Completing the quarkonium program at RHIC
- with sPHENIX

September 30, 2014

INT Workshop on
Heavy Flavor and Electromagnetic probes in Heavy Ion Collisions

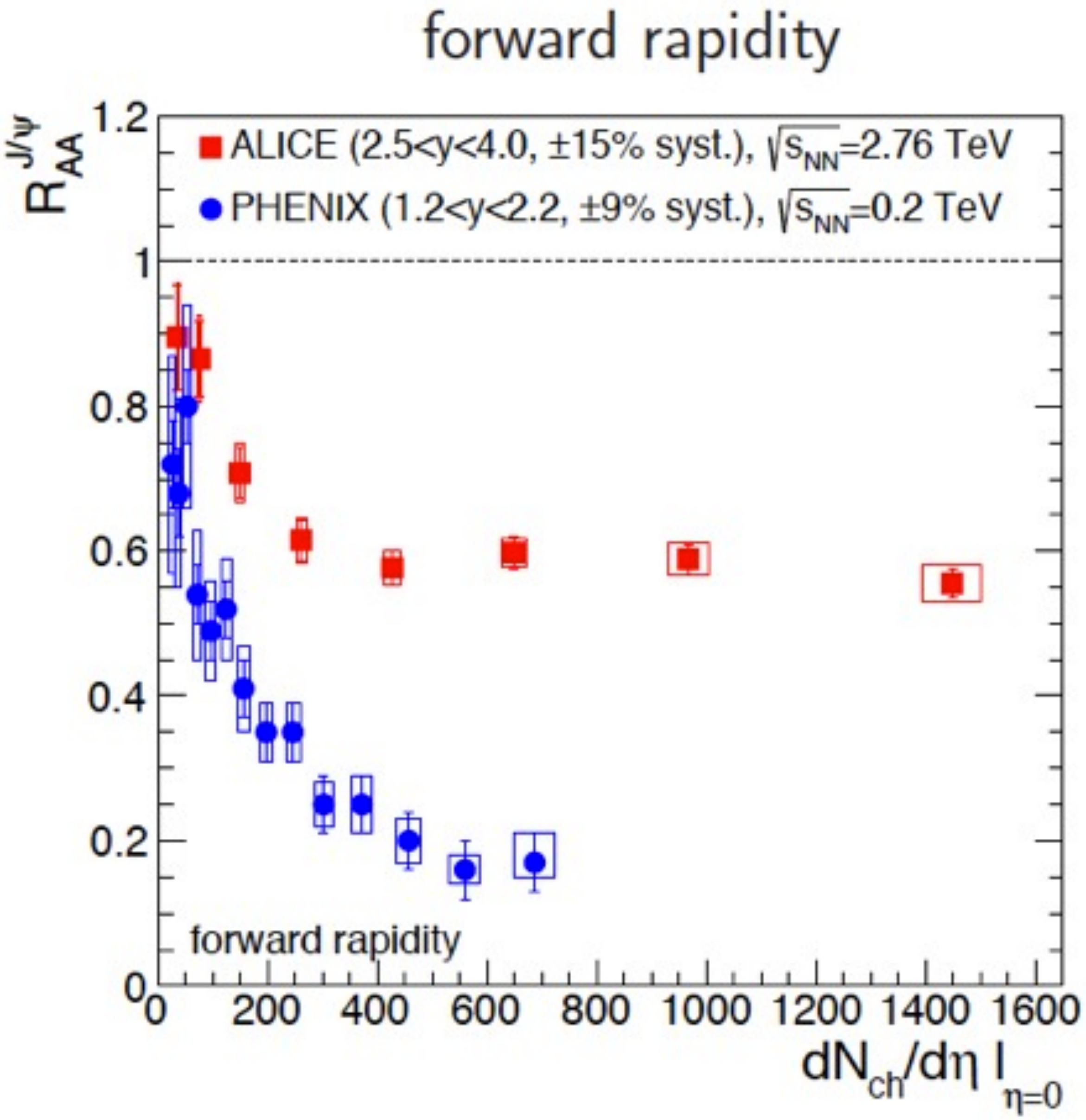
Tony Frawley

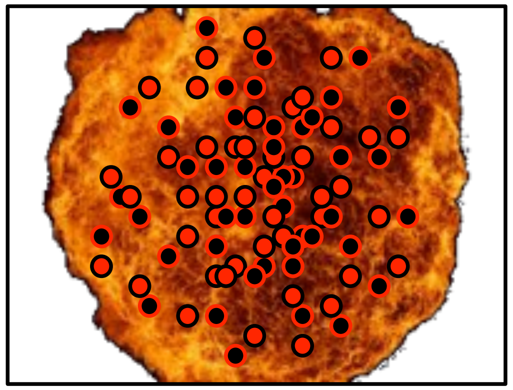
Charmonia "melt" in the QGP - but coalesce at hadronization!

Plot the modification vs charged hadron multiplicity - which is essentially proportional to **energy density** in the QGP.

Obviously, for charmonia, the suppression does **not** scale with energy density.

At LHC the number of charm quarks in a central collision is ~ 100.





The very different behavior at the same energy density is caused mostly by the difference in coalescence between 2.76 TeV & 200 GeV. **Nice physics!** but we get no direct comparison of melting of primordial Upsilons at different temperatures.

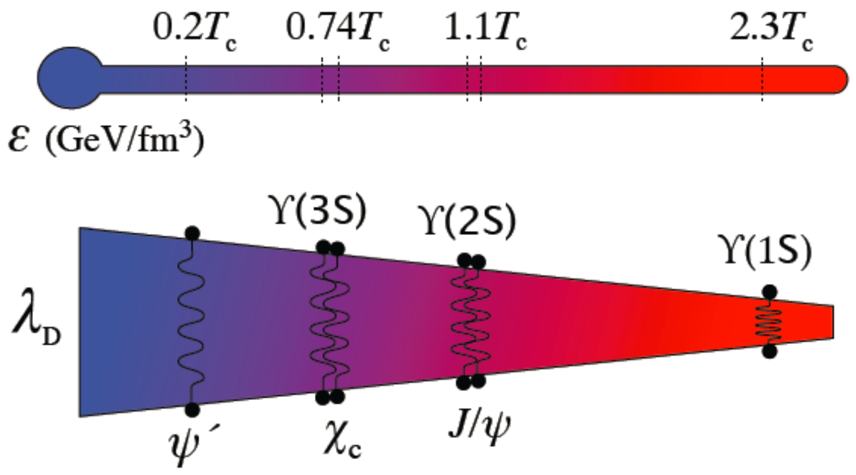
Upsilons

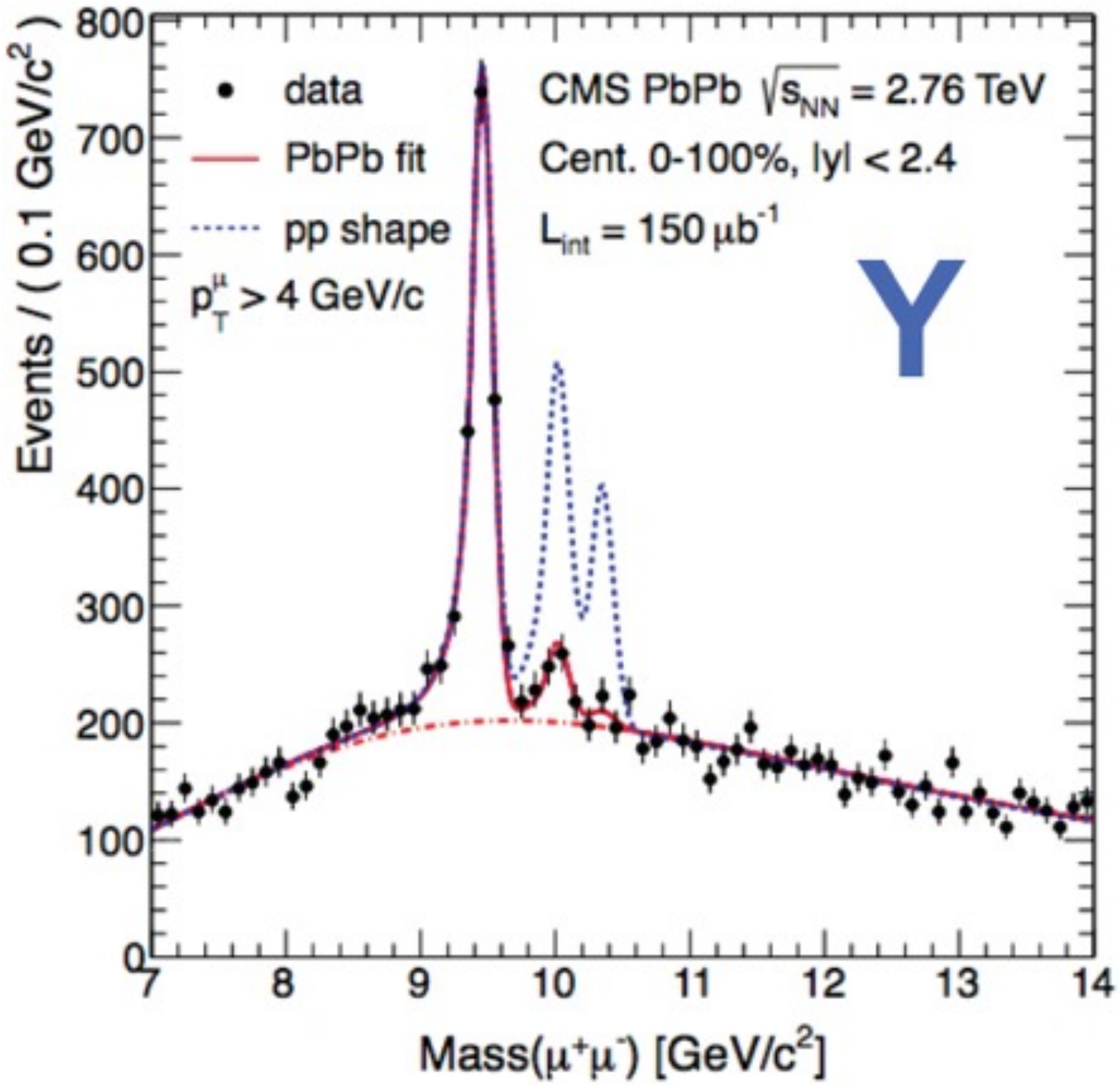
Upsilons have the advantages that:

- We measure all three states at the same time through their dielectron decays.
- Coalescence should not be large at RHIC **or** LHC.
- They span a large range of radii.

So we can directly compare melting at 200 GeV and 2.76 TeV on three states of very different size.

There are beautiful Upsilon measurements by CMS, showing dramatic suppression of the 2S and 3S states in Pb+Pb collisions at 2.76 TeV.

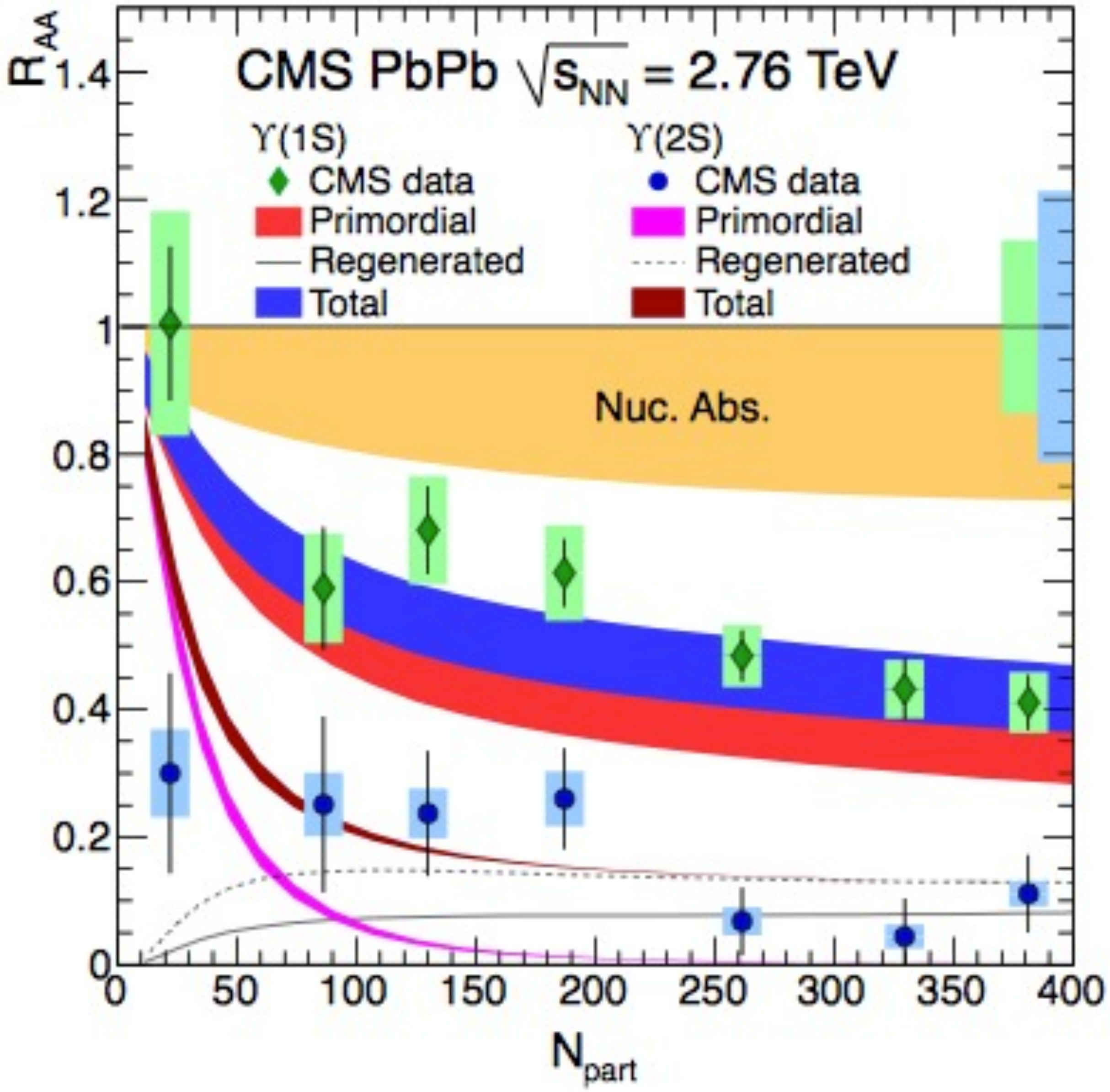




Upsilons (cont.)

