Highlights from
B Physics & Heavy Ions

B_s & Υ

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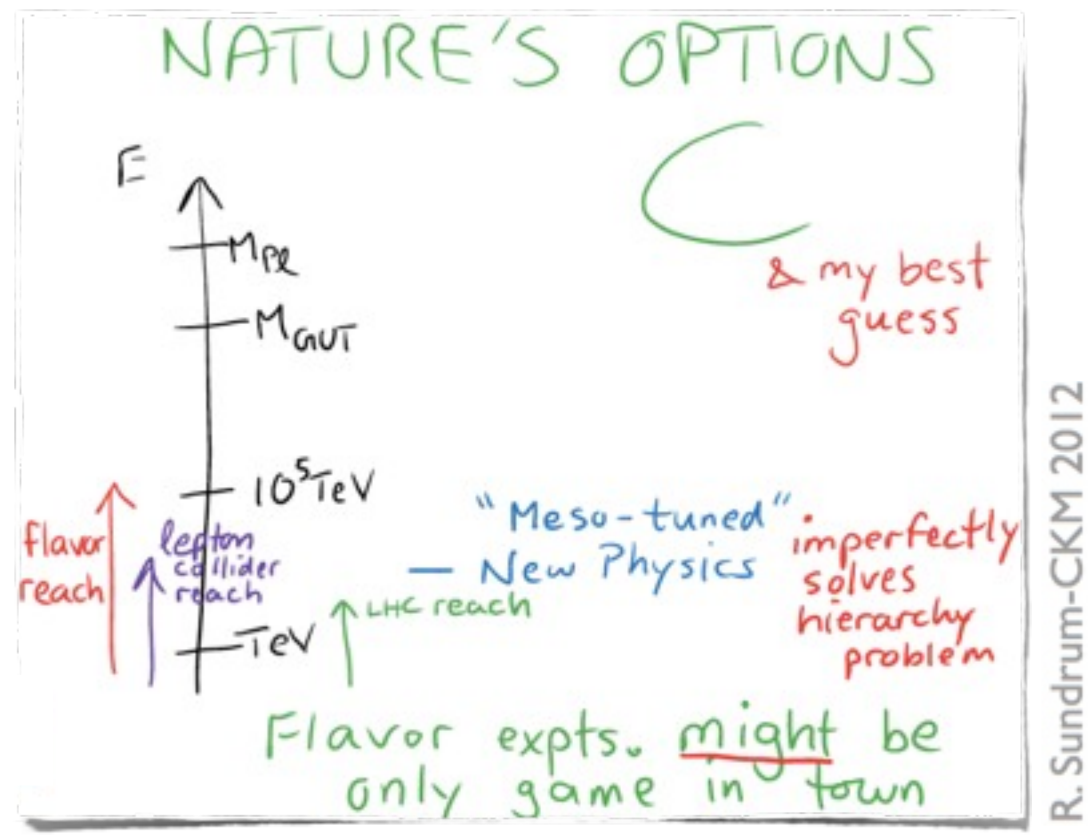
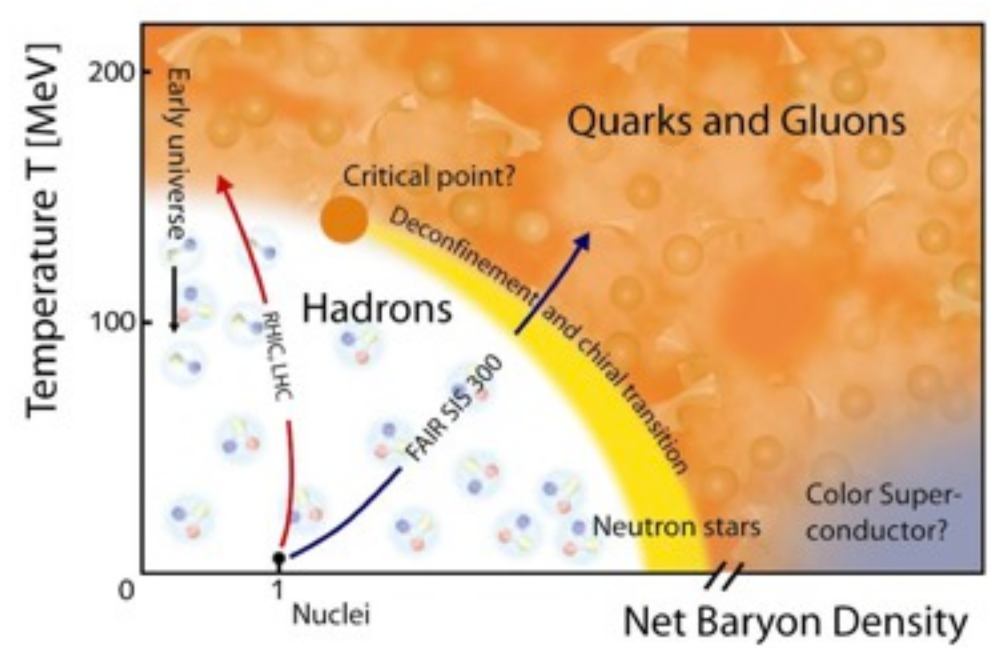
INVESTIGADOR FCT

Jornadas LIP 2014
Pavilhão do Conhecimento, Lisboa

heavy flavor *[physics goals]*

- find evidence and characterize new physics, through precision measurements and rare decay searches
  - complementary to direct searches, gain access to higher mass scales
- hadron production and properties
  - measure CP violation and FCNC
  - search for expected & exotic new states
- explore QCD matter under extreme conditions of temperature and density
  - hard probes of the quark gluon plasma





LHC *[heavy flavor factory]*

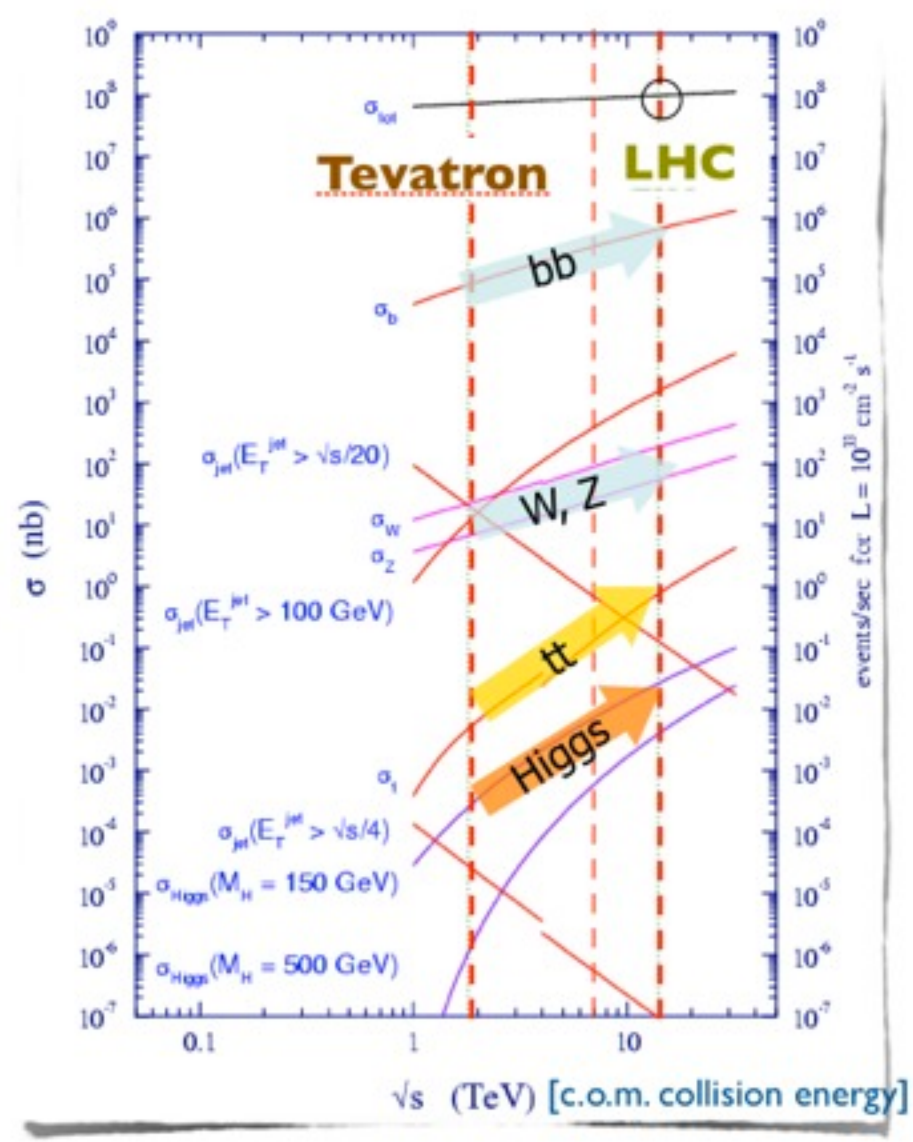
	proton-proton			**heavy-ion**		
$\sqrt{s_{NN}}$	1.96 TeV Tevatron (Run II)	➠ 7$_{(8)}$ TeV LHC Run I	➠ 13$_{(14)}$ TeV LHC Run II	0.2 TeV RHIC	➠ 2.76 TeV LHC Run I	➠ 5.5 TeV LHC Run II

