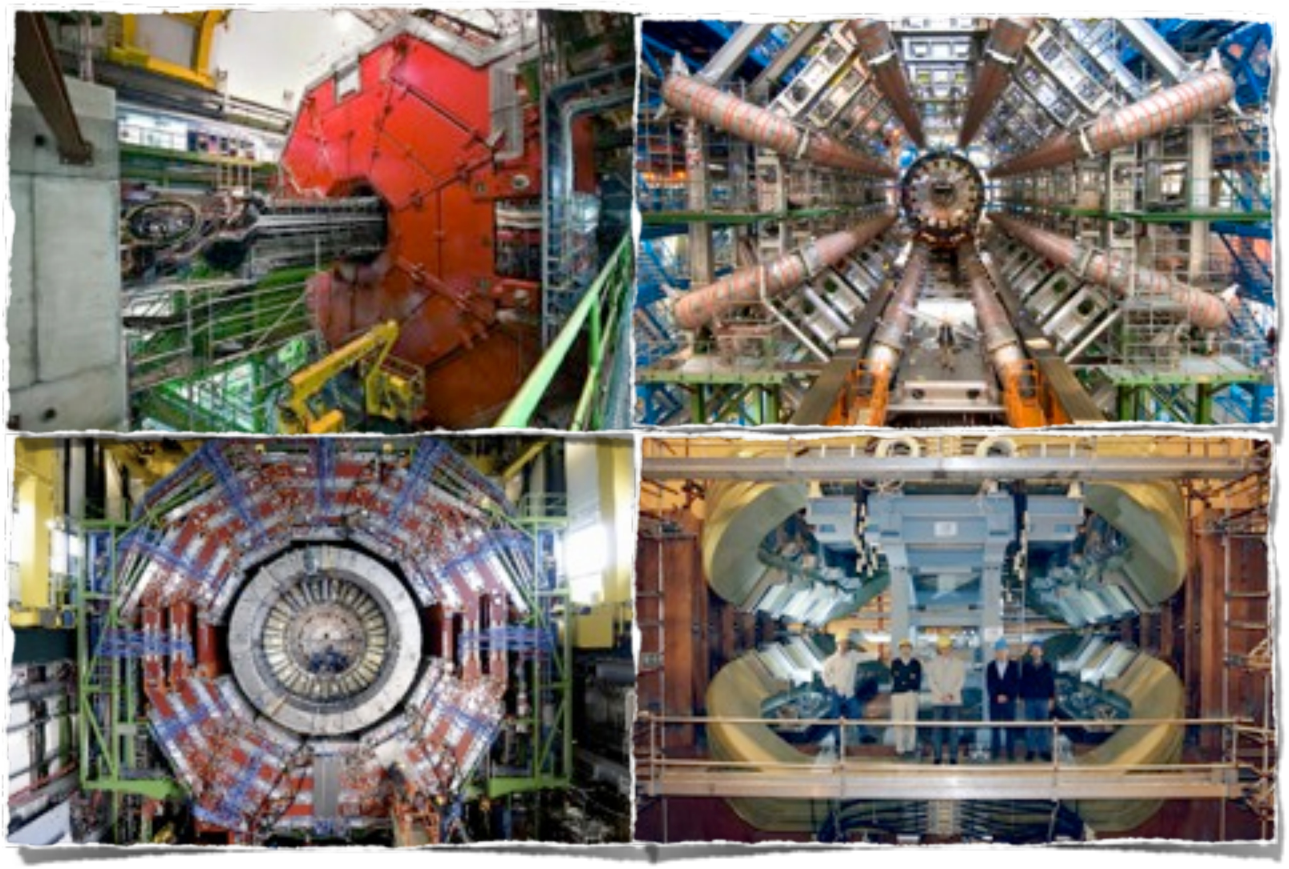
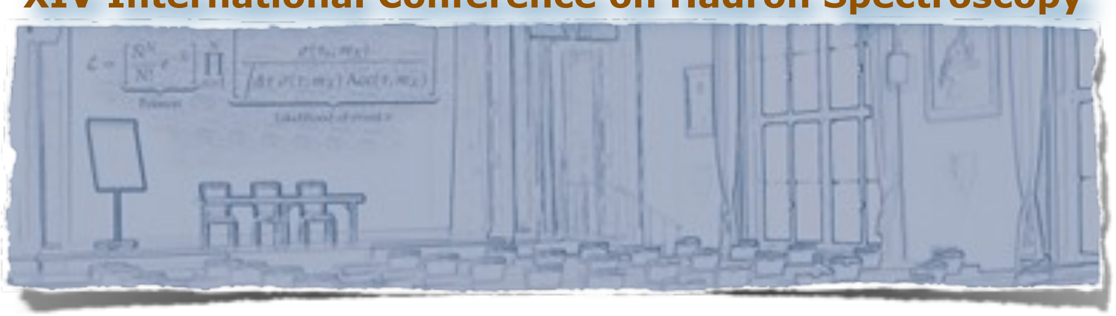


Bottomonium first results from LHC experiments

XIV International Conference on Hadron Spectroscopy



Nuno Leonardo
(Purdue University)
for the LHC Collaborations

Hadron2011
Munich, June 15, 2011

overview

introduction

- LHC
- motivations

di-lepton signals

- μμ, ee spectra
- detector resolution

pp @ 7TeV

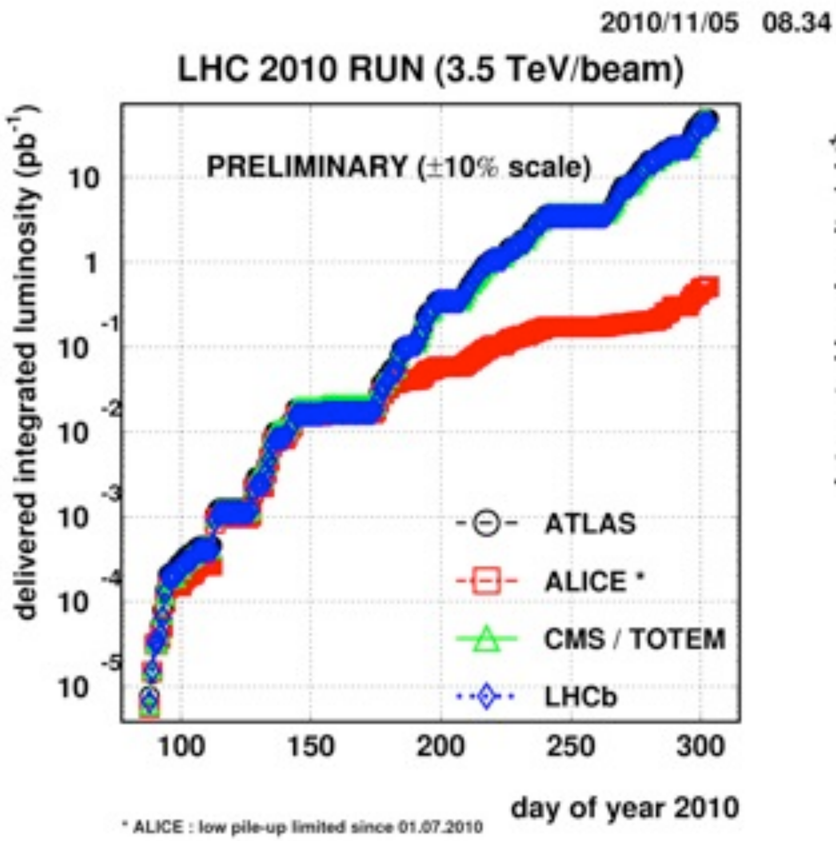
- data-driven efficiency
- cross section
- prospects

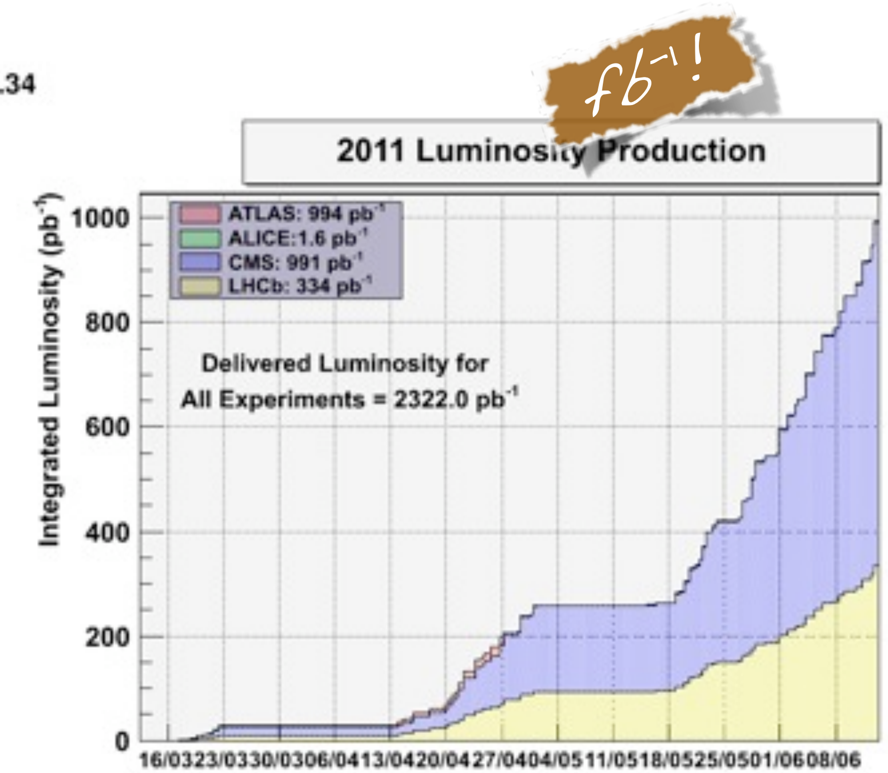
PbPb @ 2.76TeV

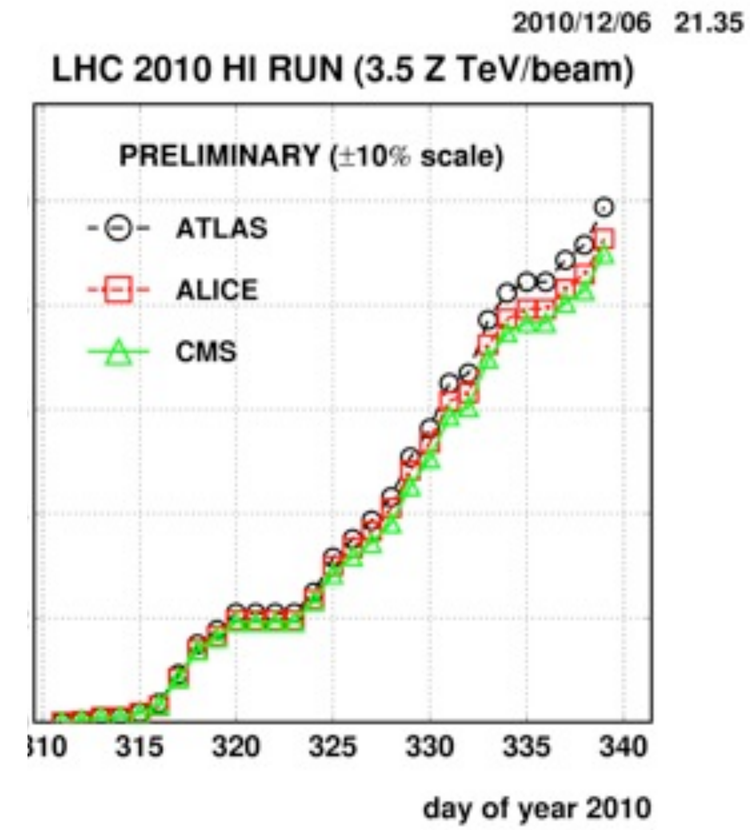
- R_{AA}, cross section
- Υ' suppression

LHC luminosity

[lpc.web.cern.ch]







pp@7TeV

2011 (2010)

ATLAS, CMS: L~1k (40) pb^{-1}

LHCb: L~300 (40) pb^{-1}

ALICE: L~2 (<1) pb^{-1}

pp@2.76TeV

ATLAS, CMS: L~ 241 nb^{-1}

LHCb: L~ 67 pb^{-1}

ALICE: L <1 pb^{-1}

PbPb@2.76TeV

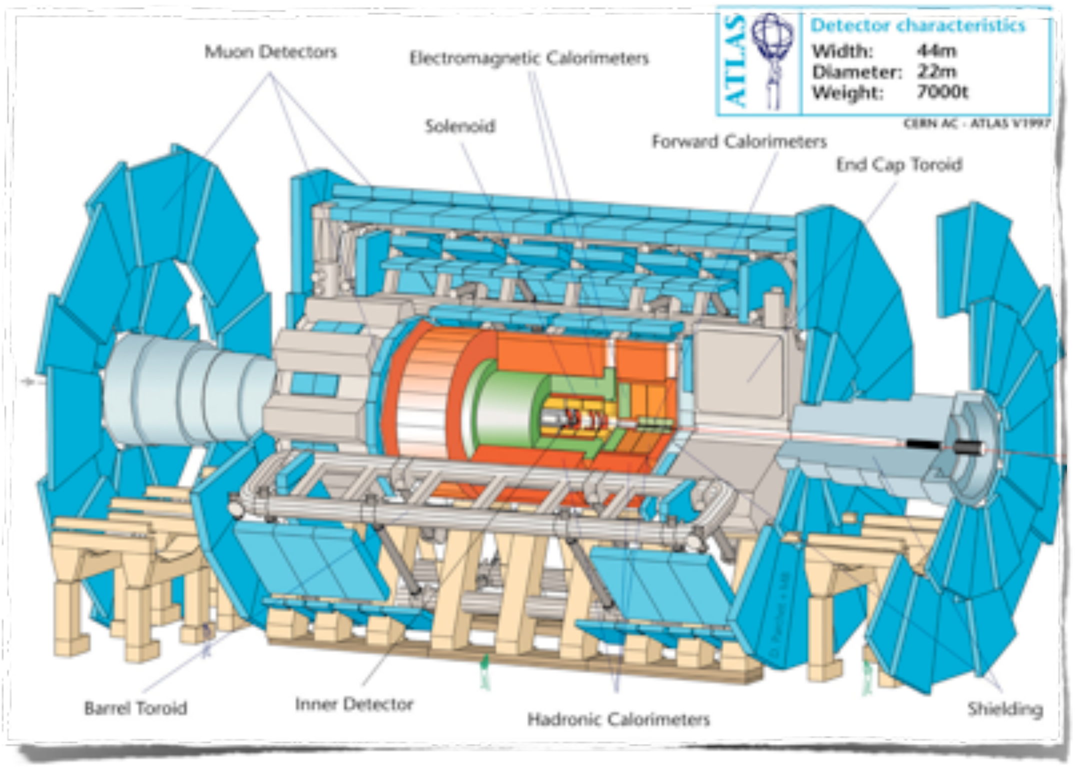
ALICE, ATLAS, CMS: L~9 μb^{-1}

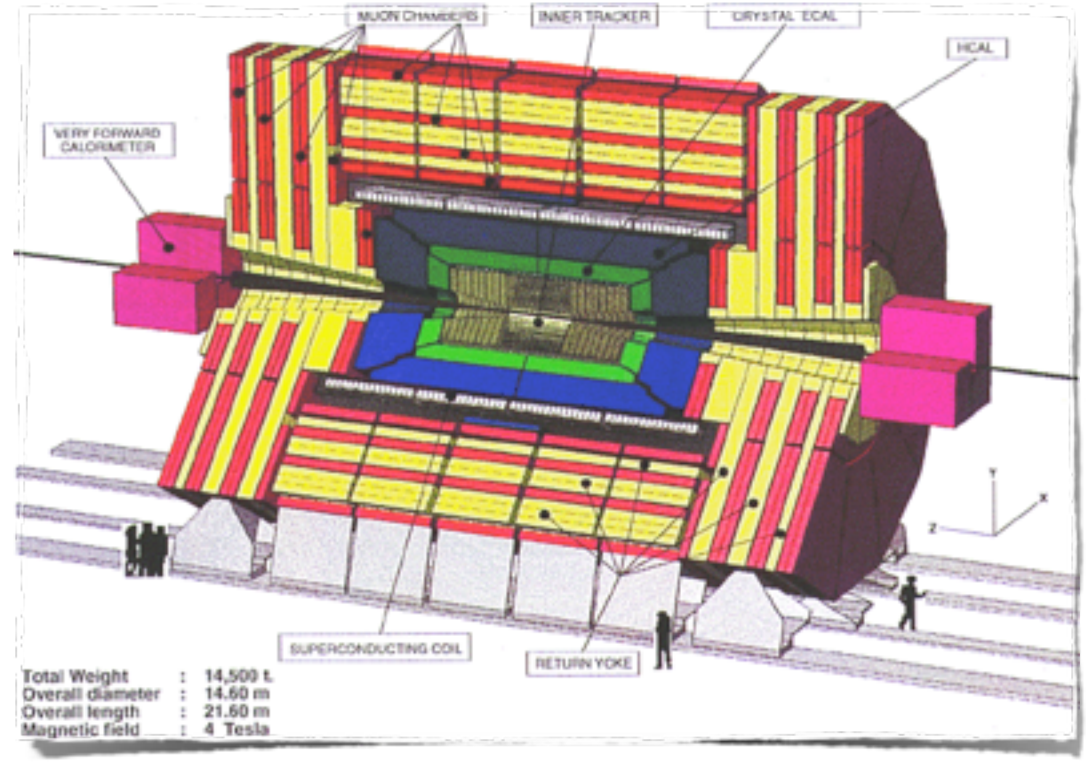
LHCb: n/a

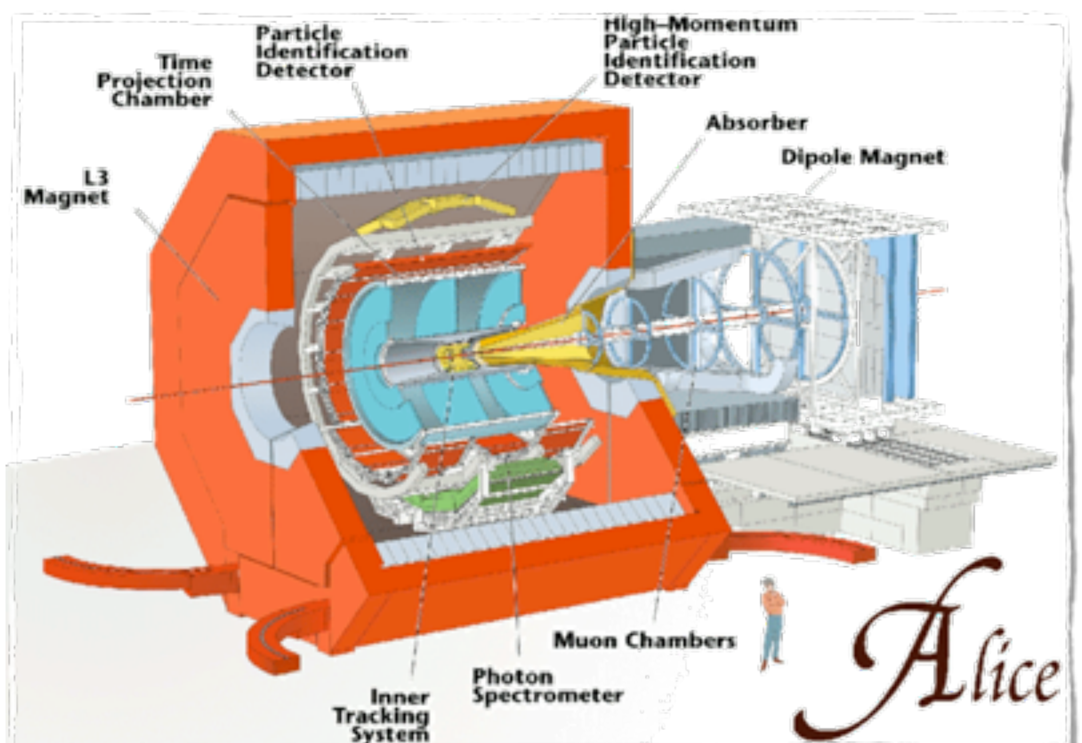
$L_{pp} \approx 10^{30} - 10^{33}$ cm^{-2} s^{-1}

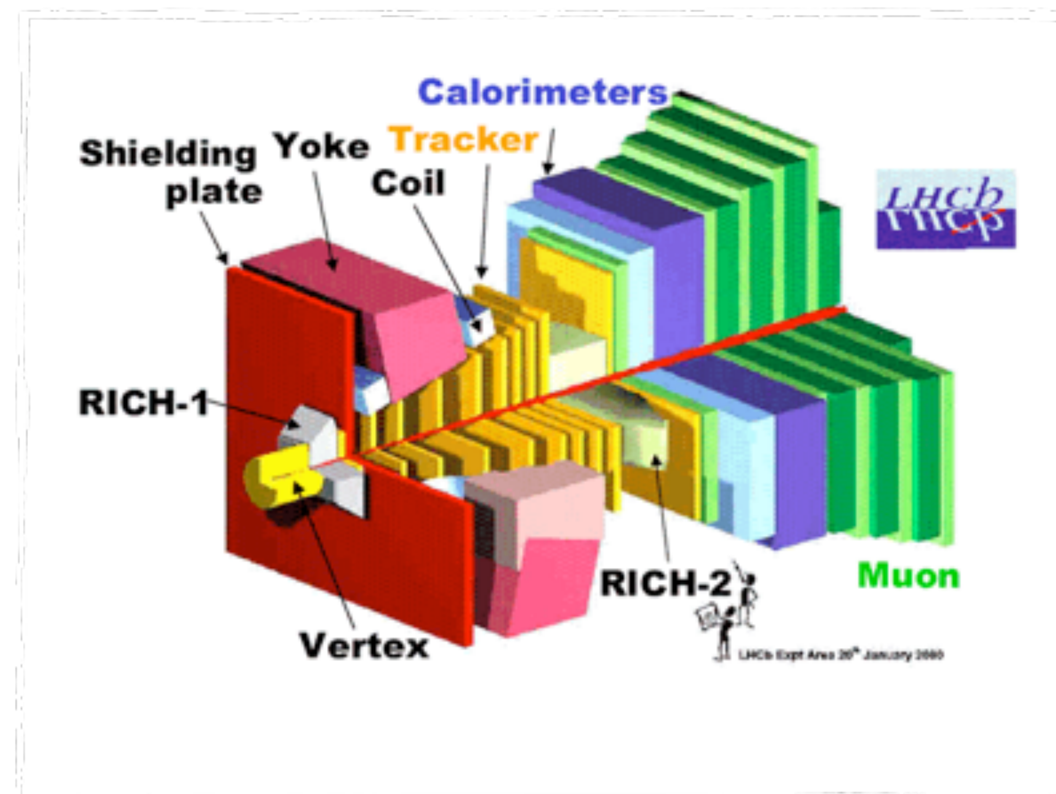
$L_{PbPb} \approx 10^{25} - 10^{27}$ cm^{-2} s^{-1}

ALICE, ATLAS, CMS, LHCb



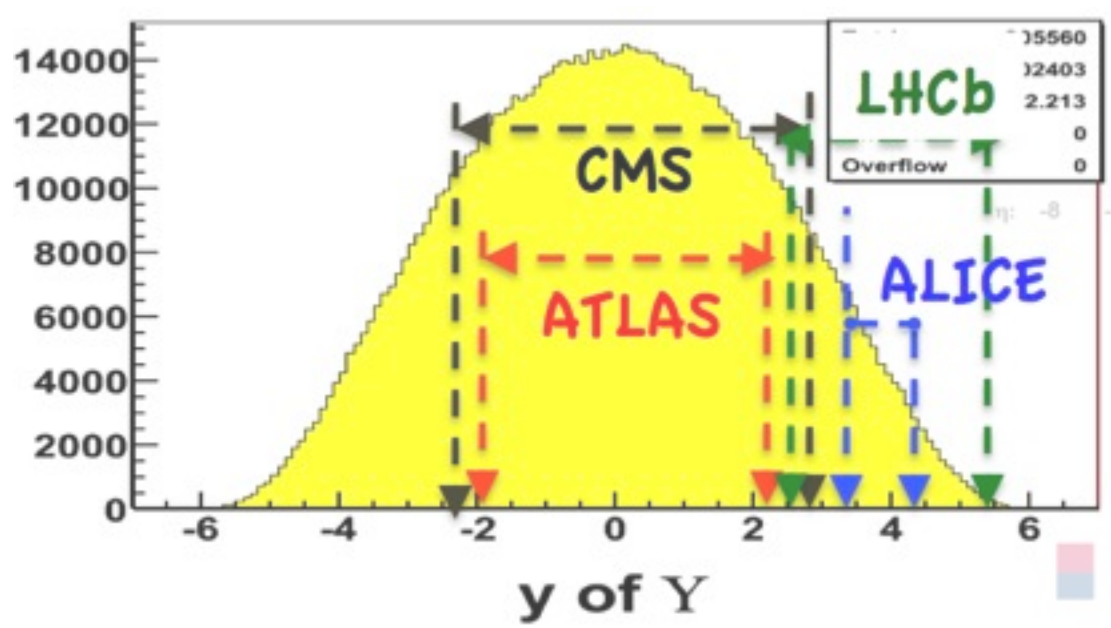


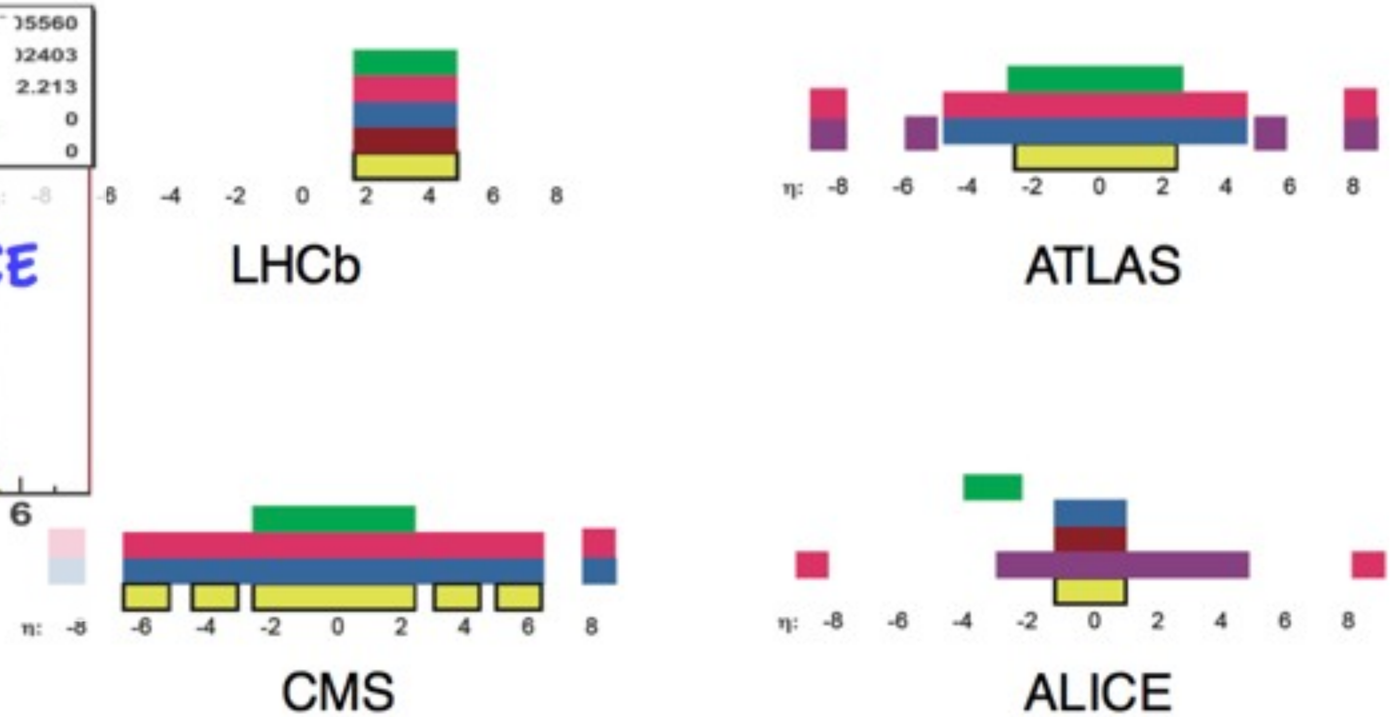




LHC experiments (cont'd)

