Quarkonium Production at CMS

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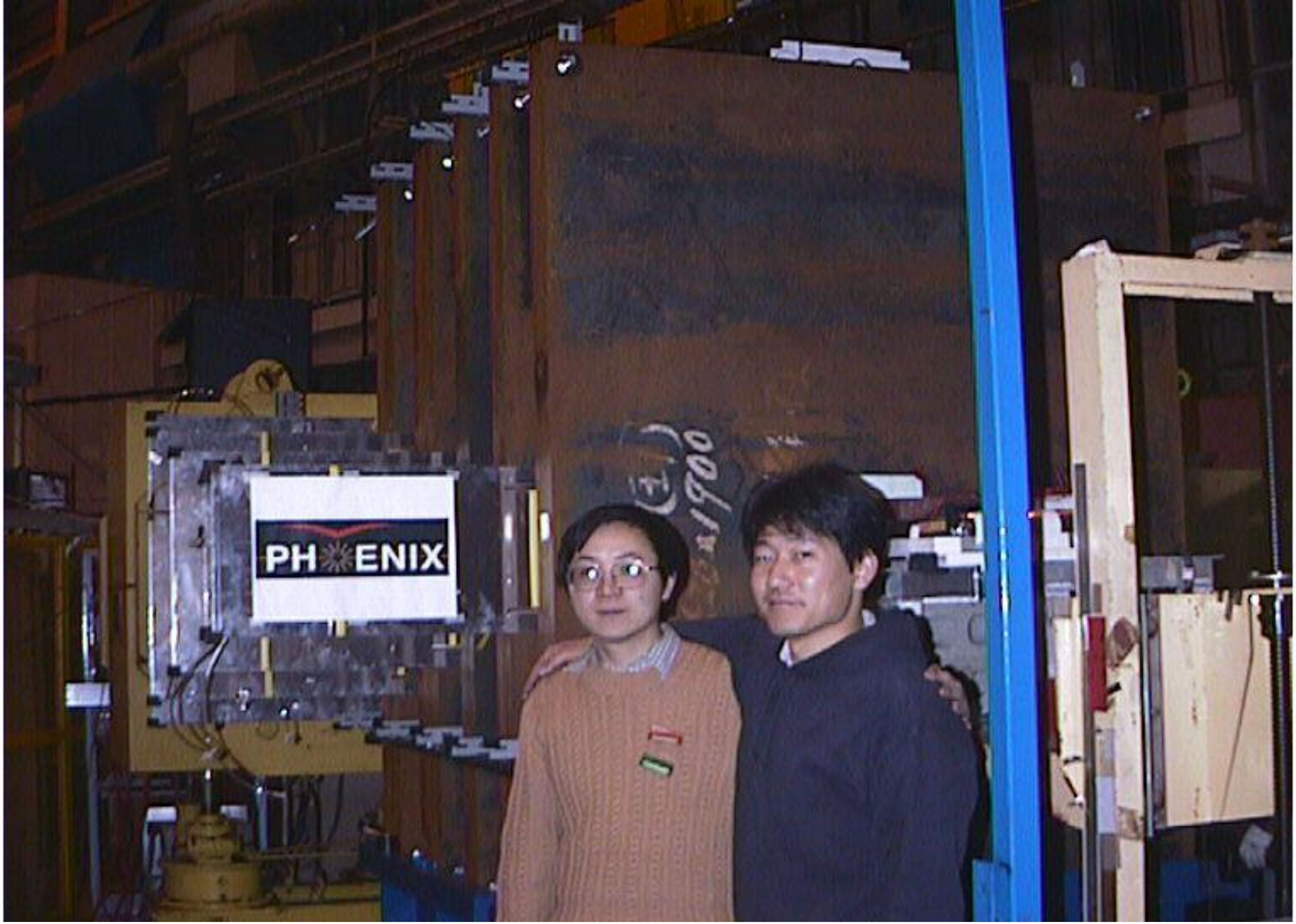
August 1st, 2013


PHENIX

Outline

- CMS Introduction
- Why Quarkonium?
- Quarkonia From pp Collision
- Quarkonia From Heavy Ion Collision
- Summary

CMS Detector

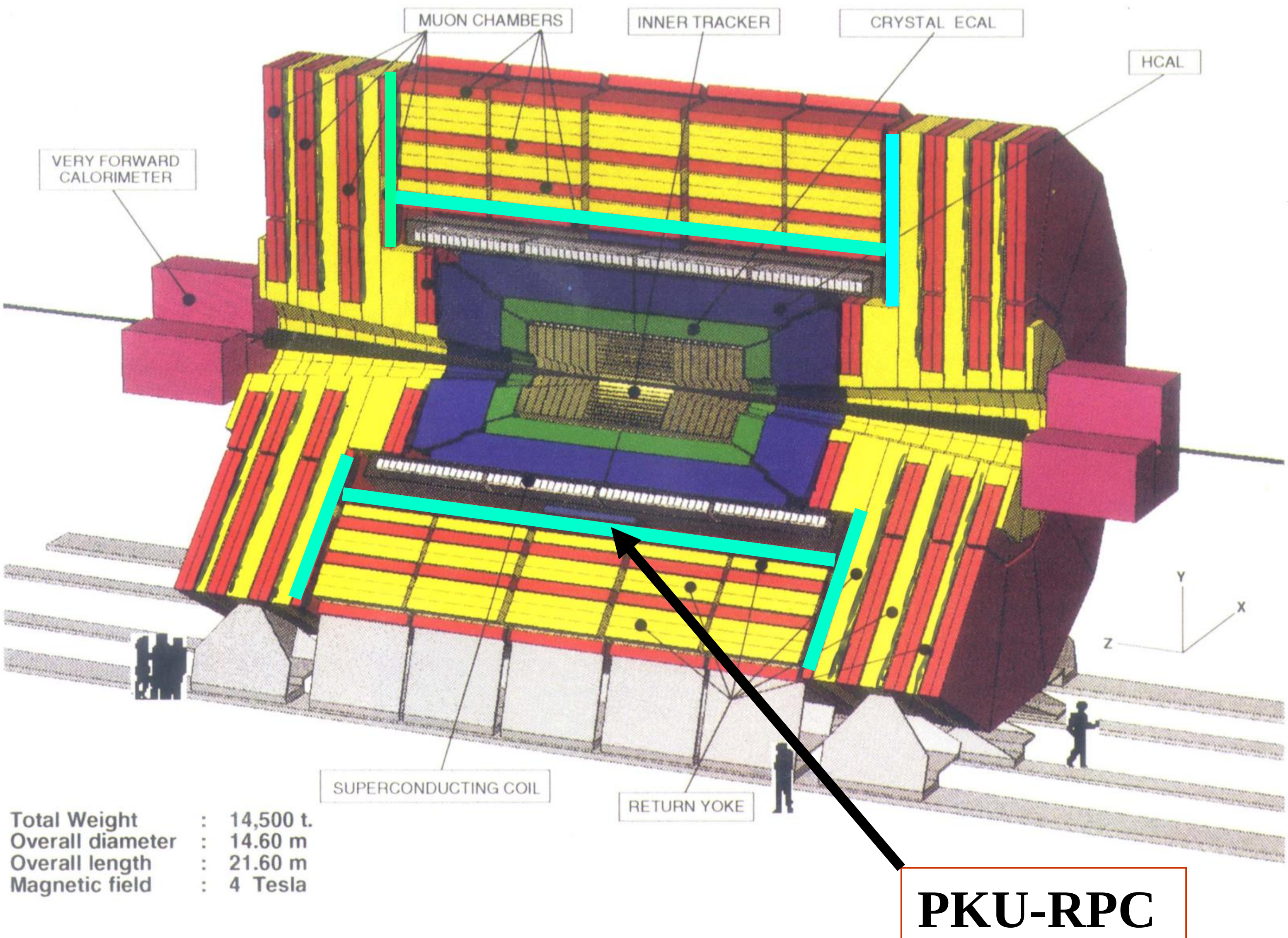
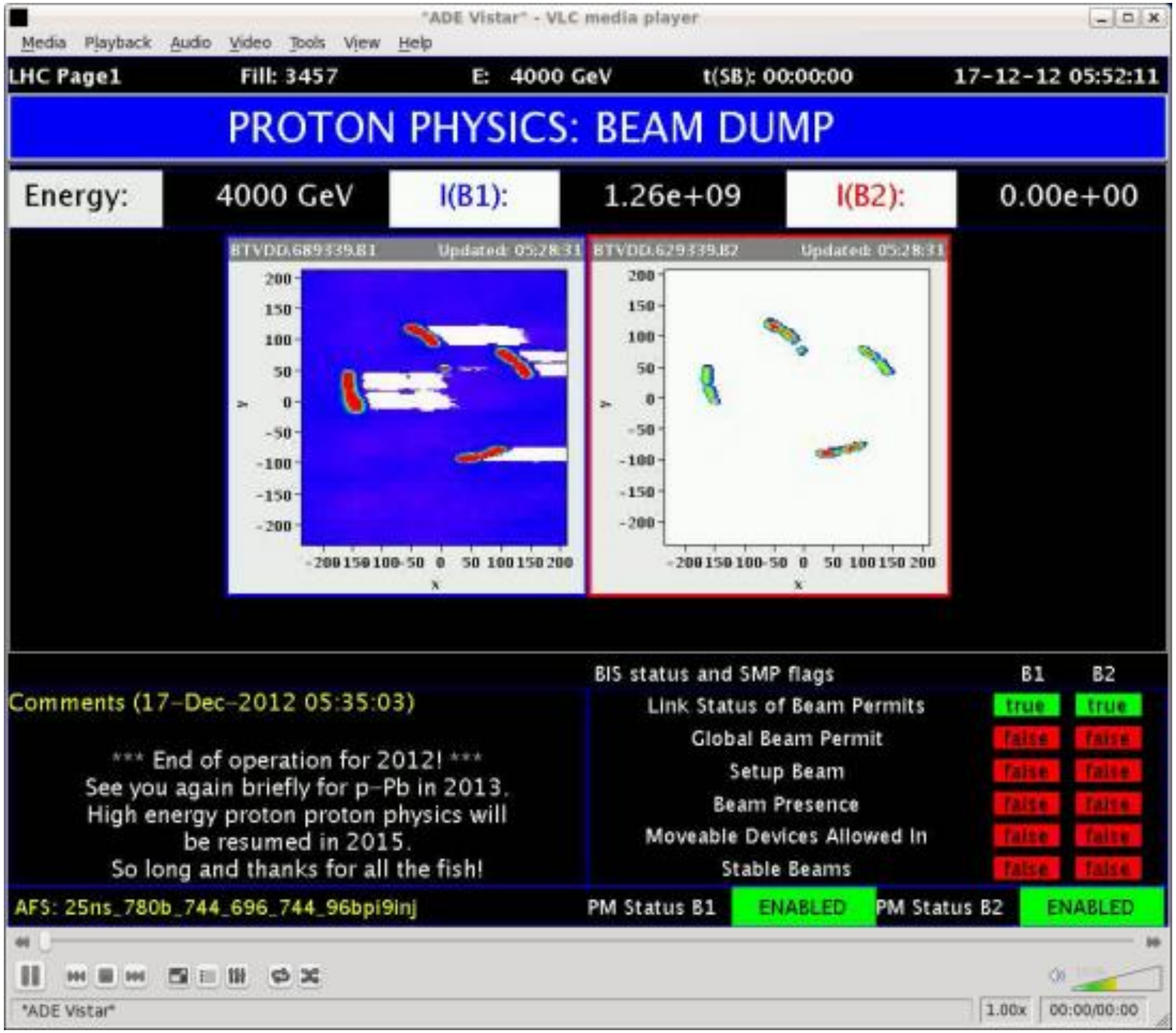


Fig. 1.1: Three-dimensional view of the CMS detector.

LHC Status

➢ **first three-year run ended on Dec.17/2012**



At the beginning of 2013, the LHC collided protons with lead ions by end February.

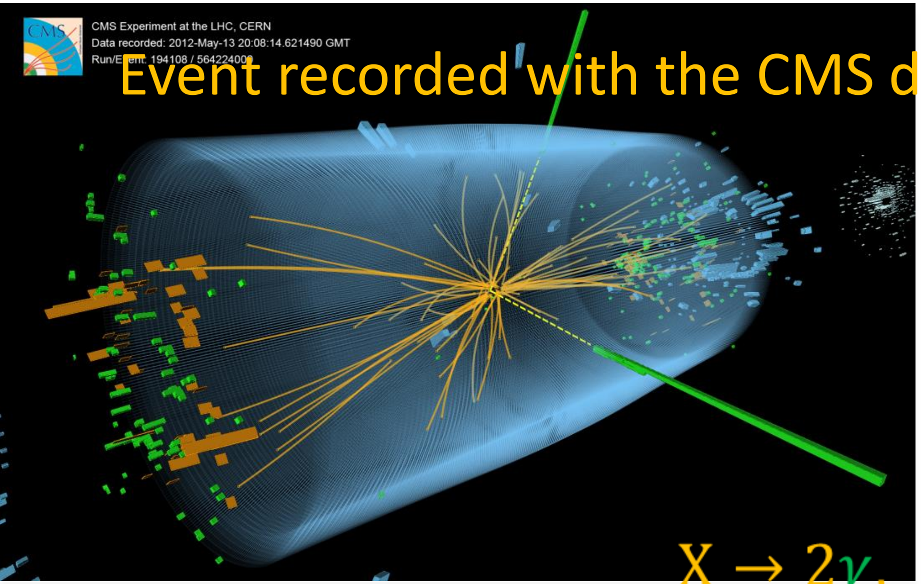
A long maintenance stop until the end of 2014.

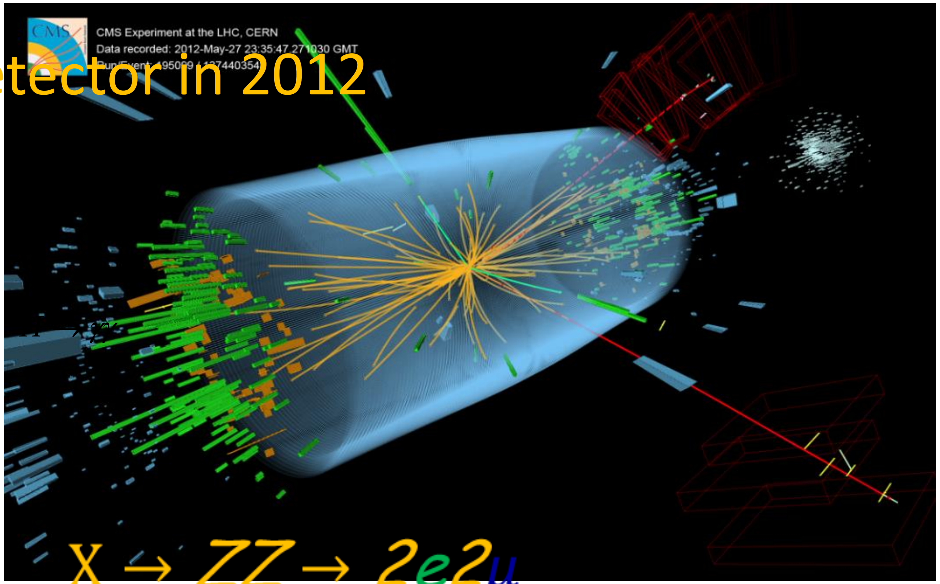
Running will resume in **2015** with increased collision energy of **13-14 TeV** and another increase in luminosity.

