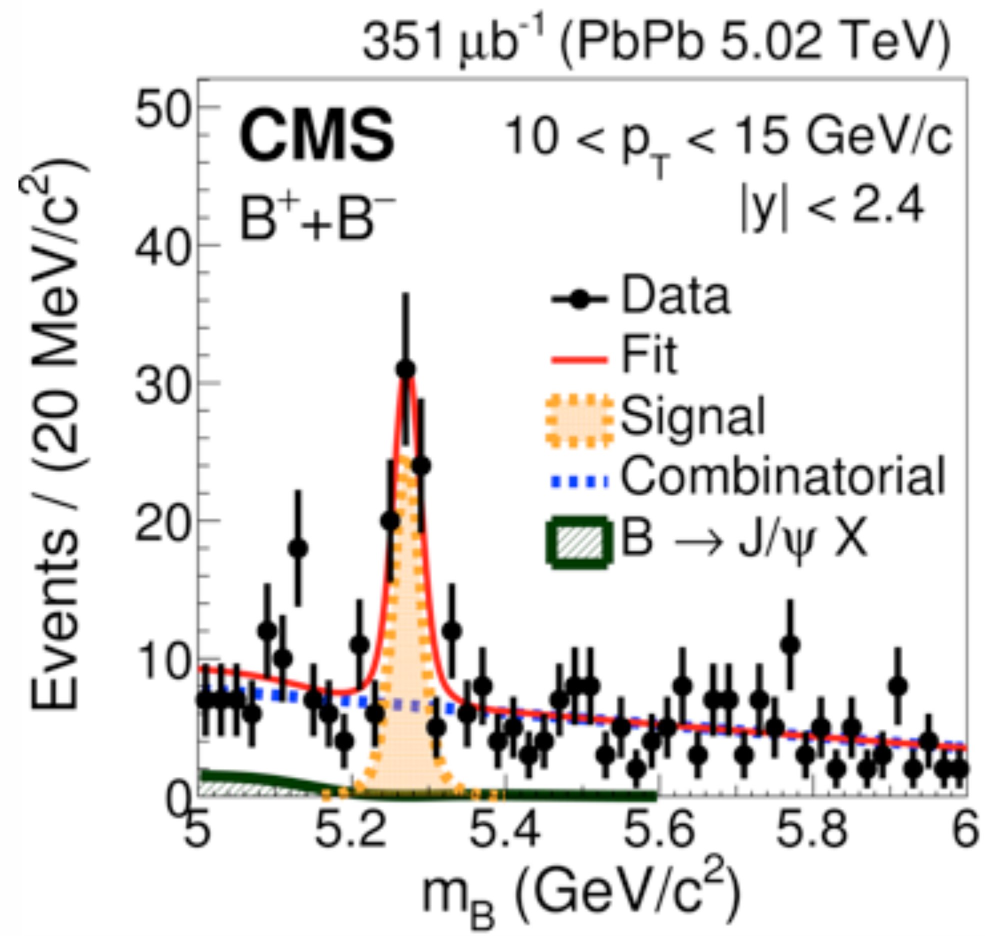
- b-hadron cross sections measured at different pp energies
  - 5, 7, 13 TeV

- exploring larger datasets, to study:
- kinematic dependencies
- additional hadrons
- rarer channels

B's in heavy-ion collisions

- b-hadron decays reconstructed for first time ever in heavy ion collisions !
  - new QGP probes





- pursue the study of additional hadrons [WORK ONGOING]
  - explore the flavor dependence of energy loss in the hot medium

lifetimes

- just delivered a set of precision measurement of effective lifetimes of various b-hadrons in various decay channels

just released at LHCP'2017

$$c\tau_{B^0} = 453.0 \pm 1.6\,(\text{stat})\ \pm 1.5\,(\text{syst})\ \mu m\ (\text{in } J/\psi K^*(892)^0)$$

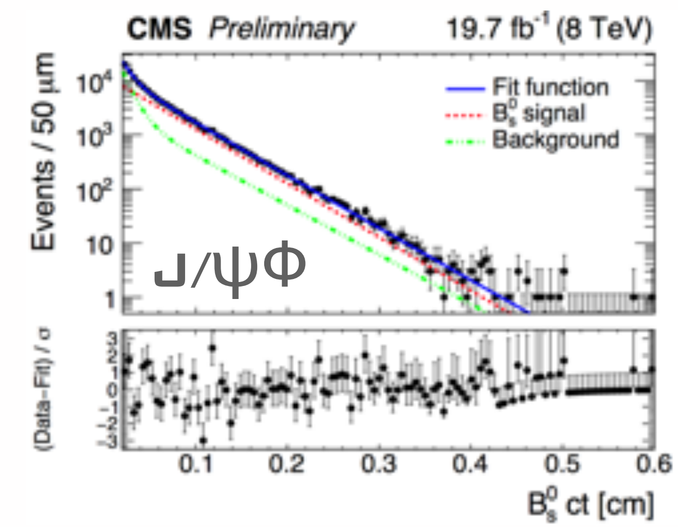
$$c\tau_{B^0} = 457.8 \pm 2.7\,(\text{stat})\ \pm 2.7\,(\text{syst})\ \mu m\ (\text{in } J/\psi K_S)$$