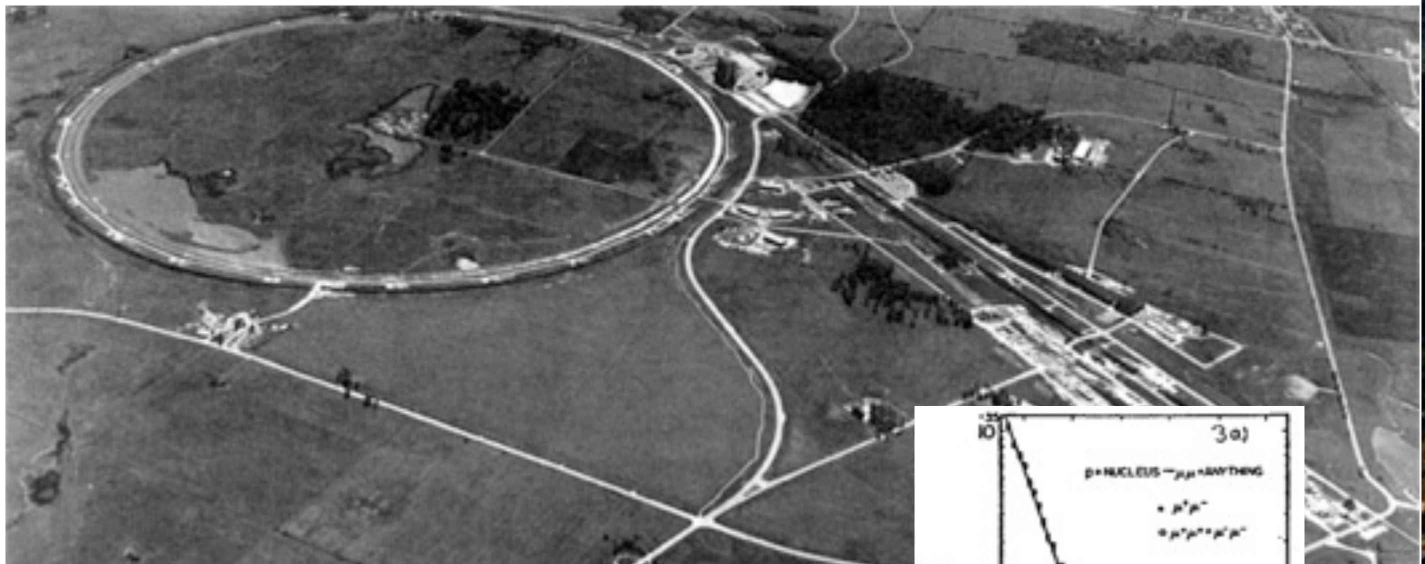
- all four detectors have the capability to study bottomonia
- complementary phase space and physics coverage
    - e.g. central vs forward rapidities, pp vs heavy-ion environments
- based on different: B field, detector technologies, DAQ capabilities, emphasis on hermeticity or particle ID

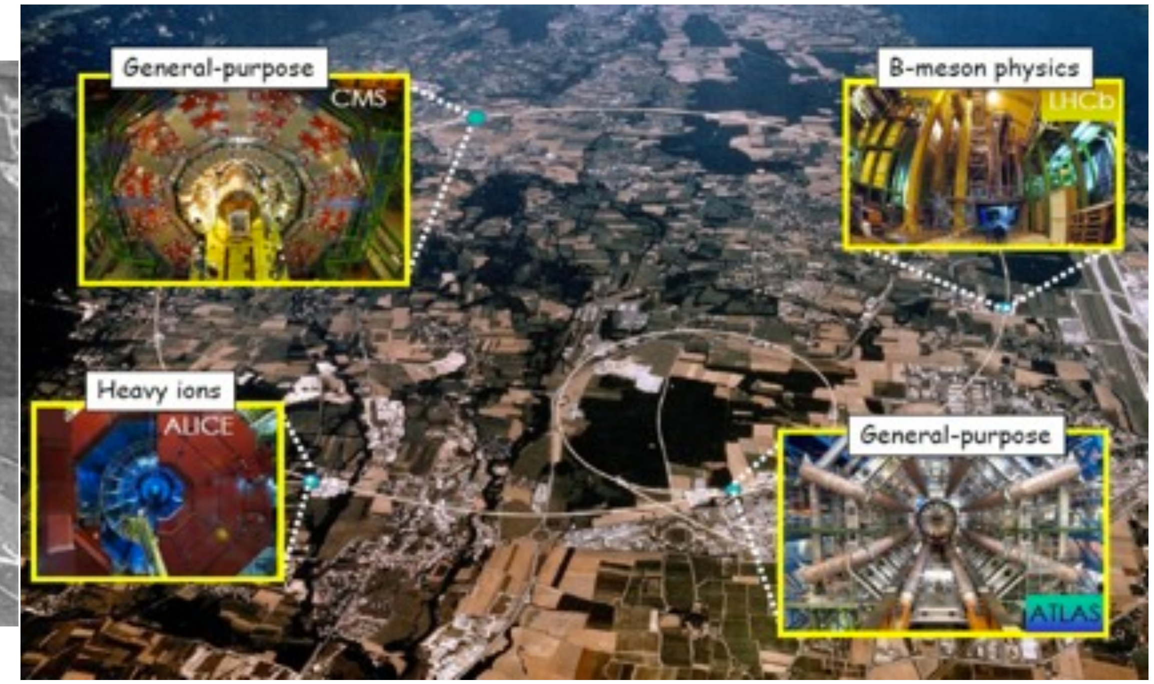




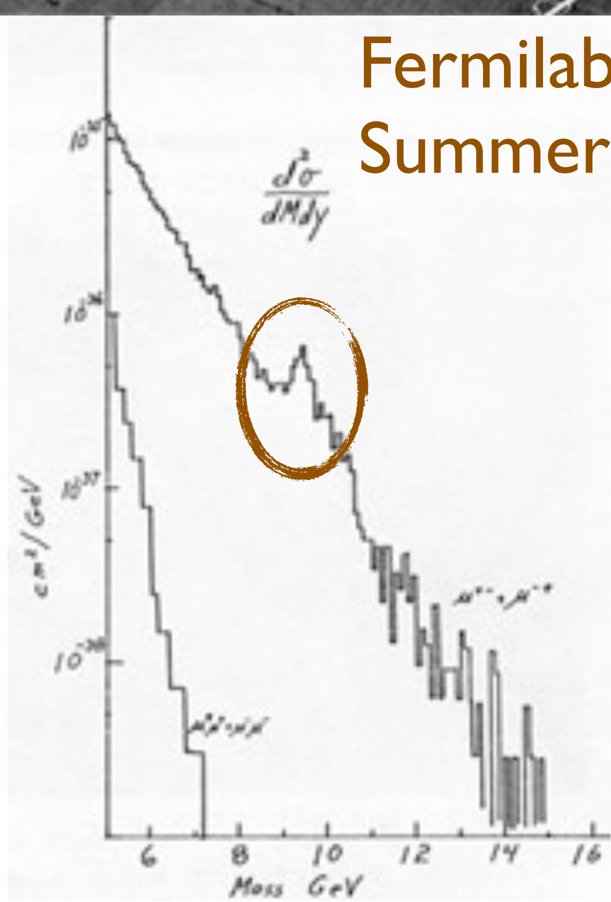
tracking, ECAL, HCAL, counters lumi, muon, hadron PID

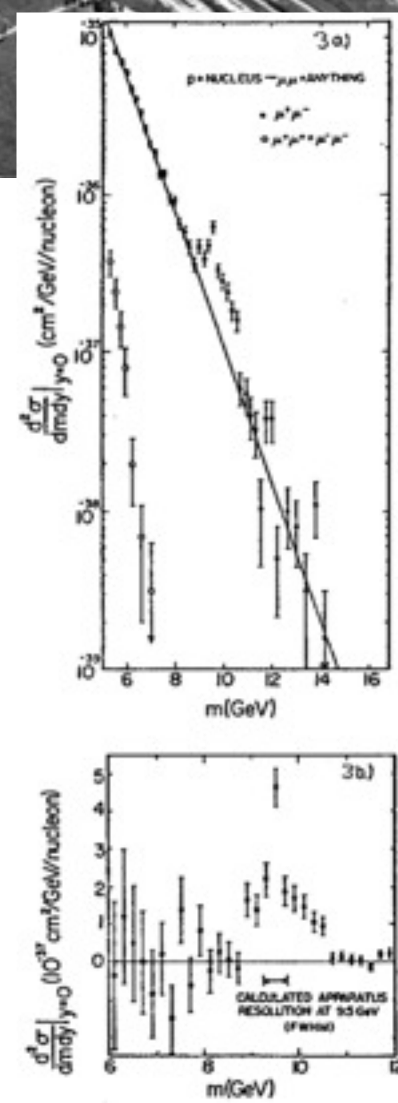
then... & now



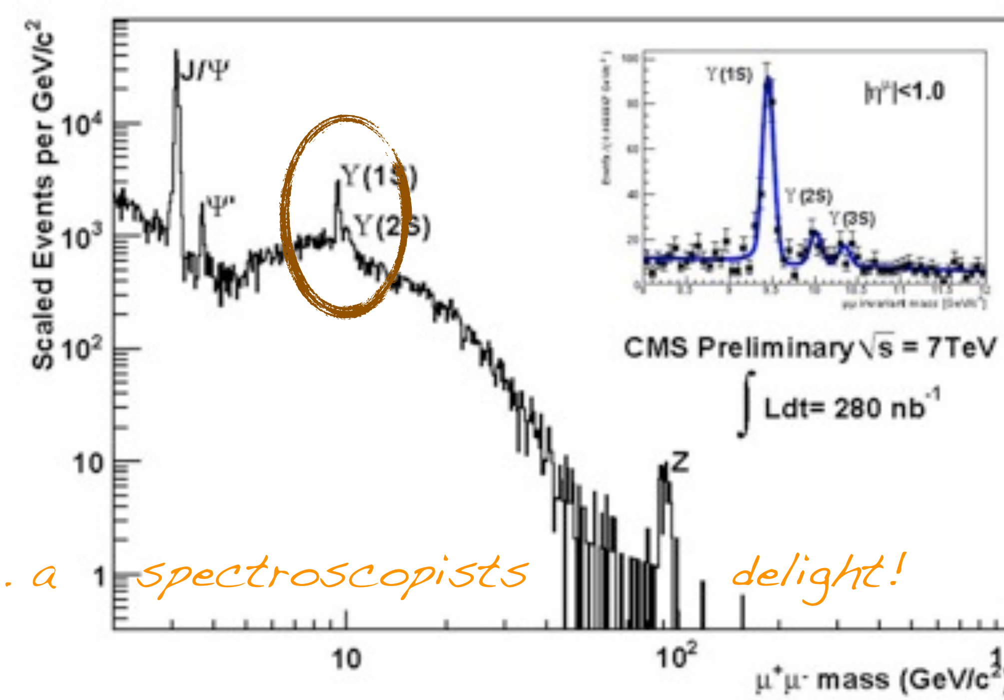


Fermilab
Summer 1977



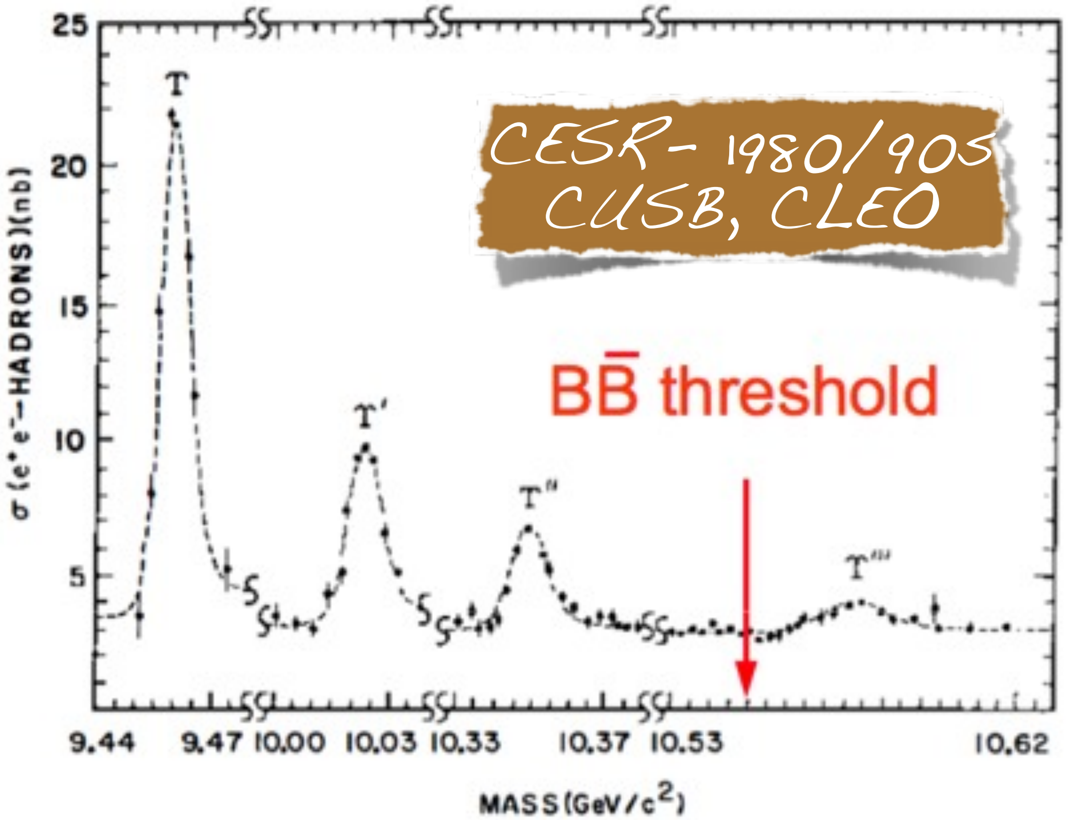


CERN, Summer 2010

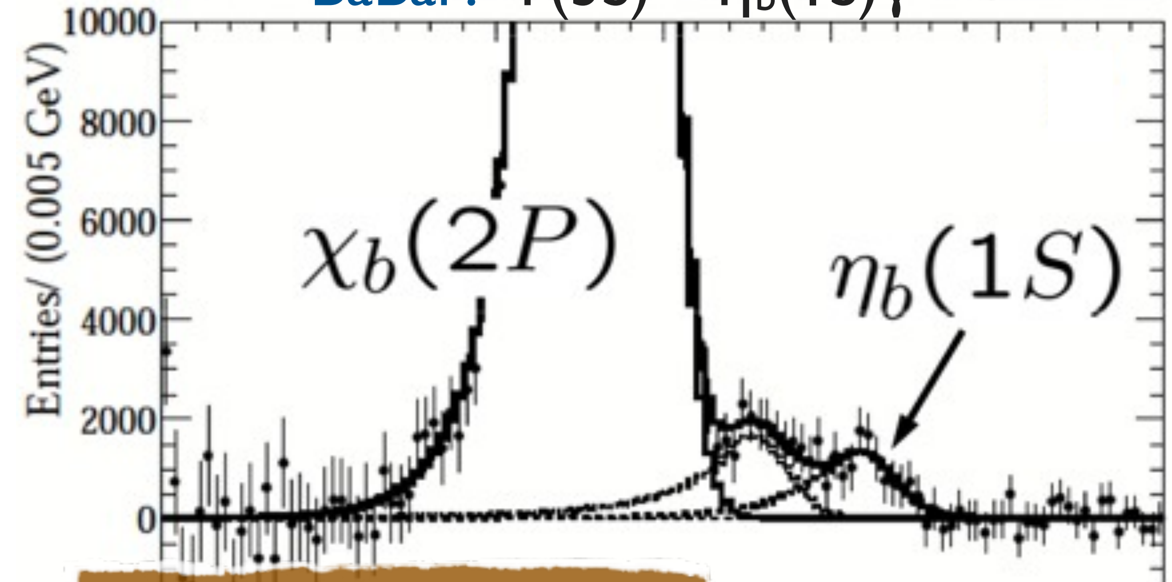


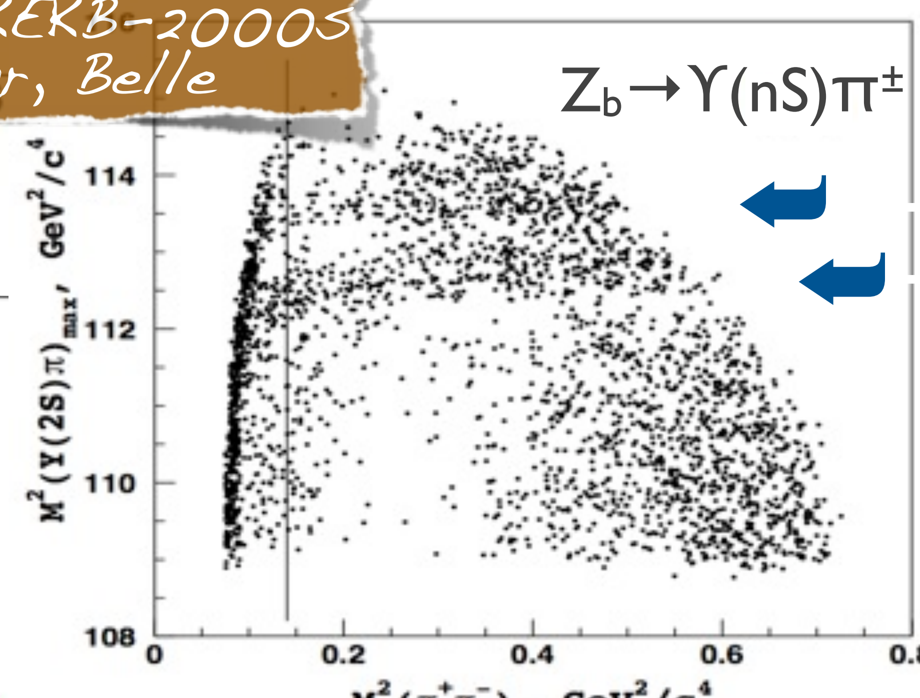
... a spectroscopists delight!

large set of results



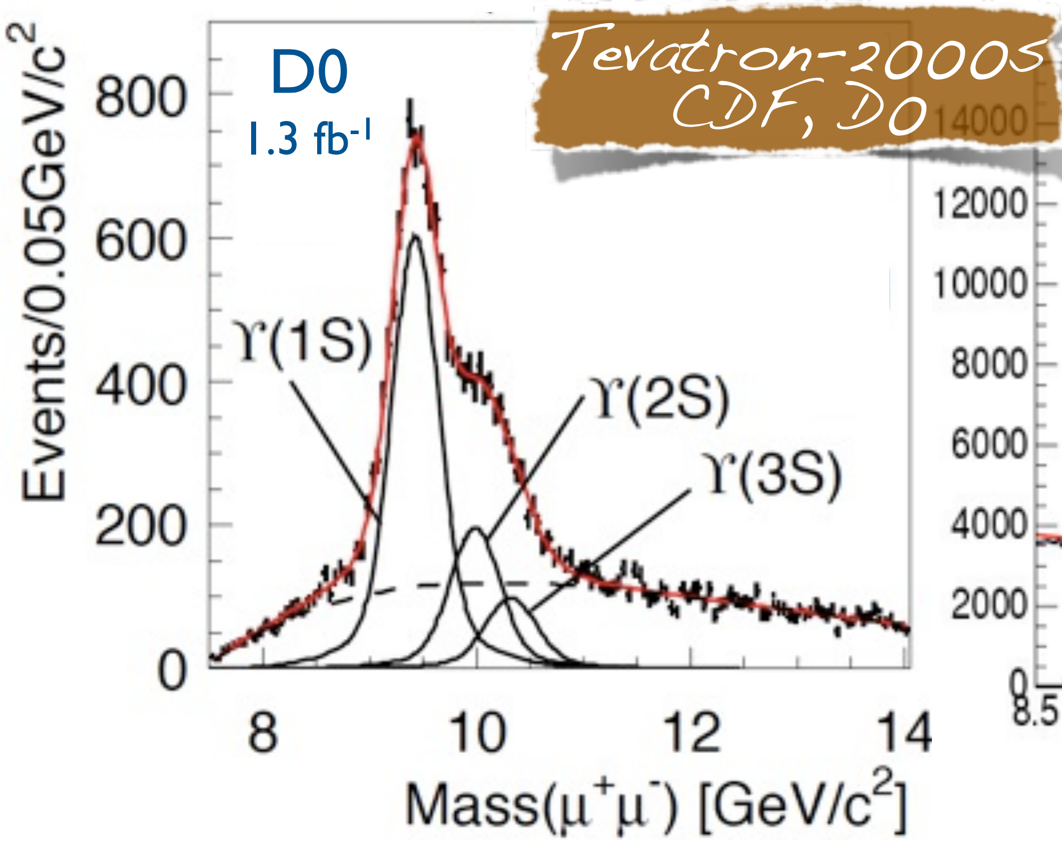
BaBar: $\Upsilon(3S) \to \eta_b(1S)\gamma$

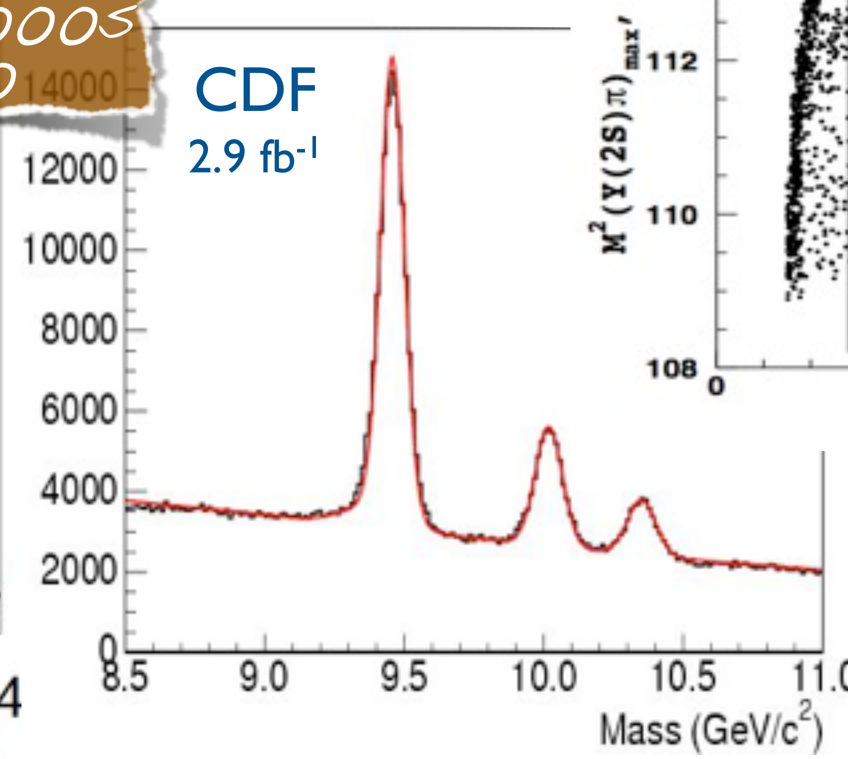




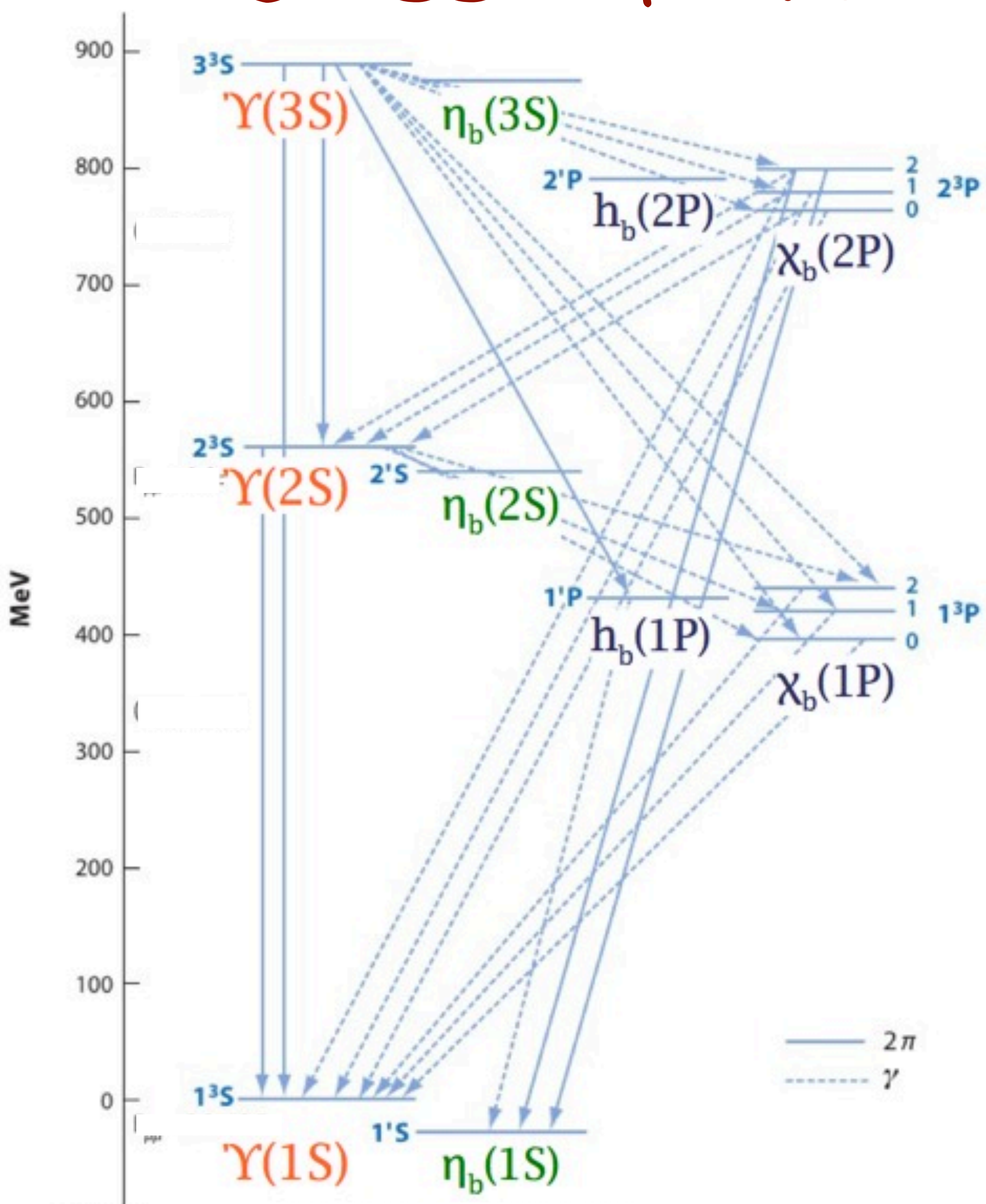
Belle: $\Upsilon(5S) \to \Upsilon(2S)\pi\pi$

