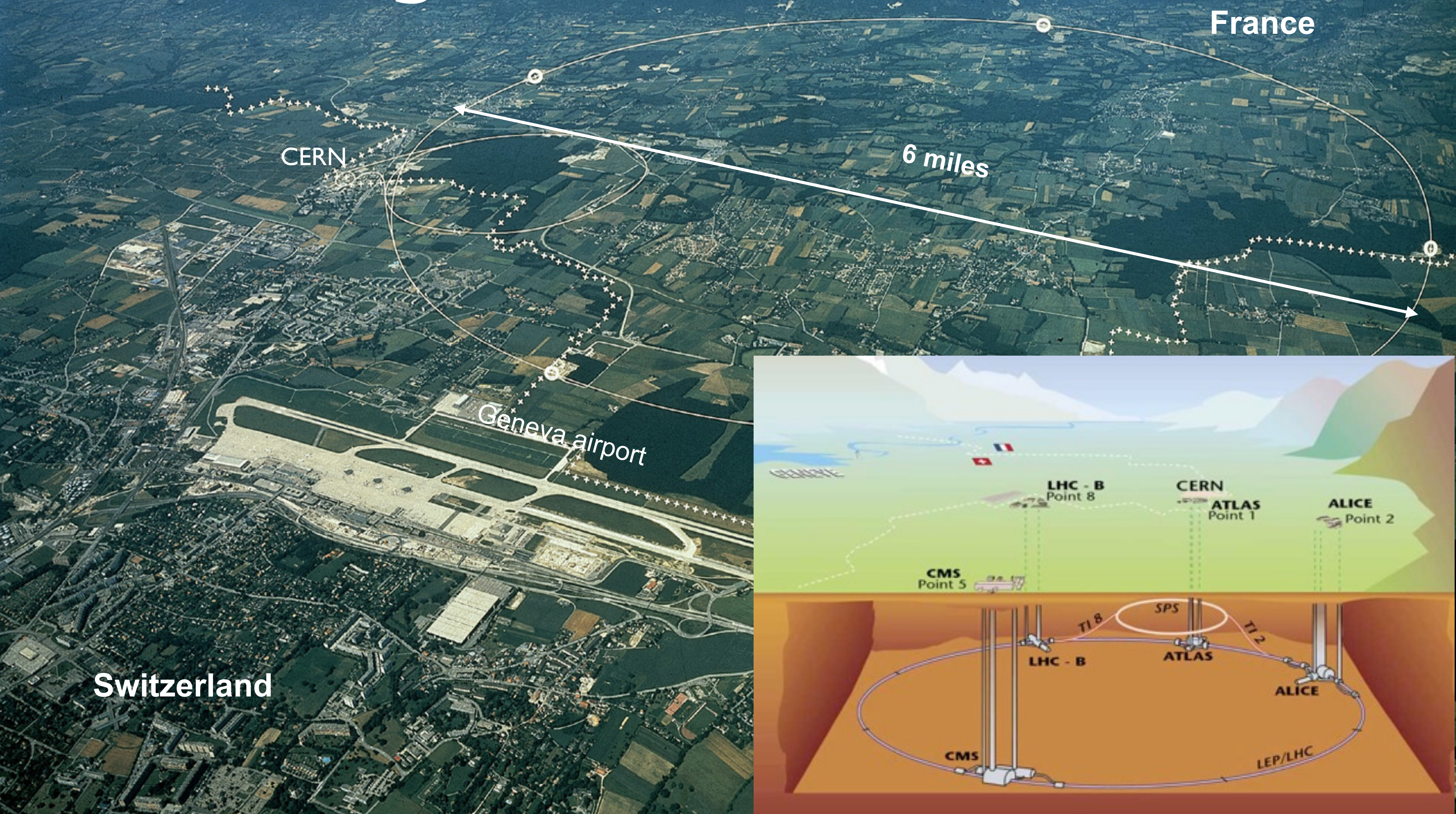
Signal resonances from few GeV to the TeV scale

Nuno Leonardo
(Purdue)

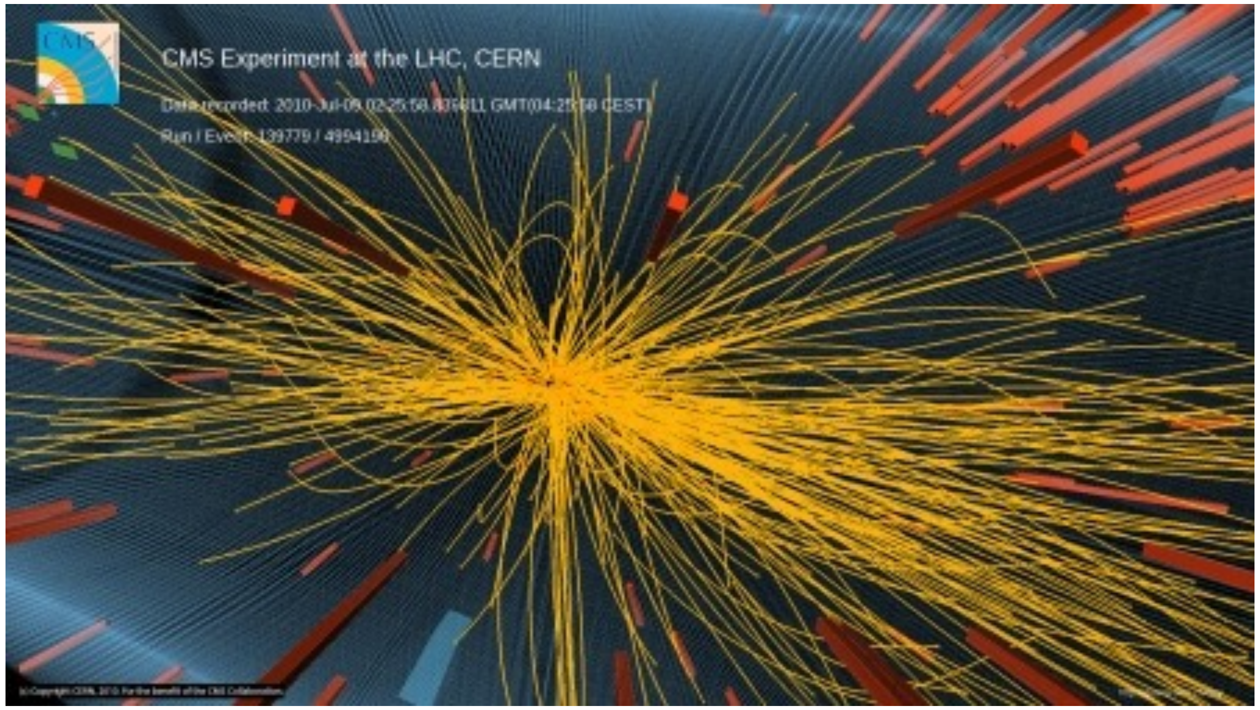
LIP/IST LHC Seminar

"Physics on the road to discovery"
Instituto Superior Técnico, 12/9/2012

The Large Hadron Collider



- Large
  - 27 km circular tunnel
  - 1,600 superconducting magnets
  - huge cryogenic facility
- Hadron Collider
  - accelerates and collides beams of hadrons (composed of quarks): protons (7-8 TeV) and atomic nuclei (PbPb, 2.76 TeV per nucleon)
- energy frontier
  - x4(7) larger wrt Tevatron
  - x14(28) larger wrt RHIC

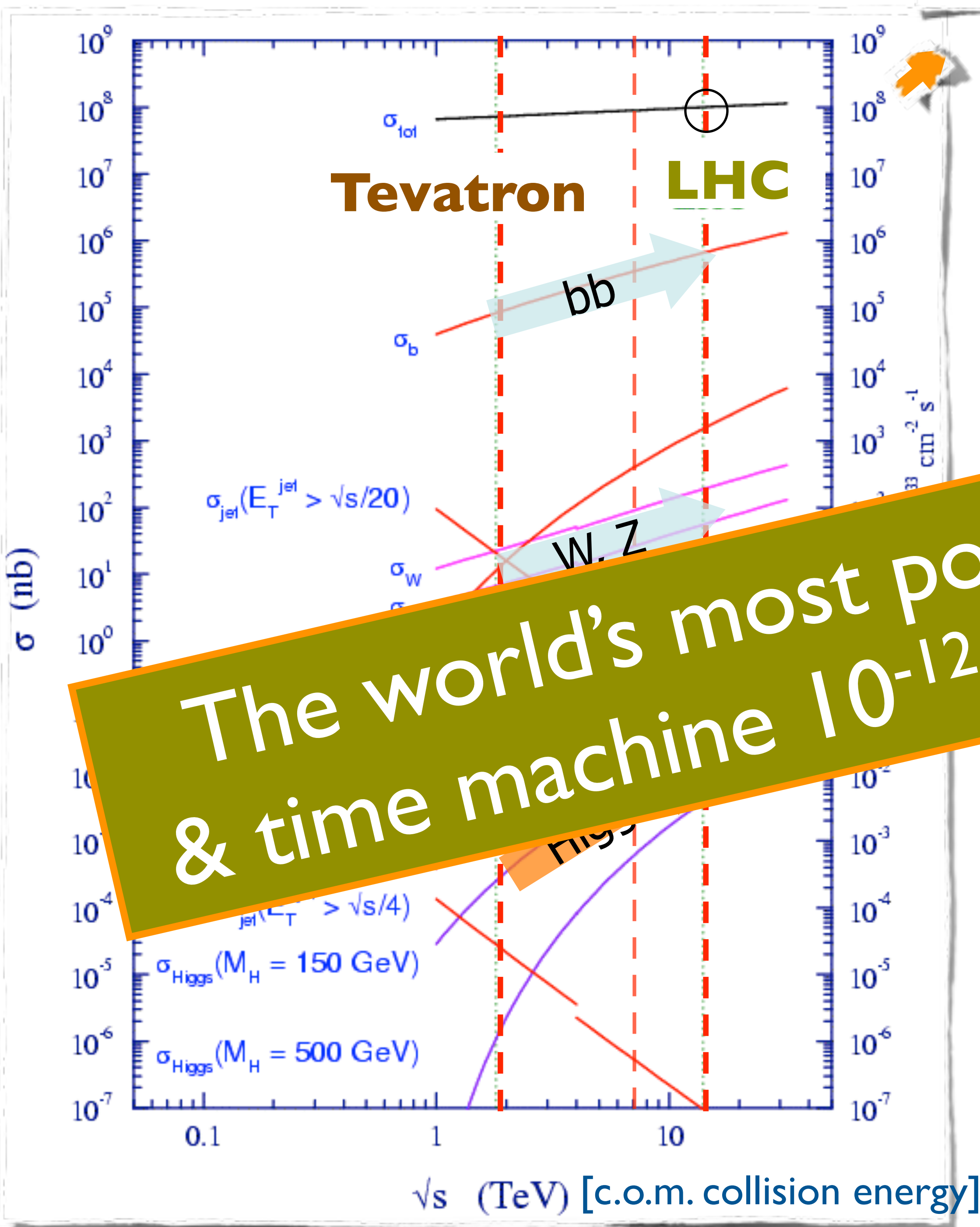


will likely remain the leading high-energy particle physics facility for next decade(s)

proton-proton

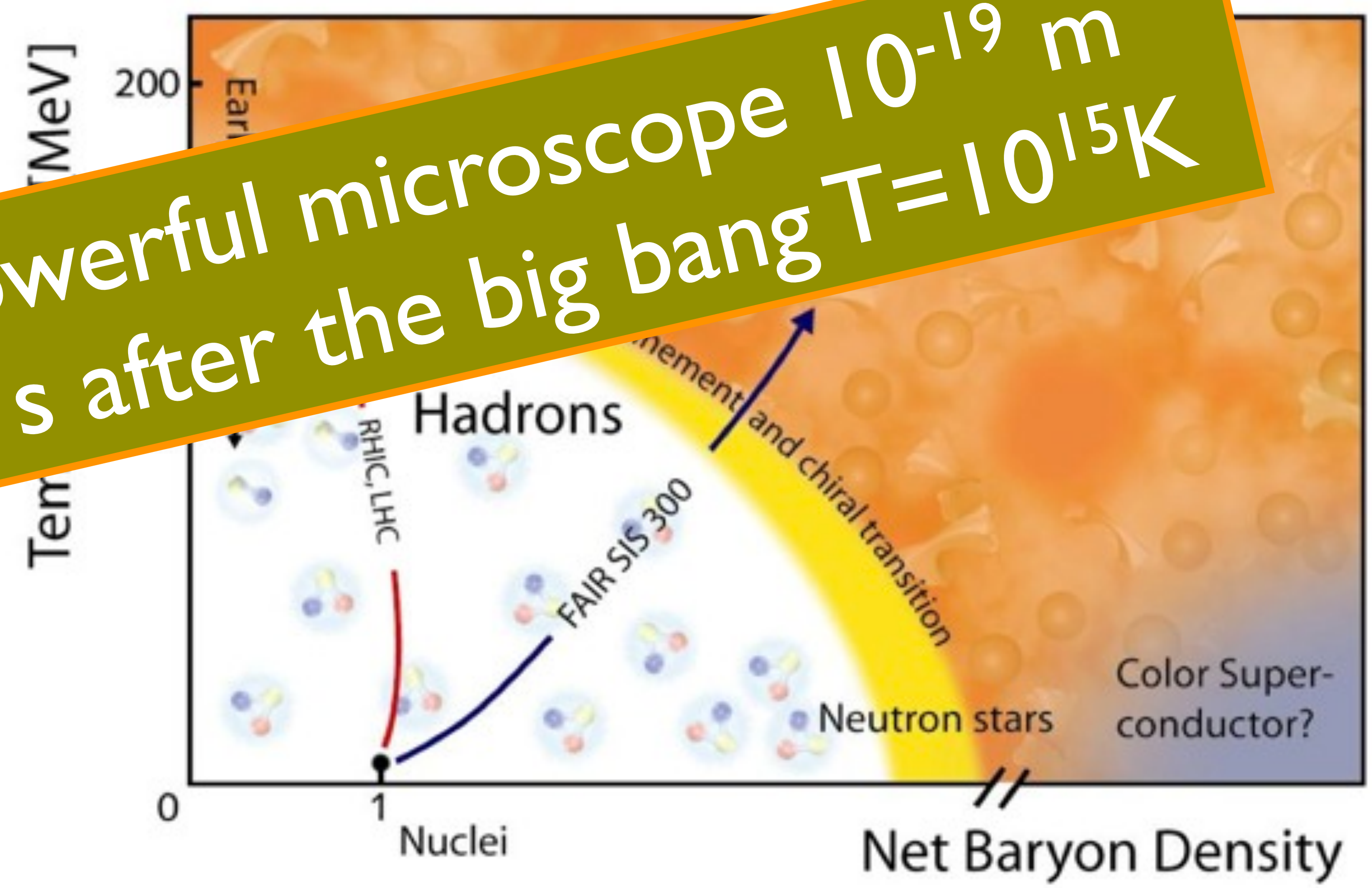
from Chicago to Geneva

10^8 evt/s



heavy-ion

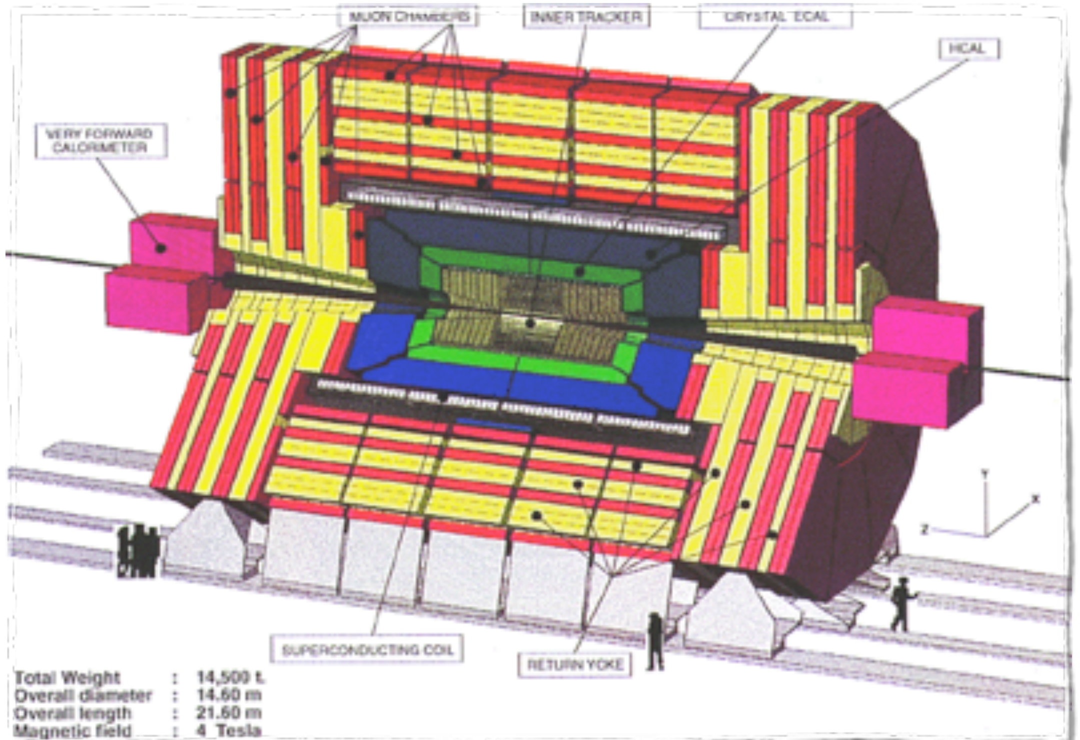
the hottest medium



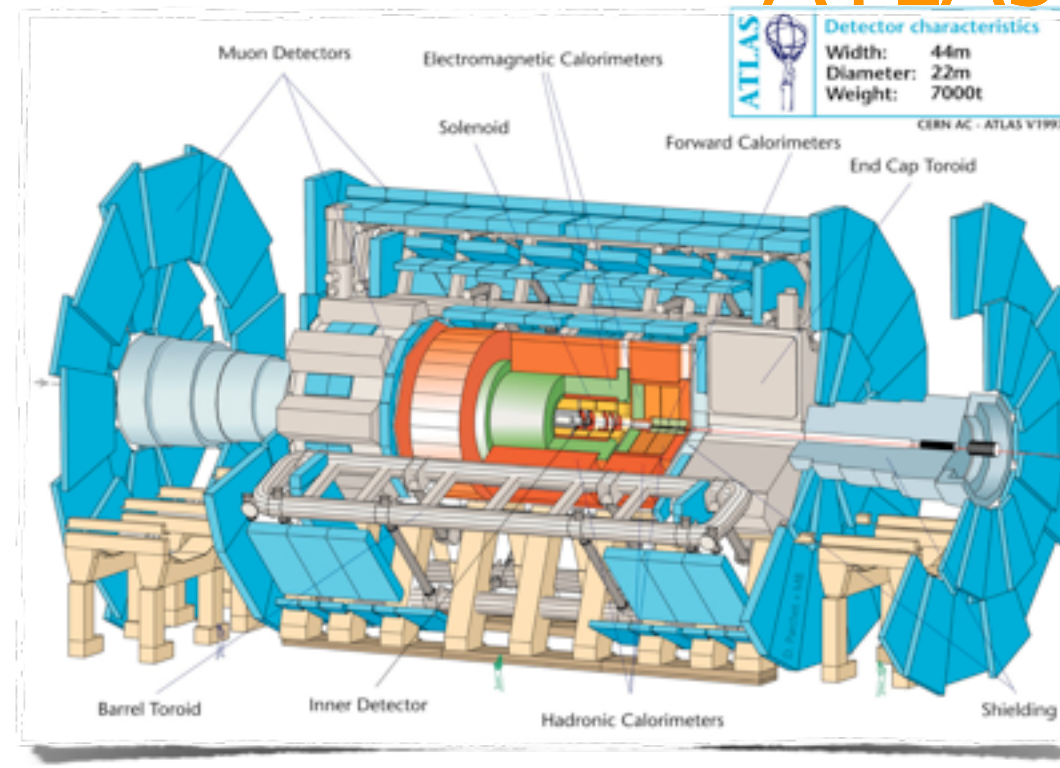
The world's most powerful microscope 10^{-19} m & time machine 10^{-12} s after the big bang $T=10^{15}$K

the LHC detectors

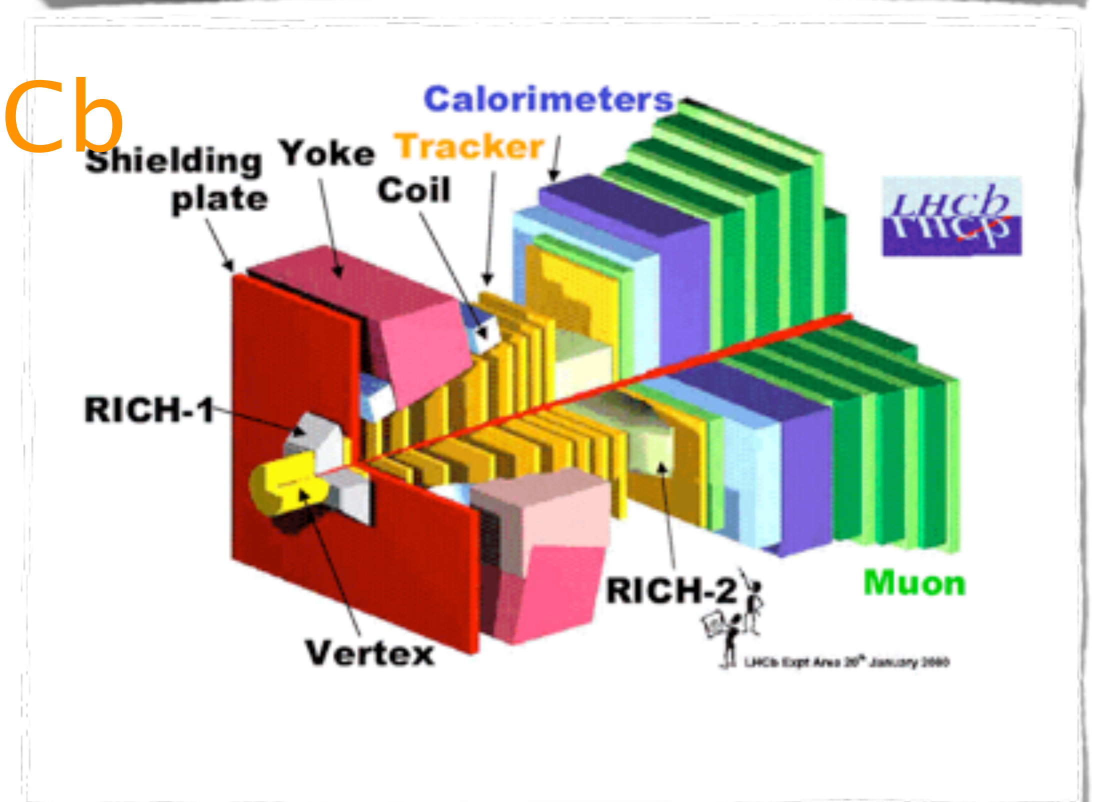
CMS



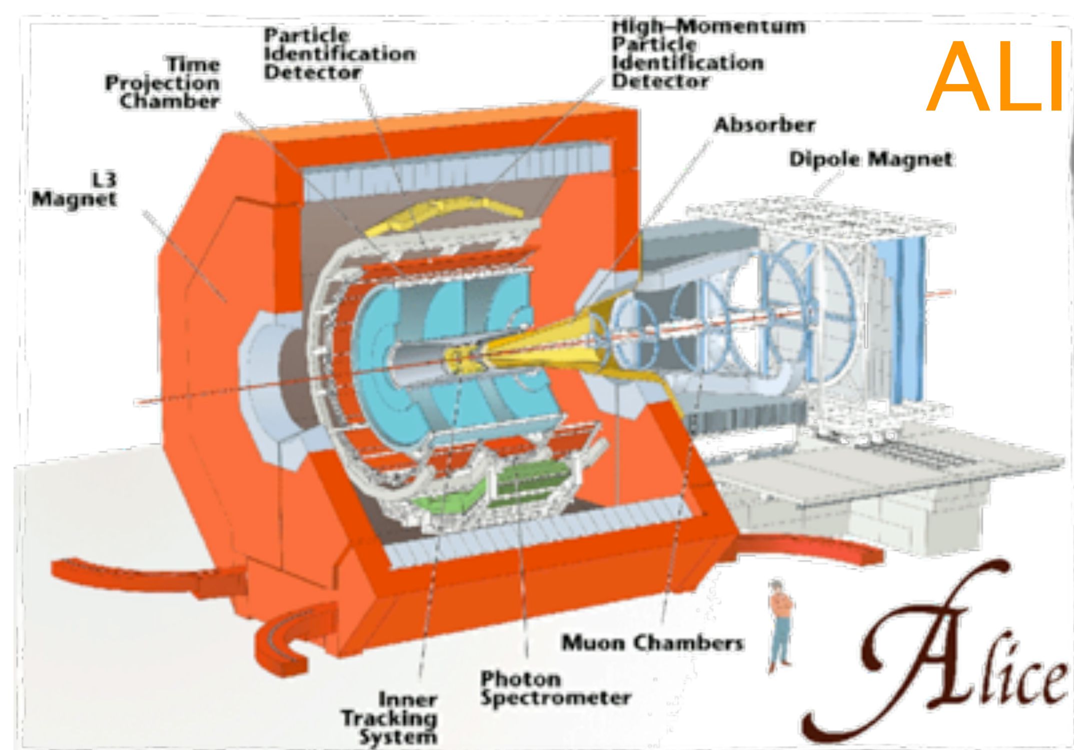
ATLAS



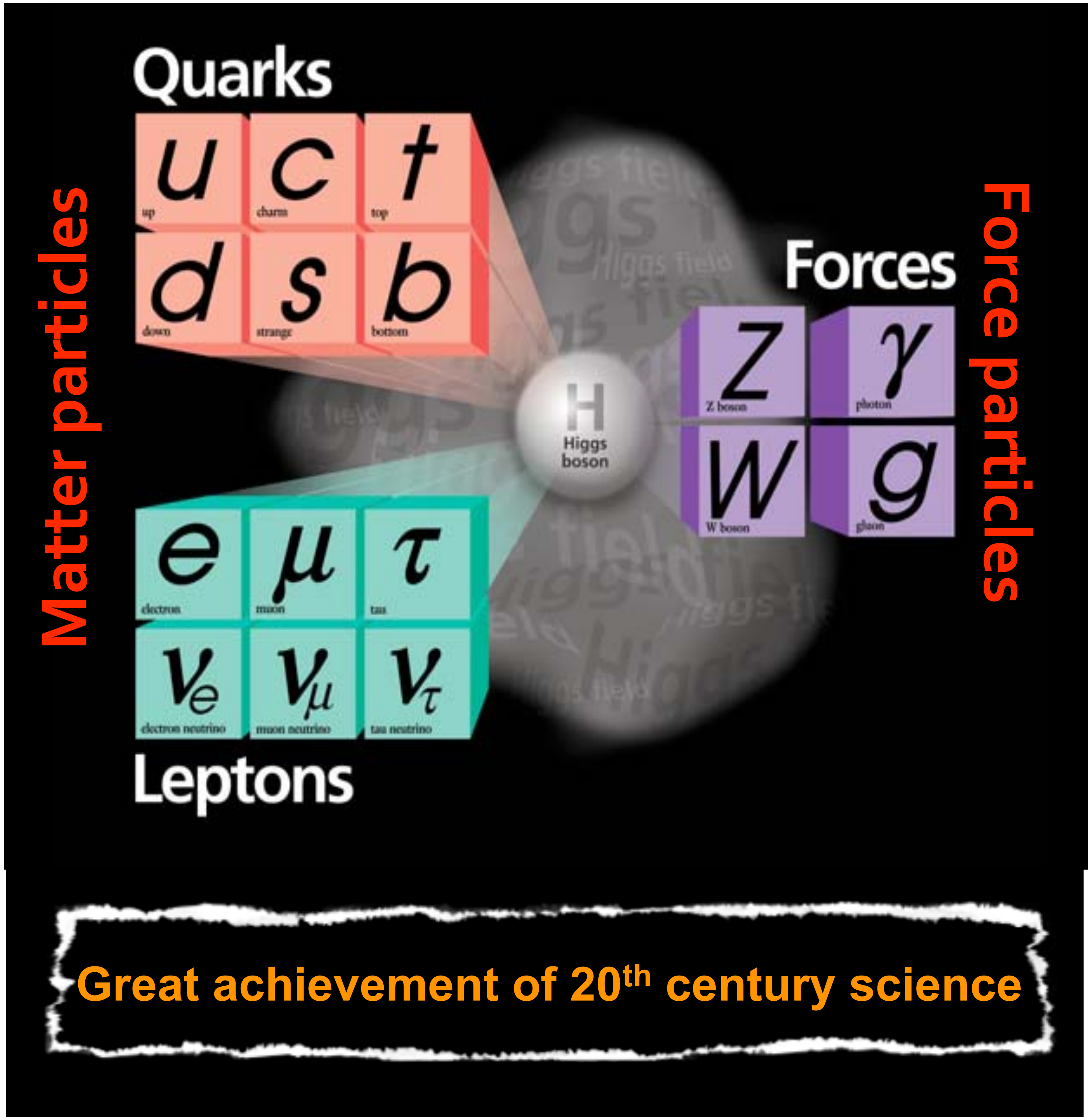
LHCb

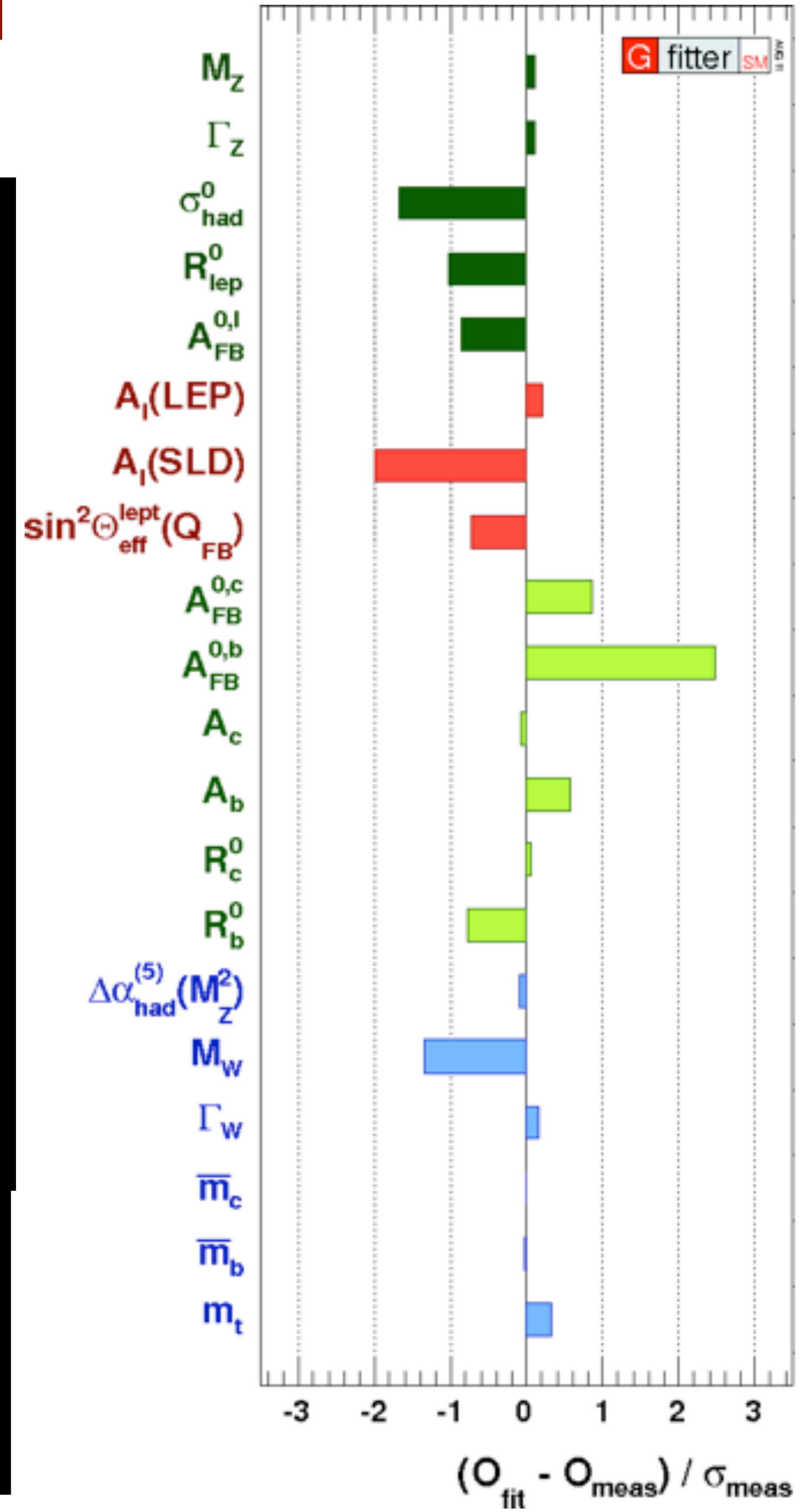


ALICE



the standard model





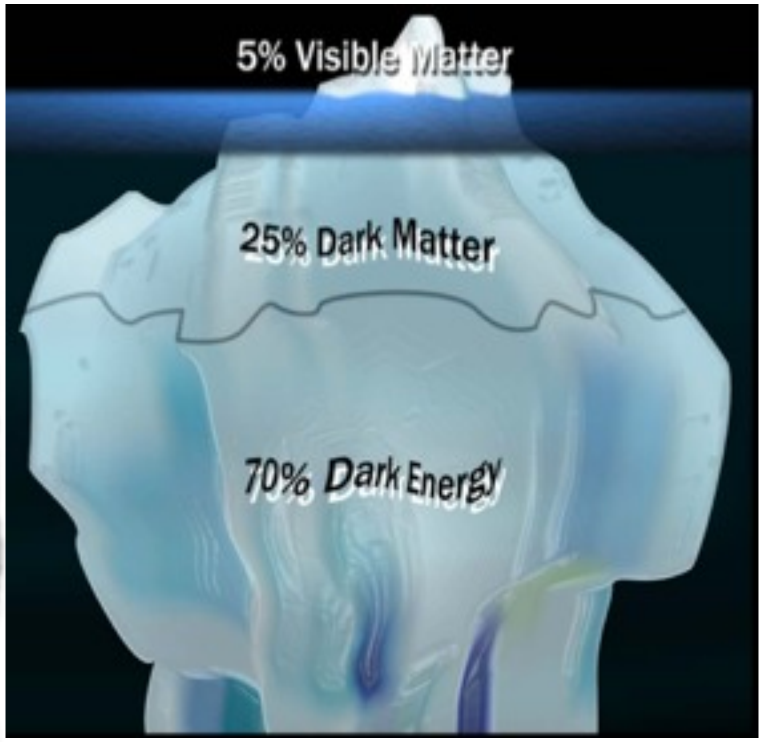
going beyond the SM

➡ The official list of big questions:

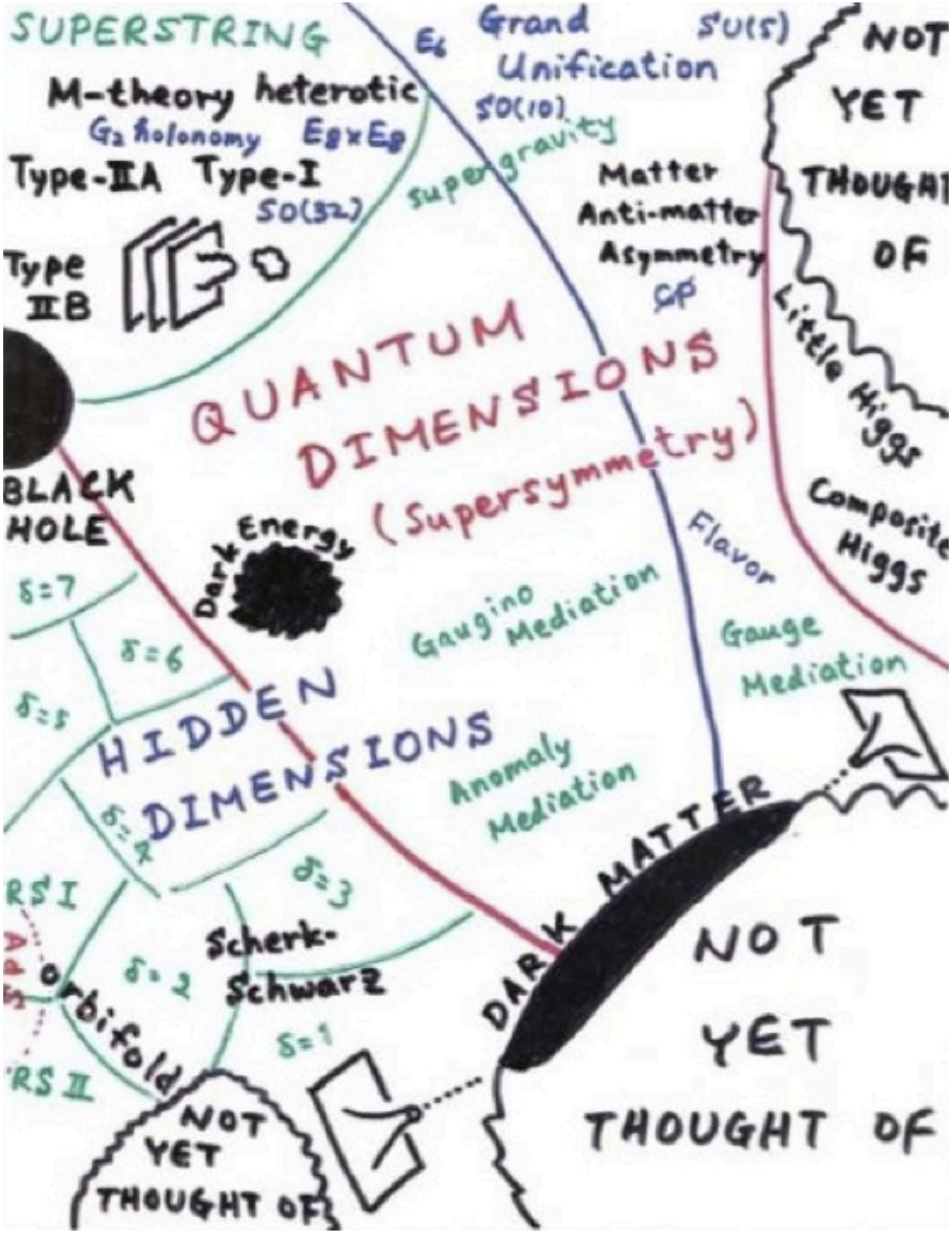
0. What is the origin of mass for fundamental particles?
1. Are there undiscovered principles of nature: new symmetries new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

Based on “The Quantum Universe,” HEPAP 2004

What we know: just the tip of the iceberg



“This is probably *not* the right list of big questions”

