Bottomonium studies with pp collisions and heavy ion collisions from CMS

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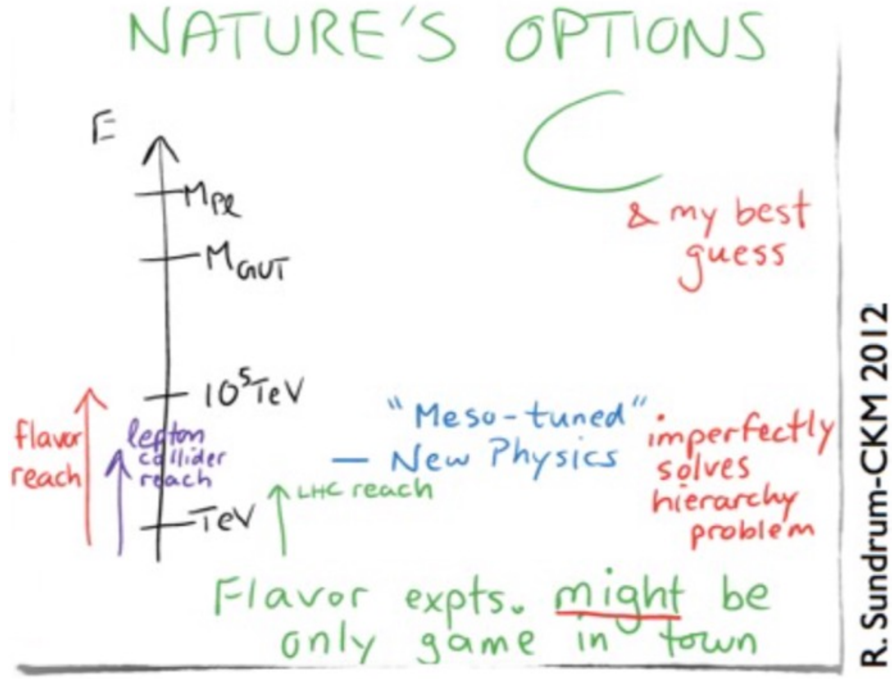
Motivation: physics

- Heavy flavor
  - Wealth of precision measurements
  - Test QCD, hadron production mechanisms
  - Characterize backgrounds in SM processes & searches for new physics (NP)
  - Find new particles and (rare) decays
  - Probe energy scales well above the TeV scale beyond those accessible via direct searches for NP



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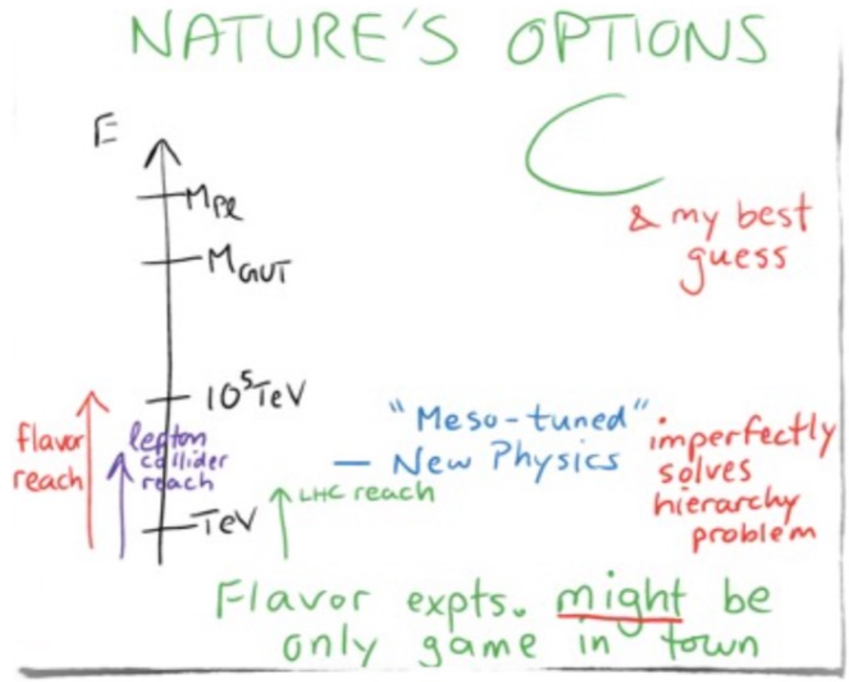
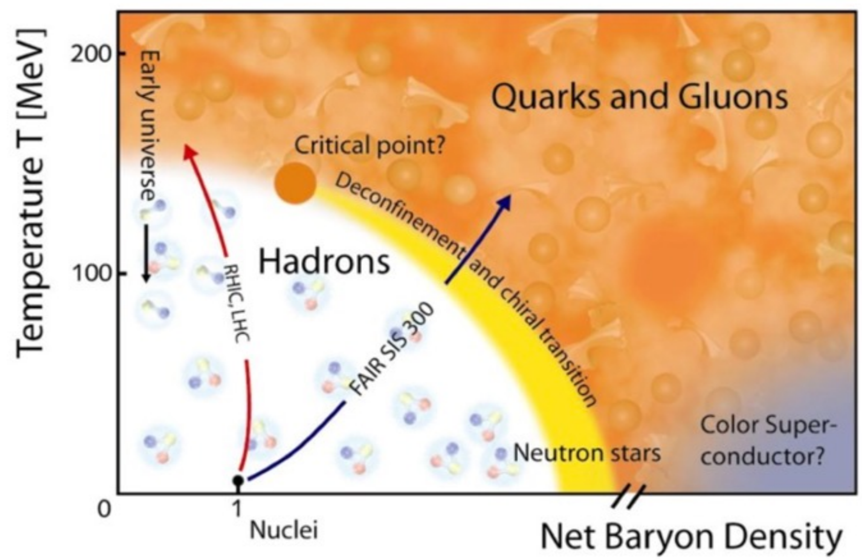
- Heavy ions
  - Explore and characterize the properties of the deconfined phase of QCD matter (Quark Gluon Plasma) created under extreme density and temperature



R. Sundrum-CKM 2012



Motivation: LHC and CMS

proton-proton

Heavy ion

Pb Pb

Energy $\sqrt{s_{NN}}$

1.96 TeV → 7(8) TeV → 13(14) TeV
Tevatron *LHC Run I* *LHC Run II*
x7

0.2 TeV → 2.76 TeV → 5.5 TeV
RHIC *LHC Run I* *LHC Run II*
x27

Intensity *L*

Very large datasets are being accumulated at the LHC

Motivation: LHC and CMS

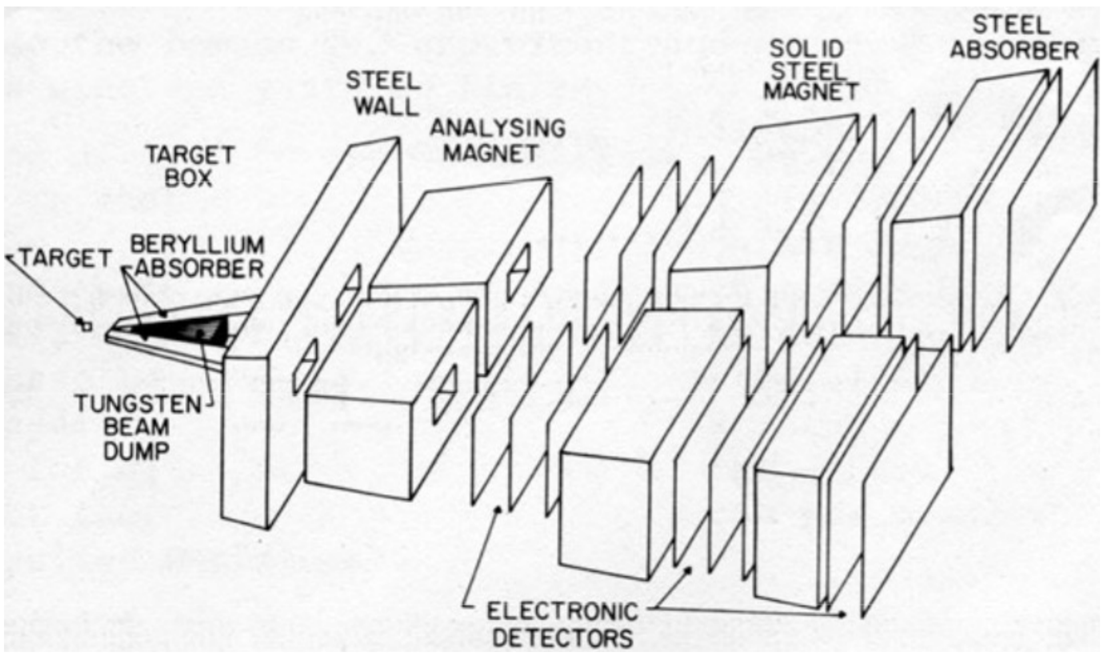
	proton-proton	Heavy ion (Pb Pb)
Energy $\sqrt{s_{NN}}$	1.96 TeV → 7(8) TeV → 13(14) TeV	0.2 TeV → 2.76 TeV → 5.5 TeV
	Tevatron → *LHC Run I* → *LHC Run II*	*RHIC* → *LHC Run I* → *LHC Run II*
	x7	x27

Intensity L: Very large datasets are being accumulated at the LHC

- vs RHIC
  - better resolution
  - additional detector capability
- vs ALICE
  - complementary acceptance (ALICE access low-pt)
  - CMS better resolution
- vs Tevatron experiments
  - extend kinematic (p_T,y) acceptance
- vs ATLAS
  - better resolution, more flexible trigger
- vs LHCb
  - complementary acceptance, LHCb great particle ID
  - worse resolution, but higher luminosity

Bottomonium (1977)

- First discovered by the E288 collaboration, headed by Leon Lederman, at Fermilab in 1977



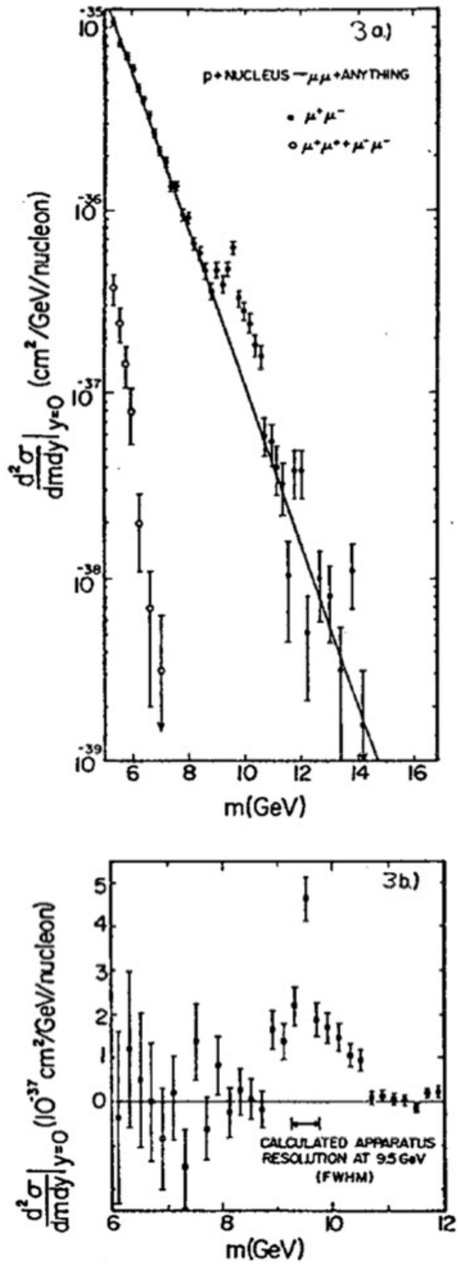


Fig. 3

Bottomonium (1977)

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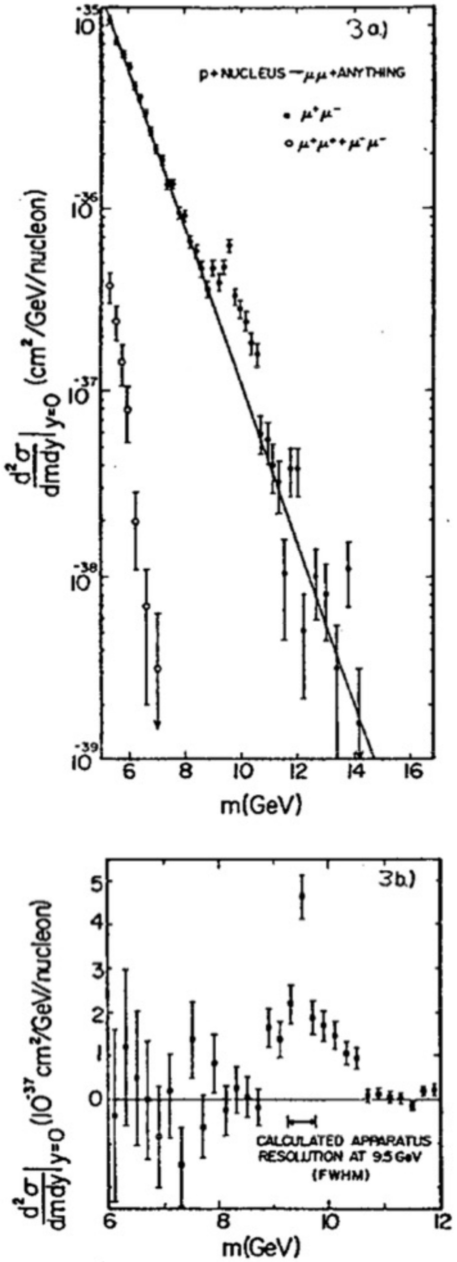
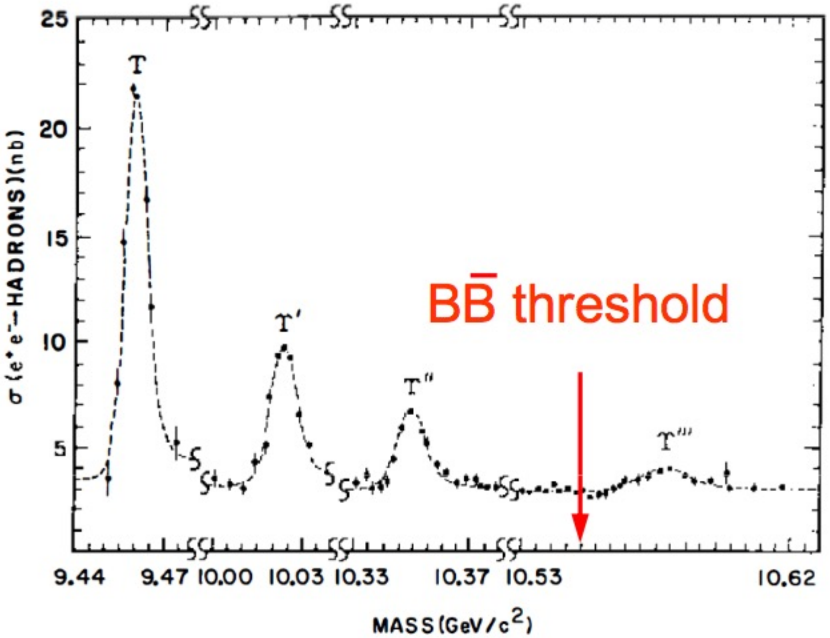


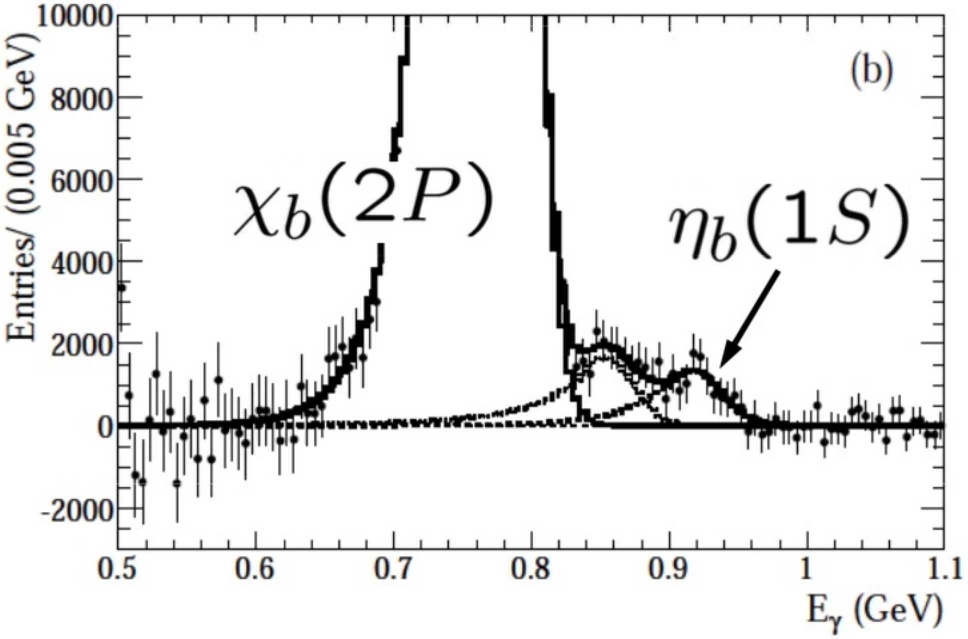
Fig. 3

Bottomonium Spectroscopy 1980-2008



CESR/CUSB (1980's)

