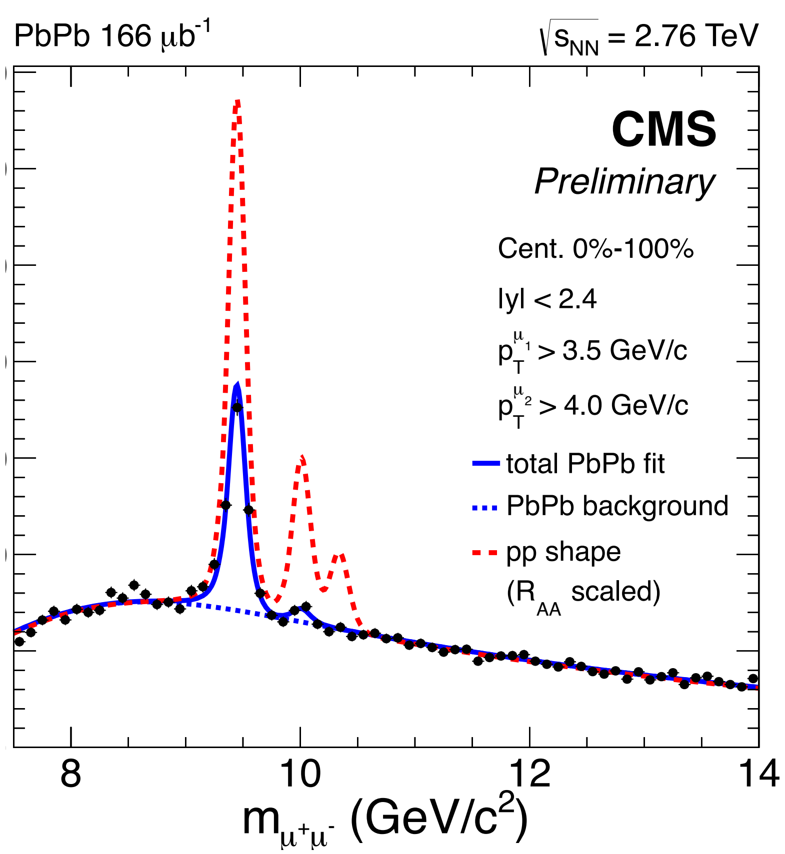
Measurements of Υ suppression in heavy ion collisions with the CMS Experiment



Nicolas Filipovic

UNIVERSITÉ PARIS SUD

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CMS
Compact Muon Solenoid

Outline

- Strong interactions
- Heavy ion collisions
- Quarkonia
- Experimental aspects
- Analysis
- Results and outlook

Strong interactions

One of the 4 fundamental
forces in observed nature

- The *strongest* interaction
  at the core of stable matter

- Strength: ~100 times electromagnetism

- Distances < 1 *fm*

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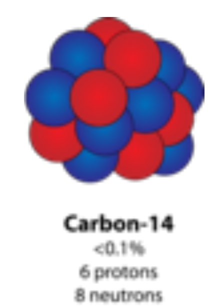
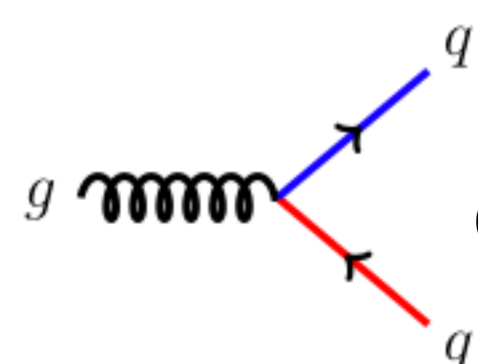
D. Hasselhoff

Caffeine



Carbon-14



Quarks and gluons

Strong interactions

One of the 4 fundamental forces in observed nature

D. Hasselhoff

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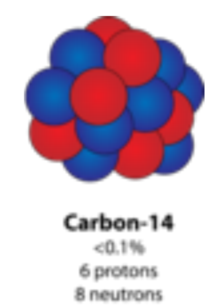
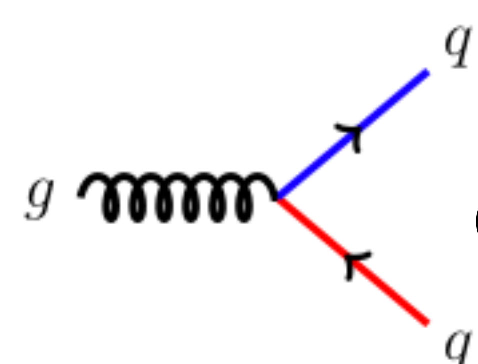


Carbon-14

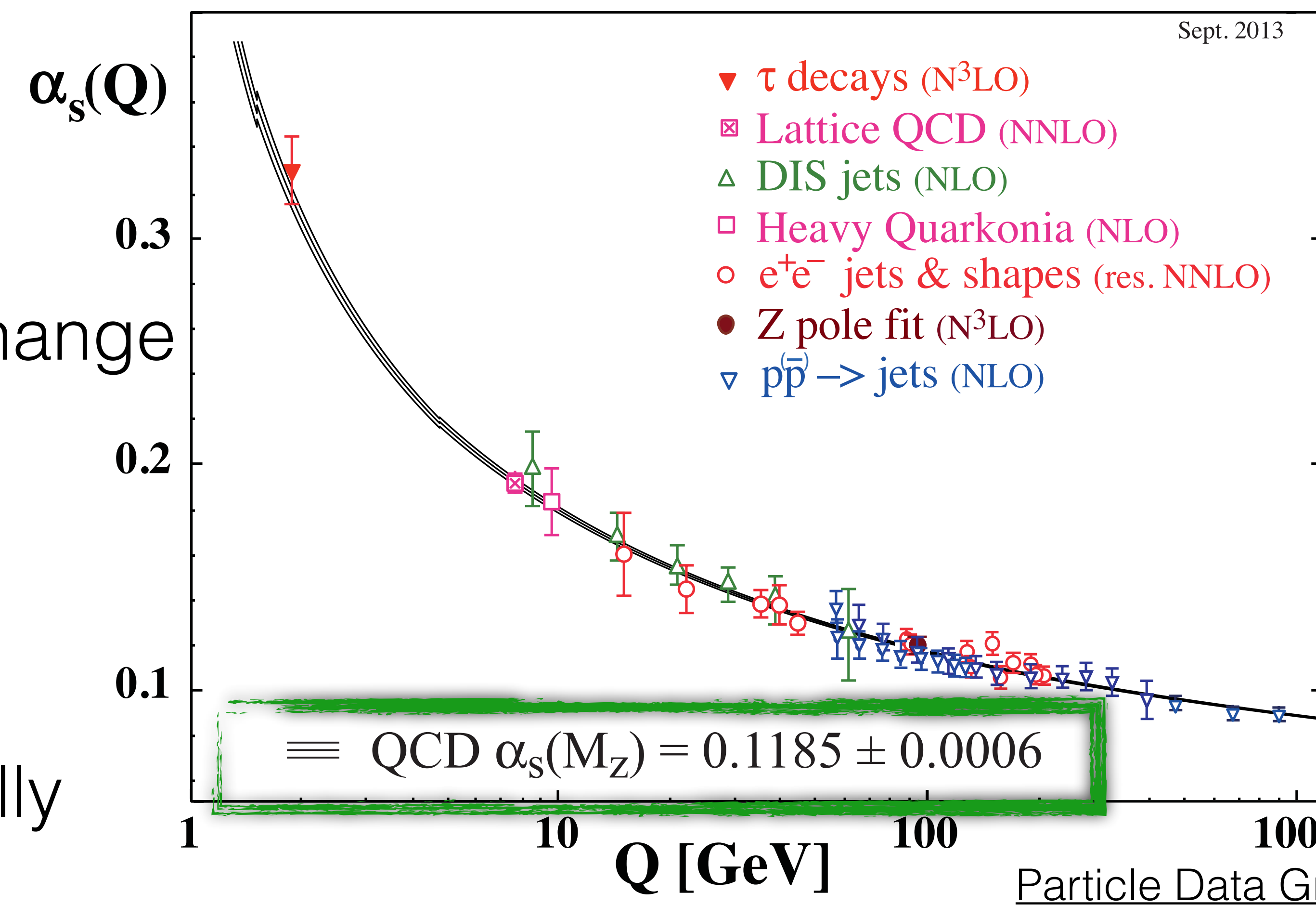
- **Quantum Chromodynamics (QCD)** is the quantum-mechanical formulation of this theory.



Quarks and gluons

Properties of QCD - 1

- Asymptotic freedom:
  - Coupling decreases with increasing momentum exchange
  - α_S can be determined experimentally, and is usually expressed at the Z mass



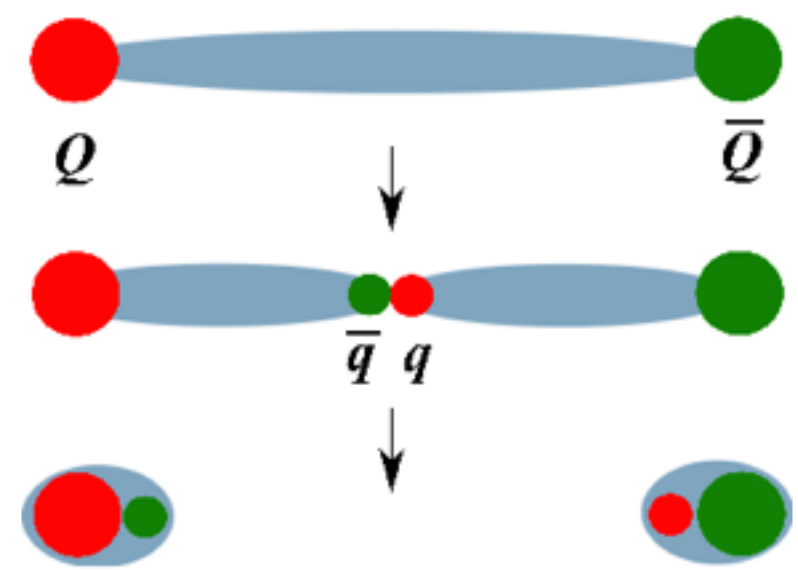
Particle Data Group

Large Q: perturbative domain
Q < 1 GeV: non-perturbative QCD

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

Properties of QCD - 2

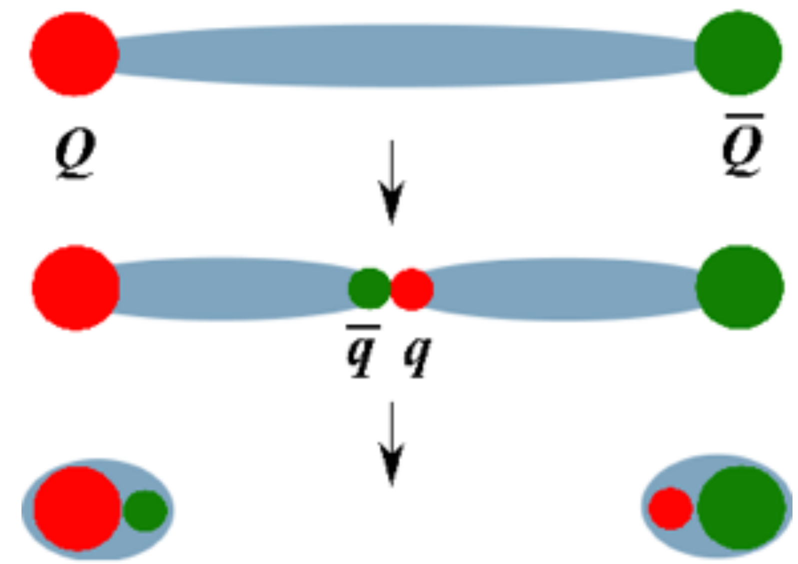
- Colour confinement:
    - Observed matter (hadrons) is **colour neutral**
    - **but quarks carry a colour, (RGB)**
    - **gluons carry two colours…**



Properties of QCD - 2

- Colour confinement:
  - Observed matter (hadrons) is **colour neutral**
  - **but quarks carry a colour, (RGB)**
  - **gluons carry two colours…**

Confinement: partons ‘dress up’
Colours equilibrate each other
Quarks and gluons are trapped



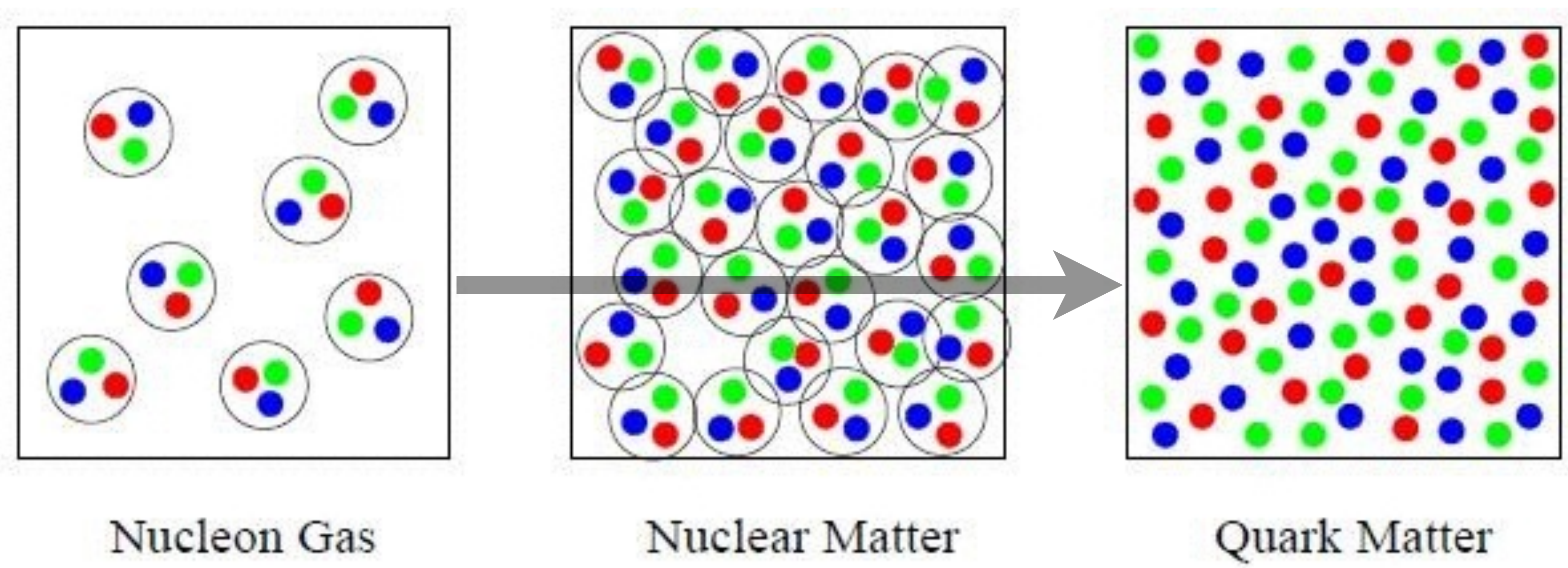
Andréa Andriya Filipovic

Towards deconfinement

- Coloured quarks and gluons are trapped in nuclear matter
- Increasing the temperature, nuclear matter undergoes a transition towards quark matter

Quark-gluon plasma

Confined



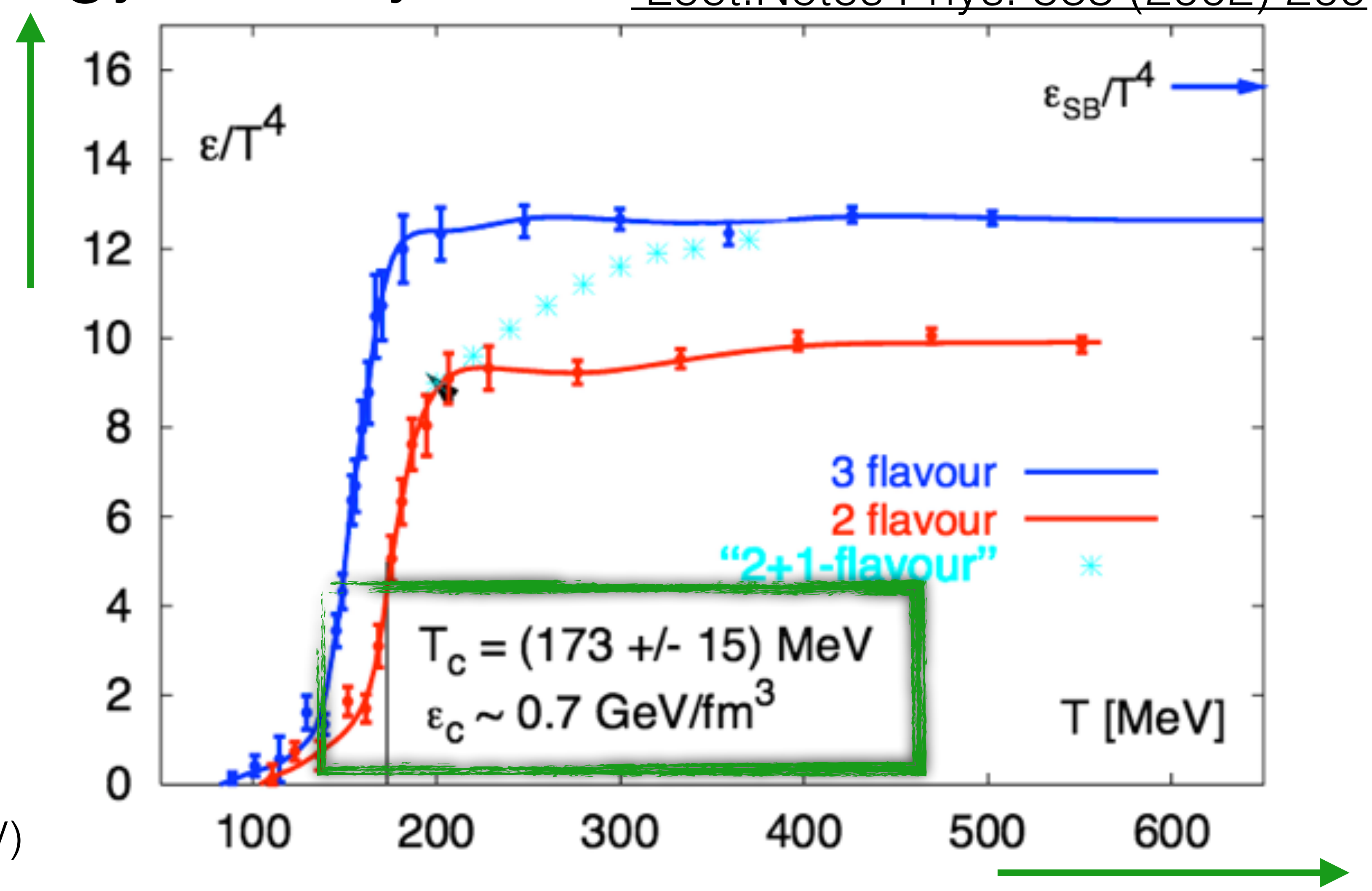
Deconfined

Quark-gluon plasma (QGP)

- Critical temperature: obtained in Lattice QCD calculations

Energy density

F. Karsch,
Lect.Notes Phys. 583 (2002) 209

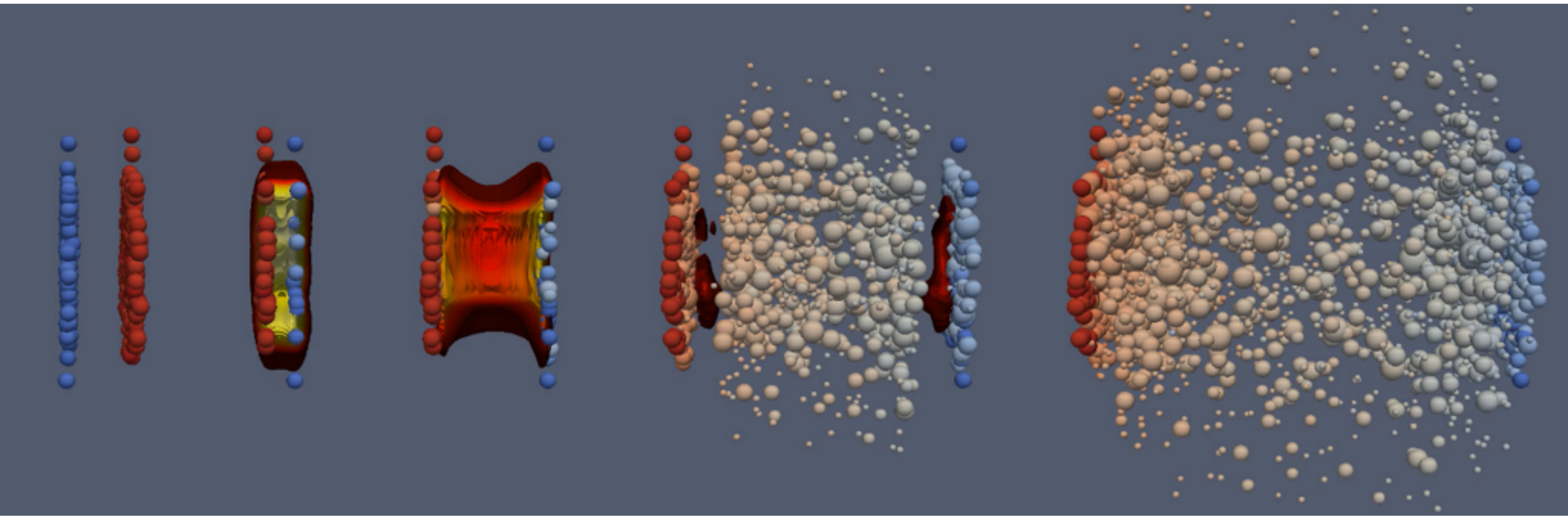


Temperature

Such temperatures and densities are experimentally achievable

(State-of-the-art calculations, T ~ 154 MeV)

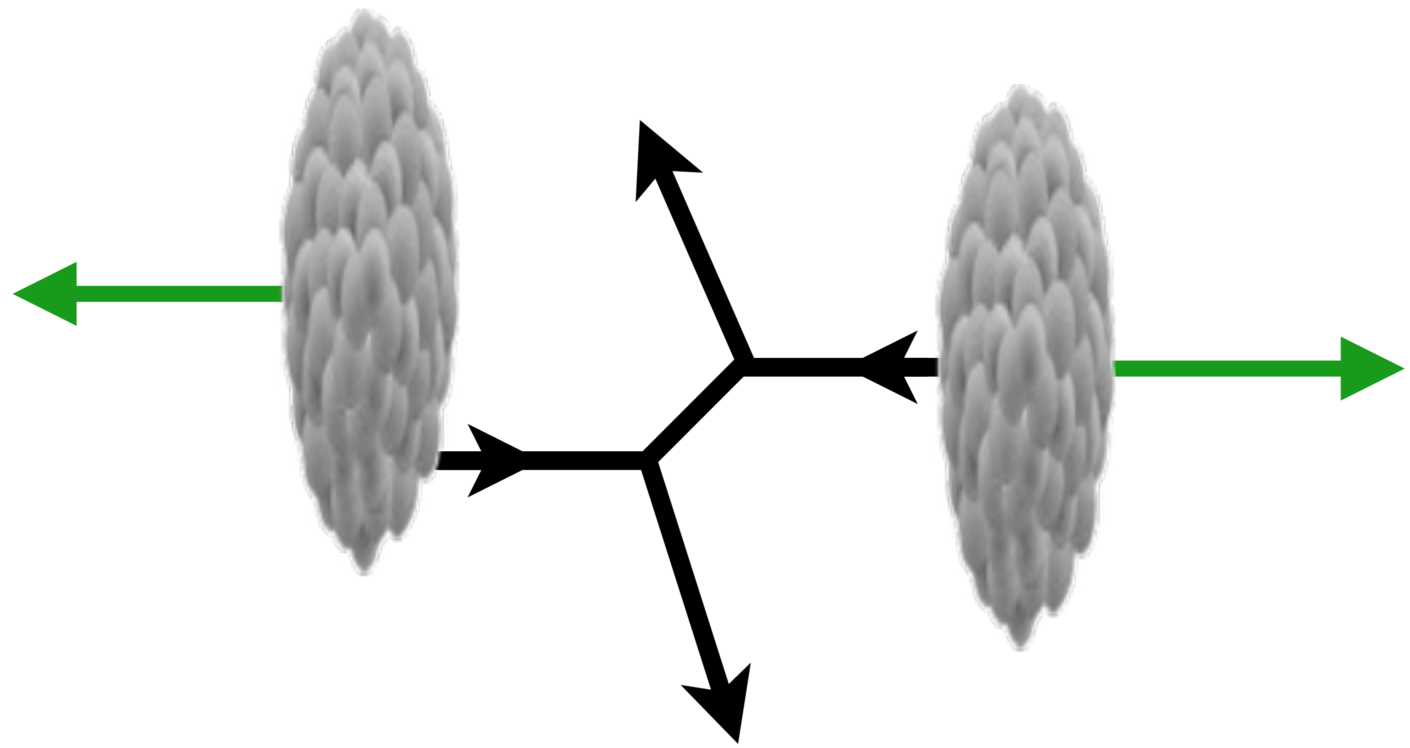
Heavy ion collisions



Heavy ion collisions

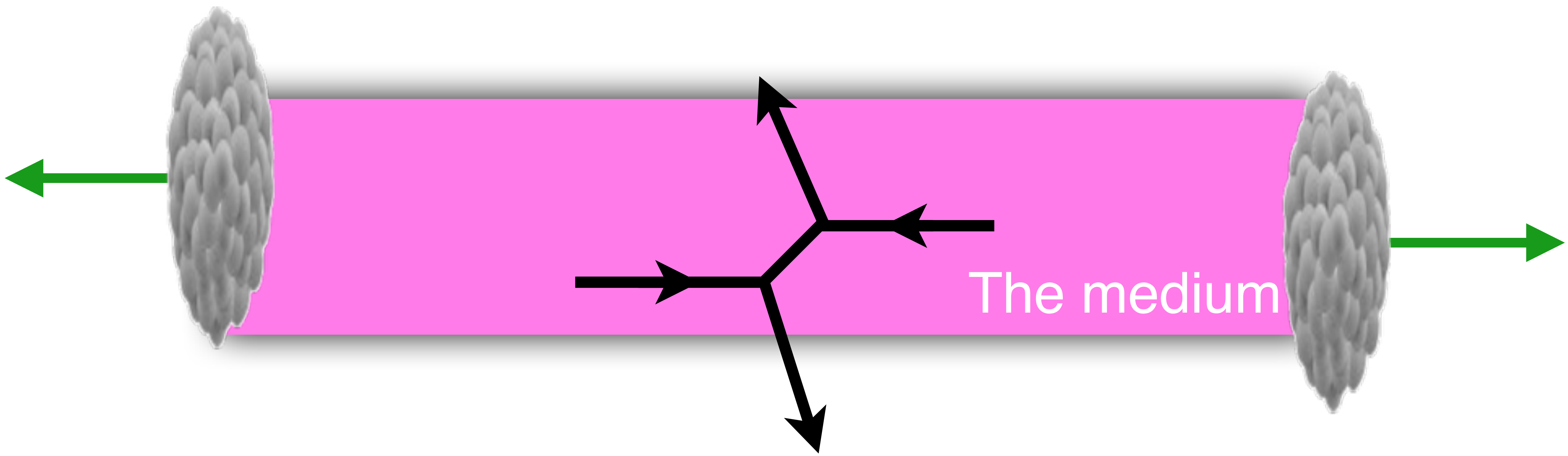
Two heavy nuclei
At LHC, ^{208}Pb
$\sqrt{s_{NN}} = 2.76$ TeV

Heavy ion physics



Early times, $\tau < 0.1$ fm/c:
hard particle production

Heavy ion physics

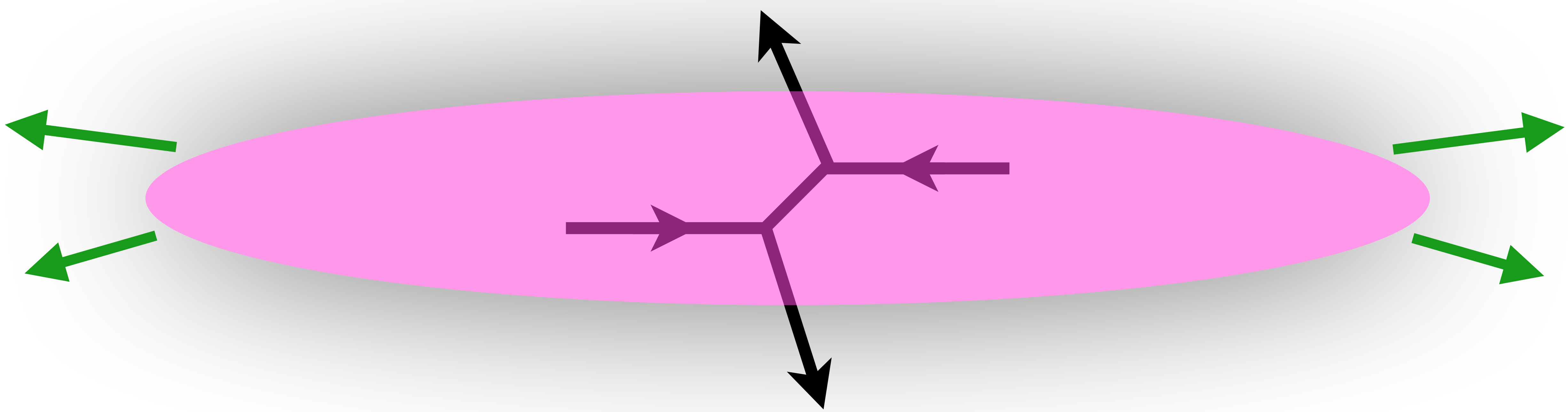


Z, W, ‘hard’ partons

- if colour-blind: unaffected
- if coloured: *affected…*

QGP at colliders

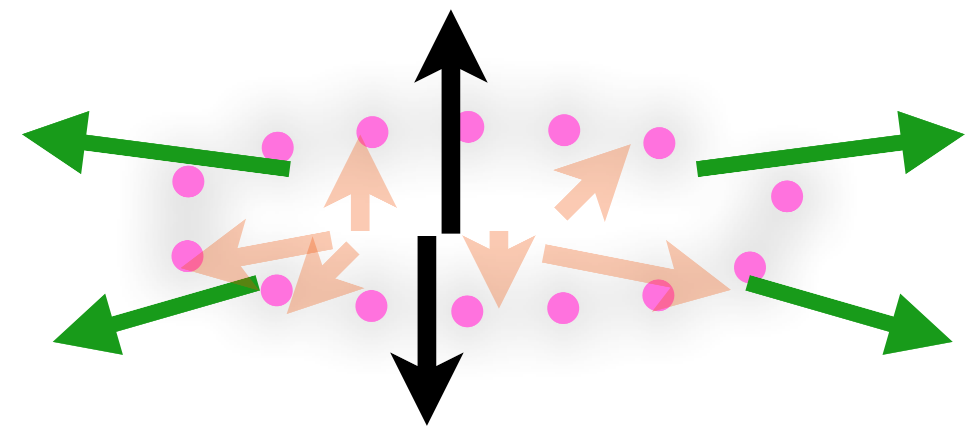
Medium expands and cools down…



τ ≲ 10 fm/c:
soft particle production, collectivity

- Quarks and gluons
- Thermal photons

Probes of the QGP



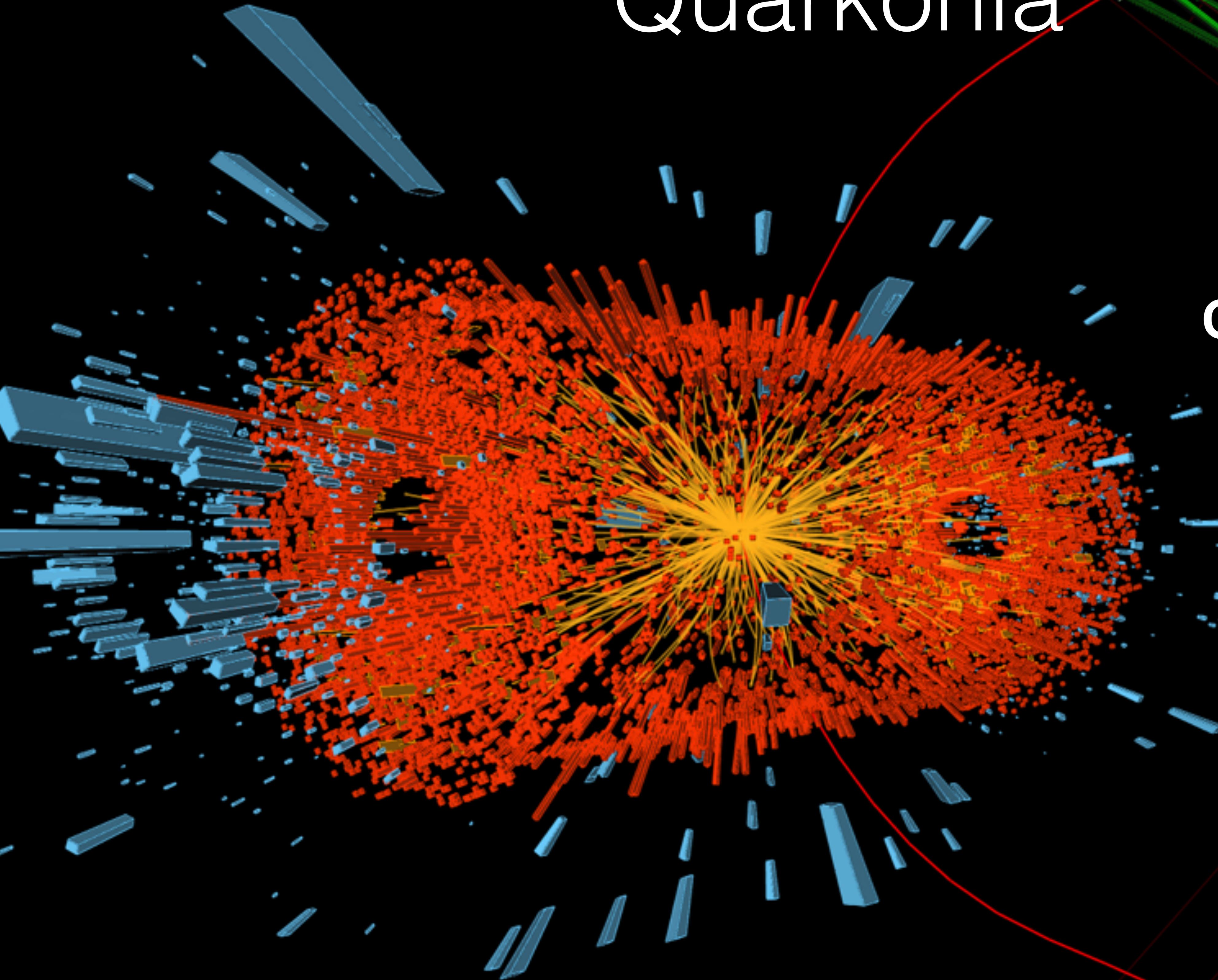
τ > 10 fm/c : final state
particles propagate to the detector

Soft probes
- Light and strange hadrons
- Thermal photons …

Hard probes
- high-p_T jets of quarks or gluons
- Heavy-flavour hadrons (B, D,…)
- **Quarkonia $Q\bar{Q}$**

Different informations on the QGP evolution

Quarkonia

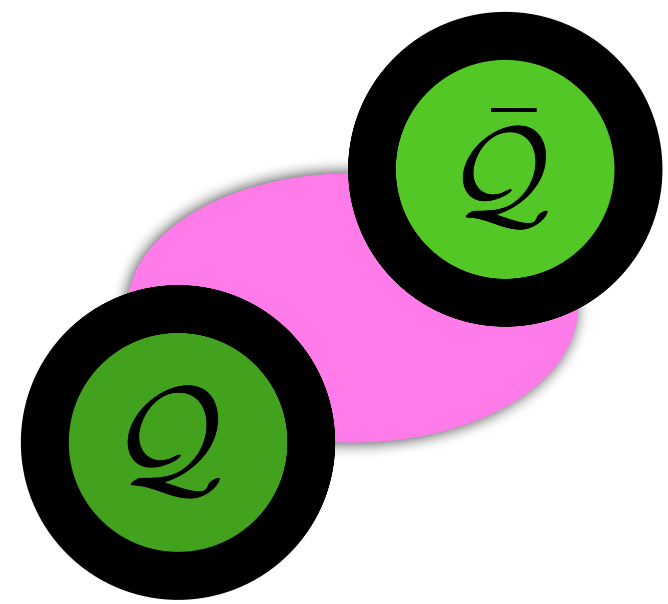


τ > 1000 fm/c :
'event display'
$Q\bar{Q} \to \Upsilon \to \mu\mu$ in a
PbPb collision
from CMS (2011)

Quarkonia

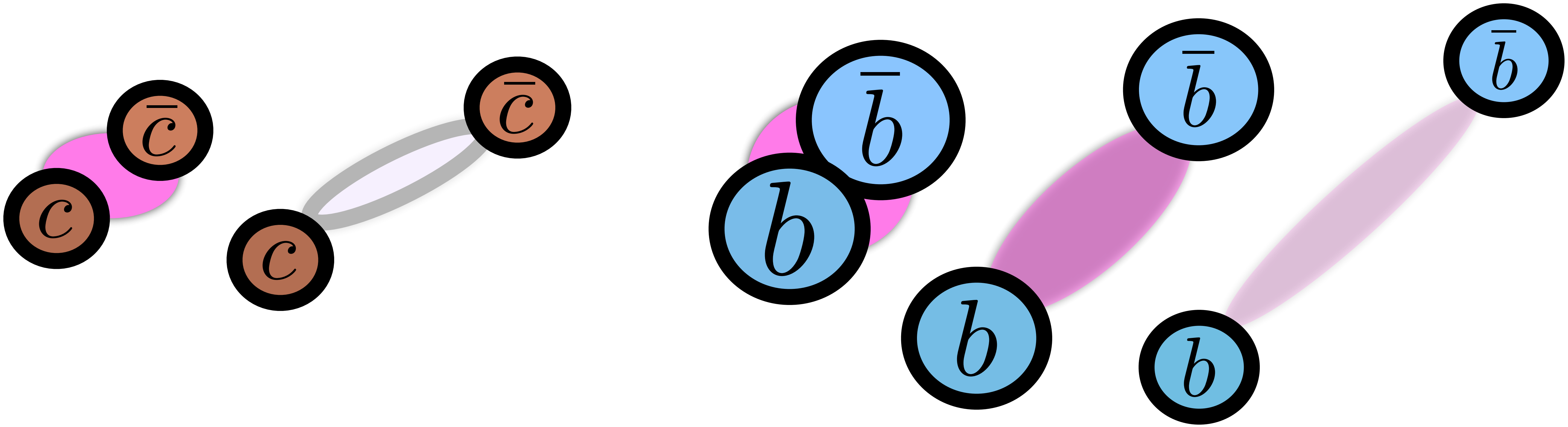
- Heavy quark-antiquark states

Gluon fusion process
Heavy quarks *b* or *c*
Easily detected via their dilepton decay



- Resonant states of various binding energy, mass

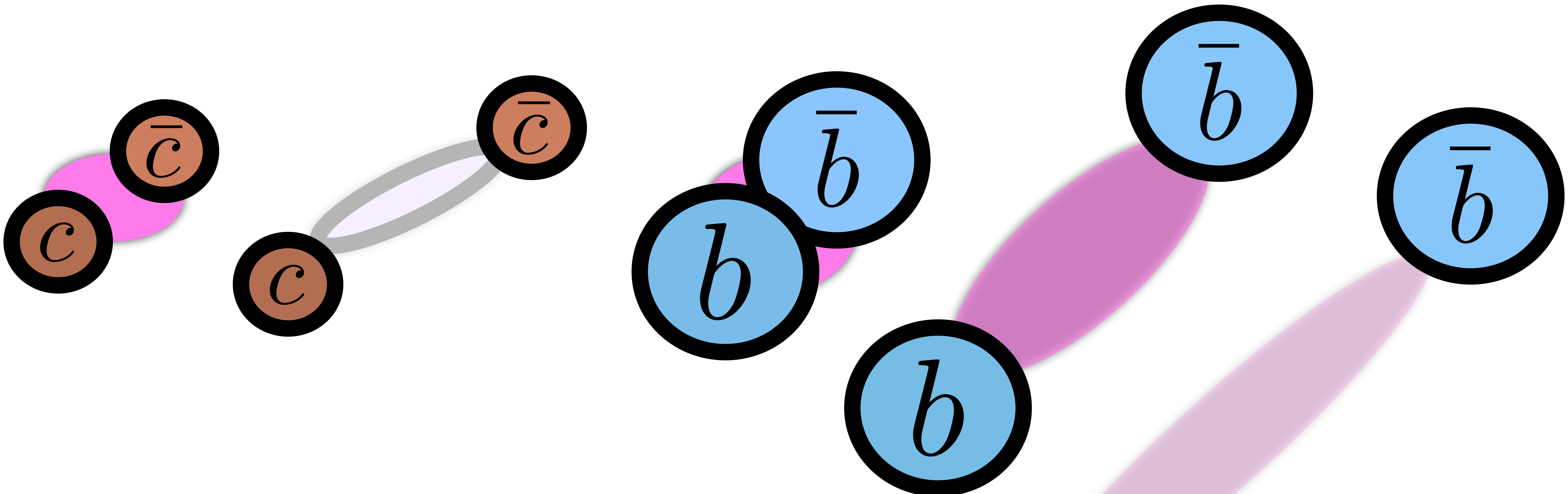
Quarkonia

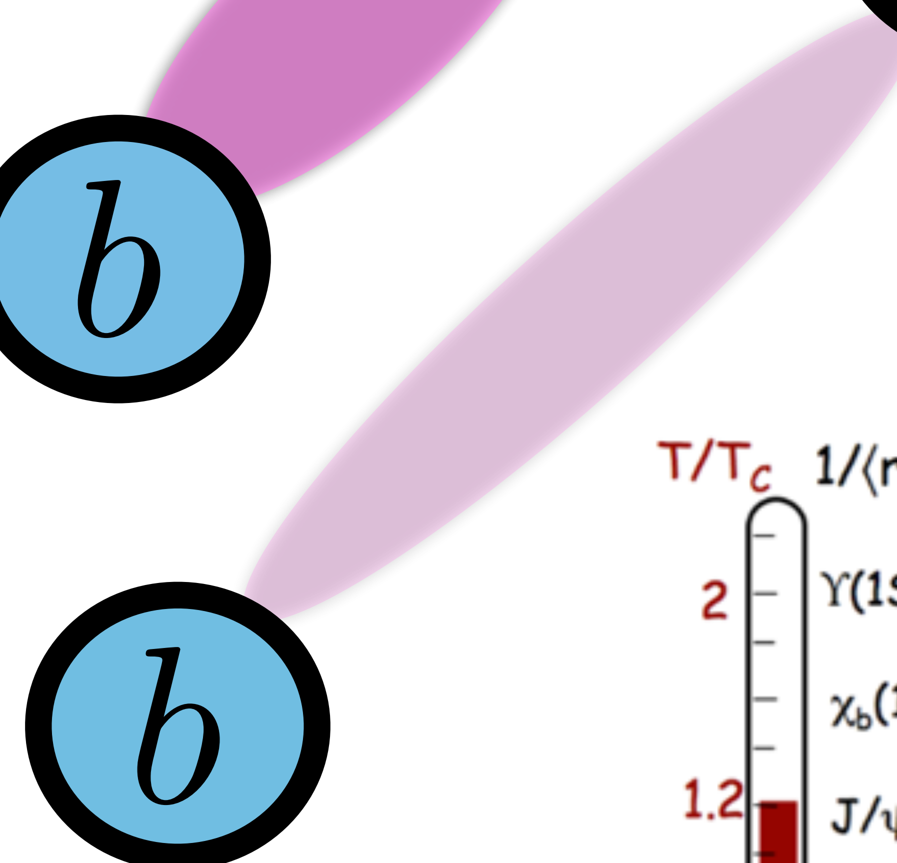


state	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
mass [GeV/c	3.10	3.69	9.46	10.02	10.36
ΔE [GeV]	0.64	0.05	1.10	0.53	0.20