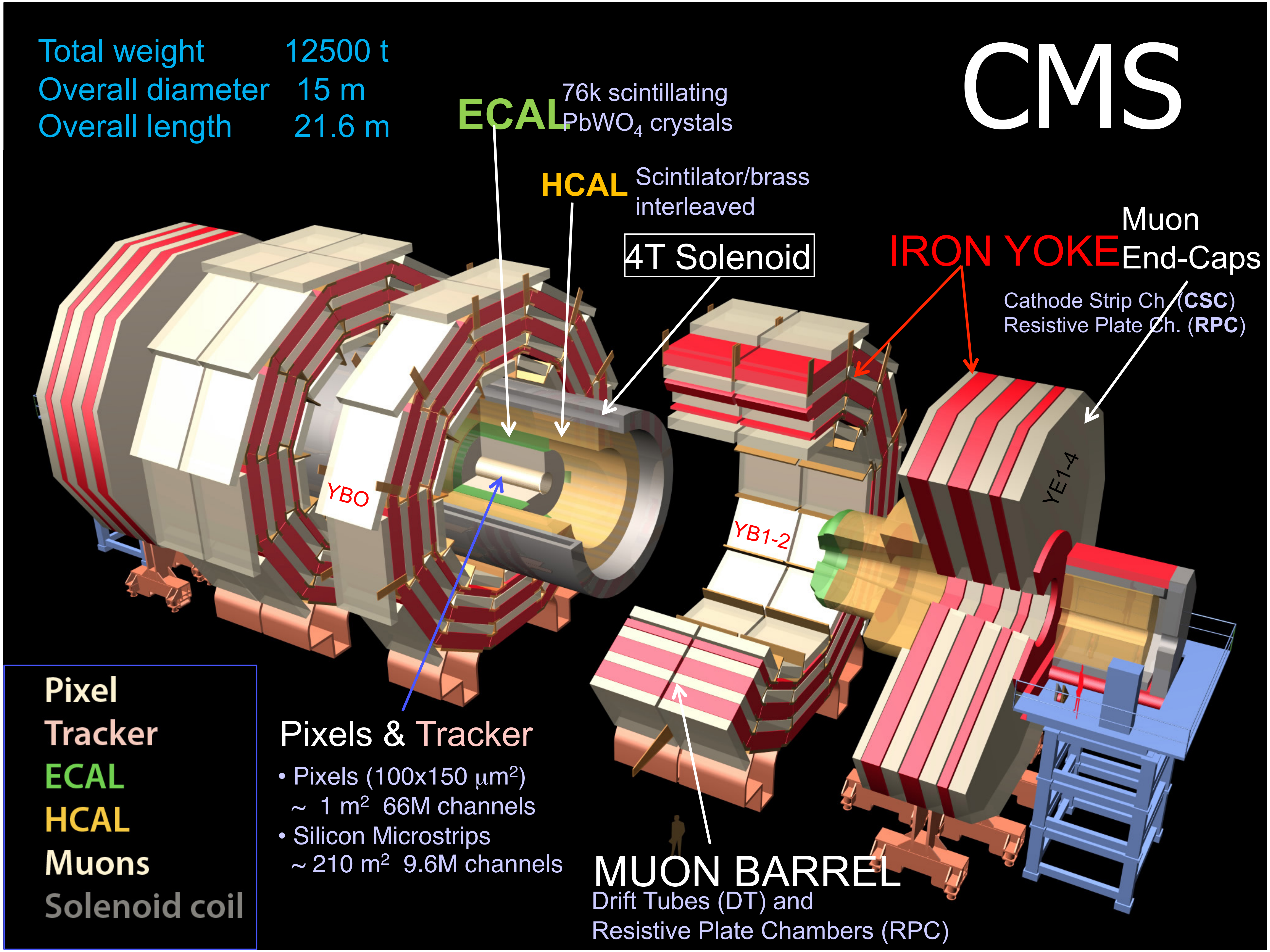


going beyond the standard model

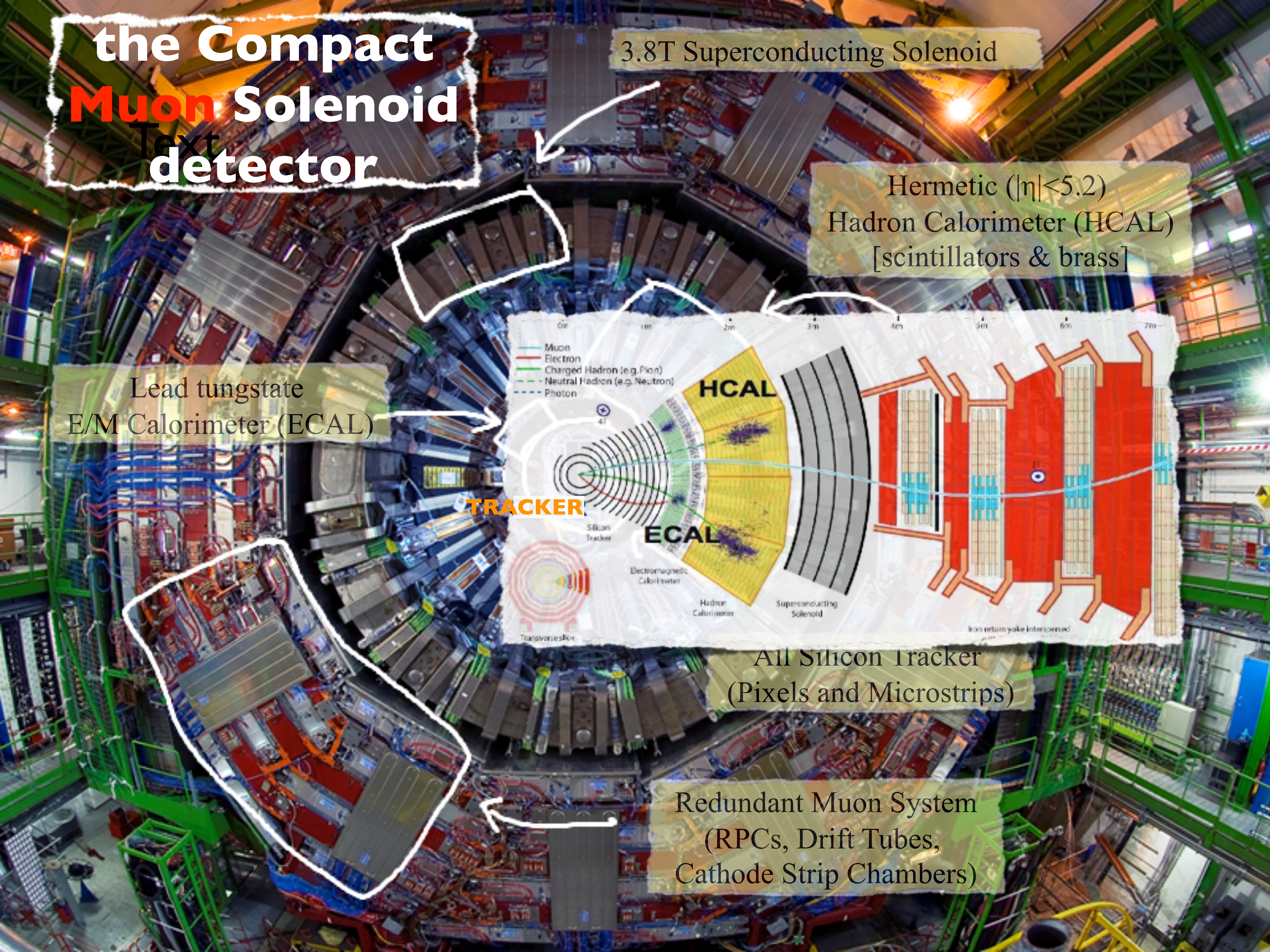
(some popular theory conjectures)

plan of action

- calibrate the detectors, understand the data
  - hardware and physics commissioning of the experiment
- measure '*known*' processes
  - explore extended LHC-accessible phase space
- search for new effects
  - find deviations from expectations
  - directly look for new phenomena, guidance from exp. signals/signatures
- explore properties of the dense medium in heavy-ion collisions
  - use pp as reference



Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
ECAL
76k scintillating PbWO$_4$ crystals
HCAL
Scintilator/brass interleaved
4T Solenoid
IRON YOKE
Muon End-Caps
Cathode Strip Ch. (CSC)
Resistive Plate Ch. (RPC)
YBO
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 66M channels
• Silicon Microstrips
~ 210 m^2 9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

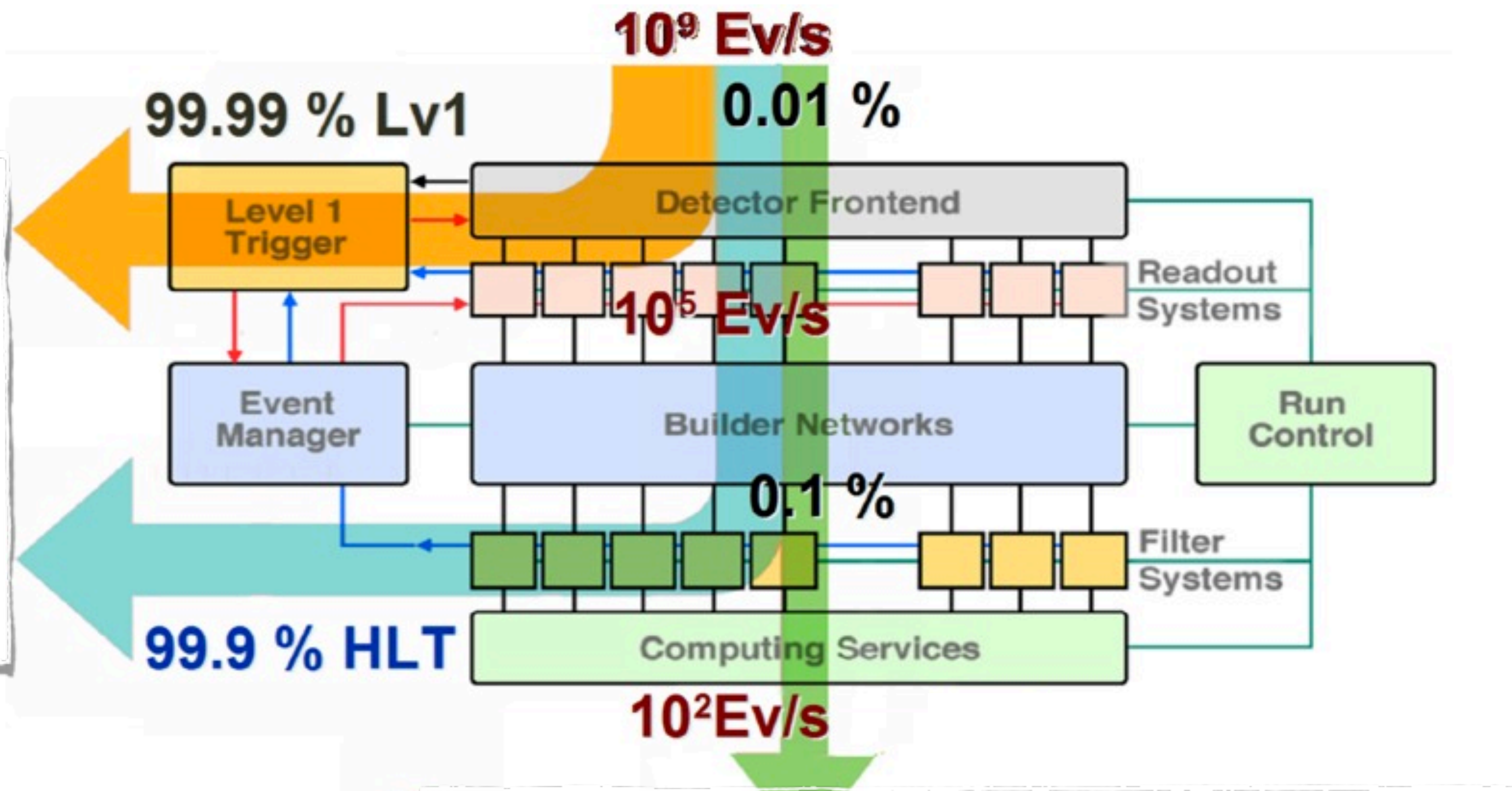


the Compact Muon Solenoid detector
Text
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
Lead tungstate
E/M Calorimeter (ECAL)
TRACKER
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)
0m
1m
2m
3m
4m
5m
6m
7m
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
HCAL
ECAL
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed
Transverse slice

trigger: real-time event selection

events
are
discarded
online

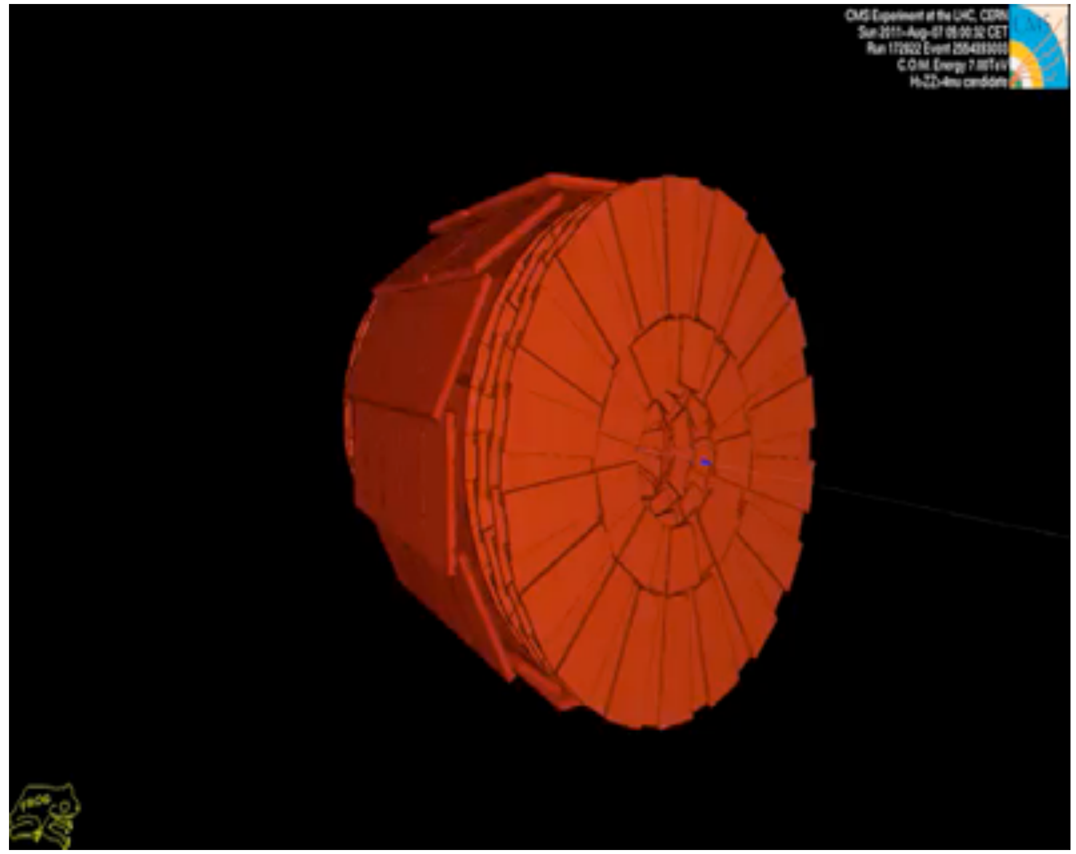
irreversibly



events saved for detailed offline analysis

trigger:

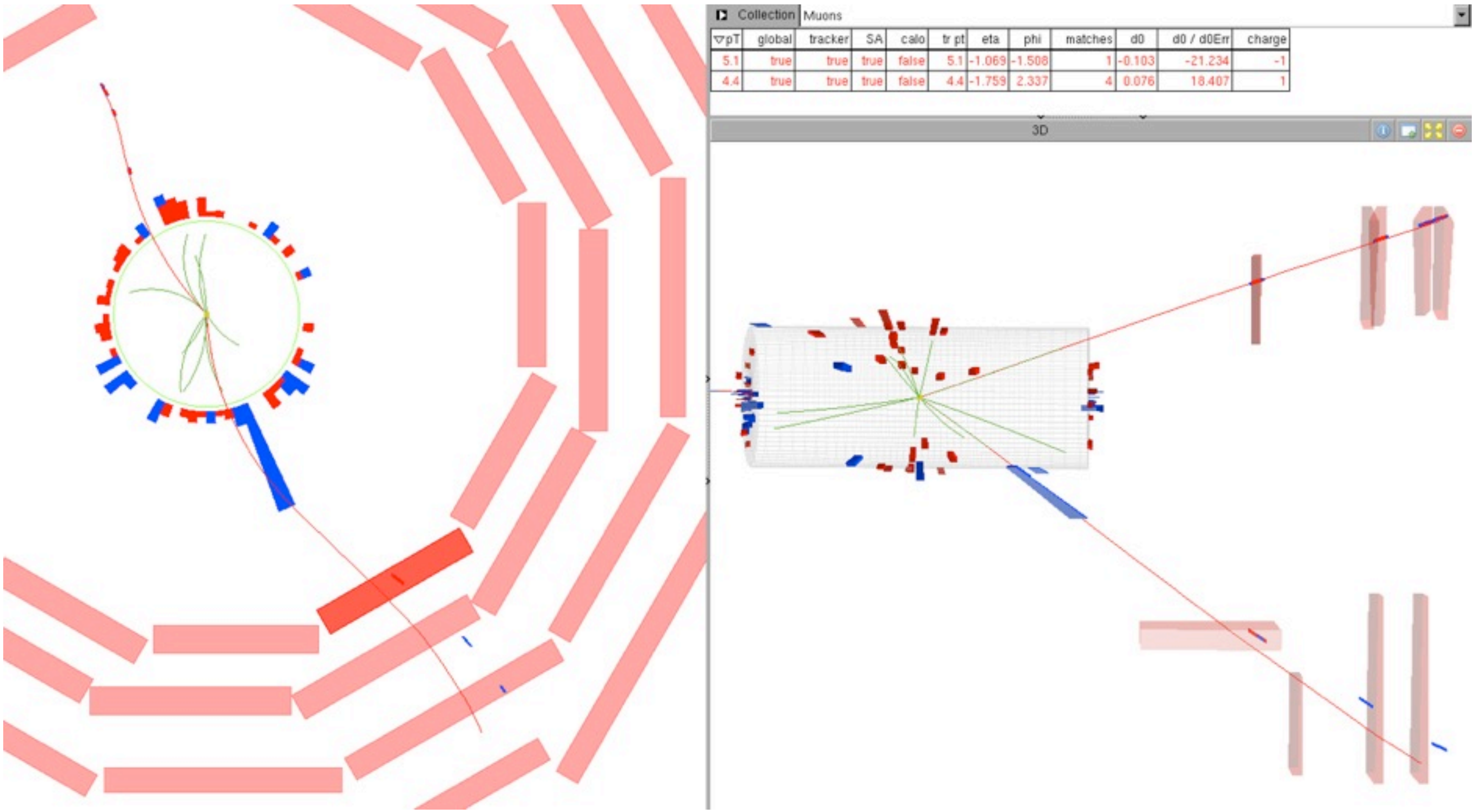
- the first determining stage of any physics analysis
- the single most important item in hadron colliders



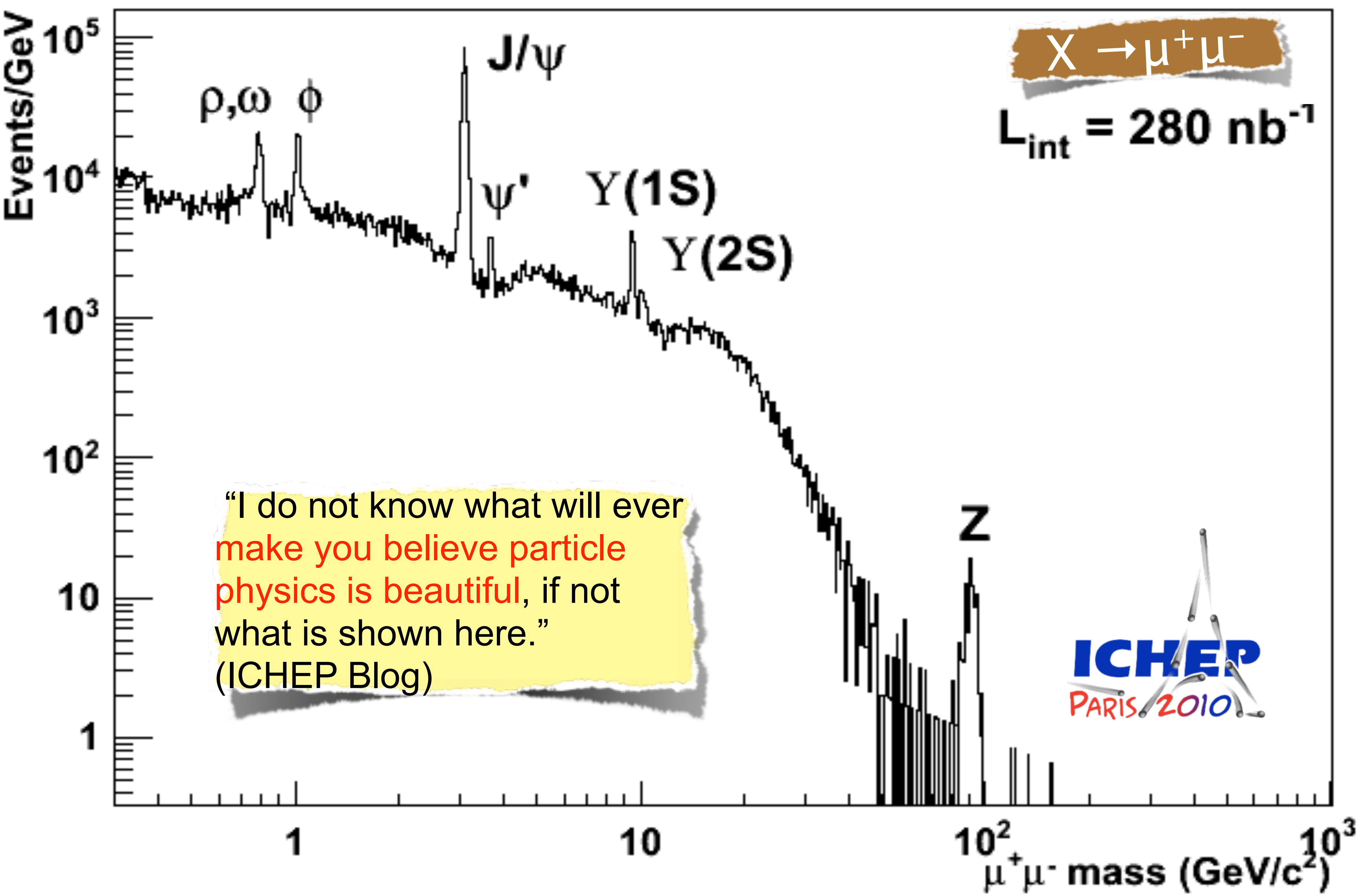
pp collisions
(@ $\sqrt{s}$=7-8 TeV)

a dimuon candidate: $X \to \mu^+\mu^-$

event display

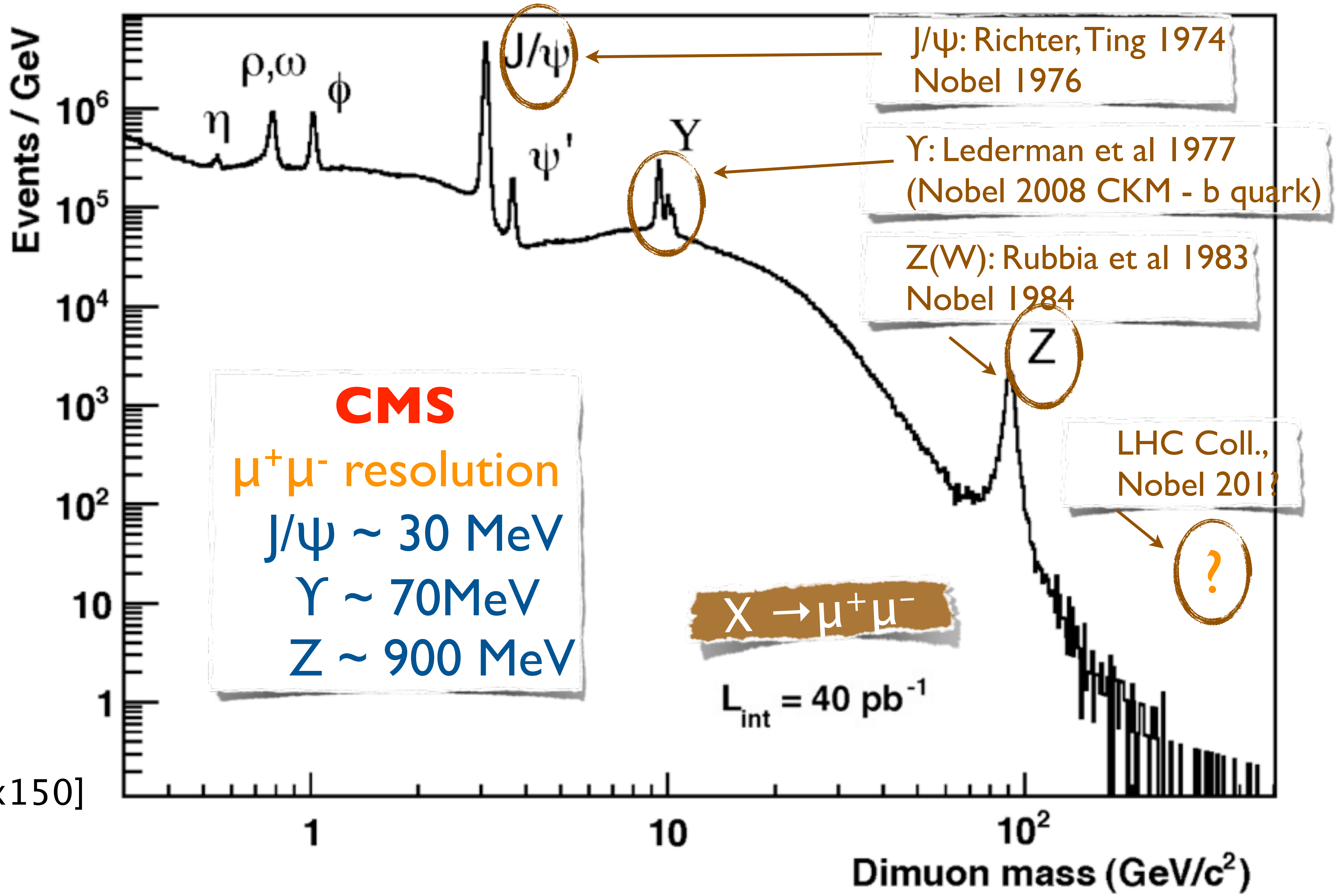


re-discovering the benchmarks of the standard model



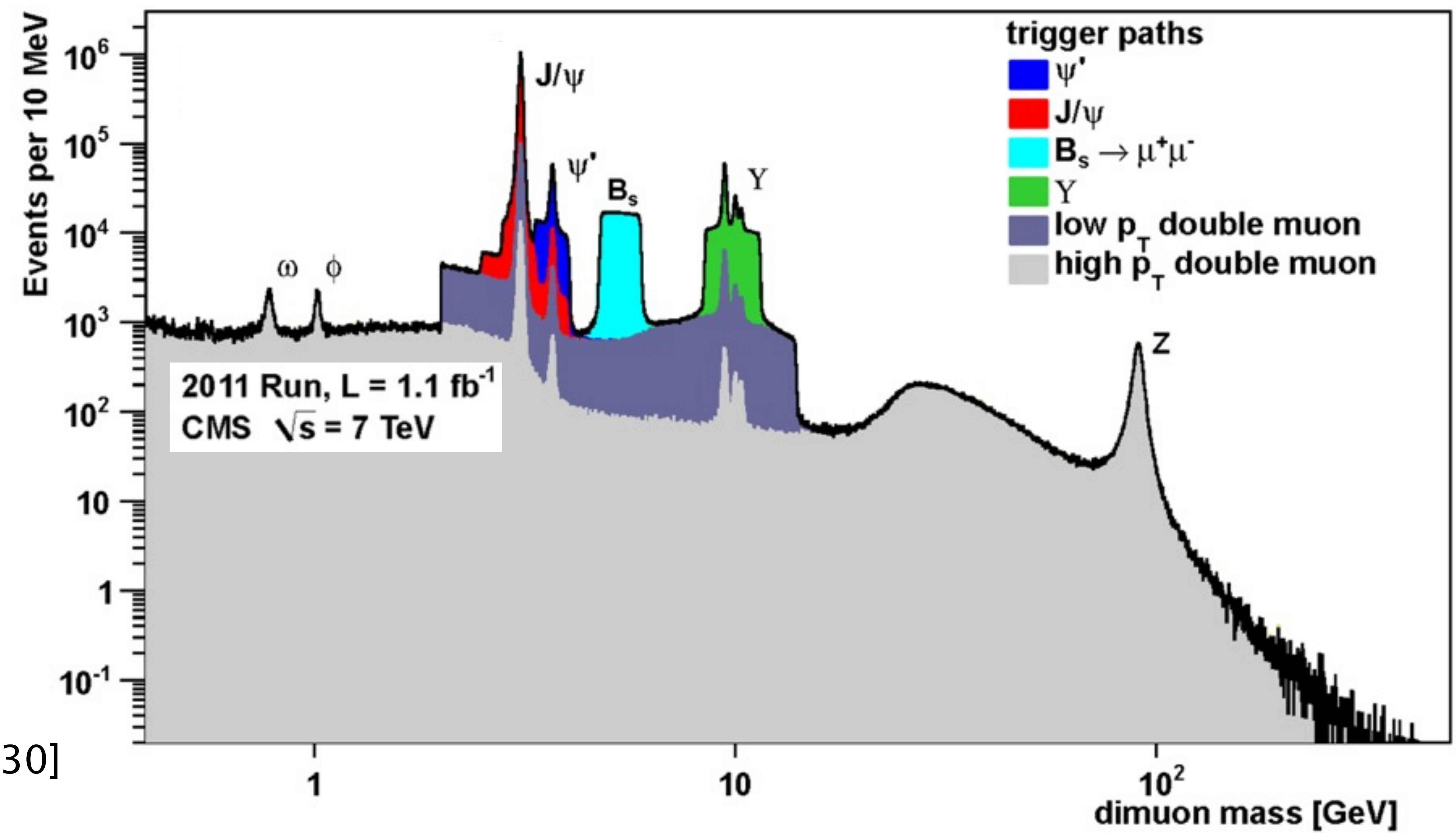
"I do not know what will ever make you believe particle physics is beautiful, if not what is shown here."
(ICHEP Blog)

re-discovering the benchmarks of the standard model



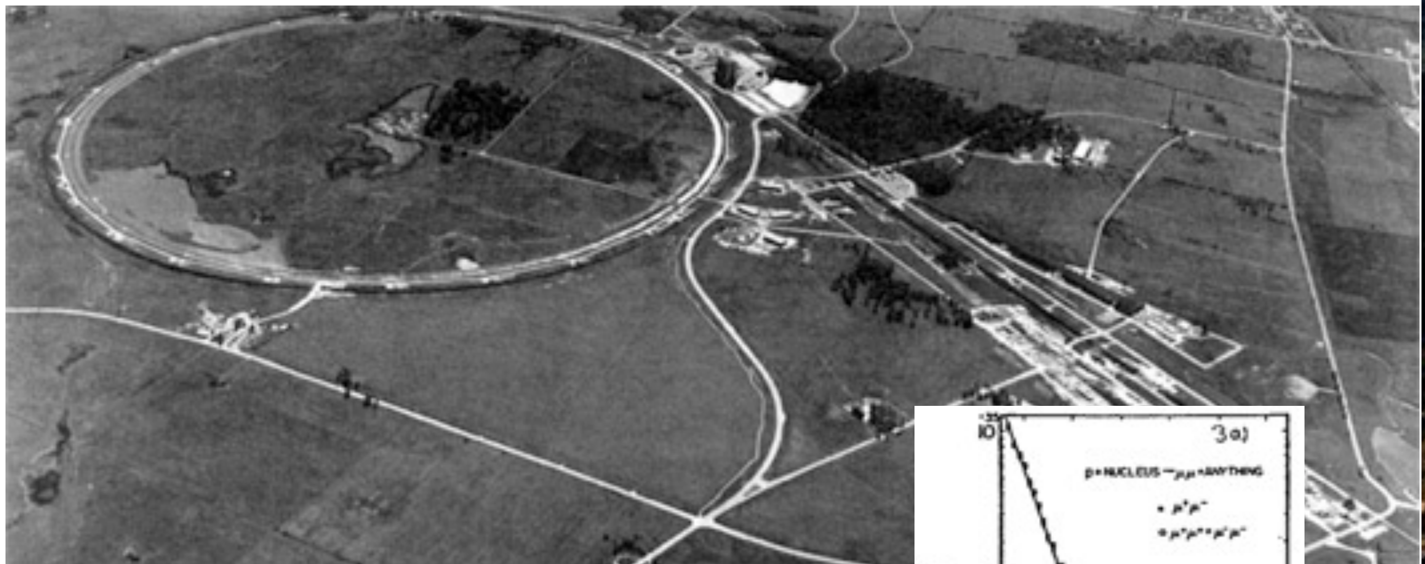
[x150]

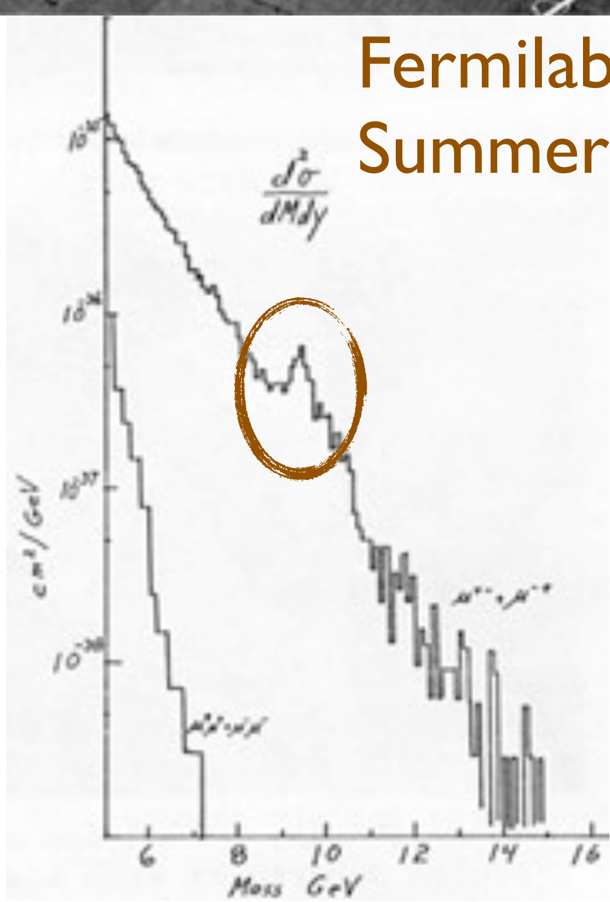
re-discovering the benchmarks of the standard model: going beyond



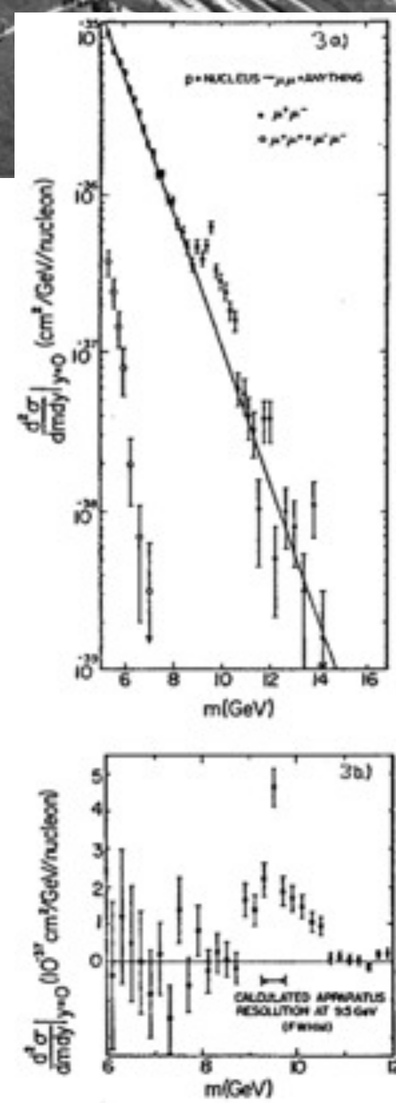
[x30]