CMS Status

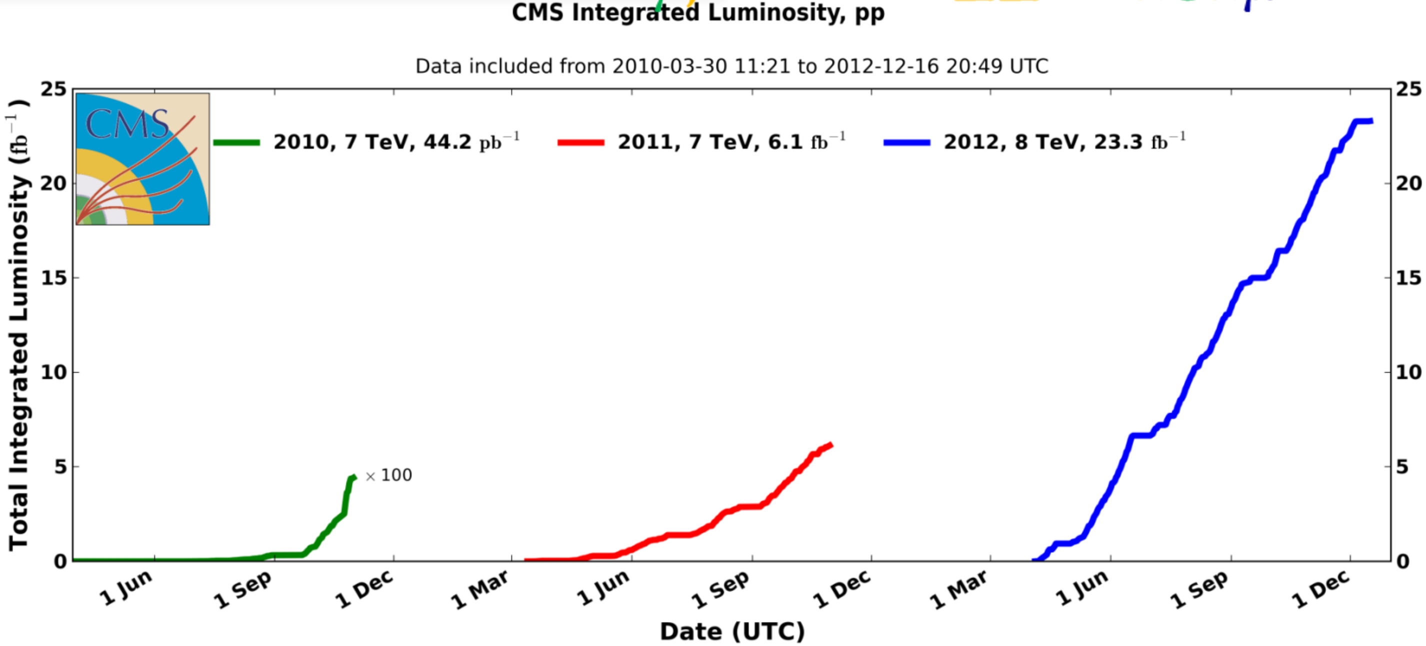
- Had been running pretty well

Event recorded with the CMS detector in 2012



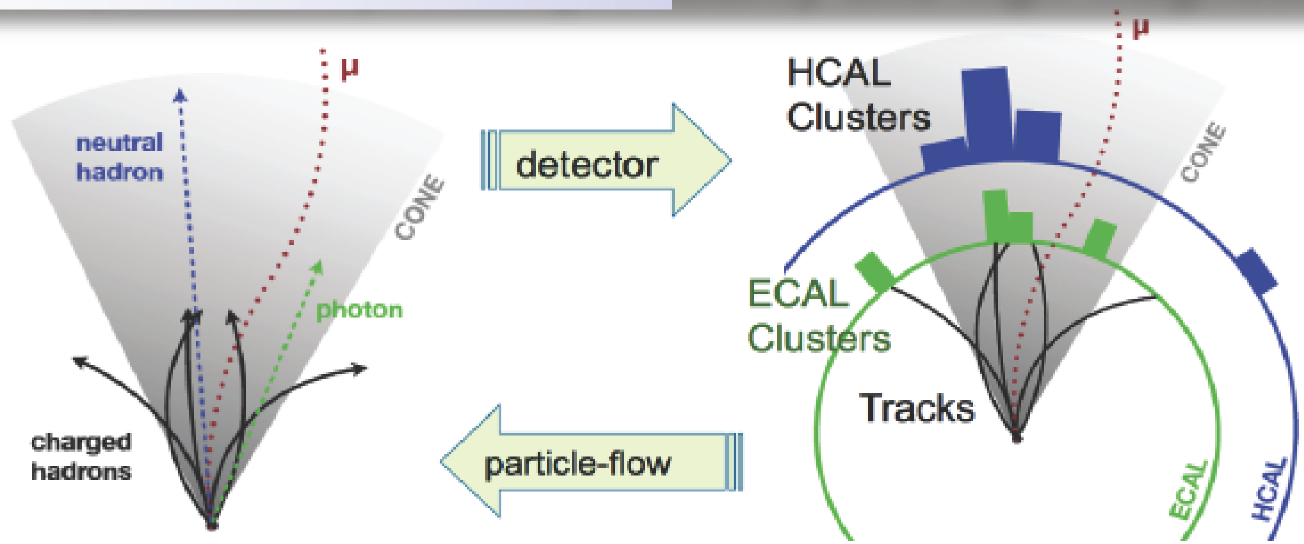


$X \to 2\gamma$, $X \to ZZ \to 2e2\mu$



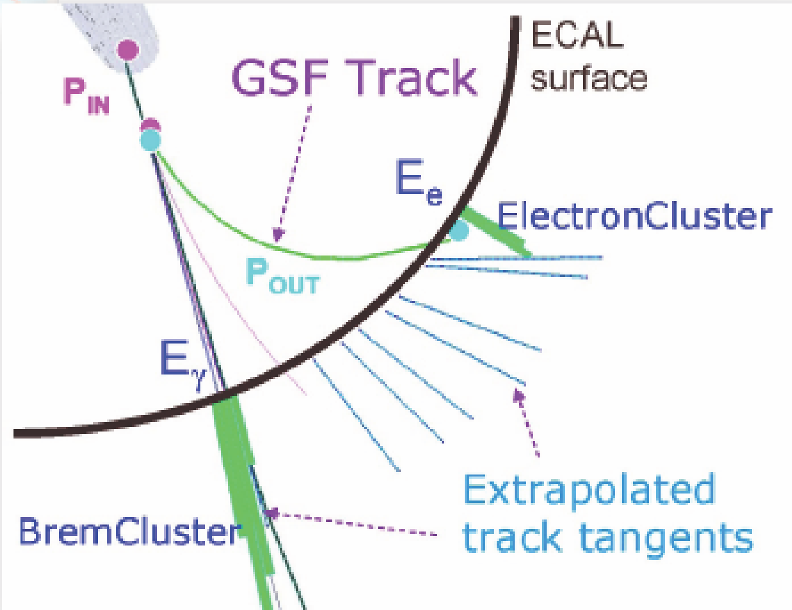
Global Event Description (Pflow)

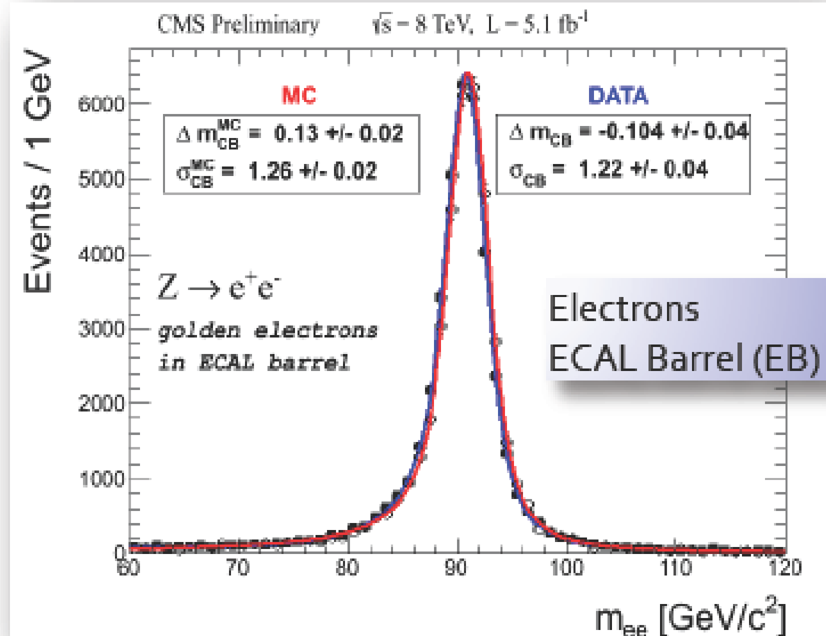
Made possible by CMS granularity and high magnetic field



- Optimal combination of information from all subdetectors
- Returns a list of reconstructed particles
  - e,μ,γ, charged and neutral hadrons
    - Used in the analysis as if it came from a list of generated particles
    - Used as building blocks for jets, taus , missing transverse energy , isolation and PU particle identification

Electron/Photon reconstruction



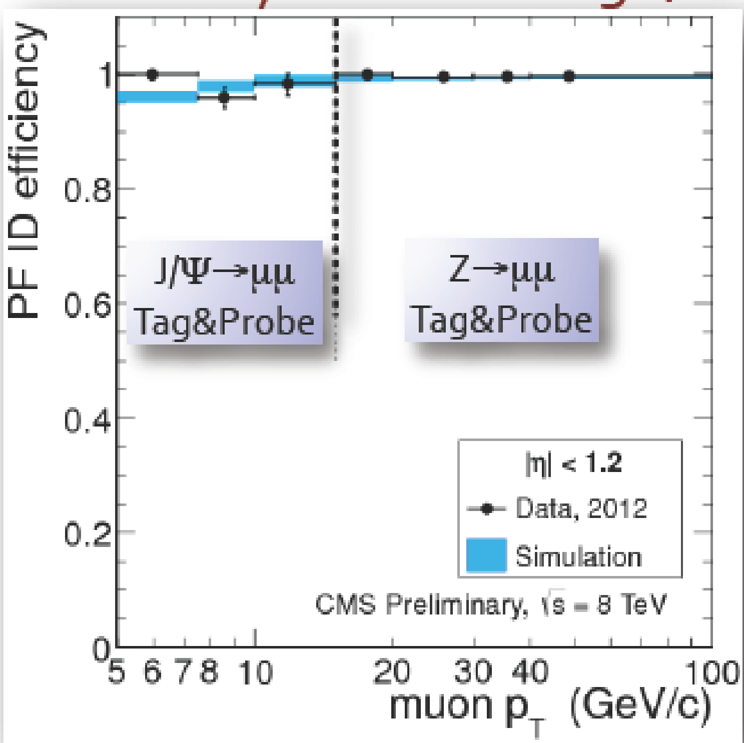


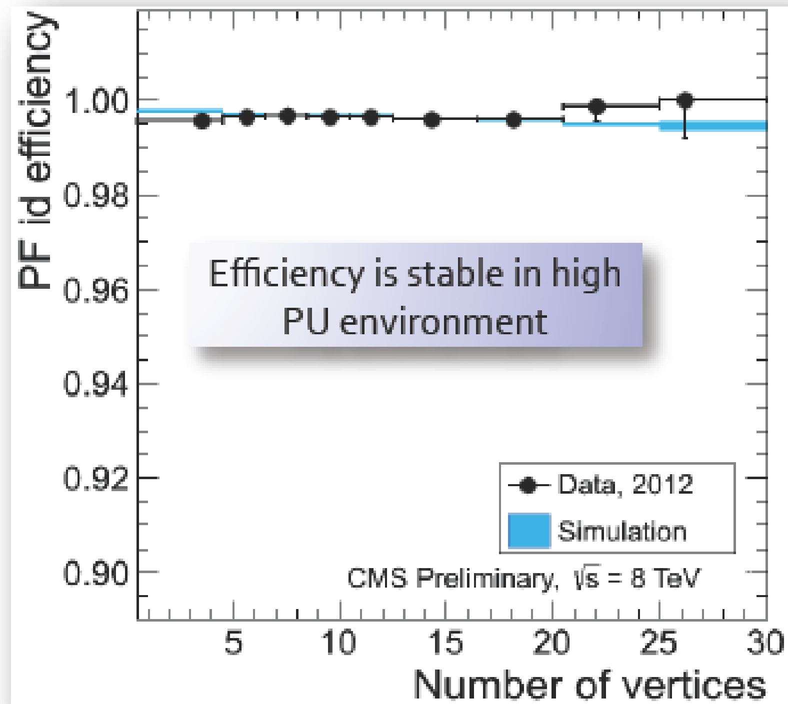
- Cluster reconstruction in ECAL
  - Common for both electrons and photons (Electrons also reconstructed as photons)
  - Designed to collect bremsstrahlung and conversions in extended phi region
- Dedicated track reconstruction for electrons
  - Gaussian Sum Filter allows for tracks w/large bremsstrahlung
- Photon identification specific to H➔γγ
- Energy scale and resolution
  - Extensive control with Z and J/ψ➔ee for both electrons and photons

Muon reconstruction and identification

- Start with particle flow muons
- Efficiency above 96% down to $p_T = 5$ GeV
  - Above 99% efficiency for $p_T > 10$ GeV
  - Efficiency in data using J/Ψ and Z peak

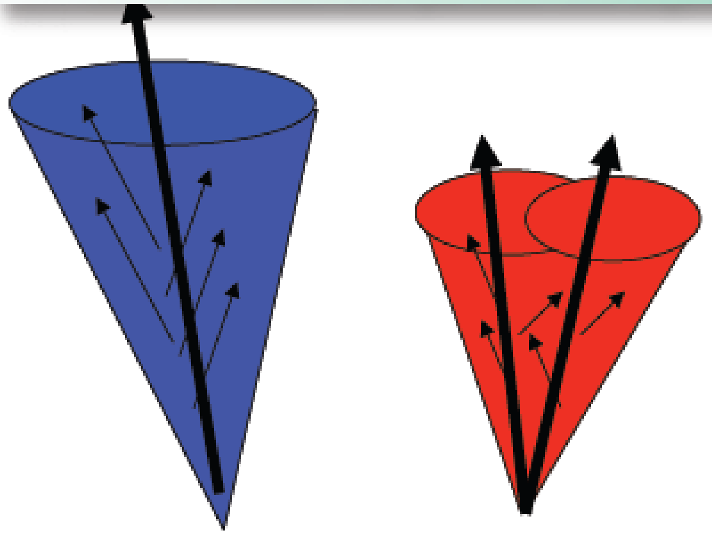
Tighter quality criteria applied in some analyses

