Heavy flavor, QCD & soft physics

recent results from CMS @ LHC

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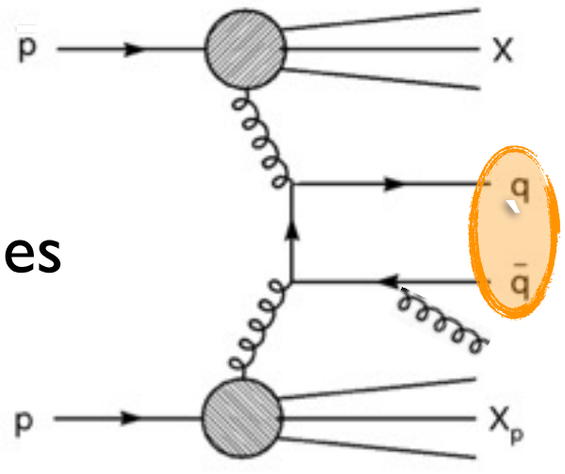
on behalf of the CMS Collaboration

La Thuile 2016: Les Rencontres de Physique de la Vallée d'Aoste

6-12 Mar 2016, La Thuile, Italy

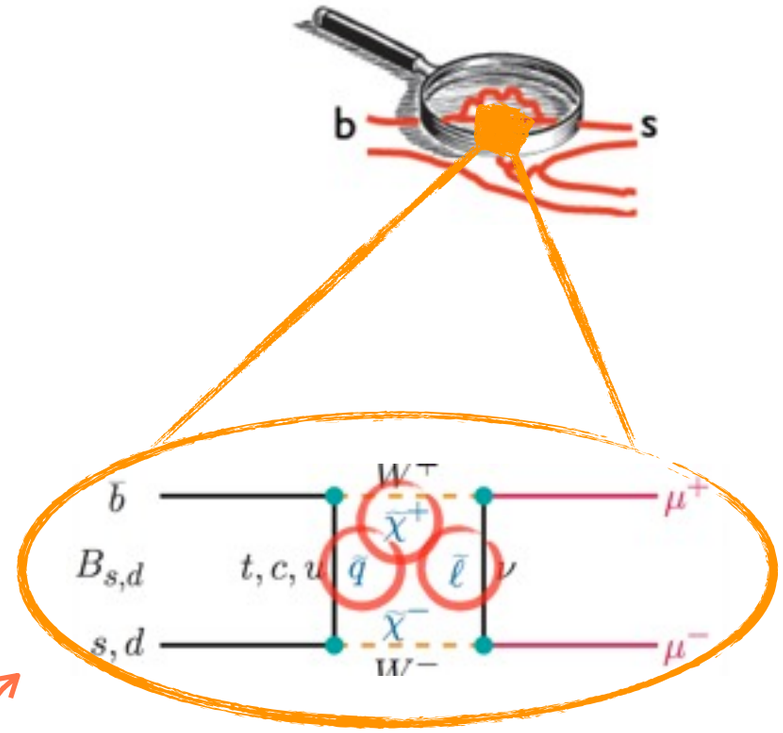
motivation

- CMS goals (in QCD & flavor physics)
- Understand underlying QCD processes
  - particle production measurements
  - measure known states and look for new and exotic ones
  - important backgrounds for NP searches, MC tuning
  - study QCD matter under extreme conditions



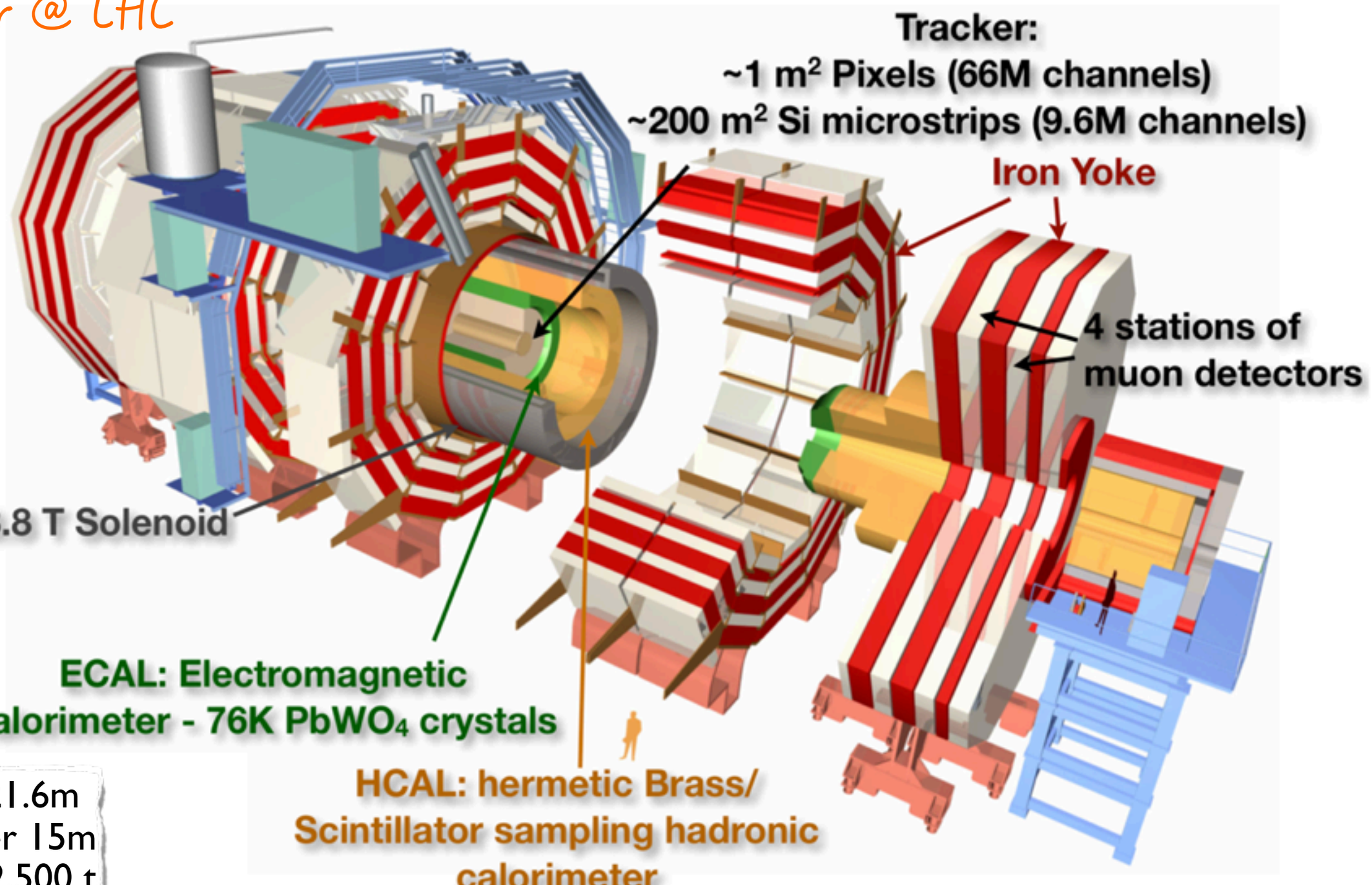
- Test the standard model to high precision
  - decay rates, lifetime, CP phases, asymmetries
- Search for new physics (NP) in the loop
  - rare decays, eg b→sll transitions

If these particles cannot be observed in direct searches, this is how one shall still look for them



the CMS detector

a multi-purpose detector @ LHC



length 21.6m
diameter 15m
weigh12,500 t
B 3.8T

the Compact Muon Solenoid detector

3.8T Superconducting Solenoid

Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]

Lead tungstate
E/M Calorimeter (ECAL)

All Silicon Tracker
(Pixels and Microstrips)

Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

the Compact Muon Solenoid

Text

detector

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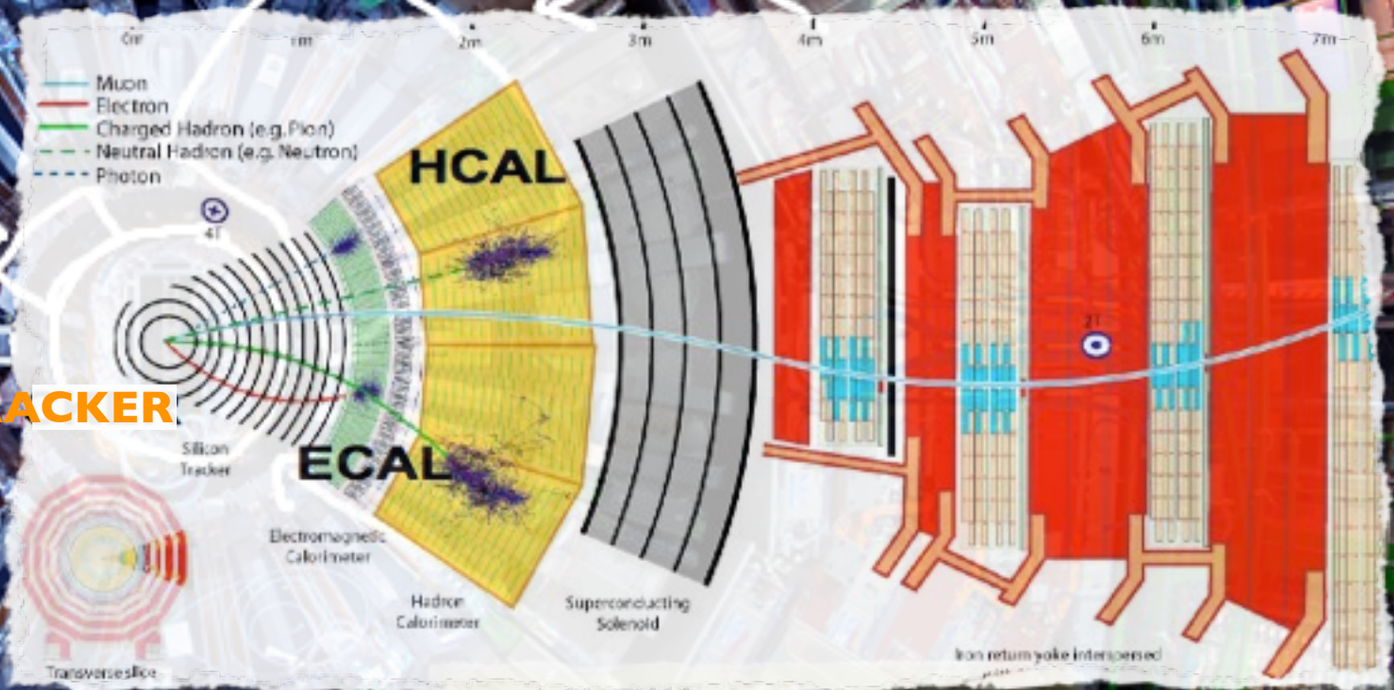


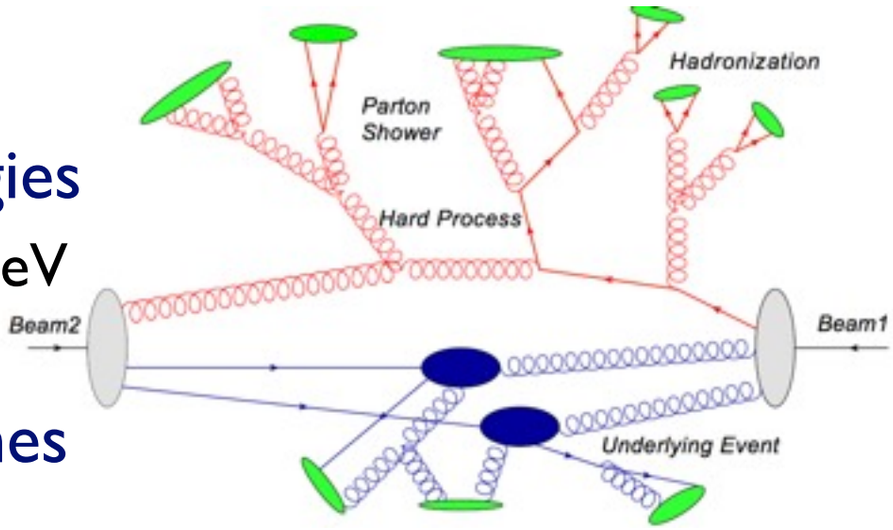
All Silicon Tracker
(Pixels and Microstrips)

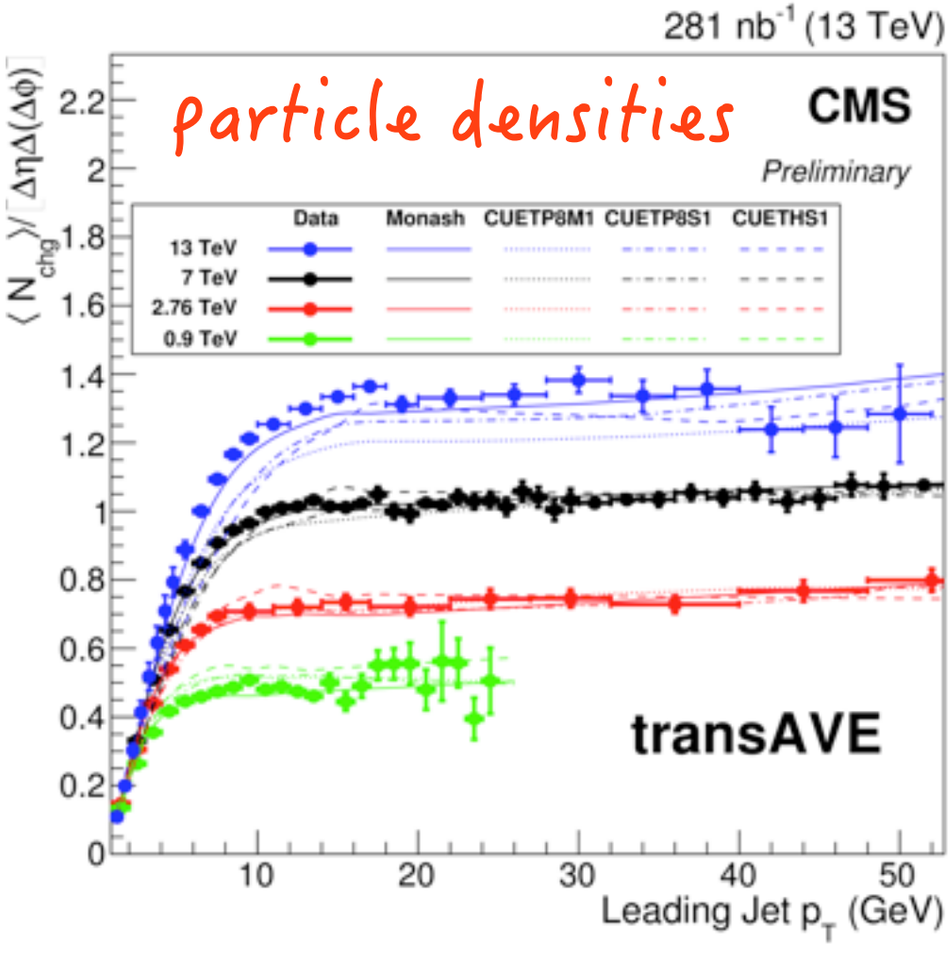
p_T resolution 1-2%
impact parameter
resolution ~15μm
dimuon mass
resolution ~0.6-1.5%
$p(\mu \mid K,\pi,p) < 0.1\%$
(MVA ID for $B \rightarrow \mu\mu$)

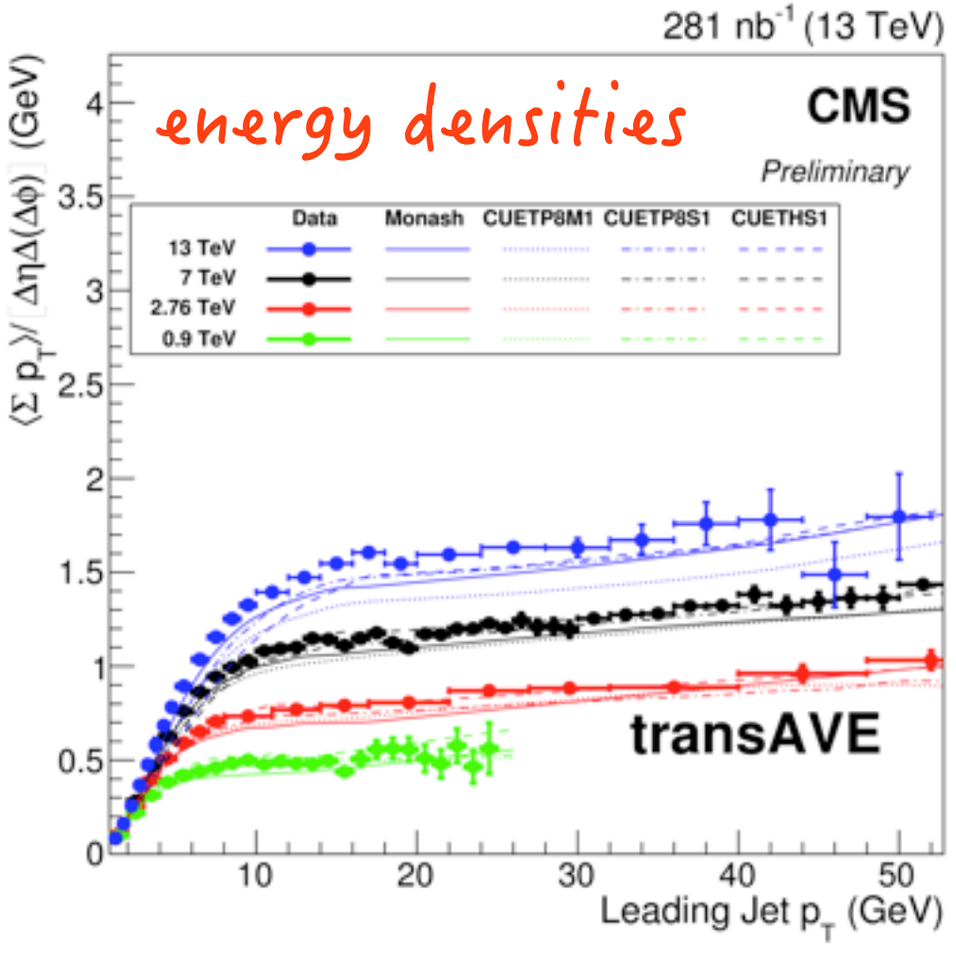
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

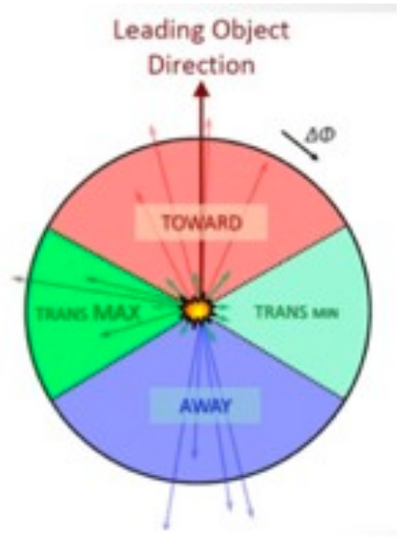
underlying event

- measurements of underlying event activity at 13TeV compared to previous measurements at lower energies
  - used data collected July 2015, 280nb^{-1} PU~1.3; $p_{T,\,trk}$>0.5GeV
  - average particle and energy densities in transverse region
- data in reasonable (10-20%) agreement with tested tunes