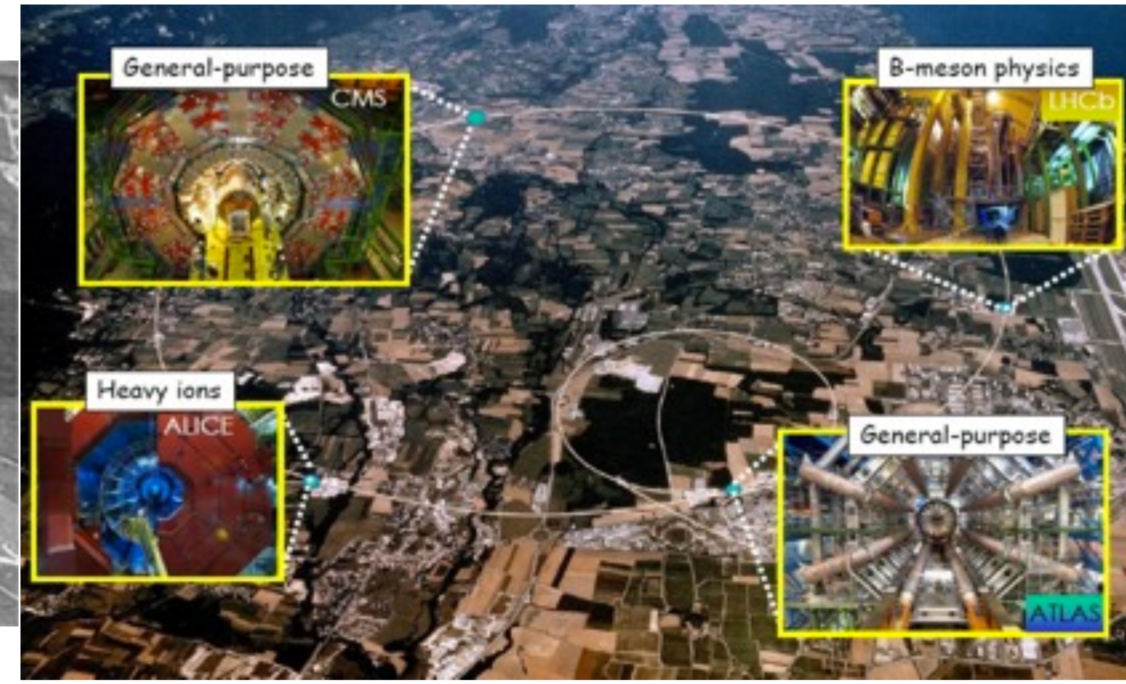
Upsilons: then... & now



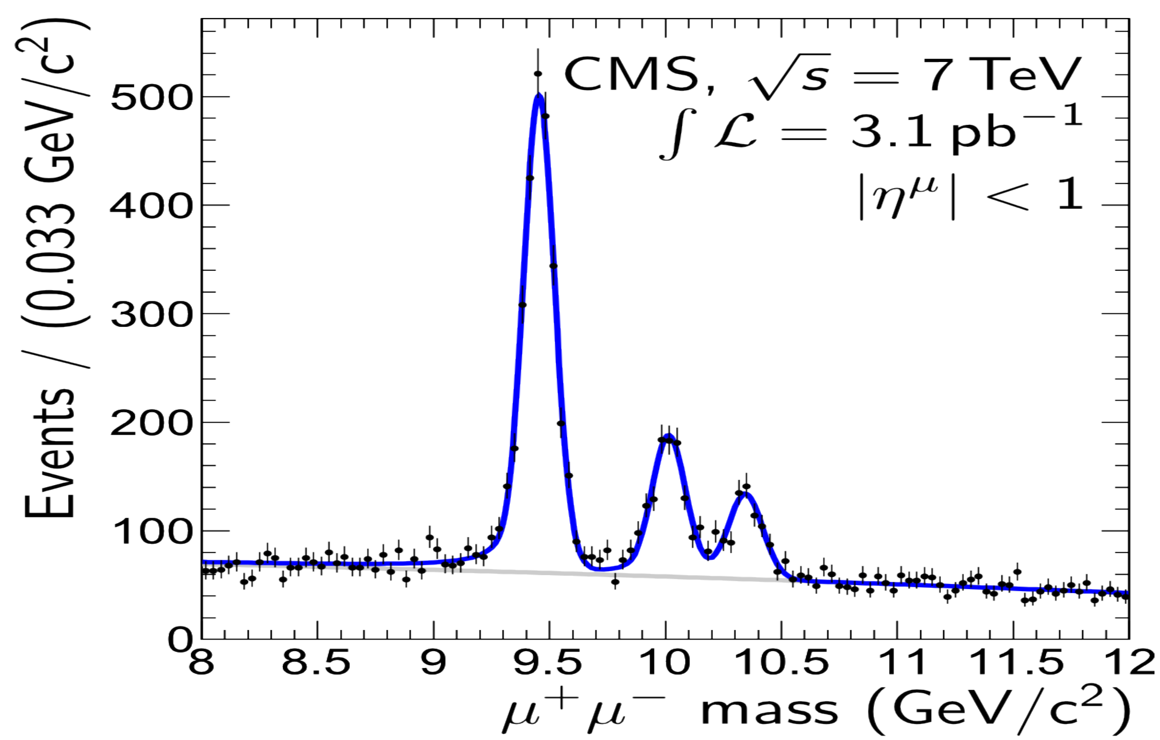


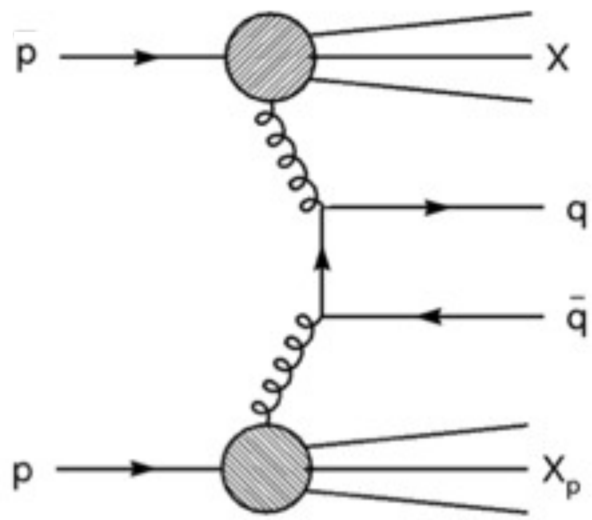
Fermilab
Summer 1977



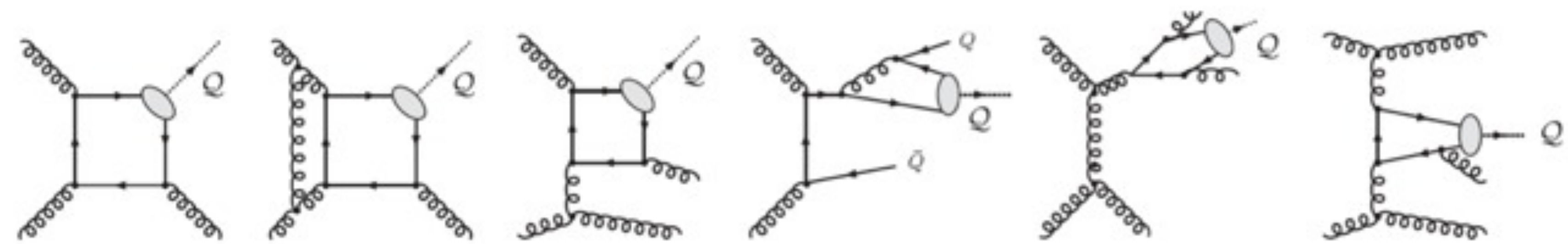


CERN, Summer 2010

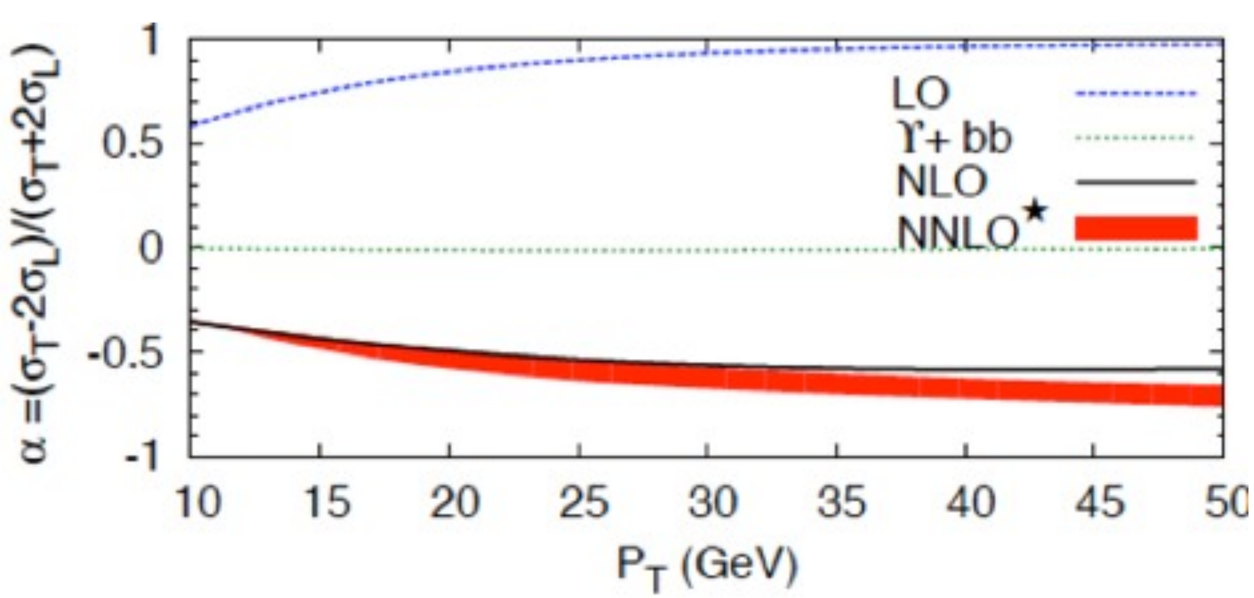


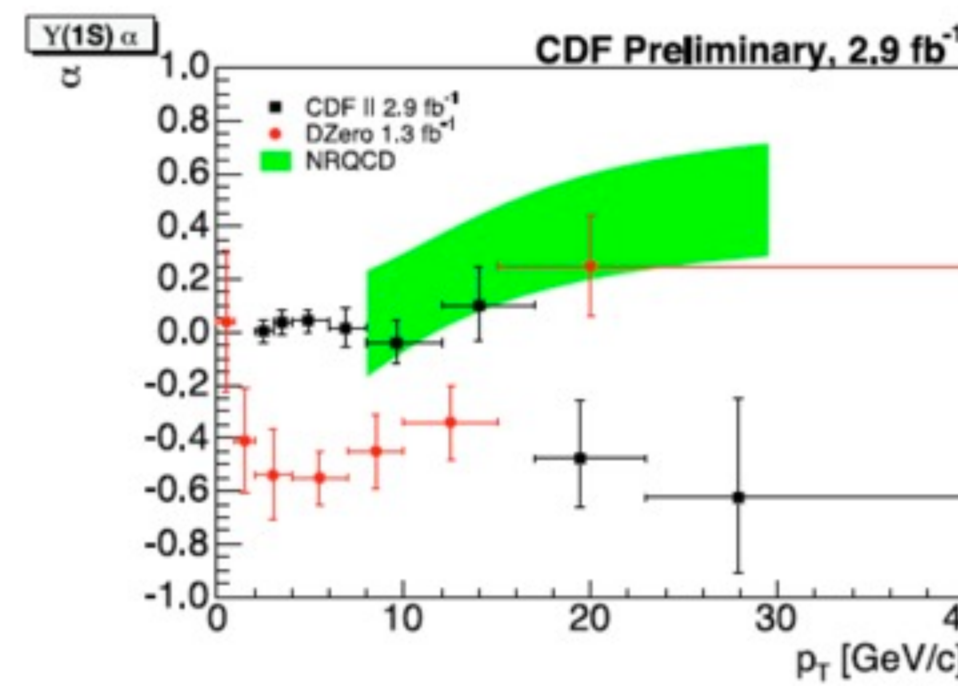


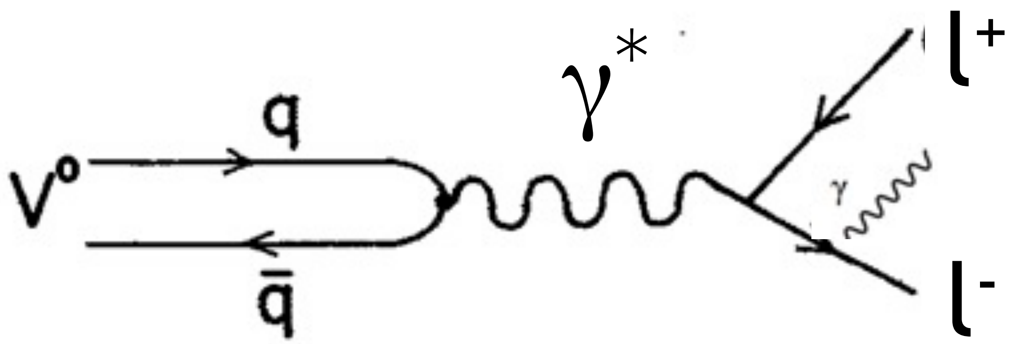
quarkonium production



- heavy quarkonia is a suitable laboratory for understanding the strong force / QCD
  - short-distance/perturbative vs long-distance, aka factorization
  - non-perturbative evolution of QQ into quarkonium: non-perturbative, effective theories (NRQCD, CSM, CEM...)
- production not satisfactorily understood -- theoretically and experimentally puzzling
  - no model is currently capable of describing both cross section and polarization

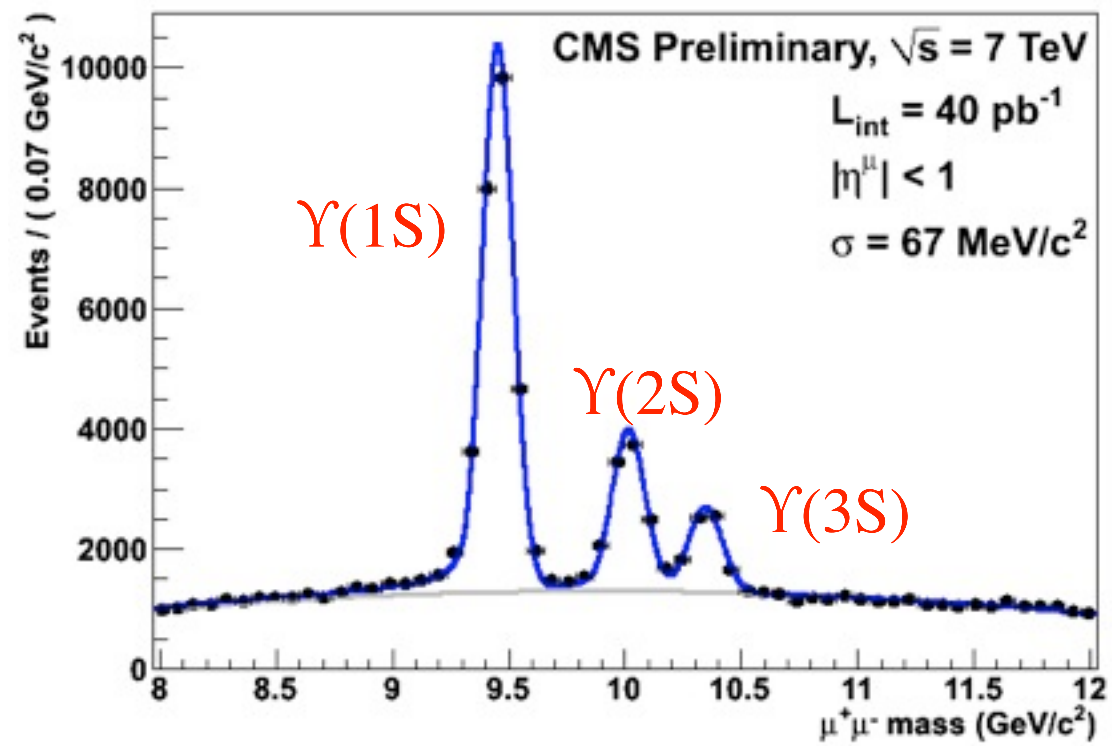




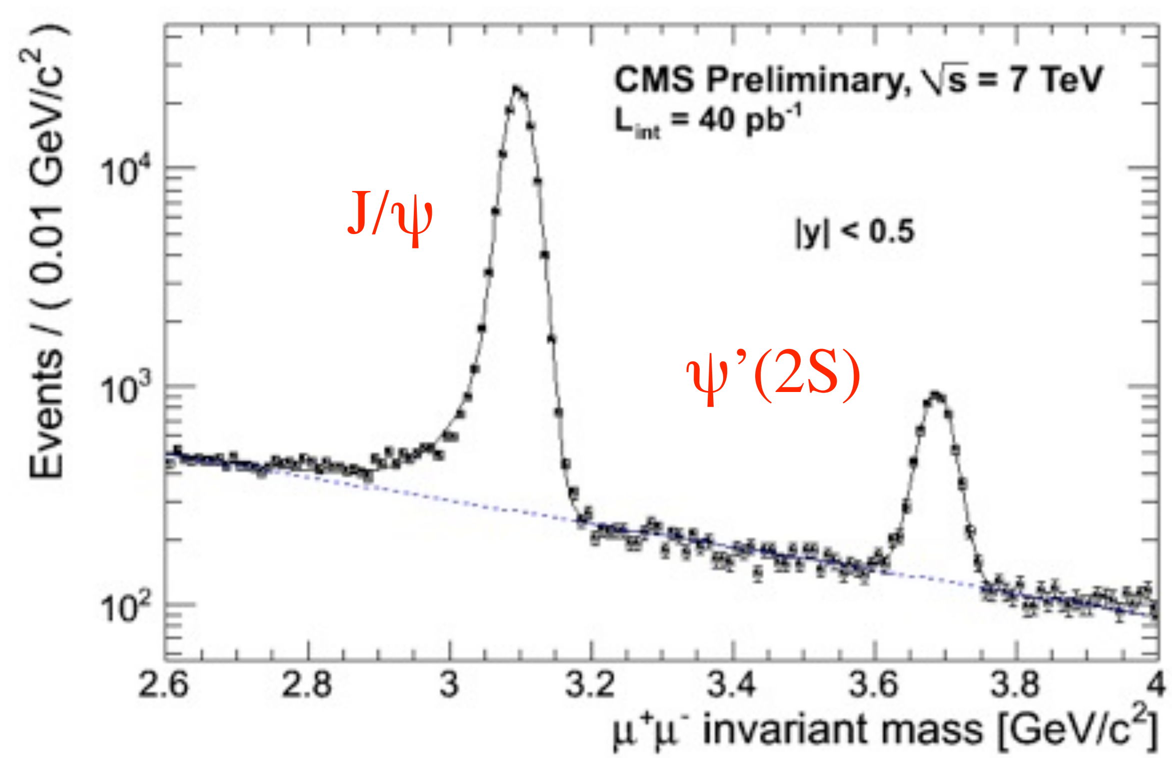


quarkonium decay

		$\to l^+l^-$	Γ	τ
ϒ	$b\underline{b}$	~2%	54 keV	1.21×10^{-20} s
J/ψ	$c\underline{c}$	~7%	93 keV	7.2×10^{-21} s



- standard model standard candles
- detector/trigger calibration tools
- and important steps to wisdom



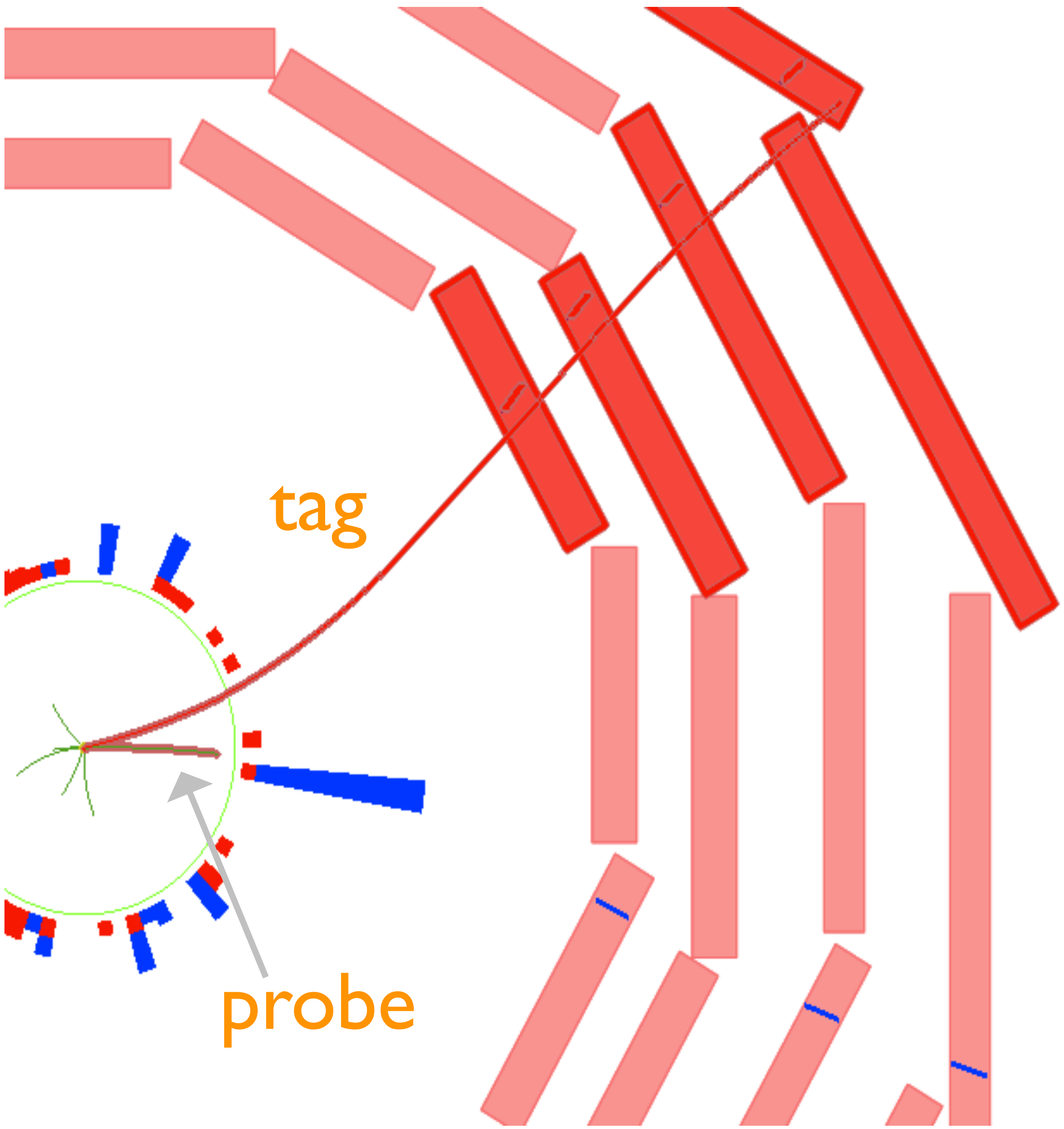
production cross section

$$\frac{d^2\sigma}{dp_T dy}(Q\bar{Q})BR(Q\bar{Q} \to \mu^+\mu^-) = \frac{N_{fit}(Q\bar{Q})}{\int Ldt \cdot A \cdot \epsilon \cdot \Delta p_T \Delta y}$$

- N: fitted signal yield
- A: detector acceptance from simulation
  - dependent on unknown production polarization
- ε: track, muon reconstruction and trigger efficiencies, from data-driven (T&P) methods
- L: integrated sample luminosity
  - Acceptance and efficiency corrections applied event-per-event or as bin averages 1/< A, ε>

tag & probe

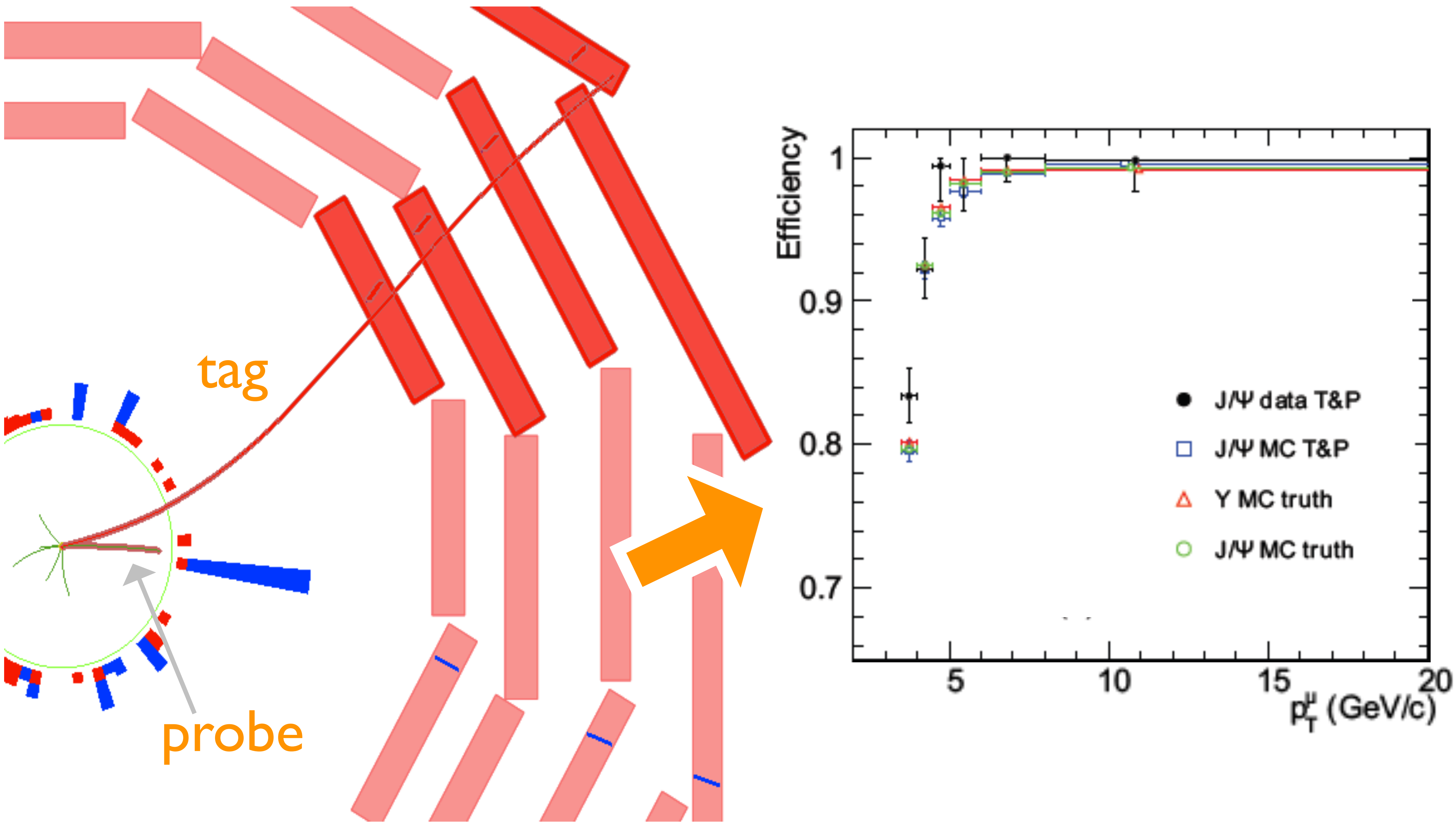
explore J/ψ, ϒ, Z→ μμ



- data driven method
- example:
  μ-identification efficiency
- data:
  - single muon dataset
- tag
  - good global muon
  - matched to single muon path to remove trigger bias
- probe
  - inner track
  - passing criteria: identified as muon

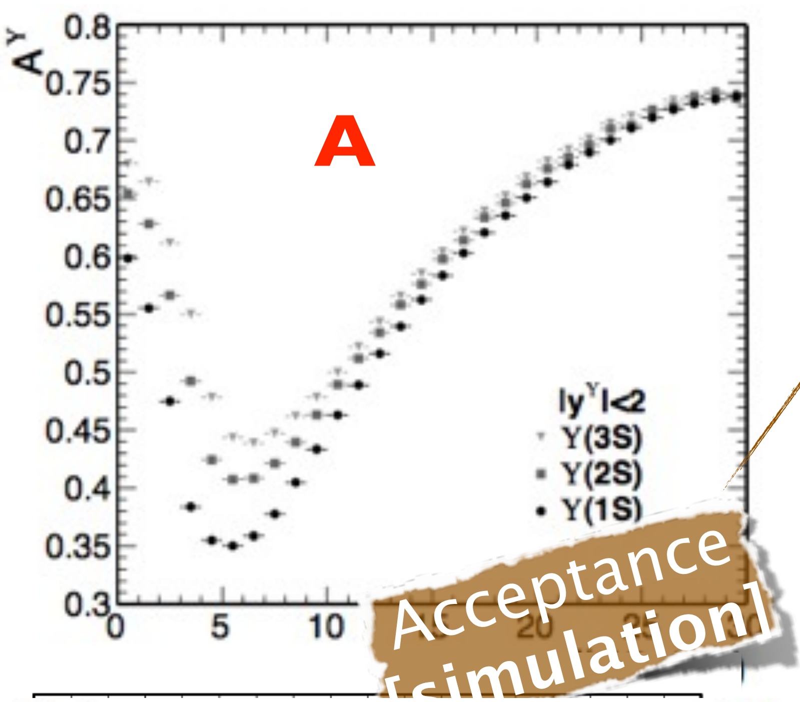
tag & probe

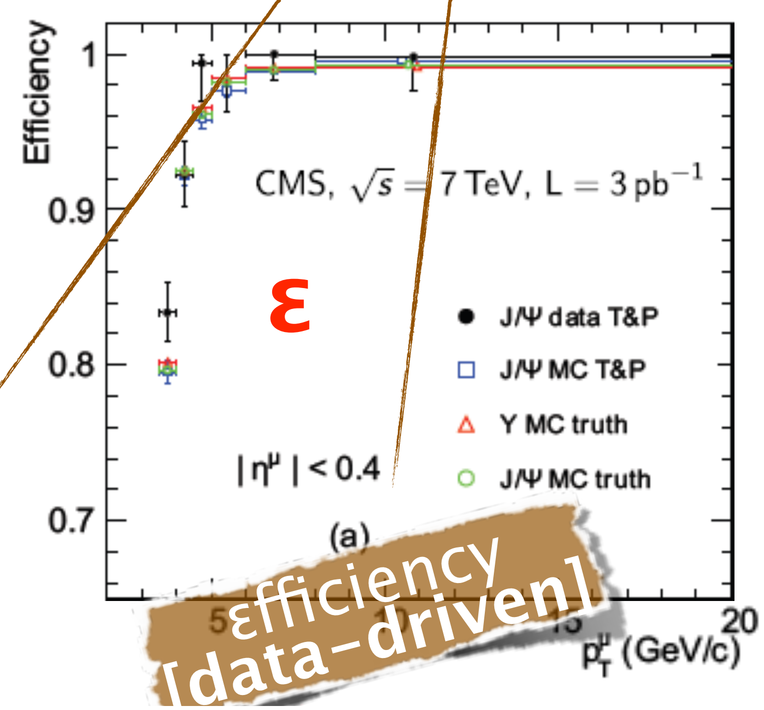
explore J/ψ, Υ, $Z \to \mu\mu$

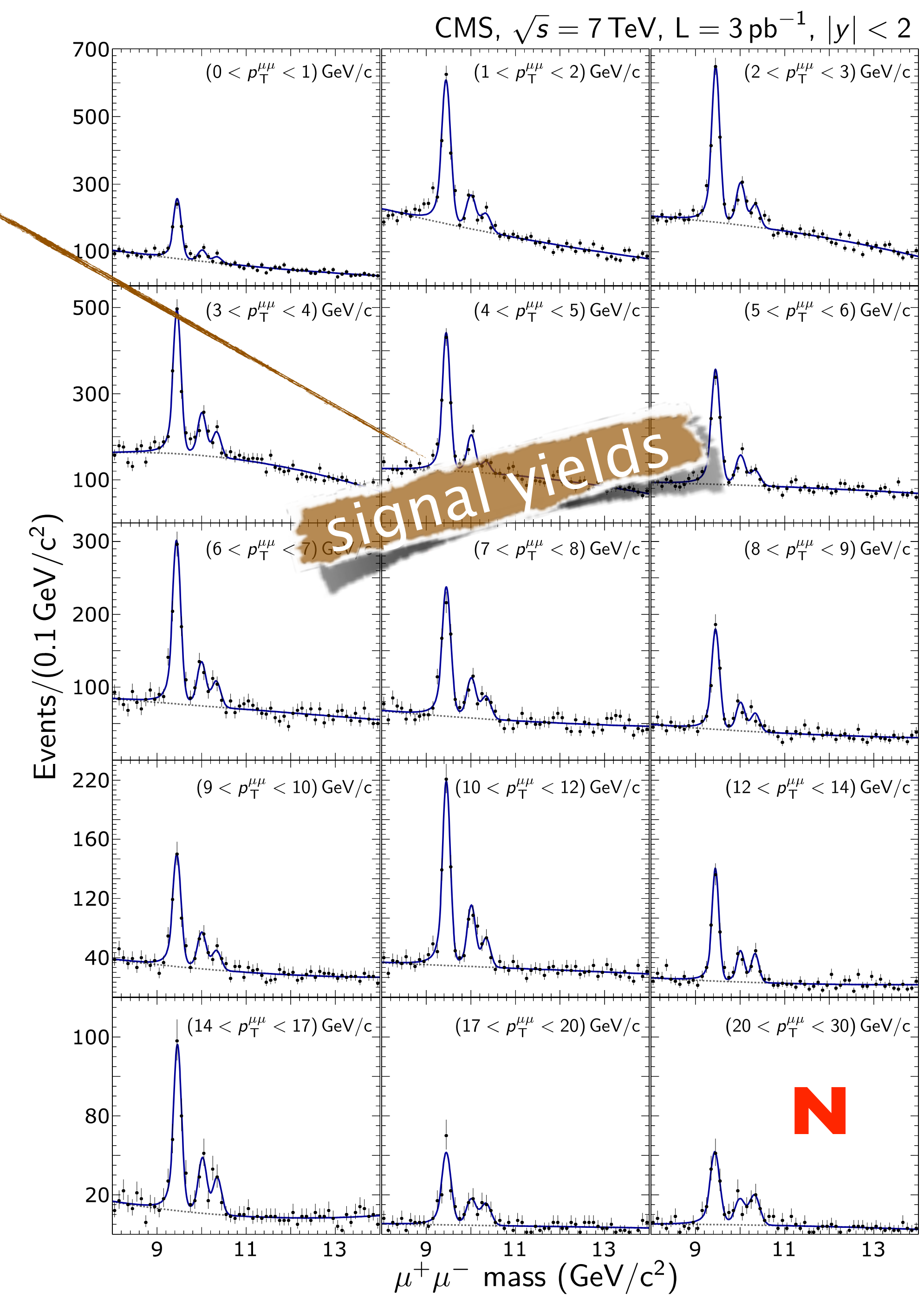


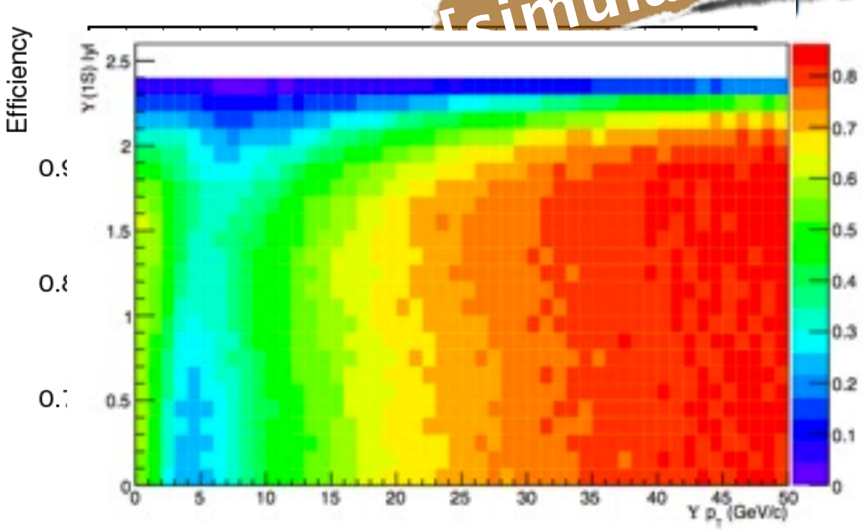
production cross section

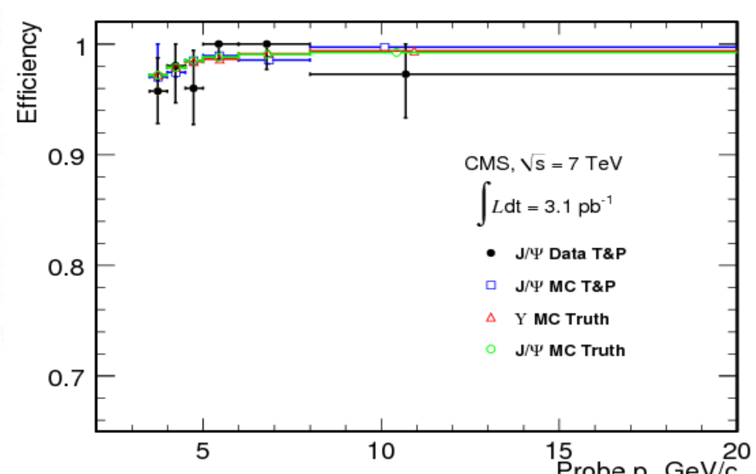
$$\frac{d^2\sigma}{dp_T dy}(Q\bar{Q})BR(Q\bar{Q} \to \mu^+\mu^-) = \frac{N_{fit}(Q\bar{Q})}{\int Ldt \cdot A \cdot \epsilon \cdot \Delta p_T \Delta y}$$