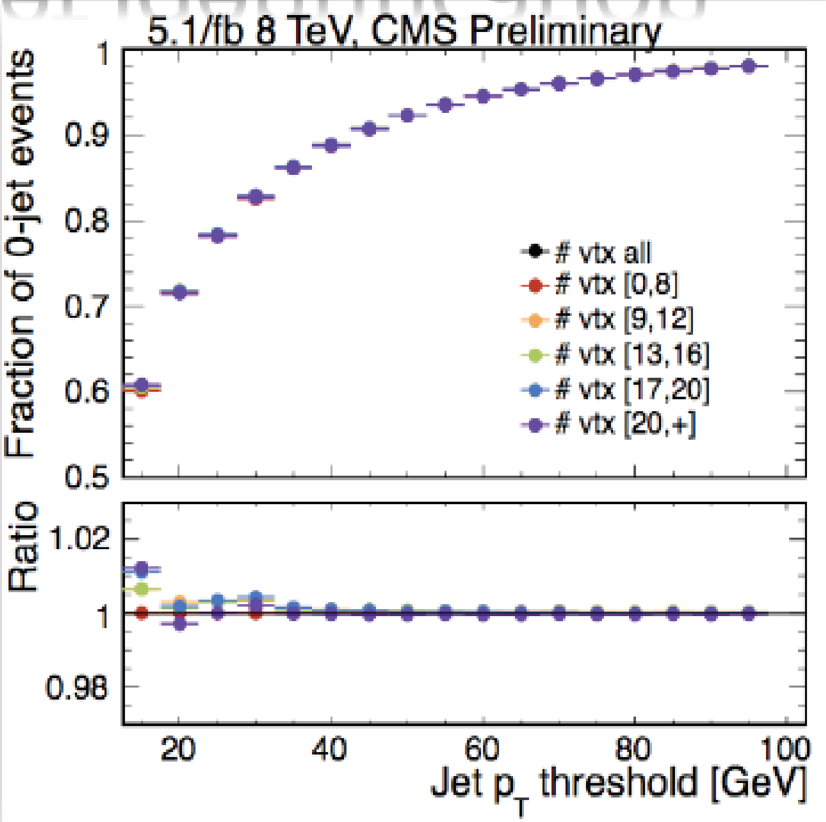




Jet Identification

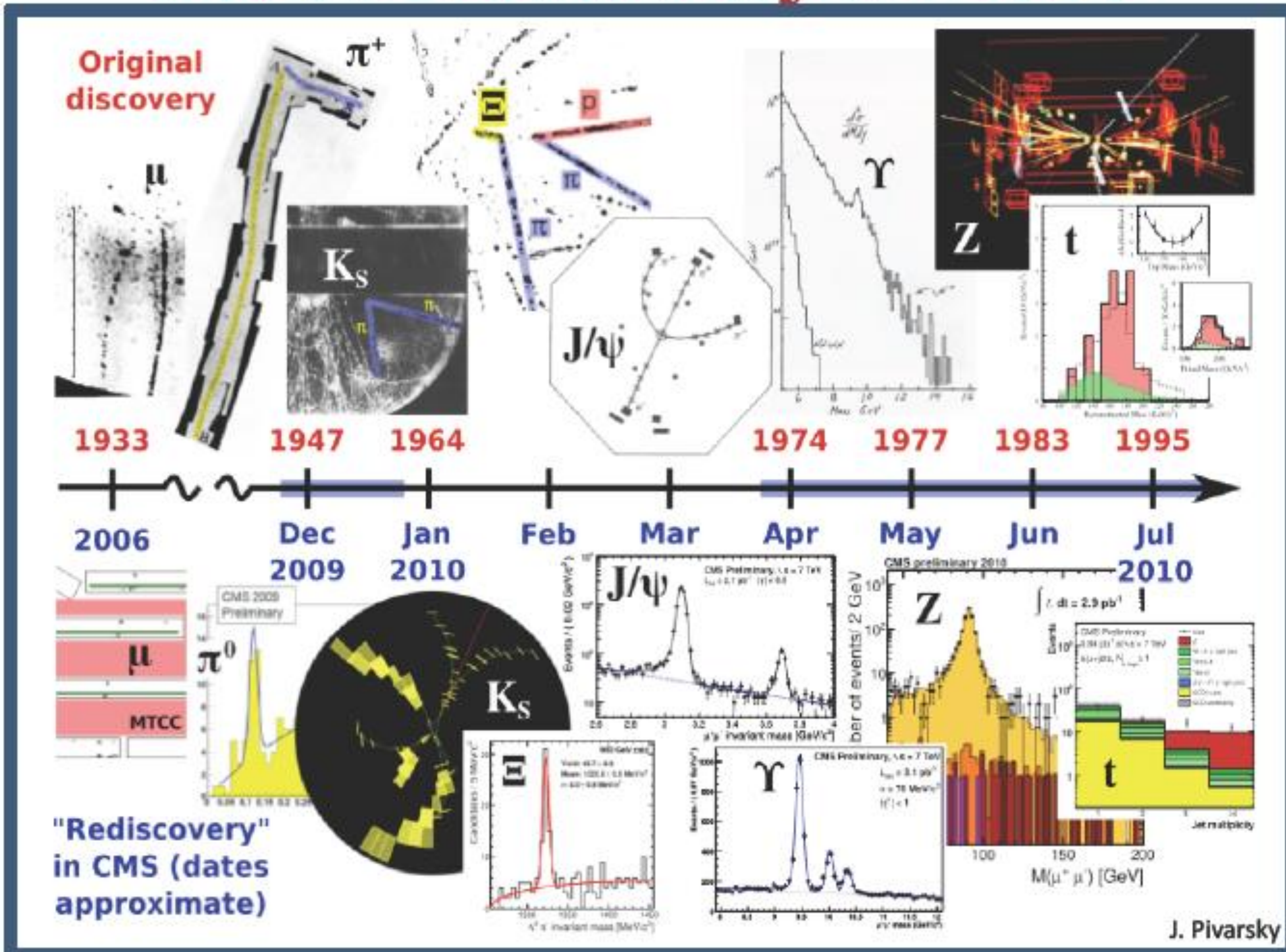
- Jet reconstruction
  - Reconstruction with particle flow objects





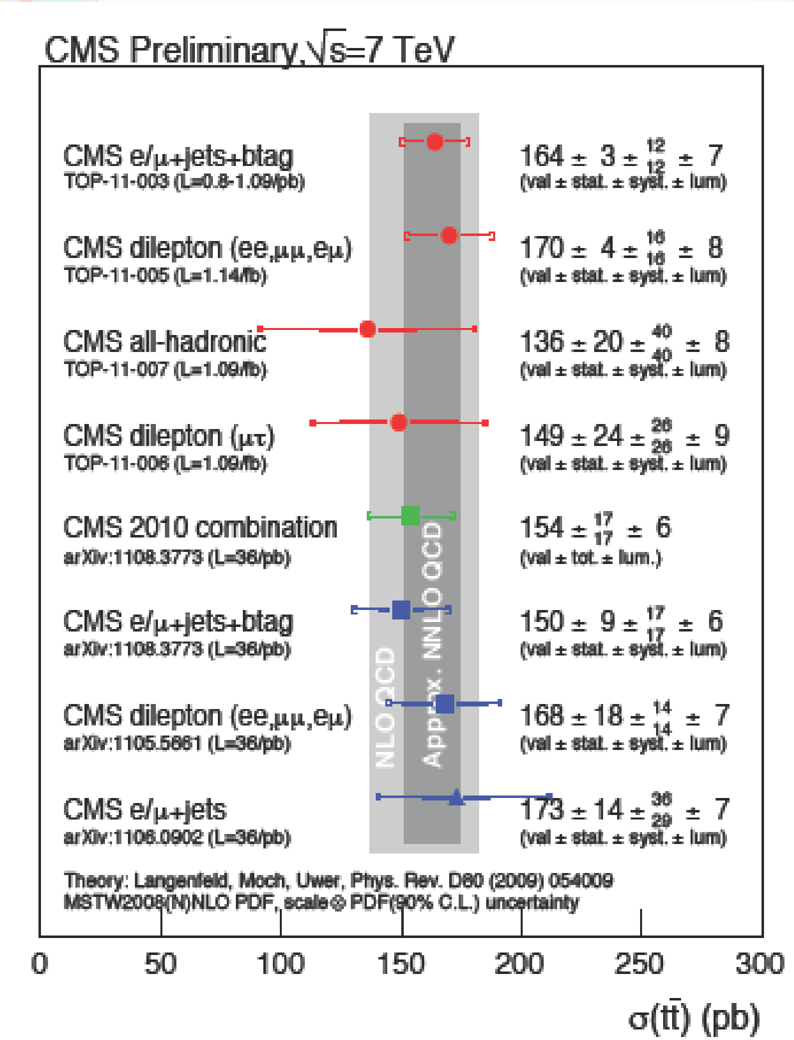
- Pileup jets structure differs wrt regular jets:
  - Pileup jets originate from several overlapping jets which merge together
  - Likelihood grows rapidly with high pileup
- Discriminant exploits shape and tracking variables
  - discrimination both inside and outside tracker acceptance

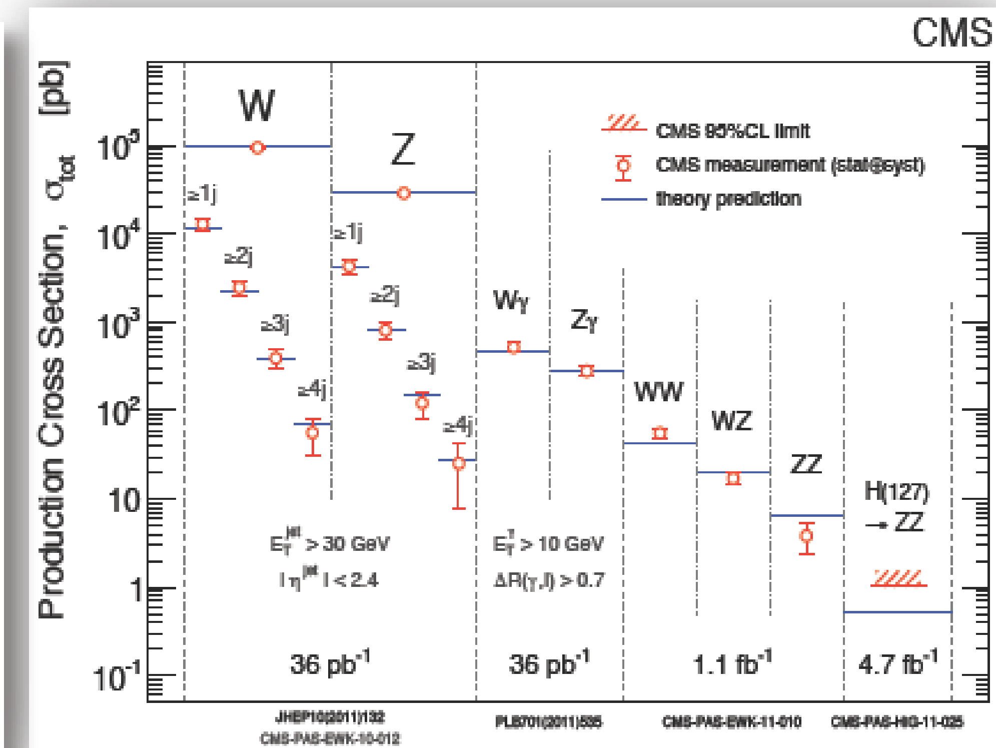
S.M. rediscovery in 2010



Standard Model at 7 TeV 2010-2011

July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION





- Fabulous agreement
- Lots of data

… on to the Higgs…

Why Quarkonium?

CSM for Onia

Conventional Mechanism of Heavy Quarkonia

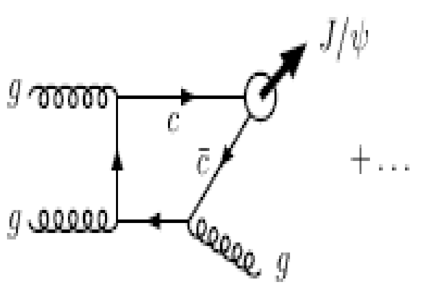
— parton interaction produces quark pair($c\bar{c}$)

— quark pair bind into quarkonia(J/ψ, ψ'...)

color *and* ***spin*** *is conserved during binding.*
The quarkonia is color-singlet, so the quark pair must be color-singlet too.

➡ ***Color Singlet Model (CSM)***

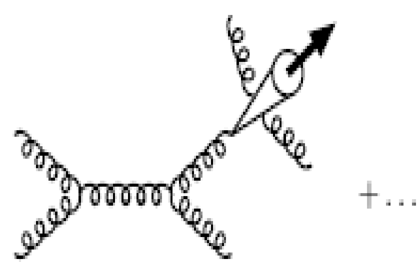
(a) leading-order colour-singlet: $g + g \to c\bar{c}[^3S_1^{(1)}] + g$



$\sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

CSM LO Feynman Diagram

(b) colour-singlet fragmentation: $g + g \to [c\bar{c}[^3S_1^{(1)}] + gg] + g$



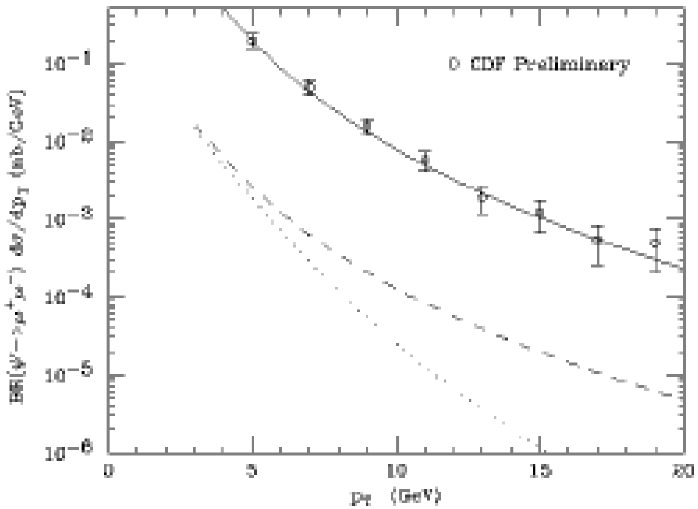
$\sim \alpha_s^5 \frac{1}{p_t^4}$

CSM Fragmentation Feynman Diagram

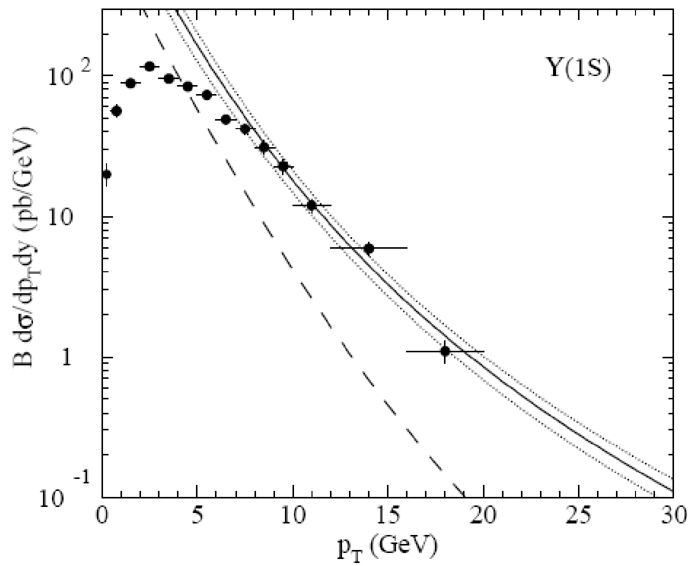
CDF Measurement vs CSM

- **1-2 order of magnitude discrepancy between CSM prediction and CDF Result**

Prompt charmonium production



Bottomonium production



black dot: CDF experiment

dashed line: color-singlet

solid line : NRQCD fit

J/Ψ: PRL, 79 (1997) 572

ϒ : PRL, 88(2001)161802

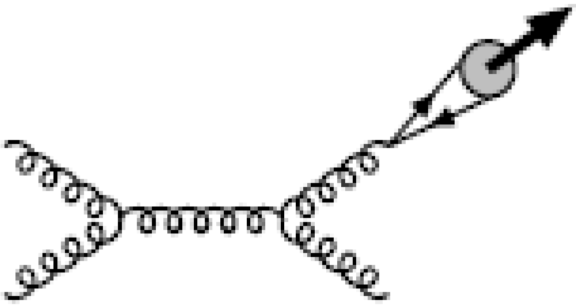
New Mechanism of Heavy Quarkonia

— parton interaction produces quark pair($c\,\bar{c}$), *quark pair can be color-octet*

— quark pair can *change color and spin through emitting gluon* and then bind into quarkonia(J/psi, psi'...)