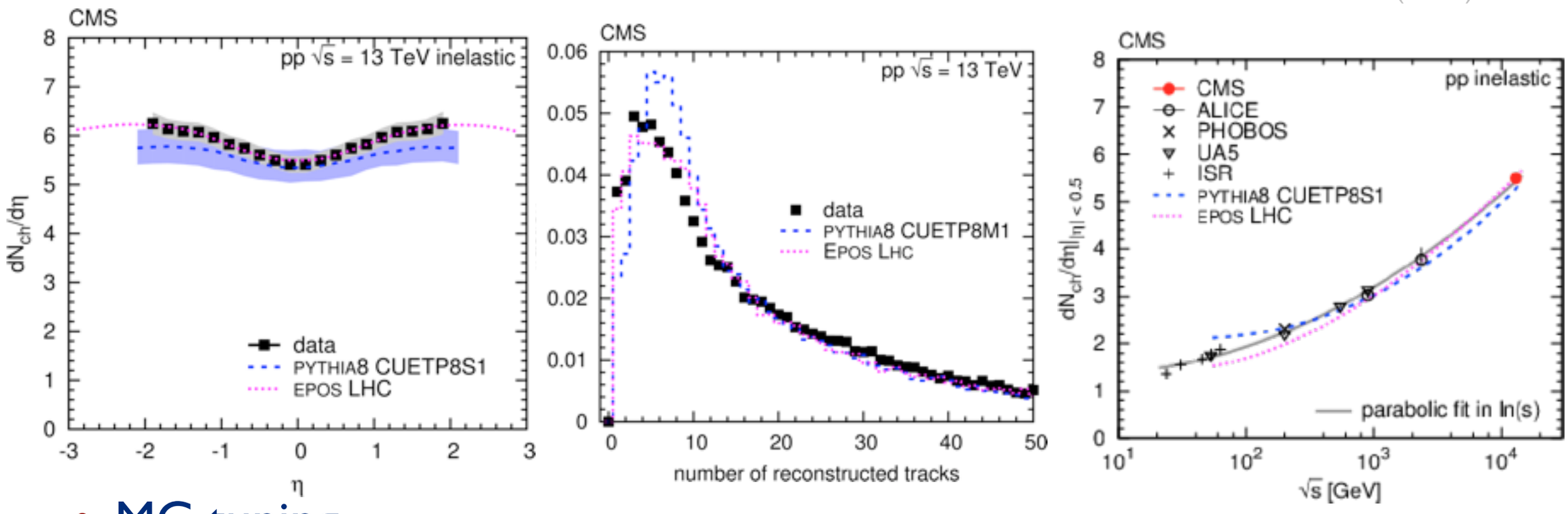


CMS-PAS-FSQ-15-007

soft particle production

- measure charged-hadron production at 13TeV
  - 170k events, special low PU (0.2-5%) run, B=0T, within pixel detector barrel ($|\eta|<2$)
- as function of pseudo-rapidity and track multiplicity
- charged hadron density in central region ($|\eta|<0.5$)
  - $dN_{ch}/d|\eta| = 5.49 \pm 0.01$ (stat) $\pm$ 0.17 (syst)
- collision energy dependence as expected

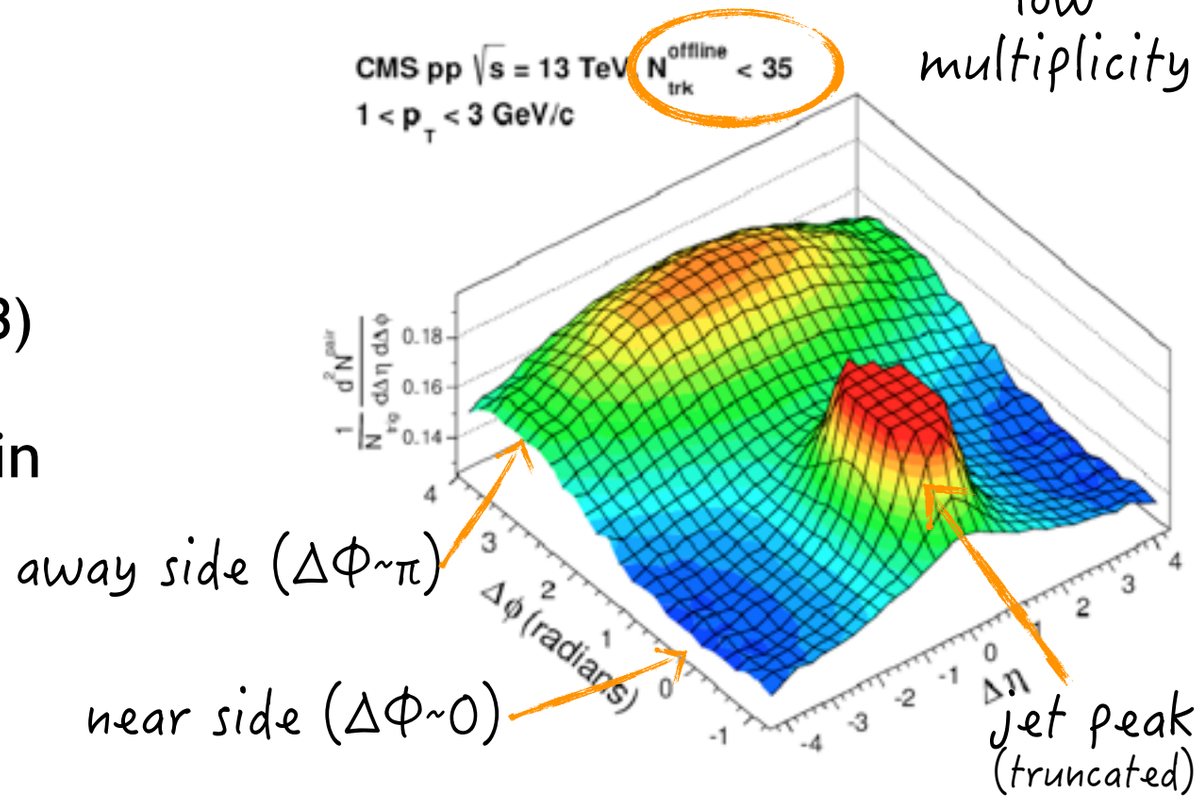
PLB 751 (2015) 143



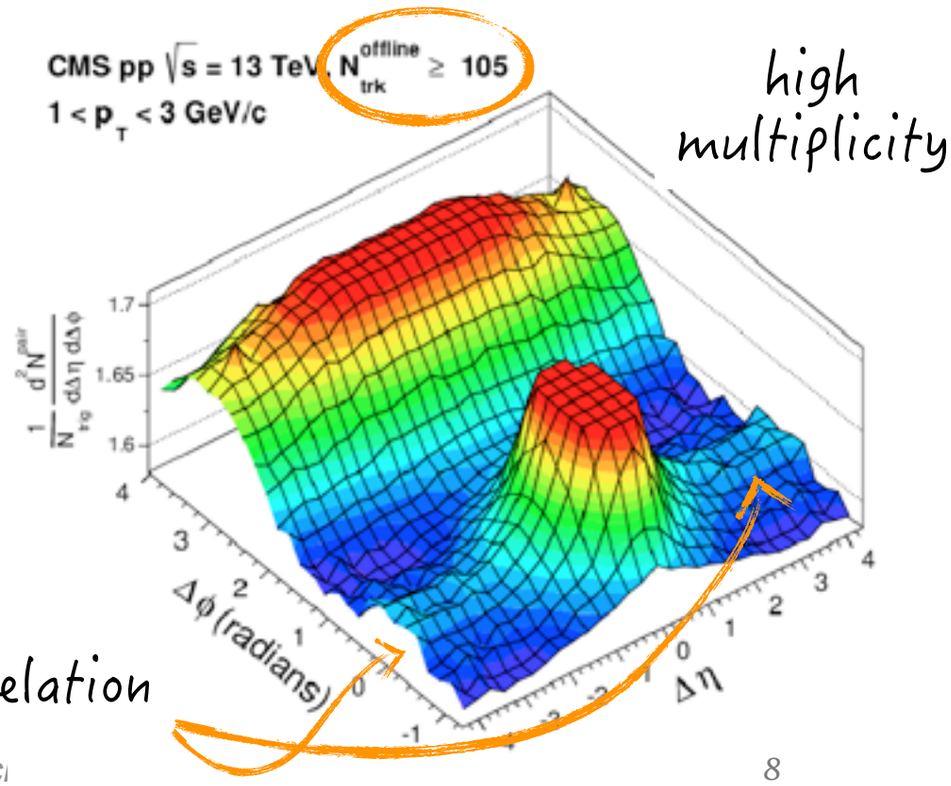
- MC tuning
  - results allow improvements of perturbative and non-perturbative QCD aspects implemented in hadronic event generators

particle correlations

- measure two-particle correlations
  - L=270 nb^{-1}, B=3.8T, low PU (average:1.3)
  - trigger particle: a hadron, in given p_T bin
  - tracks weighted by 1/efficiency



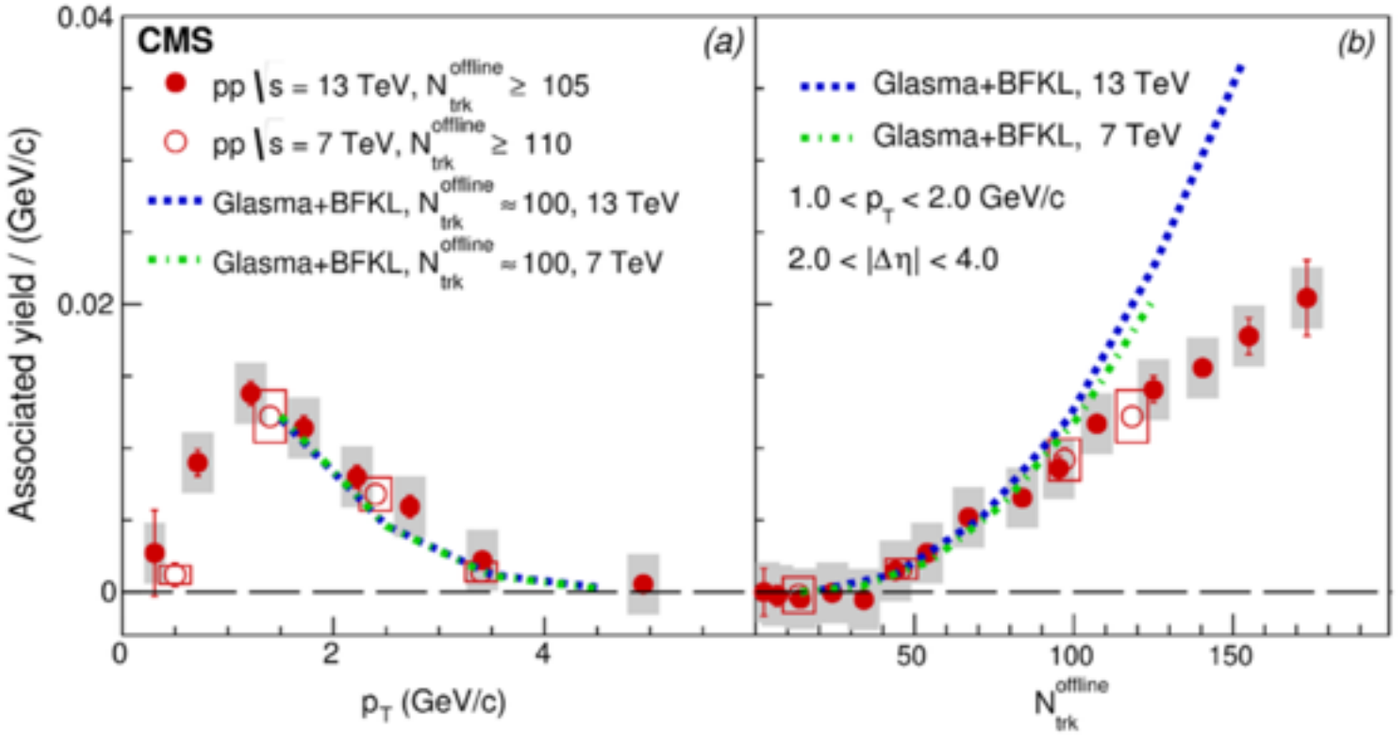
- observed structure in ($\Delta\eta$,$\Delta\Phi$)
  - near side peak around (0,0): jets
  - away side ridge: back to back jets
  - near-side, long-range correlation
    ridge-like structure observed in high multiplicity events

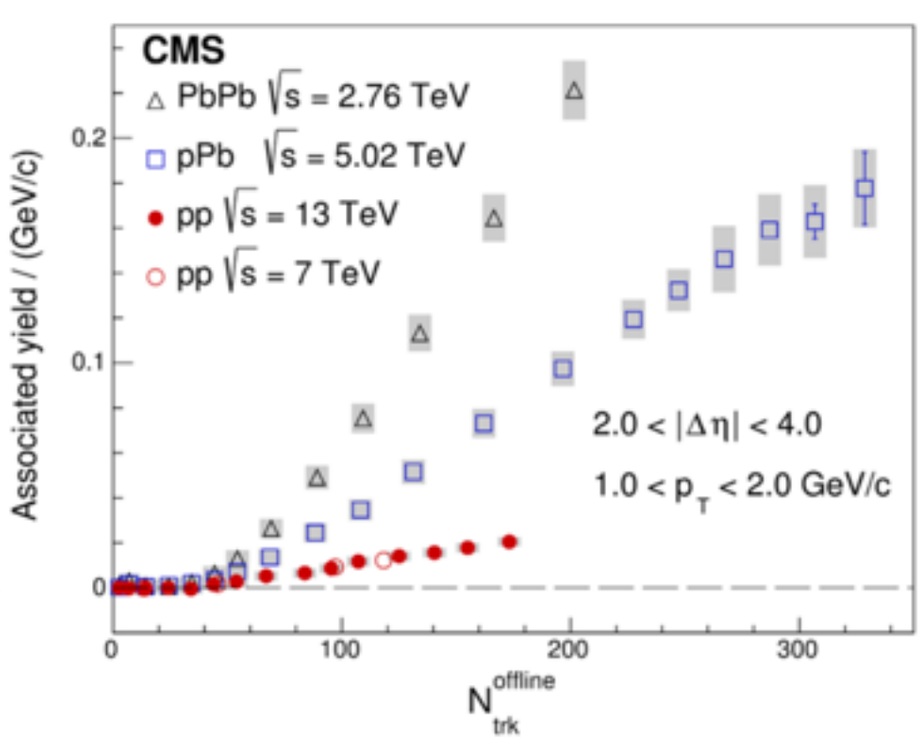


the ridge (cont'd)

- effect is most pronounced in intermediate p_T range 1-2 GeV
- effect absent in low-multiplicity region, with approximate linear increase with multiplicity for $N_{track}>40$
- no collision energy dependence of the near-side associated yield is observed: 13TeV and 7TeV results compatible (in overlapping p_T, N_{trk} regions)
- ridge observed in all collision systems (pp, pPb, PbPb) at the LHC, with a strong dependence on the collision system size
- interpretation: partonic flow (small systems, pPb, pp), medium hydrodynamics (heavy ions)

arXiv:1510.03068

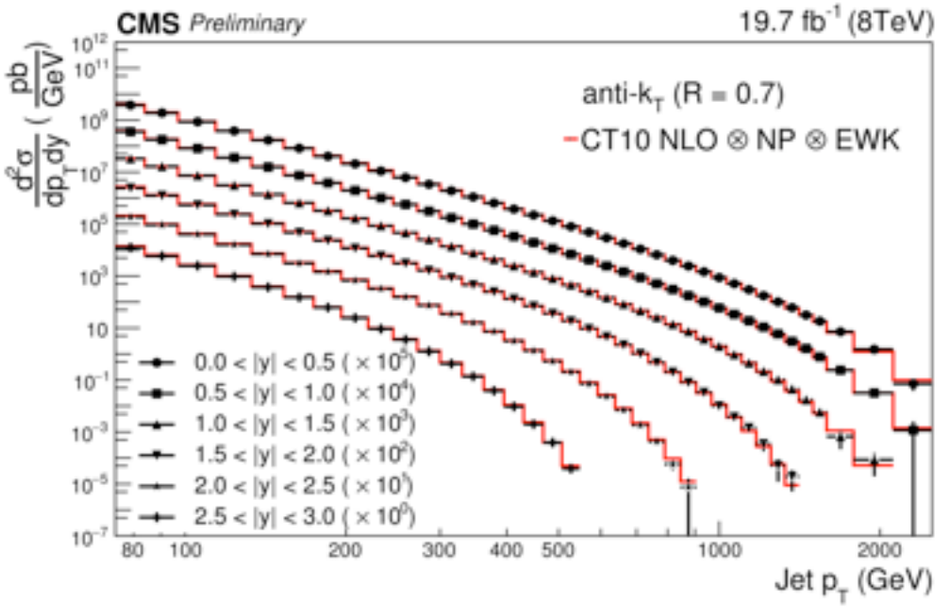


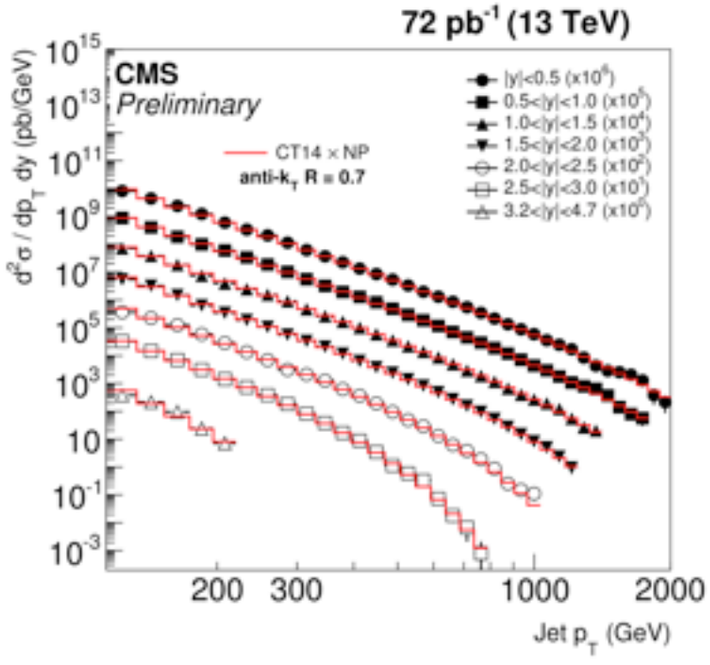


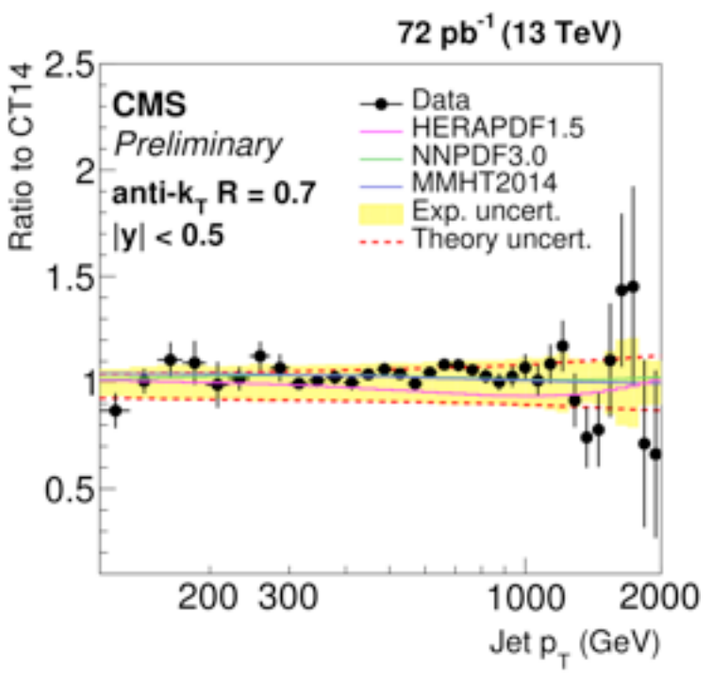
inclusive jet production

- test perturbative QCD and simulations by various MC generators
  - w/ modeling of parton showers, hadronization and multiparticle interactions
  - over several (up to 10) orders of magnitude, and wide p_T range (20-2500GeV)
- jet spectra measured at different $\sqrt{s}$ (2.76, 7, 8... and 13)TeV
  - allow ratios, where many uncertainties partially cancel
  - study new kinematic regions of momentum fraction x
- measured double differential (p_T, y) inclusive jet production at 13TeV
  - based on 72pb^{-1}, 114 < p_T < 2,000 GeV, |y|<4.7
- good agreement with predictions, various tunes tested