(Bottomonium-like exotica: 2 charged states just above open beauty B^*B, B^*B^* thresholds)





bottomonium spectroscopy



(below open beauty threshold)

Bottomonium states

direct production

$$pp \to b\bar{b} + X$$
$$\quad \llcorner \Upsilon(1S) + X$$

indirect production

contribution from feed down
transitions from heavier bottomonia

$$pp \to b\bar{b} + X$$
$$\quad \llcorner \chi_b \to \Upsilon(1S) + \gamma$$
$$\quad \llcorner \Upsilon(n'S) \to \Upsilon(1S) + X$$

➥ 30-50% of full $\Upsilon(1S)$ productions

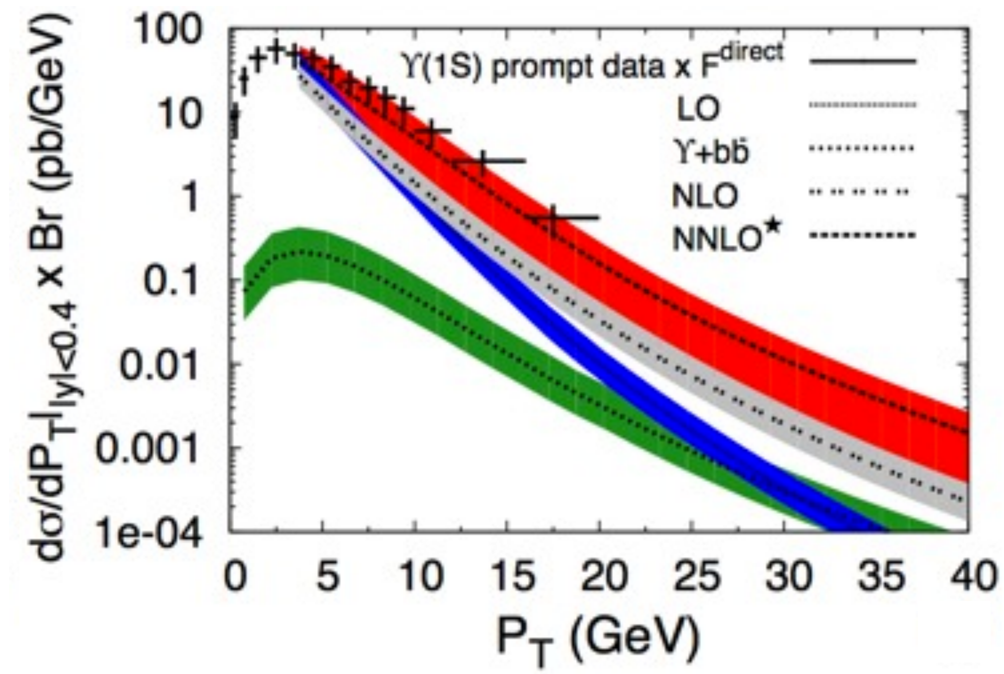
no contribution from long-lived states

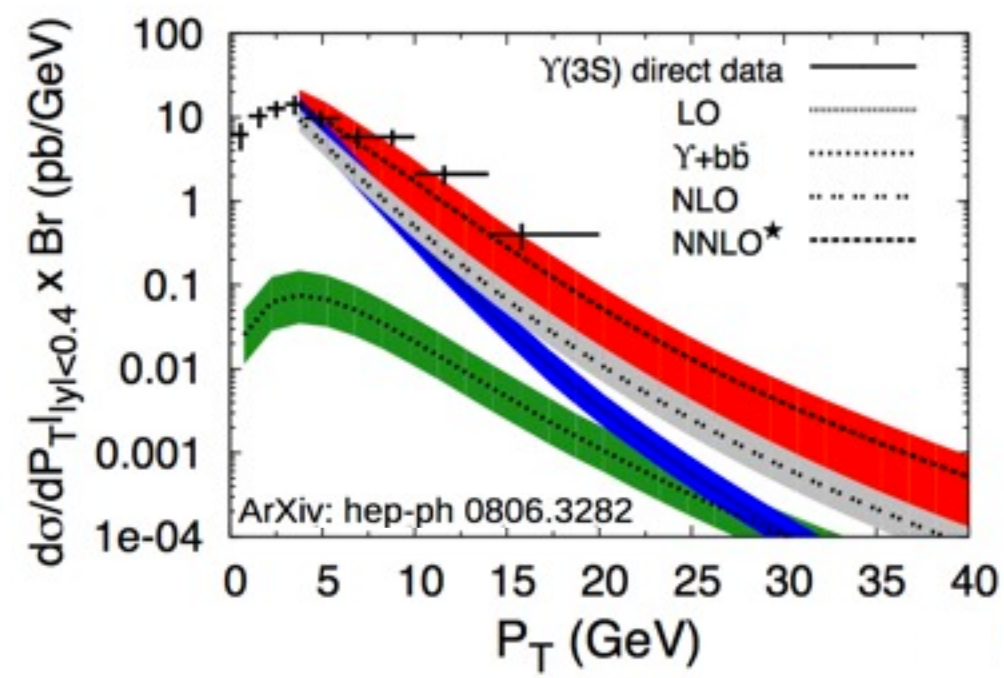
$$\Gamma(\Upsilon(nS)) \sim 20-50 \text{ KeV}$$

BR(Υ(1S)→μμ)=(2.48±0.05)%
BR(Υ(2S)→μμ)=(1.93±0.17)%
BR(Υ(3S)→μμ)=(2.18±0.21)%

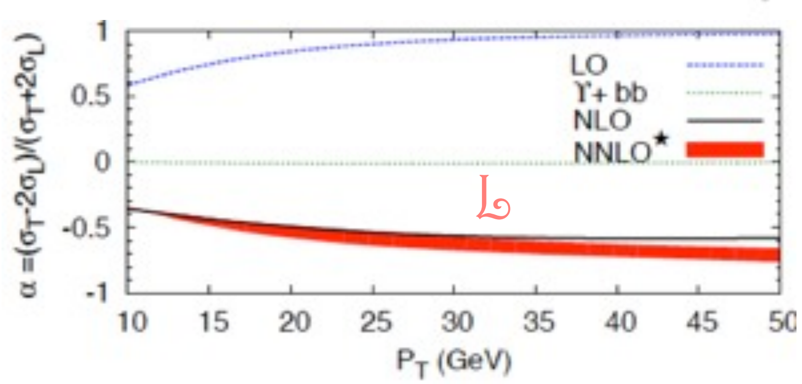
phenomenology

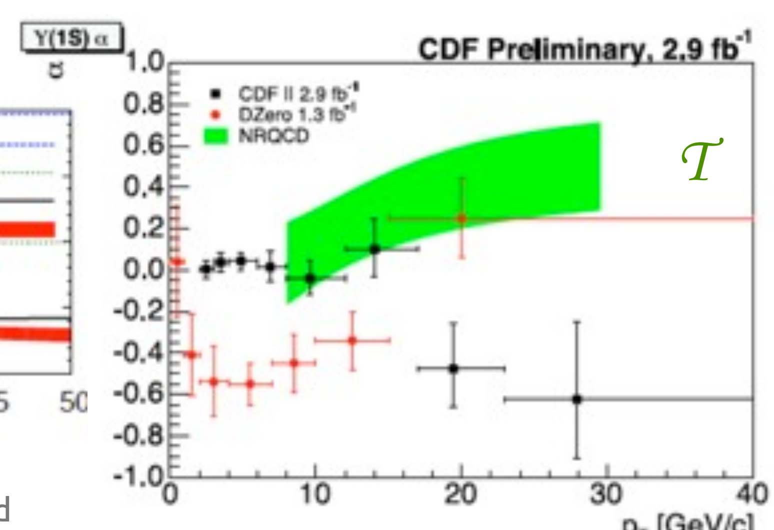
- heavy quarkonia constitute an ideal laboratory for testing interplay between perturbative and non-perturbative QCD
- bottomonium (and in general, quarkonium) production not satisfactorily understood
  - theoretically and experimentally puzzling
- no theory has simultaneously explained Tevatron measurements of both cross section and polarization
  - non-relativistic QCD (incl. color octet), color singlet model, color evaporation model, etc





(note: NNLO* is not a complete NNLO, possibility of large uncanceled logs)





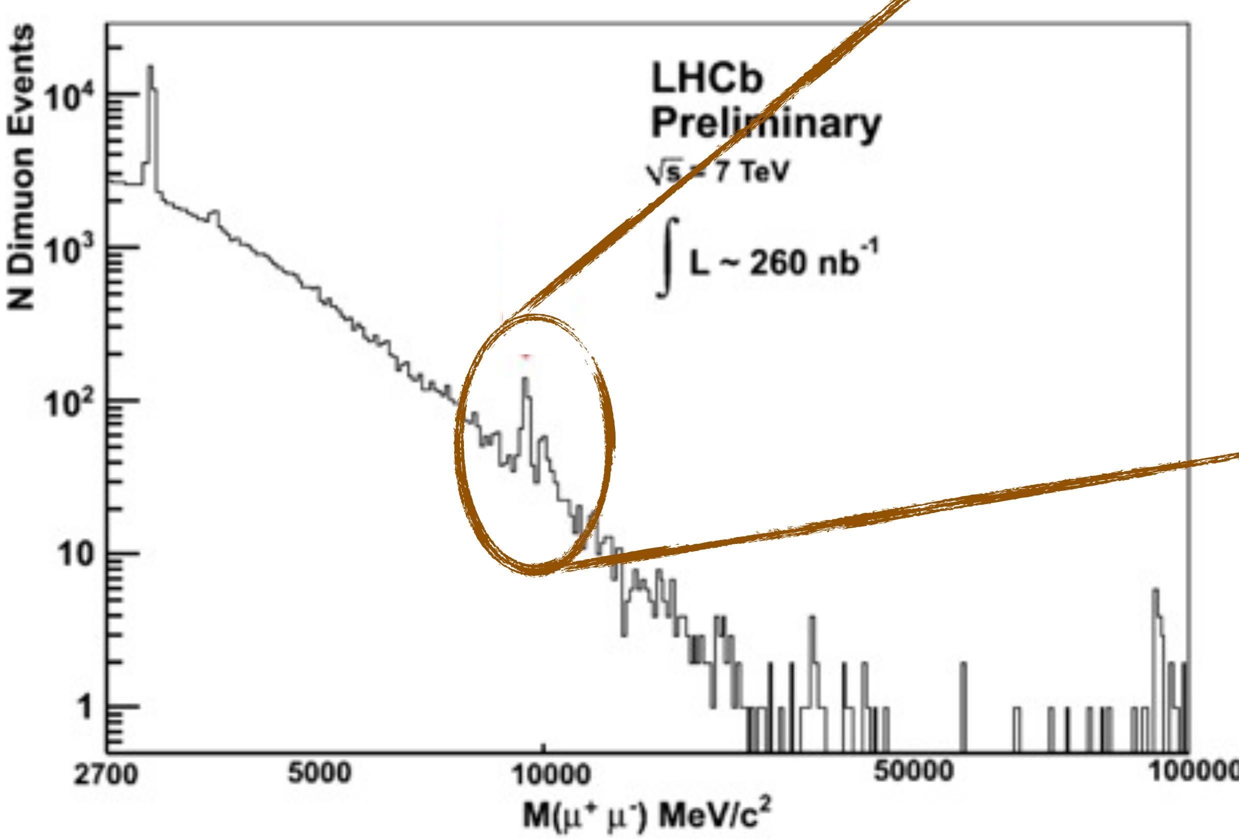
(note: drastic change of CSM predicted polarization from LO to NLO/NNLO*)

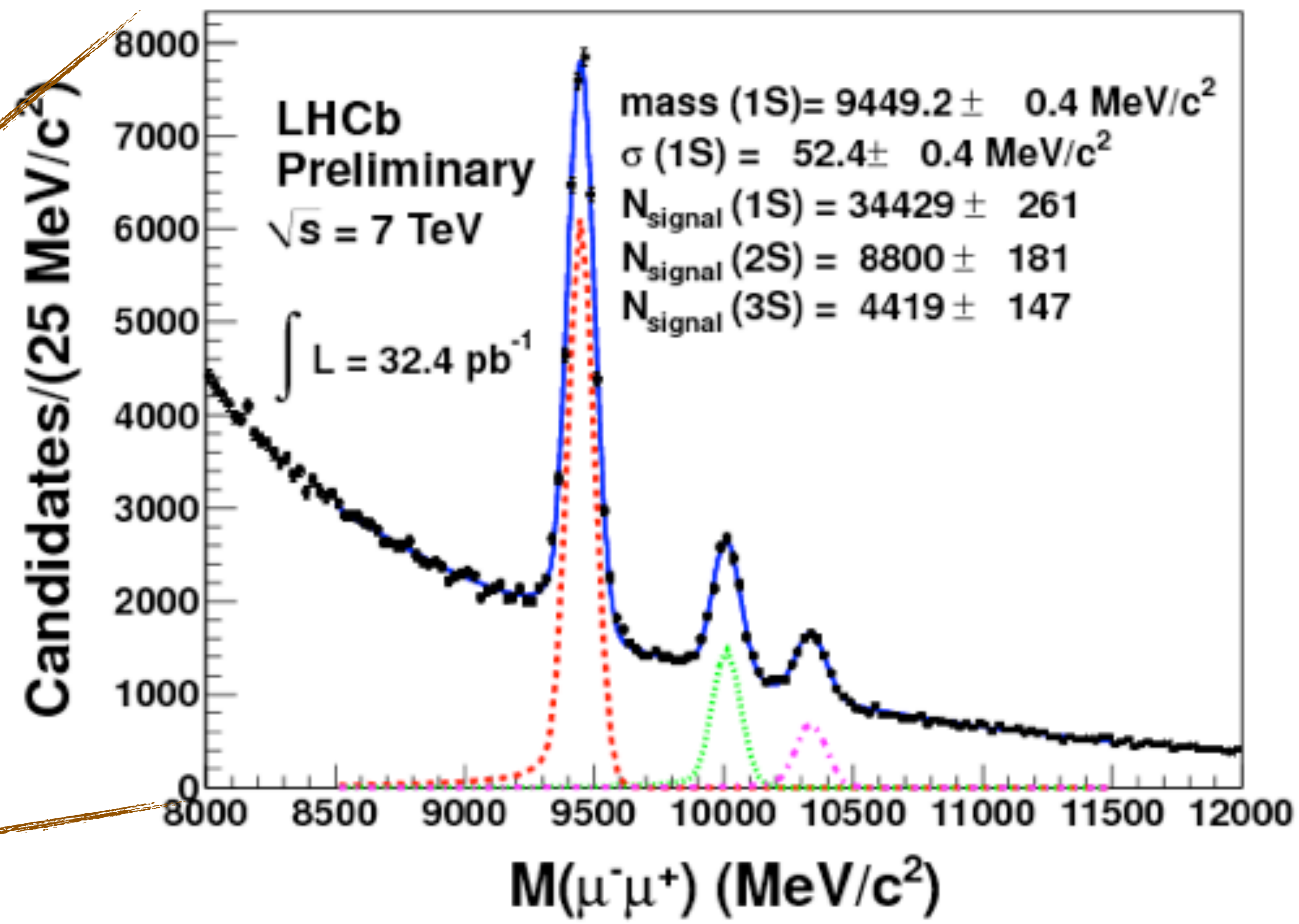
bottomonia at the LHC?

- phenomenology
  - large *b*-quark mass ⇨ non-relativistic effective approaches better realized
  - no feed-down from long-lived *b*-hadrons
- unprecedented energy regime
  - extended reach, *eg* probe p_T>20GeV, best discriminate between models
  - high cross section (and luminosity) ⇨ bottomonia produced copiously
  - allow new era of bottomonium precision measurements
- heavy ion
  - 1 month per year dedicated to heavy-ion physics run
  - cross sections ~50 times larger, energy density ~3 times higher than at RHIC ⇨ will allow first significant measurements of the Υ resonance family
  - improve overall understanding of the cold and hot nuclear matter effects
  - LHC calls for precision studies of bottomonia at high temperature