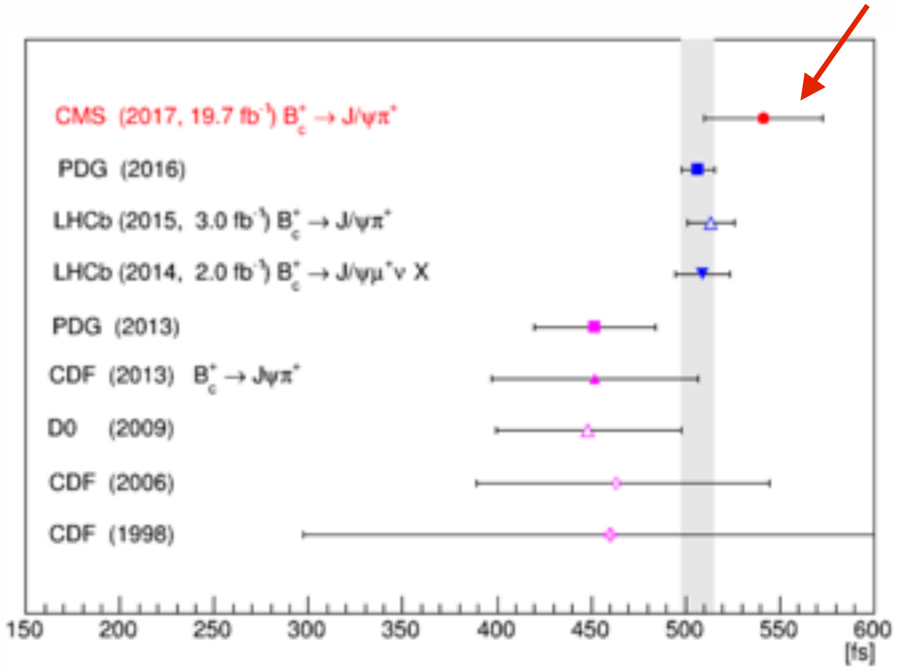
$$c\tau_{B^0_s} = 504.3 \pm 10.5\,(\text{stat})\ \pm 3.7\,(\text{syst})\ \mu m\ (\text{in } J/\psi \pi^+\pi^-)$$

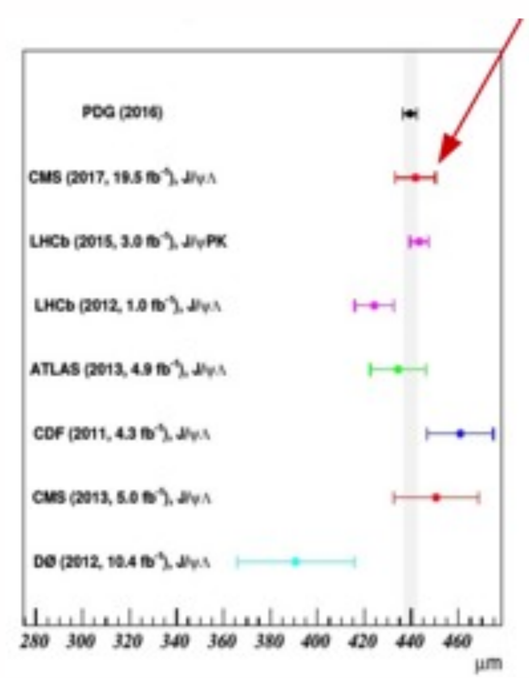
$$c\tau_{B^0_s} = 443.9 \pm 2.0\,(\text{stat})\ \pm 1.2\,(\text{syst})\ \mu m\ (\text{in } J/\psi \phi(1020))$$

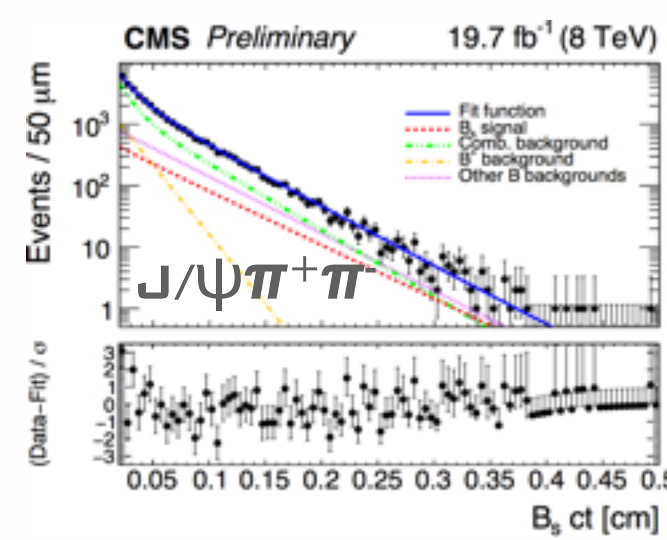
$$c\tau_{\Lambda^0_b} = 443.1 \pm 8.2\,(\text{stat})\ \pm 2.7\,(\text{syst})\ \mu m$$

$$c\tau_{B^+_c} = 162.3 \pm 8.2\,(\text{stat}) \pm 4.7\,(\text{syst}) \pm 0.1(\tau_{B^+})\ \mu m$$





