Quarkonia and Vector Boson Production in Pb-Pb Collisions at ATLAS

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Physics Motivation

- Why the quarkonia suppression in central events so interesting?
  - Suppression could be a consequence of quark-gluon plasma production[2]
  - Suppressed quarkonium yield → direct experimental sensitivity to medium temperature [3]
- Suppression of J/ψ events already observed in past experiments:
  - NA50 at CERN SPS in Pb-Pb at $\sqrt{s_{NN}} = 17.3$ GeV [4]
  - PHENIX at RHIC in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5]
- Is it useful to study it at LHC? ...yes!
  - Suppression mechanism not fully understood, additional effects might be there [6]
  - Proposal for J/ψ enhancement at high energies from charm quark recombination [7]
  - First W, Z bosons measurement is possible: no suppression expected there[8]

Introduction

- Short presentation of the Large Hadron Collider (LHC) and the ATLAS experiment
- Pb-Pb collisions at ATLAS: centrality definition
- Quarkonia measurement:
  - J/ψ suppression in Pb-Pb collisions at ATLAS
- Electroweak measurements:
  - W and Z bosons observation in Pb-Pb collisions at ATLAS
  - W suppression, W/Z ratio measurement and W charge asymmetry in Pb-Pb collisions
- Conclusions and Plans

The Large Hadron Collider At CERN

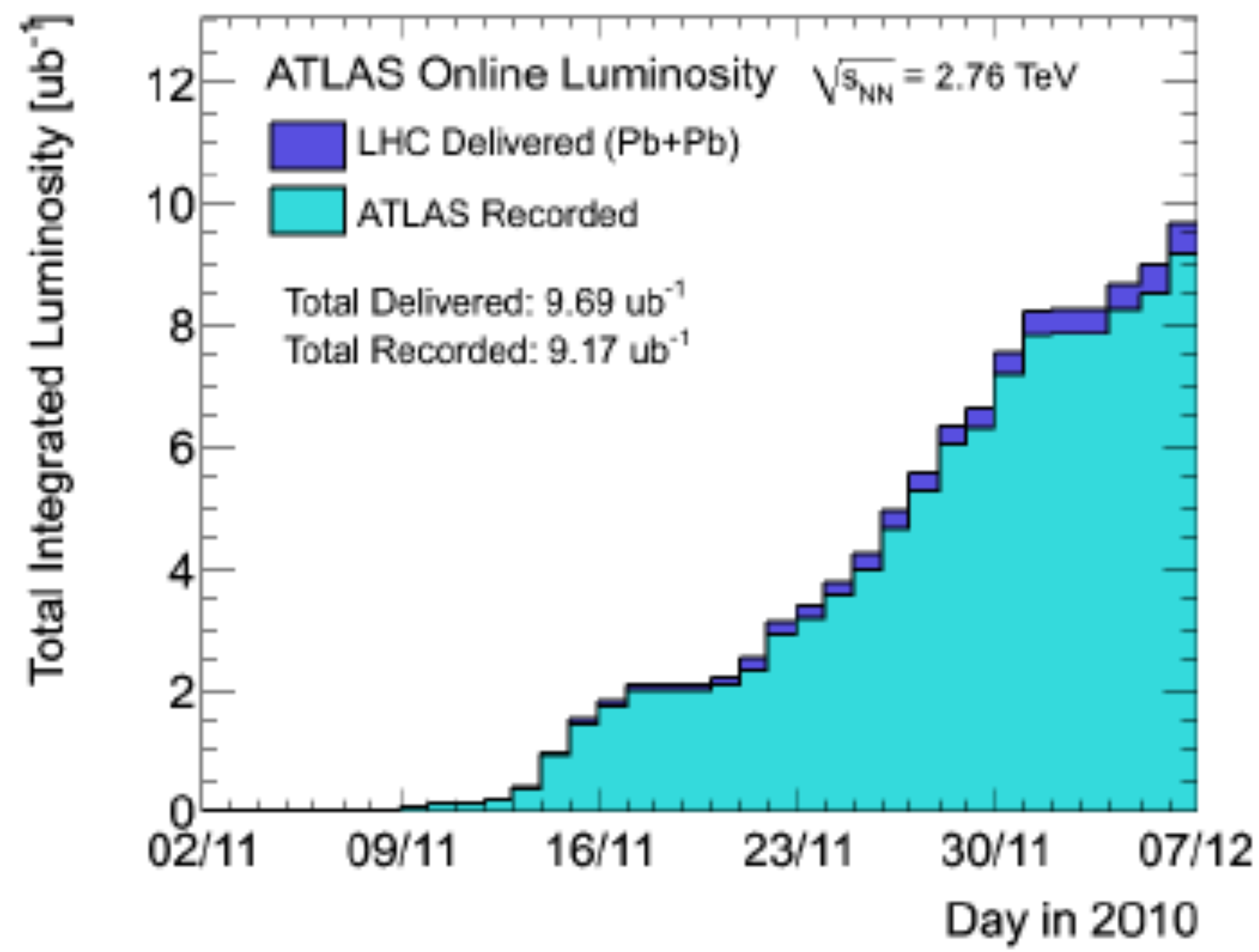
LHC 2010 Pb-Pb collisions:

* Center-of-mass energy: $\sqrt{s}$ = 2.76 TeV per nucleon
* 9.17 μb^{-1} of Pb-Pb data collected by ATLAS → data taking efficiency > 95%

