Quarkonium Physics in CMS

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On behalf of the CMS Collaboration

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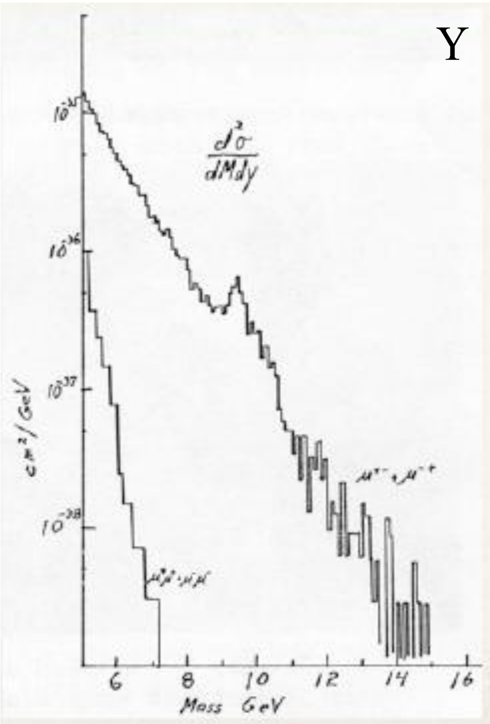
outline

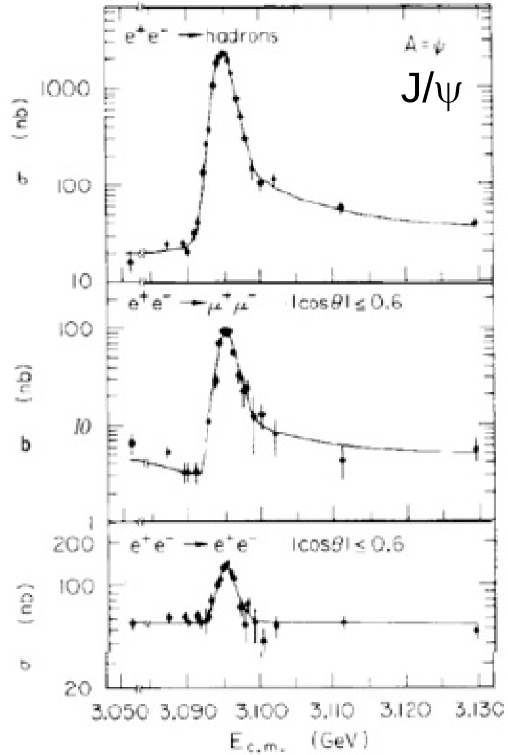
- Physics motivations for quarkonia studies at LHC
- CMS detector
- Muon reconstruction
- Data collection and dimuon event selection
- J/ψ and $\Upsilon(nS)$ early studies
    - Acceptance and efficiency determination
    - J/ψ yield and non-prompt charmonium component
    - towards inclusive cross-sections and evaluation of systematic uncertainties
- Conclusions

motivation

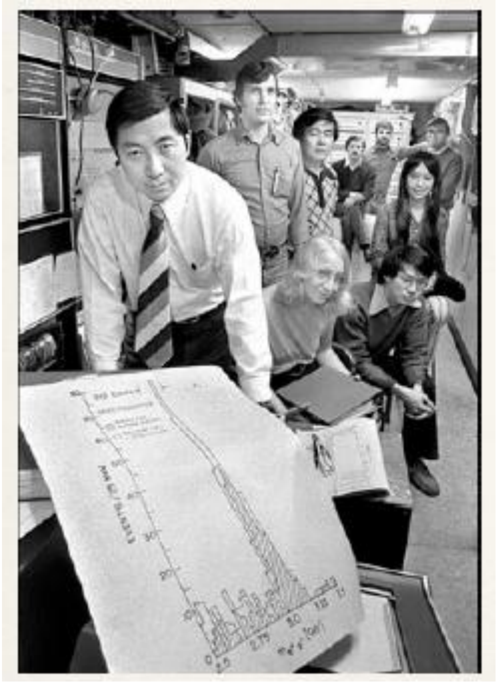
For more than 35 years after its discovery, the production mechanism of prompt quarkonium in pp collisions has remained rather puzzling



FNAL 1977



SLAC 1974



BNL 1974

… between then and now

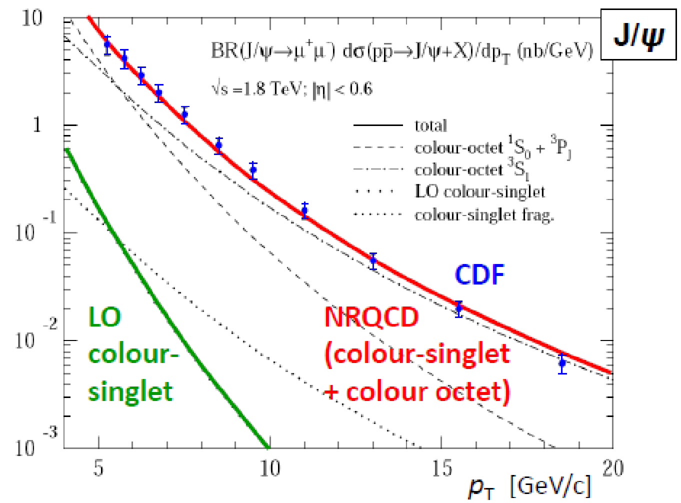
CSM and CEM (1976-1977) predictions roughly ok for early '90s fixed target data

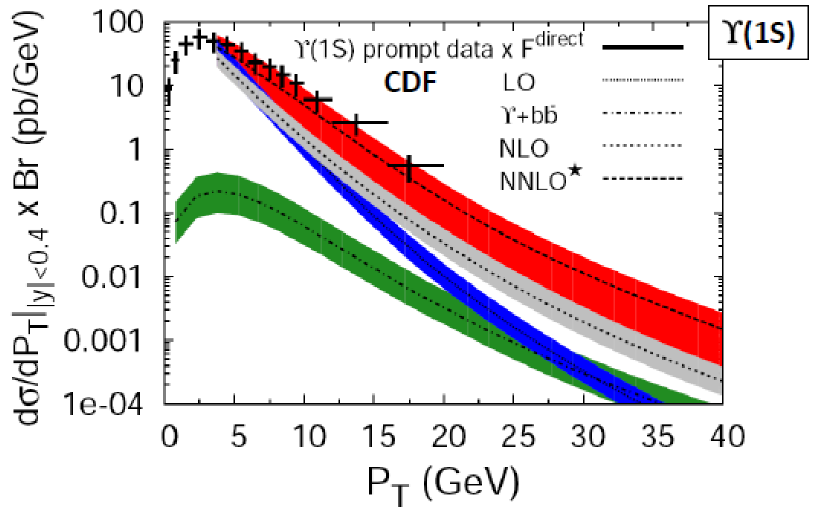
LO CSM(1993), COM, NRQCD (1995), NLO CSM struggle to explain more recent data at colliders

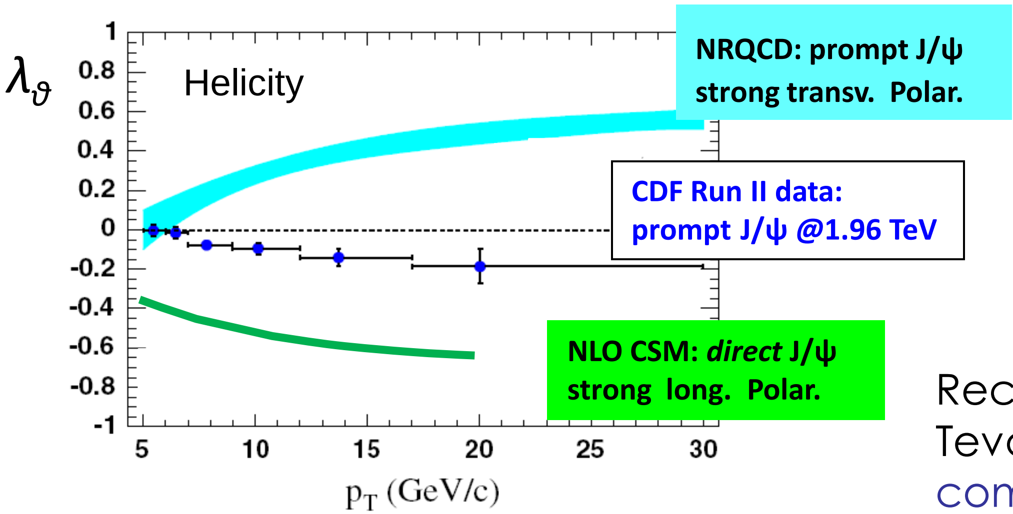
Does theory explain data?

For more than 35 years after its discovery, the production mechanism of prompt quarkonium in pp collisions has remained rather puzzling

- All theoretical models proposed so far cannot describe simultaneously the quarkonium differential cross sections and the polarization data measured at the Tevatron