CMS-PAS-SMP-14-001
CMS-PAS-SMP-15-007

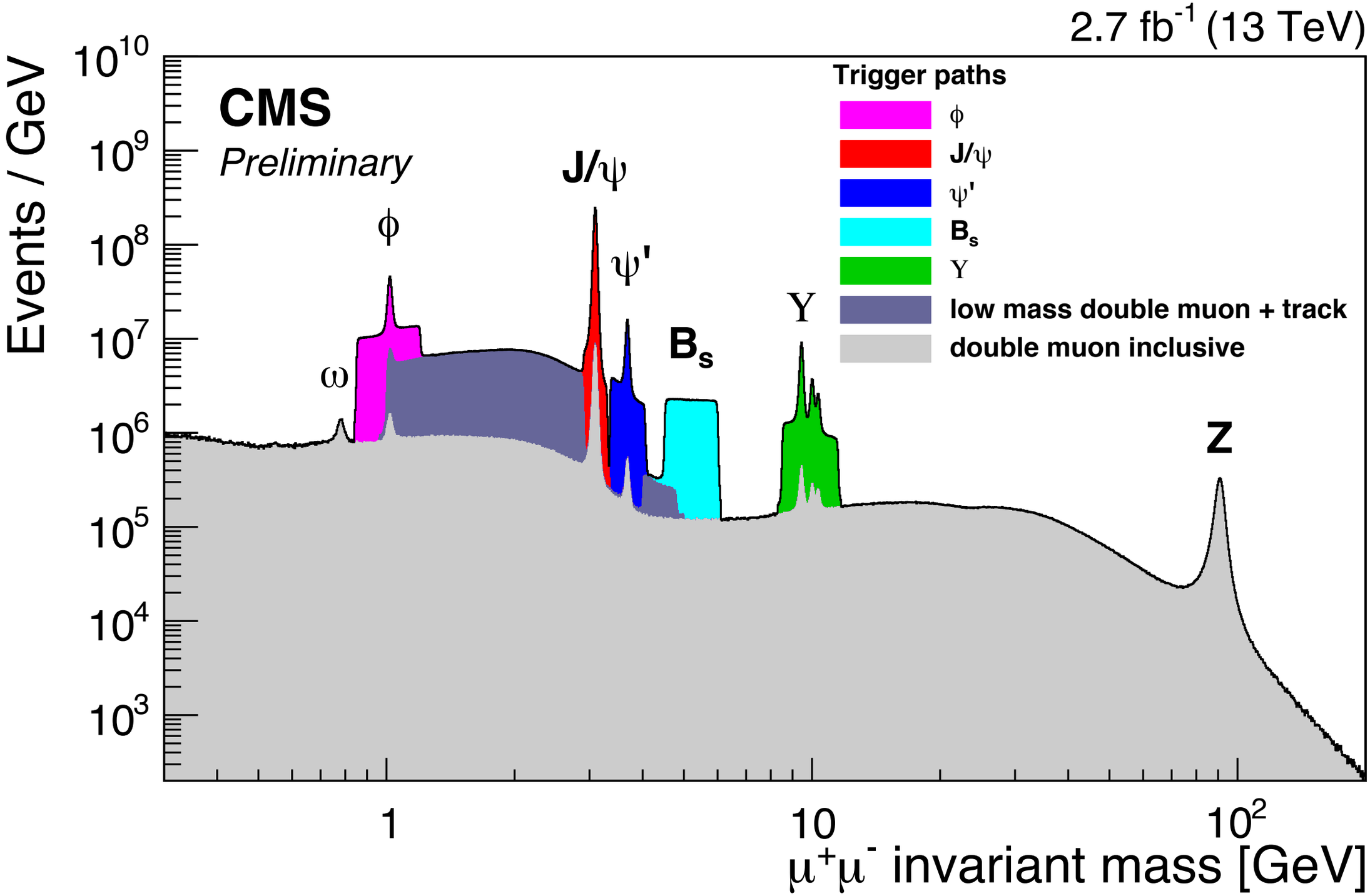






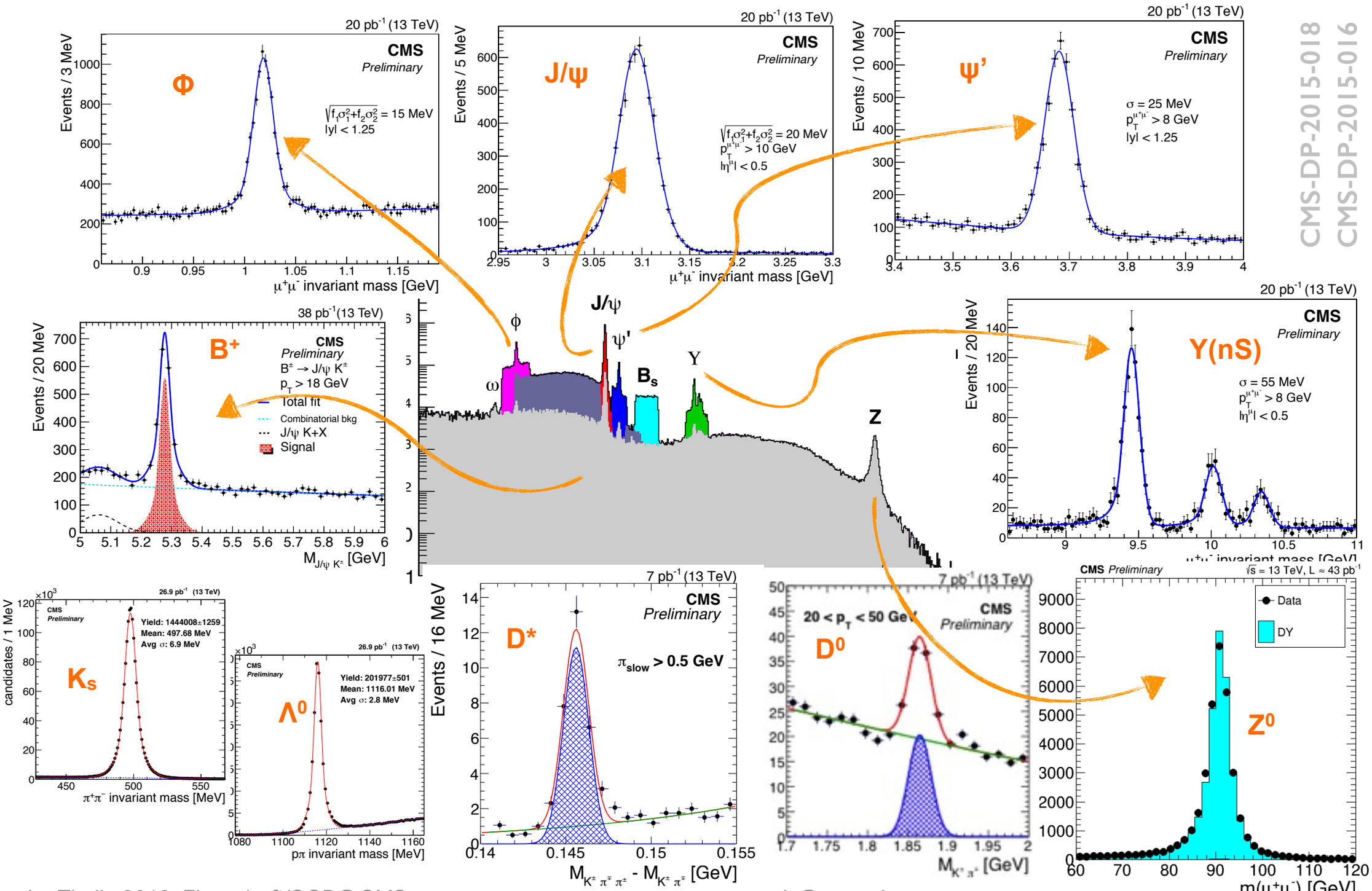
dimuon spectrum

the di-muon signature plot revisited (at 13 TeV)



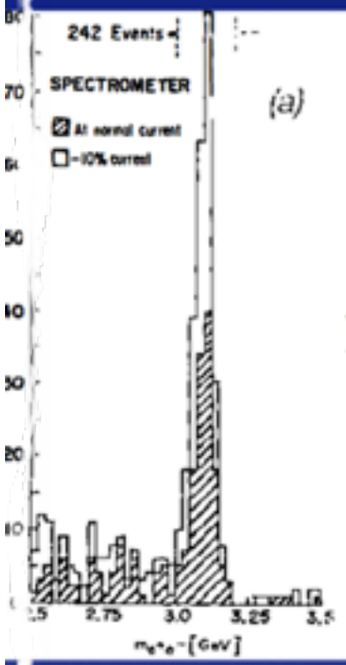
exclusively reconstructed hadrons

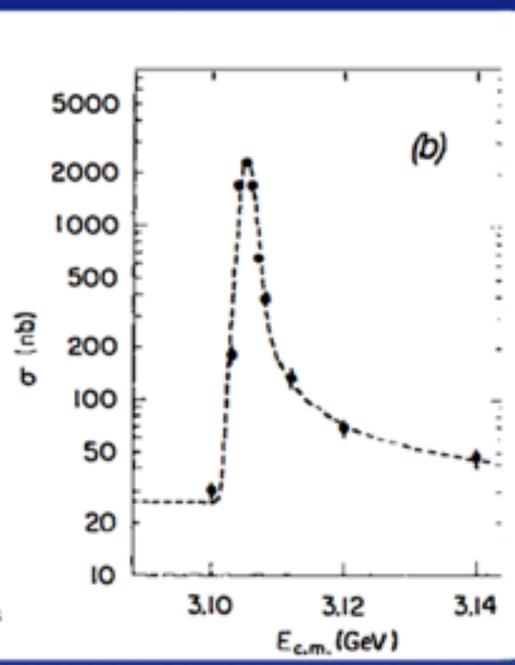
- LHC 50ns run period (2015)

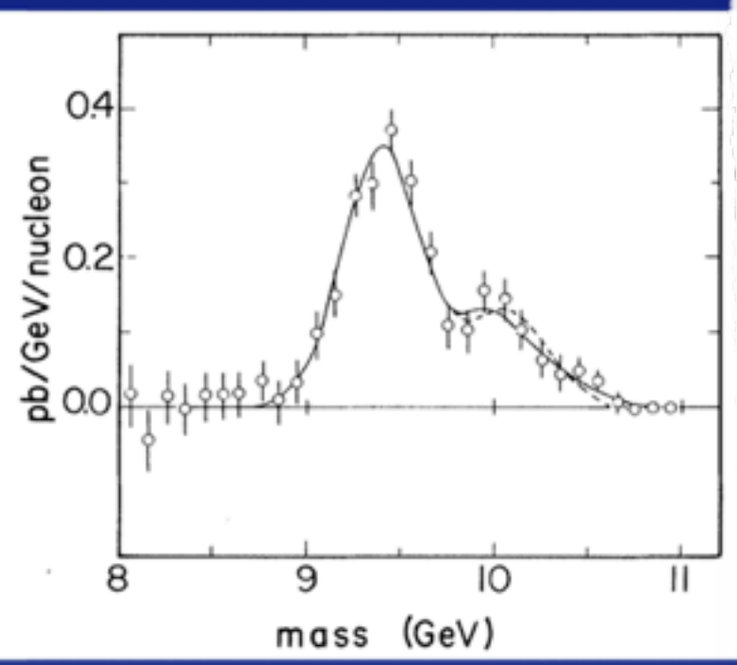


Quarkonium: The First Forty Years

Chris Quigg
Fermilab





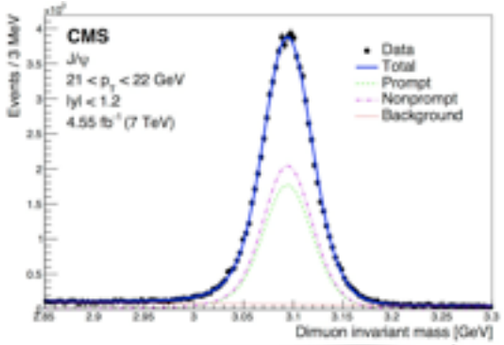


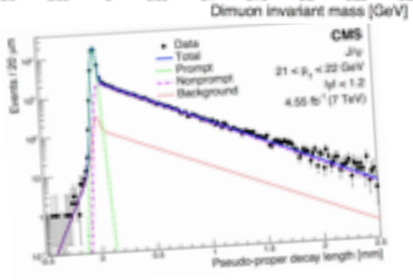
La physique valdôtaine · La Thuile · 2 March 2015

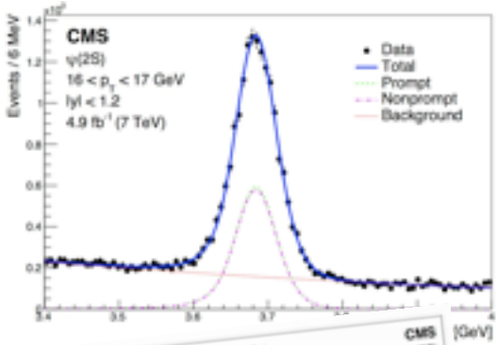
(from last year's edition of La Thuile)

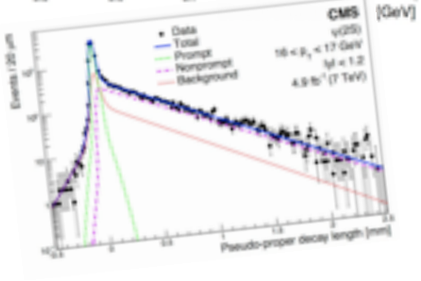
quarkonium: mass spectra at CMS

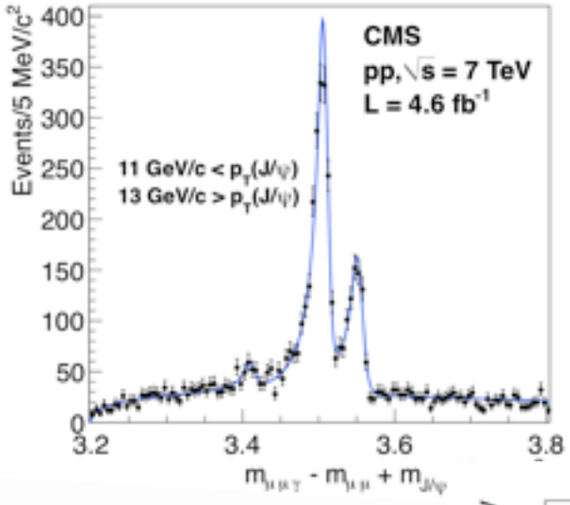
from Run I, various states, at various collision energies and collision systems