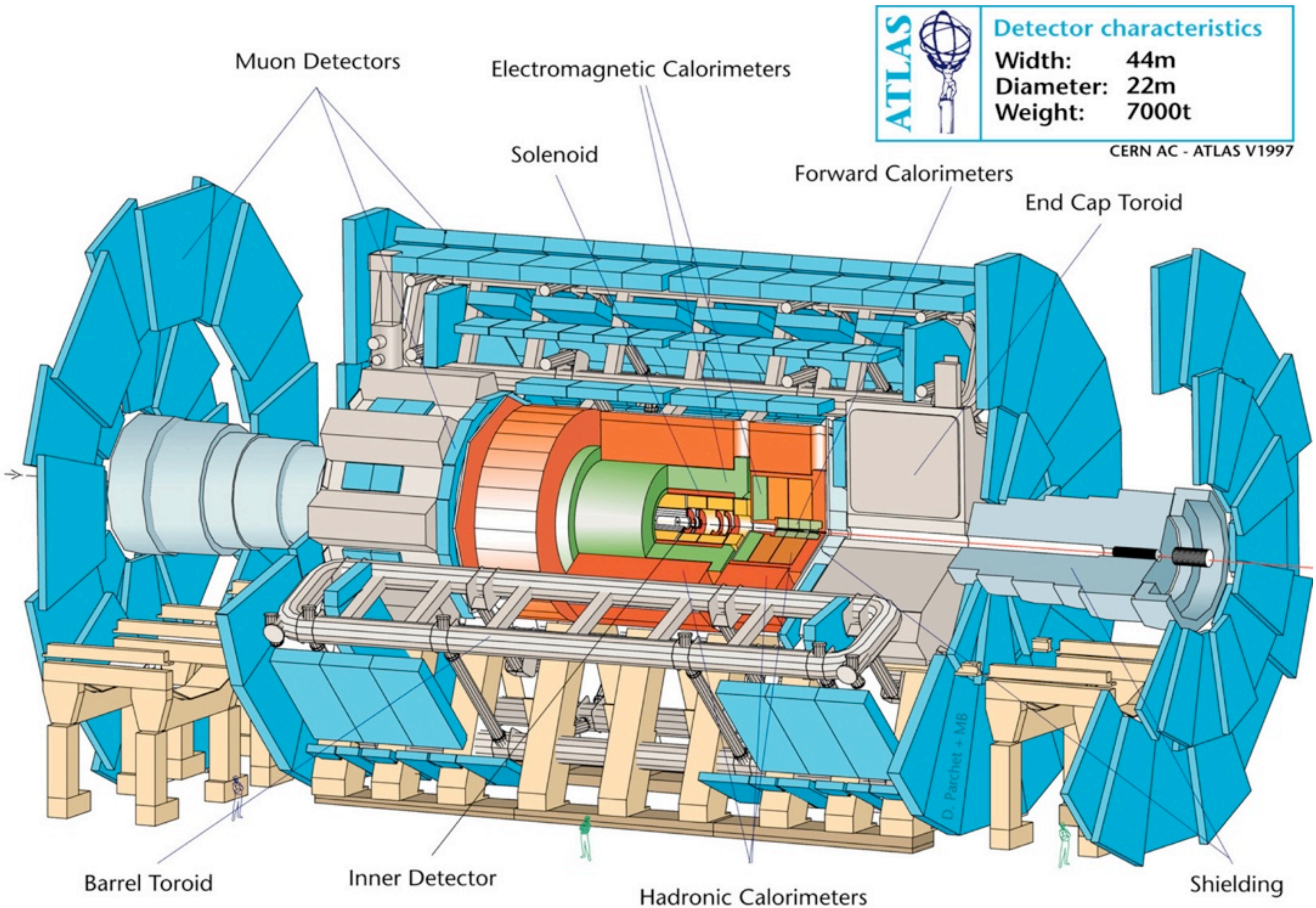
Samples used:

* Measurements use ~5 μb^{-1}
* Trigger used: Minimum Bias Trigger Scintillators ~100% efficiency
* MC sample: Pythia J/ψ (W, Z) p-p @2.76 TeV overlaid with Hijing MC

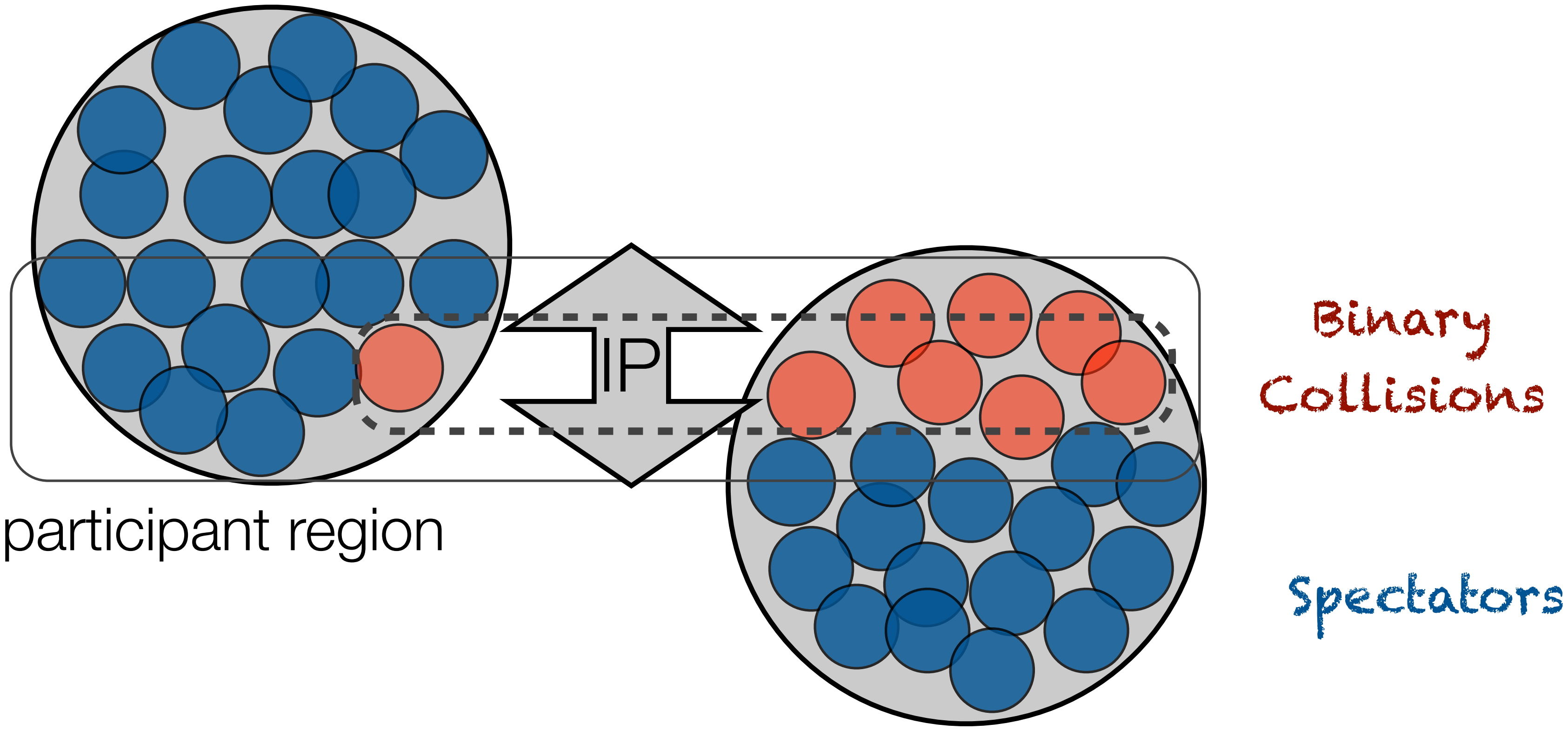
Luminosity in Pb-Pb Collisions Integrated in 2010