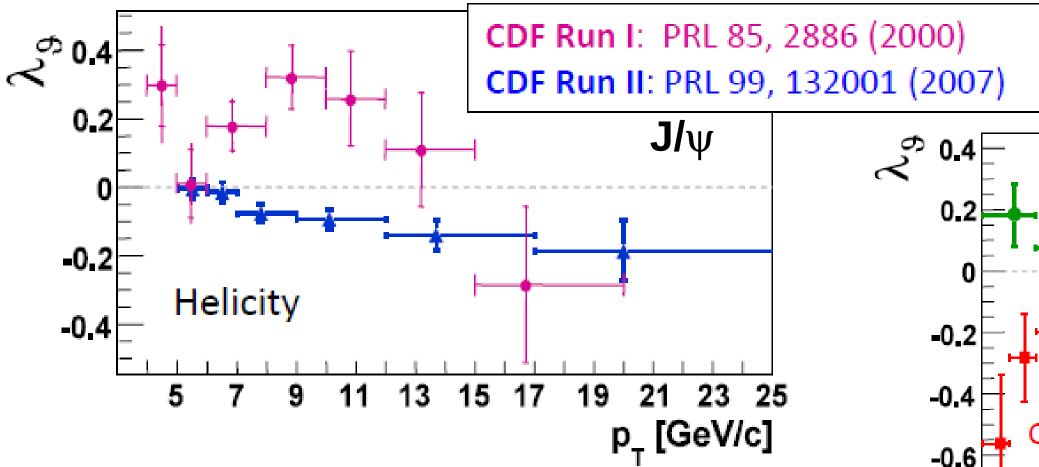


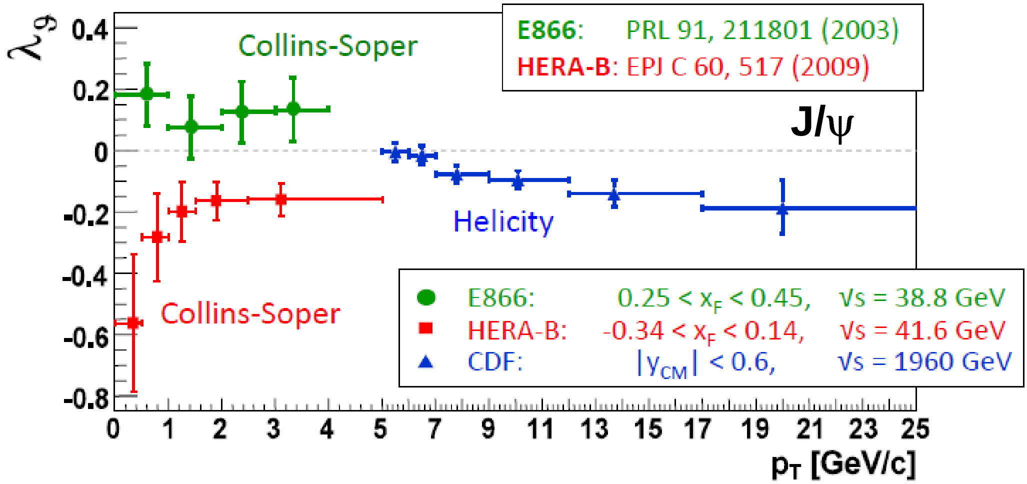




Recently, CSM + high orders well describes Tevatron Υ x-section data. A sizeable octet component is no longer required

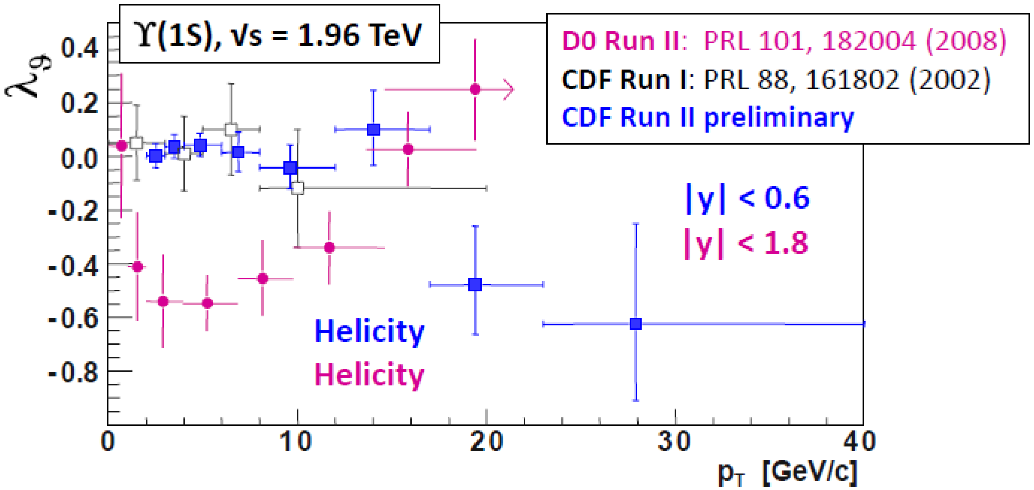
… do data make sense?





- The scenario is quite contradictory since experimental measurements require full control of systematics and efficiencies

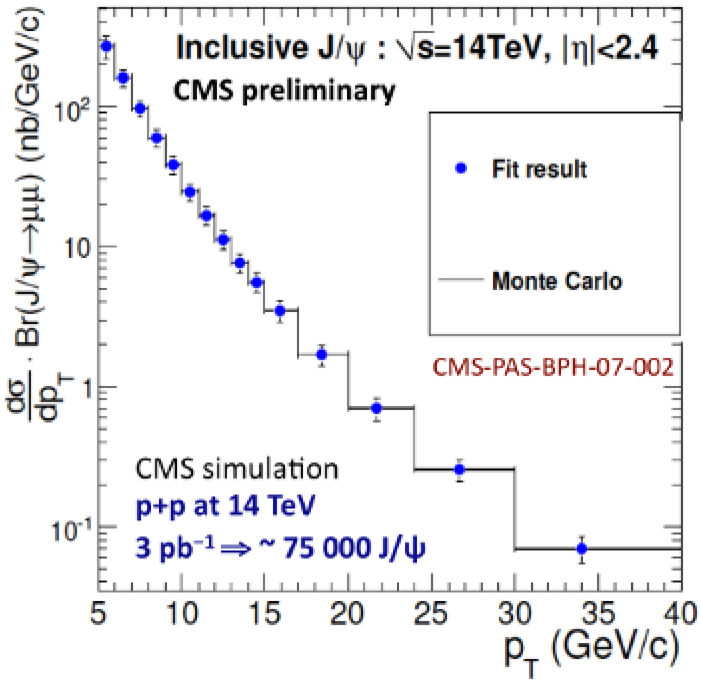
- **Need high-statistics samples and measurements of all observables (both polar and azimuthal anisotropy)**

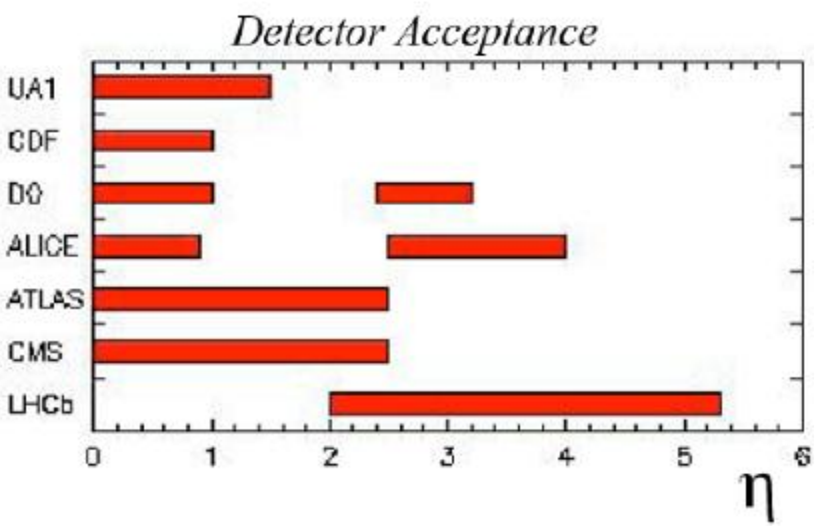


a new opportunity

At LHC one has the unique opportunity to test theoretical predictions at a much higher energy and in a wider rapidity range

- Competitive with Tevatron after only ~pb^{-1}
- Probe cross sections beyond p_T=20 GeV for the first time