→ ***Color Octet Mechanism (COM)***

(c) colour-octet fragmentation: $g + g \to c\bar{c}[{}^3S_1^{(8)}] + g$



$+ \ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

NRQCD Interpretation

NRQCD: Non-Relativistic QCD

- Non-Relativistic: heavy quark moves slowly.
- Consider both CSM and COM.
- Production of Quarkonia can be factored into 2 steps
  - Creation of the quark pair (q qbar)
  - quark pair bind into quarkonia

$$d\sigma(\mathcal{Q}+X)=\sum d\hat{\sigma}(Q\bar{Q}[^{2S+1}L_J^{(1,8)}]+X)\langle\mathcal{O}^{\mathcal{Q}}[^{2S+1}L_J^{(1,8)}]\rangle,$$

Short Distance Coefficient:
Creation of quark-antiquark pair.
This step is independent of final product.
Can computed **pertubatively**

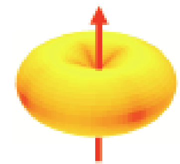
Long **D**istance **M**atrix **E**lement **(LDME):**
How likely the quark pair will bind to the quarkonia.

Problem of Onia Polarization

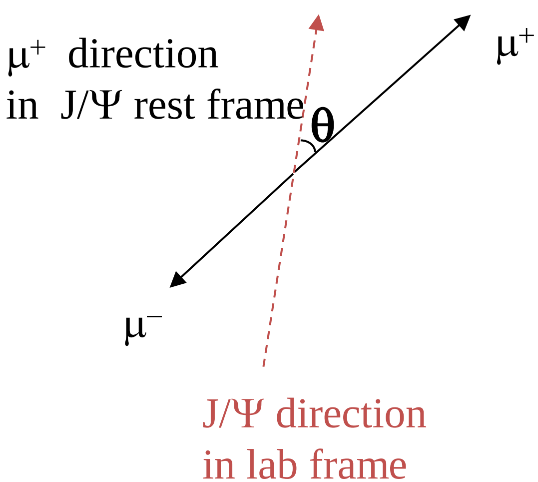
- J/ψ, ψ', $\Upsilon(nS) \to \mu\mu$
- Polarization measured through the decay angular distribution of J=1 particles:

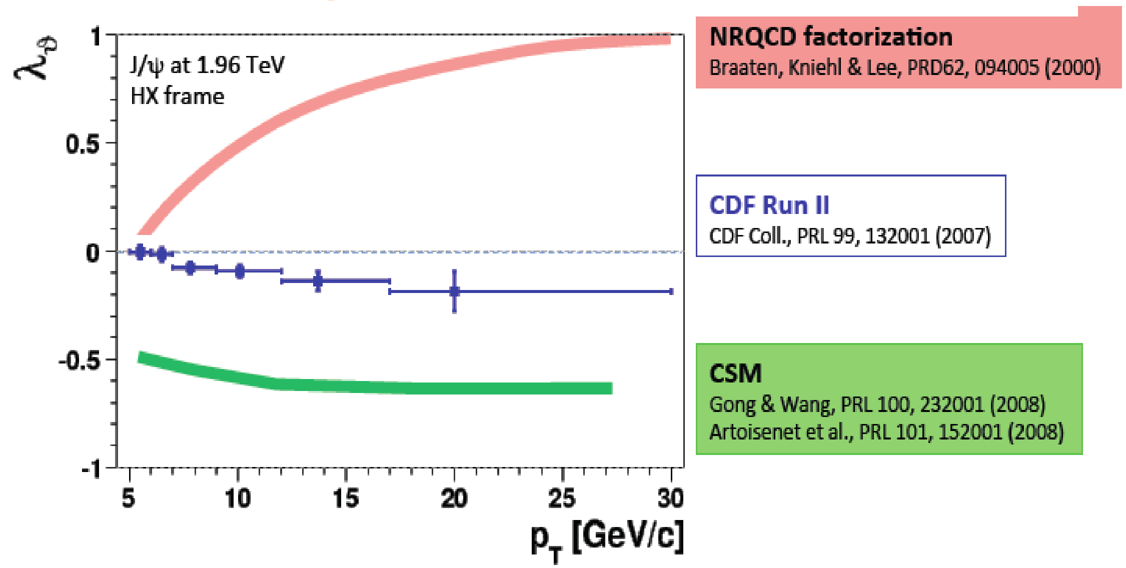
$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

$J_z = \pm 1 \to \lambda_\vartheta = +1$
"transverse" polarization



$J_z = 0 \to \lambda_\vartheta = -1$:
longitudinal polarization

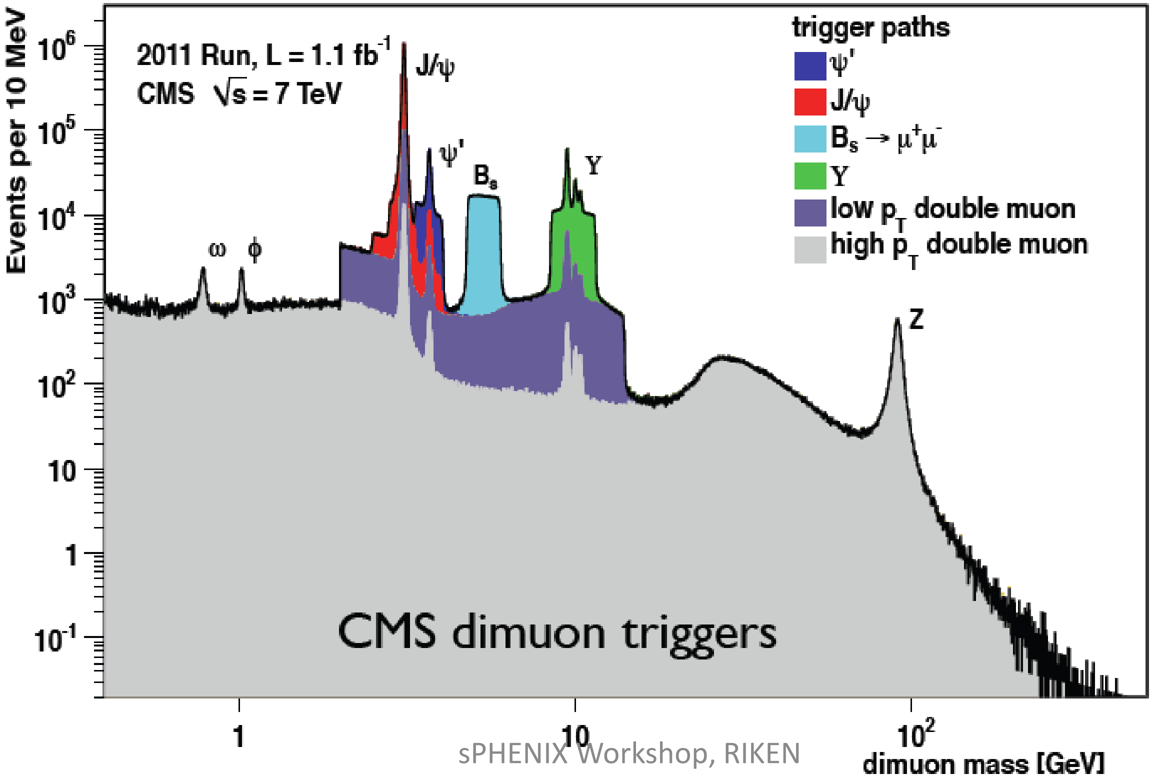




Onia Measurement @ CMS

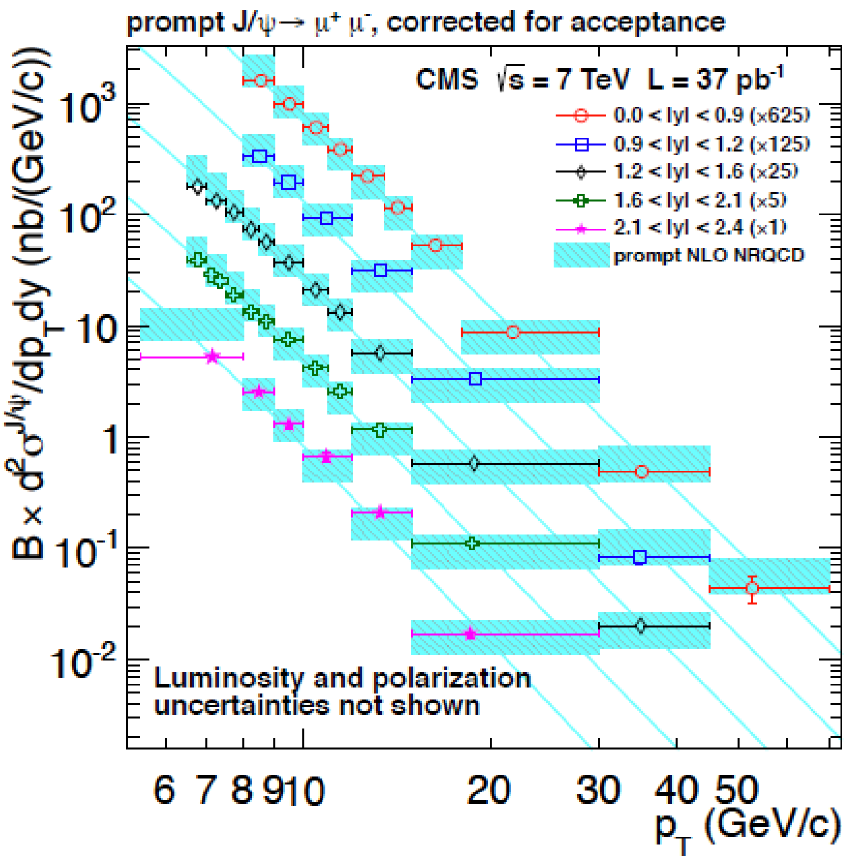
- **Test NRQCD @ CMS**

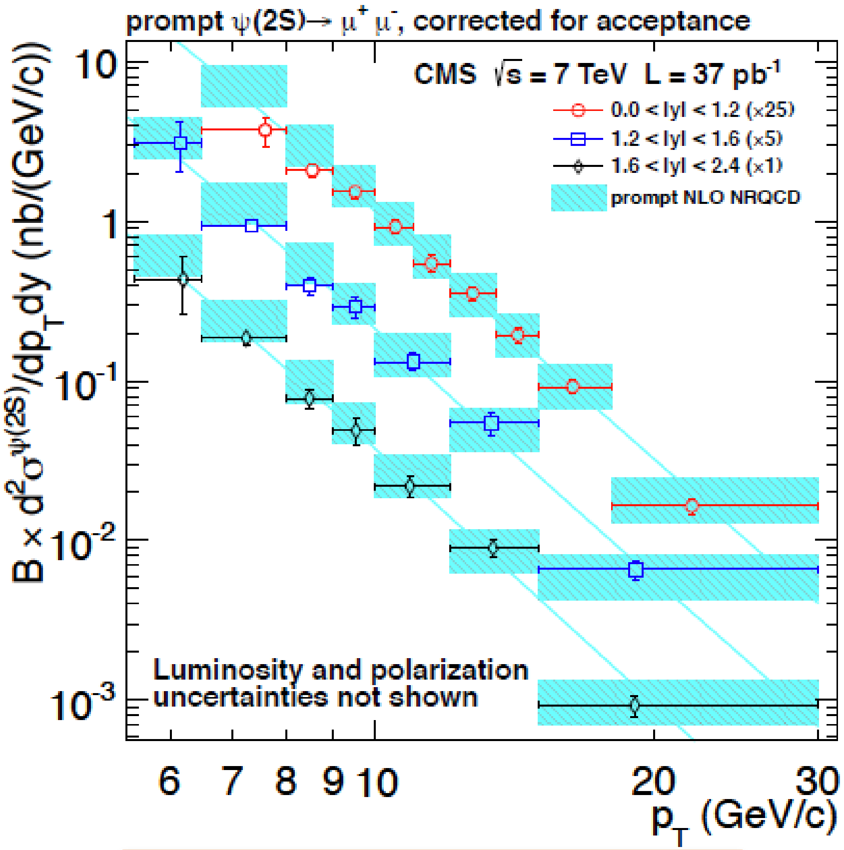
  Till now, no theory has simultaneously explained experimental results of both production cross section and polarization of quarkonium
- **LHC provides:**
  - New energy scale
  - Large pT reach
- **CMS provides:**
  - Excellent dimuon mass resolution
  - Good photon reconstruction resolution, which allows to study production and polarization of P-wave quarkonium states through radiative decays



Onia Production From pp collision

J/ψ and ψ' at $\sqrt{s}$ = 7 TeV



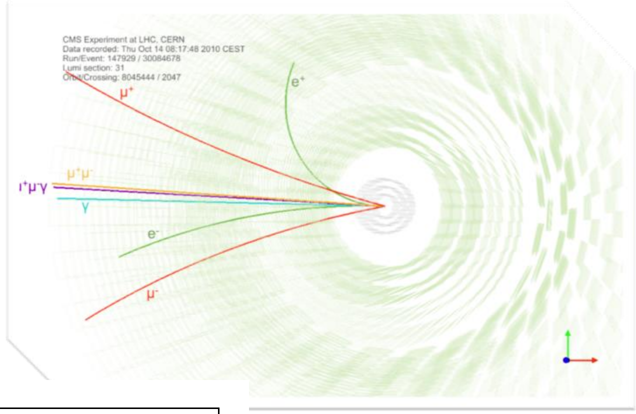


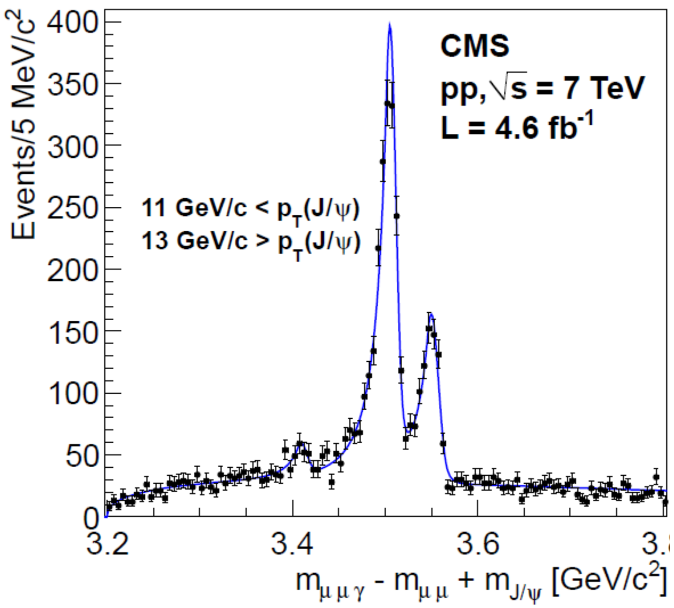
CMS, JHEP 02 (2012) 011

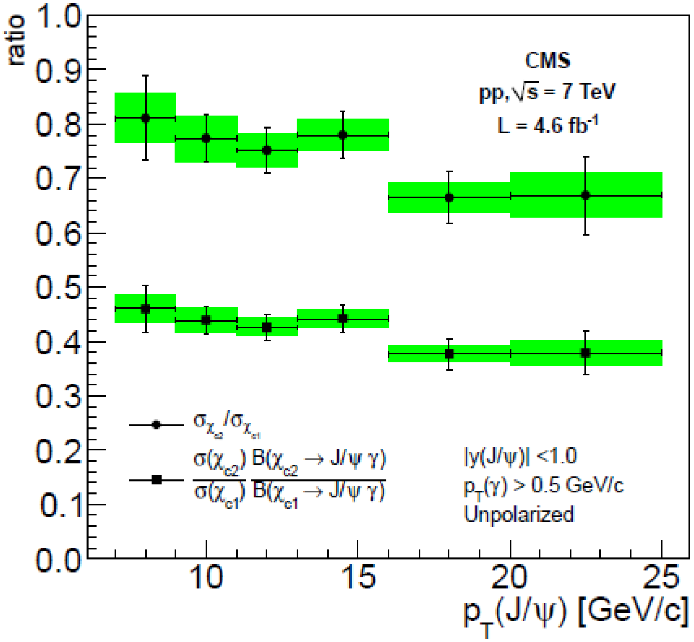
- Excellent agreement with NLO NRQCD predictions