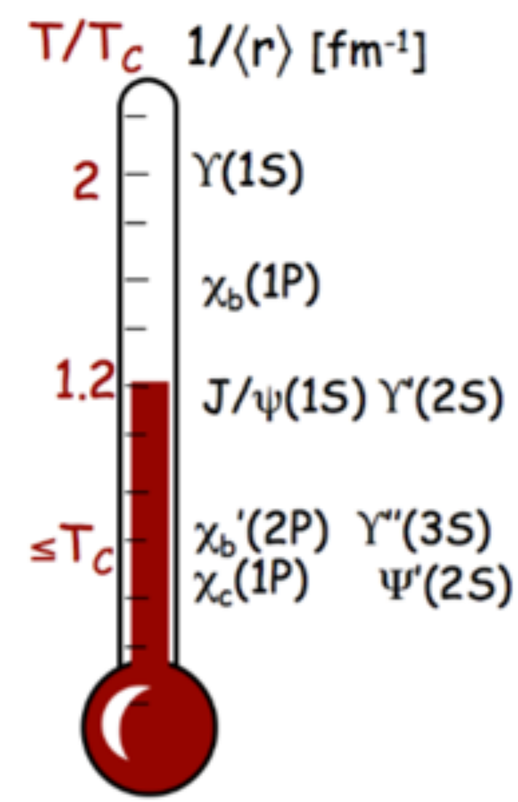
Satz, H. [J.Phys. G32 (2006) R25]

Quarkonia in quark matter





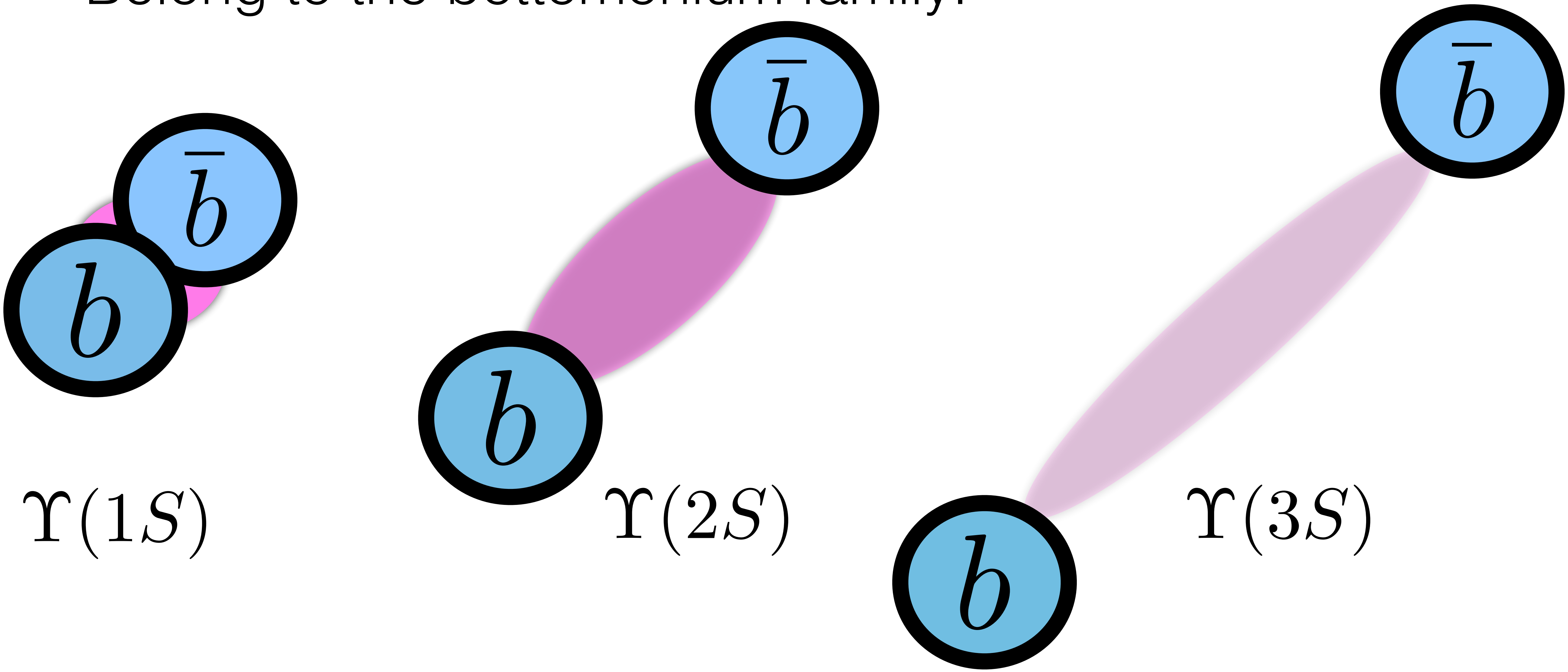
- Historical idea: ordered 'melting' of states in medium
- Quarkonia of low binding energy melt first
- « The QGP thermometer »



Mocsy, Eur.Phys.J. C61 (2009) 705

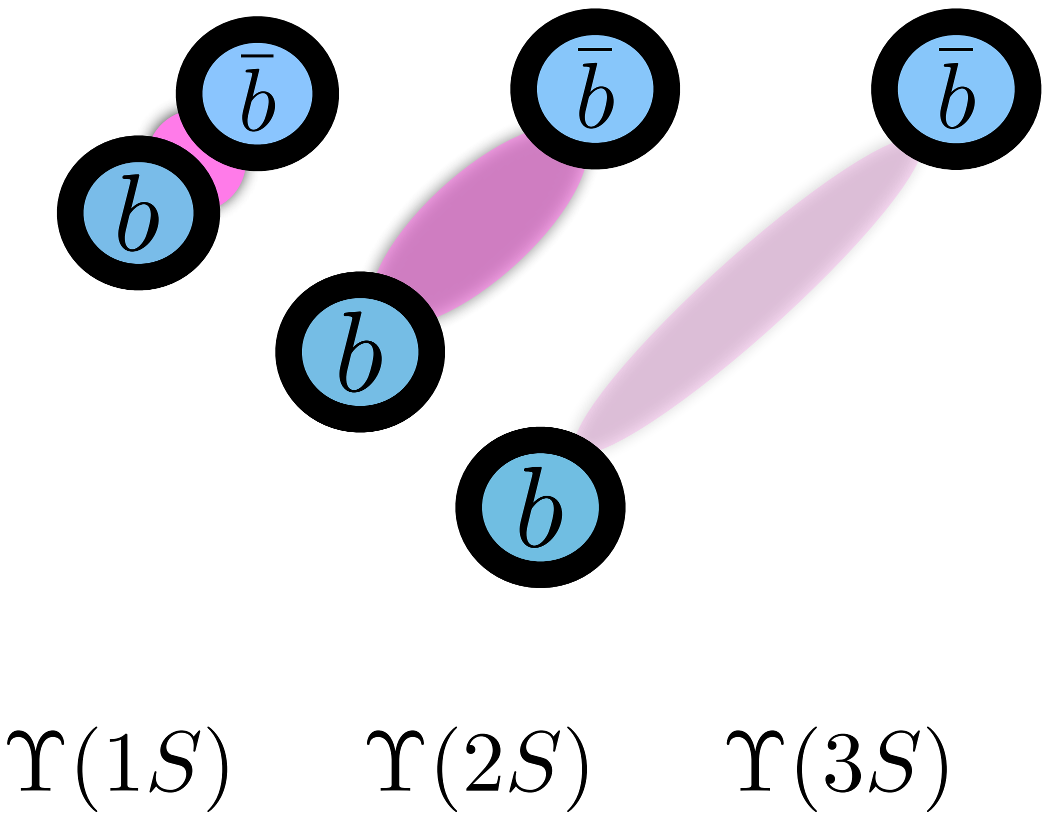
Upsilons

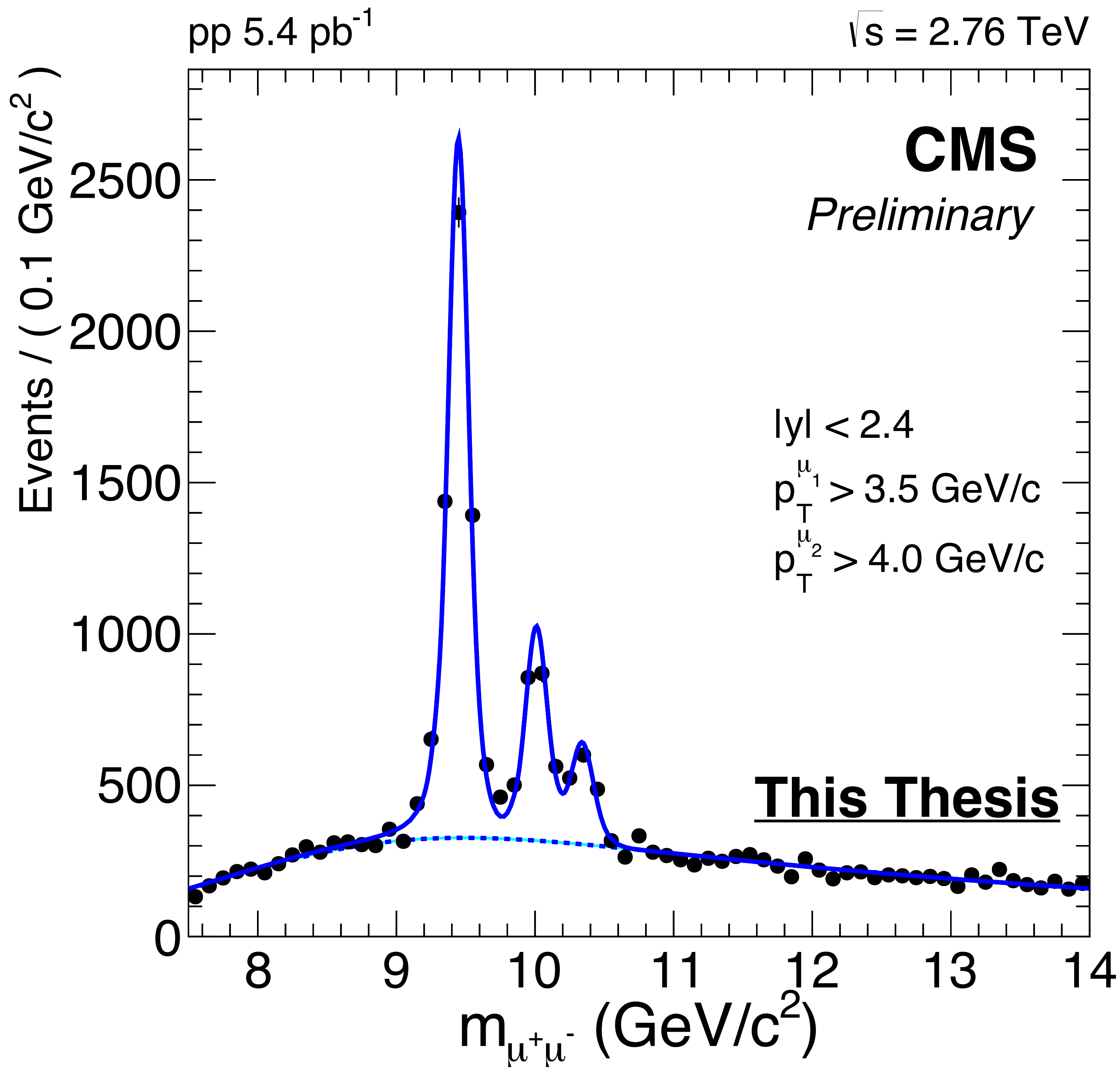
- Belong to the bottomonium family:



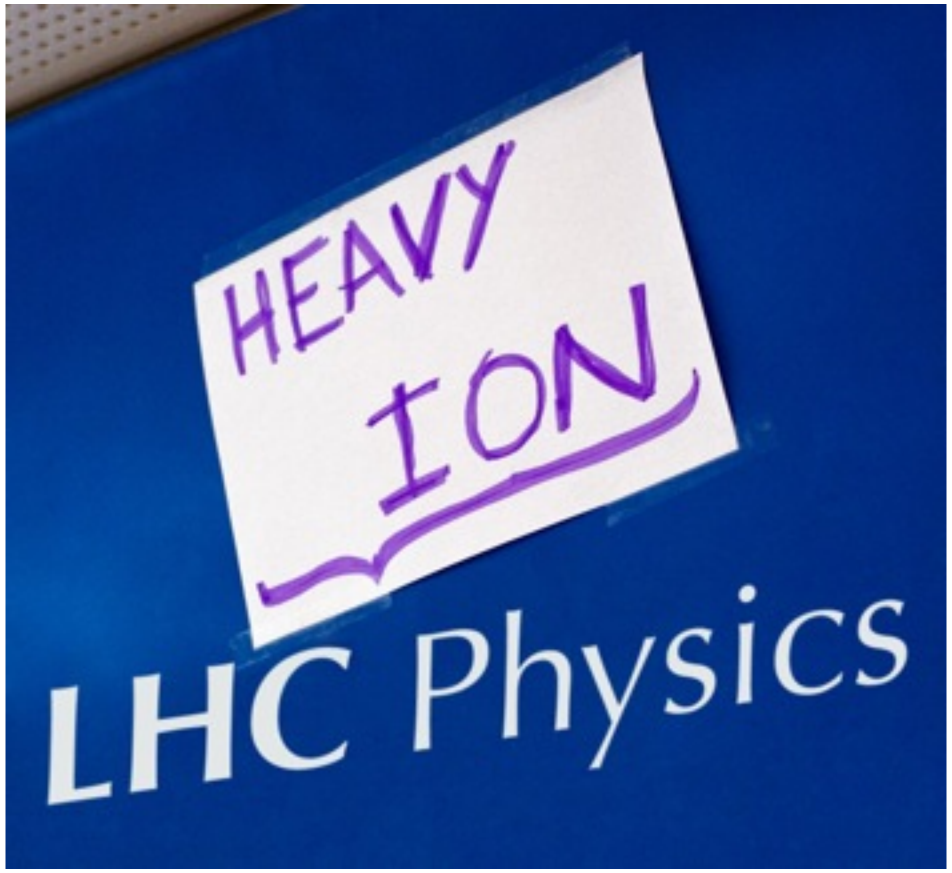
Upsilons in pp

- Upsilon decays to two muons: *B(μμ)* ~ 3 %





Experimental aspects

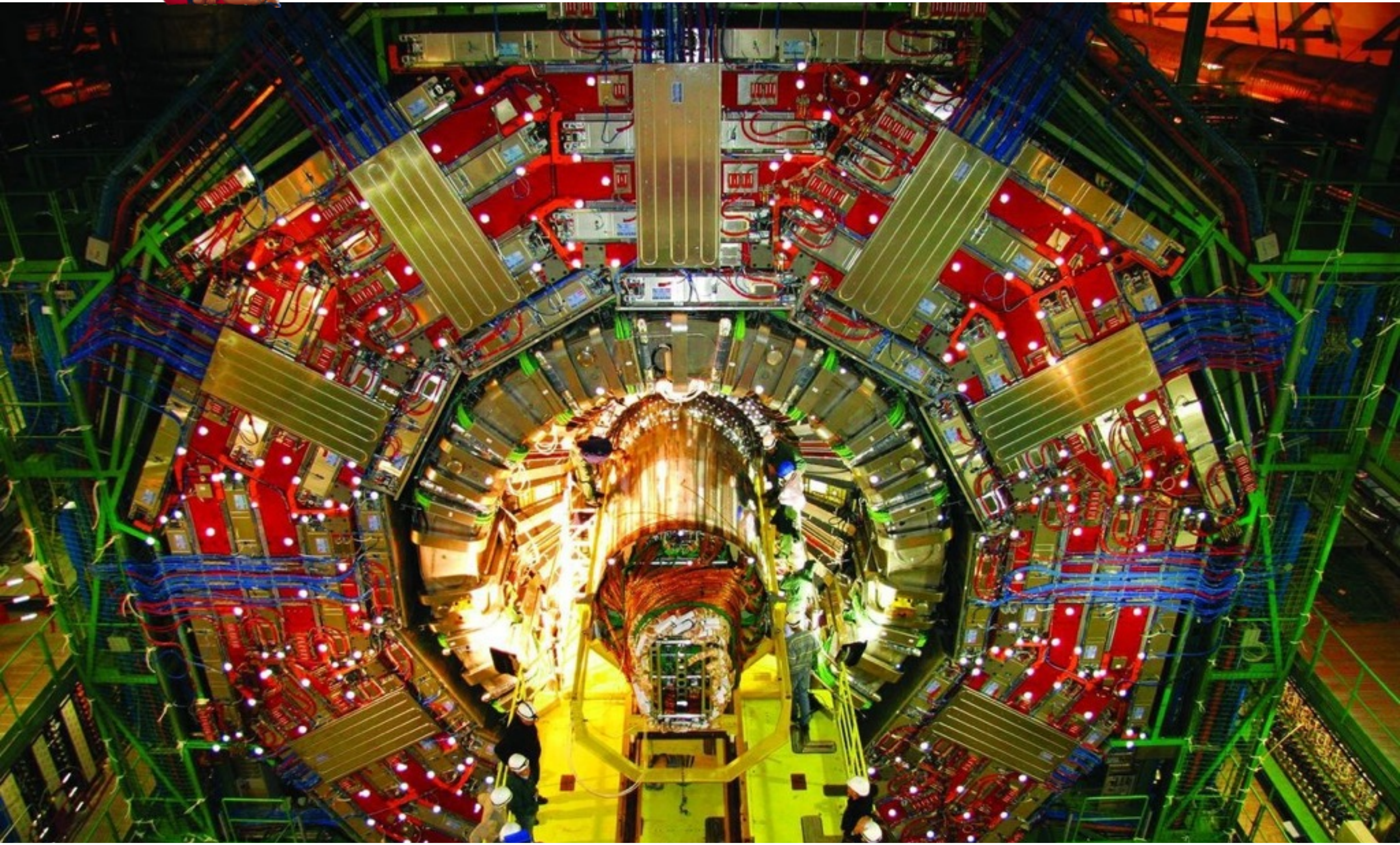


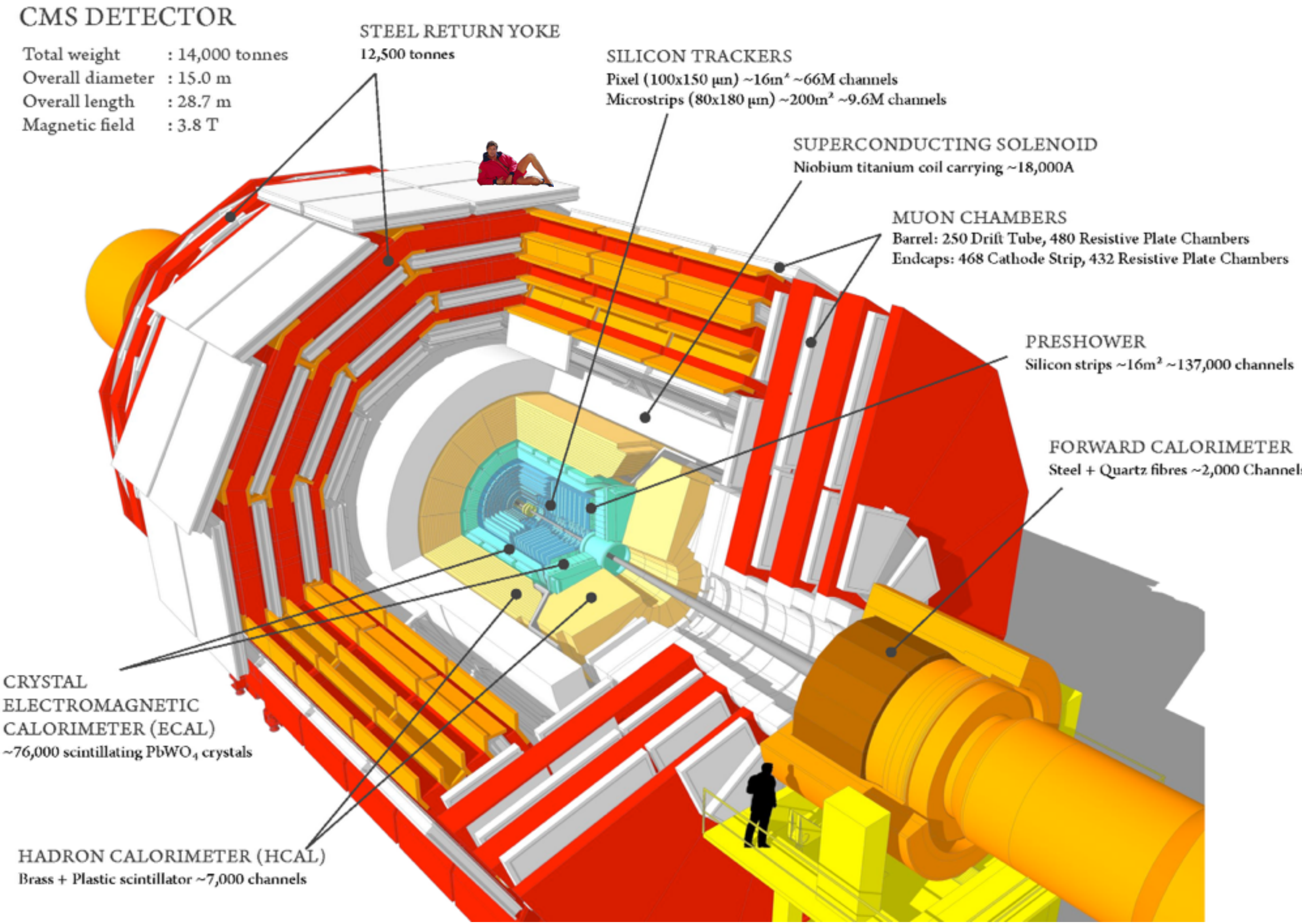
Experiment

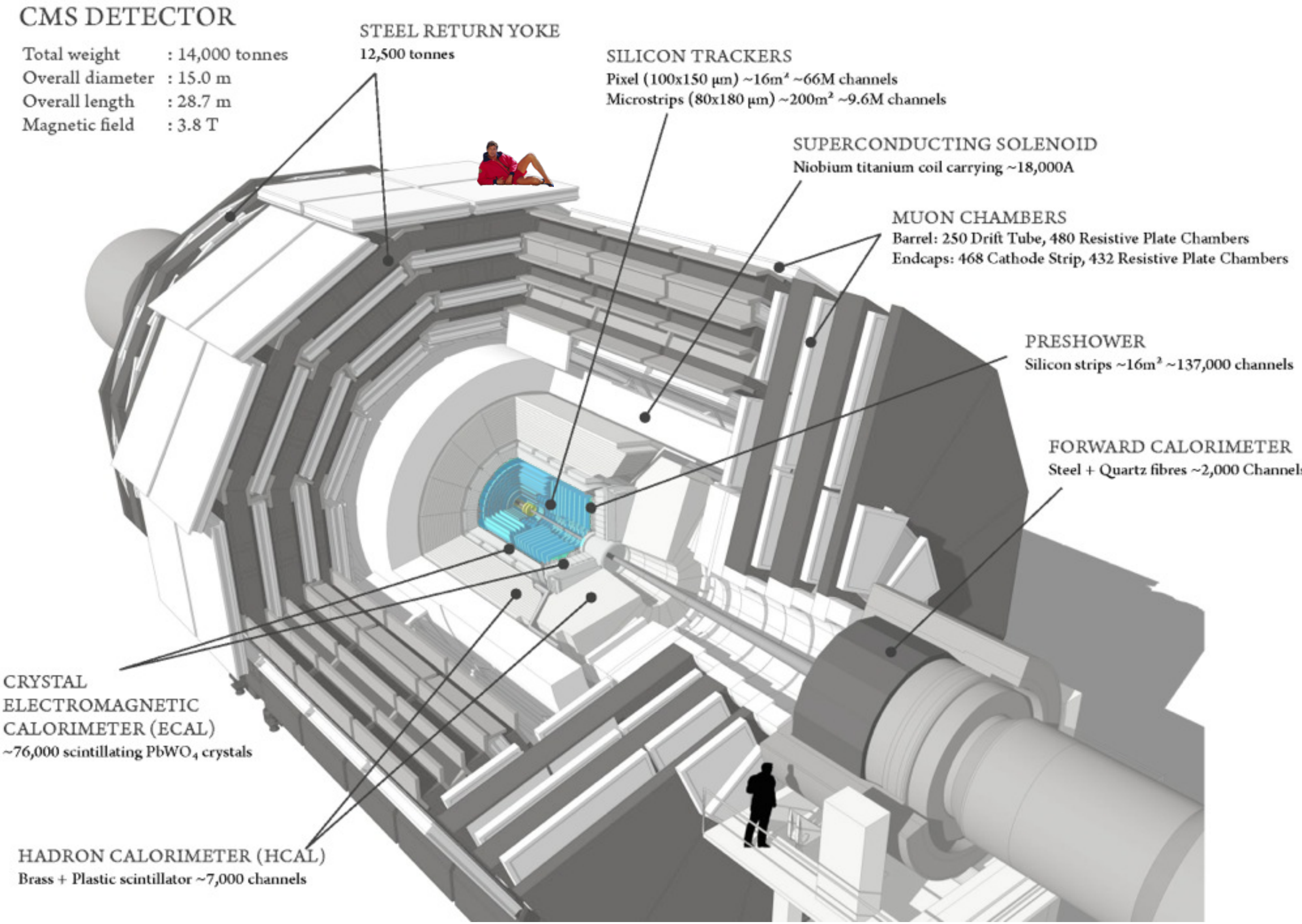
CERN's LHC located between Geneva lake and Jura mountains.

Circulating protons and ions reach TeV energies and collide in detectors at Interactions Points

The CMS detector




CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels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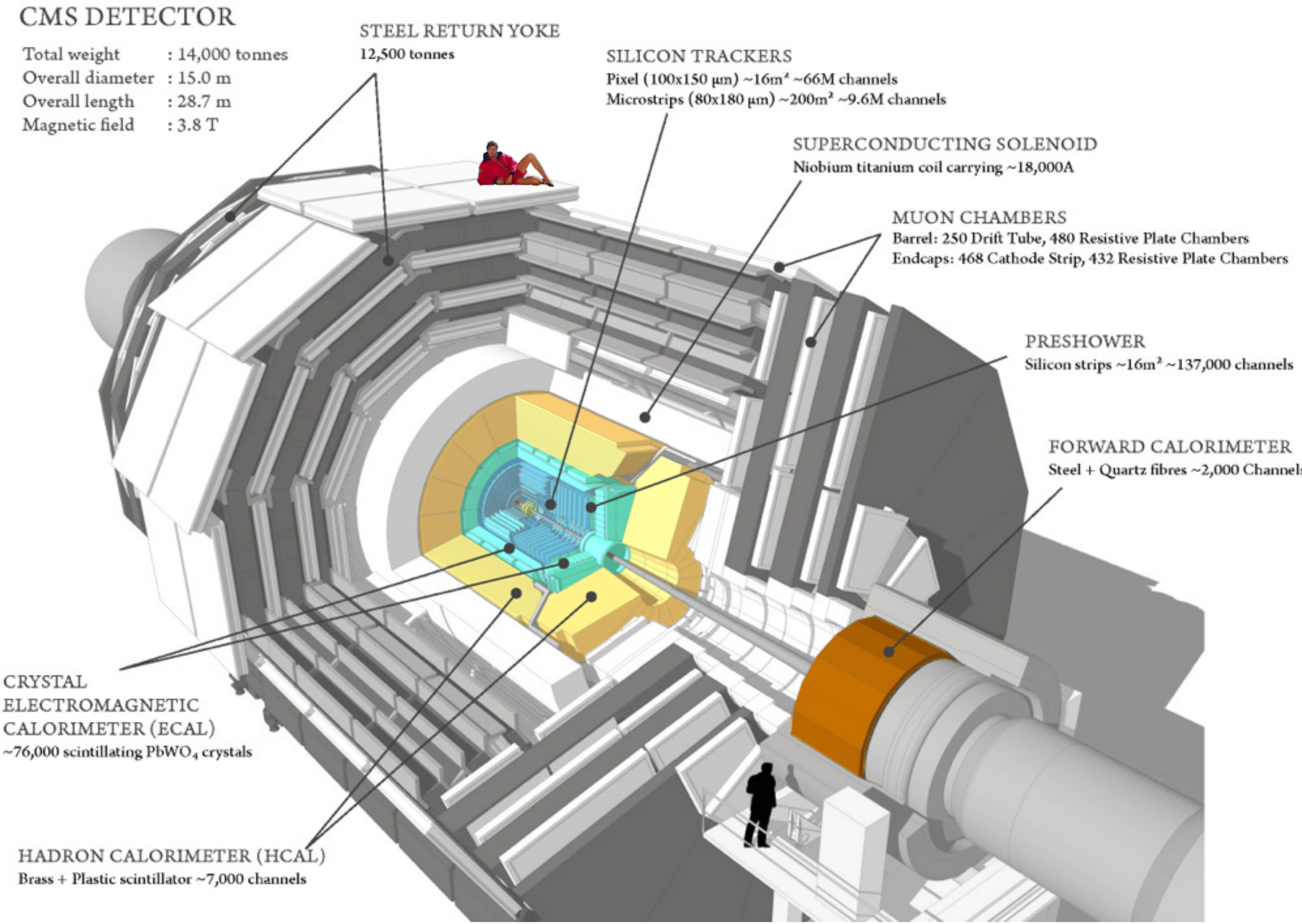
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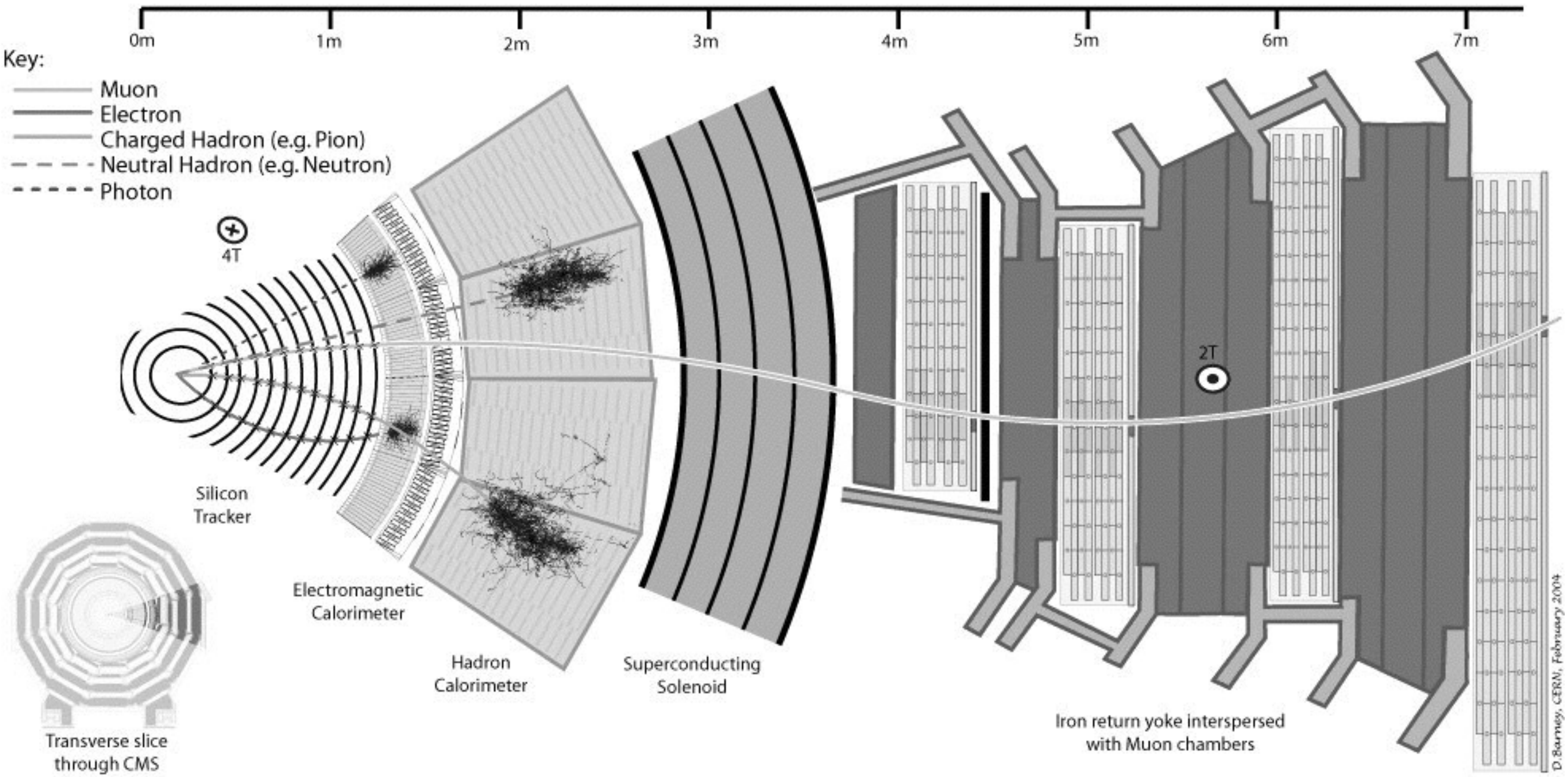
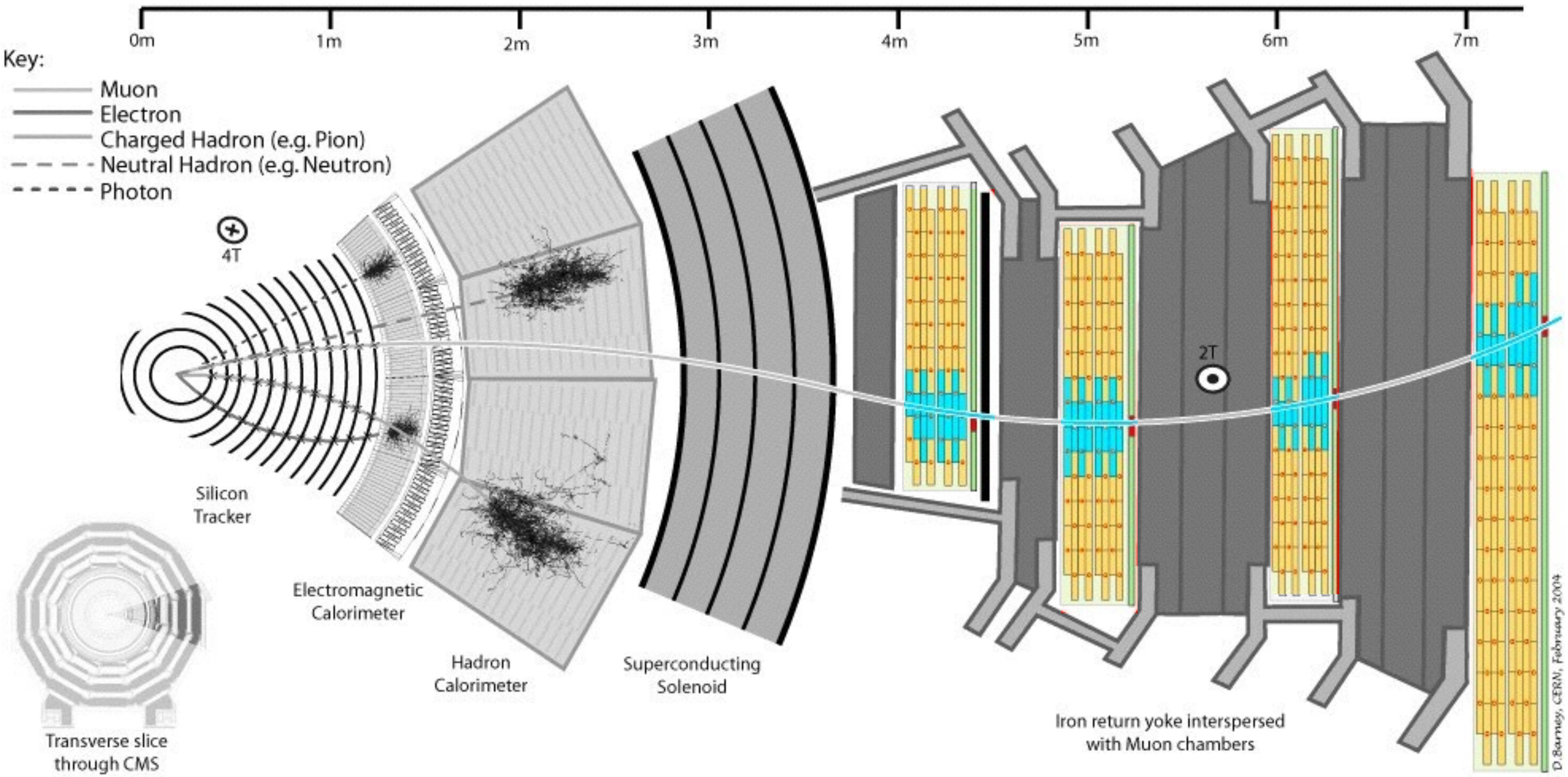
Muon reconstruction in CMS

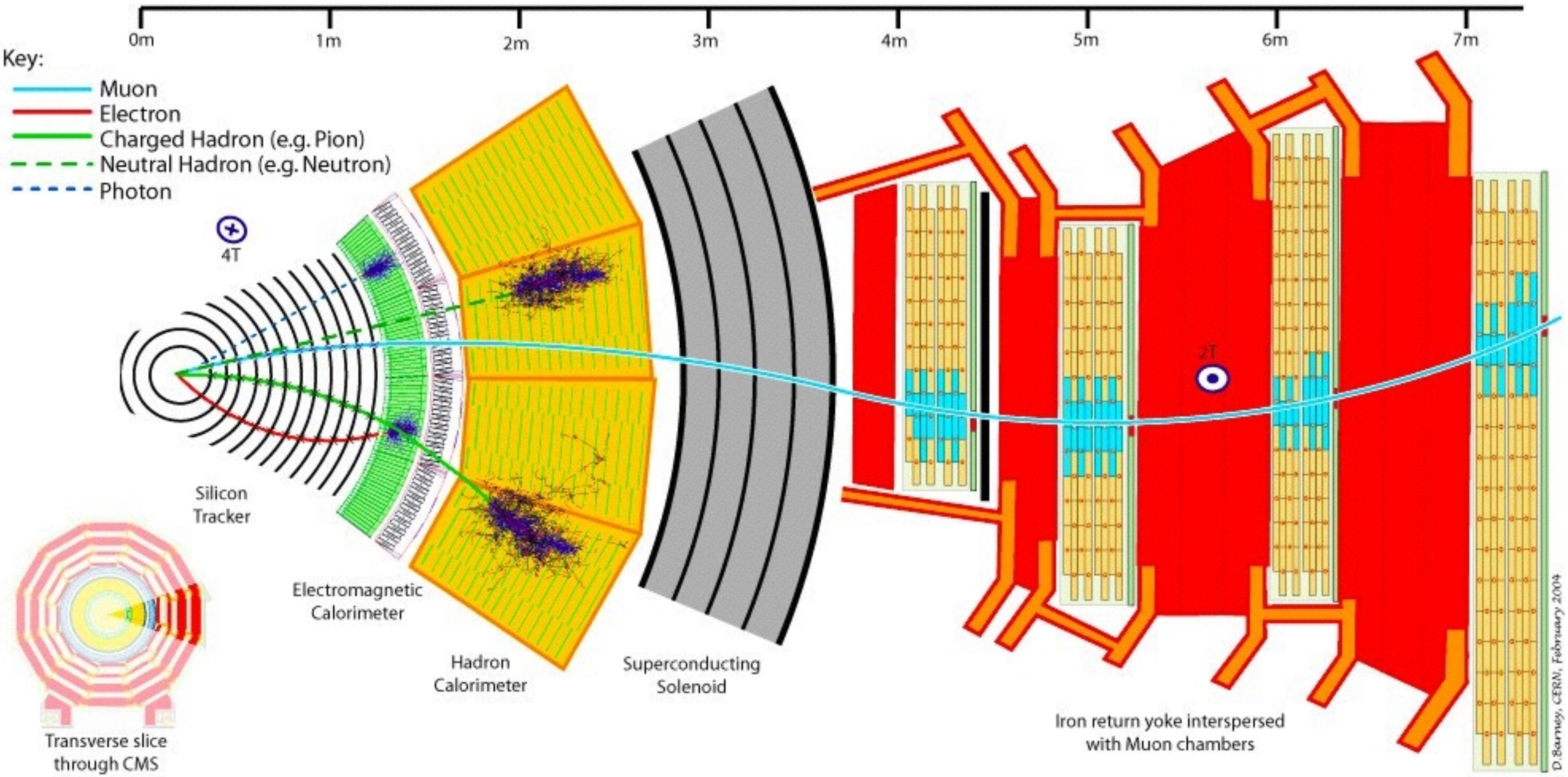


Muon reconstruction in CMS



- Muons hit up to four layers of ‘muon chambers’
- Used for triggering and reconstruction

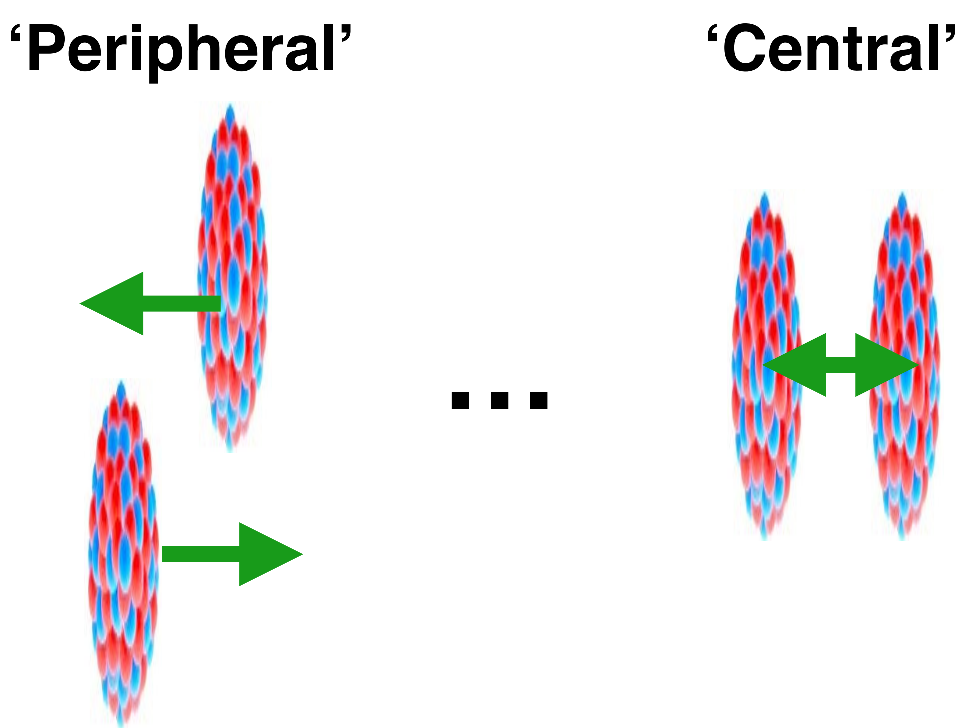
Muon reconstruction in CMS



- Muons seldom interact in ECal&HCal
- Offline: outside-in reconstruction of global muons (chambers + tracker)