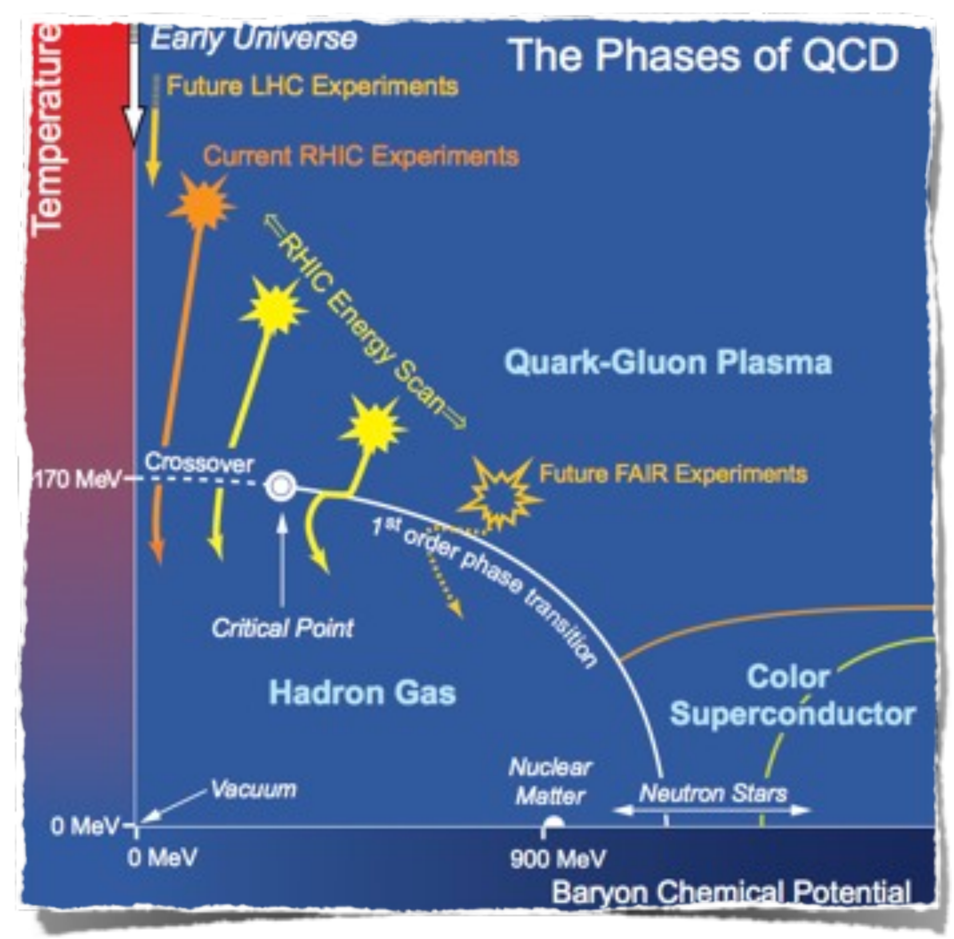
x7 **x27**

energy

$\mathcal{L}$ very large datasets are being accumulated at the LHC

intensity

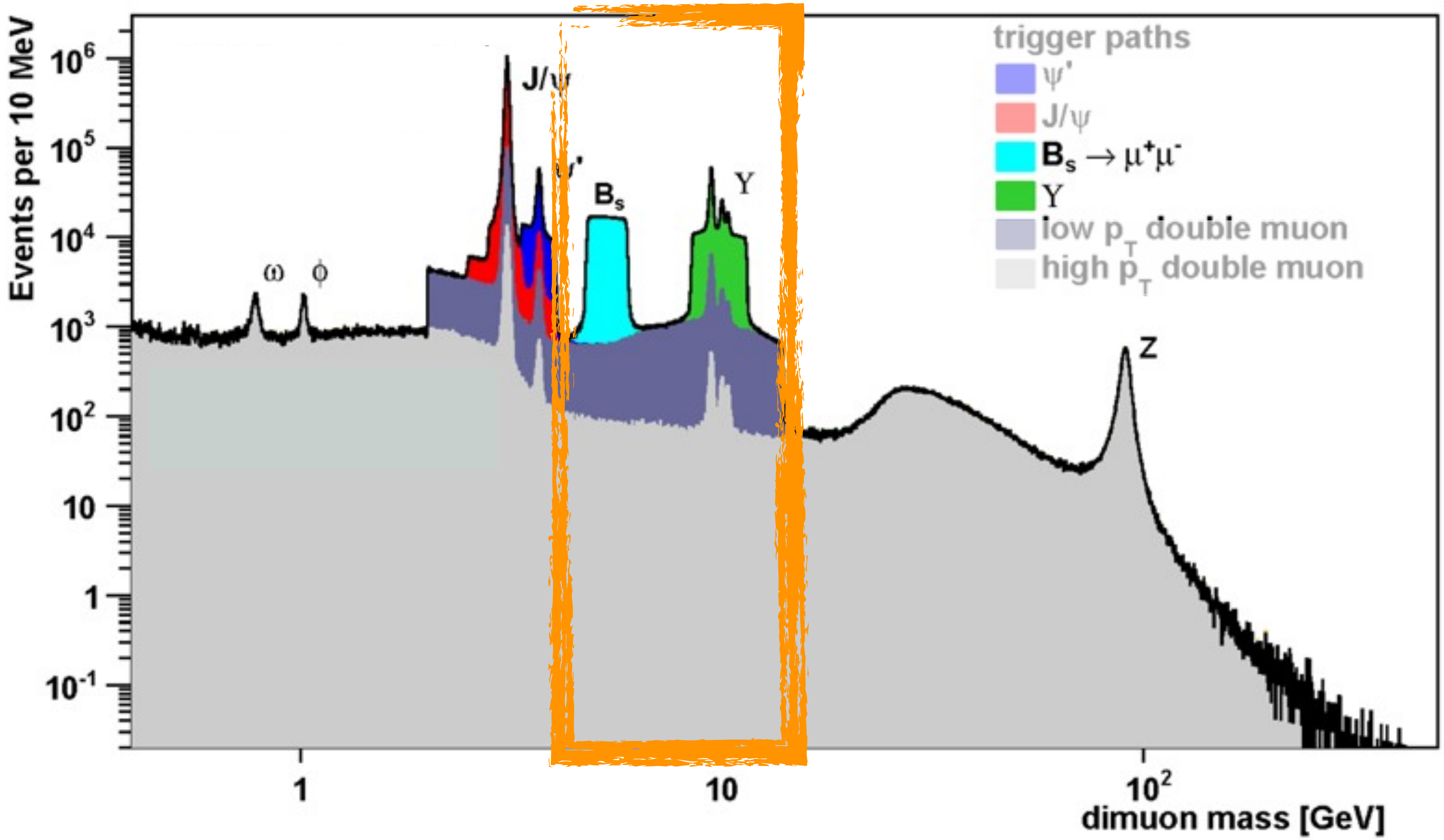




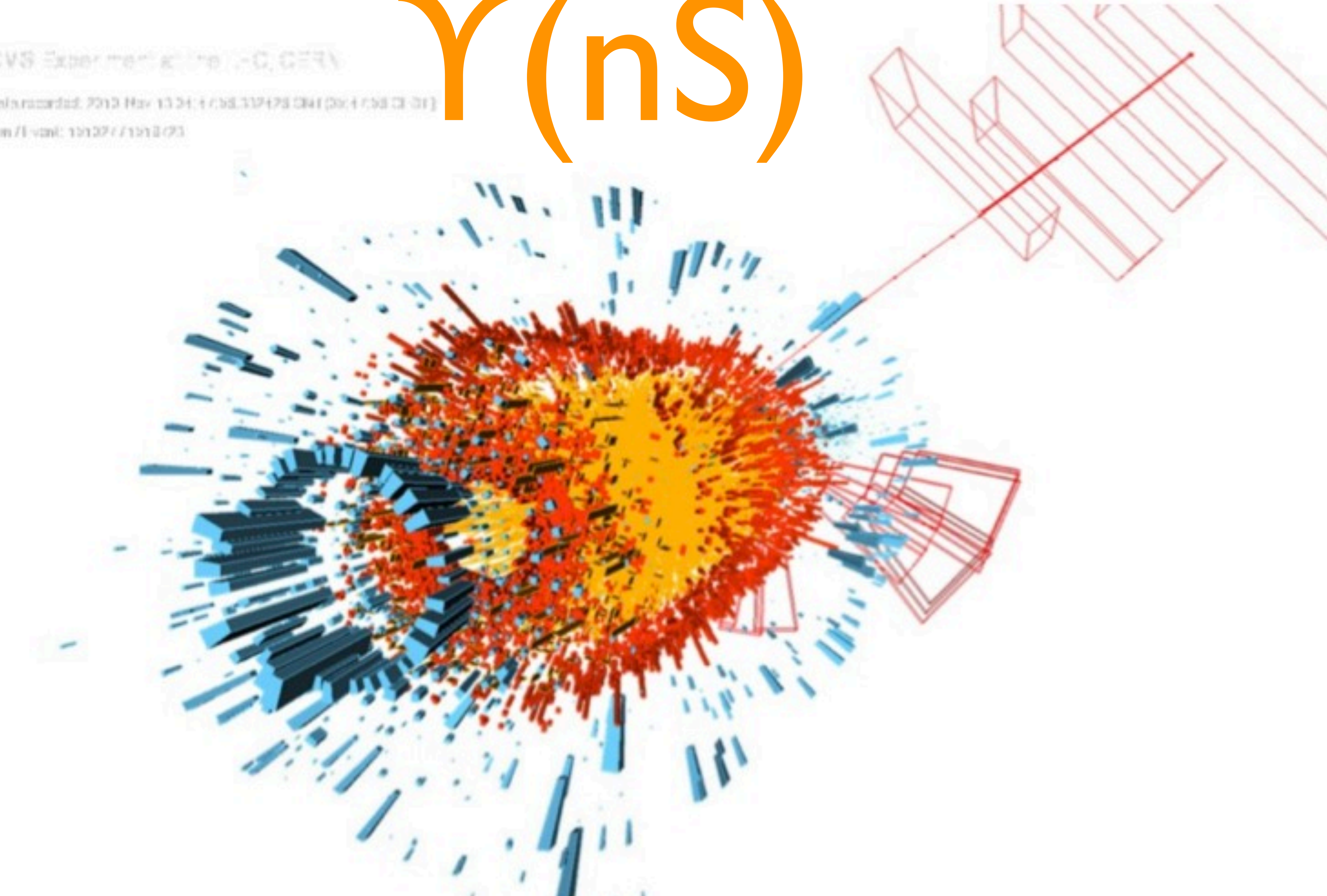
➡ LHC: energy & intensity frontier

CμS *[precision (di)muon spectrometer]*

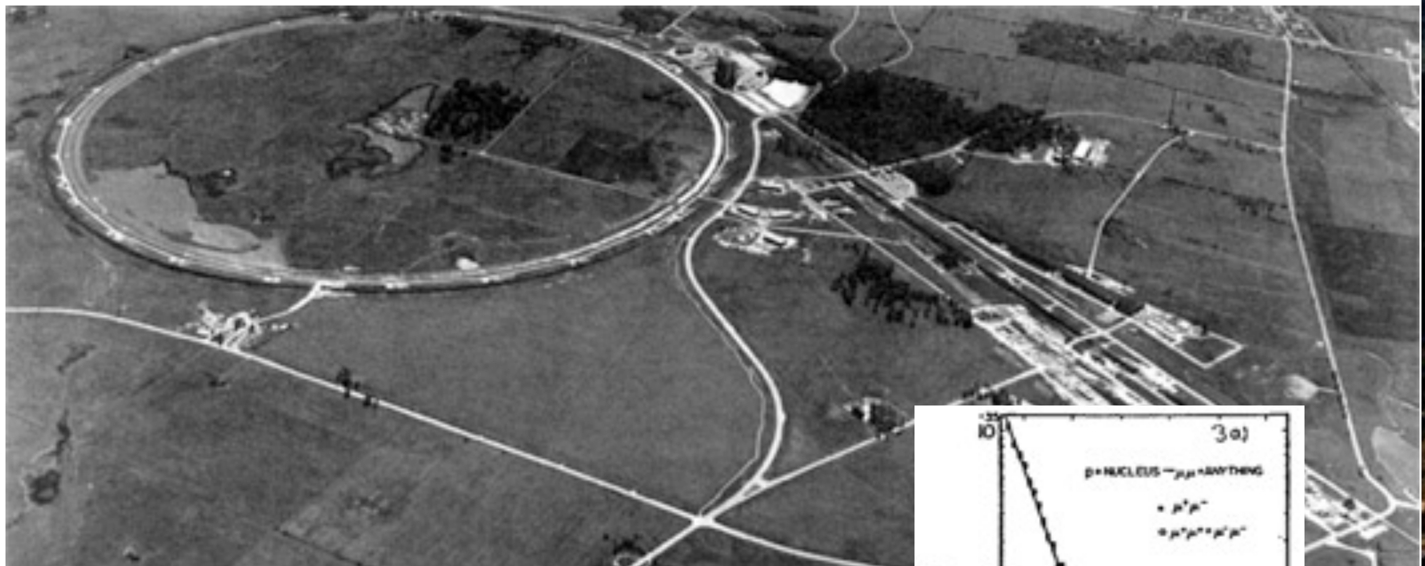
- excellent momentum resolution down to low p_T (wrt ATLAS)
- large luminosities and momentum reach (wrt LHCb, ALICE)
- flexible trigger system -- explore wide spectrum of mass/energy