di-lepton signals

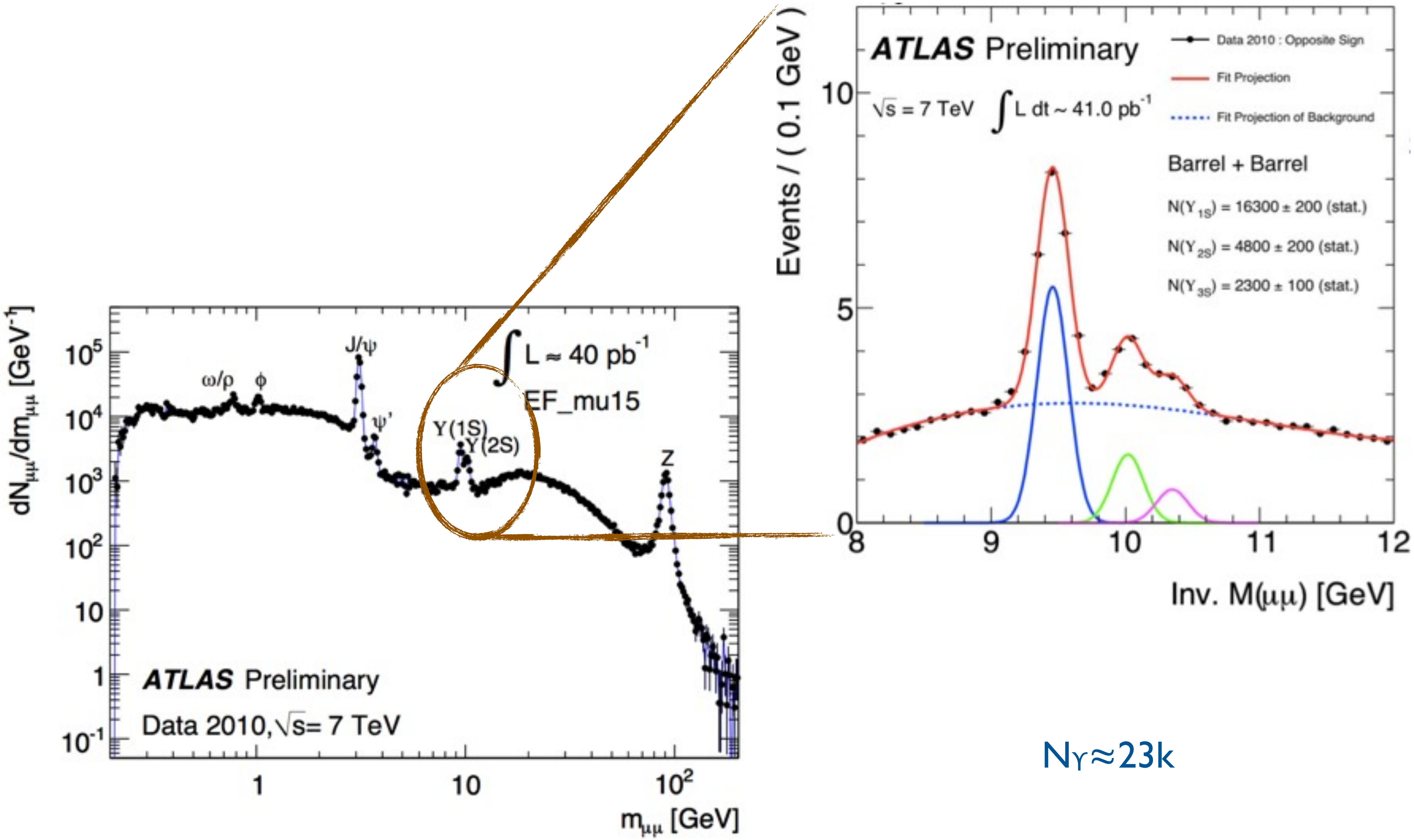
LHCb





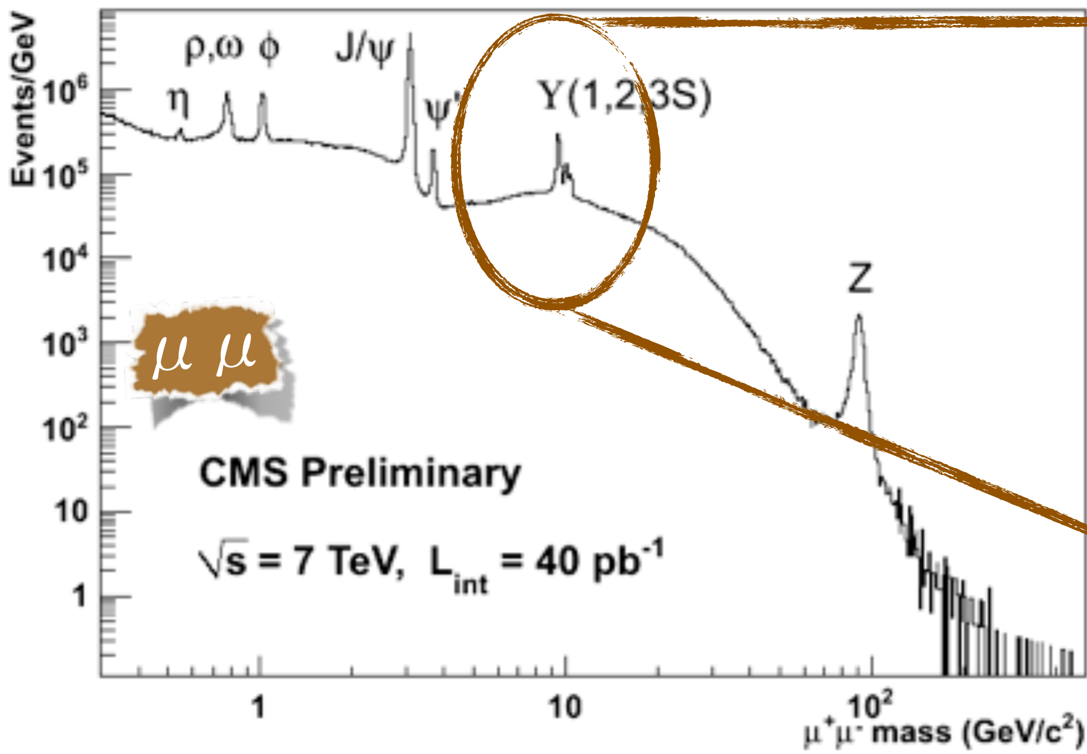
$N_\Upsilon \approx 48k$

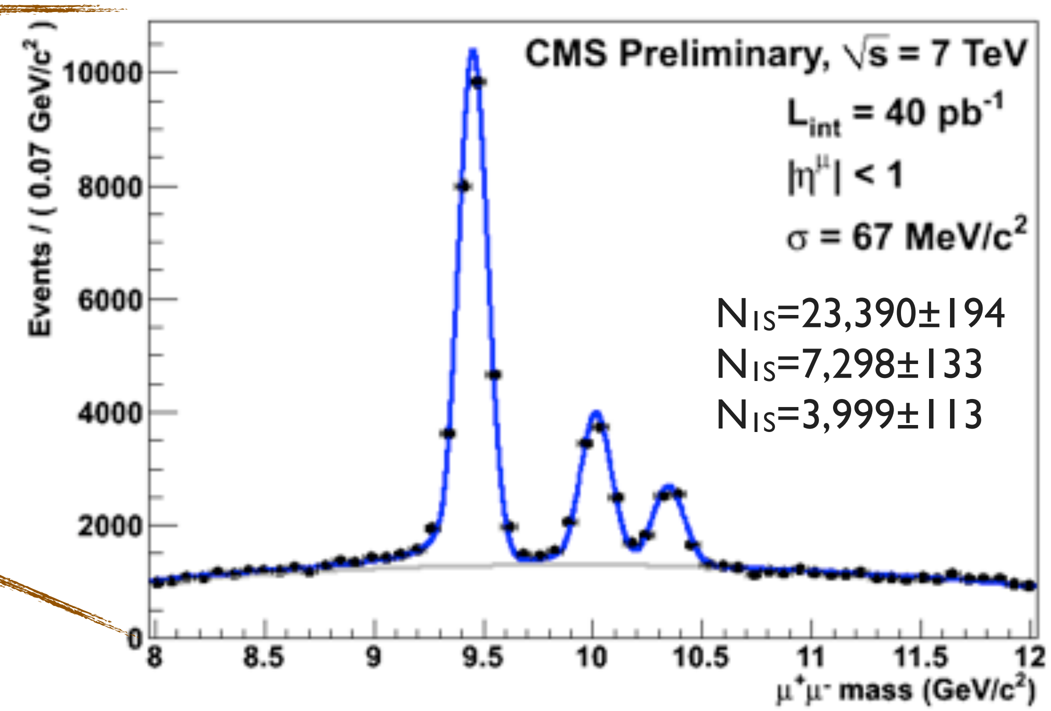
ATLAS



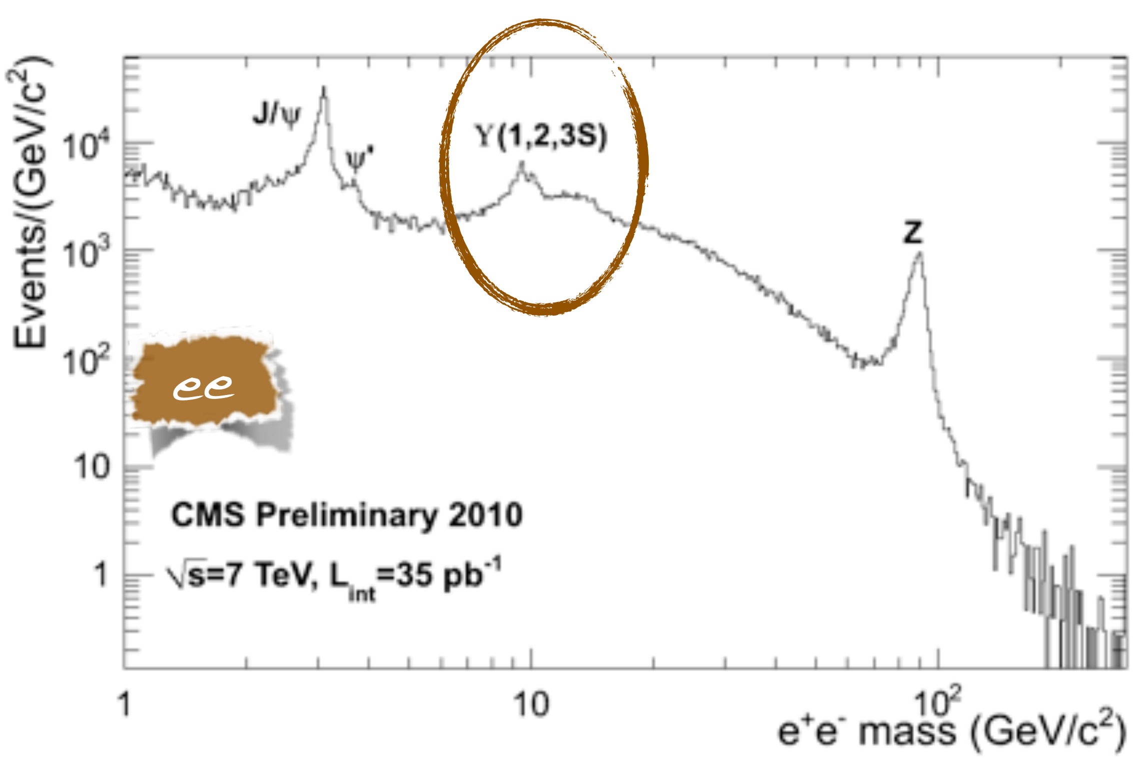
$N_{\Upsilon} \approx 23k$

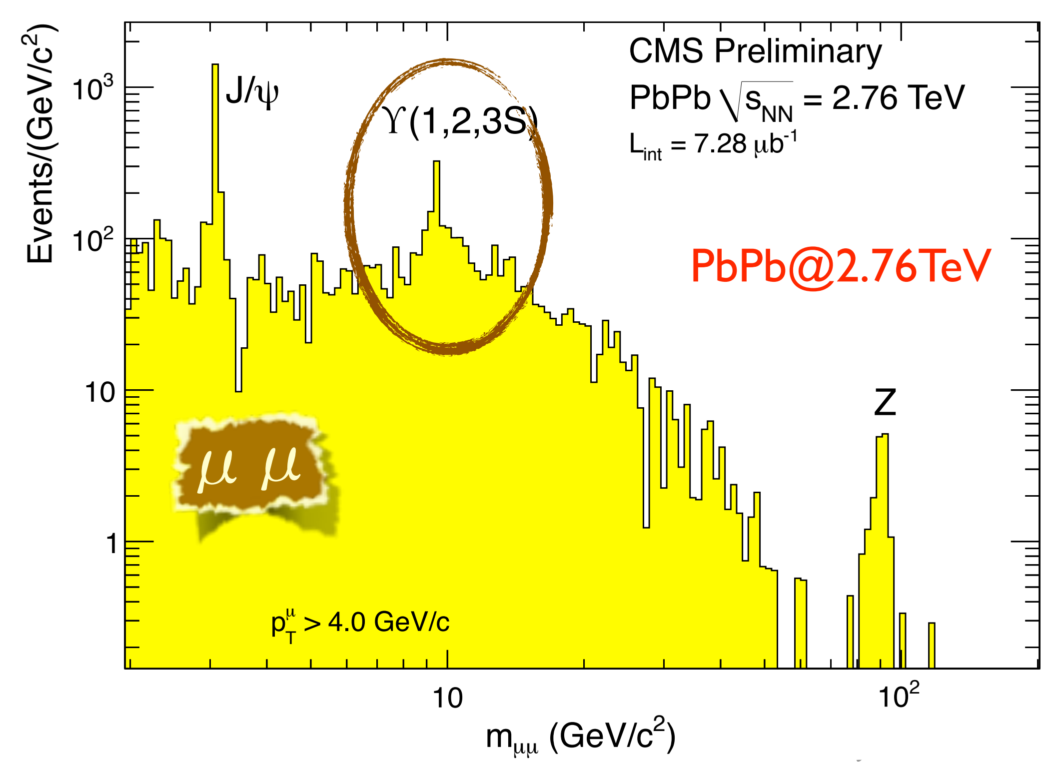
CMS



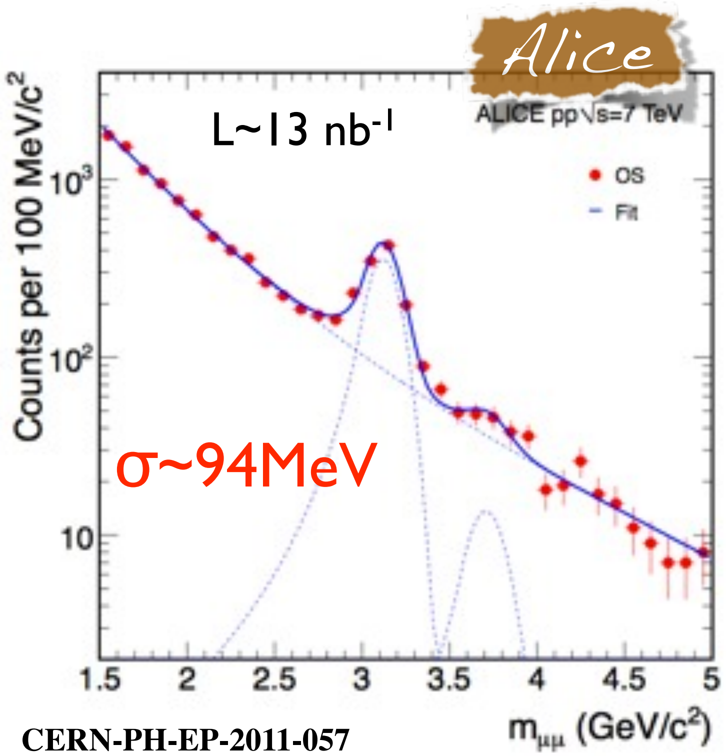


$N_{\Upsilon} \approx 138k$ ($|\eta|<2.4$)

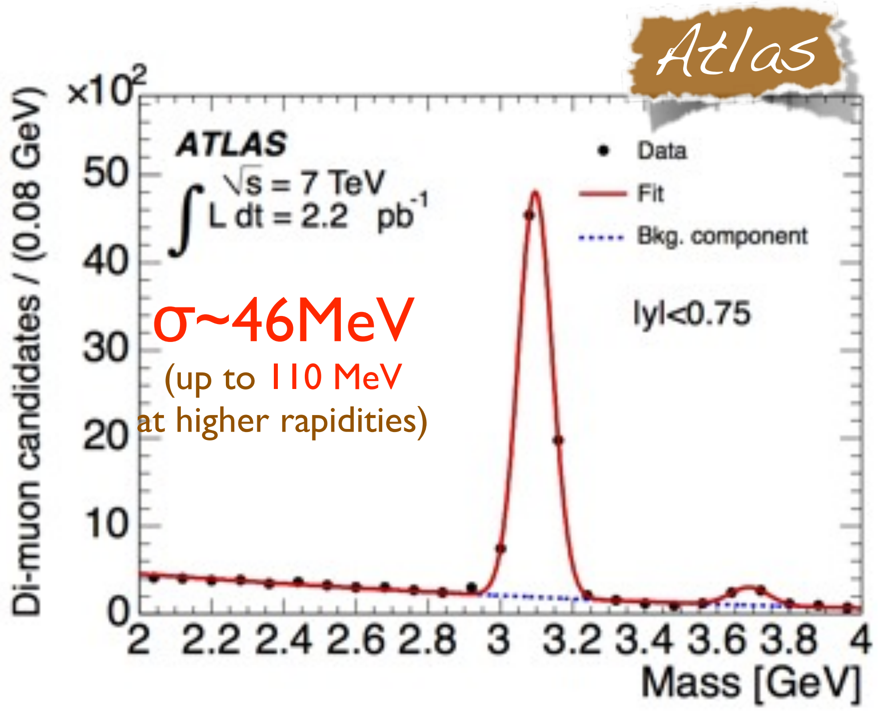




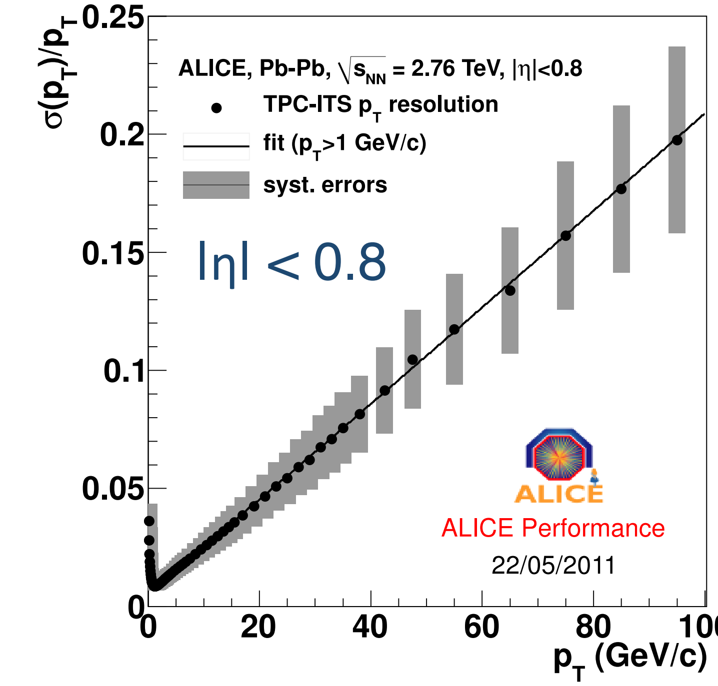
momentum/mass resolution

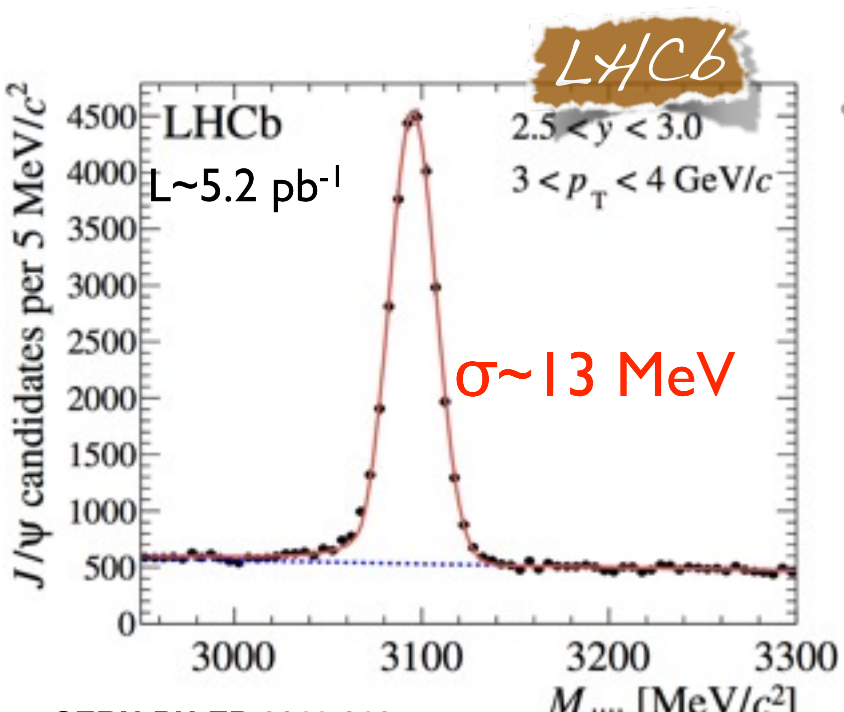


CERN-PH-EP-2011-057

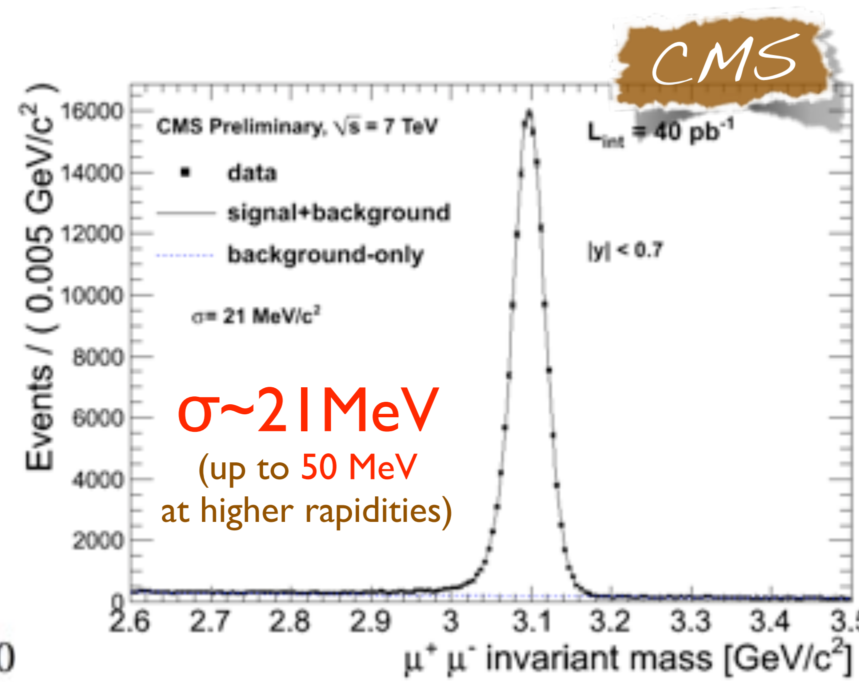


CERN-PH-EP-2011-041

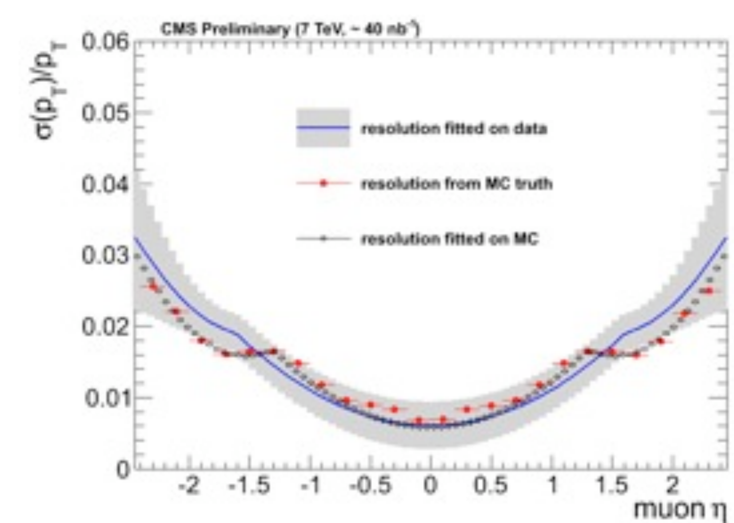




CERN-PH-EP-2011-018

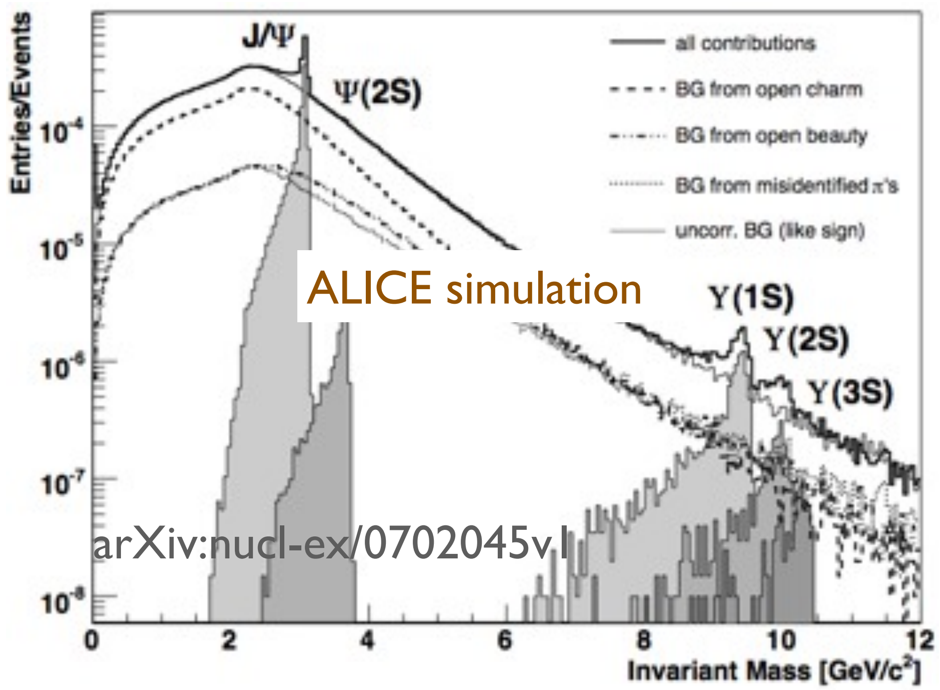


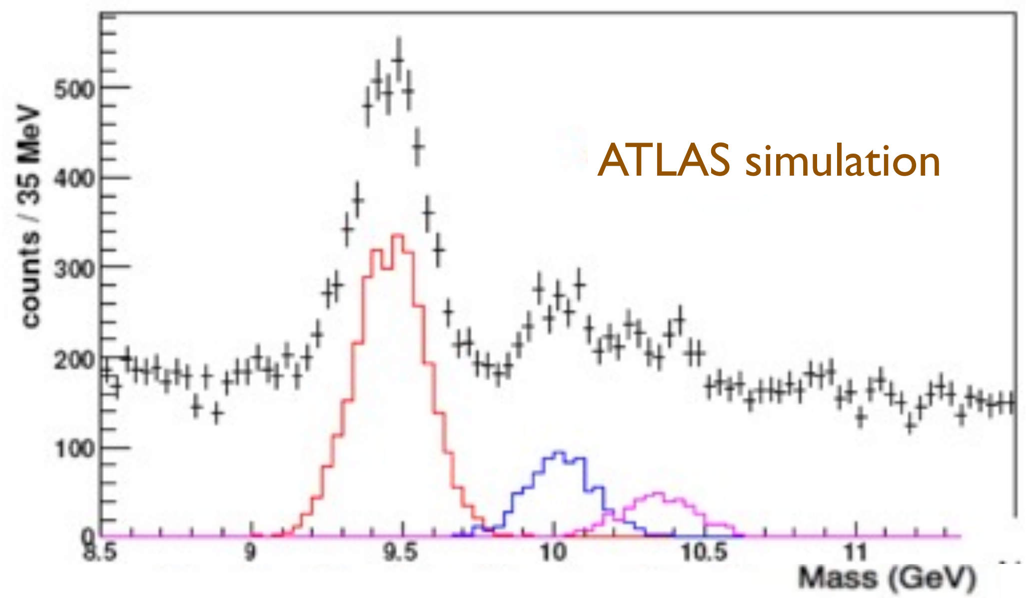
CERN-PH-EP/2010-046

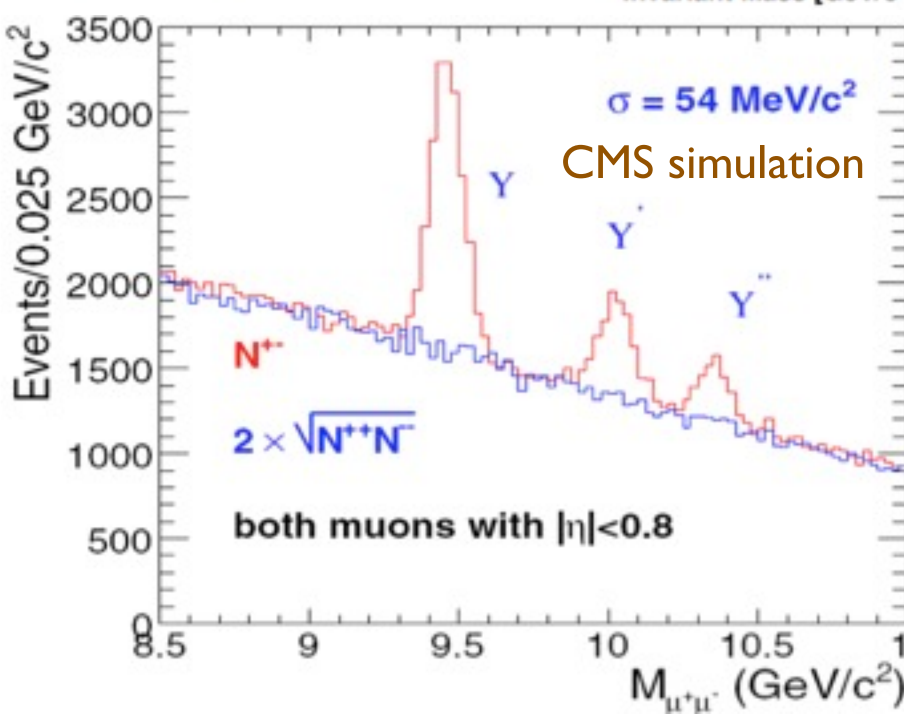


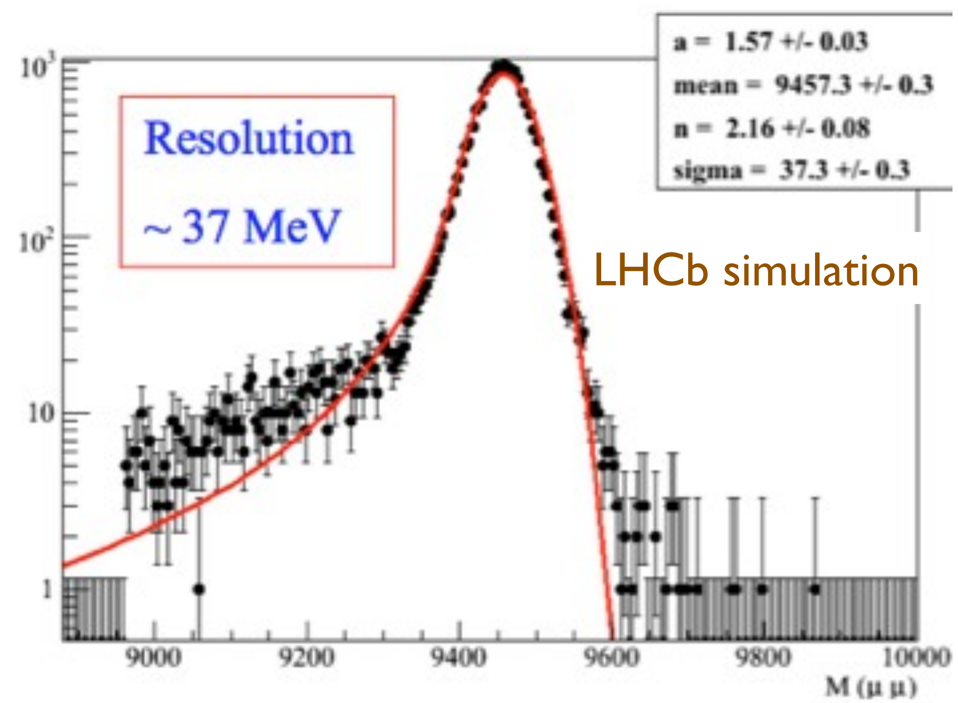
CMS-PAS-TRK-10-004

prior expectations (before LHC startup)