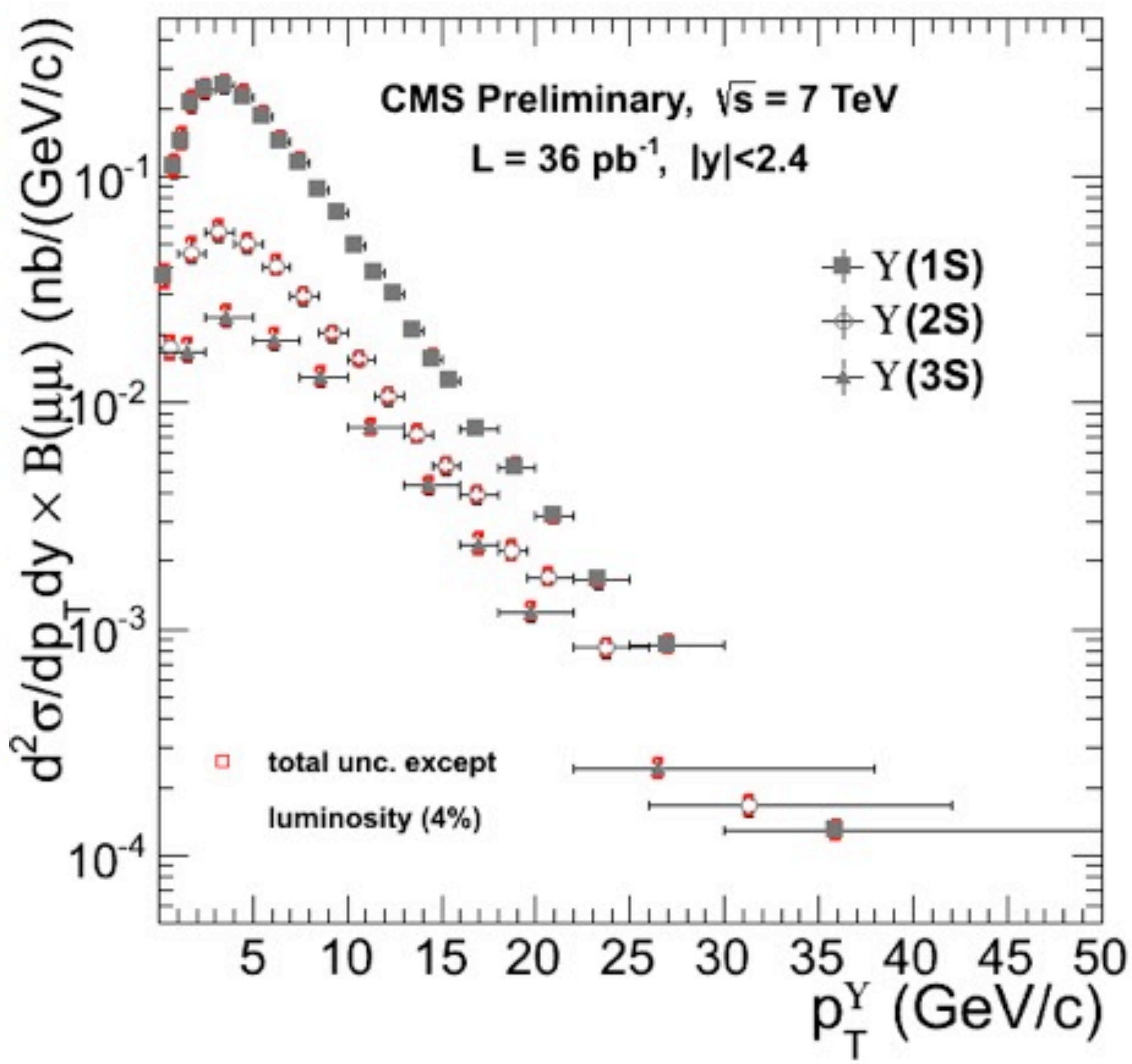


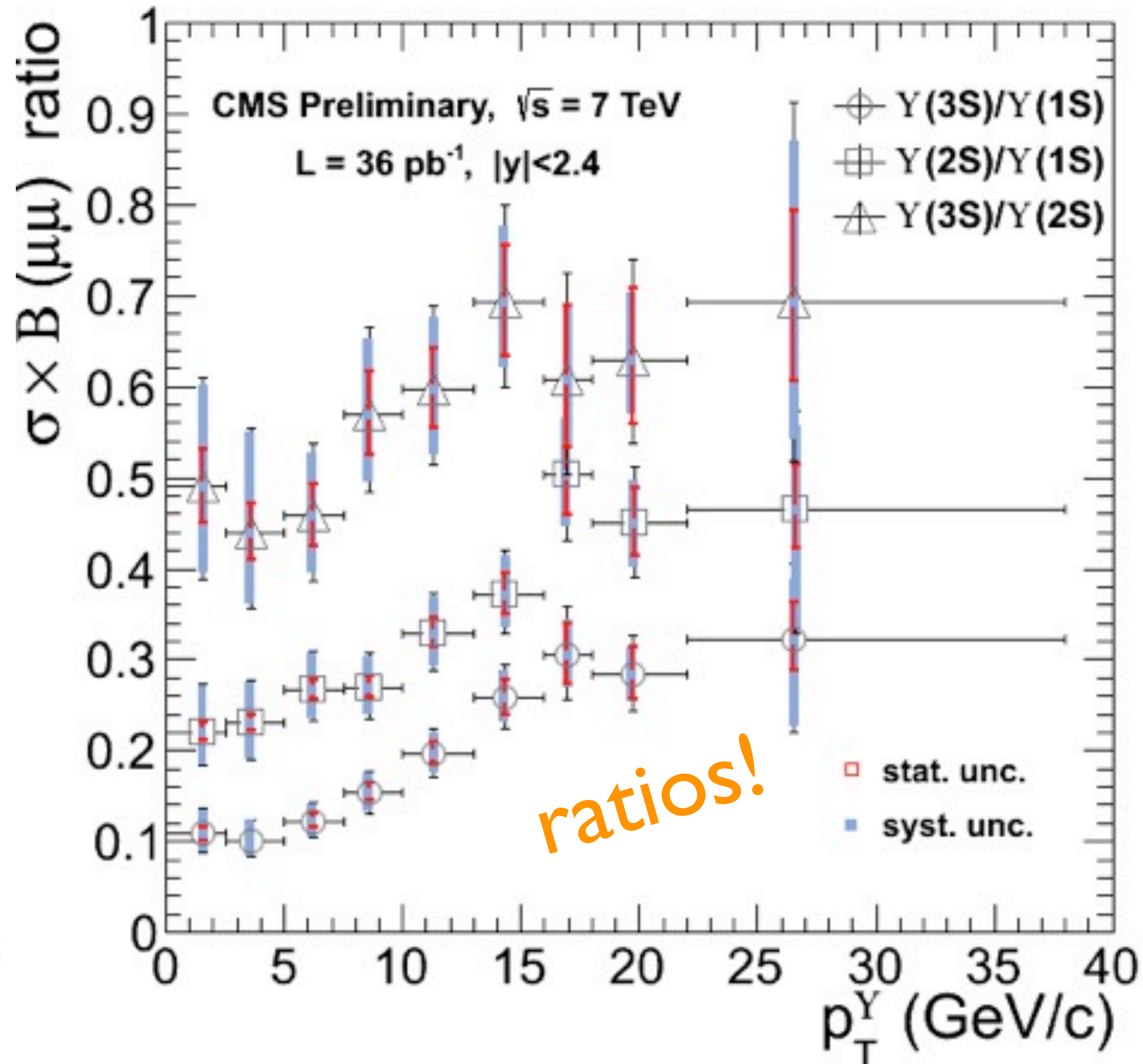






Υ(nS) differential cross sections

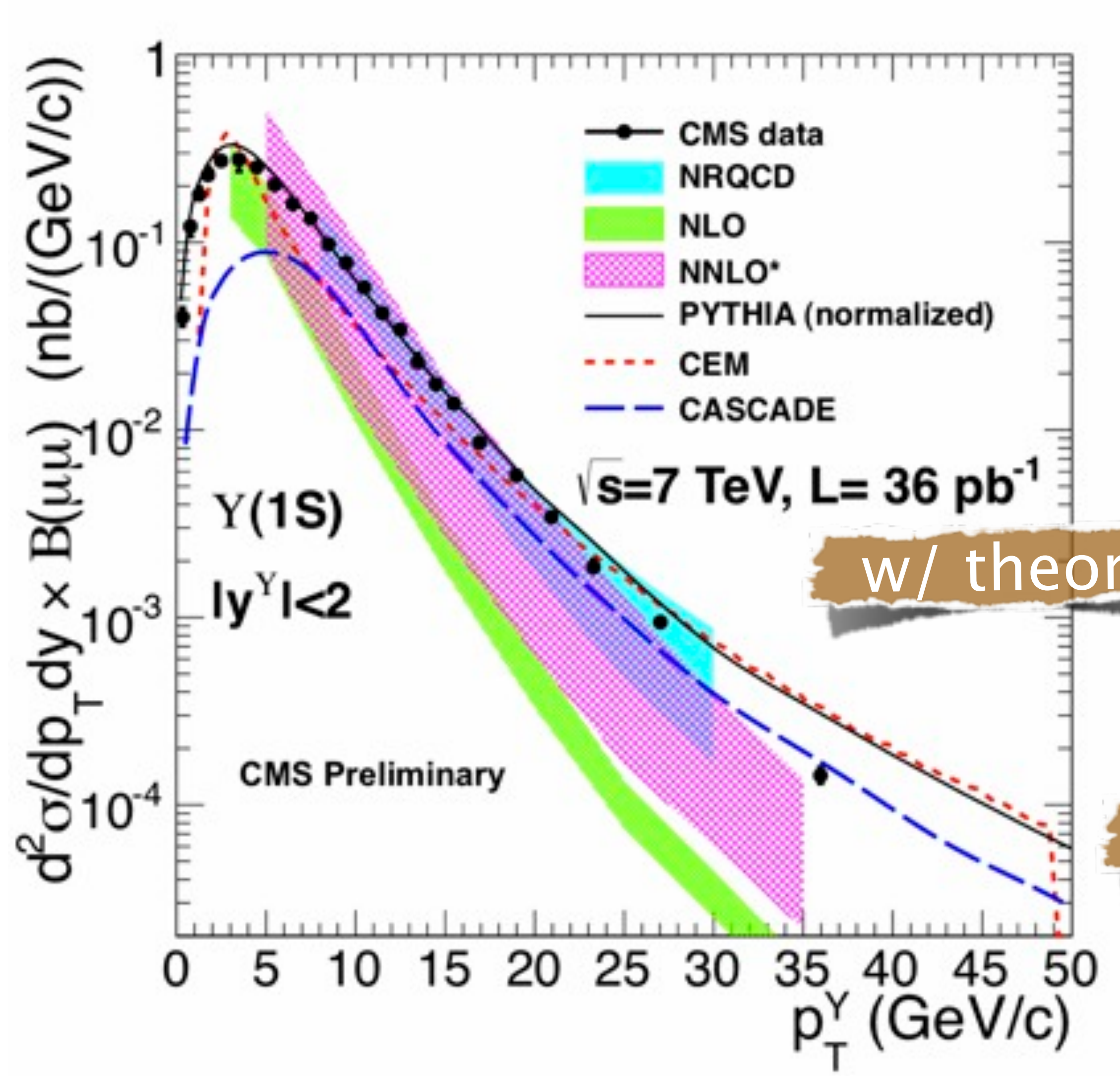




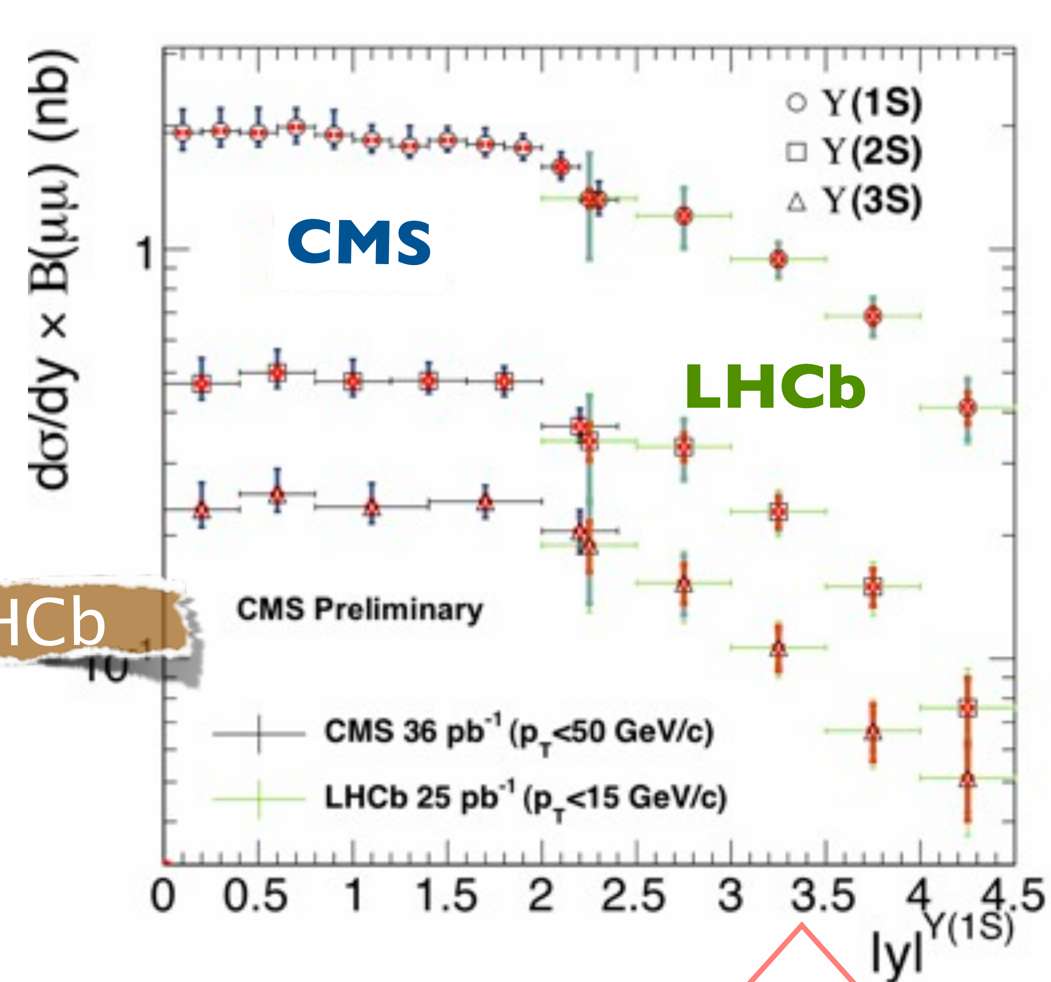
- 1st LHC Upsilon measurement
- 1st CMS paper to Phys Rev D
  arXiv:1012.5545v1
- shown recent update with 36/pb

- excited-to-ground state nS/1S cross-section ratios observed to increase with dimuon p_T

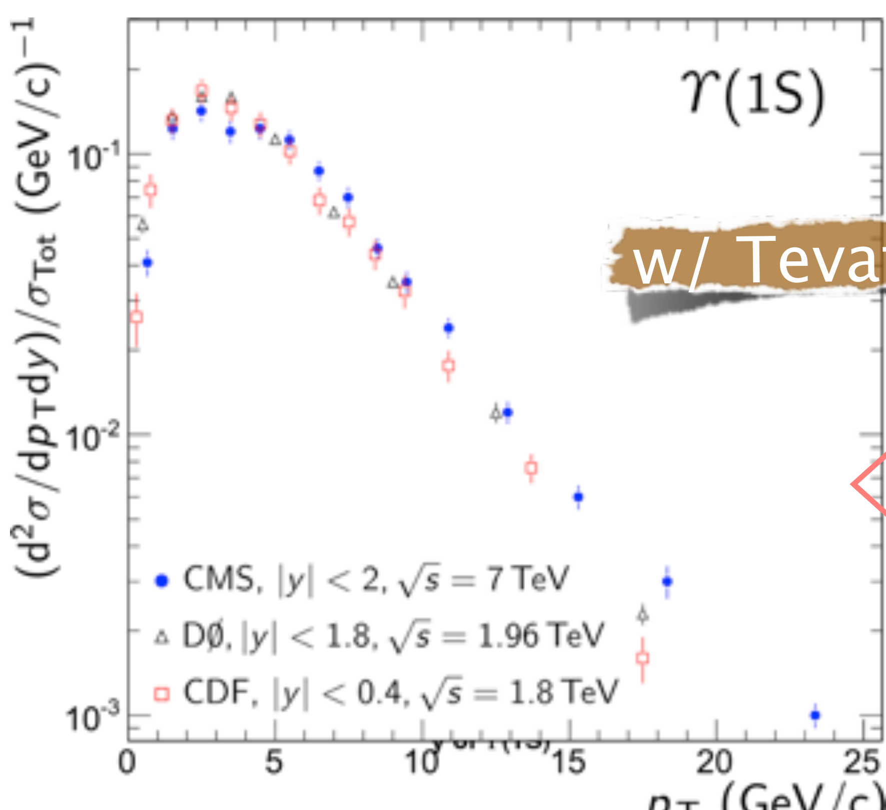
comparisons



w/ theory



w/LHCb

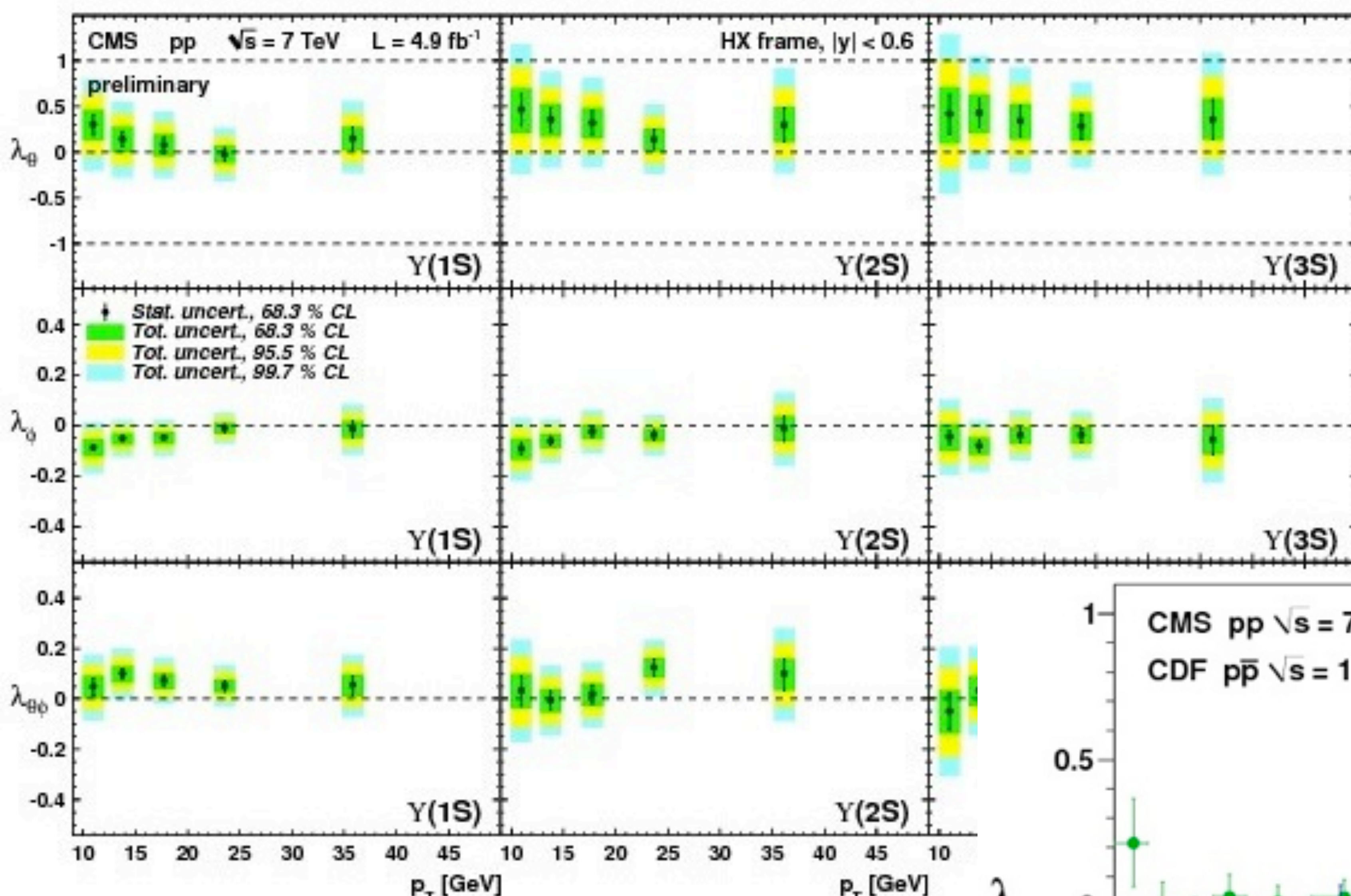


w/ Tevatron

complementary: kinematic coverage

complementarity: momentum reach
LHC cross section 3x larger than Tevatron, shape consistent

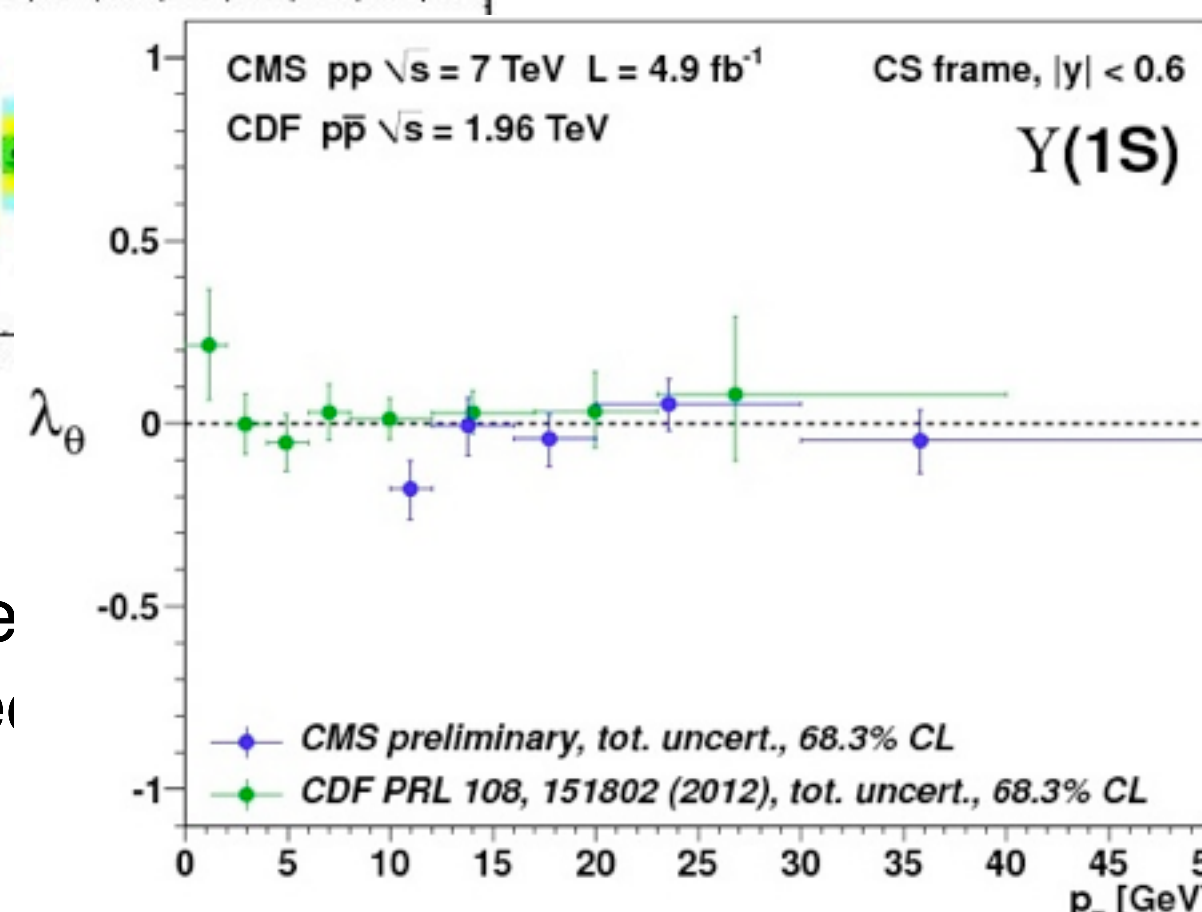
Υ(nS) spin alignment



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

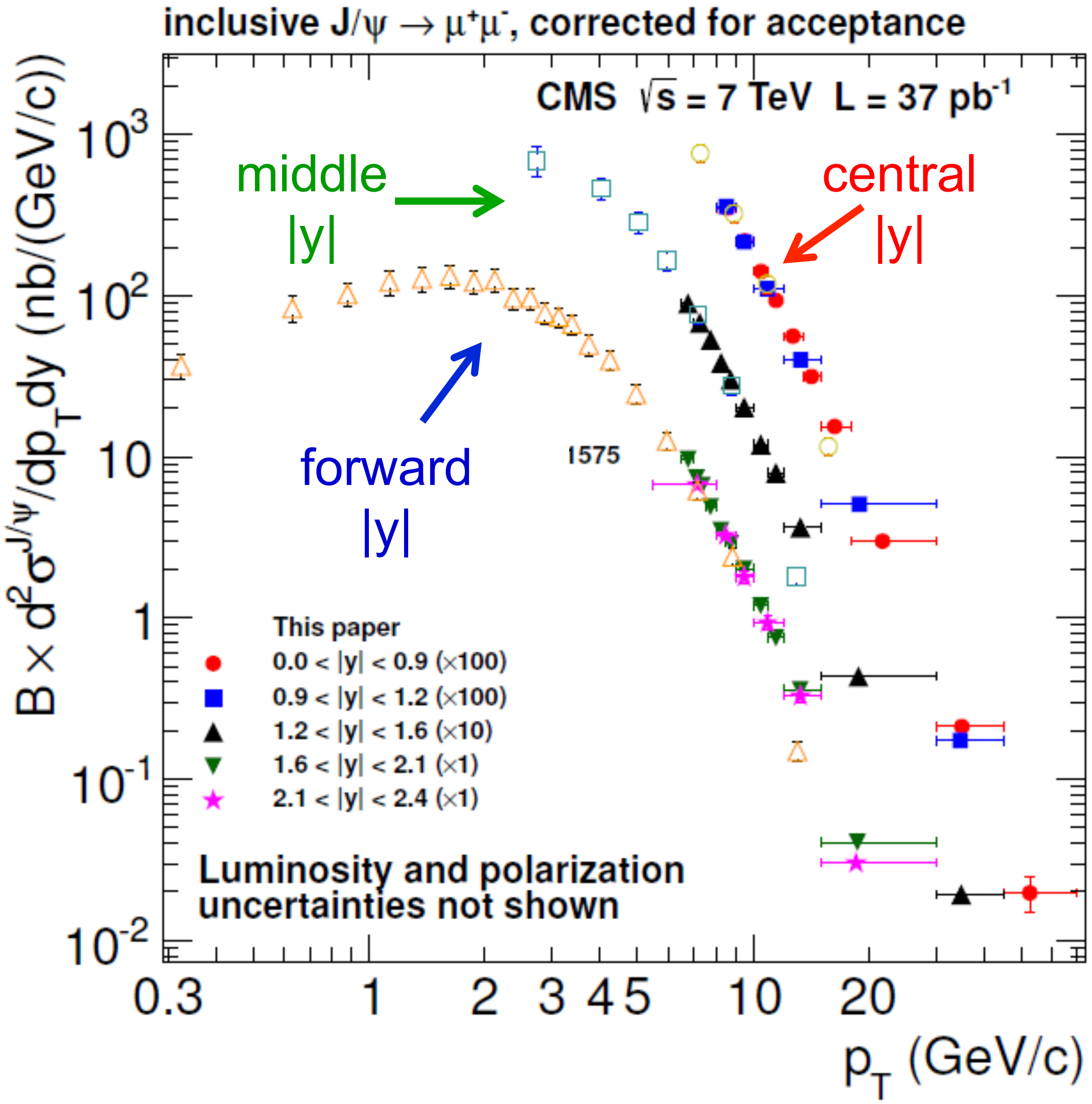
See earlier seminar by

P. Faccioli



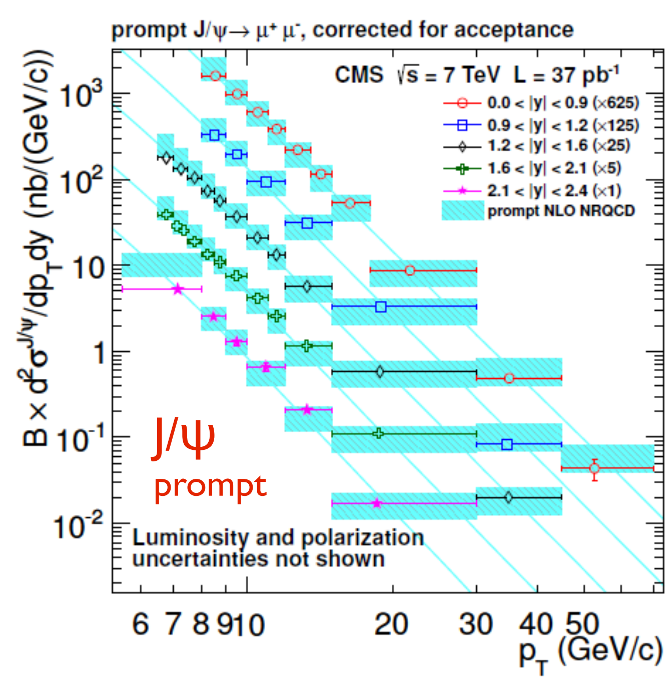
No strong polarizations, transverse or longitudinal, have been observe

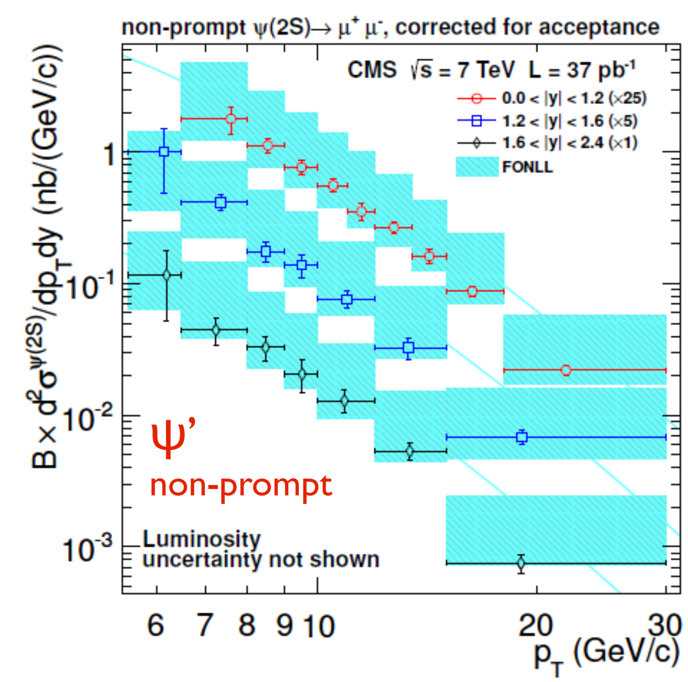
J/ψ cross section



- similar analysis strategy as employed for the Υ(nS) is applied for the J/ψ and ψ'
  - dominant systematics from efficiency measurement, dimuon correlations and polarization

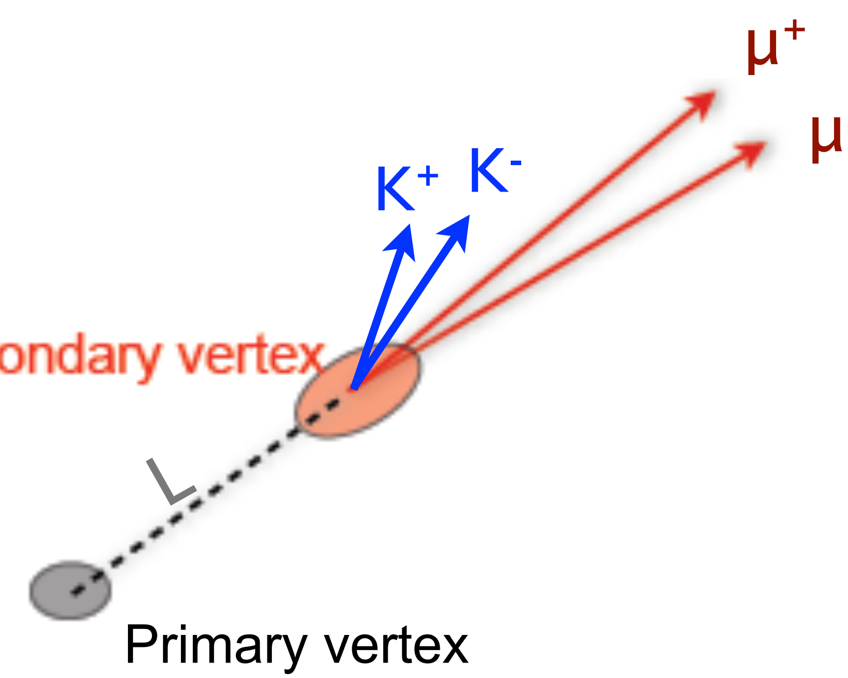
good agreement with theory predictions ➪





particle lifetime

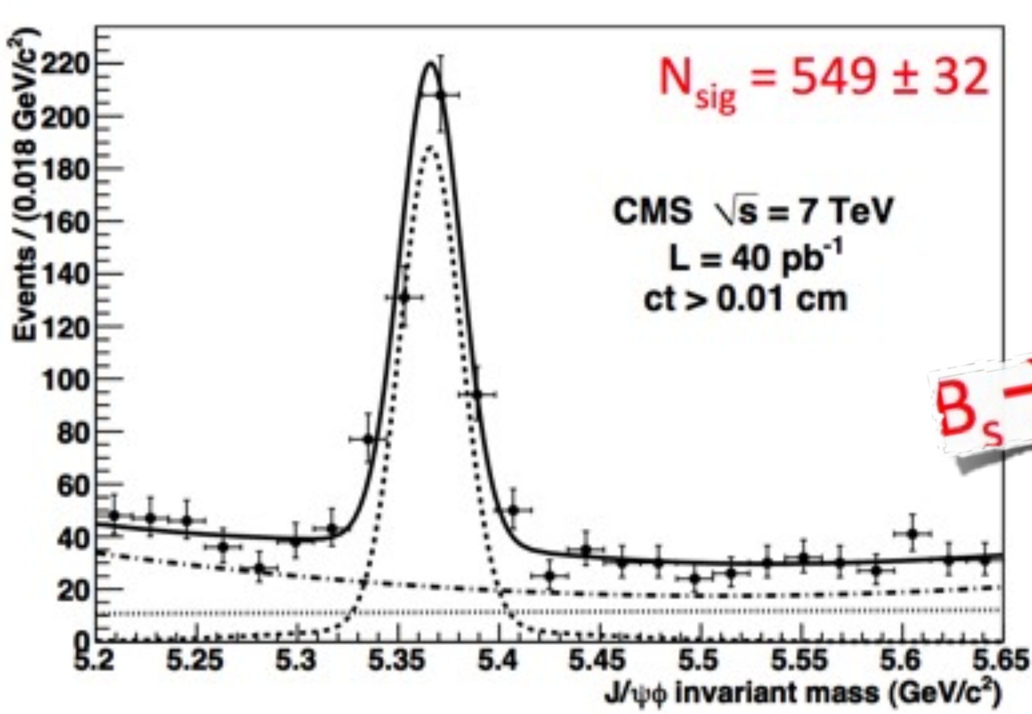
- if an unstable particle lives for a relatively long time before decaying, it may leave a distinct signature in the detector: a displaced vertex

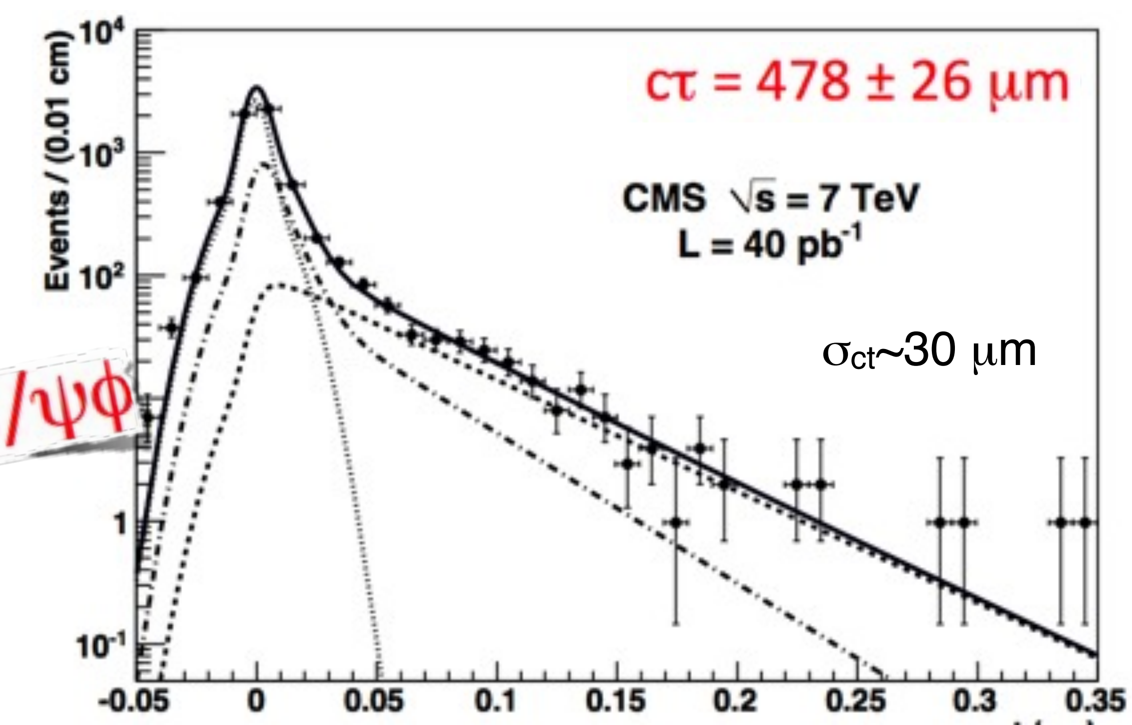


- its proper decay time **t** can then be measured from the flight distance and momentum (projected onto transverse plane)

$$\mathbf{t} = L/c\beta\gamma = \mathbf{L}\ m/\mathbf{p}$$

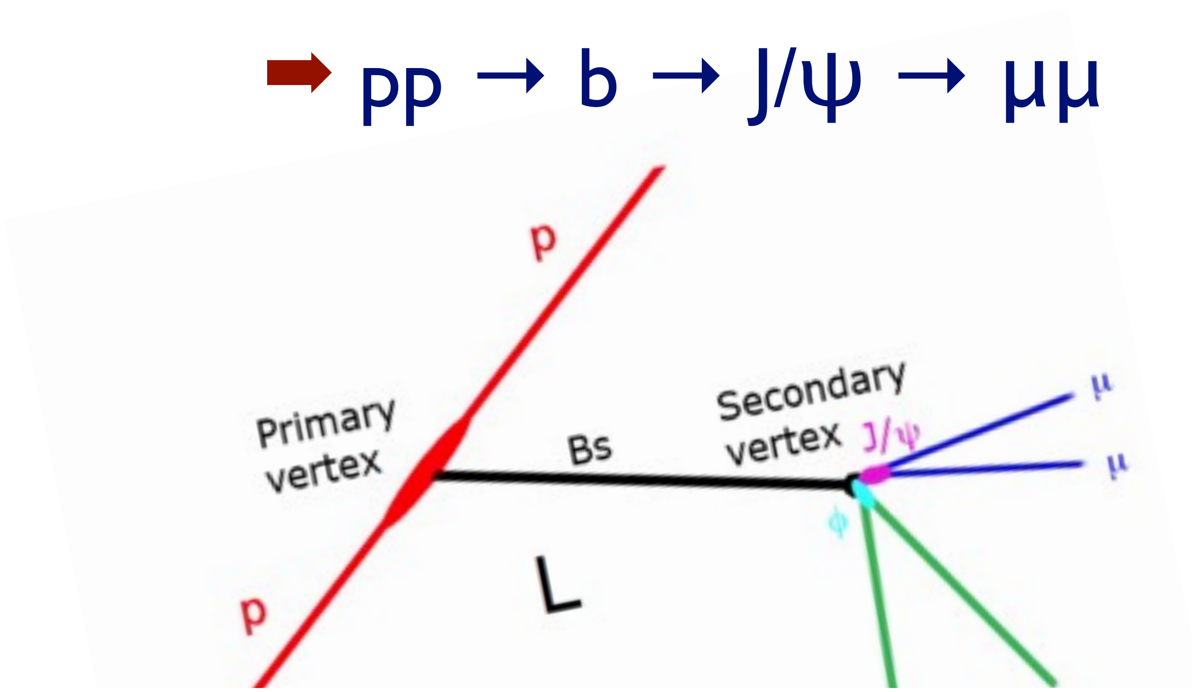
- notable example: b-hadrons

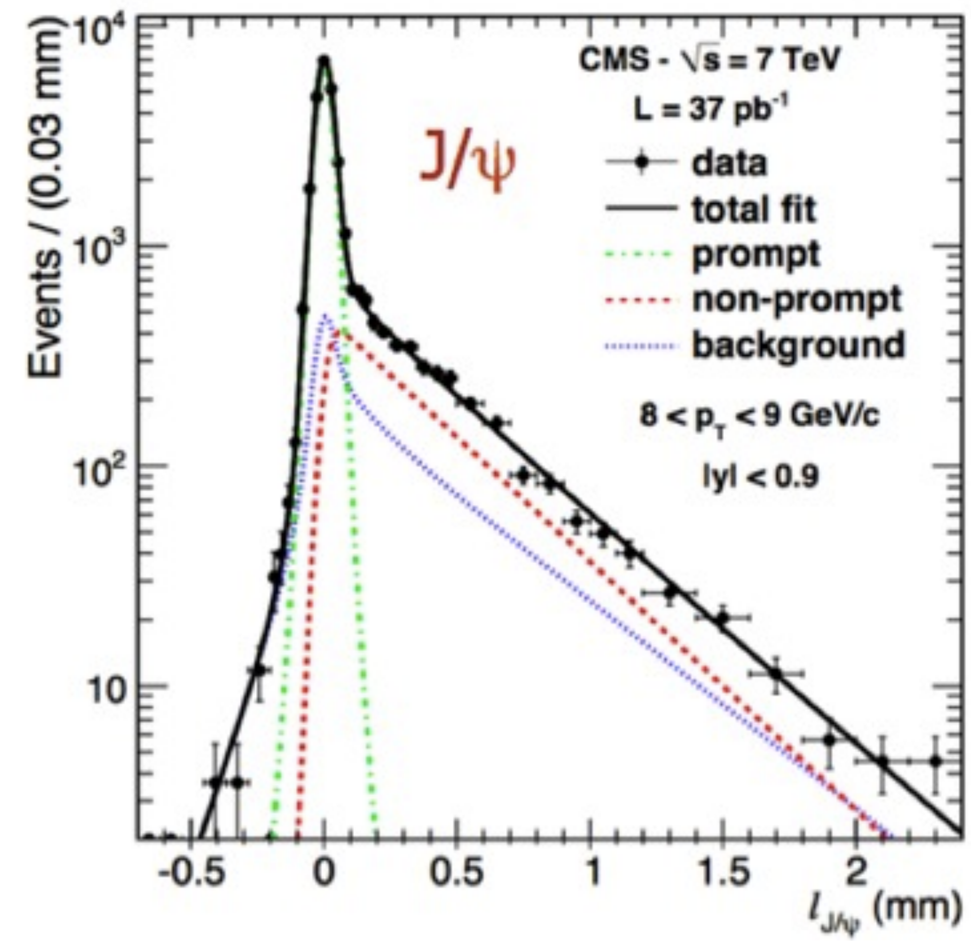


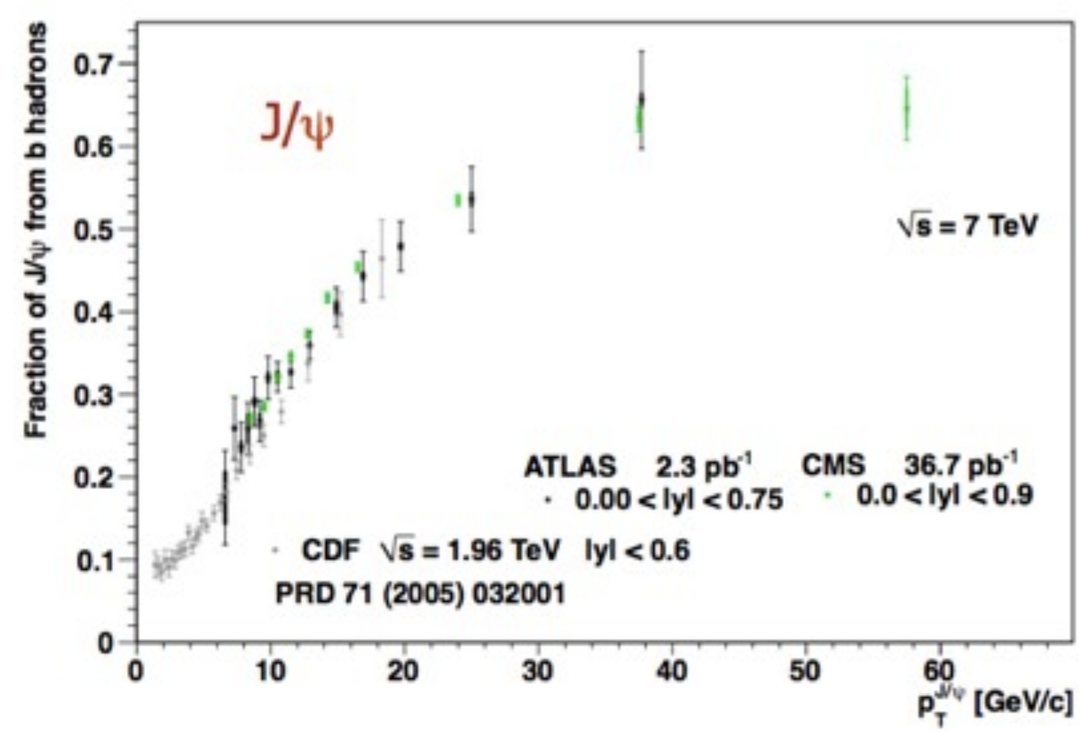


non–prompt J/ψ

- inspecting the displacement of the J/ψ decay vertex, we can separate the prompt and non-prompt components
- the J/ψ itself decays promptly(!), its displacement arises from:
  - ➡ $pp \rightarrow b \rightarrow J/\psi \rightarrow \mu\mu$





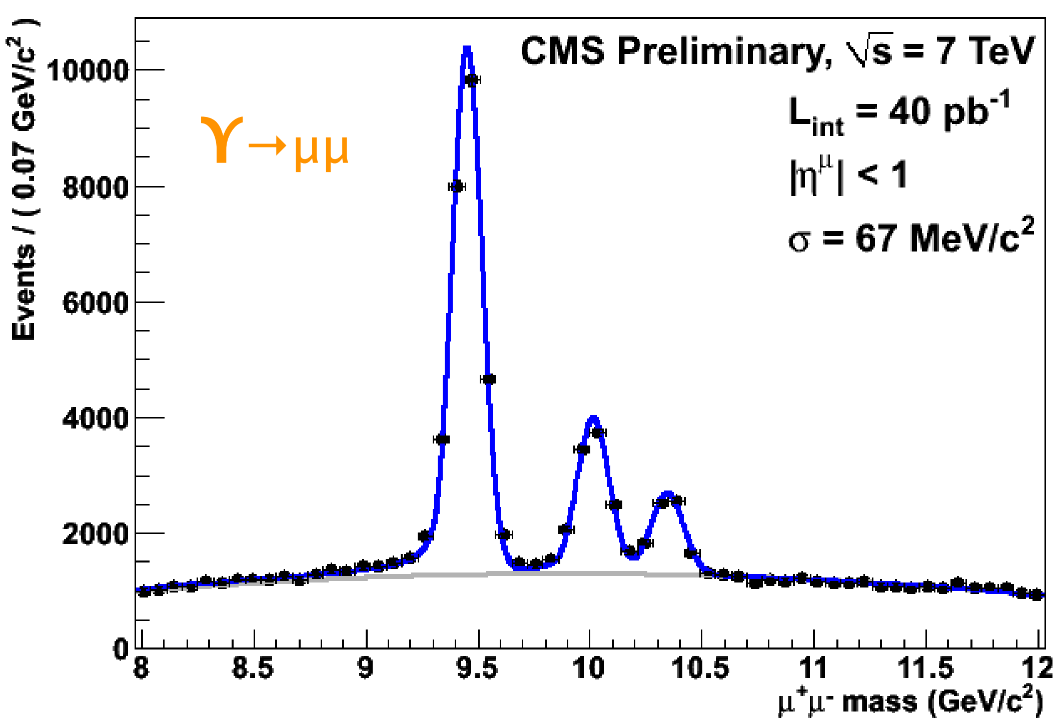


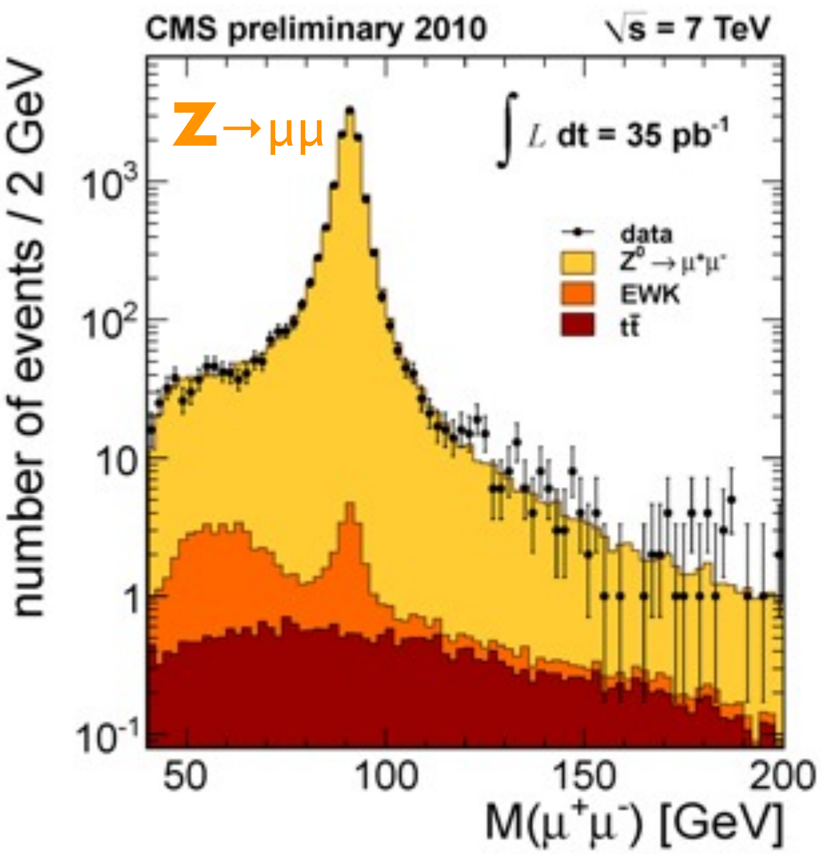
- by measuring the J/ψ displacement we inferred the contribution from another, heavier particle ...

displaced Upsilon? Zee? ...