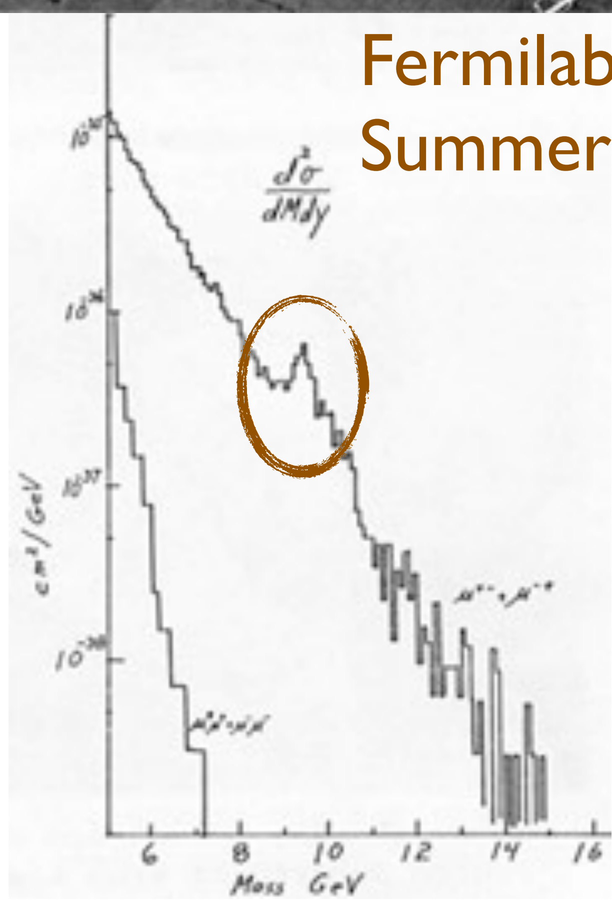


$\Upsilon(nS)$

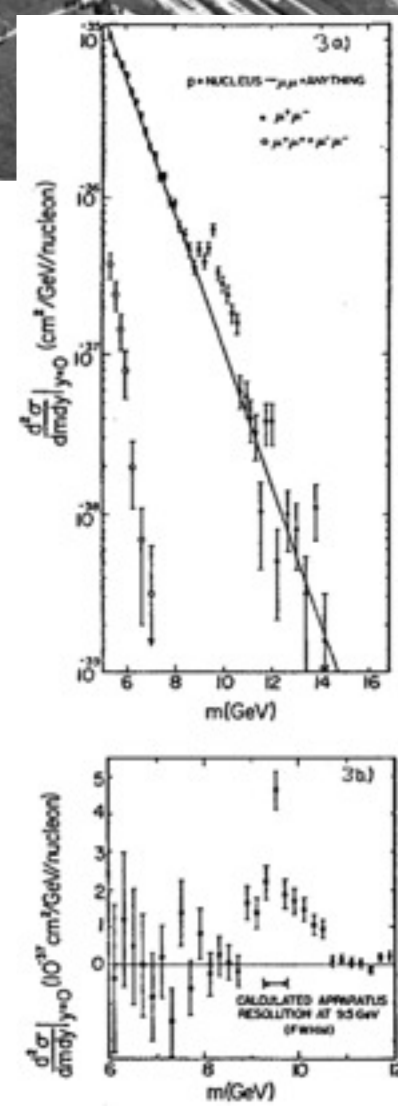


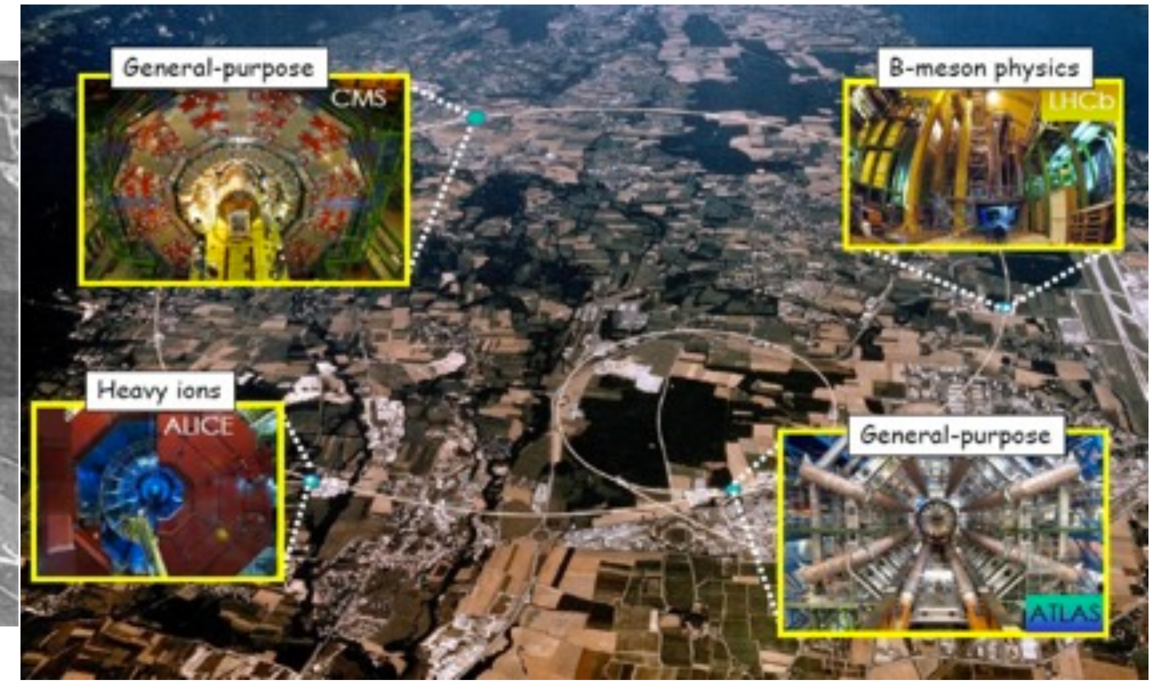
Upsilons: then... & now



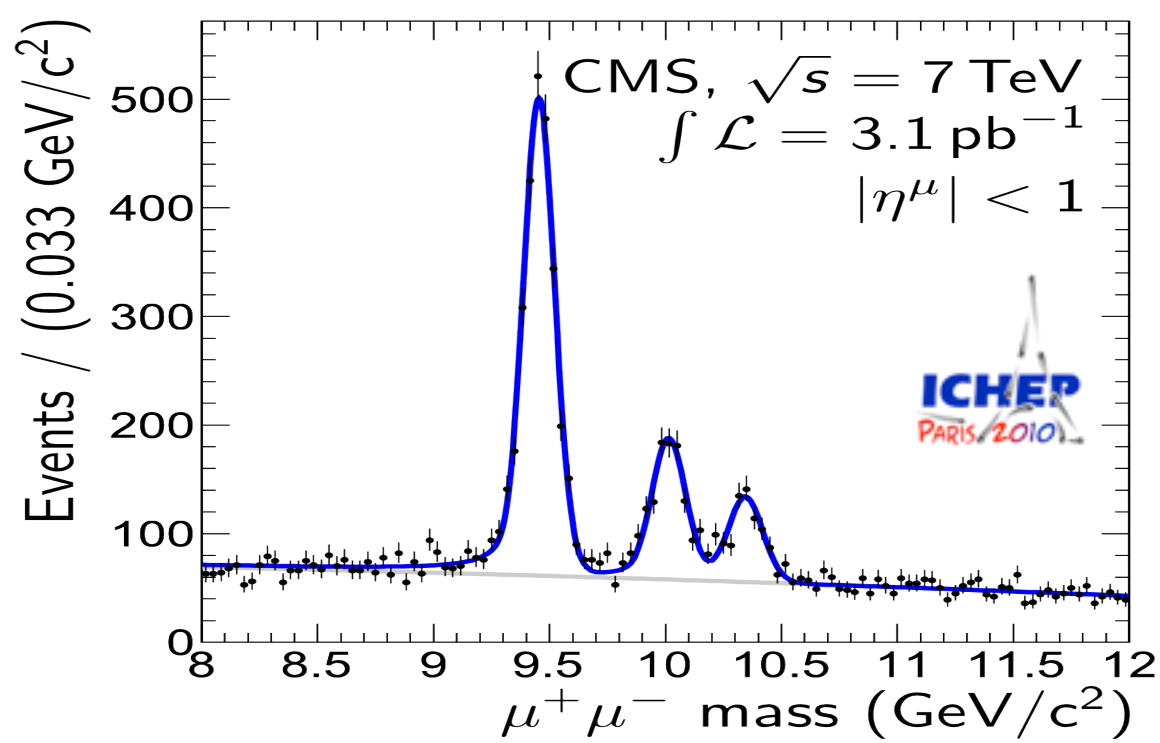


Fermilab
Summer 1977



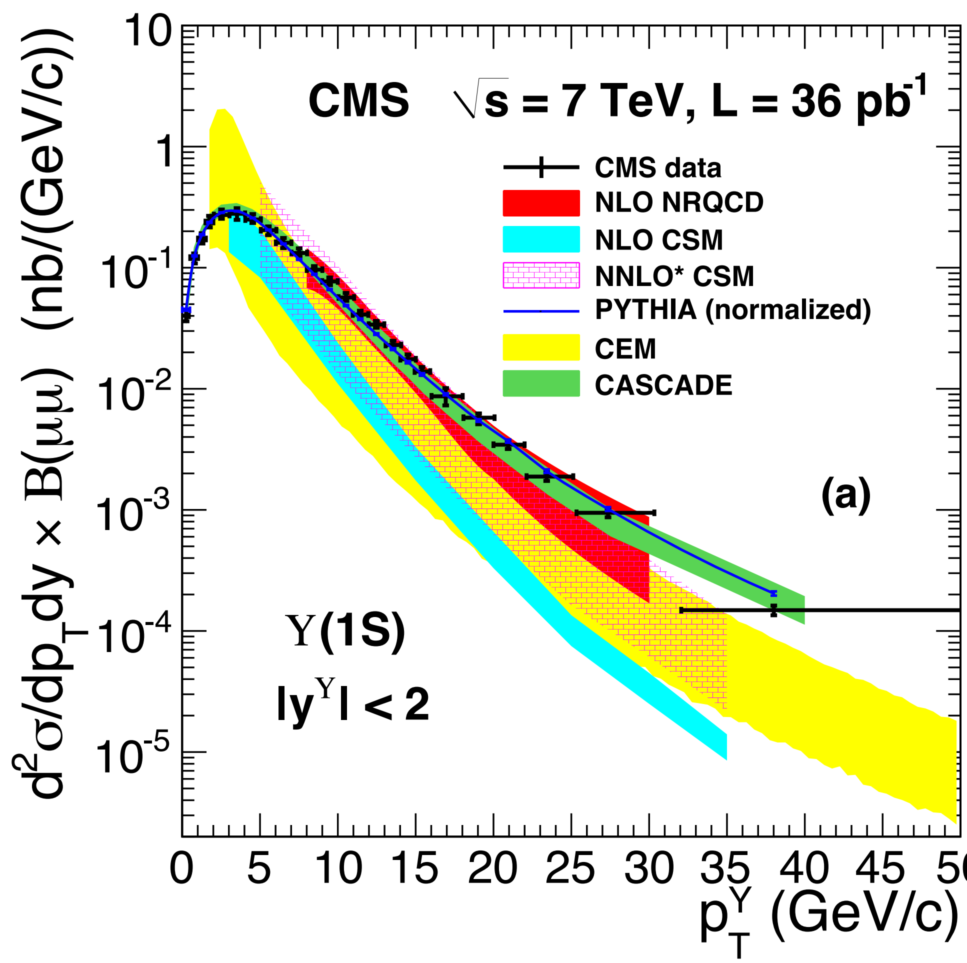


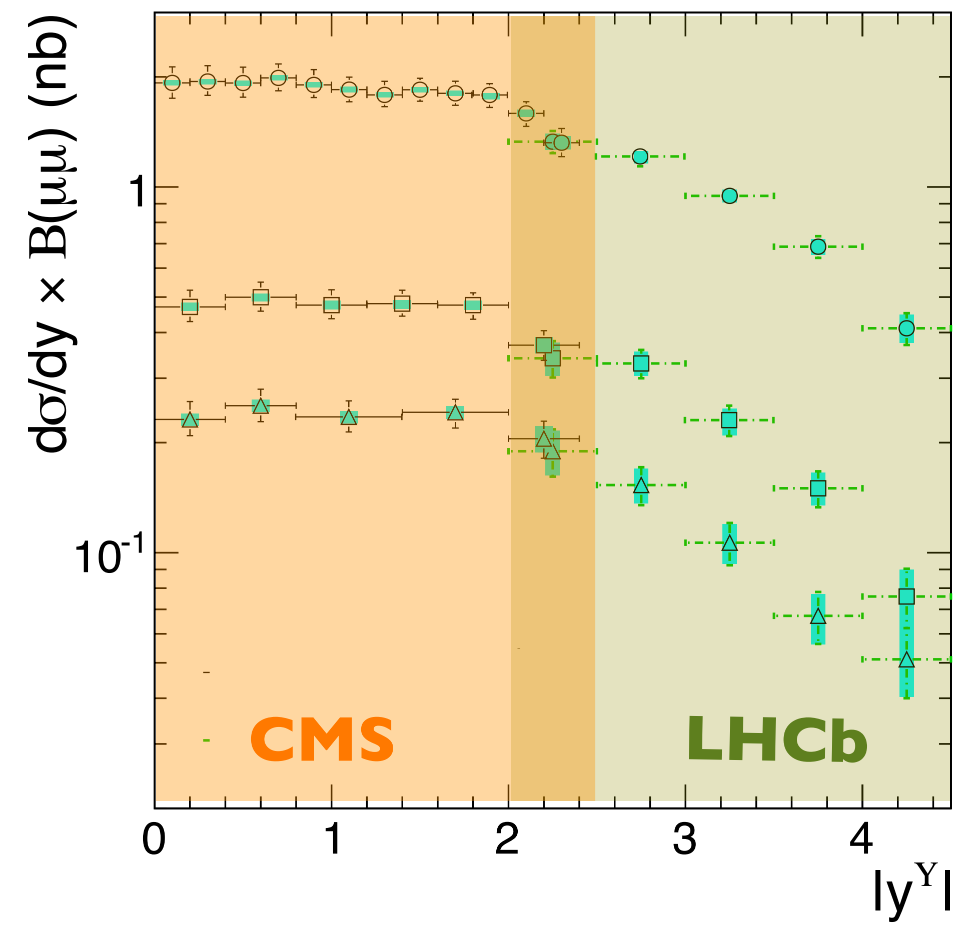
CERN, Summer 2010

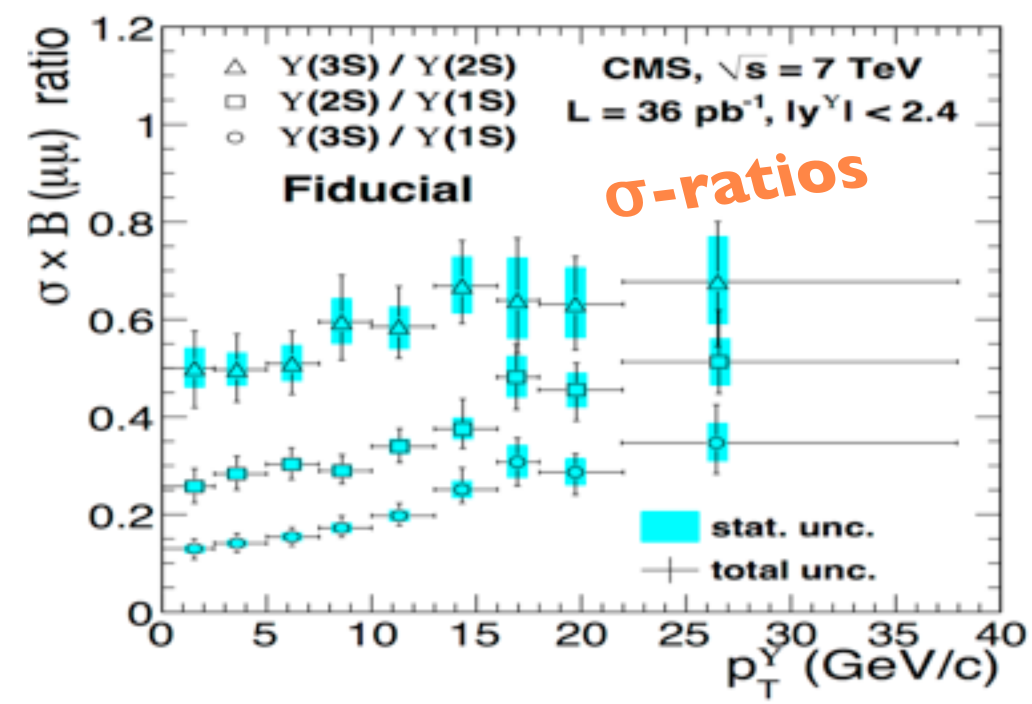


PRD 112004 (2010)
PLB 727 (2013) 101

Upsilon production *[in pp]*

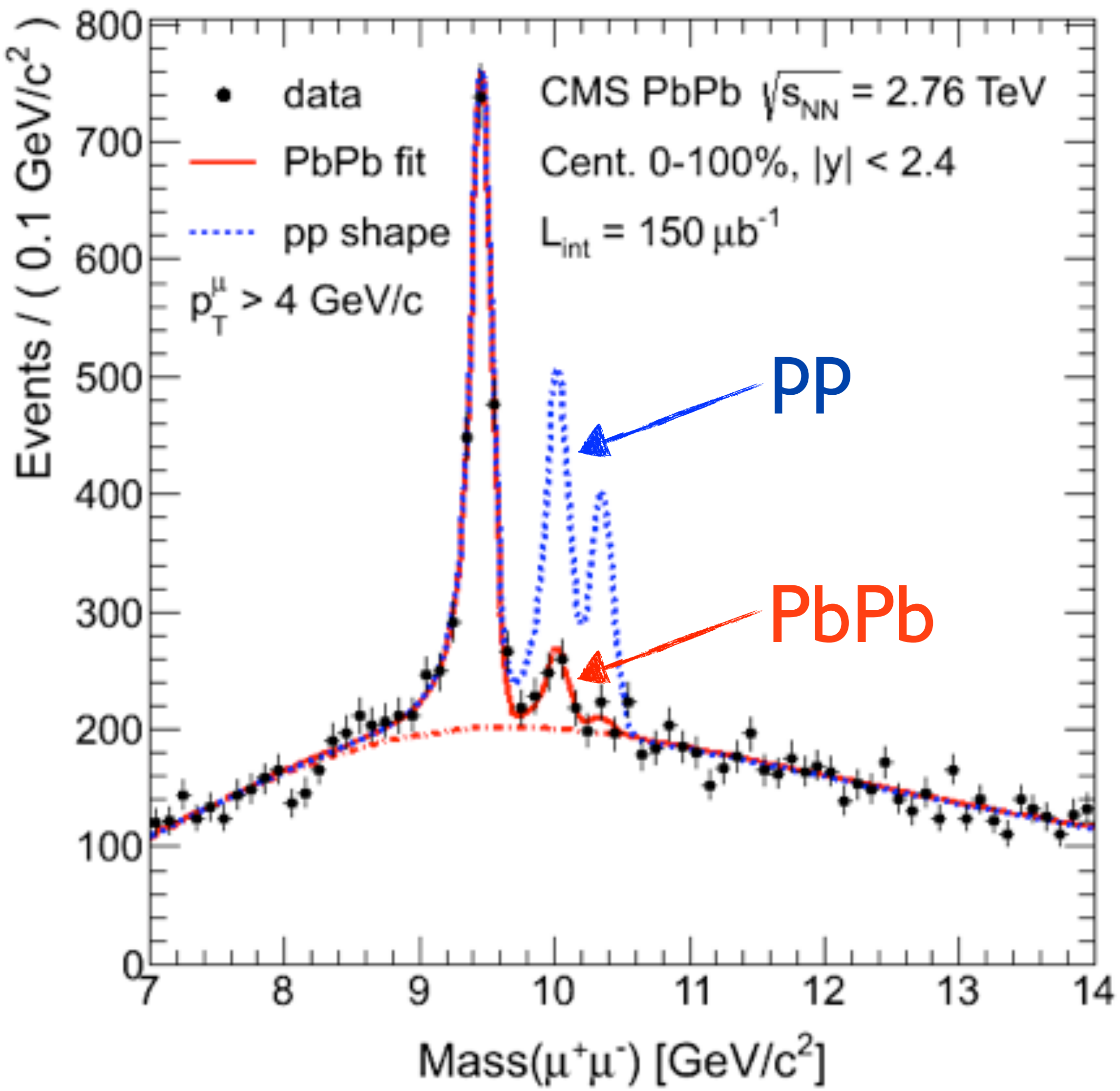






- first Υ(nS) measurements at LHC
- extended in precision and p_T reach
- differential production cross sections and polarizations

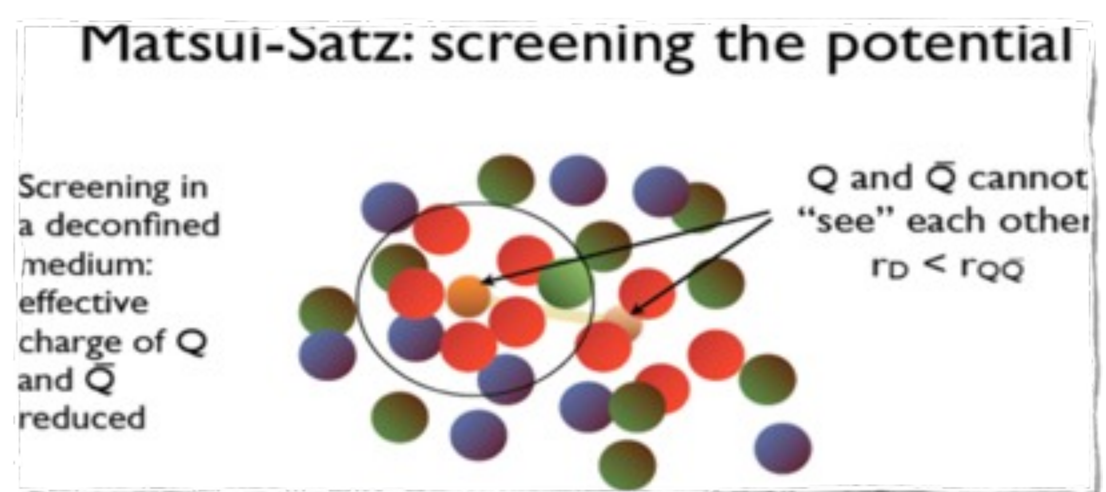
Upsilon suppression *[in PbPb]*



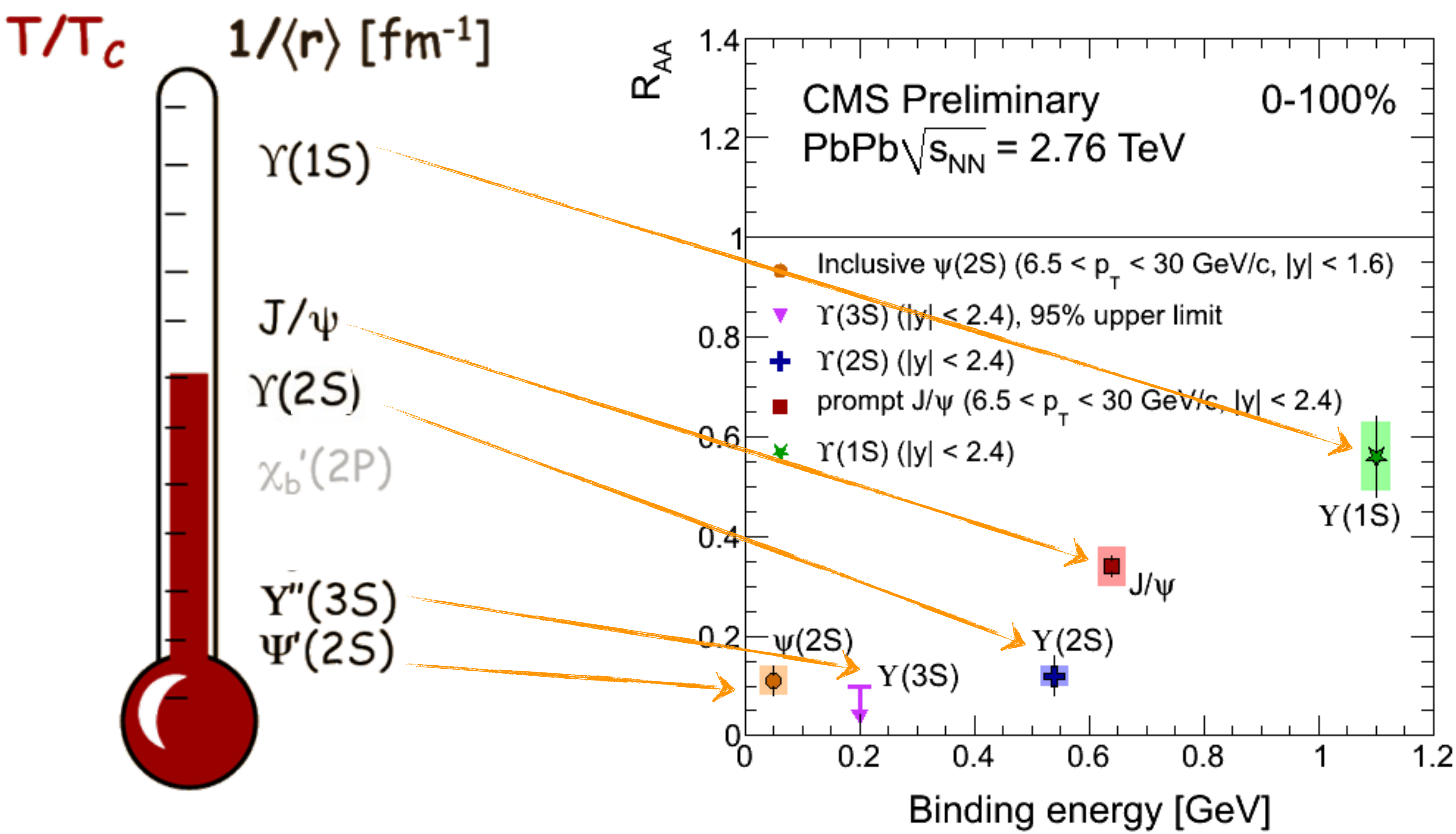
- first (quantitative) measurements of the Y(nS) states in HI collisions
- unprecedented resolutions, allowing the separate the three states
- measure double ratios
  - nS vs 1S & PbPb vs pp
  - experimentally and theoretically robust
- excited states observed (>5σ) to be more suppressed than ground state

"the LHC heavy-ion **text book** result"

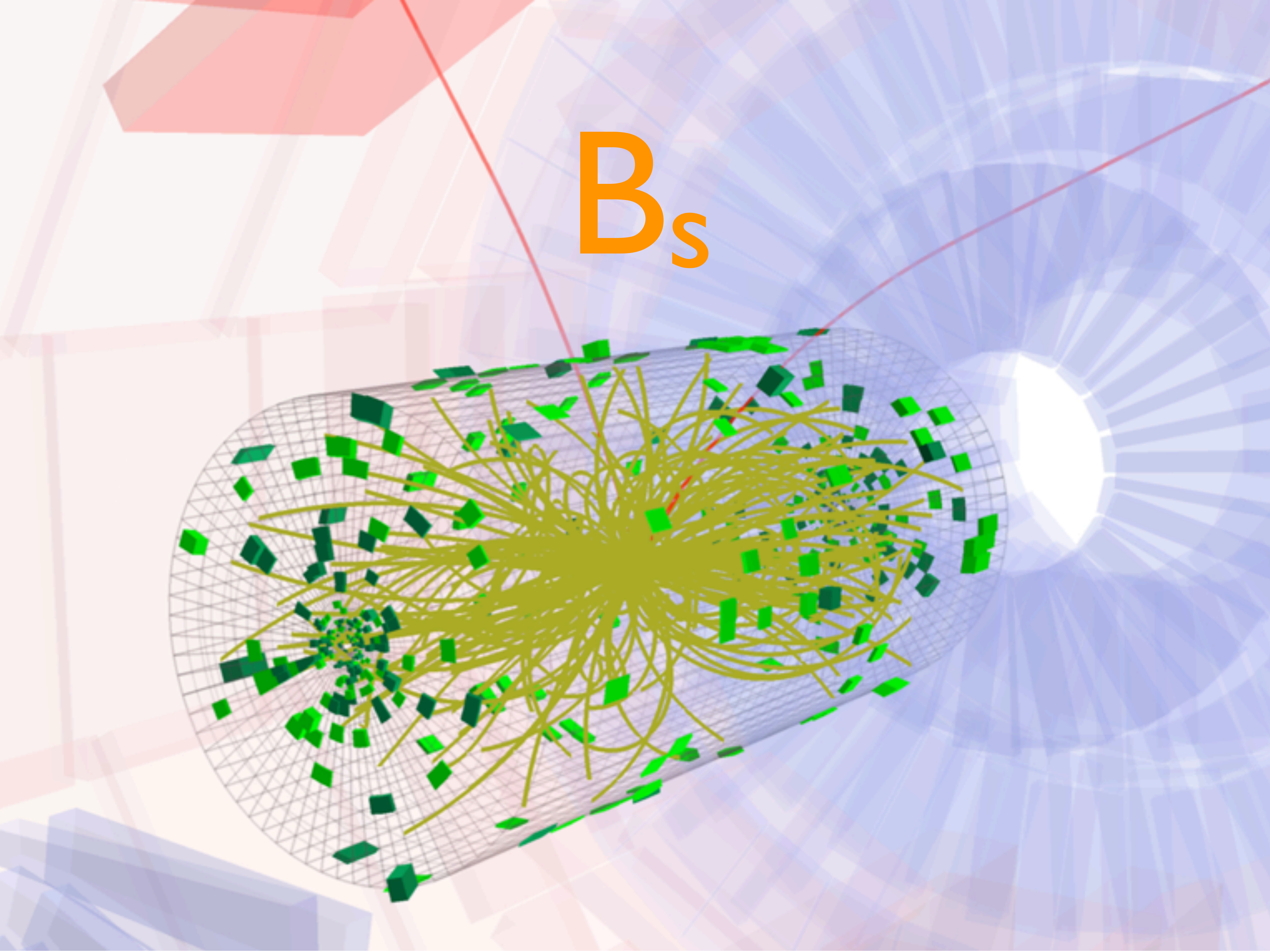
PRL 107(2011)052302, *Synopsis in Physics*
PRL 109(2012)222301, *Viewpoint in Physics*