$e^+e^- \to \Upsilon(3S), \Upsilon(3S) \to \eta_b(1S)\gamma$

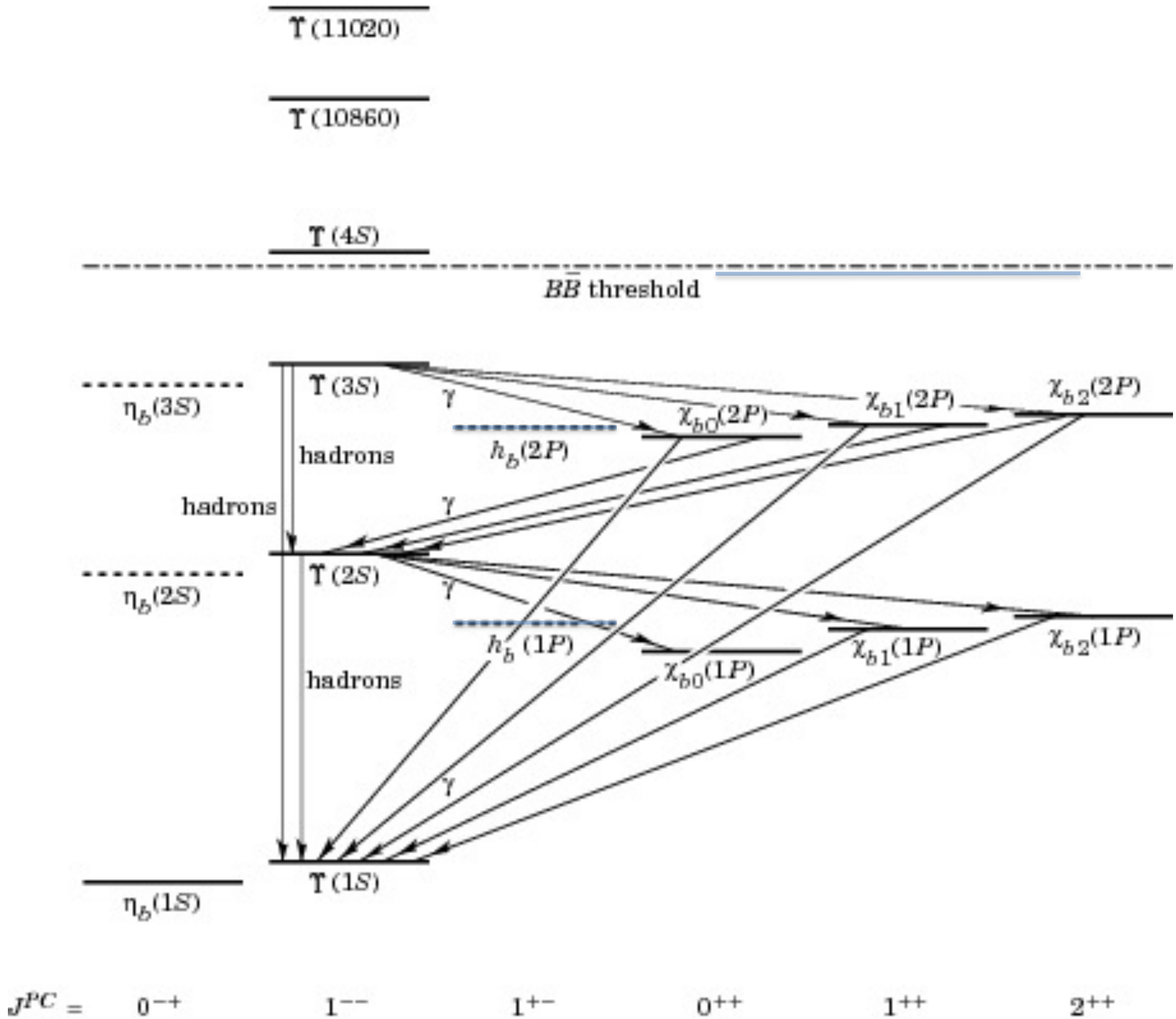


PEP II/BaBar (2008)

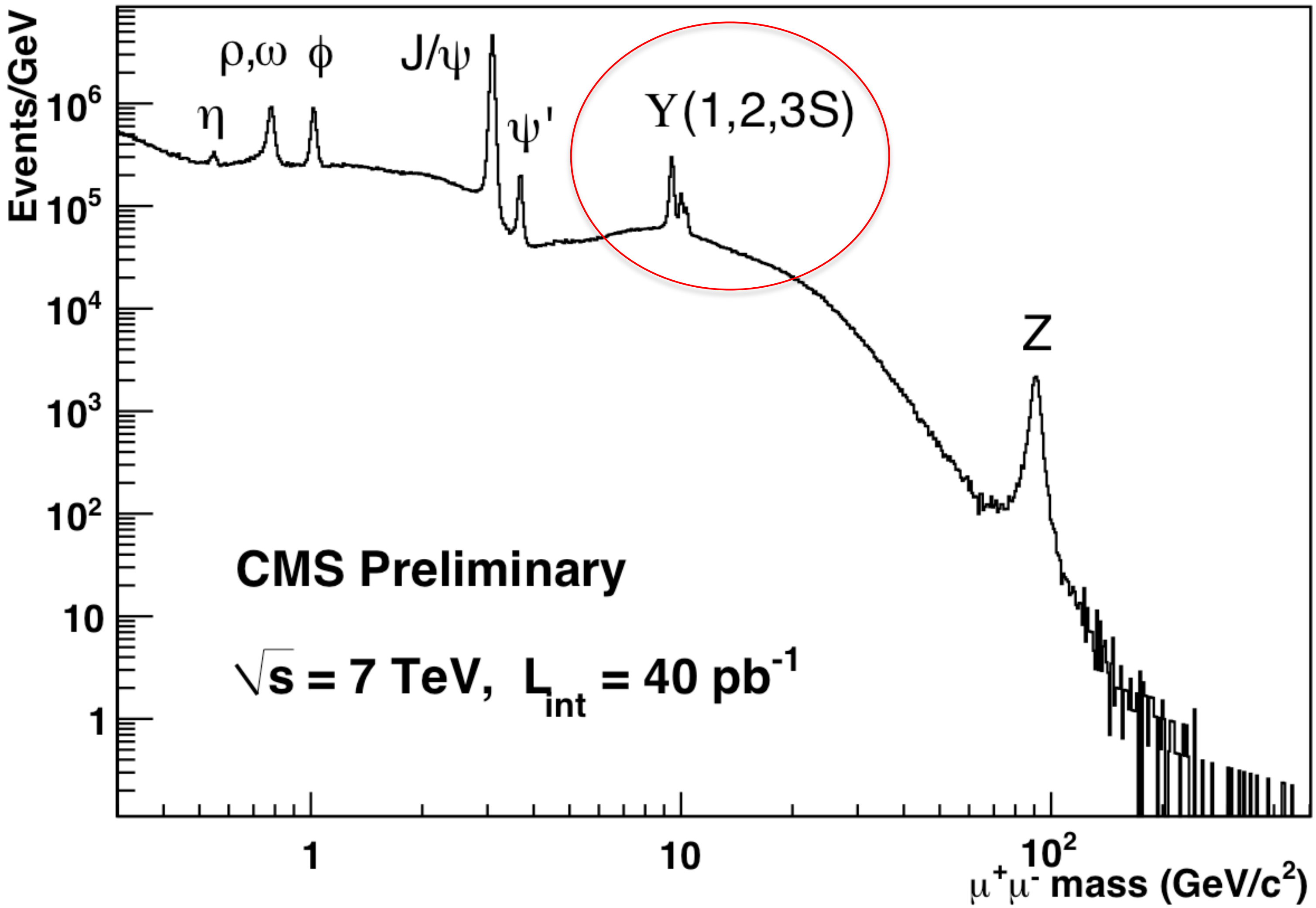
$$\Gamma(\Upsilon(\mathrm{nS})) \sim 20-50 \text{ KeV}$$

$$\mathrm{Br}(\Upsilon(nS) \to \mu^+\mu^-) \sim 2\%$$

Bottomonium Spectroscopy 1980-2008



LHC: the "re-discovery of SM" plot



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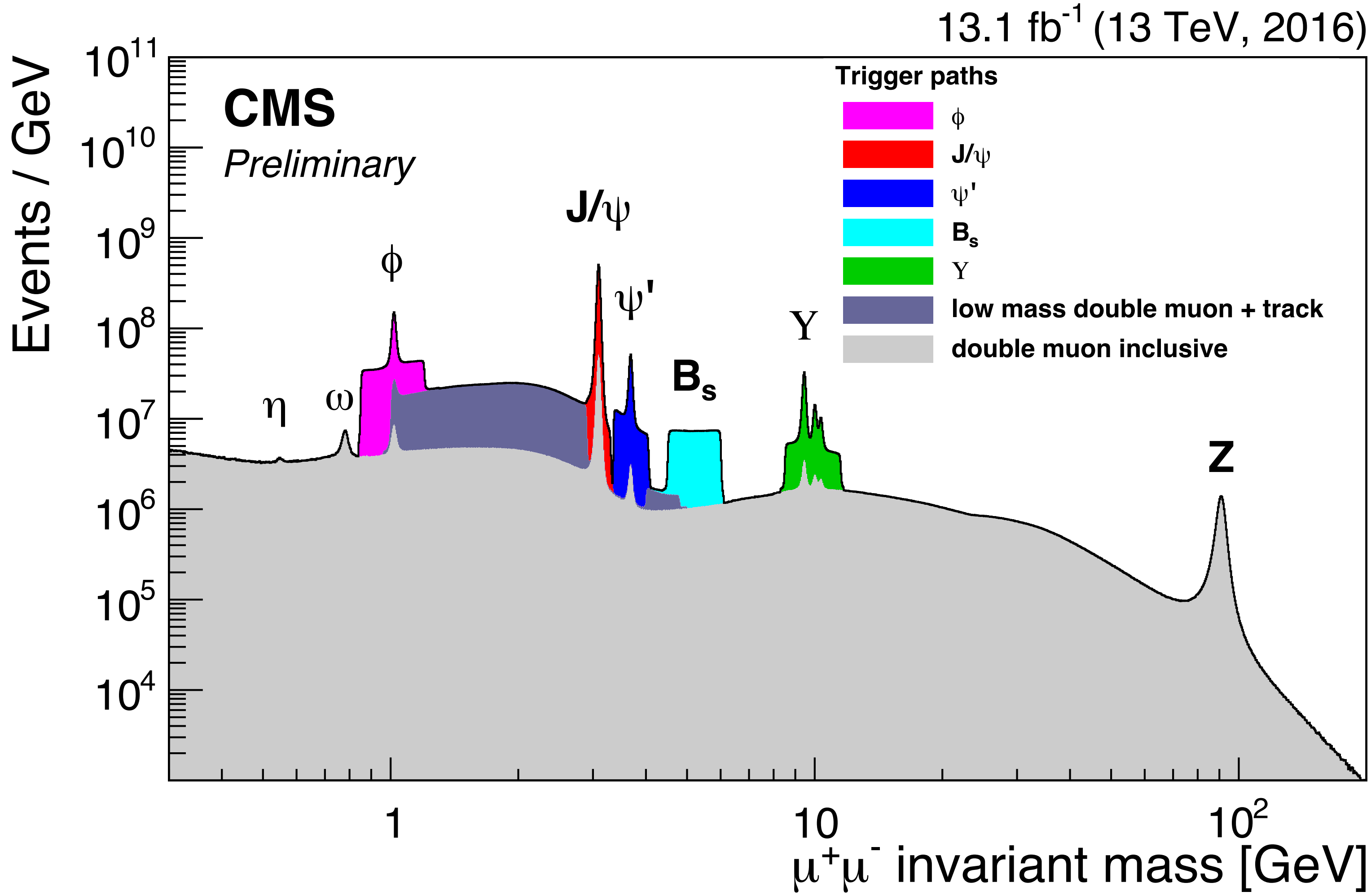
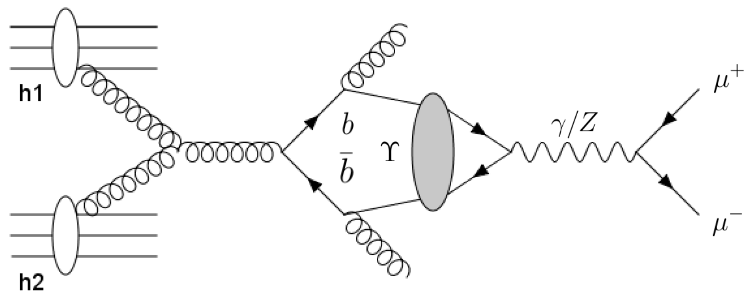


Shown by Ian Shipsey in ICHEP2016

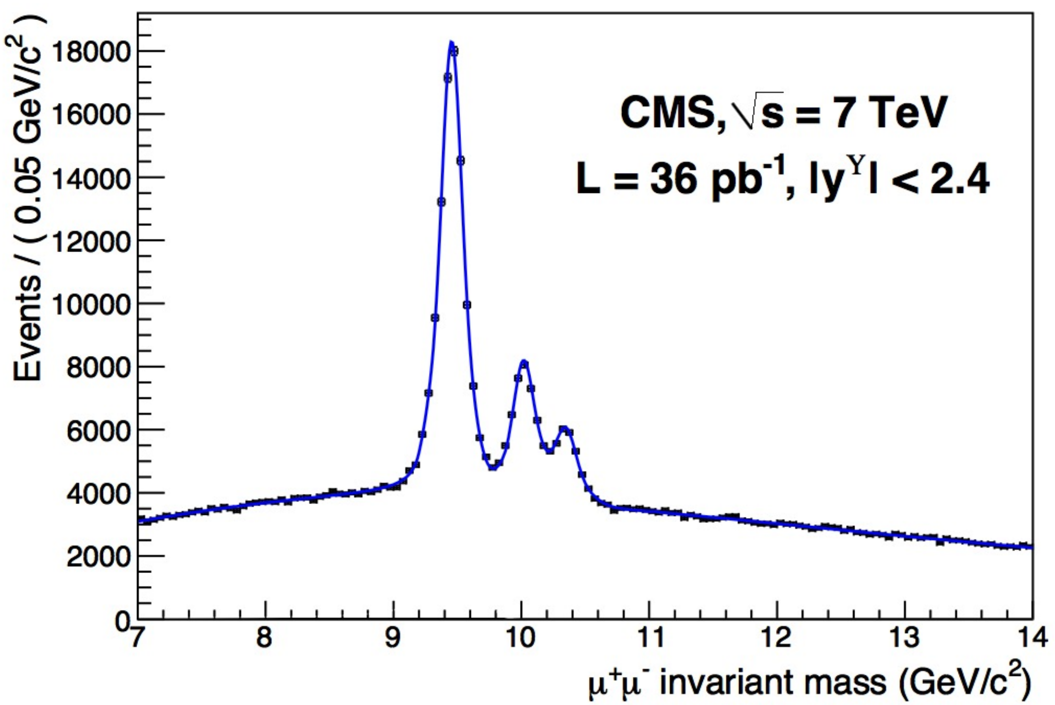
heavy-flavor program at CMS relies primarily on (di-)muon triggers

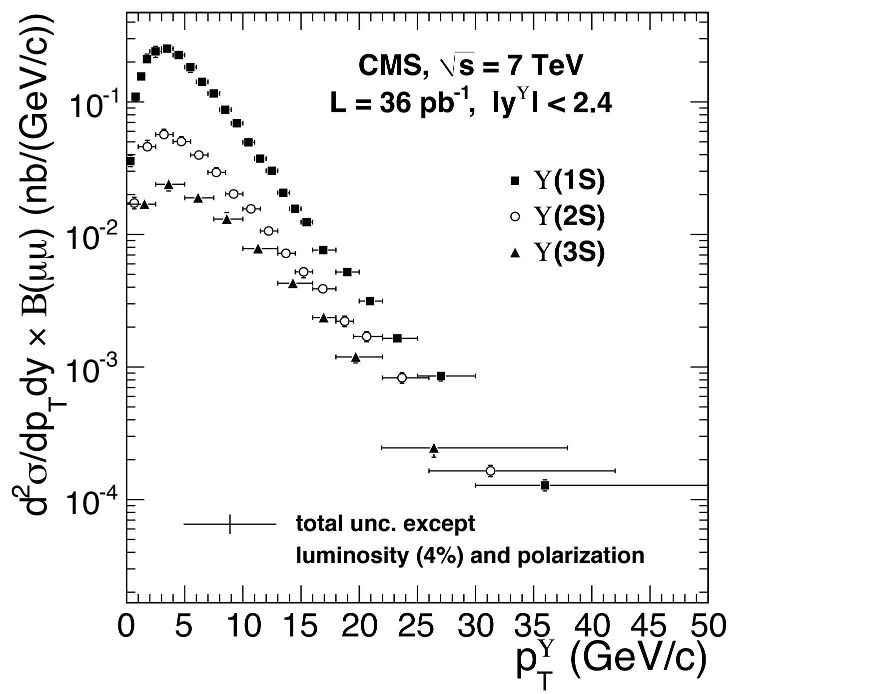
- specialized trigger paths ➠ high purity triggers
- exploit good p_T, impact parameter, mass and vertex resolutions
- bandwidth restrictions are the main limitation