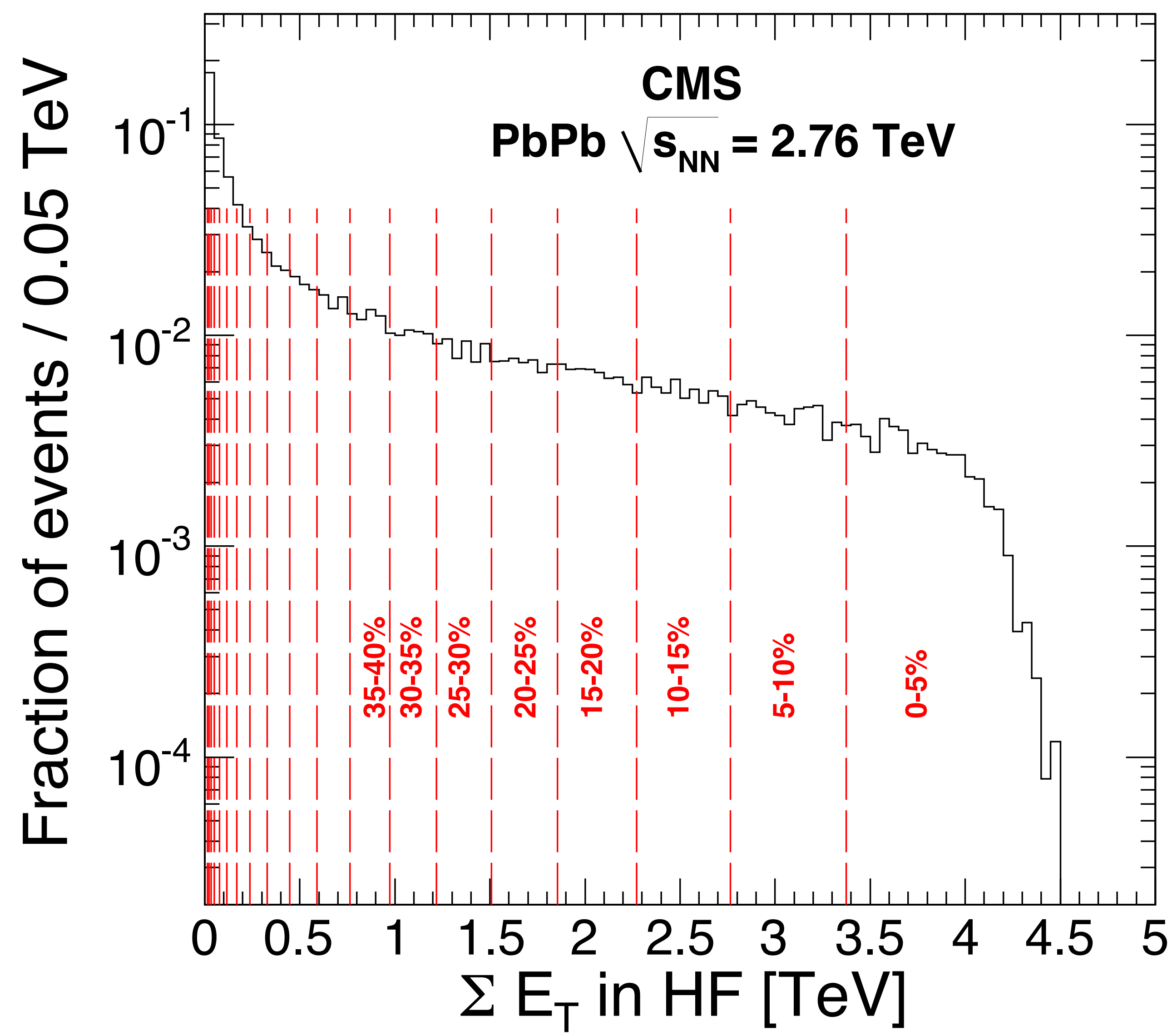
Heavy ion centrality

- Centrality: 'violence' of the collision
- Make centrality classes



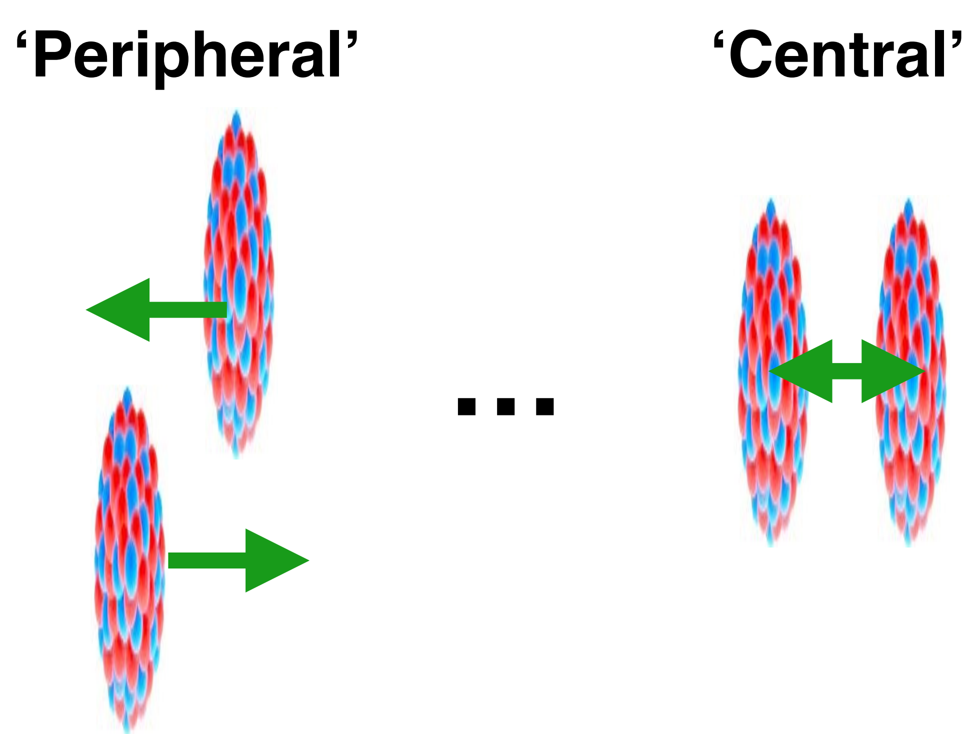
JHEP 1108 (2011) 141

Transverse energy deposit in forward HCal, in CMS



Heavy ion centrality

- Goal: relate centrality to geometrical quantities



- From a Glauber model of multi-scattering nucleons,
- Extract:
  - Number of hard scatterings
  - Number of participating nucleons,
  - Nuclear overlap function
  - impact parameter (*fm*)

$$N_{\mathsf{coll}},\ N_{\mathsf{part}},\ T_{AB},\ b$$

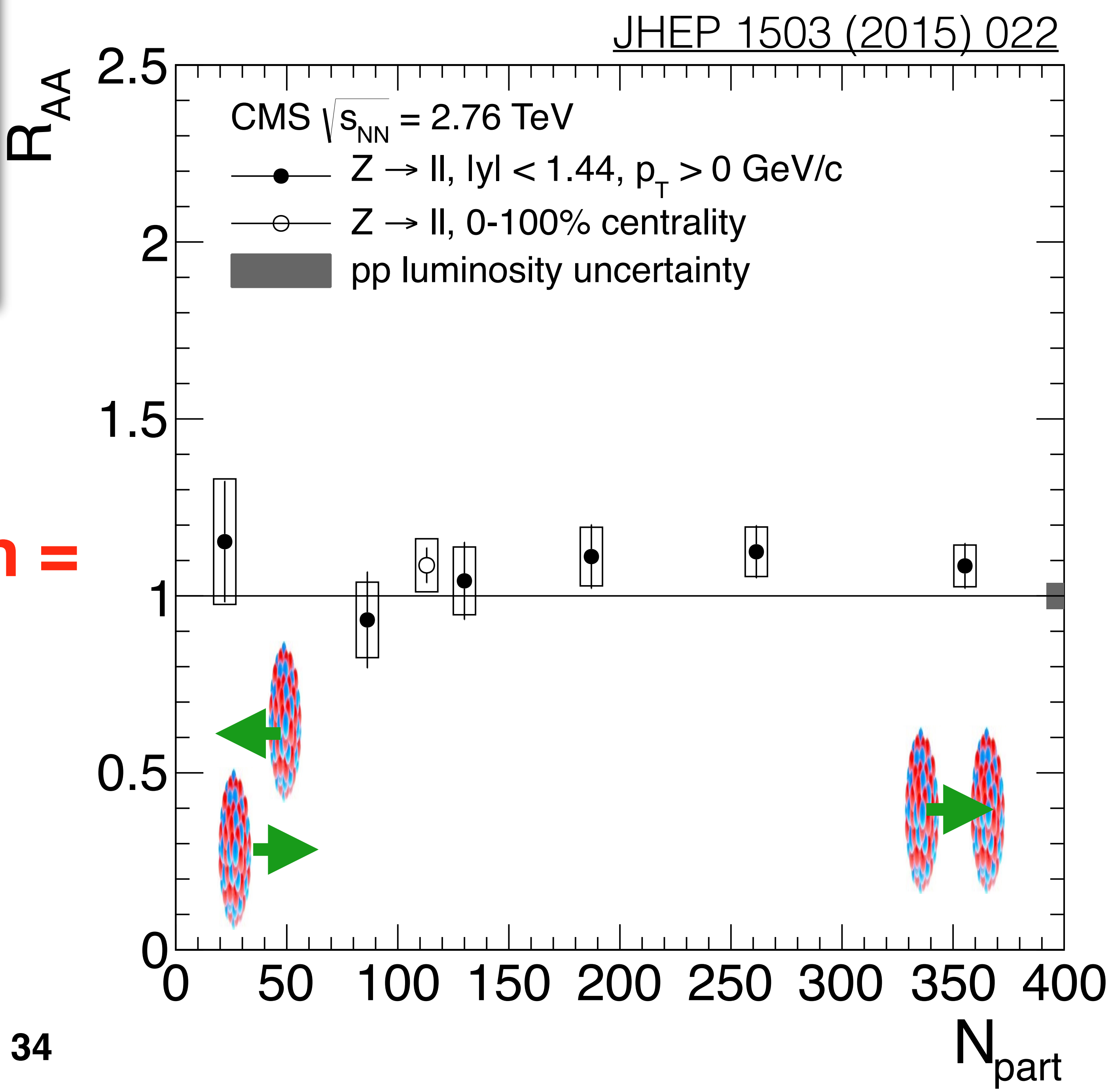
Nuclear modification factor

- Can relate production in *pp* to yields in PbPb

Define the **nuclear modification factor**

$$R_{\text{PbPb}} = \frac{\mathcal{Y}_{\text{PbPb}}}{N_{\text{coll}} \times \mathcal{Y}_{pp}}$$

- **Simple application: Z boson = unmodified**
- However, RAA ≠ 1 for interacting probes



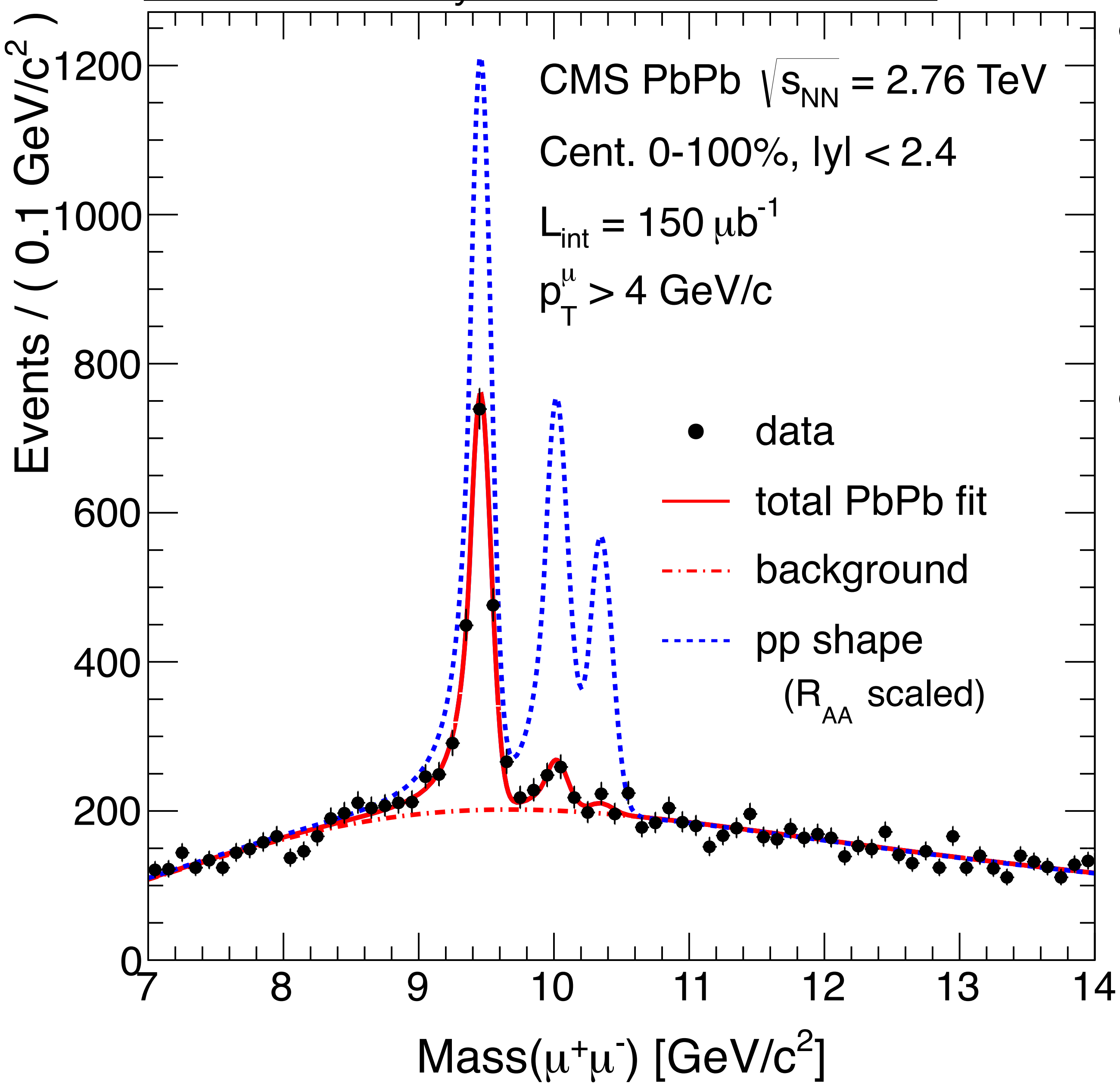
Analysis

1) what was done before the beginning of the Thesis

2) my analysis

Upsilons in the QGP

CMSPublic/PhysicsResultsHIN11011

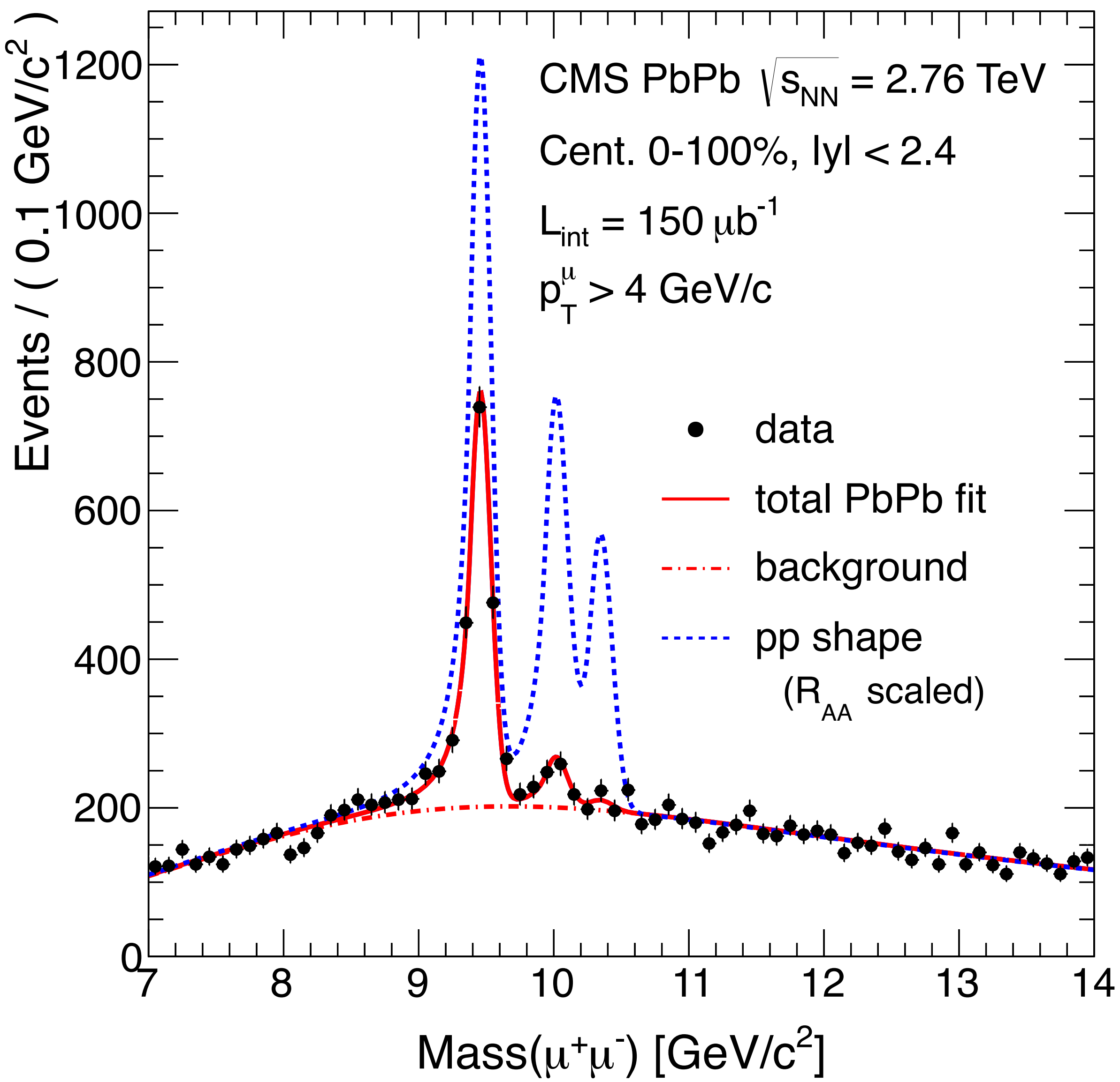


- 2010: Upsilons *are* suppressed (1st measurement, 7/μb)
- 2011: Longer PbPb run (150/μb)

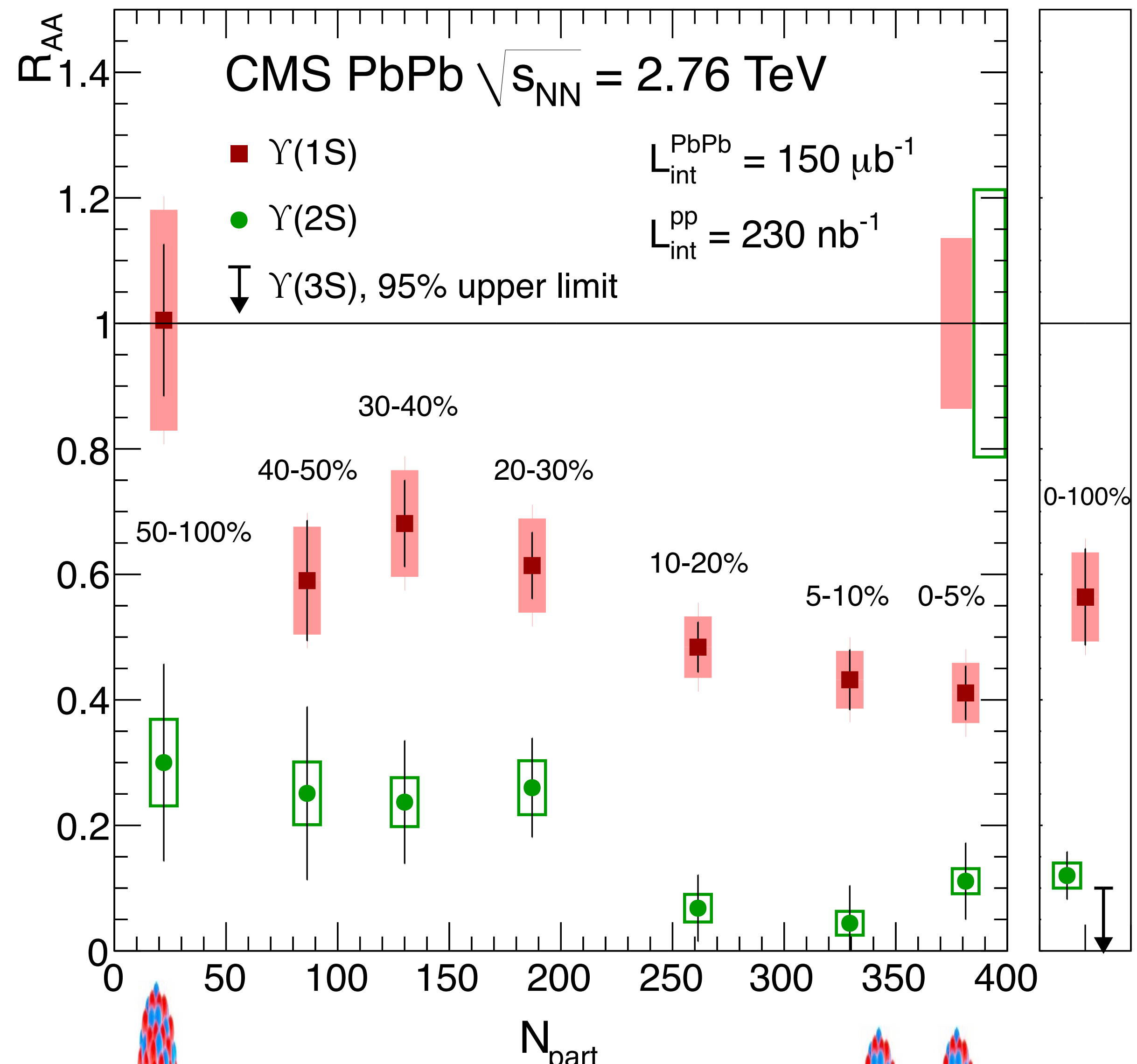
Upsilons in the QGP

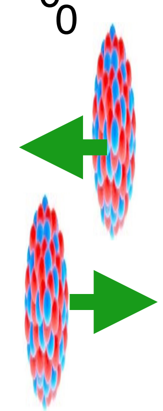
- Centrality dependent suppression
- Stronger for excited states
- Y(3S): upper limit @ 95%.

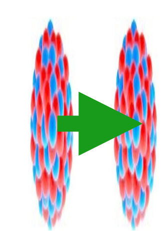
CMSPublic/PhysicsResultsHIN11011



PRL 109 (2012) 222301







Feed-down and spectroscopy

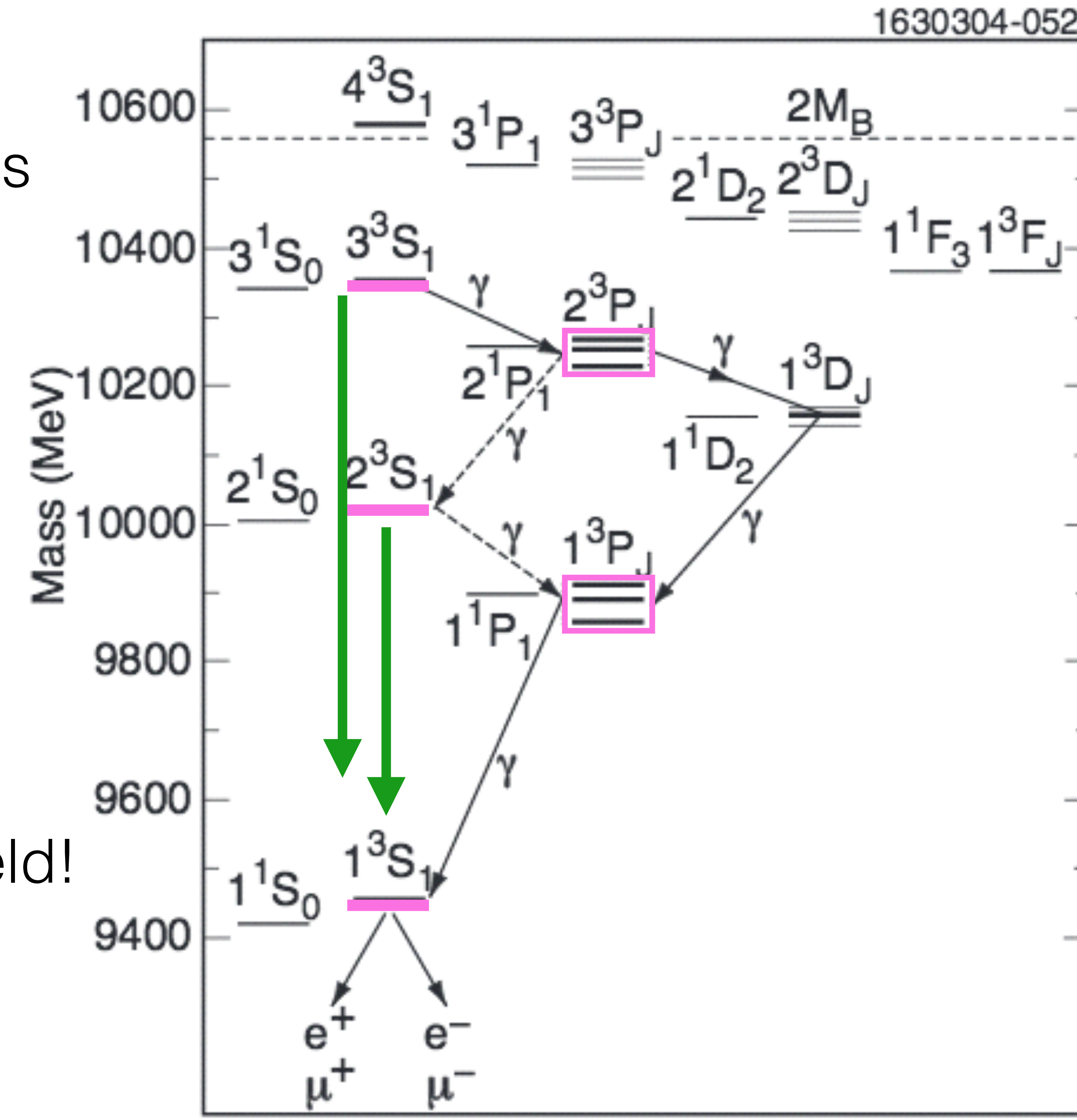
- Basic radiative transitions

$$\Upsilon(2S) \rightarrow \Upsilon(1S) + \pi\pi$$
$$\chi_{bJ}(1P) \rightarrow \Upsilon(1S) + \gamma$$

- from past experiments:

~ 50 % of 1S are *direct*

All contribute to the 1S yield!



My Thesis in context

Two open questions:

- Are direct Υ(1S) melting?
- How does the suppression depend on kinematics?

Two improved datasets:

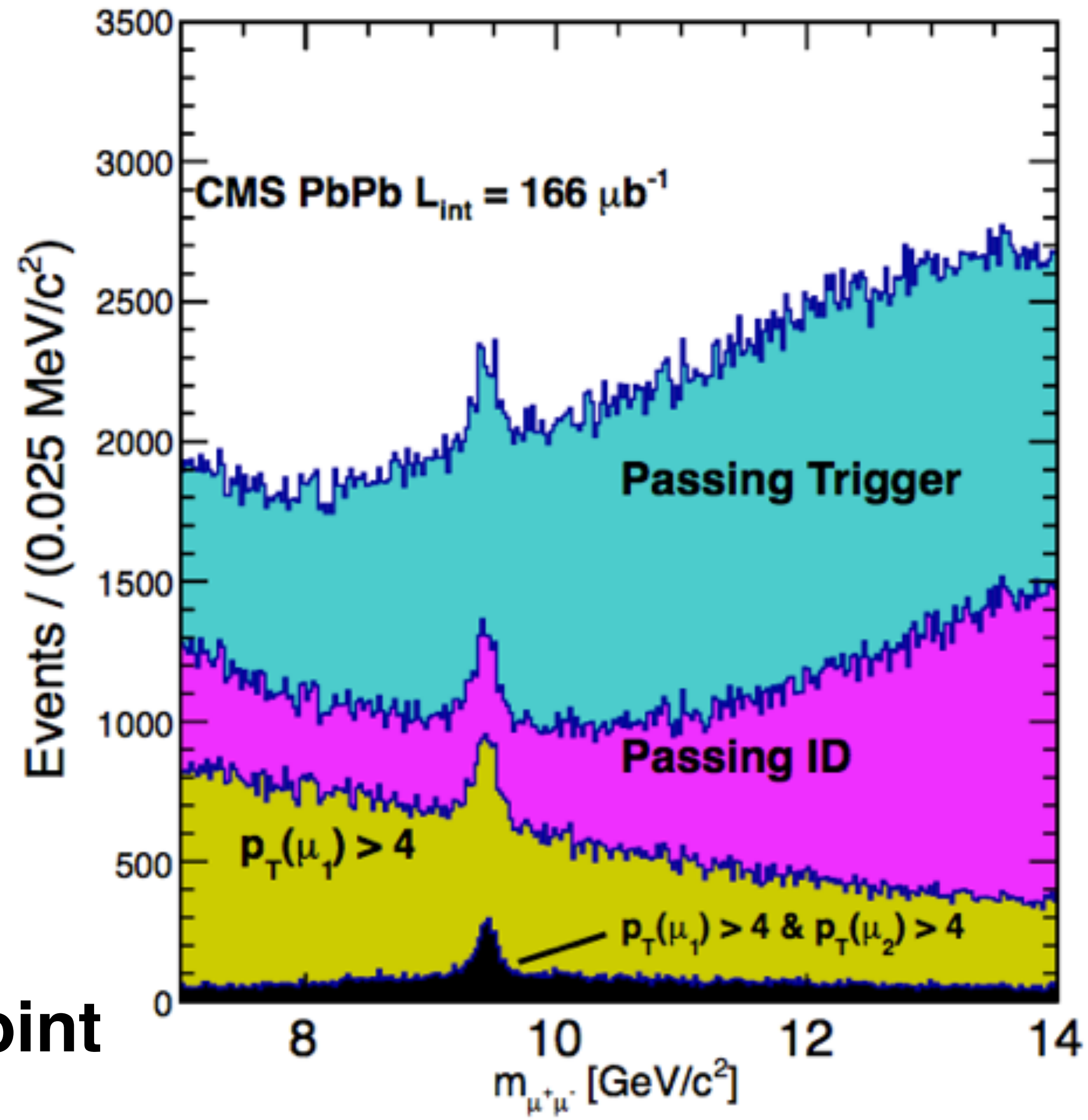
- improved PbPb reconstruction
- 20 times larger pp reference

Signal optimisation

Muon selections

- Aim to compare PbPb data and pp data
  - Equivalent trigger, quality and kinematic selections

Look at PbPb -> μμ data in mass range of the Y family

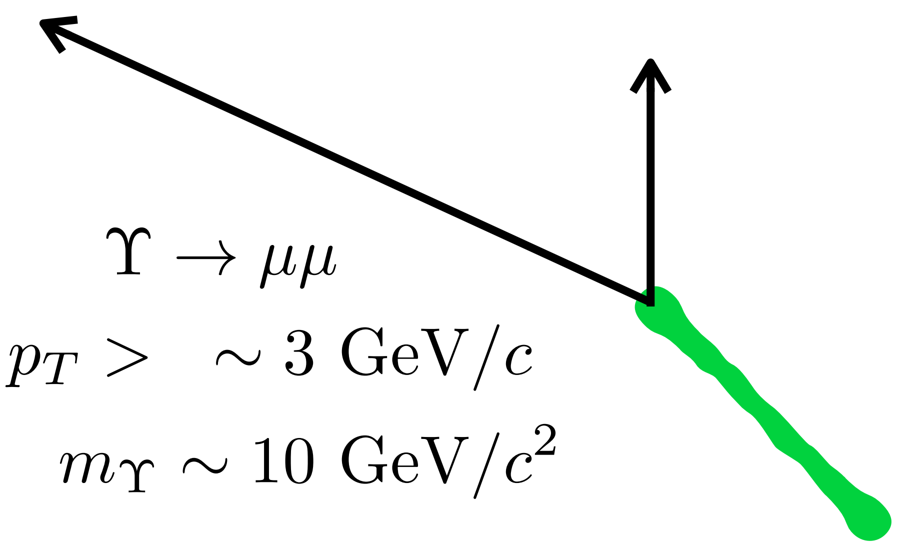


Blue: dimuon-triggered events
Pink: good quality (ID) muons
Yellow and **Black**: kinematic cuts
Kinematics: find better working point

Muon kinematics - 1

- Contribution: optimise the Y significance
- Look at Y(1S) simulations from Pythia :

- General idea: the p_T of the muons are anti-correlated

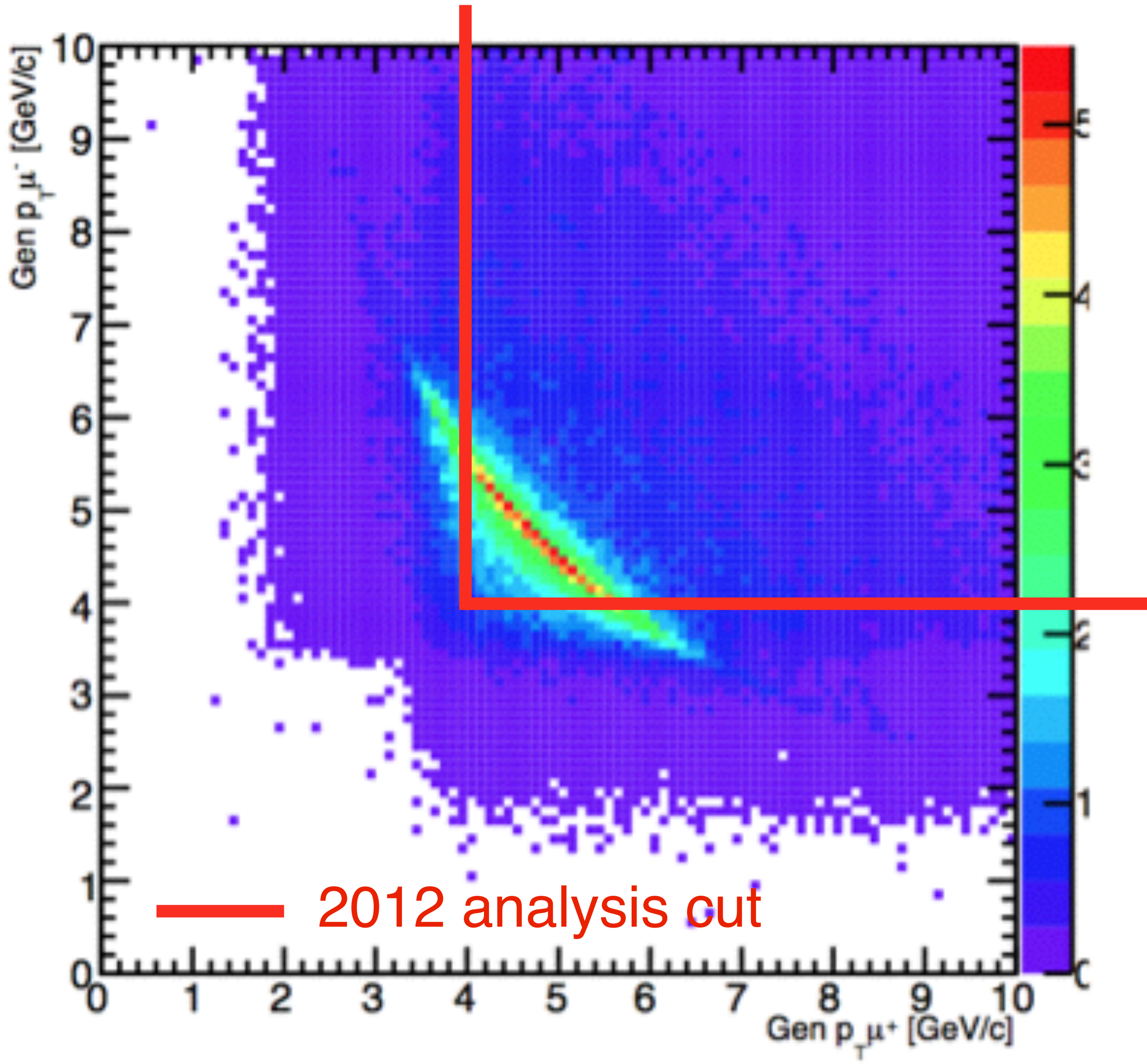


$\Upsilon \rightarrow \mu\mu$

$< p_T > \quad \sim 3 \text{ GeV}/c$

$m_\Upsilon \sim 10 \text{ GeV}/c^2$

$p_T(\mu^+)$ vs. $p_T(\mu^-)$

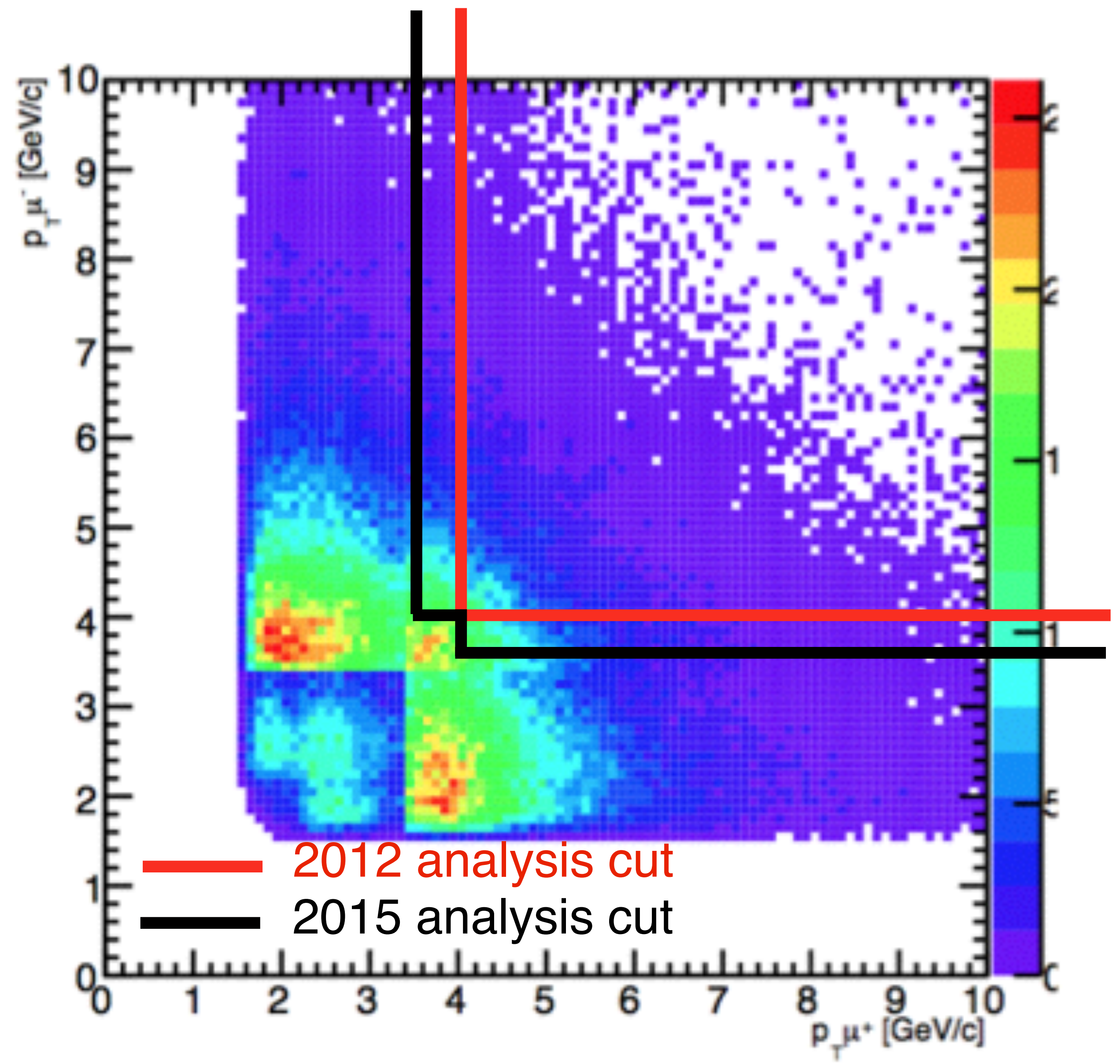


Studied the effect of asymmetric single muon pT cuts *!*

Muon kinematics - 1

- Contribution: optimise the Υ significance
- Look at Υ(1S) **PbPb data:**

$p_T(\mu^+)$ vs. $p_T(\mu^-)$



- Limit: large PbPb dimuon background at low-p_T

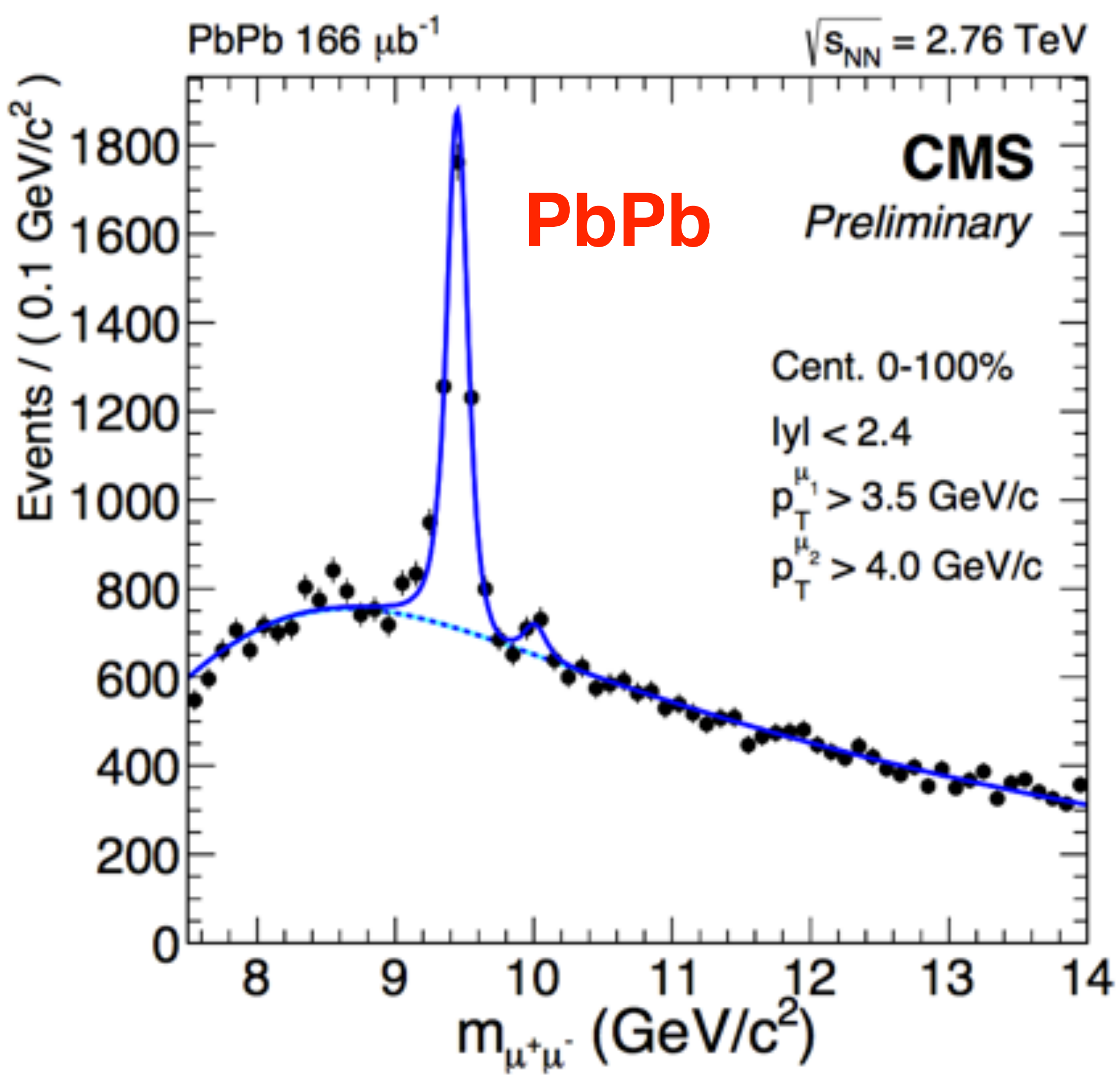
- Trade-off:
asymmetric 3.5 & 4 GeV/*c* cut !