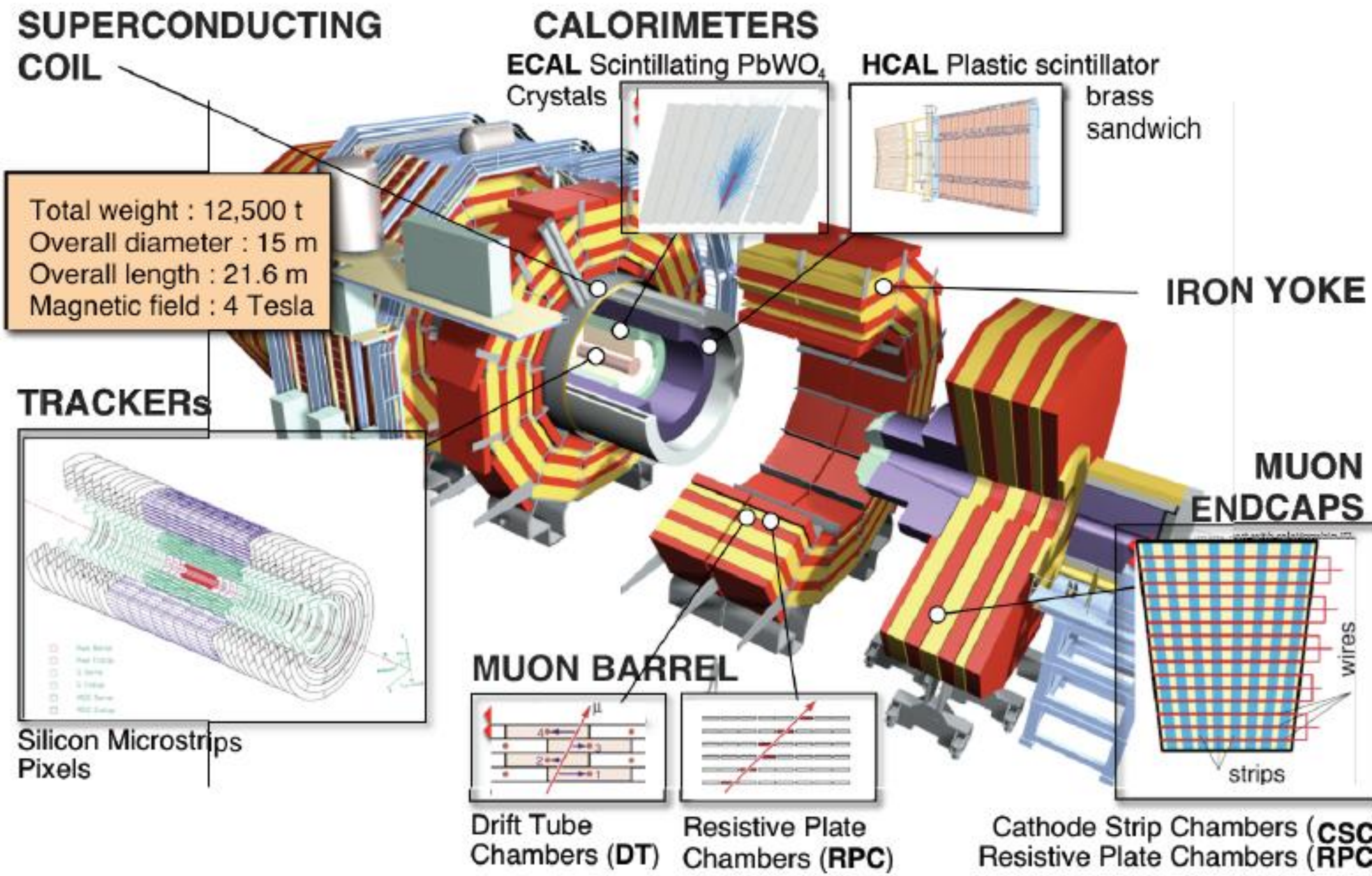


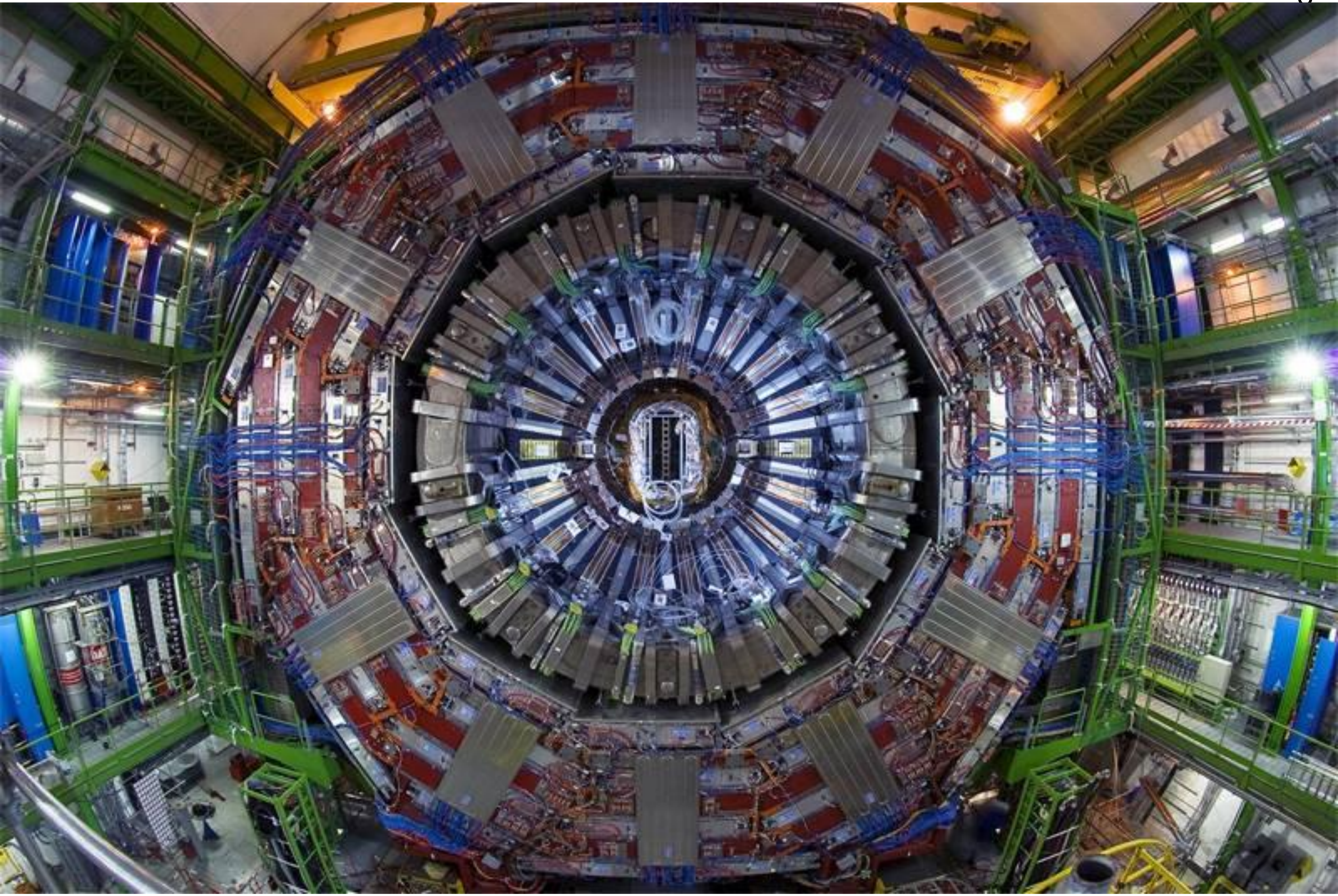


quarkonia production

- J/ψ, Υ direct production (prompt)
- J/ψ, Υ from χ_c , ψ', χ_b decays (prompt indirect)
- J/ψ from B hadron decays (non-prompt)
  - a test of QCD. Compare to FONLL (Fixed Order NLL) predictions at higher energies
  - tune MC description of b-fragmentation at TeV energies

This is CMS


SUPERCONDUCTING COIL
CALORIMETERS
ECAL Scintillating PbWO4 Crystals
HCAL Plastic scintillator brass sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
MUON ENDCAPS
MUON BARREL
μ
wires
strips
Silicon Microstrips
Pixels
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)



…and this is its **Muon** system

Large rapidity coverage

$|\eta|<2.4$

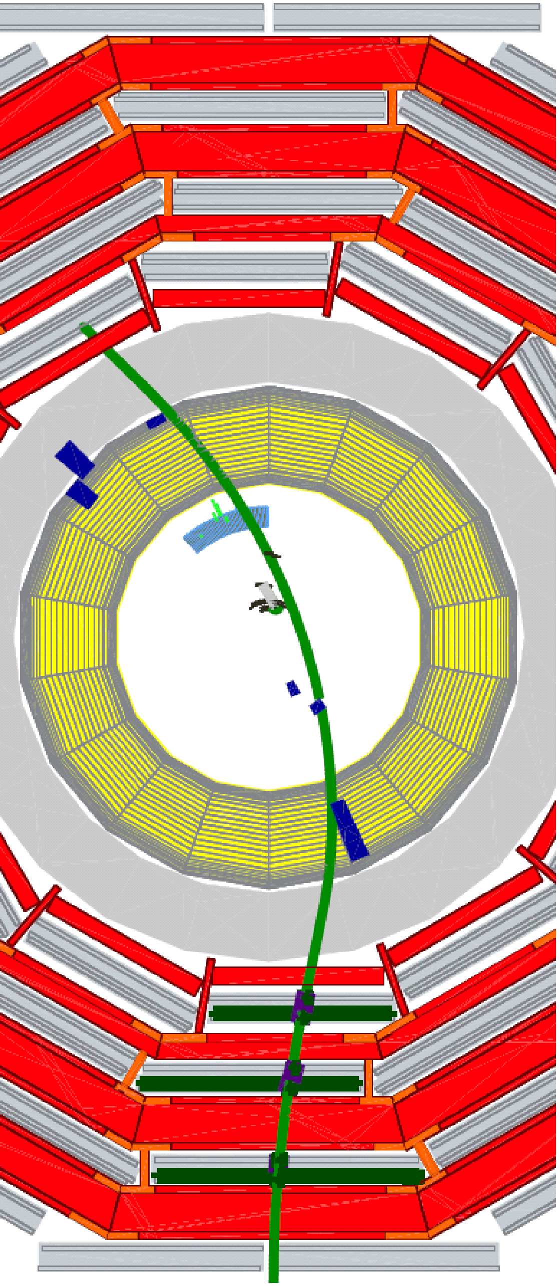
Excellent Dimuon Mass resolution

σ~20 MeV at $|\eta|$~0 to σ~40 MeV at $|\eta|$~2.2

Trigger

Trigger on single and di-muons
with different pT thresholds
Unambiguous BX identification

...and this is its **Muon** system



Strong solenoid magnetic field of 3.8T

uniform axial >3T in η>2, z~5m

highly non-uniform radial up to 1T in iron yokes

Global momentum resolution

$\Delta p/p = 1 - 2\%$ at $p = 10$ GeV

$\Delta p/p = 5 - 10\%$ at $p = 1$ TeV

requires alignment <~150 μm

Charge assignment better than

99% confidence level up to pT = 1 TeV

Position resolution: <150 μm

'bread & butter' physics in CMS @ 7 TeV

- Inclusive $J/\psi \rightarrow \mu^+\mu^-$ differential cross section
- Inclusive b cross section
- $\Upsilon(nS)$ differential cross section
- $b\bar{b}$ correlation
- Quarkonia polarization

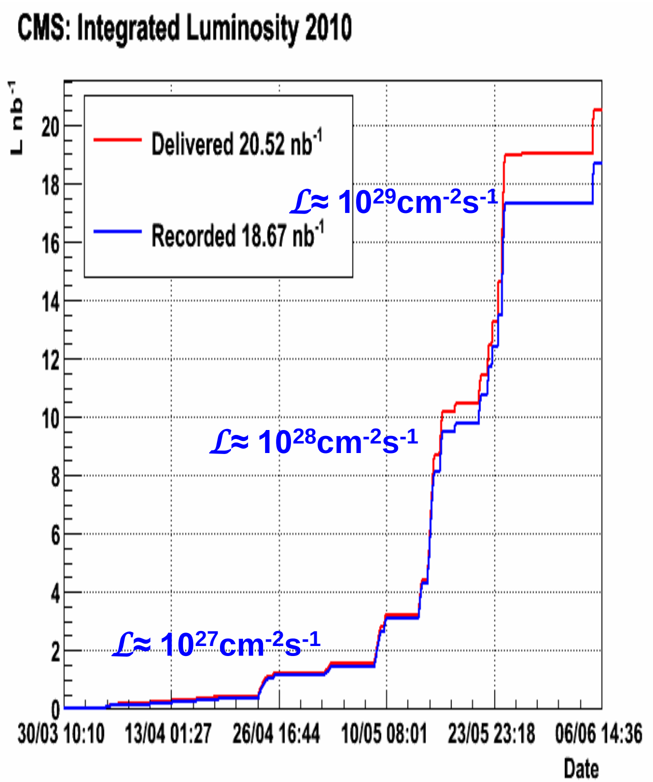
$\int L dt$

~100 nb-1

~1 pb-1

~10 pb-1

~100 pb-1



Early physics signature at LHC are anyhow extremely valuable to monitor the performance of the apparatus, to study calibration and alignment of sub-detectors and to test the reconstruction software