The ATLAS Experiment at LHC



Our Starting Point in Pb-Pb Collisions



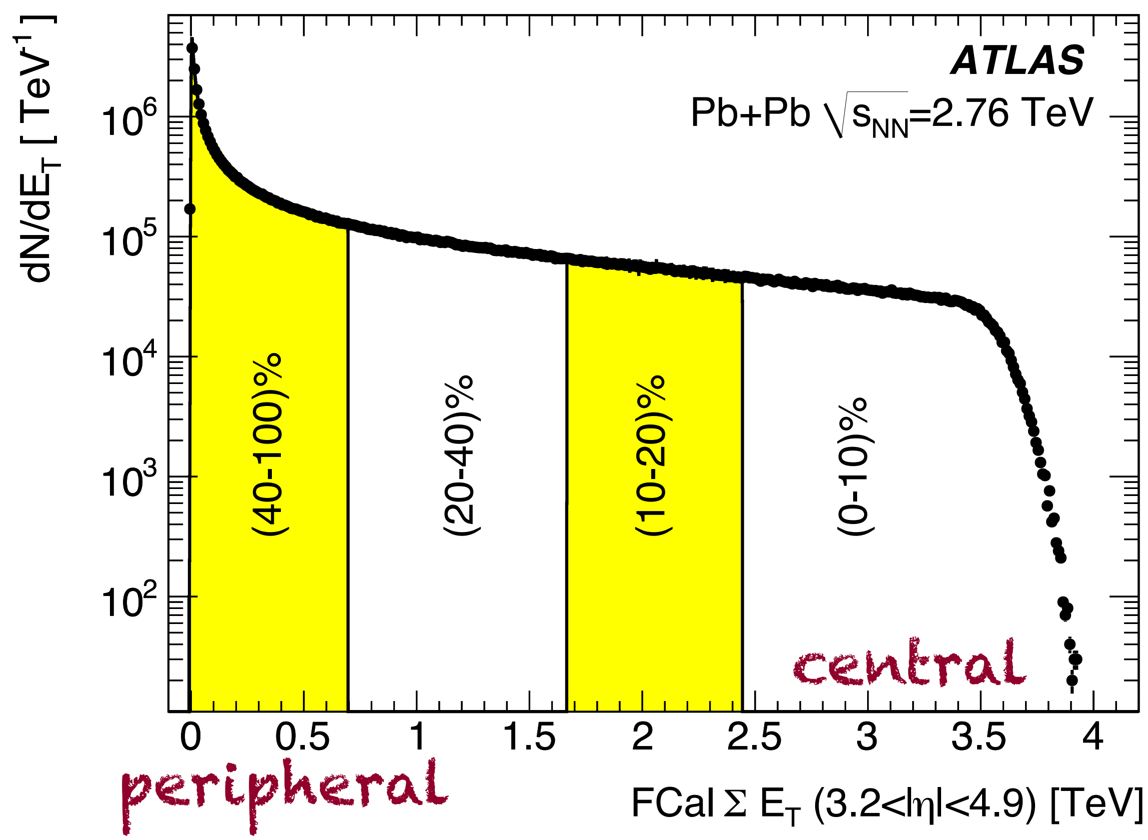
- In each heavy ion interaction two bunches of nucleons collide
- In each ion collision we have N_{coll} binary collisions between N_{part} particles
- Any yield measurement in heavy ions collisions must be normalized on N_{coll}
- Estimate of N_{coll} is done using Glauber Monte Carlo simulation
- N_{coll} depends on the Impact Parameter (IP) between the two nucleons

→ how can we measure IP in data?

N_{coll} Estimate: Centrality Definition

we cannot measure the IP directly! But..

- Multiplicity increases monotonically as IP decreases
- Using transverse energy deposited in the forward calorimeters ($3.2 < |\eta| < 4.9$)we define centrality:
  - Central event: small IP
  - Peripheral event: big IP
- Reducing last bin to 40-80% → small statistic loss and high systematic on R_{coll}



J/ψ Yield Analysis Goal

centrality bin

most peripheral centrality bin

normalized mean number of binary collisions

$R_{coll} = N_{coll,c}/N_{coll,40-80}$

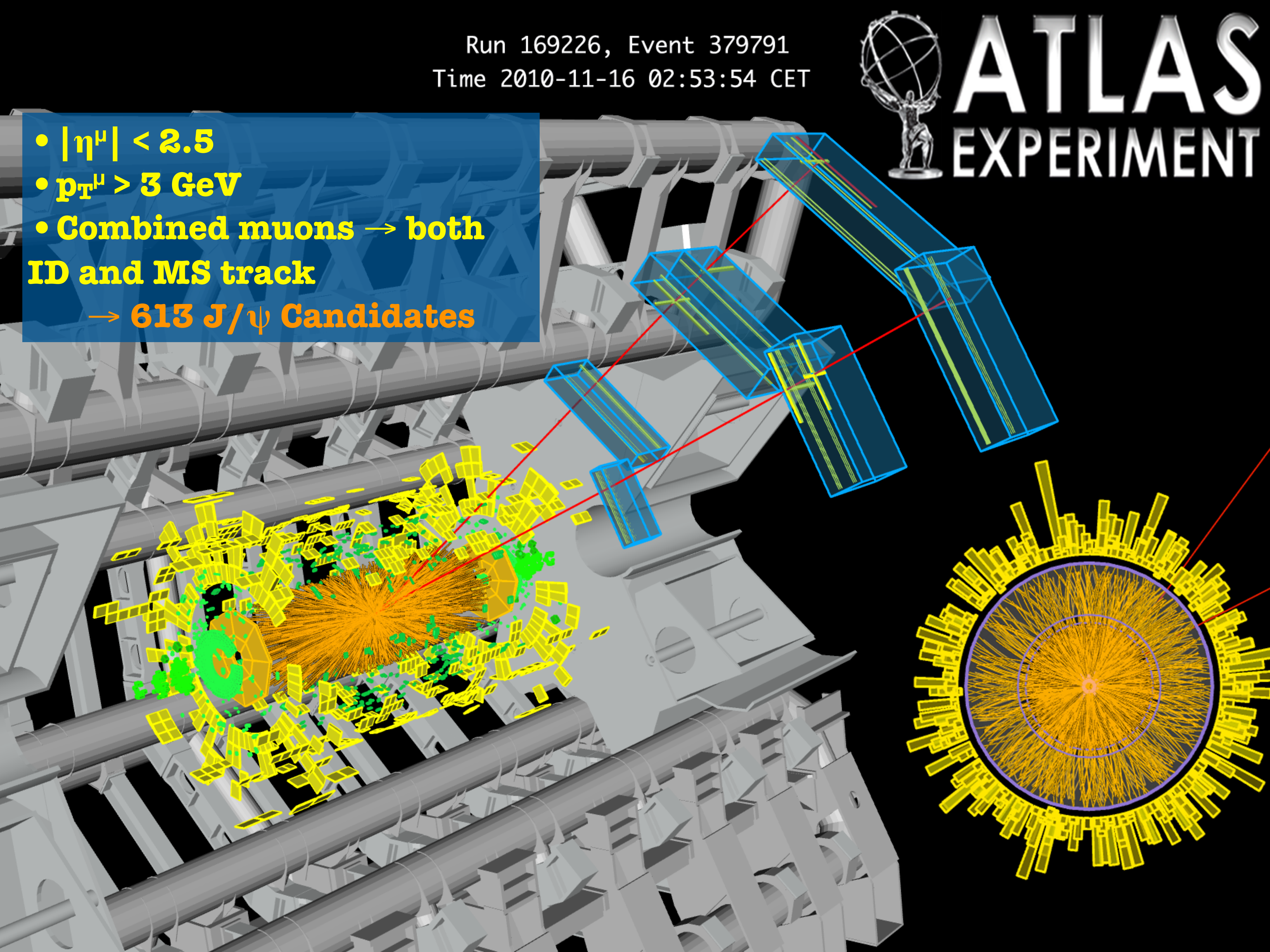
$$R_c = \frac{N_c^{corr}(J/\Psi \rightarrow \mu^+\mu^-)}{N_{40-80\%}^{corr}(J/\Psi \rightarrow \mu^+\mu^-) \cdot R_{coll}}$$