A calculation from a transport model by Ralf Rapp's group showing the relative contributions of melting and coalescence to the ϒ(1S) and ϒ(2S) states compared with CMS data.

Zhao et al., NP A 904–905 (2013) 611c



This is a model in which a lattice guided potential is immersed in a hydrodynamically expanding medium. The properties of the medium modify the width and binding energy of the state.

The ϒ(2S) yield is dominated by coalescence ("regenerated") only because the primordial population melted completely!

The ϒ(1S) modification is mostly due to the loss of **feed down** from the ϒ(2S) and ϒ(3S) states. The ϒ(1S) is not strongly suppressed.

Upsilons (cont,)

A different calculation in which the Upsilon is embedded in a hydrodynamically expanding medium.

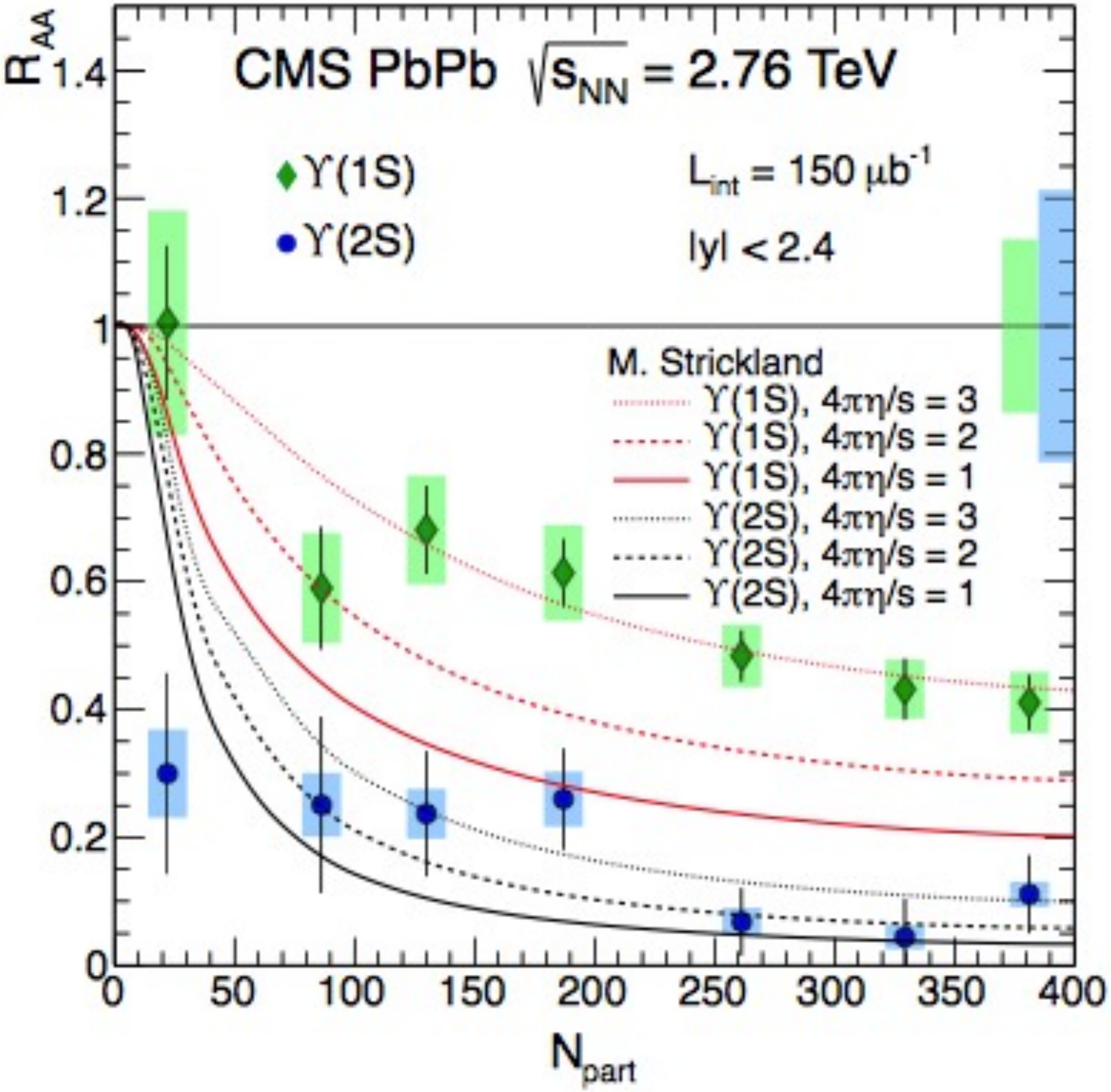
The model results depend strongly on the value used for **η/s** of the medium, since that strongly affects the time evolution of the QGP expansion.

The ϒ(1S) R_{AA} measured by CMS already constrains the model parameters, favoring **η/s ~ 0.24**.

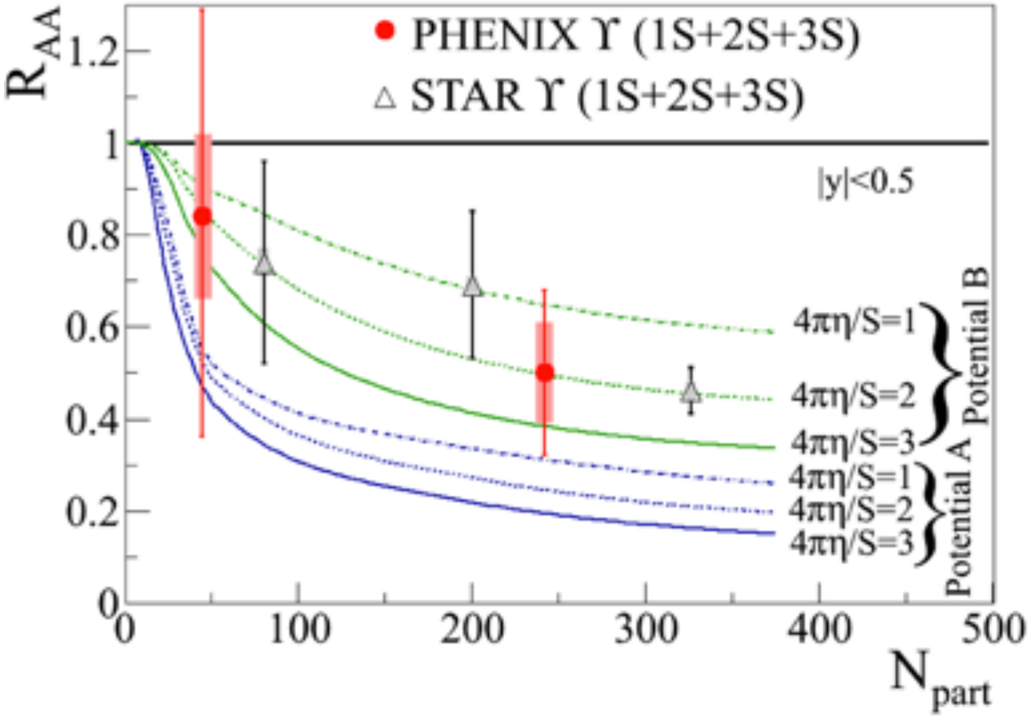
CMS will have ~ 30x this much data by 2023.

There are no such data at RHIC yet.

Strickland and Bazow N.P. A879:25 2012



Upsilon measurements at RHIC



Existing Upsilon measurements at RHIC are not comparable in quality with those at the LHC.

PHENIX measurements of Upsilons are limited to 30-40 counts with a mass resolution that does not separate the three Upsilon states.

STAR measurements of Upsilons are better than those from PHENIX because of larger acceptance, & a little better mass resolution. They will improve with the addition of the STAR **Muon Telescope Detector** upgrade, but will still have marginal mass resolution, and will have small acceptance. Also, it will not be possible to measure a statistically significant yield in p+p collisions.

PHENIX has proposed building a new detector at RHIC that will be an excellent **jet** and **Upsilon** detector. This addresses the two major areas where RHIC measurements are not good enough to be complementary to LHC measurements.

sPHENIX

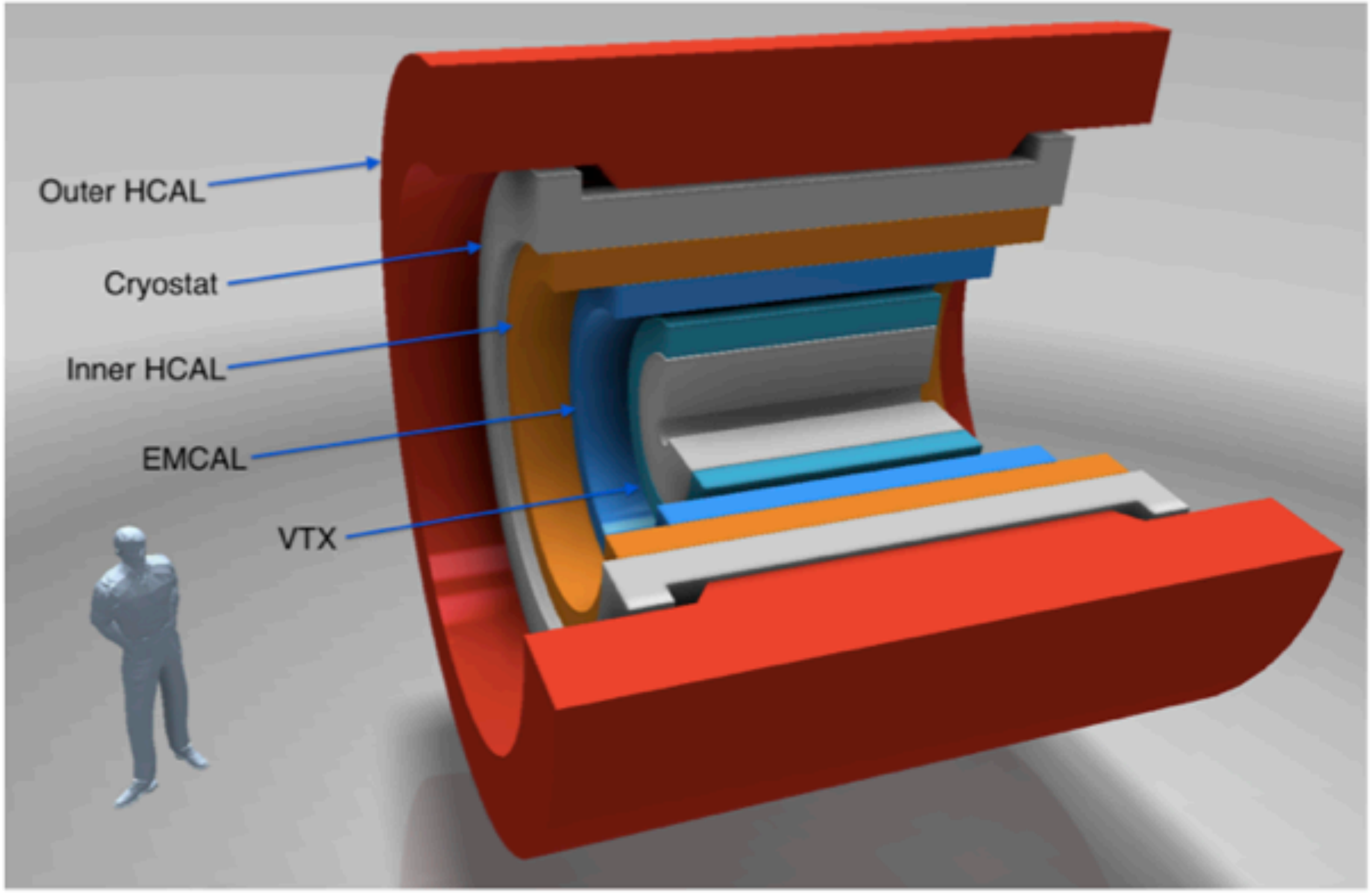
Compact detector built around a superconducting solenoid.