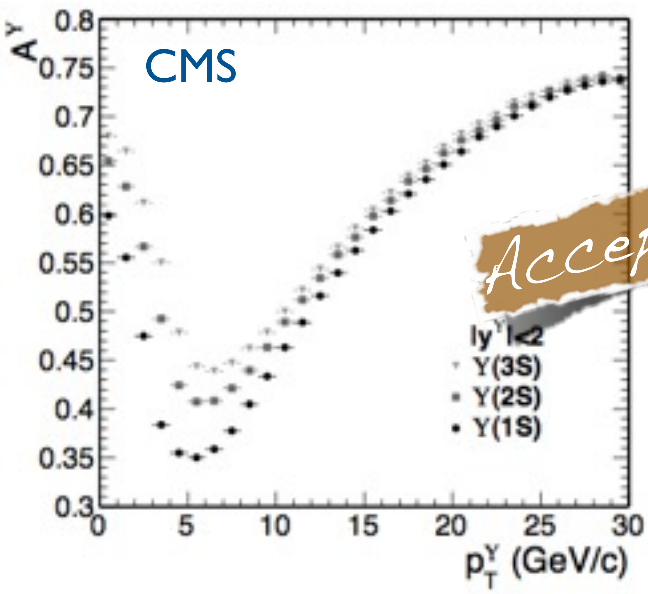


pp @ 7TeV

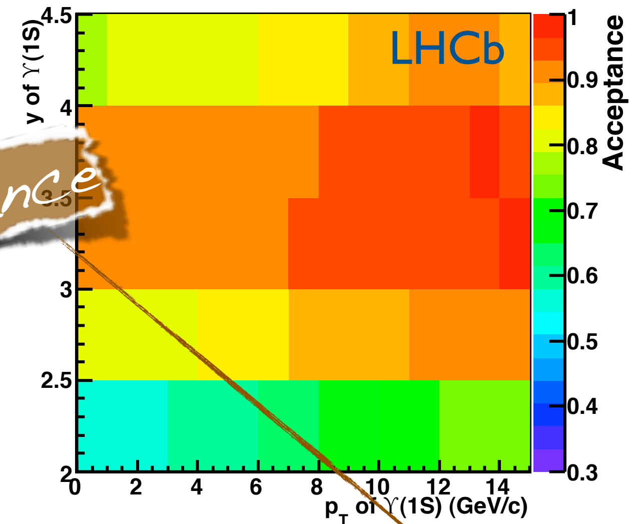
- LHCb-CONF-2011-016, 32pb^{-1}
- CMS-BPH-10-003 (arXiv:1012.5545,PRD), 3pb^{-1}

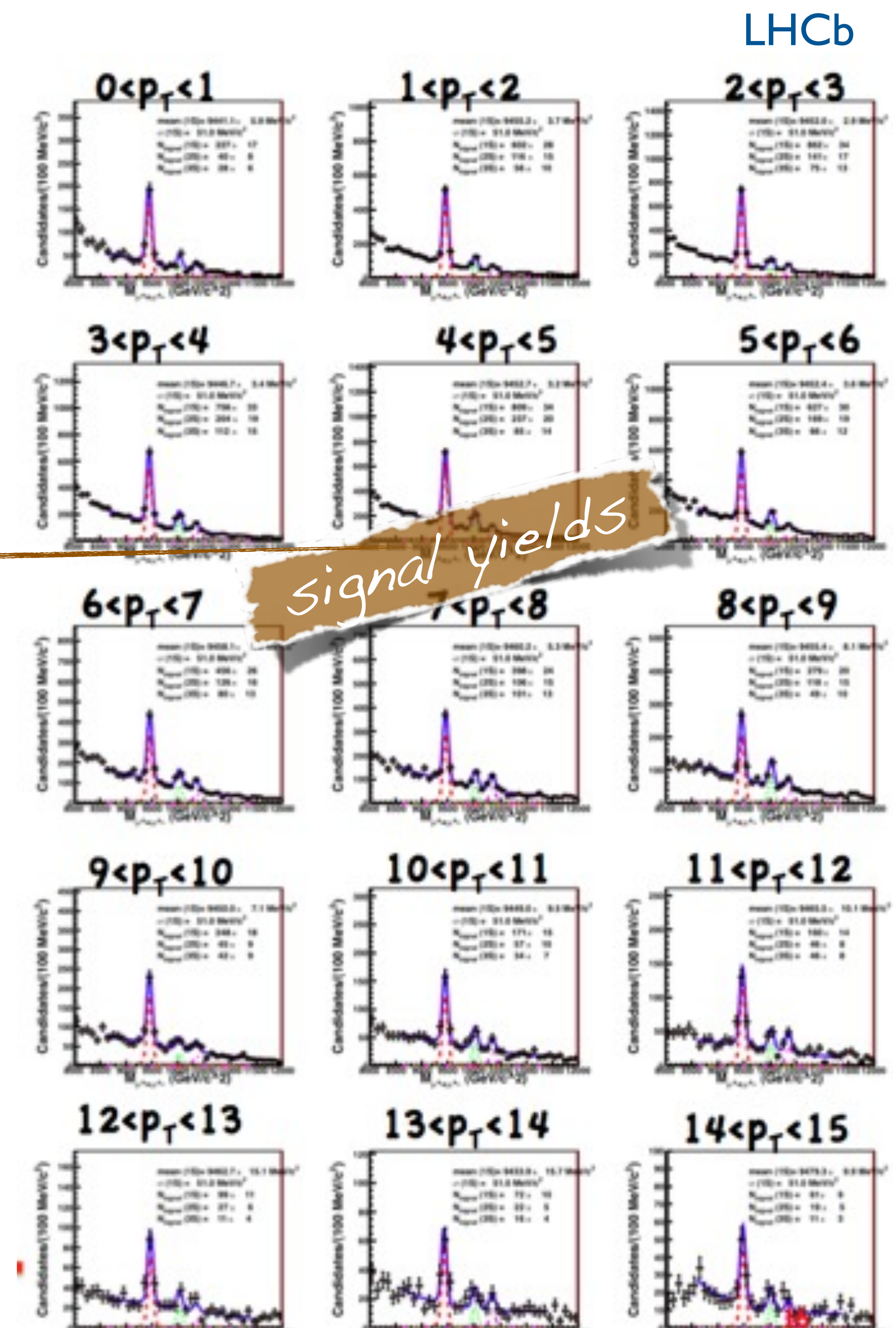
➪ see also talks by B.Akgun and G.Sabatino
on Tuesday parallel session Quarkonia/3

cross-section ingredients



Acceptance

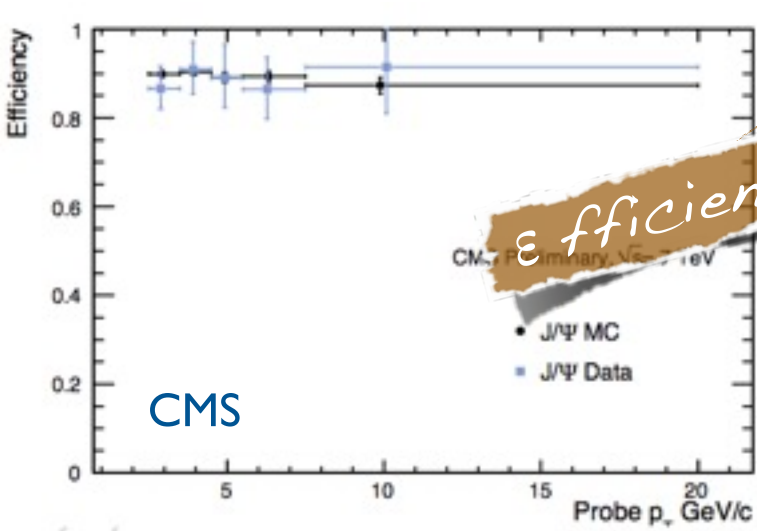


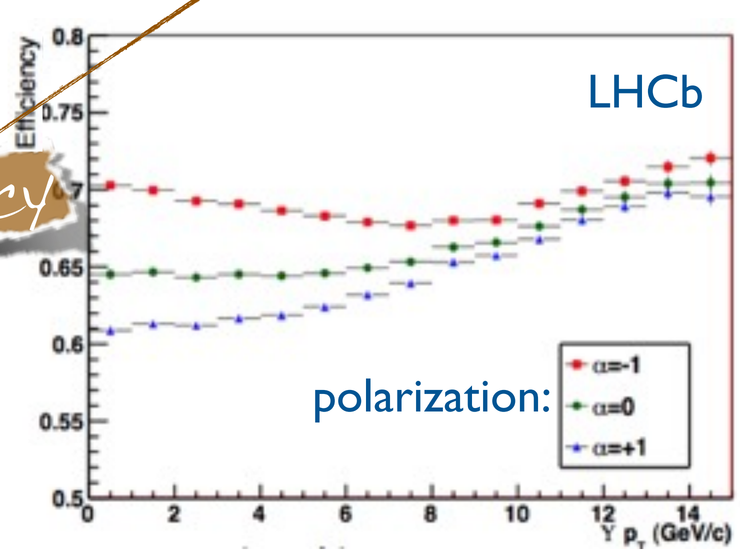


signal yields

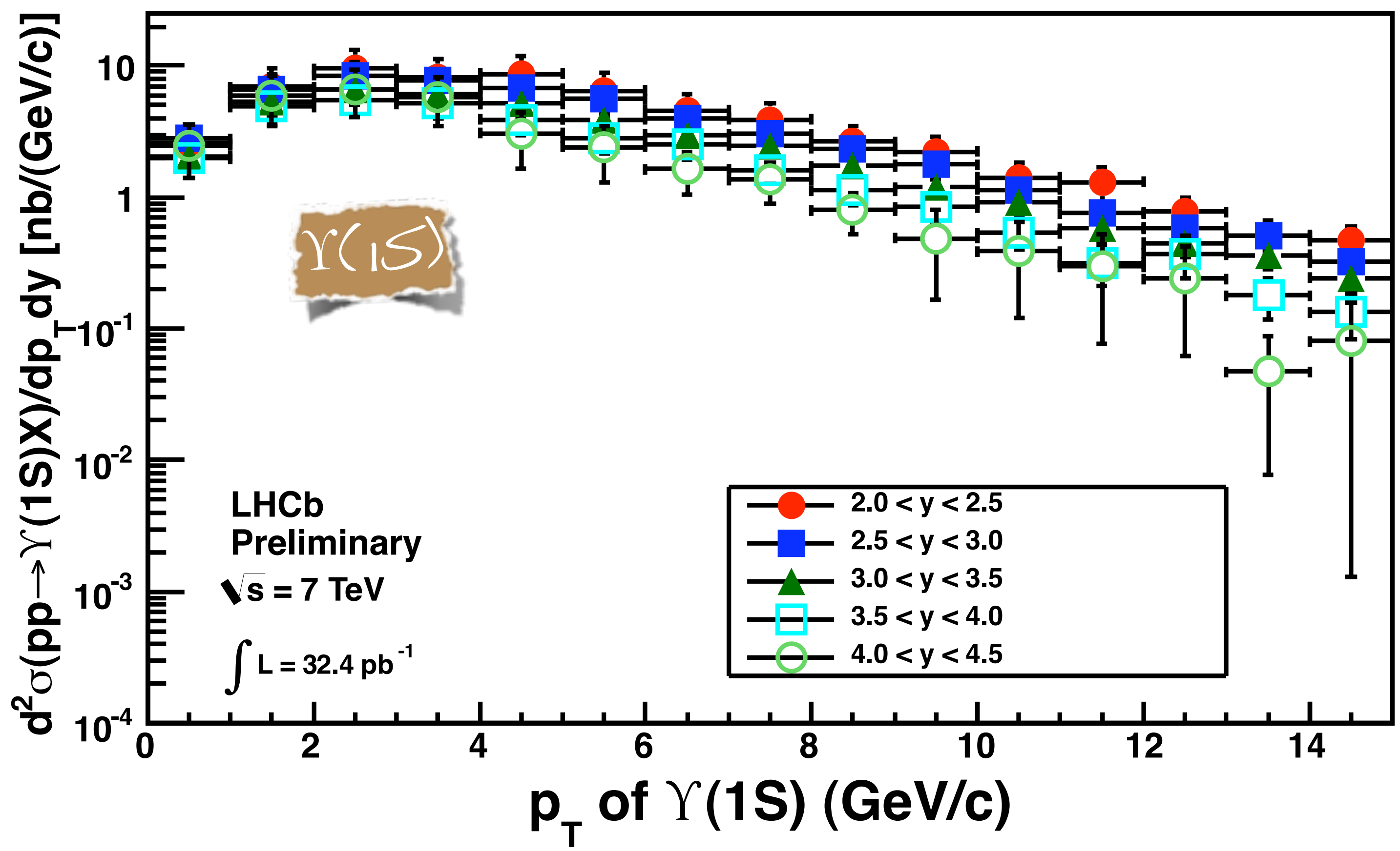
$$\frac{d^2\sigma}{dp_T dy} \cdot \mathcal{B}\left(\Upsilon(nS) \to \mu^+\mu^-\right) = \frac{N^{\rm fit}_{\Upsilon(nS)}(\mathcal{A},\varepsilon)}{\mathcal{L}\cdot \Delta p_T \cdot \Delta y}$$

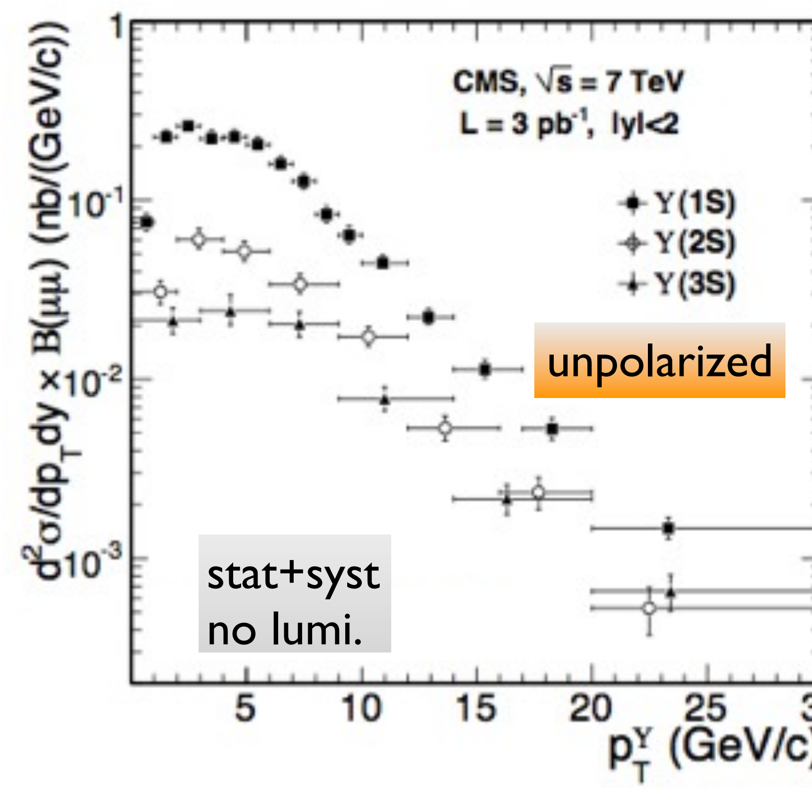
ε efficiency

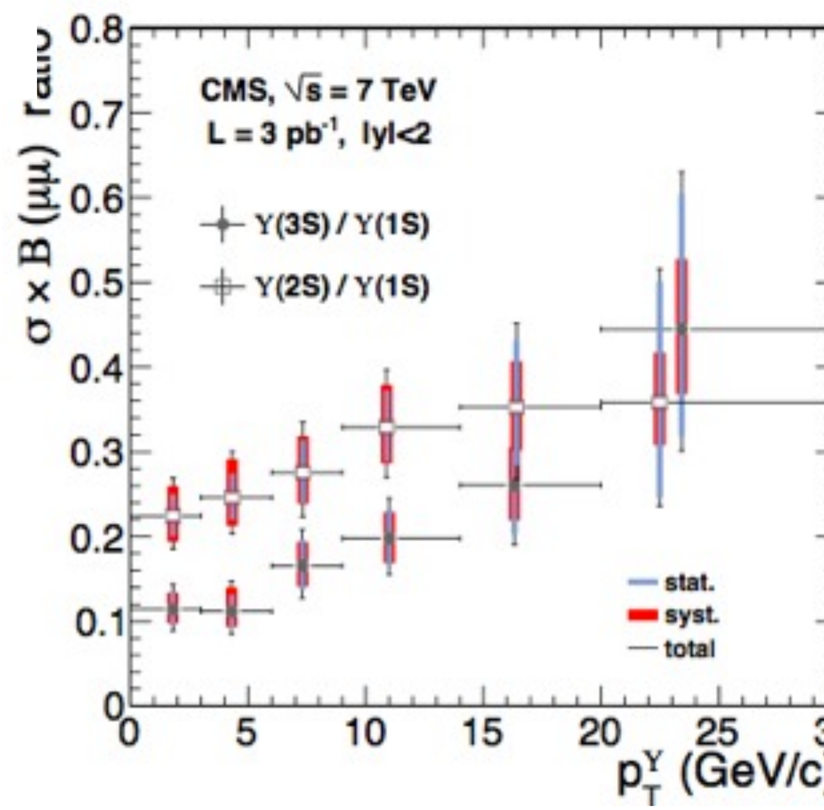




Υ(nS) differential cross sections







LHCb

$$\sigma(pp \to \Upsilon(1S)X; 0 < p_T < 15\,\mathrm{GeV}/c, 2 < y < 4.5) = 108.3 \pm 0.7^{+30.9}_{-25.8}\ \mathrm{nb}$$

CMS (unpolarized case) (|y|<2)

$$\sigma(\mathrm{pp} \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 7.37 \pm 0.13(\mathrm{stat.})^{+0.61}_{-0.42}(\mathrm{syst.}) \pm 0.81(\mathrm{lumi.})\ \mathrm{nb}$$

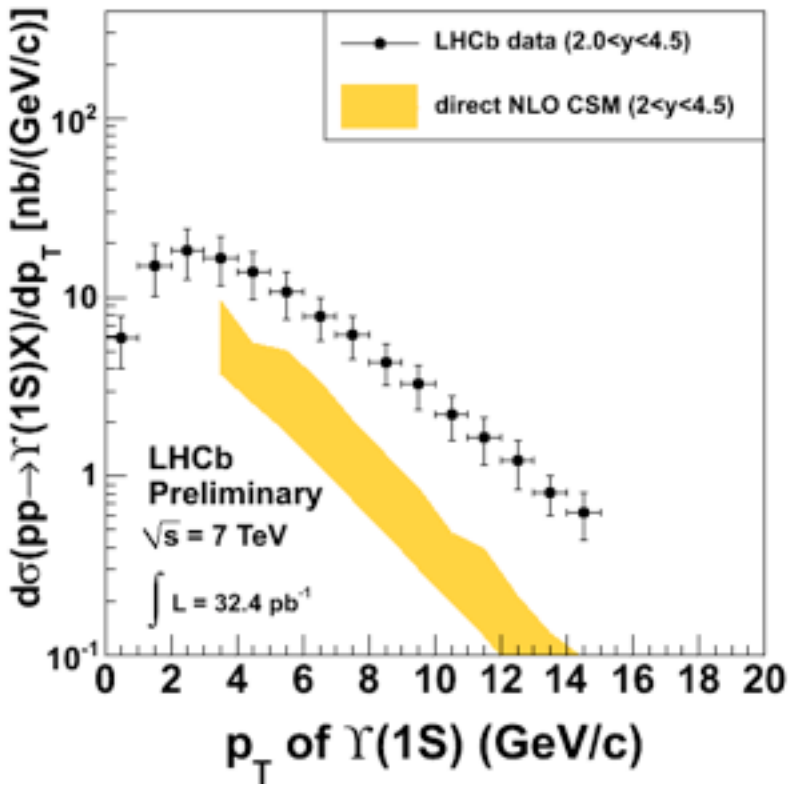
$$\sigma(\mathrm{pp} \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 1.90 \pm 0.09(\mathrm{stat.})^{+0.20}_{-0.14}(\mathrm{syst.}) \pm 0.24(\mathrm{lumi.})\ \mathrm{nb}$$

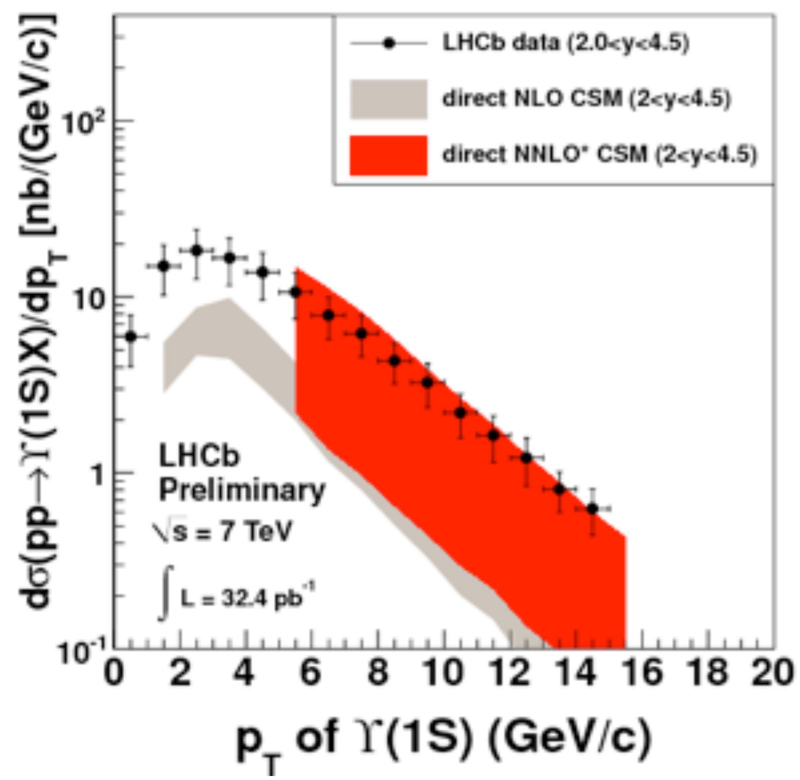
$$\sigma(\mathrm{pp} \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 1.02 \pm 0.07(\mathrm{stat.})^{+0.11}_{-0.08}(\mathrm{syst.}) \pm 0.11(\mathrm{lumi.})\ \mathrm{nb}$$

Υ(2S)/Υ(1S): 0.26±0.02±0.04
Υ(3S)/Υ(1S): 0.14±0.01±0.02

comparison: theory

P. Artoisenet, PoS ICHEP 2010 (2010) 192.

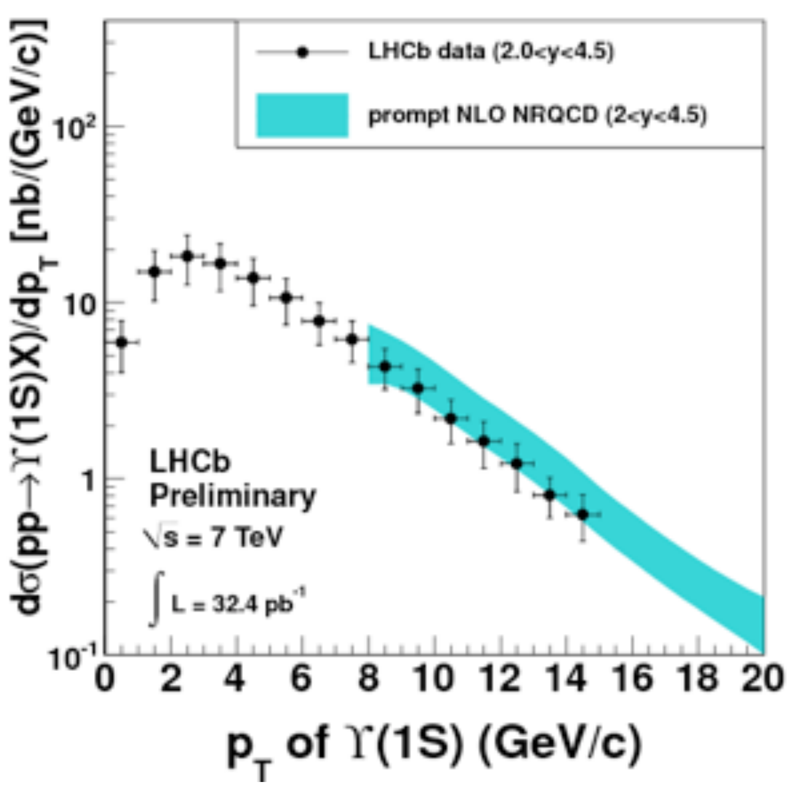


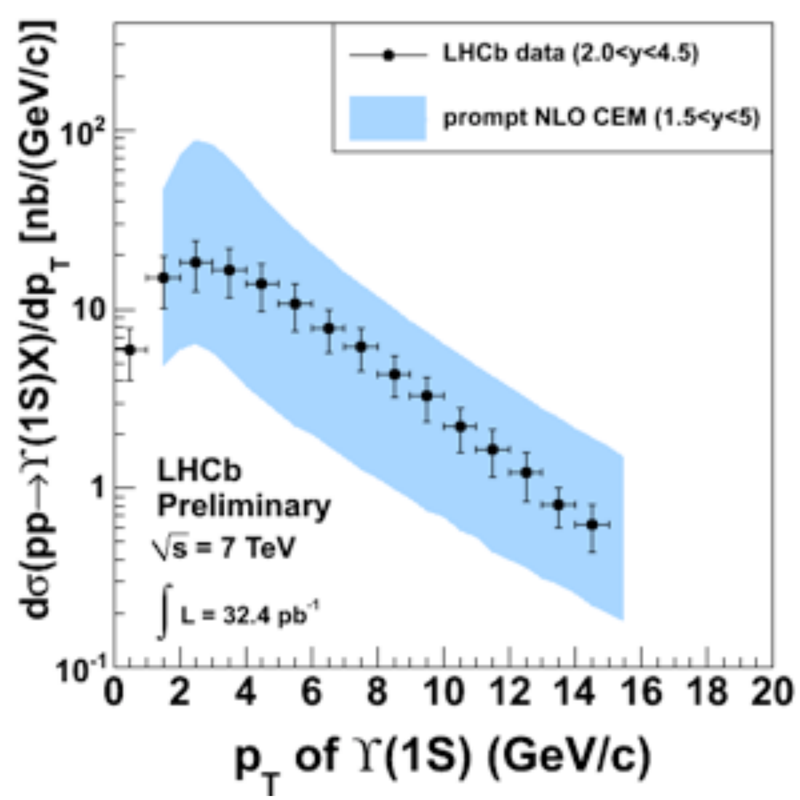


J.-P. Lansberg, Eur. Phys. J. C 61 (2009) 693

P. Artoisenet et al, PRL101,152001,2008

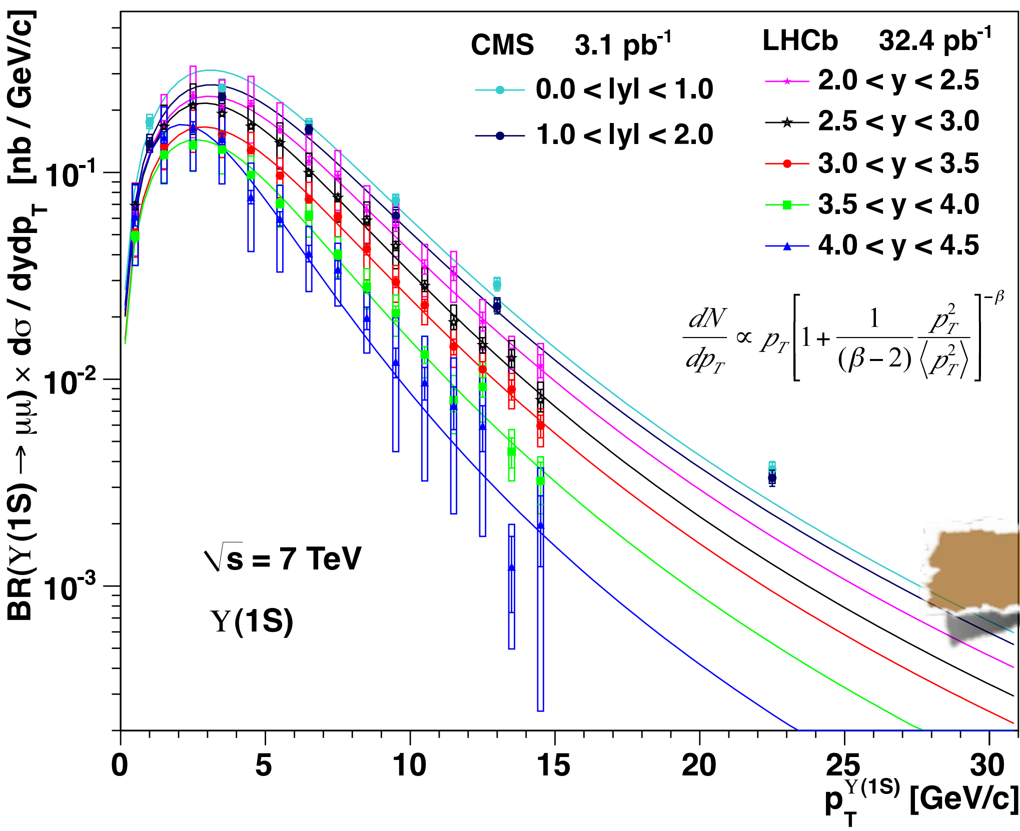
Y. Q. Ma, K. Wang and K. T. Chao, Phys. Rev. Lett. 106 (2011) 042002.