$N_c^{corr} = N_c^{meas}/(\varepsilon(J/\psi)_c \times W_c)$

reconstruction efficiency

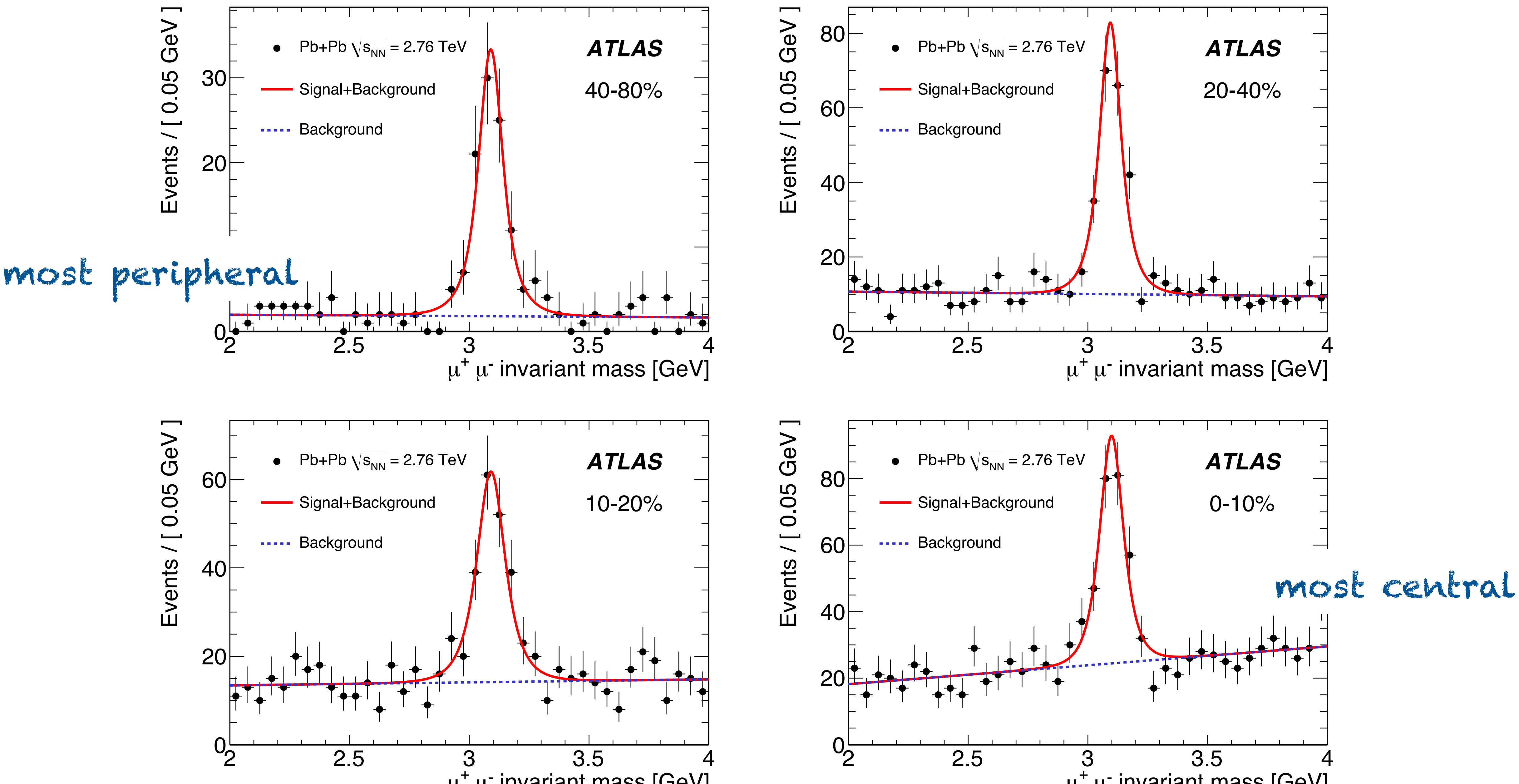
centrality bin width

- No attempt to compare with p-p results
- Normalization on most peripheral bin


Run 169226, Event 379791
Time 2010-11-16 02:53:54 CET
ATLAS
EXPERIMENT
• $|\eta^{\mu}| < 2.5$
• $p_T^{\mu} > 3$ GeV
• Combined muons → both ID and MS track
→ 613 J/ψ Candidates

J/ψ Yield Extraction

- Two extraction methods
  - Sideband subtraction method
  - Unbinned maximum likelihood fit with per-event error



Does Reconstruction Efficiency Depend on Centrality?

- Considering only reconstruction efficiency, MBTS have **ε** ~ 100%
- Small centrality dependence for Combined Muons efficiency
  - ~3-4% drop from inner detector tracks reconstruction
  - As expected: central events have higher occupancy in the ID but not in the muon chambers
- We use this efficiency variation to correct our raw yield

Efficiency correction in centrality bins:

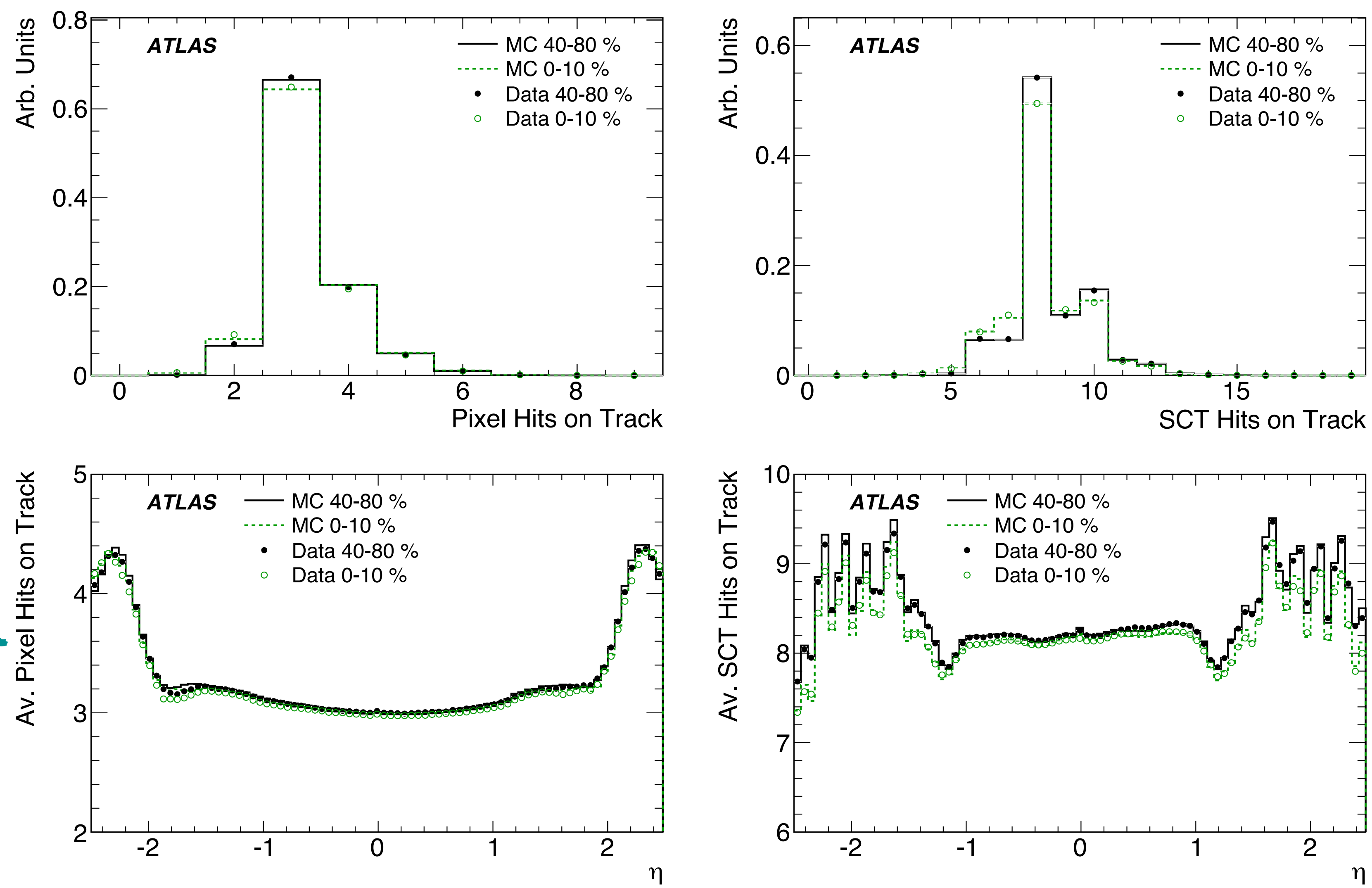
- 0-10%: 0.93 ± 0.01
- 10-20%: 0.91 ± 0.02
- 20-40%: 0.97 ± 0.01
- 40-80%: 1

all normalized on peripheral bin

Is Monte Carlo Simulation Reliable?

- Comparing (muon) track activity in MC and data
- Comparing (muon) tracks basic properties in MC and data vs centrality
- Associating a systematic uncertainty