Data collection

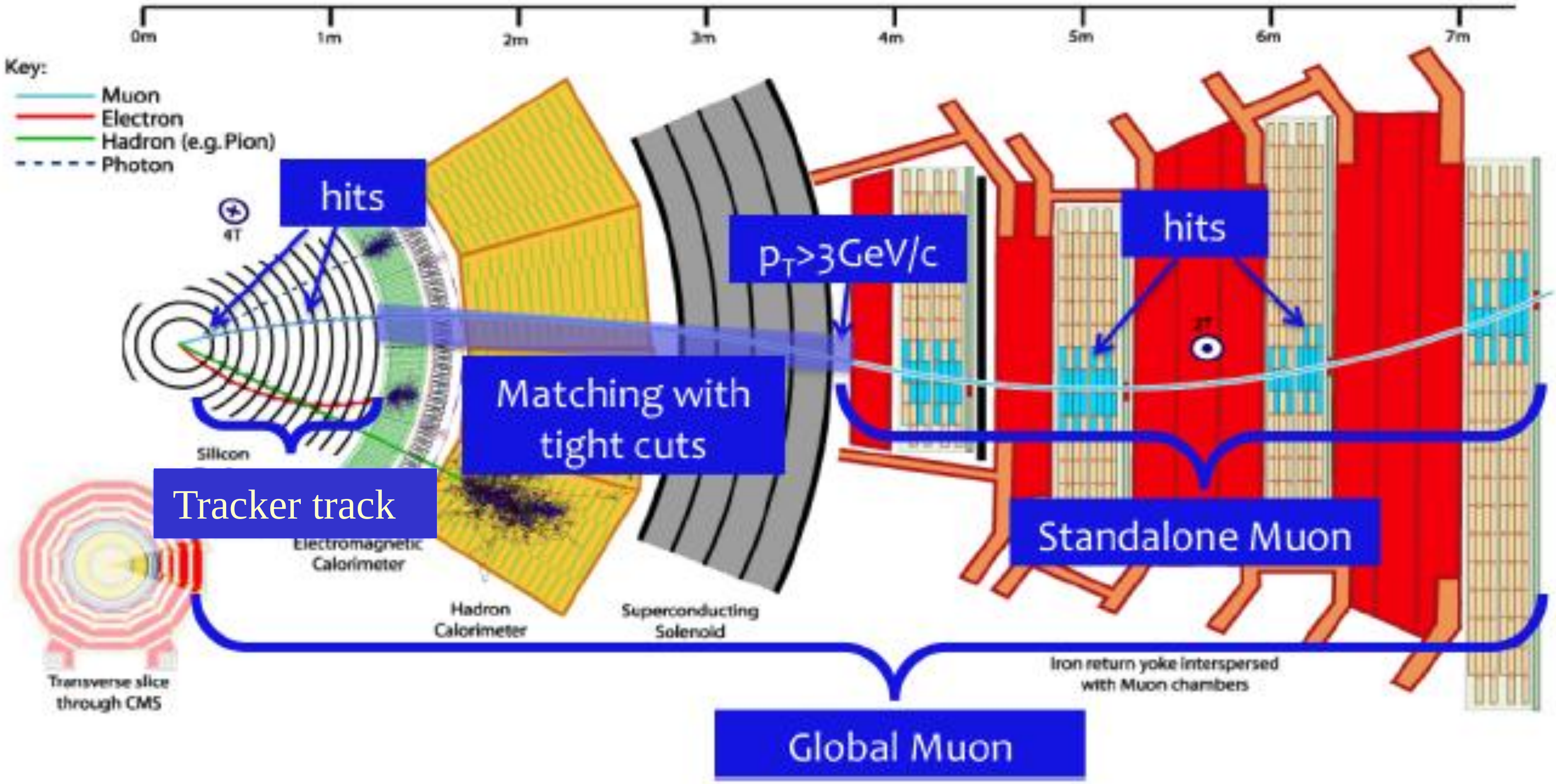
Quarkonia trigger strategy

- L<1E30 (startup scenario)
  - Very loose single and double muon **H**igh **L**evel **T**riggers are efficient for all quarkonia resonances
  - performances of HLT paths (rate, efficiency, S/B, systematics) depend on the pT coverage in different η acceptance regions
    - high trigger acceptance down to ~0 pT in forward region

- increasing L>~1E30
  - Several HLT paths turn-on as L increases, to remain un-prescaled (and maintain rate<25Hz), optimize S/B and control systematics

Whatever the L scenario, trigger choices should maximize signal yields and, more importantly, minimize the bias on the measurement of all polarization observables

muon reconstruction

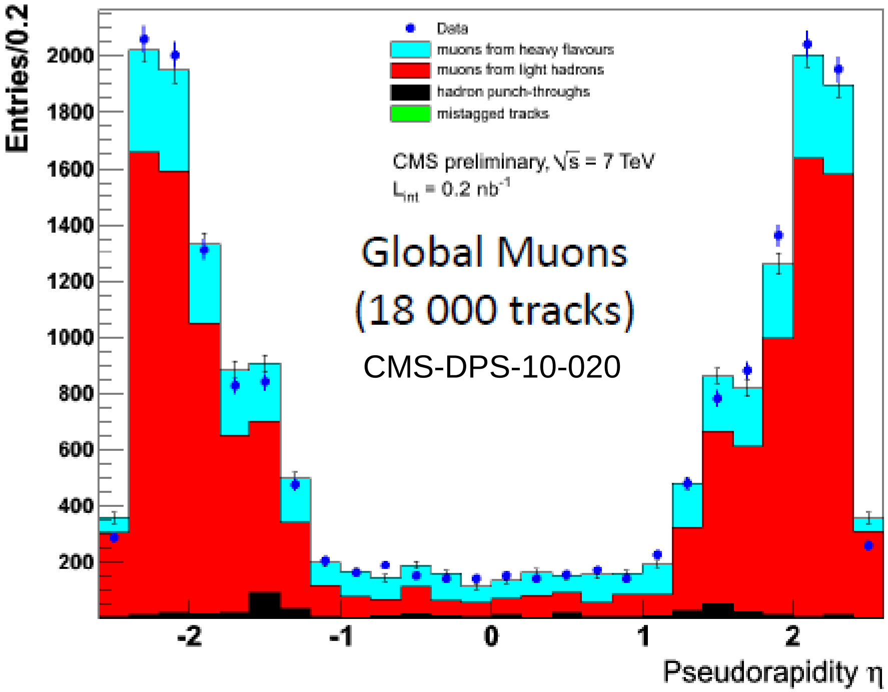


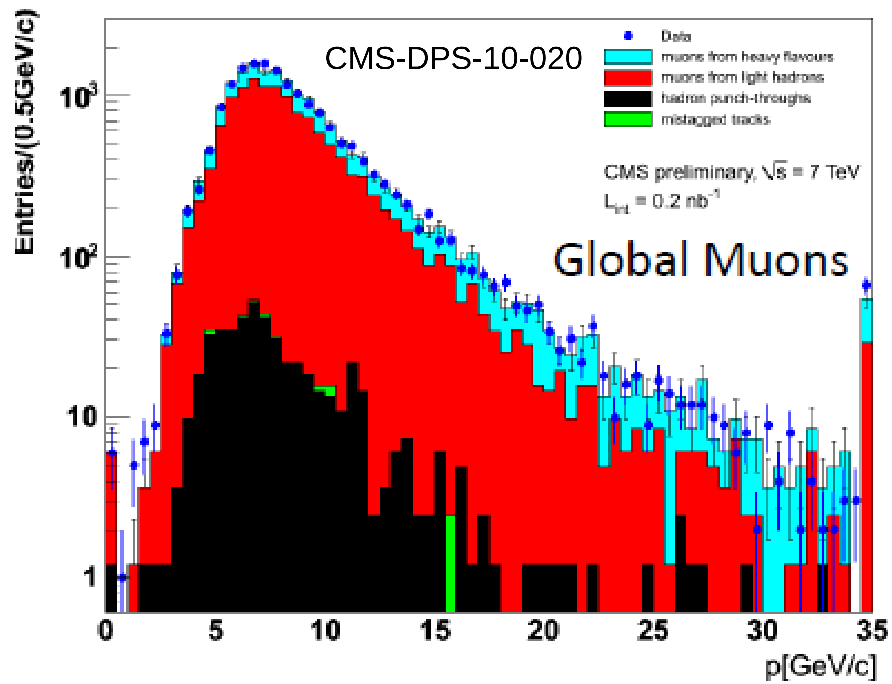
Muon selection:

• ***Global muon (GL)*** Matched tracks from Muon (Standalone muon) and Tracker (**T**racker **T**rack) systems.