Prompt χ_{c2} / χ_{c1} Production

- P-wave quarkonium states present complementary information to S-wave state production
- Production of χ_c mesons studied via $\chi_c \to J/\psi + \gamma$ decays, with tracker-only γ conversions to $e^+ e^-$



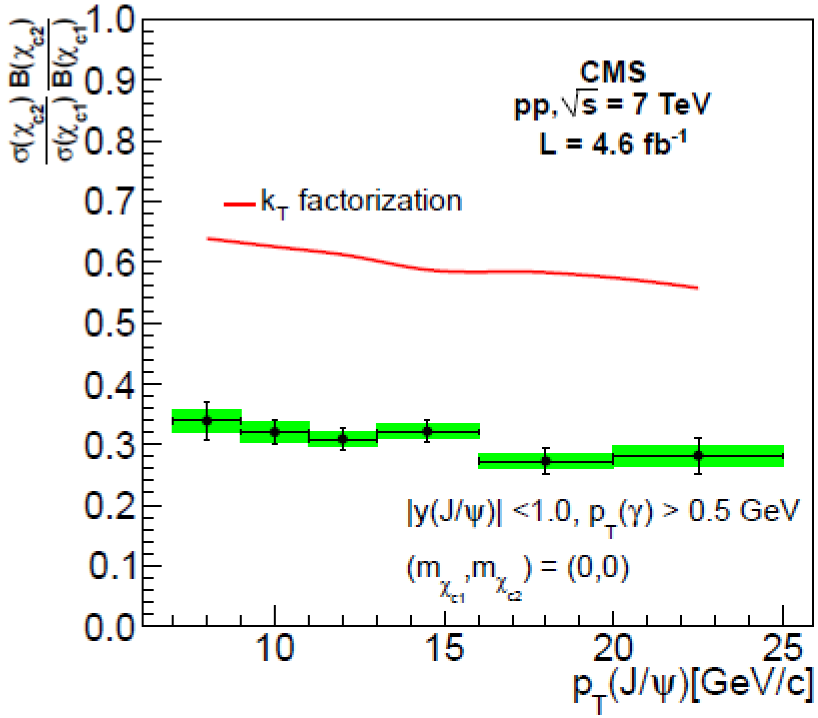


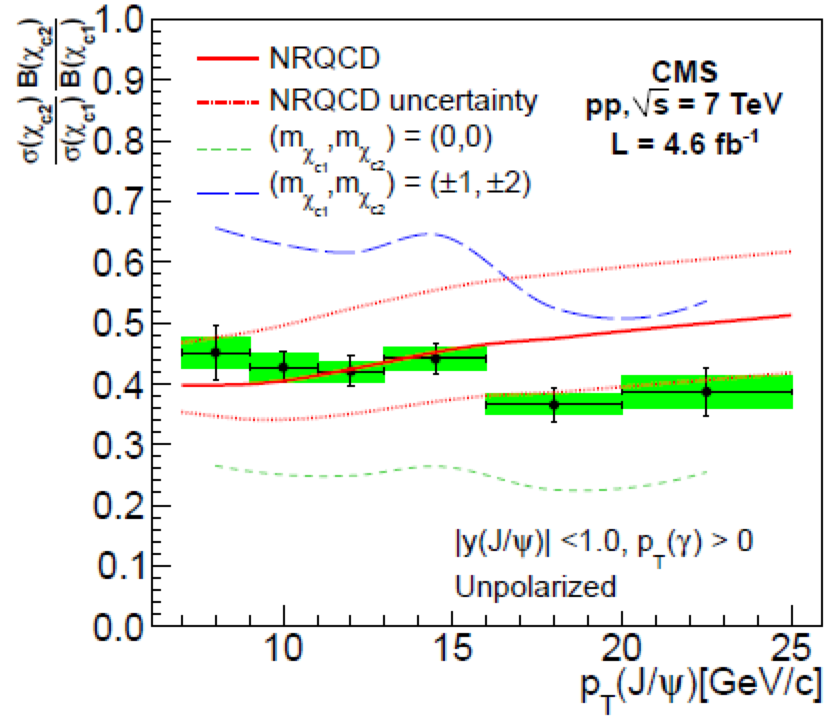


- The prompt χ_{c2} / χ_{c1} cross section ratio has been measured vs. pT

CMS [EPJC 72(2012) 2251]

Comparison to Theoretical Cal.





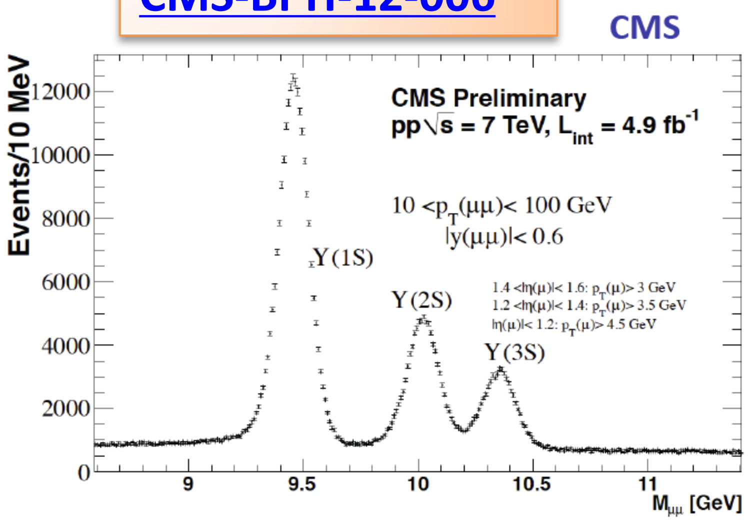
- The k_T factorization model predicts the χ_{c1} and χ_{c2} states in a $J_z^{HX} = 0$ state.
- For a proper comparison, the acceptance was recalculated under this assumption.

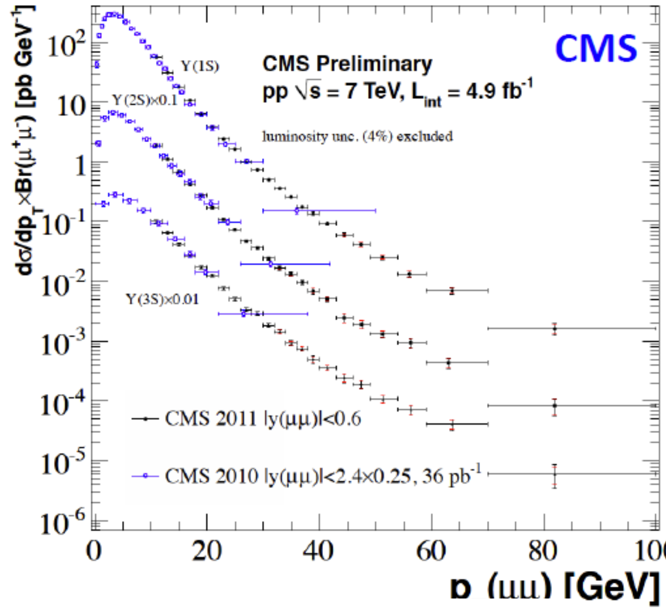
CMS [EPJC 72(2012) 2251]

- The NLO NRQCD predictions were mad w/o a cut on the photon transverse momentum. Extrapolated down to zero photon pT.
- The measurements assuming two different extreme polarization scenarios are shown by the long-dashed blue and short-dashed green lines

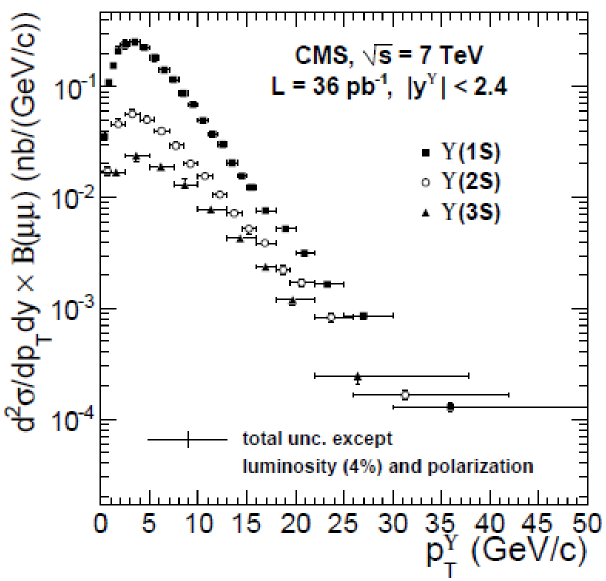
ϒ(nS) production at $\sqrt{s}$ = 7 TeV

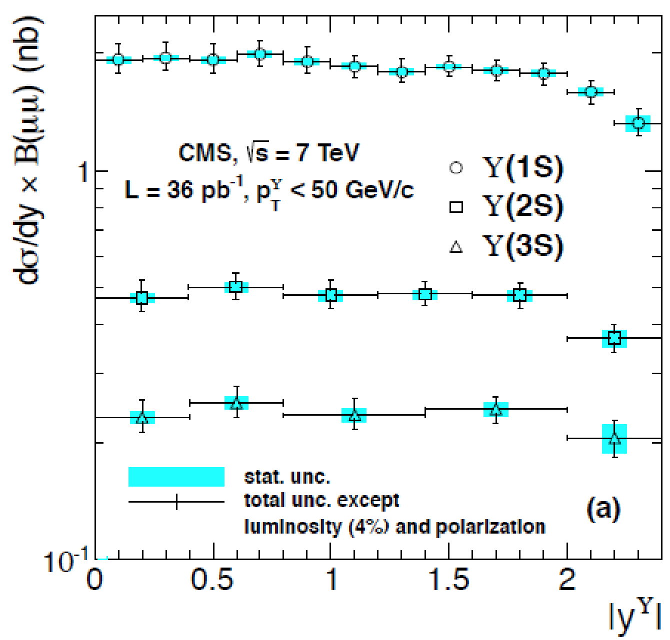
CMS-BPH-12-006





- Acceptance from measured ϒ(nS) polarization
- Cross sections measured up to very large pT (pT >> m)
- **Stringent QCD test**



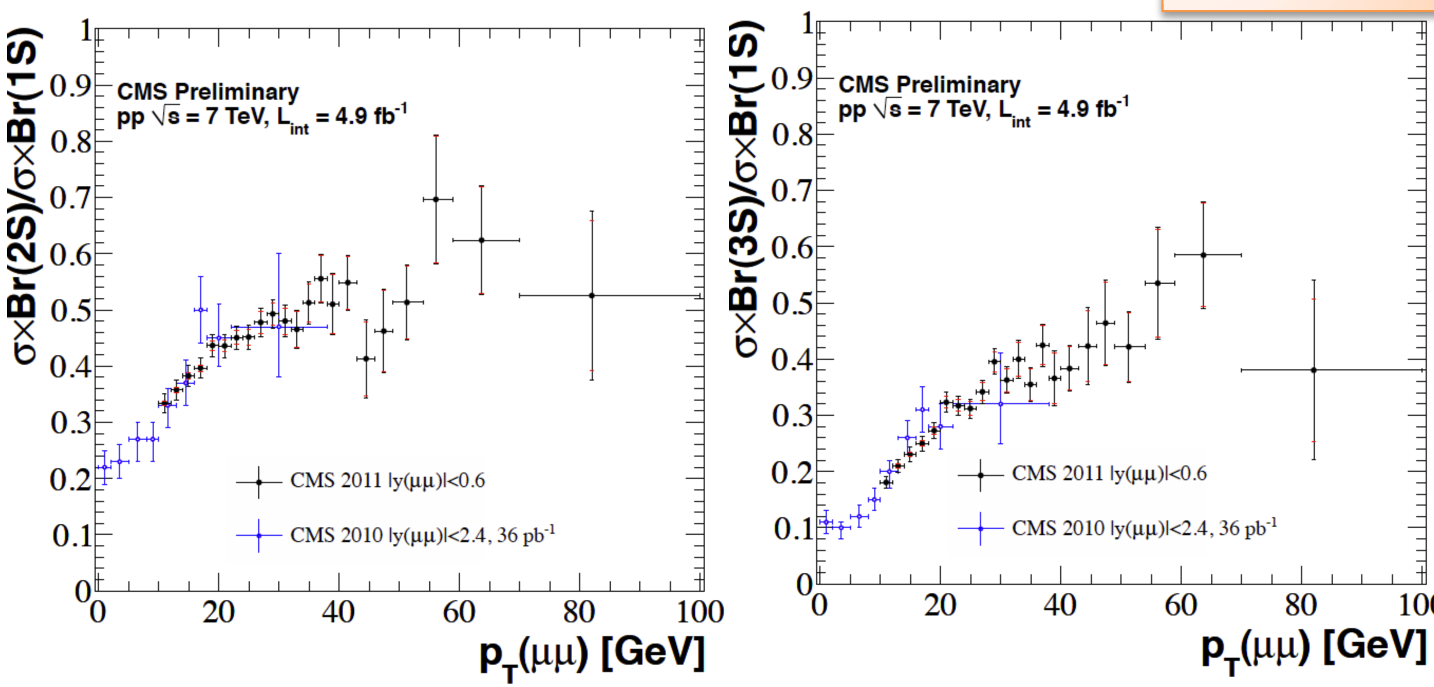


2010 data: arXiv:1303.5900

- ϒ(nS) corss section is flat until |y| ~ 2

ϒ (3S, 2S) / ϒ (1S) Production Ratio

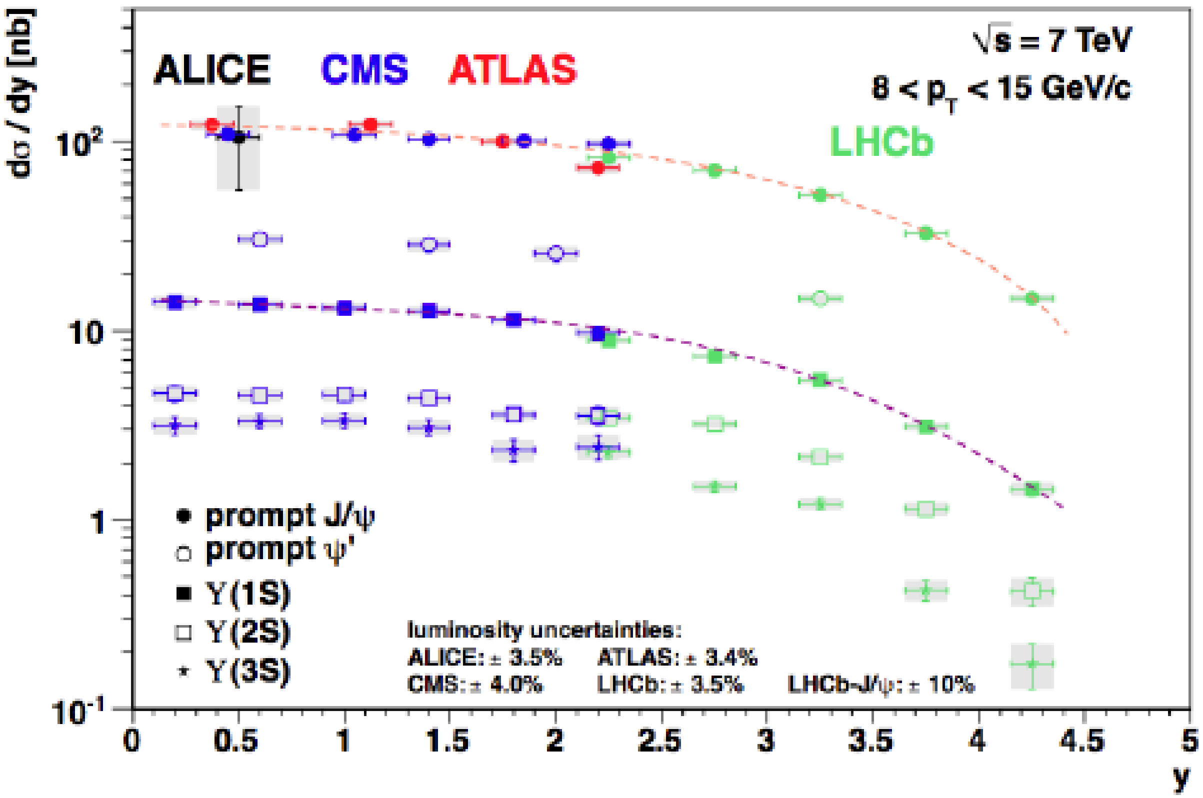
CMS-BPH-12-006



- The ϒ(nS) / ϒ(1S) ratios are flat versus rapidity
- They steadily increase with pT, and flatter for pT > ~ 30 GeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH12006