CMS Run 1 (2010) @ 7 TeV



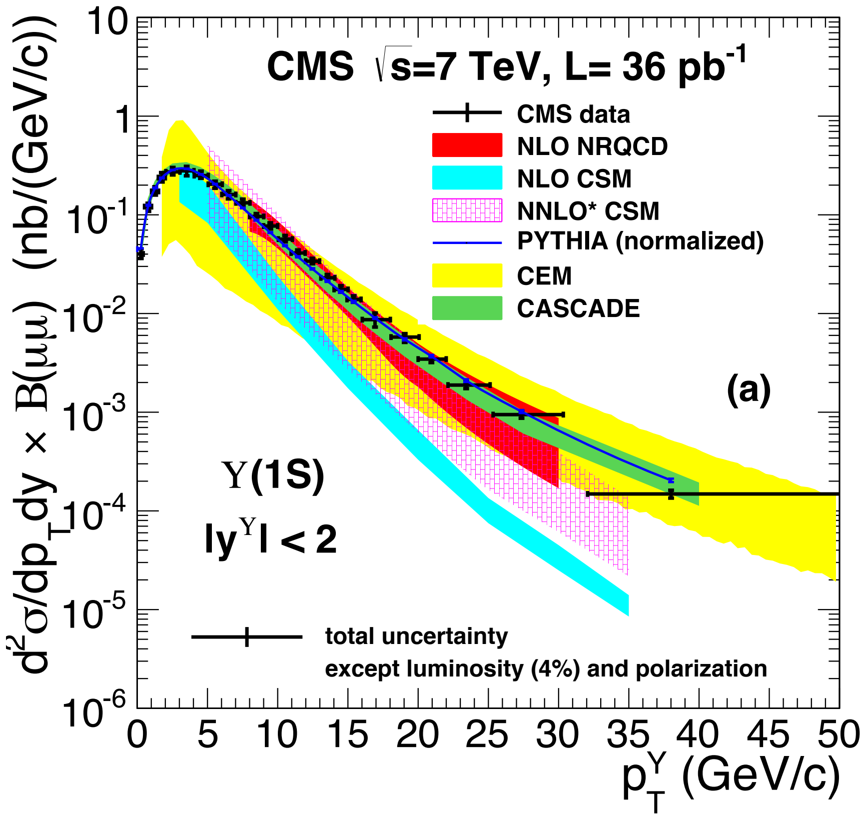
$$\frac{d\sigma(pp\to\Upsilon(nS))}{dp_T}\Big|_{|y|<2} B(\Upsilon(nS)\to\mu^+\mu^-) = \frac{N^{\text{fit}}_{\Upsilon(nS)}(p_T; A, \varepsilon_{\text{track}}\varepsilon_{\text{muID}}\varepsilon_{\text{trig}})}{\int \text{Ldt}\cdot\Delta\text{p}_\text{T}}$$



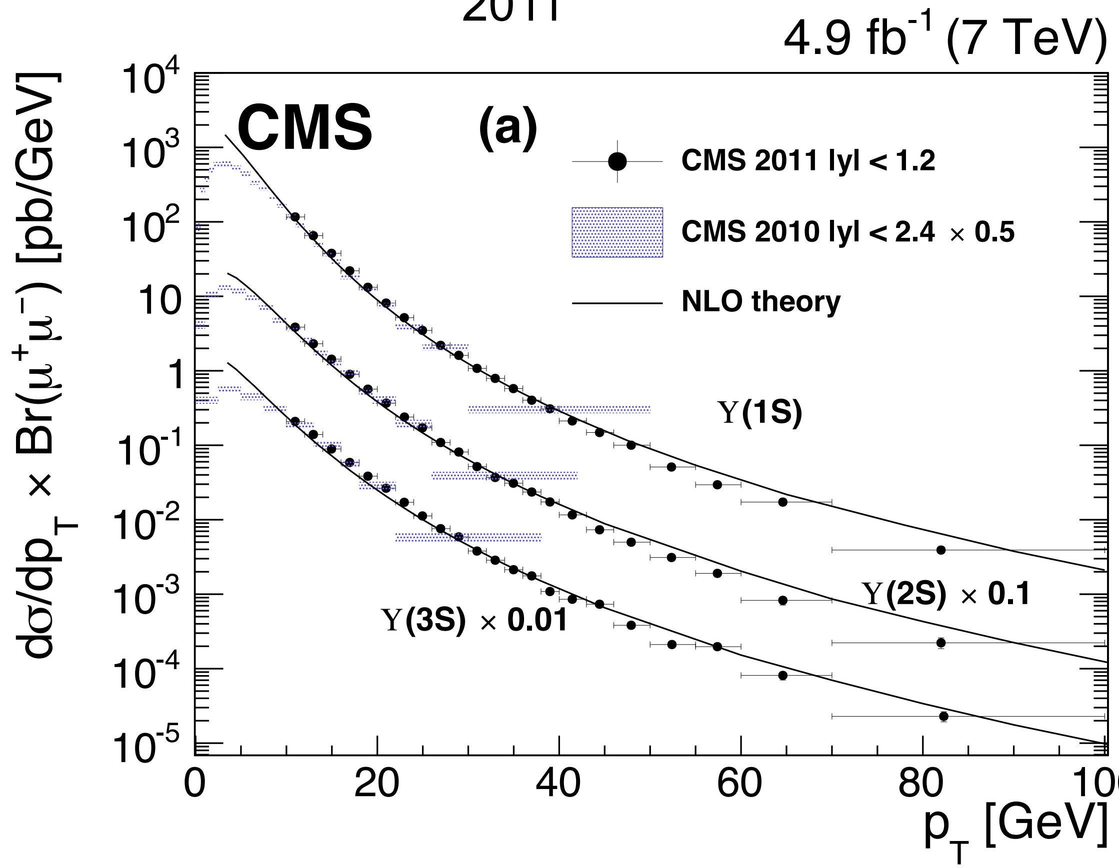


CMS Run 1 (2011) @ 7 TeV

2010

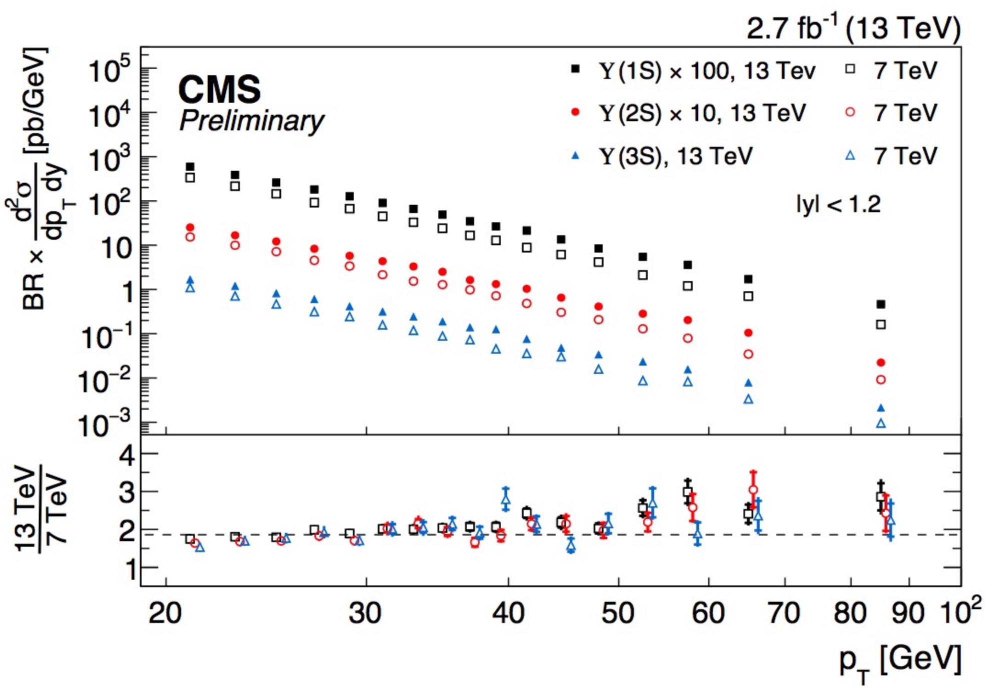


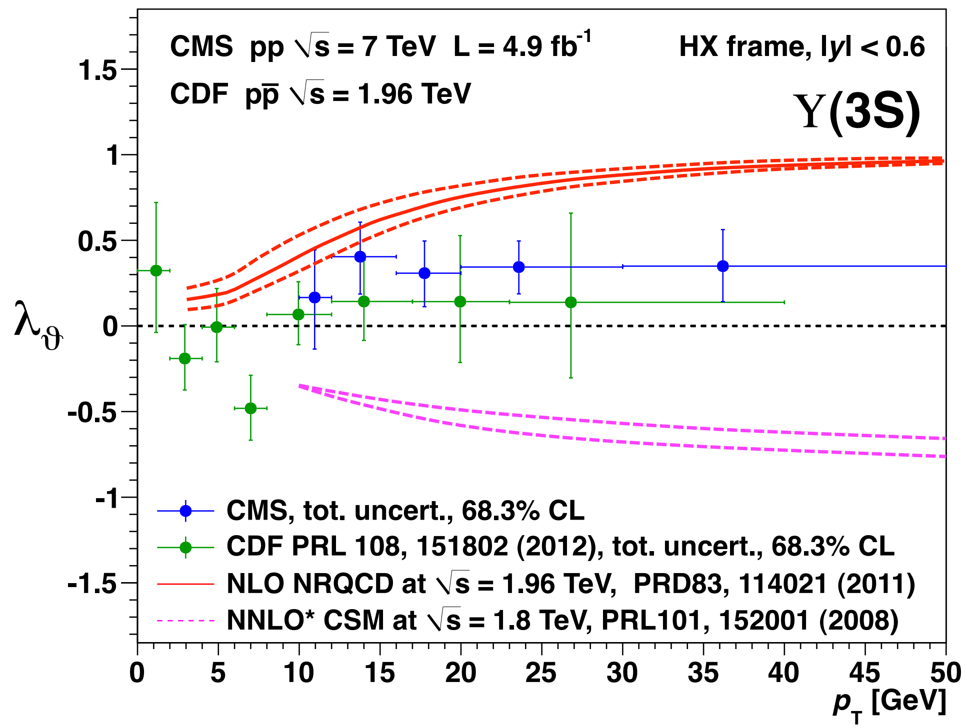
2011



- Collaborating with PKU group (Prof. K.T. Chao)
  Non-Relativistic QCD Color Octet Mechanism

CMS Run 2 (2015) @ 13 TeV



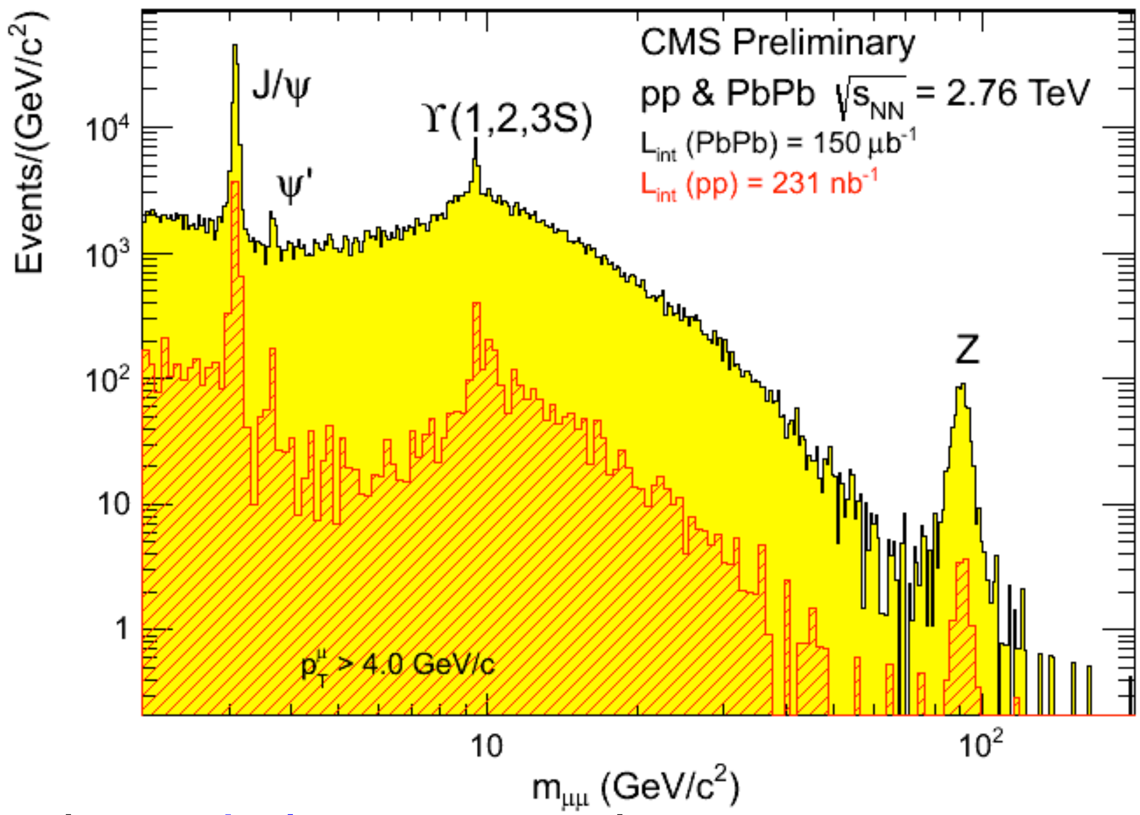


"Review of bottomonium measurements with CMS at the LHC", Z. Hu *et al.*, *Int. J. Mod. Phys. A* 32, 1730015 (2017)

CMS 2.76 TeV PbPb and pp run

PbPb data: 150 μb^{-1} at $\sqrt{s_{NN}}$ = 2.76 TeV collected in 2011

pp data: 230 nb^{-1} at 2.76 TeV collected in 2011



- A first analysis – relative suppression
  - Double ratio

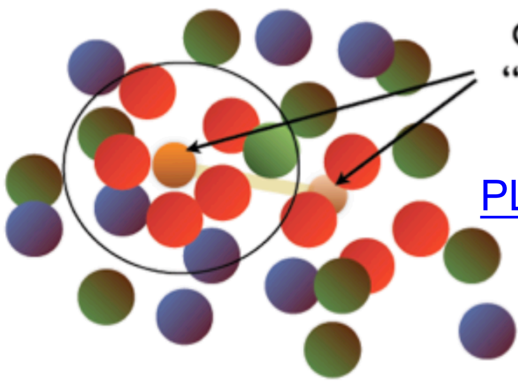
$$\frac{N_{PbPb}[\Upsilon(nS)]/N_{PbPb}[\Upsilon(1S)]}{N_{pp}[\Upsilon(nS)]/N_{pp}[\Upsilon(1S)]}$$

- A second analysis – absolute suppression
  - Nuclear modification factor

$$R_{AA} = \frac{N_{PbPb}[\Upsilon(nS)]}{N_{pp}[\Upsilon(nS)]}\frac{L_{pp}}{T_{AA}N_{MB}}\frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$

Theory - quarkonia as probe for QGP

- One of the most striking expected characteristics of QGP formation is the suppression of quarkonium states
  - Color-screening of the QQ pair binding
  - T ➚ → $r_D(T) < r_0$ → screening → melting of the bound state → yields suppressed



PLB178, 416 (1986)

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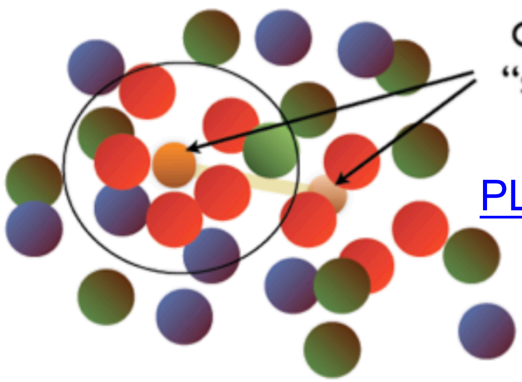

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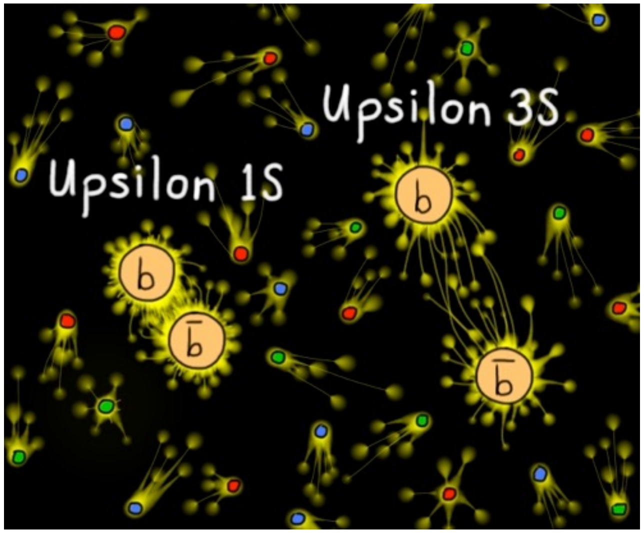


  - ϒ(nS): Screening at different T for different states → sequential melting

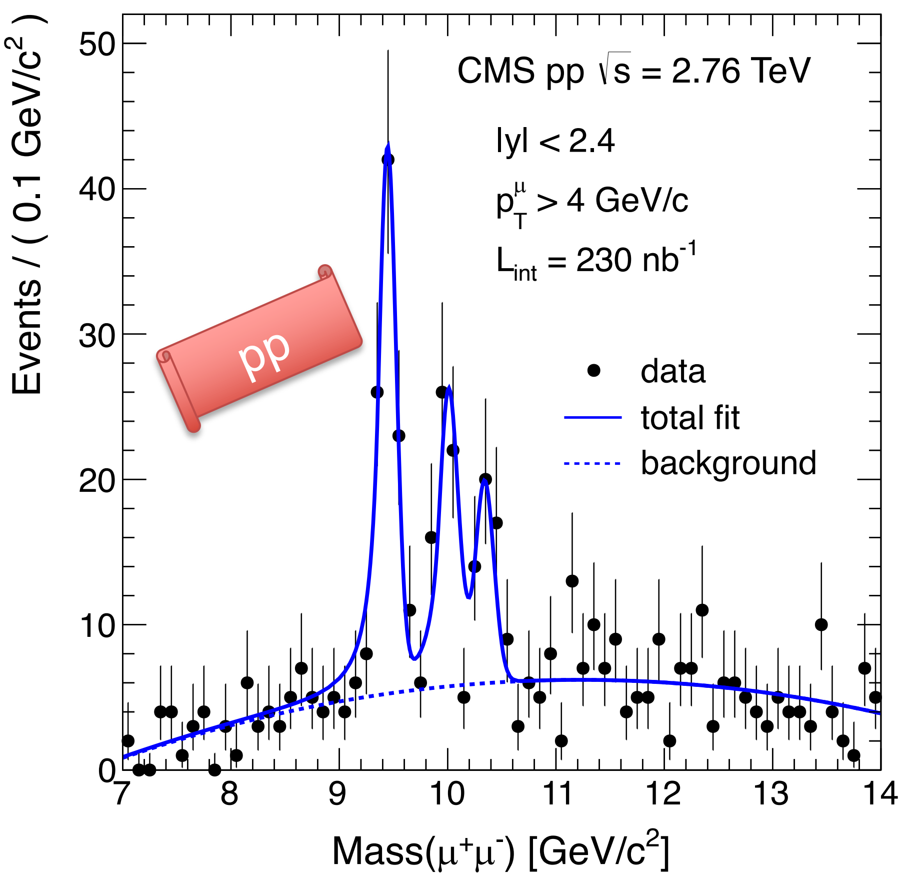
	charmonia			bottomonia				
State	J/ψ (1S)	χ_c (1P)	ψ' (2S)	Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
m (GeV/c^2)	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
r_0 (fm)	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