• ***Tracker muon (TM)*** Tracker Track matched to one Muon station segment

muons in 7 TeV collisions

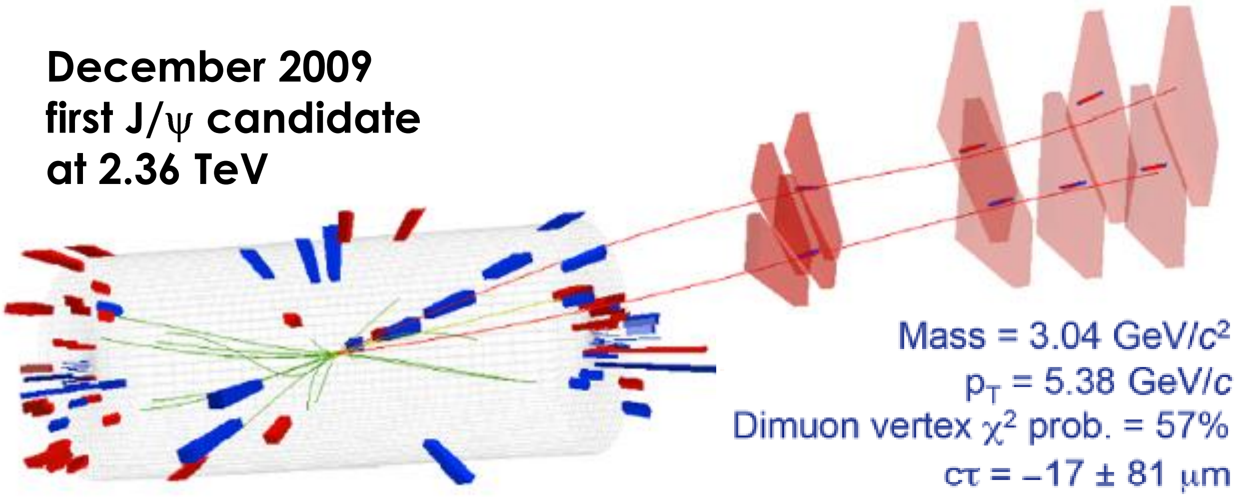




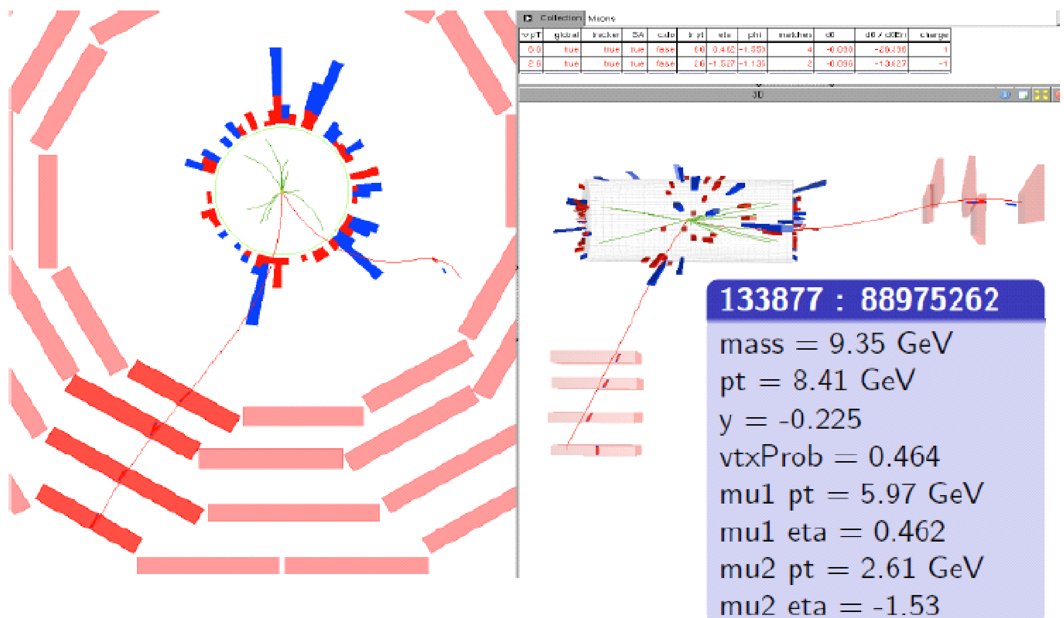
- Data-MC comparison for Minimum-bias events
- η and pT distributions dominated by **light hadron** decay muons (~73%)
- good agreement with MC prediction including **heavy flavor** decays (~25%), **punch-through** and **fakes**

early evidence of J/ψ and Υ

December 2009
first J/ψ candidate
at 2.36 TeV

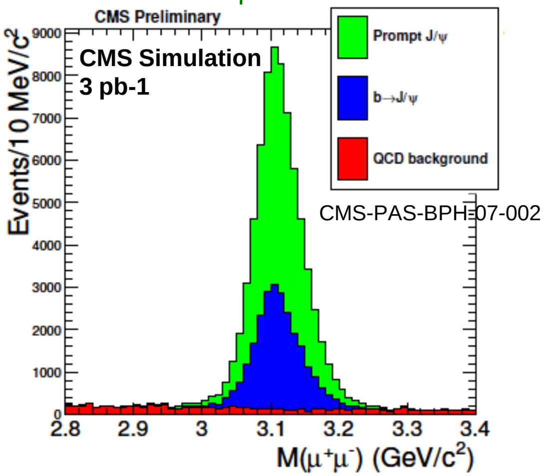


March 2010
first Υ candidate
at 7 TeV



inclusive analysis formalism

$$\frac{d^2\sigma}{dp_T dy}(Q\bar{Q}) \cdot BR(Q\bar{Q} \to \mu^+\mu^-) = \frac{N_{Q\bar{Q}}}{\int L dt \cdot A \cdot \varepsilon_{trigger} \cdot \varepsilon_{reco} \cdot \Delta p_T \cdot \Delta y}$$

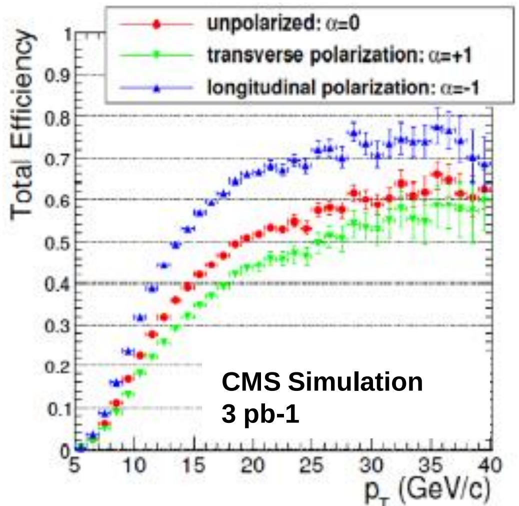


$N_{Q\bar{Q}}$ = Number of signal events in a given pT bin from the mass fit

$\int L dt$ = integrated luminosity

A = J/ψ geom and kinematical acceptance (from MC)

- strongly dependent on production polarization



$\varepsilon_{trigger} \cdot \varepsilon_{reco}$ = trigger and reconstruction efficiency (with single-μ efficiency calculated by the Tag and Probe method)

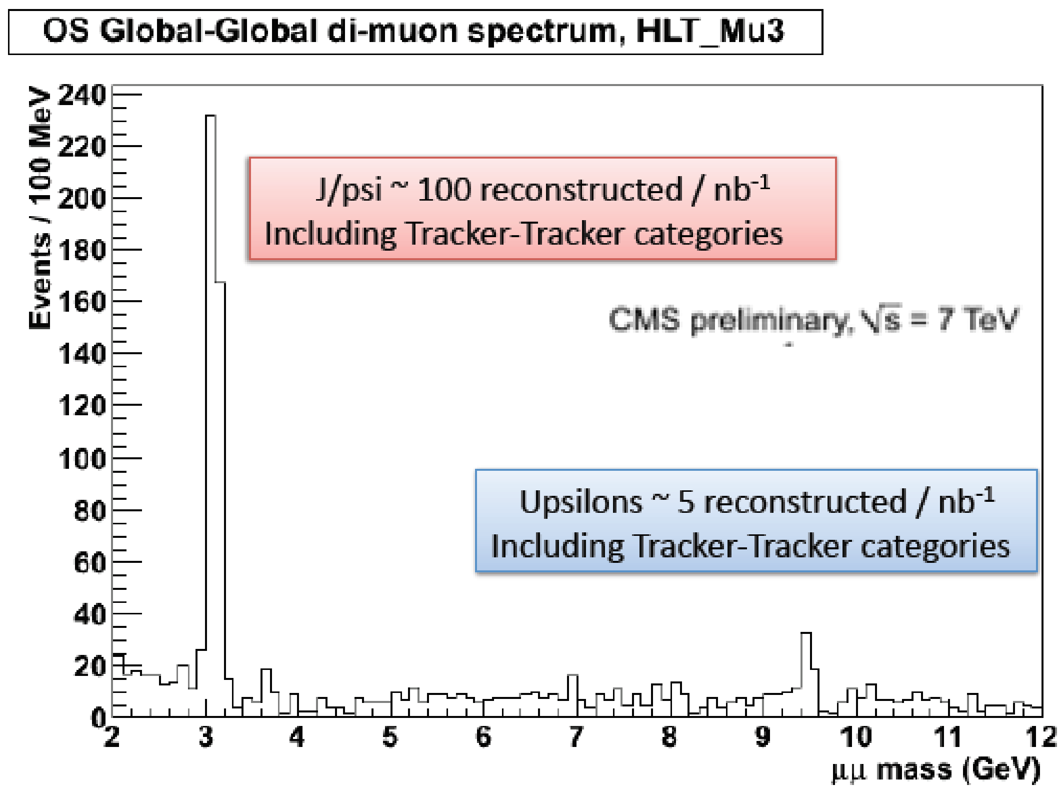
CMS-PAS-BPH-07-002

Dimuon event selection

Dataset: 15 nb^{-1}
Trigger: HLT_L1DoubleMuOpen (for low pT, high η), HLT_Mu3 (pT>3 GeV)
Events: Pairs of Global Global, Global-Tracker, Tracker-Tracker muons

in detail:

- Inner track for all muons:
  - Pixel layers with hits > 1
  - Number of pixel+strip hits > 11
  - $chi^2/dof < 5$
  - $|d0| < 3$ cm, $|dz| < 20$ cm
  - Pt > PtMin(η), $|\eta|<2.4$
- Global muons:
  - GlobalMuonPromptTight
  - isTrackerMuon
  - global $chi^2/dof < 20$
- Tracker muons:
  - TMLastStationAngTight
  - TrackerMuonArbitrated
- $\mu+\mu-$ vertex probability >0.1%
- no μ-momentum scale corrections



$J/\psi \longrightarrow$

J/ψ → μμ acceptance

prompt J/ψ acceptance depends on

- its polarization state (affects the μ lab momenta)

$$\frac{dN}{d\Omega} = \frac{3}{2(3+\lambda_\theta)} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$$

$\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$ corresponds to an isotropic decay choice

The "observed" polarization depends on

- The frame (CS: along the beam direction; HX: along the J/ψ momentum)
- The reconstructed dimuon kinematics (pT and y)

Given the strong A-to-α dependence will quote results for 5 polarization assumptions (with unpolarized as LHC-wide benchmark value)