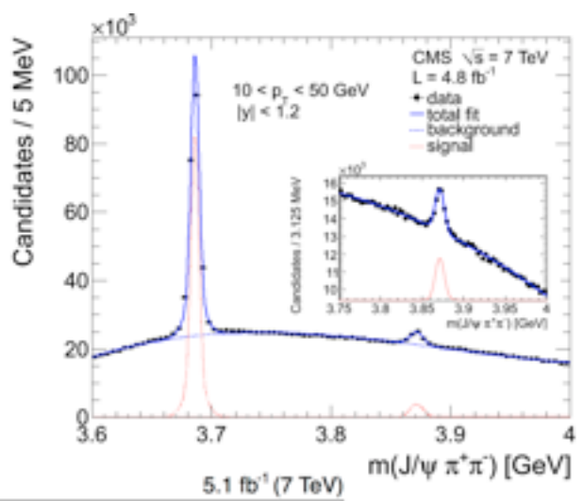


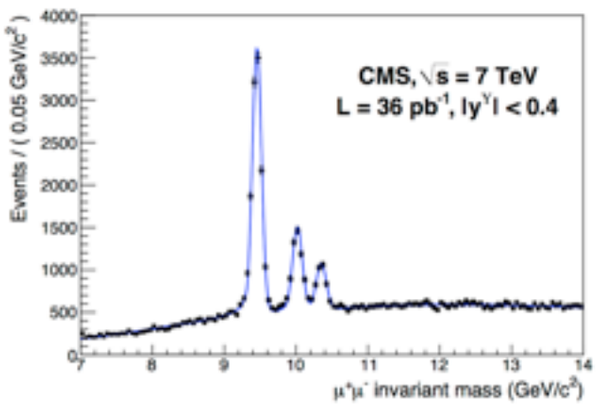


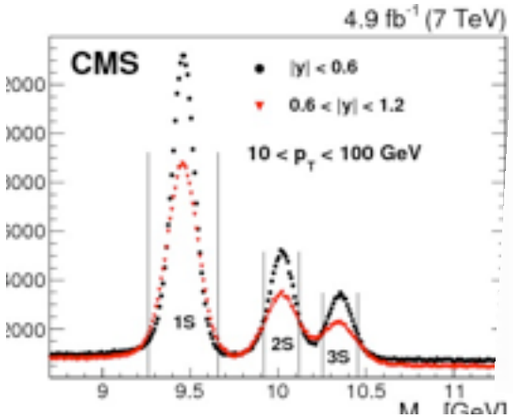


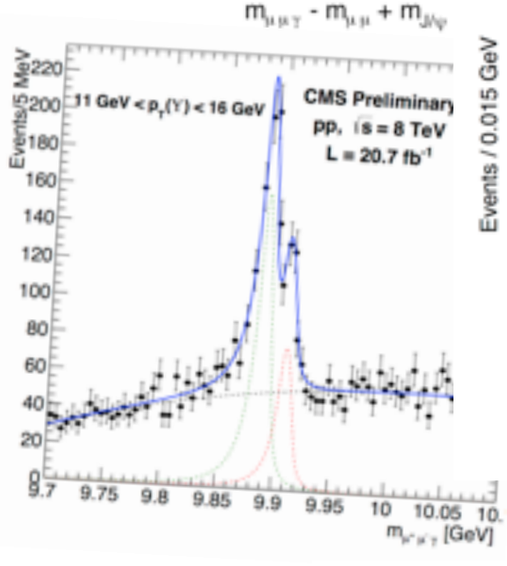


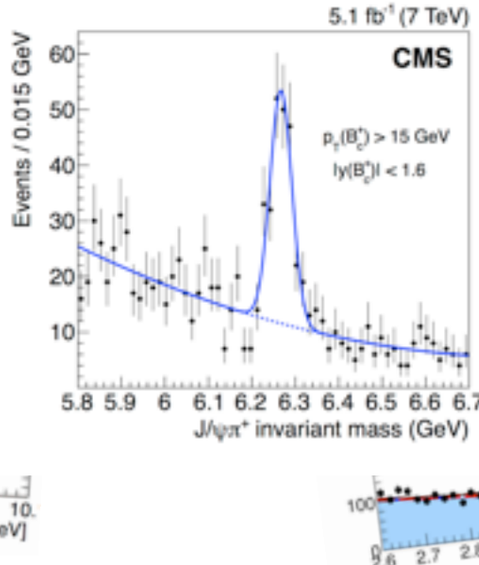


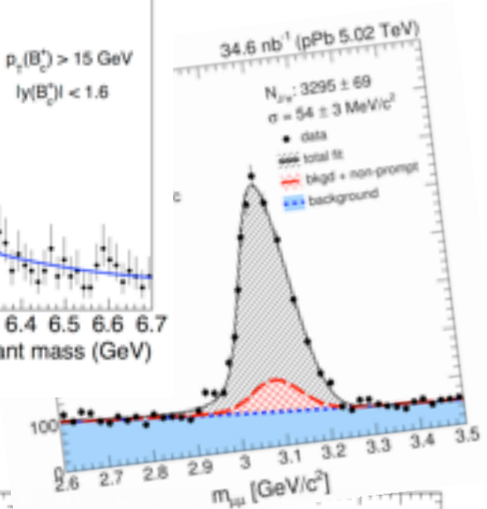


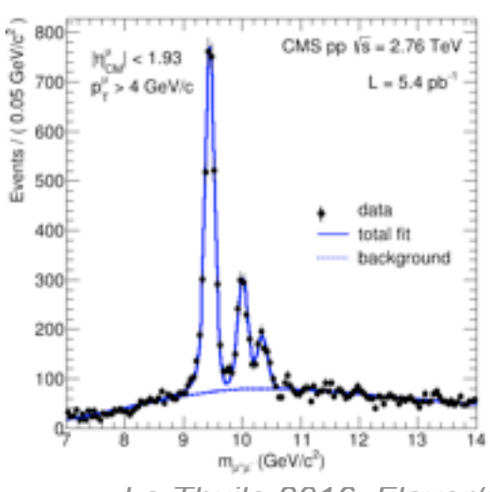


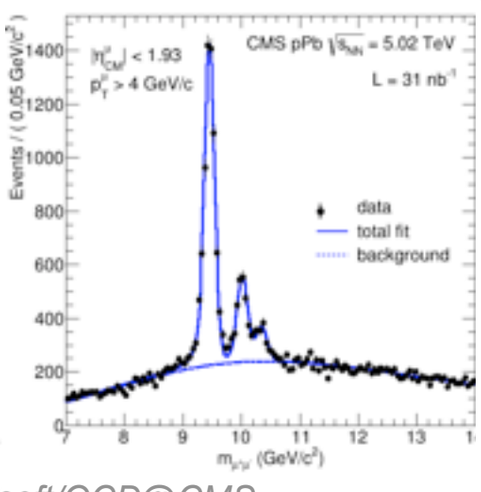


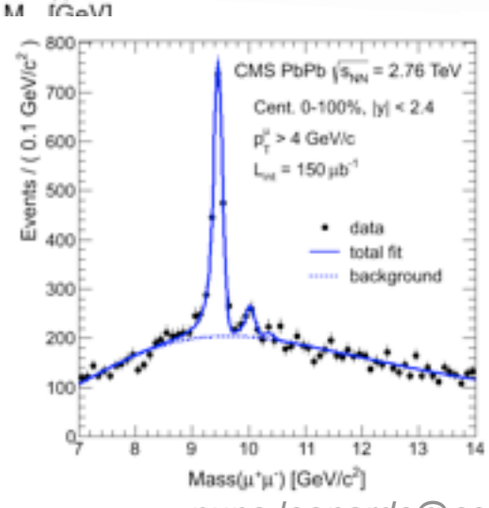


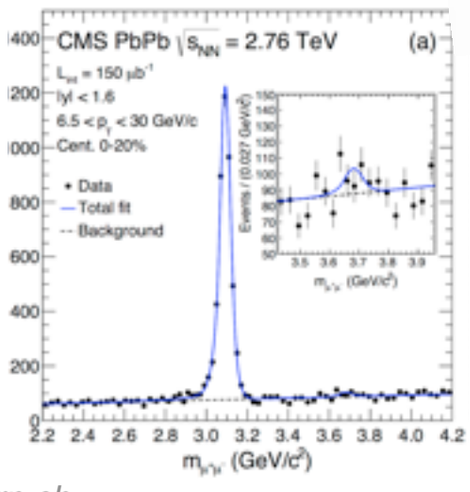


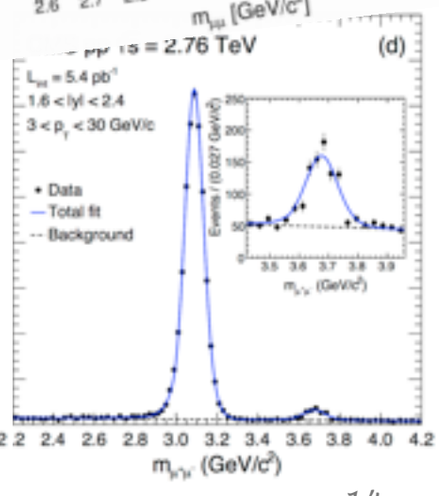






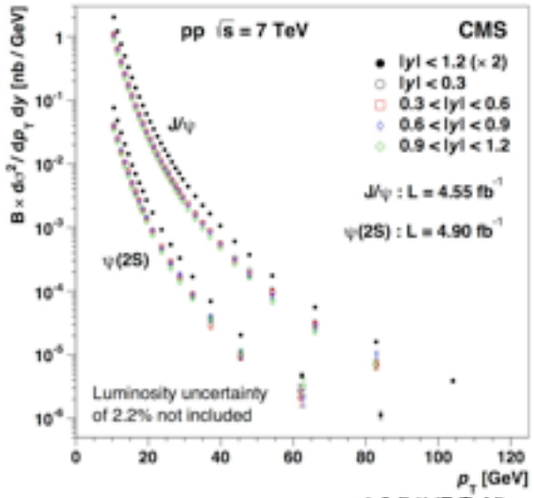


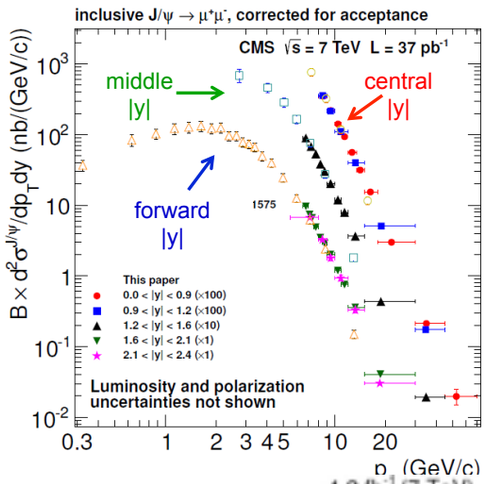


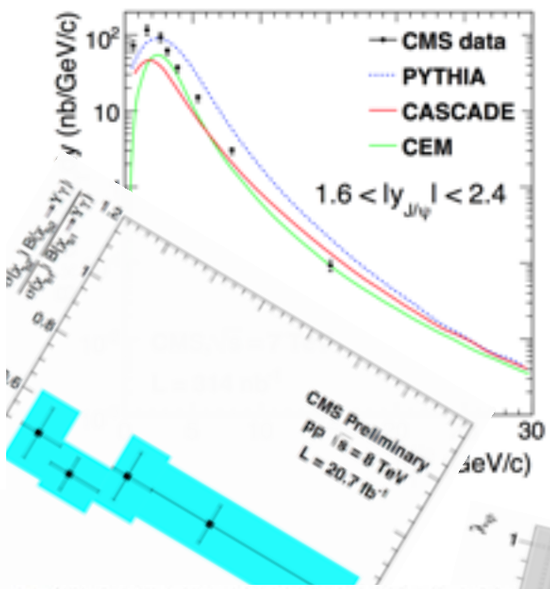


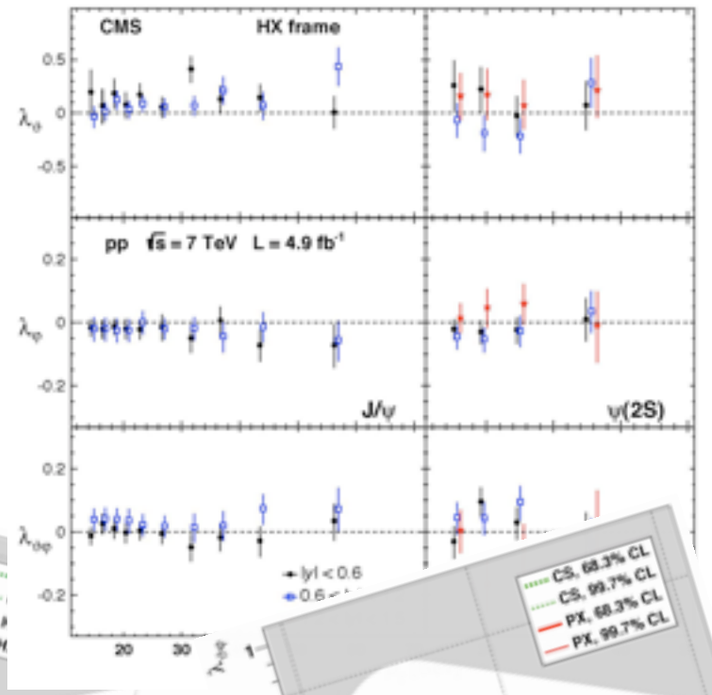
quarkonium: measurements at CMS

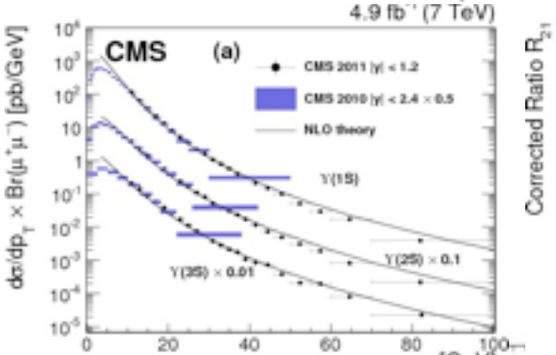
from Run I, production cross sections, ratios, and polarizations

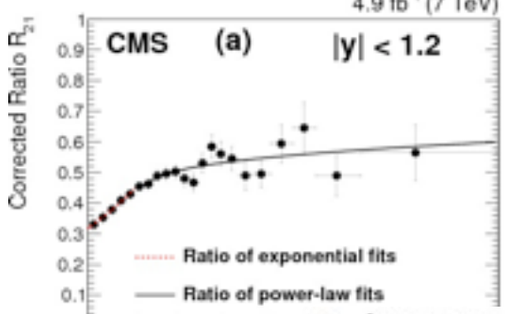


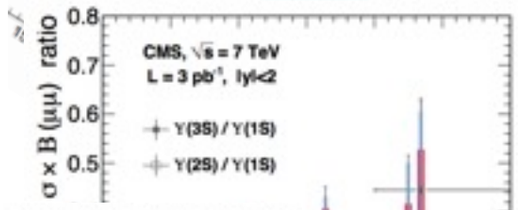


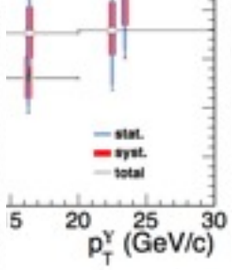


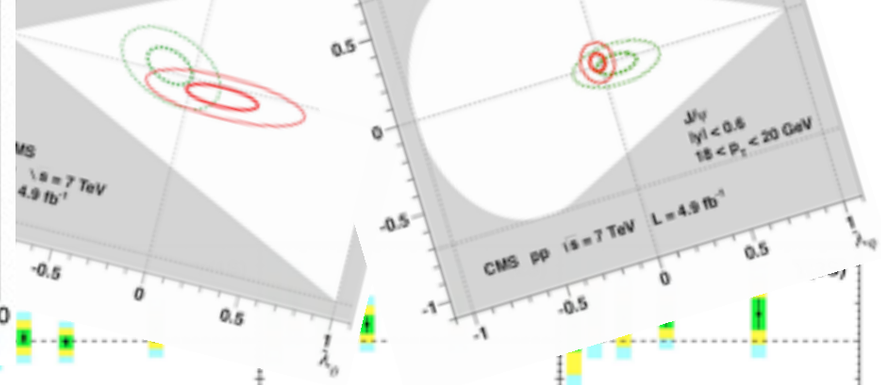


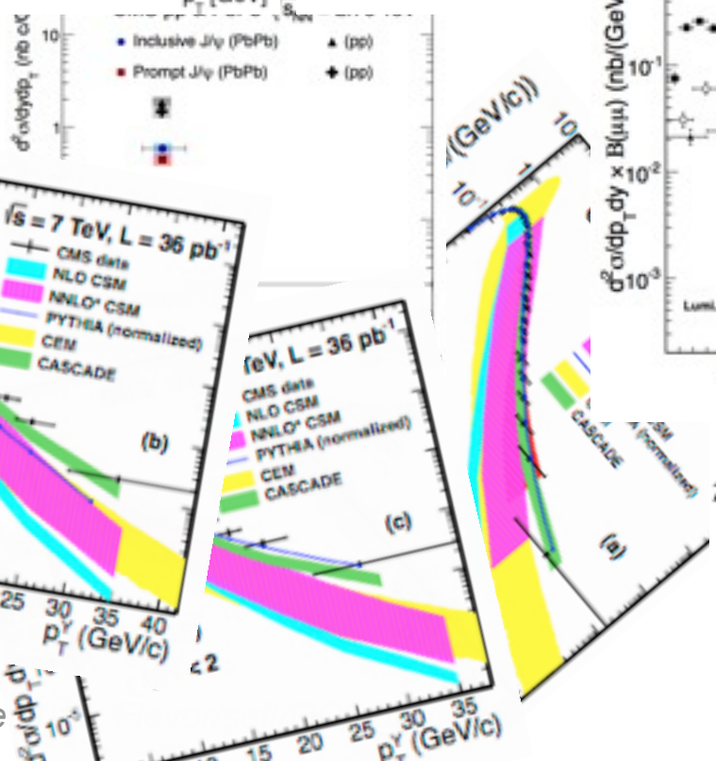


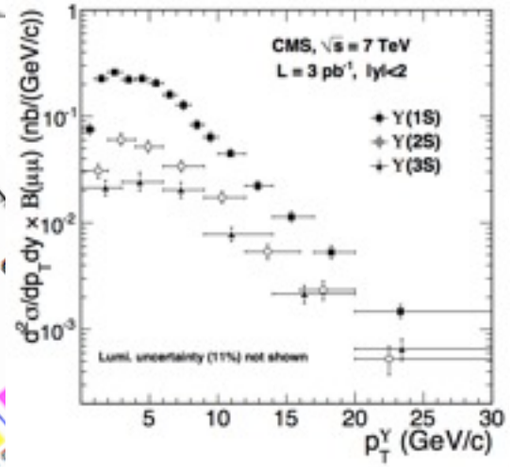


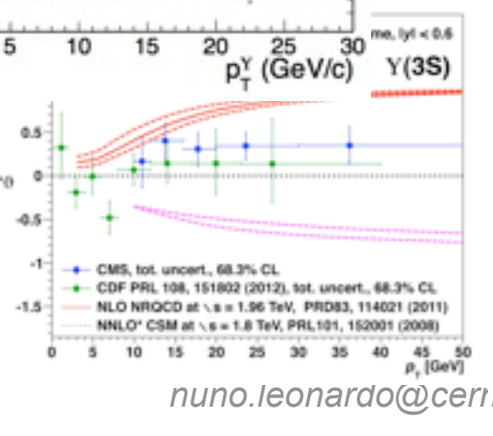


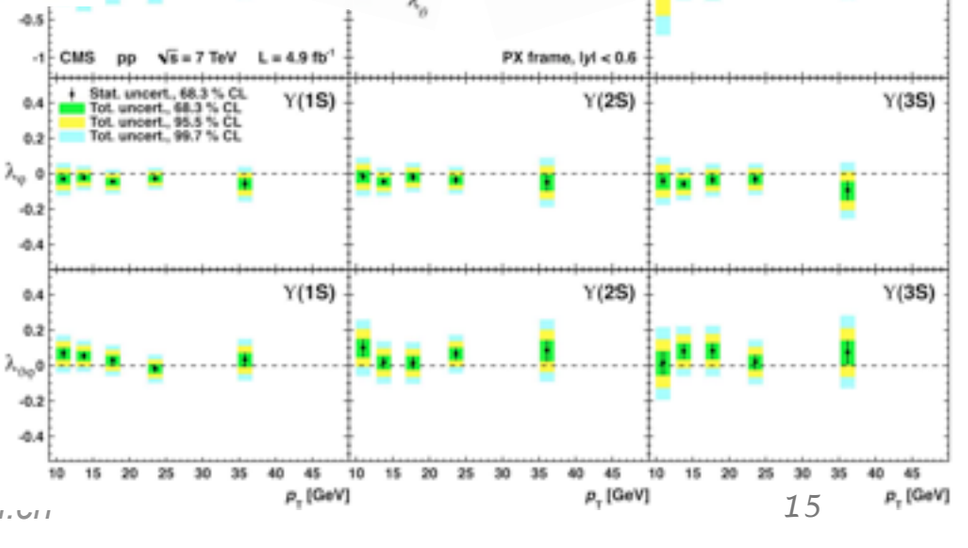






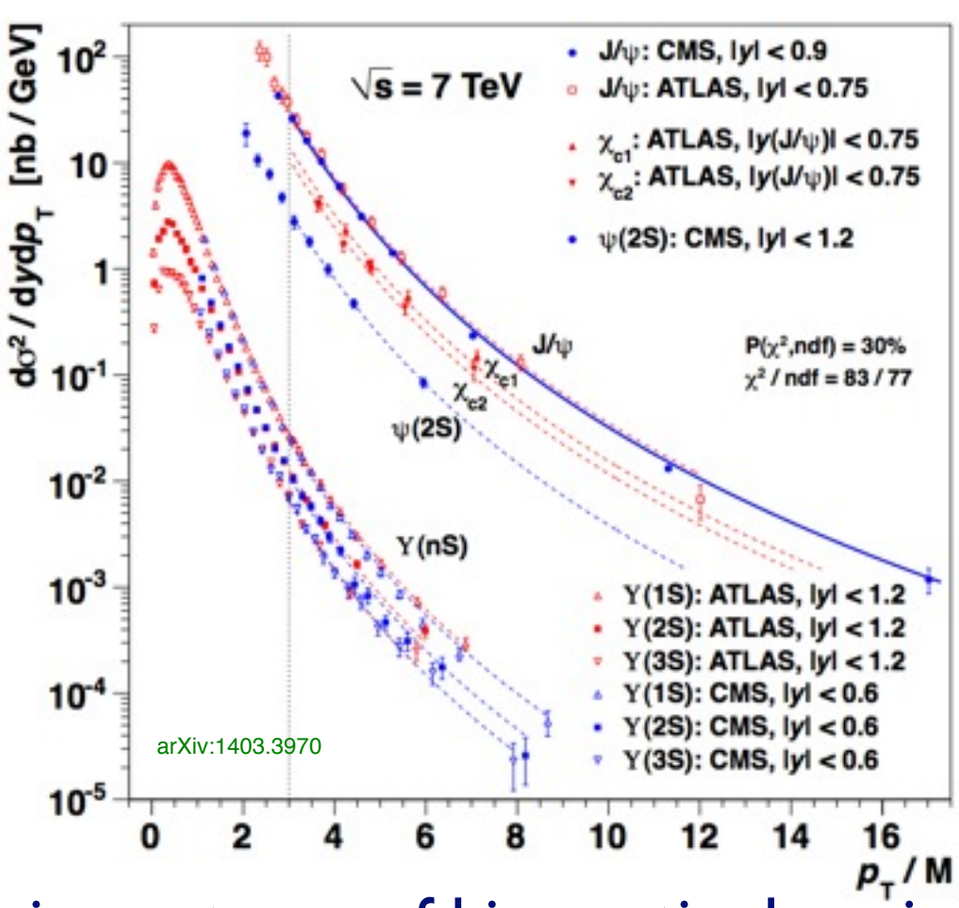


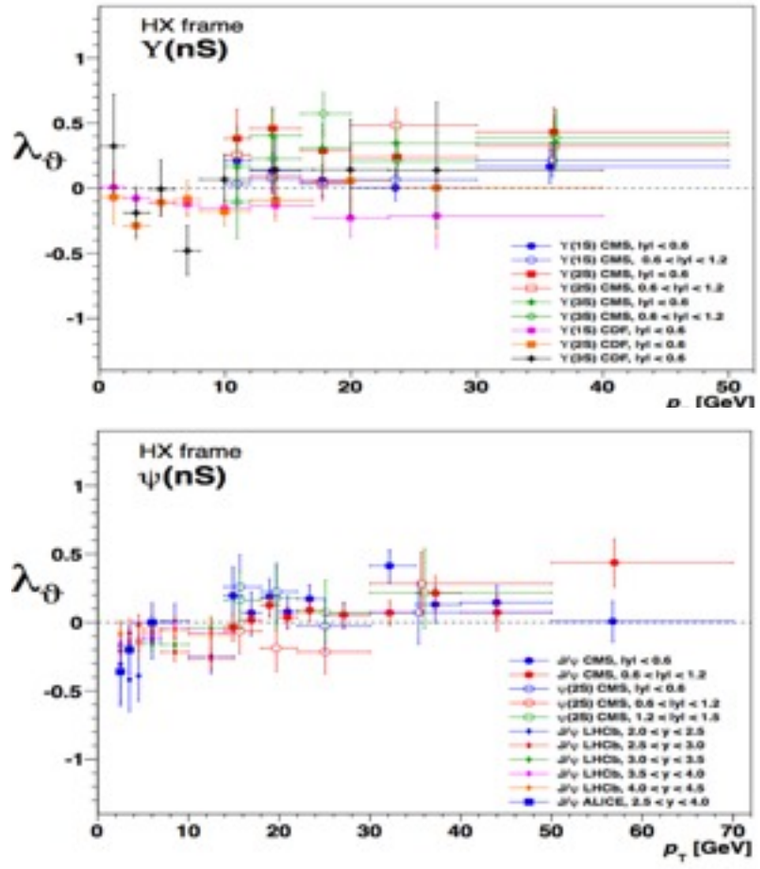




quarkonium production

- cross sections for 7 quarkonia have similar p_T/M shapes (for $p_T/M>3$)
- polarizations for 5 quarkonia tend (similarly) to unpolarized limit
  - Ockham hints: all quarkonia dominantly produced by a single mechanism(?)