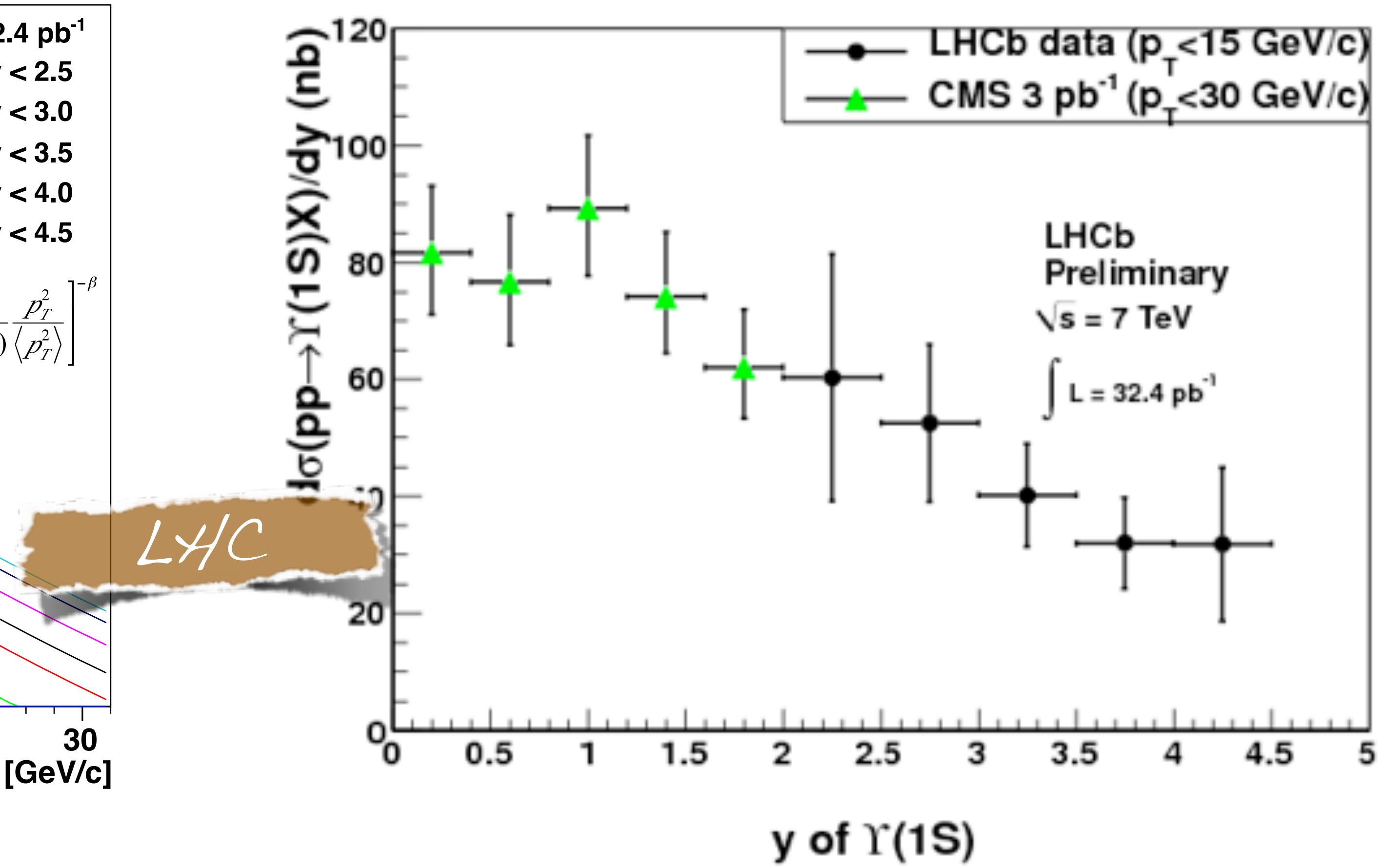


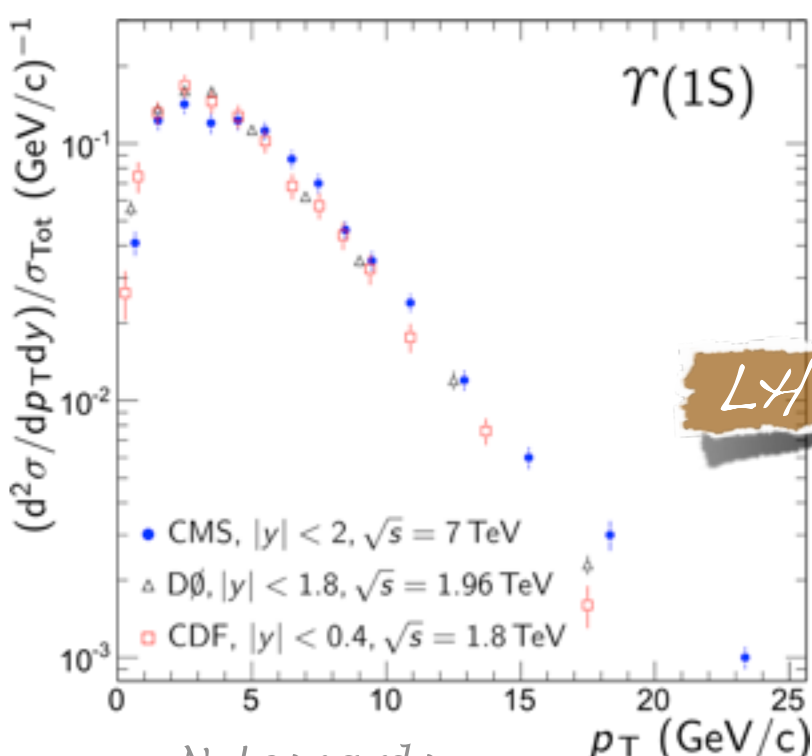


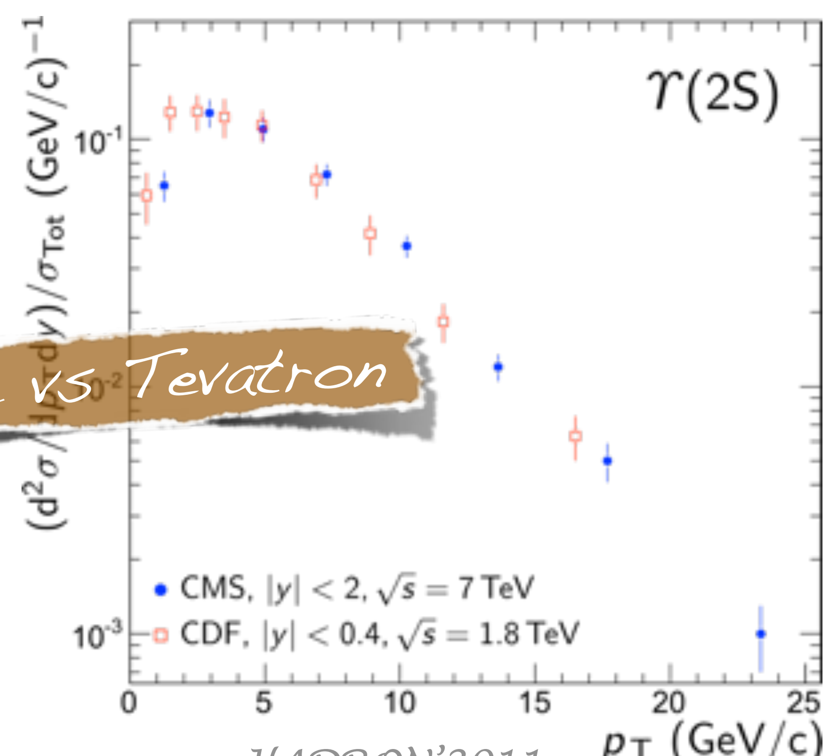
A. D. Frawley, T. Ullrich and R. Vogt, Phys. Rep. 462 (2008) 125.

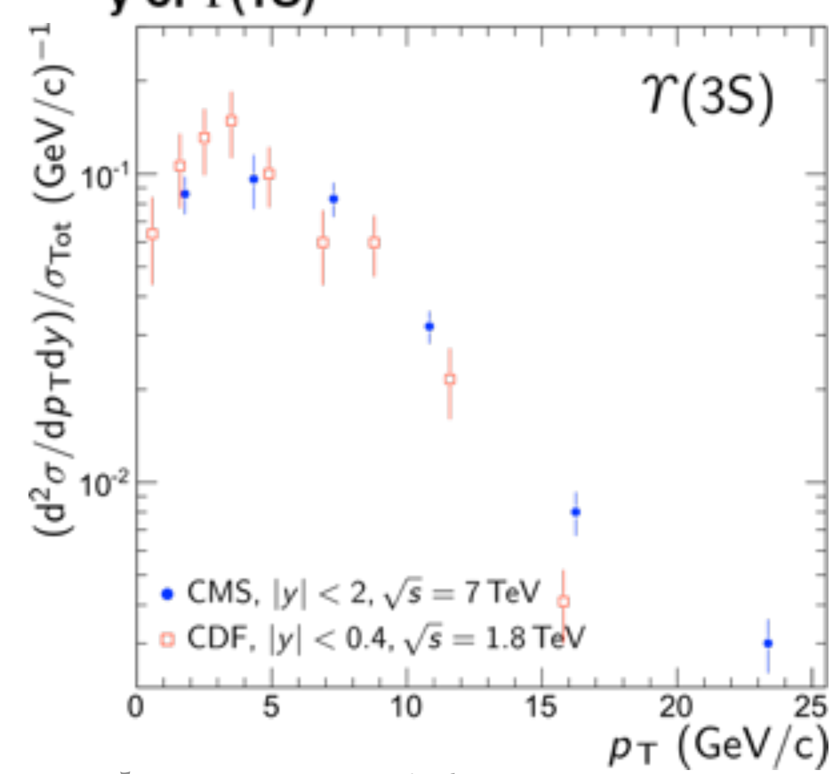
comparison: experiment



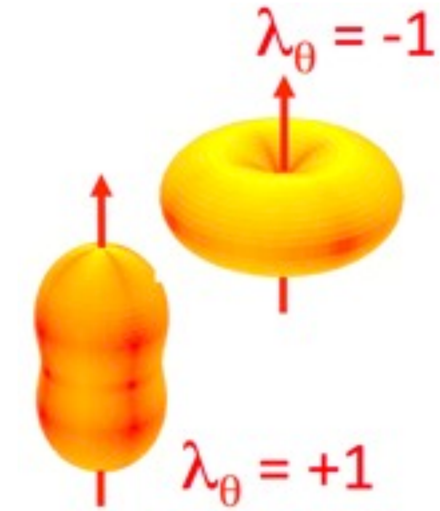








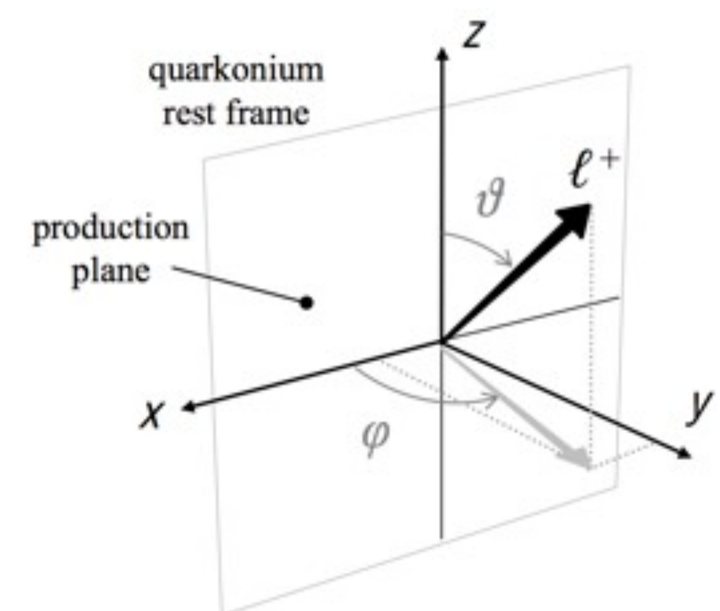
polarization

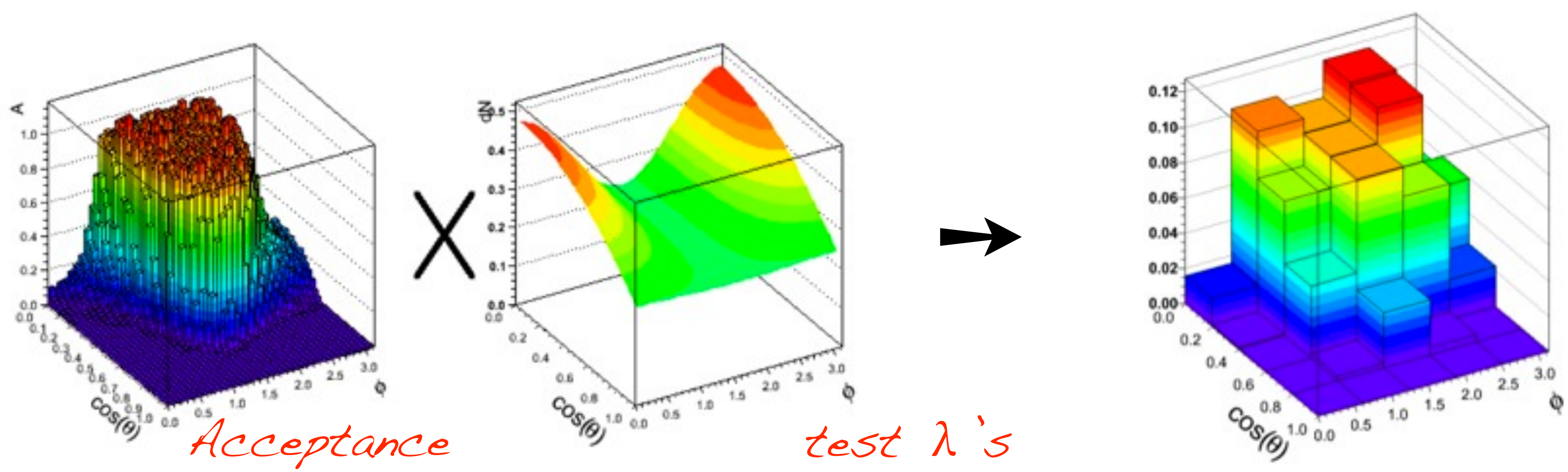


- detector acceptance sensitive to unknown polarization ➪ σ(ϒ) variations of about 20%
- measure full angular distribution of leptons

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta cos^2\theta + \lambda_{\theta\phi} sin2\theta cos\phi + \lambda_\phi sin^2\theta cos2\phi$$

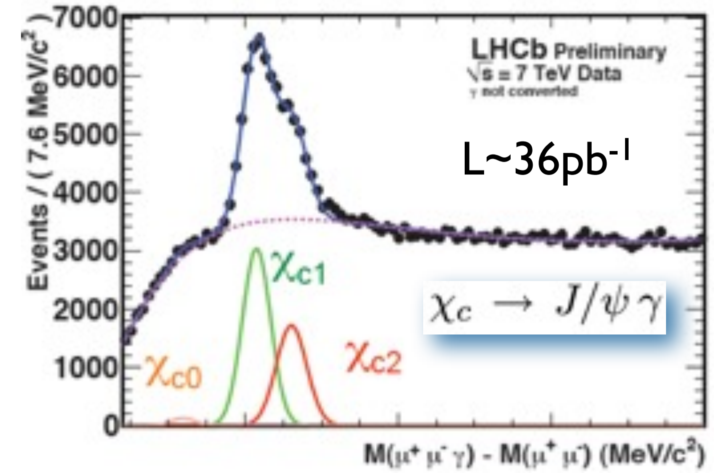
- in complementary reference frames
- also frame independent $\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$
- results binned in p_T and rapidity
- measurements being currently finalized

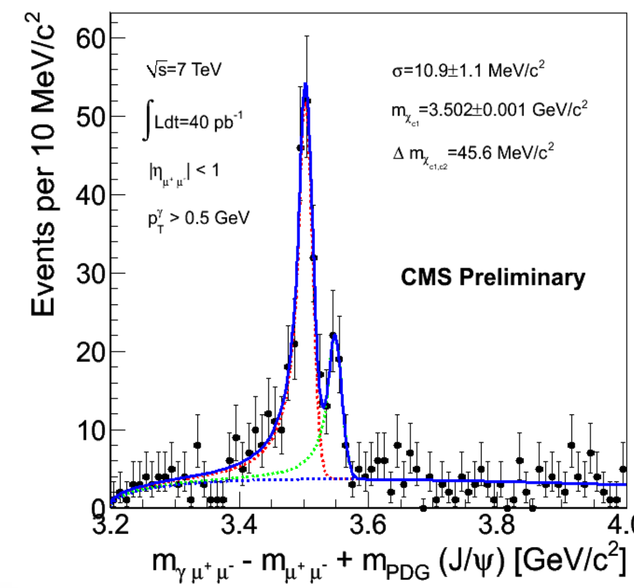


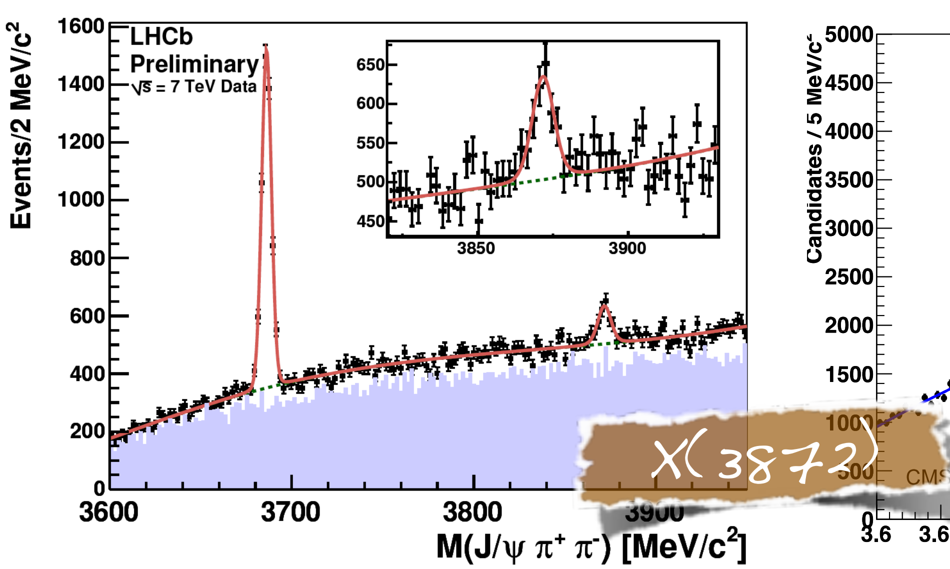


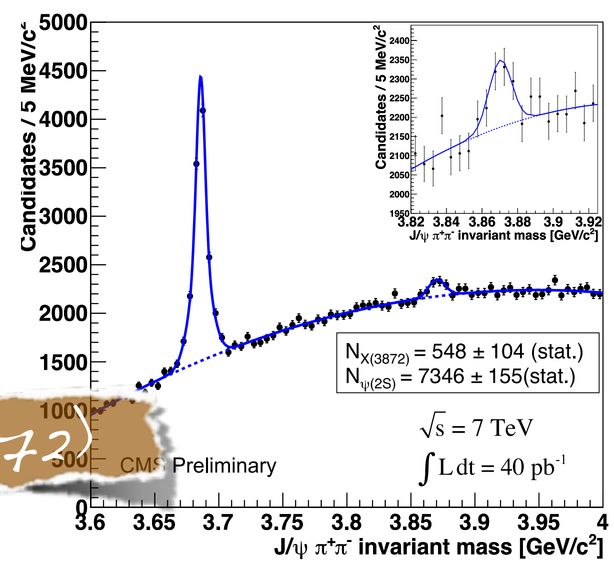
other measurements, prospects

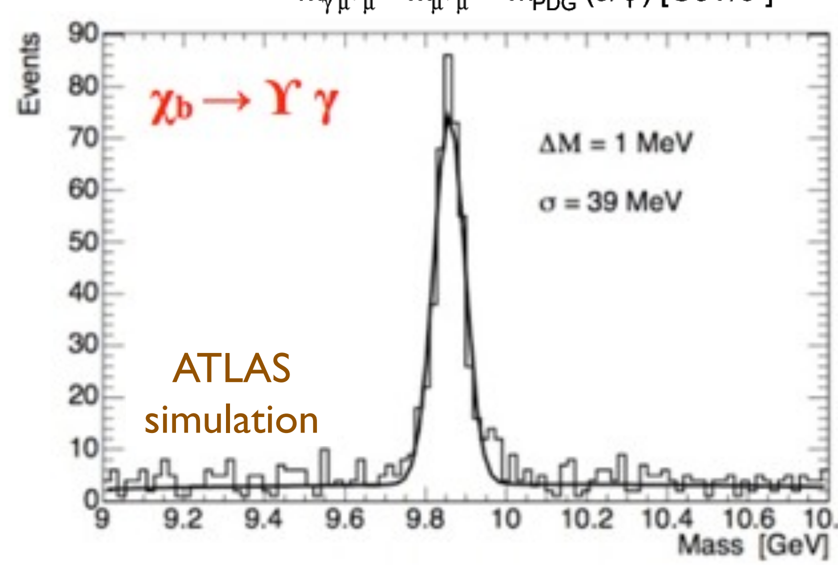
- prompt bottomonium reconstruction includes feeddown from higher states
  - eg 40-50% of Υ(1S) production from decays of excited 2S,2P,3S states [CDF, PRL84 (2000) 2094]
  - desirable to separate direct production
  - eg reconstruct $\chi_b \rightarrow \Upsilon\,\gamma$ decays
    - (plots show examples already achieved for charmonia)
- search for exotica, bottomonia-like states?
- ➩ more data required











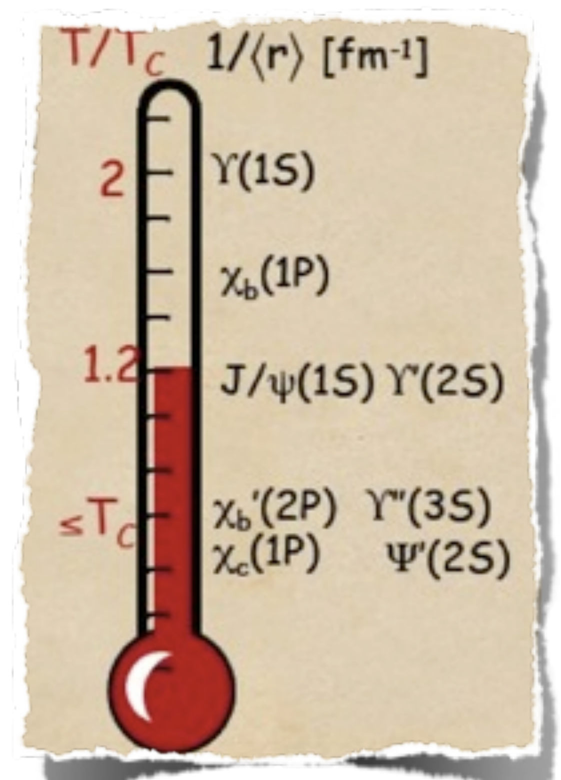
PbPb @2.76TeV

- CMS-PAS-HIN-10-006
- CMS-HIN-11-007 (arXiv:1105.4894, submitted PRL)

a.k.a. Upsilon suppression.

bottomonia as QGP probe

- at high temperatures, strongly interacting matter becomes a plasma of quarks and gluons
- suppression of quarkonia is a classical prediction of QGP signature
  - color screening of the binding potential [**T.Matsui, H.Satz PLB178, 416 (1986)**]
  - suppression pattern indicates the medium temperature (*'QGP thermometer'*)
  - role of cold nuclear matter effects also emphasized at SPS and RHIC
- bottomonium measurements at LHC help characterize the dense matter produced in heavy-ion collisions beyond the SPS and RHIC charmonium results
  - the Υ family of states is an expected powerful probe
  - Υ(1S) is the most tightly bound state ➪ last to melt down
  - provide 3 different states/handles for probing the hot medium
- quantitative bottomonium measurements accessible for first time
  - large production rates ➪ sizable datasets
  - exploit excellent mass resolution