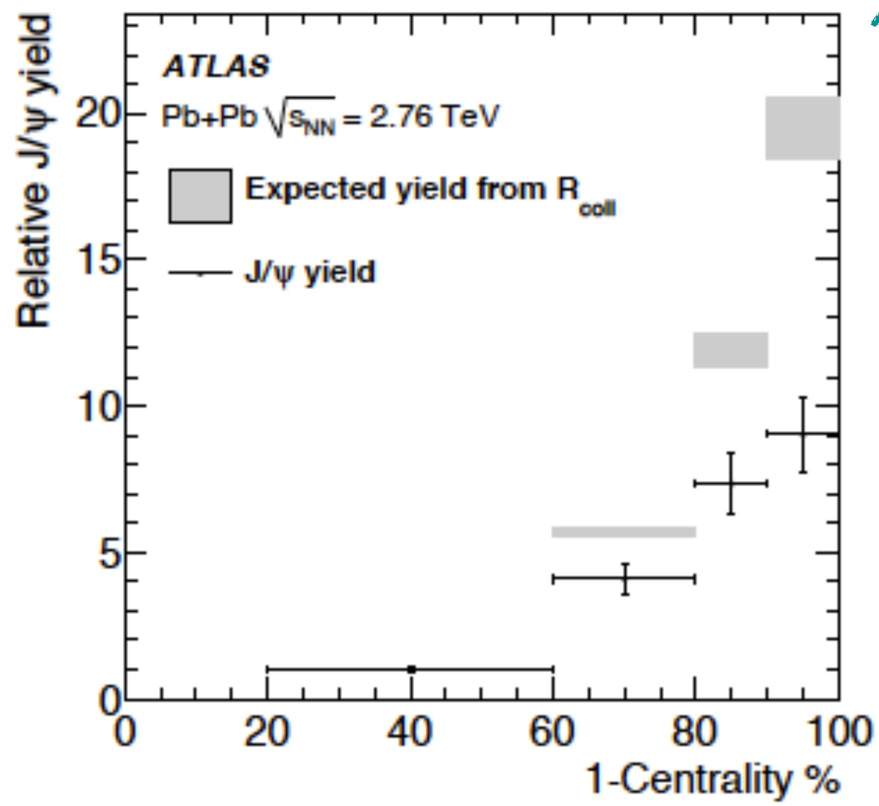
Muon tracks properties
$p_T > 0.5$ GeV



very good agreement is found

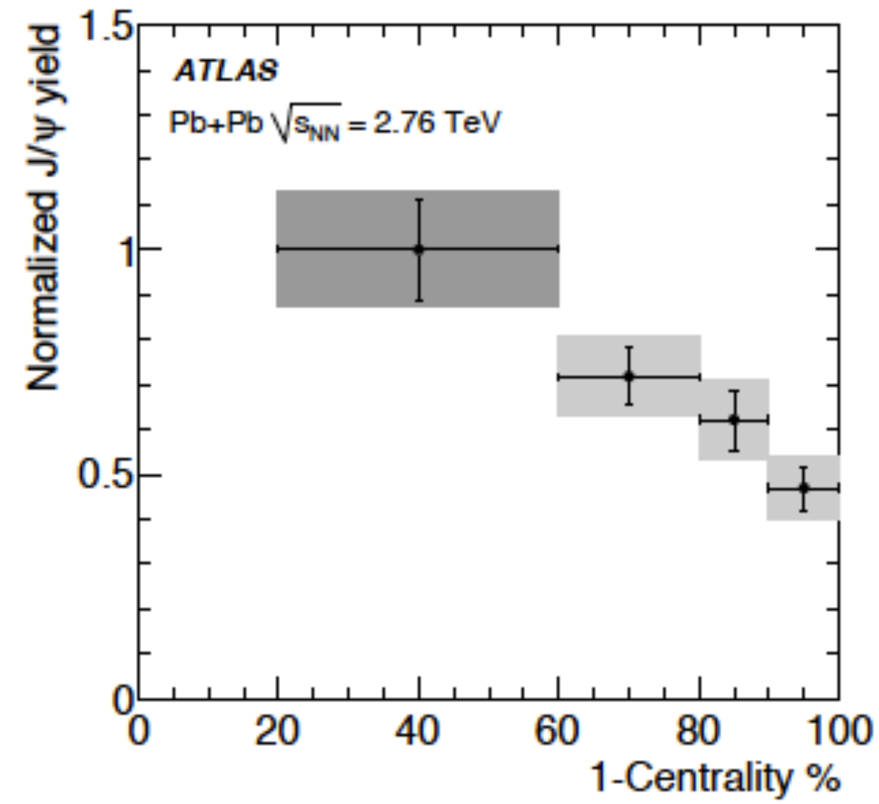
Observation of J/ψ Suppression

most peripheral → most central



Measured vs Expected Yield

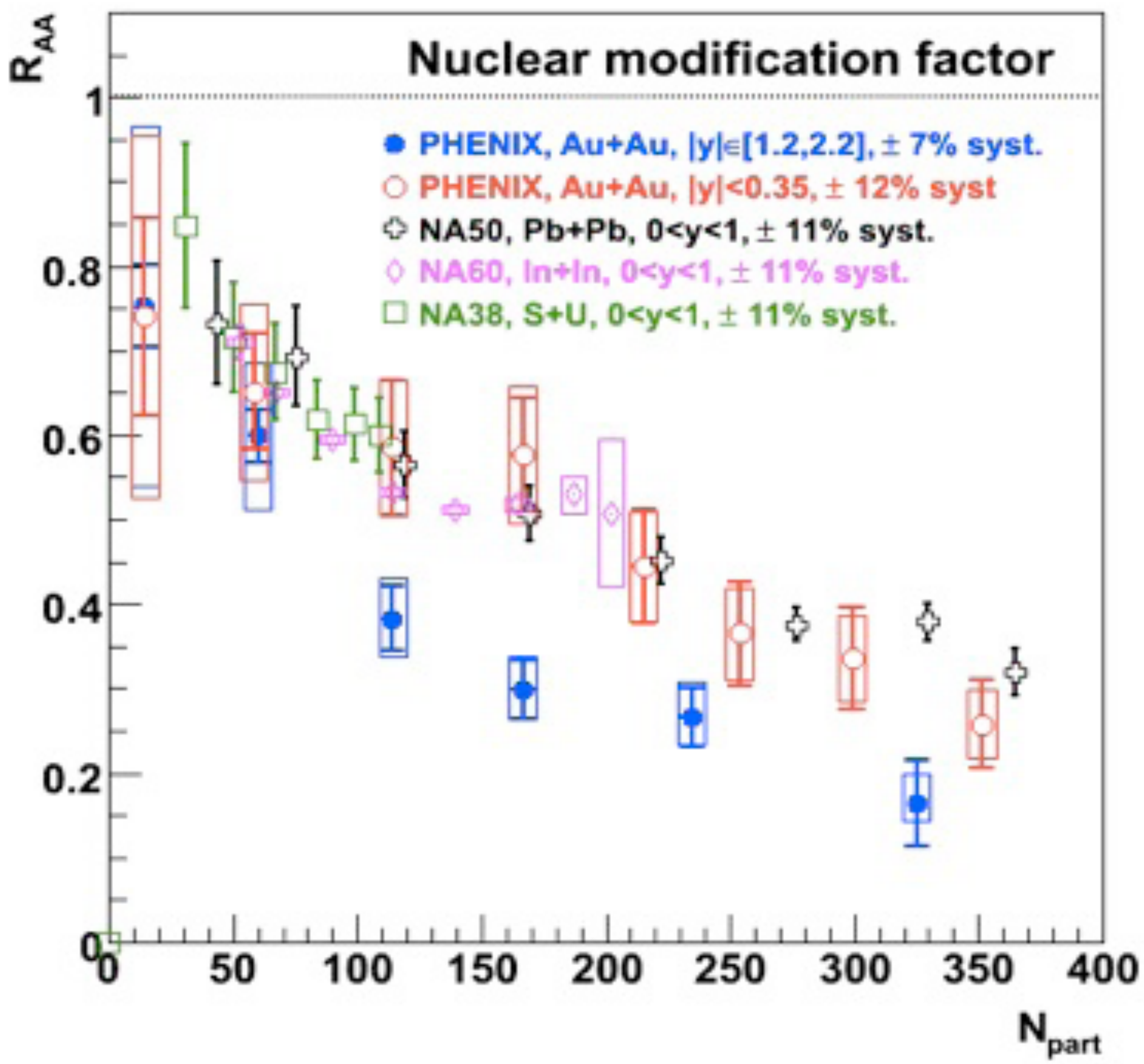
most peripheral → most central



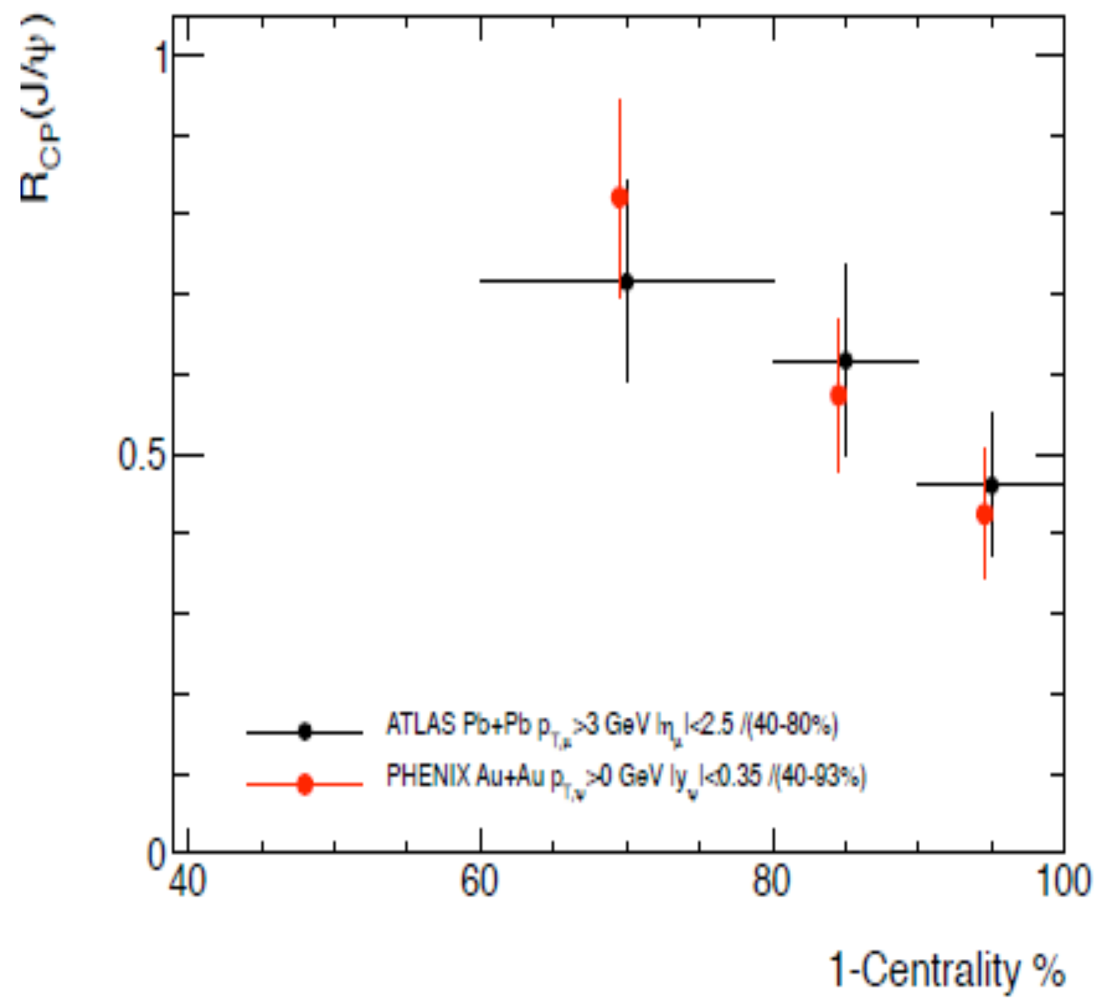
Normalized J/ψ Ratio

- Data points (right plot) are not consistent with their average: P(χ^2,NDoF = 3) = 0.11%
- Significant decrease of the ratio is observed as a function of centrality
- Qualitatively same effect as the one seen by NA50 and PHENIX at very different center-of-mass energies
- Main systematics: J/ψ reconstruction efficiency ~2.3-6.8%, signal extraction ~5.2-6.8%, R_{coll} estimate ~3.2-5.3%