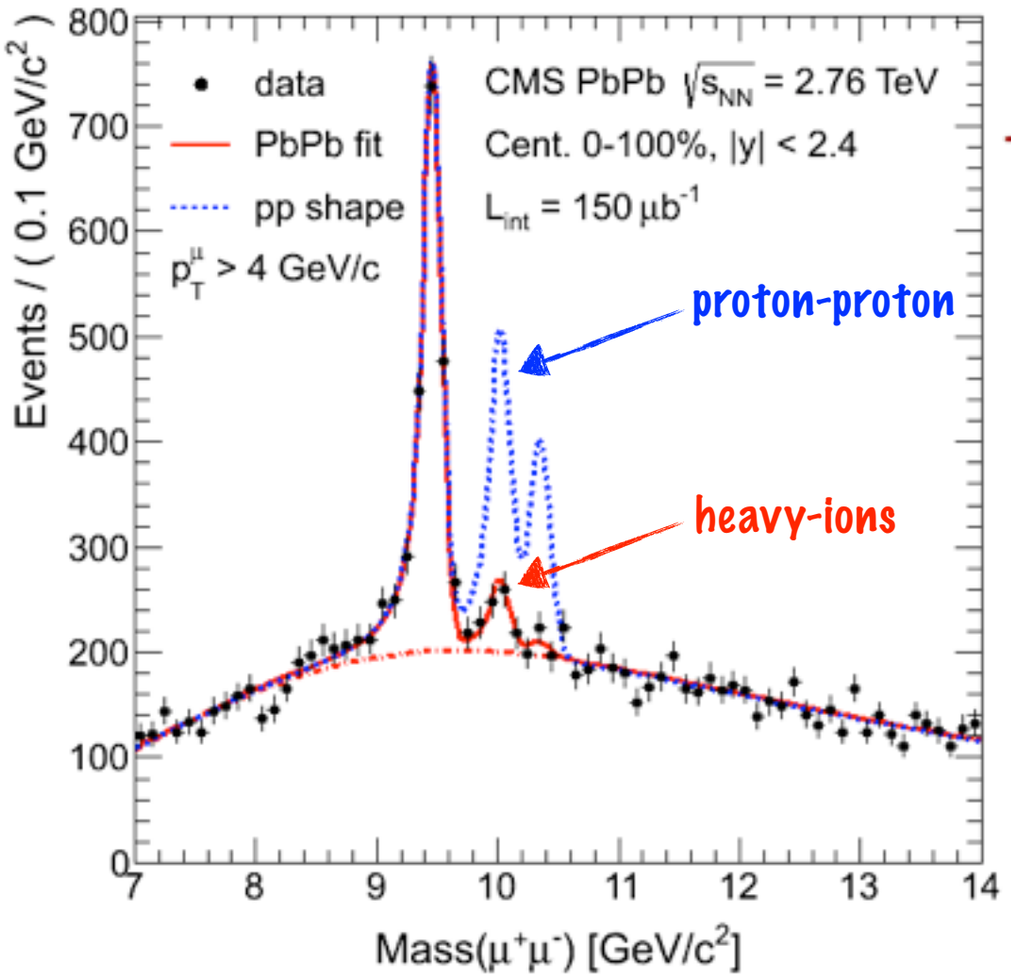
- importance of kinematic domain of high transverse momentum
  - perturbative factorization calculations work best at sufficiently high p_T
- LHC RunI thorough set of measurements contributed already enormously to a clarification of the field, towards a solution of the "*quarkonium puzzle*"

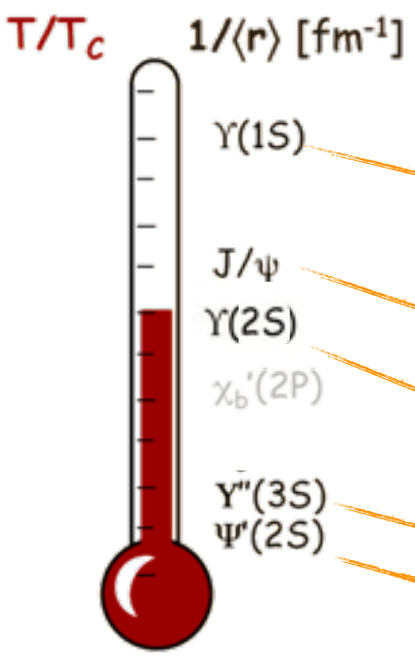
prospects, or the next ~~40~~ few years

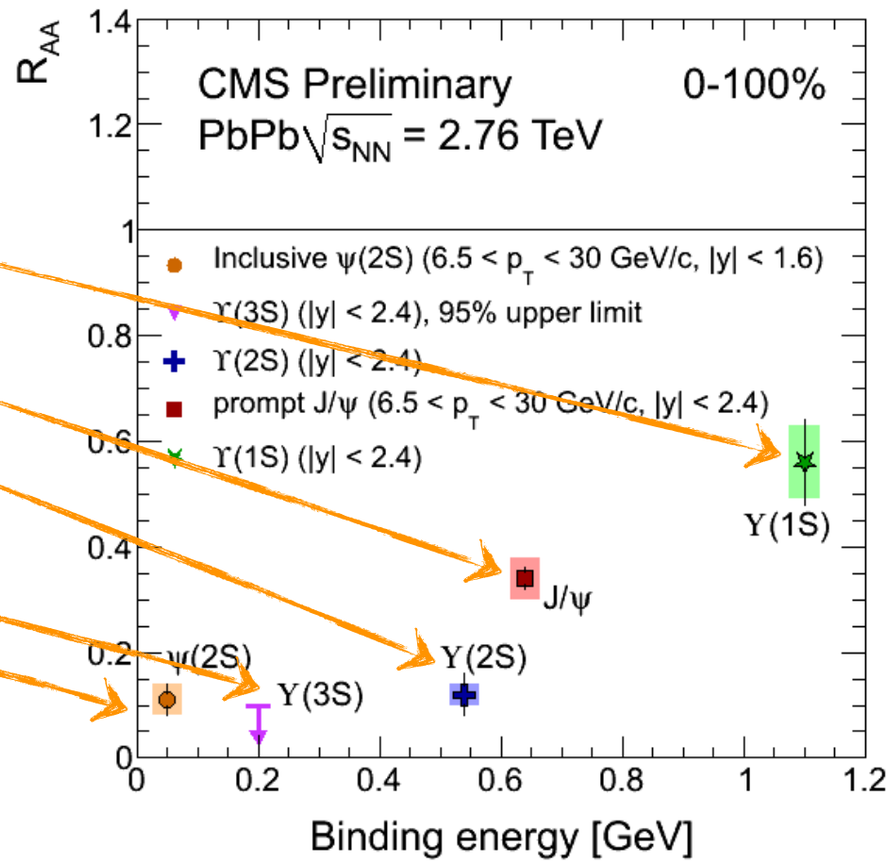
- S-wave states
  - production measurements at the new energy (arriving soon)
  - extend (considerably) the p_T reach (high sensitivity regime)
- P-wave states
  - cross sections and polarizations
  - note: current production measurements of S-wave states contain P-wave feeddown
- associated production
  - a more complete characterization of production mechanisms benefits from measurements of simultaneous production of quarkonia along with other particles
  - further quantify single vs double parton scattering contributions
  - examples: Q+Q, Q+Z/W, Q+hadrons/charged particles, etc
  - these studies are helpful for connection with ion collisions and rare decay searches
- measurement and search for associated *exotic* states
- collision systems
  - pp (reference) but also pPb (cold matter effects) and PbPb (hot matter properties)

quarkonium suppression

PRL 109 (2012) 222301, JHEP 05 (2012) 063,
PRL 107 (2011) 052302, PRL 113 (2014) 262301,
CMS-PAS-HIN-15-001





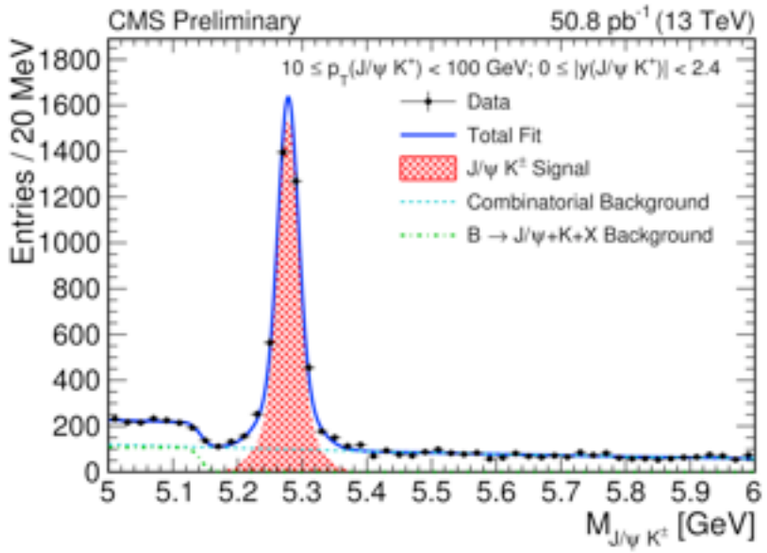


- the three Y(nS) states are reconstructed for the first time in heavy ion collisions
  - excited states observed to be more suppressed than ground state
- all S-wave quarkonium states are found to be suppressed in PbPb relative to pp
- CMS observes quarkonium sequential melting (less tightly bound states more suppressed in hot QCD medium) -- compatible with quark gluon plasma formation

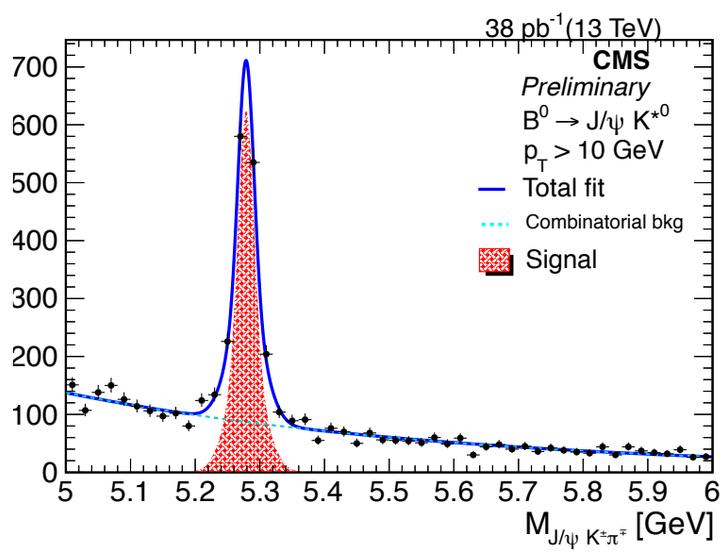
B mesons

p+p @ 13TeV

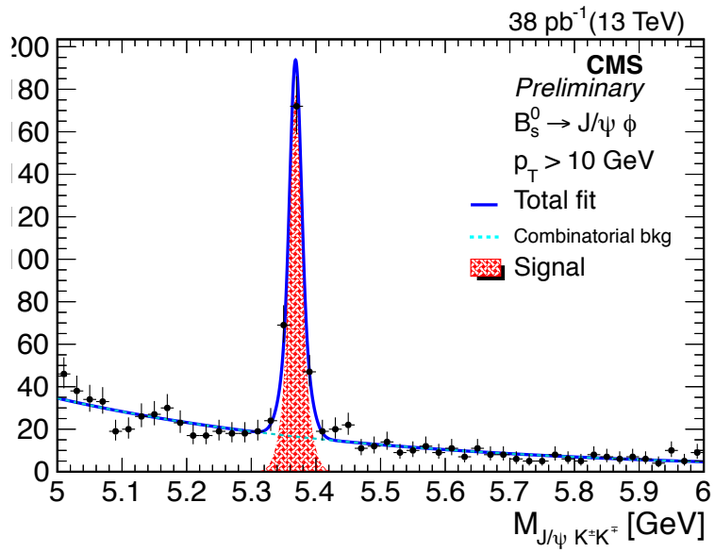
$B^{\pm} \rightarrow J/\psi\ K^{\pm}$



$B^0 \rightarrow J/\psi\ K^{*0}$

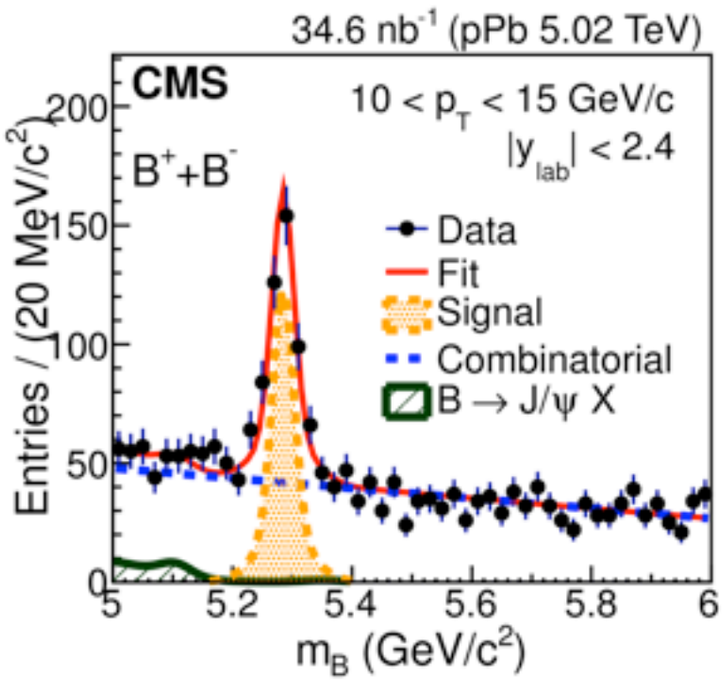


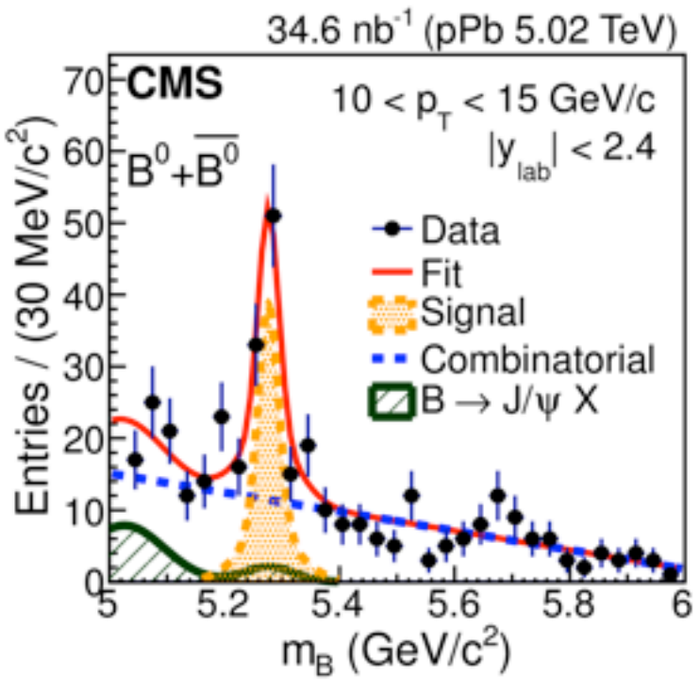
$B^0_s \rightarrow J/\psi\ \phi$

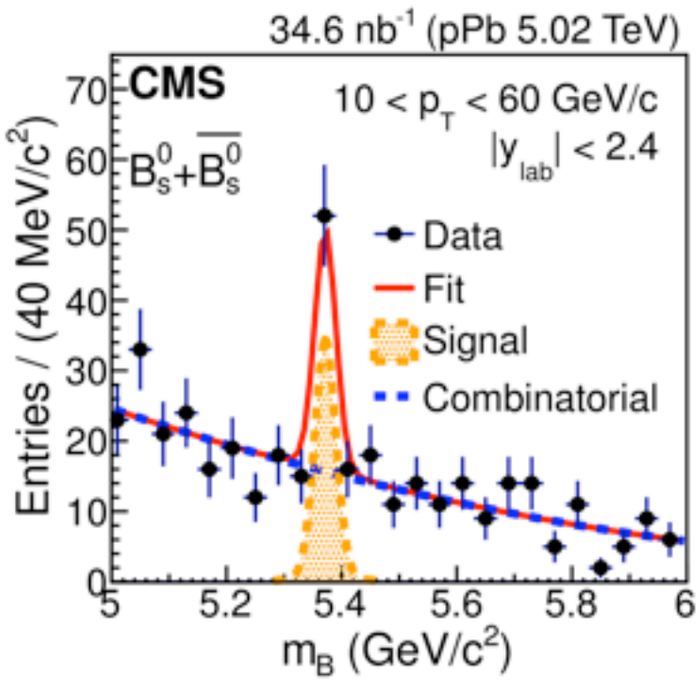


CMS-DP-2015-018

p+Pb @ 5TeV





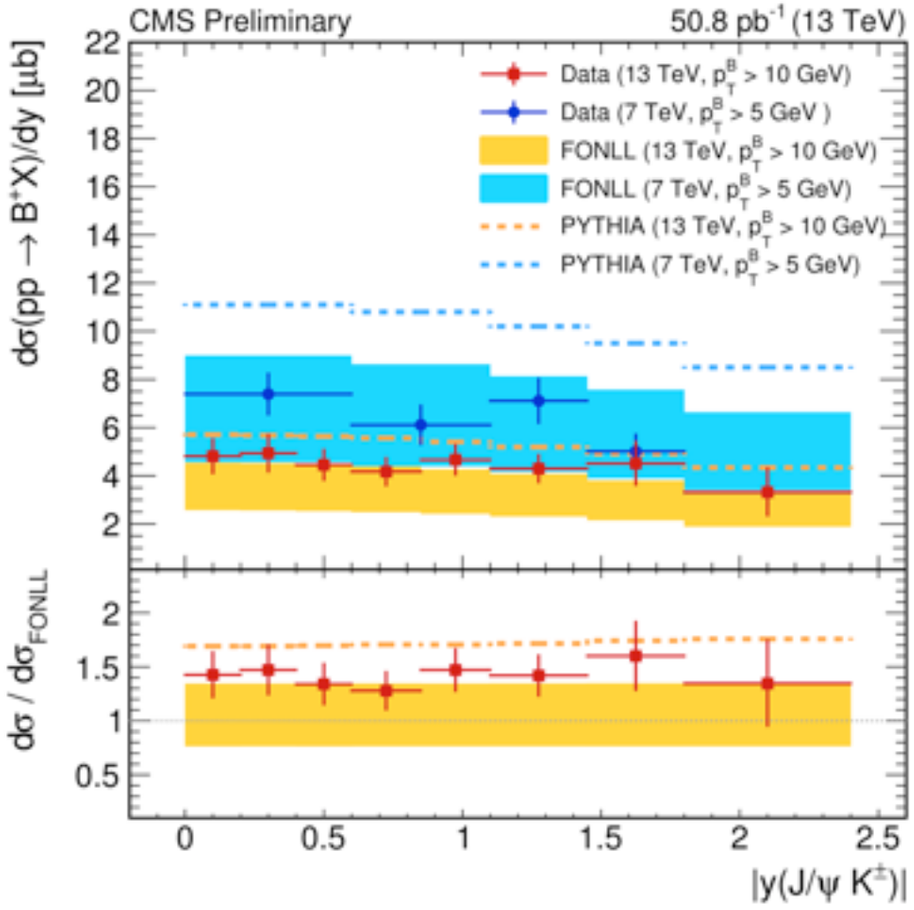


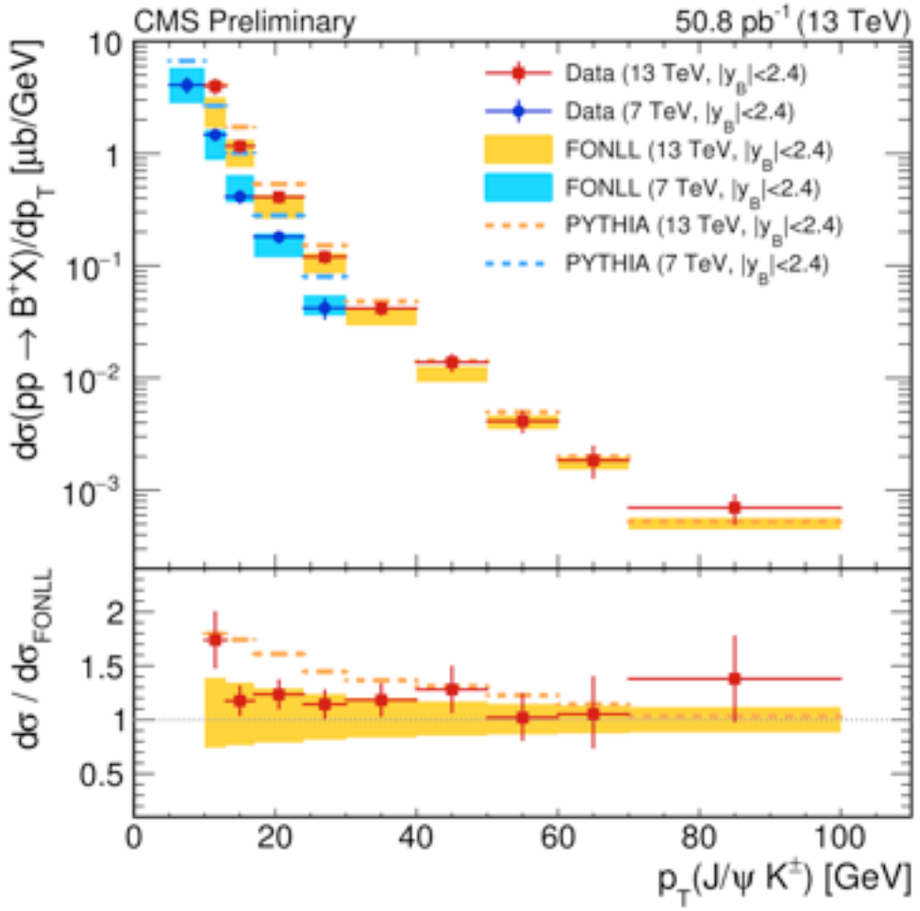
PRL 116 (2016) 032301

- first measurements of exclusive b-hadrons in pPb collisions

b hadron production at 13TeV

- measured B differential cross section measured at 13TeV
  - as a function of p_T and rapidity
  - via $B^+ \rightarrow J/\psi K^+$ channel, with $50 pb^{-1}$ (50ns LHC run period)
- theory comparison
  - good agreement with FONNL predictions
- energy dependence: compared with 7TeV CMS data