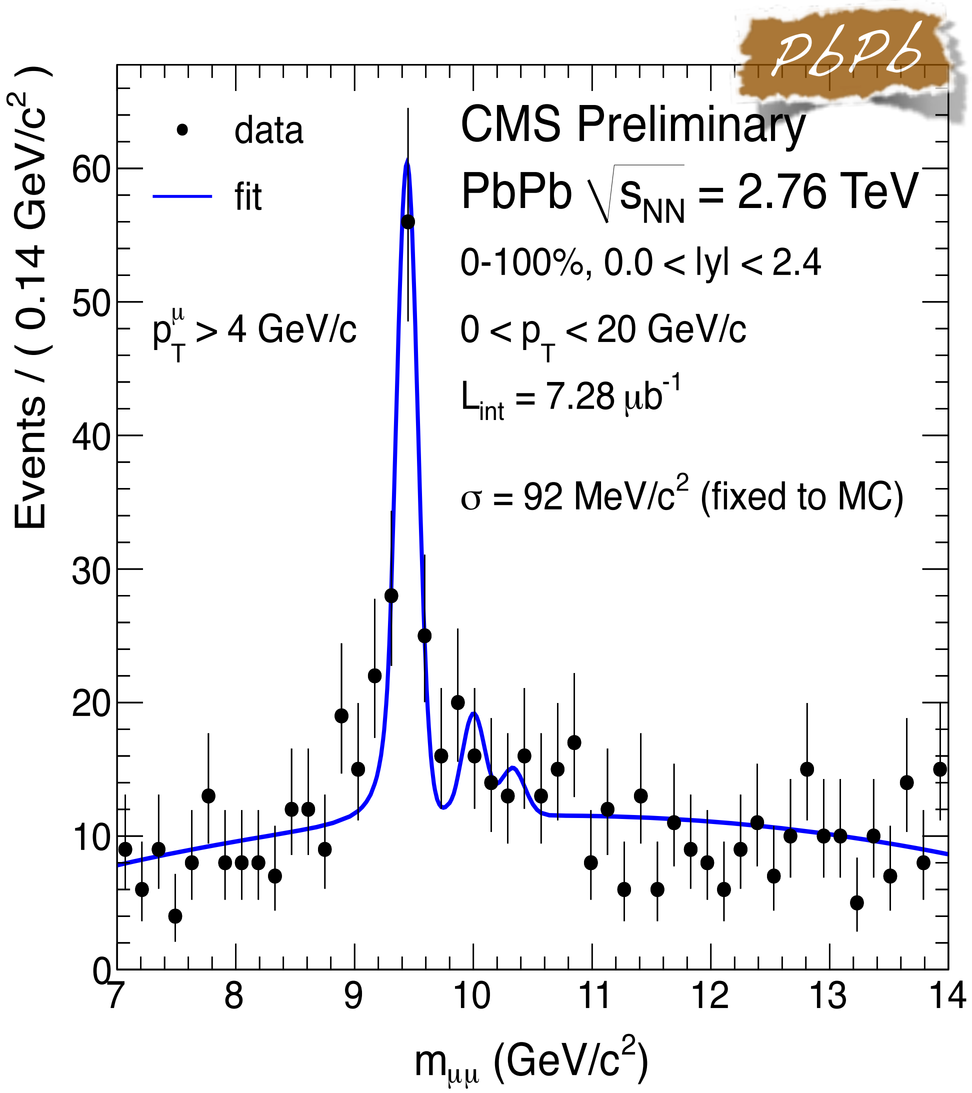
Tc ~ 150-170MeV

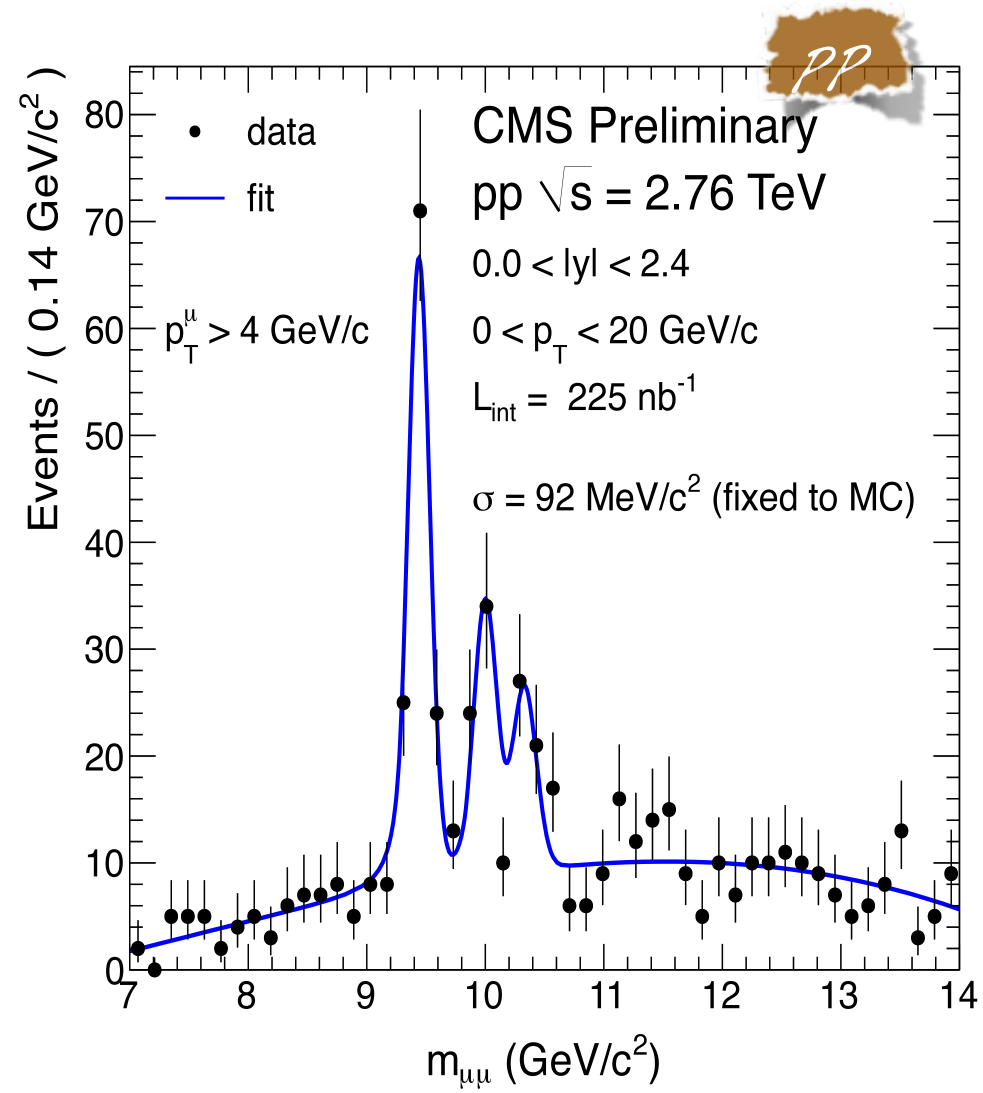
Sequential melting

State	Υ (1S)	χ_b (1P)	Υ' (2S)	χ'_b (2P)	Υ'' (3S)
m (GeV/c^2)	9.46	9.99	10.02	10.26	10.36
r_0 (fm)	0.28	0.44	0.56	0.68	0.78

decreasing binding energy ⟶

datasets



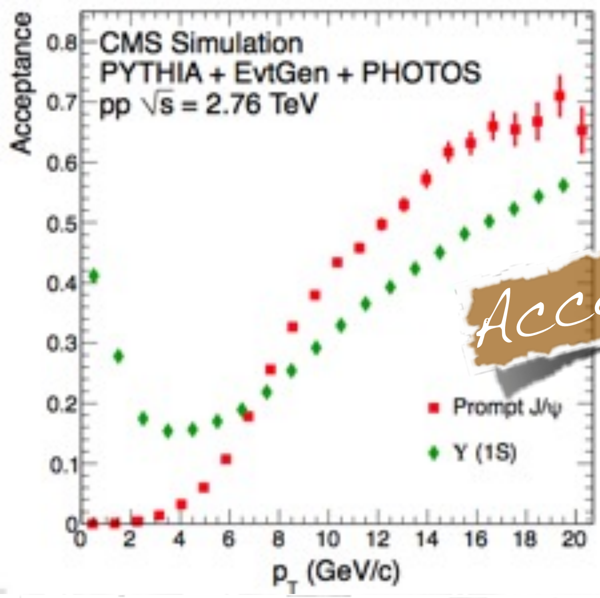


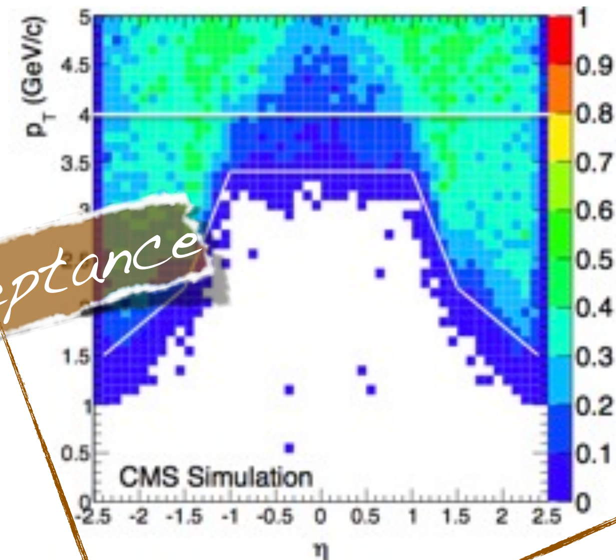
PbPb run 2010 @2.76TeV (7.28μb^{-1})

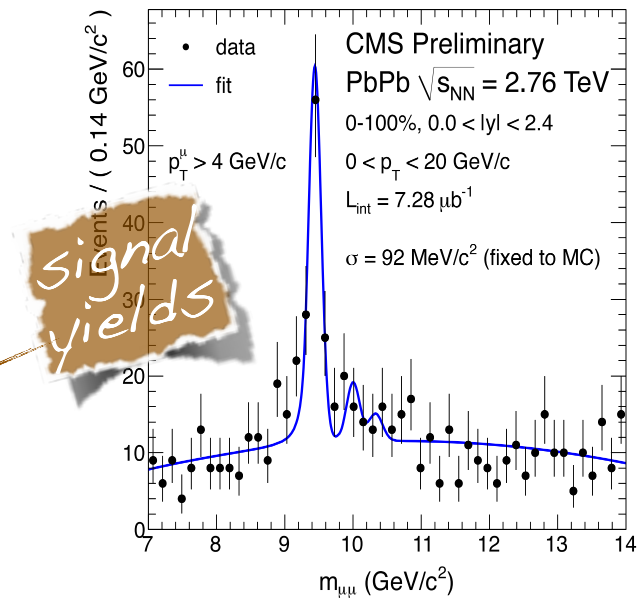
pp run 2011 @2.76TeV (225 nb^{-1})

- same online+offline selection applied to both datasets
- muon selection: quality cuts, p_T>4GeV/c, $|\eta^{\mu}|$<2.4

invariant yields

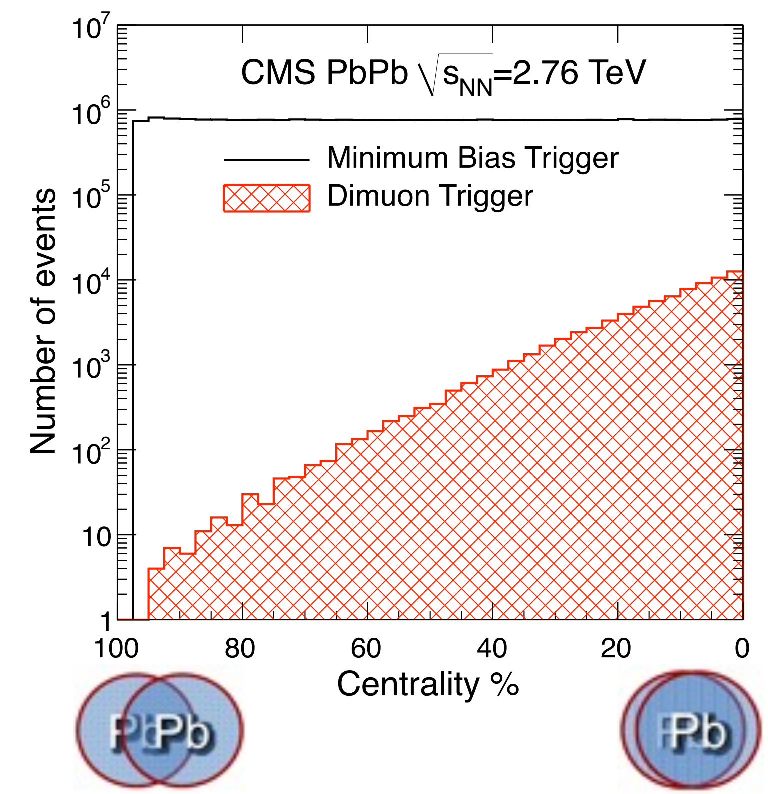


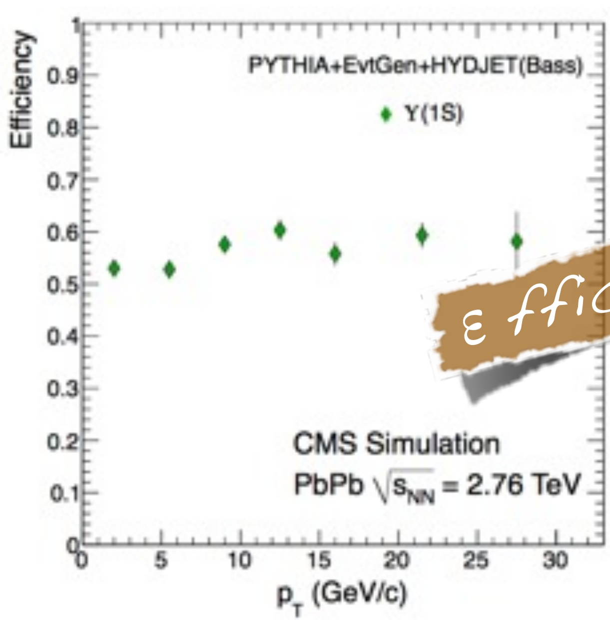


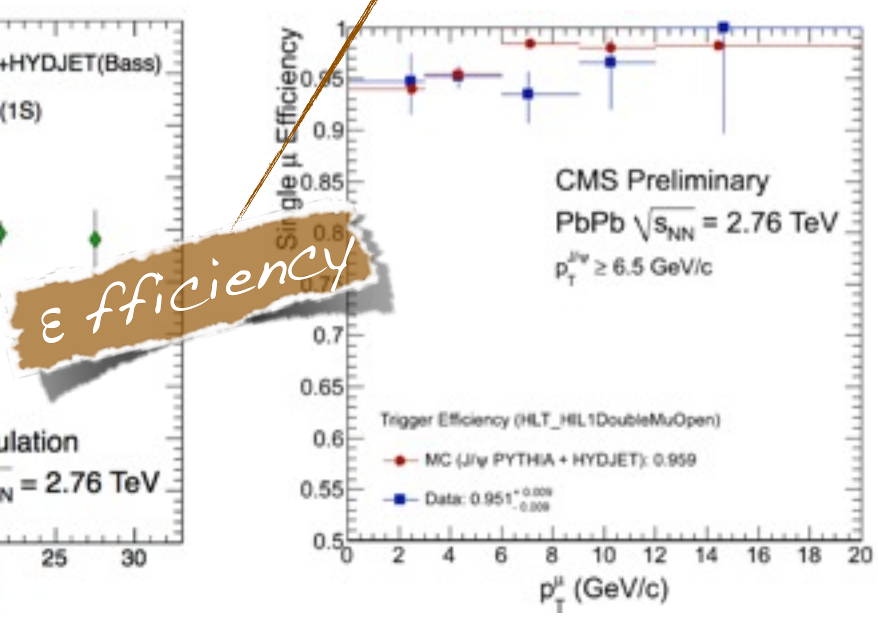


$$\frac{1}{T_{AA}}\frac{d^2N}{dp_T dy} = \frac{1}{\Delta p_T \Delta y}\cdot\frac{N_\Upsilon}{\mathcal{A}\cdot\varepsilon}\cdot\frac{1}{T_{AA}\cdot N_{MB}}$$

$$T_{AA} = N_{coll}/\sigma_{pp}^{inel.}$$

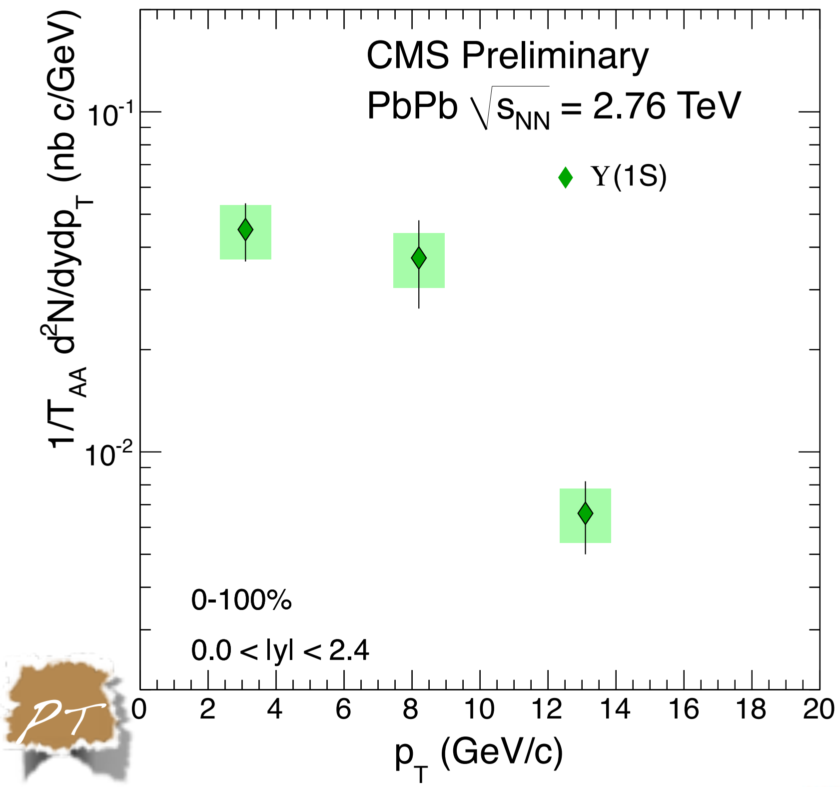


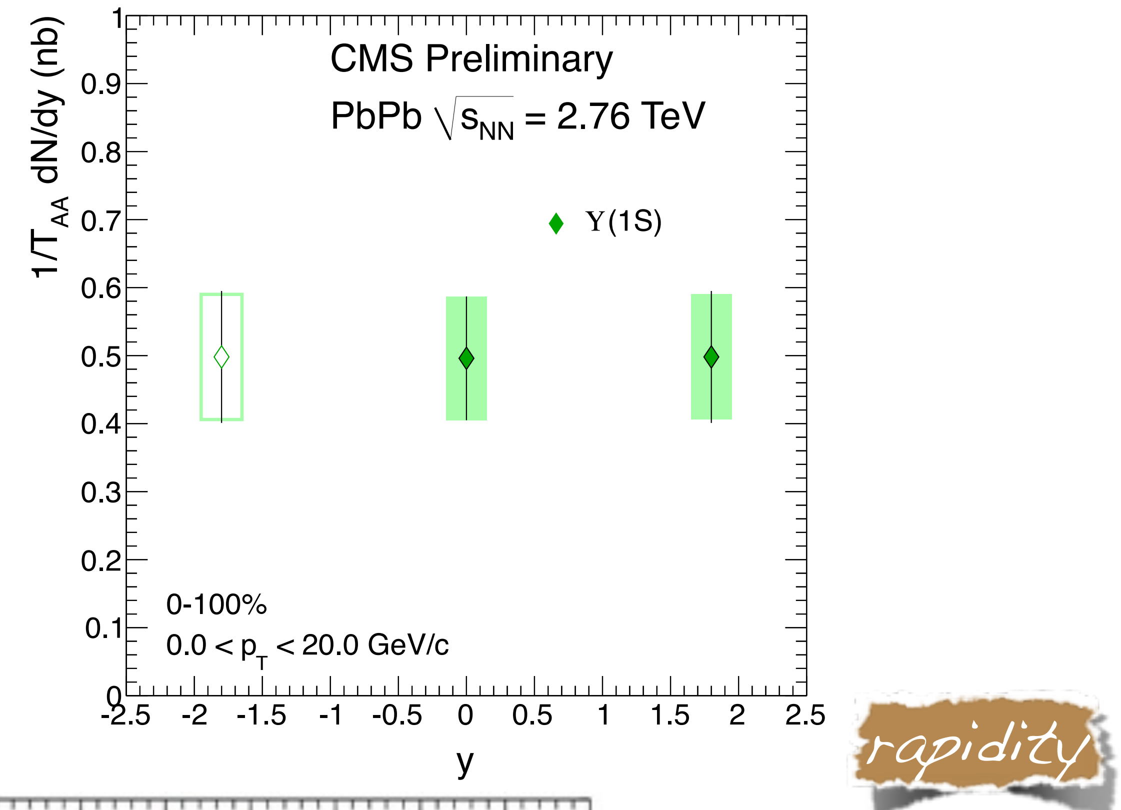


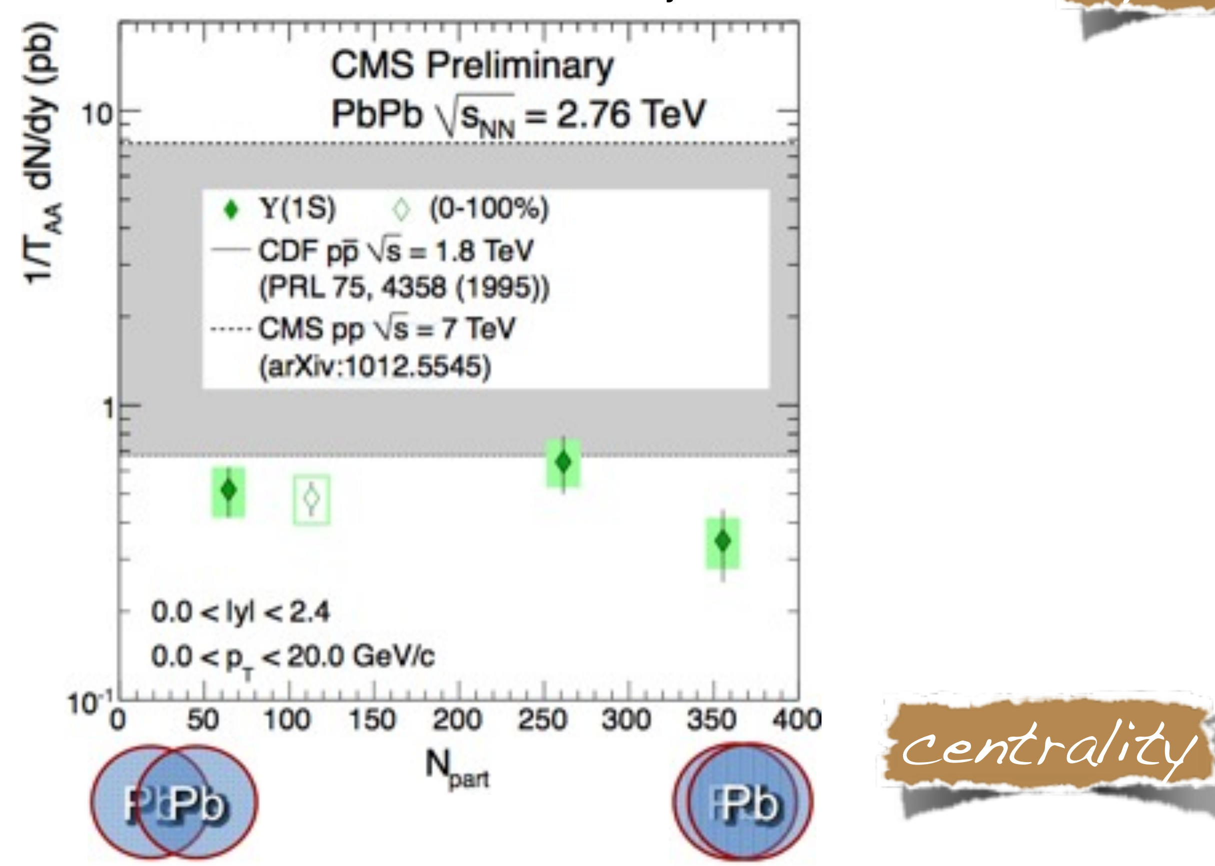


- Centrality bins: 0 - 10% , 10 - 20% , 20 - 100%
- p_T bins (GeV/c): 0 - 6.5 , 6.5 - 10 , 10 - 20
- Rapidity bins: $0 < |y| < 1.2$, $1.2 < |y| < 2.4$