- BaBar magnet (1.5 T solenoid)
- Coverage $|\eta| < 1.1$
- 7 layer Si tracker
  - Heavy flavor tagging by displaced vertex measurement
- EMCal
- Inner HCal
- Outer HCal

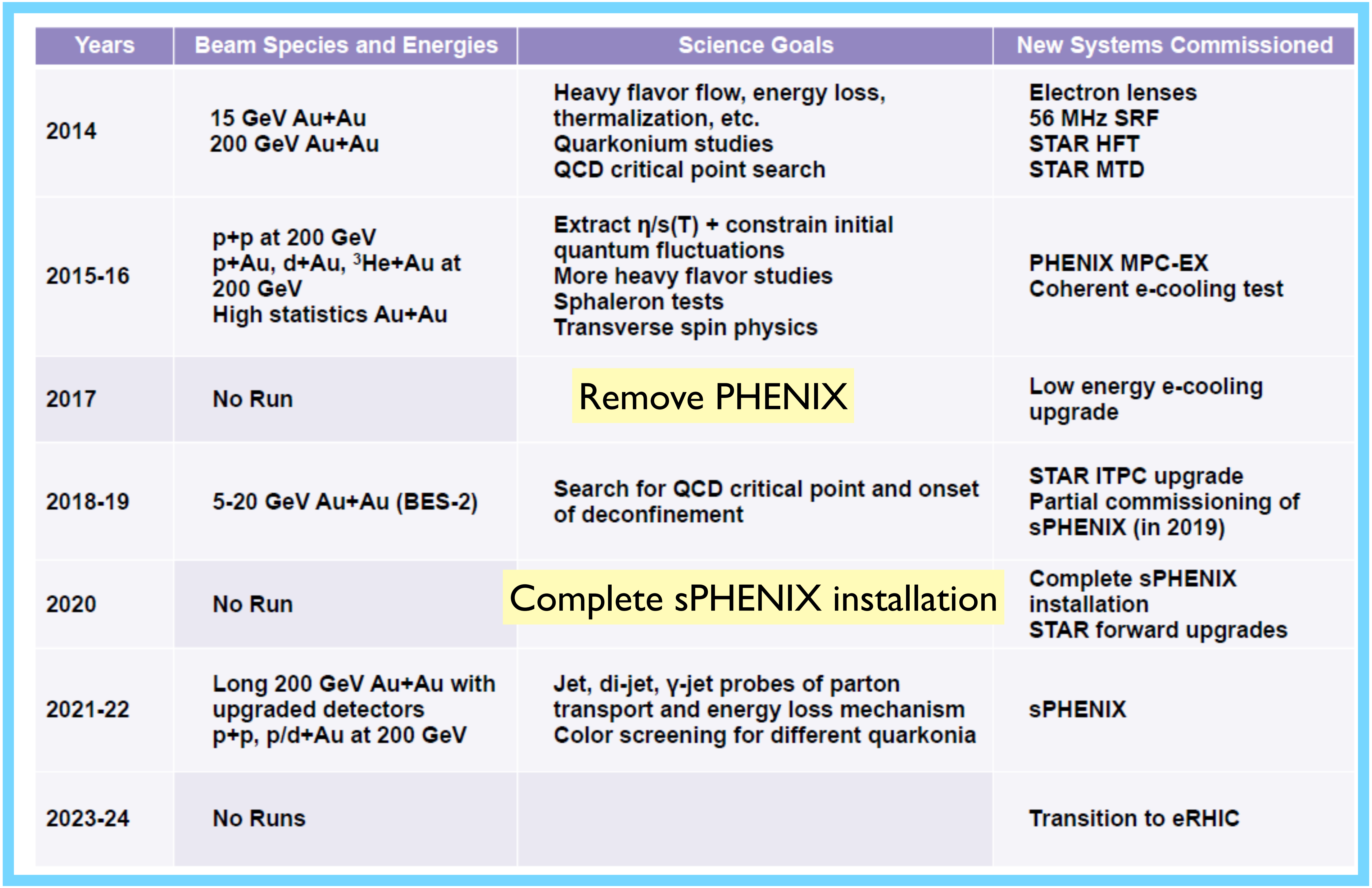
Hermetic coverage (required for good jet reconstruction).

Upsilons measured using dielectrons

Let’s look at the **time scale** before talking about the detector.



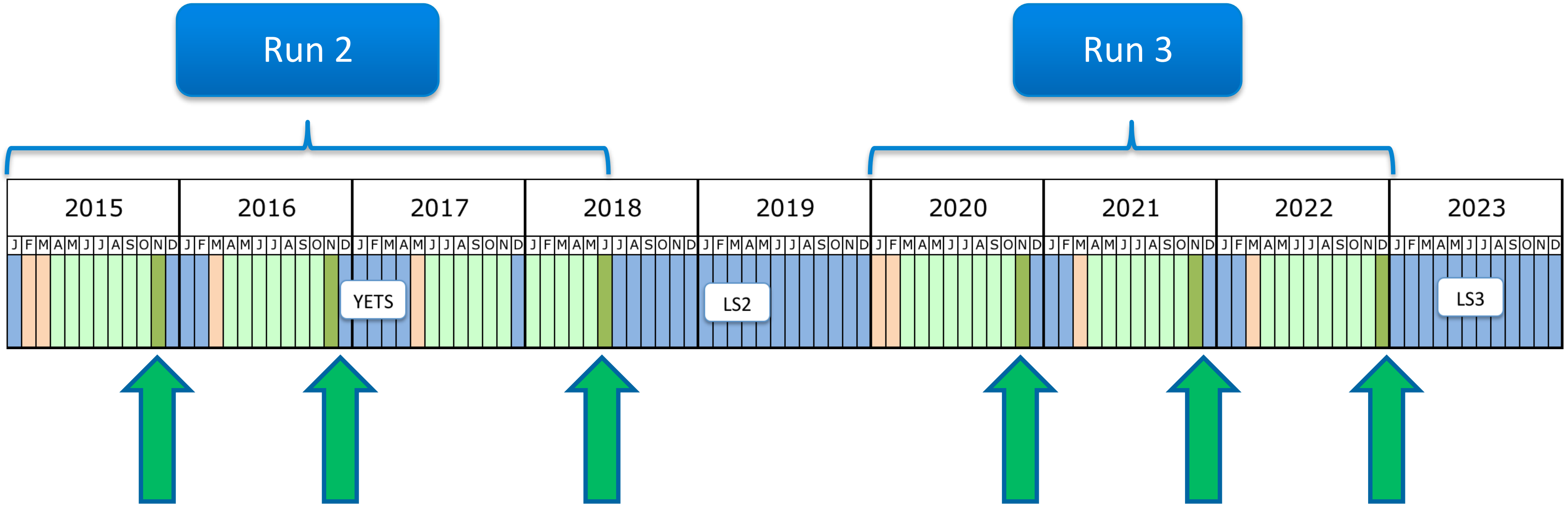
Brookhaven Lab proposed 10 year plan



Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract $\eta/s(T)$ + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX Coherent e-cooling test
2017	No Run	Remove PHENIX	Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run	Complete sPHENIX installation	Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX
2023-24	No Runs		Transition to eRHIC

sPHENIX timeline and LHC

LHC

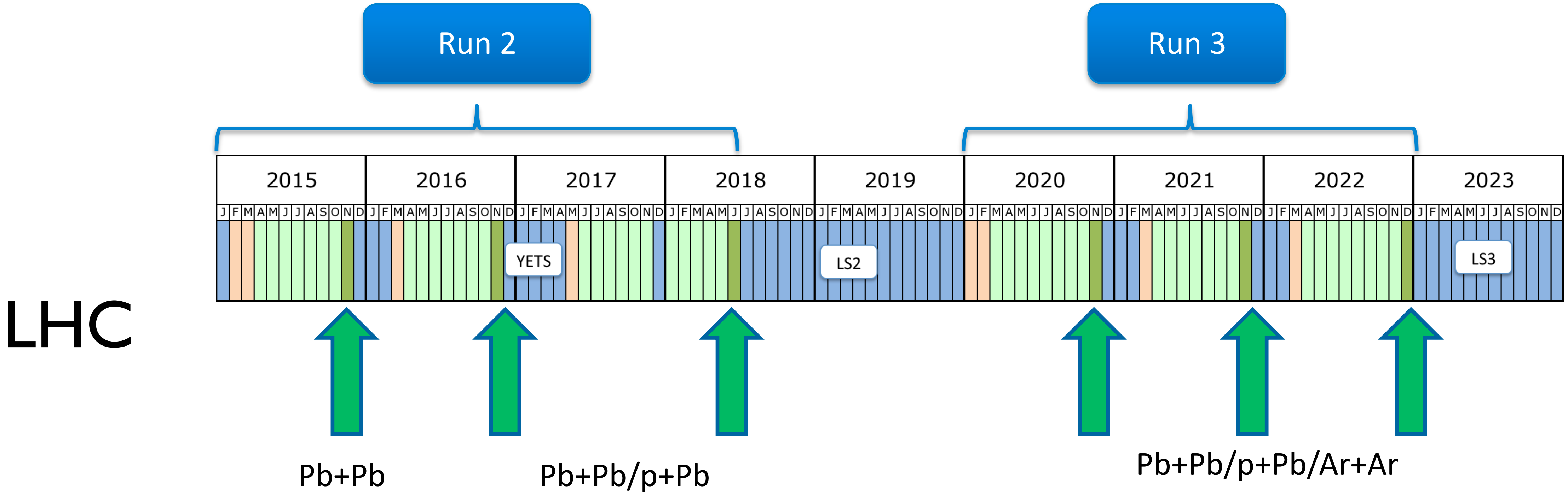


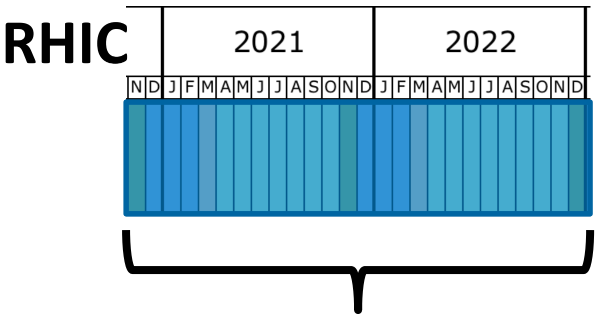
Pb+Pb

Pb+Pb/p+Pb

Pb+Pb/p+Pb/Ar+Ar

sPHENIX timeline and LHC





sPHENIX Schedule:
PHENIX shuts down in 2016
Central arm magnets and detectors removed
sPHENIX installed by 2020
Begins running in 2021

Will run for 2 (or 3) years.

sPHENIX Features for Upsilon Measurements

DAQ bandwidth **10 kHz** with **Deadtimeless DAQ**

→ Au+Au: record **50B** minbias events and sample **200B** with triggers

HCal:

- Helps reject background for Upsilon dielectron measurements

EMcal:

- Electromagnetic energy measurement.
- Electron ID via E/p cut and shower shape measurements.
  - x90 hadron rejection (with HCal) in central Au+Au at 70% single track efficiency.
- Upsilon dielectron trigger in p+p, p+Au.

Tracking:

- Measure Upsilon mass via decay electron momentum.
- Provide good pattern recognition in central Au+Au events.

Tracking Requirements for Upsilons

There are two major design issues for the tracker:

- Tracking in a high multiplicity environment - approximately 1300 charged particles into the acceptance.
- Momentum resolution adequate for the Upsilon (100 MeV mass resolution requires $\Delta p_T/p_T \sim 1.2\%$).

Accomplished using a magnetic field of 1.5 T and an all Si tracker with 7 layers:

- Two inner layers are precise pixel layers for measuring displaced vertex.
- Five strip layers for momentum measurement + pattern recognition in high multiplicity events.
- The outer layer is at 80 cm radius.

The Si tracker **thickness** needs to be minimized to:

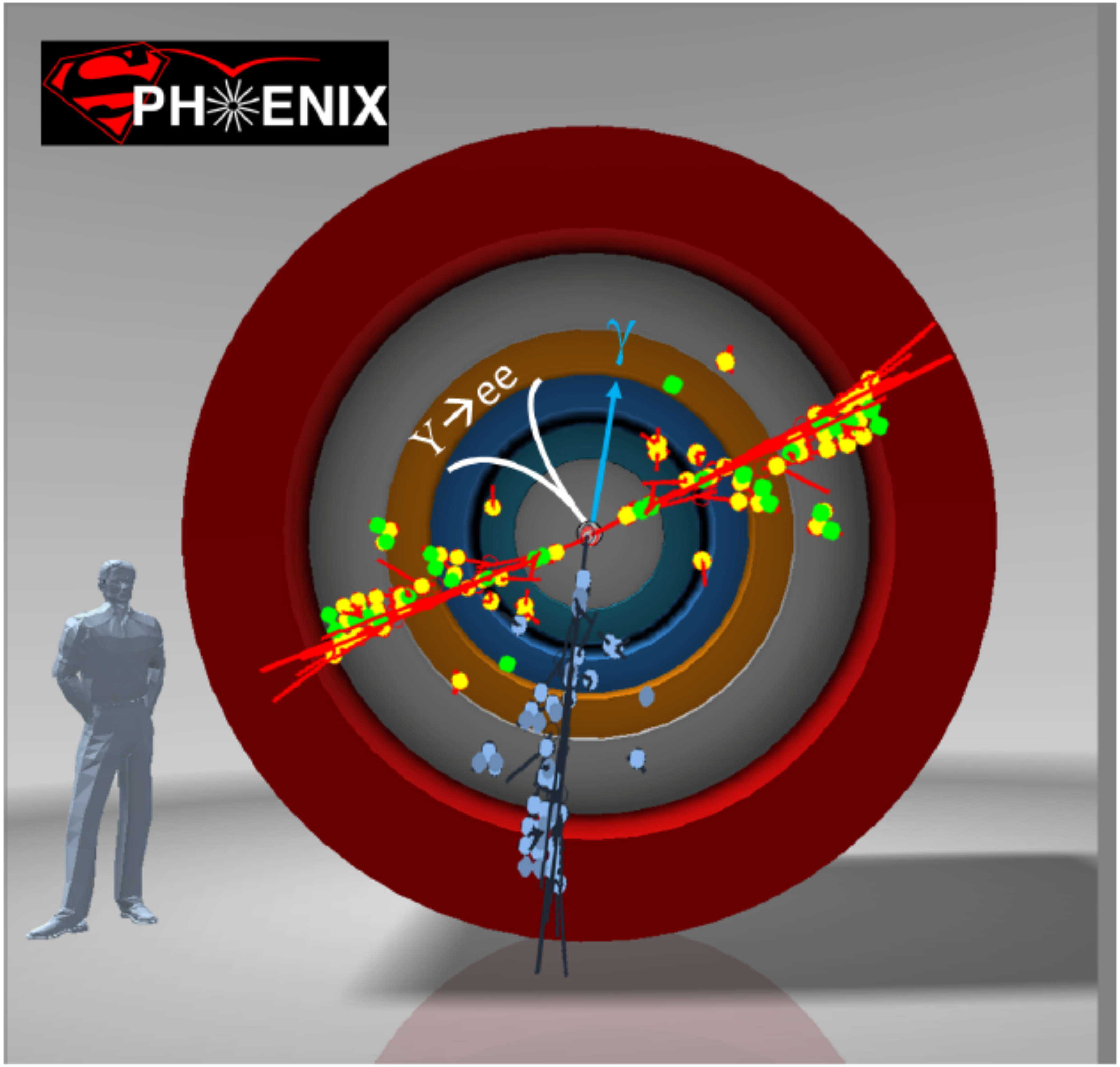
- Avoid large Bremsstrahlung tails on the Upsilon mass peaks.
- Control multiple scattering effects on momentum resolution.