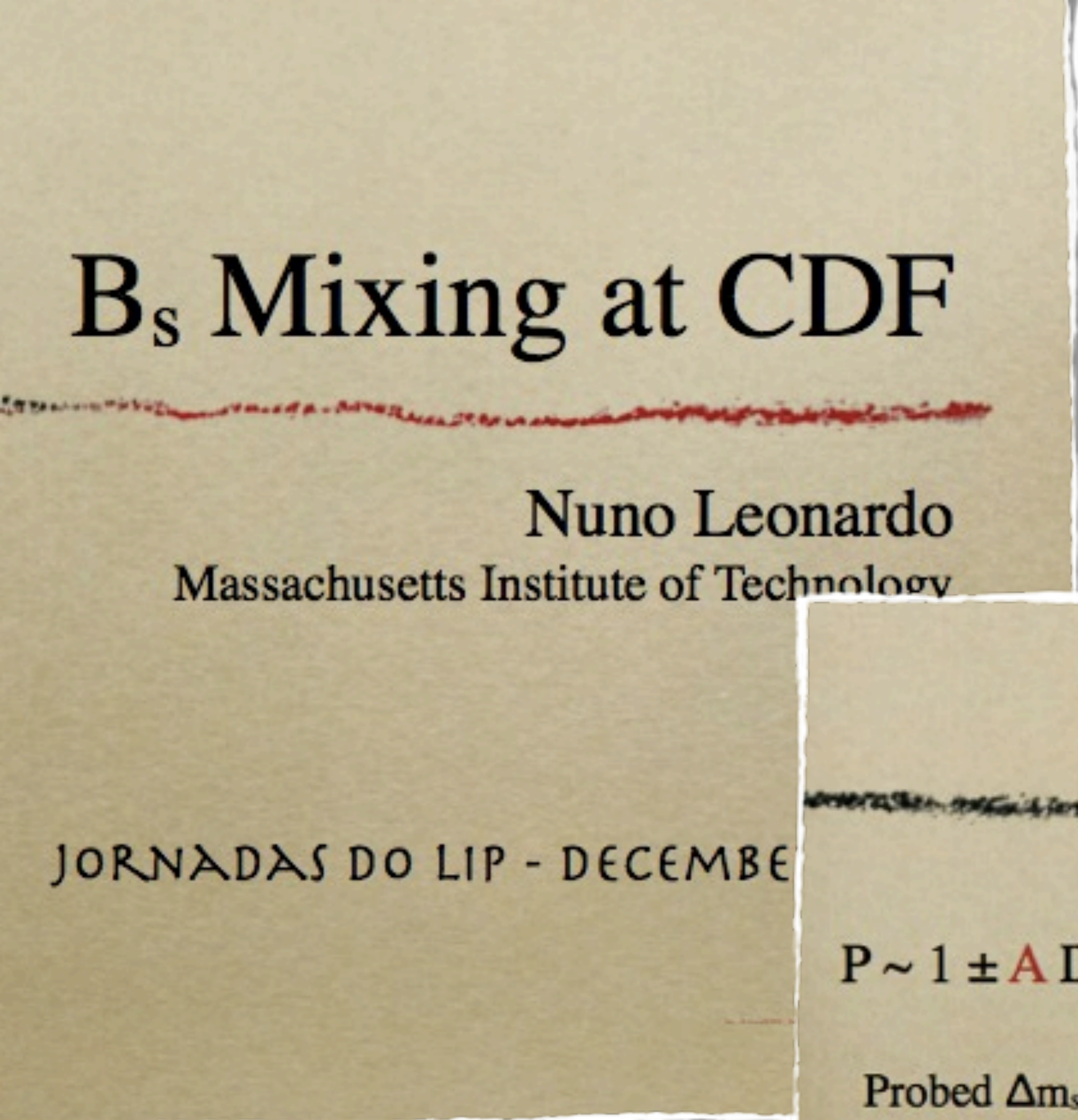
quarkonium sequential suppression

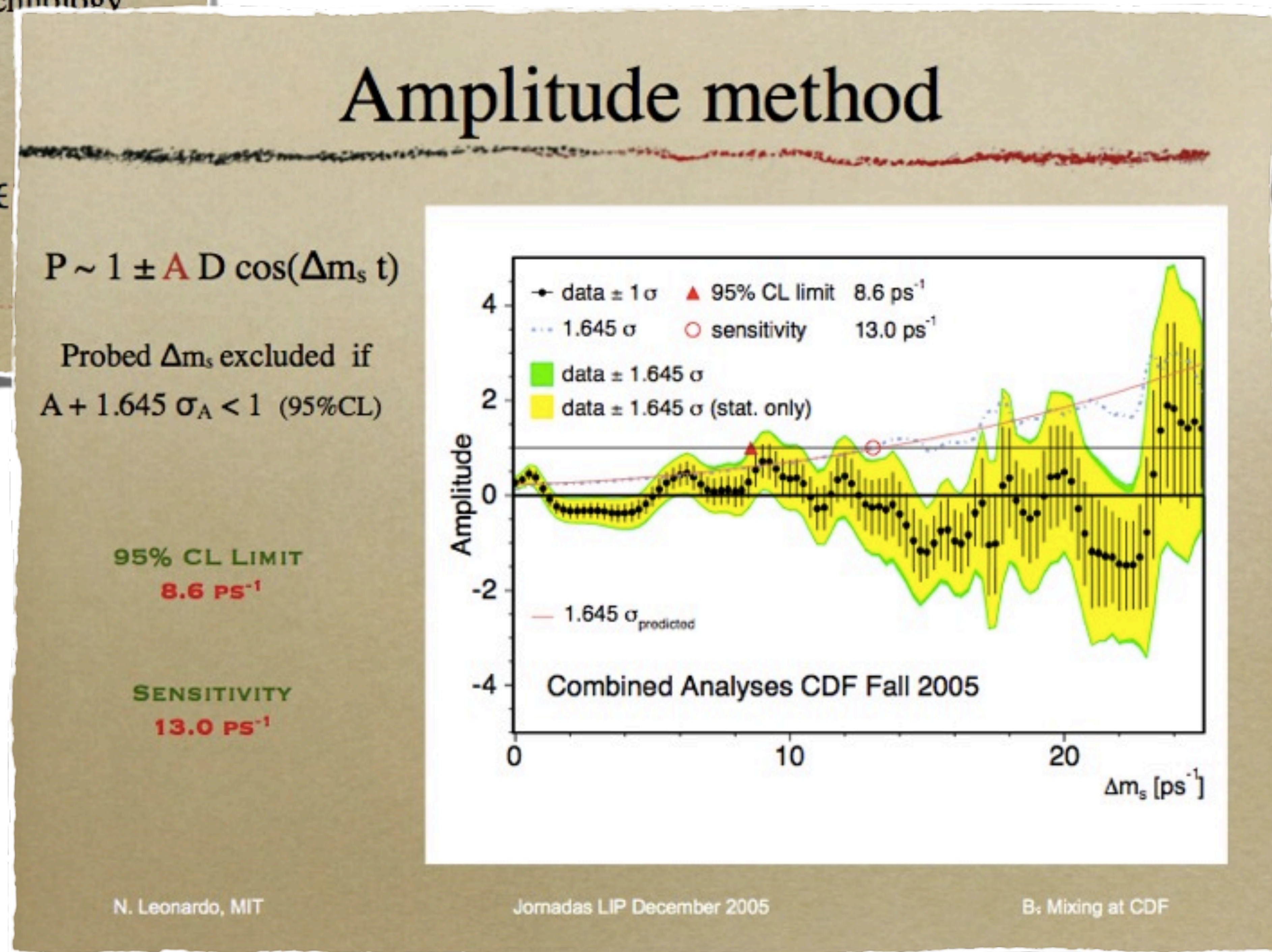


quarkonia suppression pattern experimentally established:
less tightly bound states are more suppressed in the medium


B_s

Jornadas LIP' 2005





CDF, $355 pb^{-1}$

Very first Tevatron mixing results

Sensitivity still limited

Tevatron's Run II flagship discovery

Observation of B_s mixing

N. Leonardo
CERN

CERN Seminar
April 16, 2007

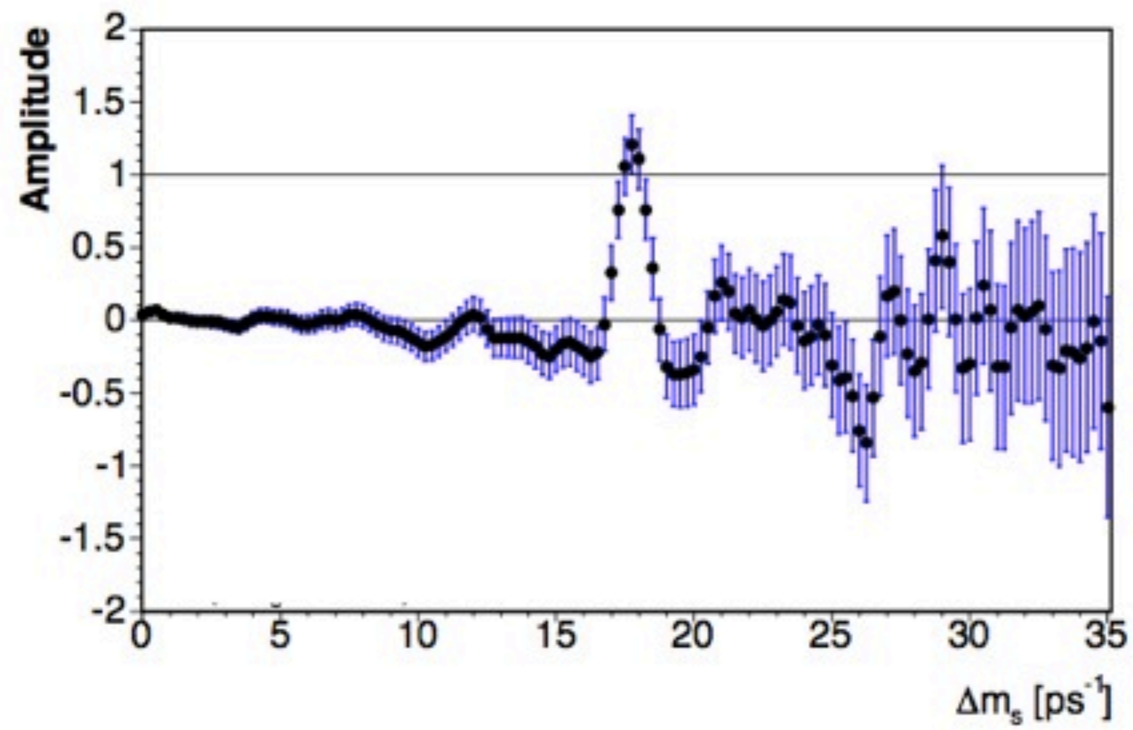
Conclusion

Long journey ended

Observation of B_s-$\bar{B}_s$ oscillations

- probability of random tag fluctuation ~ 8.10^{-8}: $>5\sigma$
- most precise measurement of oscillation frequency

$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$$



NL, ISBN 978-3843376938

PRL 97, 242003 2006

PRL 97, 242003 2006

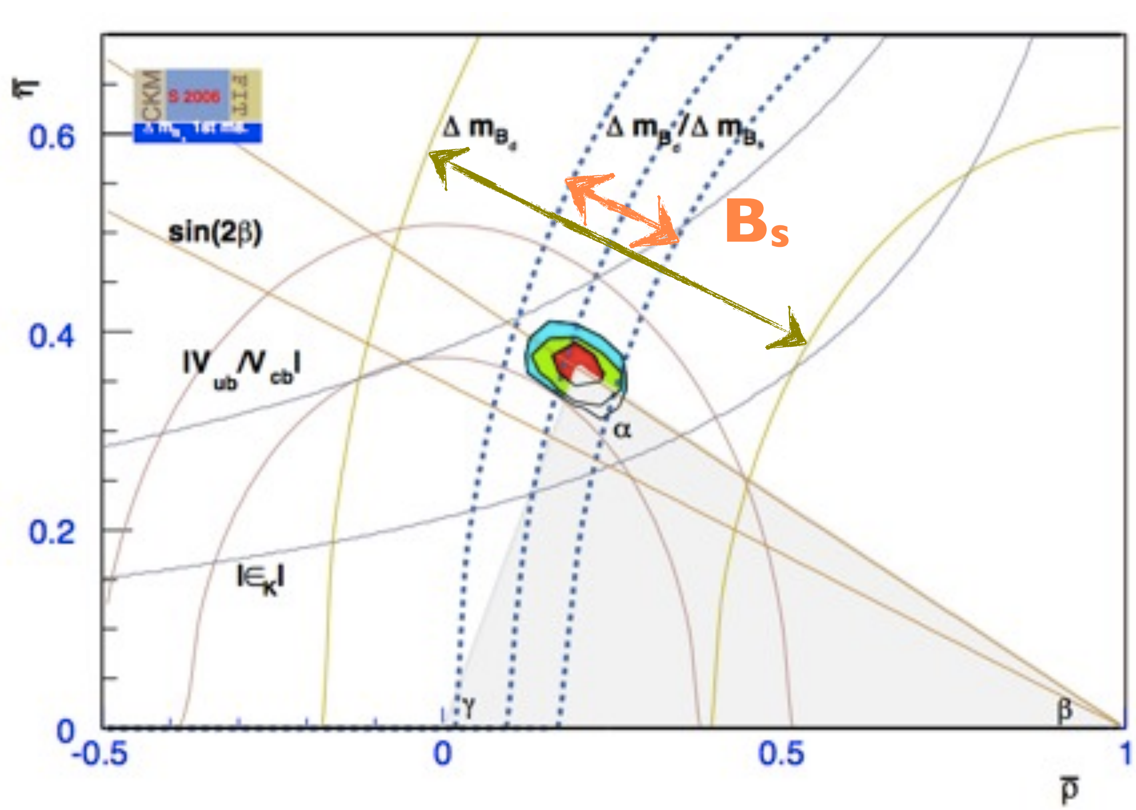
N. Leonardo, CERN-PH

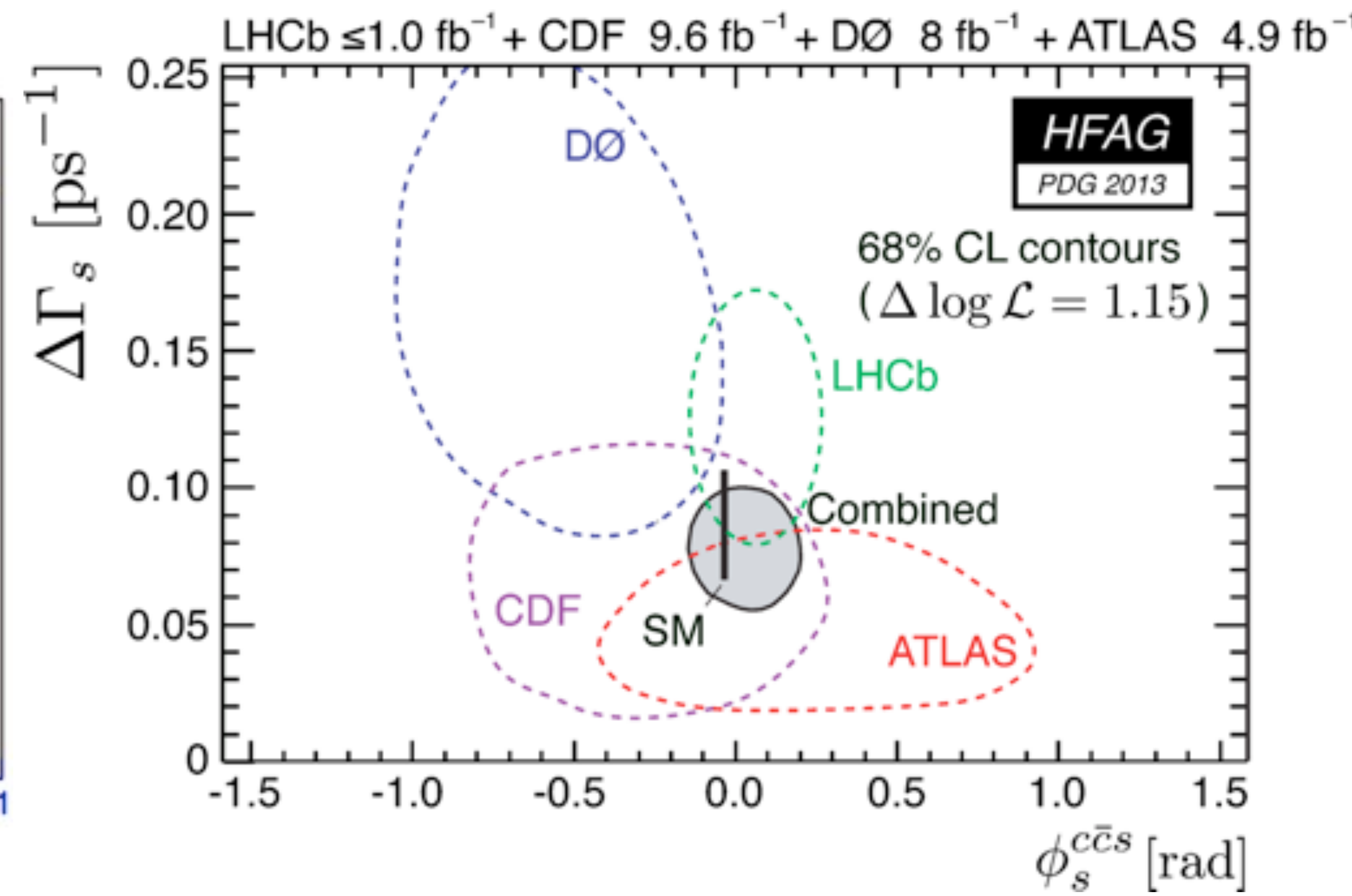
CERN Seminar

- evidence (3σ) & measurement
  - SSkT flavor tagger
- observation (5σ)
  - same data
  - new channels
  - MVA methods

B_s mixing & (B)SM

N.L., L.Sevilla, hep-ph/0603115

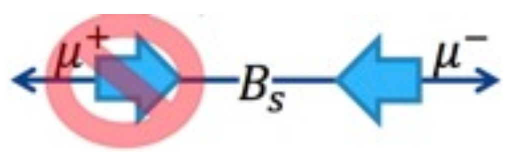




- precise measurement of B_s mixing frequency by CDF resulted in strict constraints to the Unitarity Triangle, CKM elements, and New Physics
- Tevatron's measurements of the B_s mixing phase improved by LHC
- within available precision: consistent with SM + strict constraints on NP

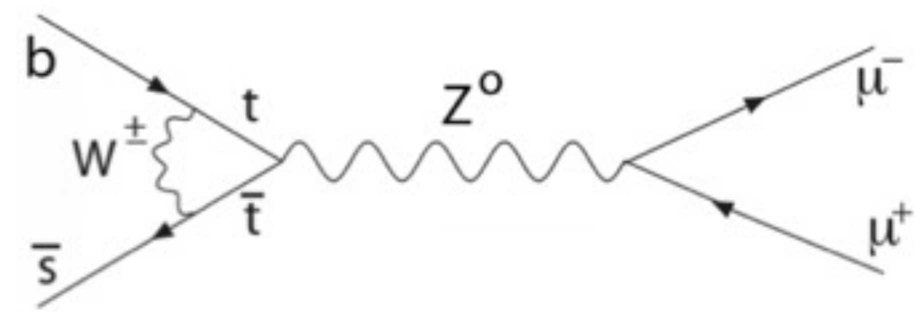
$B_s \to \mu\mu$: the 'golden' rare decay