Comparison with RHIC Data

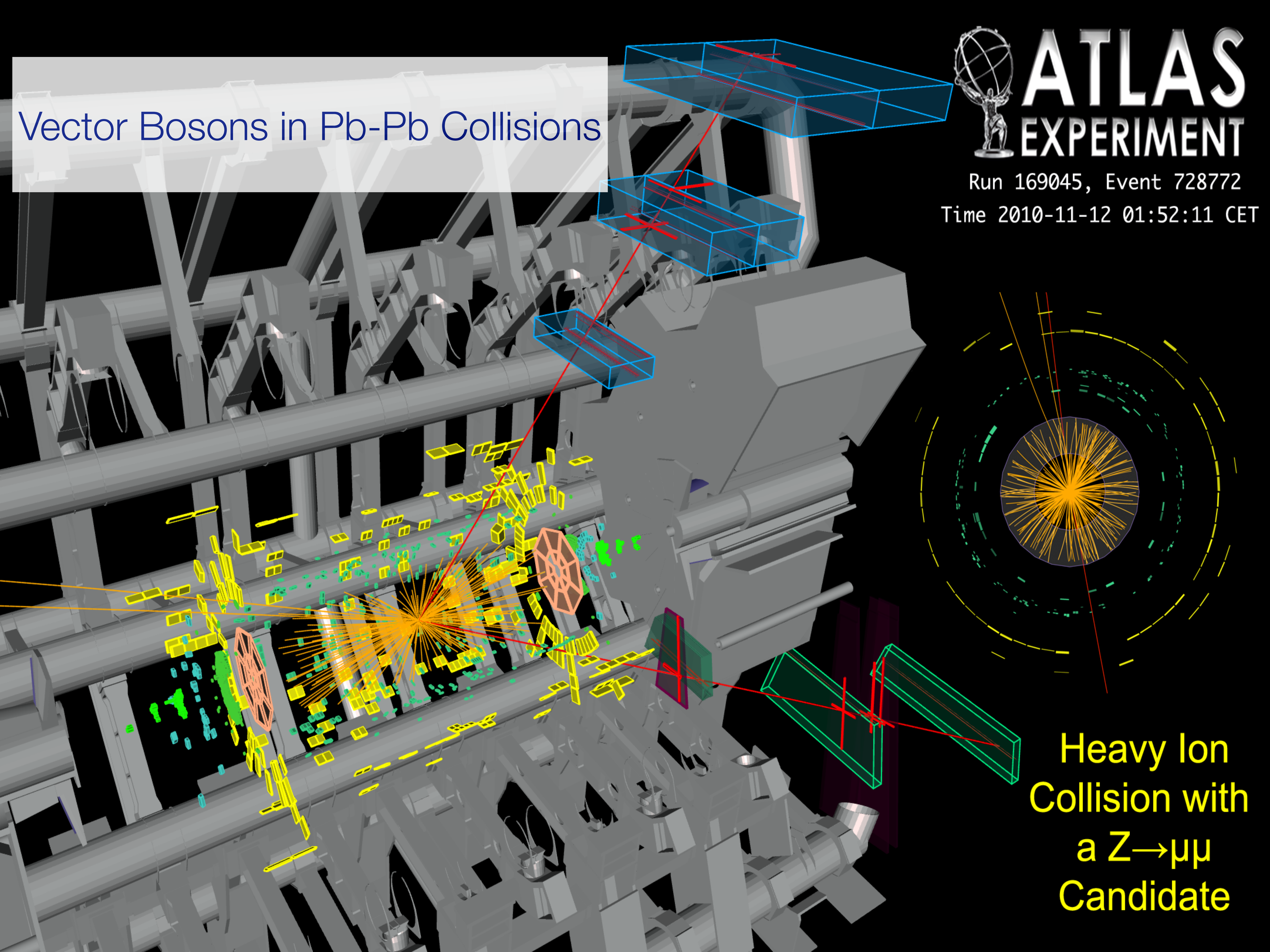


PAS & J. Jia - replotted from public data



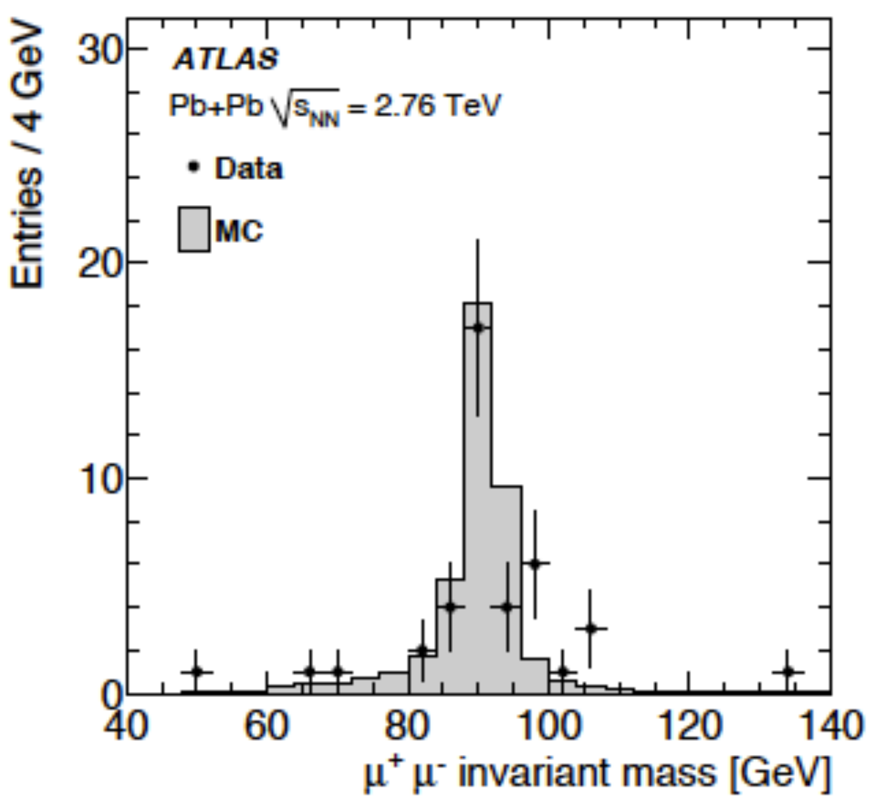
Attempt to replot PHENIX data vs Centrality [P.Steinberg, J.Jia] suggests suppression is energy-independent