We presently estimate ~ 10-12% X_0.

The tracker is about 97% efficient for reconstructing tracks with $p_T > 2$ GeV/c in central Au+Au events (the range for Upsilon decay electrons).

The Upsilon pair reconstruction efficiency is 34%.

Measurements

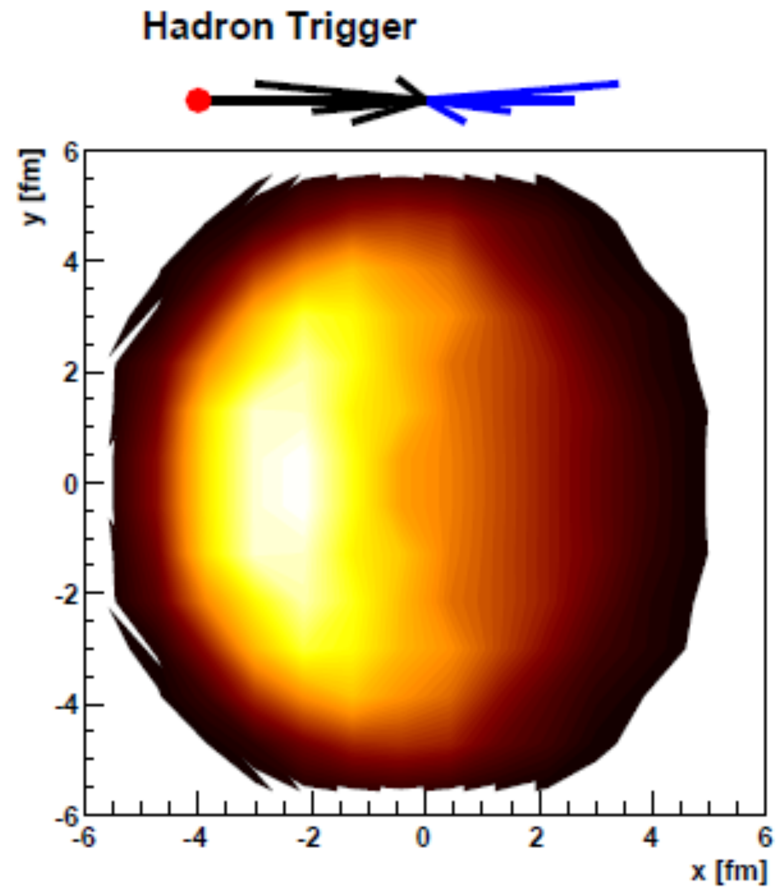


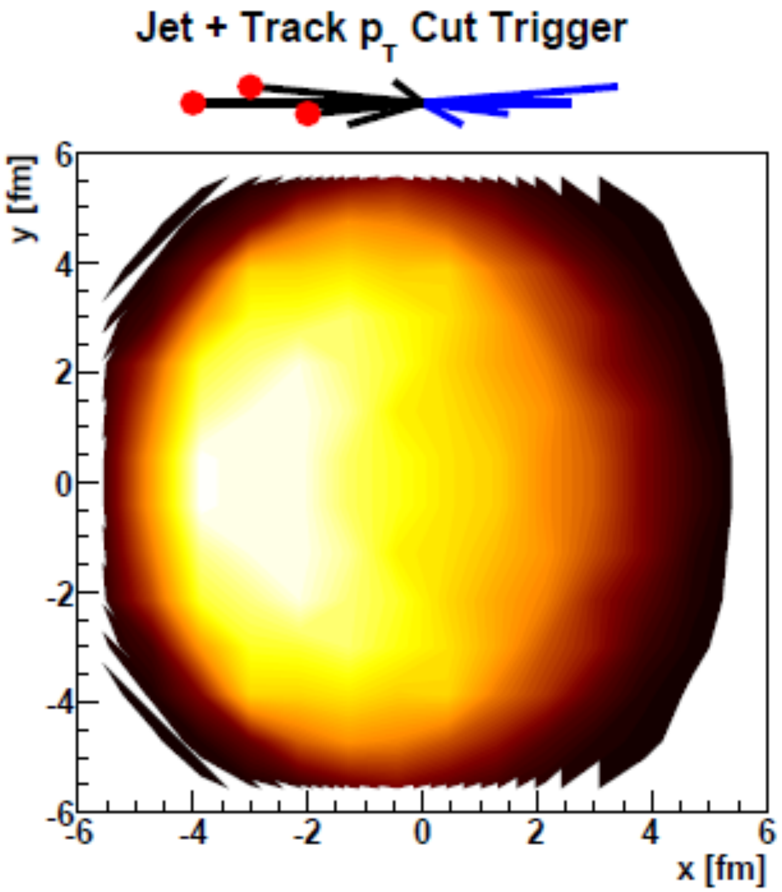
Unbiased Jet Measurements

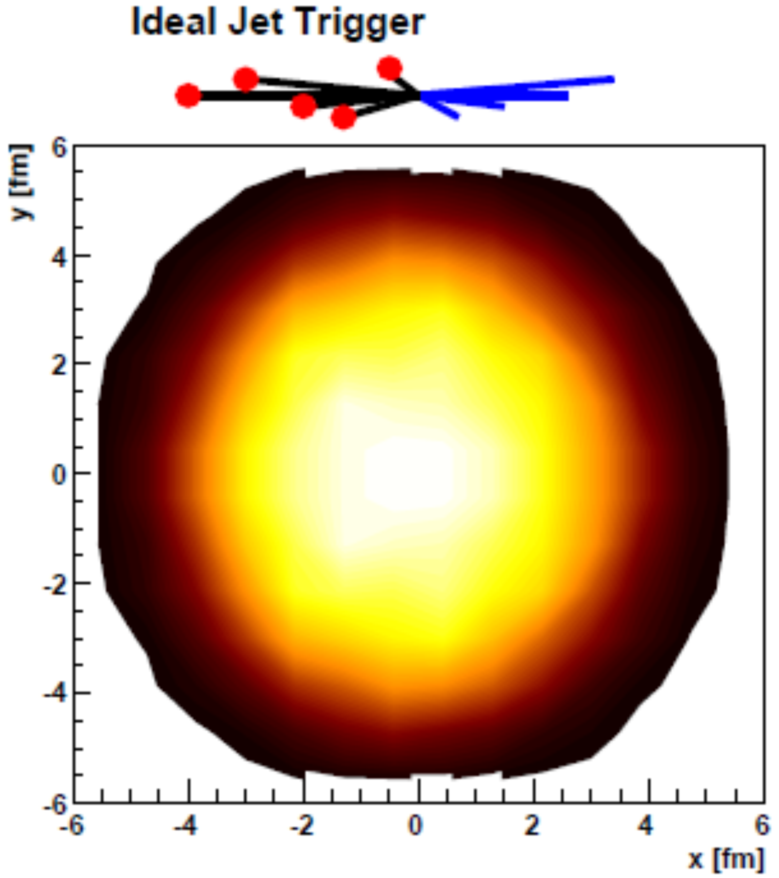
The goal of jet measurements is to learn about the effect on the jet parton of its transit through the QGP. Best done with fully reconstructed jets, to avoid assumptions about how the fragmentation functions are affected by the medium.

We want measurements of jets that are as unbiased as possible by:

- Triggers (lead to “surface bias”)
- Minimum p_T cuts on detected particles (also produce surface bias)


Hadron Trigger


Jet + Track p_T Cut Trigger


Ideal Jet Trigger

Jet rates for sPHENIX

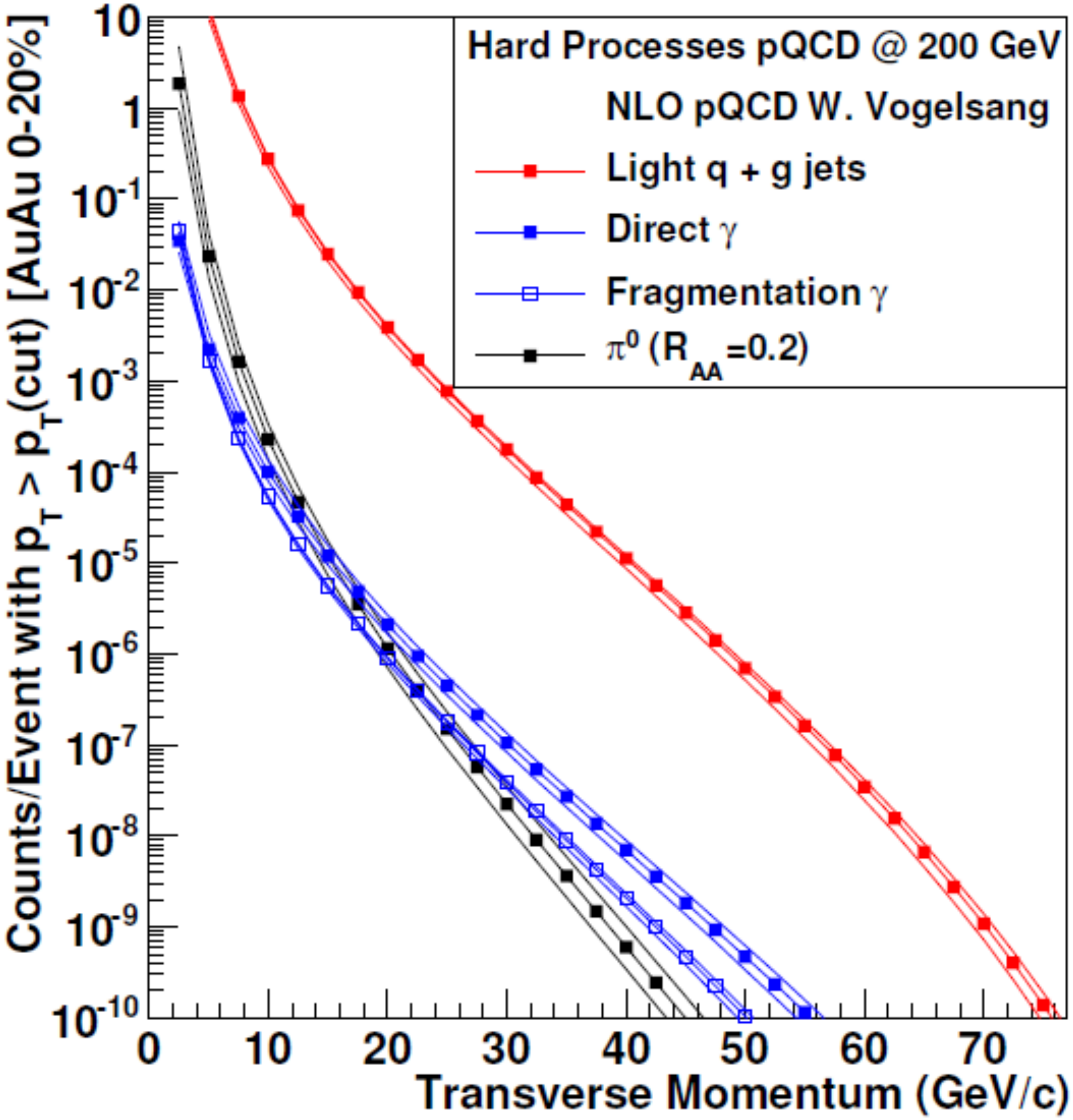
Jet yields for central Au+Au collisions in one year of running with sPHENIX

- 50 billion **minbias** Au+Au events.