- in the Standard Model $B_{d/s} \to \mu\mu$ decays are highly suppressed
  - helicity suppressed, by factor of $(m_\mu/m_B)^2$

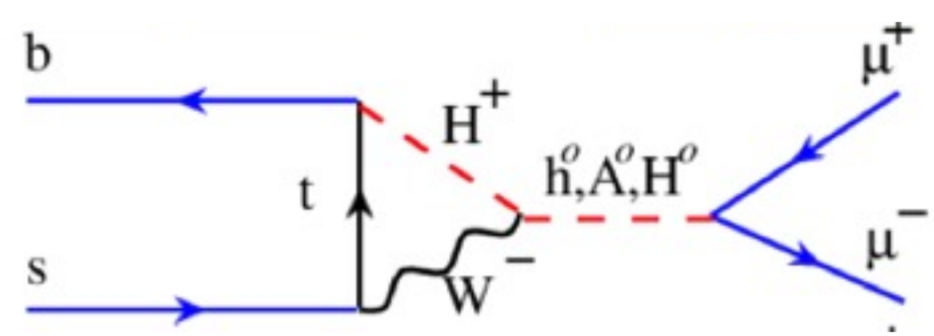


  - FCNC, forbidden at tree level, can only proceed through higher-order loop diagrams
  - Cabibbo suppressed $|V_{ts(td)}|^2$

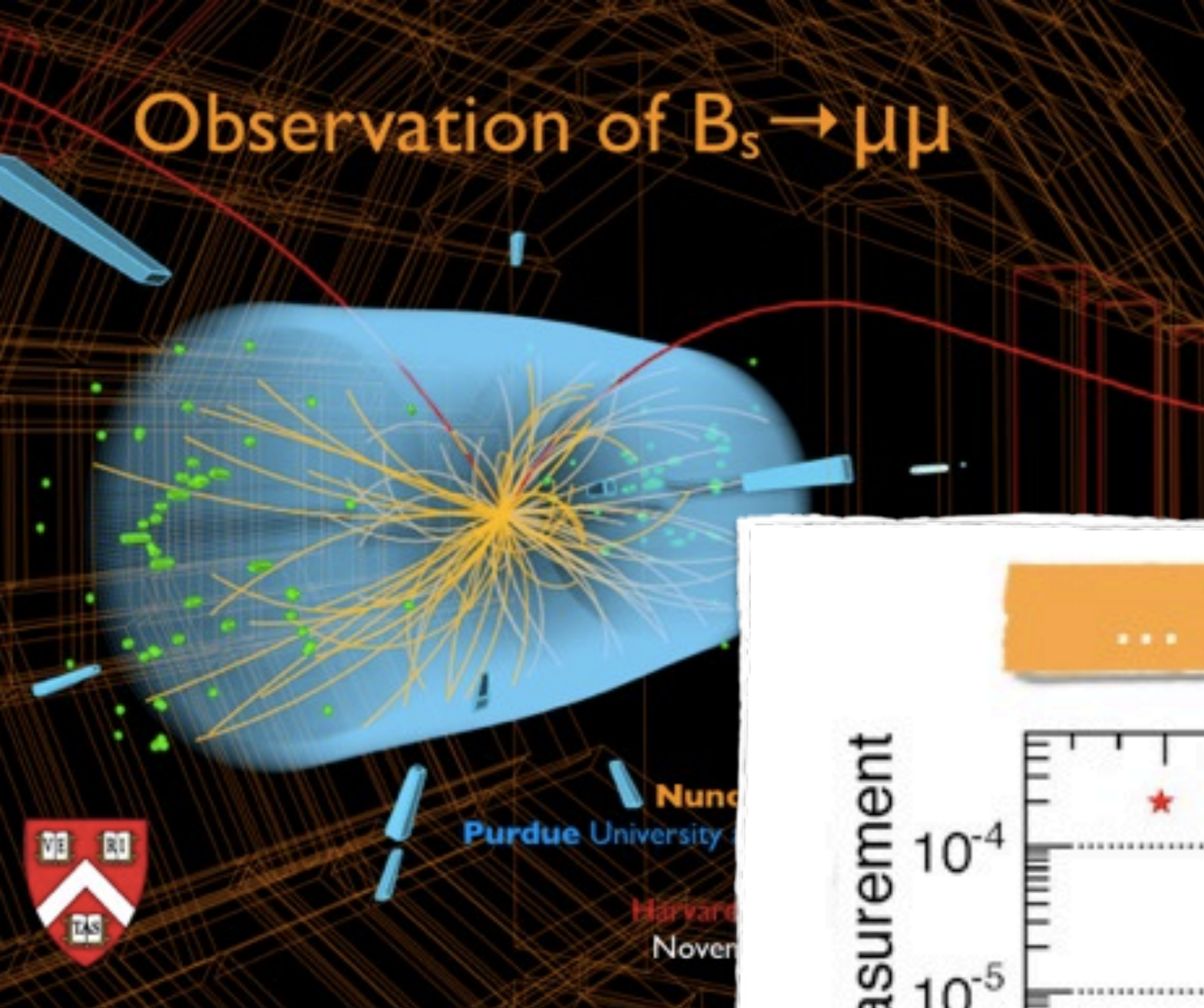
Standard Model



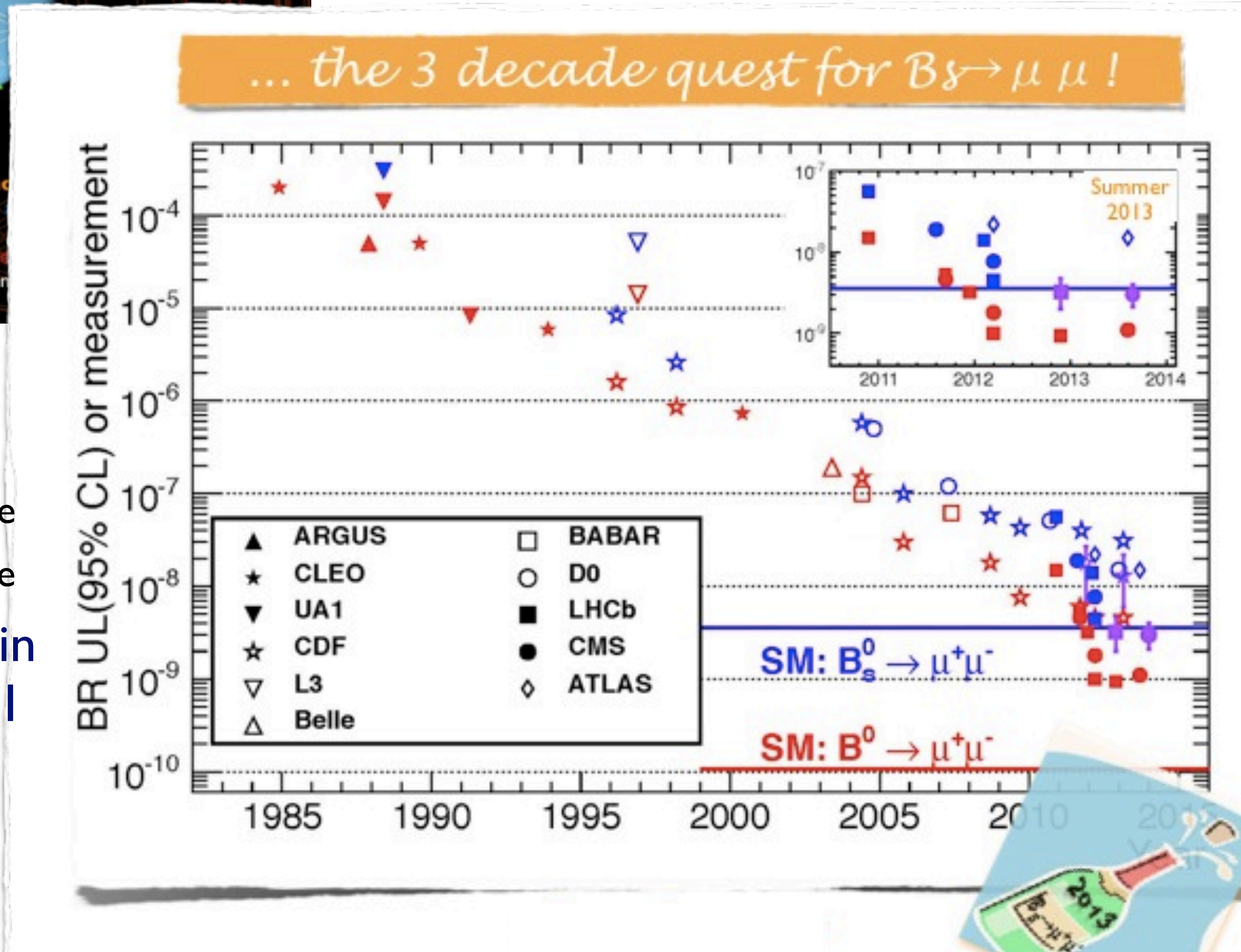
New Physics
(extended scalar sector, *eg* SUSY)



- Possible new particles in the loops!
  - may enhance *or* suppress the decay rates

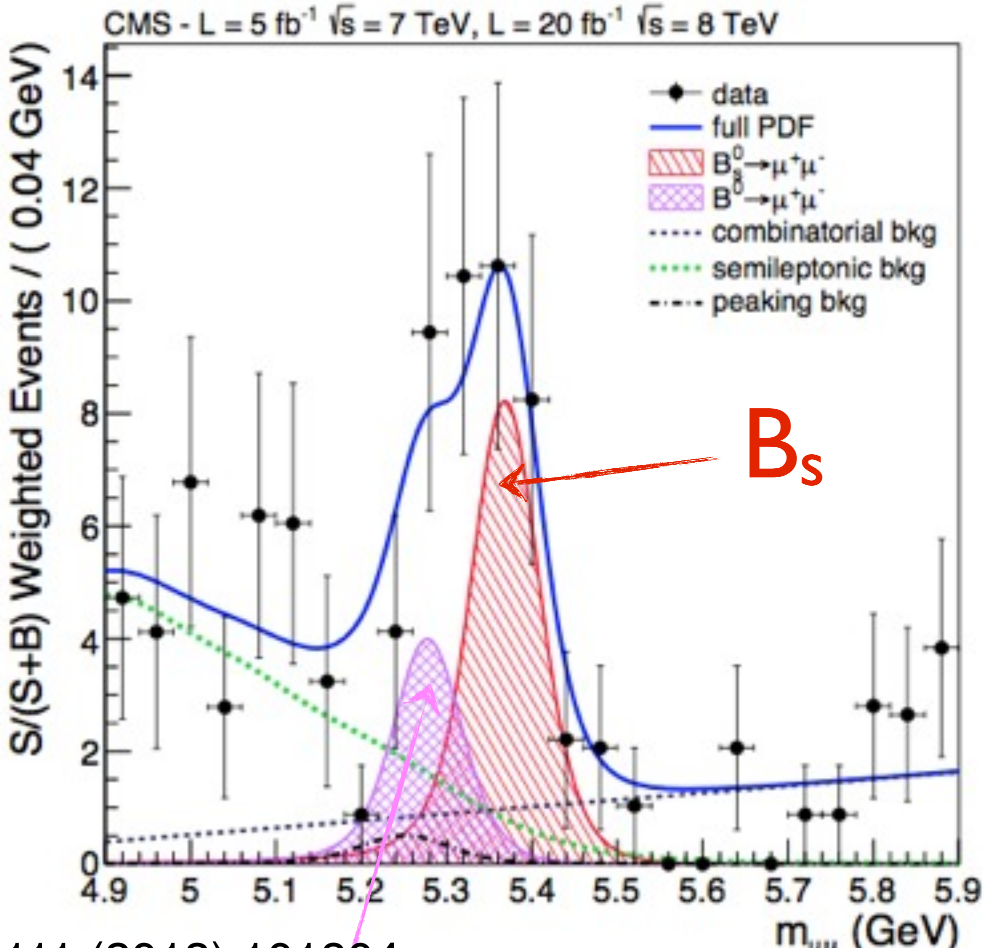


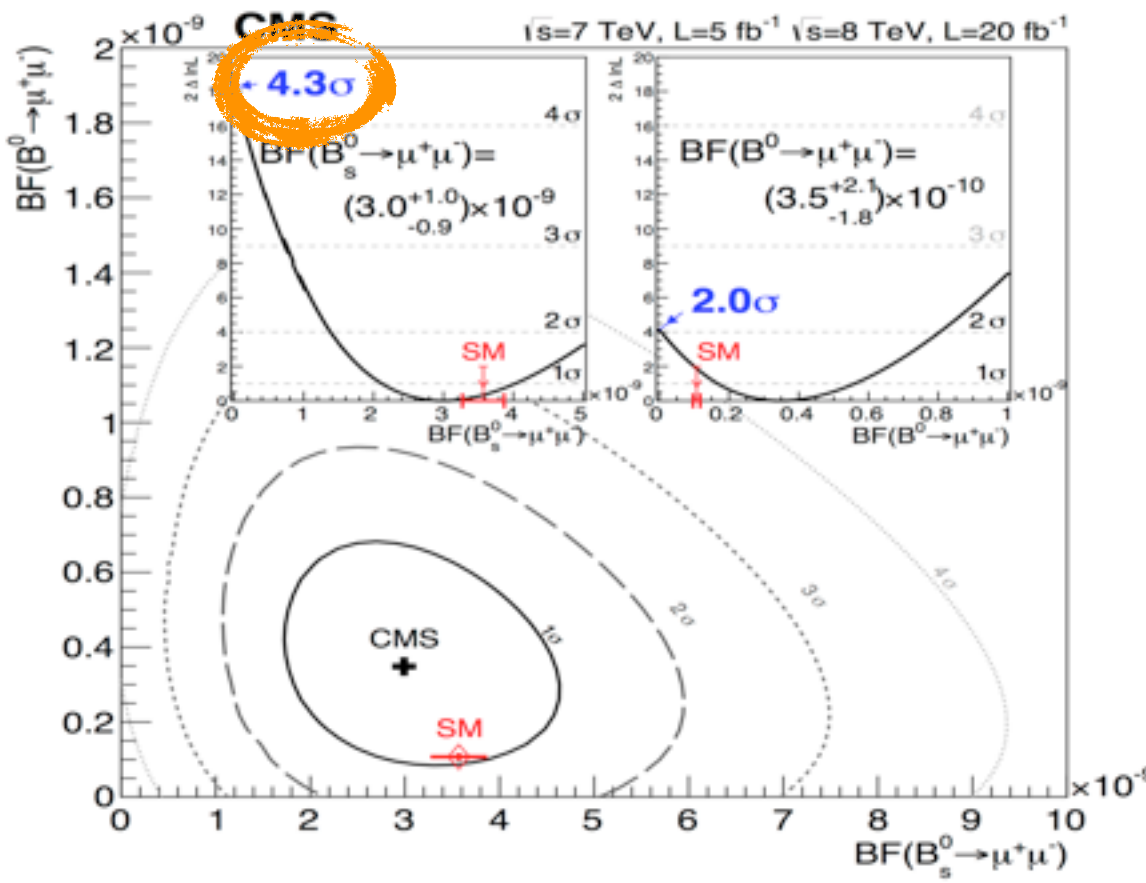
Active searches for 3 decades
at many accelerators & experiments



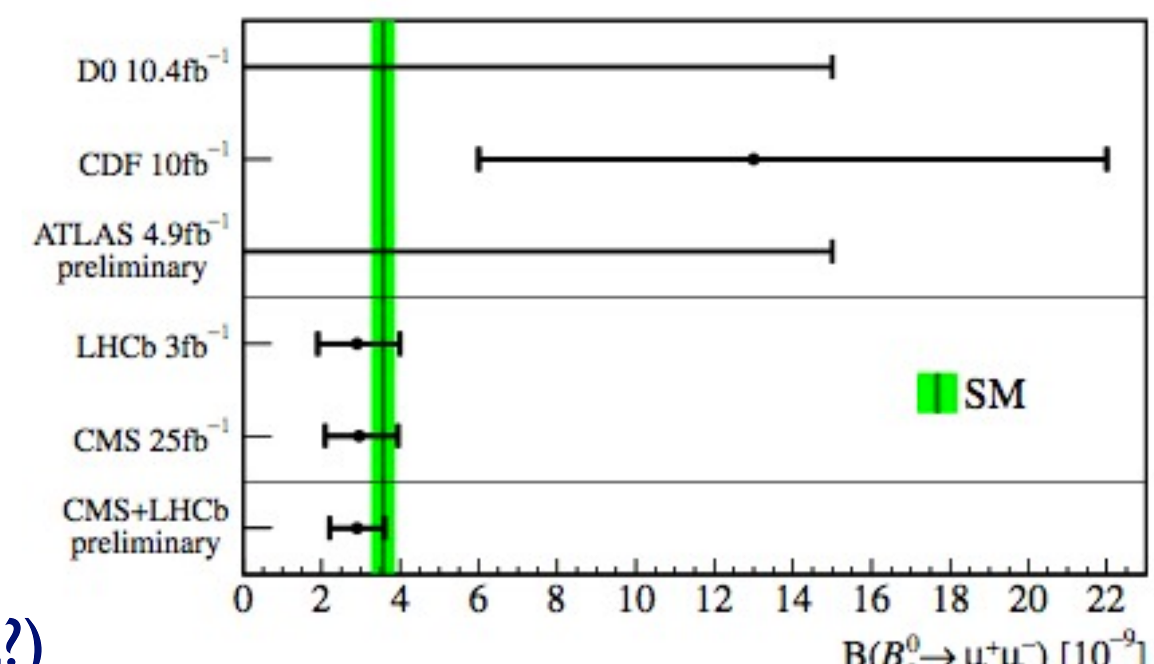
- improvements
  - >100x over last decade
  - >10x in past year alone
- SM sensitivity within reach at LHC Run I
  - for B_s (not yet B_d)