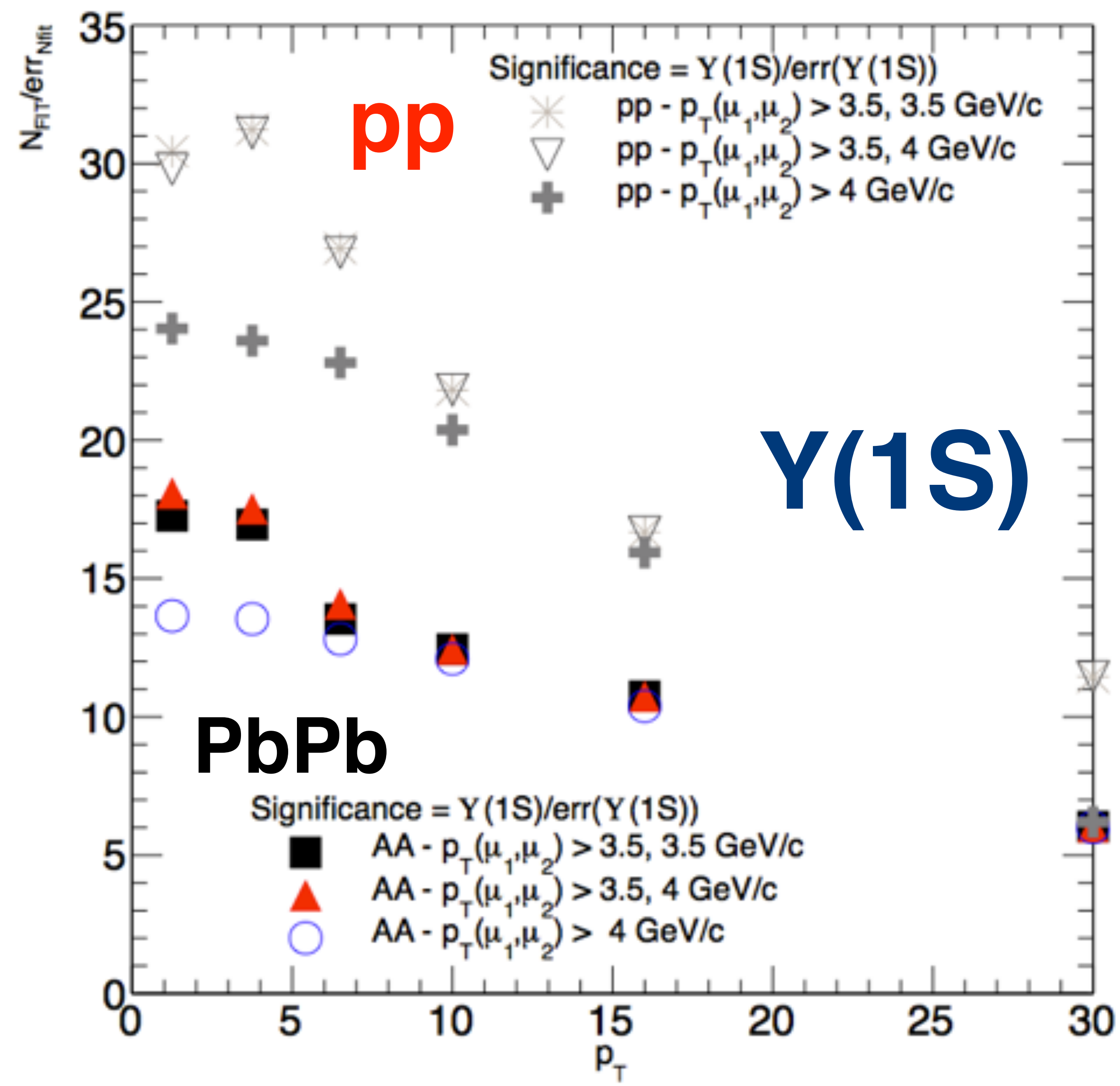
Nicolas Filipovic

Muon kinematics - 2

- Quantify the gain with a significance study

$$\Sigma = \frac{N^{\text{fit}}}{\text{err}(N^{fit})}$$





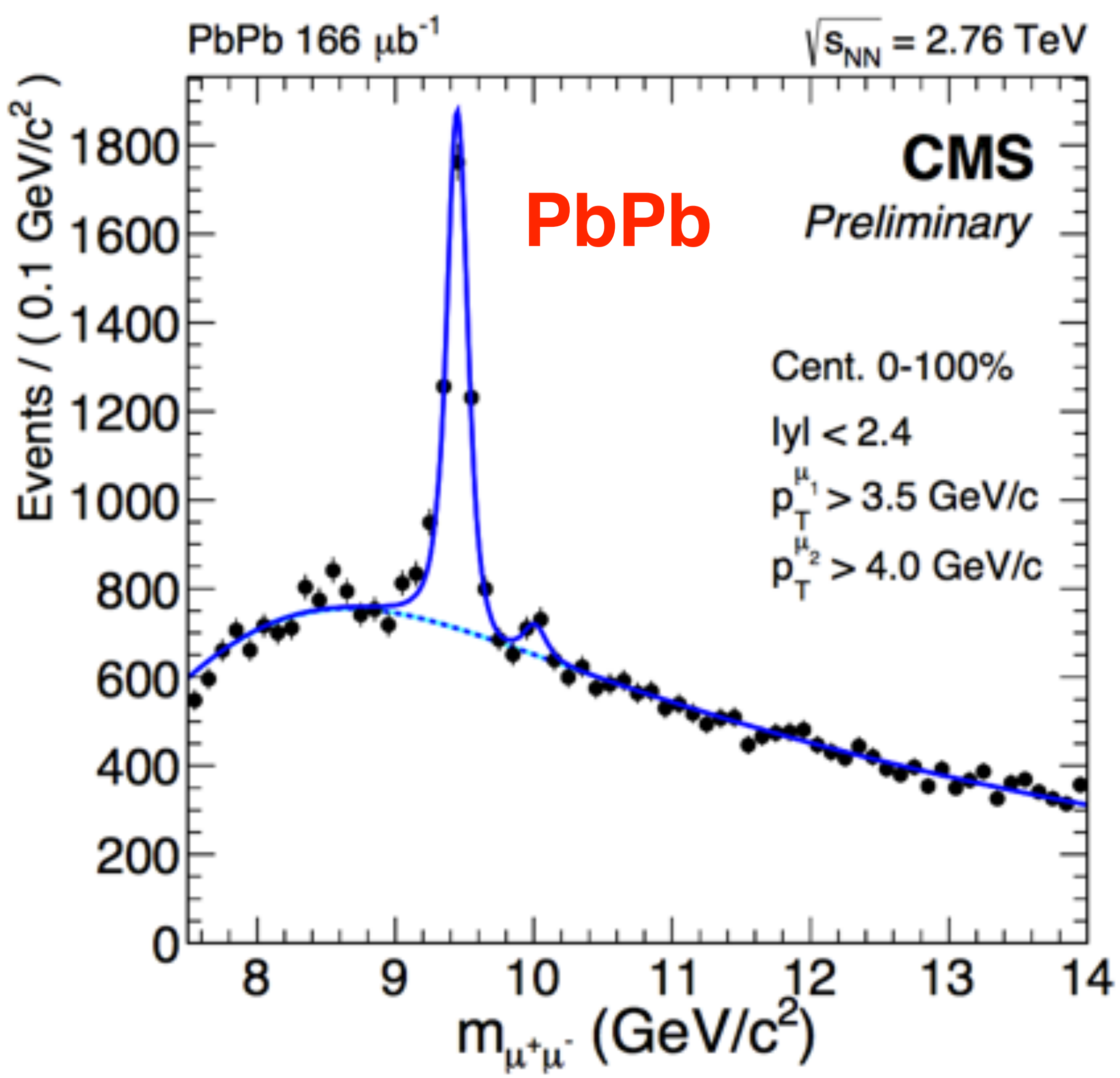
Goal: minimise uncertainty on Υ suppression

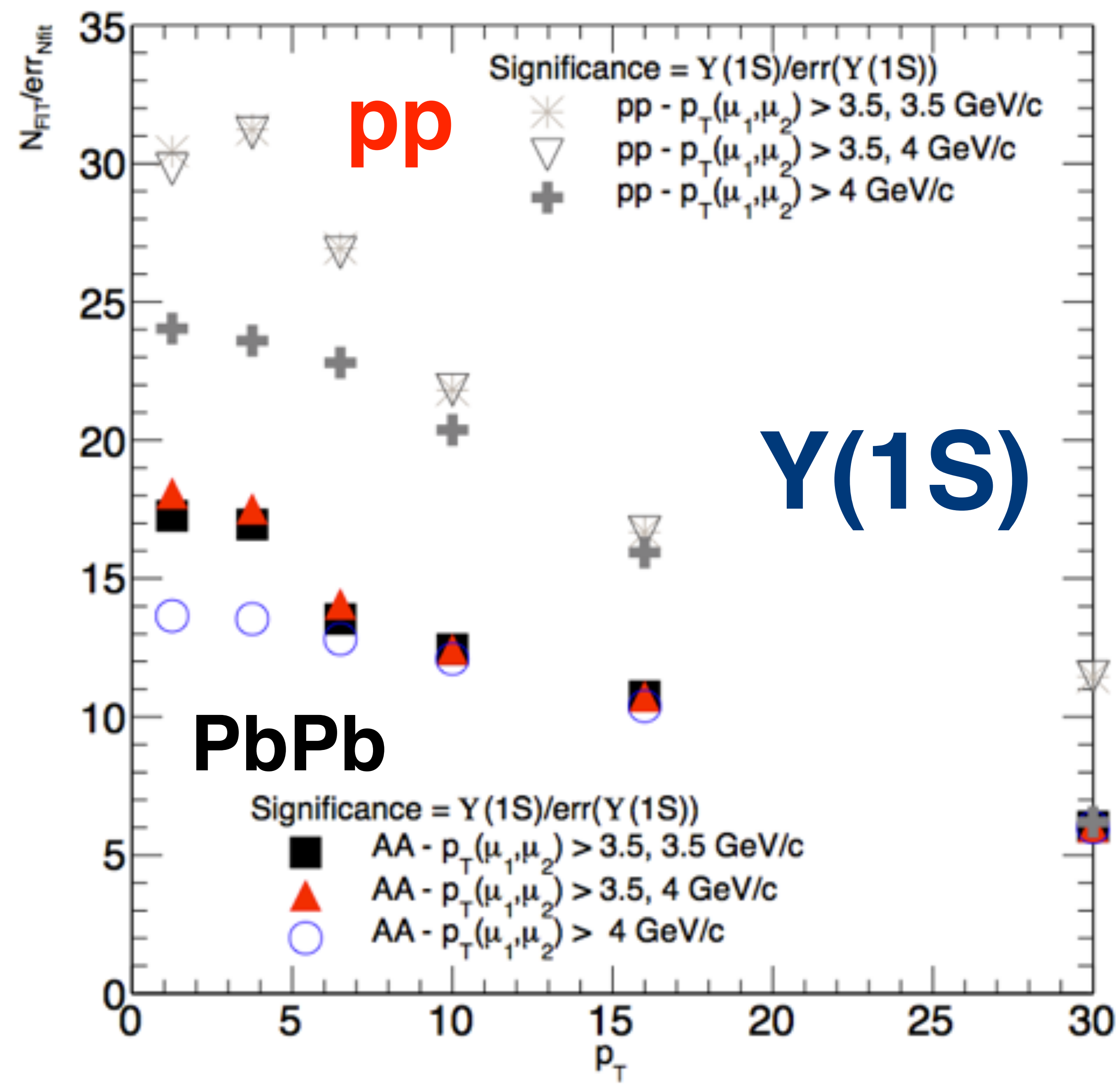
(in every bin of p_T, y, cent.)

Muon kinematics - 2

- Quantify the gain with a significance study

$$\Sigma = \frac{N^{\text{fit}}}{\text{err}(N^{fit})}$$





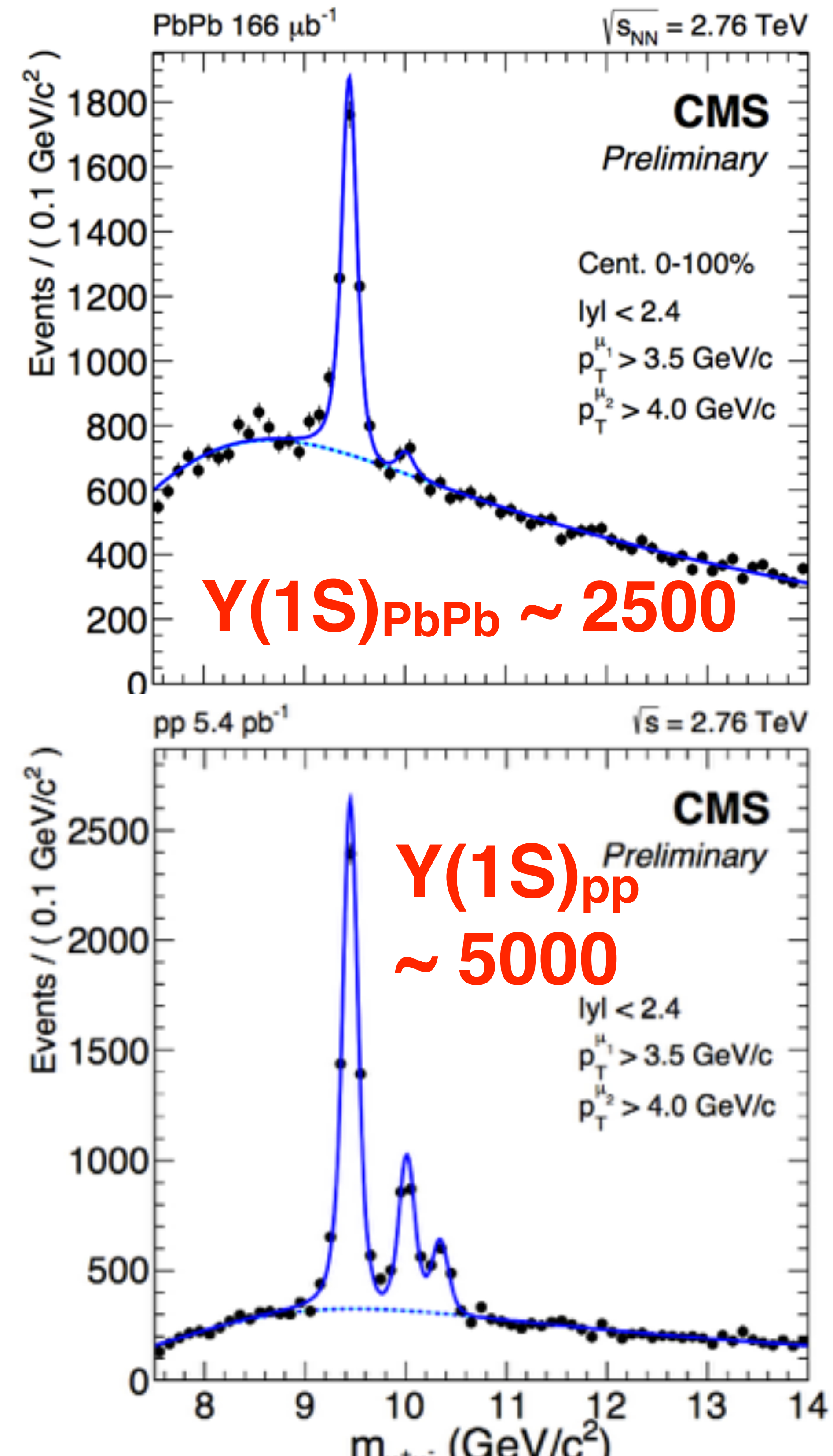
Gain in significance up to ~ 30 % in pp and PbPb

Yield extraction - 1

What I have done:

- **Extract raw yields $N_{Y(1S)}$, $N_{Y(2S)}$, $N_{Y(3S)}$**
  Unbinned max. likelihood fit of S+B
- **Signal**
  Double Crystal Ball
  Shape parameters constrained from MC
- **Background**
  Error function x exponential

$$\mathcal{B} = e^{-m_{\mu\mu}/\lambda} \times \left(1 + \text{Erf}\left(\frac{m_{\mu\mu} - m_0}{\sigma}\right)\right)$$

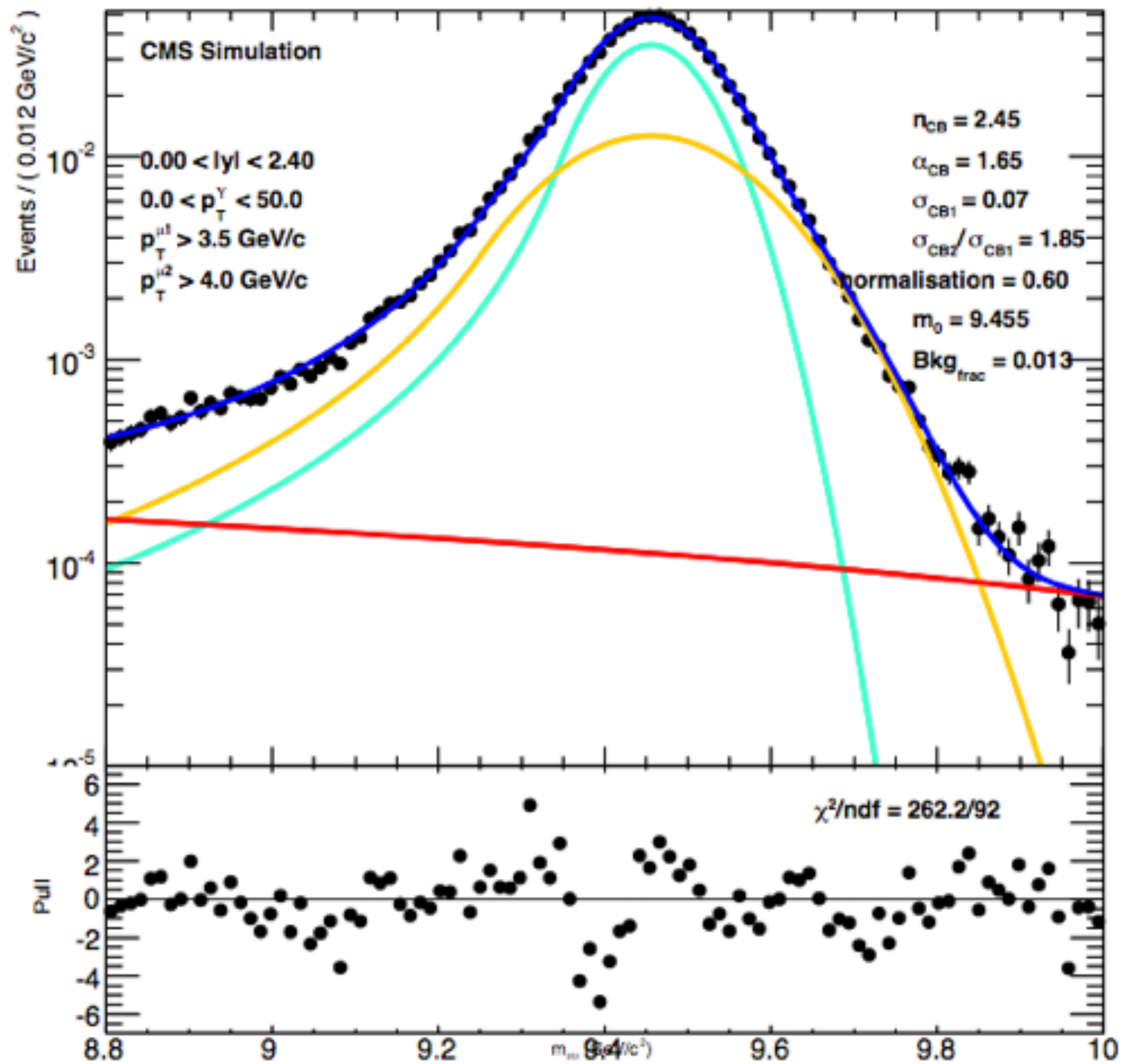


Yield extraction - 2

- μ momentum resolution varies with μ pseudorapidity
- Dimuon mass resolution varies with rapidity

Use two Crystal Ball functions

Parameters:
n: FSR power law exponent
α: FSR tail-shift
σ1/σ2: widths of CB #1/#2
f: normalisation of CBs



Constrained the signal shape for every kinematic bins

Yield extraction - 3

- **Binning: single-differential**

- 5 p_T bins p_T [GeV/c] $\in [0-2.5], [2.5-5], [5-8], [8-12], [12-20]$,
- 6 |y| bins $y \in [0-0.4], [0.4-0.8], [0.8-1.2], [1.2-1.6], [1.6-2], [2-2.4]$,
- 8 Centrality bins in Υ(1S), Υ(2S)

- Analysis performed *twice* (kinematic cuts)
- I don't see the Υ(3S)
- Integrated results:

Loose p_T cuts	$\mathcal{N}_{1S}$	$\mathcal{N}_{2S}$	$\mathcal{N}_{3S}$
PbPb	2534 ± 76	158 ± 52	-32 ± 48
pp	5014 ± 87	1580 ± 59	770 ± 49

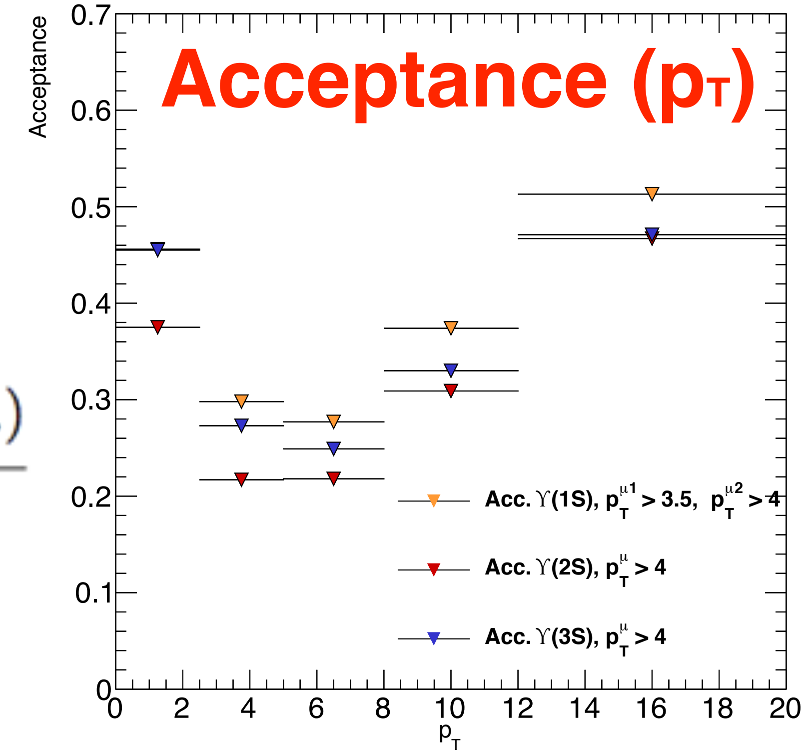
Tight p_T cuts	$\mathcal{N}_{1S}$	$\mathcal{N}_{2S}$	$\mathcal{N}_{3S}$
PbPb	1793 ± 61	173 ± 41	7 ± 9
pp	3511 ± 71	1208 ± 49	619 ± 41

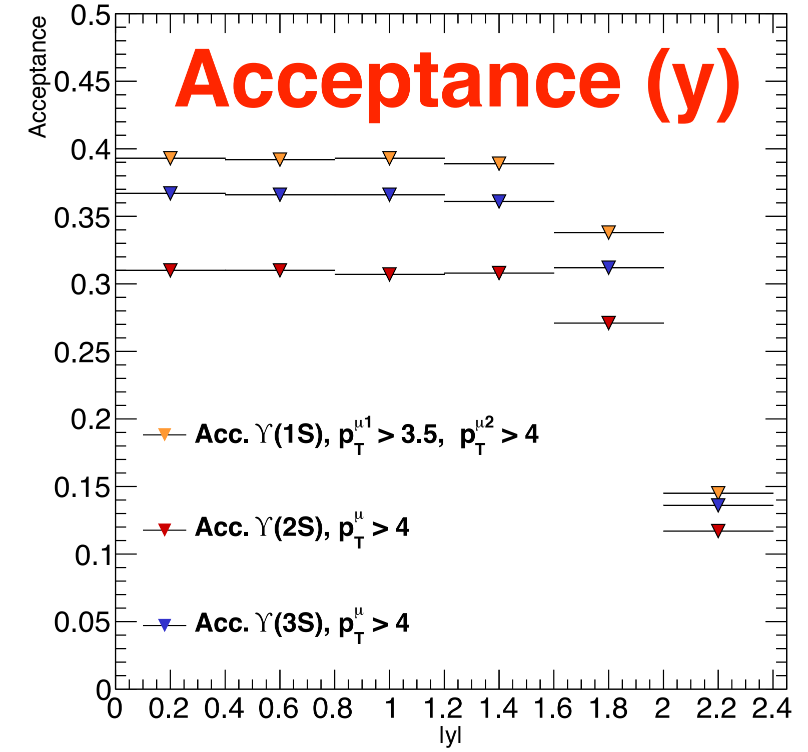
Corrections - 1

- Yields corrected with Pythia MC acceptance and efficiencies

$$\alpha(p_T, y) = \frac{N^{\mu^+\mu^-}_{\text{detectable},M}(p_T, y)}{N^{\mu^+\mu^-}_{\text{GEN}\in|y|<2.4}(p_T, y)}$$

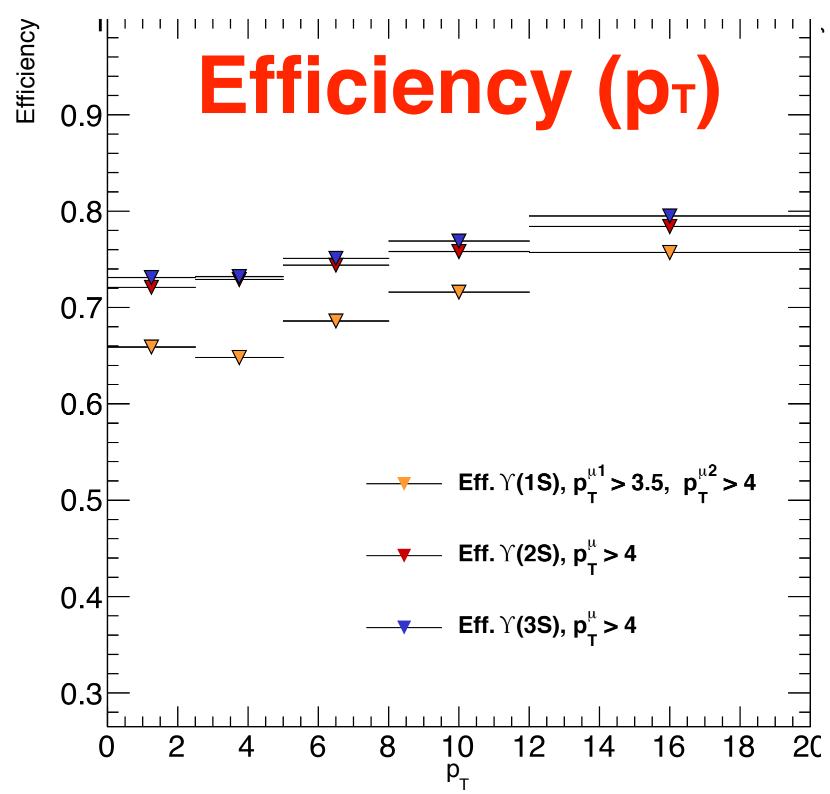
$$\varepsilon(p_T, y, \text{cent.}) = \frac{N^{\mu^+\mu^-}_{\text{Reco.},M\in[R]}(p_T, y, \text{cent.})}{N^{\mu^+\mu^-}_{\text{detectable},M}(p_T, y)}$$

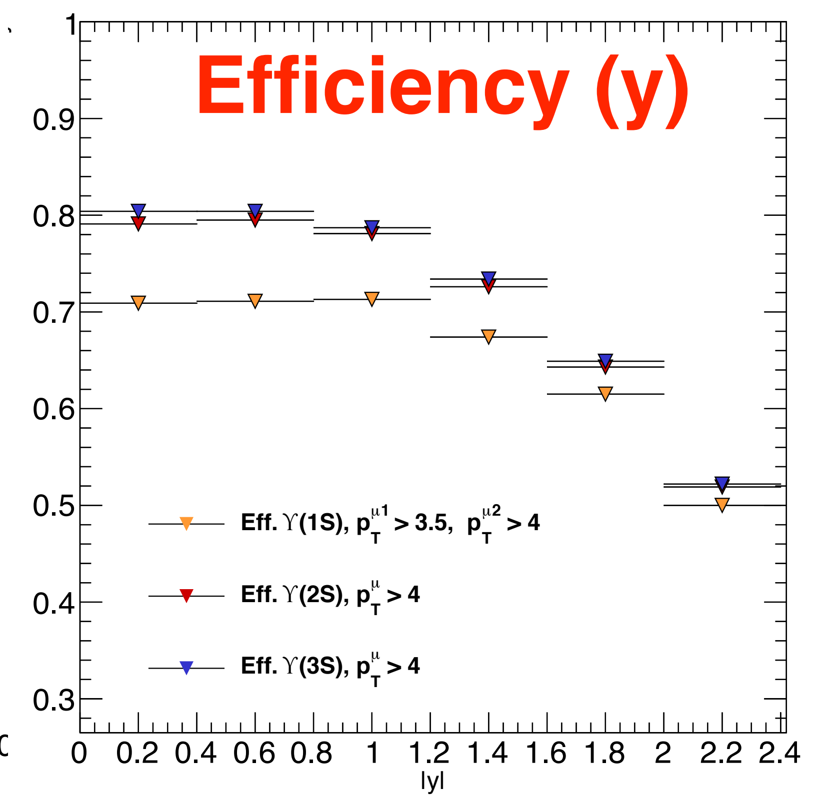




- Same strategy in PbPb

+ HYDJET background embedding
+ Centrality-dependent efficiencies (~flat)



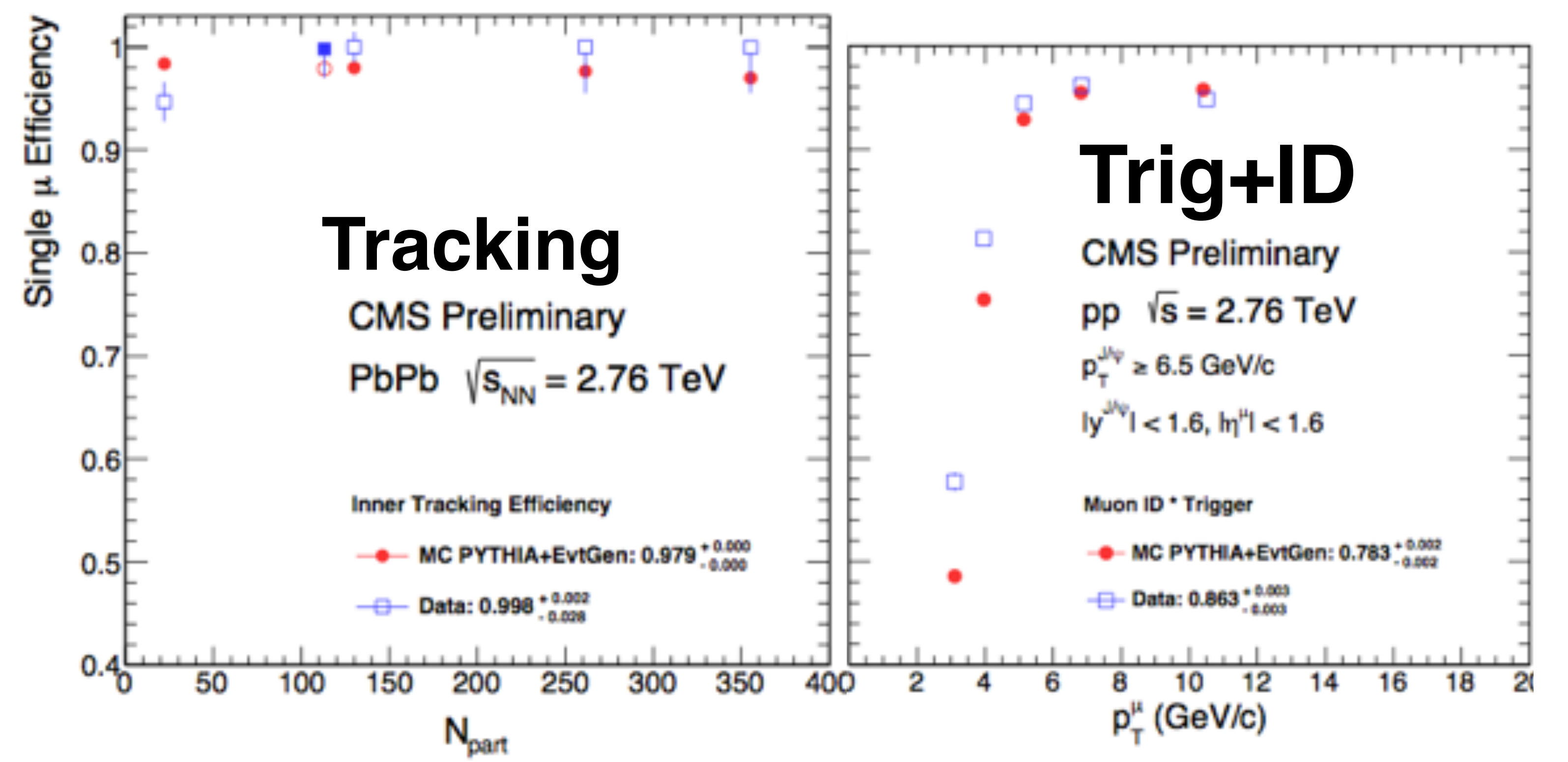


Corrections - 2

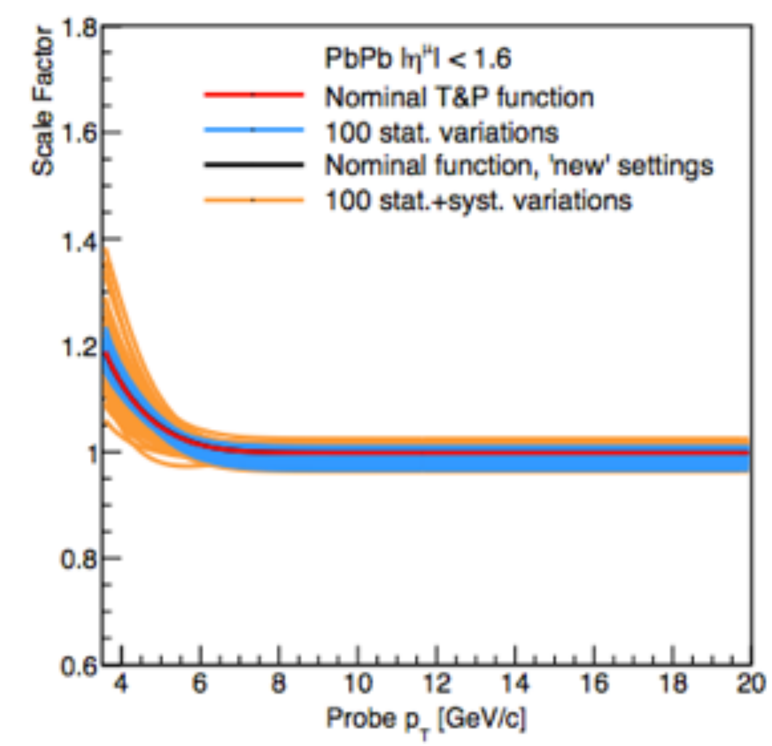
- Monte Carlo efficiencies are controlled with data
  - Tag and probe method
  - Taken from J/ψ analysis

ε^{μ}_{MC}

ε^{μ}_{Data}



- Corrections account for data-MC differences
- weights applied event-by-event, muon-by-muon
- Tracking is 95+% efficient
- Performed 100 stat.+syst. variations on Trig+ID



Systematic uncertainties

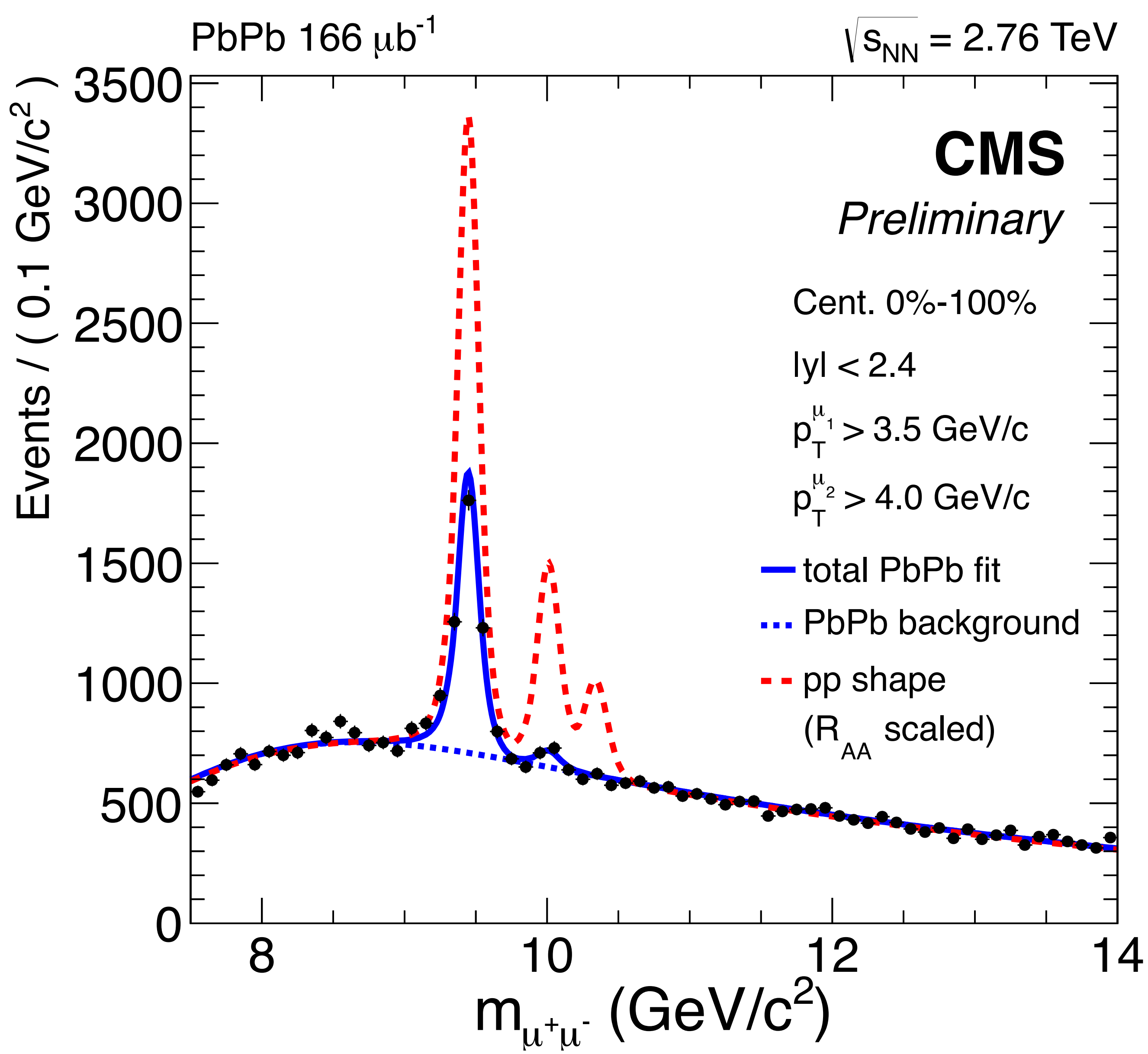
- Summary:
  - Raw yields: 7 variations (5 Sig + 2 Bkgd) per bin
  - Dominant uncertainty at low p_T (9% in PbPb Υ(1S), p_T < 2.5 GeV/c)

  - Generated Pythia spectra: affects acc.x eff.
  - on average 2.5% in pp, 8.2% in PbPb

  - Tag-and-probe in pp and PbPb
  - Trigger + muon ID: ranging from 0.4% to 15% (|y| > 2)
  - Tracking: 1.7% /μ in pp, 5% /μ in PbPb
  - recently improved for an upcoming publication

  - 'Global' uncertainties:
    - pp luminosity (3.7 %), $\mathcal{L}_{pp} = (5.4 \pm 0.2)$ pb^{-1}
    - PbPb: Minimum bias trigger 97% efficient
    - + nuclear overlap function T_{AA} (6.2 %)

Results



PbPb 166 μb-1
√sNN = 2.76 TeV
CMS
Preliminary
Cent. 0%-100%
|y| < 2.4
pT μ1 > 3.5 GeV/c
pT μ2 > 4.0 GeV/c
total PbPb fit
PbPb background
pp shape
(RAA scaled)
Events / (0.1 GeV/c2)
mμ+μ- (GeV/c2)
0
500
1000
1500
2000
2500
3000
3500
8
10
12
14

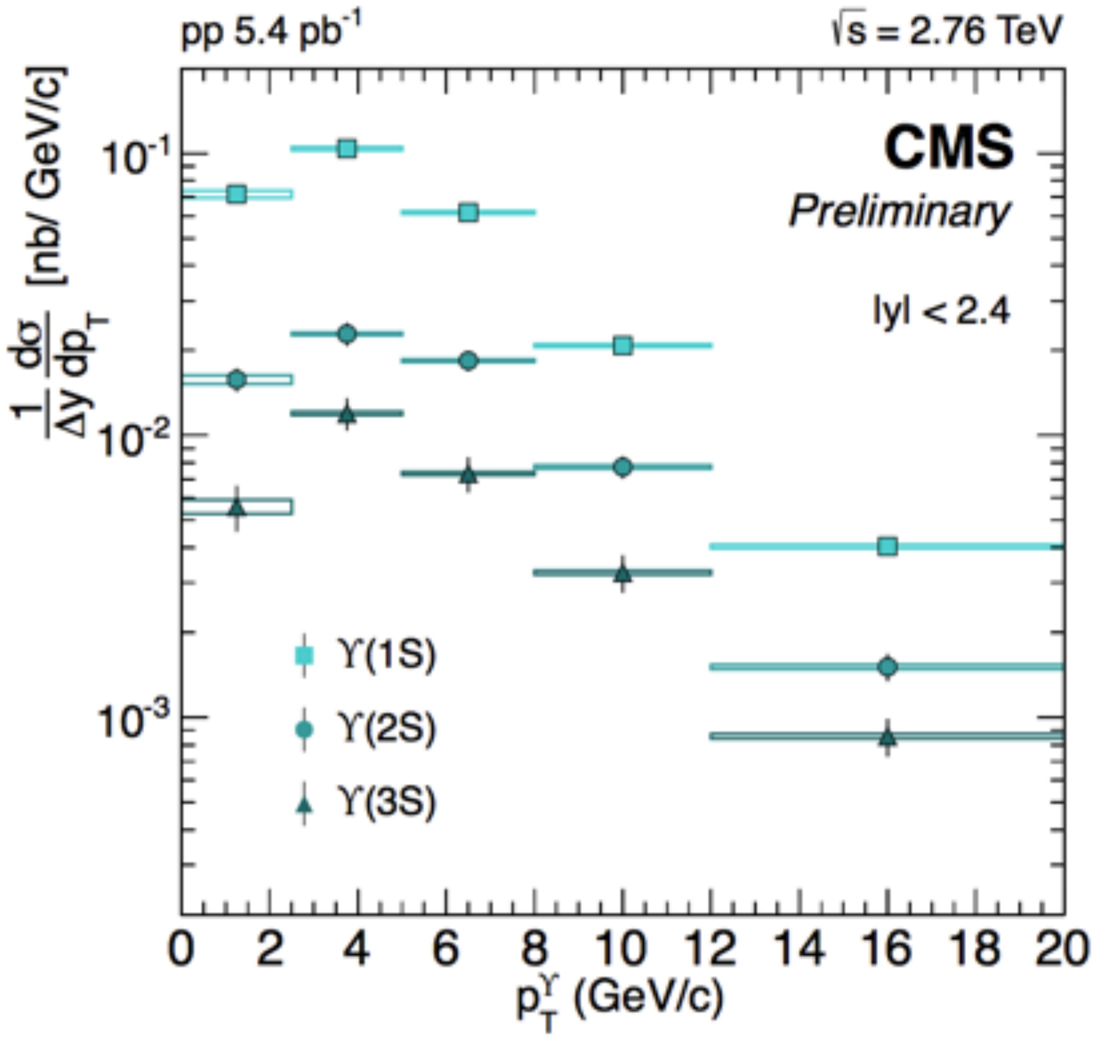
Υ(nS) cross sections in pp

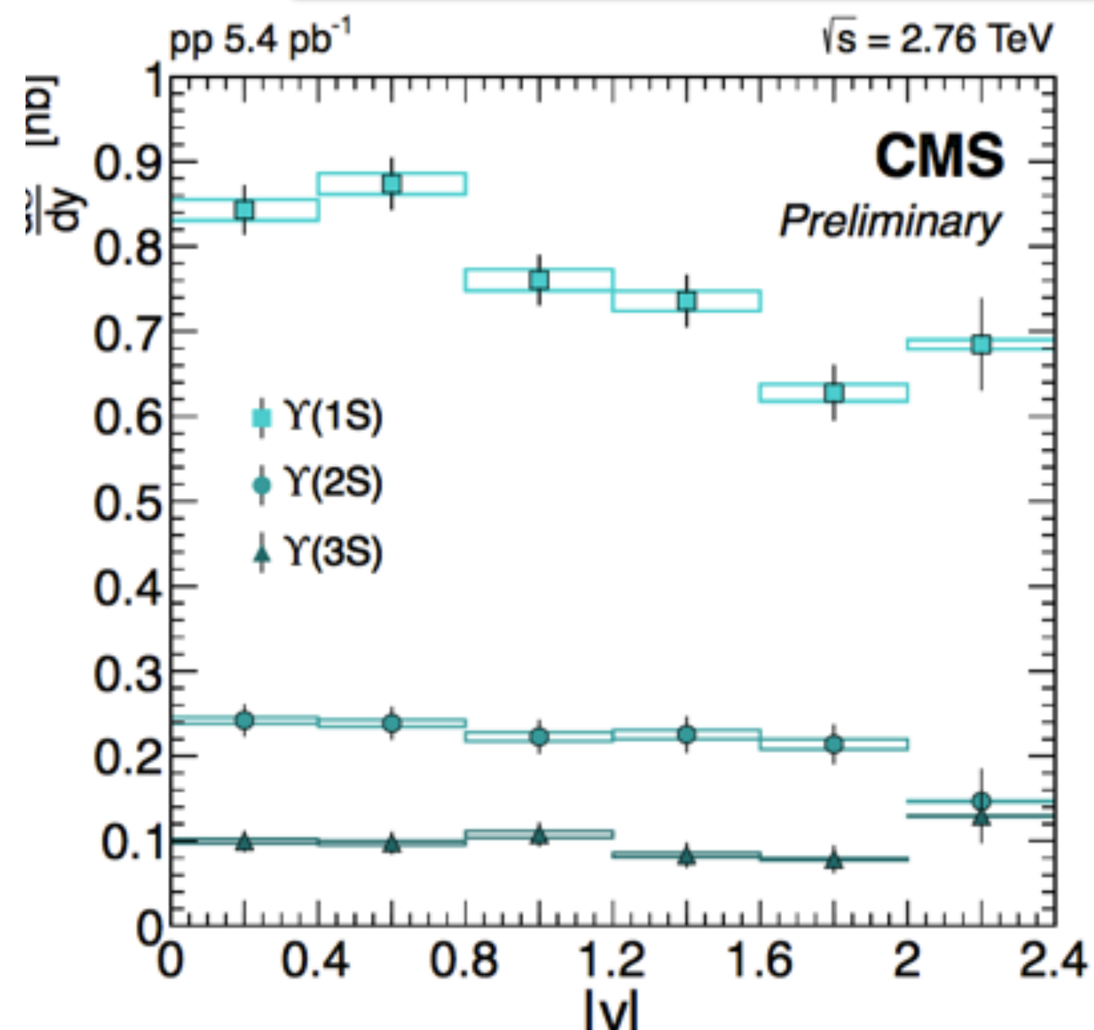
$$\frac{\mathrm{d}\sigma\,(pp \to \Upsilon(nS)X)}{\mathrm{d}y} \cdot B_{\mu\mu} \quad = \quad \frac{1}{\Delta y} \cdot \frac{1}{\mathcal{L}_{pp}} \cdot \frac{\mathcal{N}_{\mathrm{nS}}}{\alpha\ \varepsilon_{pp,w}}$$