10^7 jets > 20 GeV
10^6 jets > 30 GeV

- 80% are dijet events (i.e. both jets are inside acceptance)

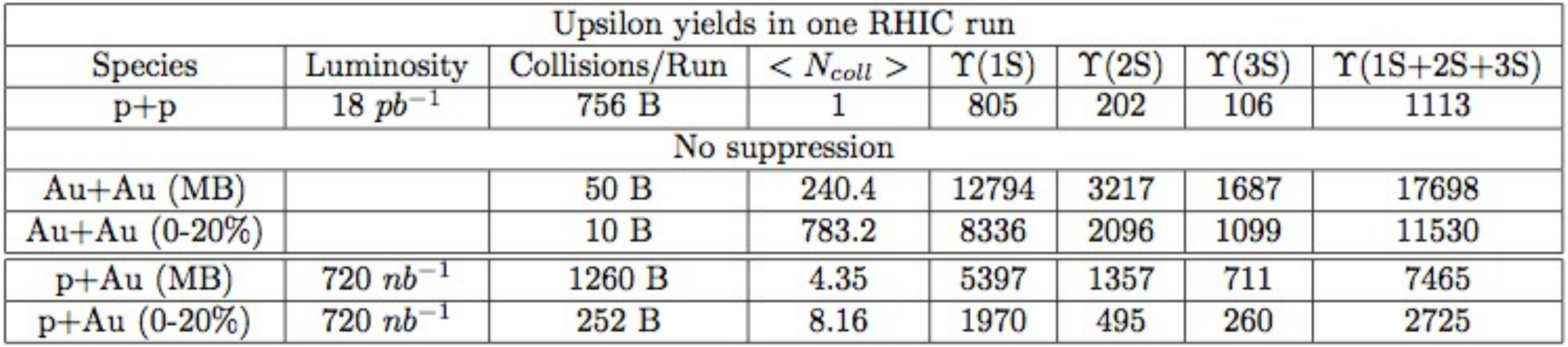
10^4 direct γ > 20 GeV



Proposed Upsilon measurements

20 weeks Au+Au @ 200 GeV (50 B minbias events)
10 weeks p+p @ 200 GeV (triggered)
10 weeks p+Au @ 200 GeV (triggered)

Upsilon measurements use
$\Upsilon \rightarrow e^+e^-$



Upsilon yields in one RHIC run

Species	Luminosity	Collisions/Run	$< N_{coll} >$	Υ(1S)	Υ(2S)	Υ(3S)	Υ(1S+2S+3S)
p+p	18 pb^{-1}	756 B	1	805	202	106	1113
No suppression							
Au+Au (MB)		50 B	240.4	12794	3217	1687	17698
Au+Au (0-20%)		10 B	783.2	8336	2096	1099	11530
p+Au (MB)	720 nb^{-1}	1260 B	4.35	5397	1357	711	7465
p+Au (0-20%)	720 nb^{-1}	252 B	8.16	1970	495	260	2725

These are for collisions with a Z vertex inside the silicon acceptance (+/- 10 cm)
The reconstruction efficiency for Upsilons is 34%. from GEANT 4 simulations.

These yields are **additionally** modified by the eID efficiency (which depends on the hadron multiplicity), assumed here to be **49%** for pairs in central Au+Au, **65%** in MB Au+Au, **100%** in p+p.

Upsilon performance

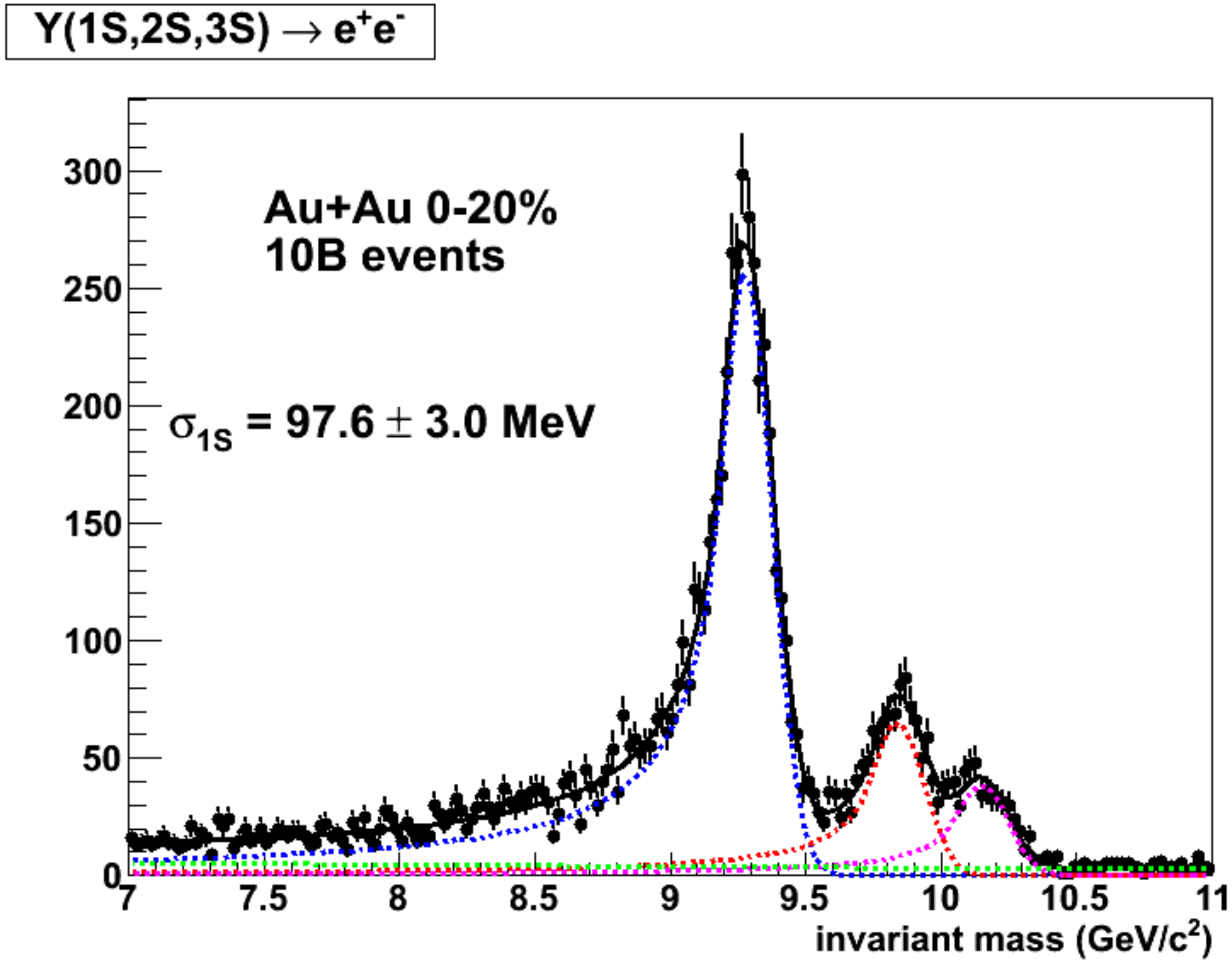
There are two major issues for the Upsilon measurement:

- Momentum resolution adequate for 100 MeV mass resolution.
- Low enough mass in the tracker to minimize Bremstrahlung tails on the mass peaks (a disadvantage of using electrons instead of muons).
- Good enough hadron rejection to keep background under the peaks small.

This plot shows the Upsilon mass spectrum for the signal only from a full GEANT 4 simulation.

The yields are what we expect **without suppression** for 0-20% centrality in a 1 year run.

The width is from a crystal ball fit.



Upsilon performance - central Au+Au

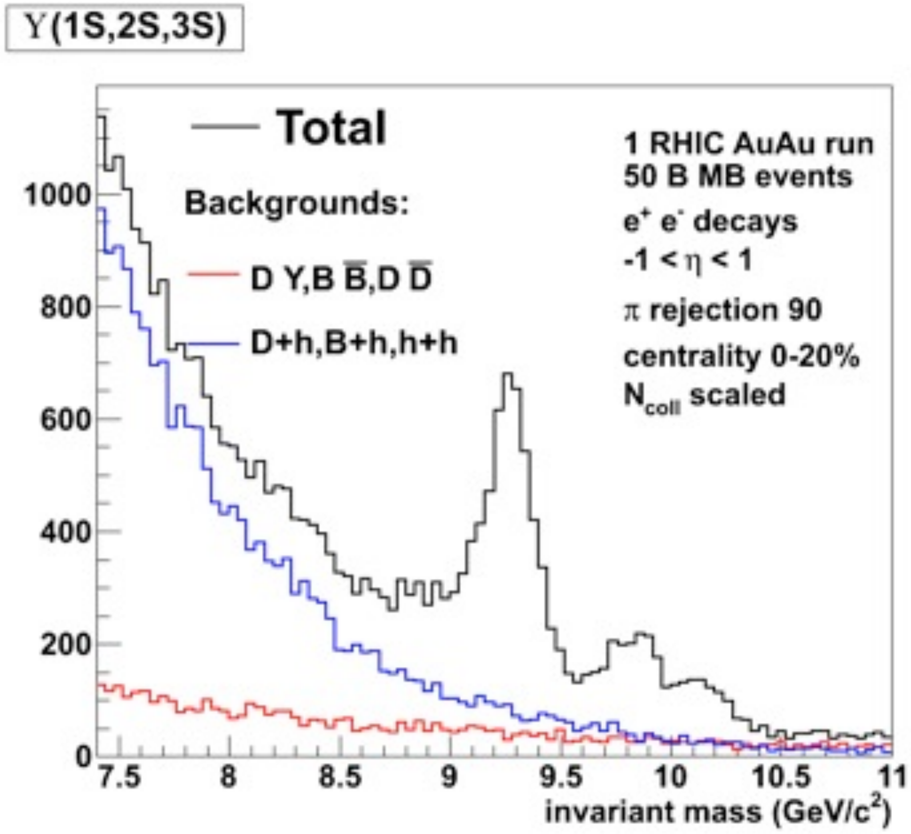
Signal+correlated background after subtraction of combinatoric background.

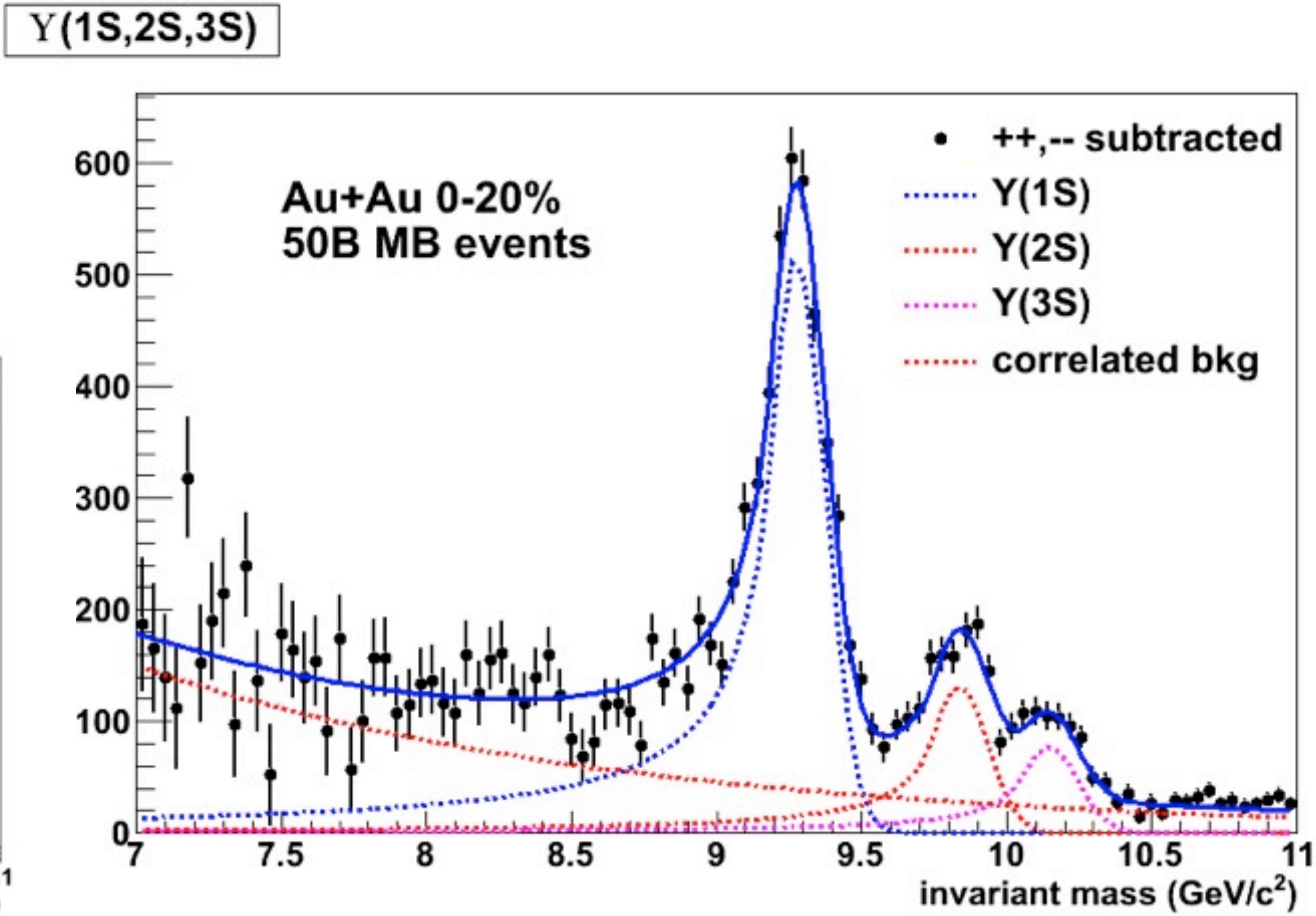
- Backgrounds from fast simulation based on measured yields in central Au+Au.

Background estimates assume a **hadron rejection of 90** using EMCal E/p, shower shape cuts and a HCal veto - rejection from GEANT 4 simulations.