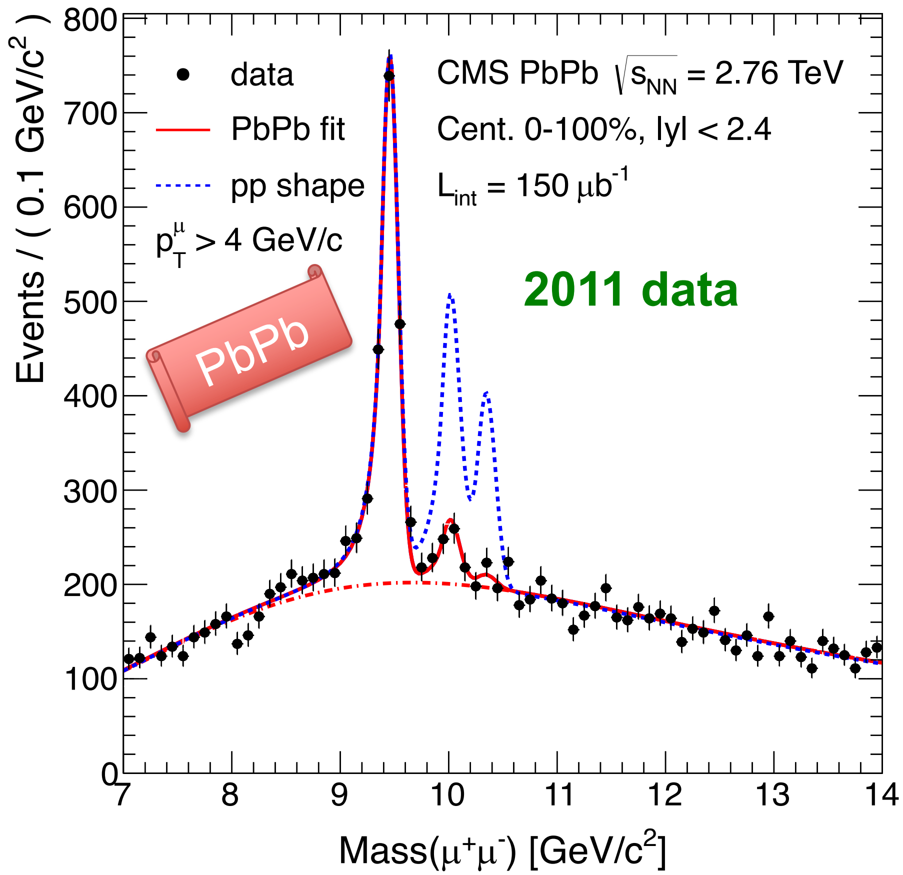
J.Phys.G32:R25,2006

Excited states relative suppression

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.15 \pm 0.05(\text{stat.}) \pm 0.02(\text{syst.})$$

Observation of 2S+3S relative suppression: significance > 5 σ

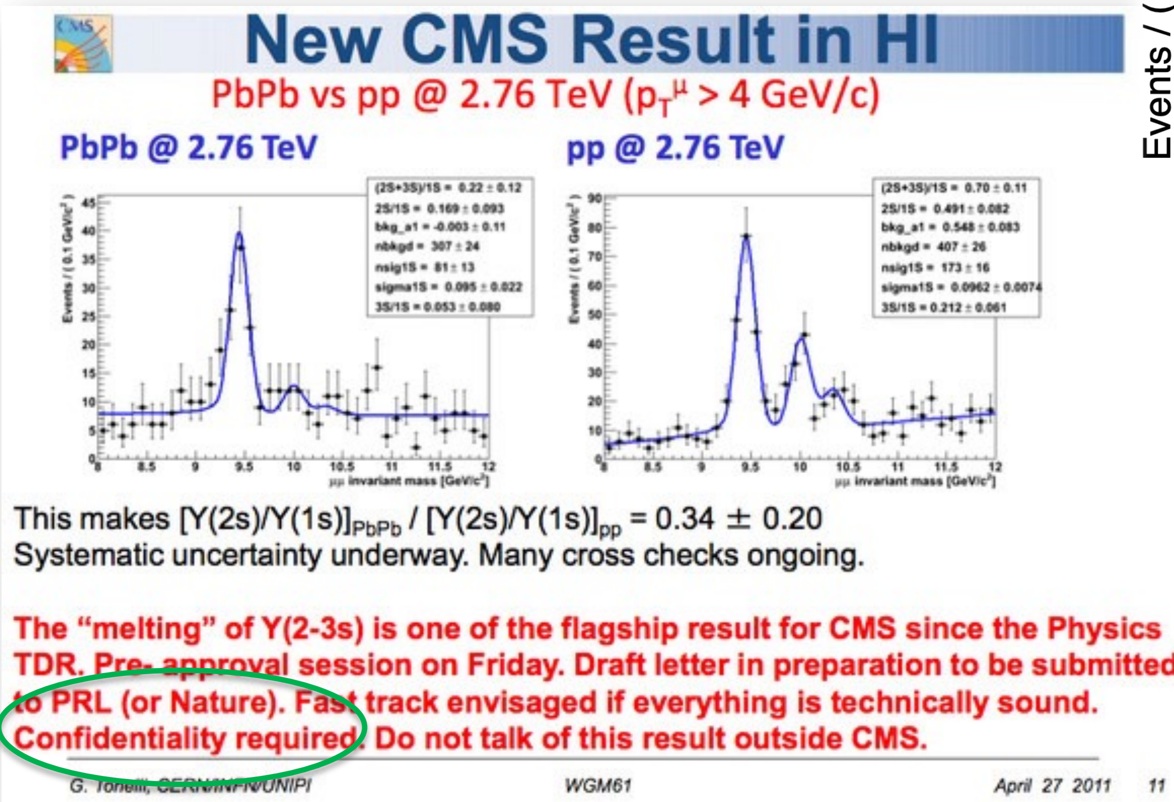


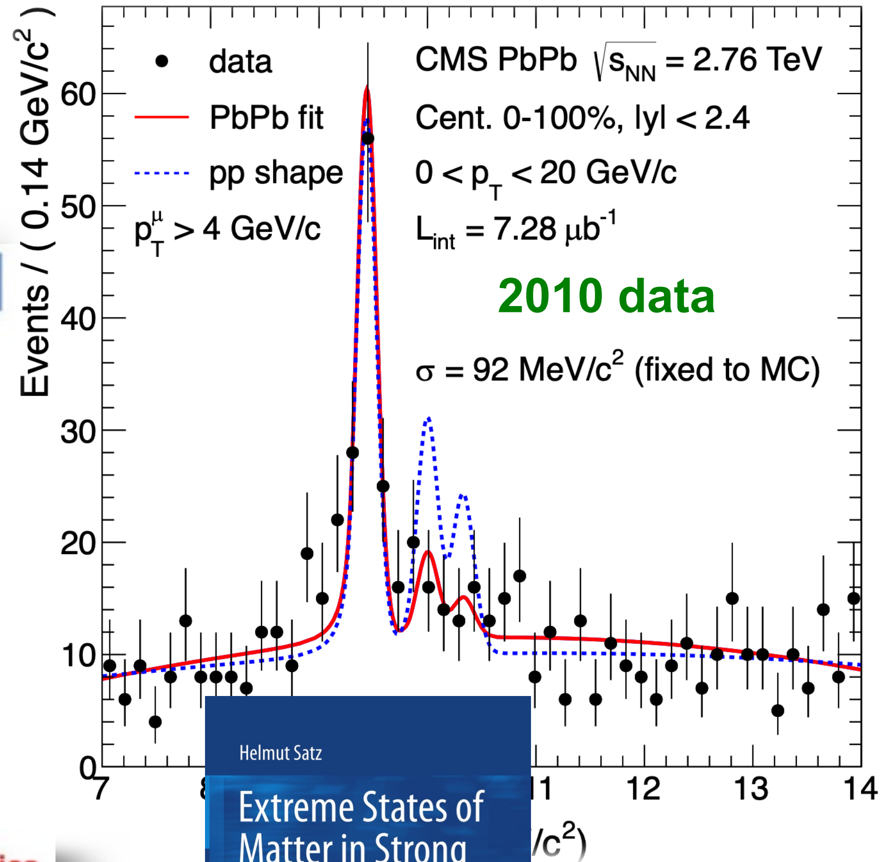


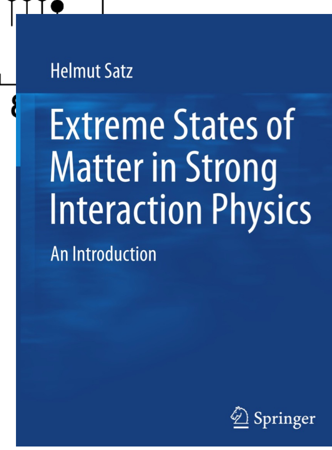
Comparison with 2010 data (first run)

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

Indication of 2S+3S relative suppression: significance ~ 2.4 σ

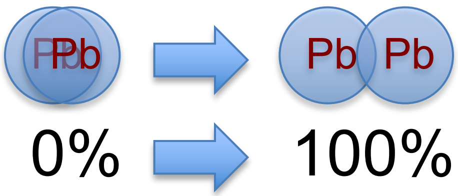


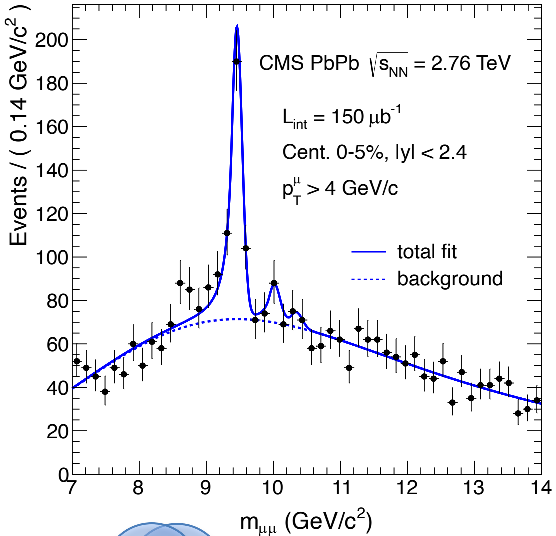


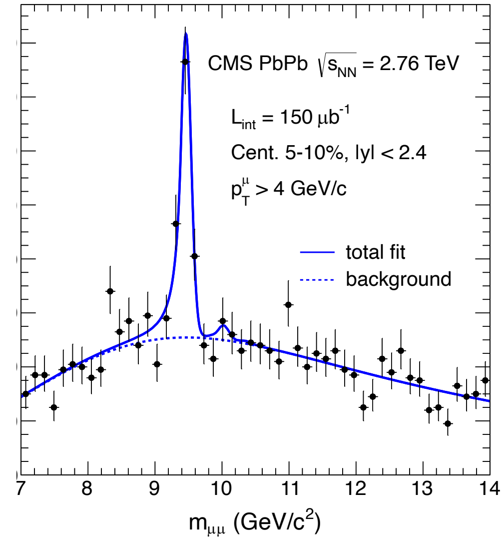


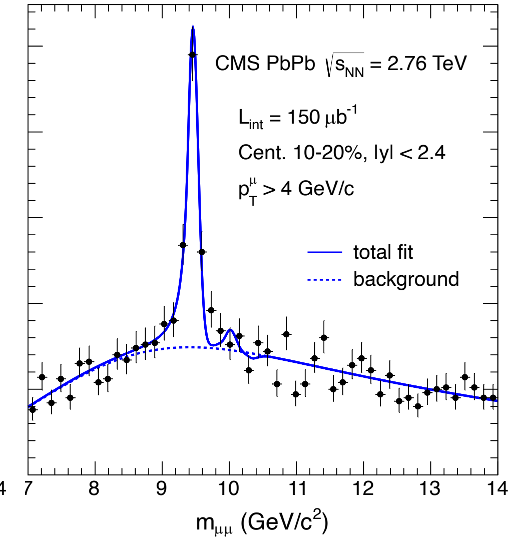
Already in text book!

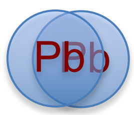
Centrality dependence



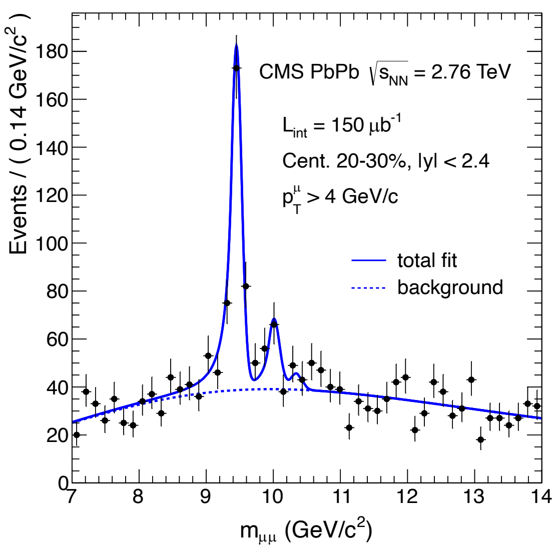


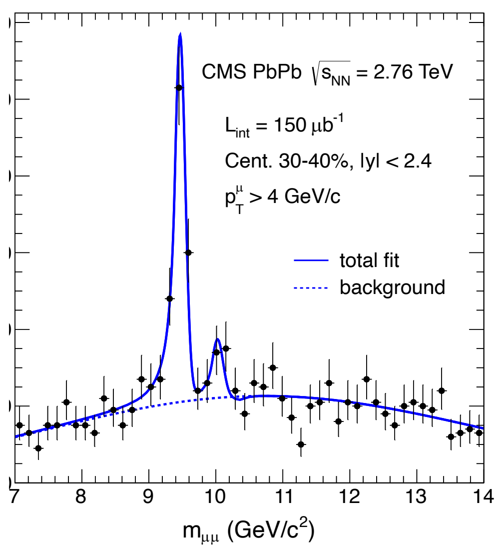


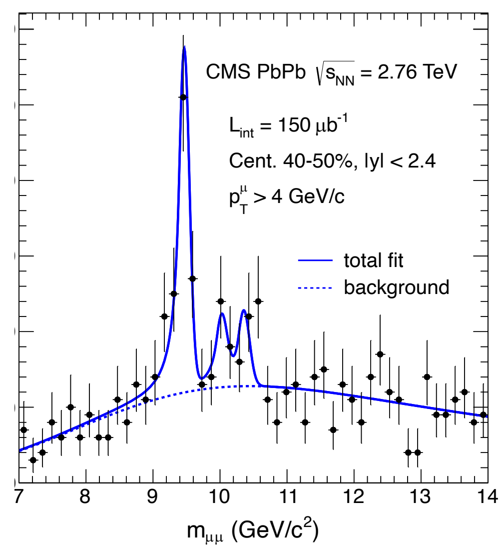


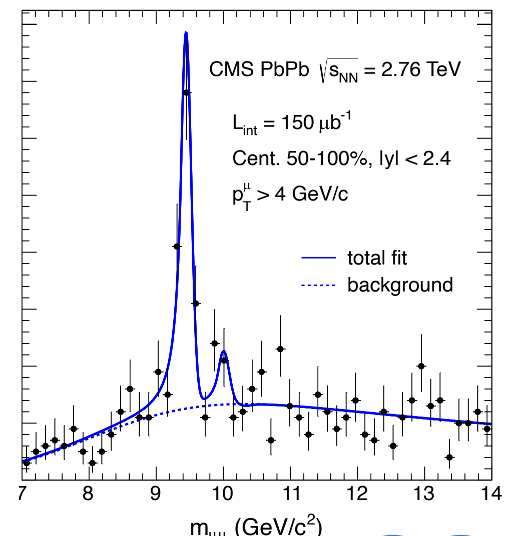


0-5% 5-10% 10-20%

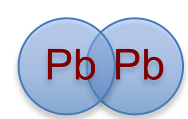




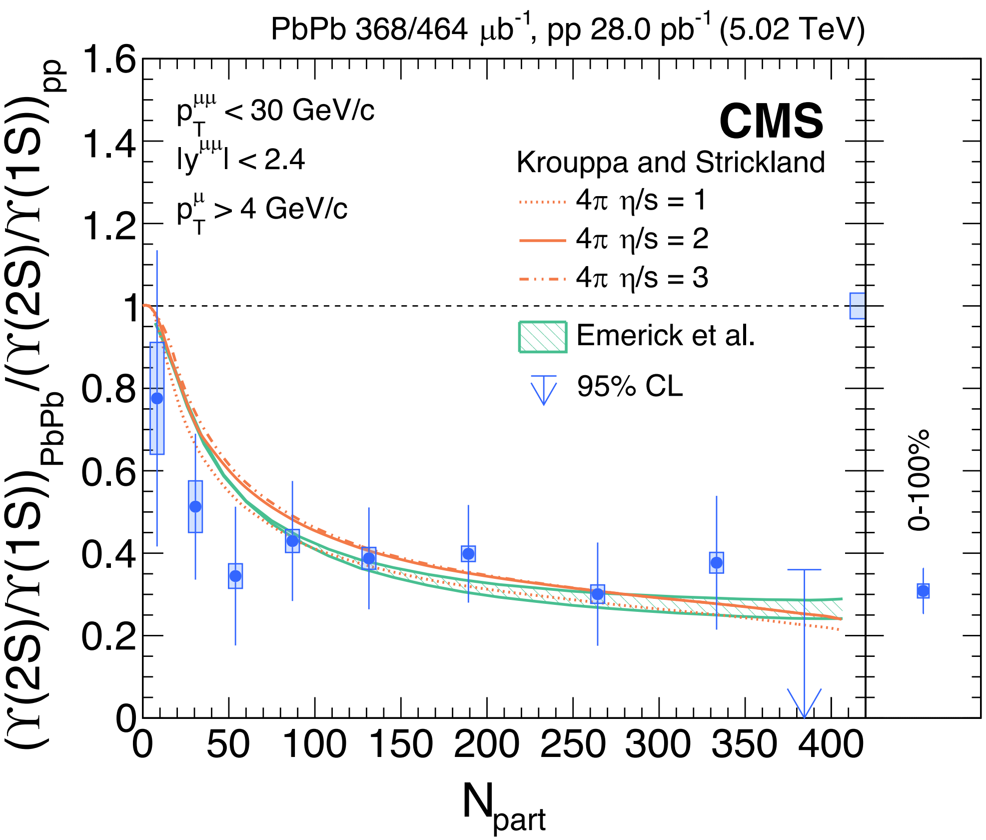




20-30% 30-40% 40-50% 50-100%



Double ratio and centrality dependence



$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07(\text{stat.}) \pm 0.02(\text{syst.})$$