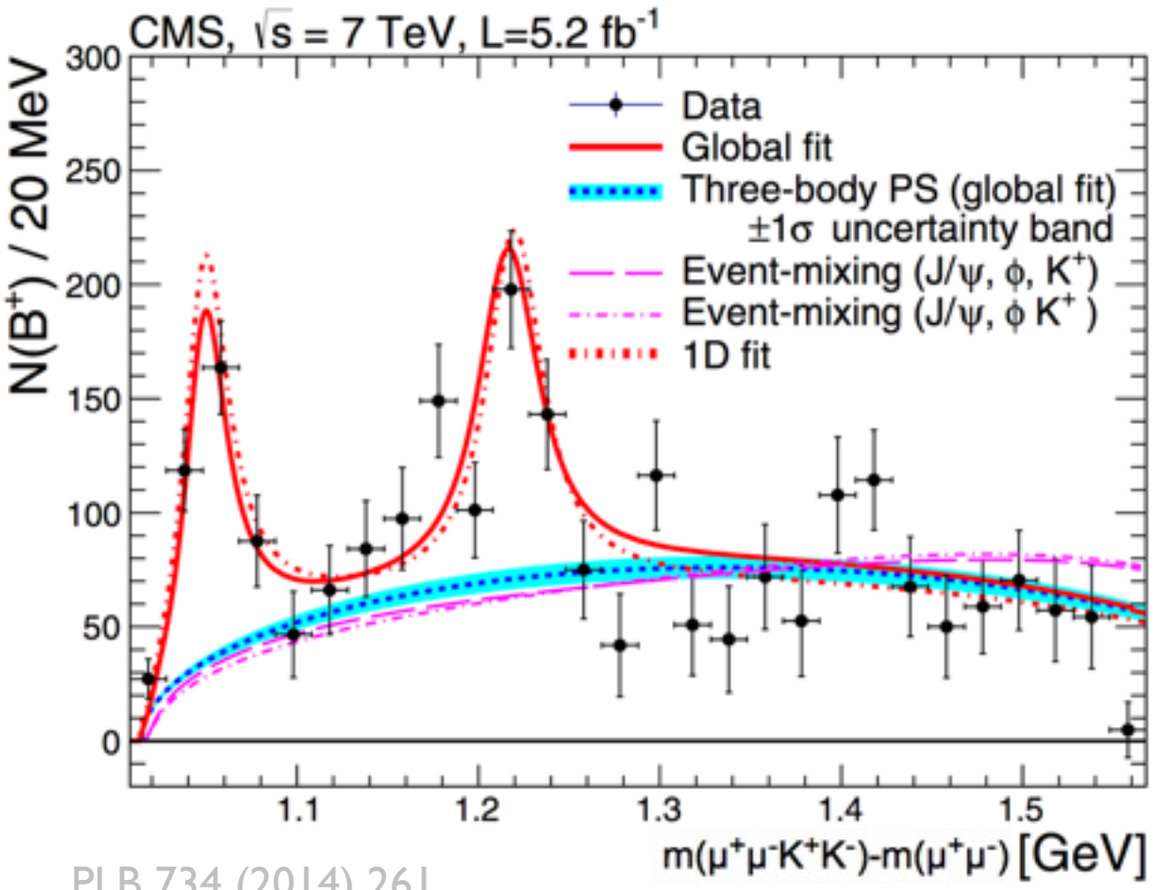




CMS-PAS-15-004

spectroscopy

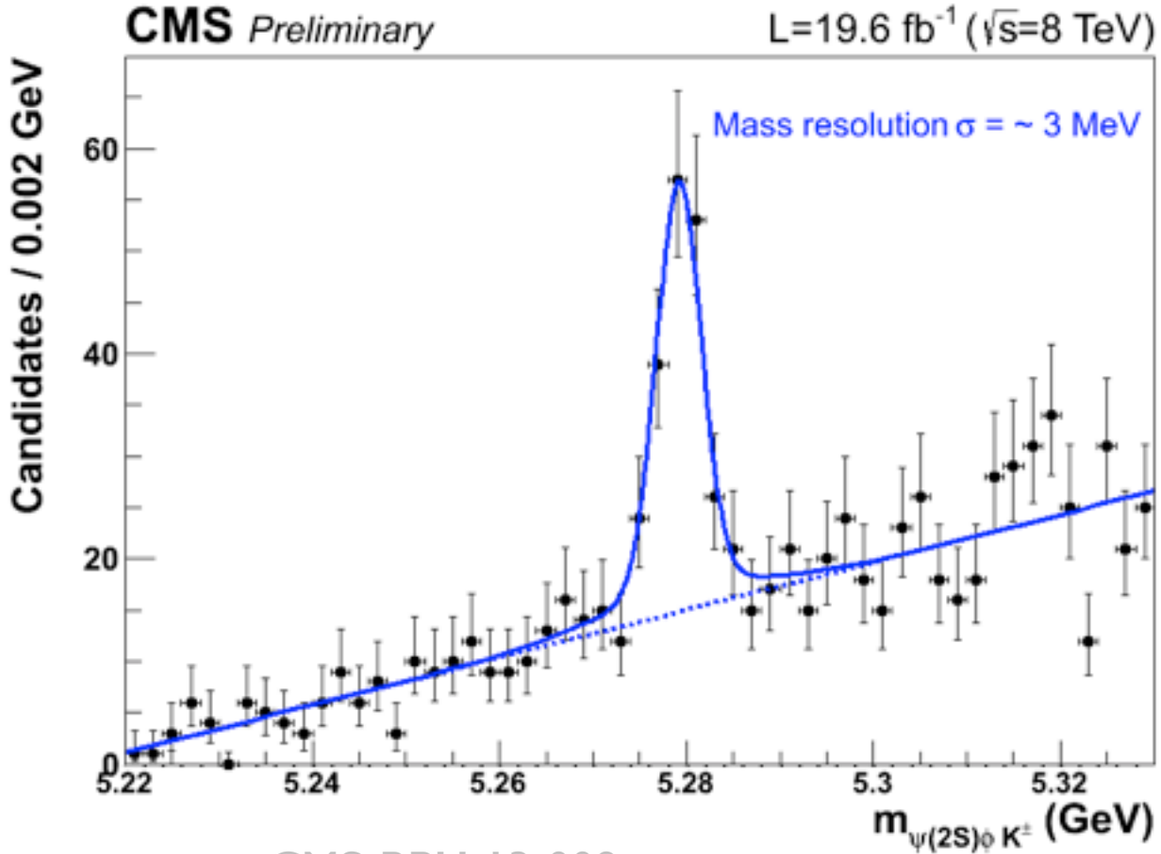
$B^+ \to J/\psi\Phi K$



PLB 734 (2014) 261

- observed (>5σ) resonance compatible with Y(4140)
  - first evidence at CDF (@3.8σ)
- candidate interpretations
  - DsDs*, cscs tetraquark, threshold kinematic effect, hybrid charmonium

$B^+ \to \psi(2S)\Phi K$

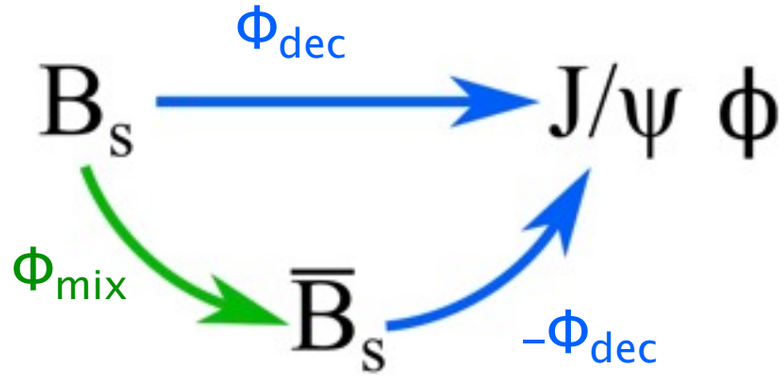


CMS-BPH-13-009

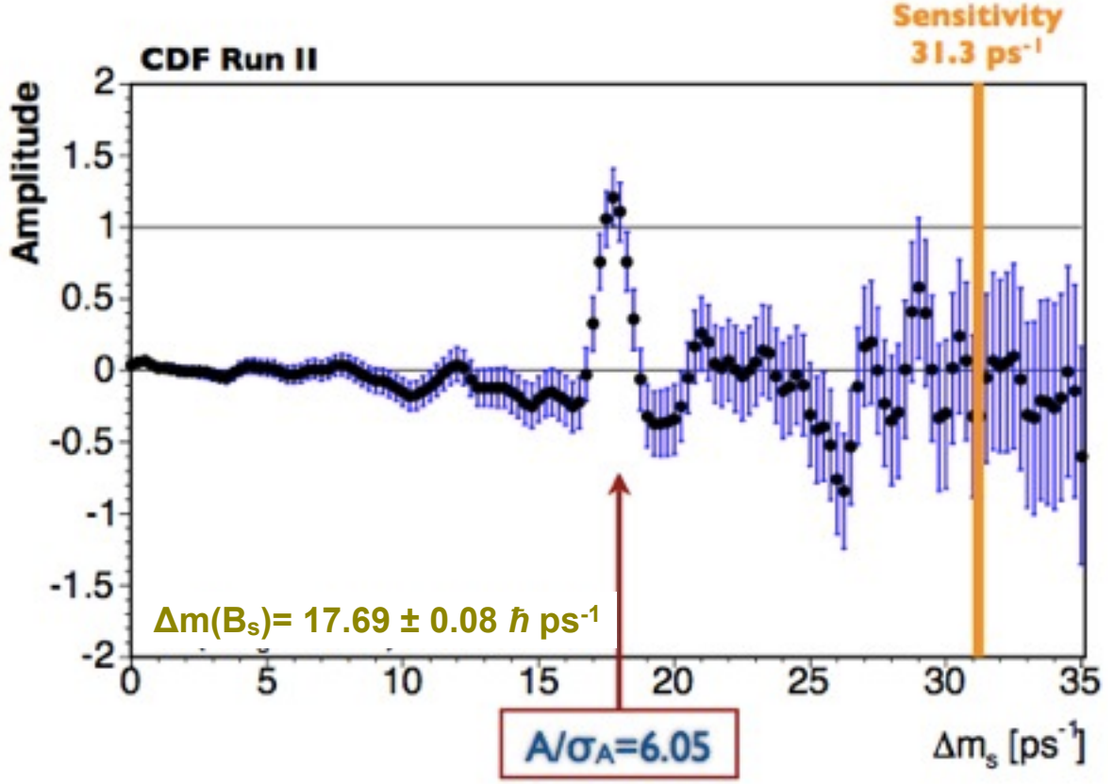
- observed new B^+ decay channel
- measurement of relative branching fraction being prepared

properties: B_s mixing

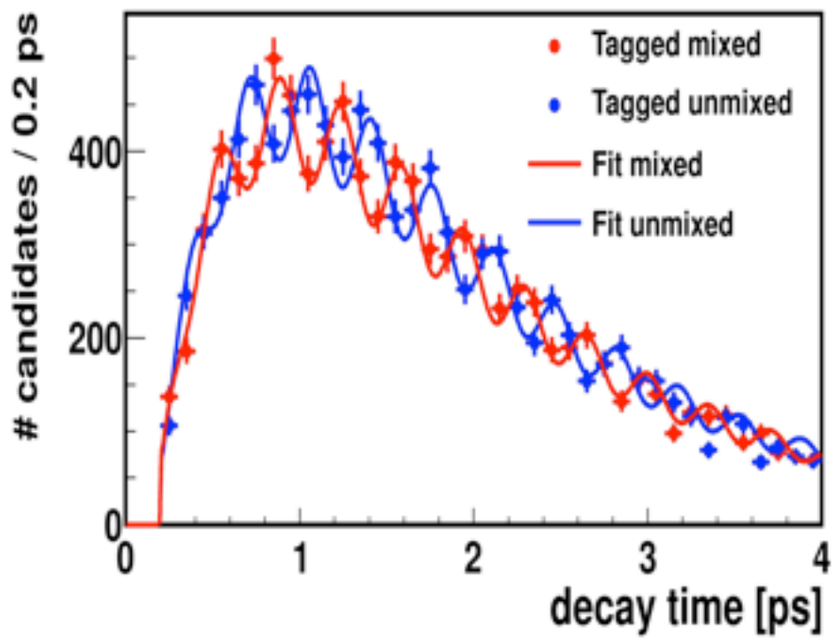
- neutral B mesons undergo B$\underline{\text{B}}$ oscillations
  - $B_s \to J/\psi\Phi \Rightarrow$ flavor unspecific $\Rightarrow \Phi_s$
  - $B_s \to D_s^- \pi^+ \Rightarrow$ flavor specific $\Rightarrow \Delta m_s$



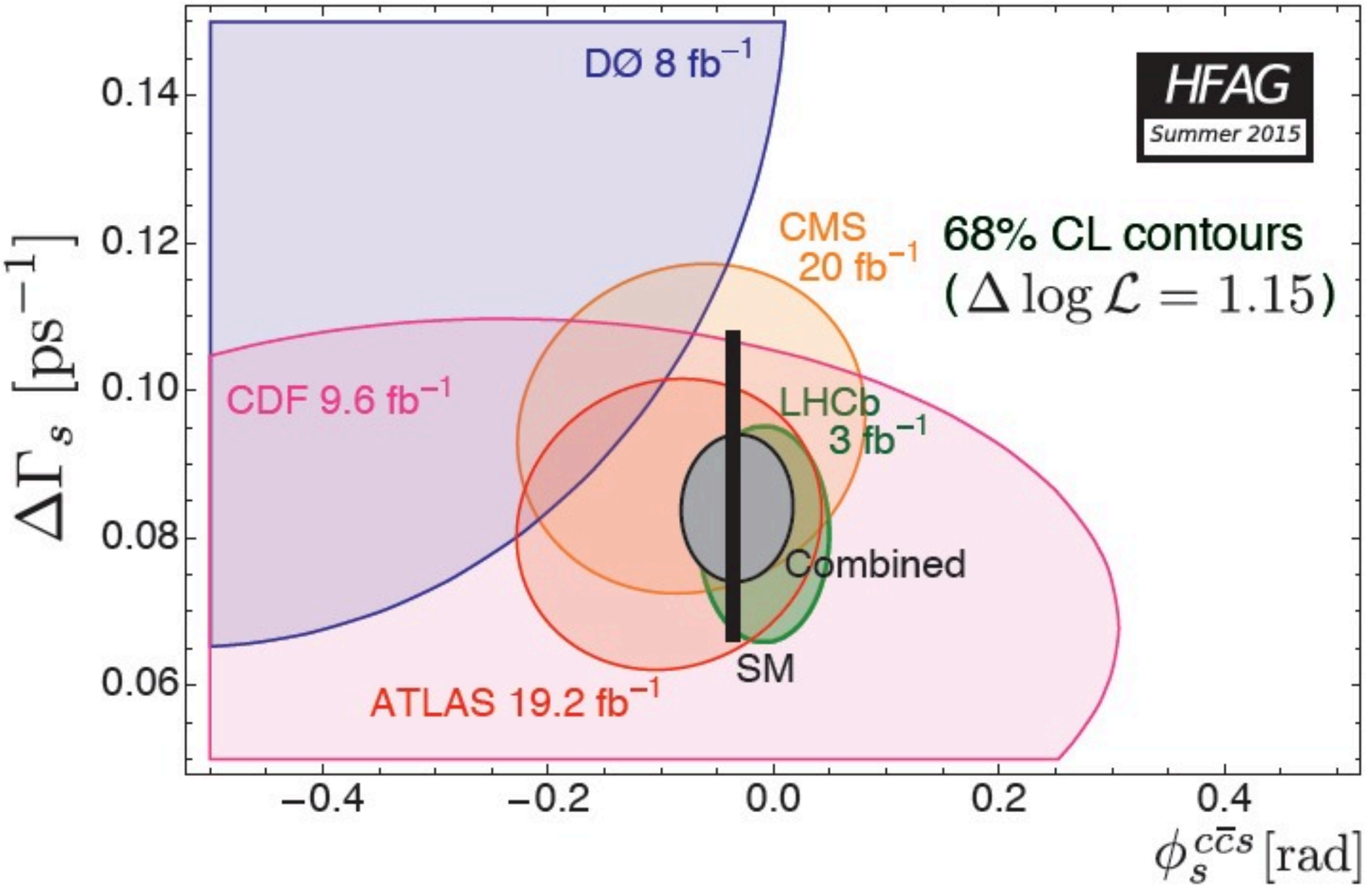
10 years ago at Fermilab!



LHCb confirmation @LHC Run1



properties: B_s mixing phase (Φs)

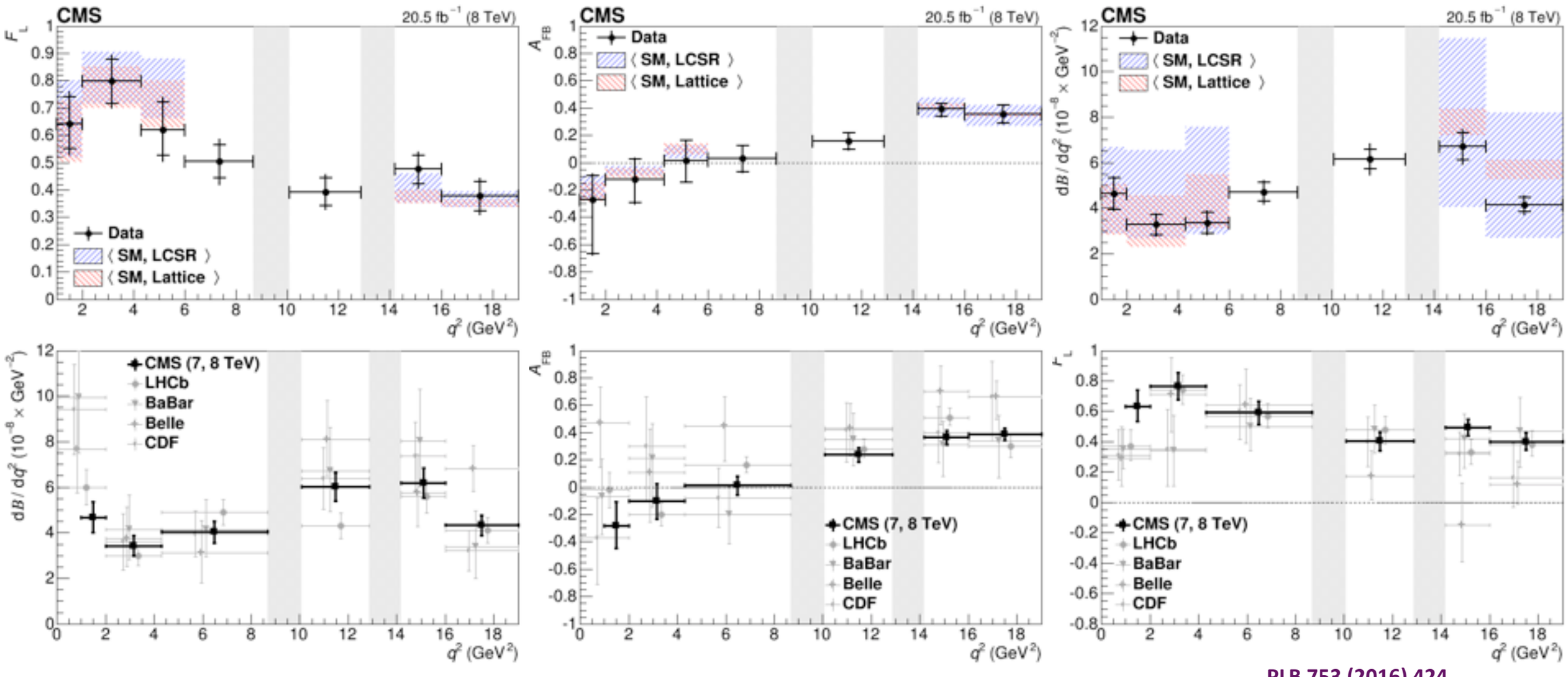


- B_s mixing measurements (both frequency and phase) appear compatible with SM
  - within current theory and experimental precisions -- the latter to be improved in Run2

rare decays: B→K*μμ

- forbidden decay at tree level, rare (BF~10^{-6}), can occur via loops
- angular analyses yields rich set of observables to compare against SM predictions: differential BF, A_{FB}, A_{CP}, P5', Isospin asymmetry,...
- CMS results consistent with theory prediction, and other experiments
- Next: investigate additional channels and variables