Correlated background:

- Drell-Yan
- Correlated charm
- Correlated bottom





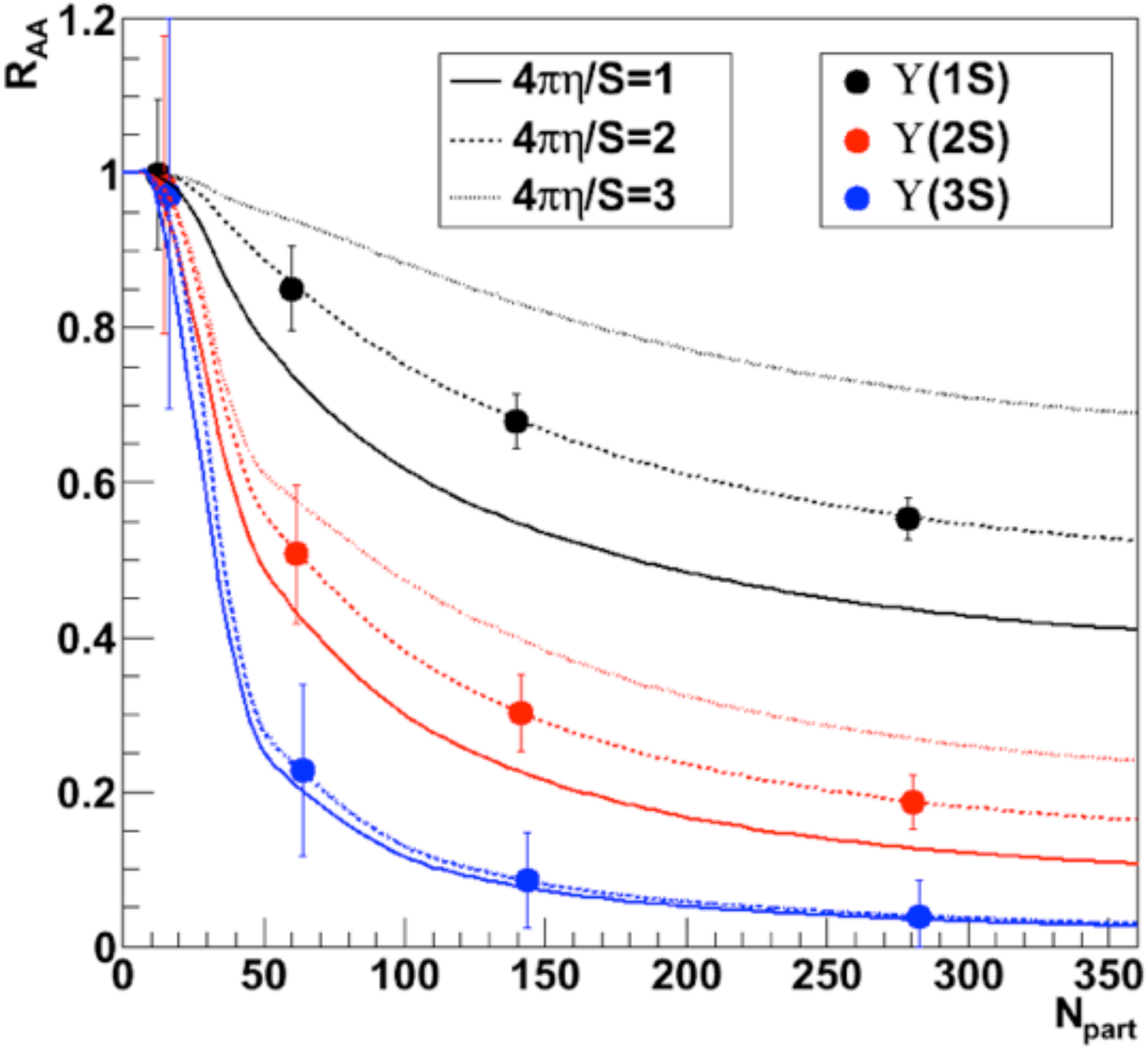
Upsilon performance - central Au+Au

This is a plot I made for a recent sPHENIX DOE review, showing the expected statistical precision for the three Upsilon states measured with sPHENIX.

The statistical precision includes the effects of the estimated signal to background ratio.

Would provide tight constraints on theoretical descriptions of RHIC energy data to complement those provided by CMS for data at LHC energy.

Strickland and Bazow N.P. A879:25 2012
(and private communication)



A comment on hot matter effects in p+A collisions

Strong collective behavior observed in p+Pb at LHC, then d+Au at RHIC.

Does this invalidate p+A as a way to calibrate cold nuclear matter effects?

How could we tell?

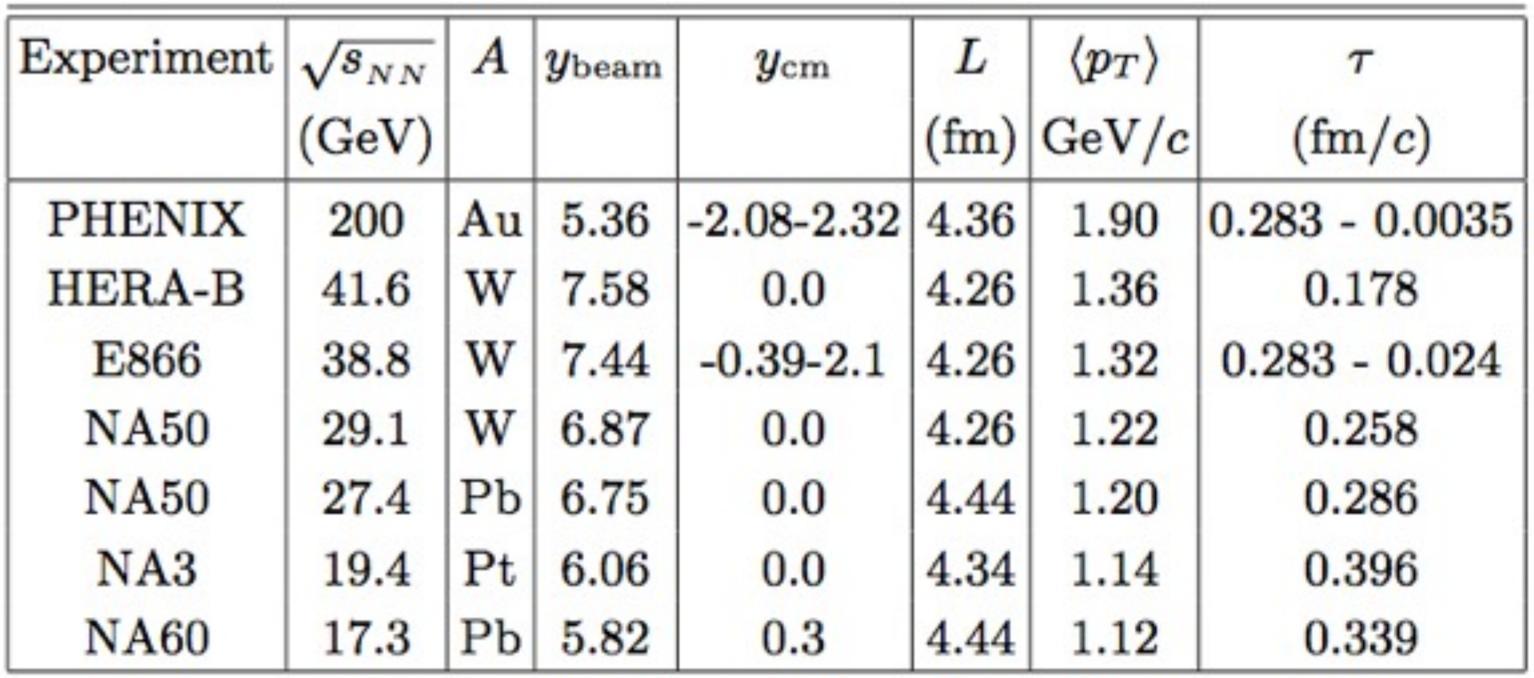
Are charmonia suppressed by hot matter effects in d+Au?

If we knew the mechanism, we could compare p+A results across a wide range of collision energies to look for onset of hot matter effects.

Effective σ_{abs} extracted from EKS98 or EPS09 corrected data for **17.3 to 200 GeV** collisions:

- Lourenco et al., JHEP02, 014 (2009).
- Arnaldi et al. (NA60), Nucl. Phys. A 830, 345C (2009).
- McGlinchey et al., Phys.Rev. C87 (2013) 054910.

In cases where the breakup is really the mechanism, σ_{abs} should depend on time spent in the target, τ. This is a strong function of energy and rapidity:



Experiment	$\sqrt{s_{NN}}$ (GeV)	A	y_{beam}	y_{cm}	L (fm)	$\langle p_T \rangle$ GeV/c	τ (fm/c)
PHENIX	200	Au	5.36	-2.08-2.32	4.36	1.90	0.283 - 0.0035
HERA-B	41.6	W	7.58	0.0	4.26	1.36	0.178
E866	38.8	W	7.44	-0.39-2.1	4.26	1.32	0.283 - 0.024
NA50	29.1	W	6.87	0.0	4.26	1.22	0.258
NA50	27.4	Pb	6.75	0.0	4.44	1.20	0.286
NA3	19.4	Pt	6.06	0.0	4.34	1.14	0.396
NA60	17.3	Pb	5.82	0.3	4.44	1.12	0.339

Large range!

$$\tau = \frac{\beta_z L}{\gamma}$$

Are charmonia suppressed by hot matter effects in d+Au?

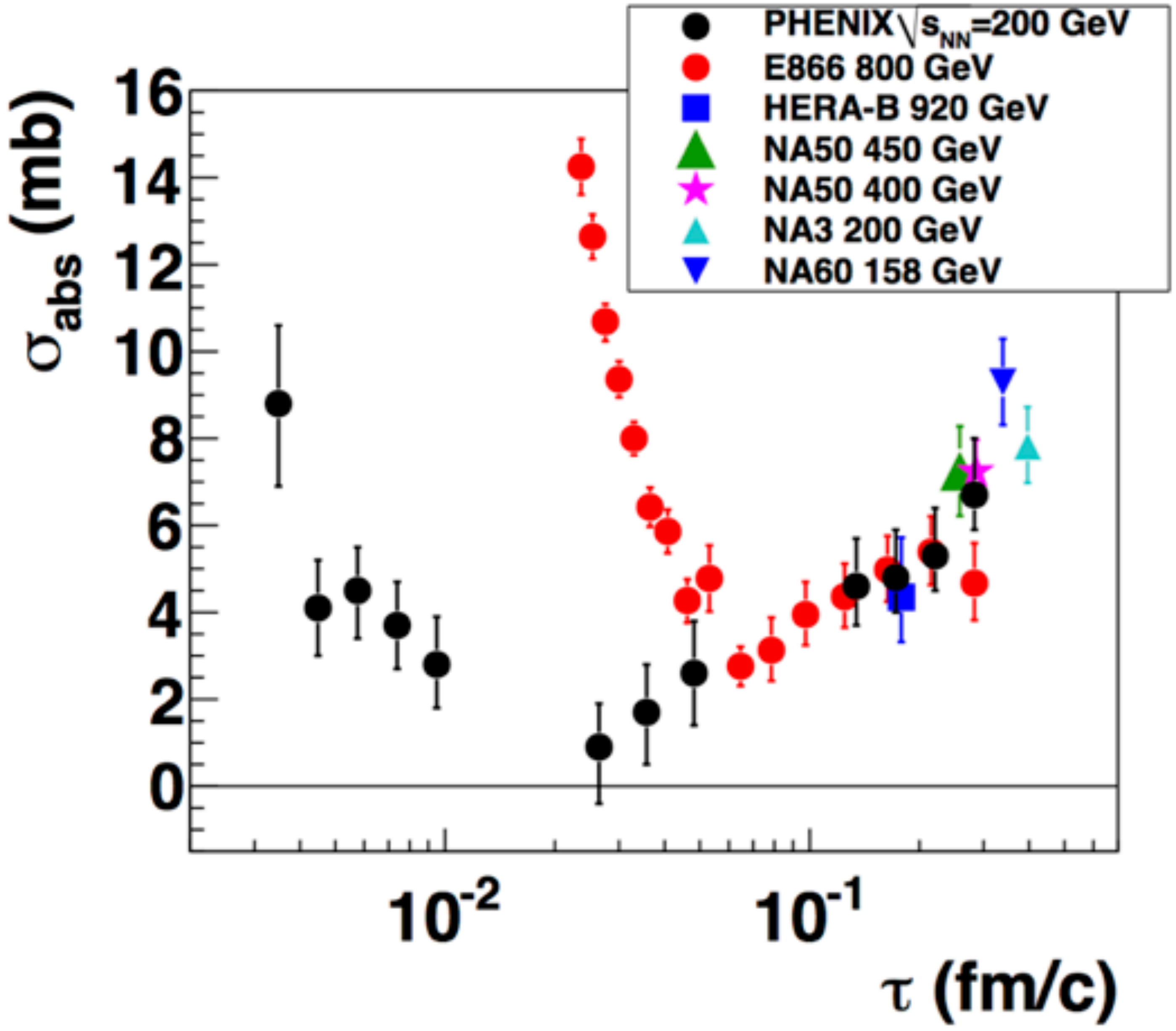
Plot the cross section vs time in the target nucleus.

We see scaling with τ above τ ~ 0.05 fm/c.

For τ < 0.05 fm/c, the scaling breaks down completely.

This change in behavior occurs at about the charm pair formation time.

Does it make sense that in the scaling region the modification is due to a breakup cross section?



Are charmonia suppressed by hot matter effects in d+Au?