Summary of Onia Production



ALICE : 5.6 nb−1

ATLAS : 2.2 pb−1

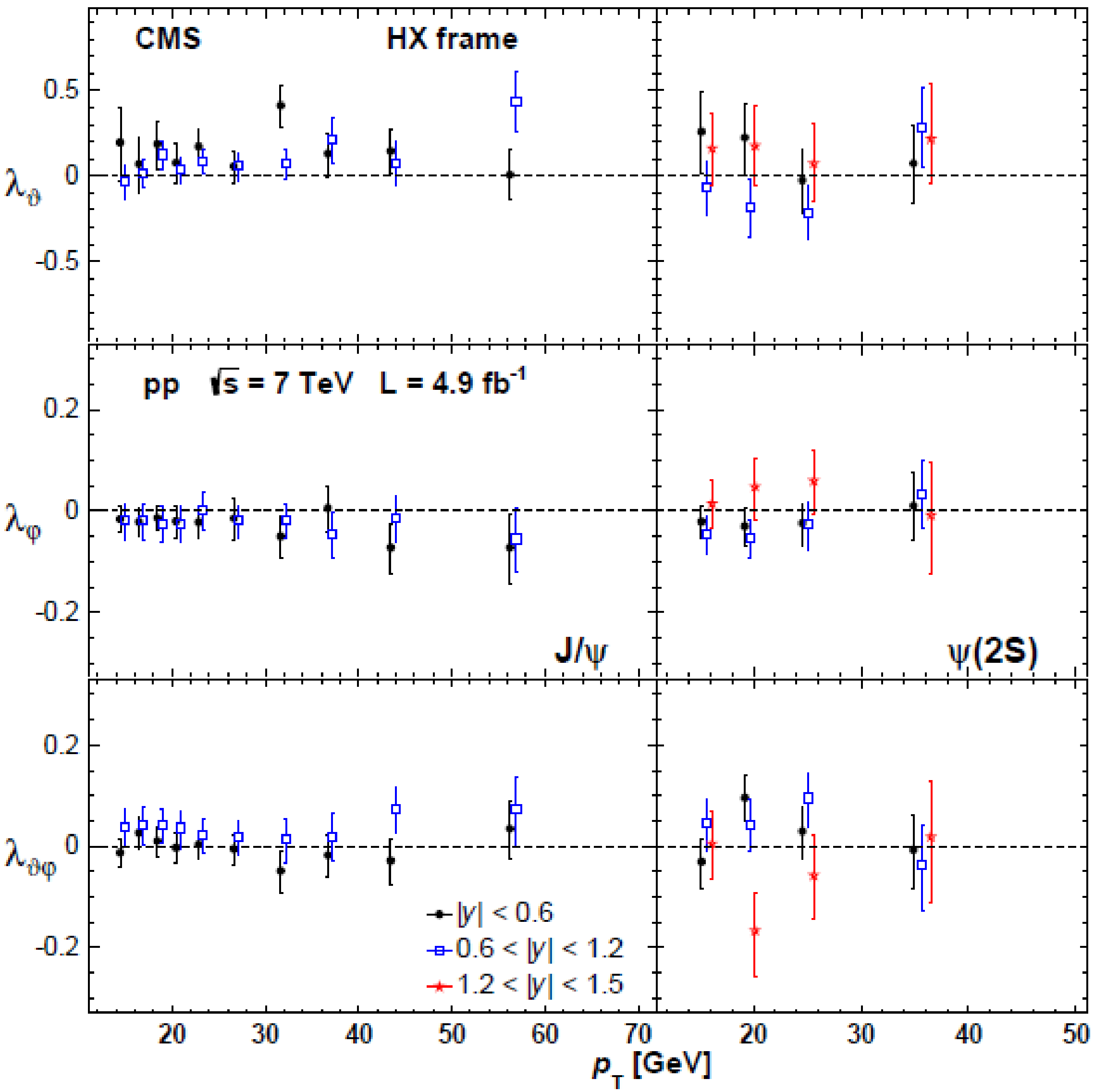
CMS : 37, 36 pb−1

LHCb : 5.2, 36, 25 pb−1

- Prompt J/ψ production has been measured by four LHC experiments for pT > 8 GeV
- Rapidity dependences (of ATLAS, CMS, and LHCb) are similar but not perfectly overlapping
- CMS and LHCb trends can also be compared for prompt ψ's and for the three ϒ states

Onia Polarization from pp

Prompt ψ(nS) Polarization in the HX frame



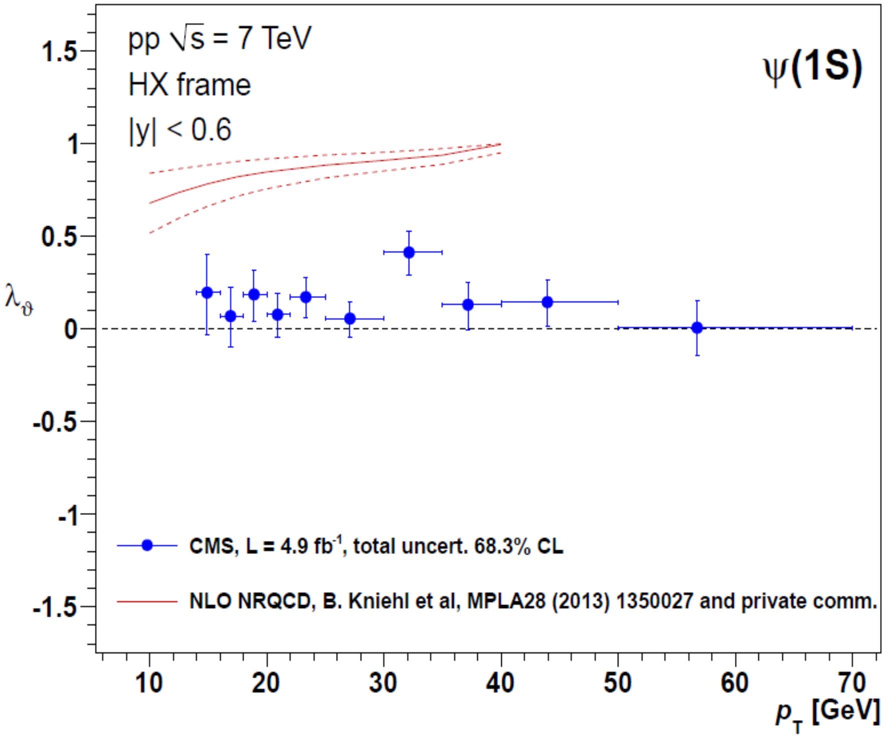
- No evidence of significant transverse or longitudinal polarizations
- For ψ(2S), there is no feed-down from heavier quarkonia

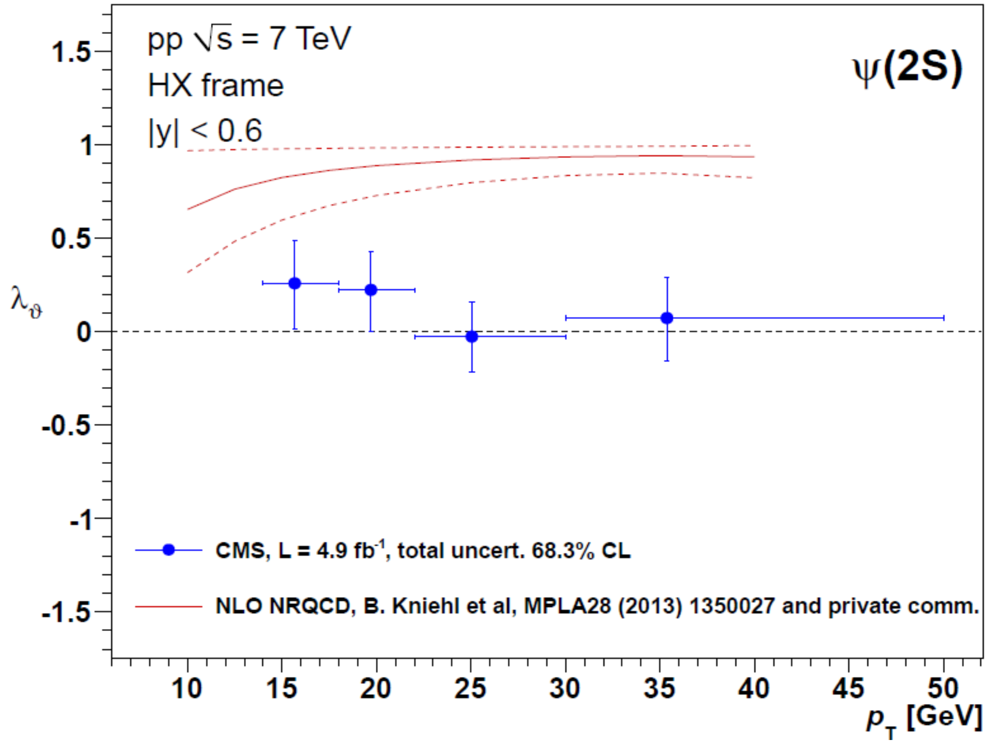
Error bars show total uncertainty at 68.3% level

arXiv:1307.6070v1

ψ(nS): Comparison to NLO NRQCD

- CMS results disagree with the NLO NRQCD calculations
- Theory predicts polarization only for directly produced ψ's





arXiv:1307.6070v1

Possible Interpretation?

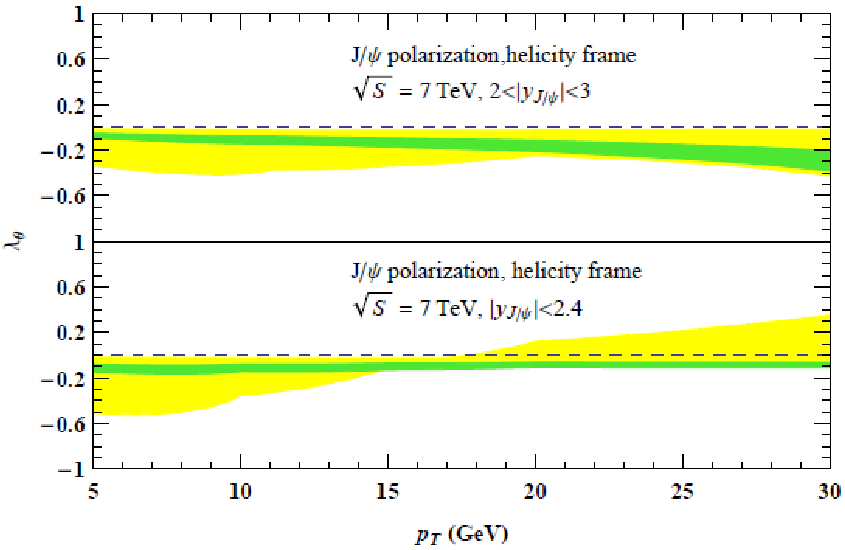


FIG. 4: (color online) NLO predictions of the J/ψ polarization observable λ_θ at the LHC. The uncertainty is shown by large yellow bands when varying the CO LDME $\langle \mathcal{O}({}^1S_0^{[8]}) \rangle$. The bounds of $\lambda_\theta = 0$ in yellow bands correspond to CO LDMEs in the third row of Table.I, while the other bounds correspond to the second row of Table.I. The small green bands are the predictions using the CO LDMEs in the first row of Table.I.

$\langle \mathcal{O}({}^3S_1^{[1]}) \rangle$ GeV^3	$\langle \mathcal{O}({}^1S_0^{[8]}) \rangle$ 10^{-2}GeV^3	$\langle \mathcal{O}({}^3S_1^{[8]}) \rangle$ 10^{-2}GeV^3	$\langle \mathcal{O}({}^3P_0^{[8]}) \rangle / m_c^2$ 10^{-2}GeV^3
1.16	8.9 ± 0.98	0.30 ± 0.12	0.56 ± 0.21
1.16	0	1.4	2.4
1.16	11	0	0

TABLE I: Different sets of CO LDMEs for the J/ψ. Values in the first row are obtained by fitting the differential cross section and polarization of prompt J/ψ simultaneously at the Tevatron [4]. Values in the second and third rows are two extreme choices for these CO LDMEs. The color-singlet LDME is calculated by the B-T potential model in [16].

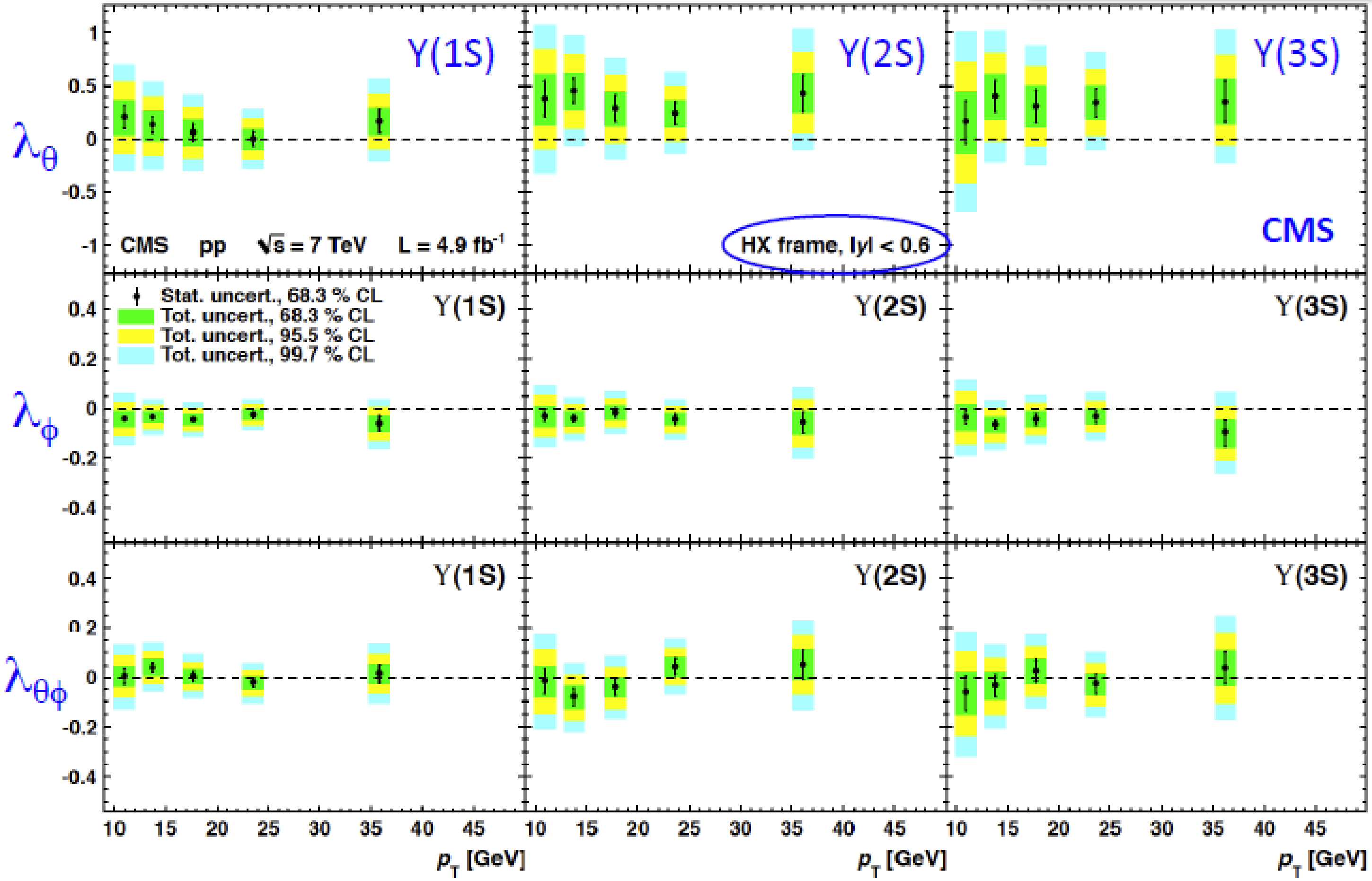
the transverse components can be largely canceled between the ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channels, leaving the remaining terms to be dominated by the unpolarized J/ψ