Υ(nS) cross sections in pp

$$\frac{\mathrm{d}\sigma\,(pp \to \Upsilon(nS)X)}{\mathrm{d}y} \cdot B_{\mu\mu} = \frac{1}{\Delta y} \cdot \frac{1}{\mathcal{L}_{pp}} \cdot \frac{\mathcal{N}_{\mathrm{nS}}}{\alpha\ \varepsilon_{pp,w}}$$

Useful reference for PbPb
To be compared with model predictions





$$\sigma\,(pp \to \Upsilon(1S)X) \cdot B_{\mu\mu} = 3.544 \pm 0.067 \pm 0.109\ \mathrm{nb}$$
$$\sigma\,(pp \to \Upsilon(2S)X) \cdot B_{\mu\mu} = 1.026 \pm 0.042 \pm 0.037\ \mathrm{nb}$$
$$\sigma\,(pp \to \Upsilon(3S)X) \cdot B_{\mu\mu} = 0.436 \pm 0.029 \pm 0.008\ \mathrm{nb.}$$

Y(nS) corrected yields in PbPb

$$\frac{1}{T_{\mathrm{AA}}} \cdot \frac{\mathrm{d}N\,(AA \to \Upsilon(nS))}{\mathrm{d}y} \cdot B_{\mu\mu} \;=\; \frac{1}{T_{\mathrm{AA}}} \cdot \frac{1}{N_{\mathrm{MB}}} \cdot \frac{\mathcal{N}_{\mathrm{nS}}^{\mathrm{PbPb}}}{\alpha\;\varepsilon_{\mathrm{PbPb}}\;\Delta y}$$

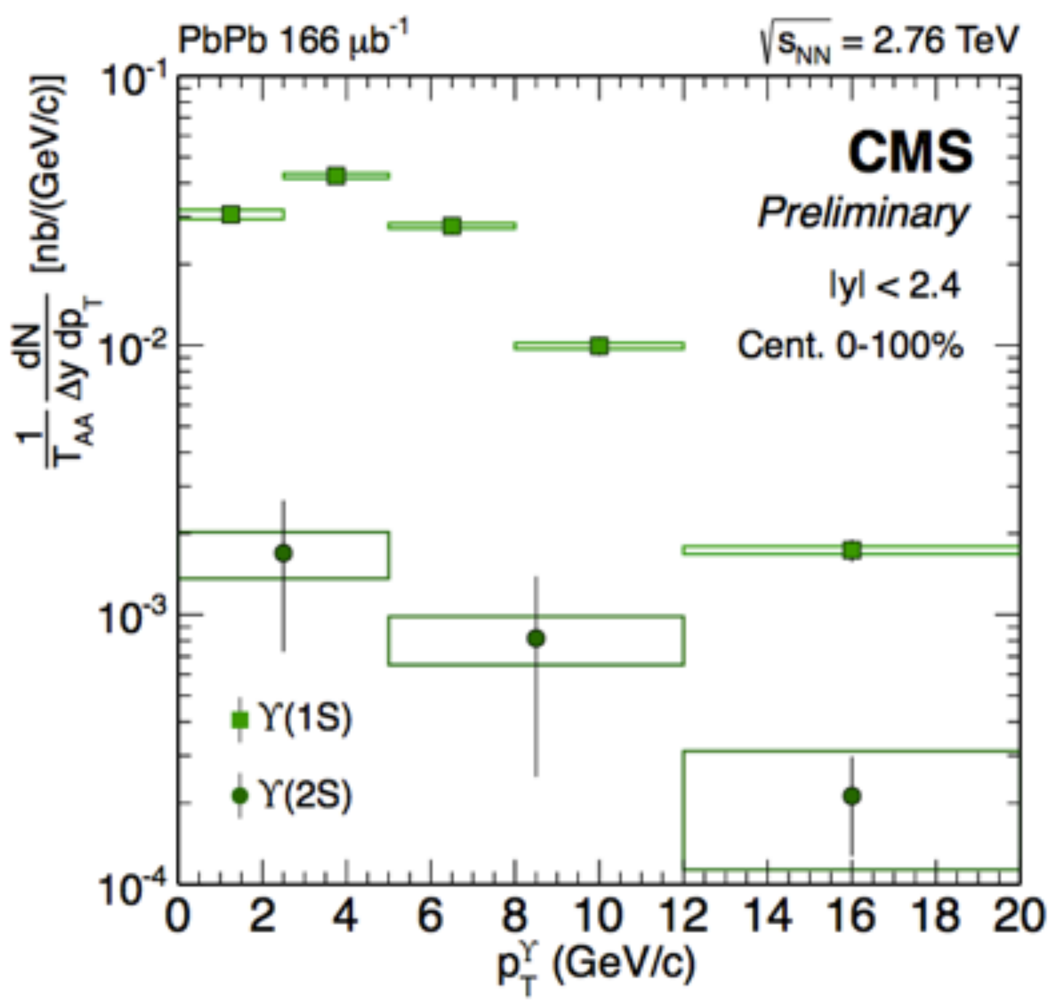
- PbPb equivalent to the *pp* cross section
- To account for the proper normalisation : $\langle T_{AA} \rangle \times N_{\mathsf{MB}}$

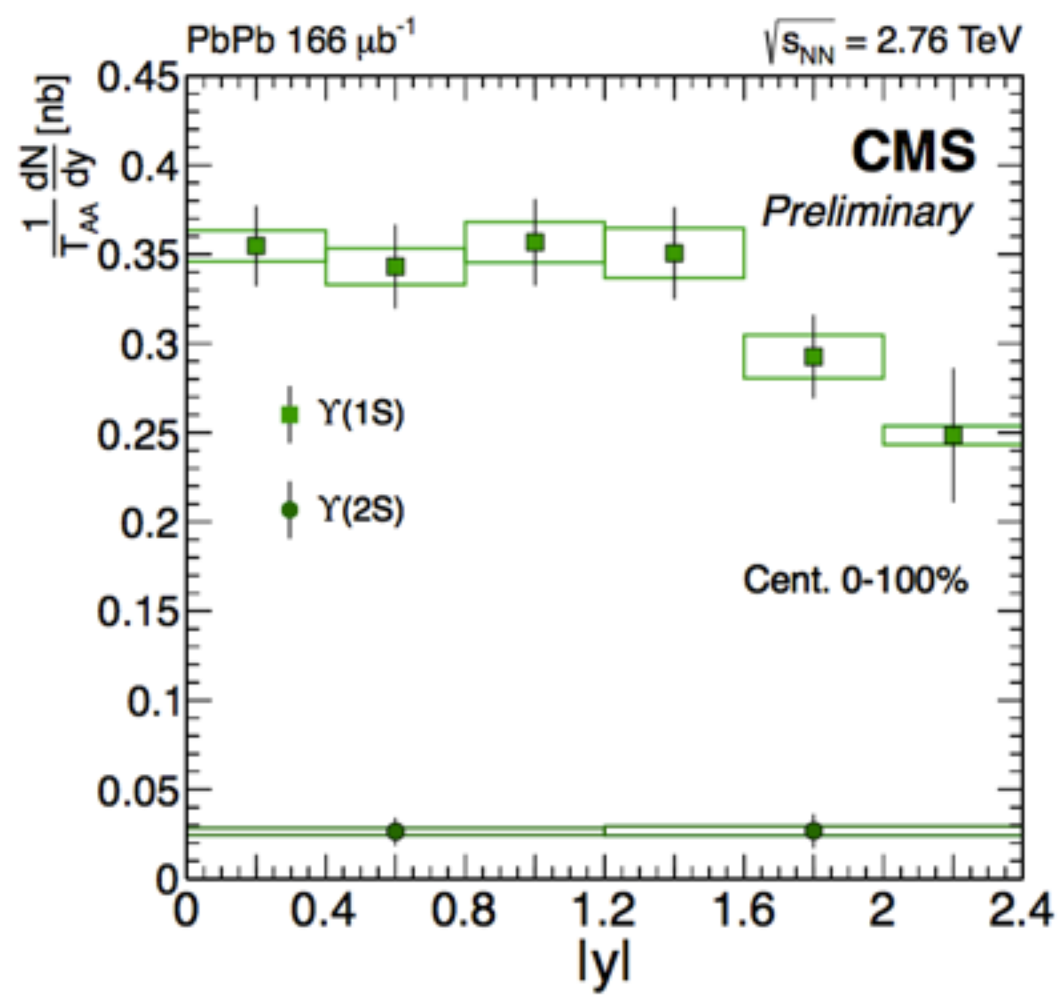
$$\langle T_{AA} \rangle \;=\; (5.66 \pm 0.35)\;\mu\mathrm{b}$$

$$N_{\mathsf{MB}} \;=\; 1.161 \times 10^{9}$$

Υ(nS) corrected yields in PbPb

$$\frac{1}{T_{\mathrm{AA}}}\cdot\frac{\mathrm{d}N\left(AA\to\Upsilon(nS)\right)}{\mathrm{d}y}\cdot B_{\mu\mu} = \frac{1}{T_{\mathrm{AA}}}\cdot\frac{1}{N_{\mathrm{MB}}}\cdot\frac{\mathcal{N}_{\mathrm{nS}}^{\mathrm{PbPb}}}{\alpha\;\varepsilon_{\mathrm{PbPb}}\;\Delta y}$$





First measurement of Υ(2S) kinematics in PbPb *!!*

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\mathcal{L}_{pp}}{T_{\mathrm{AA}} N_{\mathrm{MB}}} \cdot \frac{\mathrm{N}(\Upsilon(nS))_{\mathrm{PbPb}}}{\mathrm{N}(\Upsilon(nS))_{pp}} \cdot \frac{\varepsilon_{pp,w}}{\varepsilon_{\mathrm{PbPb},w}}$$

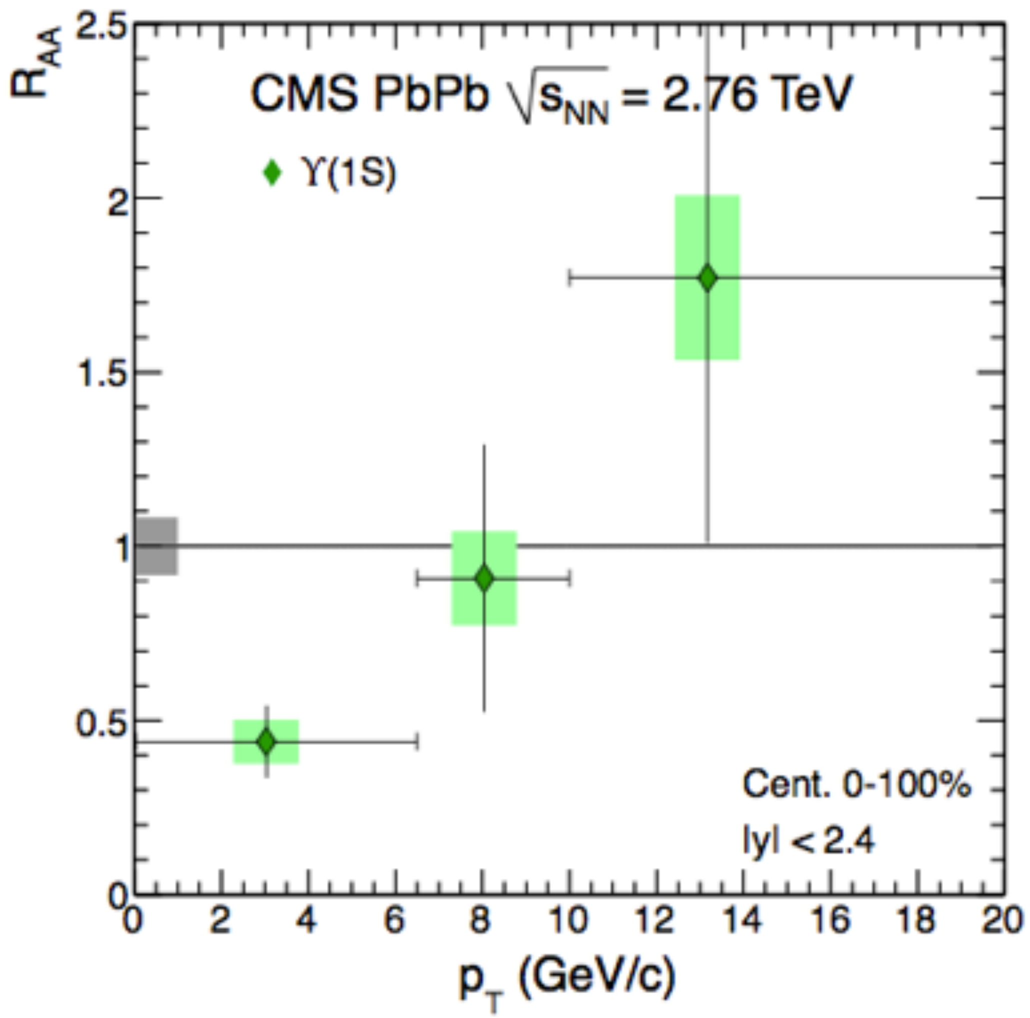
At scope:

- **Y(1S) and Y(2S) suppressions in several bins of p_T, y, centrality**
- **Y(3S): upper limit on integrated R_{AA}**

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\mathcal{L}_{pp}}{T_{\mathrm{AA}} N_{\mathrm{MB}}} \cdot \frac{\mathrm{N}(\Upsilon(nS))_{\mathrm{PbPb}}}{\mathrm{N}(\Upsilon(nS))_{pp}} \cdot \frac{\varepsilon_{pp,w}}{\varepsilon_{\mathrm{PbPb},w}}$$

- **2010…**

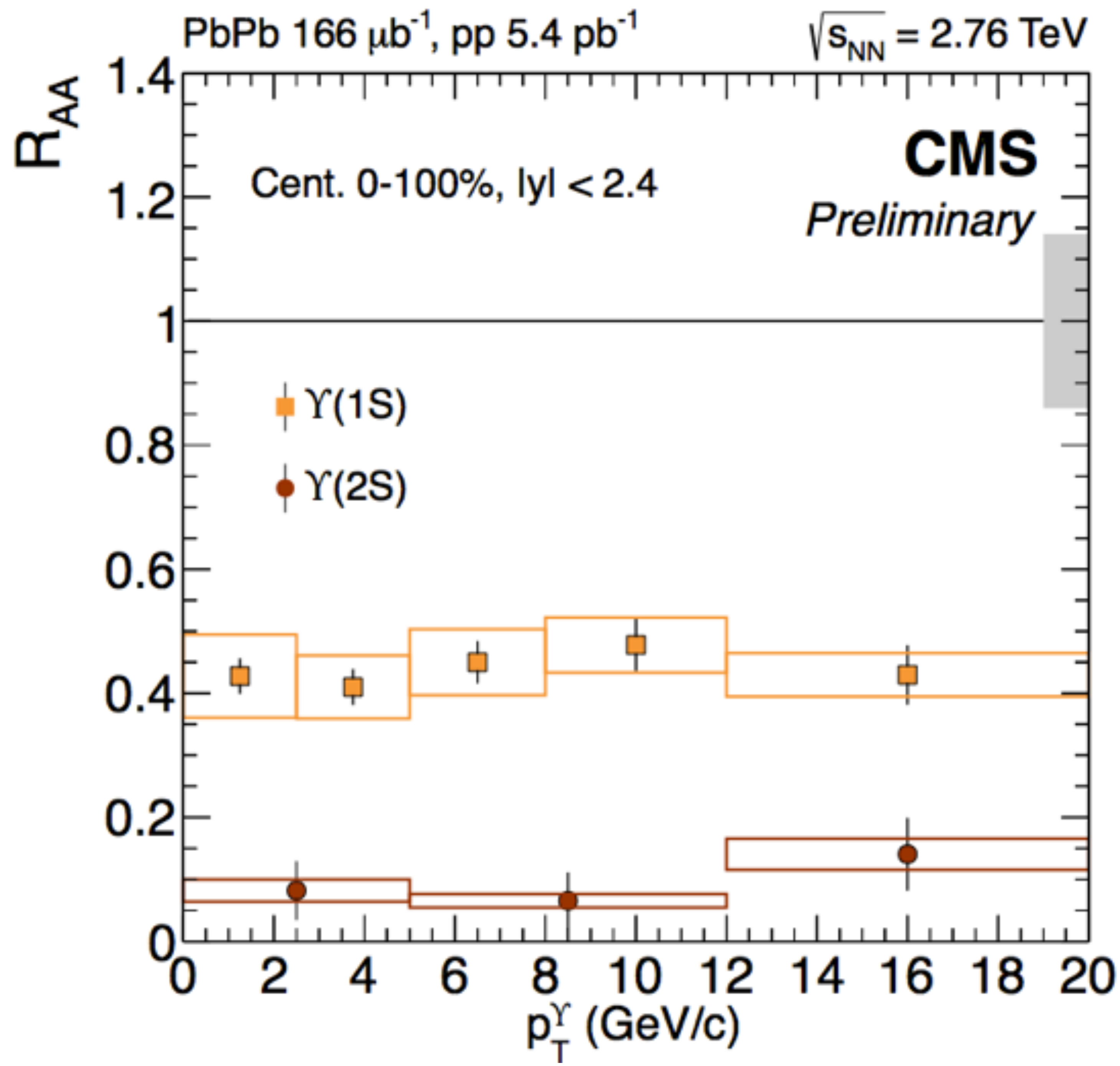


Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\mathcal{L}_{pp}}{T_{\mathrm{AA}} N_{\mathrm{MB}}} \cdot \frac{\mathrm{N}(\Upsilon(nS))_{\mathrm{PbPb}}}{\mathrm{N}(\Upsilon(nS))_{pp}} \cdot \frac{\varepsilon_{pp,w}}{\varepsilon_{\mathrm{PbPb},w}}$$

- **Now!**

Breaking News:
Upsilon suppression does not depend on p_T up to ~ 20 GeV !

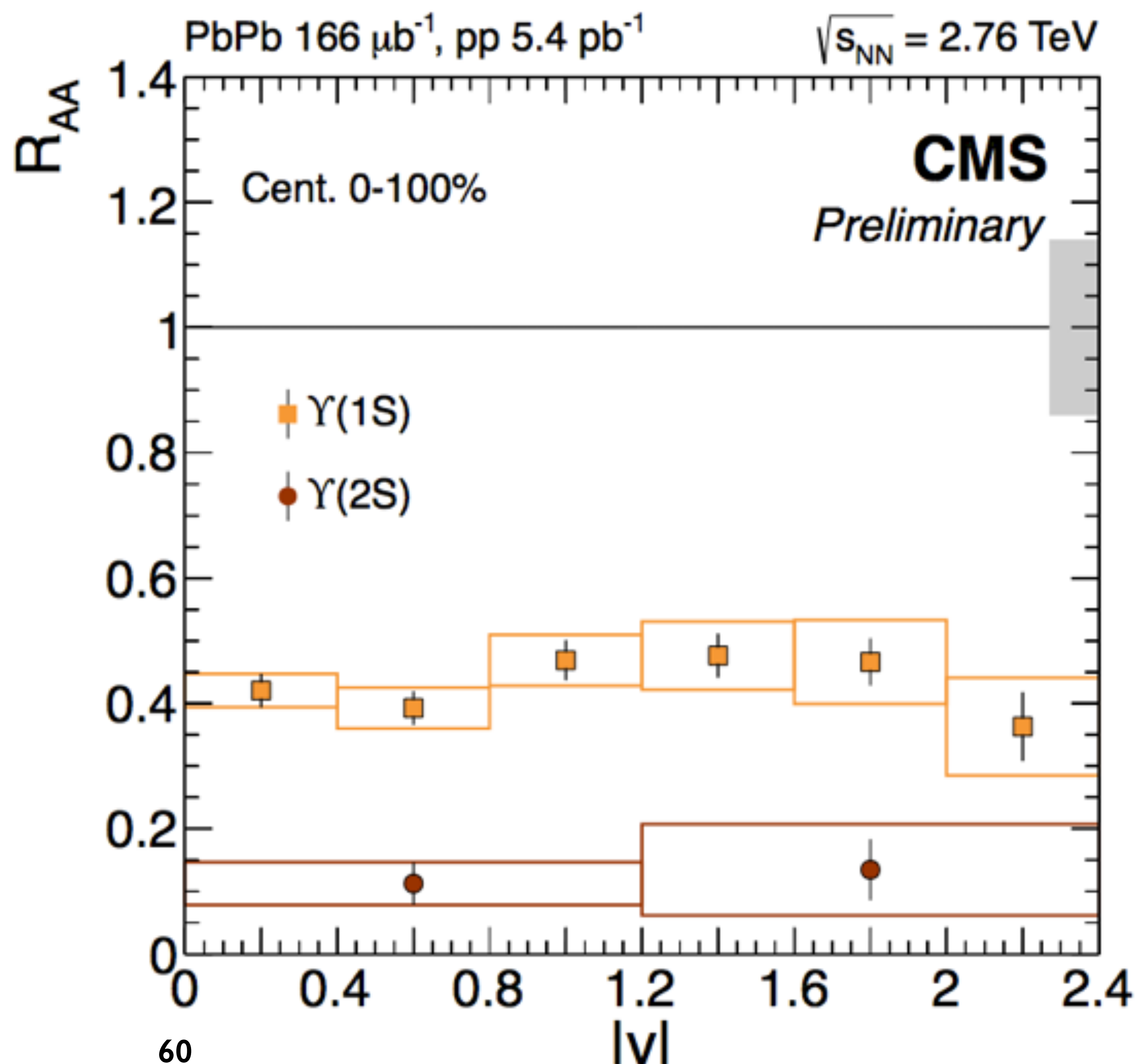


Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\mathcal{L}_{pp}}{T_{\mathrm{AA}} N_{\mathrm{MB}}} \cdot \frac{\mathrm{N}(\Upsilon(nS))_{\mathrm{PbPb}}}{\mathrm{N}(\Upsilon(nS))_{pp}} \cdot \frac{\varepsilon_{pp,w}}{\varepsilon_{\mathrm{PbPb},w}}$$

- **Rapidity < 2.4:**

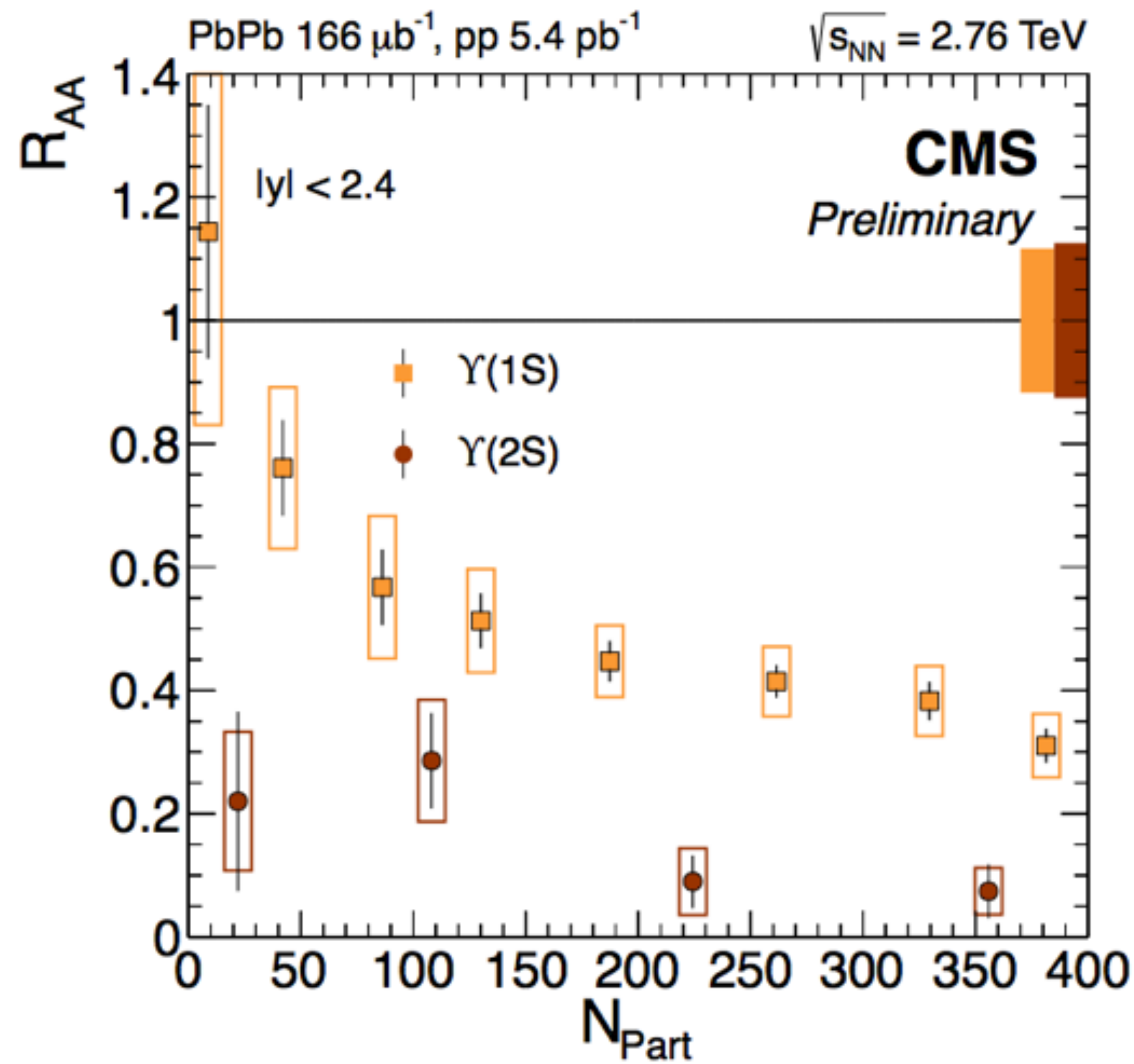
Breaking News:
Upsilon suppression is relatively constant over CMS rapidity range



Nuclear modification factor

$$R_{AA}(\Upsilon(1S)) = 0.425 \pm 0.029\ (\text{stat.}) \pm 0.070\ (\text{syst.}),$$
$$R_{AA}(\Upsilon(2S)) = 0.116 \pm 0.028\ (\text{stat.}) \pm 0.022\ (\text{syst.}),$$
$$R_{AA}(\Upsilon(3S)) < 0.14 \text{ at } 95\% \text{ C.L.}$$

- **Centrality dependence:** confirmed
- **New:** 70-100% centrality
- Computed a 95% C.L. upper limit on R_{AA} Υ(3S), using Feldman-Cousins method

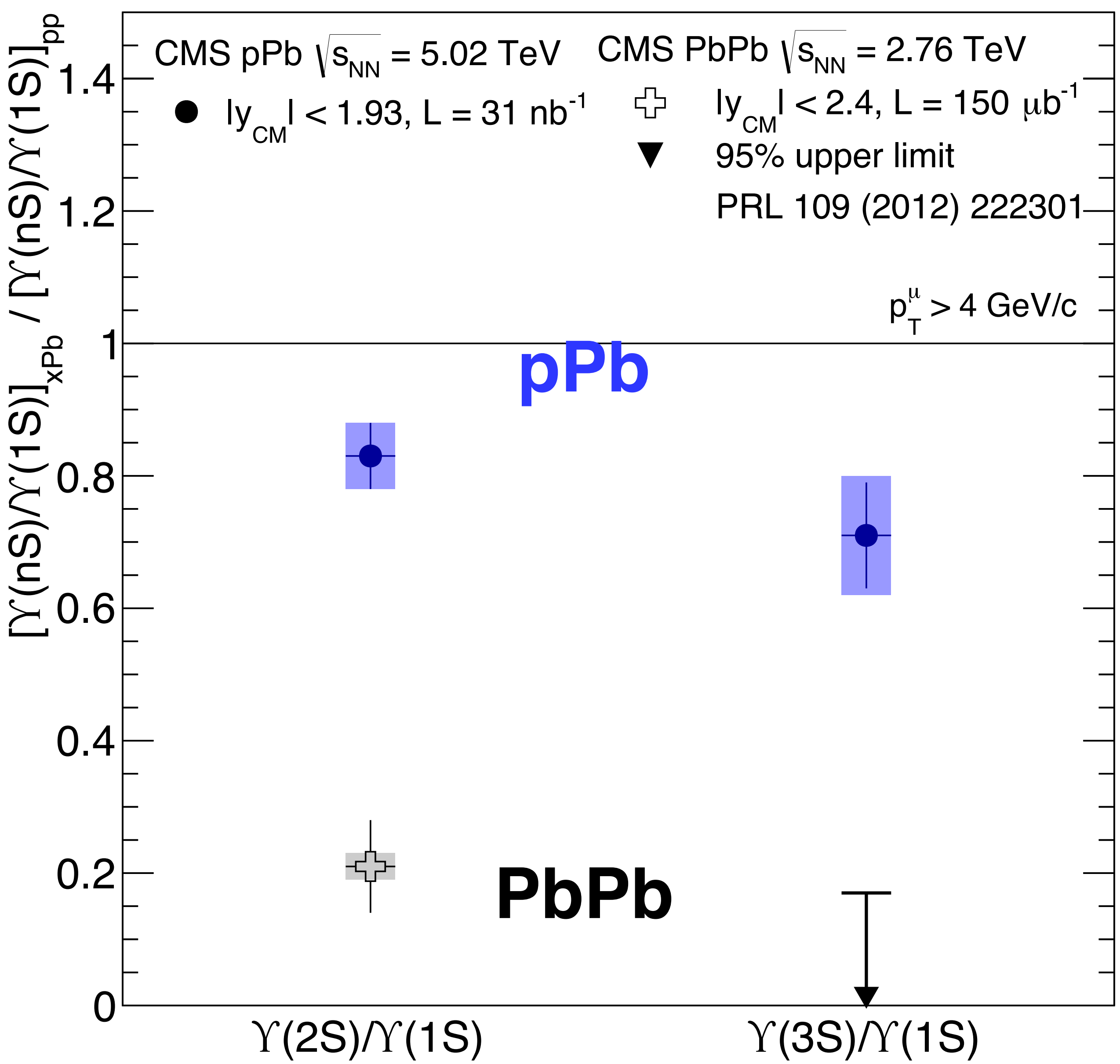


Before leaving the building

- Some experimental comparisons
- Some theory curves overlaid
- Outlook

CMS Pb-Pb vs. p-Pb

- Early contribution to pPb analysis:
  - Monitoring the muon triggers in pp/p-Pb;
  - cross-checking fits



- In pPb, slight extra modification of excited states vs. ground state

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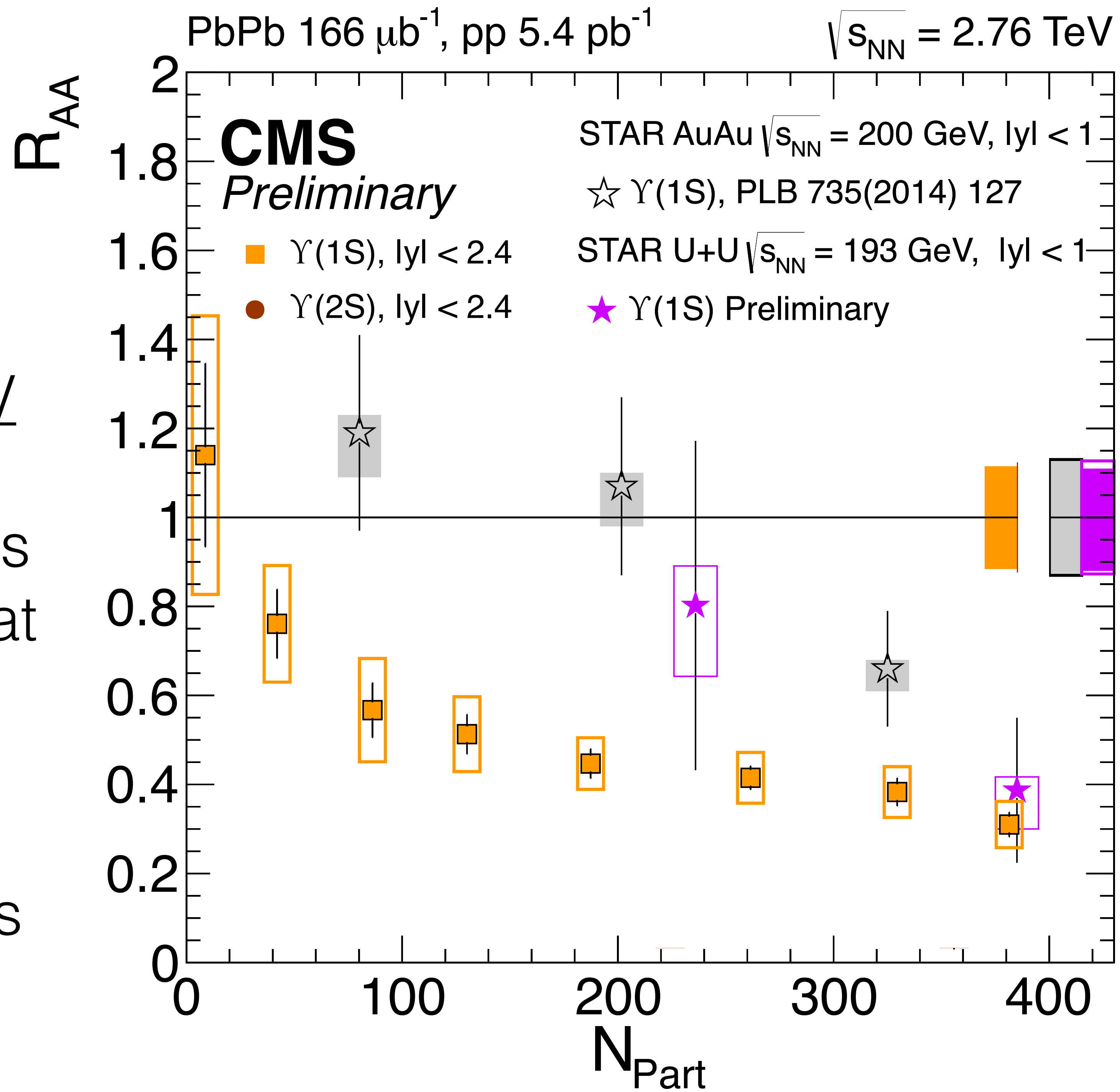
LHC vs. RHIC

- $\sqrt{s_{NN}}$ = 200 GeV
- gold ions (A=198)

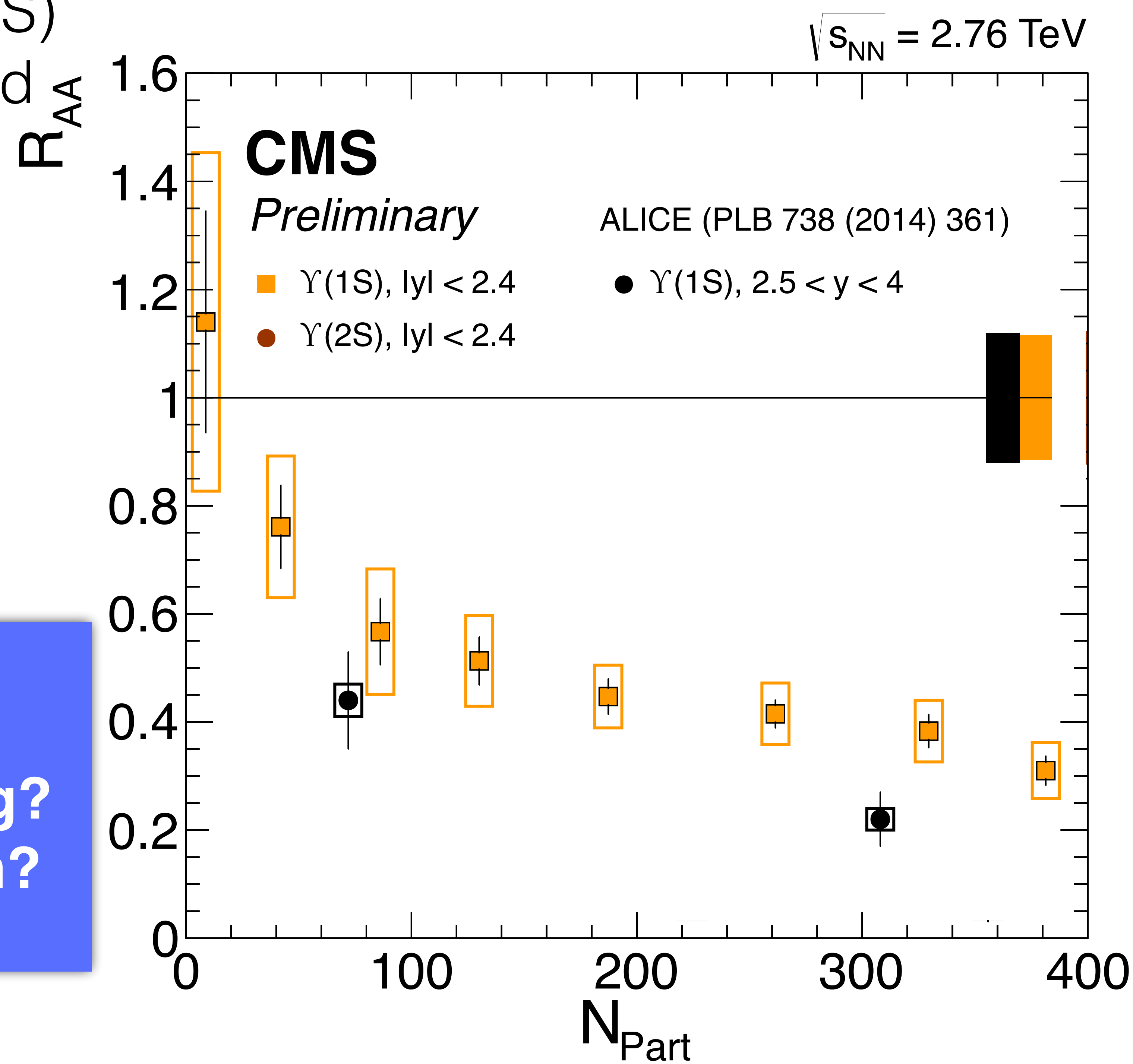
→ smaller energy density

- STAR |y|<1
- + short U+U run at 193 GeV
- Starting at higher centralities Suppression is also strong at RHIC!
- Soon: more precise STAR data with detector upgrades



LHC: CMS vs. ALICE

- *Stronger* suppression of Y(1S) seen by ALICE in the forward region
- ALICE coverage 2.5 < y < 4

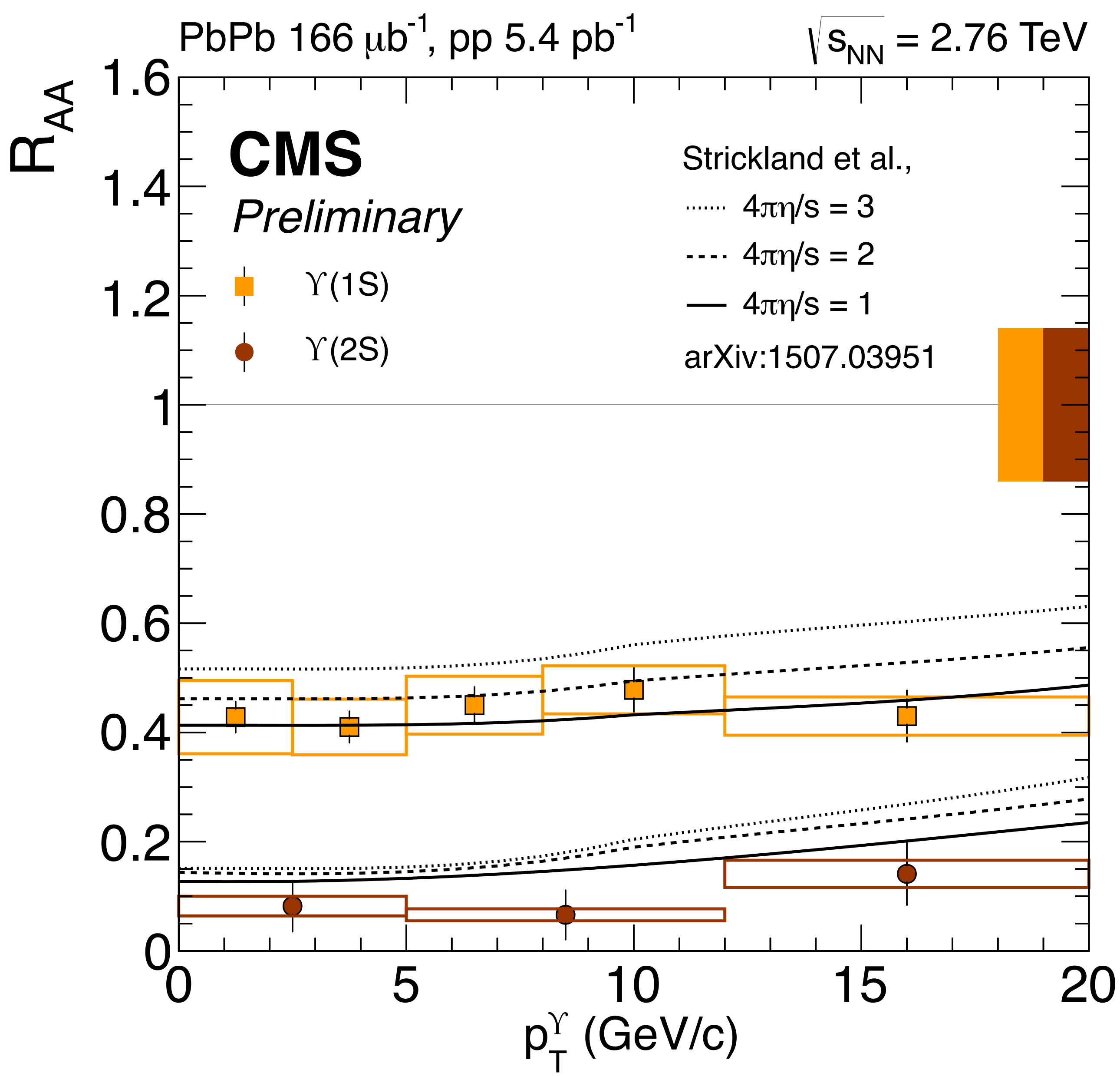


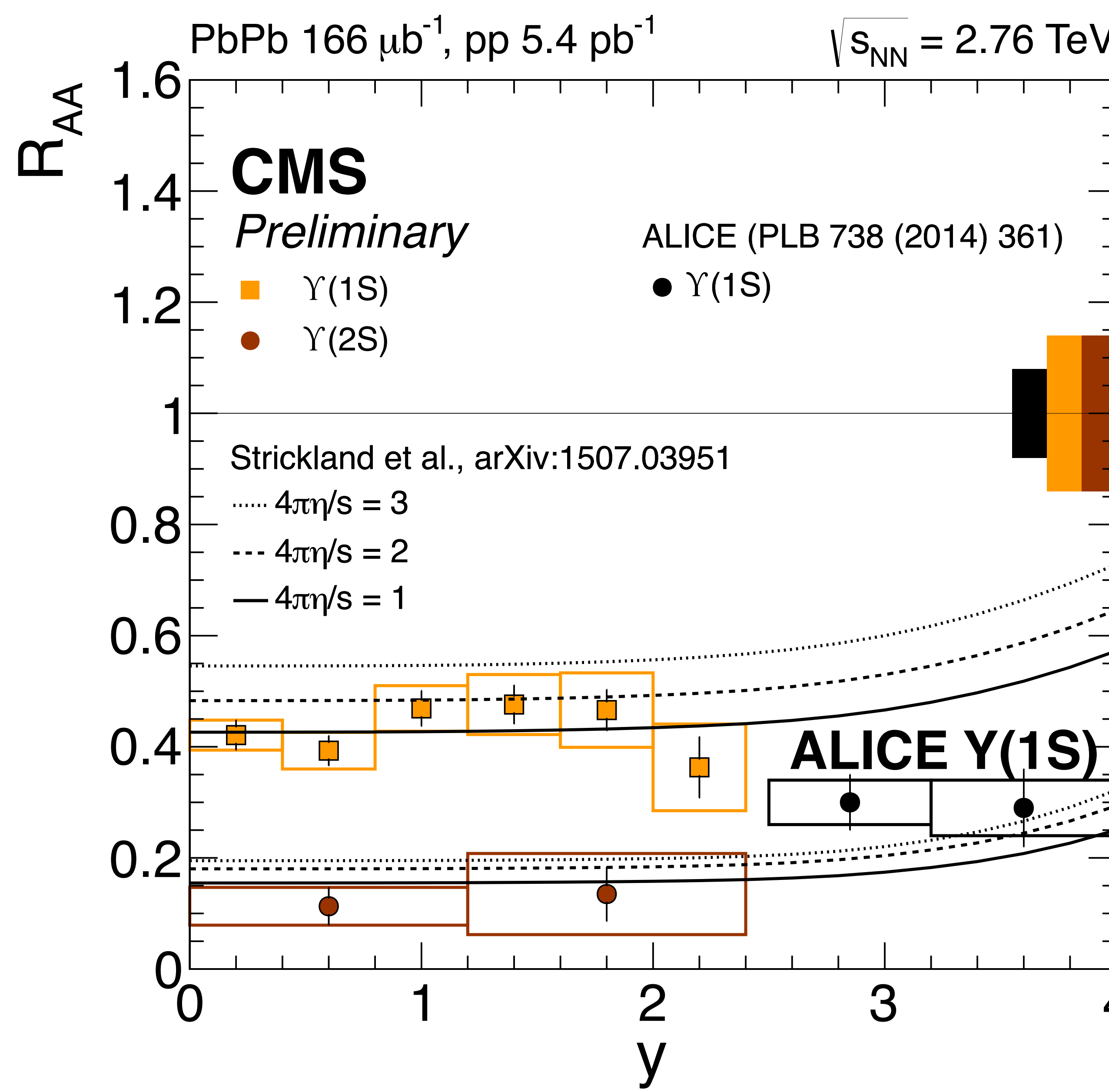
RAA(0-20%) ~ 0.2 !
Has the Y(1S) started melting?
Why in the forward direction?