➡ a long-lived signal component would be smoking gun for new physics

- but would these not have been detected already elsewhere?
  - relevant exotic scenarios may become accessible only at LHC energies





- can apply standard lifetime technique, for Υ and Z as just done for J/ψ
- alternative: generic displaced-vertex search, performed with lifetime threshold

search for new resonances

➡ look for new, exotic bumps in the dilepton mass spectrum

1. prompt

- eg: light scalars (SM&BSM Higgs), new gauge bosons Z', RS graviton G_{kk}, ...
- use known resonances eg $Z \rightarrow \mu\mu$ peak for normalization
- *direct* search for NP

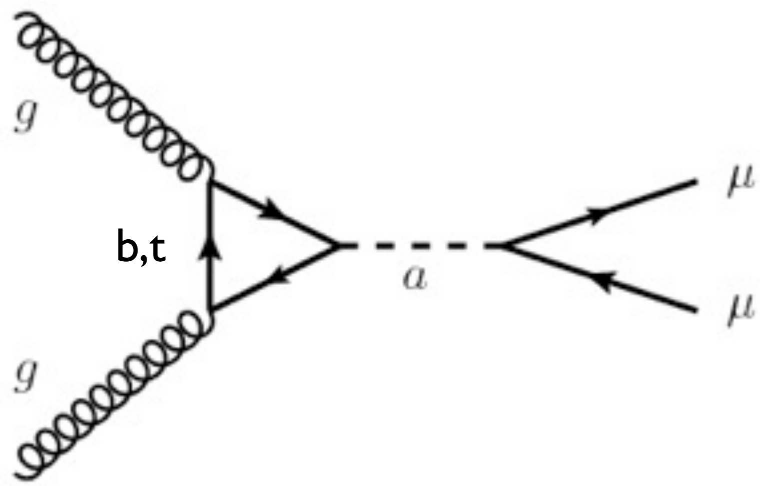
2. short lived

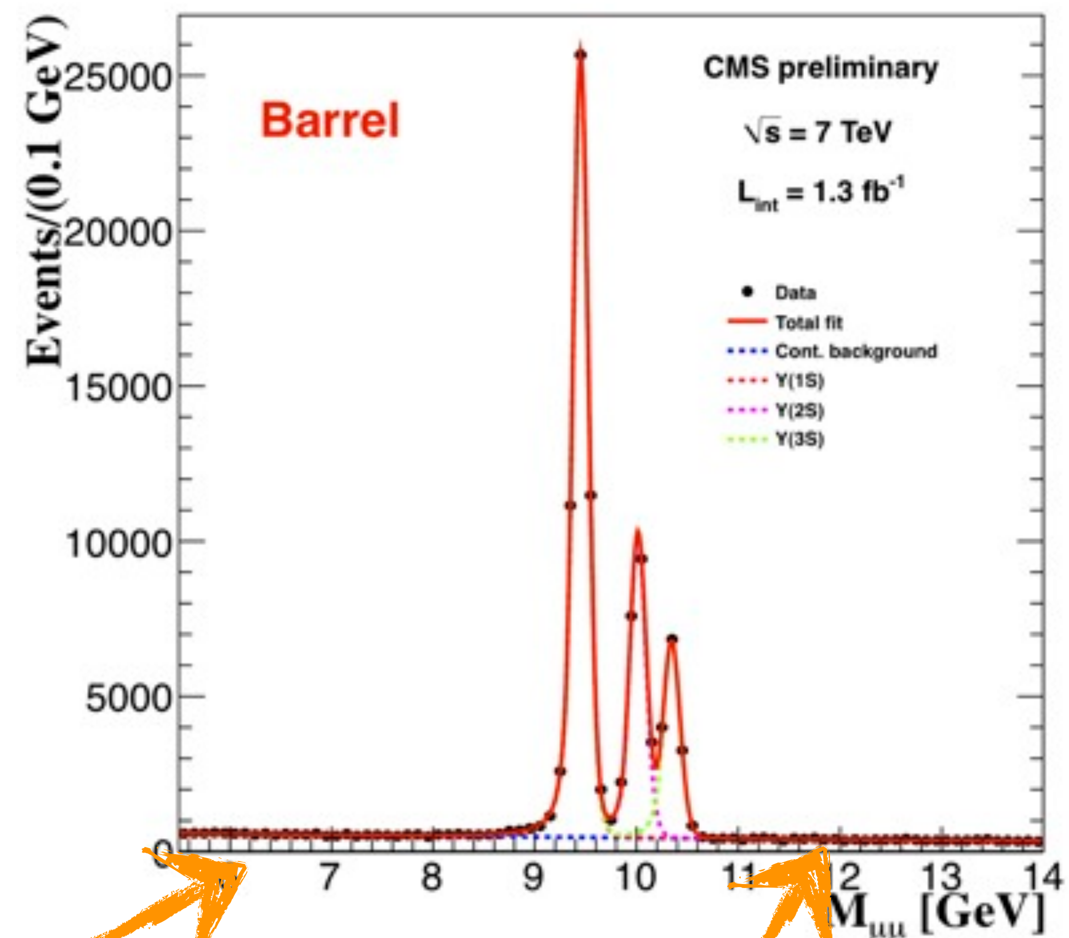
- eg: D, B $\rightarrow \mu\mu$: tiny in SM, may be enhanced by new physics (SUSY)
- low mass: use other known B,D decays for normalization
- *indirect* search for NP

3. long lived

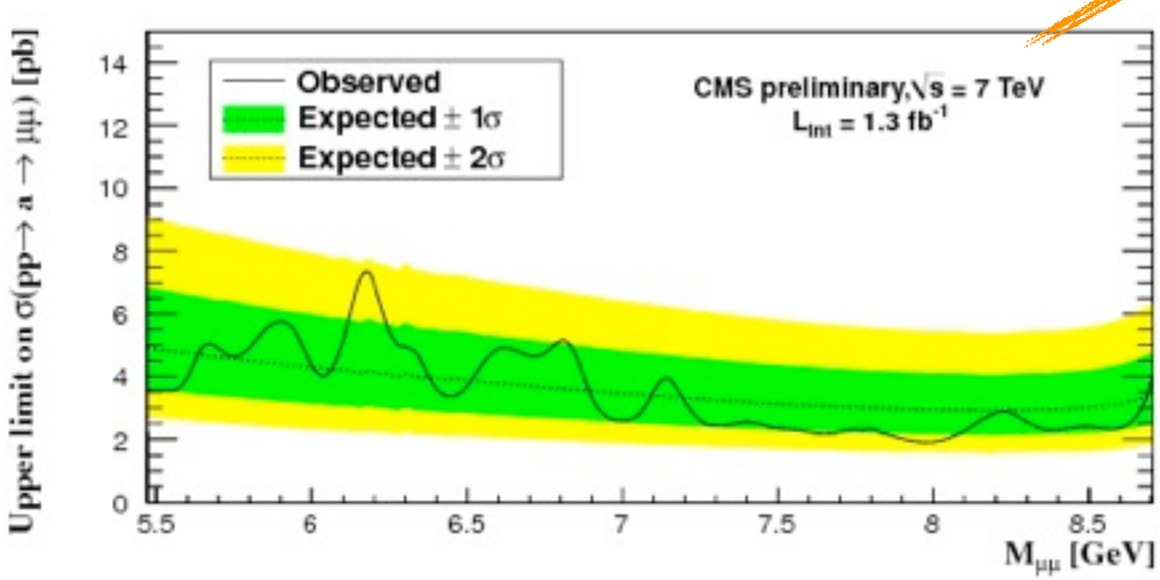
- eg: SUSY with weak R-parity violation, 'hidden' SUSY, hidden valleys
- distinct topological signature: (highly) displaced vertices
- *direct* search for NP

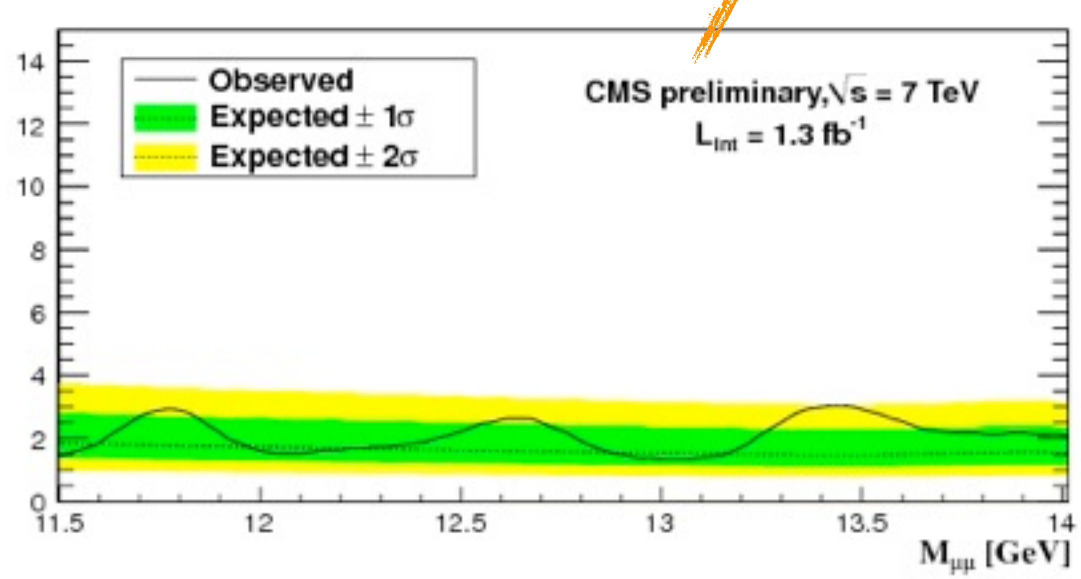
$h_0 \rightarrow \mu\mu$ [prompt]



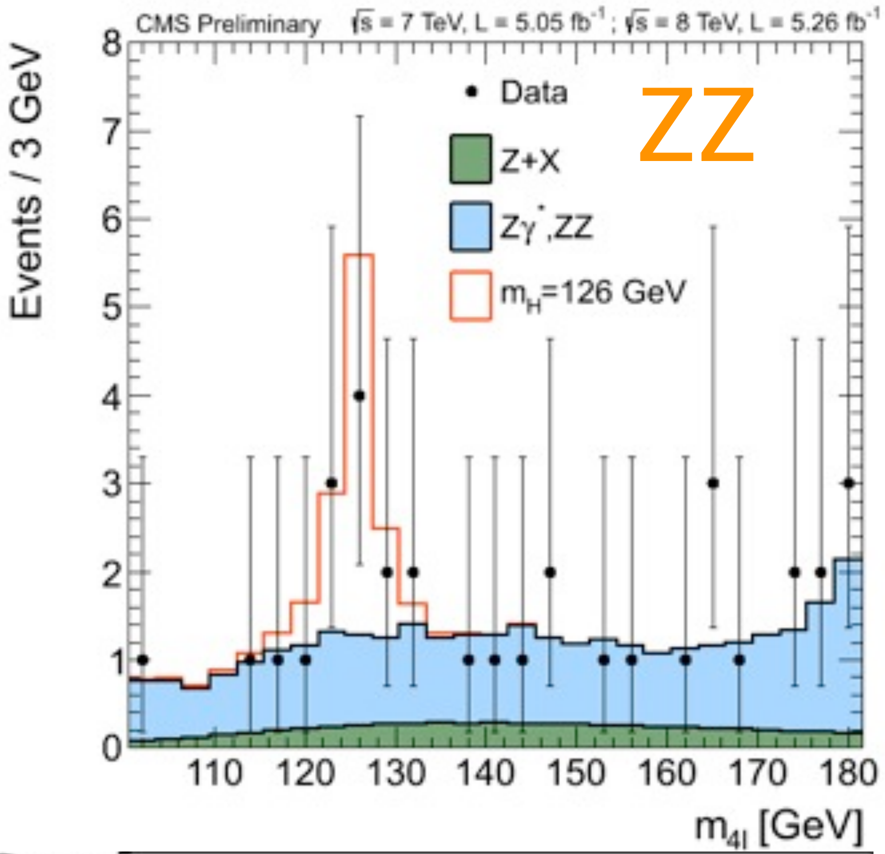


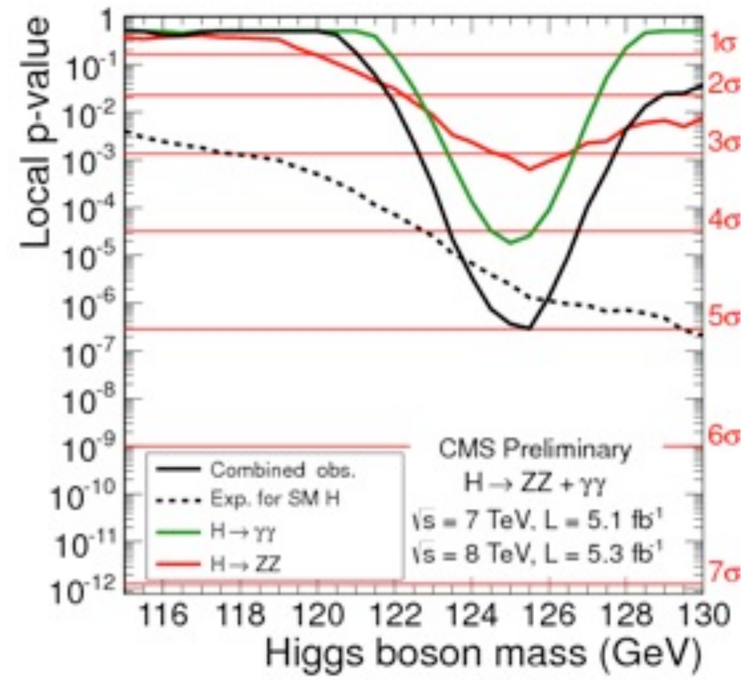
- light Higgs predicted eg NMSSM
    - add singlet scalar to MSSM
- search in range 5.5 -- 14 GeV around the Υ(nS) region
- no excess found above SM background, set limit on $\sigma(pp \rightarrow a) \times BR(a \rightarrow \mu^+\mu^-)$

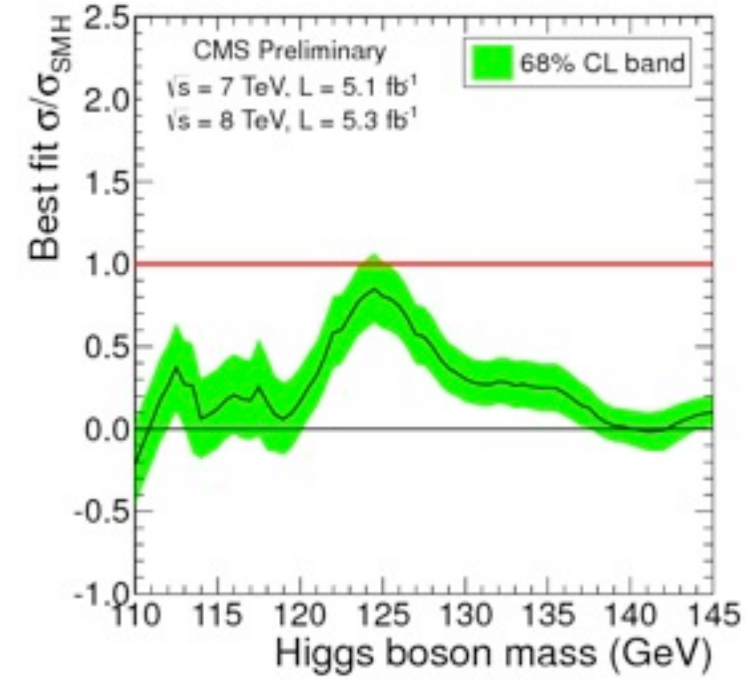


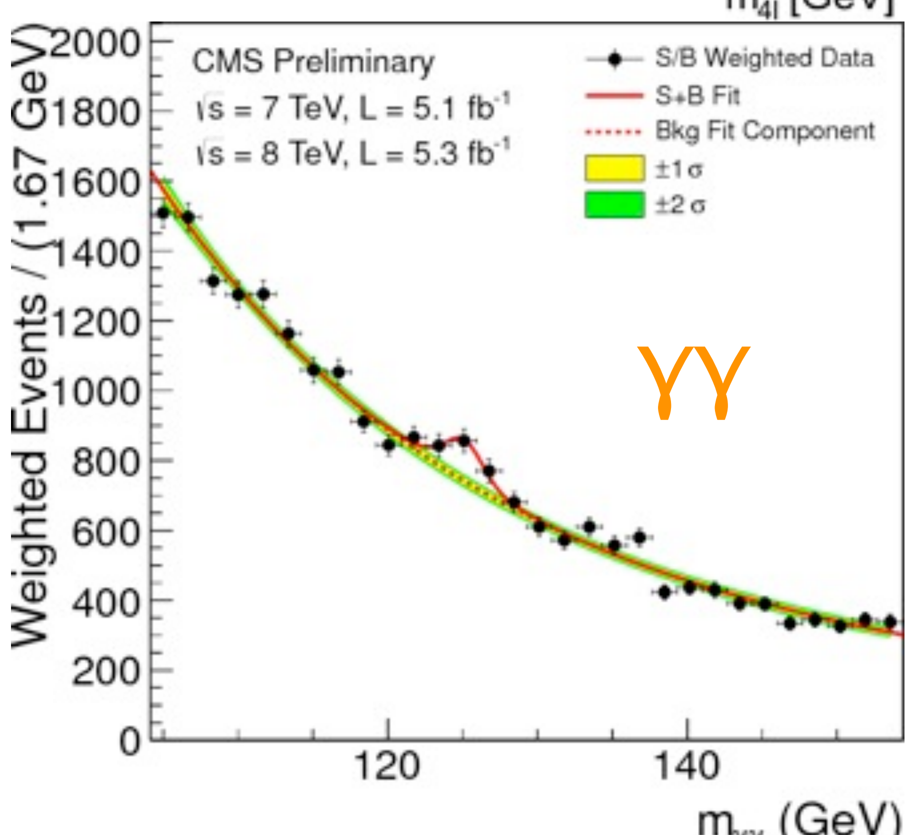


SM Higgs search: H→4l,2γ [prompt]









- the new light boson resonance found at

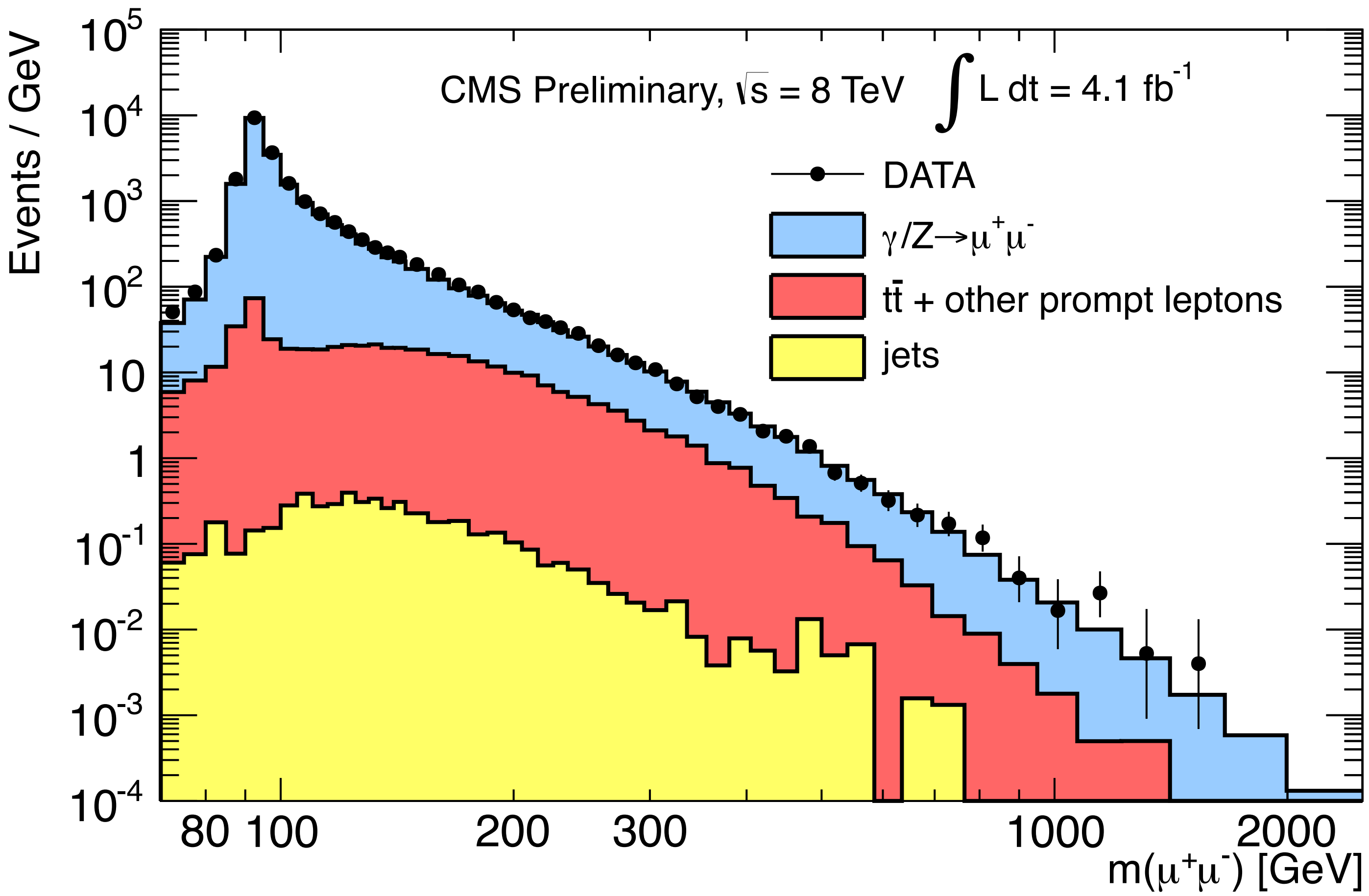
$$m = 125.3 \pm 0.4 \pm 0.5 \text{ GeV}$$

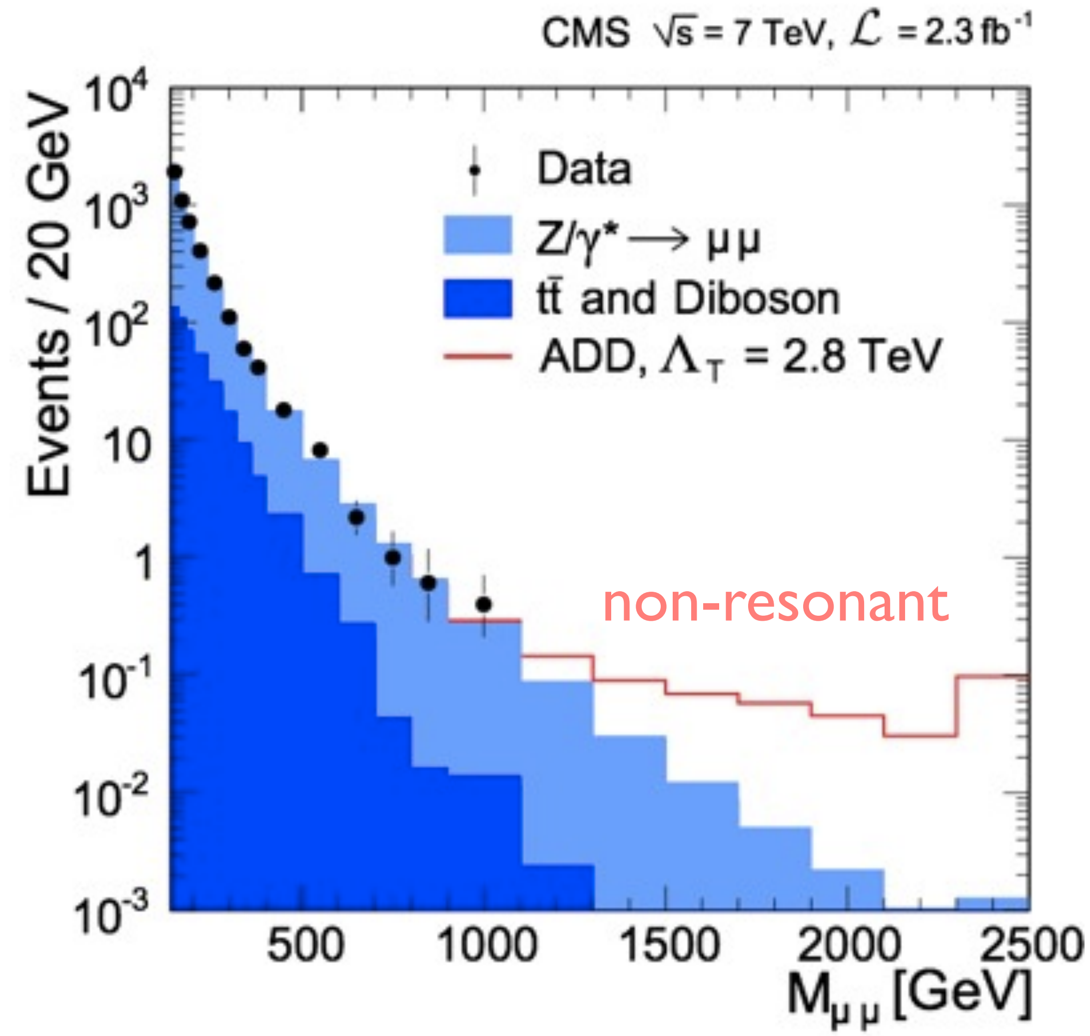
$$\text{best fit } \sigma/\sigma_{SM} = 0.80 \pm 0.22$$

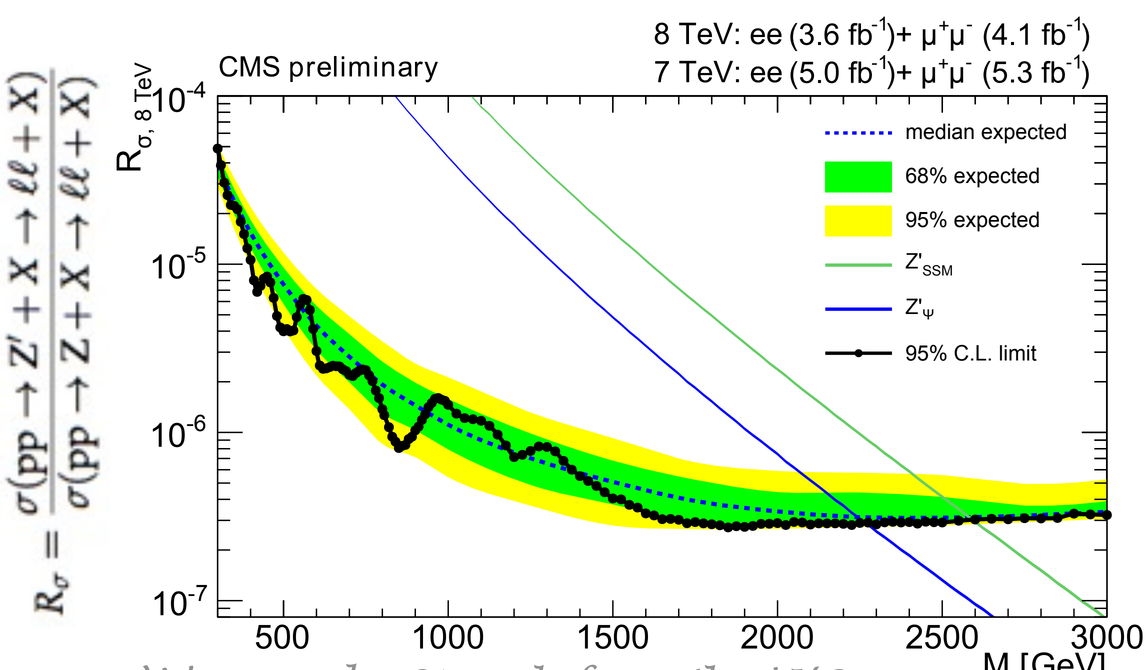
significance (local p-value): 5σ

- ➠ see previous seminar (5/7/2012) by **Prof. João Varela**

Z', Gkk→μμ [prompt]



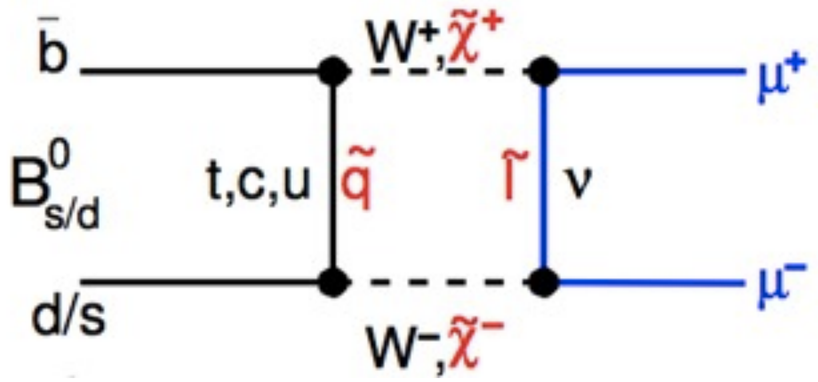


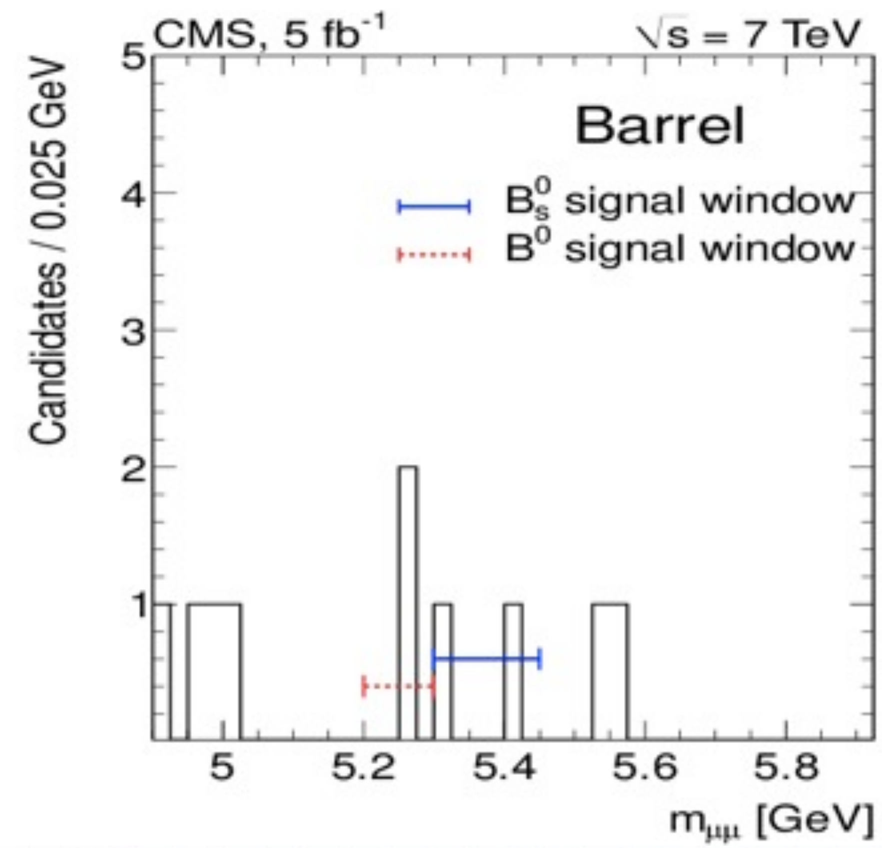


no excess found above SM background

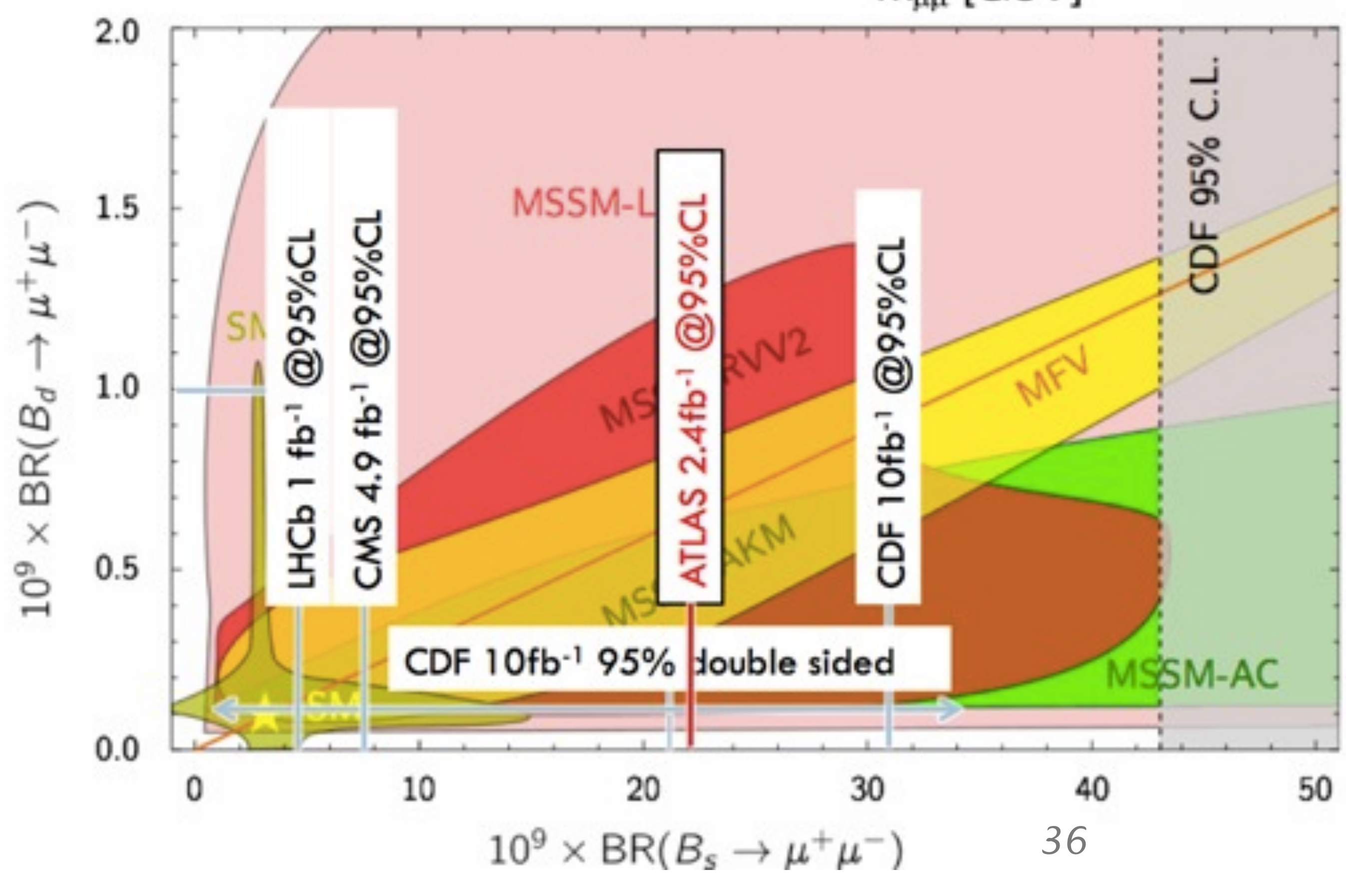
- ADD 95% CL limits in 2.5-3.8 TeV
- RS 95% CL limits in 1.8-2.1 TeV (k/MPl 0.05-0.1)
- Z' 95% CL limits in 2.0-2.3 TeV ➟ 2.3-2.6 TeV

B→μμ [short lived]