$J/\psi \to \mu\mu$ acceptance

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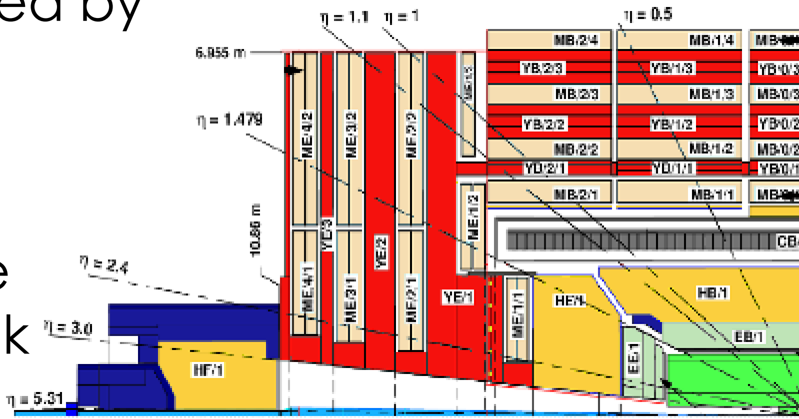
non-prompt J/ψ polarization differs. The acceptance for

- 2-body B-decay modes → generated using EVTGEN
- Many-bodies → angular distribution from pure phase space

With the MC acceptance weighted by the predicted B-fraction in each pT-bin

μ acceptance

- The J/ψ *pT* and *y* strongly depend on the minimum μ-pT threshold to reach the first muon station as imposed by
  - the traversed material budget
  - the B-field curvature



- Muons must leave at least 3 hits in the muon system to form a detectable track

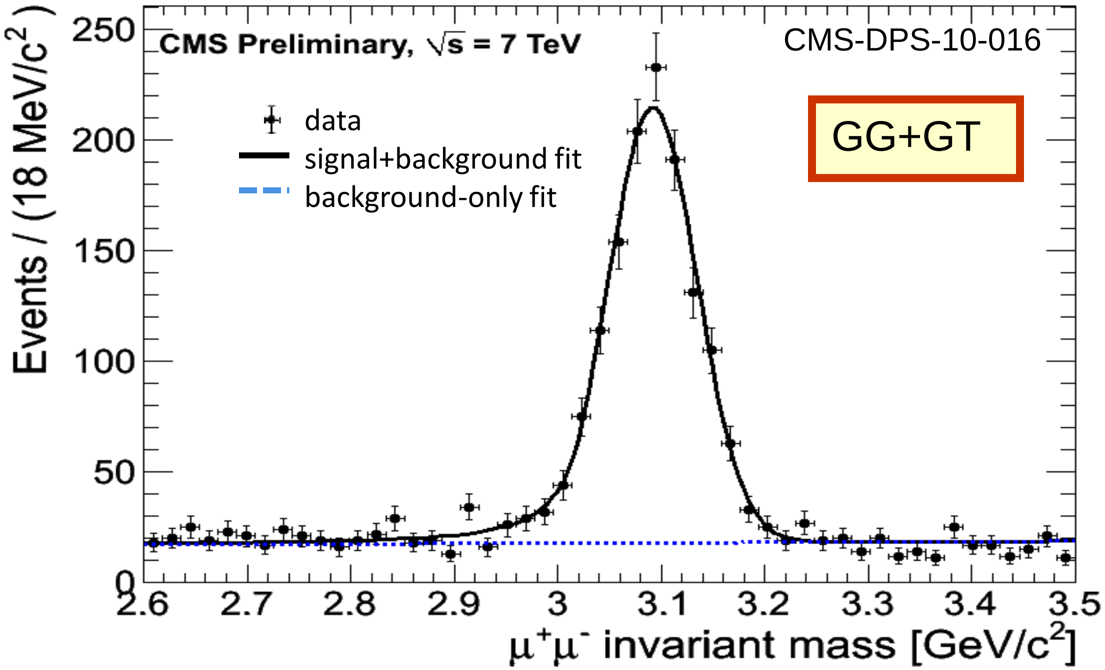
- From MC J/ψ →μμ studies of the acceptance *p, pT,* η 2D-contours

μ-kinematic requirements: • IηI<1.3 pT > 3.3 GeV • 1.3<IηI<2.2 p > 2.9 GeV • 2.2<IηI<2.4 pT > 0.8 GeV

- Above criteria guarantee a single-μ acceptance efficiency >10%

J/ψ signal yield

$\int L dt = 15\ nb^{-1}$



Signal events: 1230 ± 47
Sigma: 42.7 ± 1.5 (stat.) MeV
M_0: 3.092 ± 0.001 (stat.) GeV
S/B = 5.4 ($M_0 \pm 2.5\sigma$)
χ^2/ndof = 1.1
w/o momentum scale corr.

Mass Fit

- MLL with exponential (for the background) + Crystal Ball for the signal (detector resolution + FSR tails)
- Parameter of exponential fixed from a fit to the side bands

μ and J/ψ efficiency

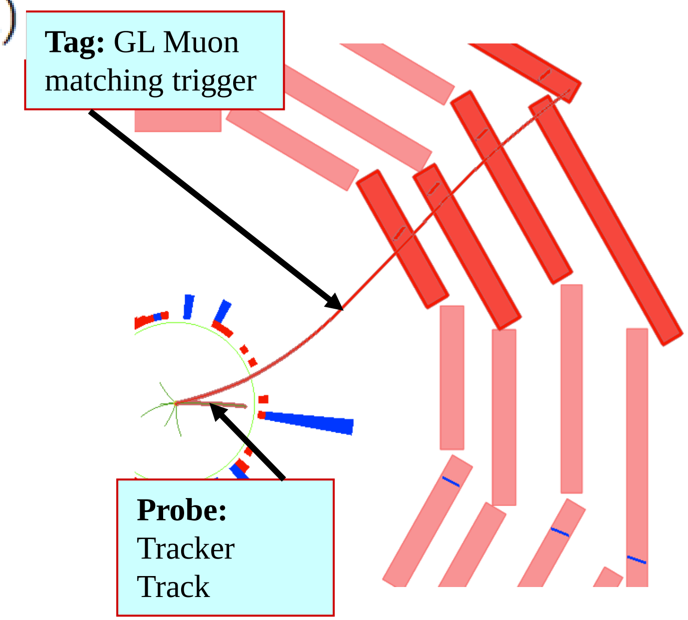
Use the **Tag & Probe** data-driven method to determine single-μ ε^{μ}_{Trg} ε^{μ}_{ID} $\varepsilon^{\mu}_{track}$ in several (p_T, η) bins, and define

$$\varepsilon(\text{total}) = \epsilon(\text{trig}|\text{id}) \times \epsilon(\text{id}|\text{track}) \times \epsilon(\text{track}|\text{accepted})$$

Tag: high quality reco-triggering "μ", paired to
Probe: loosely selected "μ" of opposite charge
M(T&P) consistent with resonance mass

Get **ε** from the #(Probe) satisfying requirement

Method limitations:
- Tag & Probe correlations at small Δr
- Bias on Probe from Tag
- Fitting accuracy and (p_T, η) bin size



ε^{μ}_{Trg} ε^{μ}_{ID} have a strong dependence on pT, $\varepsilon^{\mu}_{track}$ varies little with η and ϕ

J/ψ efficiency in a given *(pT, y)* bin is obtained from factorizing the single-μ efficiencies with a vertex efficiency and with a correction factor (from MC) which accounts for any residual correlations

cross section: workflow validation

Generate J/ψ sample corresponding to $\int L dt$ = 0.5 pb-1

Generated σ is recovered by the analysis

*With the present data sample the inclusive cross section can only be calculated in wide **(pT, y)** bins and with large systematic uncertainties mostly related to T&P measured efficiencies* → *more @ **ICHEP***

Relying on LHC quickly delivering more data

- With ~150 nb-1 we expect a precision on the inclusive cross section of ~20% per *(pT,y)* bin
- In addition, the fraction of J/ψ from B-decay should be measured with an expected precision of ~10% per bin

*We are OK with inclusive cross section, can we now disentangle **prompt** from **non-prompt** J/ψ?*

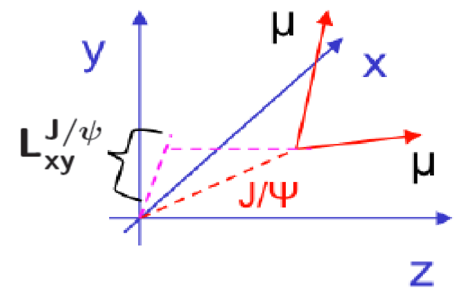
B-fraction

extracting non-prompt J/ψ

Measure B→J/ψ fraction

- From a 2D unbinned MLL fit to mass and "pseudo" proper decay length

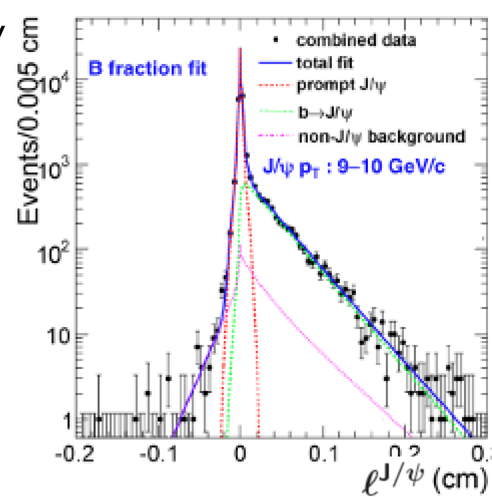
$$\ell^{J/\psi} = \frac{L_{xy}^{J/\psi} \cdot M_{J/\psi}}{p_T^{J/\psi}} \qquad L_{xy}^{J/\psi} = \frac{\vec{L} \cdot \vec{p}_T^{J/\psi}}{\left|\vec{p}_T^{J/\psi}\right|}$$

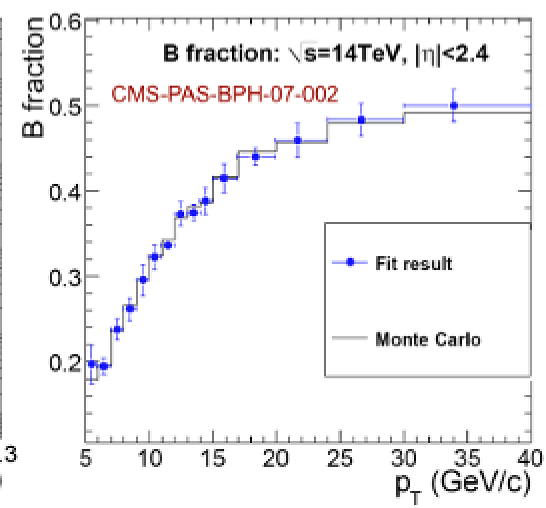


For prompt events expect a δ-function (smeared by resolution)
For non-prompt events should be exponential ~ λ_{eff}^{B} convoluted with a decay-length and a boost resolution functions
[due to $(M/p_T)_{J/\psi}$ instead of $(M/p_T)_B$ boost factor]
For non-resonant background use events from mass sidebands