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})$$

Υ(nS) absolute suppression

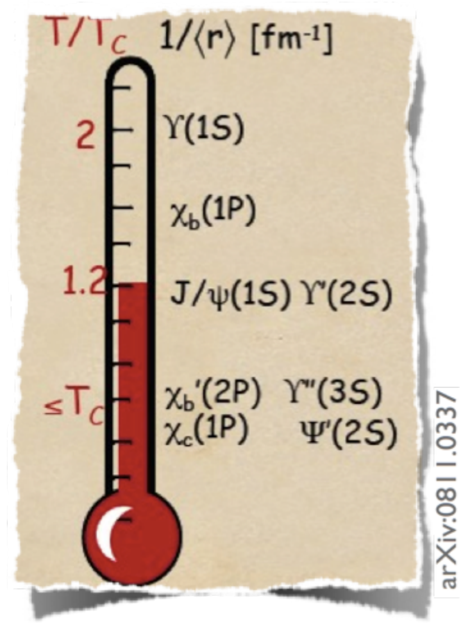
$$R_{AA} \equiv \frac{N_{PbPb}[\Upsilon(nS)]}{N_{pp}[\Upsilon(nS)]} \frac{L_{pp}}{T_{AA}N_{MB}} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}} \begin{cases} >1: \text{enhancement} \\ =1: \text{no medium effect} \\ <1: \text{suppression} \end{cases}$$

- First time the nuclear modification factors are measured for three Υ states:

$$R_{AA}[\Upsilon(1S)] = 0.56 \pm 0.08(\text{stat.}) \pm 0.07(\text{syst.})$$
$$R_{AA}[\Upsilon(2S)] = 0.12 \pm 0.04(\text{stat.}) \pm 0.02(\text{syst.})$$
$$R_{AA}[\Upsilon(3S)] = 0.03 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.})$$

- Υ states are suppressed sequentially

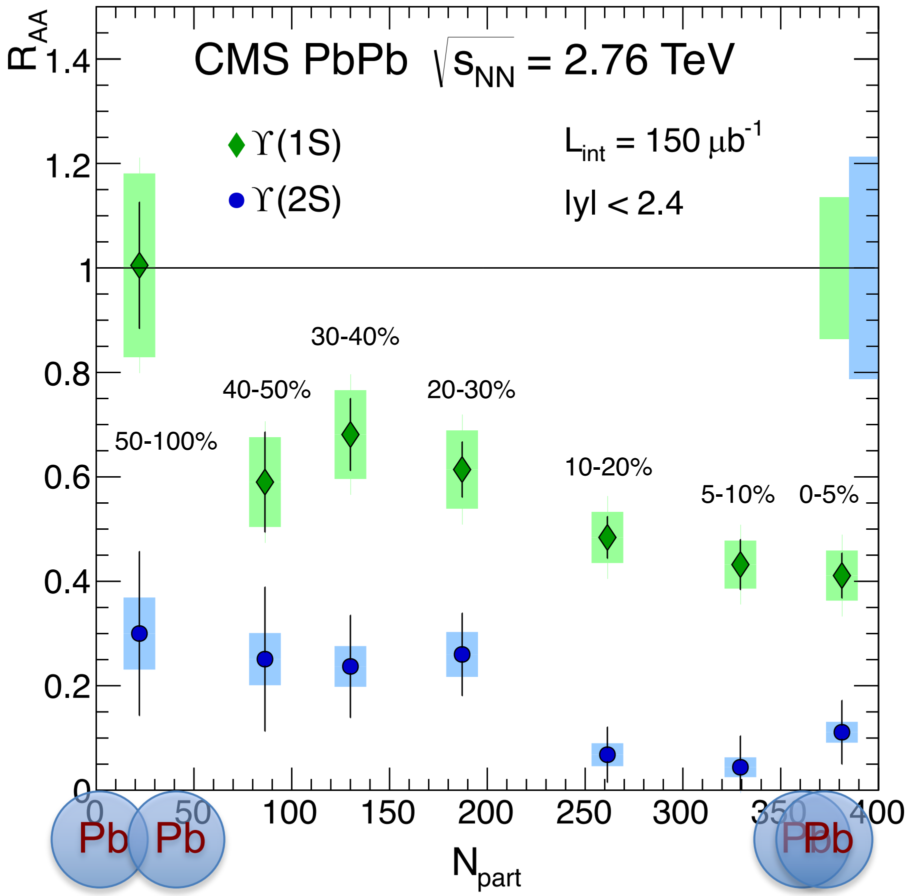
$$R_{AA}[\Upsilon(1S)] > R_{AA}[\Upsilon(2S)] > R_{AA}[\Upsilon(3S)]$$



$\Upsilon(1S)$ & $\Upsilon(2S)$ R_{AA} vs centrality

pp run lumi : 231/nb [6%]

N_{MB}: 1.13 B T_{AA}: 5.7 mb^{-1}



Global errors shown at unity on y-axis, do not affect bin-to-bin trend

- Suppression observed to increase with centrality of the collisions
- Strong suppression for the most central bin 0-5%

$$R_{AA}[\Upsilon(1S)] = 0.41 \pm 0.04(stat.) \pm 0.07(syst.)$$

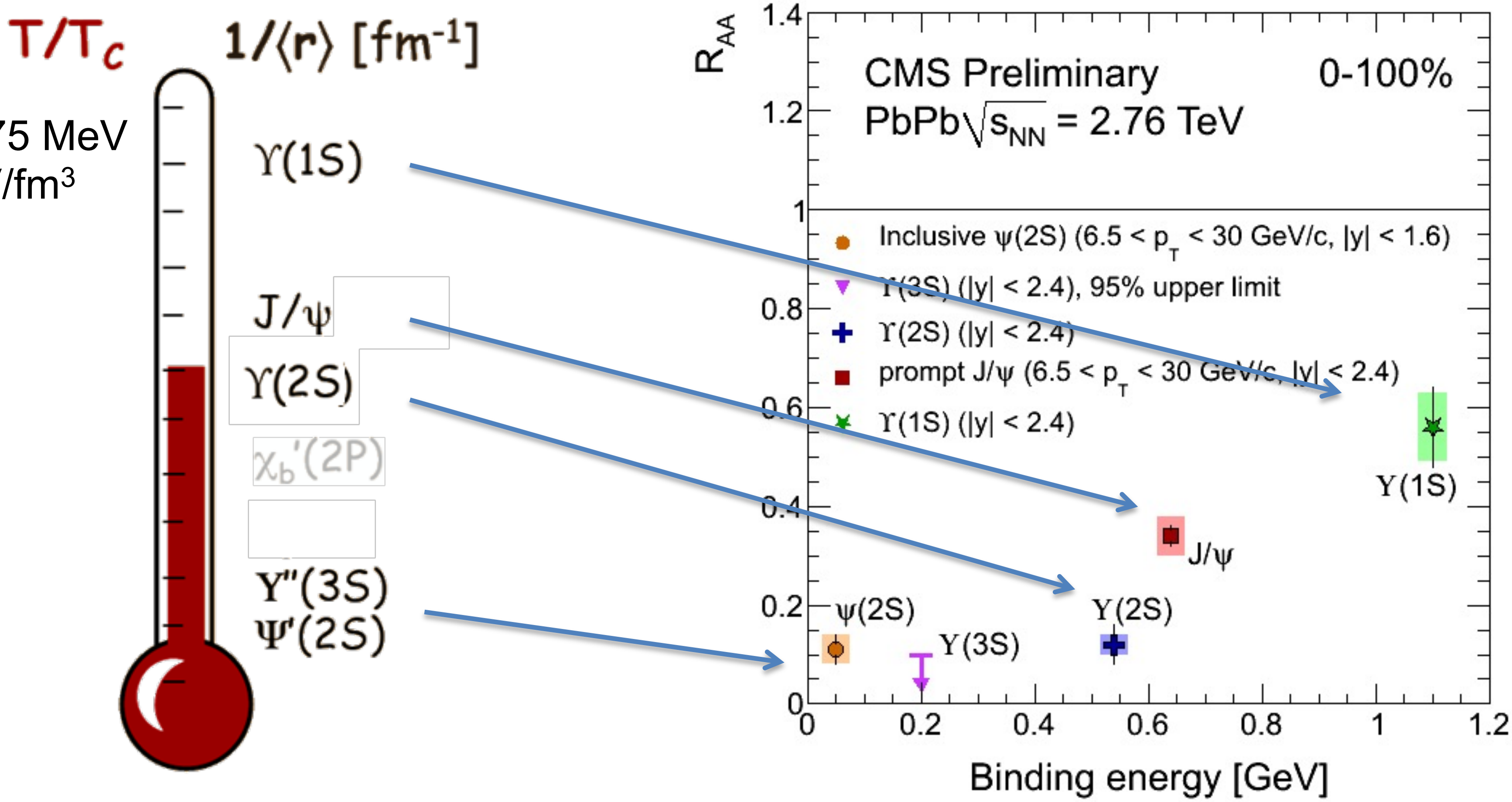
$$R_{AA}[\Upsilon(2S)] = 0.11 \pm 0.06(stat.) \pm 0.03(syst.)$$

- Υ(2S) always more suppressed than Υ(1S)

Experimental comparison - CMS

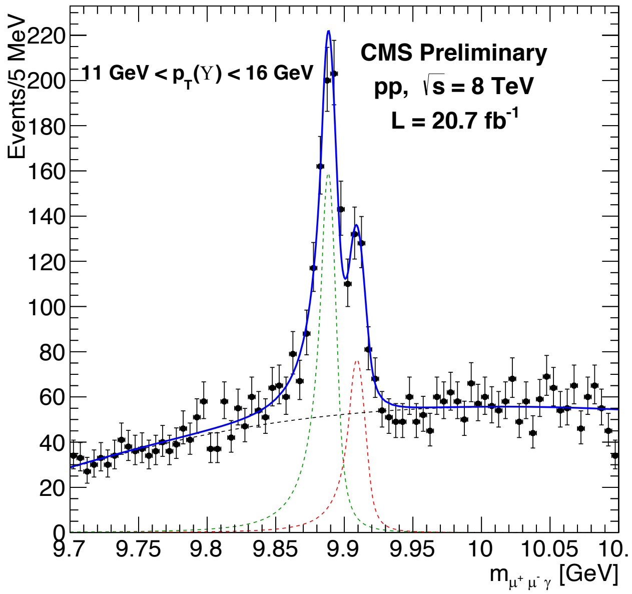
$$R_{AA}[\Upsilon(3S)] < R_{AA}[\Upsilon(2S)] < R_{AA}[J/\psi] < R_{AA}[\Upsilon(1S)]$$

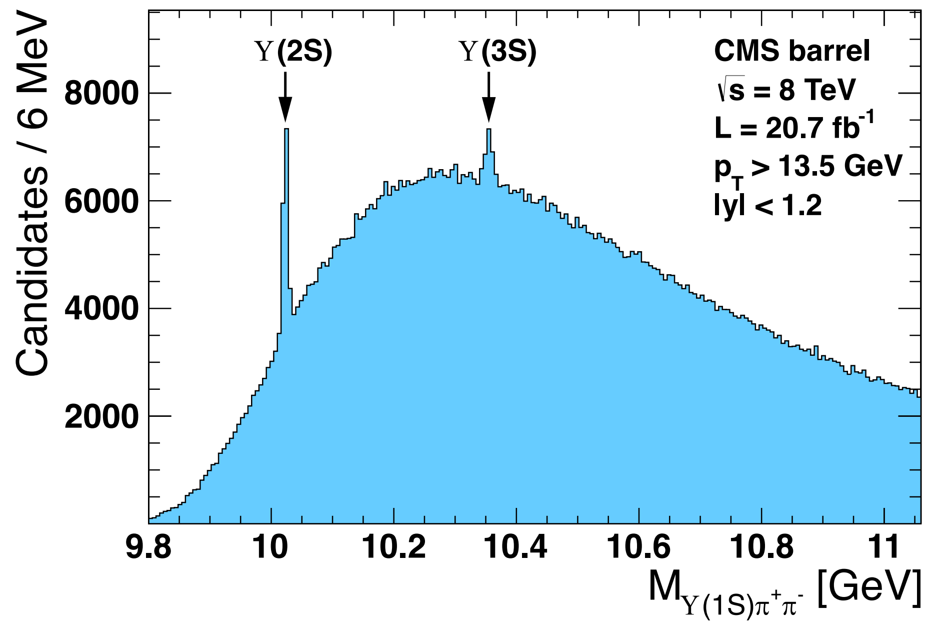
T_c~150-175 MeV
E_c~1 GeV/fm^3

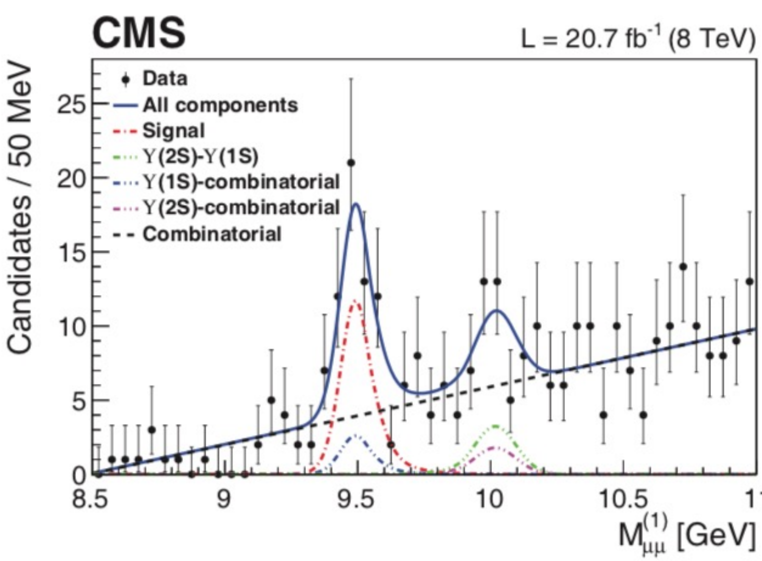


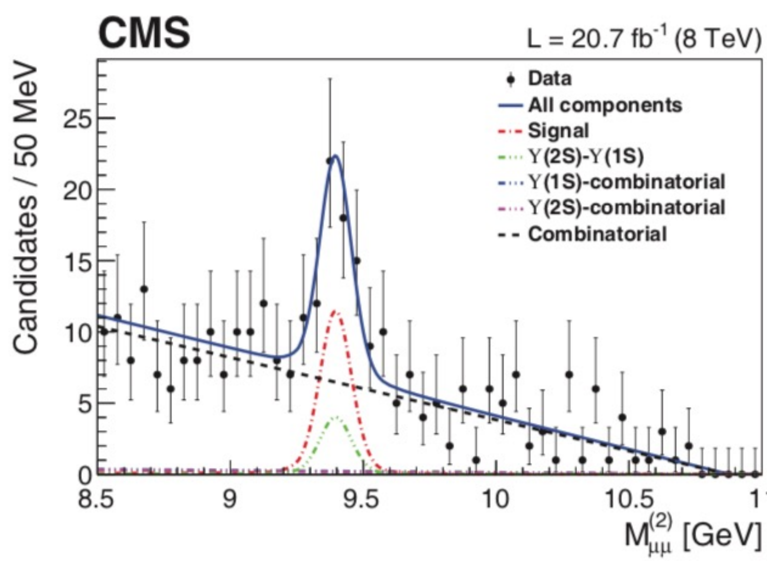
- The sequential melting map is experimentally drawn
  - Map includes: hot and cold effects (feed-down, nuclear absorption, etc)
  - Looser bound states are more suppressed than the tighter bound states

Other bottomonium measurements from CMS



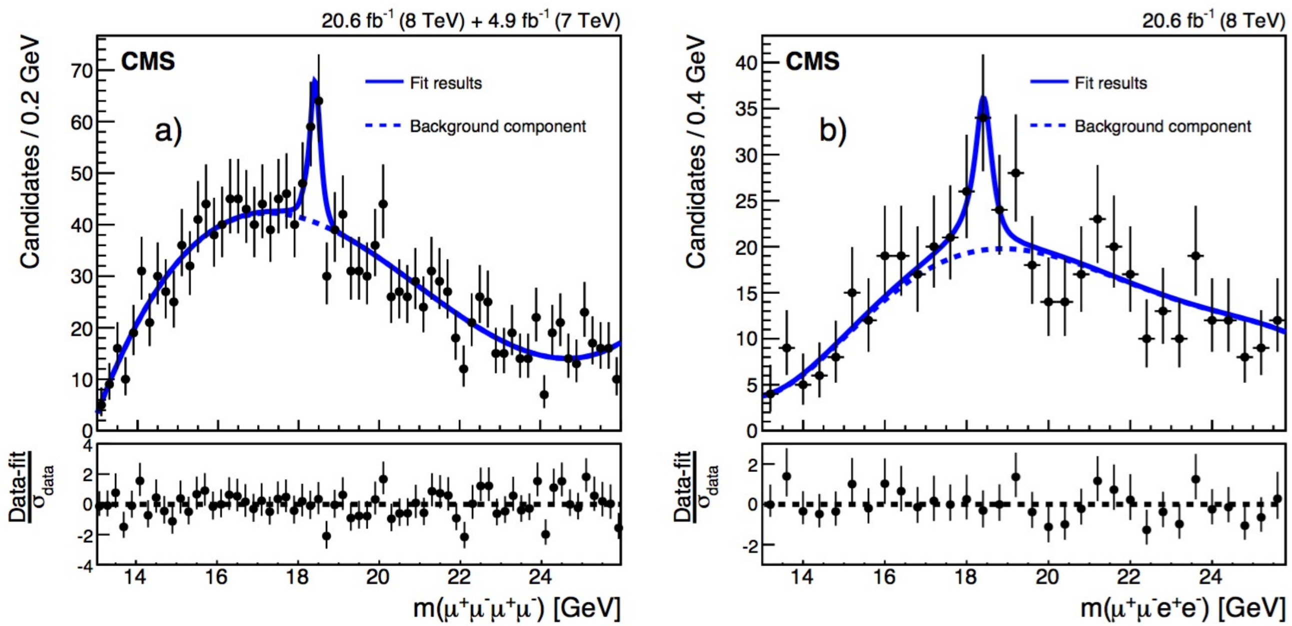






$\Upsilon(1S)l^+l^-$ Run 1 analysis

- An excess near 18.5 GeV in $\Upsilon(1S)\mu^+\mu^-$ and $\Upsilon(1S)e^+e^-$ final states



Figures shown on APS meeting

- The combination of two channels:
  - Mass: 18.4±0.1(stat)±0.2(syst) GeV
  - Yield: 44 ± 13 for $\Upsilon(1S)\mu^+\mu^-$ and 35 ± 13 for $\Upsilon(1S)e^+e^-$
  - local significance of ~4.8 σ, global significance ~3.5 σ

Outlook: 5 ongoing CMS analyses

- $\Upsilon\Upsilon$ inclusive cross-section with CMS full Run-2 data
  - No experimental result at 13 TeV
  - SPS vs DPS

- Above 4b threshold: X → $\Upsilon\Upsilon$ → $\mu^+\mu^-\mu^+\mu^-$
  - T_{4b} ?

