Future Quarkonia Measurements at RHIC and LHC

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Introduction

Quarkonia measurements at the LHC and RHIC in the 2020's will be heavily impacted by accelerator and detector upgrades now underway.

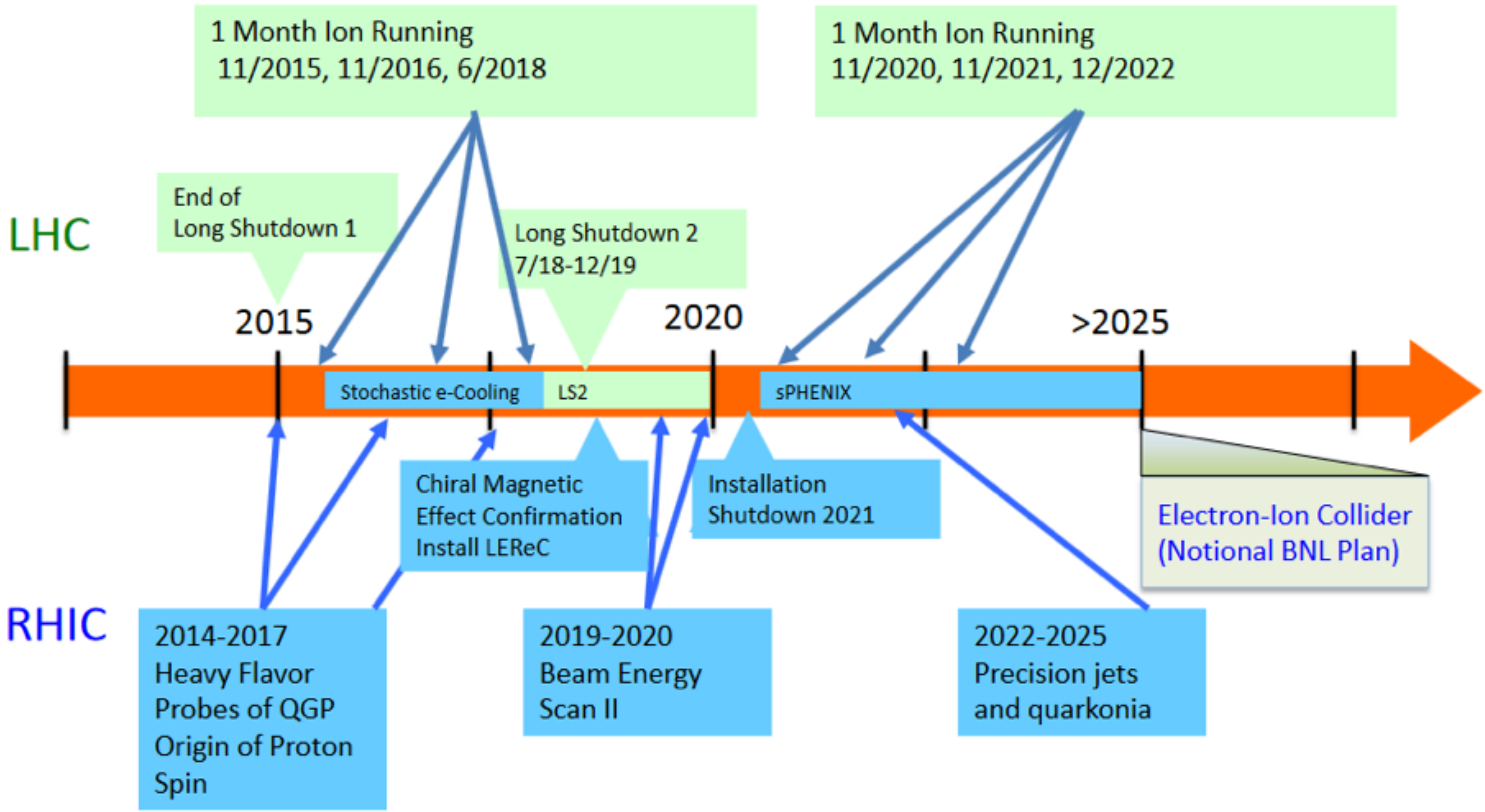
At RHIC, the sPHENIX detector is planned to start taking data in 2023. Luminosity upgrades are expected to produce Au+Au collision rates up to 200 kHz during sPHENIX running.

By 2021, LHC luminosity upgrades will increase the integrated Pb+Pb luminosity by an order of magnitude, and detector upgrades - particularly to ALICE - will allow the detectors to take advantage of the high luminosity.

I will review the prospects for quarkonia measurements in the 2020's.

- I will focus on Au+Au and Pb+Pb due to time constraints.

RHIC / LHC Timeline



This was shown by Tim Hallman of the DOE in 2016. It is a little dated now, but it shows the LHC and RHIC timelines together.

LHC Timeline (to 2029)

LHC Run	Years	Integrated Luminosity
2	2015-2018	1 nb^{-1}
(LS2)	2019-2020	Upgrades
3	2021-2023	6 nb^{-1}
(LS3)	2024-2026	Upgrades
4	2026-2029	7 nb-1

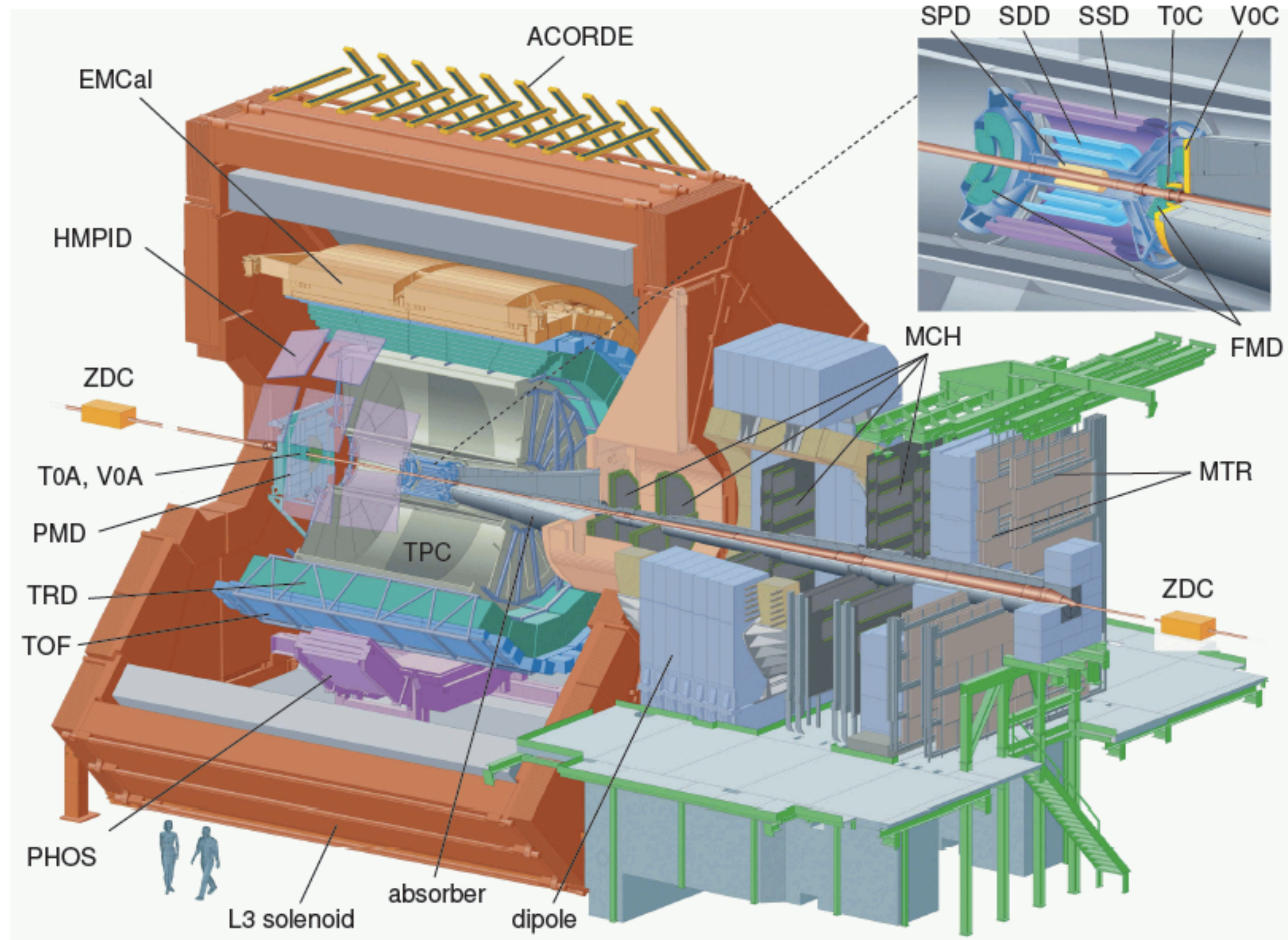
For ALICE Runs 3 & 4 total 10 nb^{-1} at full field + 3 nb^{-1} at reduced field

ALICE at the LHC

Quarkonia measurements:

Dimuons: $2.5 < y < 4$

Dielectrons: $|y| < 0.9$



For quarkonia, upgrades address:

Readout rate in central arm limits the MB data rate:

- Only triggerable HF signals fully sample the luminosity.

No displaced vertex capability at forward rapidity

- Can only measure inclusive quarkonia.

ALICE Upgrades in LS2 (2019-2020)

ITS upgrade - 7 layers of MAPS pixels ($|\eta| < 0.9$)
Improve track impact parameter resolution for HF decays.

Muon Forward Tracker - 3 layers of MAPS pixels ($2.5 < \eta < 3.5$)
Measure track impact parameter for HF muons.

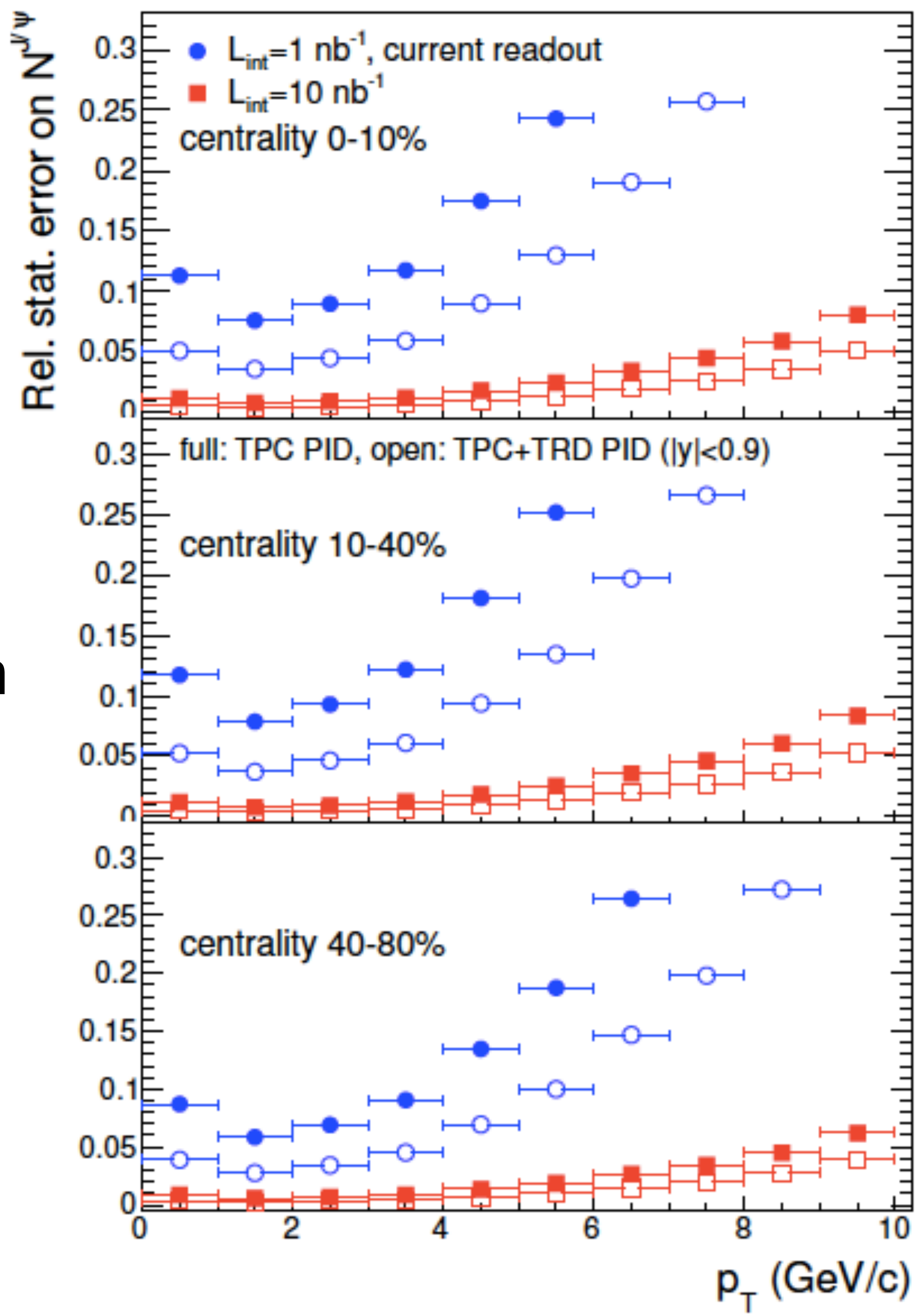
GEM readout chambers for TPC
Allow Pb+Pb continuous readout at up to 50 kHz (x100 increase).
Reduce space charge distortions.