Theory comparisons in PbPb

- Strickland: Sequential melting in a hot + anisotropic QGP
- Satisfactory vs. pT

- However fails to reproduce the forward full rapidity (non-)trend!



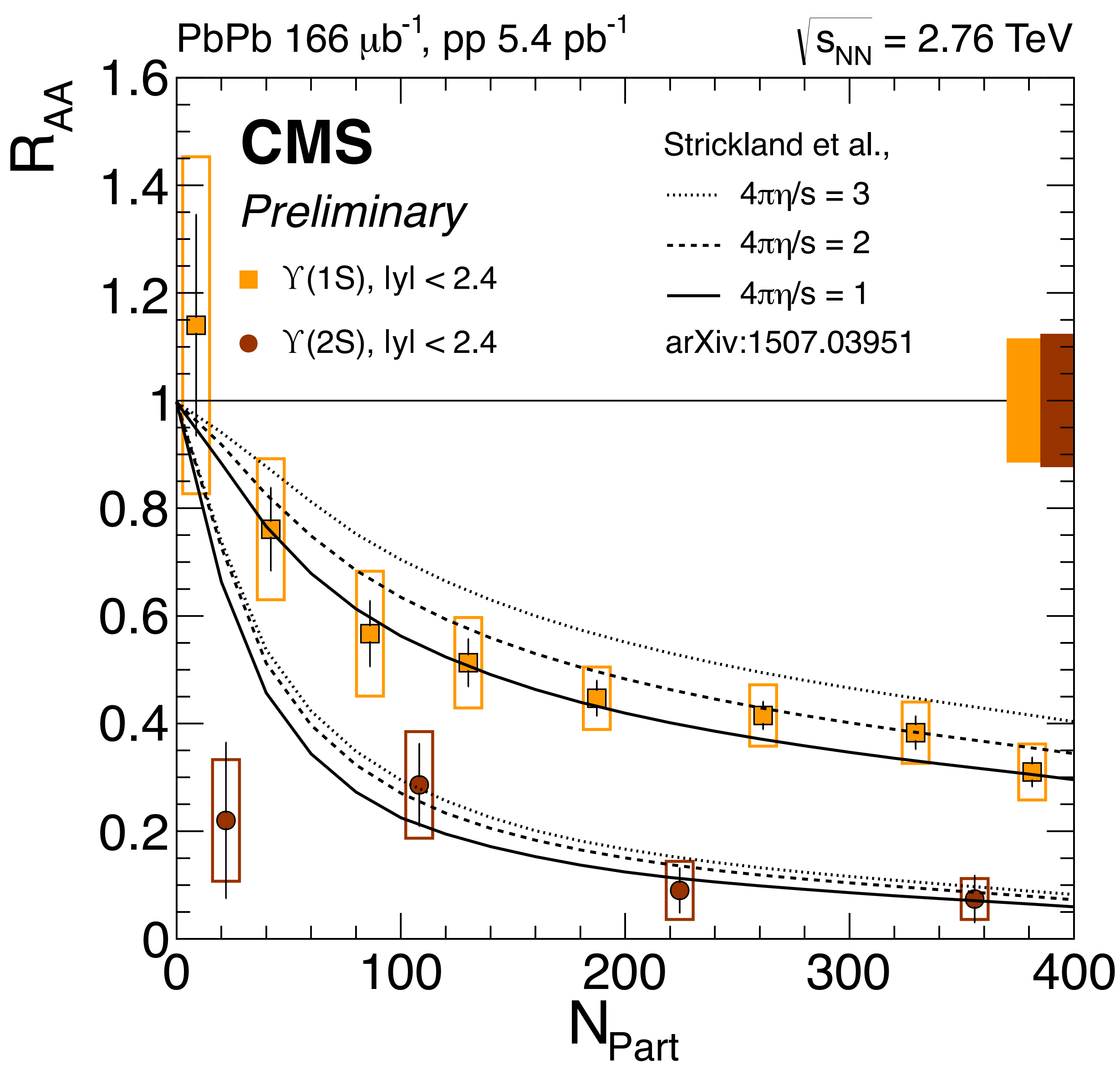


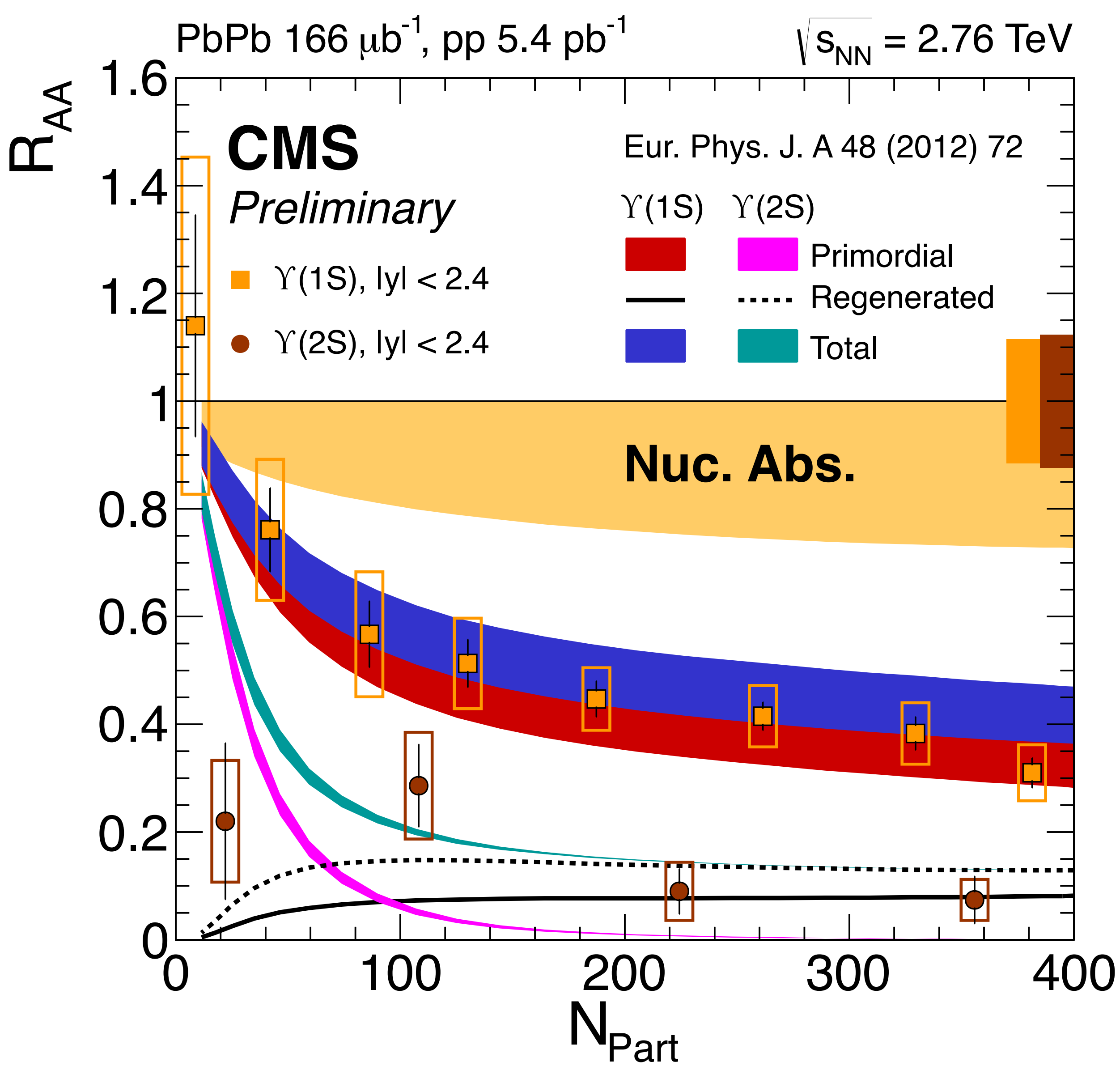
Nucl. Phys. A 879, 25-58 (2012)

Theory vs. Experiment vs. Centrality

- Strickland vs. N_{part}
- Satisfactory agreement

- Another model: TAMU
- Surprising regeneration component for Υ(2S)





Outlook

Preliminary results (CMS-PAS-HIN-15-001) [contact person]

- Ordered suppression,
  fitting well in sequential melting picture
- Υ(1S) suppression is flat versus p_T up to 20 GeV/*c*
  - *Simple and constant melting?*
  - *Interplay of effects?*
- Higher suppression in forward ALICE needs to be understood

Beyond this Thesis, HIN-15-001 to be published

- Reduced systematic uncertainties (T&P)

Coming soon: new PbPb+pp data, at 5 TeV

- Will the Υ(1S) be (further) suppressed?
- Will the Υ(3S) be measured?

Υ(3S) Nuclear modification factor

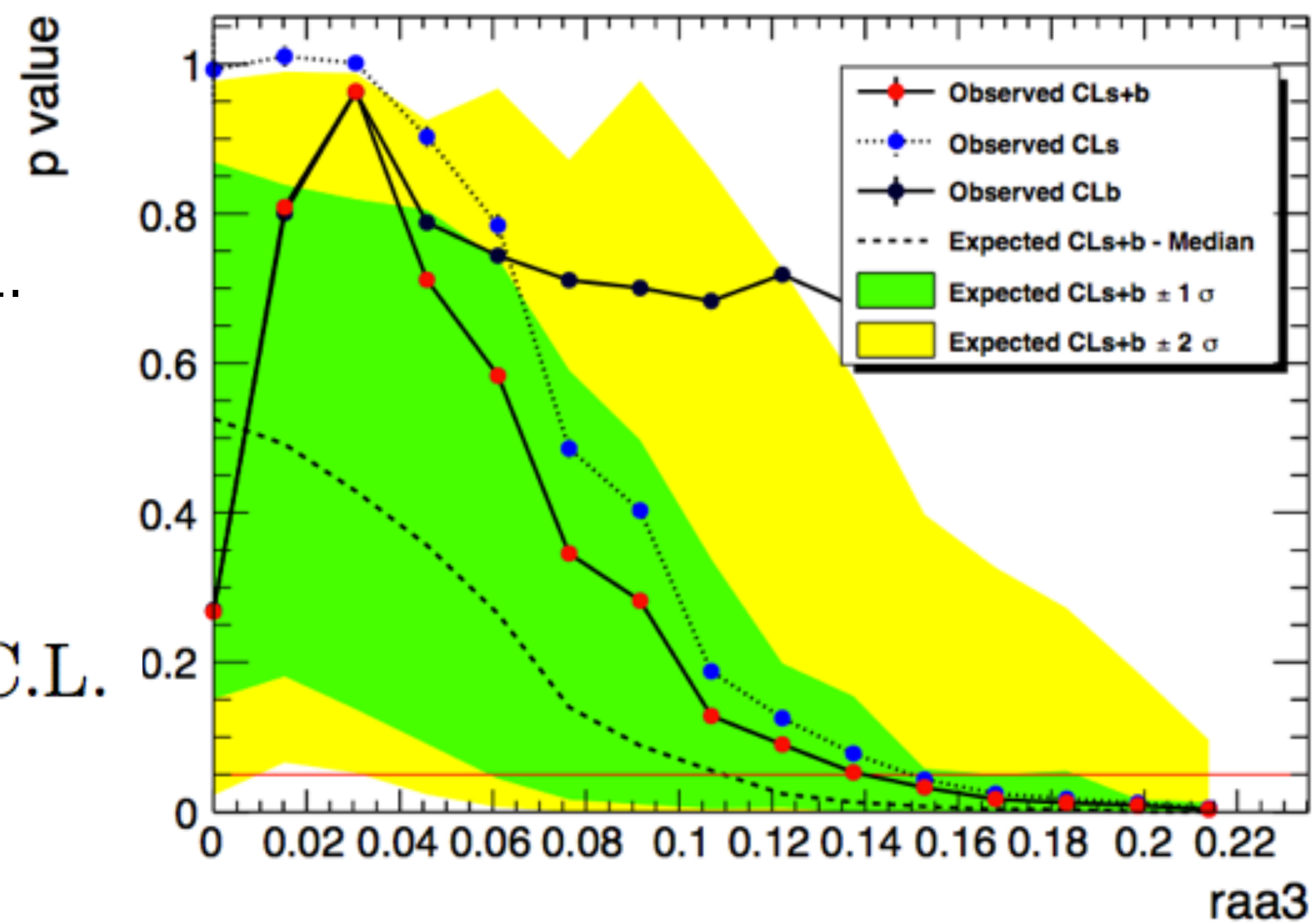
- Strategy: apply a Feldman-Cousins method to the Υ(3S) yield ratio

$$x_3 = \frac{N(\Upsilon(3S))_{\text{PbPb}}}{N(\Upsilon(3S))_{\text{pp}}}$$

- Normalisations and uncertainties inserted in the computation as nuisance parameters

- Compute a 95% (68%) C.L. upper limit on R_{AA} Υ(3S)

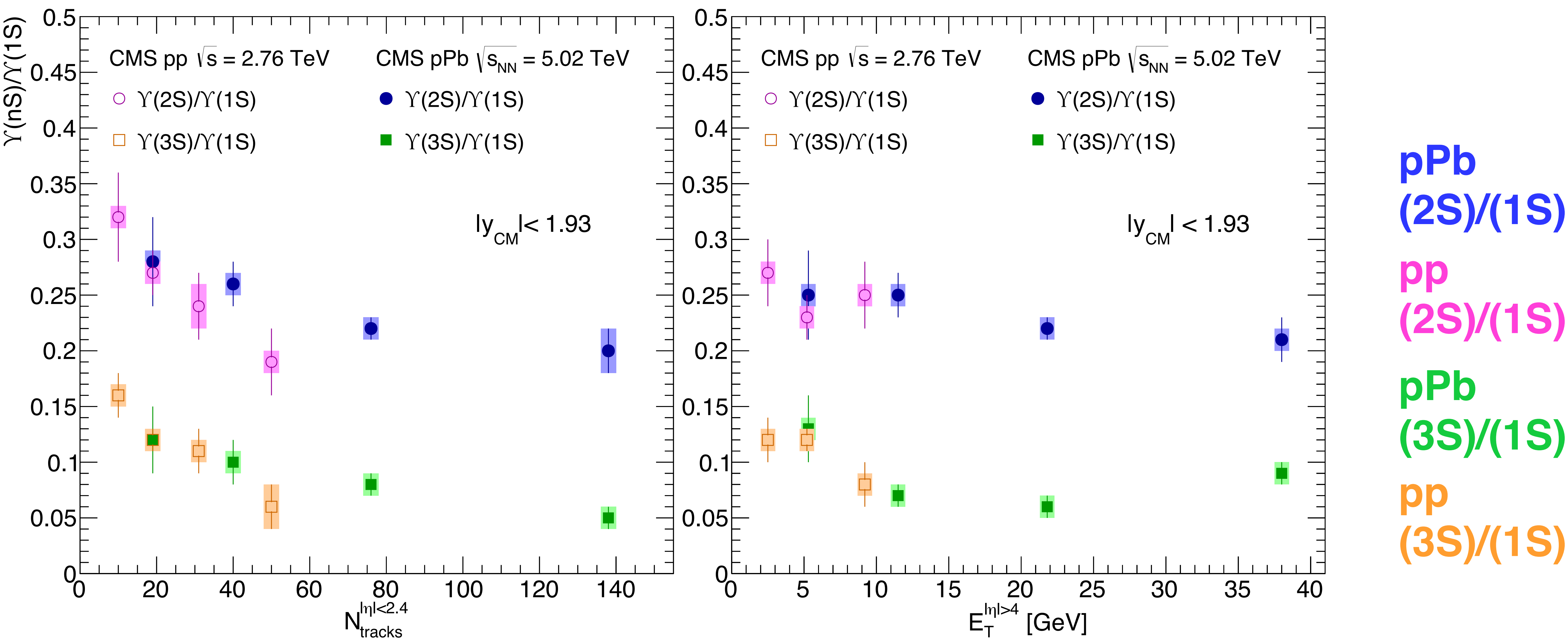
$$R_{\text{AA}}(\Upsilon(3\text{S})) \quad < \quad 0.14 \text{ at } 95\% \text{ C.L.}$$



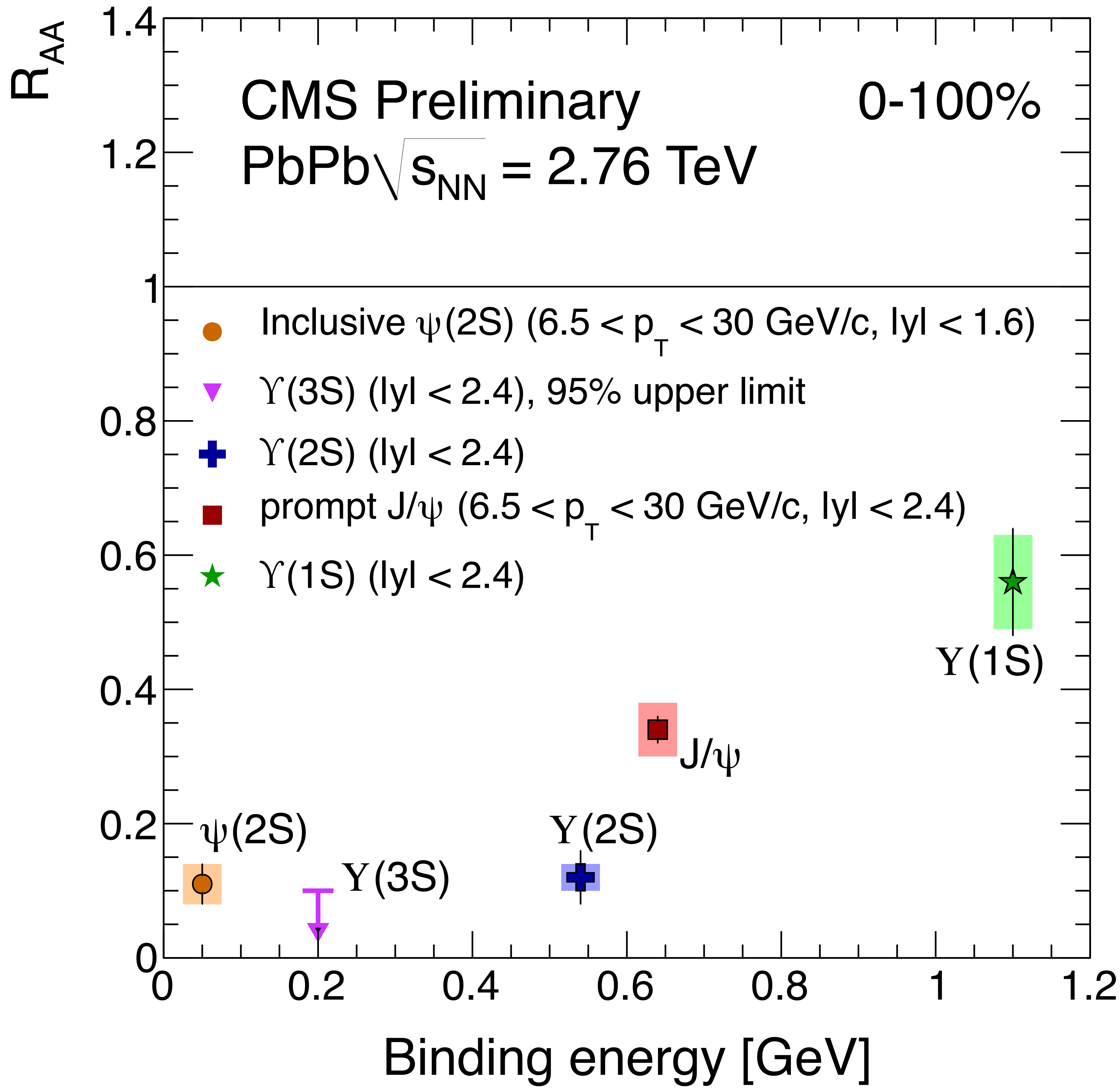
Relative production in pp, p-Pb

- Tracker multiplicity (|eta|<2.4)
- Excited-over-1S single ratio
- Super interesting multiplicity dependent effect in pp & pPb…

- Total transverse energy in HF calo
- No apparent dependence in E_T(HF)

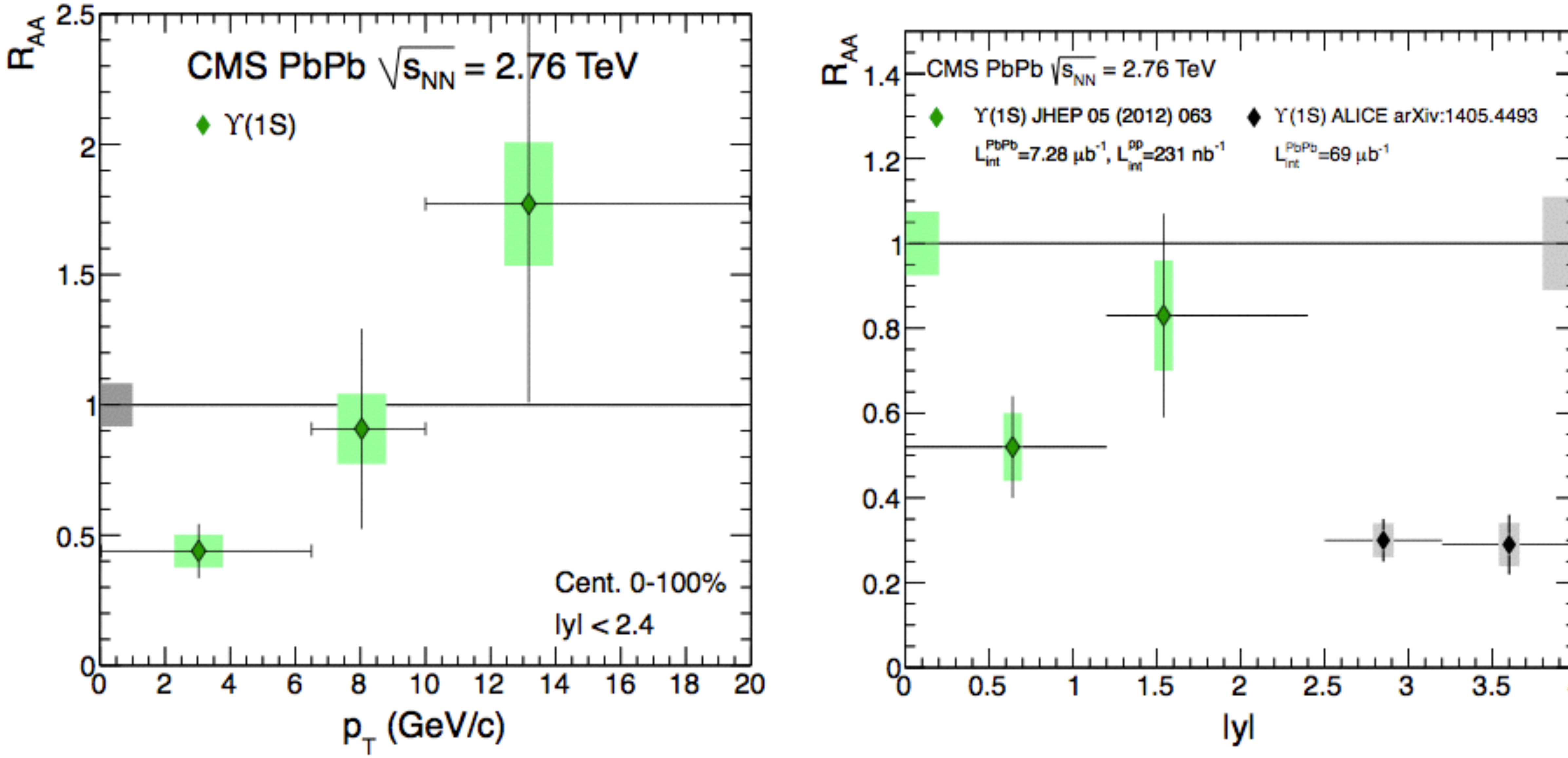


RAA vs binding energy



Nicolas Filipovic

2010 measurements



in nuclear matter

- 1986: « Charmonia should melt »
- Assuming a so-called 'Cornell' potential

$$V(r) = -\frac{\kappa}{r} + \sigma r$$

σ x r: confining part
- κ/r: Coulomb-like part

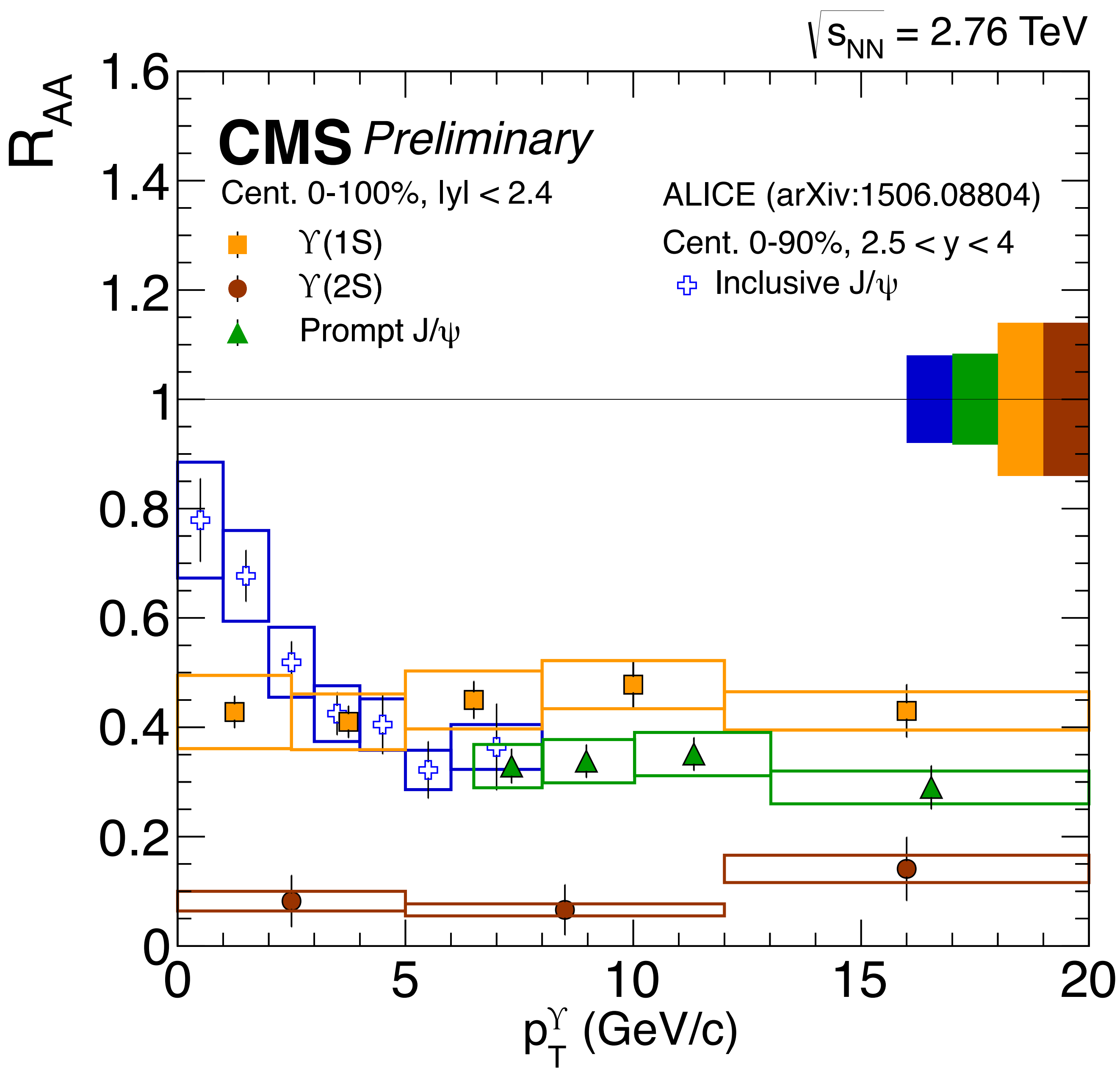
<u>depend on T</u>

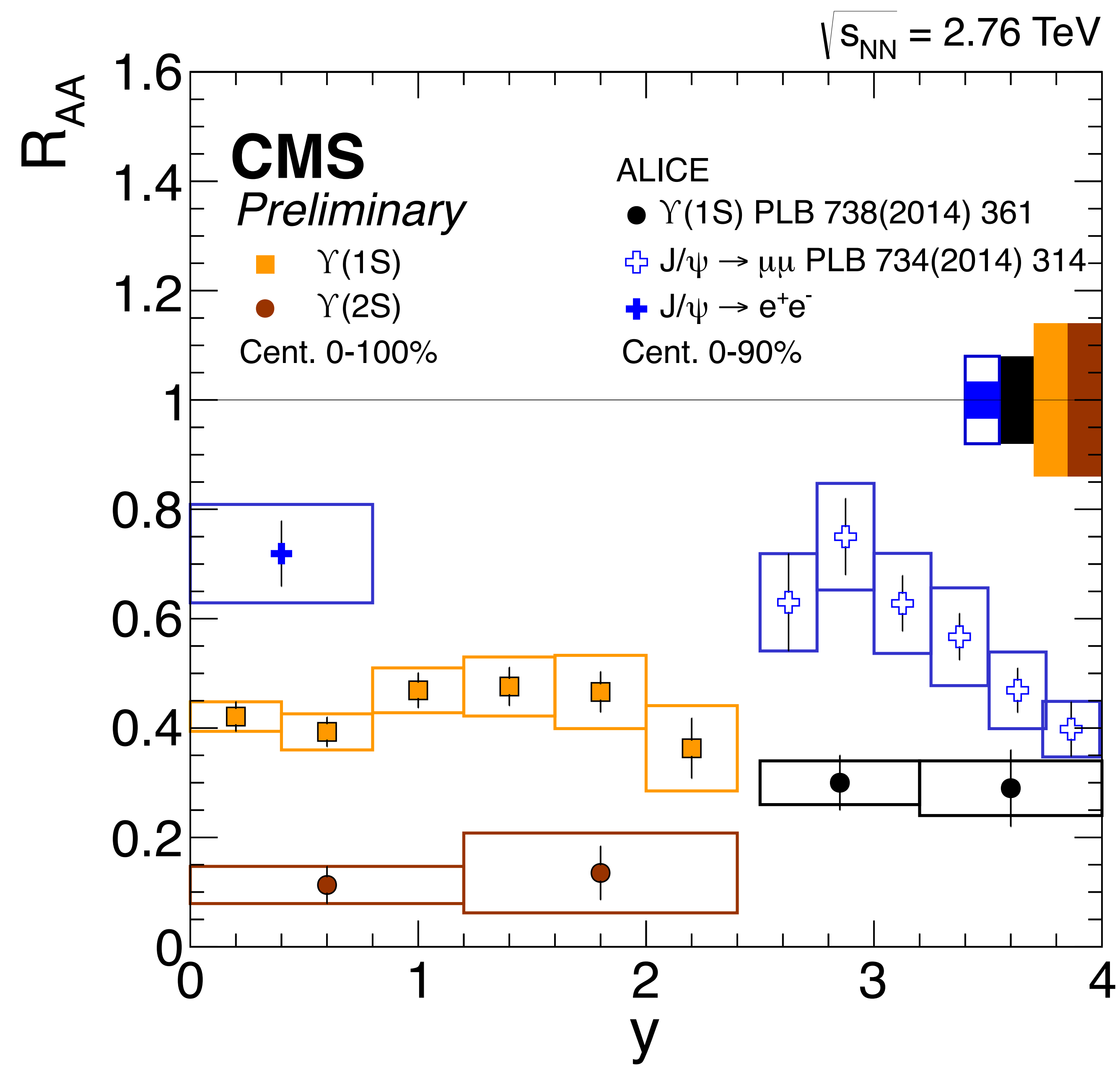
Above critical temperature, <u>colour-screened</u> potential

Introduces:

- **Debye radius**
- ***T_d* for each state**

J/psi vs. Upsilons ?

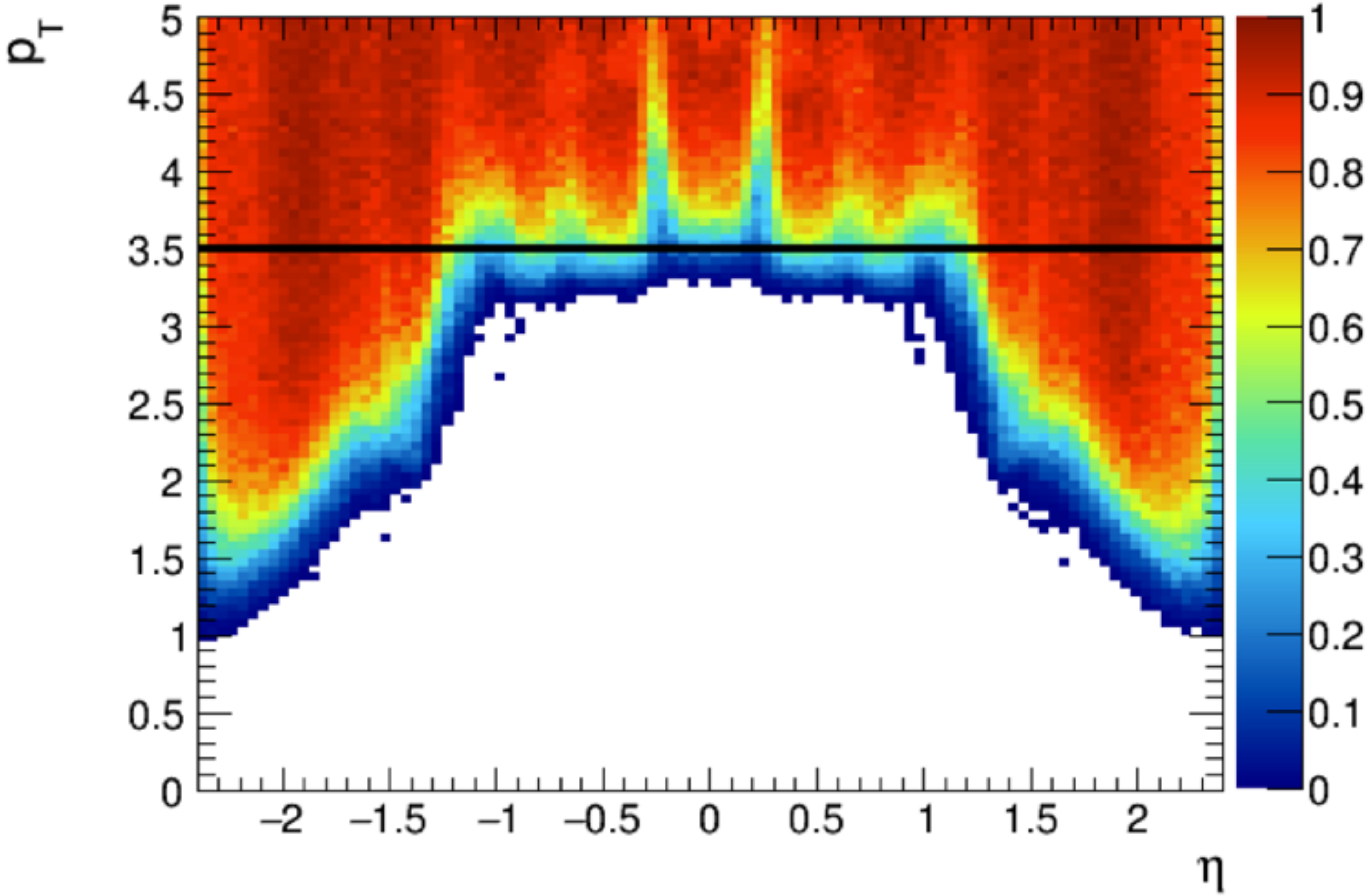




- Wish list for Xmas 2015:
- ALICE's Y(2S) and psi(2S)
- CMS's psi(2S)

Muon kinematics

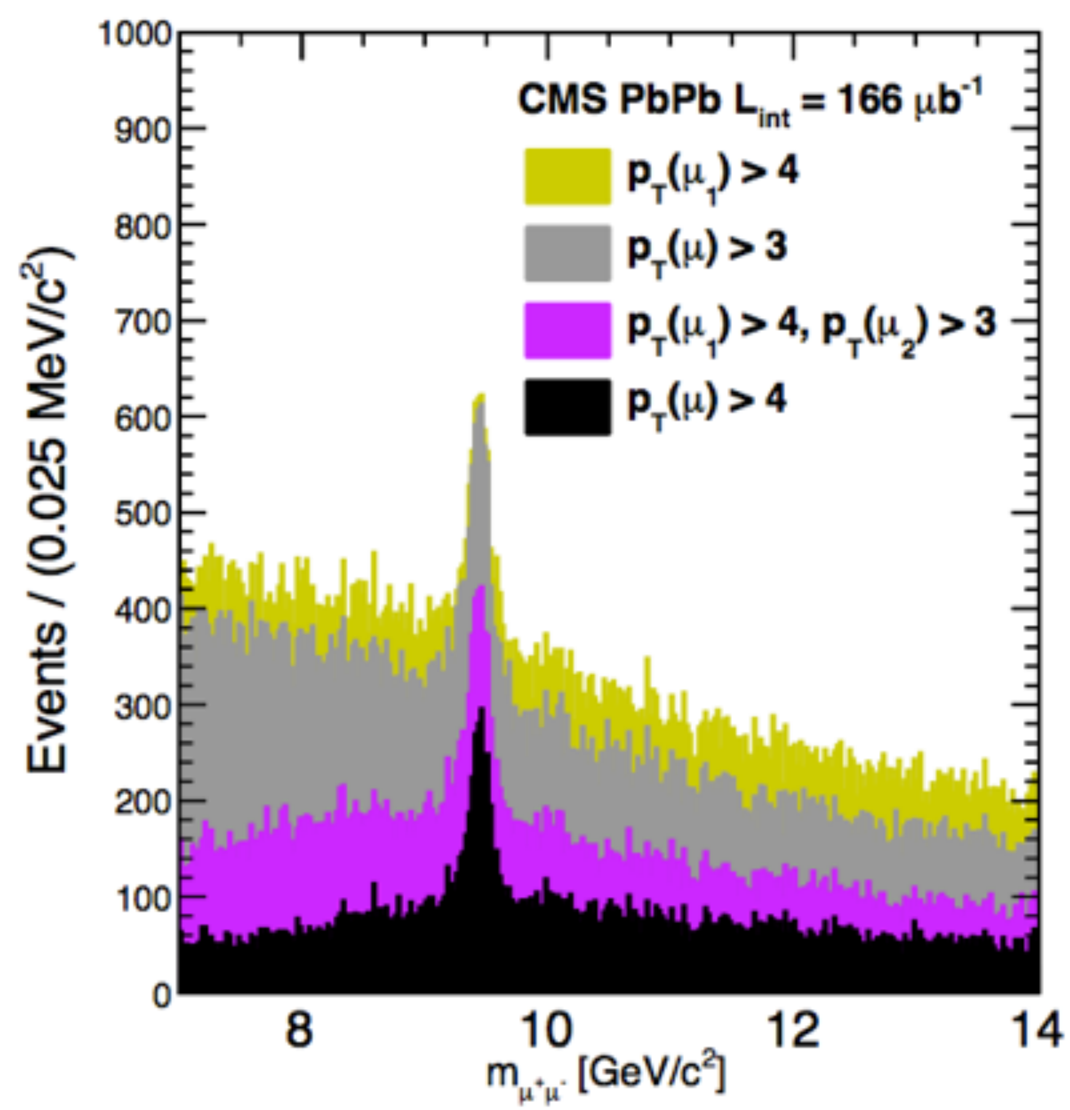
- Edge of the acceptance :
  3 GeV and below !