Fit results
CMS simulation @ 14 TeV

- Systematic errors dominated by uncertainty on luminosity and polarization
- Additionally by inner detector misalignment, beam spot stability, PV resolution
- and choice of model functions



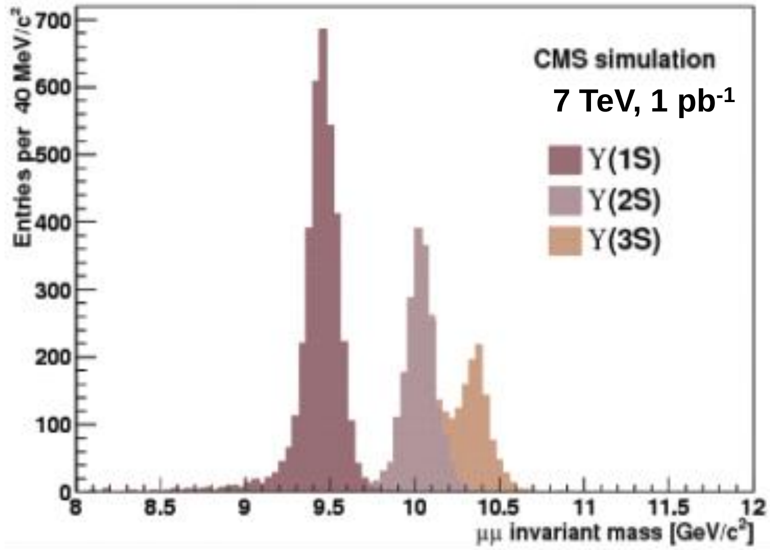


$\Upsilon(nS) \longrightarrow$

Υ(nS) → μ+ μ-

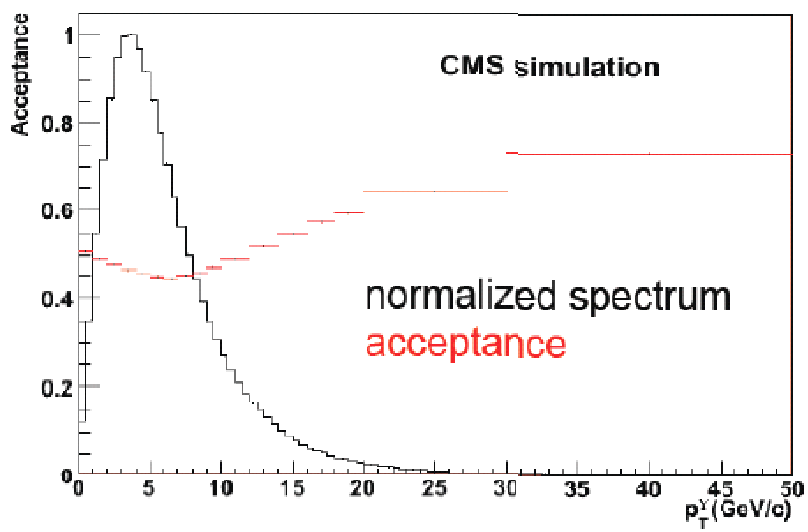
CMS expects a few thousands reconstructed $\Upsilon(nS) \to \mu^+\mu^-$ per pb^{-1}

- explore 20-30 GeV pT-range and |y|>1.2
- measure ratio Υ(2S)+Υ(3S) to Υ(1S)
  (to get rid of many systematics)



Υ acceptance

- strongly dependent on production polarization (which depends on pT)
- MC Υ→μμ using EVTGEN with 5 different polarization assumptions



Υ(nS) mass fit

Signal yield corrected for acceptance and efficiency event-by-event

- Υ efficiency for early data obtained from J/ψ efficiency (despite substantial differences) by re-weighting probe sample (accuracy ~1% for pT>3 GeV)

Invariant Mass fit

- un-binned MLL with 3-double CB for Υ(1S), Υ(2S), Υ(3S) and a polynomial for background

- fix ratios of Υ(nS) mass difference to PDG values, leave Υ(1S) mass parameter free (to absorb momentum scale uncertainty)

Inclusive cross section (validate analysis workflow)

- Generate Υ(nS) sample corresponding to $\int L dt$ = 0.1 pb-1

Generated σ is recovered by the analysis

systematic uncertainties

Quarkonia cross sections

- Luminosity
- production polarization (avoidable if quoting for different polarizations)
- acceptance uncertainties
  - J/ψ pT spectrum, MC statistics, *(pT, y)* bin size, material budget, momentum scale and resolution, difference between prompt and non-prompt J/ψ, beam spot size and position, vertex resolution
- efficiency uncertainties
  - T&P biases, statistical error
  - correlation effects in single-μ efficiencies
- signal fit
  - choice of PDF, free/fixed parameters, binning

B-hadron cross section

- inner tracker misalignment
- signal fit (B-decay length resolution model)
- uncertainty on BR($B \rightarrow J/\psi X$)

wrap-up and conclusions

- "The rediscovery of the Standard Model, which is necessary before we can confidently say we're ready for new physics, is well underway in CMS" *- Cern DG R. Heuer*

- Quarkonia provides an ideal benchmark both from the experimental as well as from the theoretical point of view

- First look at the $\mu\mu$ data well underway in CMS and looking promising. J/ψ and Υ signals have been rediscovered!

- Analysis machinery in place and tested extensively. Should be able to produce cross sections and (early!) polarization measurements of charmonium and bottonium as soon as we collect a few hundred nb-1. *Thus … stay tuned and see you at*

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ba

cup

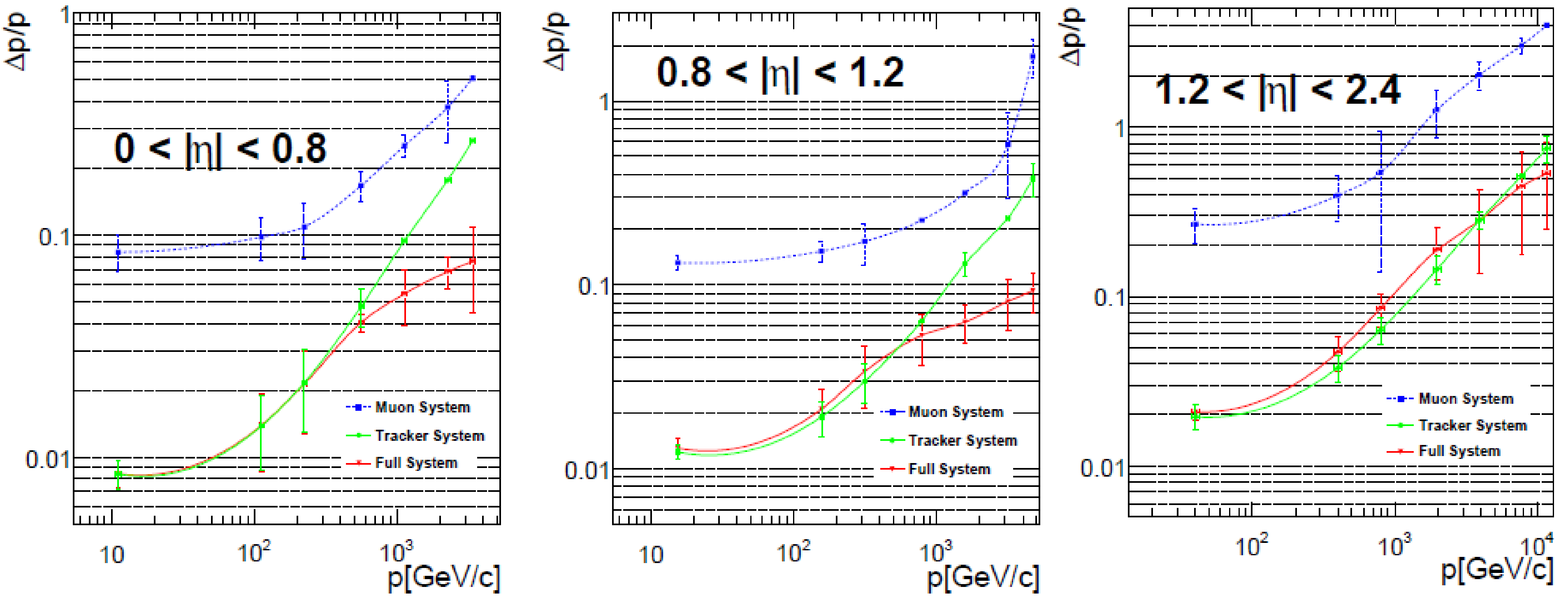
systematic uncertainties

CMS-PAS-BPH-07-002

Parameter affected	Source	$\Delta\sigma/\sigma$
Luminosity	Luminosity	$\sim$ 10 %
Number of J/ψ	J/ψ mass fit	1.0 - 6.3 %
Number of J/ψ	Momentum scale	$\sim$ 1 %
Total efficiency	J/ψ polarization	1.8 - 7.0%
Total efficiency	J/ψ p_T binning	0.1 - 10 %
Total efficiency	MC statistics	0.5 - 1.7 %
$\lambda_{reconstruction}$	Non-perfect detector simulation	$\sim$ 5 %
$\lambda_{trigger}$	Non-perfect detector simulation	$\sim$ 5 %
B fraction	ℓ_{xy} resolution model	0. - 1.9 %
B fraction	B-hadron lifetime model	0.01 - 0.05 %
B fraction	Background	0.1 - 3.0 %
B fraction	Misalignment	0.7 - 3.5 %
Total systematic uncertainty 13-19 %		

Summary of systematic uncertainties in the J/ψ cross section measurement using CMS early data. All the uncertainties are $p_T^{J/\psi}$ dependent, except for the uncertainty from luminosity. The total uncertainty is about 13% in the region $p_T^{J/\psi}$ >20 GeV/c and around 19% in the lowest $p_T^{J/\psi}$ bin, 5-6 GeV/c.