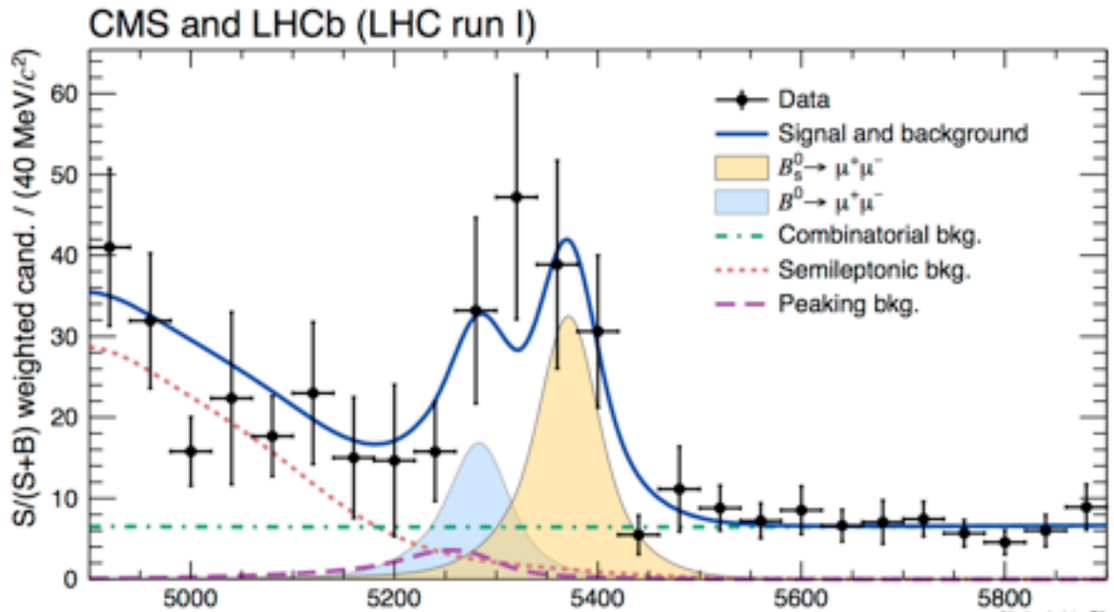
PLB 753 (2016) 424



PLB 753 (2016) 424

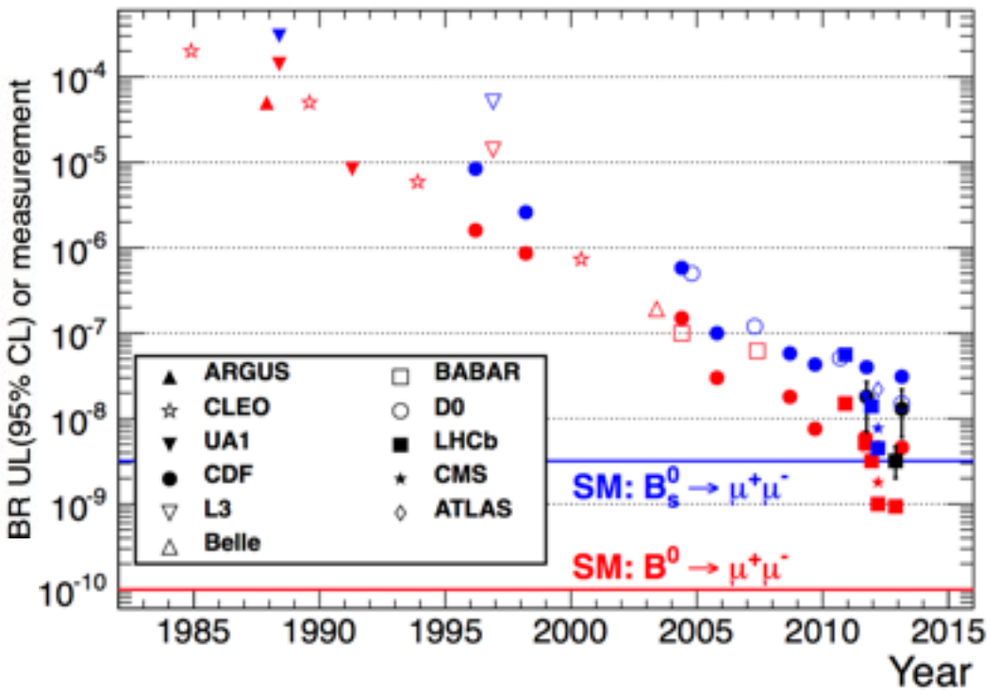
rare decays: B→μμ, RunI observation

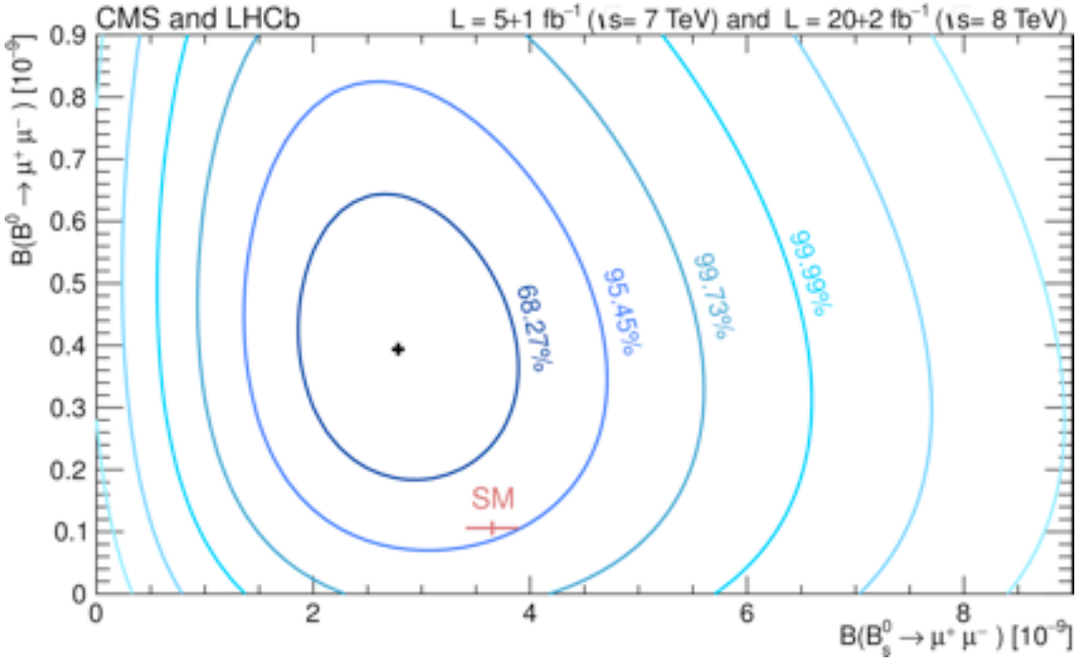
- we've finally observed the long sought, 'golden' decay channel
  - $B_s \to \mu\mu$ (CMS:4.3σ;LHCb: 4.0σ; comb.: 6.2σ)
- and a hint of the decay $B^0 \to \mu\mu$
  - from combined CMS+LHCb data
  - SM compatibility 1.2σ (B_s), 2.2σ(B^0)



Nature 522 (2015) 68, PRL 111 (2013) 101804

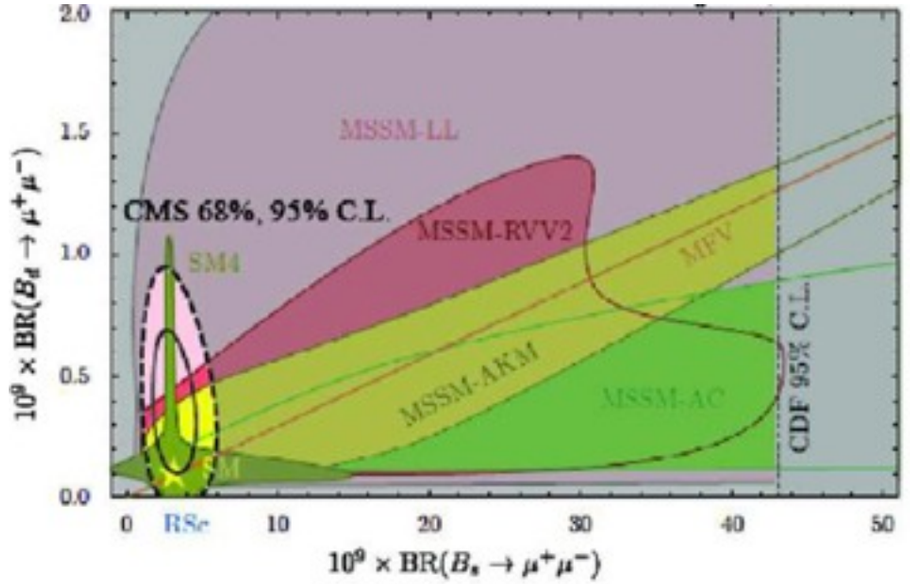
a 3 decade long search





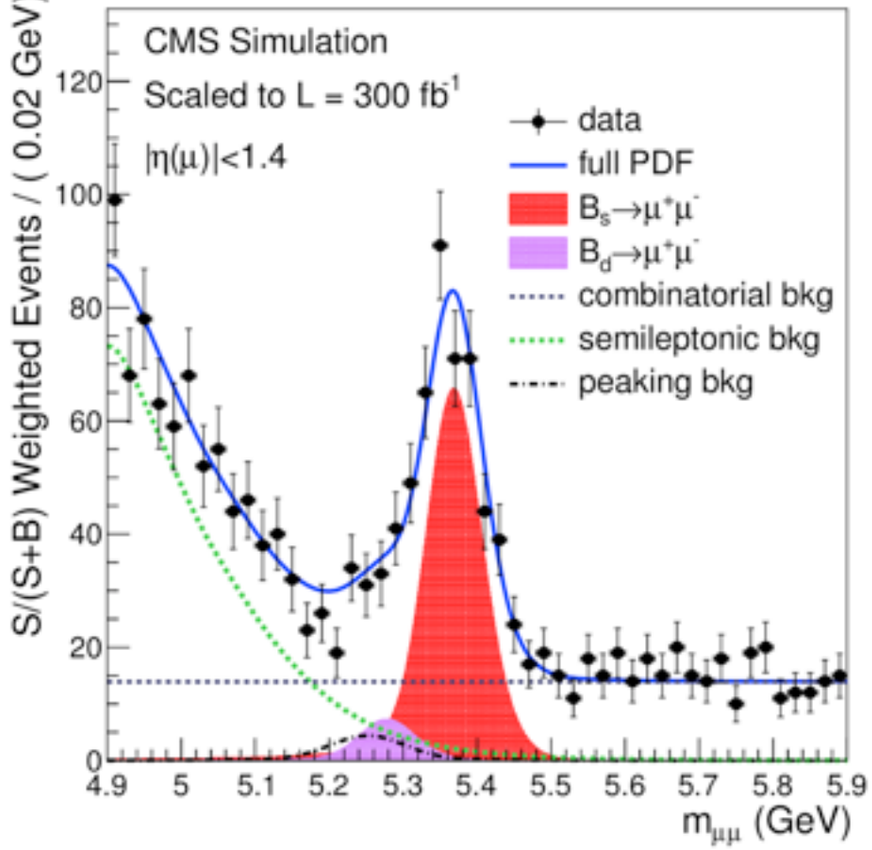
rare decays: B→μμ, Run2 prospects

- Run I
  - observed the B_s channel
  - did not find New Physics (yet)
  - strong constraints in regions of NP parameter space (eg SUSY w/large tanβ)



D. Straub et al, arXiv:1012.3893

- Run 2
  - not enough data just yet
  - pursue search for B^0 channel
  - measure B_s/B^0 ratio
  - pursue measurement of observables with complementary sensitive to NP
  - eg effective lifetime (PRL 109 (2012) 041801)

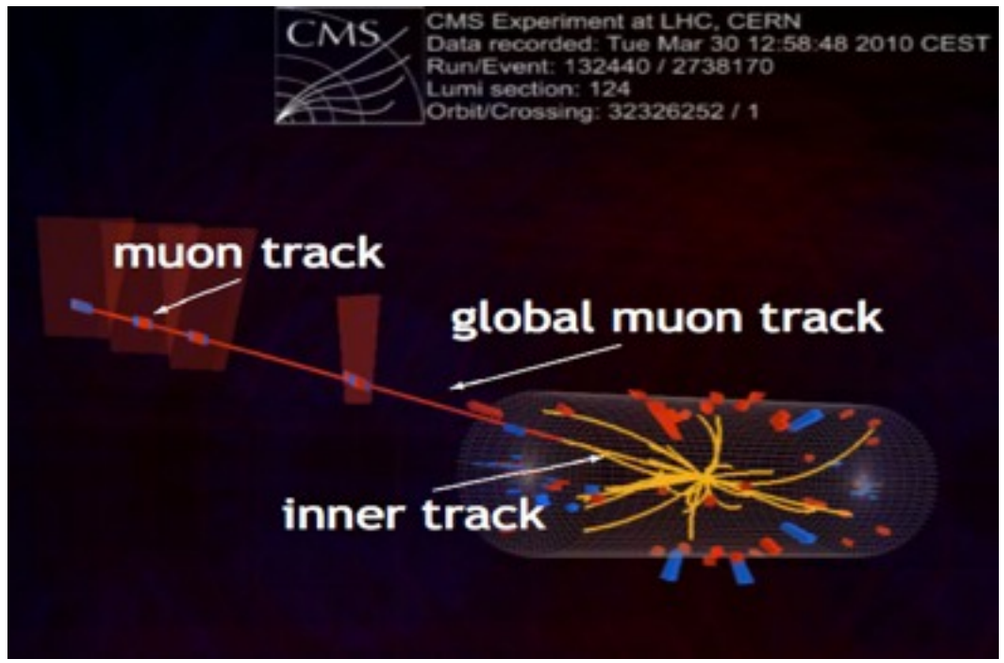


CMS-PAS-FTR-14-015

summary

- CMS has delivered first results at 13TeV based on 2015 data
  - Baseline particle production measurements delivered
  - Used for tuning MC simulations and map energy dependencies
  - Cross section measurements found in agreement with expectation
- Run I has demonstrated CMS' ability to deliver powerful results in the areas of QCD and flavor physics, from production to rare decays
  - exploring high LHC luminosities and cross sections, precision tracking and robust muon identification, across different collision systems
- Physics run is soon resuming
  - will allow higher precision, extended and new measurements and the exploration of rarer phenomena

diMuon *trigger & reconstruction*



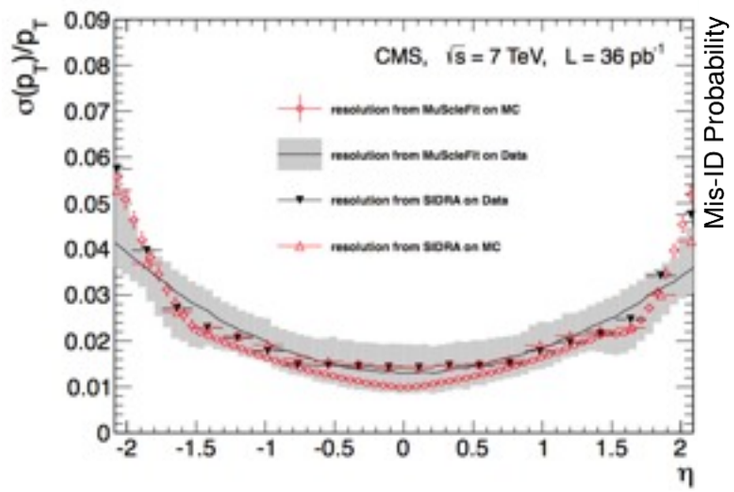
a dedicated dimuon trigger path

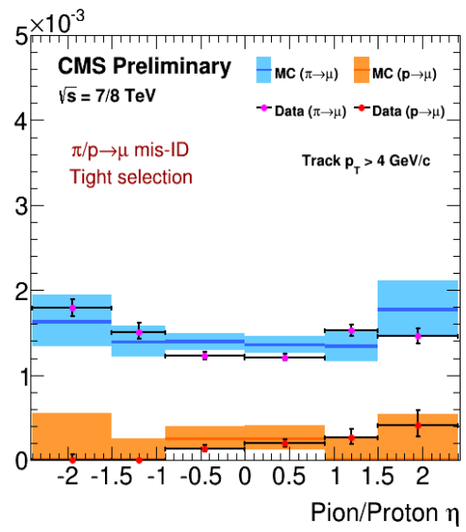
Hardware trigger
$p_T(\mu)>3$GeV (few kHz)

High level trigger 2011 (2012)

central region ($|\eta|<1.8$):
$p_T(\mu)>4(3)$GeV, $p_T(\mu\,\mu)>3.9(4.9)$GeV
forward region ($1.8<|\eta|<2.2$):
$p_T(\mu)>4$GeV, $p_T(\mu\,\mu)>7$GeV, Prob(VTX)>0.5%

$4.8<M(\mu\,\mu)<6.0$GeV



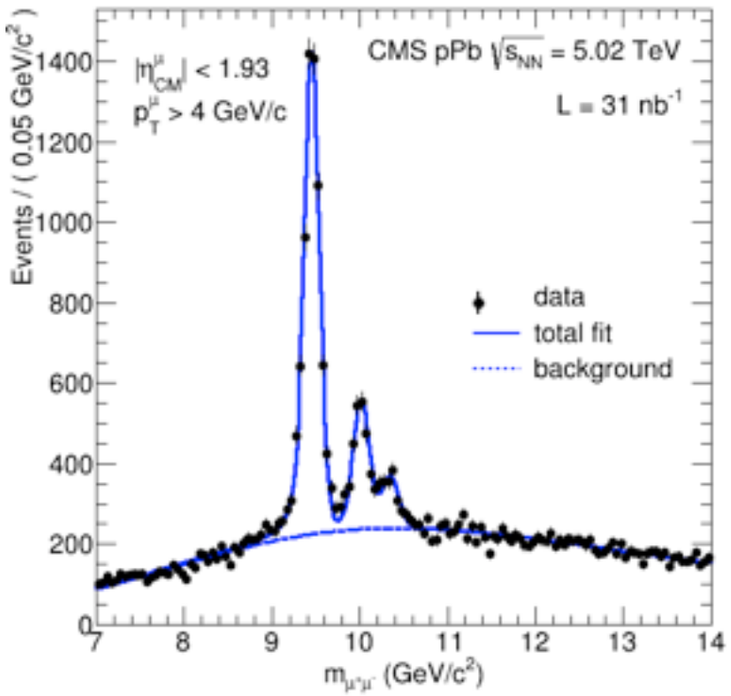


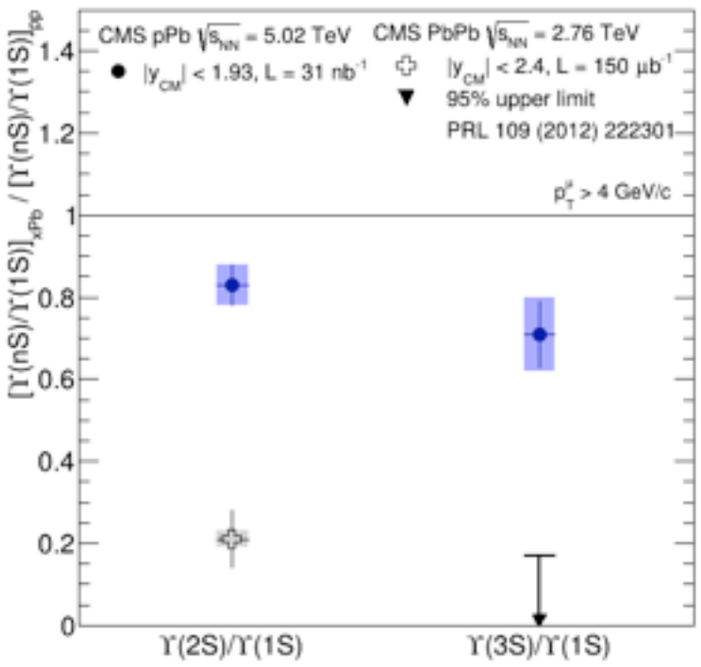
- tracks
  - good p_T resolution (down to ≈1% in barrel)
  - tracking efficiency >99% for central muons
  - good vertex reconstruction and impact parameter resolution down to ≈15μm
- muon candidates
  - match between muon segments and a silicon track, in a large rapidity coverage $|\eta|<2.4$
- BDT-based muon identification
  - exploits kinematic quantities, silicon-tracker and combined silicon/muon track fit information
  - fake rates estimated in MC and data (D^*, K_s, Λ)