Plus readout electronics, trigger and DAQ upgrades to enable recording of Pb+Pb collisions at 50 kHz.

The next few slides show some examples from the ALICE upgrade LOI (Abelev et. al. J. Phys. G: Nucl. Part. Phys. 41, 087001 (2014))

J/ψ R_{AA} precision - ALICE 10 nb^{-1}

Being able to record Pb+Pb MB data at 50 kHz in run 3 enables high statistical precision for signals that do not have a trigger.



Relative statistical error for J/ψ yield in Pb+Pb at mid rapidity with 10 nb^{-1} integrated (red).

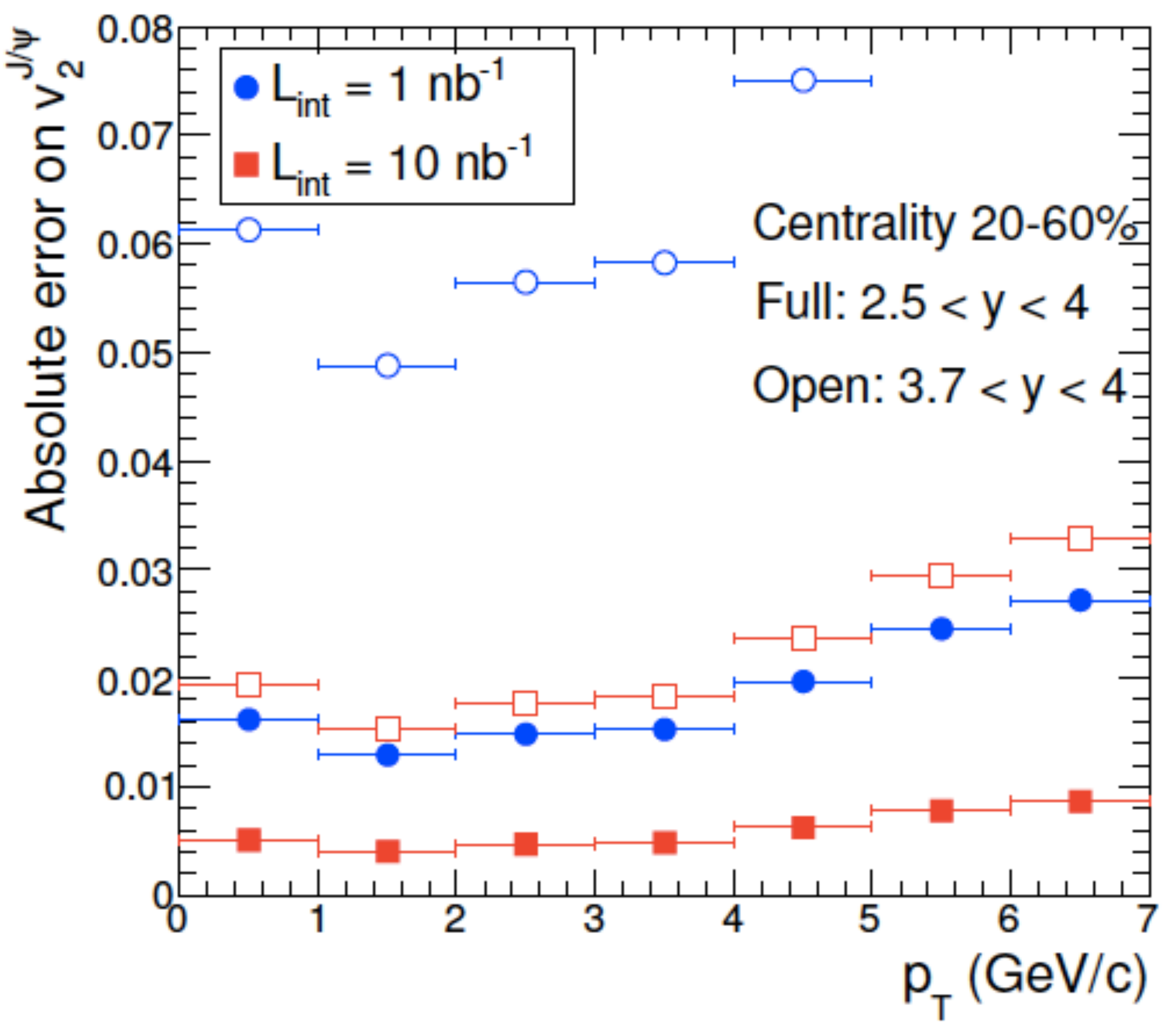
From upgrades to TPC readout and DAQ + luminosity.

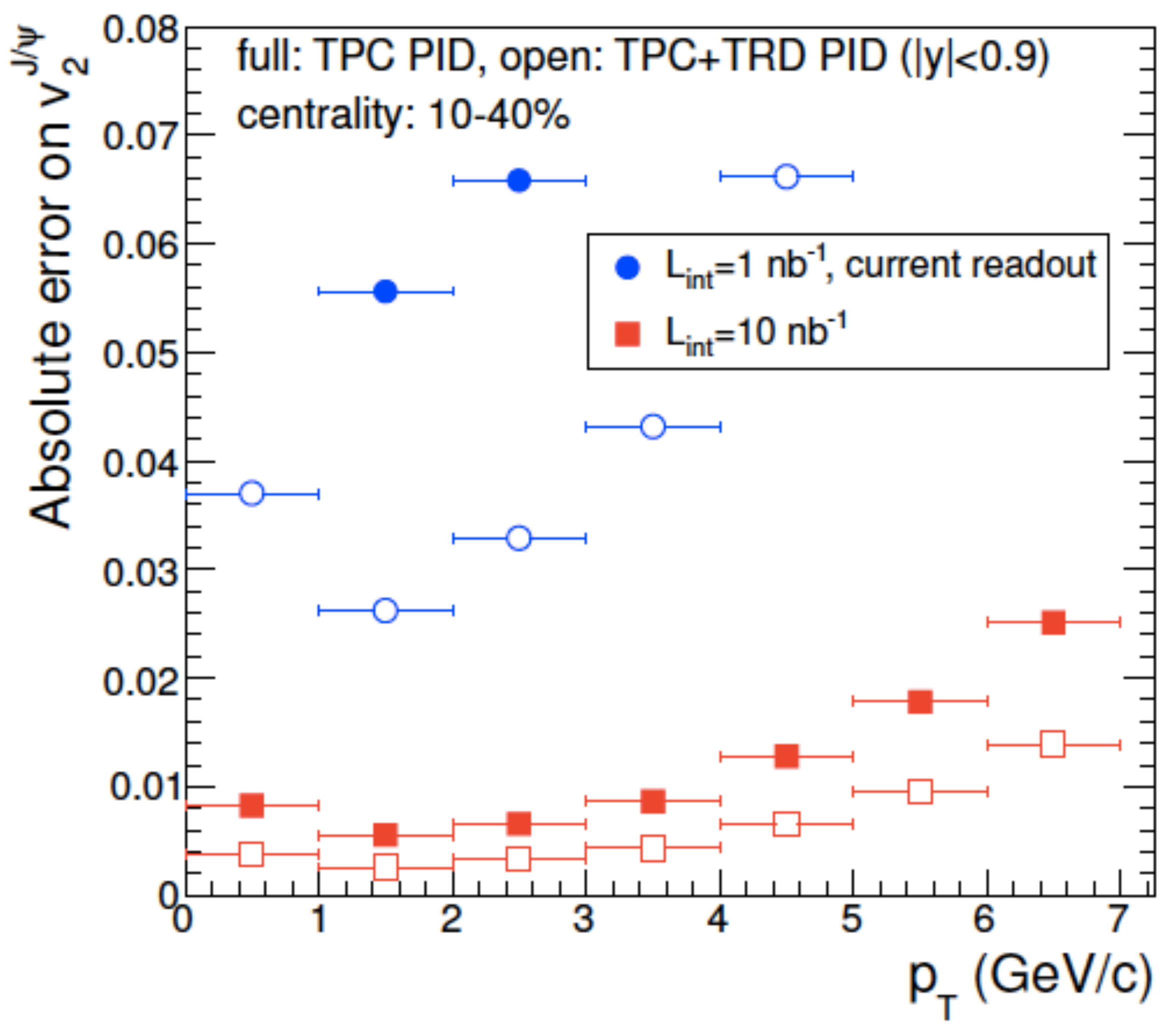
Improves precision by ~ order of magnitude at midrapidity.

J/ψ v_2 precision - ALICE 10 nb^{-1}

Statistical error for J/ψ v_2 in Pb+Pb with 10 nb^{-1} integrated (red).

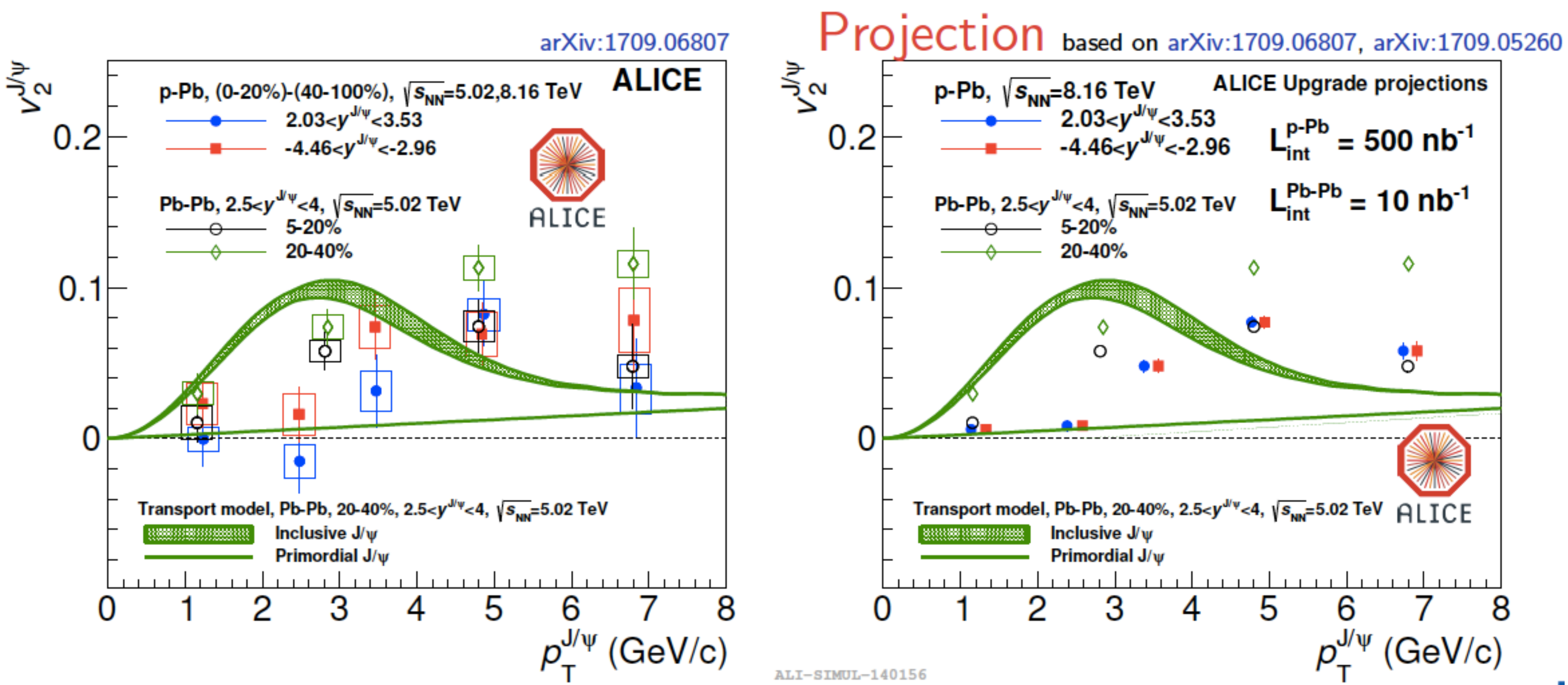
Mid rapidity (right) shows effect of TPC readout upgrades.
Both rapidities show effect of large integrated luminosity.