Chao et al, PRL108, 242004 (2012)

Upsilon Polarization

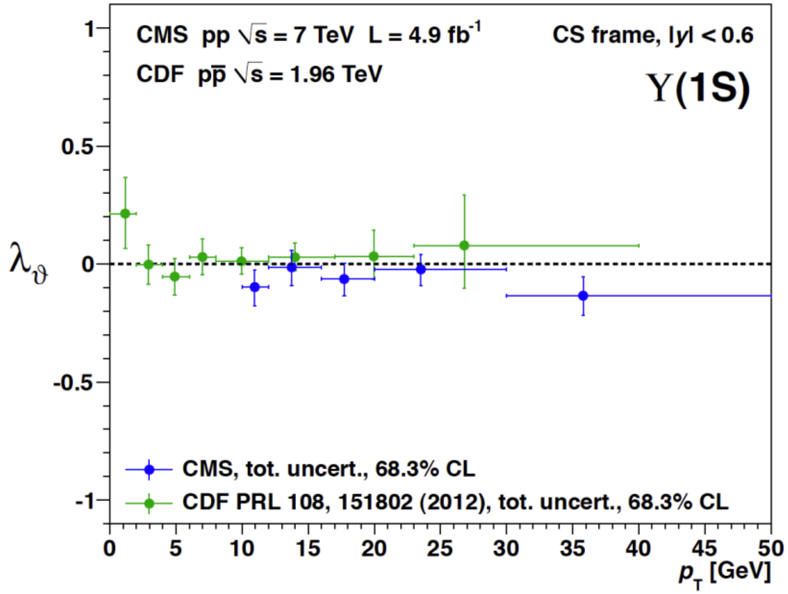
- CMS measured the $\Upsilon(nS)$ polarizations vs. pT in two |y| bins and three polarization frames: helicity (HX), Collins-Soper (CS) and perpendicular helicity (PX)

CMS, PRL 110 (2013) 081802

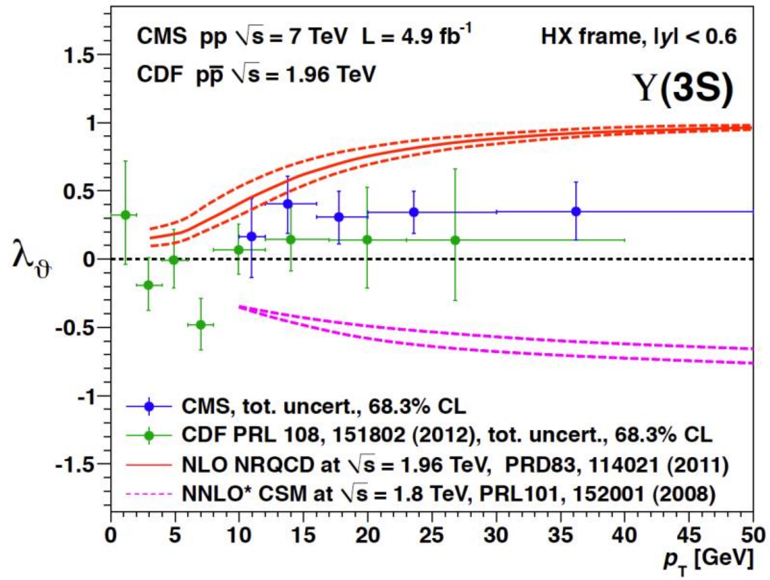


Comparison to CDF

- CMS extends the measurements beyond the pT and |y| ranges probed by CDF and Tevatron
- Theory is more reliable for pT >> m
- Υ(1S) has a very large χ_b feed-down contribution, of un-know polarization



- Υ(3S) should be almost free from feed-down
- Measured polarizations are much weaker than expected by the theory models



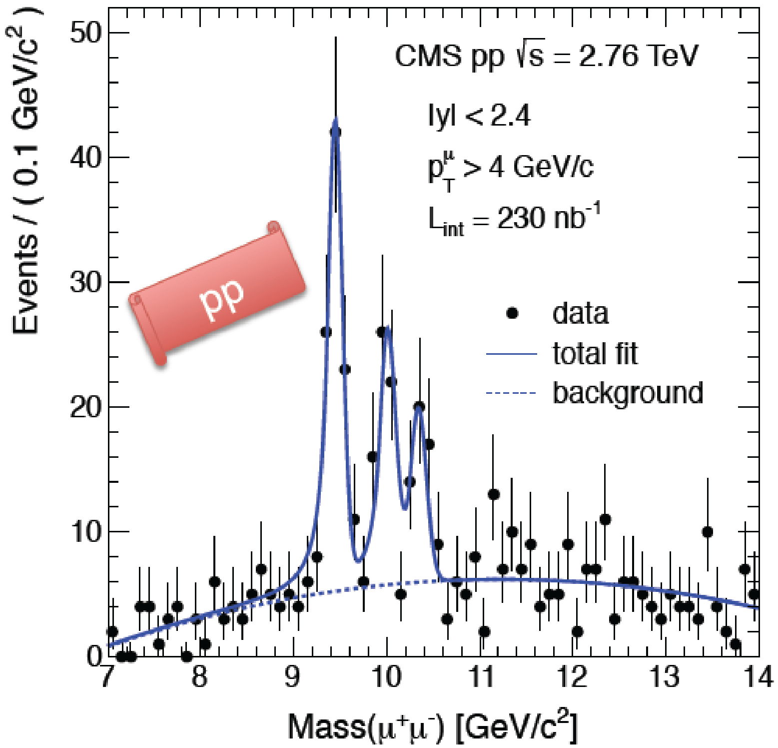
Onia From HI collision

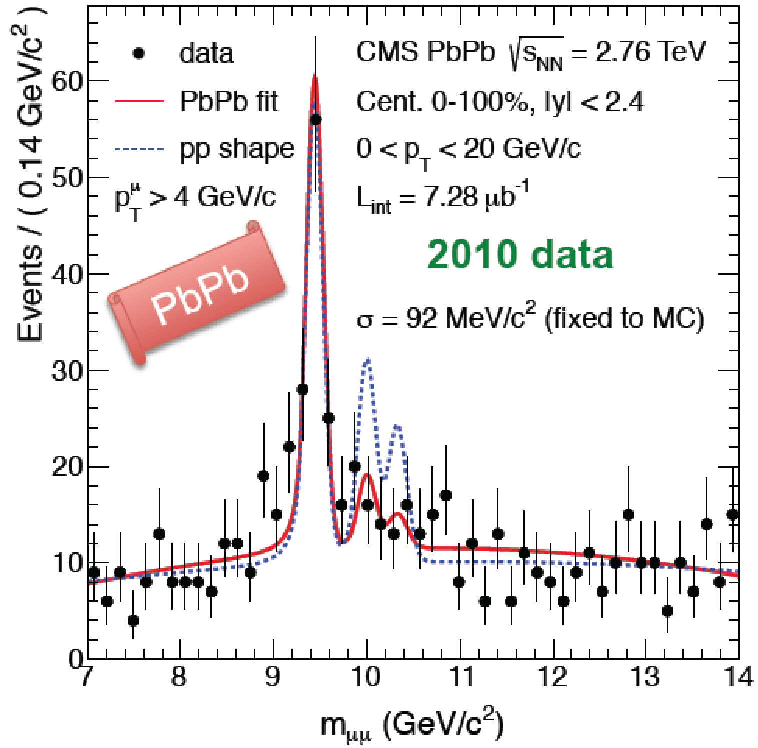
Upsilon from PbPb($7.28 \mu b^{-1}$)

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

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

PRL 107 (2011) 052302





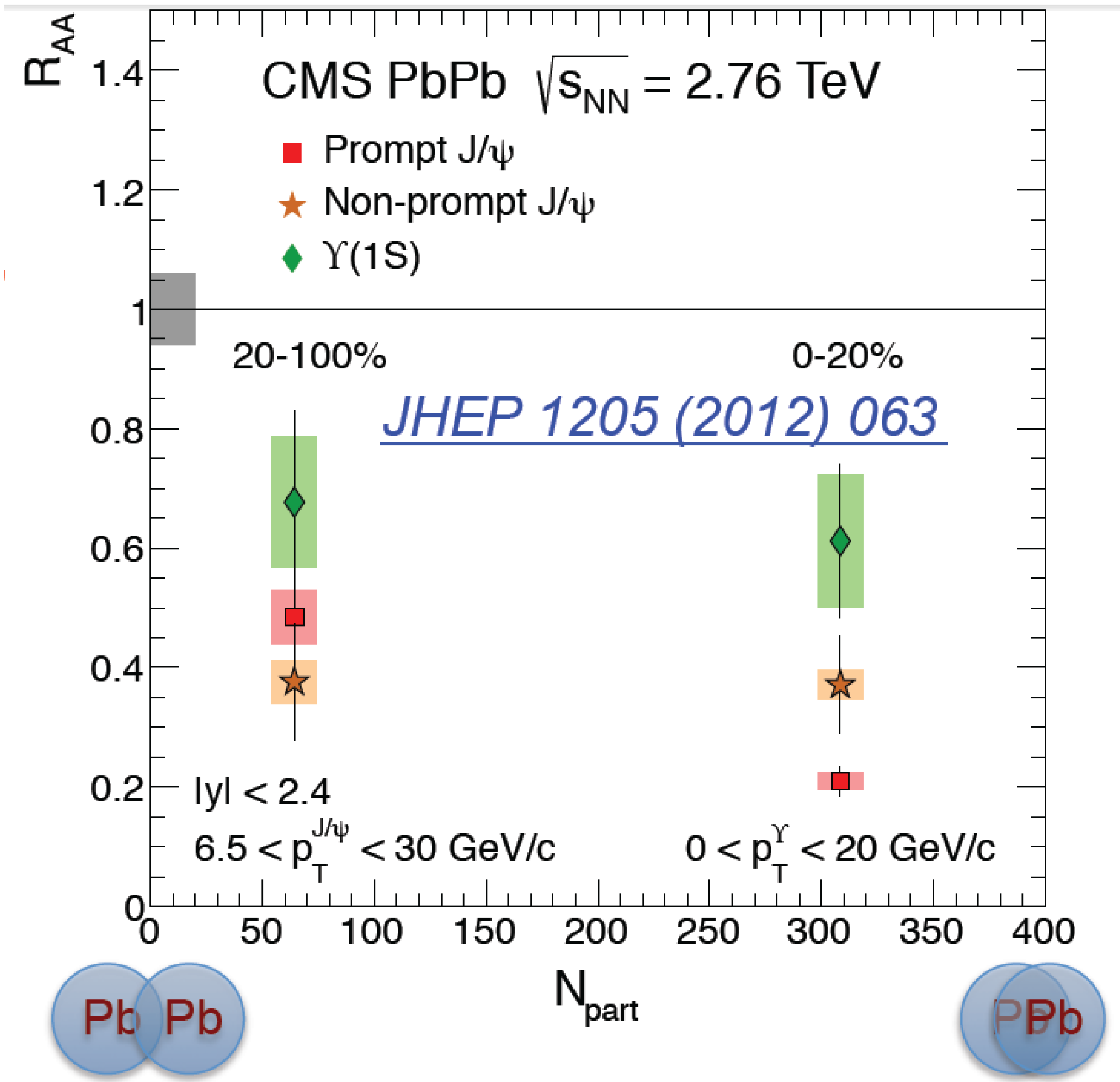
Signal :

- PbPb and pp: 3 x CB
- Common shape & parameters for 2 samples

Background :

- 2nd order polynomial
- Float separately in 2 samples

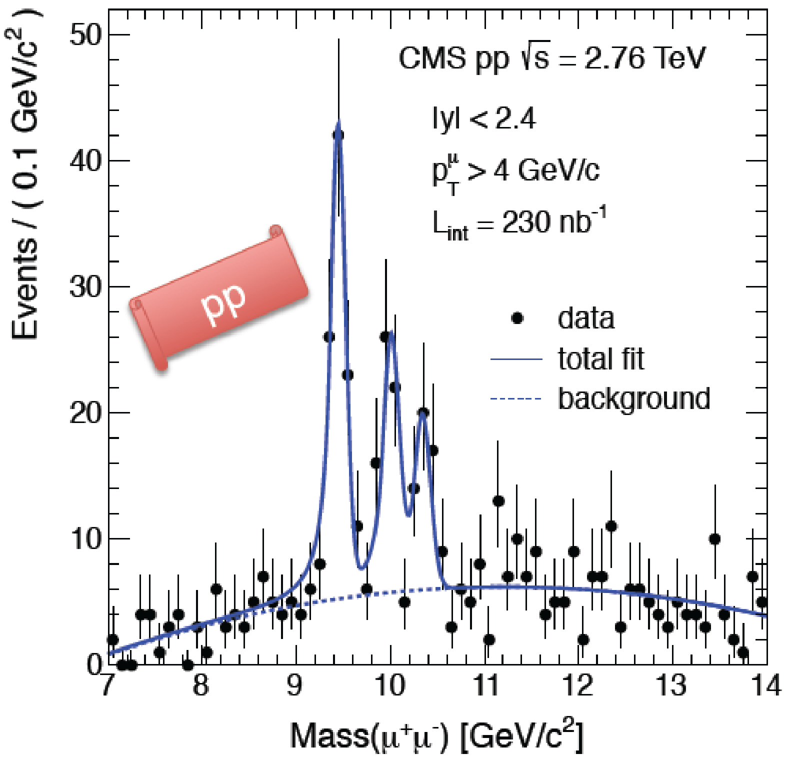
Onia Suppression in PbPb

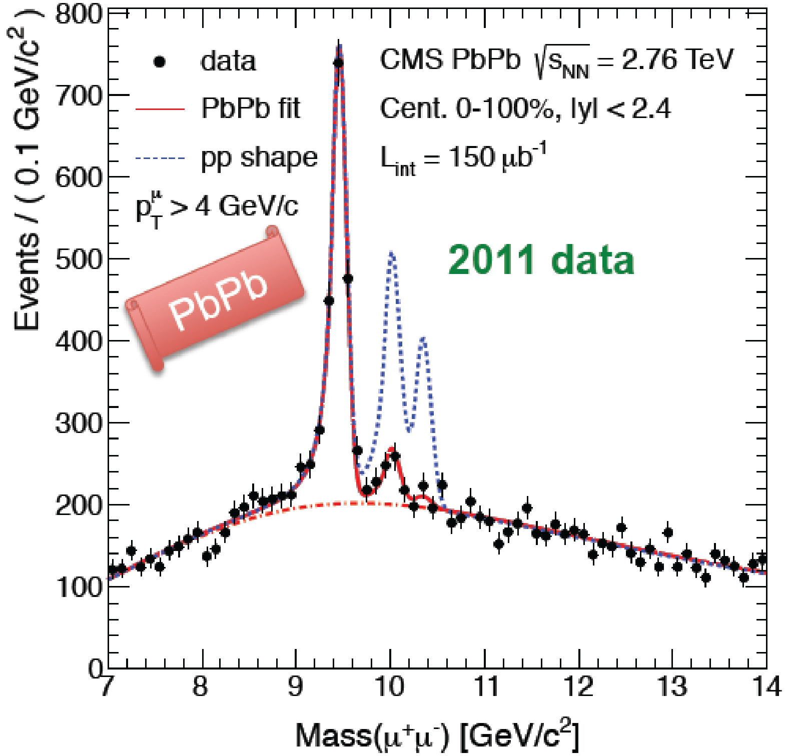


Upsilon from PbPb($150\mu b^{-1}$)