$\varepsilon(\mu|\pi) \leq 0.15\%$, $\varepsilon(\mu|K) \leq 0.20\%$, $\varepsilon(\mu|p) \leq 0.10\%$

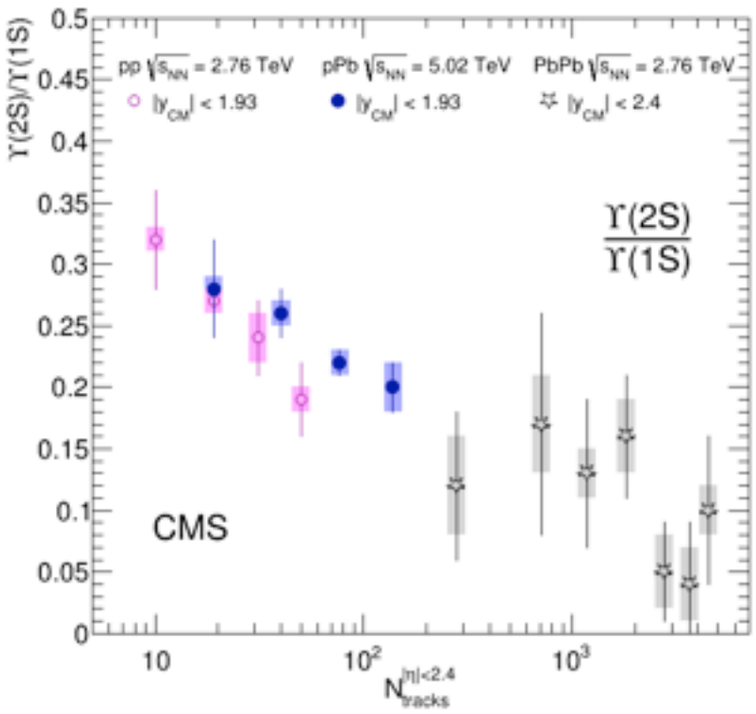
environment dependence

- pp and PbPb, but also pPb

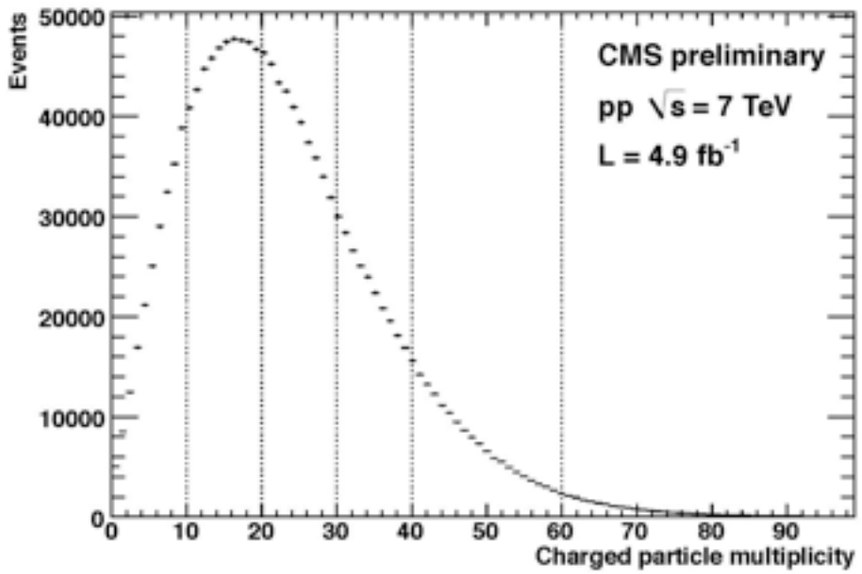


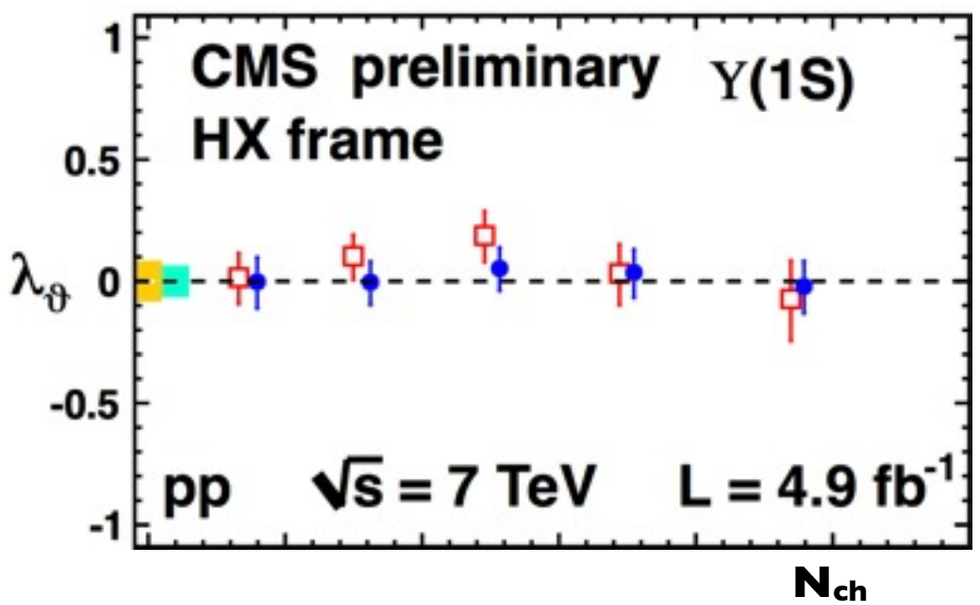


JHEP 04 (2014) 103



- extending polarization measurements (as a function of multiplicity)





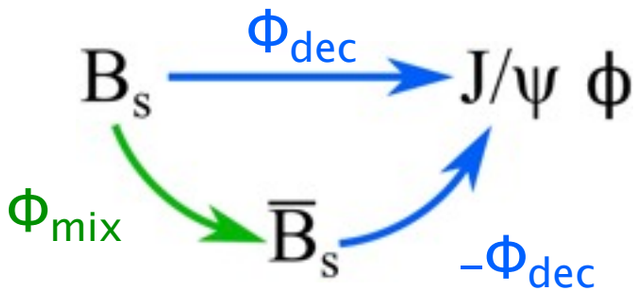
new from Run I

CMS-PAS-HIN-15-003

$B_s \to J/\psi\Phi$

- 'golden' mode to explore CP violation in B_s system
  - flavor non-speific, experimentally clean final state
- analysis ingredients
  - mass and proper decay time
  - flavor tagging (infer initial particle/antiparticle state of B_s)
  - angular analysis (to disentangle CP-even/-odd states)

CP violation
in interference
of decay and mixing

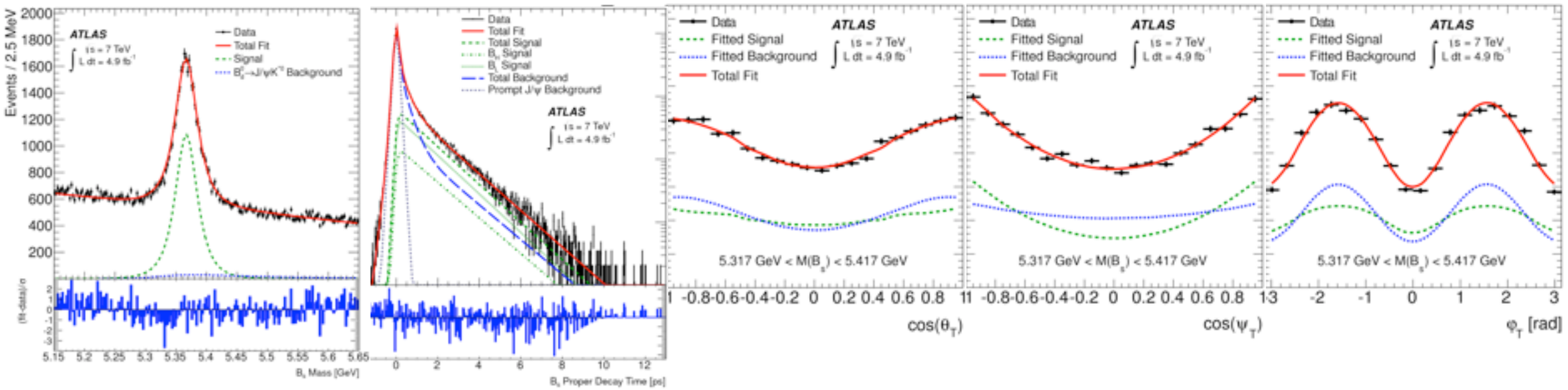


$$\Phi_s = \Phi_{mix} - 2\,\Phi_{dec} \sim -0.04\,(\mathrm{SM})$$

$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = X(\Theta,\alpha,t) = \sum_{i=1}^{10} O_i(\alpha,t).g_i(\Theta)$$

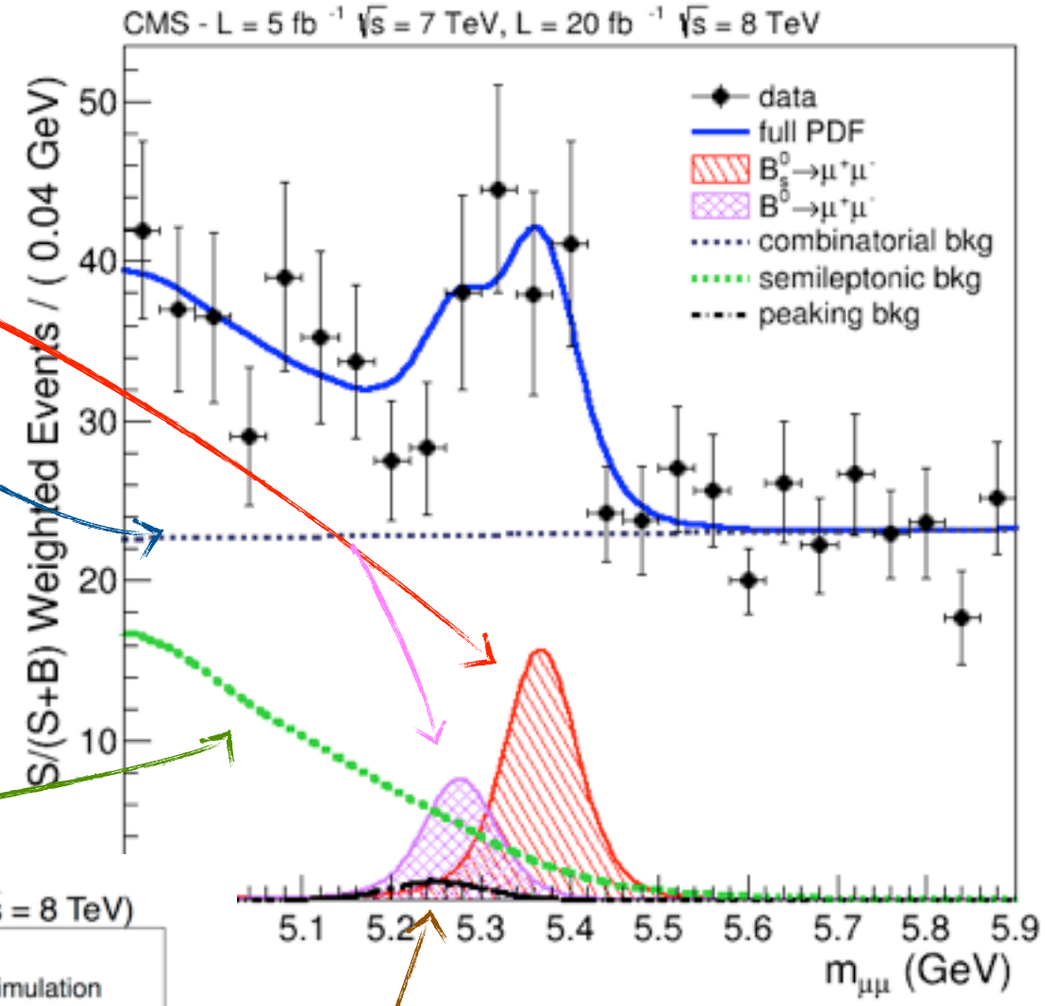
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

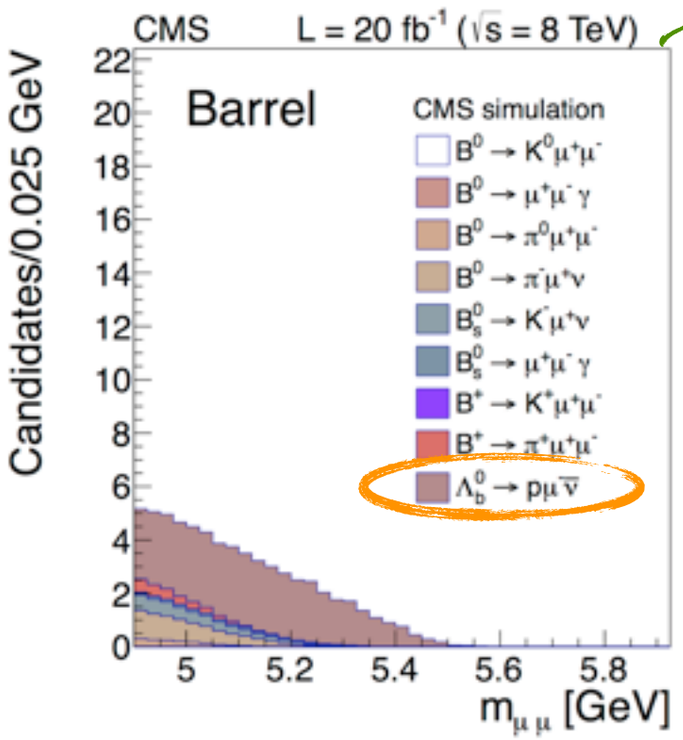
$$O_i(\alpha,t) = N_i e^{-\Gamma_s t}\left[a_i \cosh(\frac{1}{2}\Delta\Gamma_s t) + b_i \sinh(\frac{1}{2}\Delta\Gamma_s t) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t)\right]$$

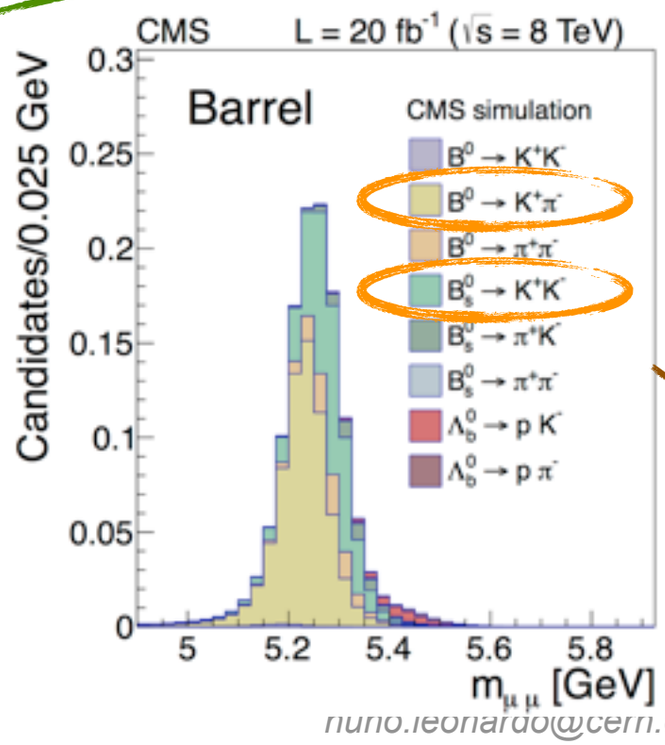


physics backgrounds

- B_d and B_s signals
  - Crystal Ball, fixed shape,
  - normalization floating
- combinatorial background
  - first-degree polynomial
- rare semileptonic background ($b \to q\mu\nu$)
  - fixed shape, constrained normalization
- rare peaking background
  - constrained to expectation



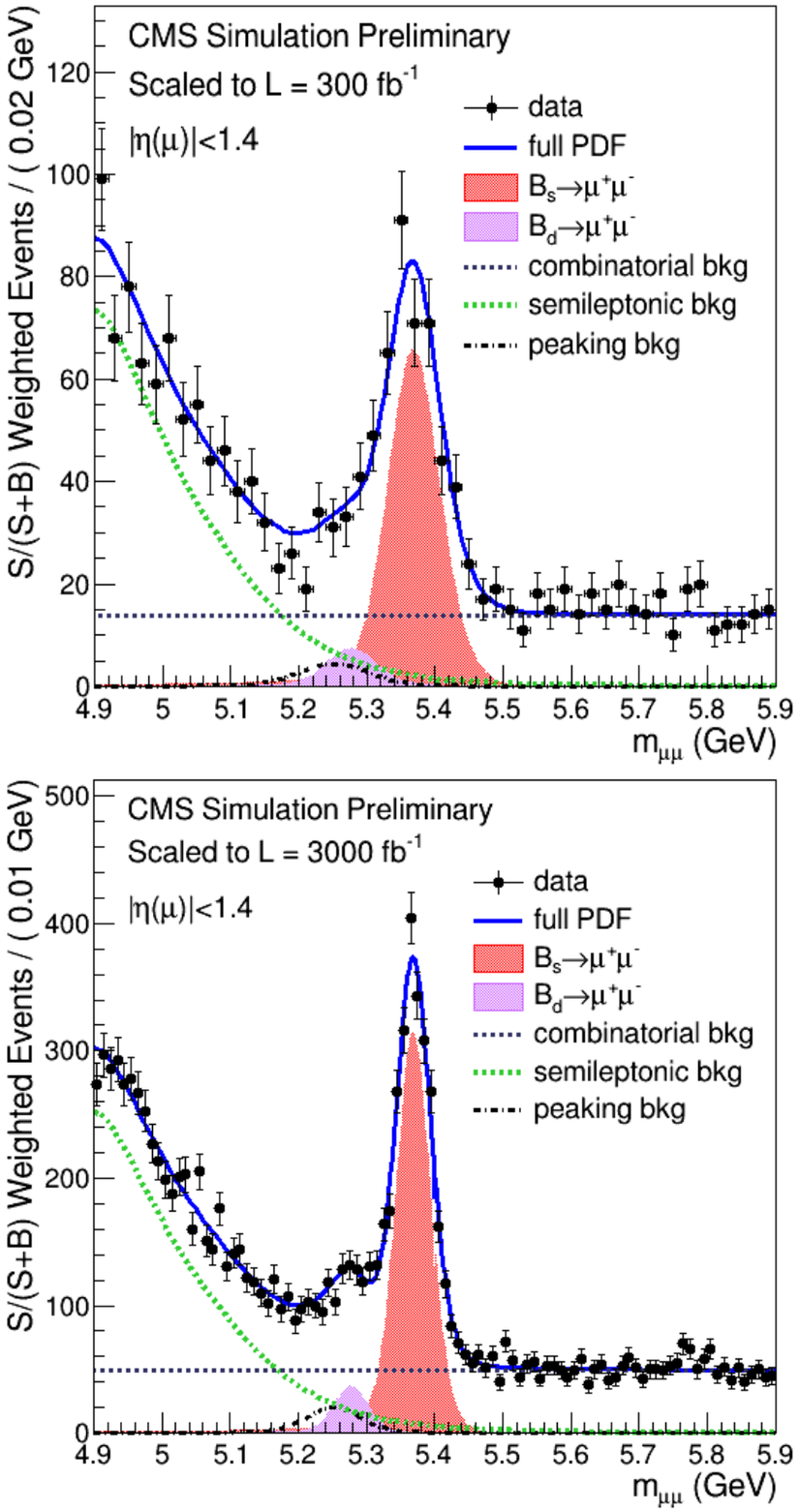




- rare physics backgrounds normalized to B^+ yields in data, for each analysis channel

sensitivity: B→μμ

[CMS, LHCb]



- Sensitivity estimated based on expected detector performance by re-scaling results of Run I analysis
- SM prediction for B_d/B_s ratio assumed
- B_d observation (>5σ) within reach (HL-LHC)
- theory errors on branching fraction (ratio) will remain smaller than experimental sensitivity
- will explore additional observables with complementary sensitivity, e.g. effective lifetime and possibly time-dependent CP asymmetries