- Below 4b threshold: X → $\Upsilon\Upsilon^*$ → $\mu^+\mu^-\mu^+\mu^-$
  - 18.5 GeV ?

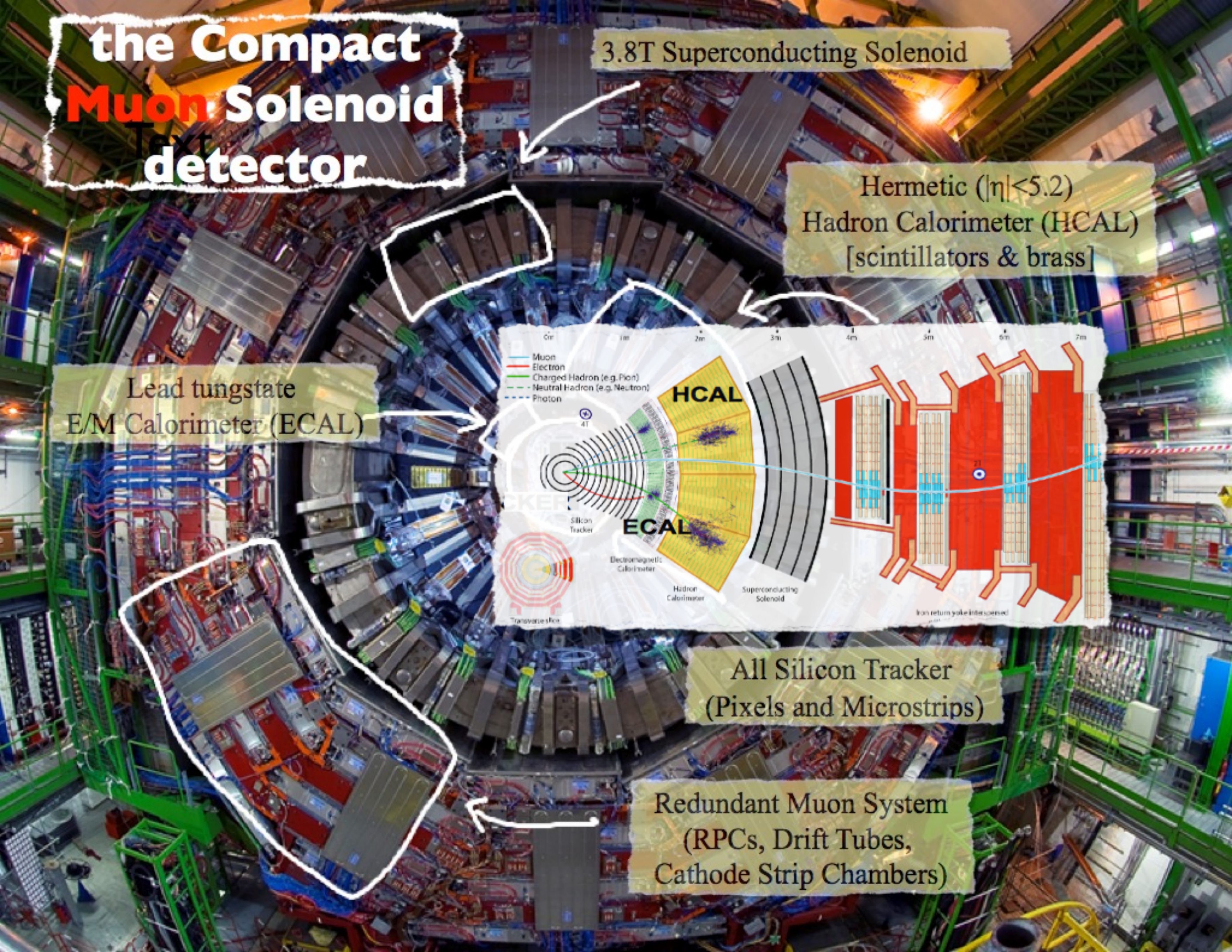
- Above 2b2c threshold: X → $\Upsilon J/\psi$ → $\mu^+\mu^-\mu^+\mu^-$
  - T_{2b2c} ?

- η_b → $J/\psi J/\psi$ → $\mu^+\mu^-\mu^+\mu^-$
  - First direct measurement of η_b

Thank you

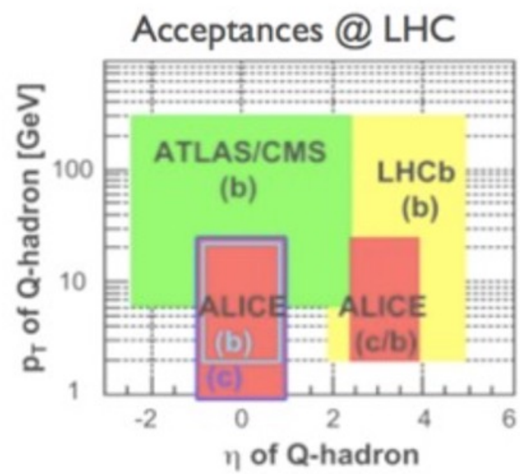
Thank you

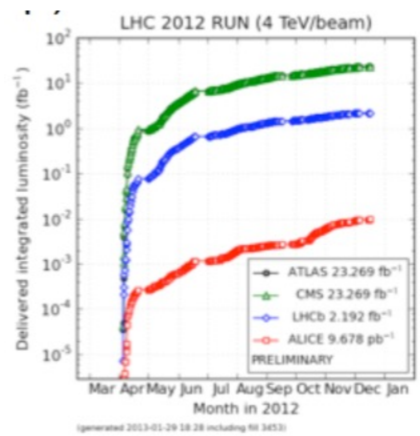
Back Up

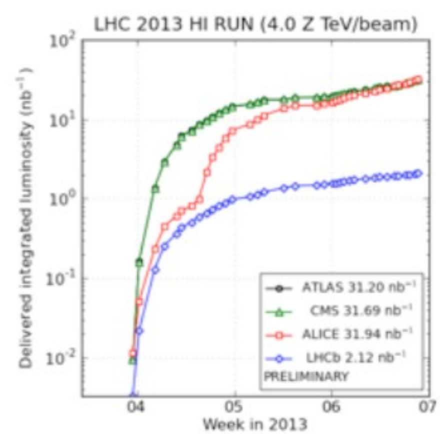

the Compact Muon Solenoid detector
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
Lead tungstate
E/M Calorimeter (ECAL)
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

Motivation: CMS

- vs RHIC
  - better resolution
    - CMS' 1st Υ(1S,2S,3S) measurements in HI
  - additional detector capability
    - CMS' 1st secondary vertex meas. in HI (eg b→J/ψ)
- vs ALICE
  - complementary acceptance (ALICE access low-pt)
  - CMS better resolution
- vs Tevatron experiments
  - extend kinematic (p_T,y) acceptance
- vs ATLAS
  - better resolution, more flexible trigger
- vs LHCb
  - complementary acceptance, LHCb great particle ID
  - worse resolution, but higher luminosity
  - LHCb does not collect ion-ion collisions





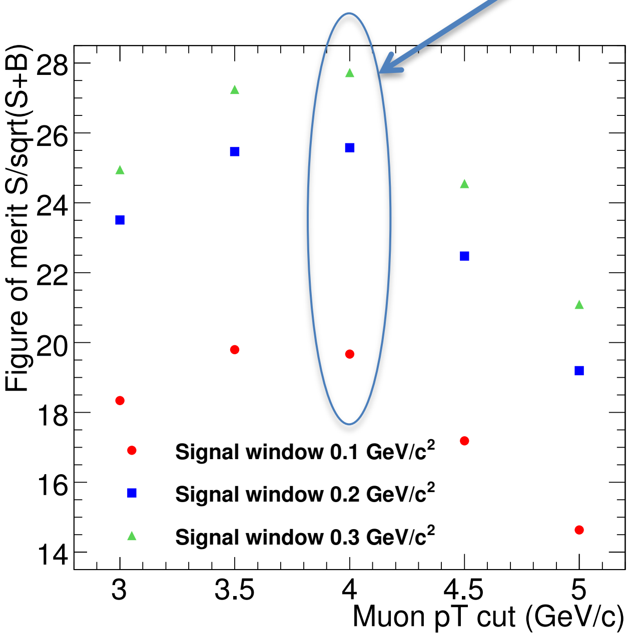


	LHCb	CMS
Run I	3/fb	25/fb
Run II	~10/fb	~90/fb

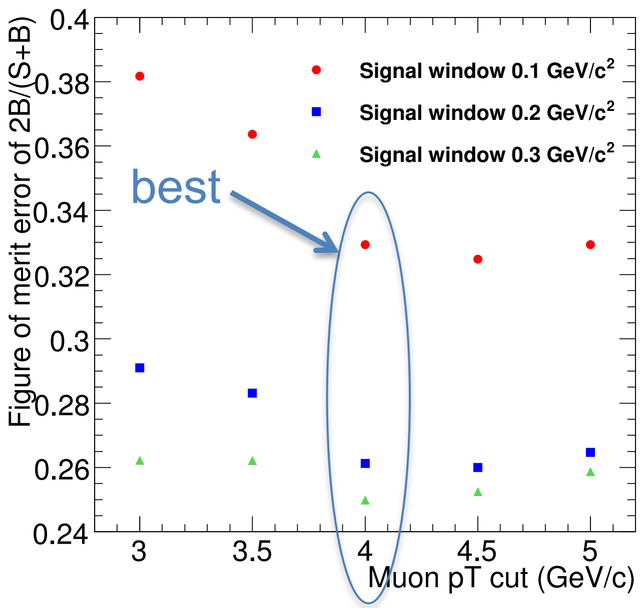
Offline selection

- Extensive optimization study
- Muon p_T threshold:
  - statistical optimization: muon p_T > 4 GeV/c

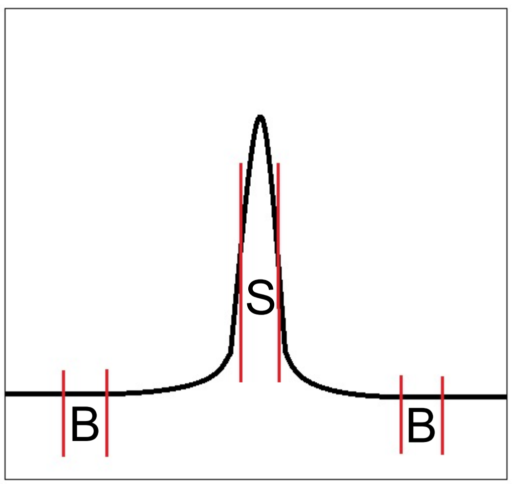
Cut Variable
InnerTrackHits > 10
PixeLayers > 0
InnerTrackχ^2/ndf $<4.$
Dxy $< 3.$ cm
Dz $< 15.$ cm
GlobalTrackχ^2/ndf <20
vProb > 0.05



Significance of $\Upsilon(1S)$ peak $S/\sqrt{S+B}$



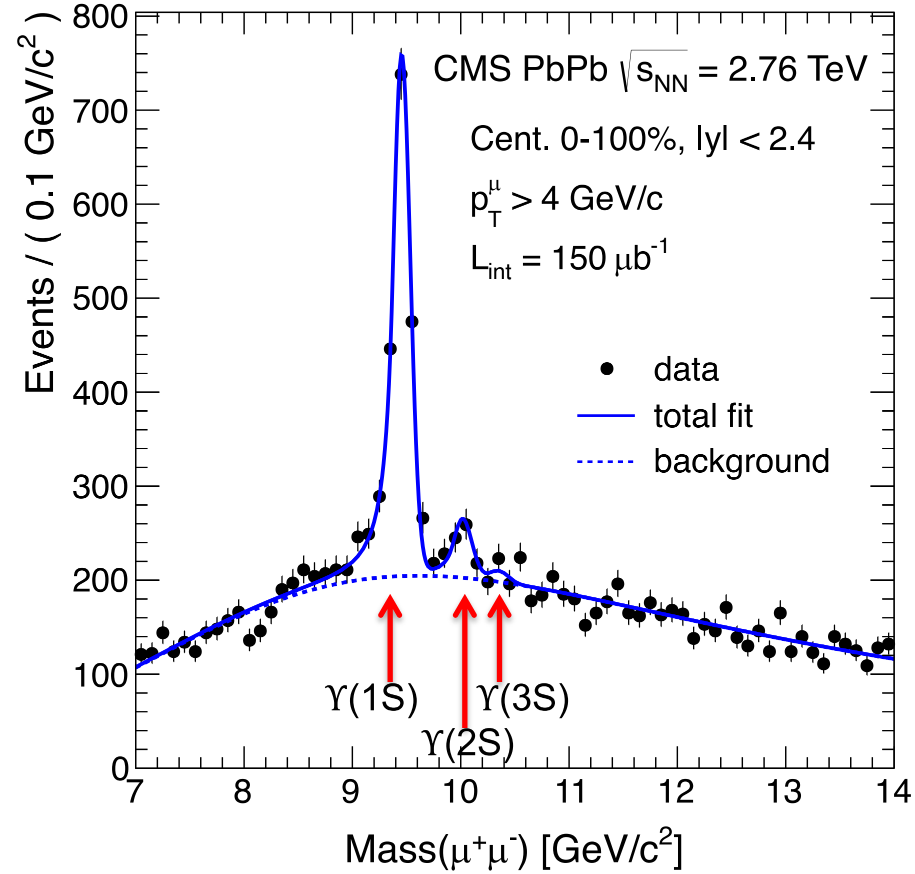
Uncertainty on the 2B/(S+B) quantity



S: signal counted from MC
B: background in the signal window determined from data sidebands