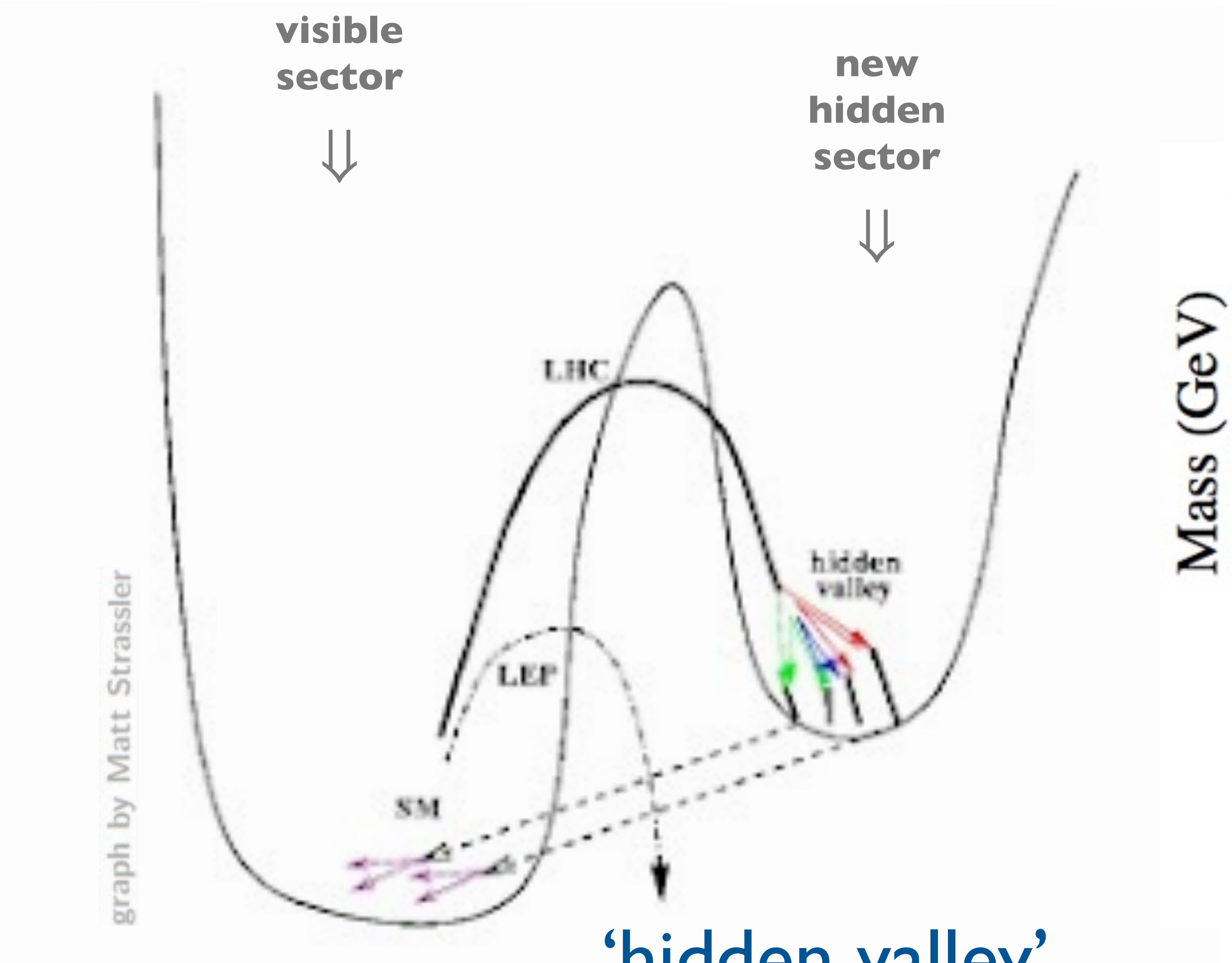




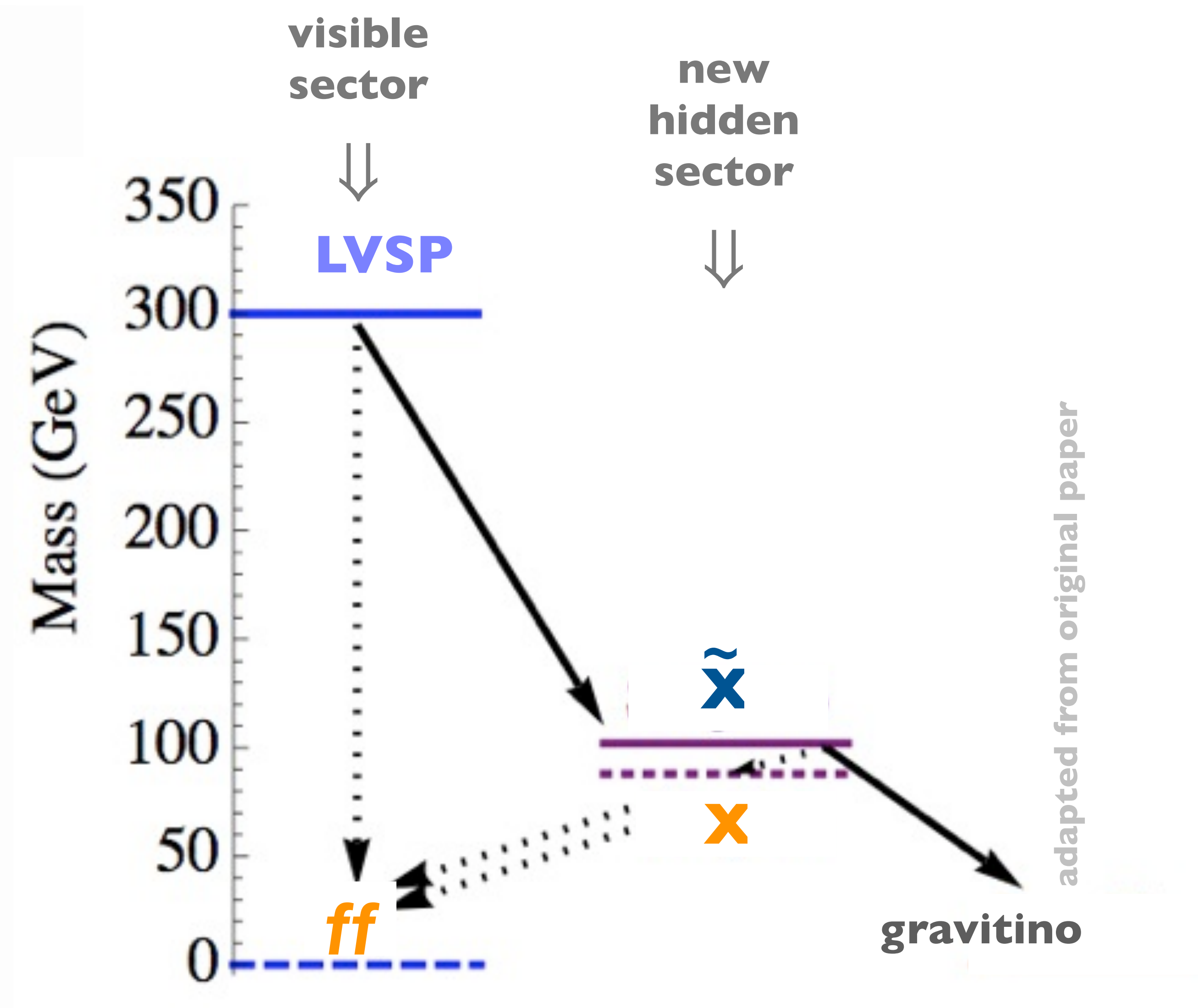
- highly suppressed in SM
  - effective FCNC, helicity suppressed
  - $B(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$
  - $B(B_d \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$
- high sensitivity to new physics
  - eg MSSM: $B \propto (\tan\beta)^6$
- no NP enhancement detected
  - strict constraints to NP phase phase, flavor sector contributions



phenomenology [long lived]



'hidden valley'
[arXiv:hep-ph0604261]



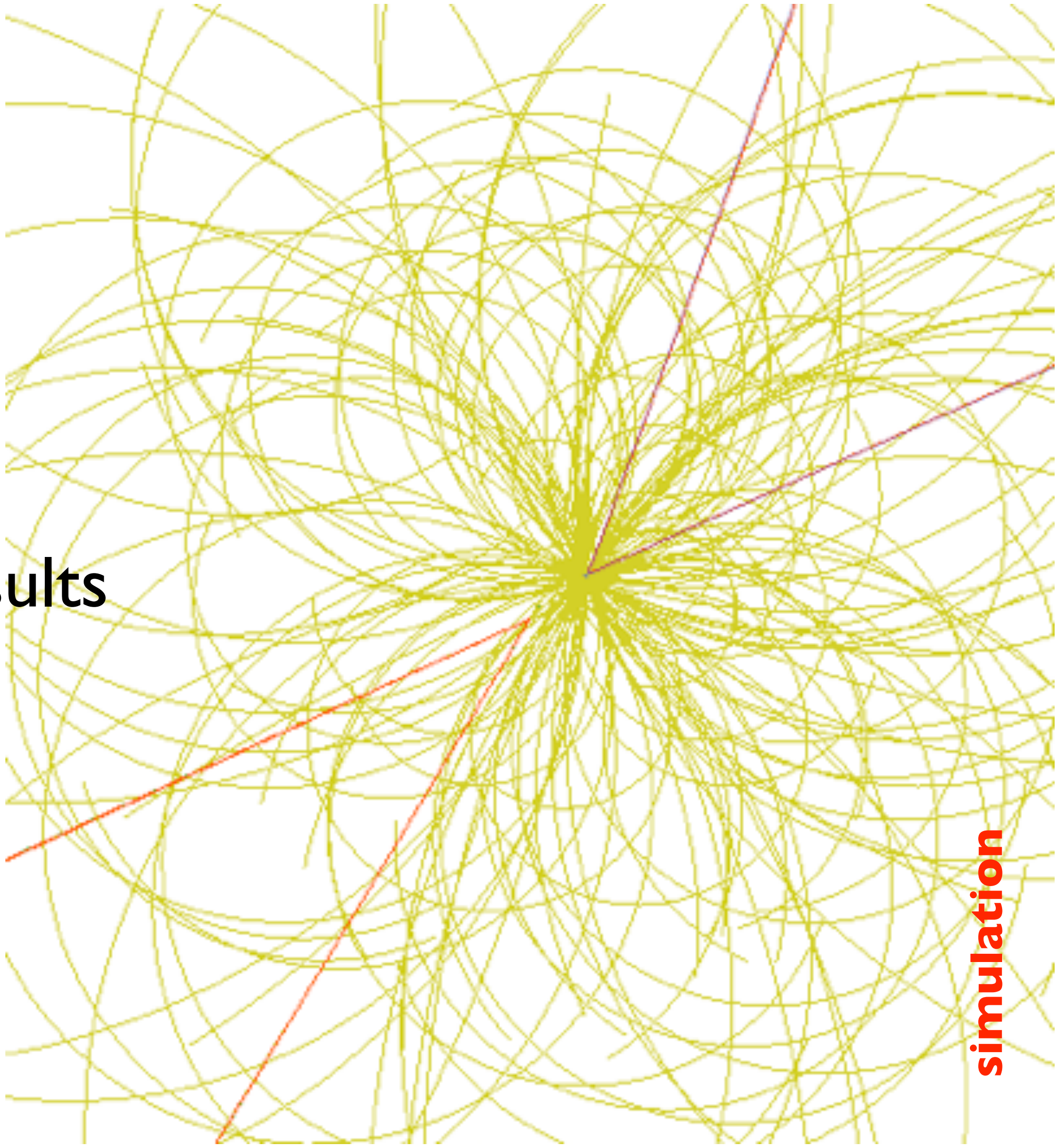
'stealth susy'
[arXiv:1105.5135]

VS ~ NHS suppressed coupling ➼ long lived hidden particles

displaced vertices search

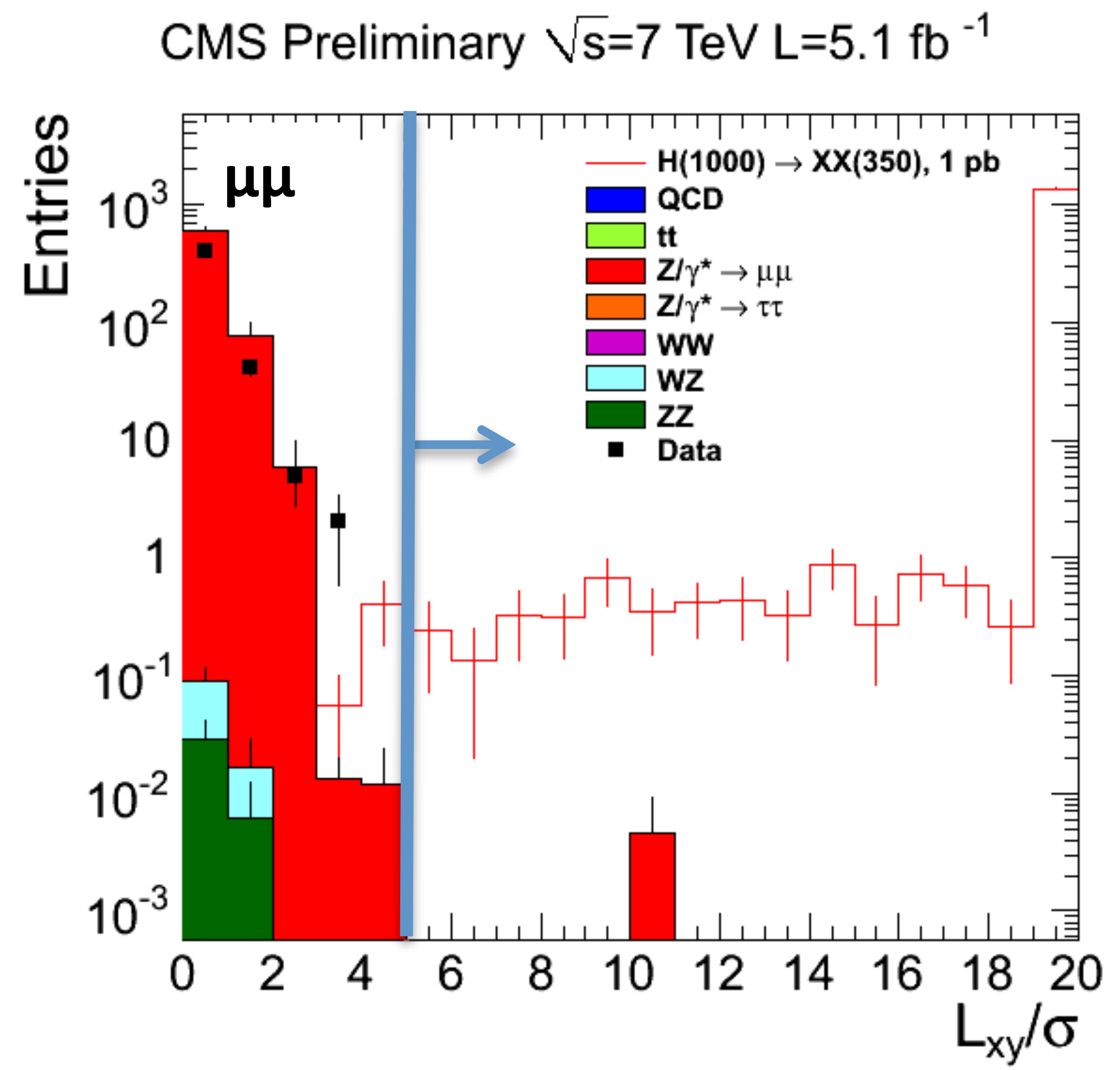
➡ search for neutral, long lived, narrow heavy resonances decaying to leptons inside the CMS tracker volume

- benchmark signal model:
  - Higgs (scalar) decay: $H^0 \to 2X$, $X \to l^+l^-$
  - variety of Higgs mass, X mass/lifetime
  - further models constrained by our results
- backgrounds:
  - QCD, tt, Z/γ, Z+jets, WW/WZ/ZZ
- look for a (displaced)peak in invariant mass spectrum of $X \to \mu\mu$



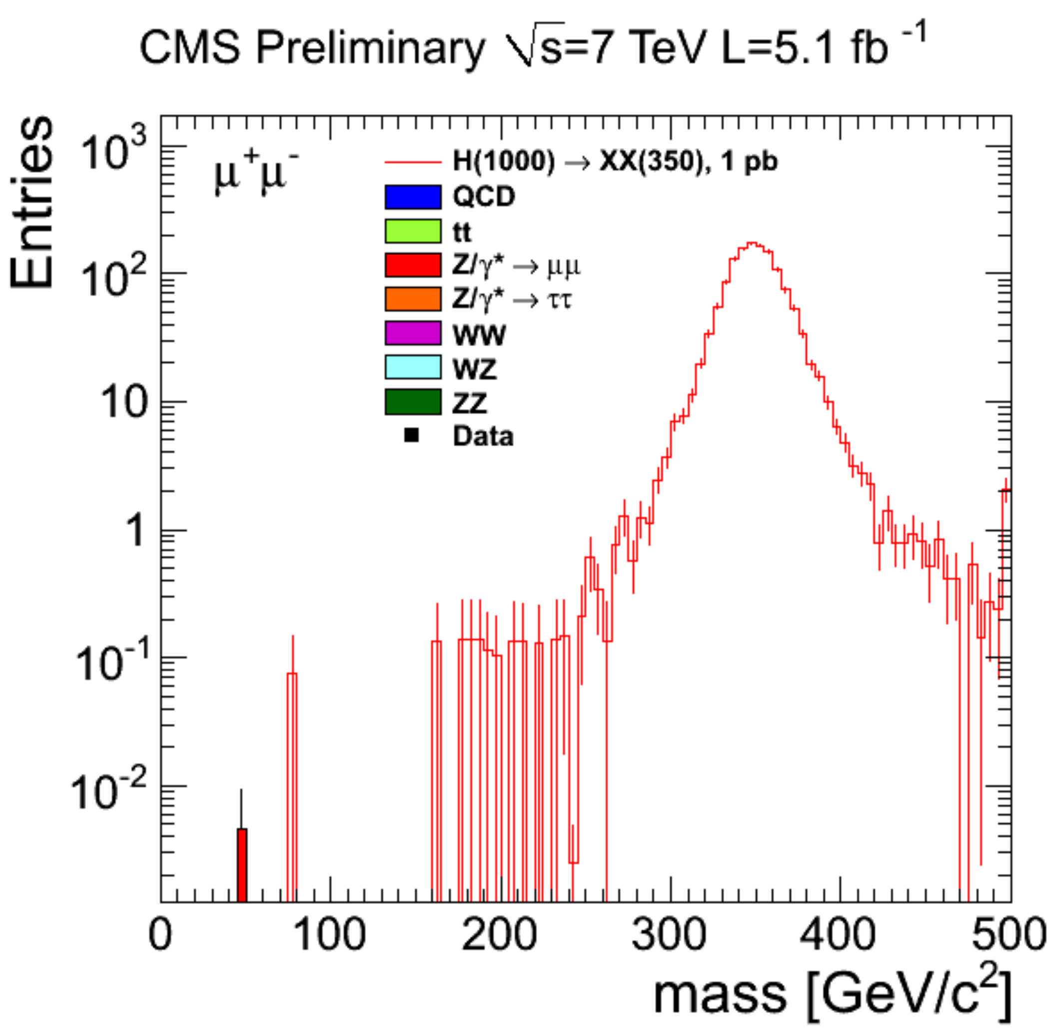
candidate selection

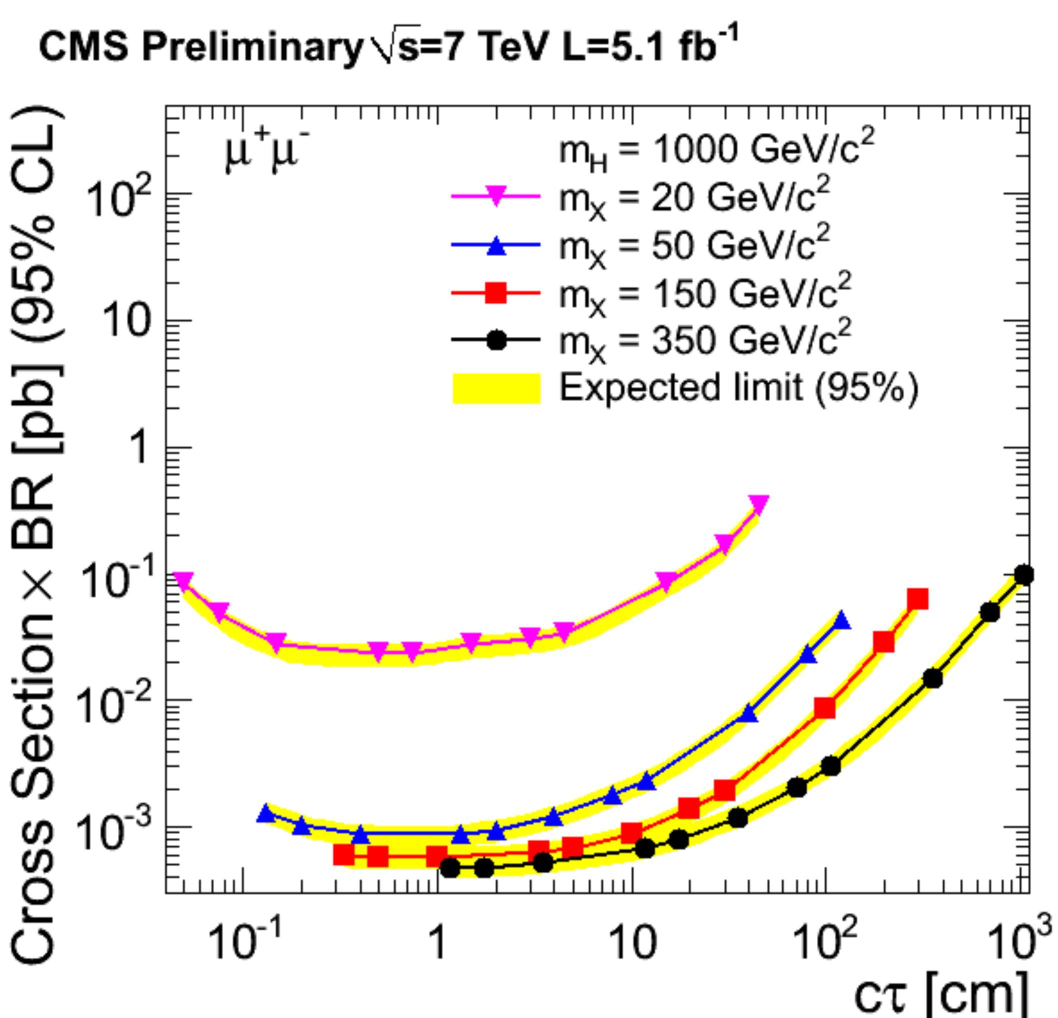
- online selection
  - dedicated double muon trigger, with no tracker nor vertex requirements
- track selection
  - high purity, oppositely charged tracks
  - impact parameter: remove prompt tracks
  - muon ID = matching trigger muon
  - isolation
- vertex selection
  - vertex fit quality
  - vertex displacement from PV ⇒
  - collinearity angle (p_t,L_{xy})
  - back to back tracks: eliminate cosmic rays
  - dimuon separation, ΔR>0.2, to avoid region of poor trigger efficiency



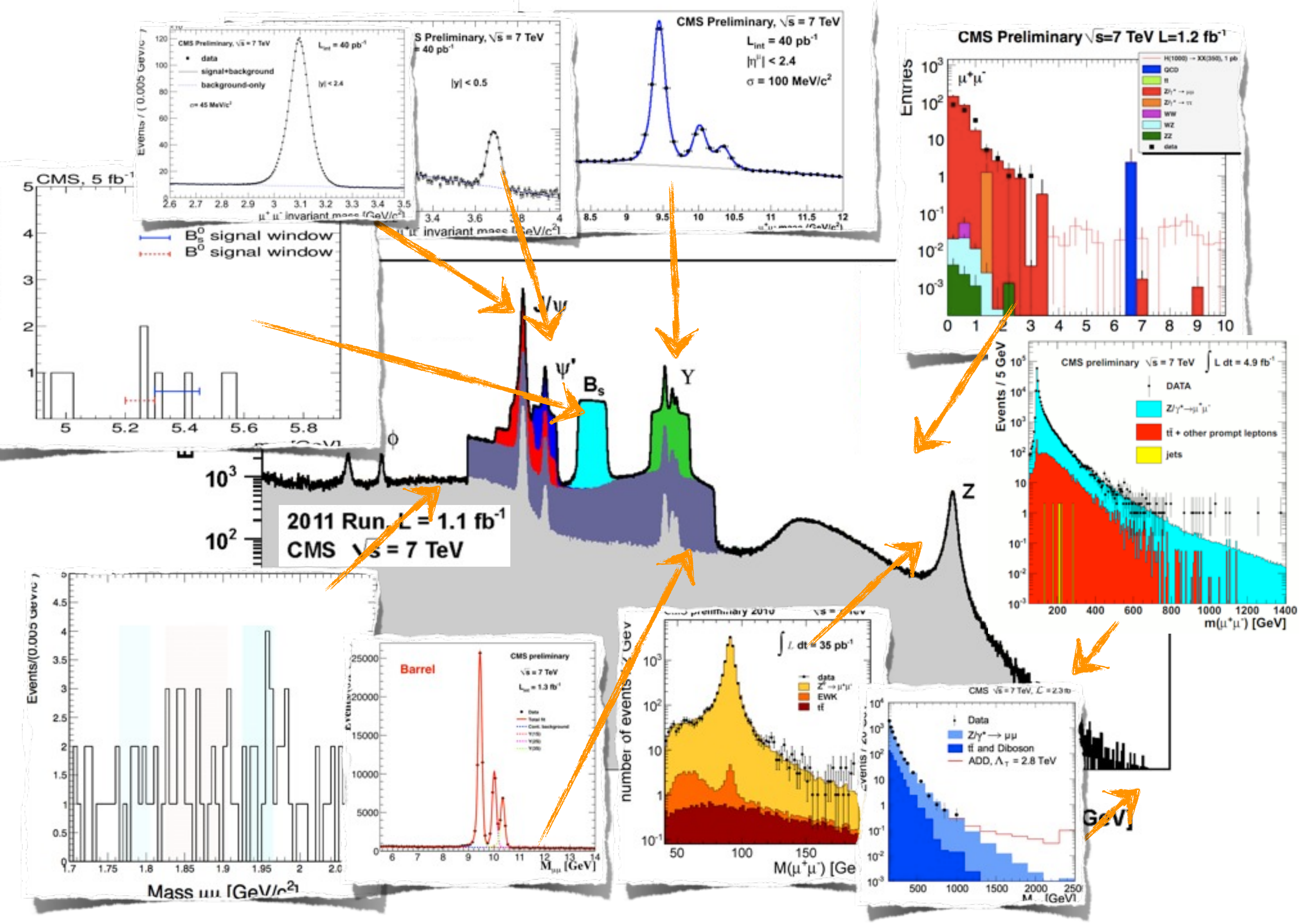
results & limits

- look for signal as a narrow resonance in dilepton mass spectra
- no excess observed so far ⇒ limits set for ranges of m_H, m_X, τ_X
  - observe zero (4) events in μμ (ee) channel, expected: 0.02±0.09 (1.4±1.8)
- exclusion limits from Tevatron significantly extended

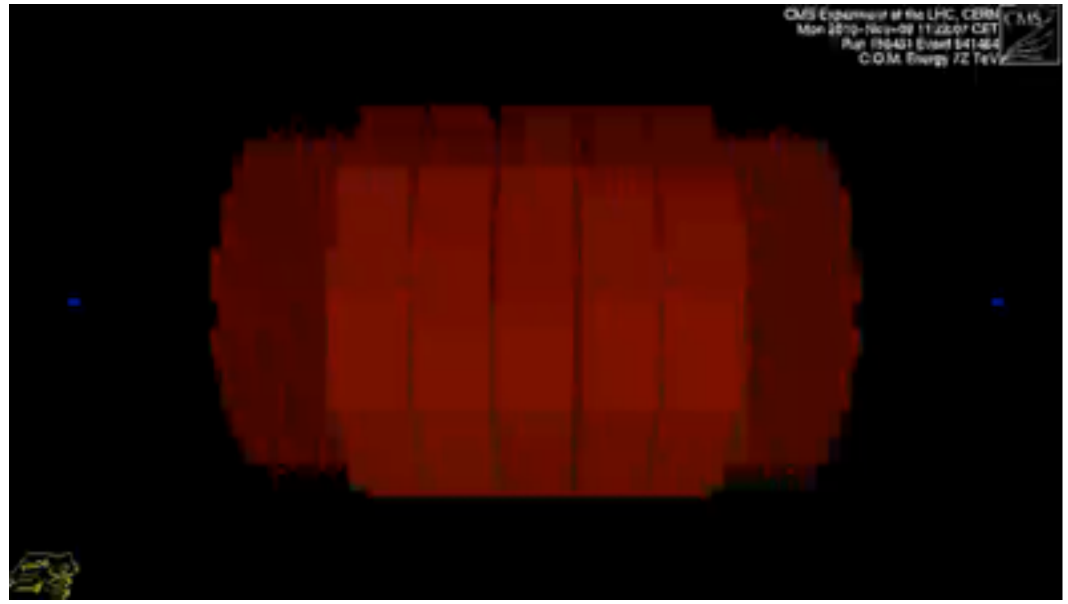




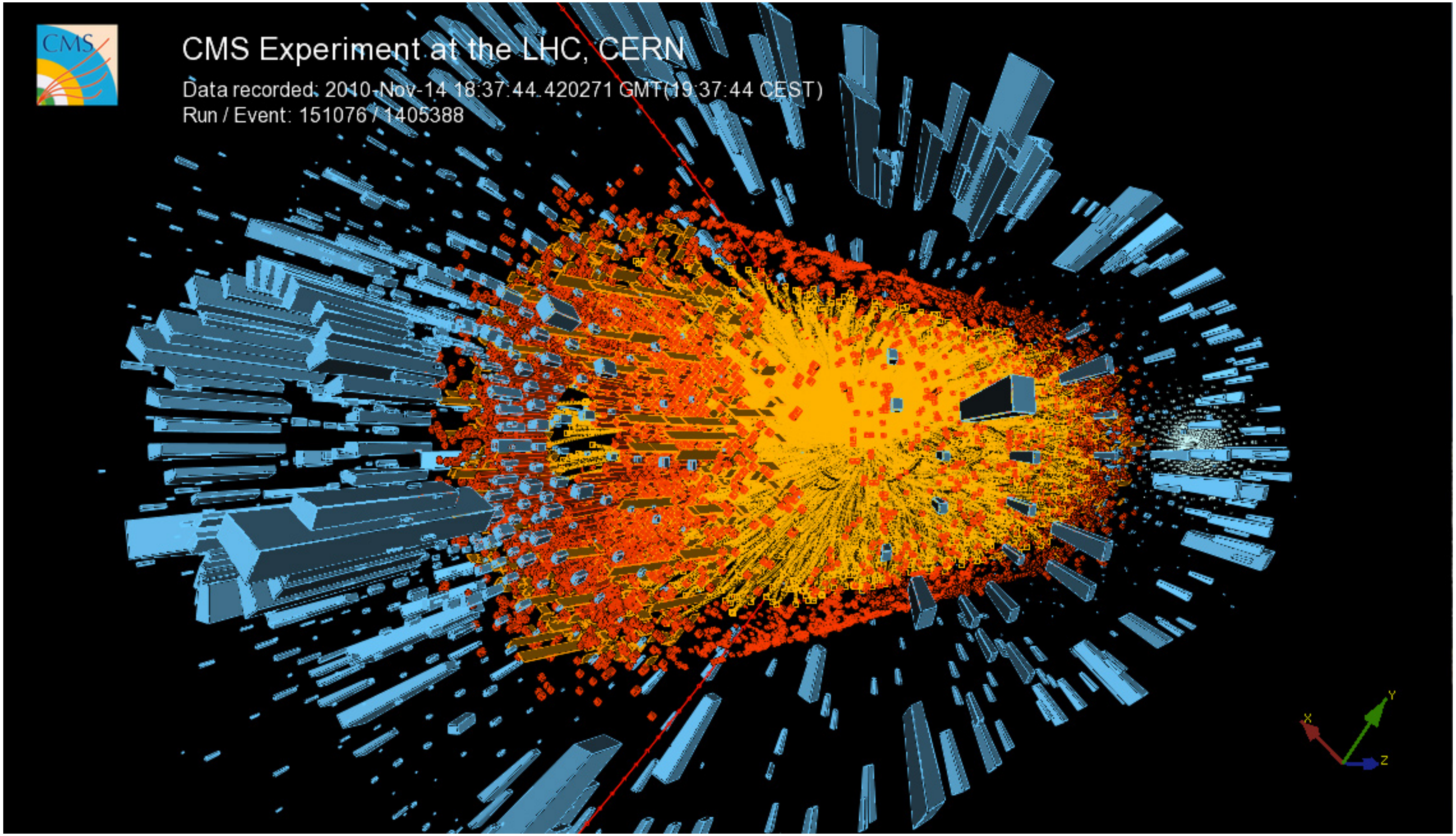
⇧ Limits ~ 0.7-10 fb



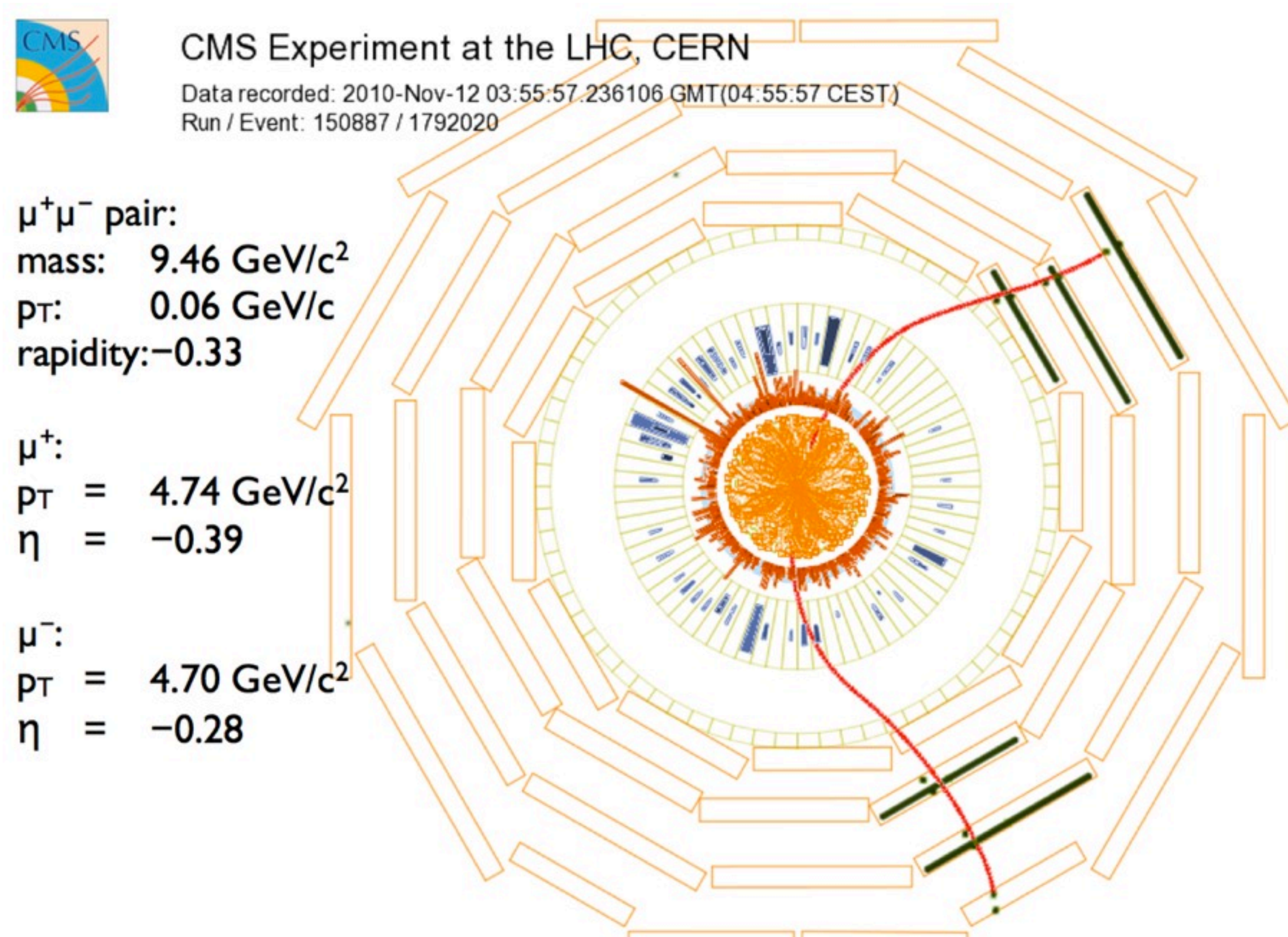
2011 Run, L = 1.1 fb^{-1}
CMS $\sqrt{s}$ = 7 TeV
J/ψ
ψ'
B_s
Υ
φ
Z
CMS, 5 fb^{-1}
B_s^0 signal window
B^0 signal window
CMS Preliminary, $\sqrt{s}$ = 7 TeV
L_{int} = 40 pb^{-1}
|y| < 0.5
|η$^\mu$| < 2.4
σ = 100 MeV/c^2
CMS Preliminary $\sqrt{s}$=7 TeV L=1.2 fb^{-1}
Entries
CMS preliminary $\sqrt{s}$ = 7 TeV $\int$ L dt = 4.9 fb^{-1}
DATA
tt̄ + other prompt leptons
jets
Events / 5 GeV
m(μ$^+$μ$^-$) [GeV]
Barrel
CMS preliminary
$\sqrt{s}$ = 7 TeV
L_{int} = 1.3 fb^{-1}
$M_{\mu\mu}$ [GeV]
Events/(0.005 GeV/c^2)
Mass μμ [GeV/c^2]
number of events
EWK
Data
Z/γ* → μμ
tt̄ and Diboson
ADD, Λ_T = 2.8 TeV

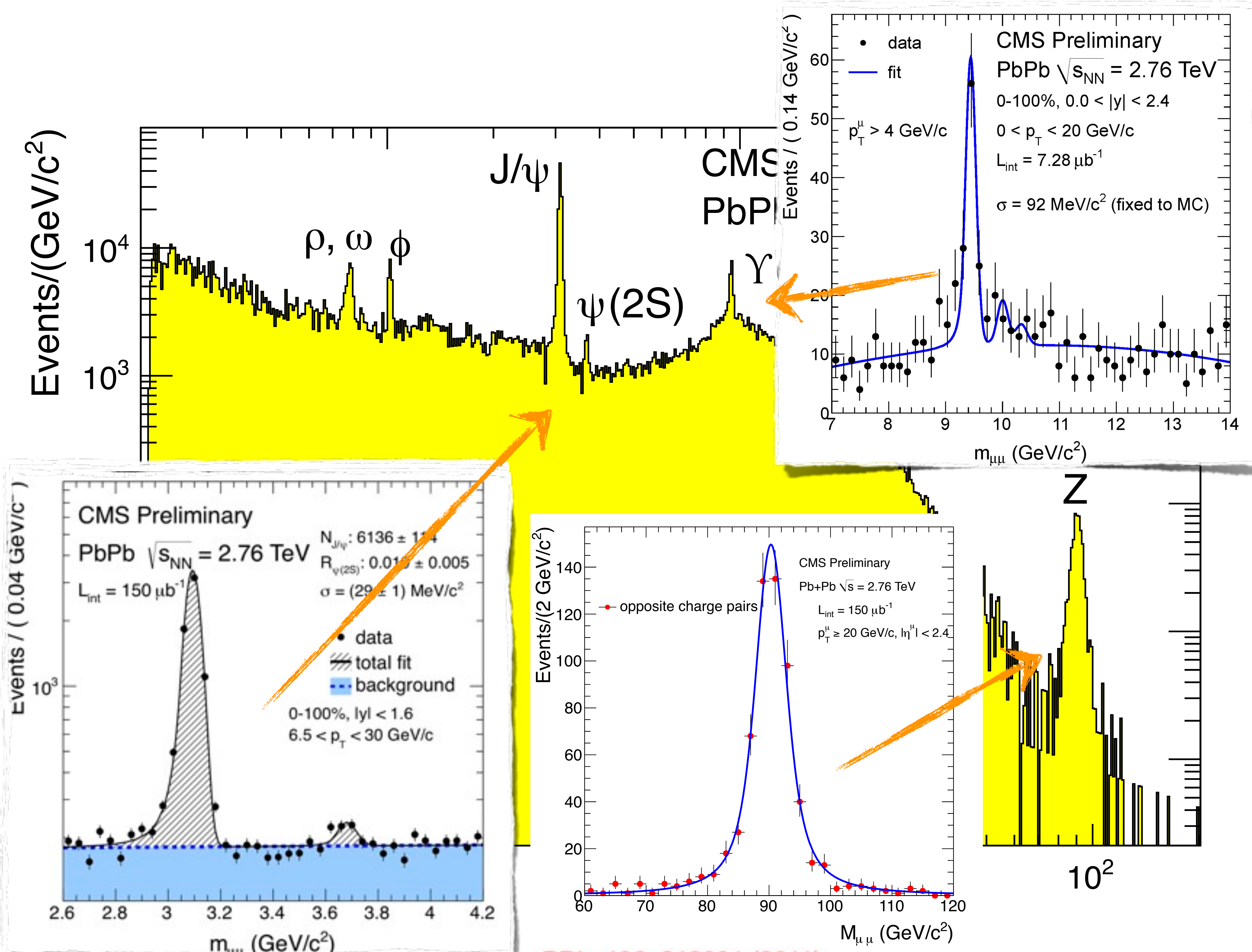


PbPb collisions
(@ $\sqrt{s_{NN}}$=2.76 TeV)


CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST)
Run / Event: 151076 / 1405388
X
Y
Z

Dimuon (ϒ) candidate in PbPb





PRL. 107, 052302 (2011)

arXiv:1208.2826, submitted PRL

JHEP 1205 (2012)

CMS-HIN-12-014 (2012)