Υ(1S) invariant yields in PbPb





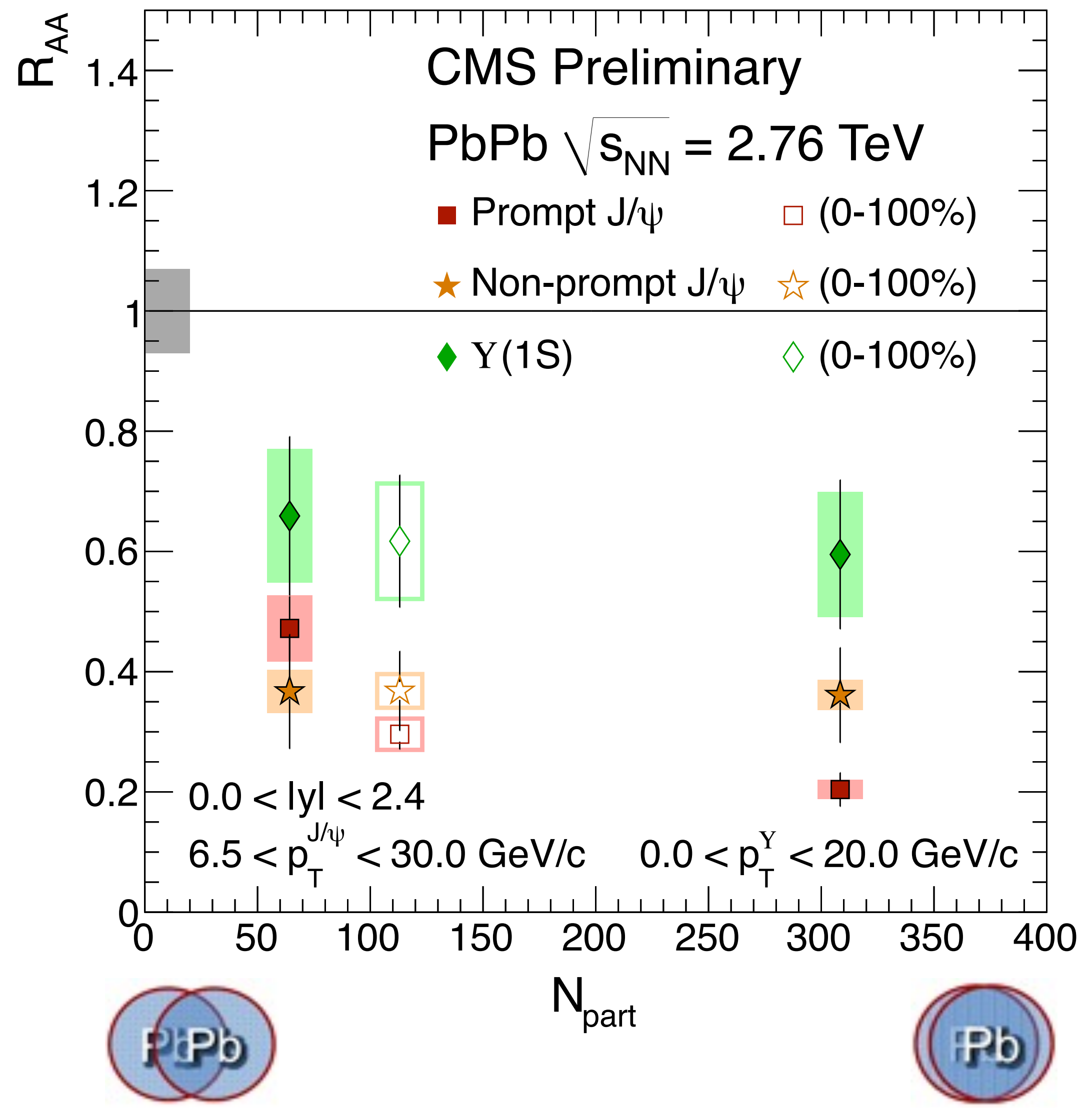


- Systematic uncertainties
  - yield extraction: 8-14%
  - acceptance: 1-5%
  - efficiency: 14%
  - T_{AA}: 4.3-15%
- Statistical uncertainties: 5-20%

nuclear modification factor, R_{AA}

$$R_{AA} = \frac{\mathcal{L}^{pp}_{\text{int}}}{T_{AA} N_{\text{MB}}} \frac{N^{\text{PbPb}}_{Q\bar{Q}}}{N^{pp}_{Q\bar{Q}}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{\text{PbPb}}(\text{cent})}$$

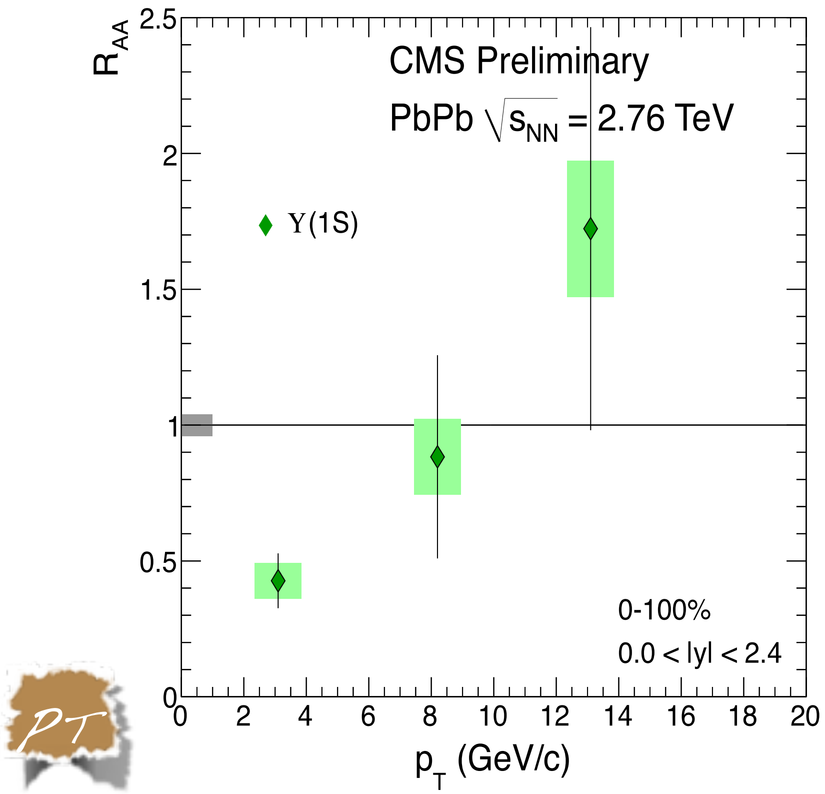
N_{PbPb} = 86 ± 12[stat] ± 3[syst]
N_{pp} = 101 ± 12[stat] ± 3[syst]
T_{AA} = 5.66 mb^{-1}
N_{MB} = 55.7M MB PbPb collisions
L_{pp} = 225 nb^{-1}

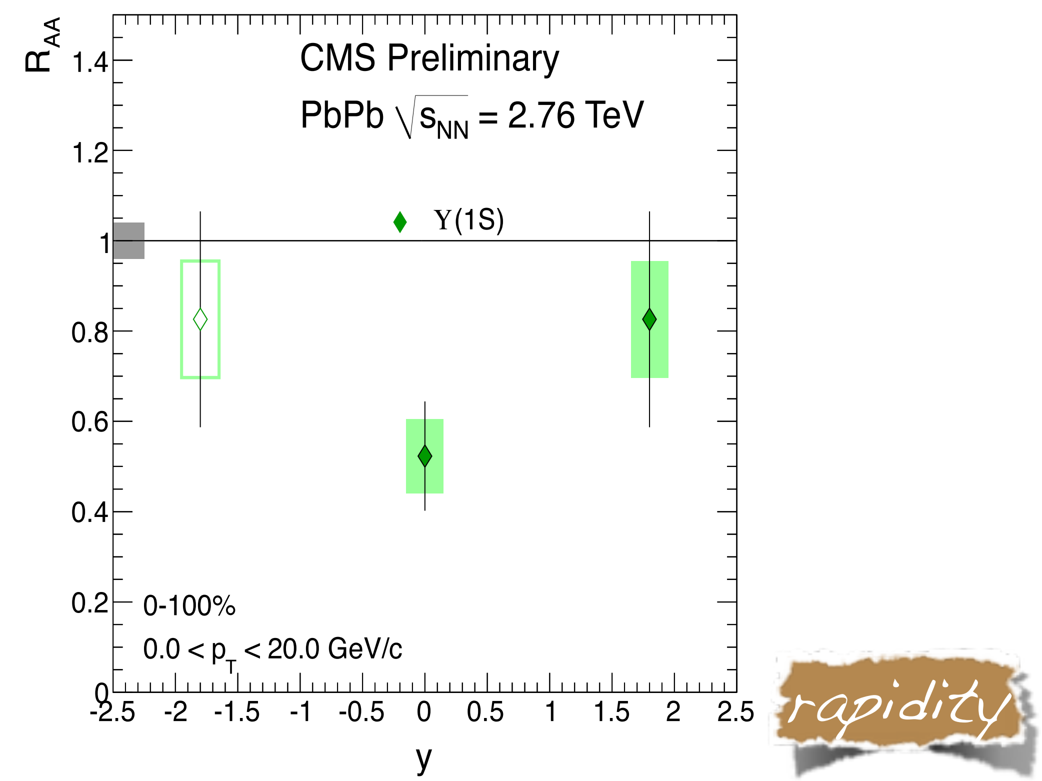


- R_{AA}(1S) in 20% most central bin
  - 0.60 ± 0.12$_{\text{stat.}}$ ± 0.10 $_{\text{syst.}}$
- 1S yields affected by large feeddown
- suppression might be due to melting of excited states (2S, 2P, 3S)

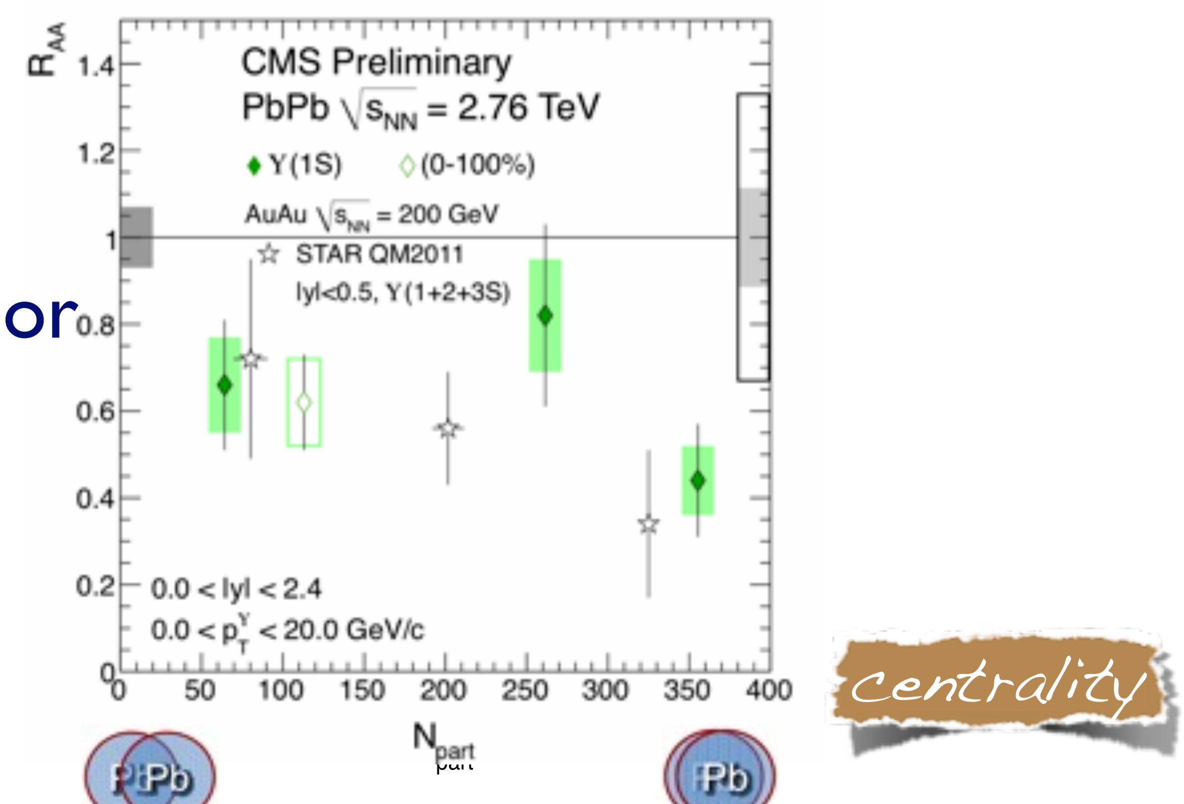
$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}}{d\sigma_{pp}} \begin{cases} >1\text{: enhancement} \\ =1\text{: no medium effect} \\ <1\text{: suppression} \end{cases}$$

Υ(1S) differential R_{AA}





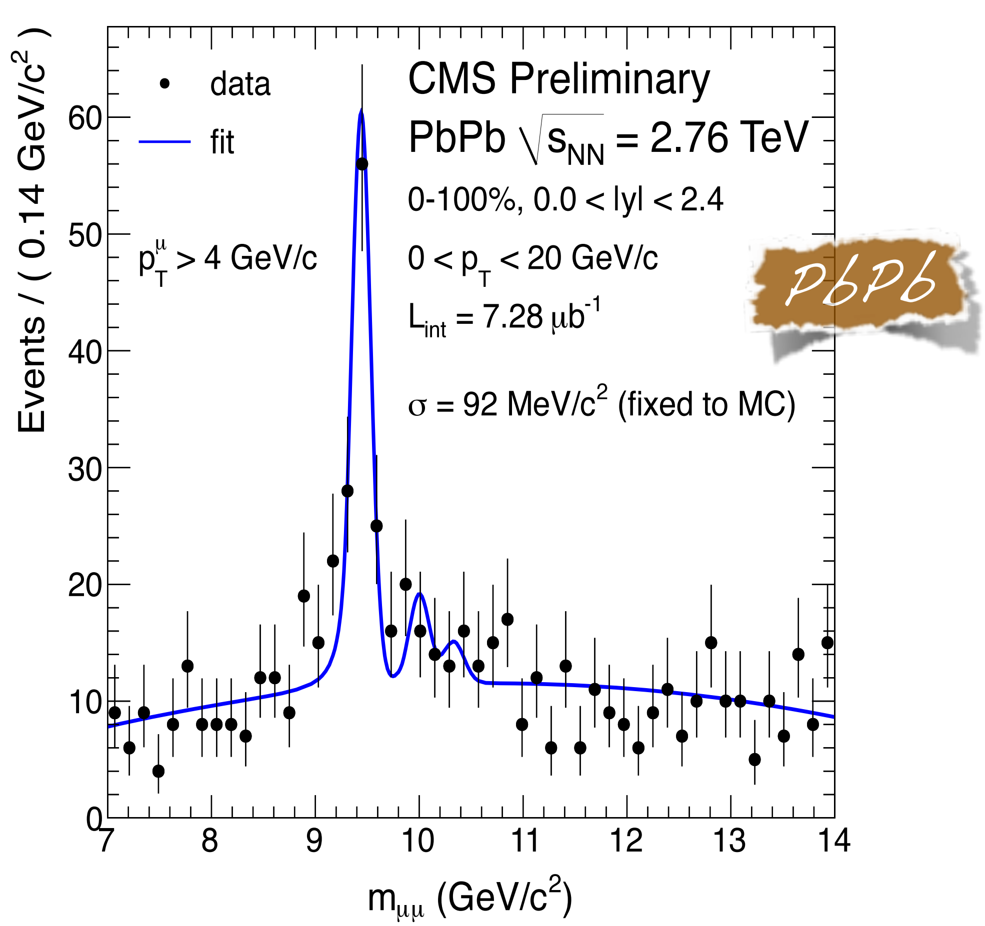
- 1S inclusive (minimum bias) R_{AA}
  - $0.62 \pm 0.11_{\text{stat.}} \pm 0.10_{\text{syst.}}$
- no clear dependency on rapidity or centrality; high p_T not as suppressed?
- will be answered with more data
  - also separate 2S, 3S measurements



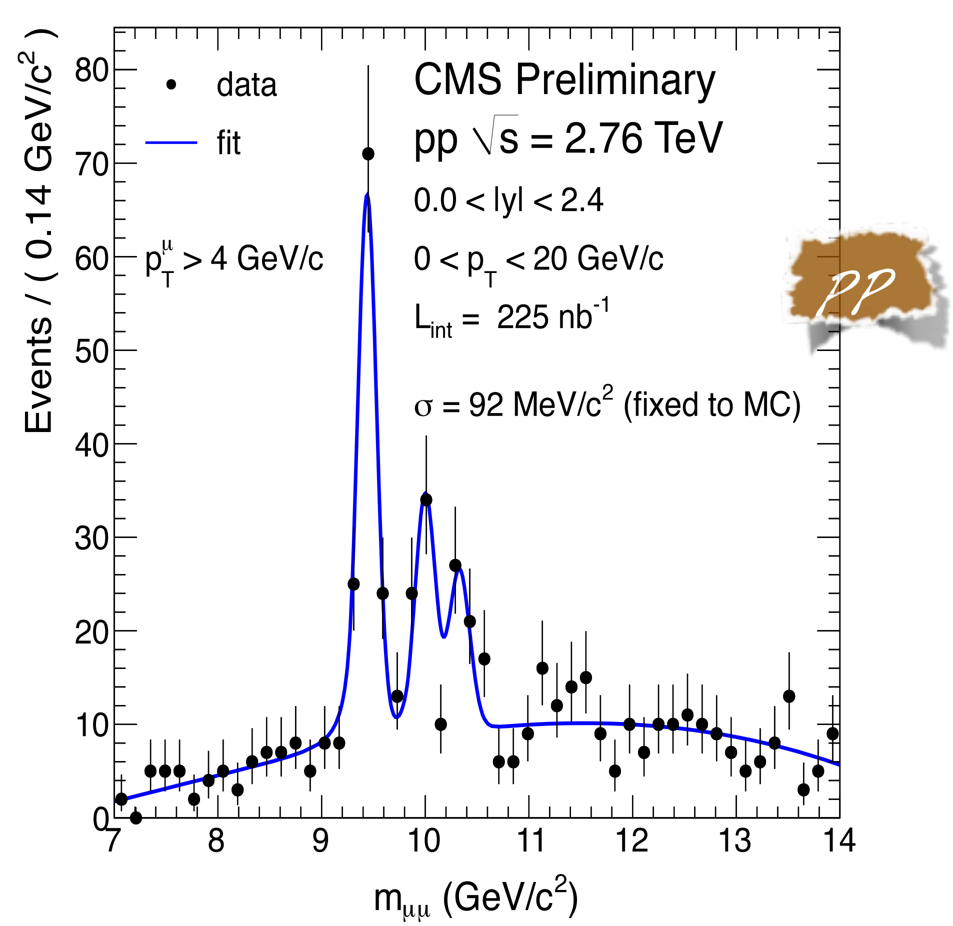
Υ(2S+3S) vs Υ(1S)

- measure fraction of excited states Υ(2S+3S) relative to Υ(1S)
- extracted directly from fit to PbPb and pp data samples

$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$



$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

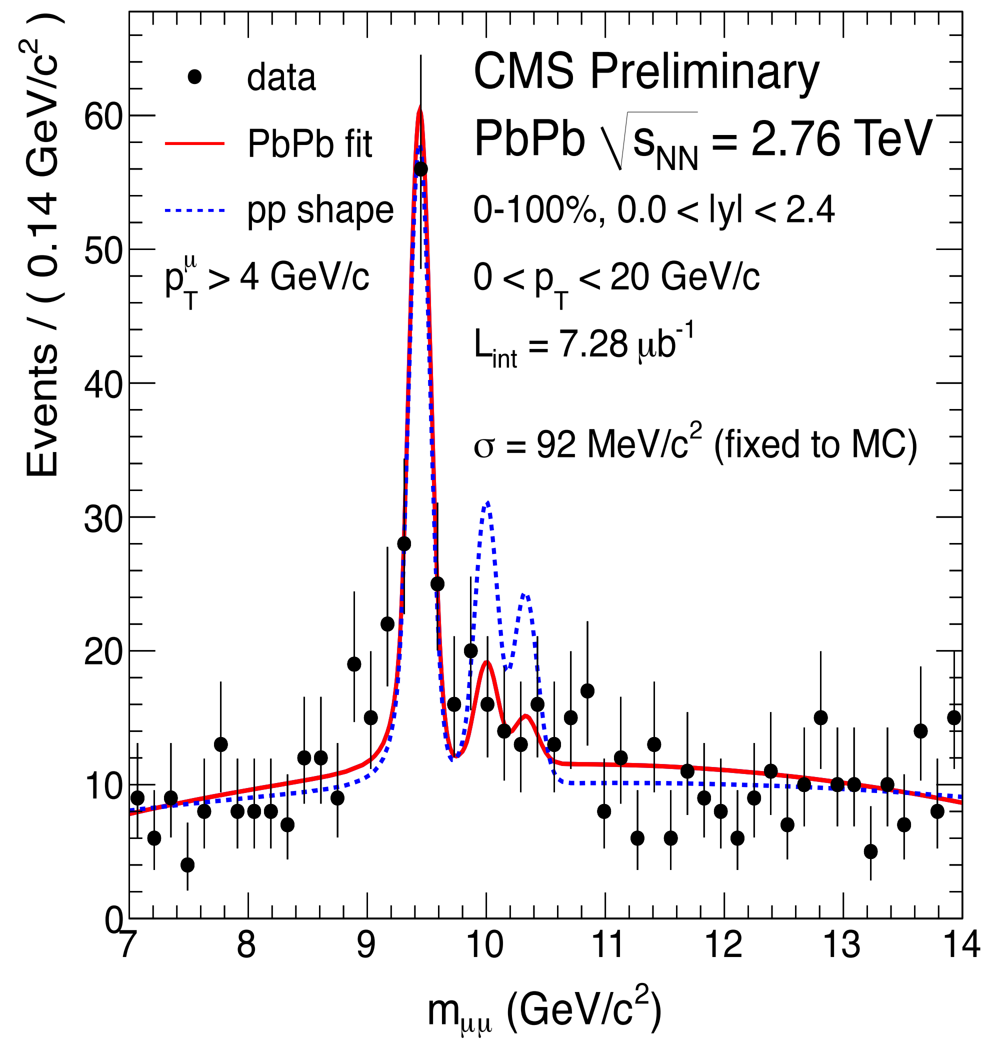


Υ(2S+3S) suppression

- extract double ratio directly from simultaneous fit to both samples

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

- advantages of double ratio
  - acceptance, efficiency, luminosity cancel
  - remaining systematics 9% from fit lineshape model
  - measurement is statistics dominated



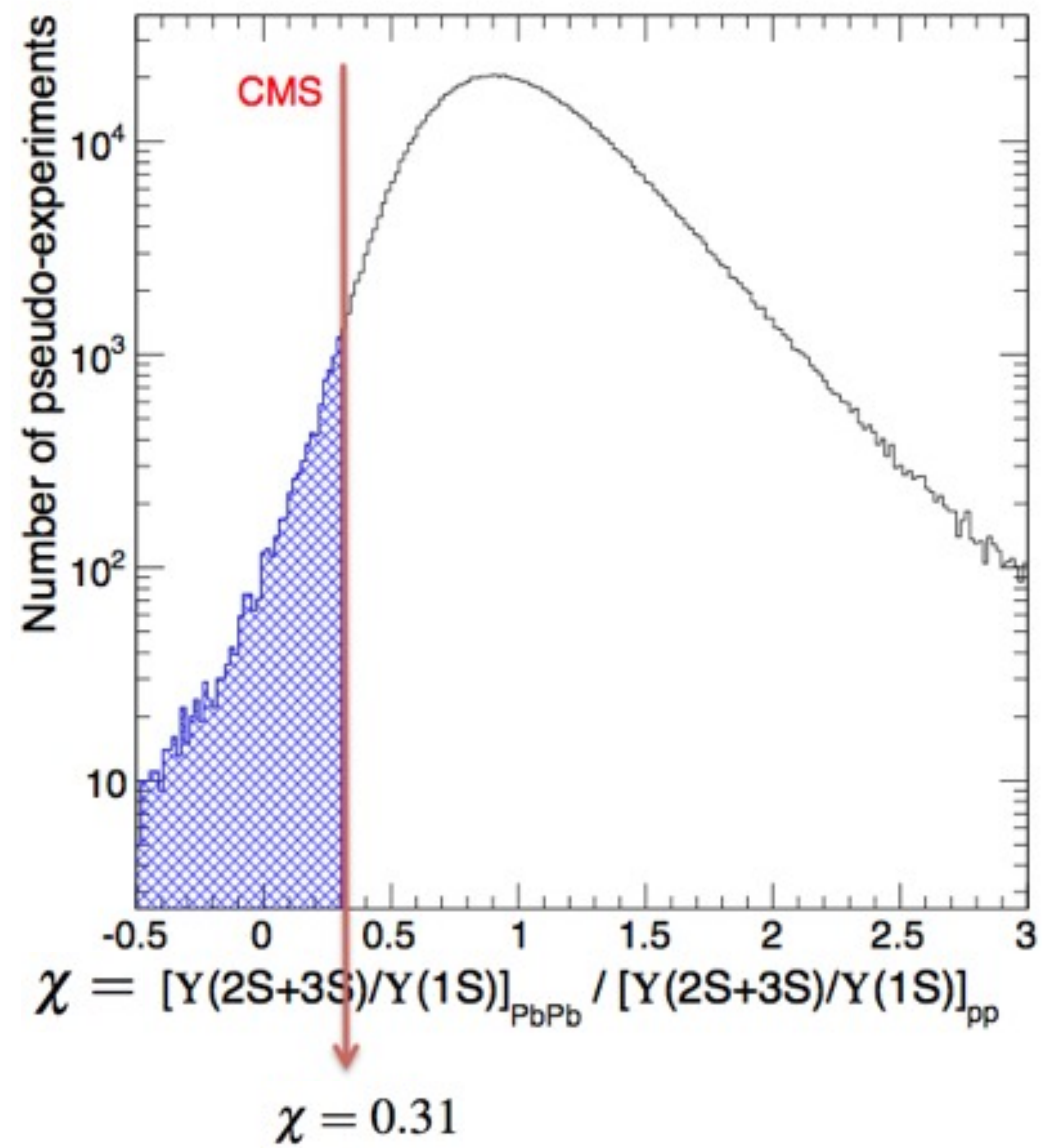
first observation of suppression of excited Υ states

Υ' suppression: p-value

- 'what is probability for a background fluctuation to mimic the observed result?'
  - generate pseudo-experiments assuming the null hypothesis (ie no suppression)
  - fit pseudo-data samples with nominal fit
  - count fraction of occurrences for which ratio (taken as test statistic) is same or lower than observed
- p-value: 0.9%, or
- significance 2.4σ (1-sided Gaus. test)

null hypothesis: $\chi = 1$ (no suppression)

p-value < 1%



Summary

- first measurements of Υ(nS) differential cross sections and ratios at $\sqrt{s}$=7TeV have been performed
  - very good agreement between all LHC results, contributing to an improved understanding of quarkonium production
  - polarization studies being finalized, will shed further light on existing puzzles
- bottomonia also studied in PbPb collisions at $\sqrt{s_{NN}}$=2.76TeV
  - first observation of relative suppression of excited Υ states
  - 40% suppression of Υ(1S) ➪ consistent with melting of excited states only
- pp and PbPb 2011 LHC runs will allow to:
  - probe high p_T spectrum
  - improve precision and significance of the measurements
  - measure further bottomonia/-like states