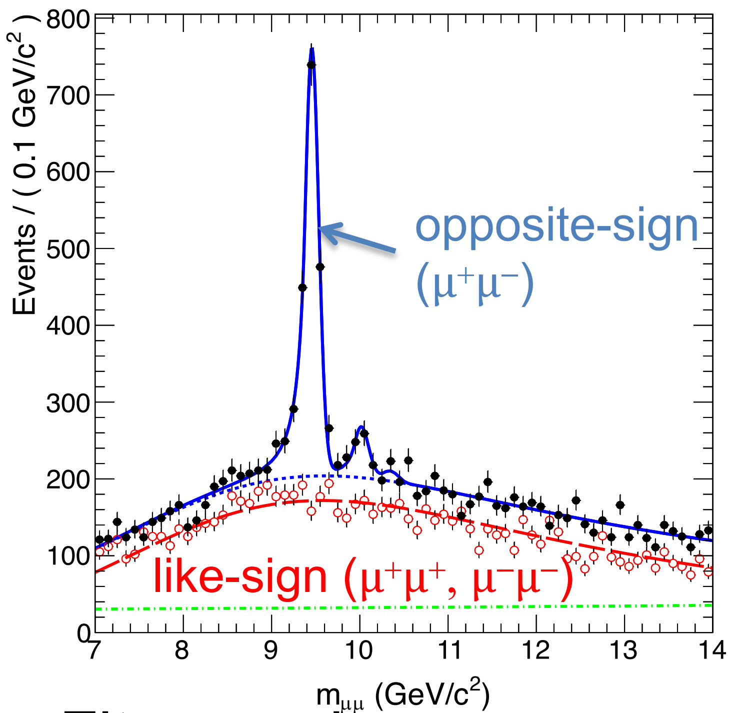
Fitting model

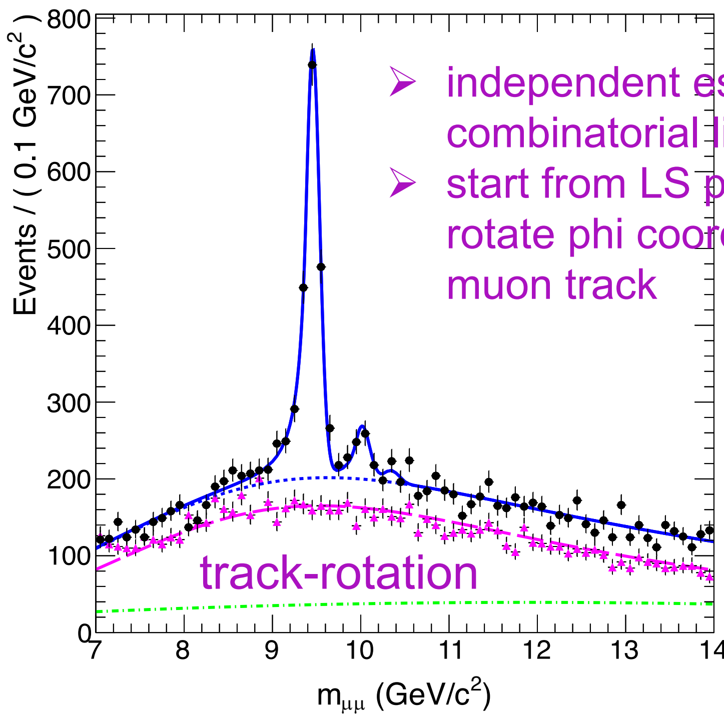
- Unbinned max. likelihood fit
  - Six Signal and four background parameters float in the fit
- Signal
  - Three resonances modeled by crystal-ball function: Gaussian resolution and FSR power-law low mass tail
  - The mass differences of three resonances are fixed to PDG
  - Float FSR & resolution (fixed in 2010 data analysis)
- Background (mainly combinatorial)
  - Exponential x error-function (Erf describes kinematic turn-on)
- Variations of the models checked as systematic



$$\Upsilon(2S)/\Upsilon(1S)|_{PbPb} = 0.12 \pm 0.03(stat.) \pm 0.02(syst.)$$
$$\Upsilon(3S)/\Upsilon(1S)|_{PbPb} = 0.02 \pm 0.02(stat.) \pm 0.02(syst.)$$

Background study



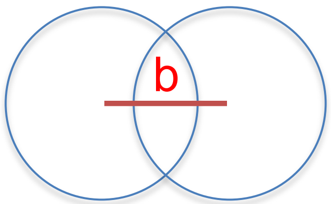


- independent estimate of combinatorial like-shape
- start from LS pairs, randomly rotate phi coordinate of one muon track

- Fit procedure:
  - fit like-sign (LS) or track-rotation (TR) spectrum with nominal background model, erf x exp
  - constrain shape normalization in fit to opposite-sign (OS) data
  - allow additional polynomial, to absorb possible/small differences between the LS/TR and OS spectra
- Alternative approach: non-parametric estimation of background
  - LS or TR Template obtained from dataset smoothing (RooKeysPdf)

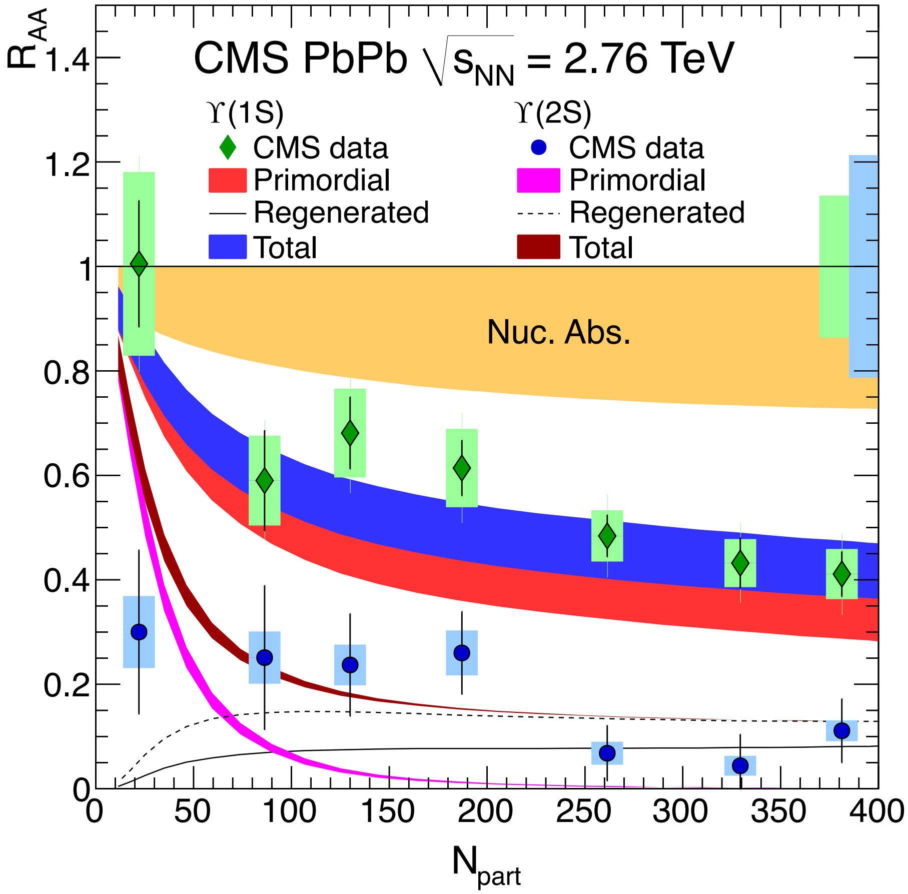
Centrality

- A key parameter in the study of the properties of QCD matter at extreme temperature and energy density, because it is related directly to the initial overlap region of the colliding nuclei
- Geometrically, it is defined by
  - the impact parameter, b: the distance between the centres of the two colliding nuclei in a plane transverse to the collision axis.
  - Centrality is thus related to the fraction of the geometrical cross-section that overlaps, which is proportional to $\pi b^2/\pi(2R_A)^2$, where R_A is the nuclear radius.

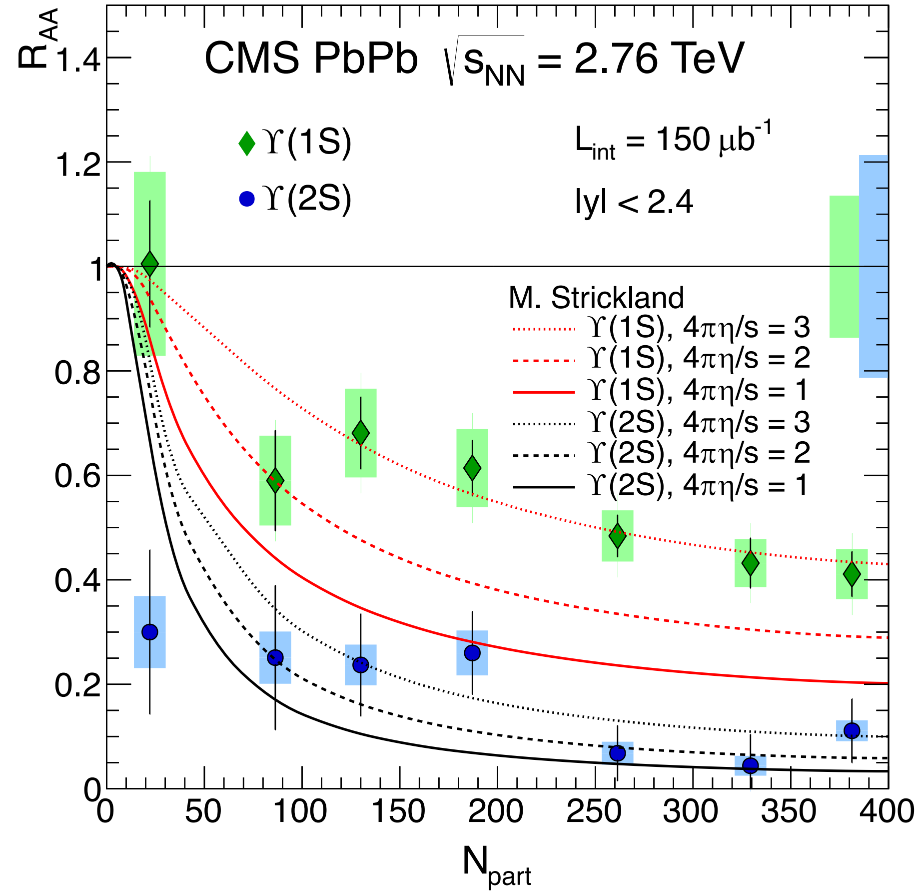


- It is customary in heavy-ion physics to characterize the centrality of a collision in terms of :
  - the number of participants (N_{part}), i.e. the number of nucleons (208 for Pb) that undergo at least one collision, or
  - the number of binary collisions among nucleons from the two nuclei (N_{coll})

Theoretical comparison



Emerick, X.Zhao, R.Rapp (Eur. Phys. J. A48 (2012) 72)

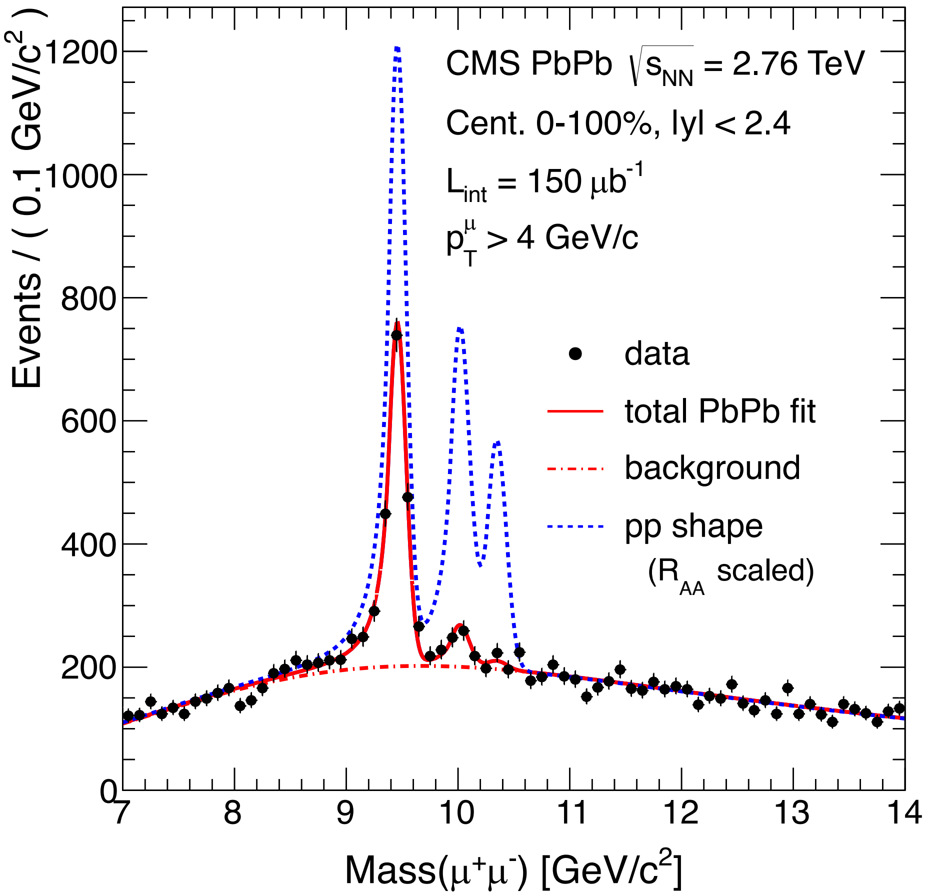


Strickland and D. Bazow (PRL 107 (2011) 132301)

- CMS data consistent within uncertainties with range of suppression predicted for both ϒ(1S) and ϒ(2S)

Summary

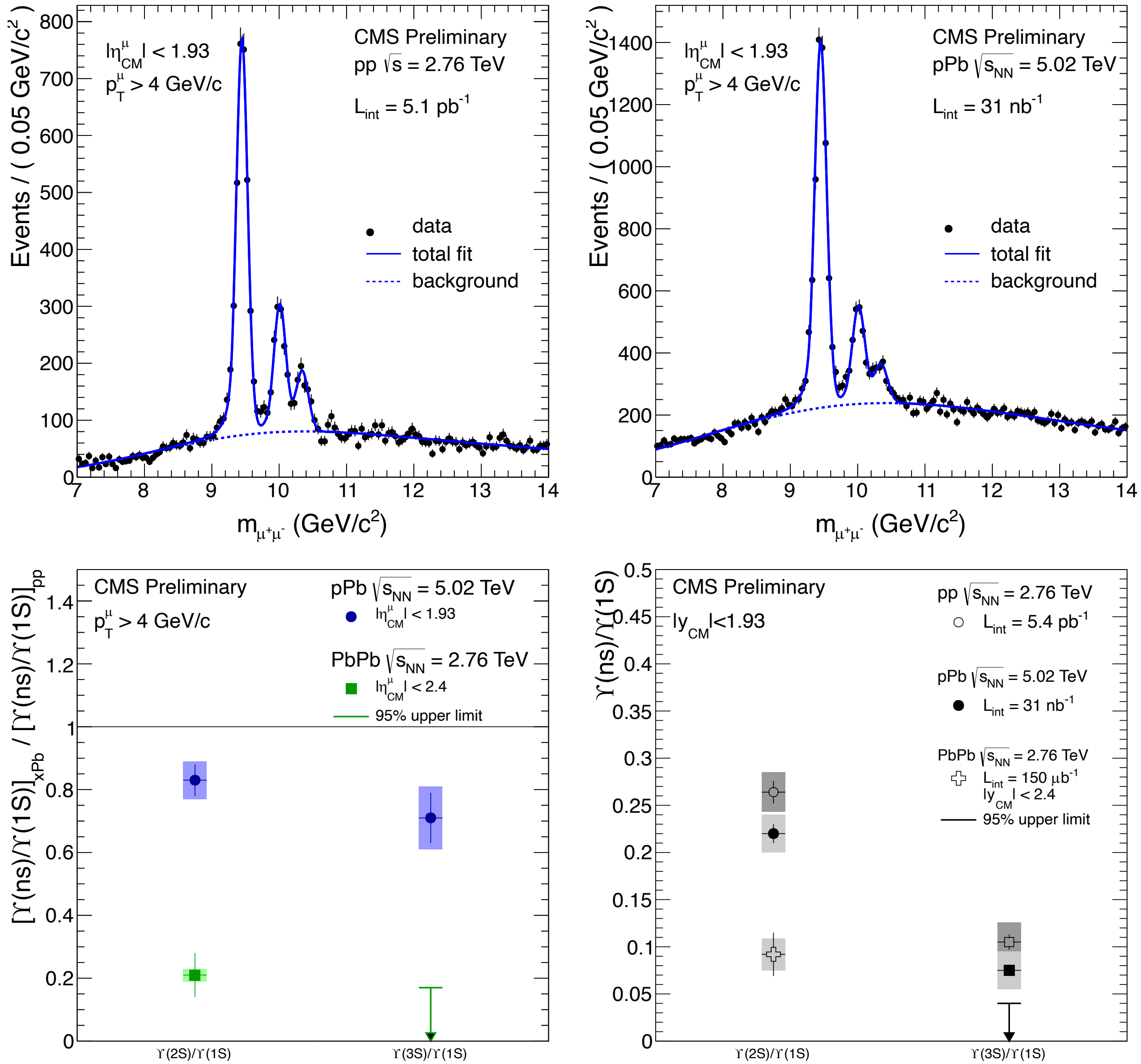
- First measurements of the individual Υ states in the heavy-ion environment
  - Based on full data sample of the second PbPb run @ 2.76 TeV (150 μb^{-1})
- Relative excited-to-ground states suppression is observed with significance > 5 σ
- Suppression pattern (sequential "melting") has been established
  - Measured $\Upsilon(nS)$ R_{AA}
- Measured the centrality dependence of the double ratio, $\Upsilon(1S)$ R_{AA}, and $\Upsilon(2S)$ R_{AA} for the first time



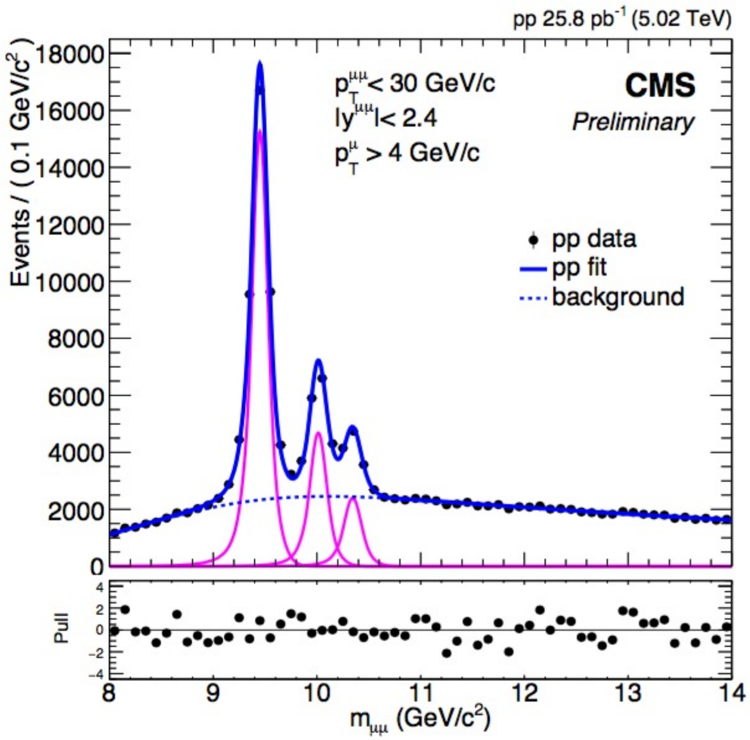
Υ in pPb (HIN-13-003)