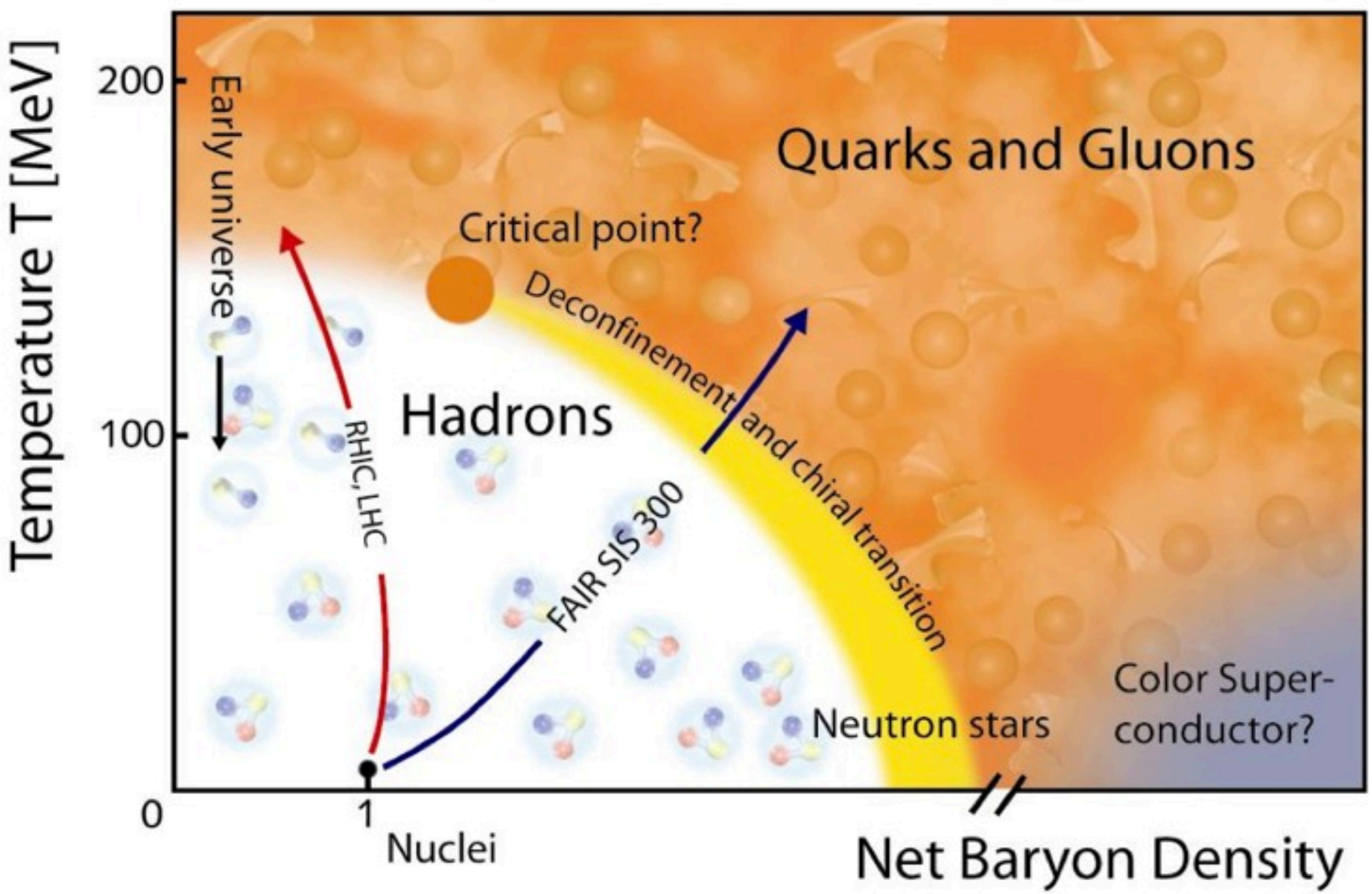
PRL. 106, 212301 (2011)

CMS-HIN-12-008 (2012)

aim: explore the QGP

➡ at large energy densities, QCD predicts the existence of a deconfined state of quarks and gluons -- the quark gluon plasma (QGP)

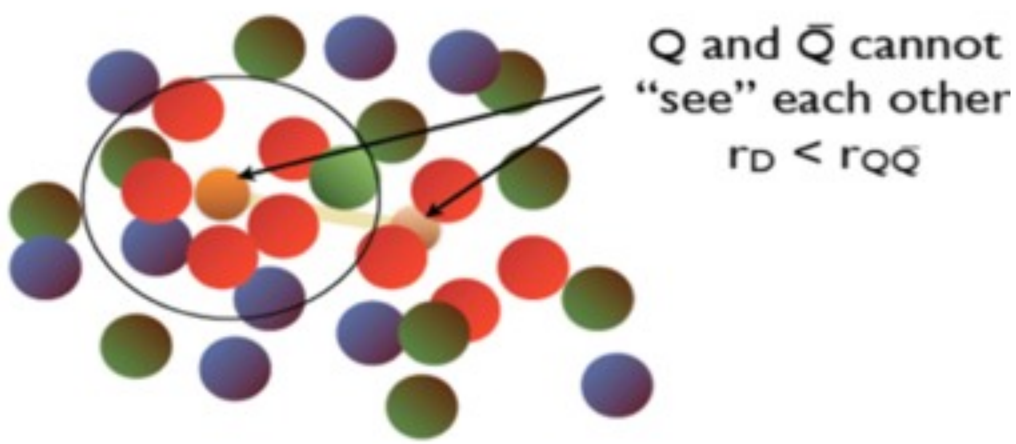
- the goal is to characterize and quantify the properties of the dense and hot medium produced at the unprecedented LHC energies



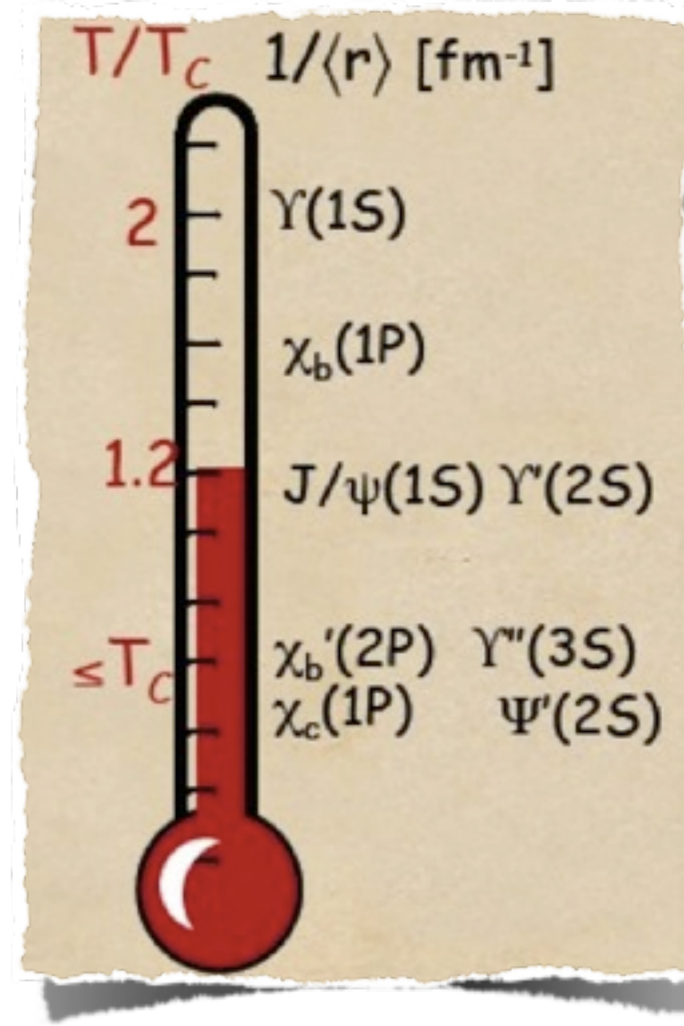
quarkonia as probe for QGP

- heavy quarks produced early in the collision
  - they map the evolution of the medium
- quarkonia state in a deconfined, color-charged medium: Debey screening
  - induced the suppression of individual states
  - different states melt at different temperatures

PLB178, 416 (1986)



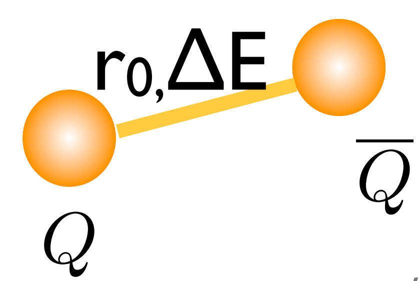
QCD thermometer



arXiv:0811.0337

State	J/ψ	ψ′	Υ	Υ′	Υ′′
mass [GeV]	3.10	3.68	9.46	10.02	10.36
ΔE [GeV]	0.64	0.05	1.10	0.54	0.20
radius [fm]	0.25	0.45	0.14	0.28	0.39

Sequential melting



R_{AA} & centrality

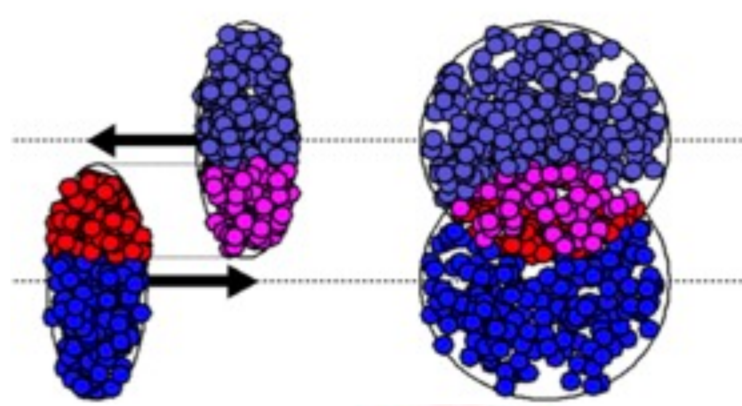
- pp data employed as baseline for heavy-ion measurements
- nuclear modification factor, **R_{AA}**

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

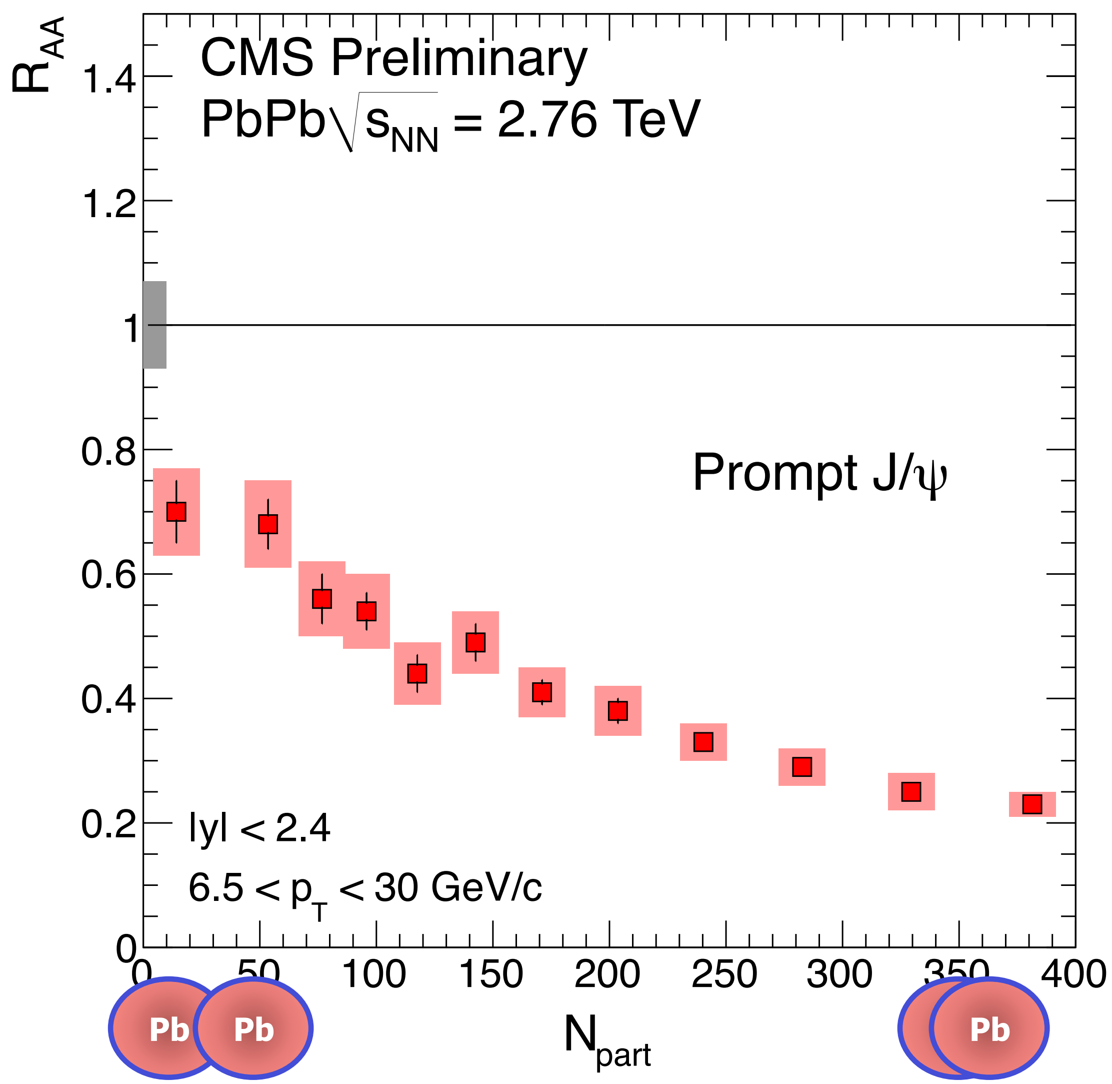
⇑ average number of NN collisions in AA collisions

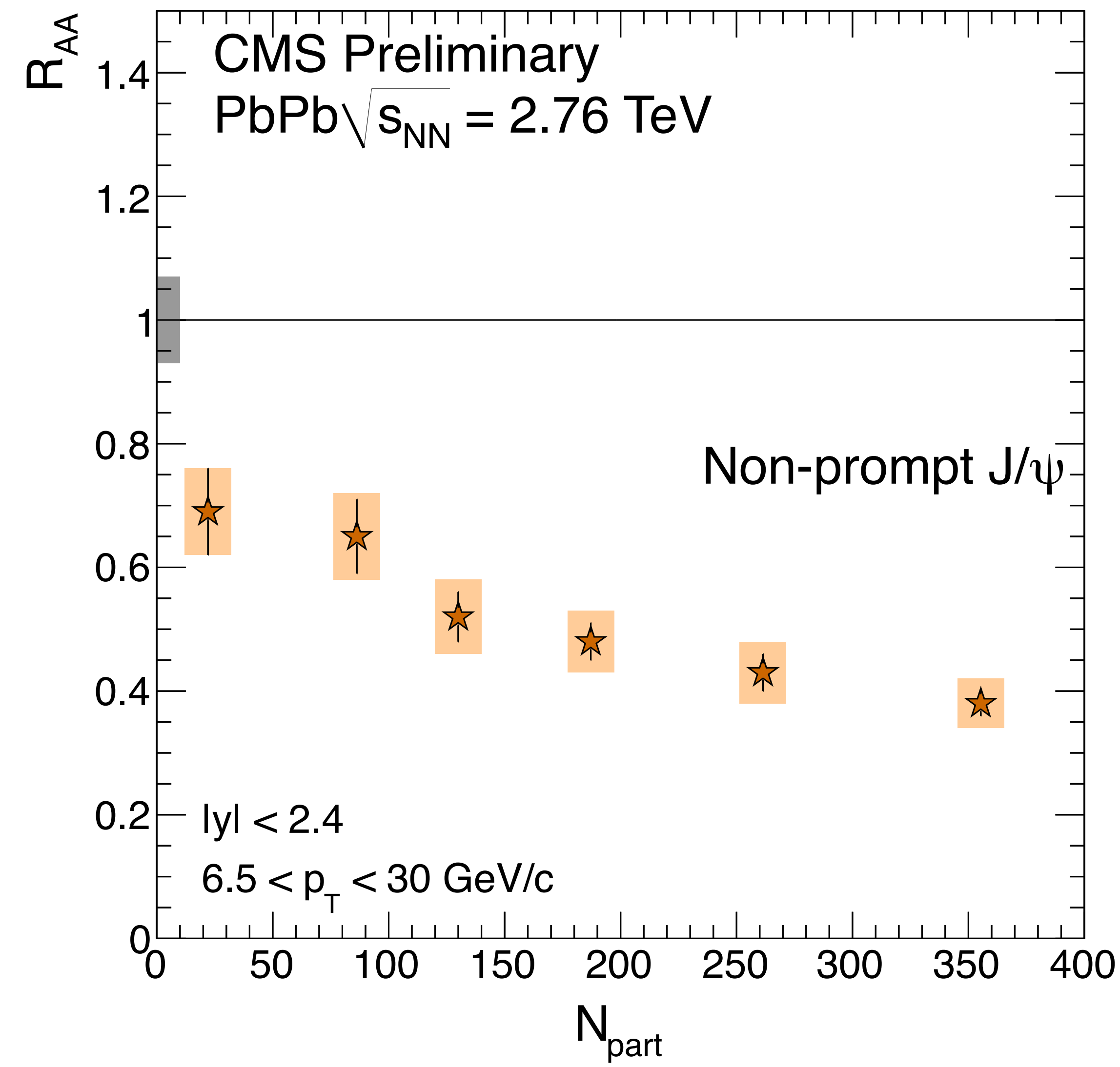
- > 1 enhancement
- = 1 no medium effect
- < 1 **suppression**

- **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)
  - measured from energy deposit in HF



J/ψ suppression





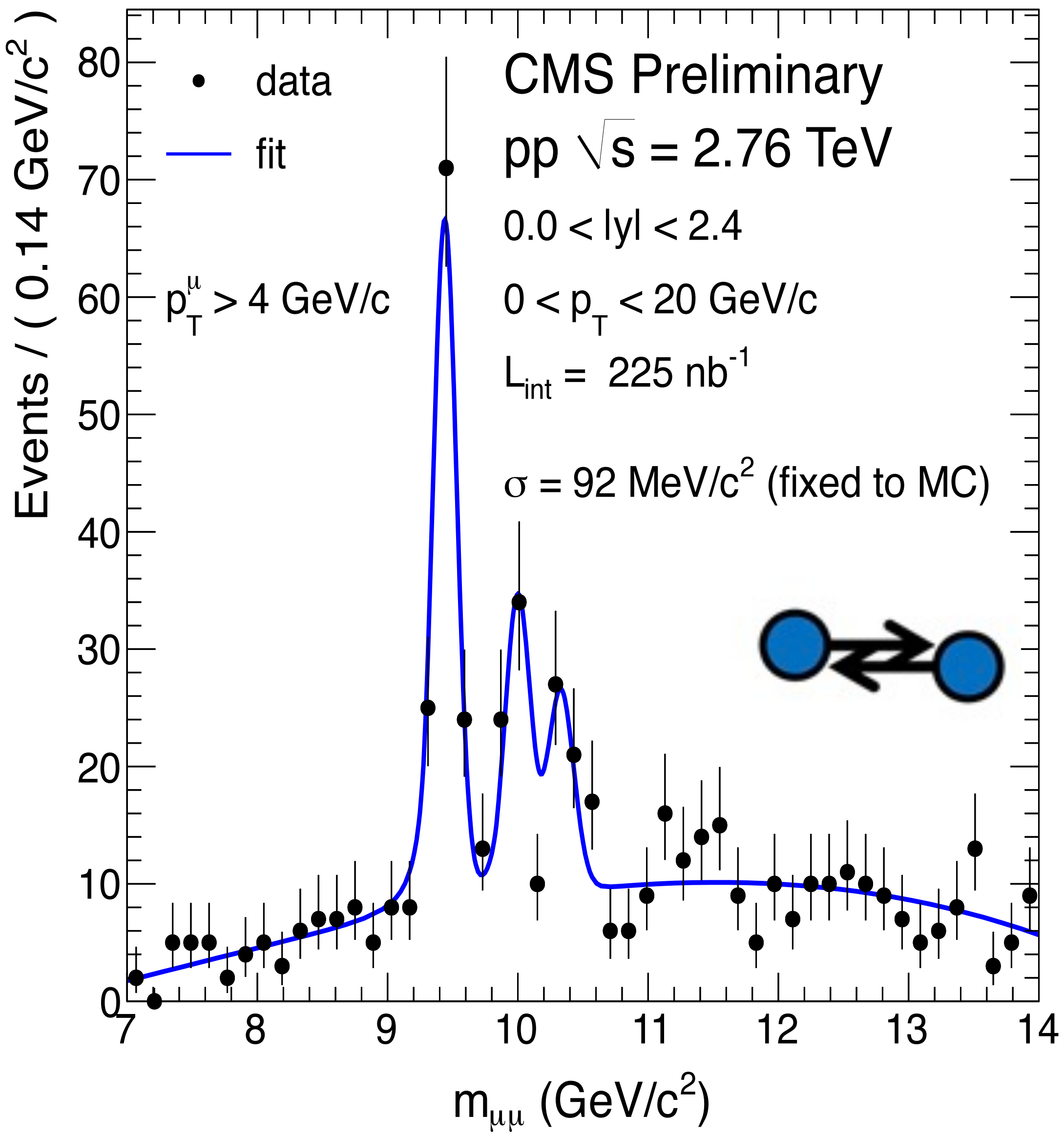
- prompt and non-prompt J/ψ separated for first time in heavy-ions
- prompt J/ψ is strongly suppressed as a function of coll. centrality
- non-prompt J/ψ shows for first time b-jets are quenched (high p_T)

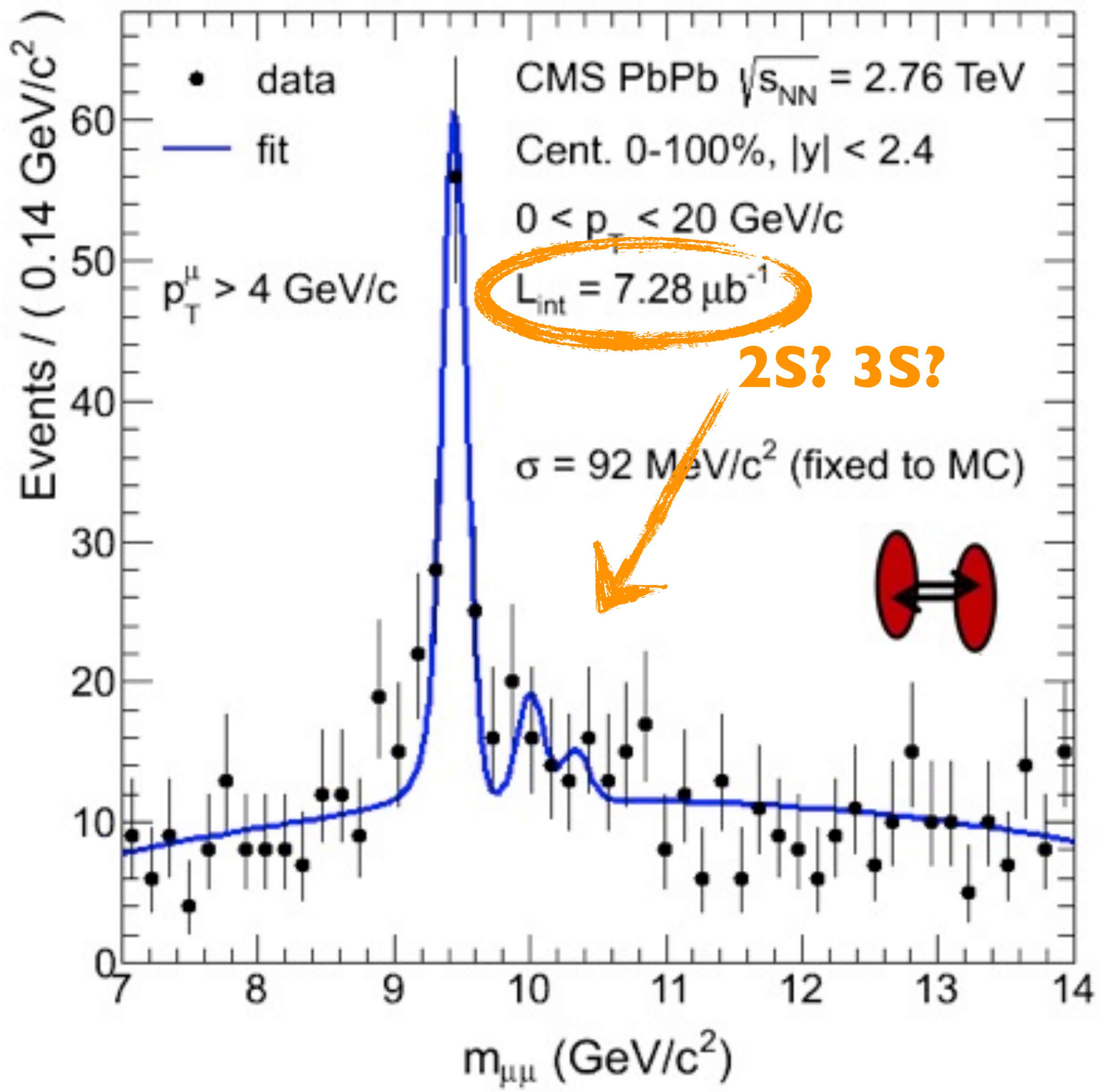
charmonia vs bottomonia

- J/ψ
  - extensively studied already at the SPS and RHIC
  - various competing factors complicate interpretation of observed suppression: feeddown (incl. b-hadrons), possible regeneration, etc ...
  - at CMS & LHC access higher p_T reach; detailed ψ(2S) studies needing larger datasets
- Υ
  - individual states measured for the first time by CMS (before unavailable)
  - no b feeddown; 3S not significantly affected by feeddown
  - Υ(nS) system offer multiple states: study relative peak suppression, where many ‘cold-nuclear effects cancel; statistical regeneration likely negligible;
  - bottomonia provide a powerful new QGP probe, opens a new avenue @LHC

Υ(nS) in pp... and in PbPb: where did Υ' go?

2010 PbPb data



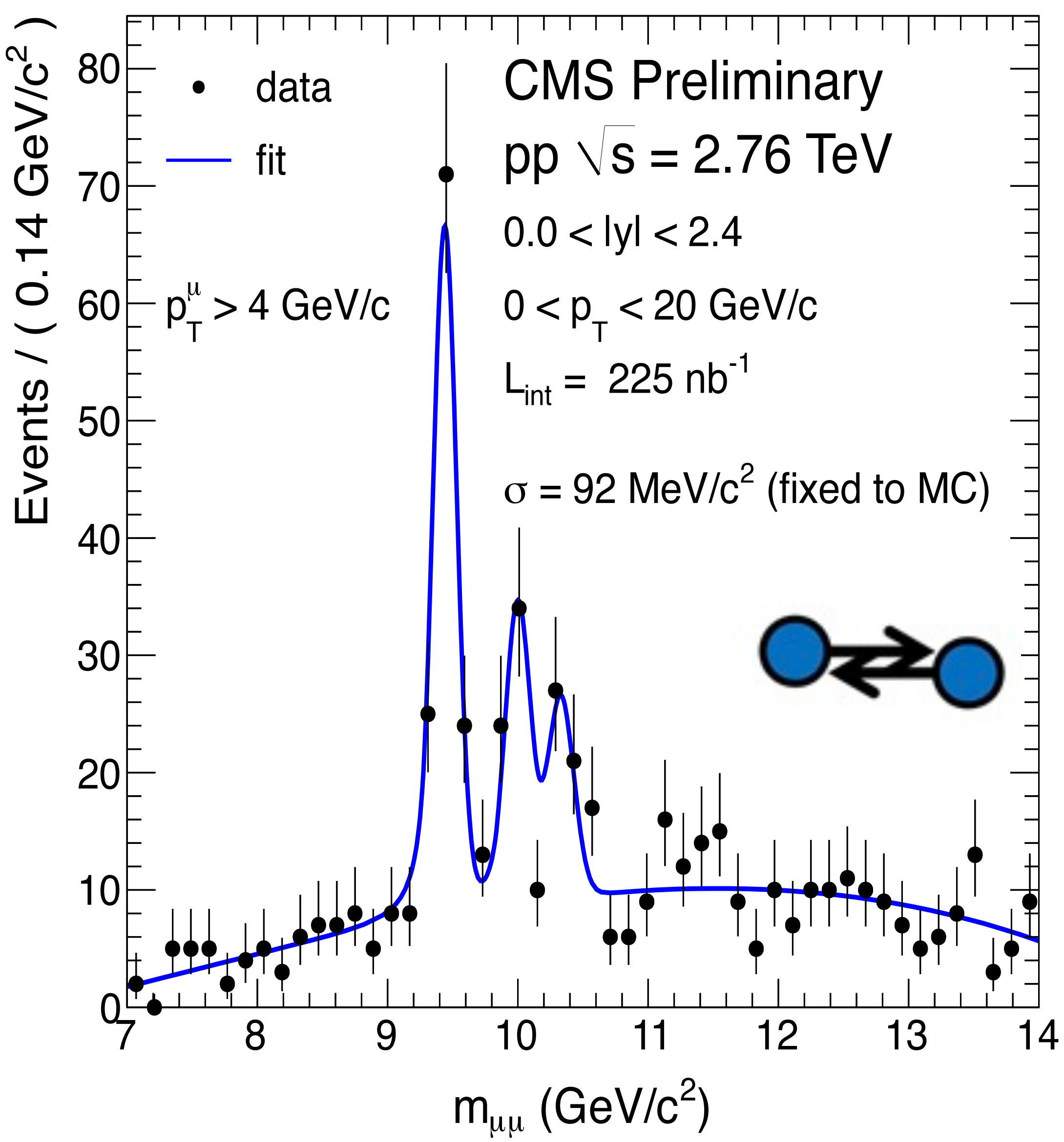


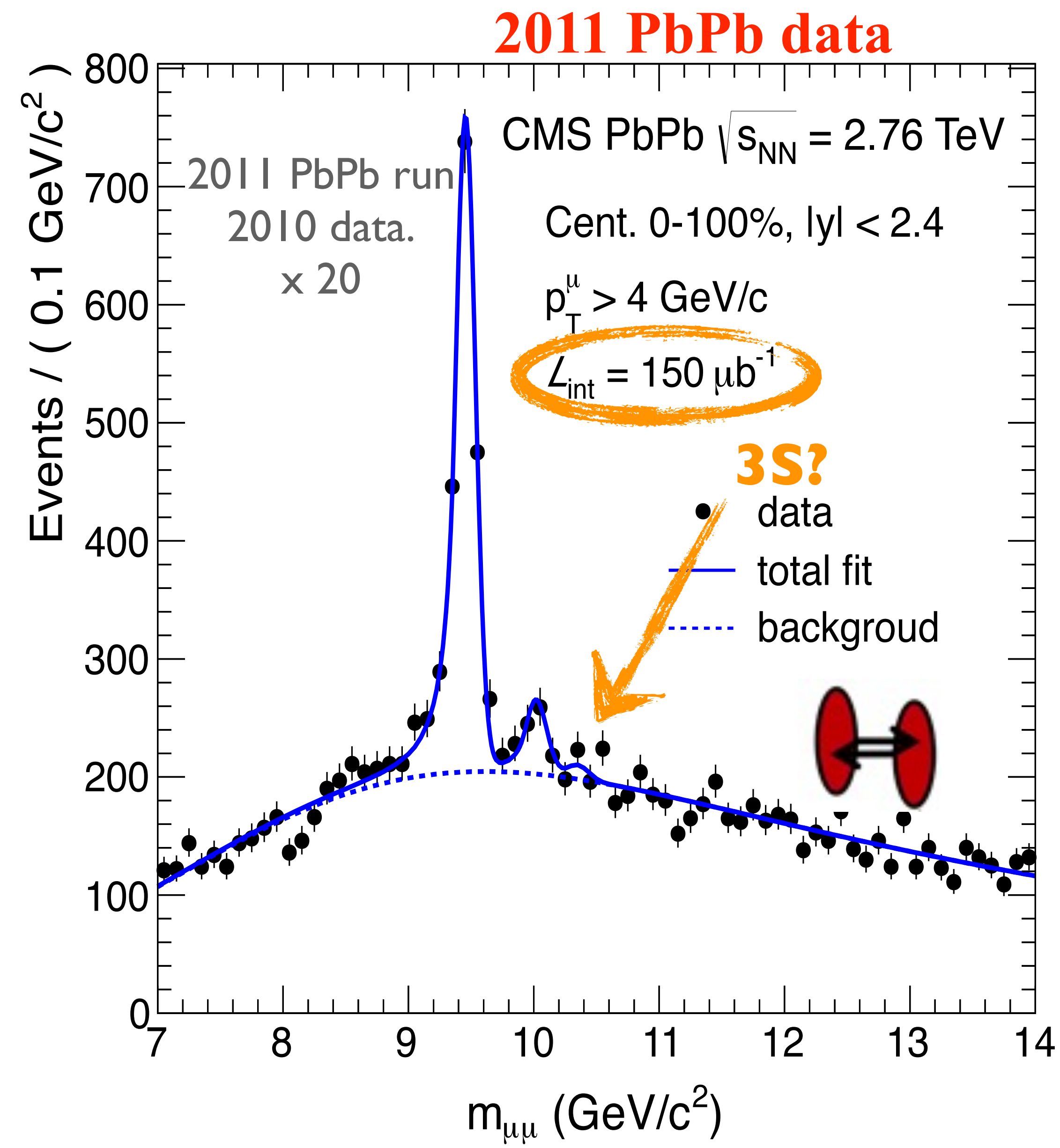
$$\chi_{23} = \frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

2S and 3S excited states suppressed
significance of effect 2.4σ (p-value 0.9%)

CMS, PRL107 (2011) 052302

Υ(nS) in pp...   and in PbPb: where did Υ' go?





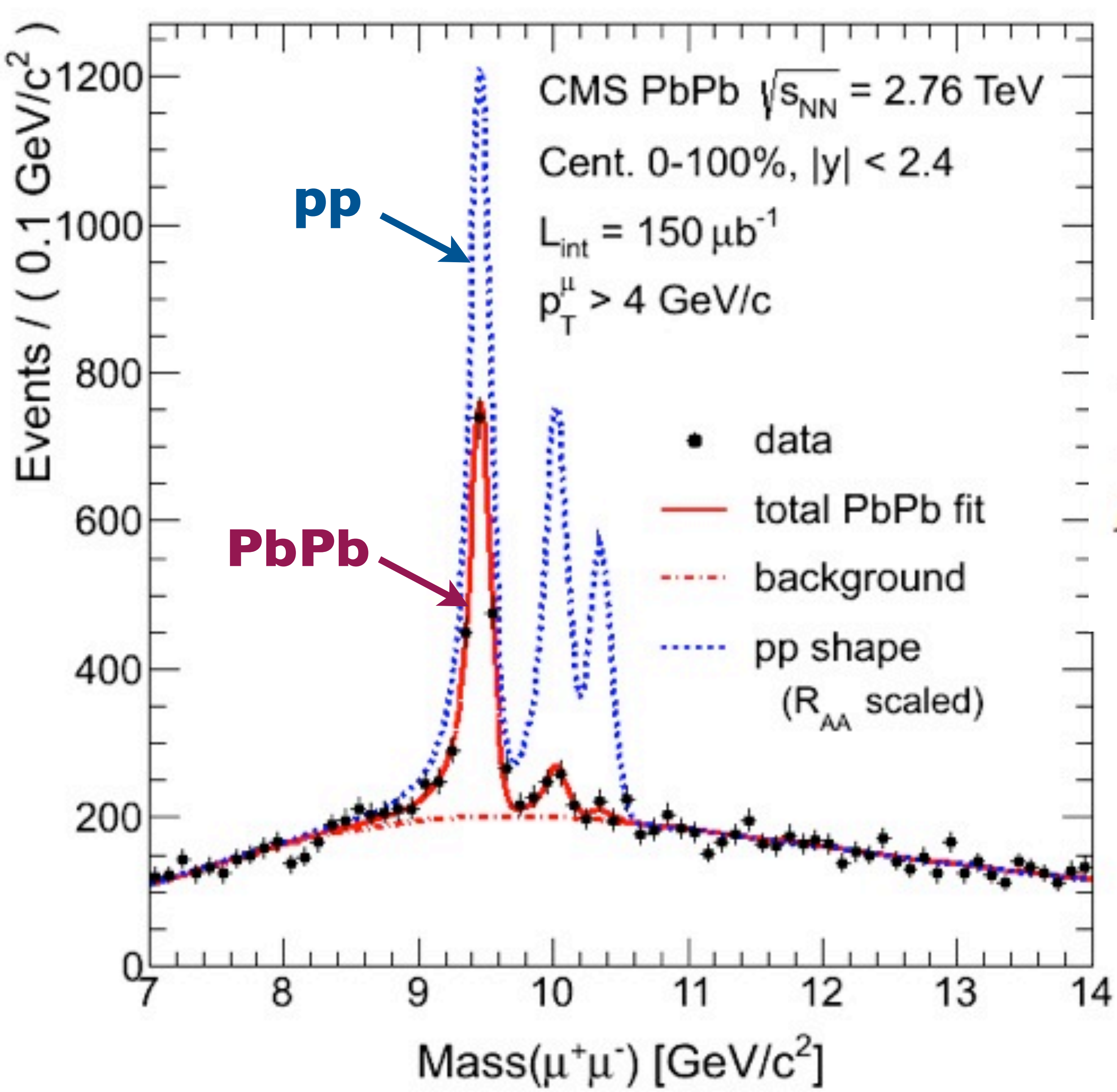
$\chi_{23} = 0.15 \pm 0.15 \pm 0.03$

⇨ 'no or *reduced Υ signal*'
(=suppression) is our signal !

observation of relative suppression
of the excited 2S and 3S states wrt 1S

statistical significance >5σ

Υ(nS) suppression



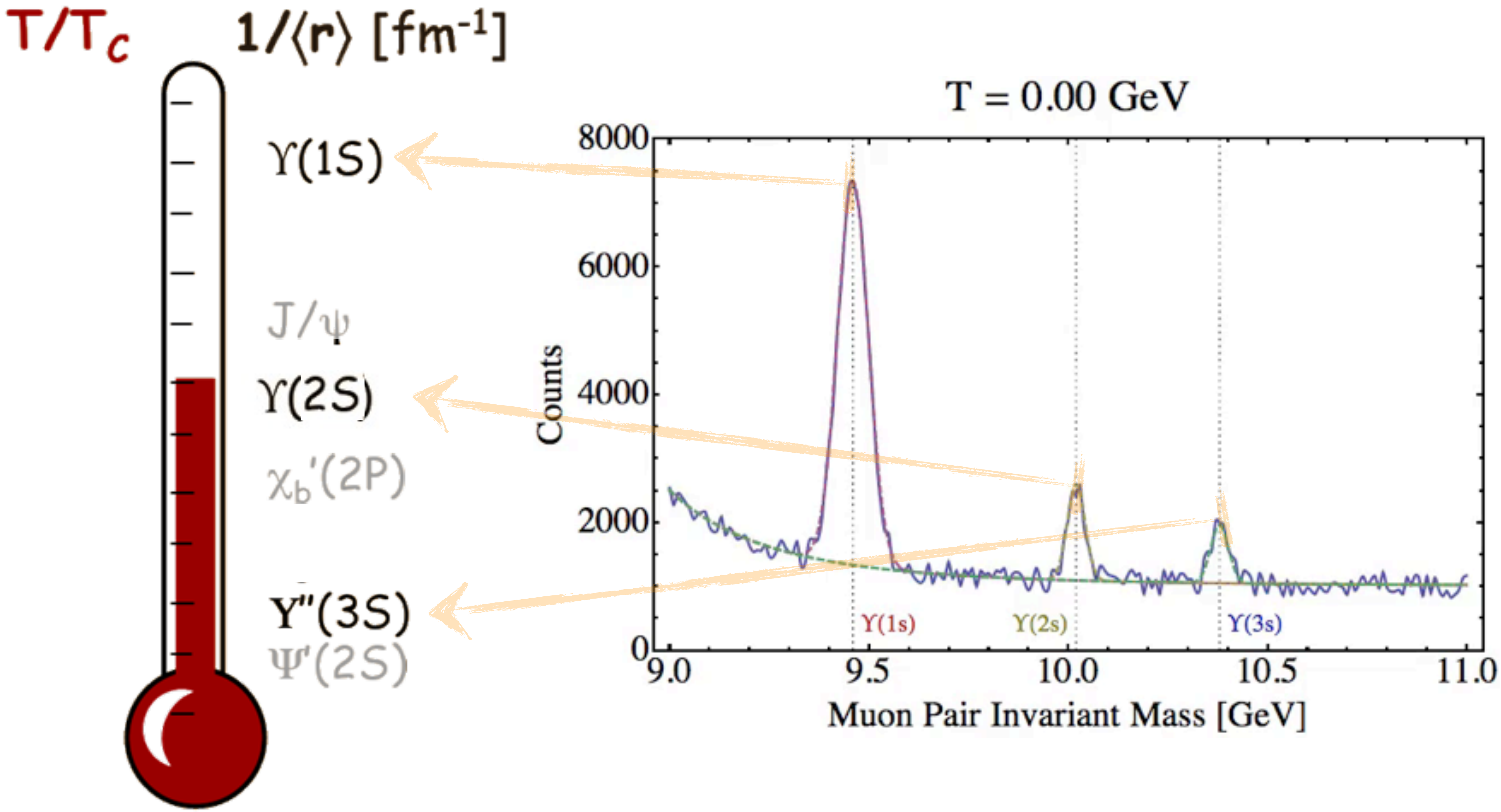
$$R_{AA} = \frac{\sigma(\text{PbPb})}{\sigma(\text{pp})}$$

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

$$\begin{aligned} R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.}) \\ R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.}) \\ R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \\ &< 0.10 \quad (95\%\ \text{C.L.})\,. \end{aligned}$$

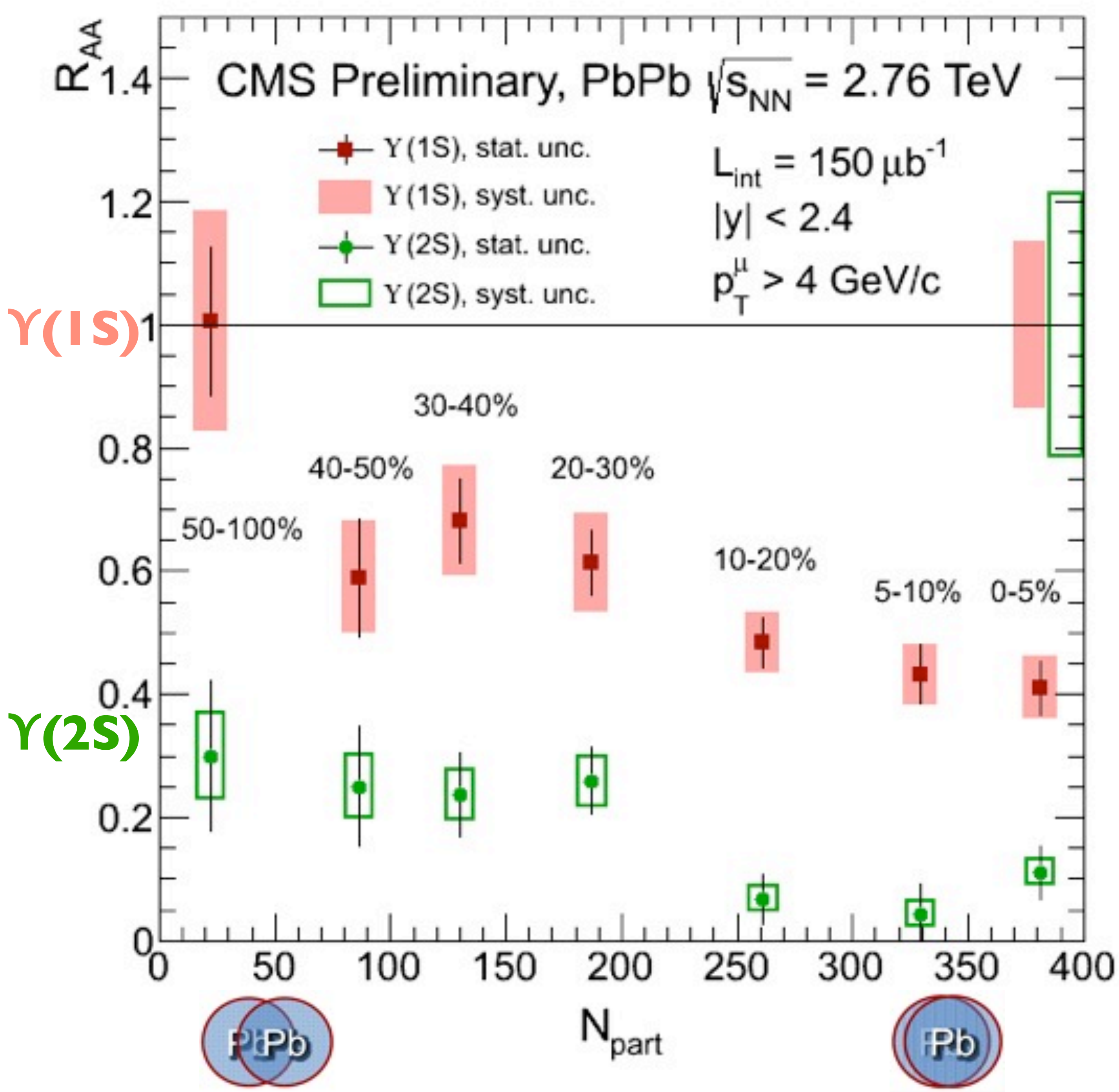
- all Υ states are suppressed, and *sequentially*
  - Υ(3S) → Υ(2S) → Υ(1S)

ϒ sequential melting!