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

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





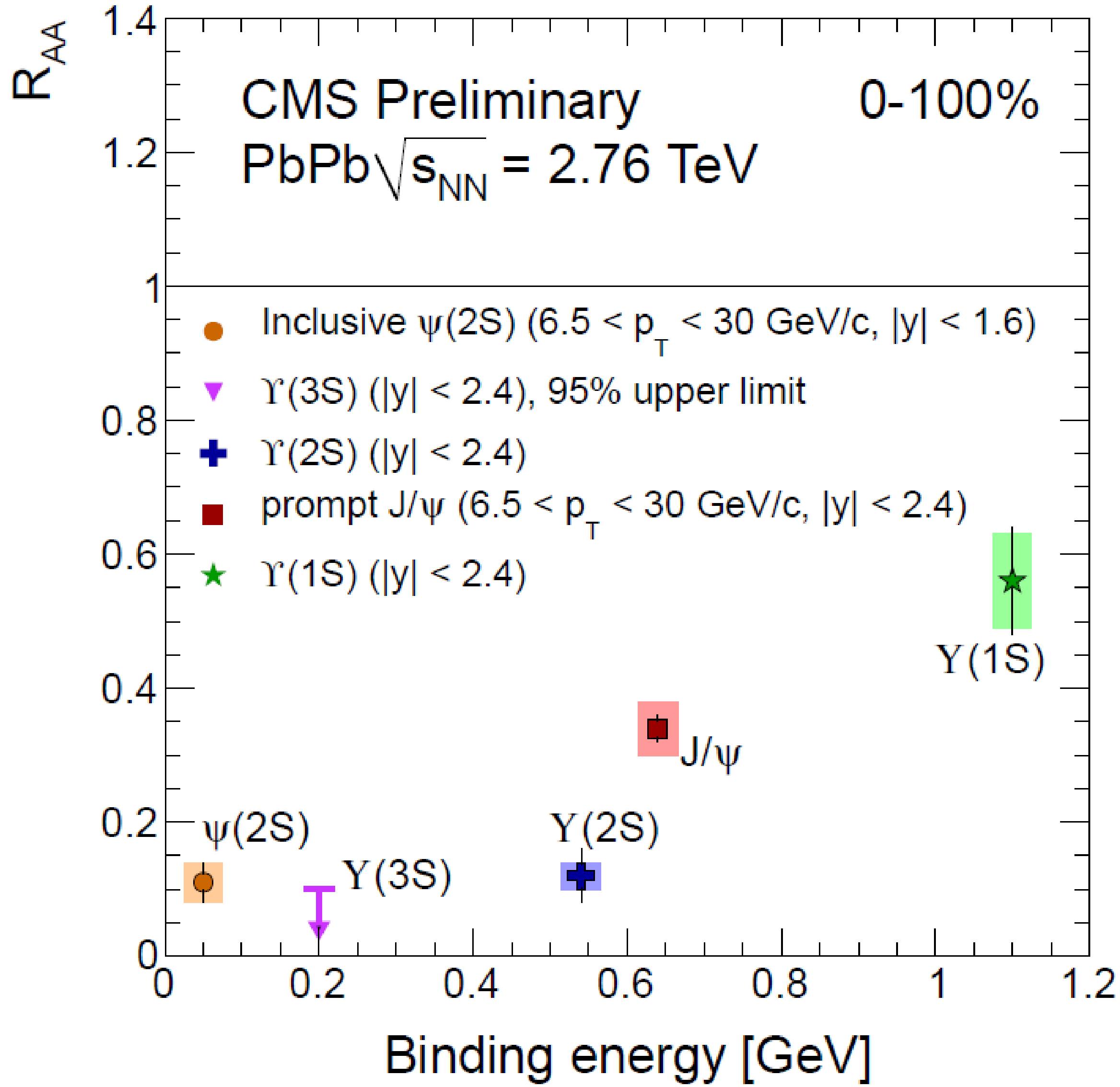
Signal :

- PbPb and pp: 3 x CB
- Common shape & parameters for 2 samples

Background :

- PbPb: erf • exp;   pp: 2^{nd} order poly.
- Float separately in 2 samples

Onia Suppression in PbPb(Updated)

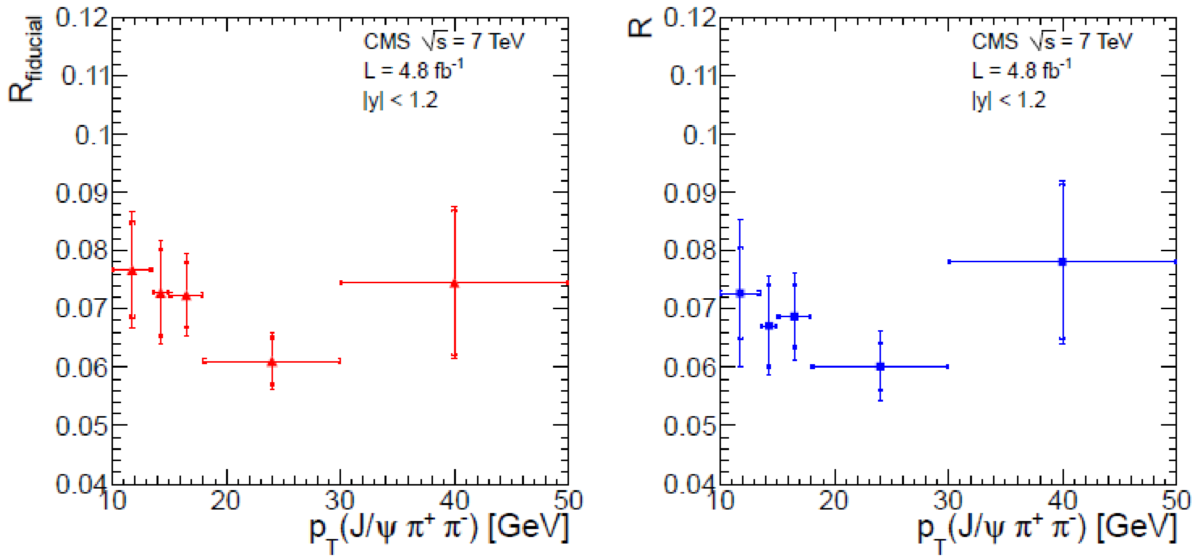


https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsHIN12014/raaVSdE_minbias_allOnia.pdf

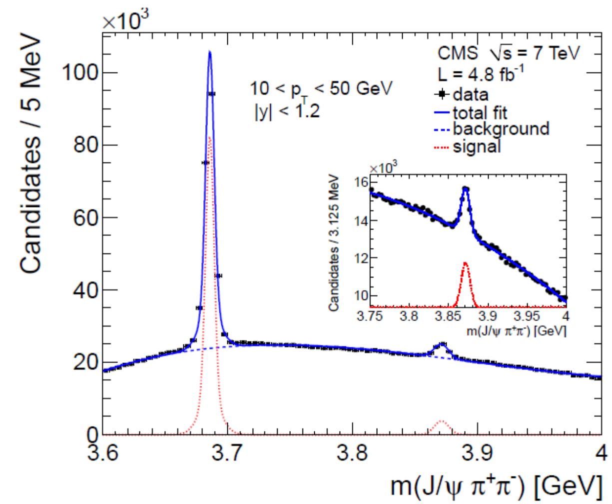
Other Onia Related Measurements

X(3872) Measurement

- CMS measures X(3872)-> J/ψ π π decays with |y| < 1.2, 10 < pT < 50 GeV
- L_{int} = 4.8 fb^{-1}: ~ 12,000 X(3872) candidates with pT(μ) > 4 GeV, pT(π) > 0.6 GeV



Ratios of the X(3872) and ψ(2S) cross sections times branching fractions, without (left) and with (right) acceptance corrections for the muon and pion pairs



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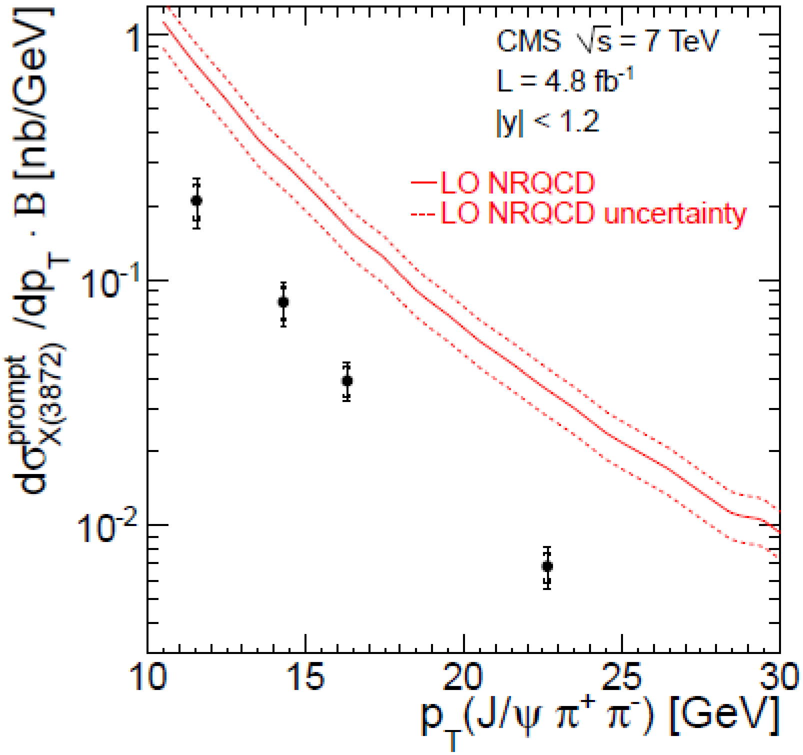
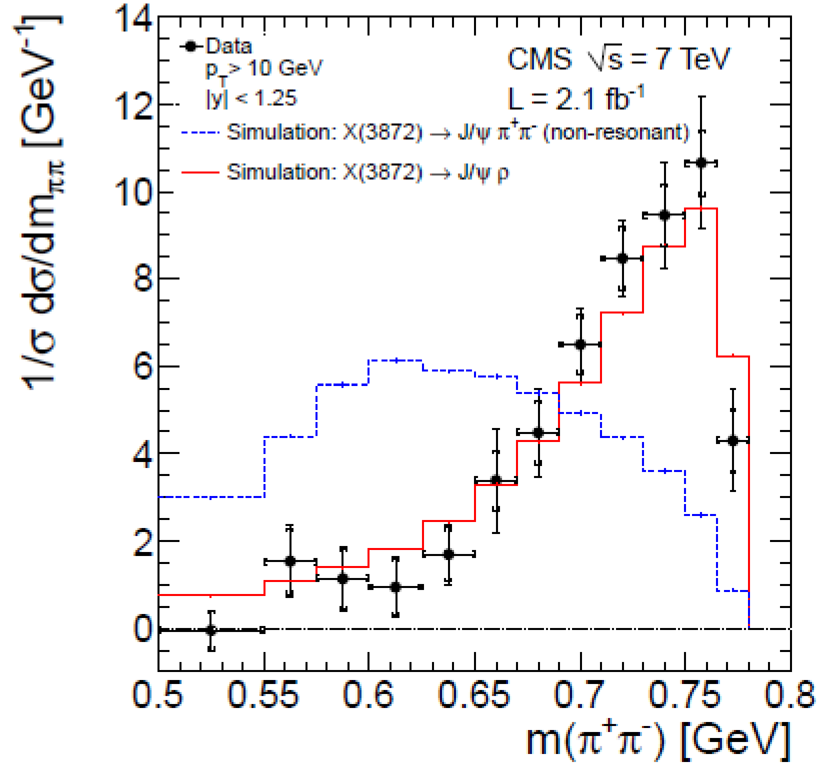
X(3872) Production Xsection





$\sigma^{prompt} \cdot \mathbf{B} = \mathbf{1.06 \pm 0.11(stat.) \pm 0.15(syst.)nb}$

Fits to J/ψππ spectrum in m(ππ) bins -> confirm resonant decay through J/ψ ρ

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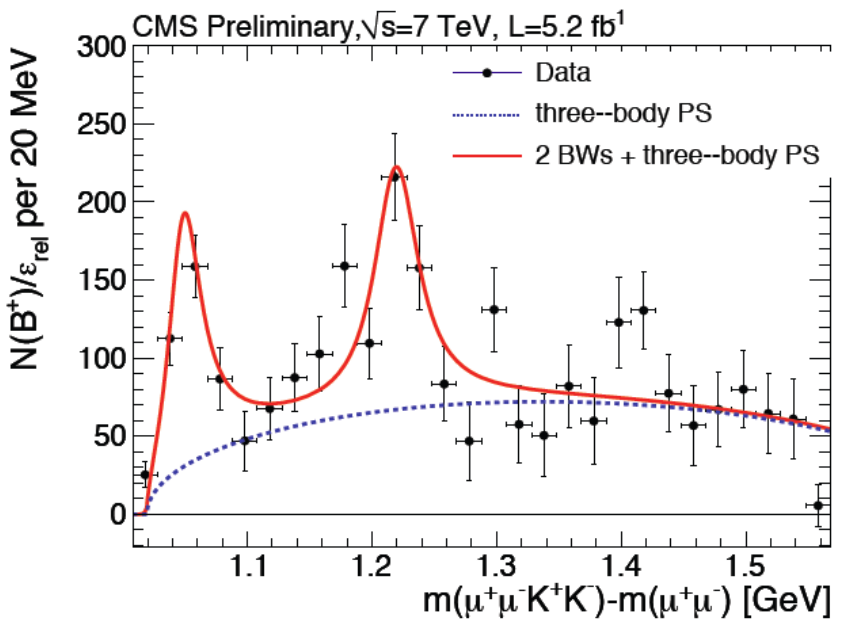
Observation of Structures via J/ψφ

- CDF observed the Y(4140) structure with a significance greater than 5 σ

- CMS confirmed a structure at 4148 MeV with a significance greater than 5 σ and saw an evidence for the second structure in the same mass spectrum.

CMS-BPH-11-026

$m(1^{st}) = 4148.2 \pm 2.0(stat) \pm 5.2(sys)$ MeV
$m(2^{nd}) = 4316.7 \pm 3.0(stat) \pm 10.0(sys)$ MeV



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026

Summary

- **CMS has been run pretty well for both the detector and the physics**
- **Quarkonia have been measured as ideal probes to study NRQCD, QGP, etc**

The production mechanism is not fully understood yet (pp)

Sequential suppression is observed (PbPb)

**Thanks to LinLin Zhang (pp) and Zhen Hu(PbPb)
for their help on preparing this talk**


Thank you!