J/ψ v_2 precision - ALICE 10 nb^{-1}

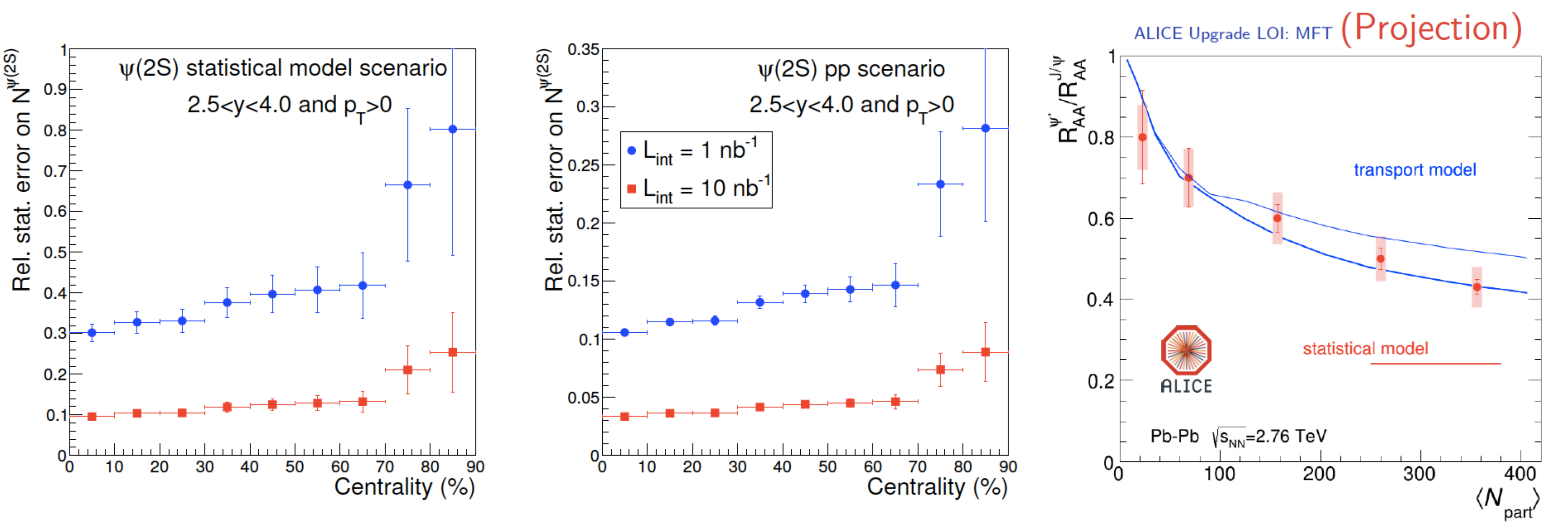
Statistical error for J/ψ v_2 in Pb+Pb with 10 nb^{-1} integrated (red).



Precision for ψ(2S) - ALICE 10 nb^{-1}

Statistical error for ψ(2S) in Pb+Pb with 10 nb^{-1} integrated (red).

Results from large MB data sample available with upgrades.

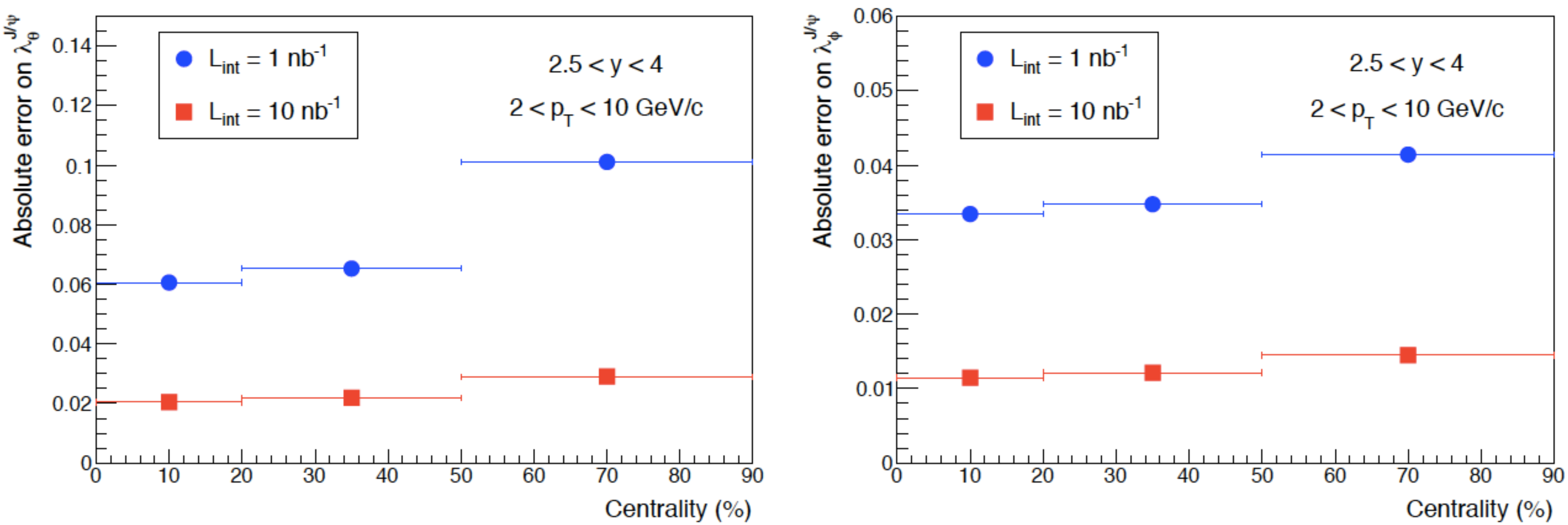


Also

- Forward MAPS detector enables separation of prompt J/ψ from non-prompt at forward y.

- ITS upgrade improves separation of prompt and non-prompt J/ψ at midrapidity.

- Improved J/ψ polarization measurement at forward rapidity.



CMS Upgrades

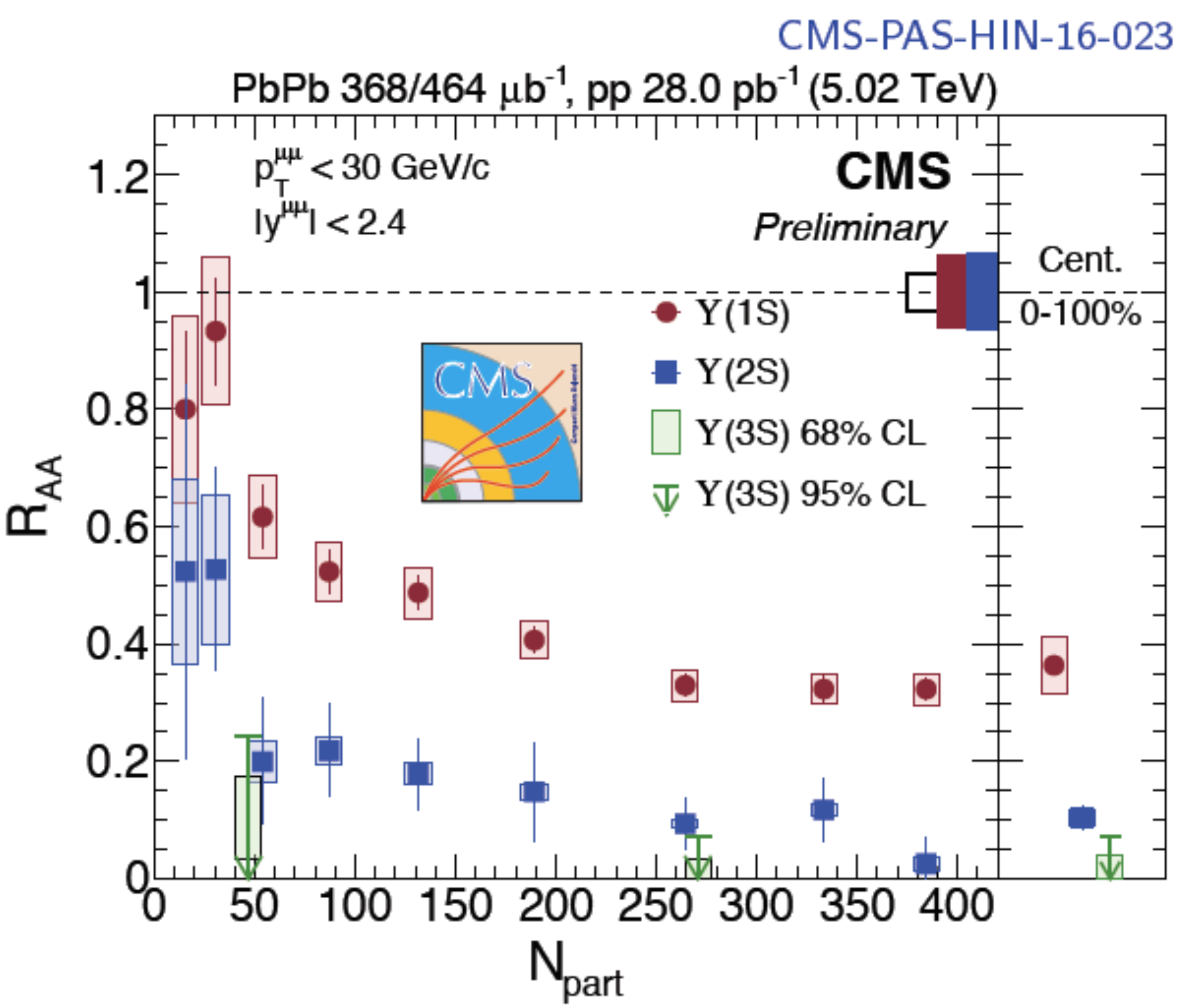
Upgrades to improve triggers, bandwidth, efficiency. Include:

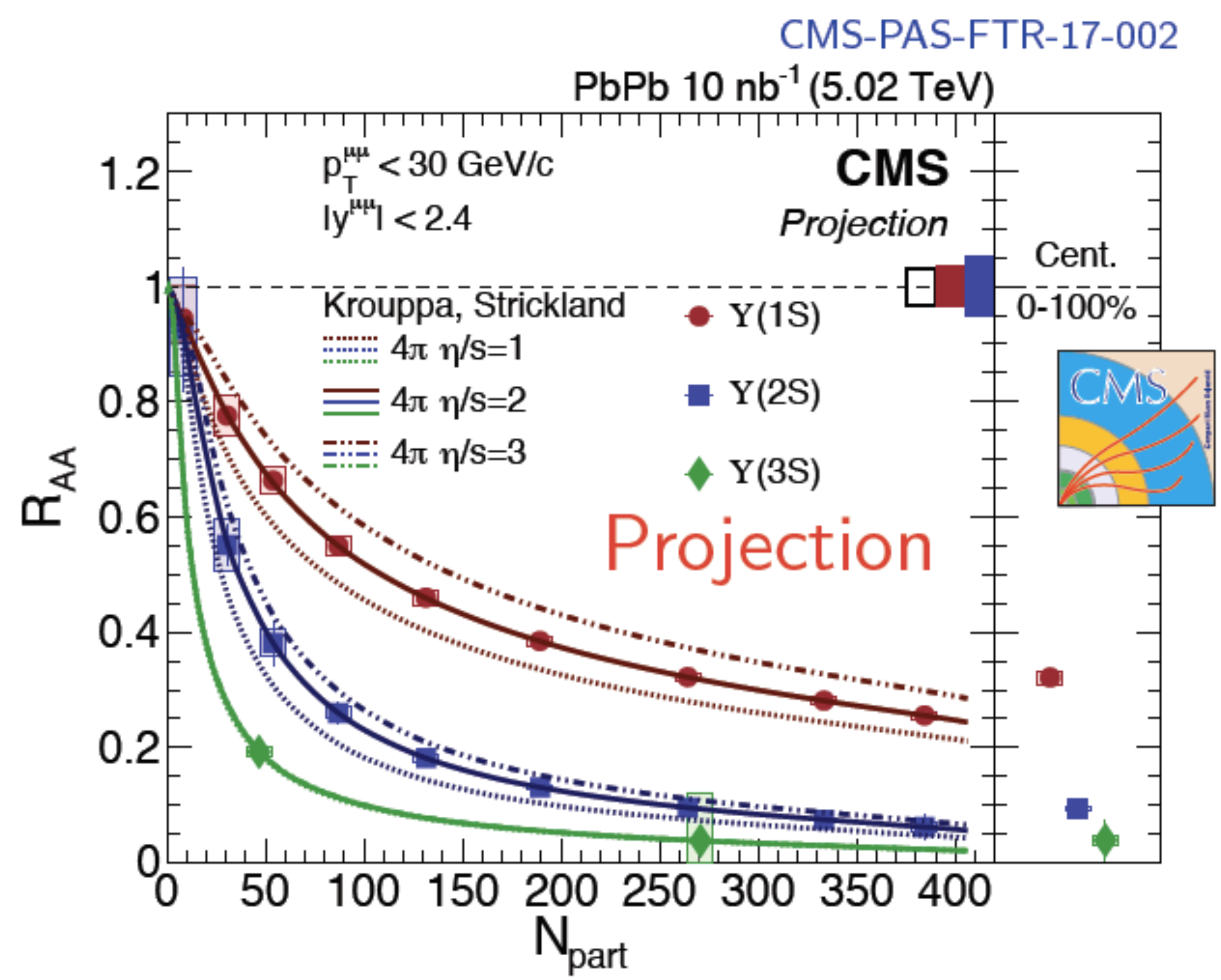
- Upgrade to a 4-layer pixel system
  - Improves tracking efficiency in high multiplicity
- Upgrade of the inner tracker
- Trigger upgrade
- Upgrade of the data acquisition system

These allow CMS to take full advantage of the high luminosity in Run 3 and Run 4.

Impact of CMS Upgrades on Quarkonia

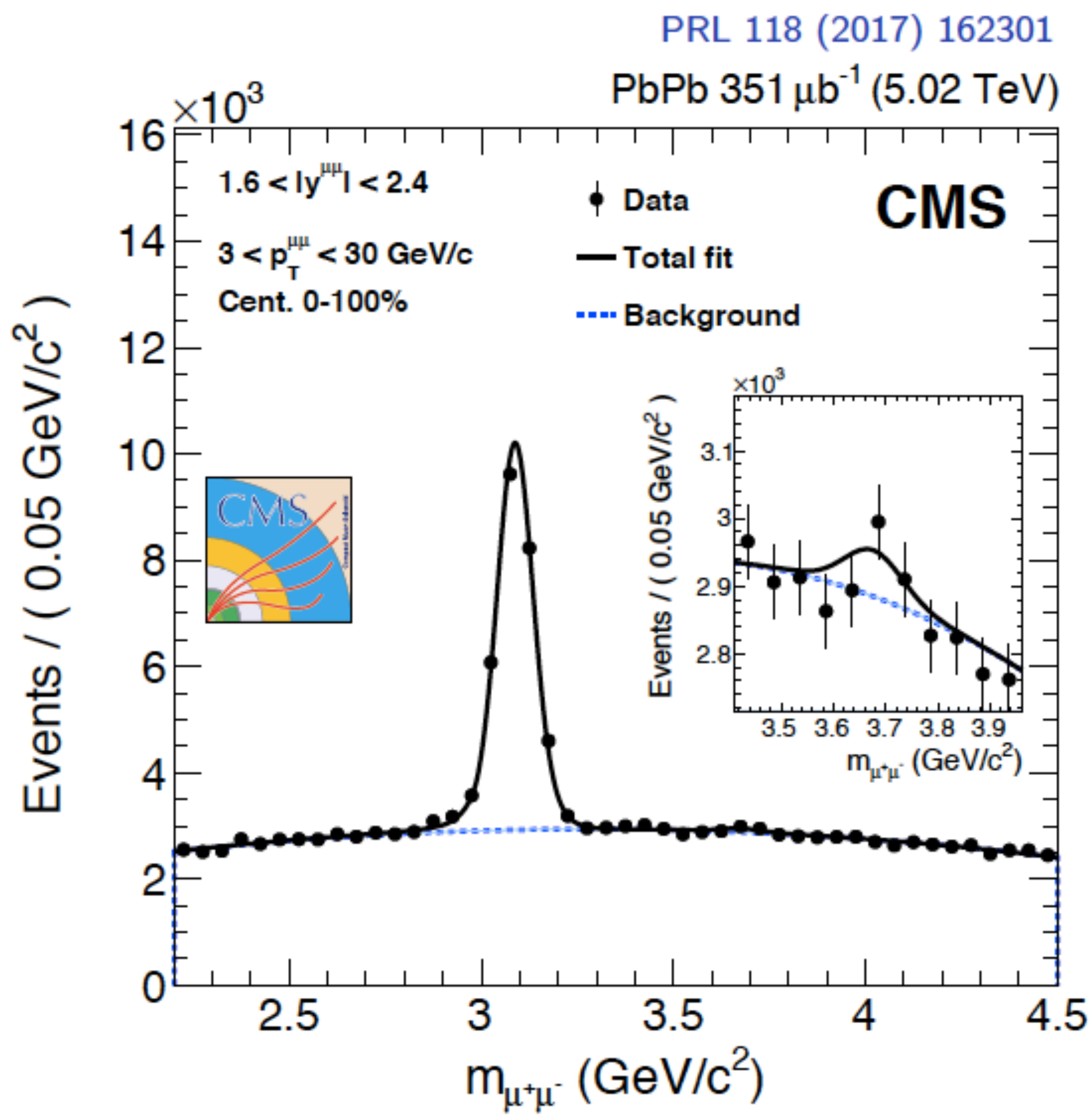
For an integrated luminosity of 10 nb^{-1}, the yield for the Upsilon states in Pb+Pb collisions will increase by ~ 30 over the 5.02 TeV.

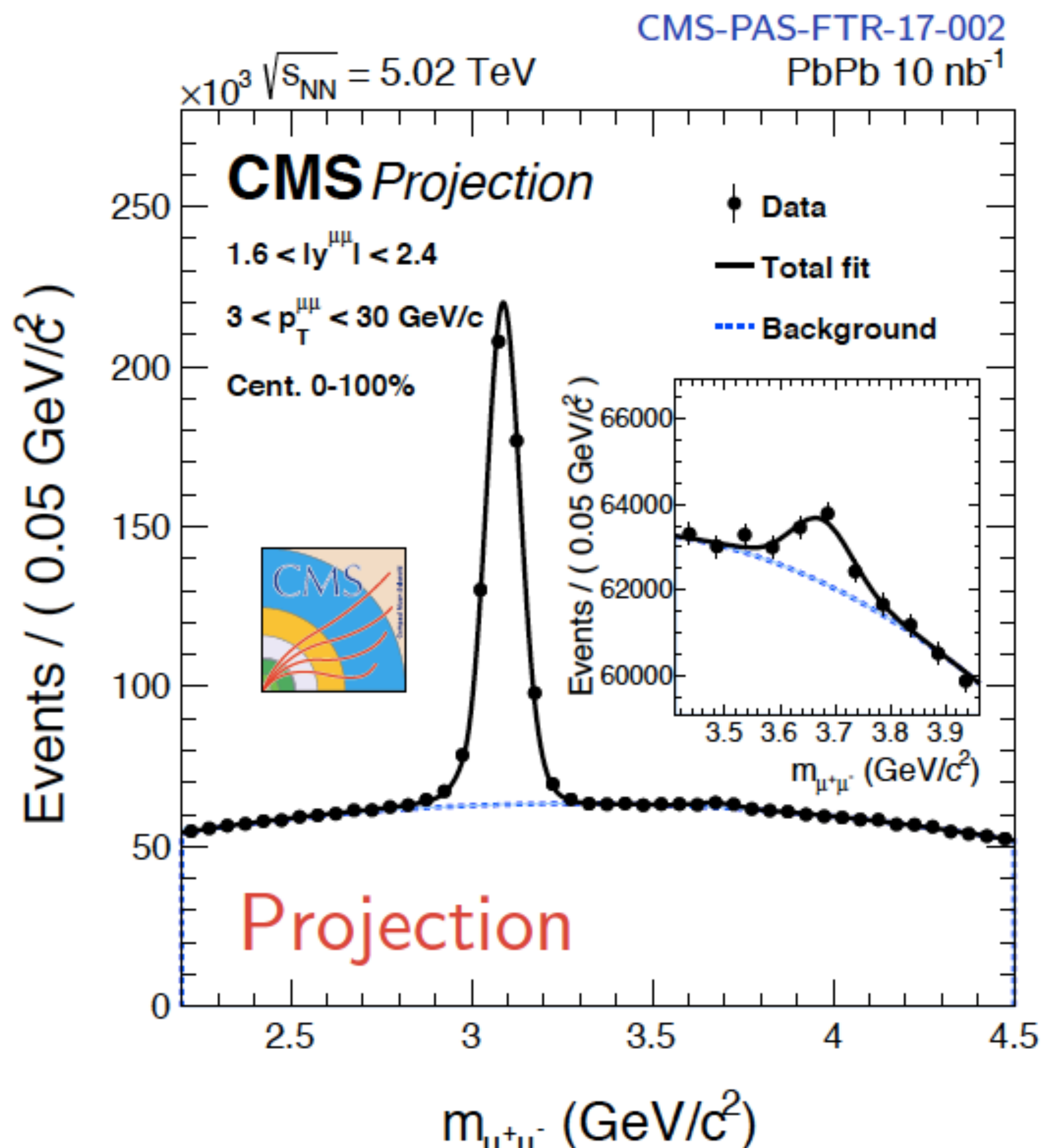




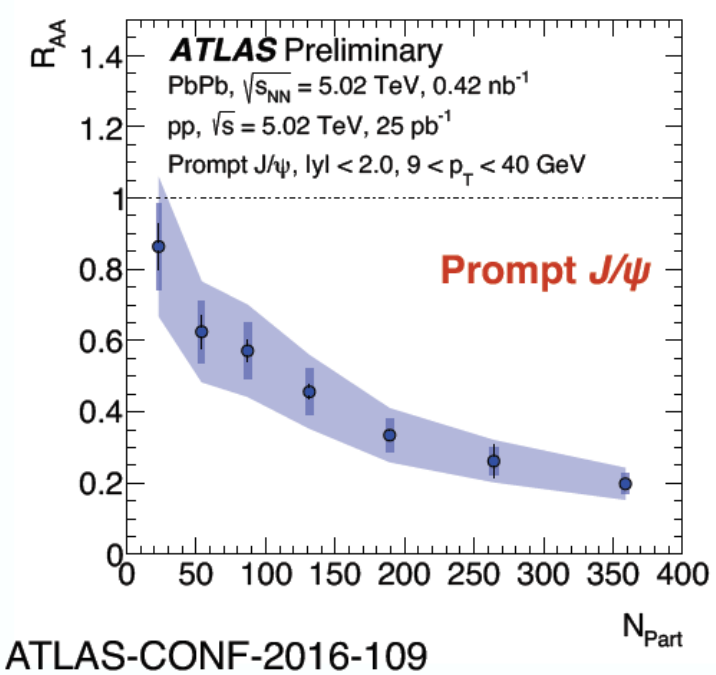
Impact of CMS Upgrades on Quarkonia

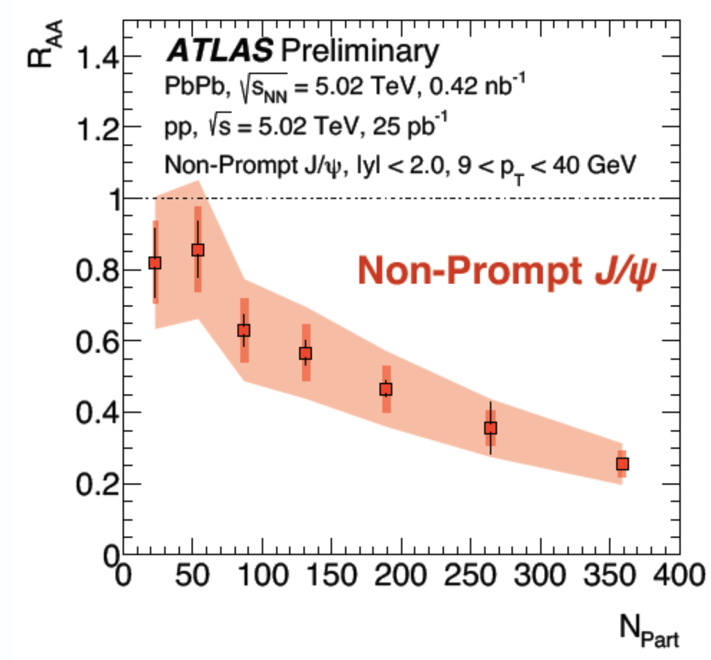
Major improvement in the precision of ψ(2S) measurements in Pb+Pb collisions (pT > 3 GeV/c).