ϒ suppression pattern established: ϒ(1S) < ϒ(2S) < ϒ(3S)

sequential suppression

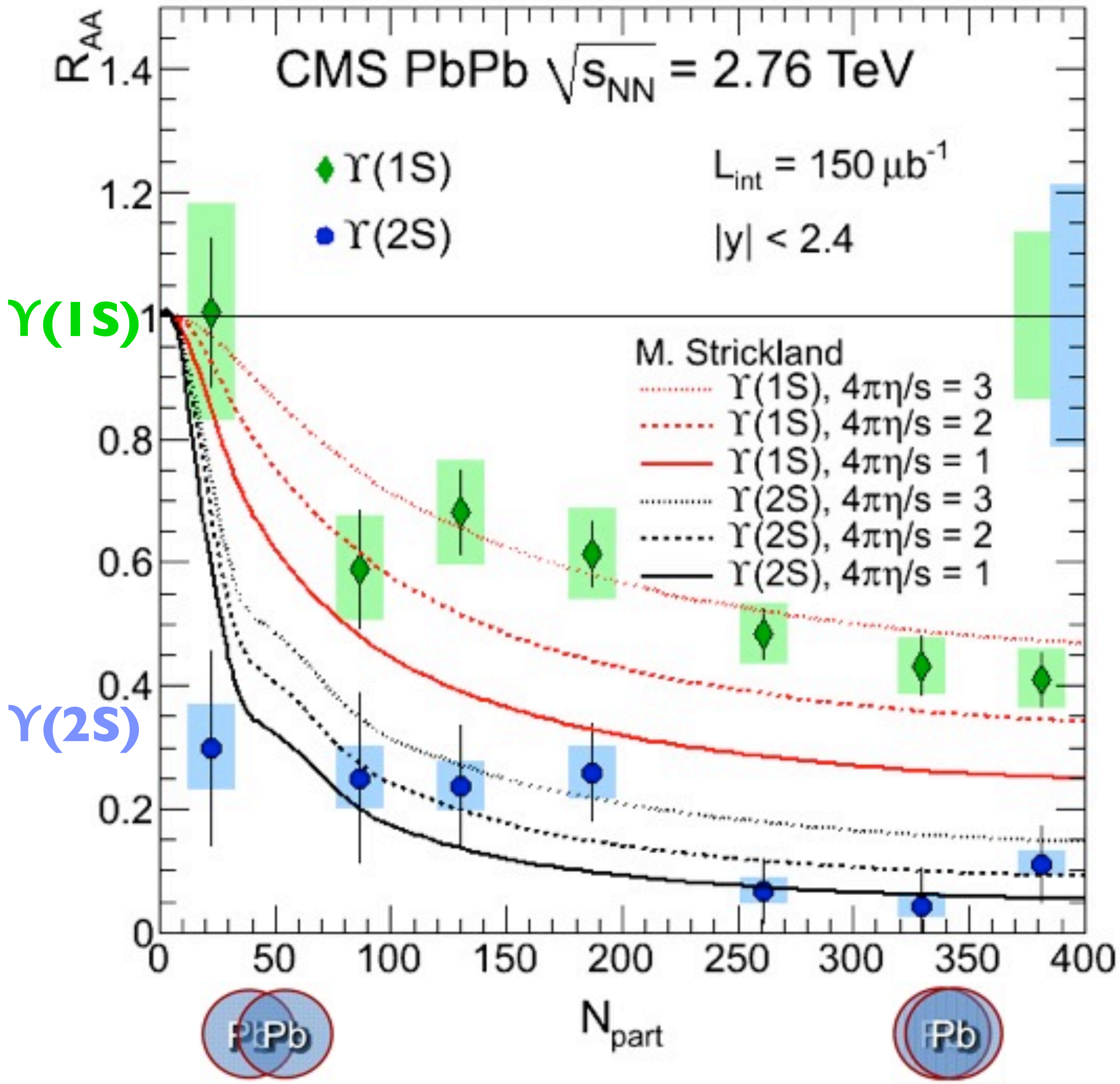


(centrality dependence)

- both 1S and 2S suppressions increase with centrality/N_{part}
- 2S,3S are more suppressed than 1S

suppression pattern observed: Υ(1S) < Υ(2S) < Υ(3S)

sequential suppression

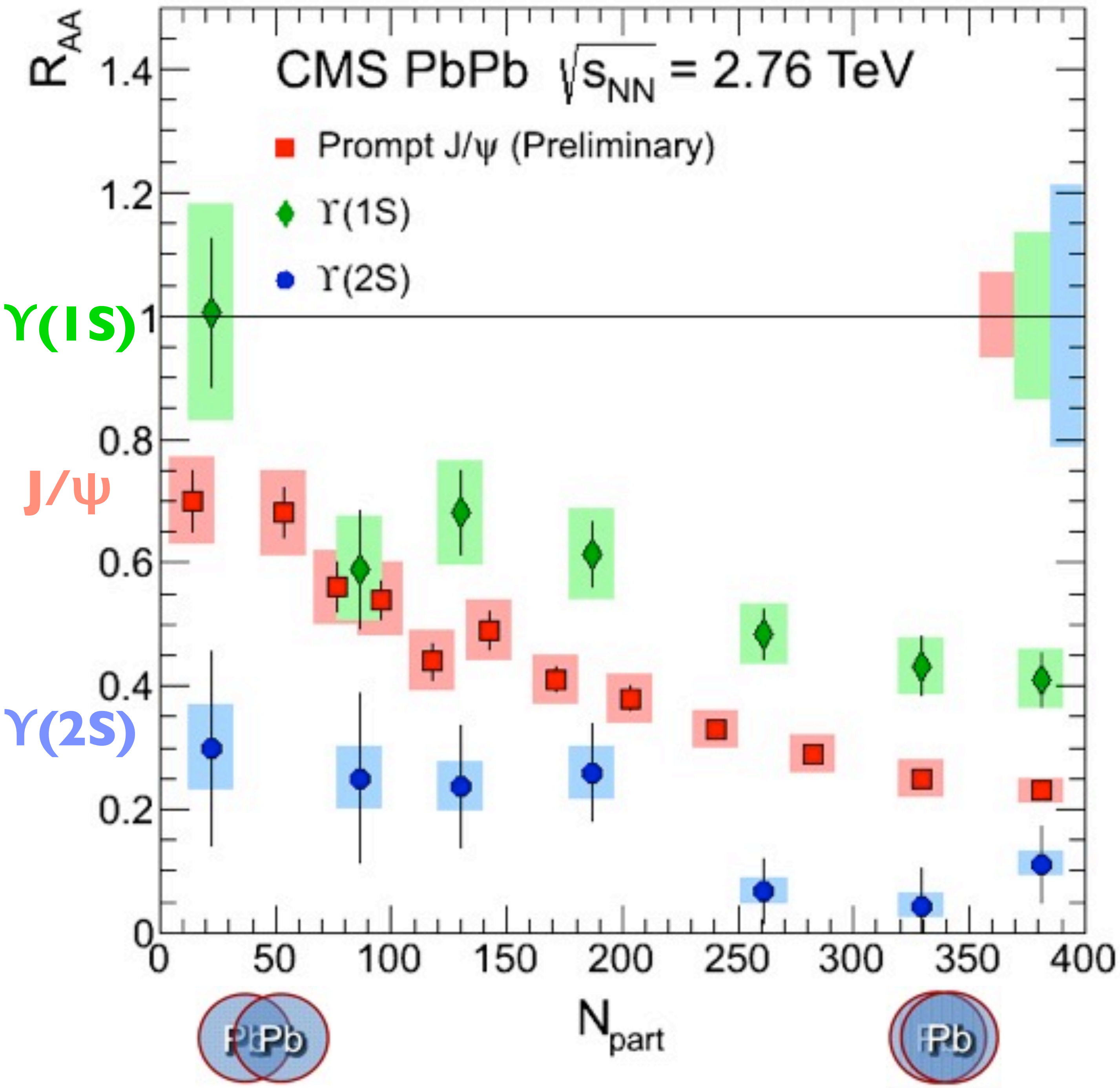


(centrality dependence)

- both 1S and 2S suppressions increase with centrality/N_{part}
- 2S,3S are more suppressed than 1S
- data allow discrimination amongst models/parameters

suppression pattern observed: ϒ(1S) < ϒ(2S) < ϒ(3S)

sequential suppression

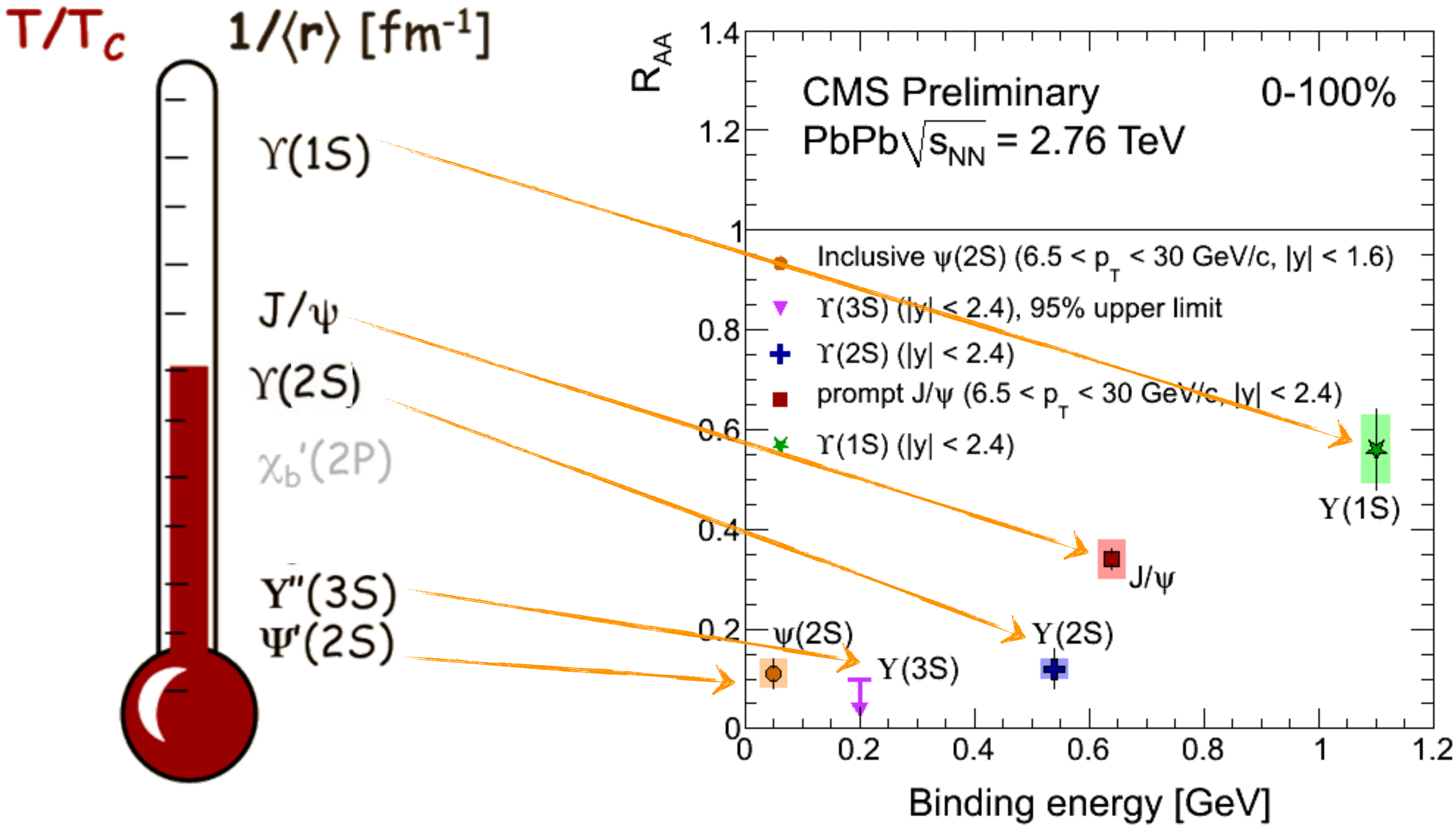


(centrality dependence)

- both 1S and 2S suppressions increase with centrality/N_{part}
- 2S,3S are more suppressed than 1S
- data allow discrimination amongst models/parameters
- J/ψ is more suppressed than ϒ(1S), and less than ϒ(2S)

suppression pattern observed: ϒ(1S) < J/ψ <ϒ(2S) < ϒ(3S)

quarkonia sequential suppression



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

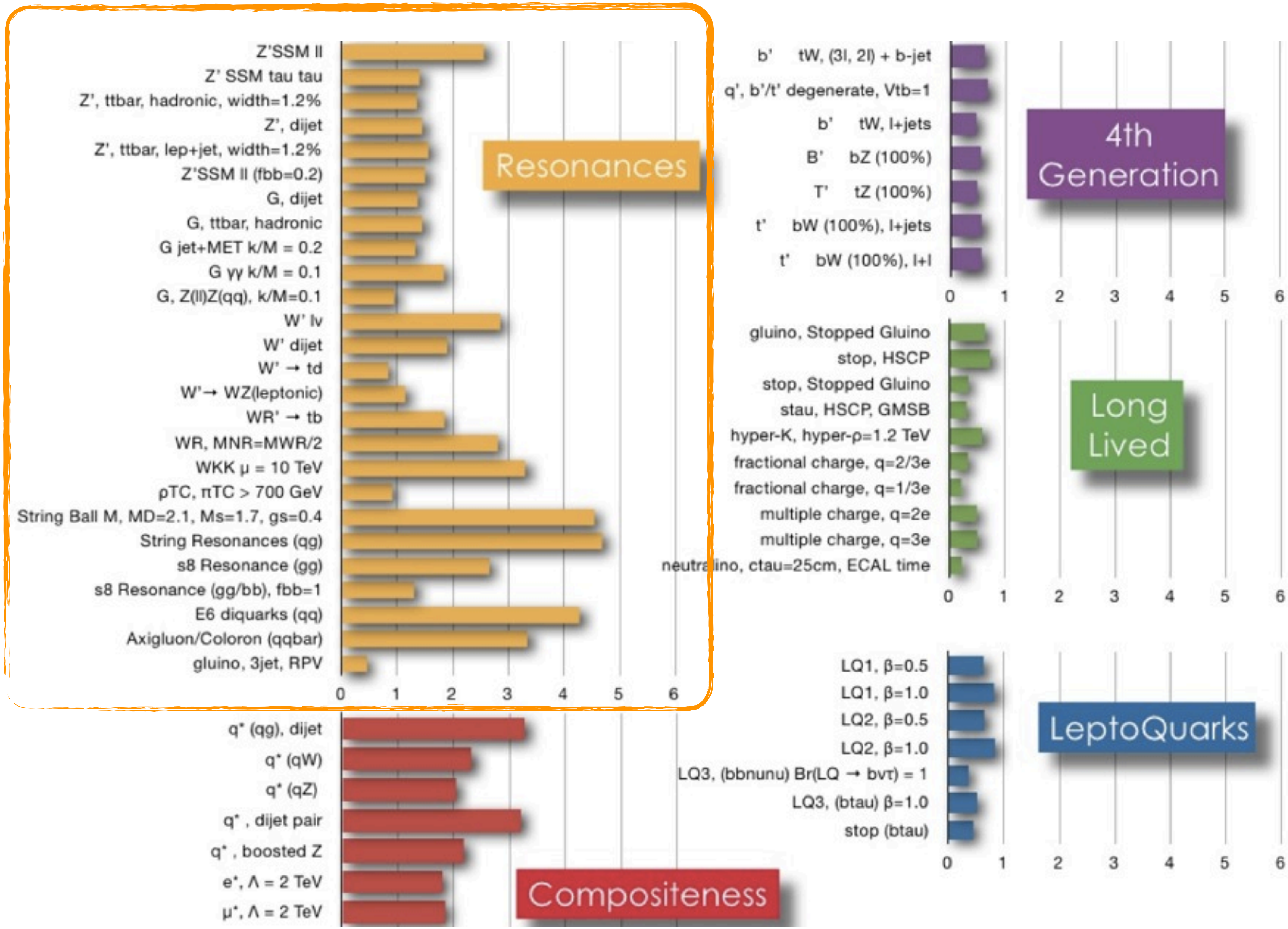
summary

- the LHC machine and experiments are doing fantastically well
- many signals have been extracted, and many relevant measurements continue to be diligently carried out
- a new boson observed with about 125 GeV, consistent with SM Higgs
- no clear evidence for signals from Beyond the Standard Model − yet
  - search reinforced with higher energy, luminosity, and extended approaches
- observed suppression of quarkonium states in strongly-coupled medium
  - and established its sequential pattern
- more data (pp, PbPb, pPb) will continue to be accumulated, allowing extended measurements and novel searches
  - evidence for new phenomena, ground breaking signals remain excitingly imminent.

Thank you.

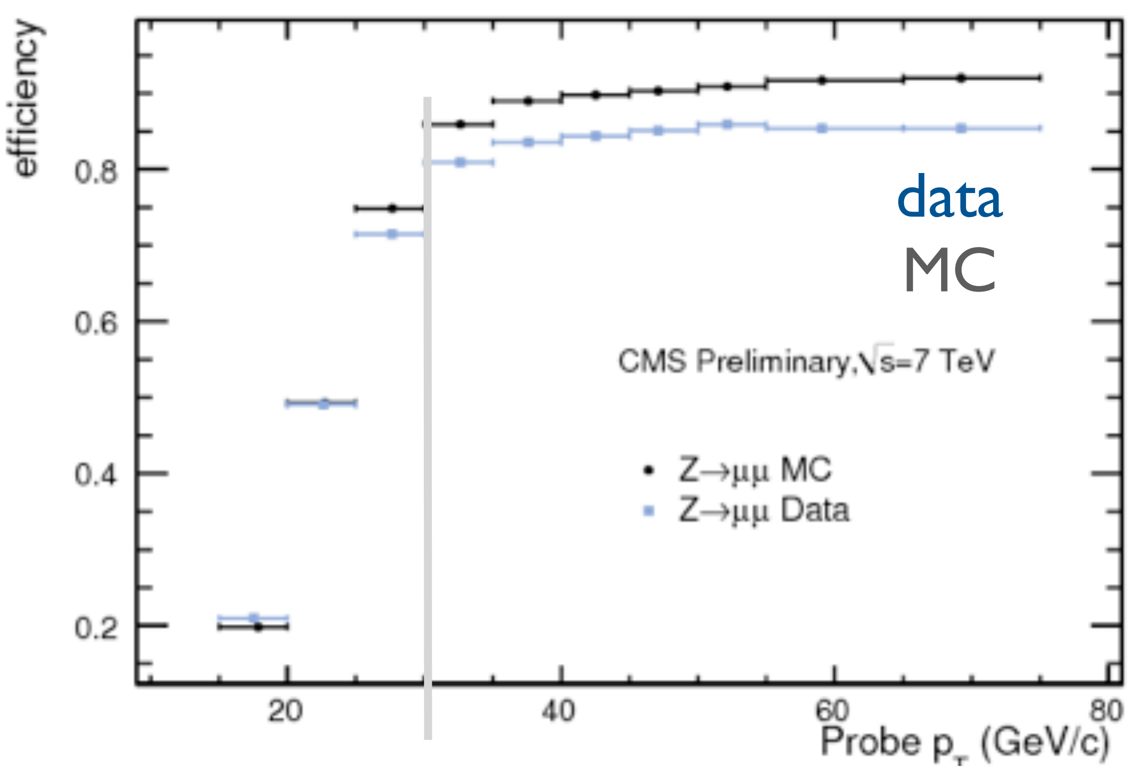
[exotica exclusion thresholds]

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



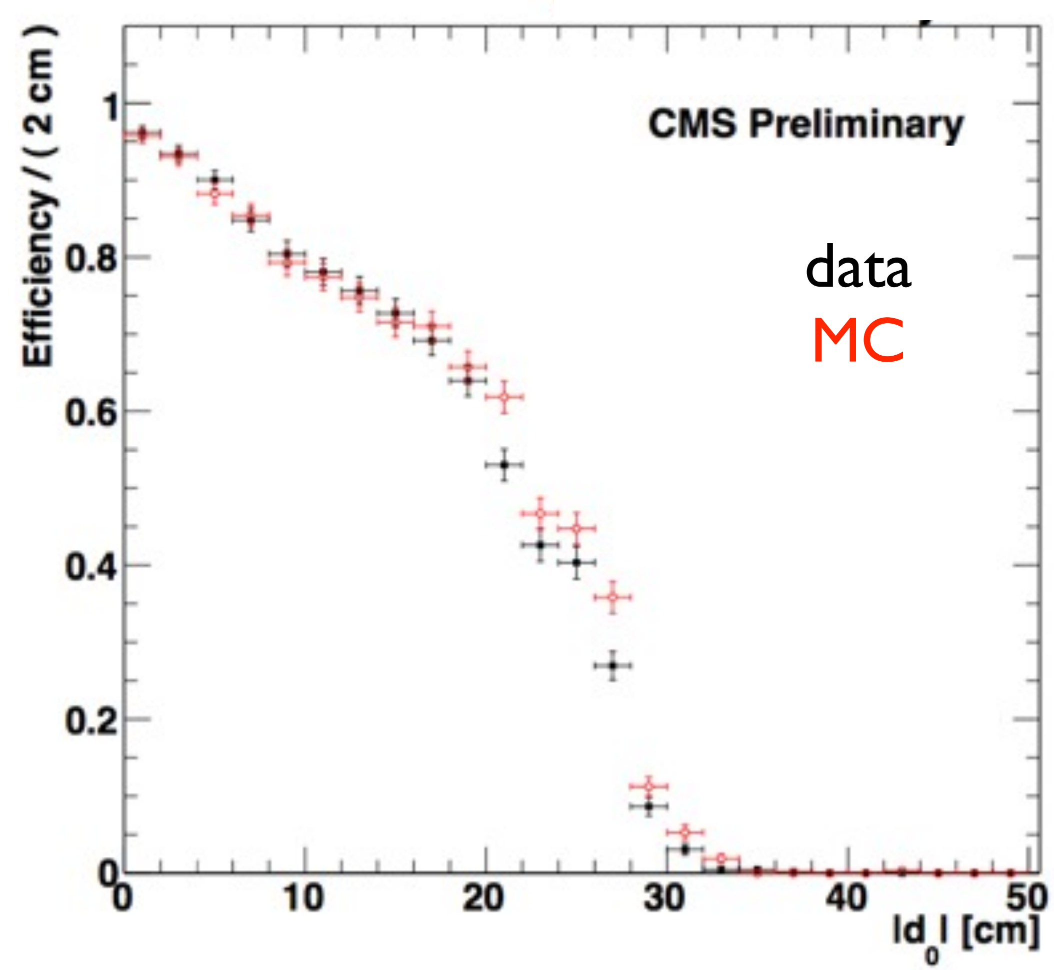
[long-lived exotica]
data-driven efficiencies

- trigger efficiency: evaluated with tag & probe on Z peak
  - (also J/ψ for boosting effects)
  - data-mc systematic: 11%



- tracking efficiency: evaluated employing cosmic muon data
  - data-mc systematic: 20%

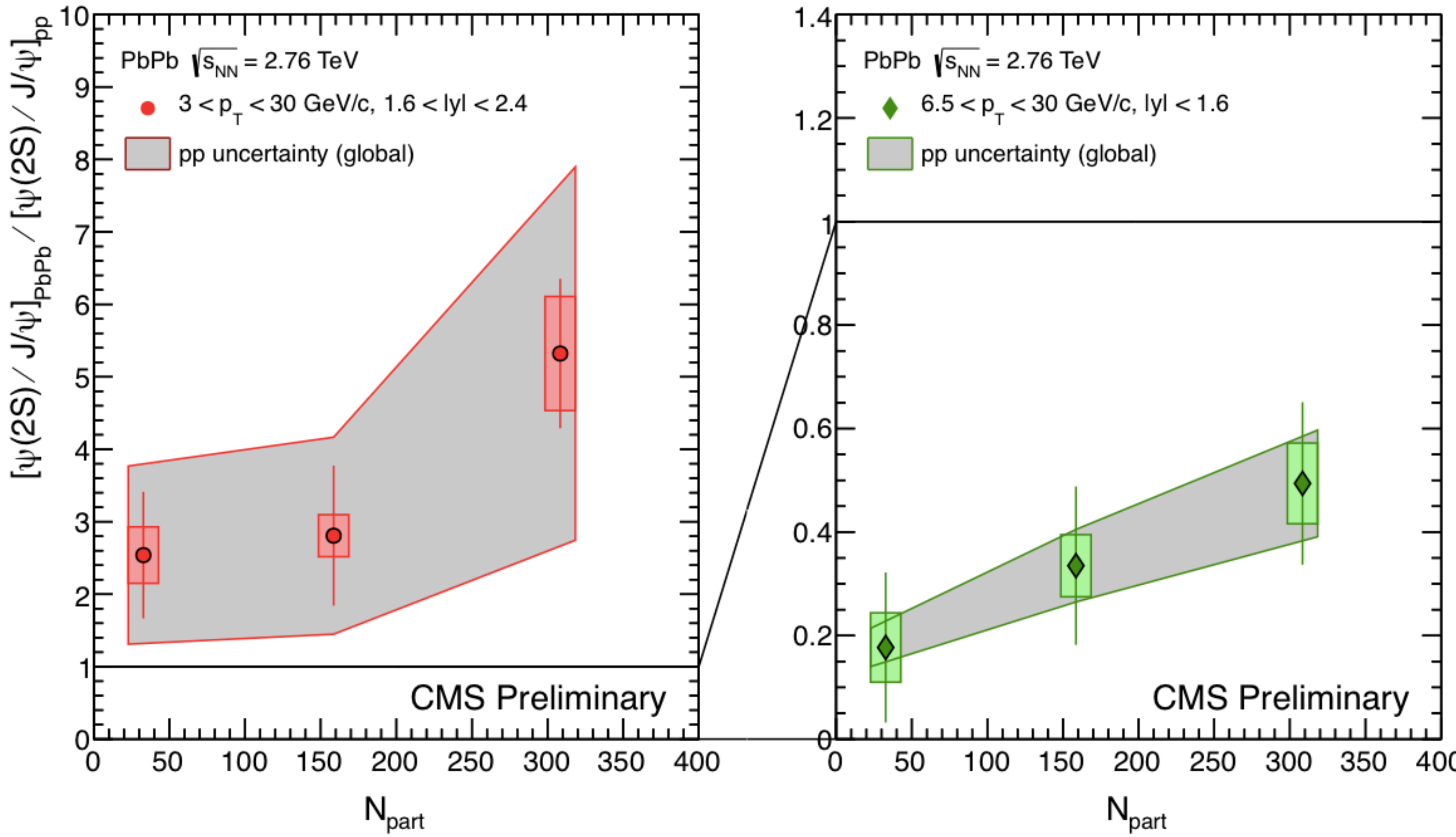
CMS EXO-11-101



Overall signal efficiency range 4-30% (electrons), 5-50% (muons)

[excited charmonium suppression]
ψ(2S) vs J/ψ

double ratio



CMS-HIN-12-007

For p_T>3 GeV/c and 1.6<|y|<2.4:
Indication of ψ(2S) being less suppressed than J/ψ, but more pp data is needed.

⇓

$$R_{AA}^{0-100\%}(\psi(2S)) = 1.54 \pm 0.32\,(\text{stat}) \pm 0.22\,(\text{syst}) \pm 0.76\,(\text{pp})$$

R_{AA} (J/ψ) = 0.41 ± 0.06

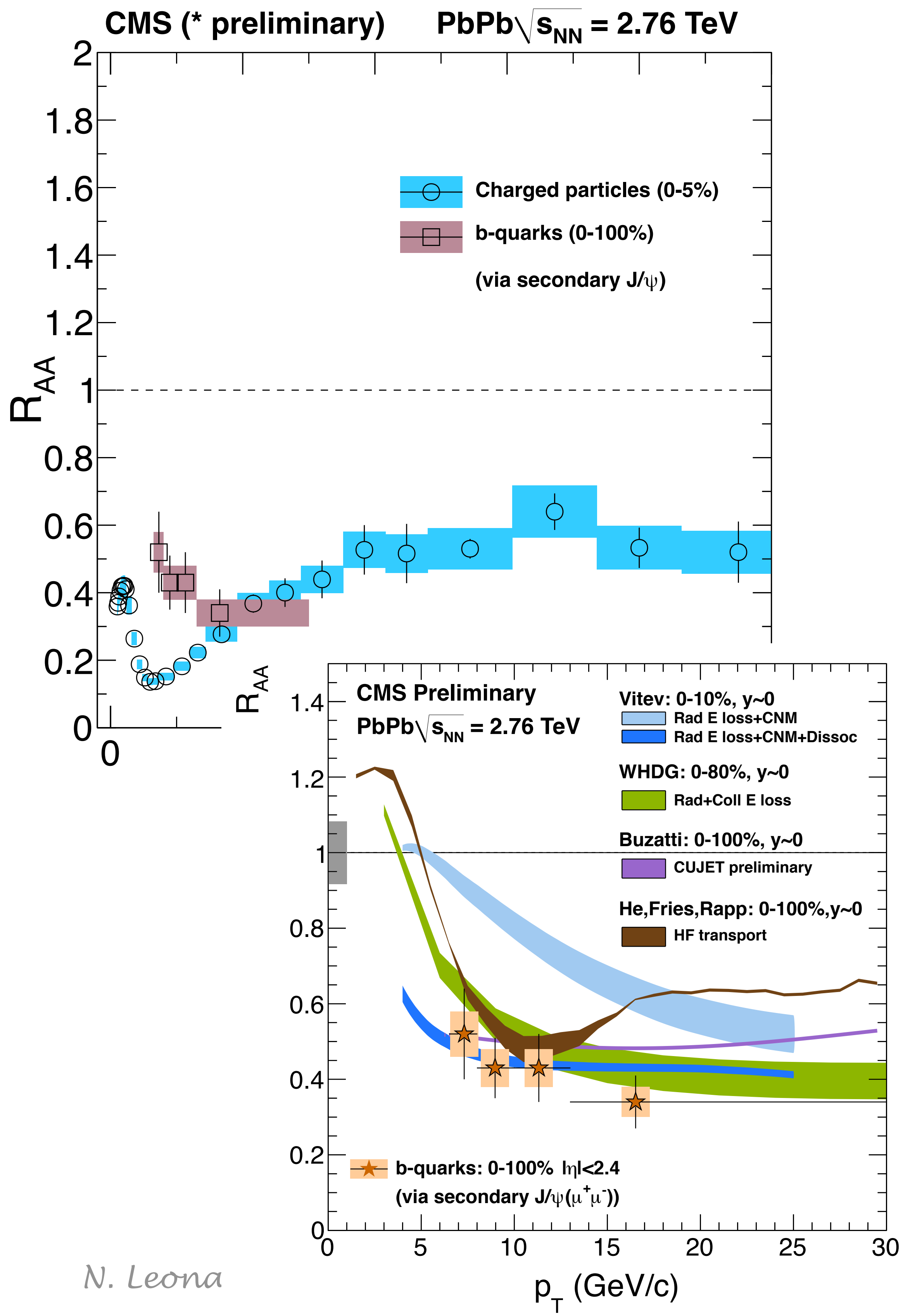
For p_T >6.5 GeV/c and |y|<1.6:
ψ(2S) are more suppressed than J/ψ

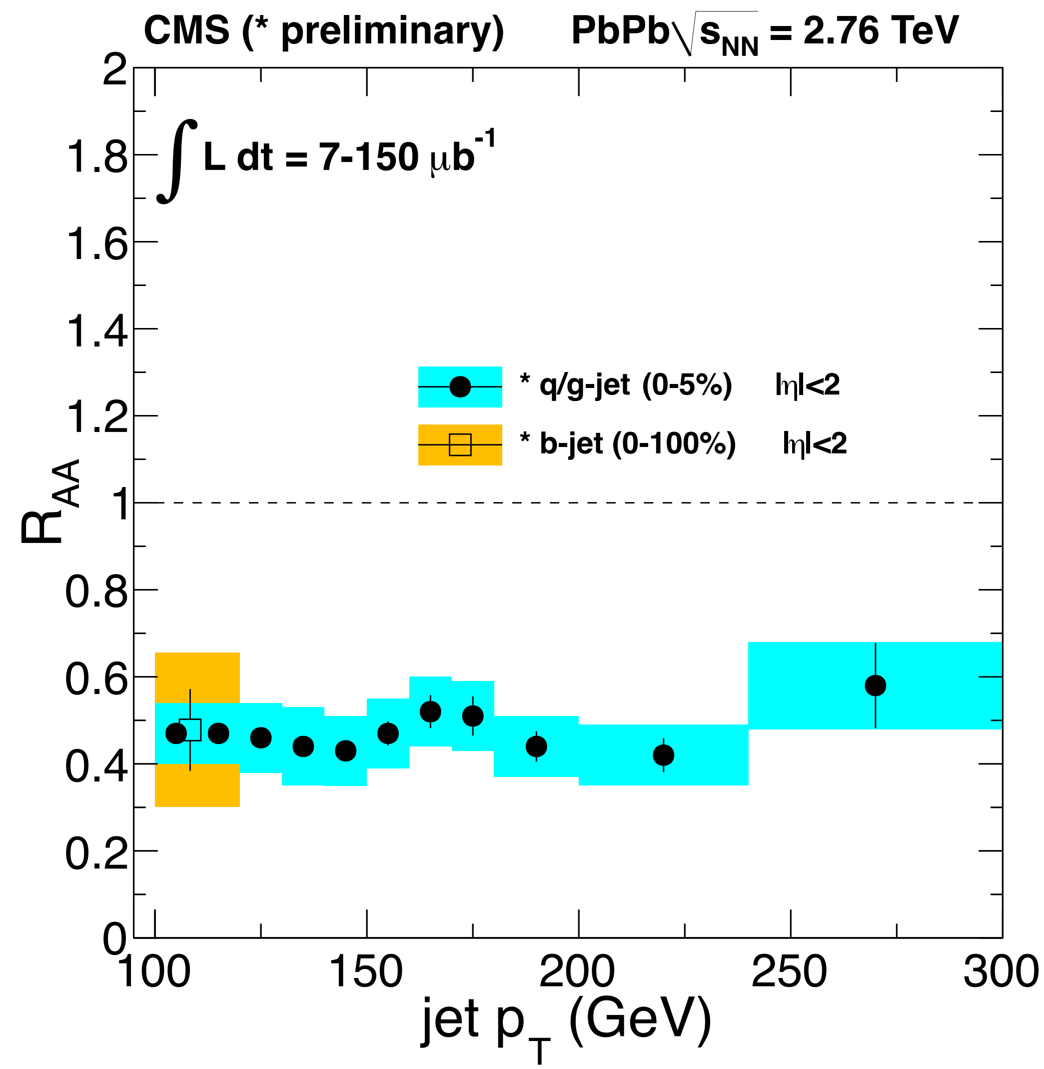
⇓

$$R_{AA}^{0-100\%}(\psi(2S)) = 0.11 \pm 0.03\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.02\,(\text{pp})$$

R_{AA} (J/ψ) = 0.29 ± 0.05

parton energy loss [in the medium]





at low-p_T:
different suppression pattern than light

at high-p_T:
b and light similar suppression

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CMS-PAS HIN-12-004
CMS-PAS HIN-12-014