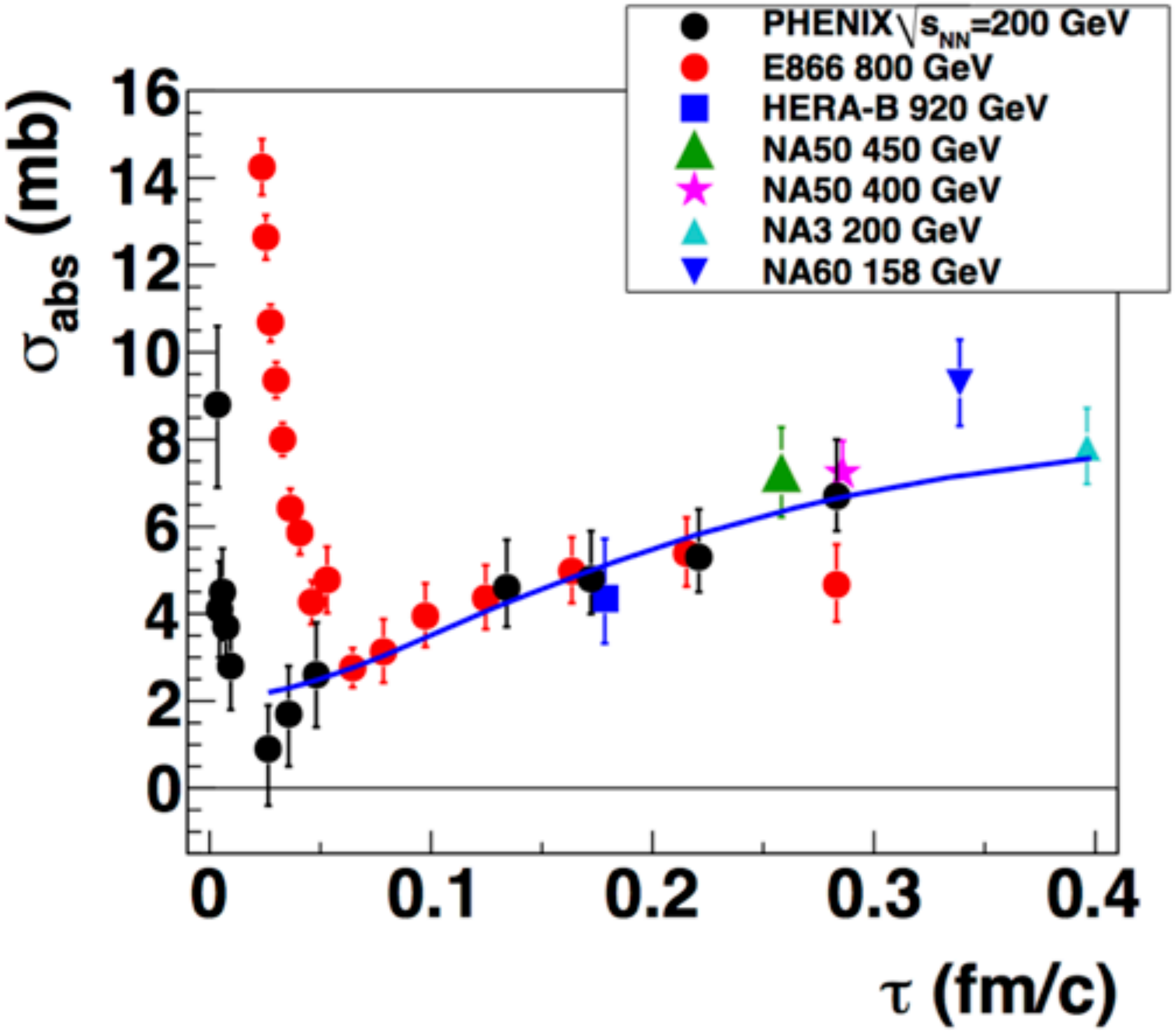
Scaling behavior at large τ is consistent with a model of a **color neutral charm pair** expanding inside the nucleus (**Arleo et al., Phys. Rev. C 61 (2000) 054906**) fitted to shadowing corrected data (McGlinchey et al., Phys.Rev. C87 (2013) 054910).

The fit has a χ^2/dof of about 1.0.

For $\tau > 0.05$ fm/c, backward rapidity data from 200 GeV collision energy show the same scaling with τ as the low energy data.

Backward rapidity has the highest particle multiplicity.

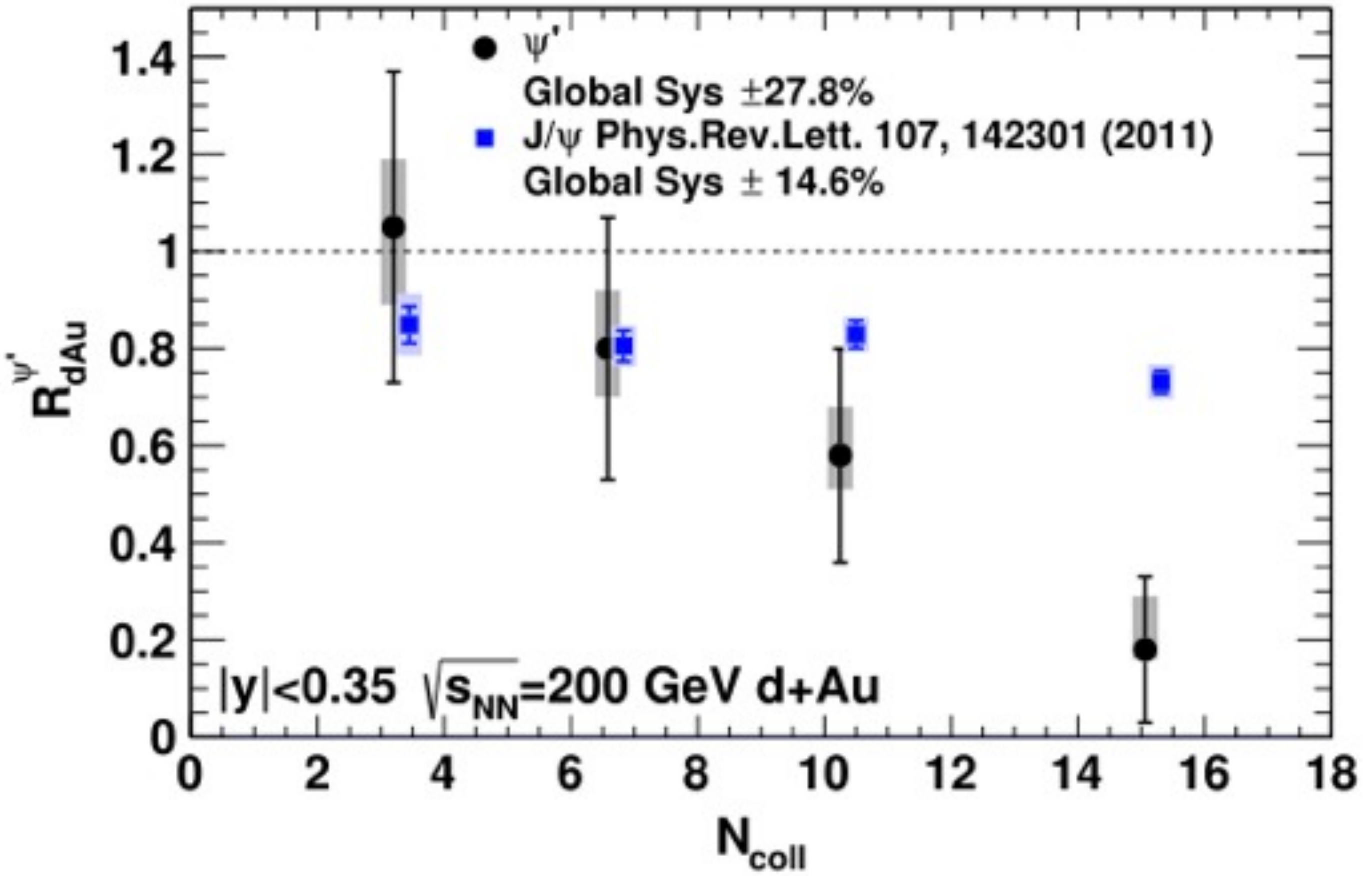
Implies little modification of inclusive J/ψ (60% J/ψ + 30% χ_c + 10% ψ').



Caveat - the J/ψ yield is not very sensitive to ψ’ feed-down

We have evidence of strong suppression of the ψ’ relative to the J/ψ in central d+Au collisions.

But the ψ’ feed down is only ~ 10%.



The ψ’ is more suppressed in d+Au at RHIC than lower energies, but the effect may be too small to notice by measuring inclusive J/ψ suppression.

And we do not know if the strong ψ’ suppression in d+Au collisions is caused by hot matter effects.