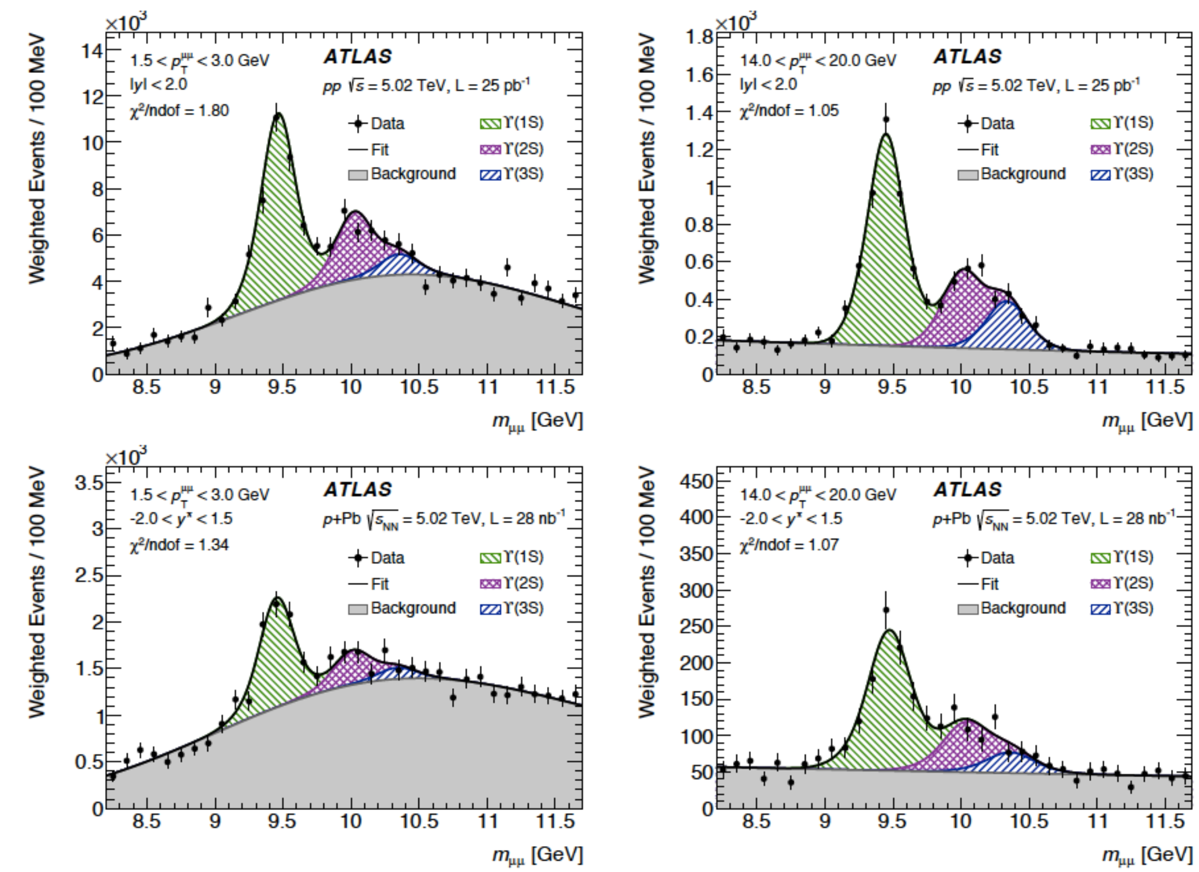


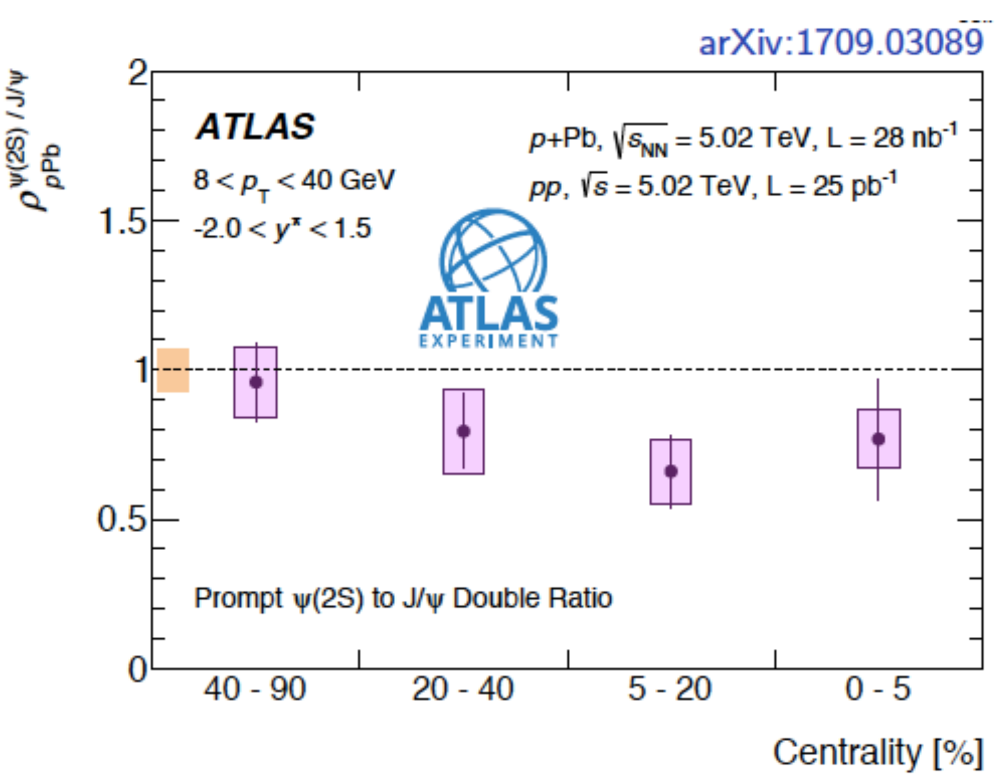
ATLAS Quarkonia

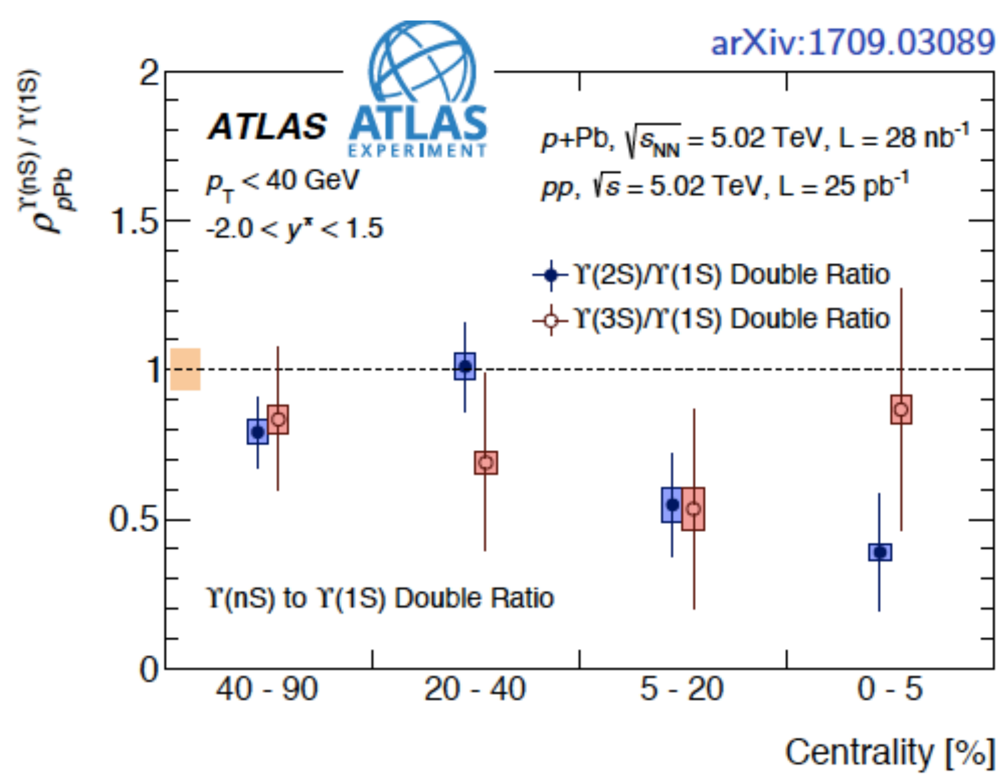




ATLAS-CONF-2016-109







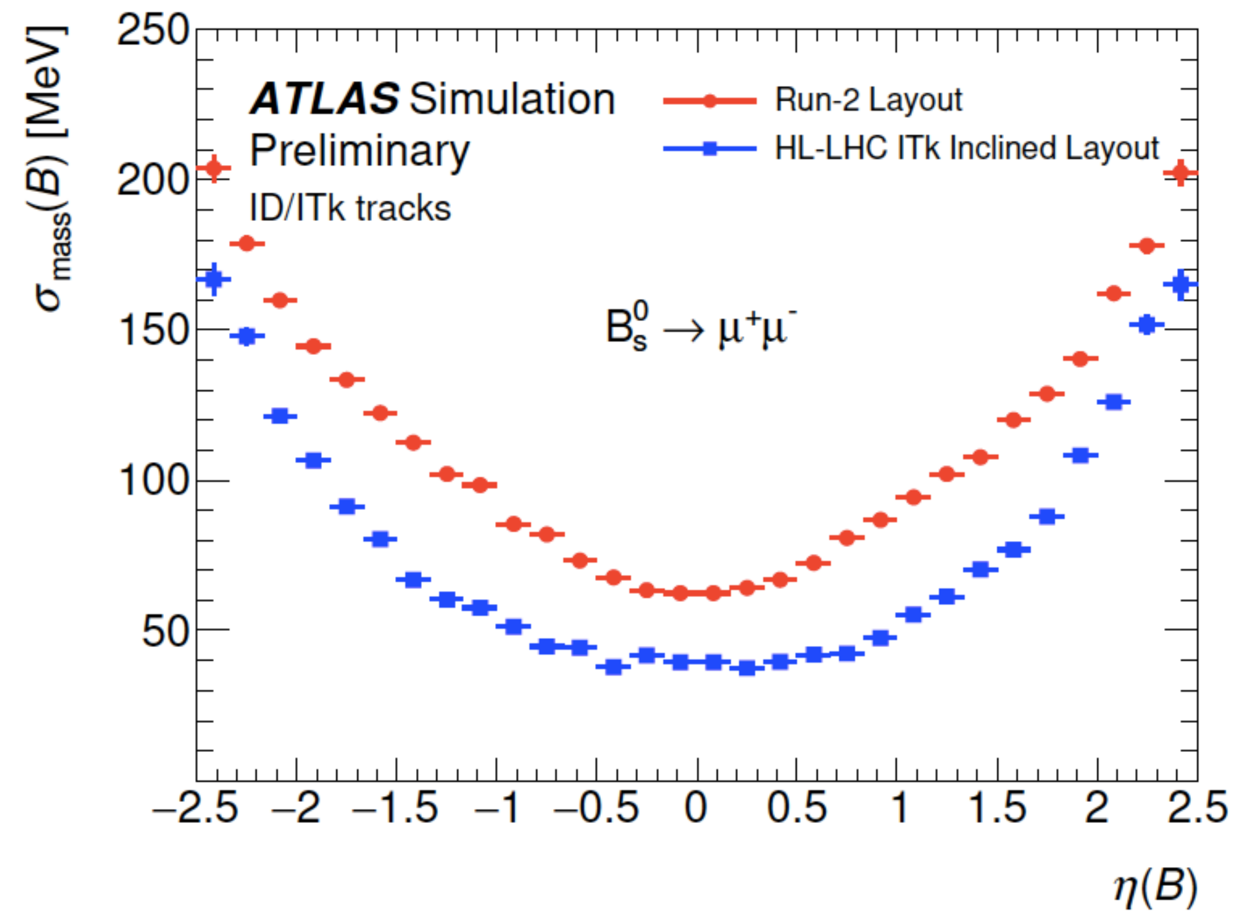
Impact of ATLAS Upgrades on Quarkonia

LS2:

Fast Tracking Trigger (high multiplicity tracking)

Muon trigger upgrades

- Improved triggering for muons
- Extend J/ψ p_T down to 6 GeV/c



LS3:

New inner tracking detector

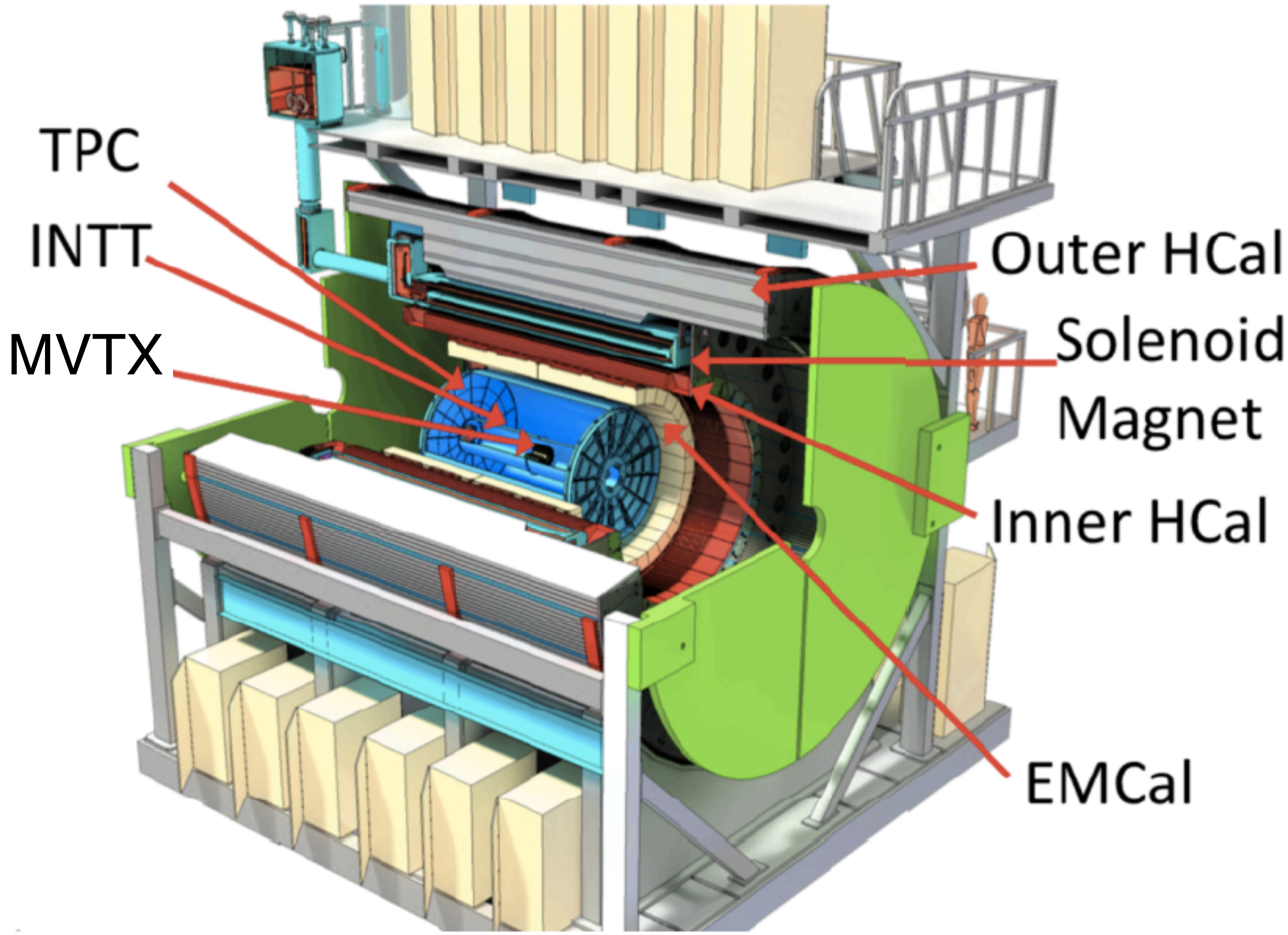
- Extends tracking to η = 4.0
- Improves track p_T resolution to ~ 1% for |y| < 1 and p_T < 20 GeV/c.
  - Big improvement in Upsilon mass resolution.
  - Example plot shows improvement for dimuon mass from B decay.

sPHENIX at RHIC

Goal: Compact, state of the art jet detector at RHIC

Physics program aimed at:
- Jets
- HF tagged jets
- Upsilons

Hermetic detector covering
-1.1 < η < 1.1
- EM Calorimeter
- Hadronic calorimeter
- Precise vertexing
  - MAPS pixel inner barrel
- Precise tracking
  - intermediate Si strips
  - Compact TPC outer tracker



Uses BABAR superconducting solenoid (1.4 T)
Recording rate for Au+Au collisions = 15 kHz

Received CD0 in late 2016

sPHENIX at RHIC - Upsilons

The Upsilon measurement uses dielectron decays and requires:

Good momentum resolution

- Need $\Delta p_T/p_T < 1\%$ (3-10 GeV/c)
- The Upsilon measurement is the driver for tracking performance.

Electron ID

- Use energy measurement from EMCal/HCal for E/p.
- No other particle ID planned at the moment.

Low mass tracking (to limit radiative tails).

High tracking efficiency in central Au+Au collisions.

TPC Tracker - some comments

Continuous readout TPC.

At 200 kHz Au+Au rate, the maximum drift time of 35 μs means the TPC contains hits from an average of 3.5 "pileup" collisions before and after the triggered event.

- BUT: the Si strip intermediate tracker can resolve a single beam crossing

Controlling space charge distortions of the primary ionization drift path is important

- Requires minimizing ion back flow from the readout.
  - Compromise with dE/dx performance.
- Geometric design of TPC can help a lot!
  - Inner field cage at 20 cm, readout only for > 30 cm.
- Simulations include estimates of precision, accuracy of corrections

Luminosity Projections (& a run scenario)

Year	Species	Physics weeks	Recorded MB Luminosity IZI < 10 cm	Sampled Luminosity IZI < 10 cm	Sampled Luminosity All Z
2023	Au+Au	16	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
2024	p+p	11.5		48 pb^{-1}	267 pb^{-1}
2024	p+Au	11.5		0.33 pb^{-1}	1.46 pb-1
2025	Au+Au	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
2026	p+p	23.5		149 pb^{-1}	783 pb^{-1}
2027	Au+Au	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

Luminosity Totals - All Runs Together

Luminosity totals by species for the run scenario on the previous slide.

Species	Recorded MB Luminosity IZI < 10 cm	Sampled Luminosity IZI < 10 cm	Sampled Luminosity All Z
Au+Au	35 nb^{-1} (240 B MB events)	80 nb^{-1} (550 B MB events)	214 nb^{-1} (1.5 T MB events)
p+p		197 pb^{-1}	1.0 fb^{-1}
p+Au		0.33 pb^{-1}	1.46 pb^{-1}

Luminosity Totals - All Runs Together

Luminosity totals by species for the run scenario on the previous slide.

For Upsilons, the MVTX is not required, so may be able to use the sampled luminosity in wider Z range with an Upsilon trigger.

Species	Recorded MB Luminosity IZI < 10 cm	Sampled Luminosity IZI < 10 cm	Sampled Luminosity All Z
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sPHENIX Upsilon Capability

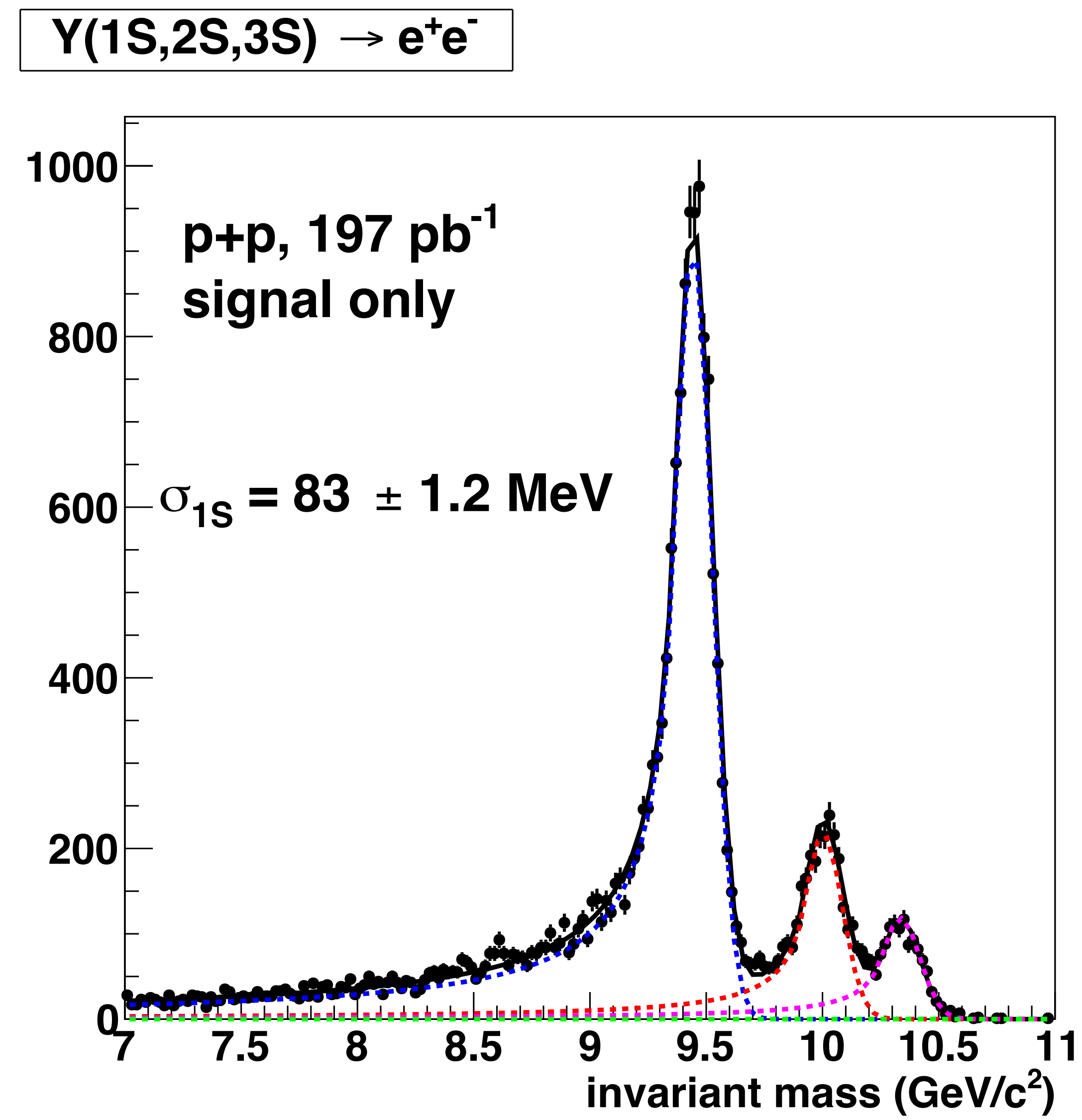
Use dielectron decay channel $\Upsilon \to e^+e^-$

- Mass resolution from tracking < 90 MeV in pp
- Hadron rejection via E/p (only) using EMCal / HCal

Use of electrons results in some radiative tailing, but the inner tracker mass is only ~ 5% of X_0 and the TPC is a very thin tracker.