Muon kinematics

- Personal goal: optimise the Y signal with basic cuts
- Long-term goal: high R_{AA} significance in all bins
- Challenging in PbPb: higher background than pp

Y(1S): clear signal
Y(2S), Y(3S): strong suppression



Yield extraction

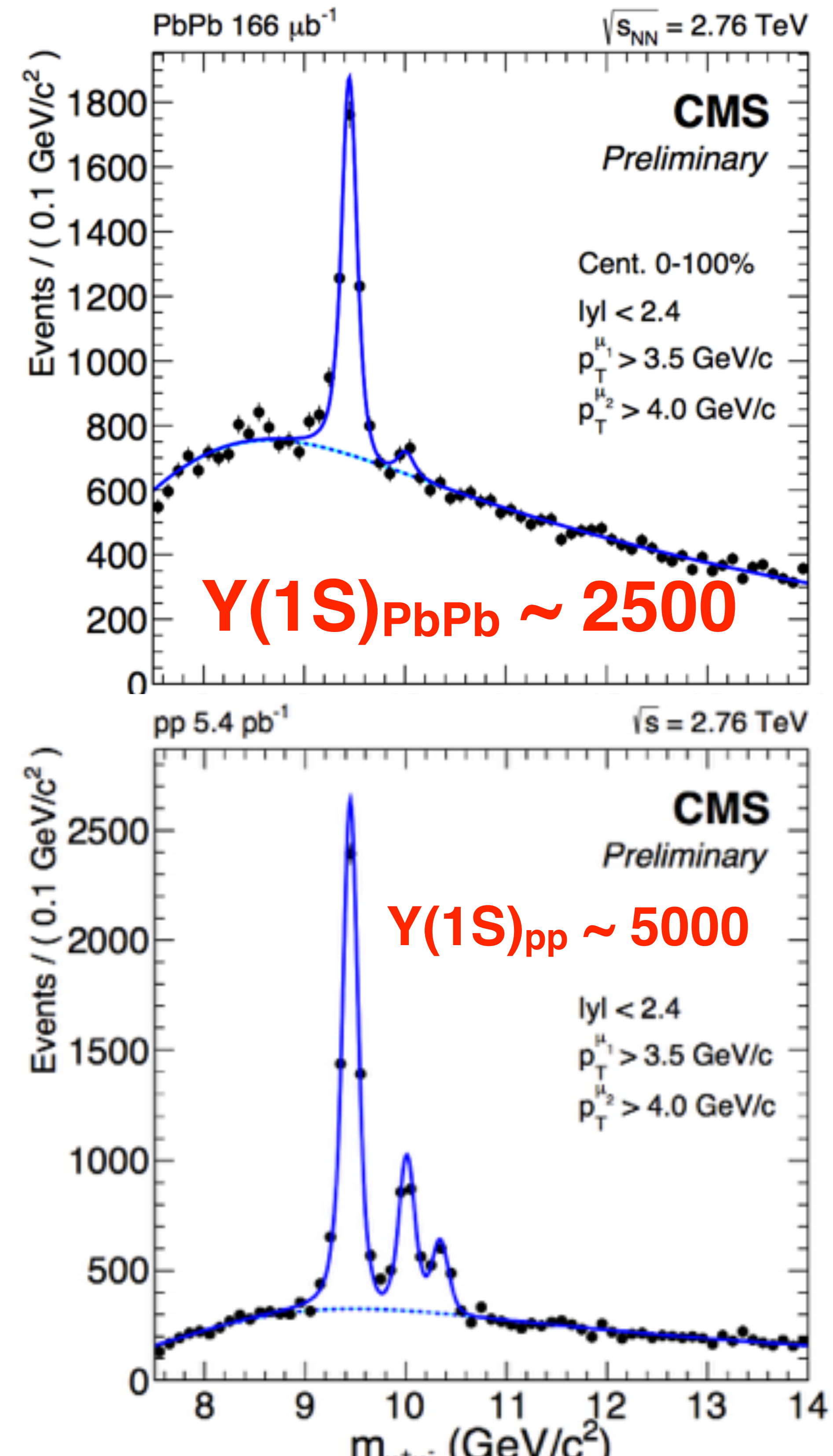
- **Extract $N_{\Upsilon(1S)}$, $N_{\Upsilon(2S)}$, $N_{\Upsilon(3S)}$**
  Unbinned max. likelihood fit of S+B

- **Signal**
  Double Crystal Ball
  <u>shape parameter constraints (from MC)</u>

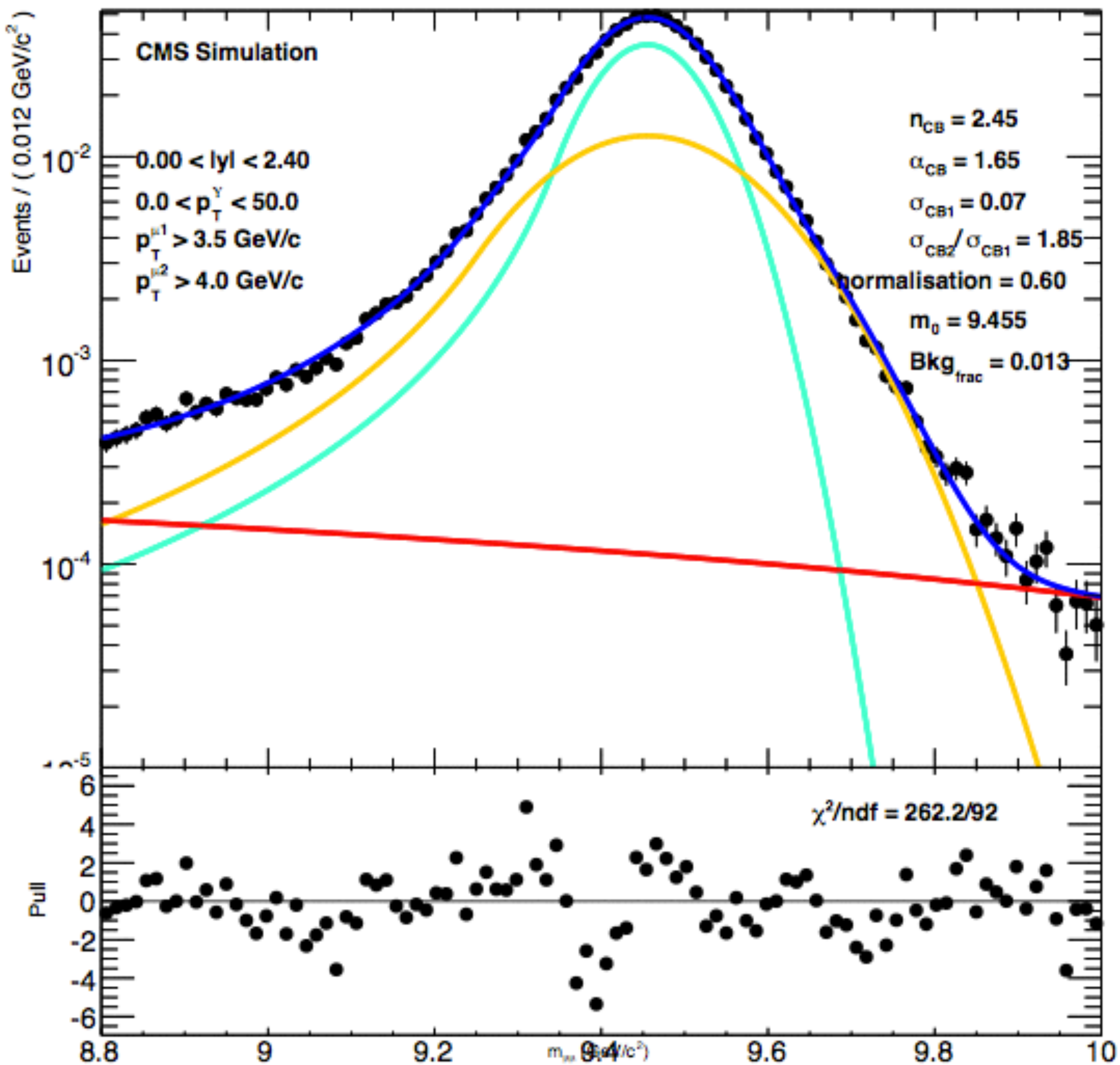
- **Background**
  PDF=Erf(turnOn,width,x)*exp(-x/decay)
  Parameters kept free

- **One bin, one fit**
  free parameters: yields, background
  fixed parameters: signal shape

- **For systematics: 7 fit variations**
  (5 for signal shape, 2 for background)



MC lineshape study



Nicolas Filipovic

QCD dynamics

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^{A}_{\alpha\beta} F^{\alpha\beta}_{A} + \sum_{\text{flavours}} \bar{q}_a (i\not{D} - m)_{ab} q_b + \mathcal{L}_{\text{gauge-fixing}}$$

Quark fields

Required for gauge invariance

Gauge fields:

$$F^{A}_{\alpha\beta} = \partial_\alpha \mathcal{A}^{A}_{\beta} - \partial_\beta \mathcal{A}^{A}_{\alpha} - g f^{ABC} \mathcal{A}^{B}_{\alpha} \mathcal{A}^{C}_{\beta}$$

QCD Coupling constant: $\alpha_S \equiv g^2/4\pi$

SU(3) non-Abelian gauge theory

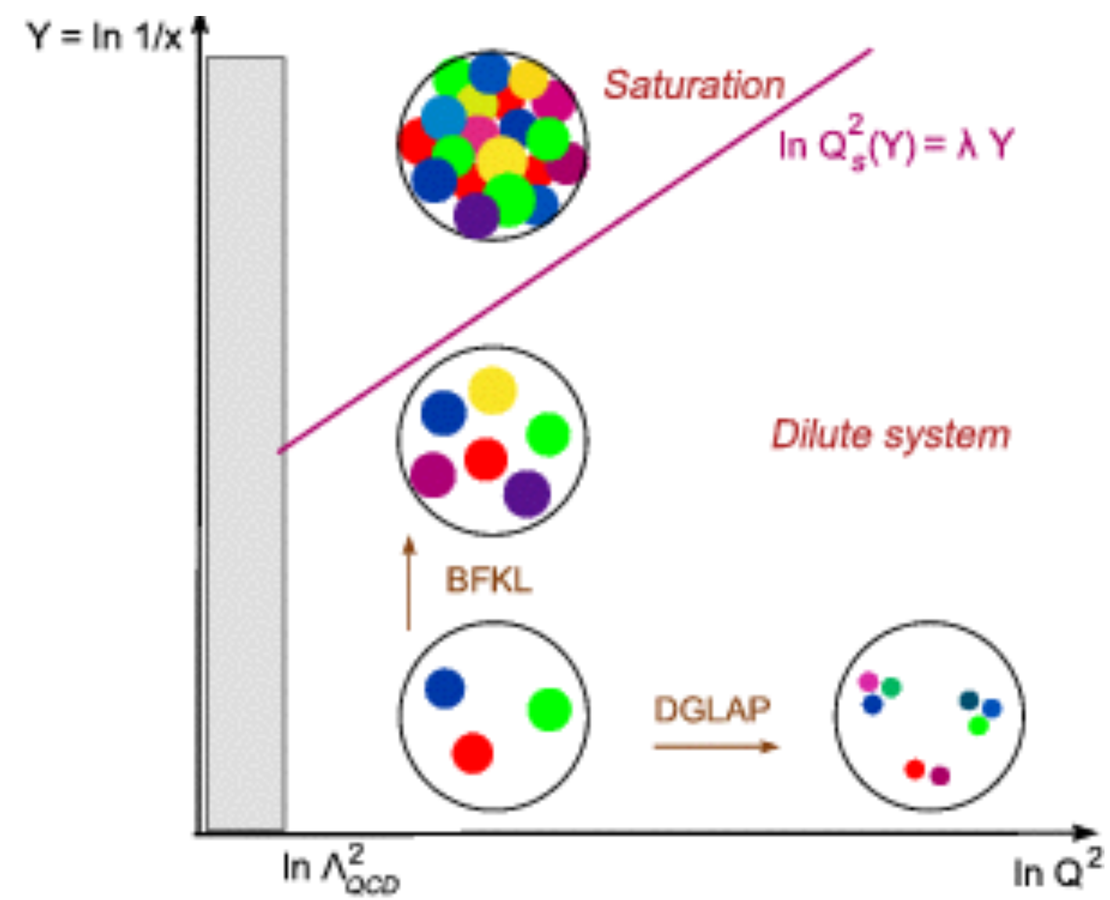
high-energy collisions

- In a high-energy collision, the tomography of the target varies with
    - Momentum exchange between projectile and target

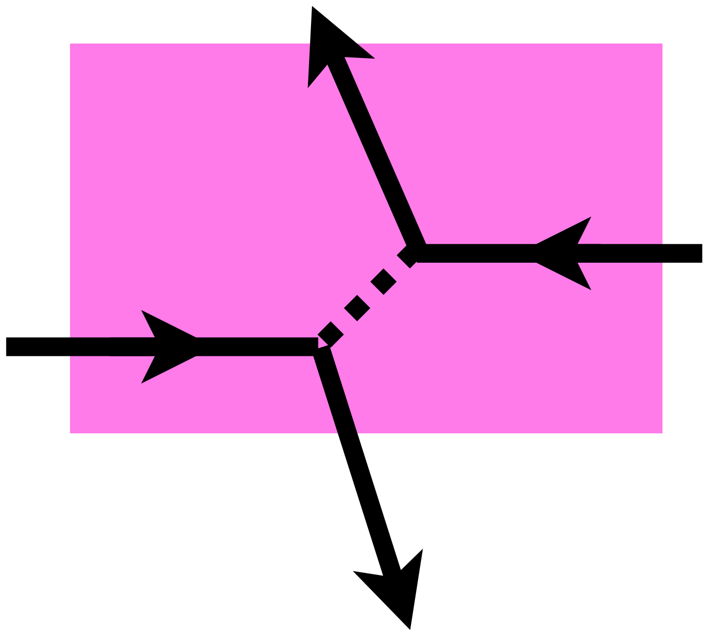
More partons ‘pop up’

- Energy of the hitting projectile

More partons ‘pop up’



Hard probes in the QGP - 1



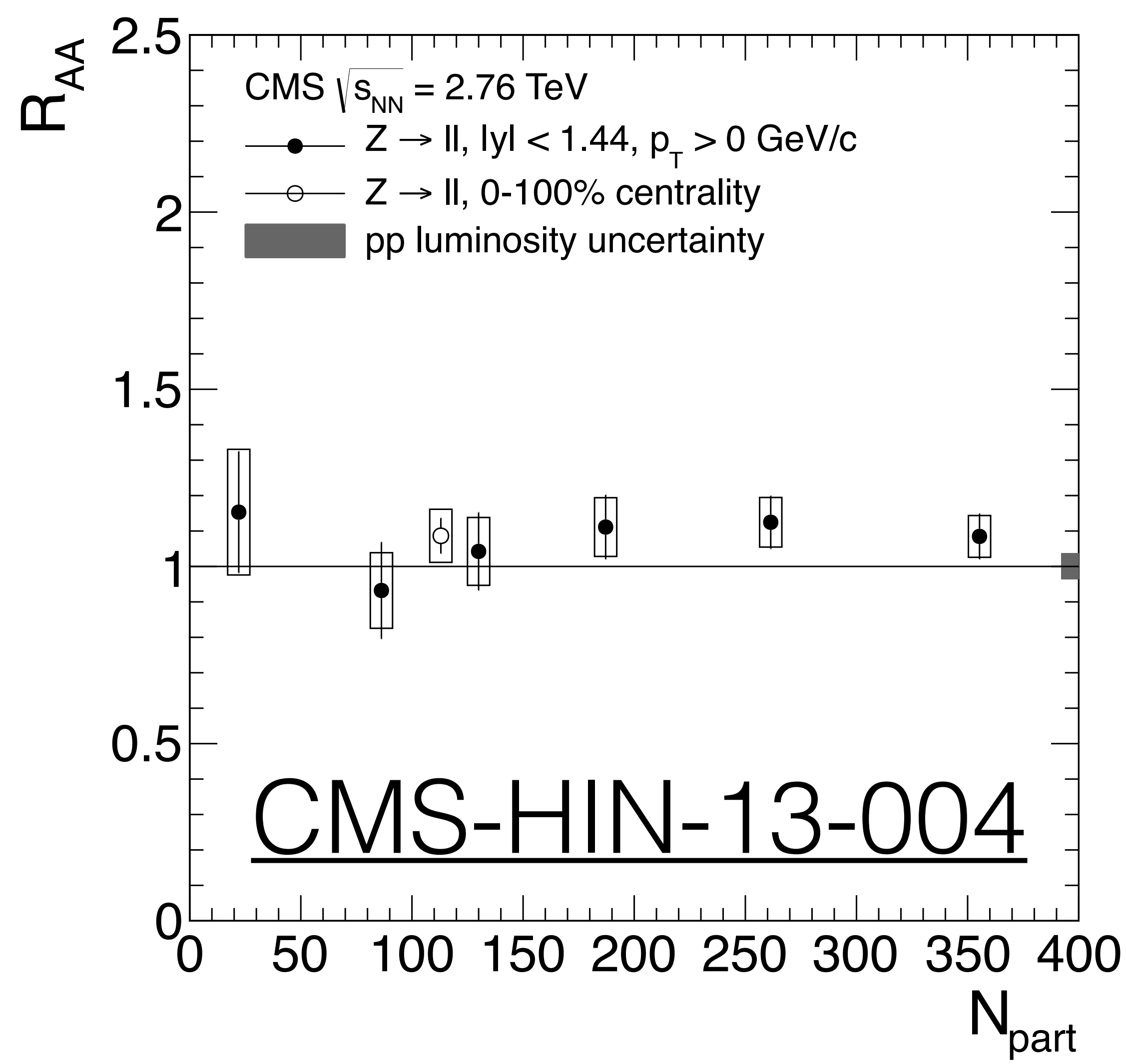
Z, W, photons : electroweak bosons

- colourless: unaffected by QGP
- production rate in PbPb ~ N_{coll} x pp

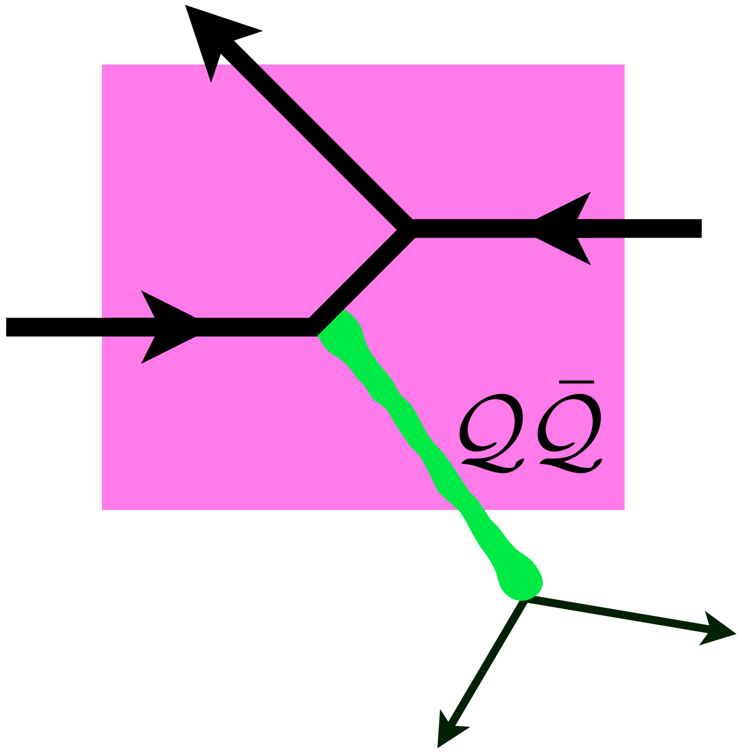
Define the nuclear modification factor, R_{AA}

(A = Pb)

$$R_{\text{PbPb}} = \frac{N_{\text{PbPb}}}{N_{\text{coll}} \times \sigma(pp)}$$



Hard probes in the QGP - 3



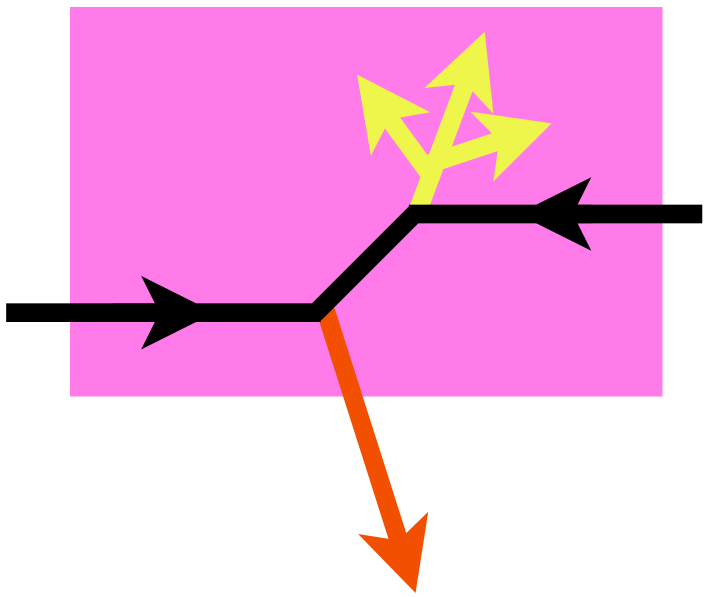
Quarkonia

- $Q >> \Lambda_{\mathrm{QCD}}$ still applies, but
- Production: **long-standing puzzle**
- Coloured object ?
- Finite size ~ 1 / binding energy

strategy followed

1. Measure Υ family in PbPb
2. Compare to Υ in pp @ 2.76 TeV
3. Conclude

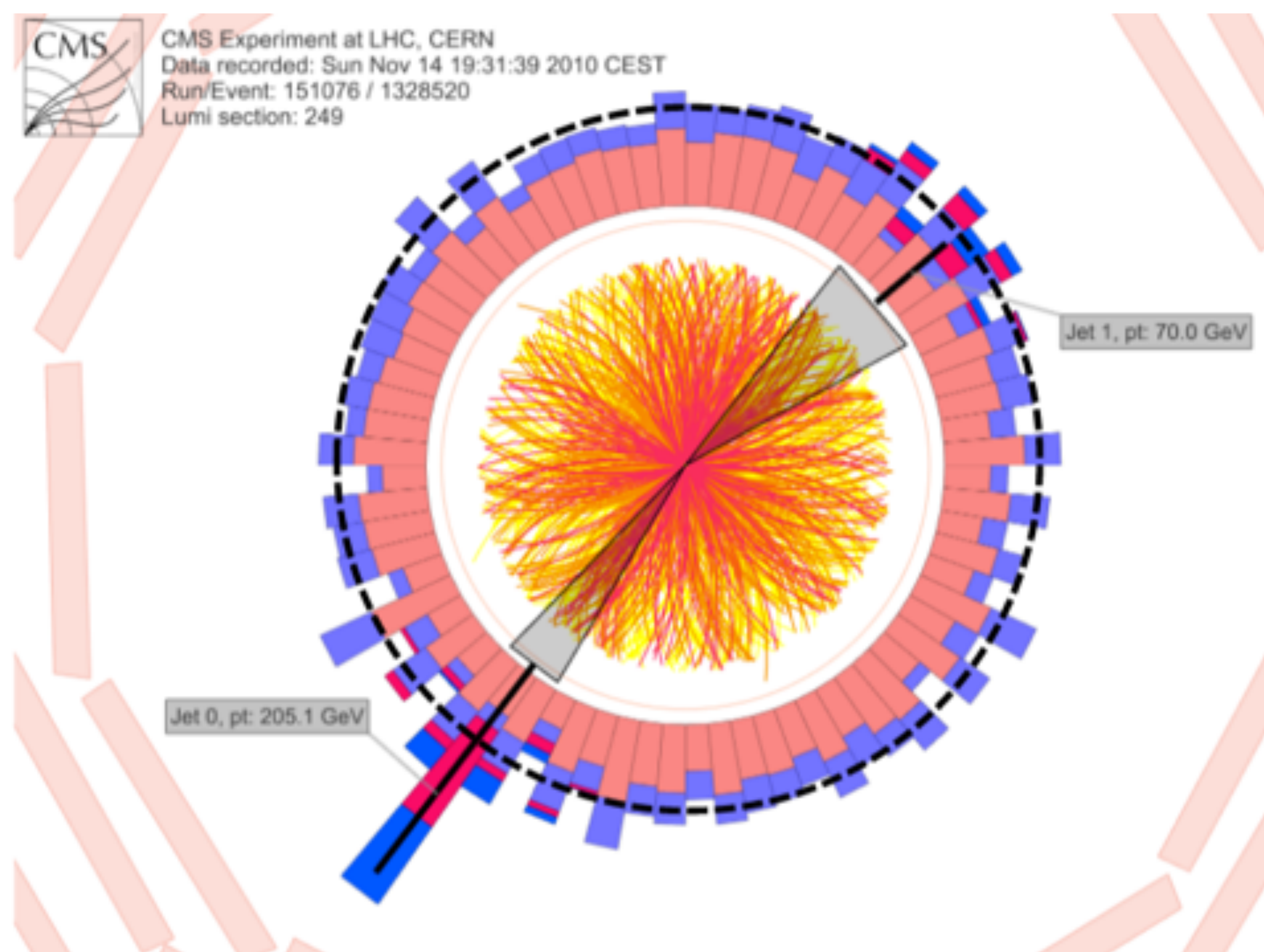
Hard probes in the QGP - 2



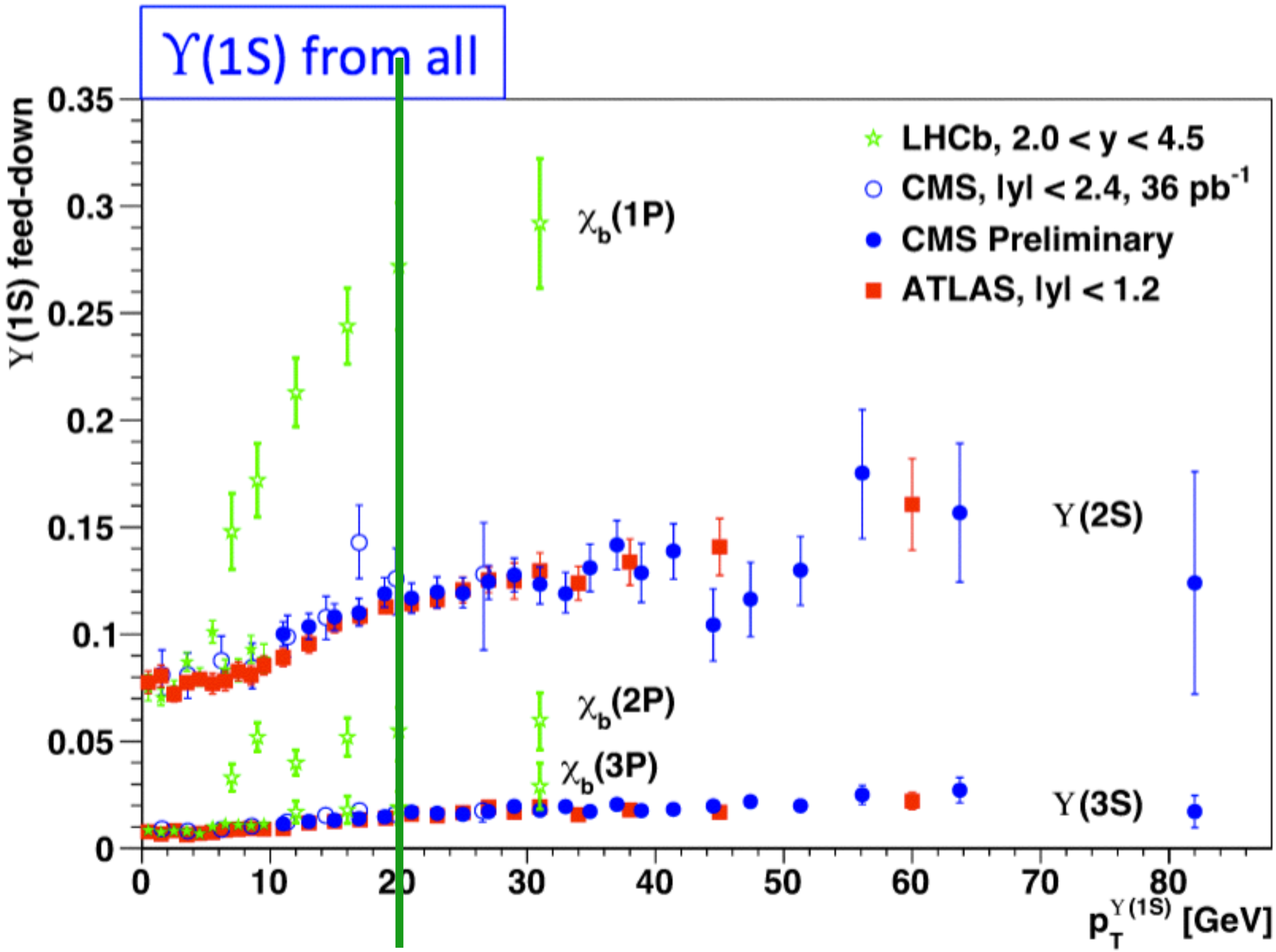
<u>Jets</u> of quarks & gluons

- hard scale: distinguishable from soft QCD background $Q >> \Lambda_{\mathrm{QCD}}$
- coloured objects: lose energy in QGP

jet quenching:
modifications of jet spectrum, fragmentation and shapes



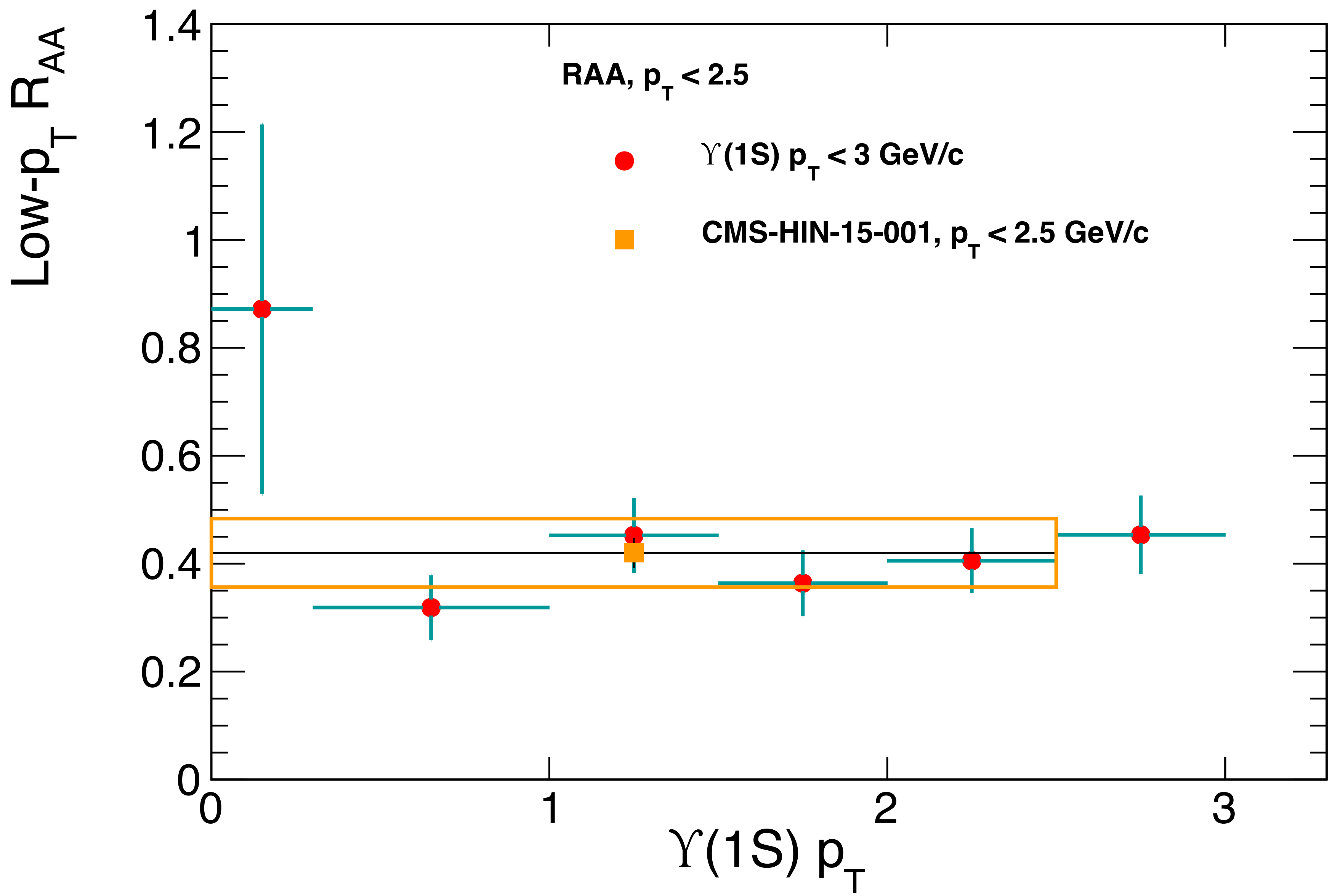
Feed down of Upsilons



Low pT Upsilons

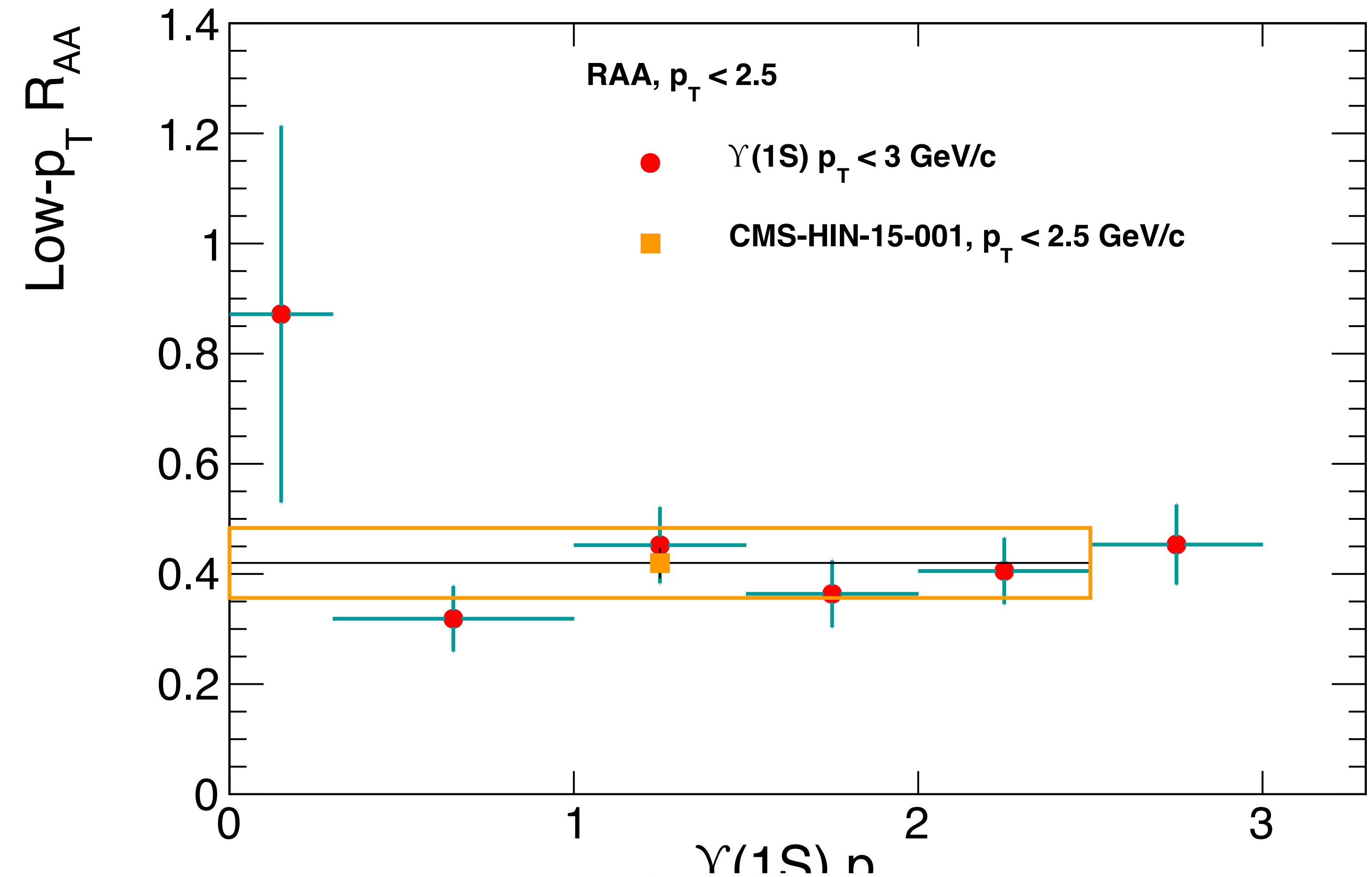
<u>Mind the stats!</u>

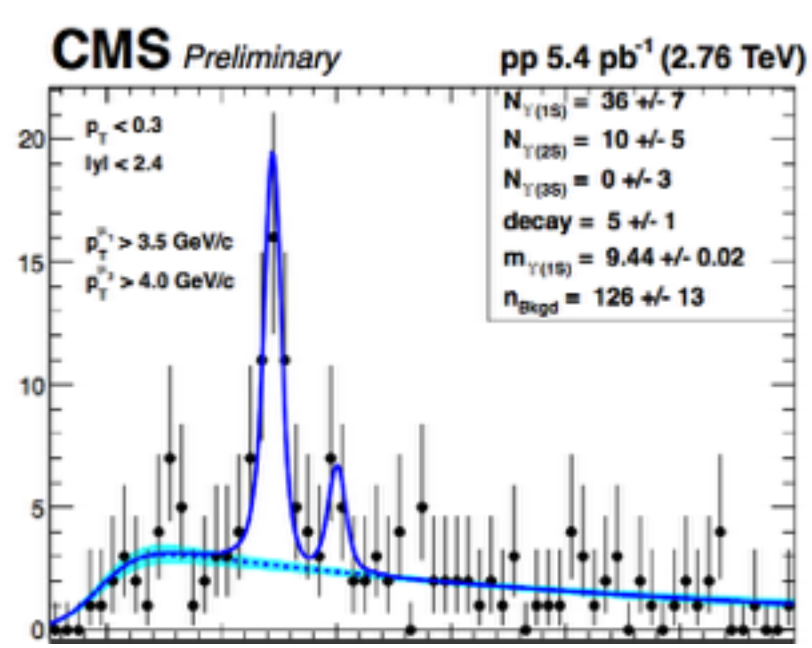
~35+/- 10 events at the 1S mass,
at $p_T(Y) < 0.3$ GeV