momentum resolution

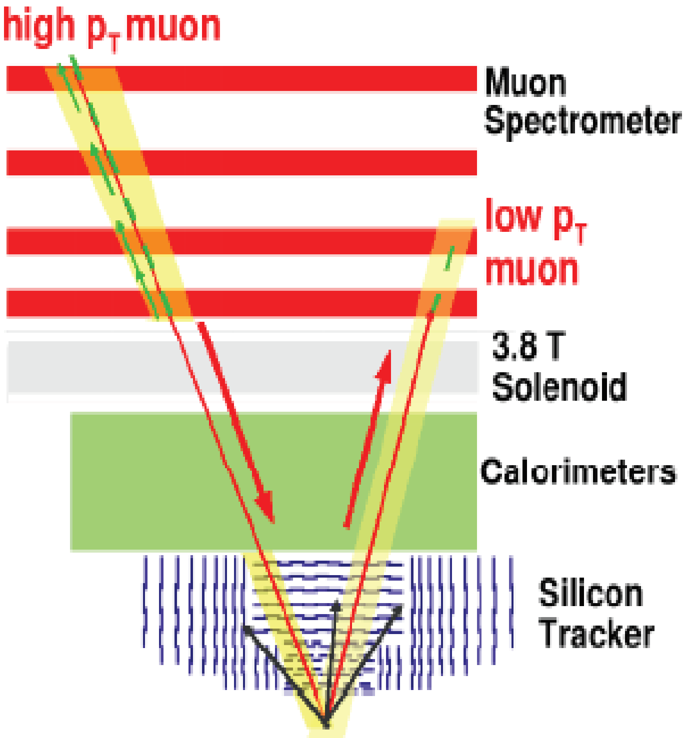


barrel

overlap region

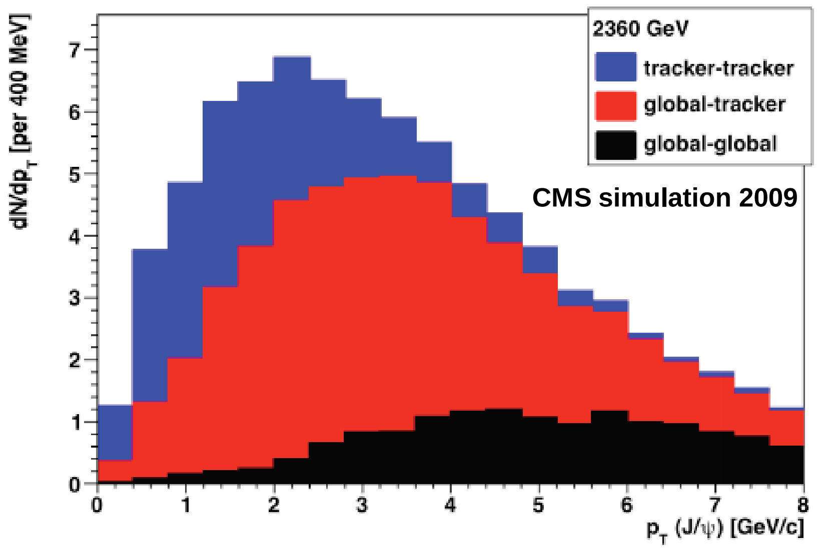
endcap

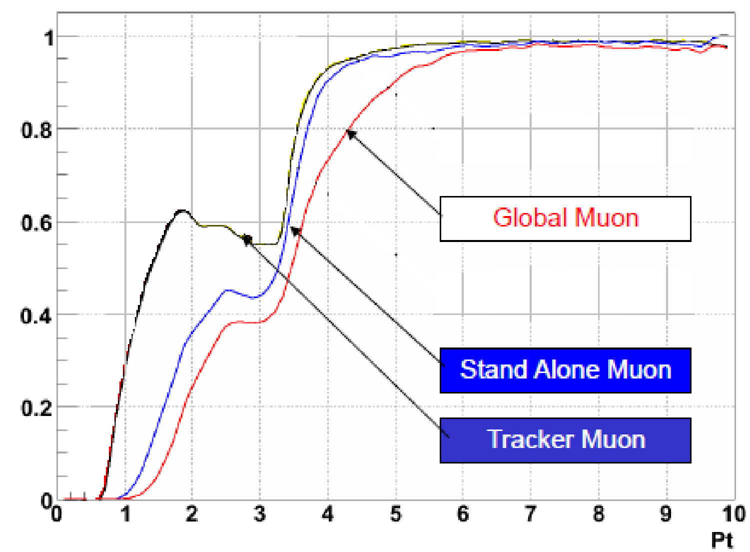
Why Tracker muons



In order to recover efficiency at low pT (<~5 GeV) in the barrel, where the Standalone muon reconstruction fails (not enough hits)

Avoid fitting a track through a non-uniform B-field, accounting for large dE/dx and multiple scattering



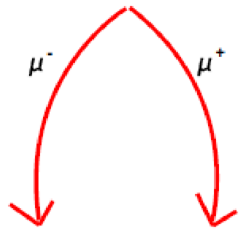


μ-correlation effects

Correlation effects are important when estimating J/ψ, Υ(nS) efficiencies from single-muon efficiency, in particular when the two muons are close-by

- muons are rather well separated at J/ψ decay vertex
- can be very close in the muon system

$J/\psi \rightarrow$ cowboys



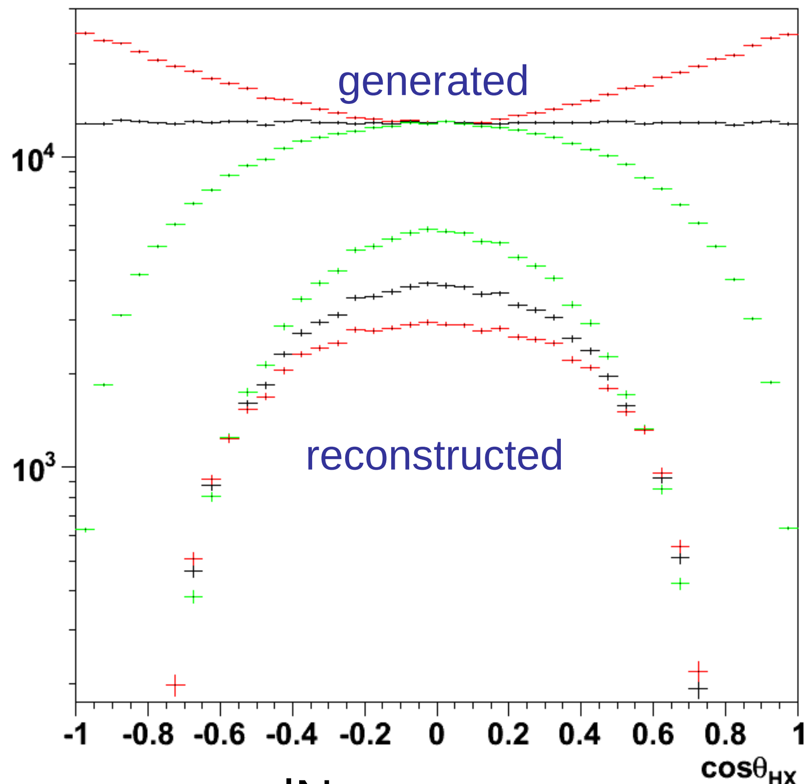
$J/\psi \rightarrow$ seagull

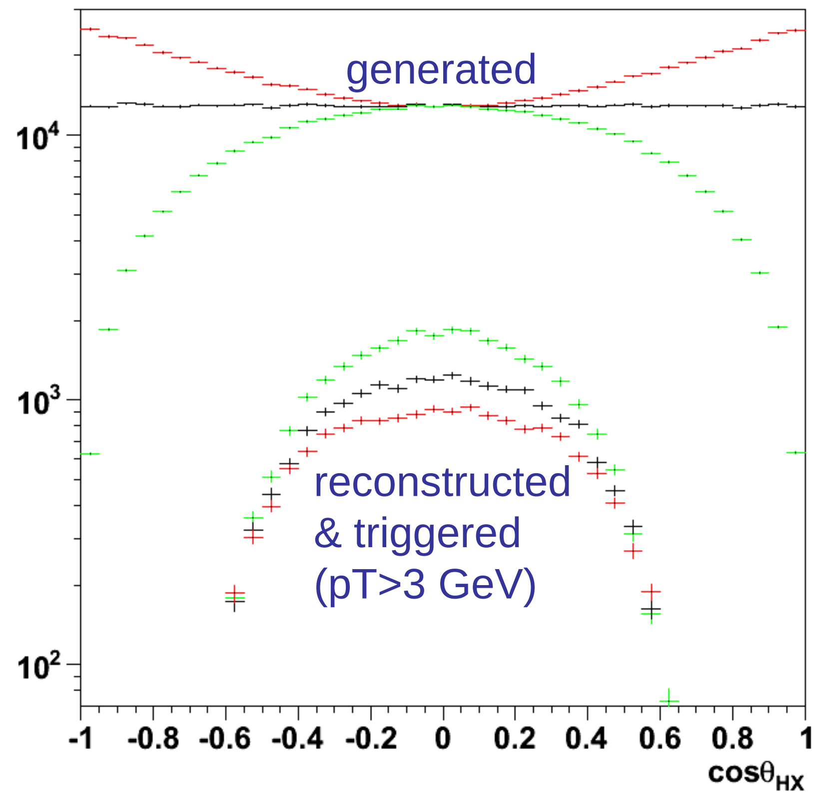
$\Delta\phi$ at the muon system distinguishes cowboys from seagulls. Correlation effects are more significant for J/ψ, much reduced for Υ

- Depends on the sign of $\Delta\phi$ between μ+ and μ-
- if crossing of cowboys occurs in the endcap, most likely this happens in the first muon chamber layer
- the efficiency can be degraded by as much as 5%

acceptance effects on polarization

Transverse, Isotropic and **longitudinal** polarization ($q\bar{q}$) *private simulation*





$$\frac{dN}{d\cos\theta} \propto 1 + \lambda_\vartheta (\cos\theta)^2$$

$\boldsymbol{\theta}$ = angle between lepton direction (in the J/ψ rest frame) and J/ψ lab direction (helicity axis)

λ_ϑ > 0: transverse (= photon-like)

λ_ϑ < 0: longitudinal