- Tailing is not so bad.
- Fit with line shapes.

The plot shows the expected (signal only) mass spectrum for the total p+p luminosity, sampled inside |Z| < 10 cm.



In central Au+Au collisions the mass resolution degrades, but is still below 100 MeV.

sPHENIX Upsilon Capability

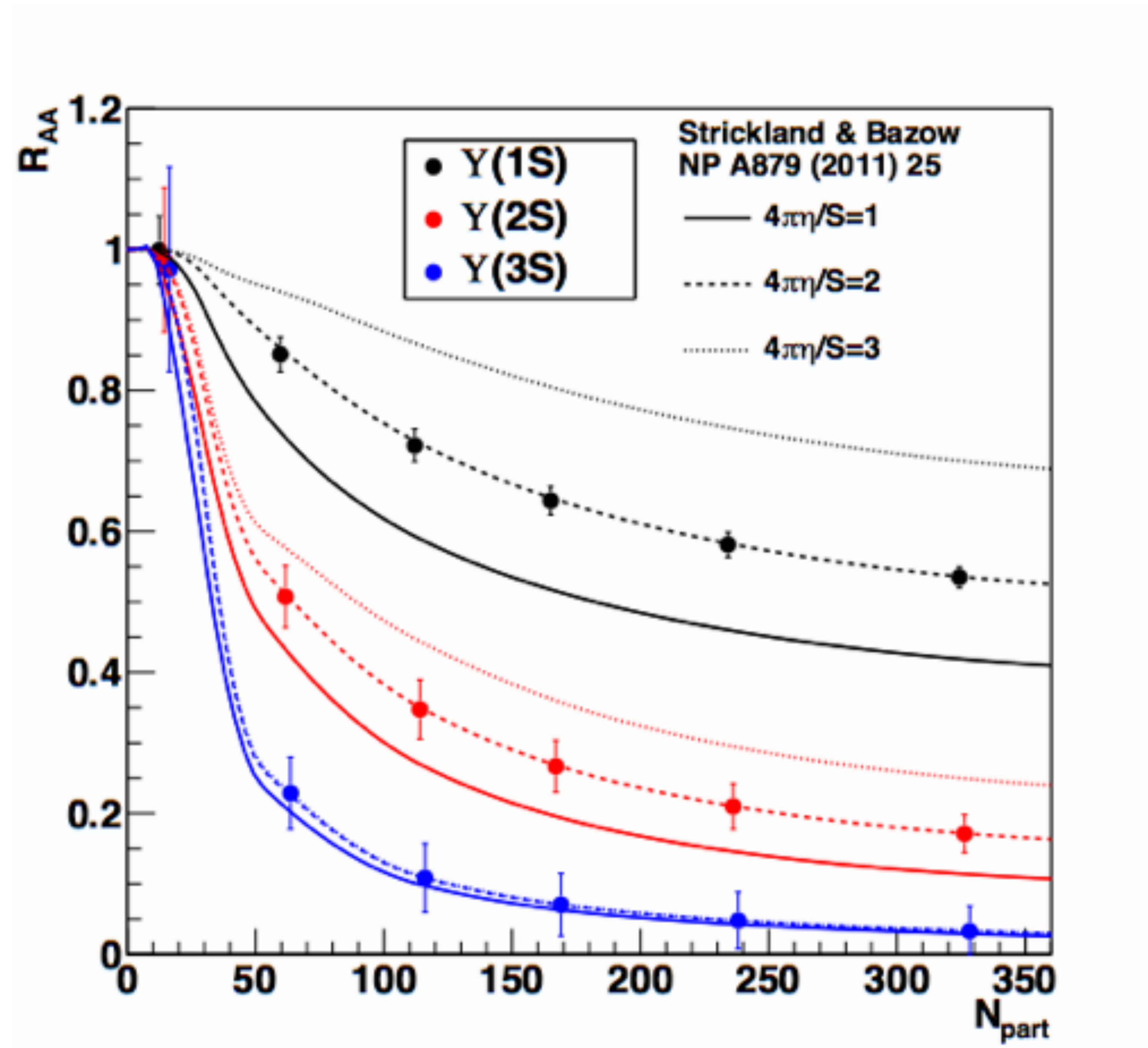
Plot from the sPHENIX proposal.

Shows precision of R_{AA} vs number of participants for the best estimate of the background at the time, using the best estimate of the luminosity at the time.

Since then, the expected luminosity has gone up by over a factor of two.

But so has the estimated background ….

This mostly affects the Υ(3S) precision, which was overly optimistic.



Status of simulations

There has been an ongoing effort to improve the realism of the sPHENIX Upsilon simulations. This effort follows on from:

- Evolution of the RHIC working run plan
- Increased maturity of the detector design (especially tracking)
- A major upgrade of the sPHENIX tracking simulations and software

Included in this effort:

- Increased luminosity in line with present thinking about the run plan.
- A more careful evaluation of the backgrounds that affect the Upsilon measurement.
- Extraction of Upsilon yields using Crystal Ball fits to simulated data with realistic backgrounds and suppression of all states.

Upsilon background estimates

Backgrounds arise from combinatorial association of:

- Hadrons misidentified as electrons
- Single electrons from heavy flavor decays

There are also backgrounds due to correlated electron pairs from:

- Heavy flavor (HF) decays
- Drell Yan

The correlated HF pair backgrounds, HF single electrons and Drell Yan yields are obtained from PYTHIA 6, with cross sections tuned using HF data (PHENIX, Phys.Rev. C96 (2017) no.2, 024907).

The misidentified hadron spectrum is generated using a full GEANT IV simulation of sPHENIX to evaluate the hadron rejection power of E/p cuts that lead to 90% electron acceptance.

Hadron Rejection from E/p

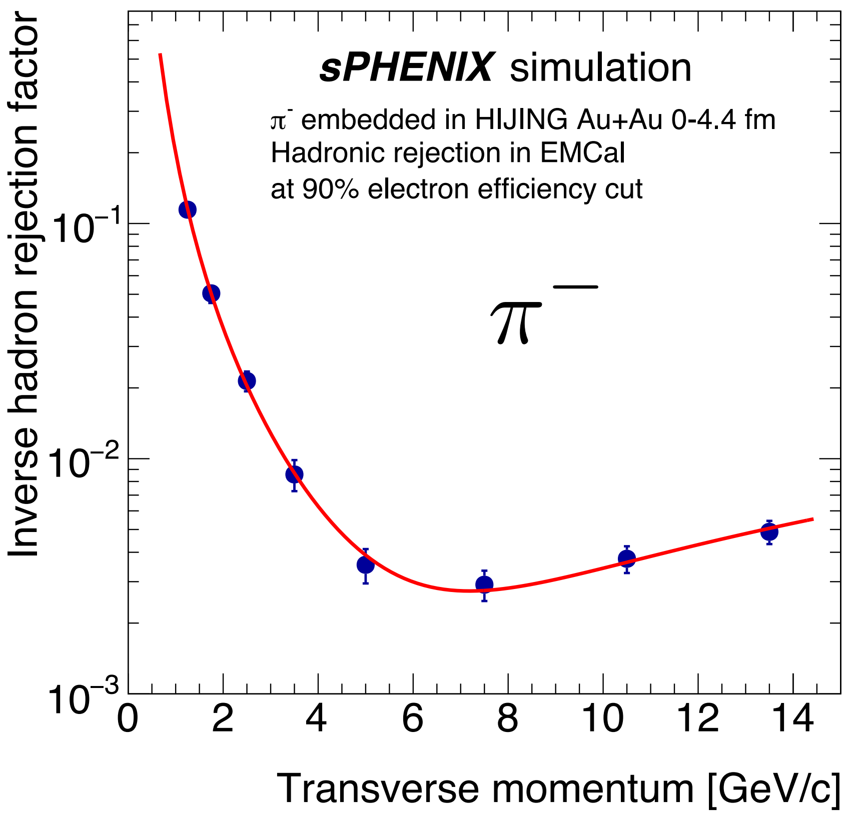
Inverse hadron rejection factors for 90% eID efficiency.

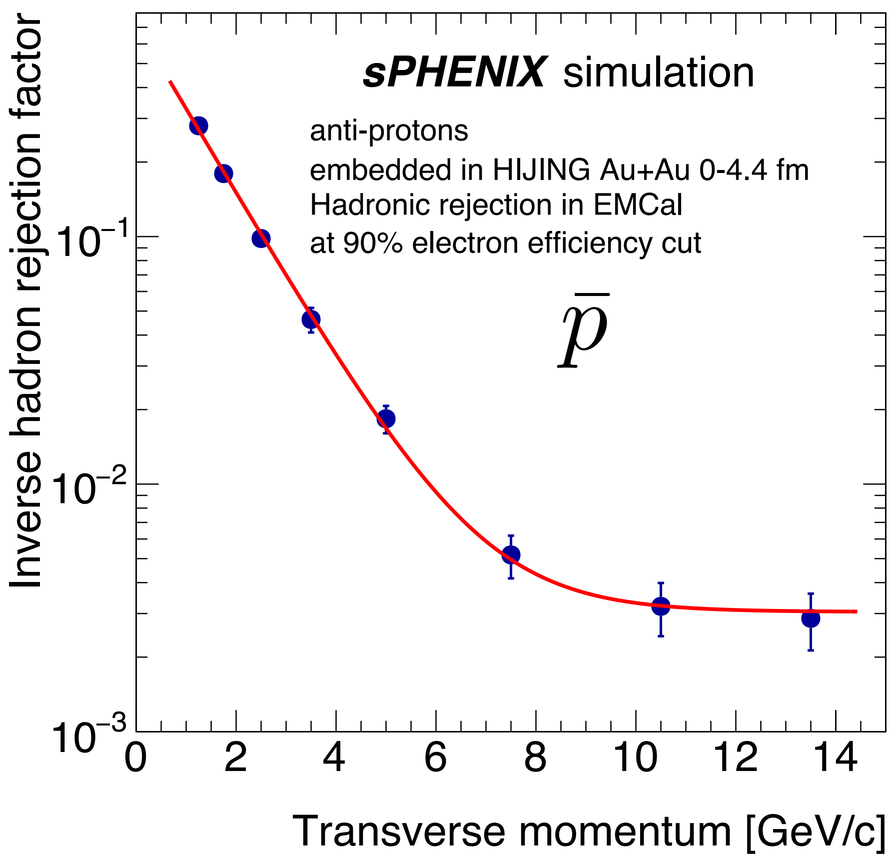
From GEANT IV simulation of:
- Tracking
- EMCal
- HCal

Studied for
- pions, kaons, protons, antiprotons

Examples shown for pions, antiprotons.

The antiproton background is significant, and was not included in the original estimates.