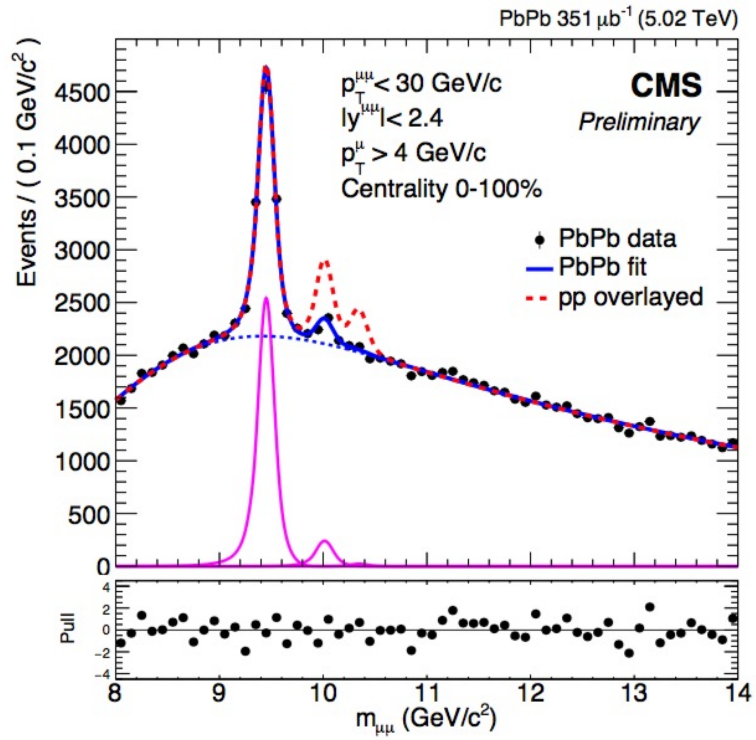
- Υ(ns) in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

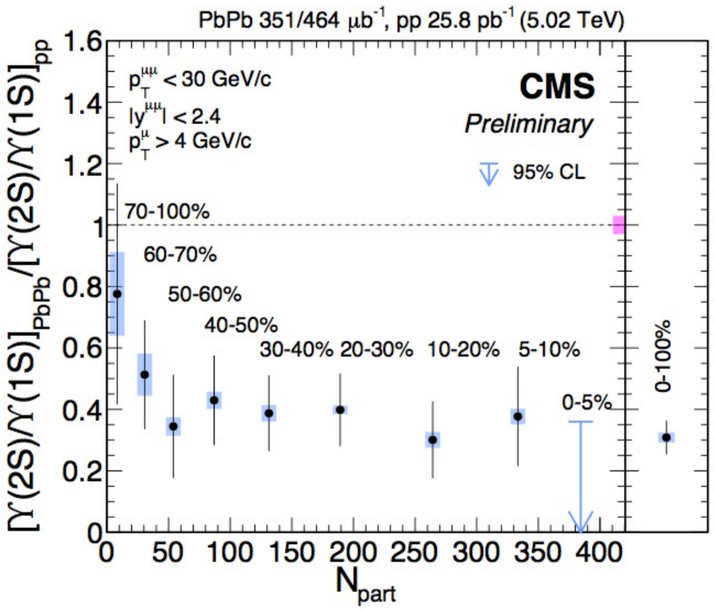
- Y suppression is confirmed (not only wrt pp but also) wrt pPb
- Indications of suppression in pPb wrt pp, but with a low significance between 2-3 sigma
- There are indications of dependence of the Y ratios on track multiplicity (seen in pPb and pp). Work in progress.



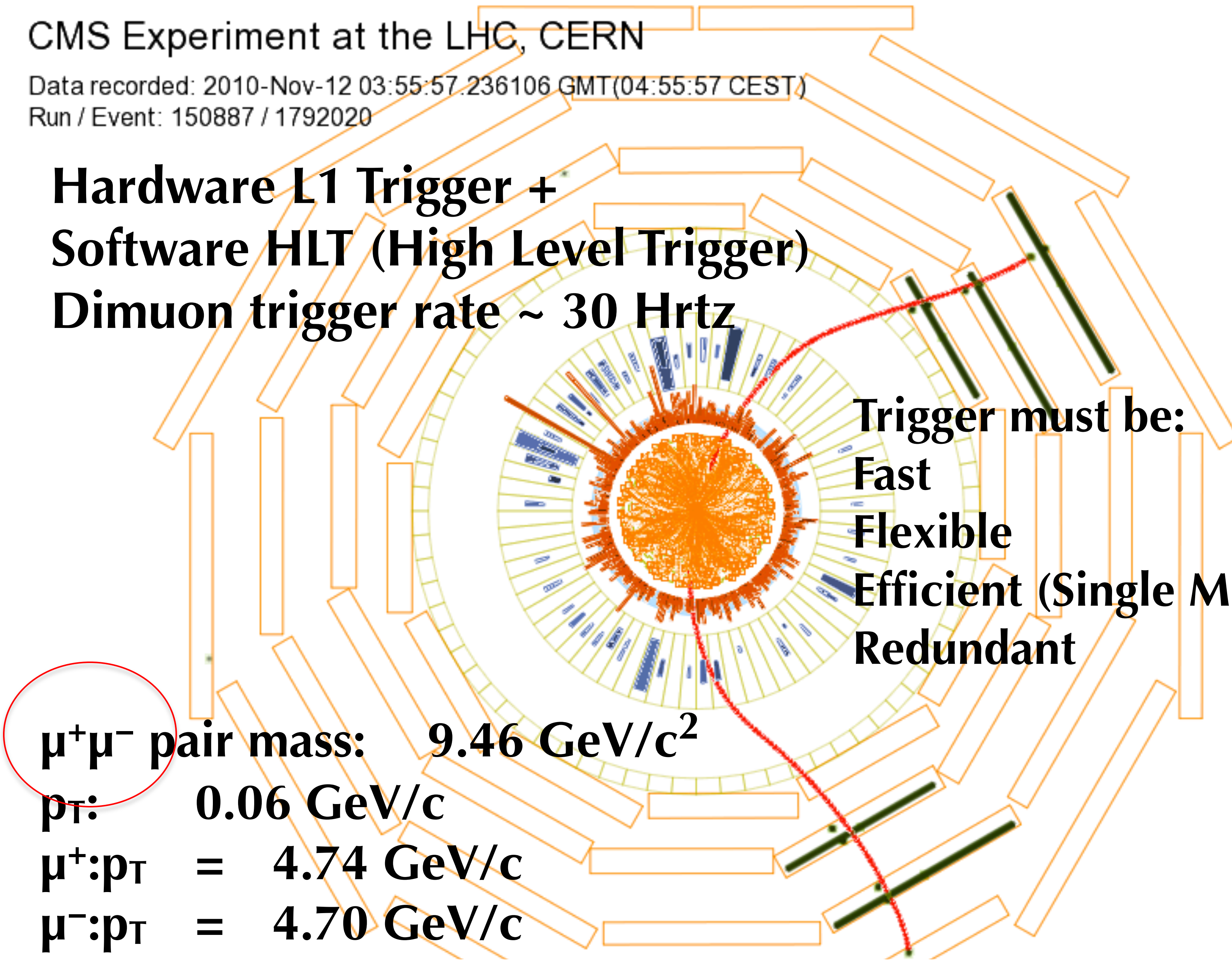
PbPb at 5.02 TeV







ϒ candidate in PbPb @ 2.76 TeV



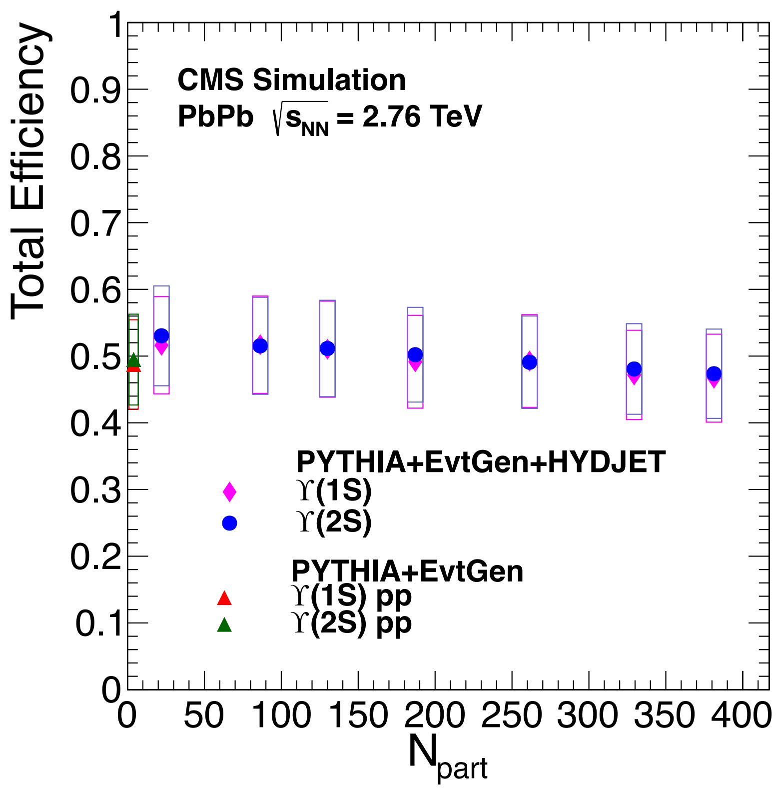
Hardware L1 Trigger +
Software HLT (High Level Trigger)
Dimuon trigger rate ~ 30 Hrtz

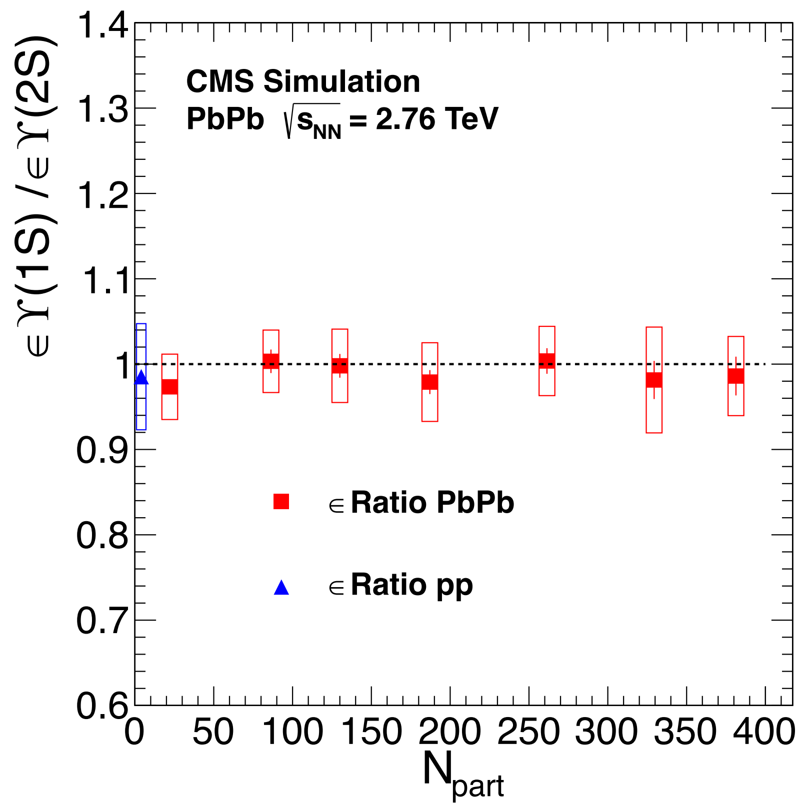
Trigger must be:
Fast
Flexible
Efficient (Single Muon Eff. ~95 %)
Redundant

$\mu^+\mu^-$ pair mass: 9.46 GeV/c^2
p_T: 0.06 GeV/c
μ^+:p_T = 4.74 GeV/c
μ^-:p_T = 4.70 GeV/c

Efficiency

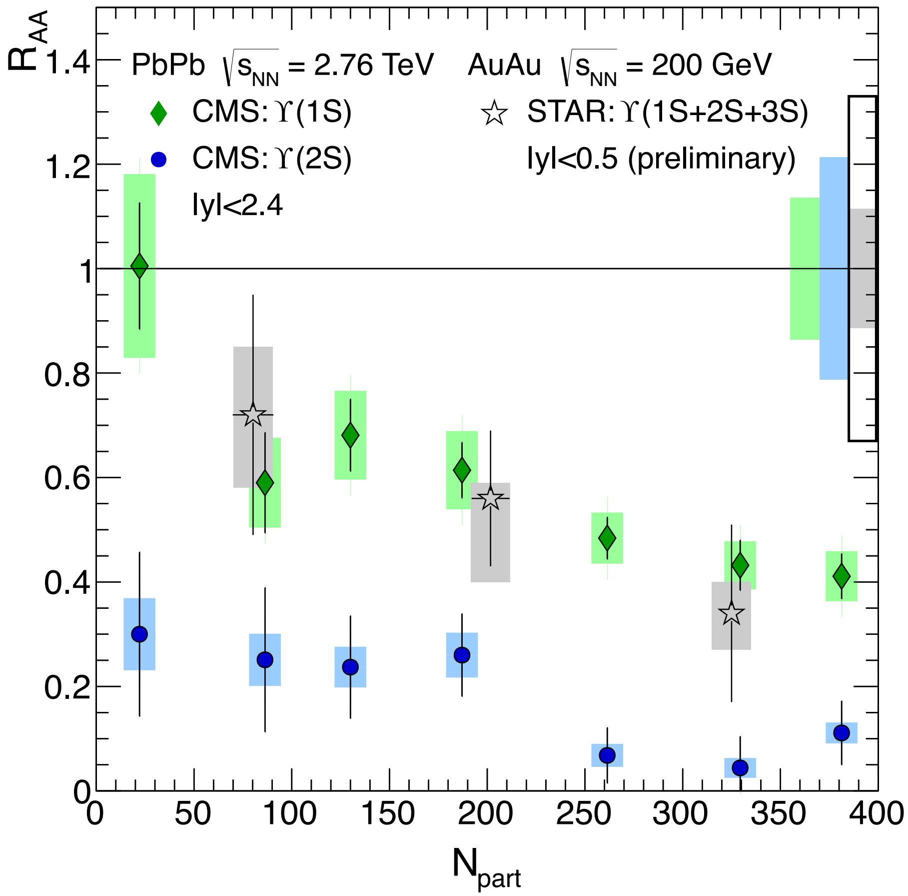
- Check efficiency of Υ(1S) and Υ(2S) between PbPb and pp collisions and their dependencies on centrality
- Efficiency correction is applied to R_{AA} $\frac{\varepsilon_{\Upsilon(1S)}|_{PbPb}}{\varepsilon_{\Upsilon(1S)}|_{pp}}$ $\frac{\varepsilon_{\Upsilon(2S)}|_{PbPb}}{\varepsilon_{\Upsilon(2S)}|_{pp}}$

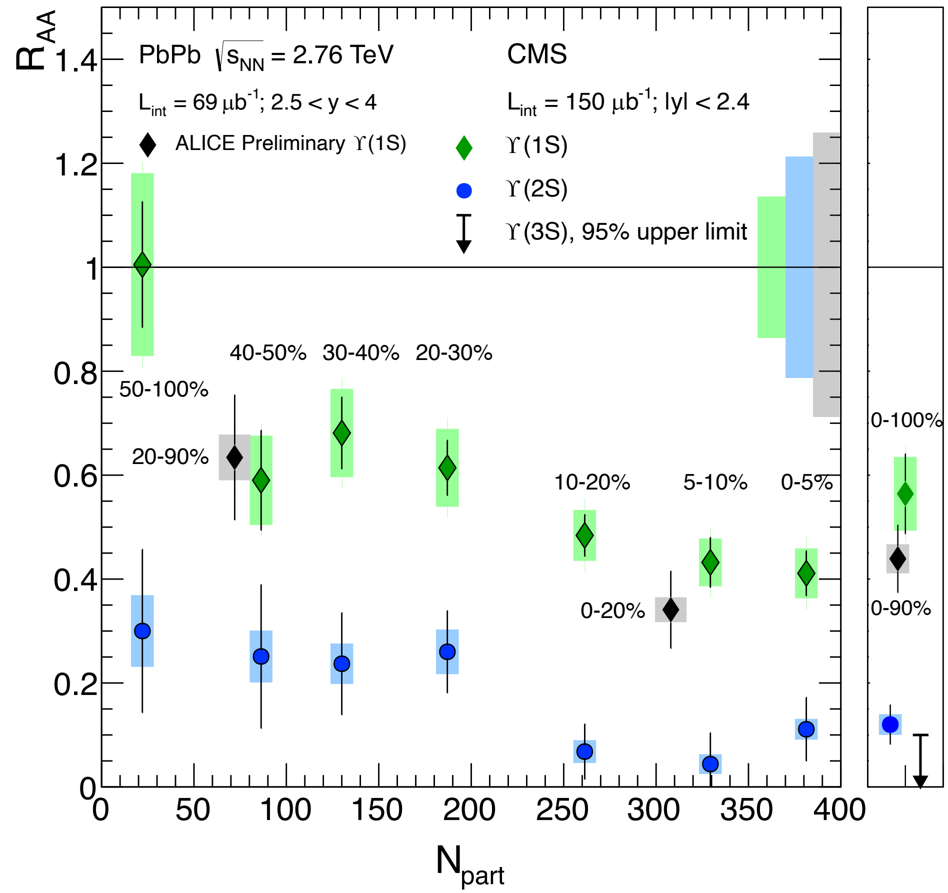




- Using Tag&Probe data driven as cross check. Difference taken as systematic

Experimental comparison - others





- Comparison with STAR

  ϒ(1S+2S+3S) combined states

- Comparison with ALICE

  Forward rapidity range (2.5<y<4)