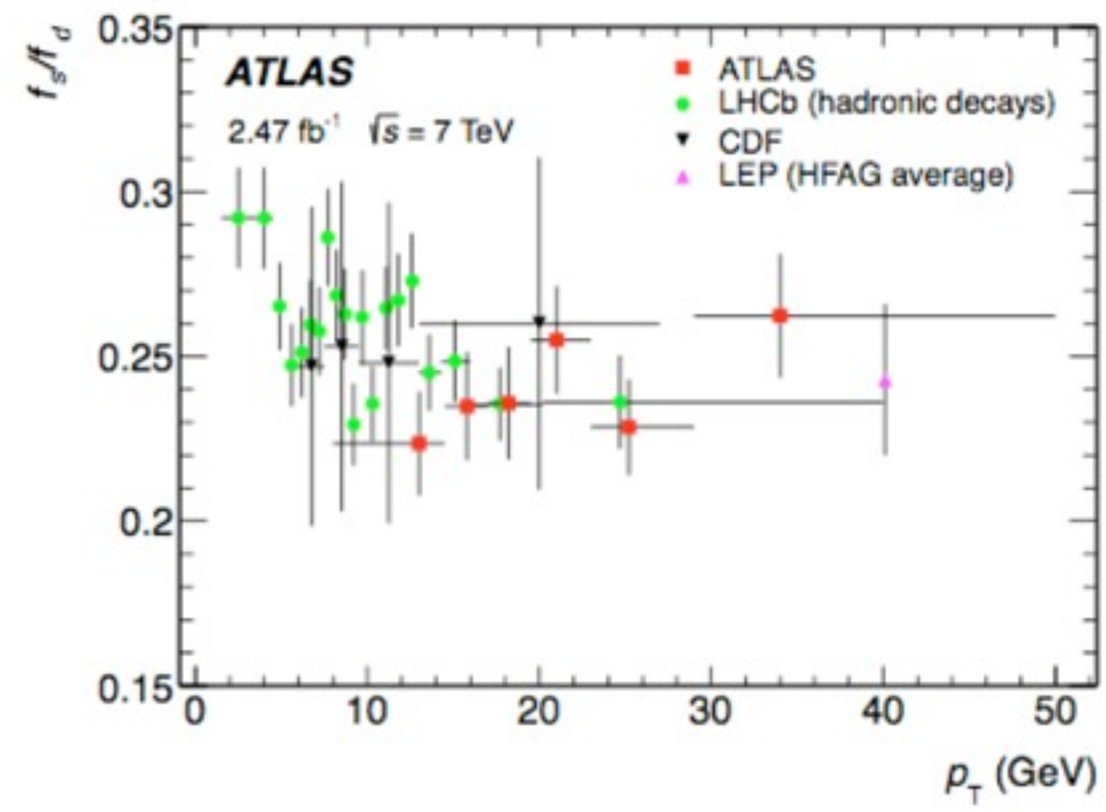




fragmentation fractions

- probability for b-quark to fragment into given b hadron species
  - eg f_s=P(b→B_s+X)
- important ingredient in measurements b-hadron production and decay branching fractions
- pursuing first measurement at CMS, using larger datasets
- strategy: measure yield ratios of B^0 and B_s mesons, with corresponding efficiency and branching fraction corrections

$$\frac{f_s}{f_d} = \frac{N_{B_s}}{N_{B^0}} \frac{\mathcal{B}(B^0 \to J/\psi\, K^{0*})\,\mathcal{B}(K^{0*} \to K\pi)}{\mathcal{B}(B_s \to J/\psi\, \phi)\,\mathcal{B}(\phi \to KK)} \frac{\epsilon_{B^0}}{\epsilon_{B_s}}$$



[WORK ONGOING]

- fragmentation fractions are *not* necessary ‘constants’
- focus on probing possible kinematic dependencies

summary

- exploring CMS' unmatched capabilities for the study of heavy-flavor hadrons across different collisions systems
- hidden flavor
  - explore heavy quarkonia to shed light on hadroproduction mechanisms
  - first measurements of the bottomonium family in heavy ion collisions, discovery of sequential suppression
- open flavor
  - explore heavy hadrons for testing QCD (+EWK+BSM)
  - first exclusive measurements of b-hadrons in heavy ion collisions
- larger LHC datasets will allow for increased precision, to reach higher momentum region, and the exploration of new states