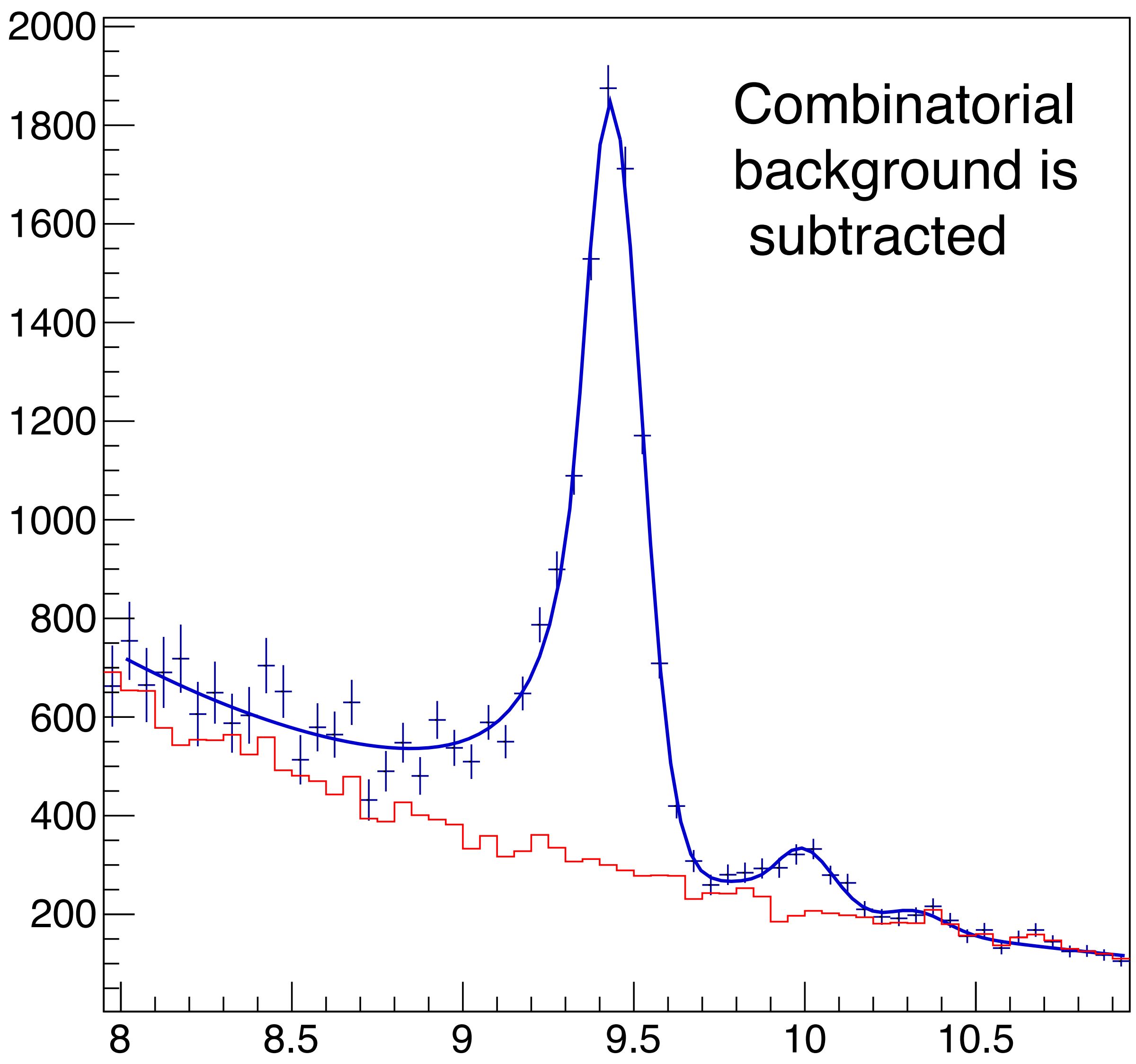


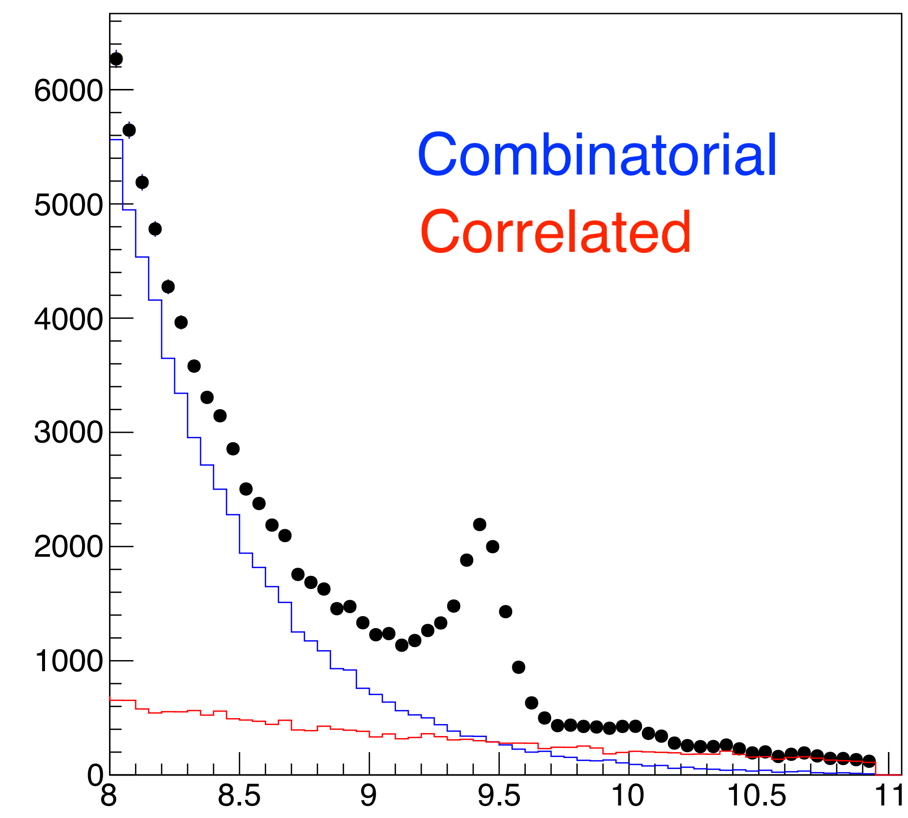
Mass spectrum - 0-10% centrality

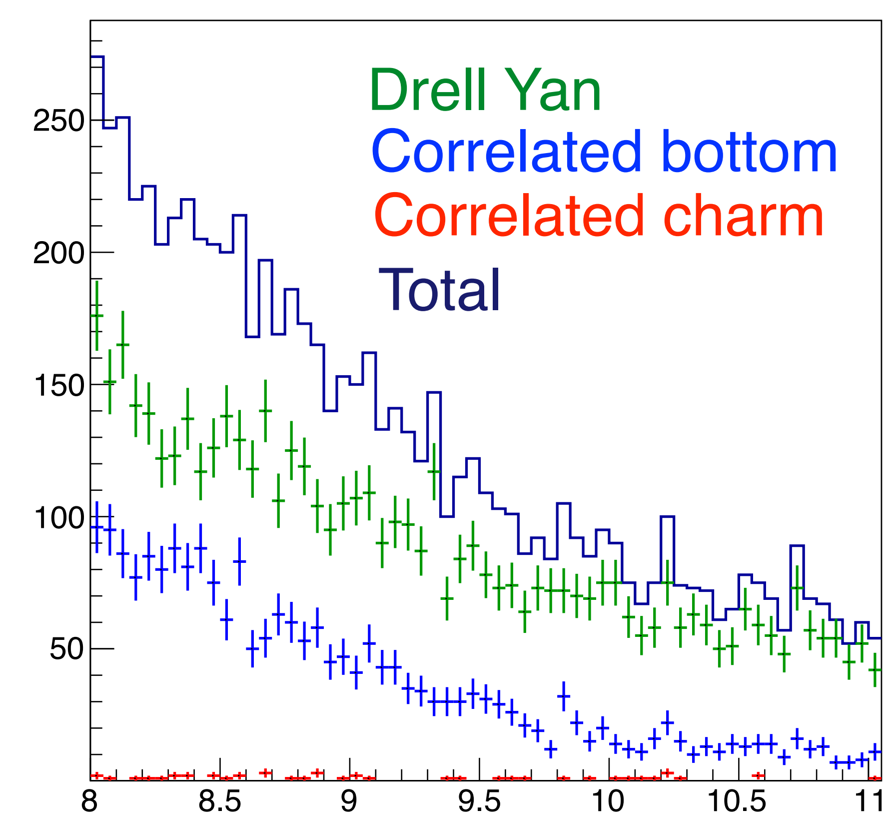
24 B central events, integrated over p_T

- Upsilons embedded in central Hijing
- Suppression:
  - Strickland & Bazow, Nucl. Phys. A879 25, (2012)

The DY estimated background has increased x2



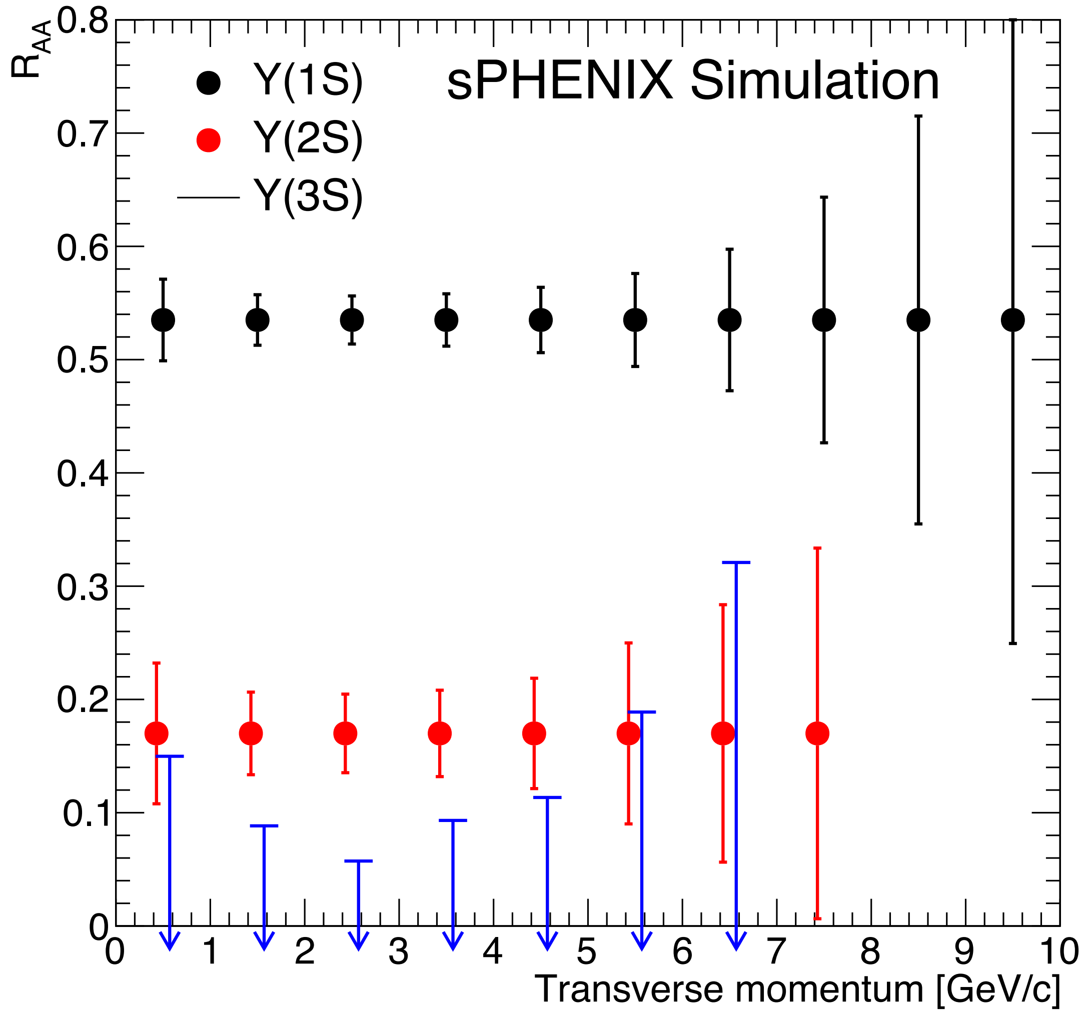




R_{AA} for 0-10% centrality

Projection for Upsilon R_{AA} vs p_T for central Au+Au collisions

- From 240 B MB events.
- Sampling up to 1.5 T events possible with triggering
  - Under investigation



Only 90% confidence limit for Υ(3S)

The Υ(3S) measurement is limited mostly by the background due to DY pairs.

- Physics background - not reducible.
- Only more statistics will help.

These new studies are now being extended to other centralities.

Under development (or TBD)

Upsilon triggering

- High energy electron trigger
- Require ~ 5000 rejection for pp
- Could potentially sample up to 1.5 T MB events in Au+Au
  - Upsilon trigger in Au+Au will be challenging

Measuring the v_2 of Upsilons

Charmonium measurements at high p_T.

- Need to study E/p cut rejection at high p_T.
- Could significantly increase the charmonium p_T reach at RHIC.
- Separate prompt and non-prompt components

Summary

The prospects for quarkonia measurements in the 2020's are very bright!

Increases in luminosity at LHC and RHIC, combined with major detector upgrades, will provide:

High precision data sets for Υ(nS) states at LHC and RHIC energies.

Next generation charmonium measurements at LHC (low and high p_T)
- Precise J/ψ v_2 and polarization measurements.
- Precise ψ(2S) R_{AA} measurements.

Increased charmonium p_T reach at RHIC is likely with sPHENIX (under study).
- Can very well separate prompt and non-prompt components.

Backups

RHIC luminosity vs store life

From SPH-TRG-001