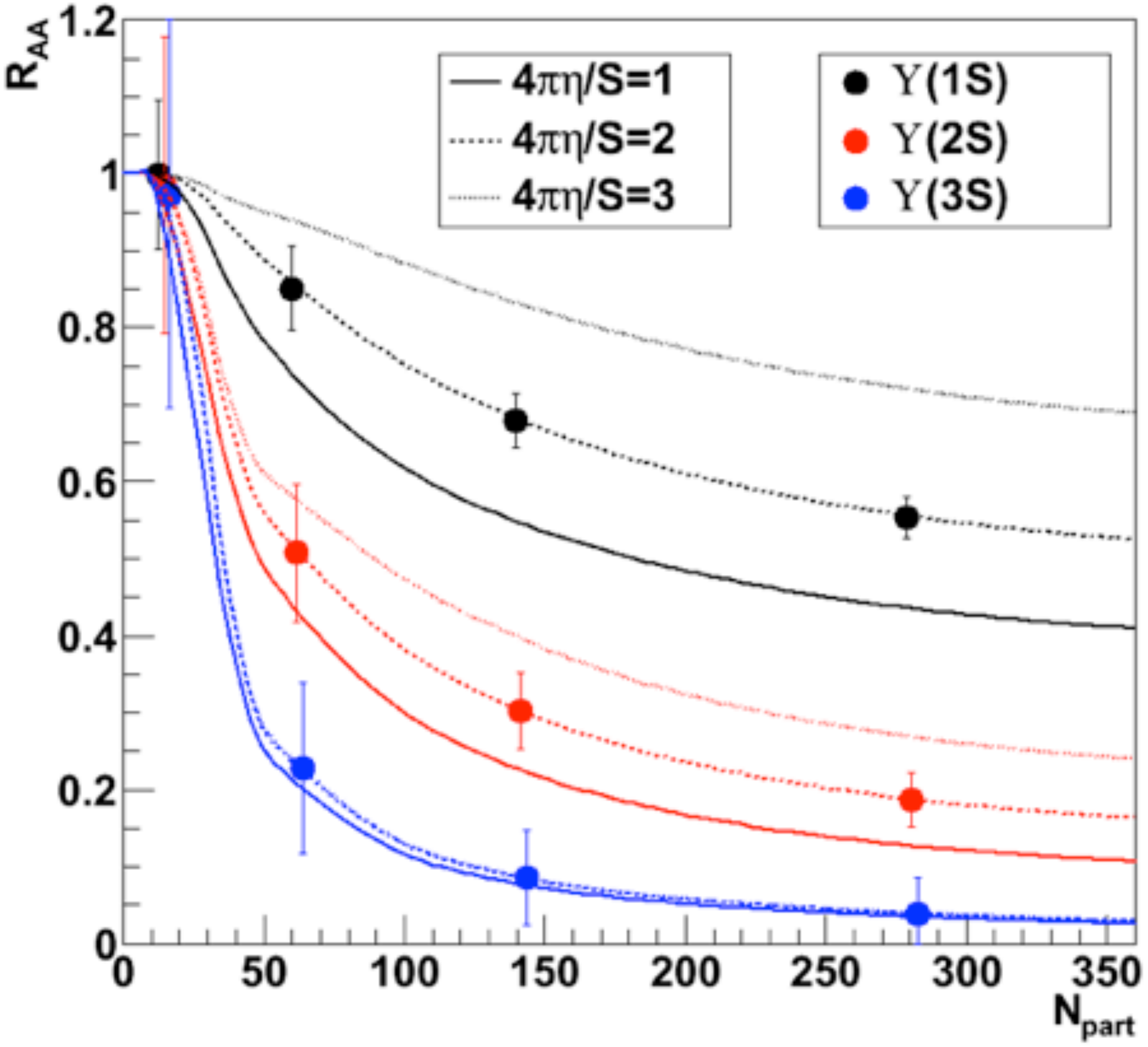
Backups

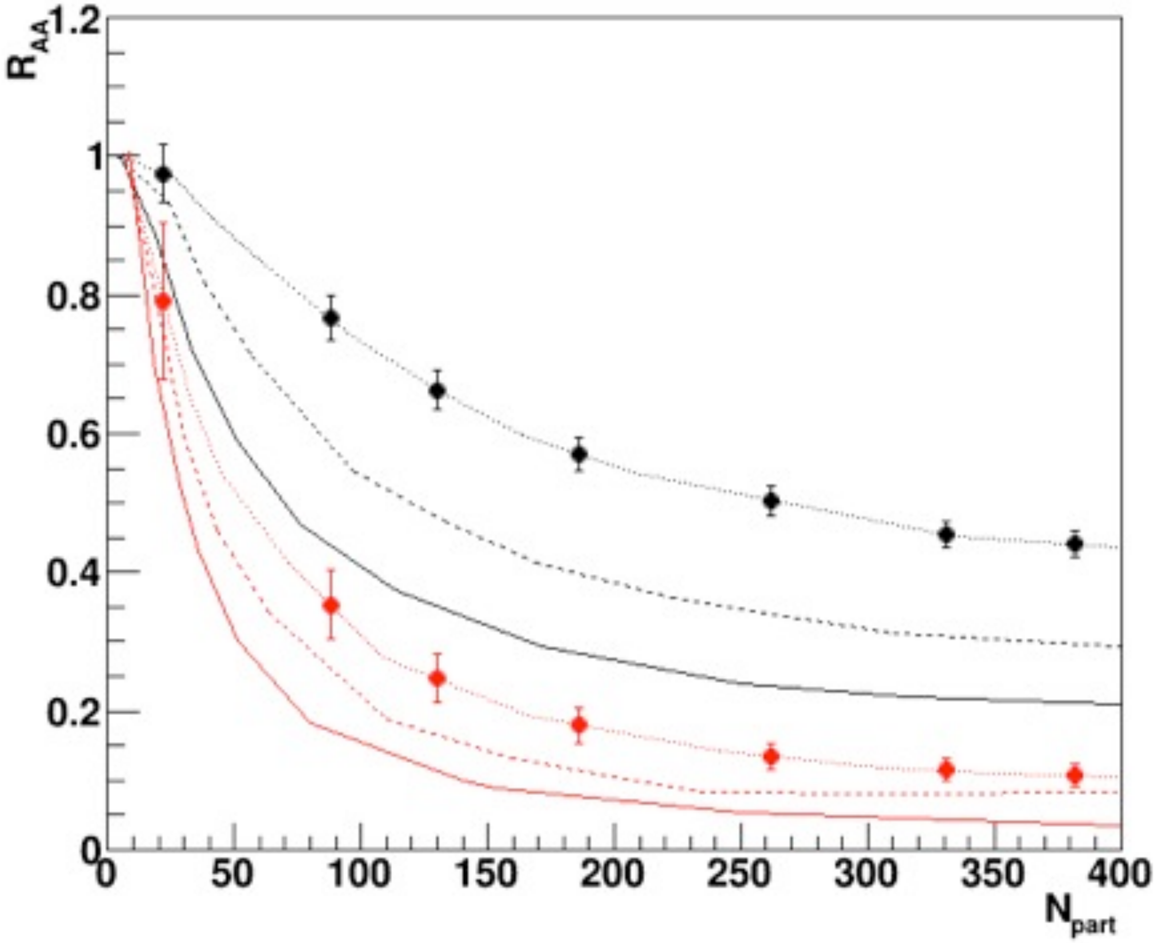
Tracking configuration

Layer	radius	Type	pixel/strip dimensions (µm x mm)	X resolution (microns)	Z resolution (mm)	θ resolution (mrad)	Thickness (% X/X_0)
B1	2.7	Pixel	50 x 0.425	15	0.12	4.8	1.3
B2	4.6	Pixel	50 x 0.425	15	0.12	2.4	1.3
S0a	9.5	strip	60 x 8	18	2.3	24.2	2.7
S0b	10.5	pattern recognition	240 x 2	70	0.58	5.5	
S1a	44.5	strip	60 x 8	18	2.3	5.5	2.0
S1b	45.5	pattern recognition	240 x 2	70	0.58	1.4	
S2	80	strip	60 x 8	18	2.3	3.1	2.0

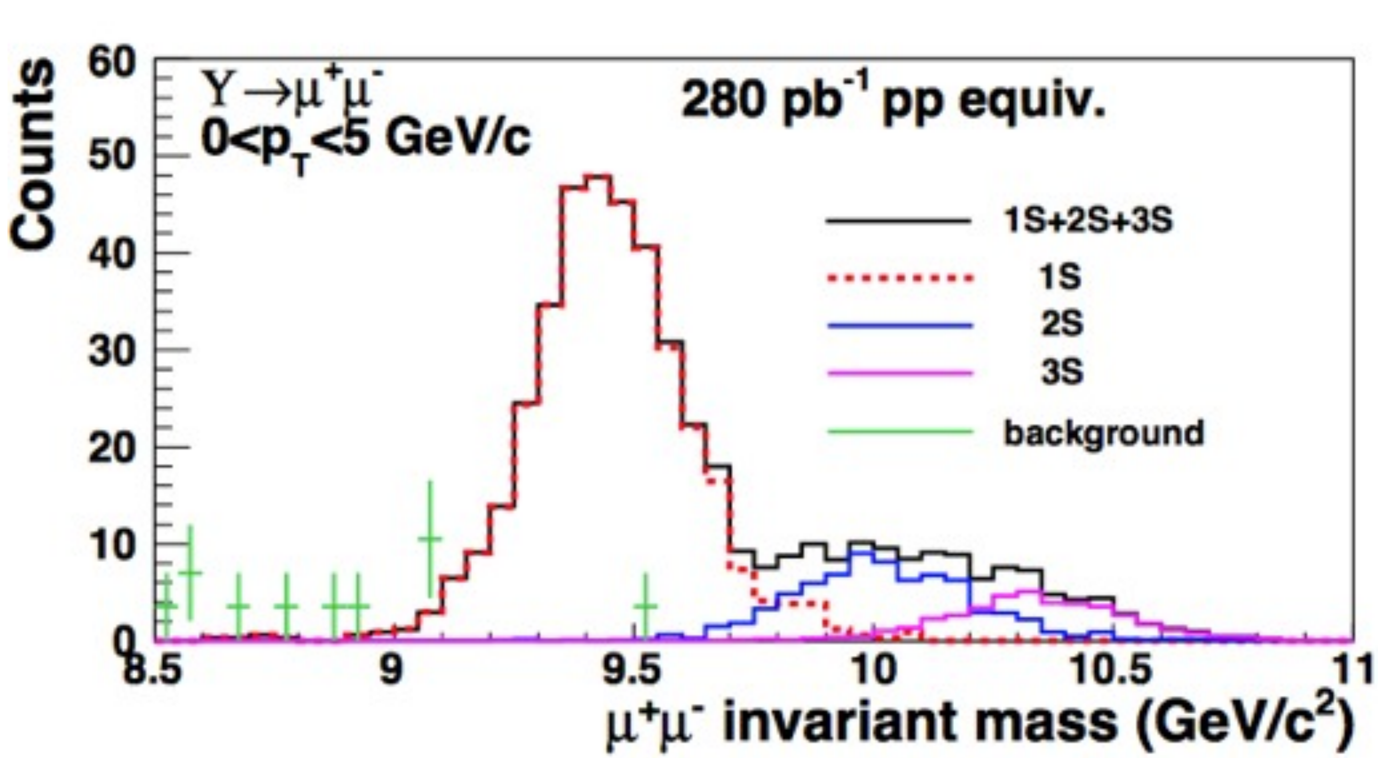
CMS sPHENIX comparison - 2023

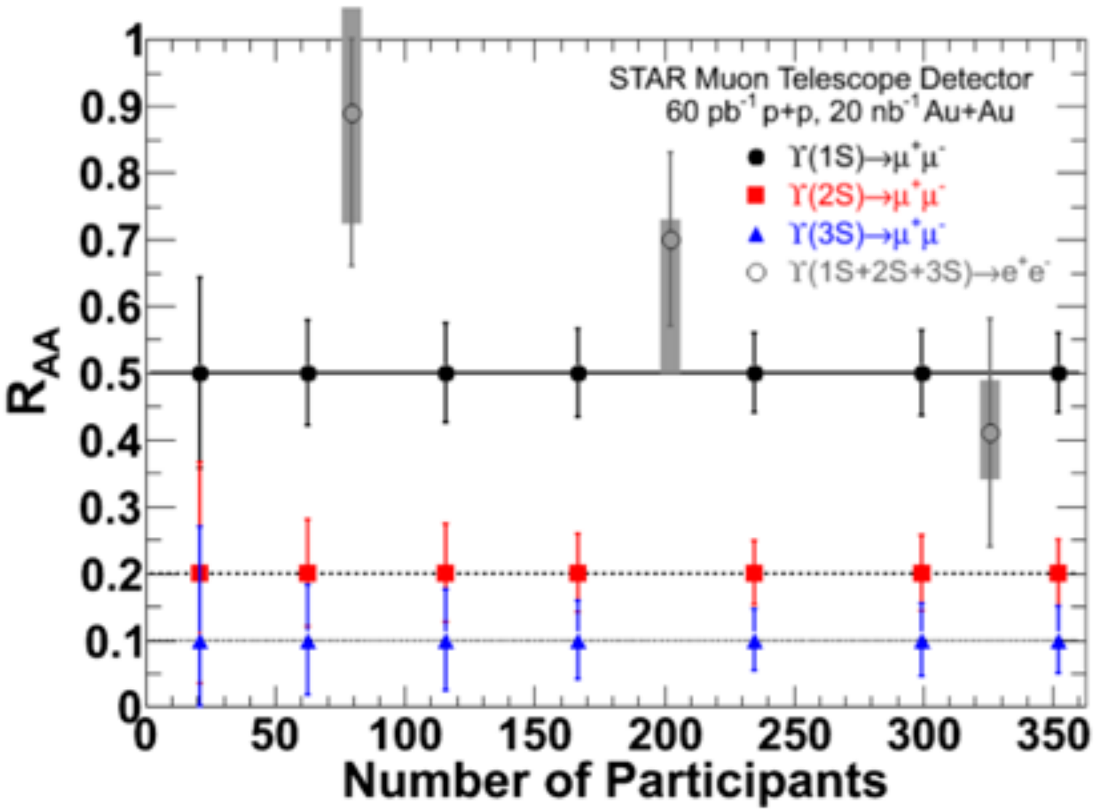
Expected statistical precision from CMS Upsilon measurements (below) and from sPHENIX (right) by 2023.





STAR MTD performance





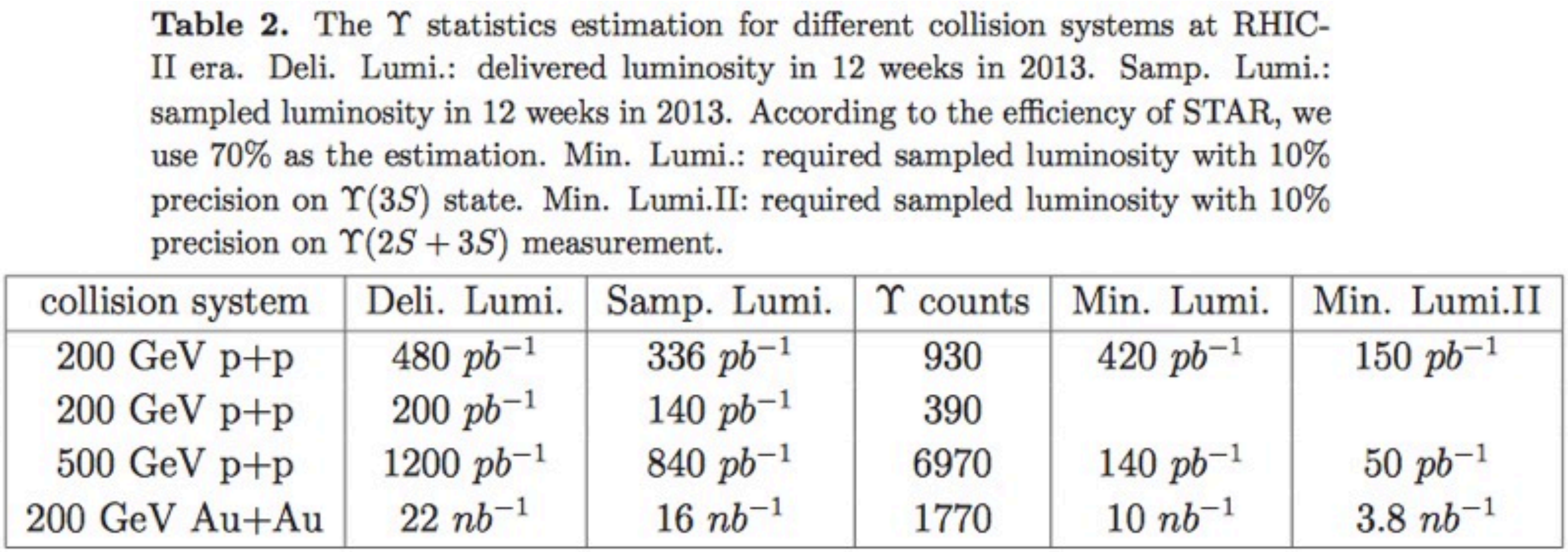


Table 2. The Υ statistics estimation for different collision systems at RHIC-II era. Deli. Lumi.: delivered luminosity in 12 weeks in 2013. Samp. Lumi.: sampled luminosity in 12 weeks in 2013. According to the efficiency of STAR, we use 70% as the estimation. Min. Lumi.: required sampled luminosity with 10% precision on $\Upsilon(3S)$ state. Min. Lumi.II: required sampled luminosity with 10% precision on $\Upsilon(2S+3S)$ measurement.

collision system	Deli. Lumi.	Samp. Lumi.	Υ counts	Min. Lumi.	Min. Lumi.II
200 GeV p+p	480 pb^{-1}	336 pb^{-1}	930	420 pb^{-1}	150 pb^{-1}
200 GeV p+p	200 pb^{-1}	140 pb^{-1}	390		
500 GeV p+p	1200 pb^{-1}	840 pb^{-1}	6970	140 pb^{-1}	50 pb^{-1}
200 GeV Au+Au	22 nb^{-1}	16 nb^{-1}	1770	10 nb^{-1}	3.8 nb^{-1}