$B_s \to \mu\mu$: this past Summer's LHC observation





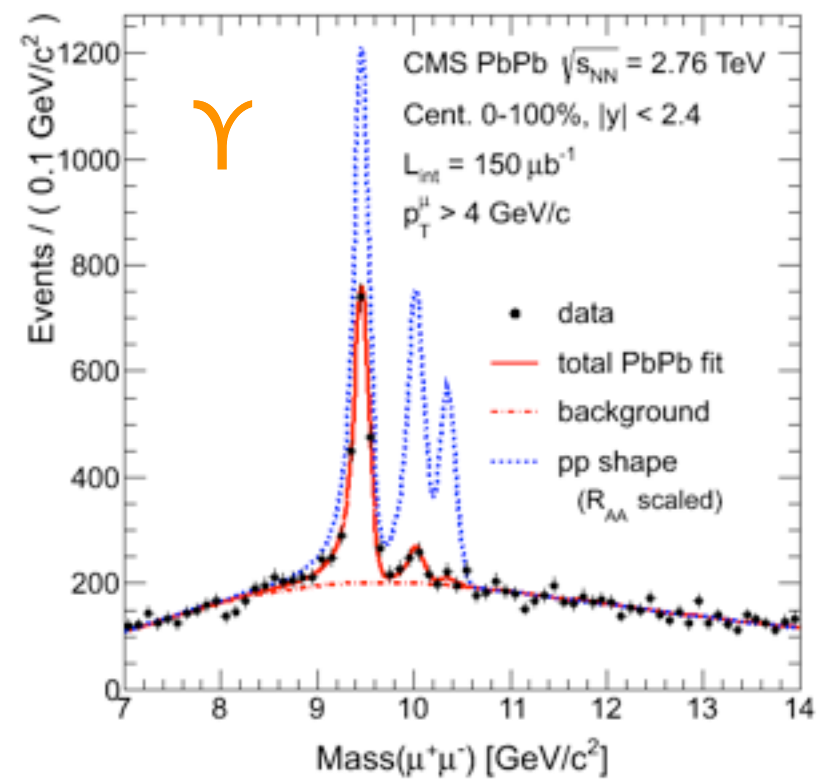
PRL 111 (2013) 101804

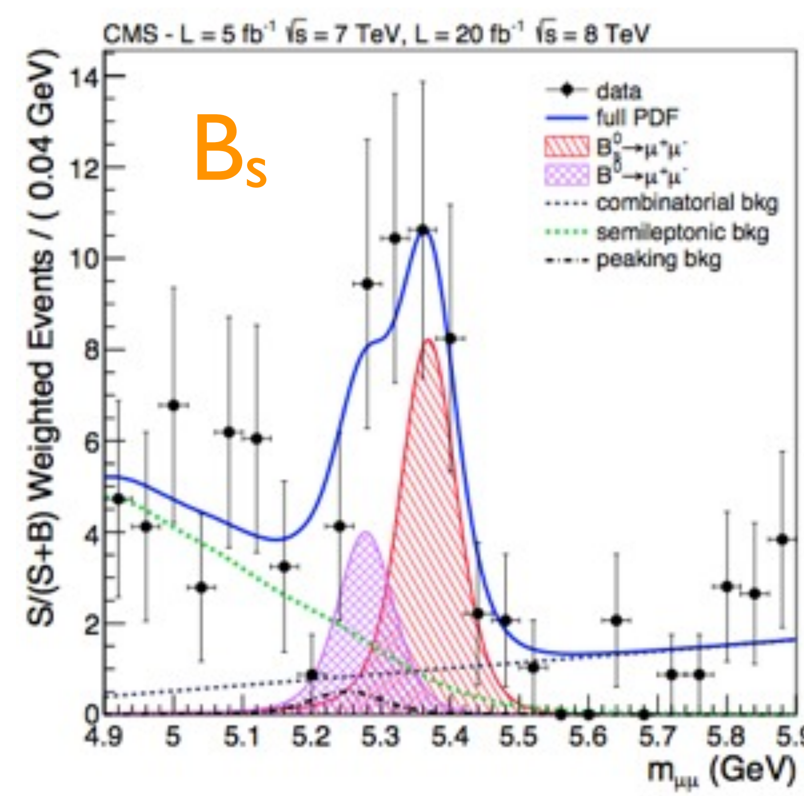


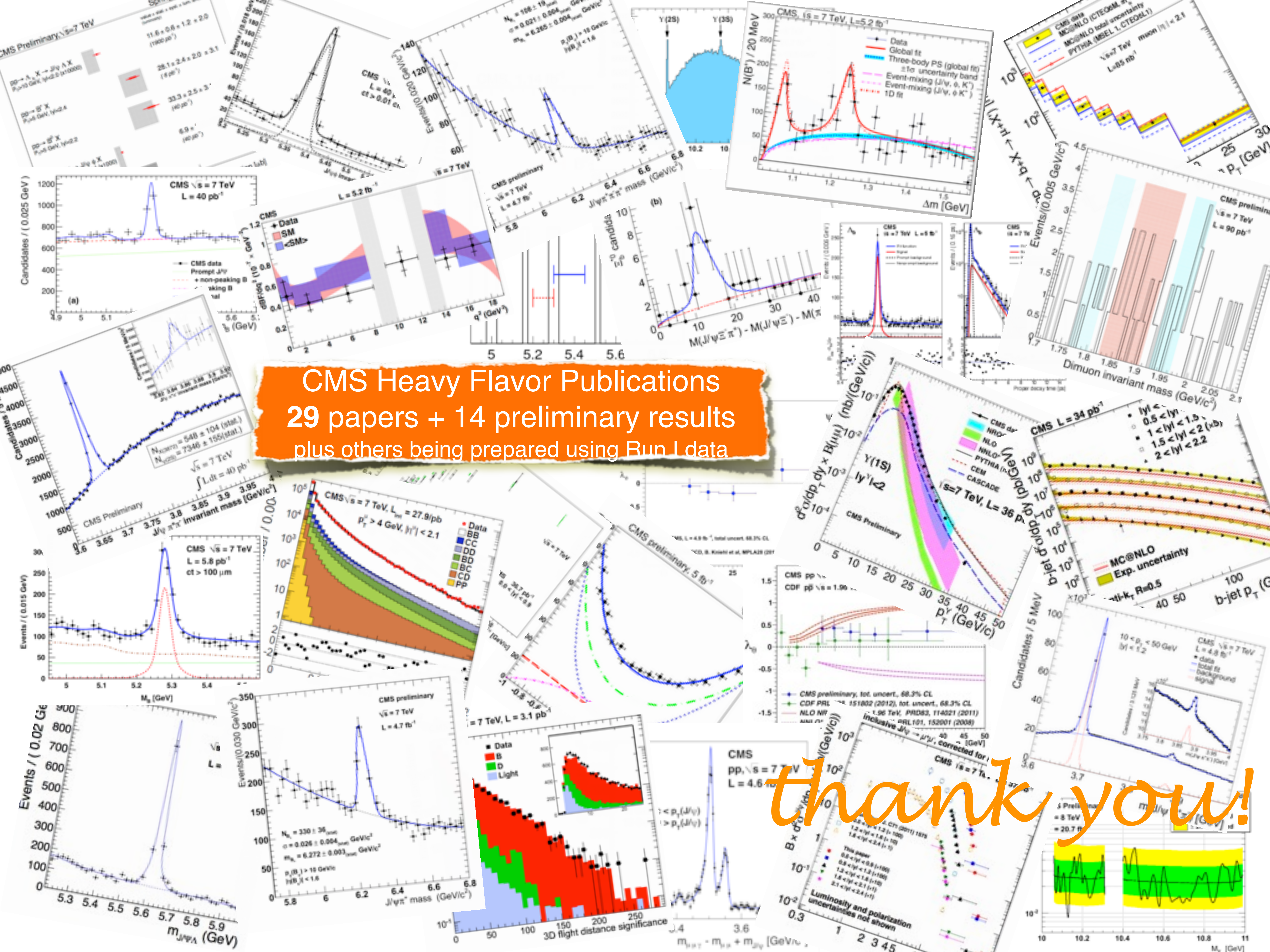
- CMS observes the Bs decay at 4.3σ level
- CMS + LHCb(4.0σ): >5σ significance
- B_s result compatible with SM expectation
  - strong constraints on NP
- B_d decay: focus of next LHC run (3σ hint?)

Summary

- very successful heavy flavor program based on LHC Run I pp / pPb / PbPb data
  - dimuon signals successfully explored at CMS!
- focused on the two most emblematic results from B physics and heavy ions
  - observation of sequential quarkonium suppression in PbPb collisions
  - observation of the rare B_s decay
- there are many more!
  - + 2012 and 2013 datasets still being analyzed
- perspectives for next runs
  - explore more rare decays (B_d!) and new states
  - first measurements of exclusive B decays, and the top quark, in heavy ion collisions







CMS Heavy Flavor Publications

29 papers + 14 preliminary results

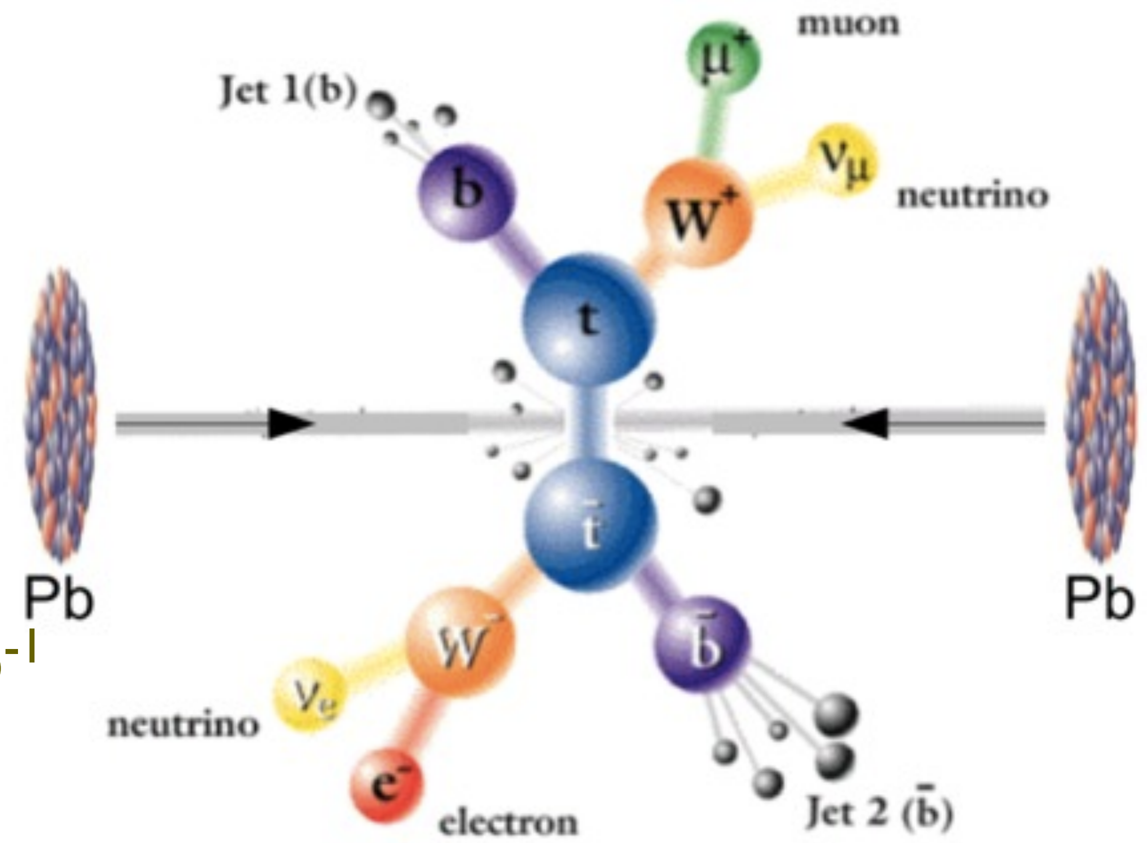
plus others being prepared using Run I data

thank you!

perspectives: heavy ions

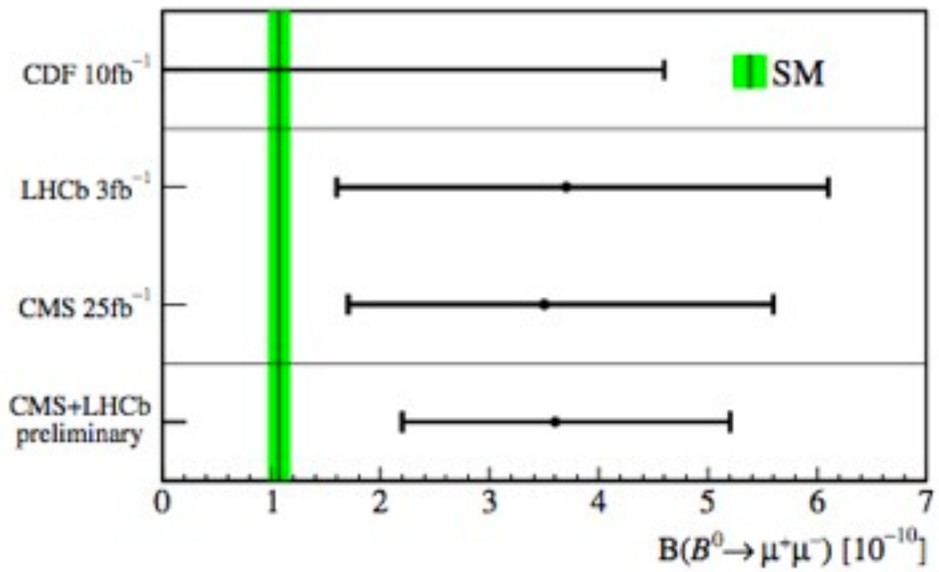
- continue re-discovery of the Standard Model... in HI collisions!
- exclusive bottom (and charm) exclusive decays, eg $B_{ucds} \rightarrow J/\psi\ K/\pi$
- disentangle quarkonia feeddown (eg $X_{b,c}$) and attempt polarization

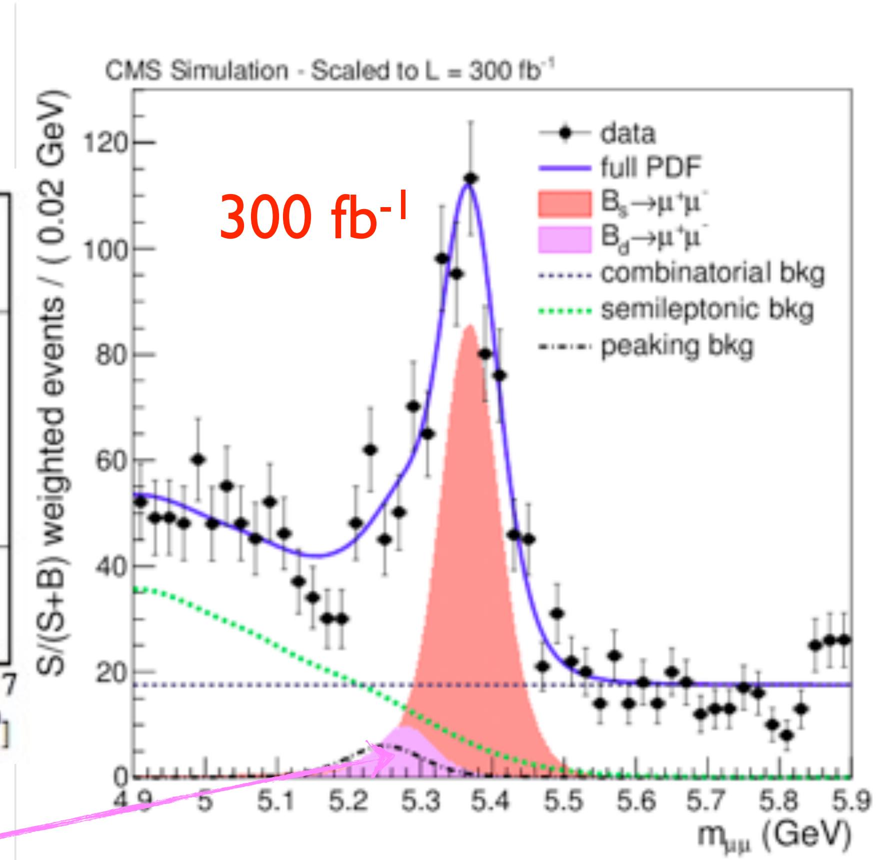
- ... and (why not?) the **top** quark!
  - $\sigma(t\underline{t})$~81pb(5.5TeV) ➡ 3,500$t\underline{t}$
  - ε~1.5% (reconstructions, BRs)
  - ➡ 530 $t\underline{t}$ pairs to be *observed* in 10nb^{-1}
  - study a "bare" quark
  - (access the earliest timescales in the collisions)

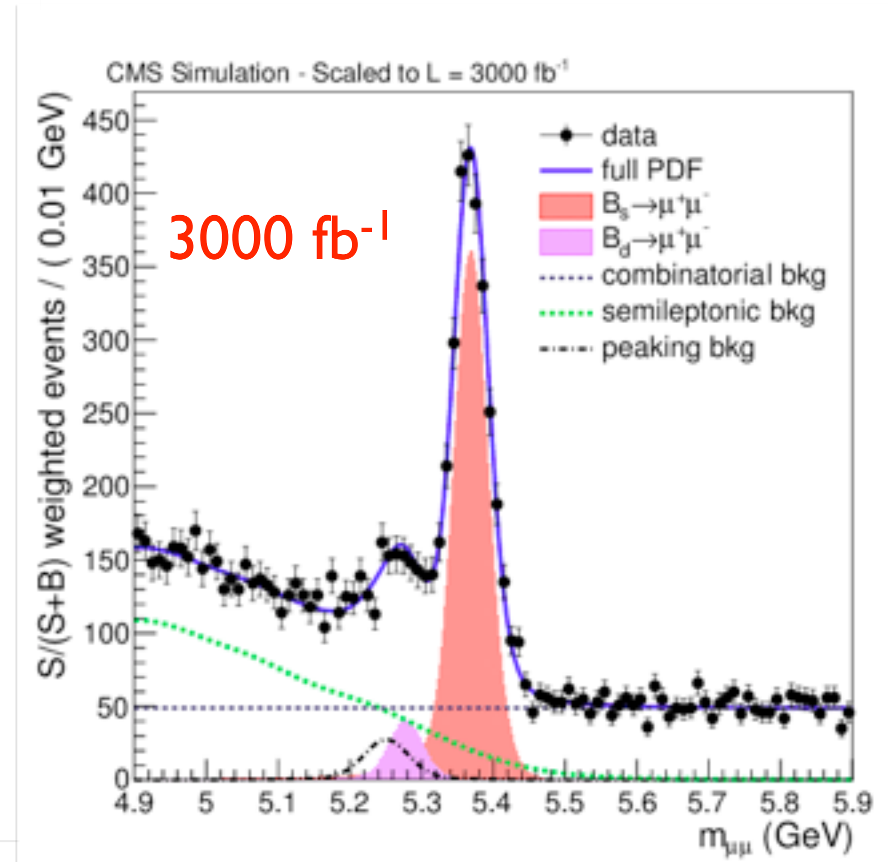


perspectives: B physics

Run I (25 fb^{-1})