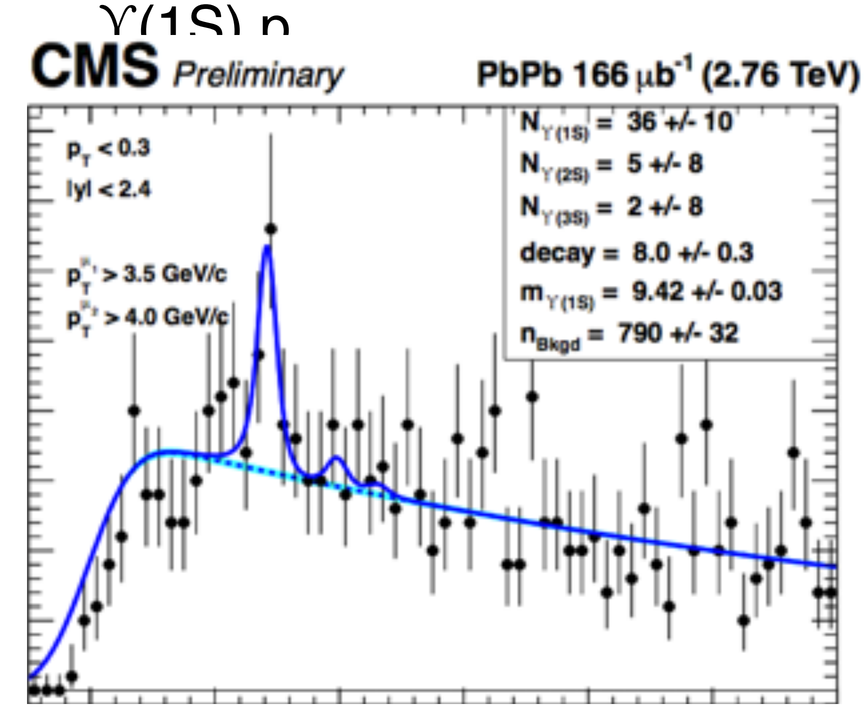


Low pT Upsilons

<u>Mind the stats!</u>

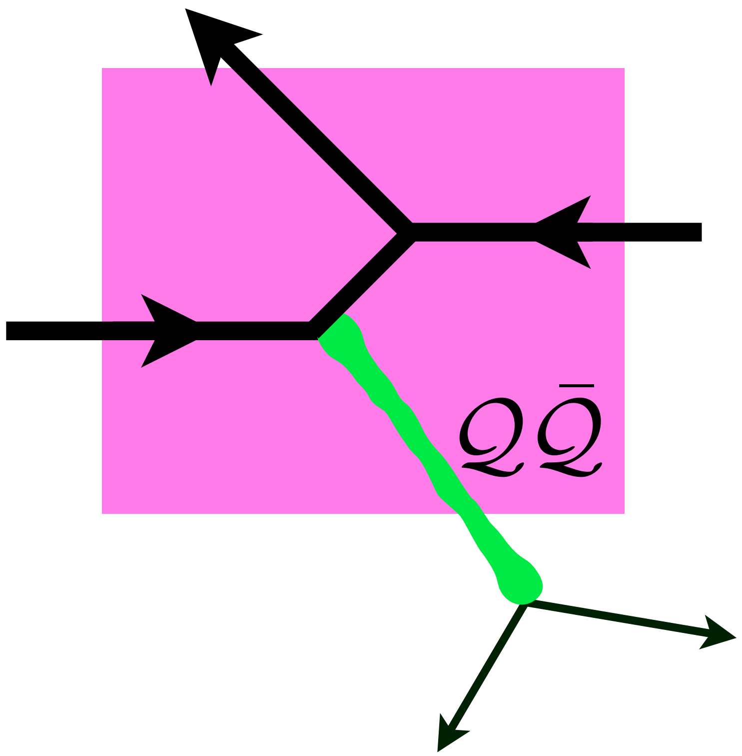


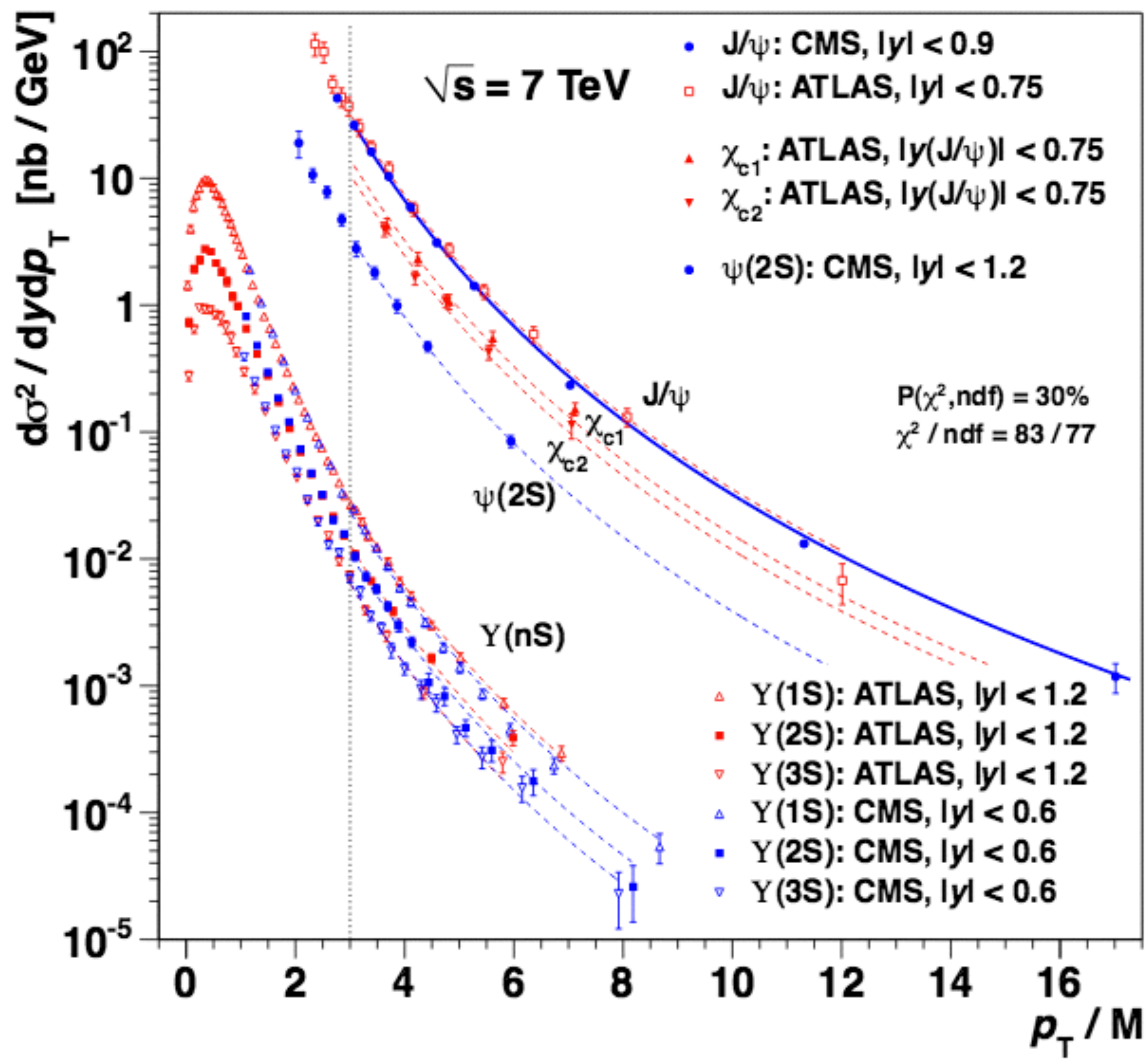




Quarkonia in pp

$$J/\psi,\ \psi(2S), \chi_{c1},\ \chi_{c2};\ \Upsilon(1S, 2S, 3S),$$

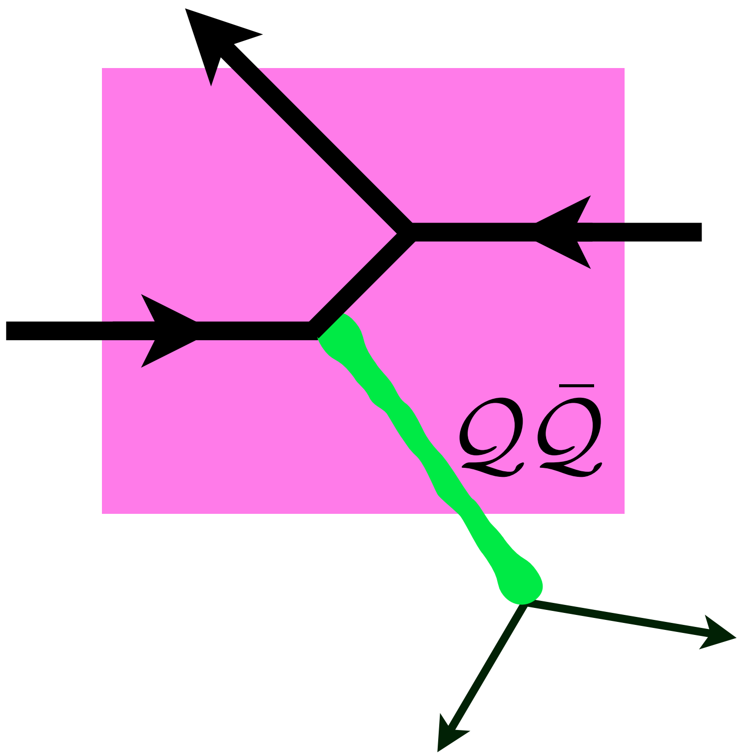




Spectrum:
measured for many quarkonium states

$$Q^2 >> \Lambda_{\rm QCD}$$

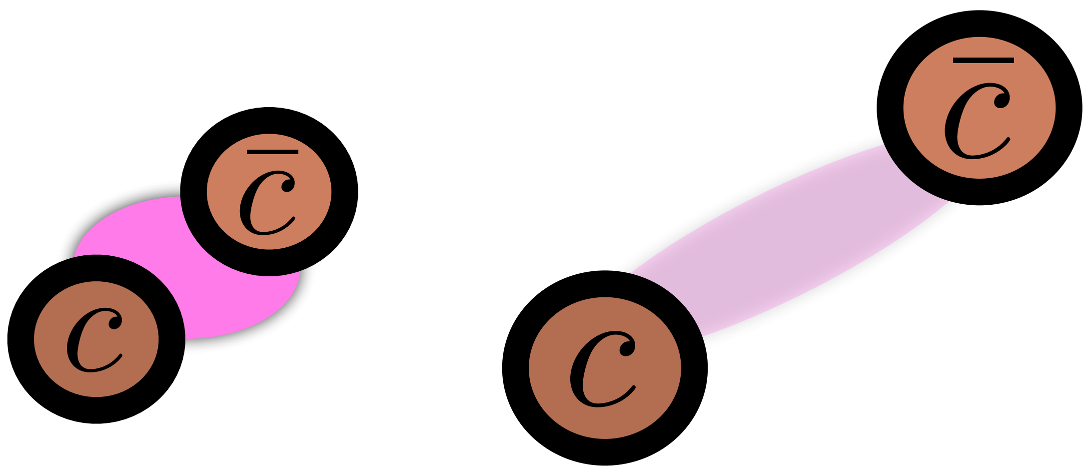
Hard probes in the QGP - 3



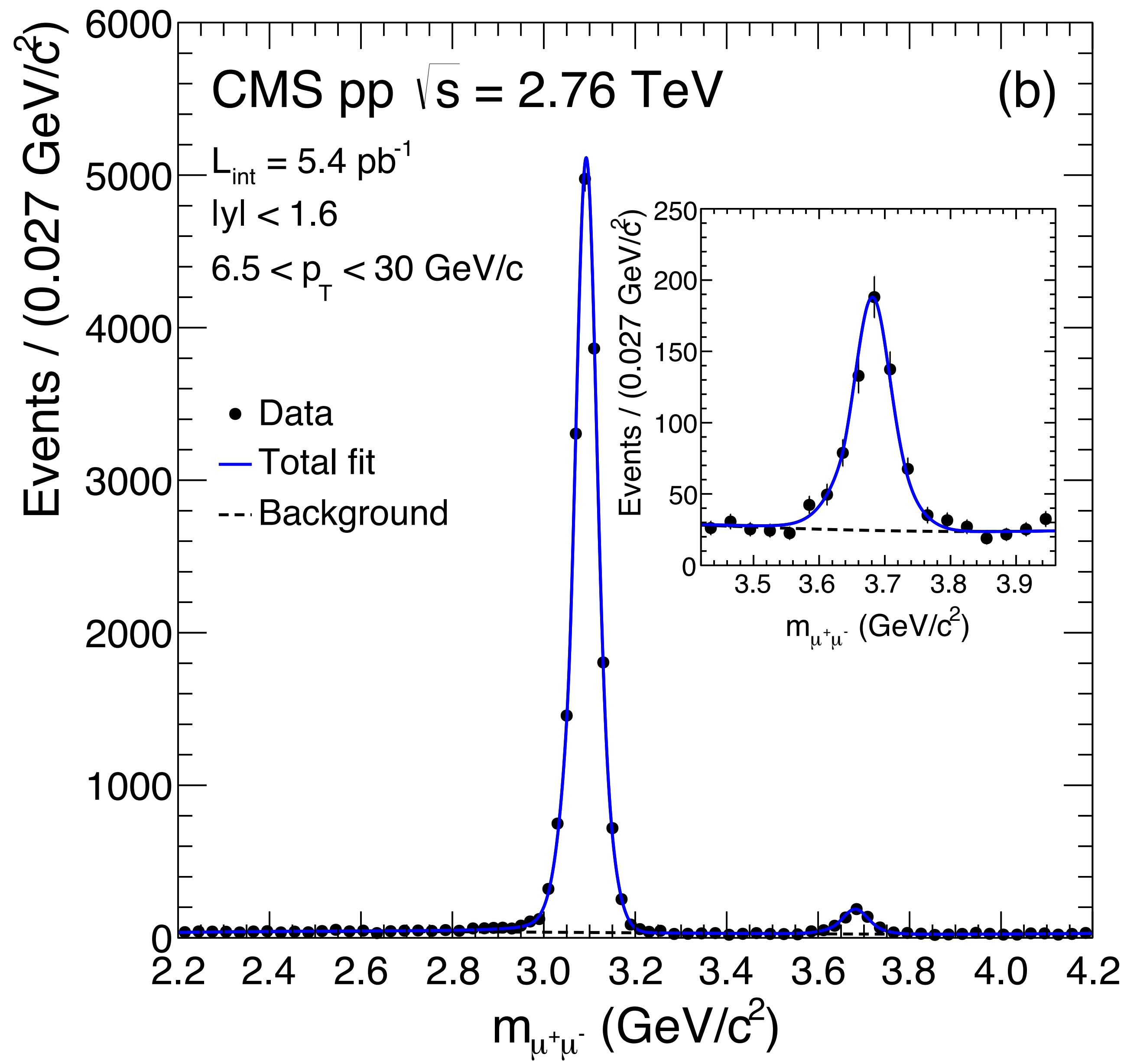
Quarkonia

- $Q >> \Lambda_{\mathrm{QCD}}$ still applies, but
- Production: **long-standing puzzle**
- Coloured object ?
- Finite size ~ 1 / binding energy

Charmonium



- B(μμ) ~ 6%
- easily detected in CMS



state	J/ψ	$\psi(2S)$
mass [GeV/c	3.10	3.69
ΔE [GeV]	0.64	0.05

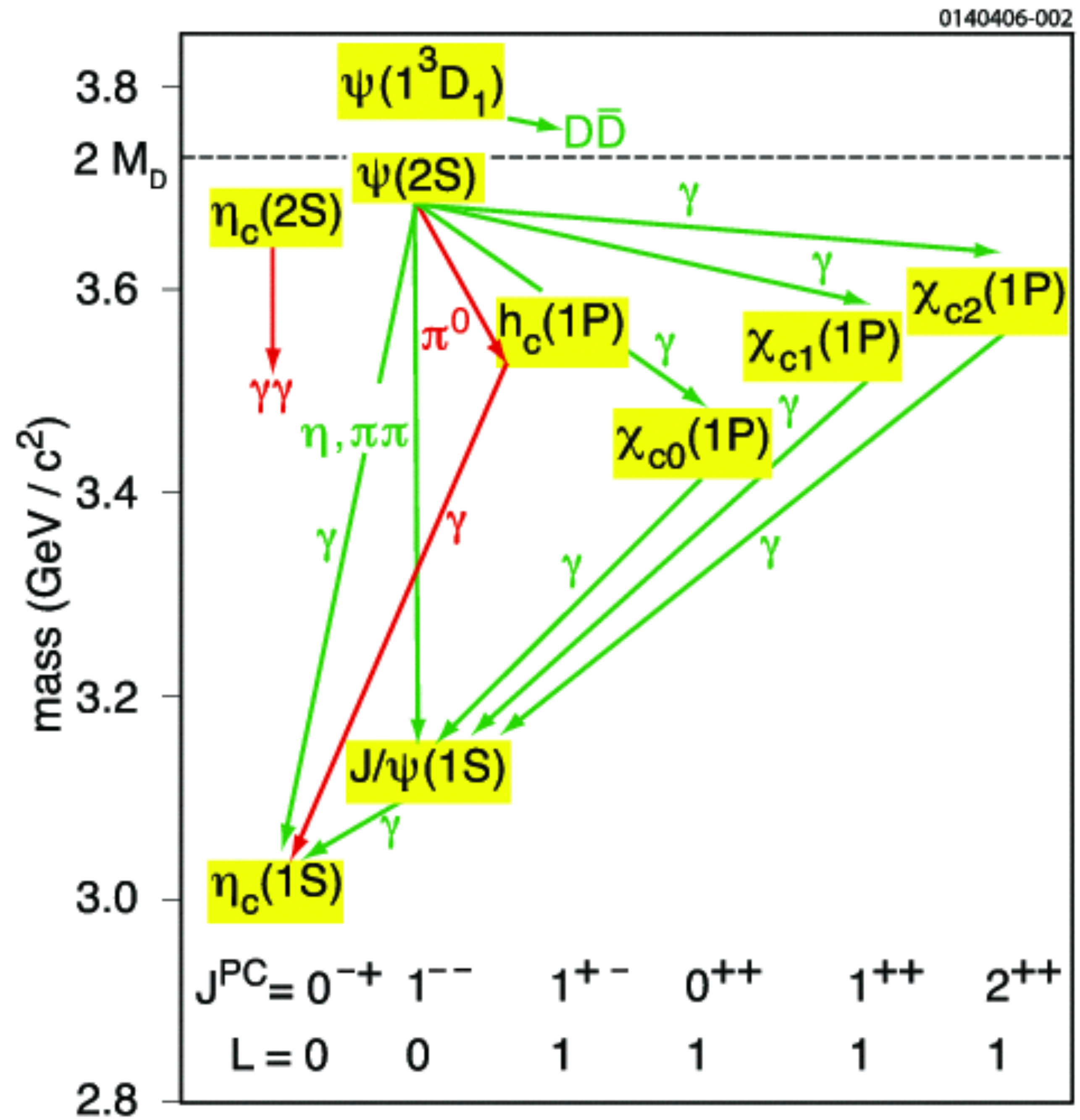
Satz, H. [J.Phys. G32 (2006) R25]

CMS-HIN-12-007

Charmonium spectroscopy

- Spectral levels of various J^{PC}
- Feed down to lower levels
- for J/ψ, ~50% feed-down

Population equation
prompt J/ψ = direct production + feed-down ψ(2S) , χ_c(0,1,2)
(non-prompt: from B decays)



Charmonia in the QGP

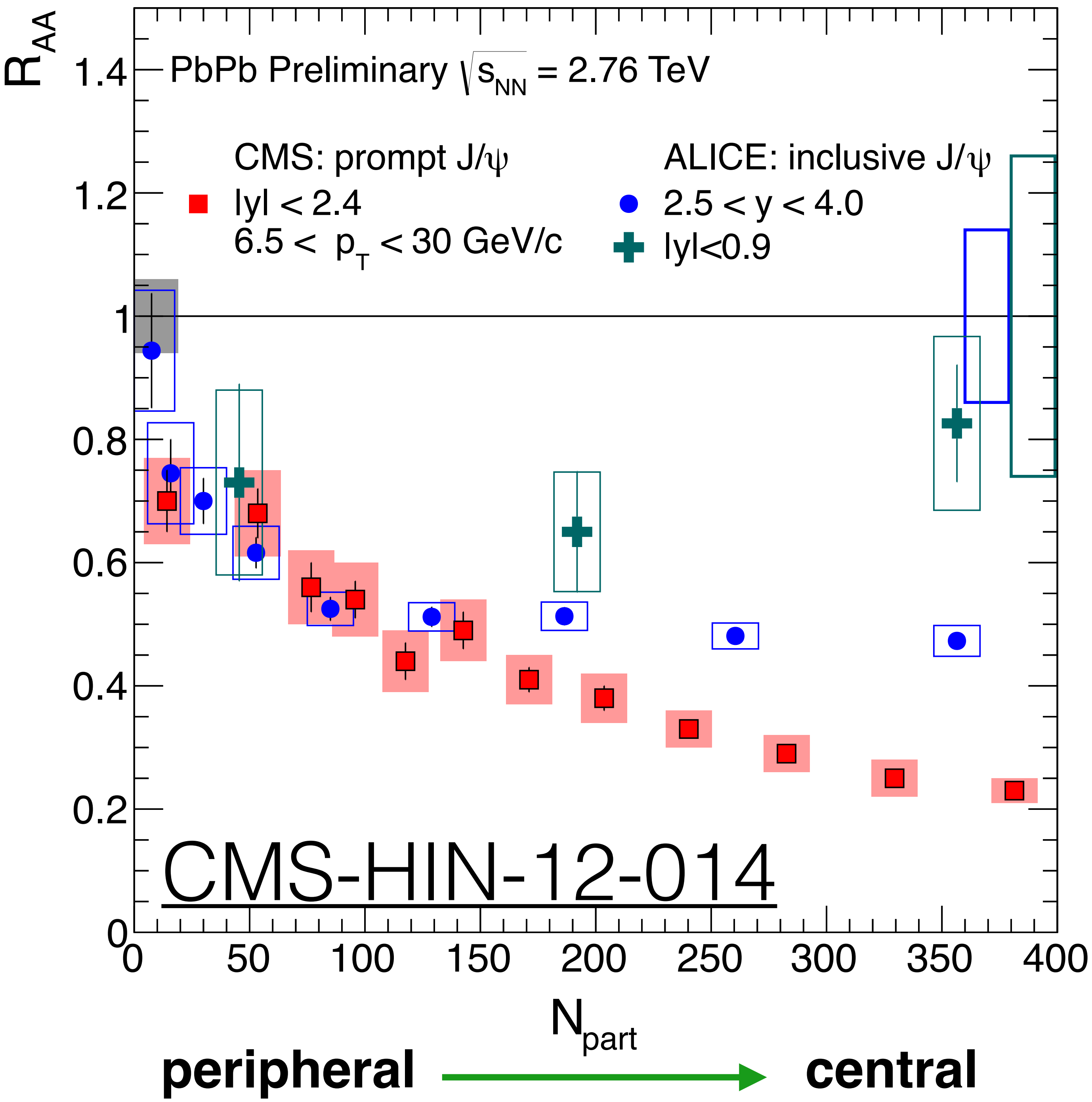
- 30 years of charmonium in nuclei
- long story short…it's not over.

Method: measure J/ψ or ψ(2S), varying:

- ☑ collision systems (pp, p-A, A-A, A-B)
- ☑ c.o.m. energy (17 GeV -> 5 TeV)
- ☑ target/projectile nuclei (cf. periodic table)
- ☑ centrality, momentum, rapidity

Charmonia in the QGP

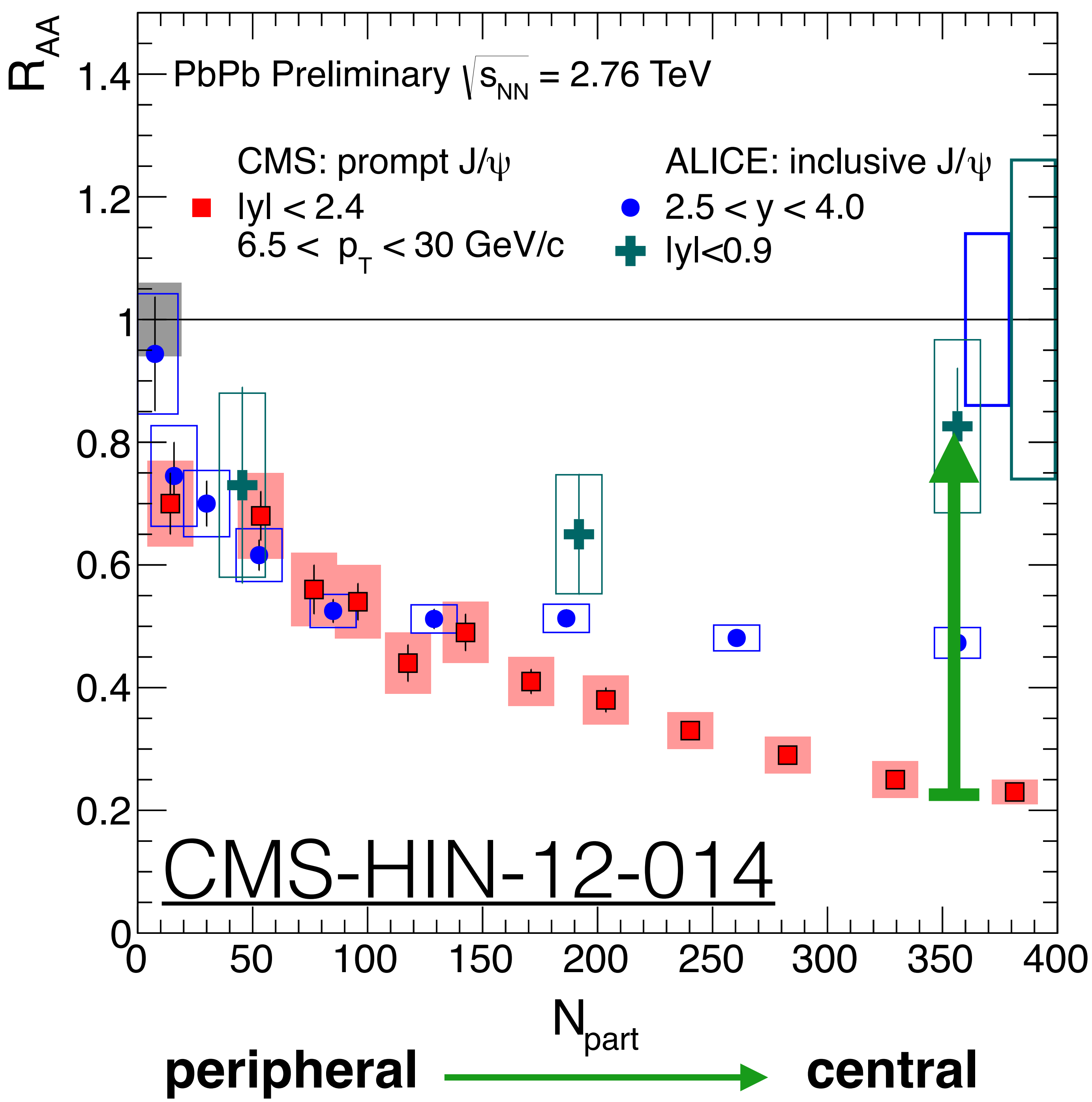
- Recent 'milestones':



- **High-p_T:** strong suppression
- **p_T -inclusive:** less suppressed
- **central rapidity:** further 'lack' of suppression

Charmonia in the QGP

- Recent ‘milestones’:

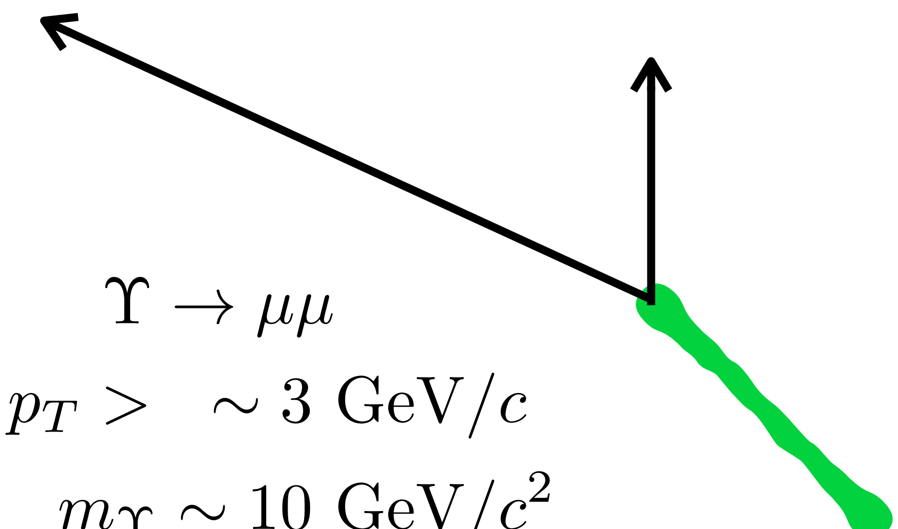


- **High-p_T:** strong suppression
- **p_T -inclusive:** less suppressed
- **central rapidity:** further ‘lack’ of suppression

Interplay of several effects !

Muon kinematics

- General idea: Υ decays are slightly imbalanced

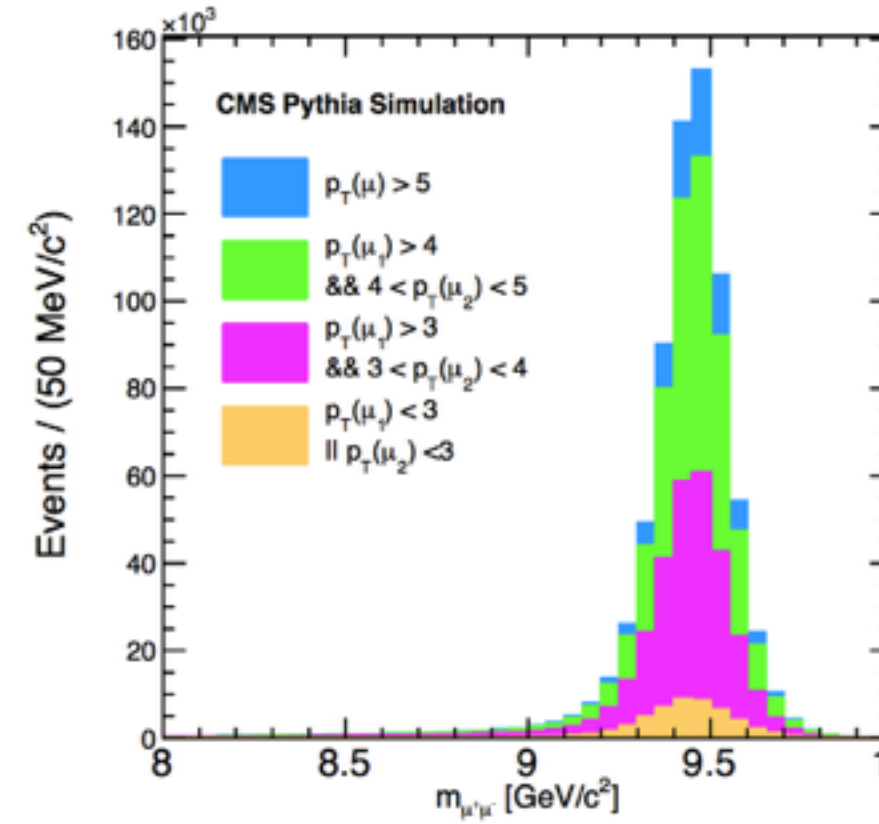


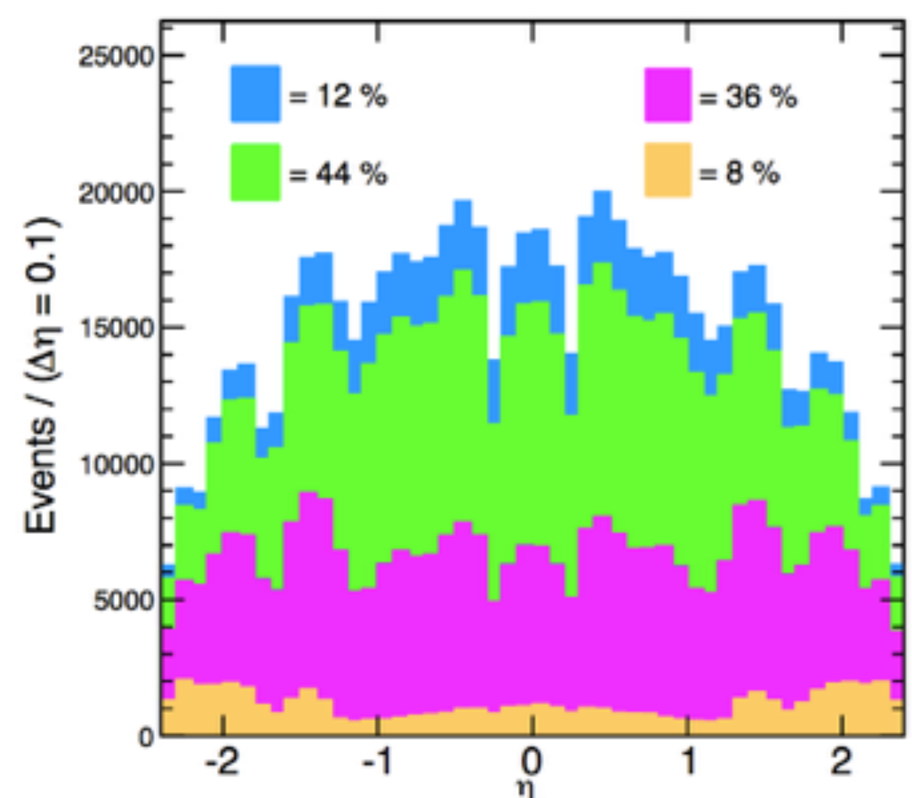
$$\Upsilon \to \mu\mu$$

$$< p_T > \quad \sim 3\ \mathrm{GeV}/c$$

$$m_\Upsilon \sim 10\ \mathrm{GeV}/c^2$$

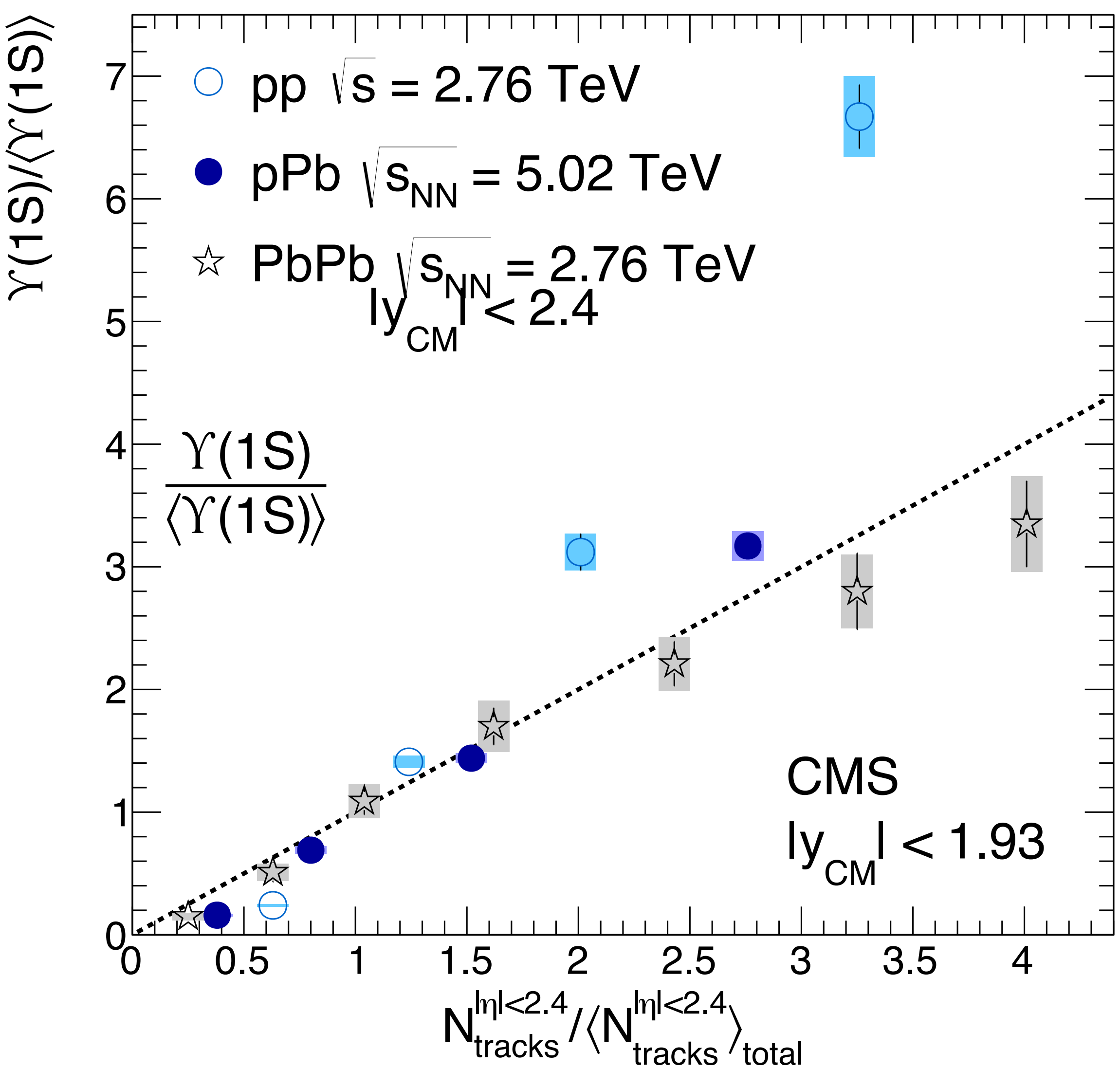
- Look in Υ(1S) simulations:
- 40+% reco events with $p_T(\mu) < 4$

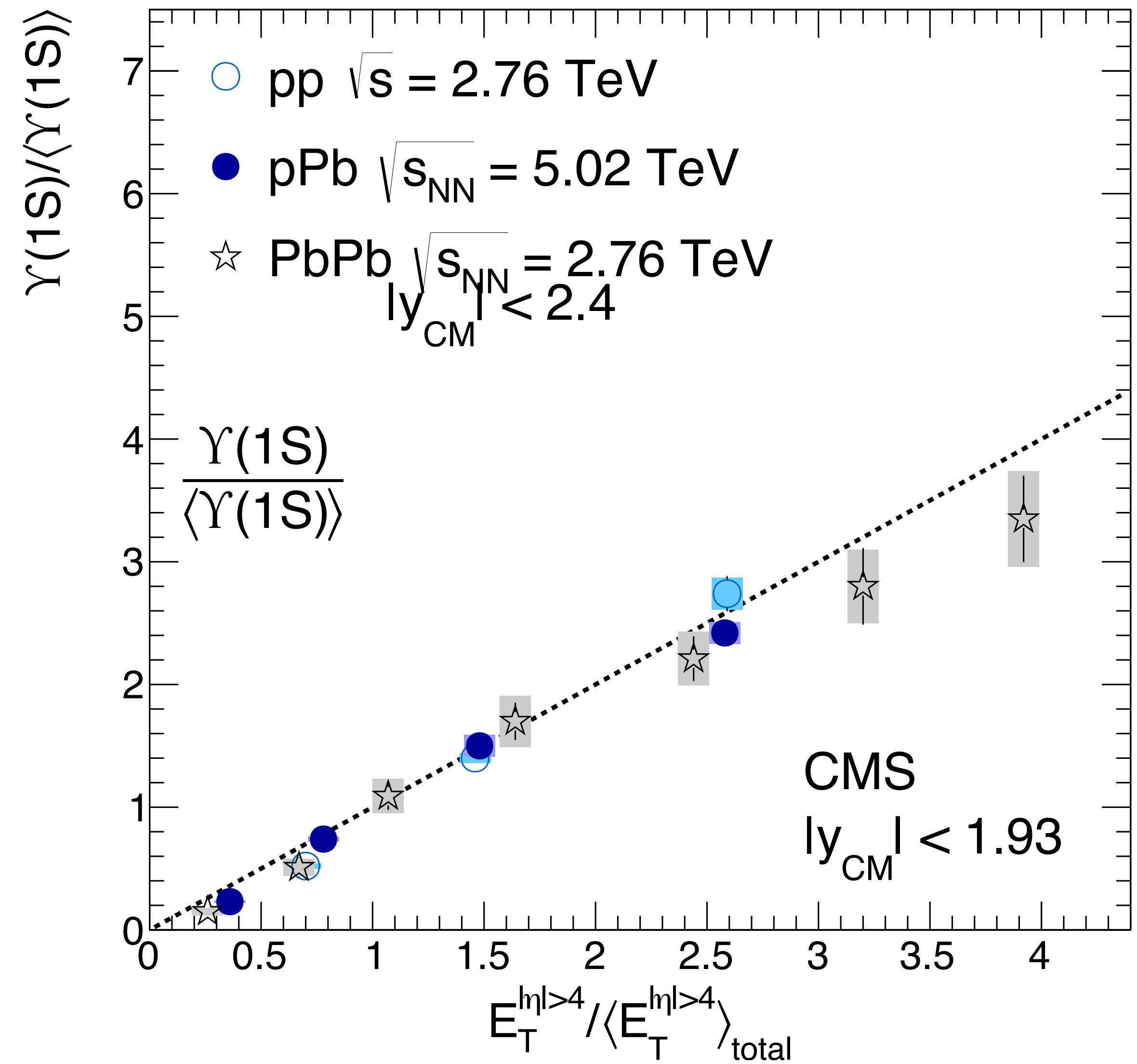




Self-normalised cross-sections

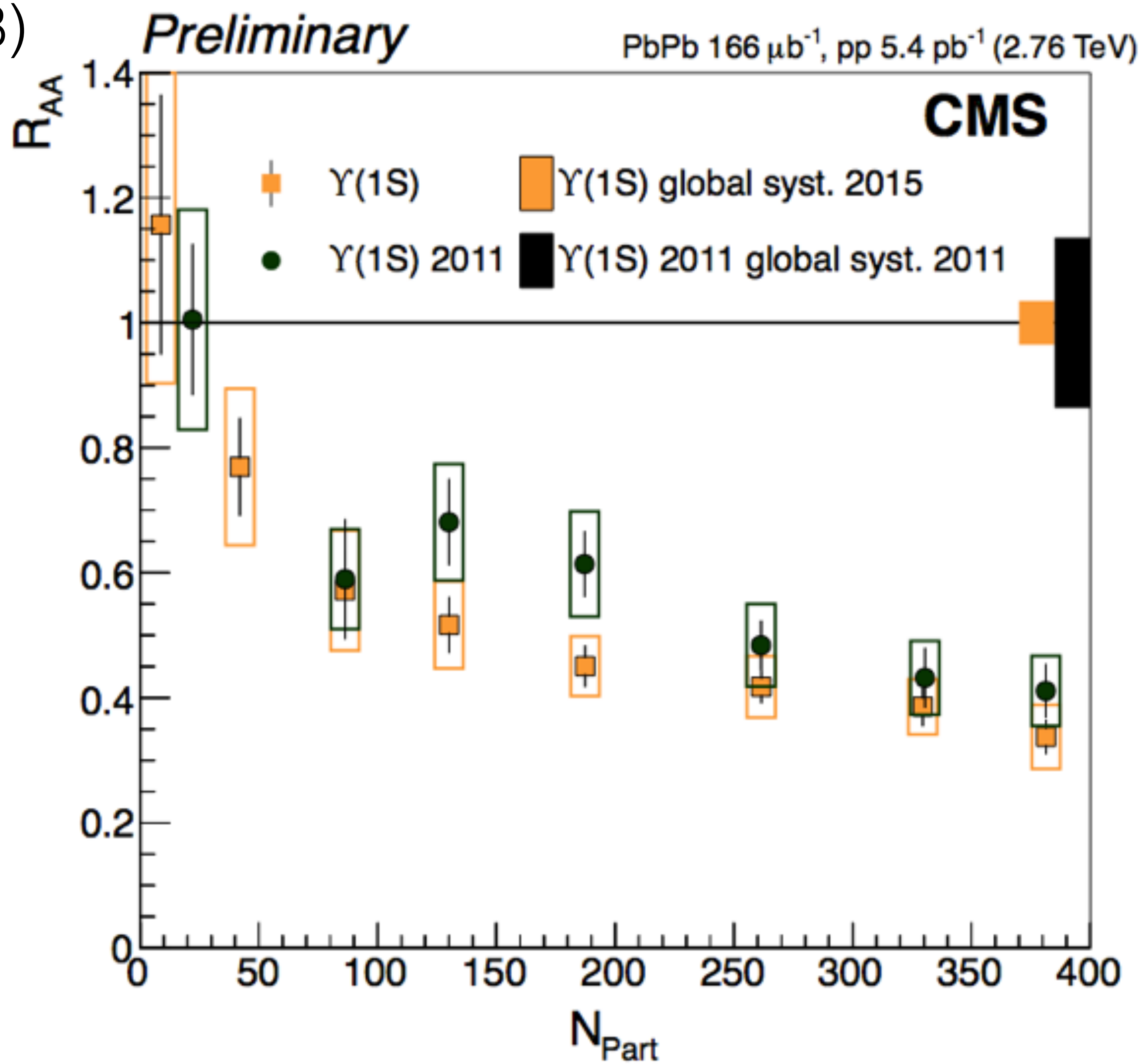
- x axis: Tracker multiplicity (|eta|<2.4) normalised by average
- y axis: Cross section as a function of multiplicity, normalised by its integrated value





RAA Υ(1S) compared with past results

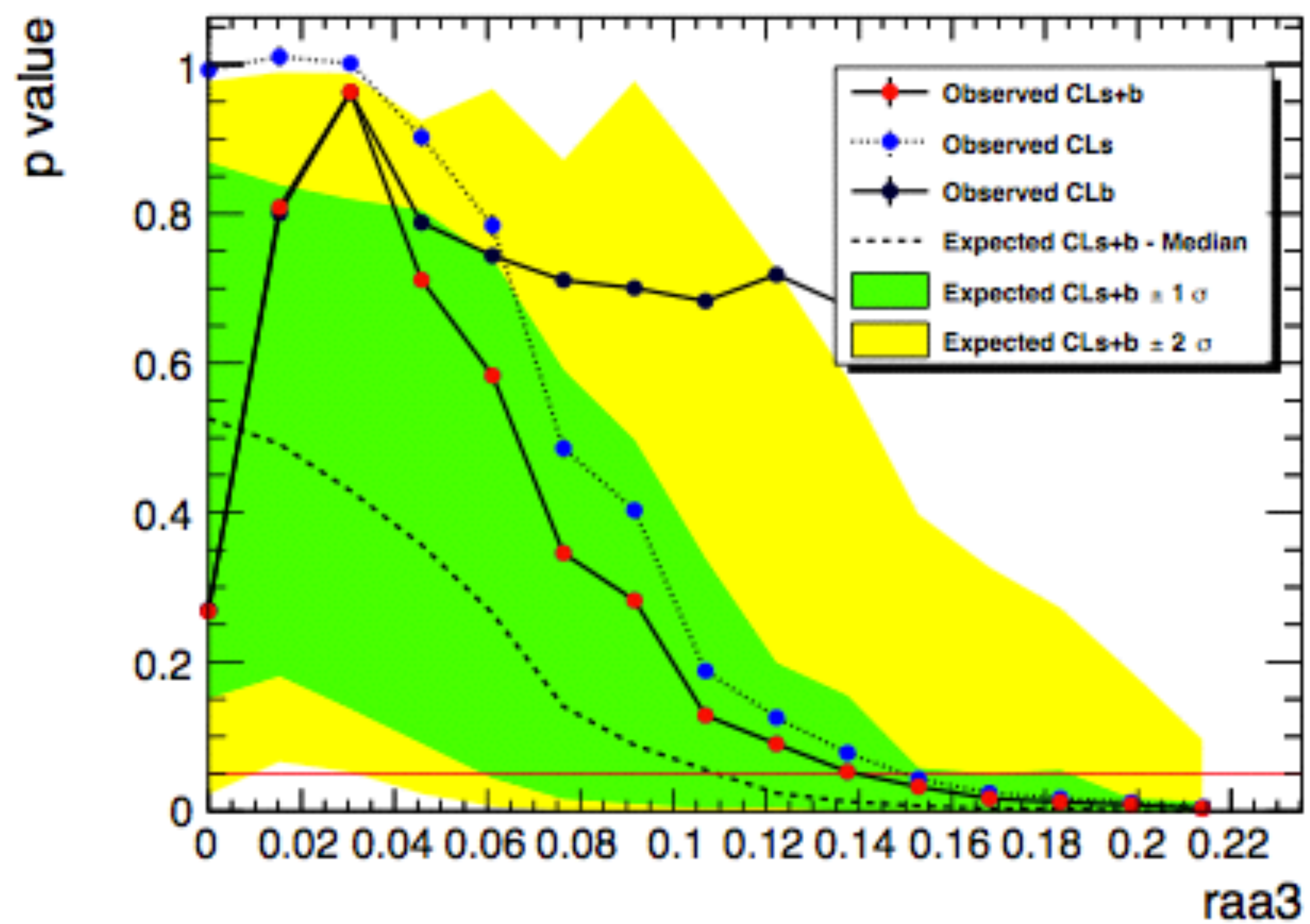
Orange: this result
Black: 2011 result (cf. slide 38)



RAA Y(3S)

- Feldman-Cousins method provides a set of well-defined confidence intervals for any true value of RAA Y(3S)
- Allows a smooth transition from one-sided to two-sided intervals in case of significant measurement

$$R_{AA}(\Upsilon(3S)) \quad < \quad 0.014 \text{ at } 95\% \text{ CL.}$$



Fully-frequentist result

Outlook

- My contributions over the Thesis:
  - Contact person for the analysis of Υ PbPb/pp data
    - Extracted raw yields for all Υ states,
    - Optimised the kinematic selections,
    - Re-branded the fitting strategy,
    - Applied signal constraints for every kinematic bins,
    - Helped in cross-checking the tag-and-probe method

  - Contributed to writing technical notes
  - Service task on muon triggers in 2013 (pp,pPb)
  - Helped in the early stage of Υ in pPb paper JHEP 04 (2014) 103

Thank you for your attention !