- B_d decay: 2-3σ hint? focus of next LHC run
- larger datasets will allow high precision measurements of B_s and B_d
  - including ratio, effective lifetimes, and additional variables sensitive to NP
  - expect 11.2σ sign. for B_s with 100 fb^{-1}
  - expect >5σ sign. for B_d with 3000 fb^{-1}
- detector upgrades for HL-HLT
  - yield improvement in p_T resolution by factor of 1.5 in the barrel ➟ important to help disentangling peaking backgrounds and signals

Backup

$B_s \to \mu\mu$ (analysis overview)

- full LHC Run I datasets
  - $5\,fb^{-1}$ ($\sqrt{s}$=7TeV, 2011) and $20\,fb^{-1}$ ($\sqrt{s}$=8TeV, 2012)
- blind signal region (until selection is fixed)
- multivariate candidate selection
- unbinned likelihood fit to dimuon mass
  - fit simultaneously the $B_s \to \mu\mu$ and $B_d \to \mu\mu$
- normalization sample: $B^+ \to J/\psi K^+$
  - avoid uncertainties from the b production cross section, and luminosity
  - (nearly) identical selection to reduce systematic uncertainties (efficiencies)

Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu 1 \mu 2} < 5.90$
blinding window	$5.20 < m_{\mu 1 \mu 2} < 5.45$
$B^0 \to \mu^+\mu^-$ window	$5.20 < m_{\mu 1 \mu 2} < 5.30$
$B_s \to \mu^+\mu^-$ window	$5.30 < m_{\mu 1 \mu 2} < 5.45$

Data split in two categories:
- Barrel: 2 μ in barrel $|\eta|<1.4$
  - ➠ better sensitivity, σ_M~40MeV
- Endcap: ≳1 μ in endcap $|\eta|>1.4$
  - ➠ more events, σ_M~60MeV

B-hadron composition (from LHCb meas.)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N(n_{obs}, n_B, n_S)}{N(B^\pm \to J/\psi K^\pm)} \frac{A_{B^+}}{A_{B_s^0}} \frac{\varepsilon^{ana}_{B^+}}{\varepsilon^{ana}_{B_s^0}} \frac{\varepsilon^{\mu}_{B^+}}{\varepsilon^{\mu}_{B_s^0}} \frac{\varepsilon^{trig}_{B^+}}{\varepsilon^{trig}_{B_s^0}} \frac{f_u}{f_s} \mathcal{B}(B^+ \to J/\psi[\mu^+\mu^-]K)$$

trigger efficiency

μ identification

analysis selections

acceptance

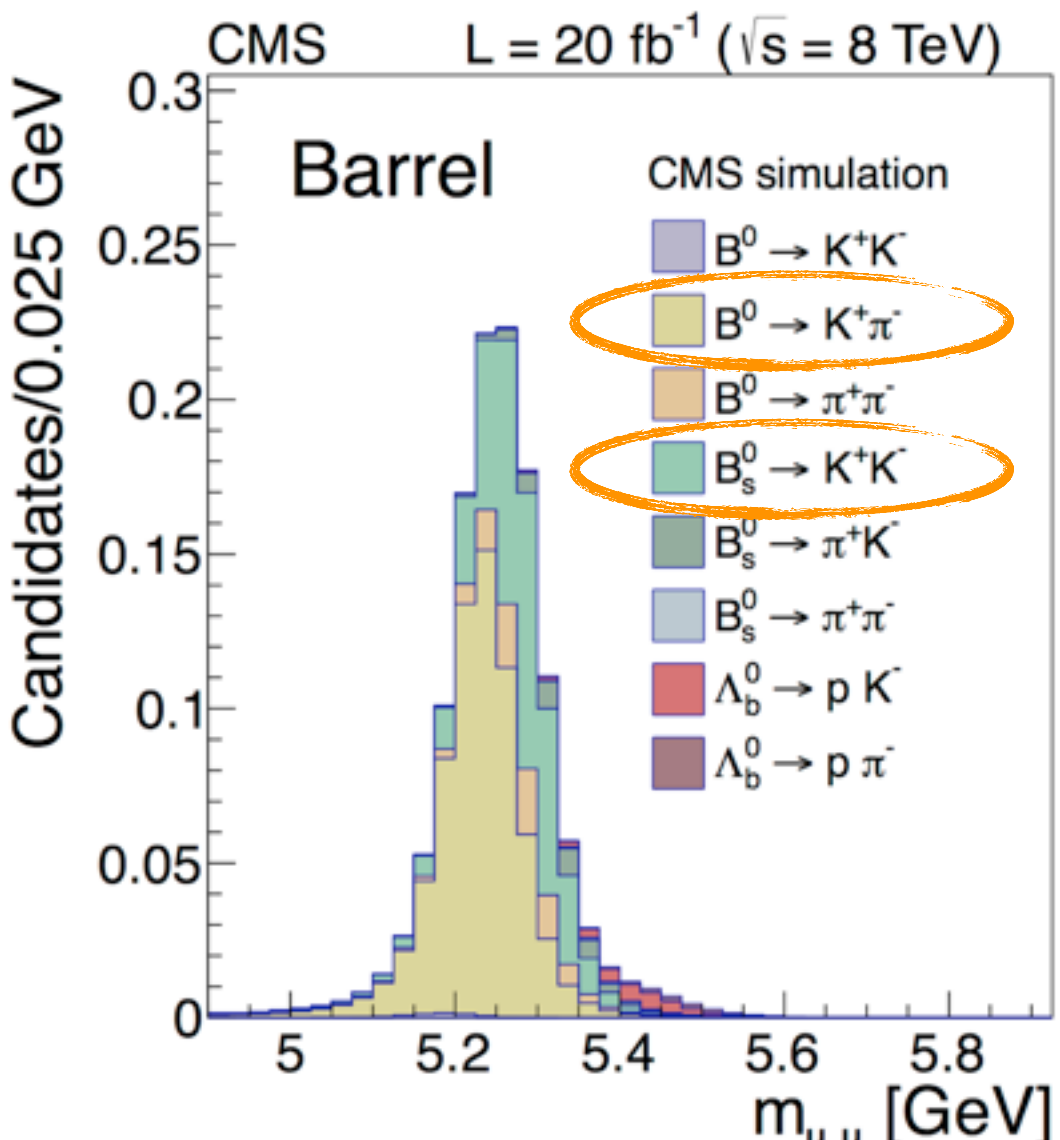
- control sample: $B_s \to J/\psi\Phi$
  - calibrate and validate MC

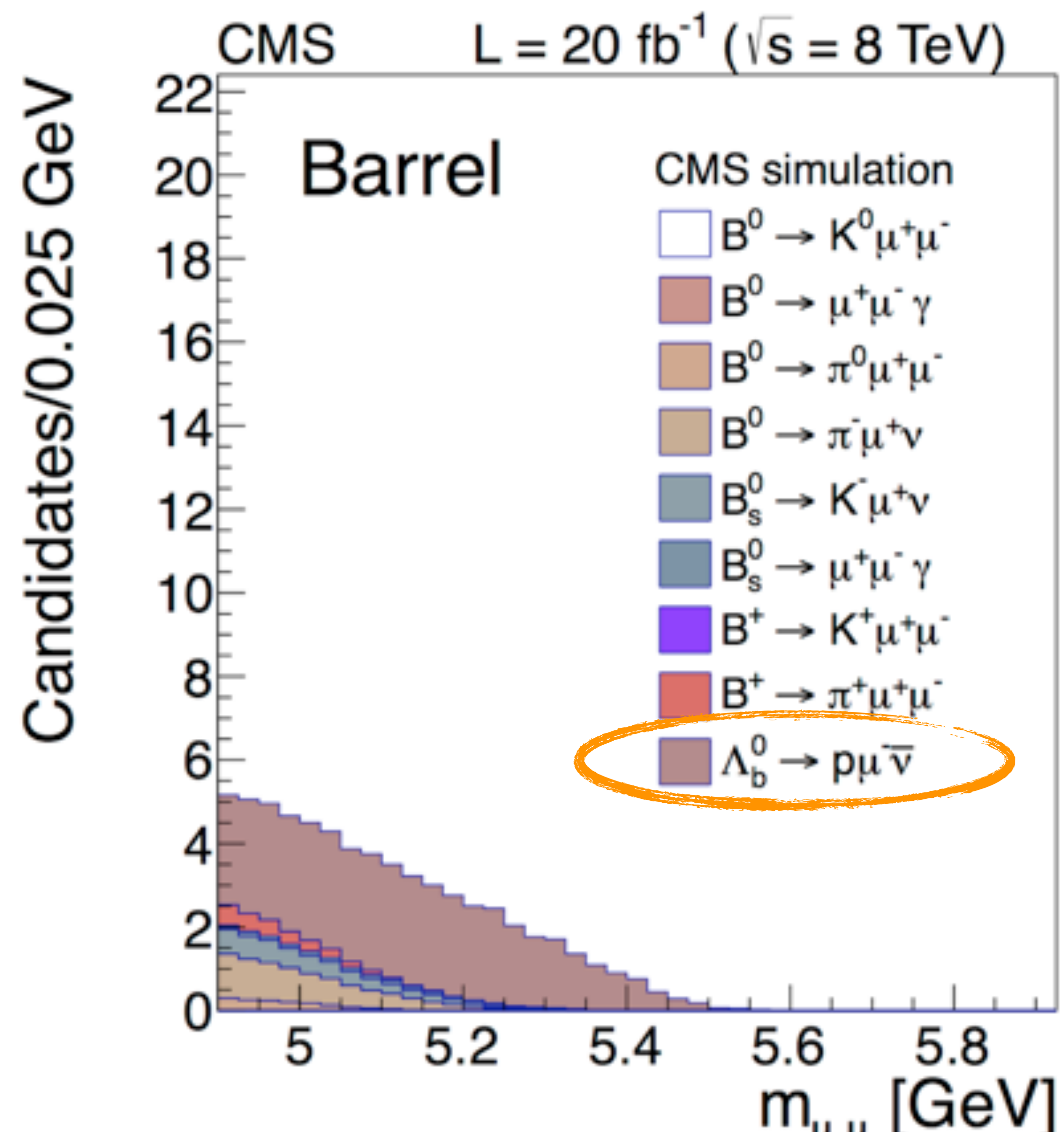
rare backgrounds

- expected no. of events in each channel normalized to $B^{\pm}$ in data

$$N(X) = \frac{Br(Y \to X)}{Br(B^{\pm} \to J/\psi K^{\pm})} \frac{f_Y}{f_u} \frac{\varepsilon_{tot}(X)}{\varepsilon_{tot}(B^{\pm})} N_{obs}(B^{\pm})$$

- weighted with muon misidentification rates and ε_{trig}





R_{AA} & centrality

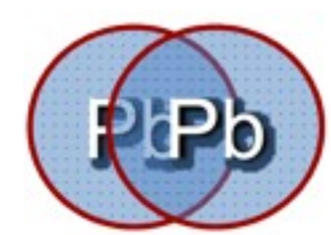
- pp data employed as baseline for heavy-ion measurements
- nuclear modification factor, **R_{AA}**

$$R_{AA} = \frac{\text{Yield (PbPb)}}{\text{Yield (pp)} \times \langle N_{coll} \rangle} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(Q\overline{Q})}{N_{pp}(Q\overline{Q})} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}}$$

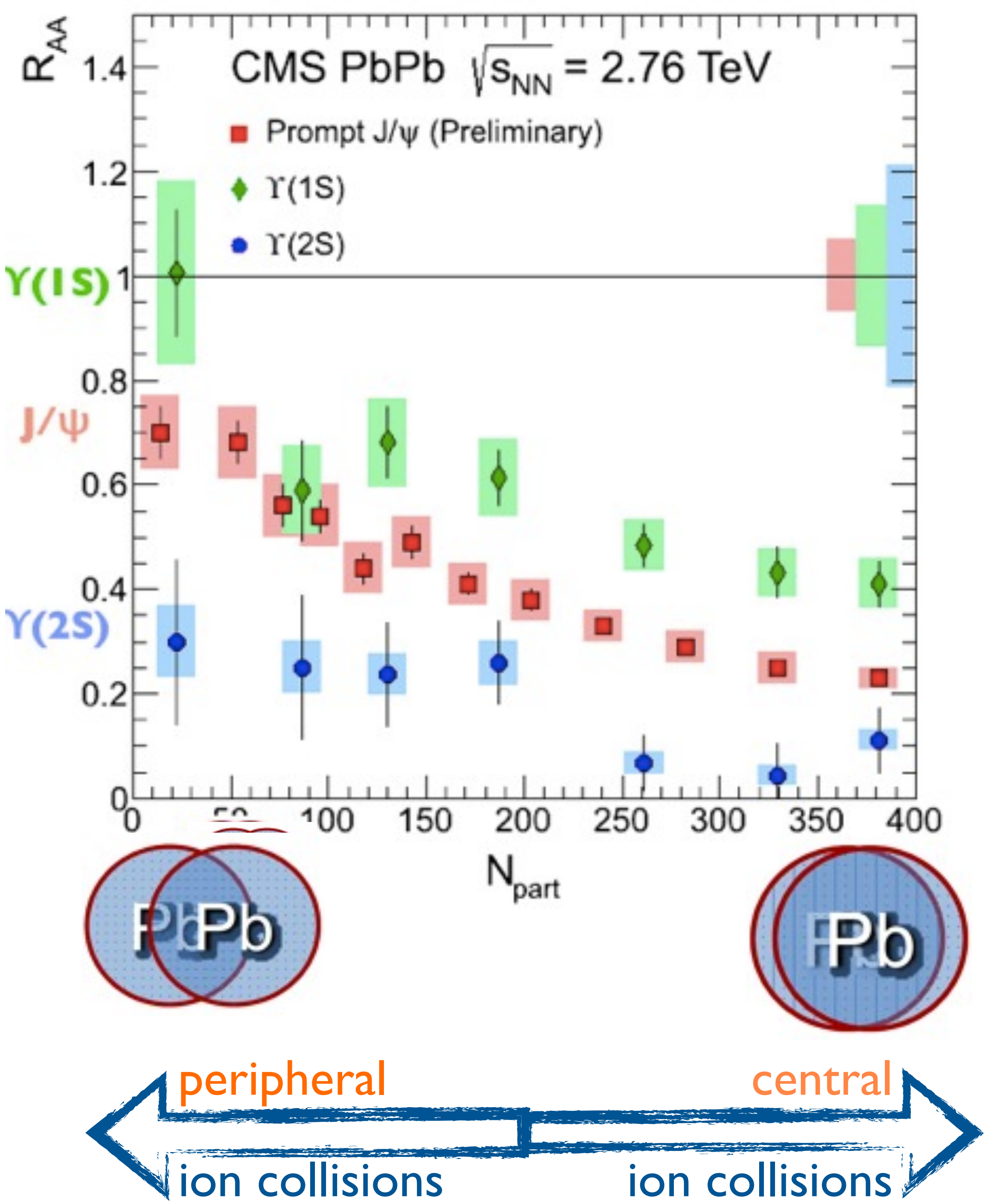
$\Uparrow$ average number of NN collisions in AA collisions

>1 enhancement
=1 no medium effect
<1 **suppression**

- **centrality** dependence
  - impact parameter, b, of the collision
  - central collisions (small b): hot, large N_{part} (number of participating nucleons)
  - peripheral collisions (large b): cold, large spectators (fly away undisturbed)



suppression vs centrality



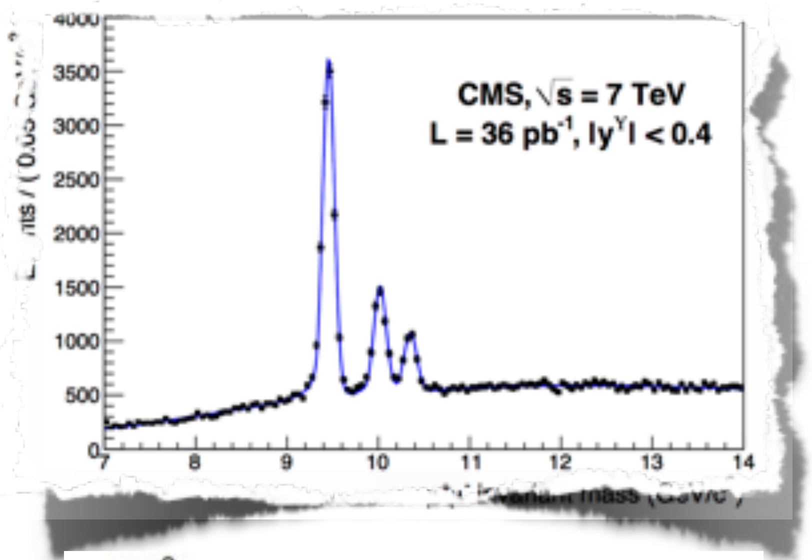
- nuclear modification factor

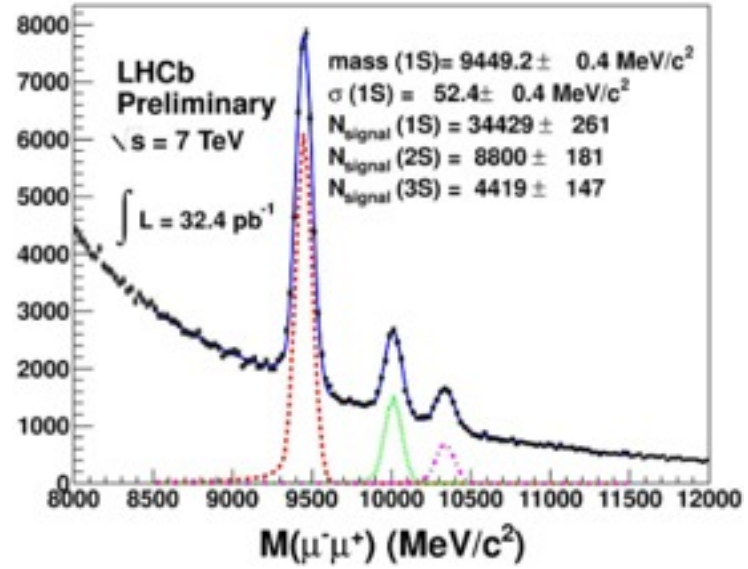
$$R_{AA} = \frac{\text{Yield (PbPb)}}{\text{Yield (pp)} \times \langle N_{coll} \rangle}$$

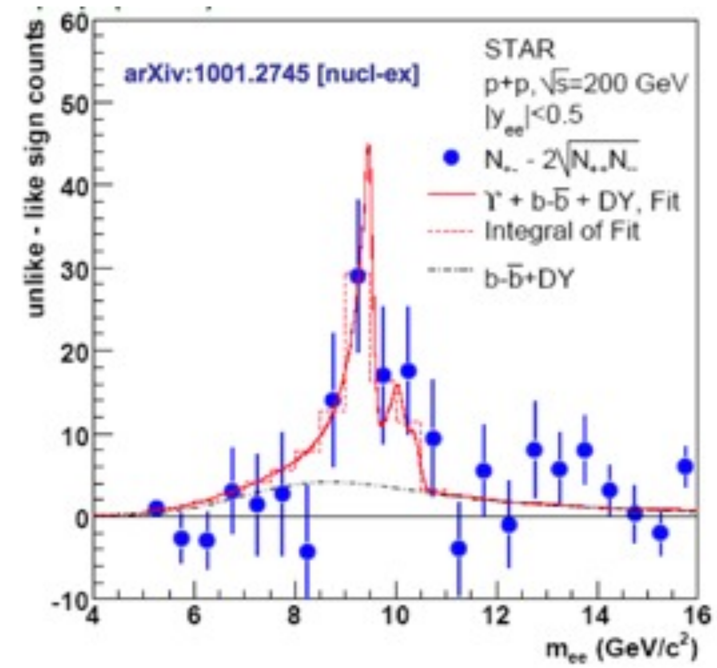
>1 enhancement
=1 no medium effect
<1 **suppression**

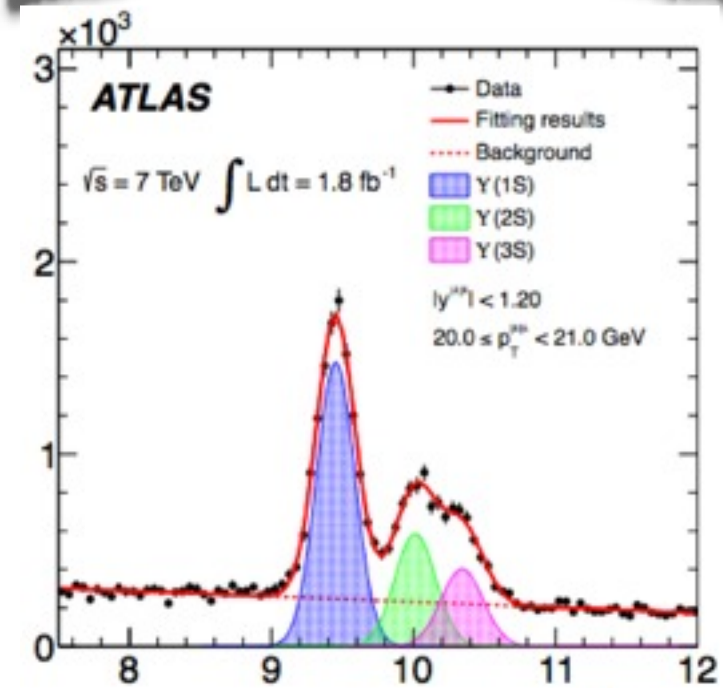
- Υ&ψ states are suppressed
- suppression increases with the centrality of ion-ion collision
- observed suppression pattern
  - Υ(1S) < J/ψ <Υ(2S) < Υ(3S)
- consistent with QGP formation

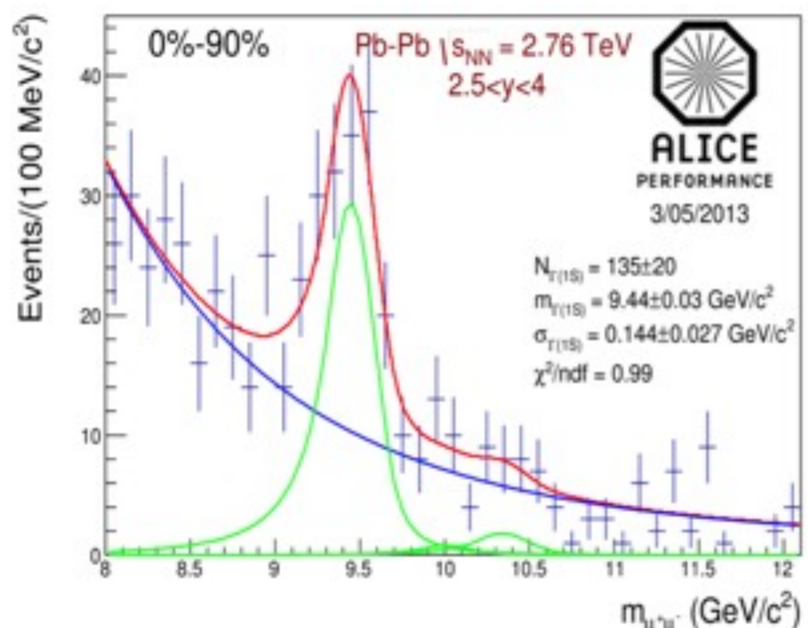
JHEP 1205 (2012) 063

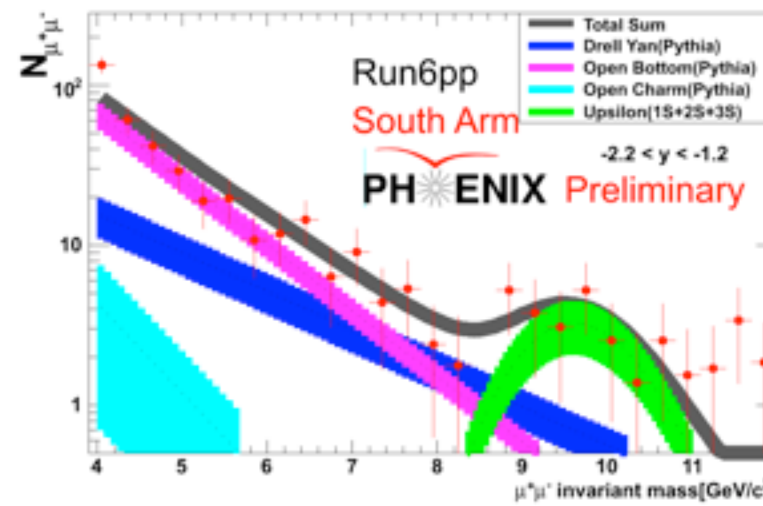

CMS, √s = 7 TeV
L = 36 pb⁻¹, |y^Υ| < 0.4

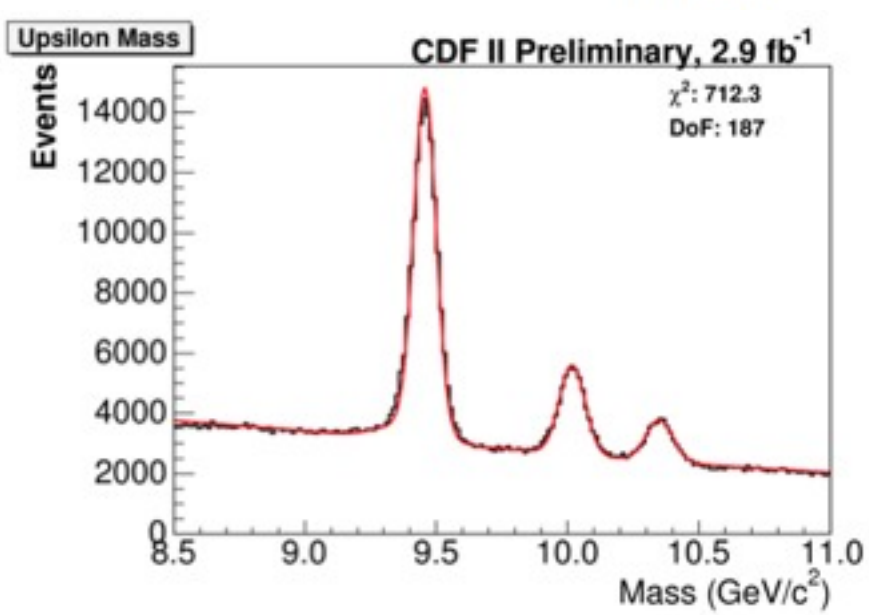

LHCb
Preliminary
√s = 7 TeV
∫L = 32.4 pb⁻¹
mass (1S)= 9449.2 ± 0.4 MeV/c²
σ (1S) = 52.4± 0.4 MeV/c²
N_signal (1S) = 34429 ± 261
N_signal (2S) = 8800 ± 181
N_signal (3S) = 4419 ± 147
M(μ⁻μ⁺) (MeV/c²)

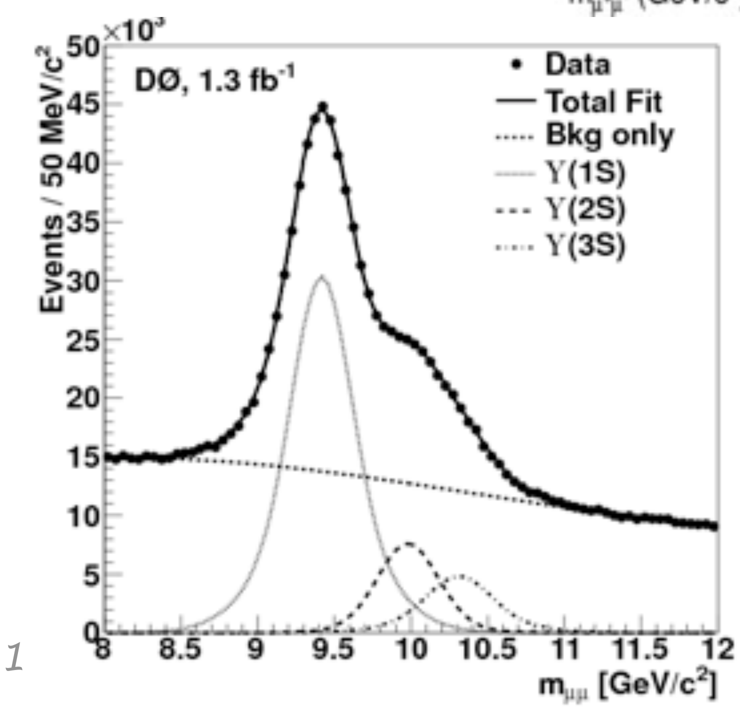

arXiv:1001.2745 [nucl-ex]
STAR
p+p, √s=200 GeV
|y_ee|<0.5
Υ + b-b̄ + DY, Fit
Integral of Fit
b-b̄+DY
unlike - like sign counts
m_ee (GeV/c²)

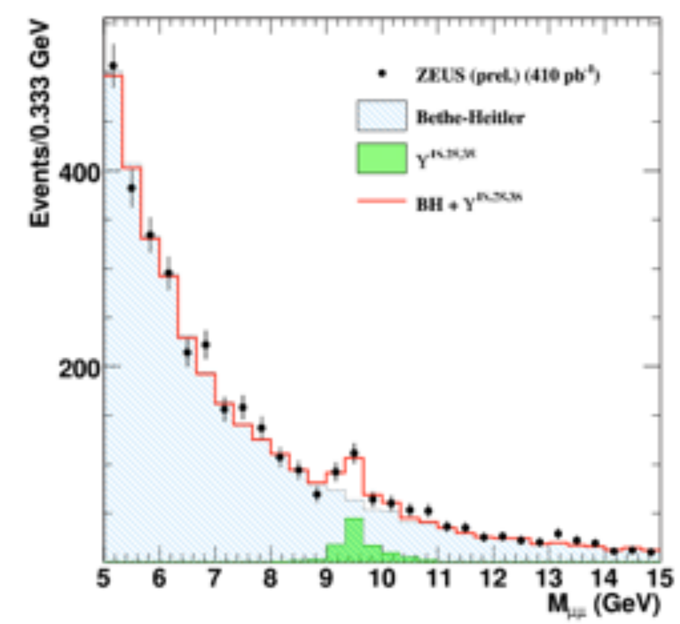

ATLAS
Data
Fitting results
Background
Υ(1S)
Υ(2S)
Υ(3S)
√s = 7 TeV ∫L dt = 1.8 fb⁻¹
|y| < 1.20
20.0 ≤ p_T < 21.0 GeV

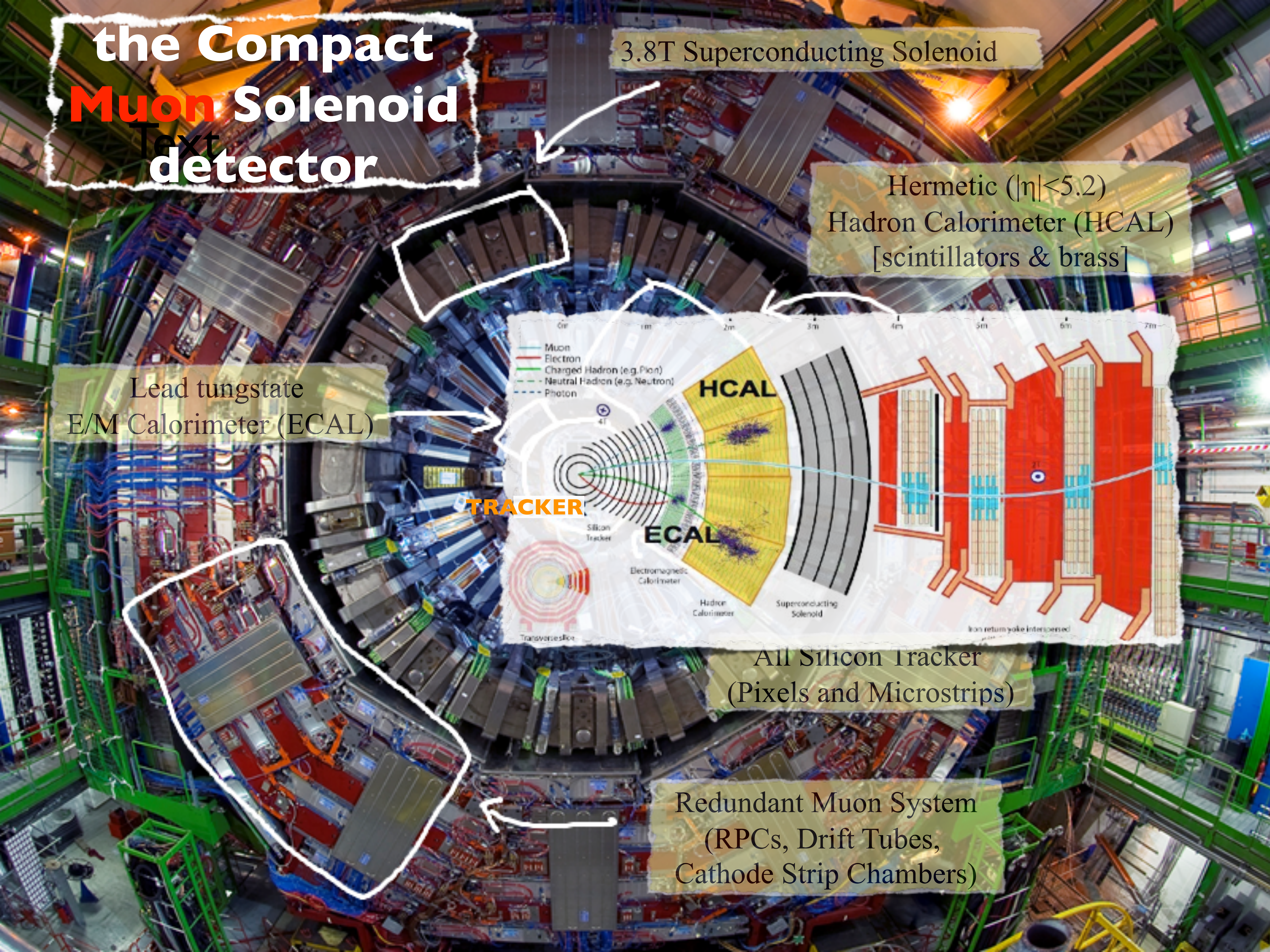

0%-90%
Pb-Pb √s_NN = 2.76 TeV
2.5<y<4
ALICE
PERFORMANCE
3/05/2013
N_Υ(1S) = 135±20
m_Υ(1S) = 9.44±0.03 GeV/c²
σ_Υ(1S) = 0.144±0.027 GeV/c²
χ²/ndf = 0.99
Events/(100 MeV/c²)
m_μ⁺μ⁻ (GeV/c²)


Total Sum
Drell Yan(Pythia)
Open Bottom(Pythia)
Open Charm(Pythia)
Upsilon(1S+2S+3S)
Run6pp
South Arm
-2.2 < y < -1.2
PHENIX
Preliminary
μ⁺μ⁻ invariant mass[GeV/c²]


Upsilon Mass
CDF II Preliminary, 2.9 fb⁻¹
χ²: 712.3
DoF: 187
Events
Mass (GeV/c²)


DØ, 1.3 fb⁻¹
Data
Total Fit
Bkg only
Υ(1S)
Υ(2S)
Υ(3S)
Events / 50 MeV/c²
m_μμ [GeV/c²]


ZEUS (prel.) (410 pb⁻¹)
Bethe-Heitler
BH + Υ
Events/0.333 GeV
M_μμ (GeV)


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