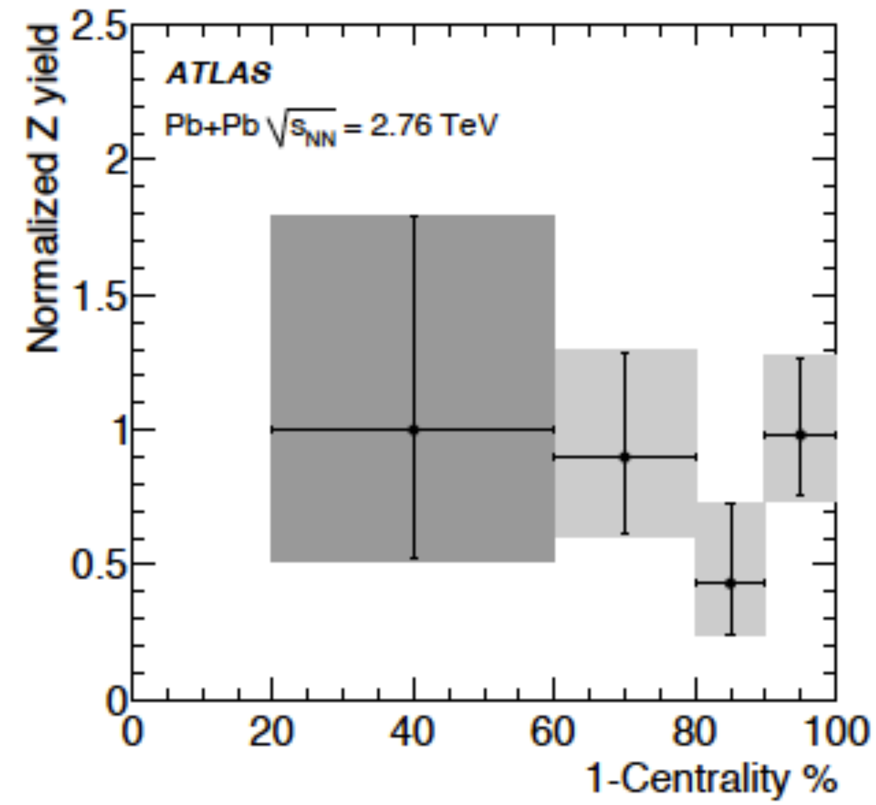
Vector Bosons in Pb-Pb Collisions



Observation of Z Boson in Pb-Pb Collisions

38 Z Candidates found





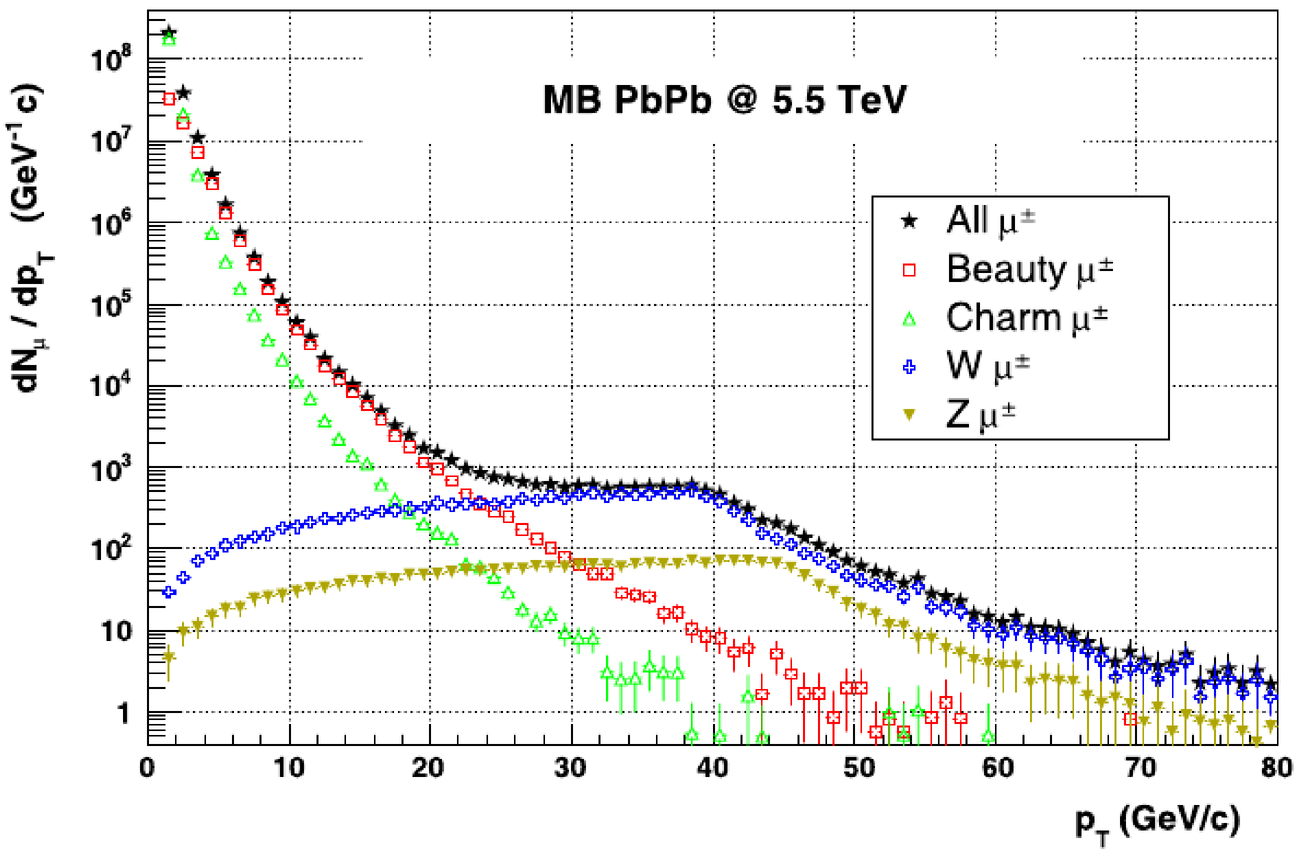
- Z Boson reconstructed in heavy ions Pb-Pb collisions
- Normalized yield doesn't show a trend: **not enough statistics** but still useful as a cross-check
- Systematic on the measurement conservatively the same as for J/ψ

→ performed cross-checks to verify this assumption

$W^{\pm}$ Analysis Goal

- Theory Predicts an order of magnitude more W than Z produced at 2.76 TeV and decaying in muons
  - W allows for a more precise measurement of electroweak suppression in deconfined matter when limited by statistics
- $W \rightarrow \mu\nu$ is more difficult to reconstruct, especially in heavy ions environment
  - Missing energy term has a strong dependence on centrality → cannot be used here
  - Isolation requirements on the muon introduce a centrality dependent systematic effect as well
- We can only rely on the muon p_T distribution
  - We apply some additional quality checks on the muon to reduce background from decays in flight, fakes, ...

W Identification in Heavy Ion Environment

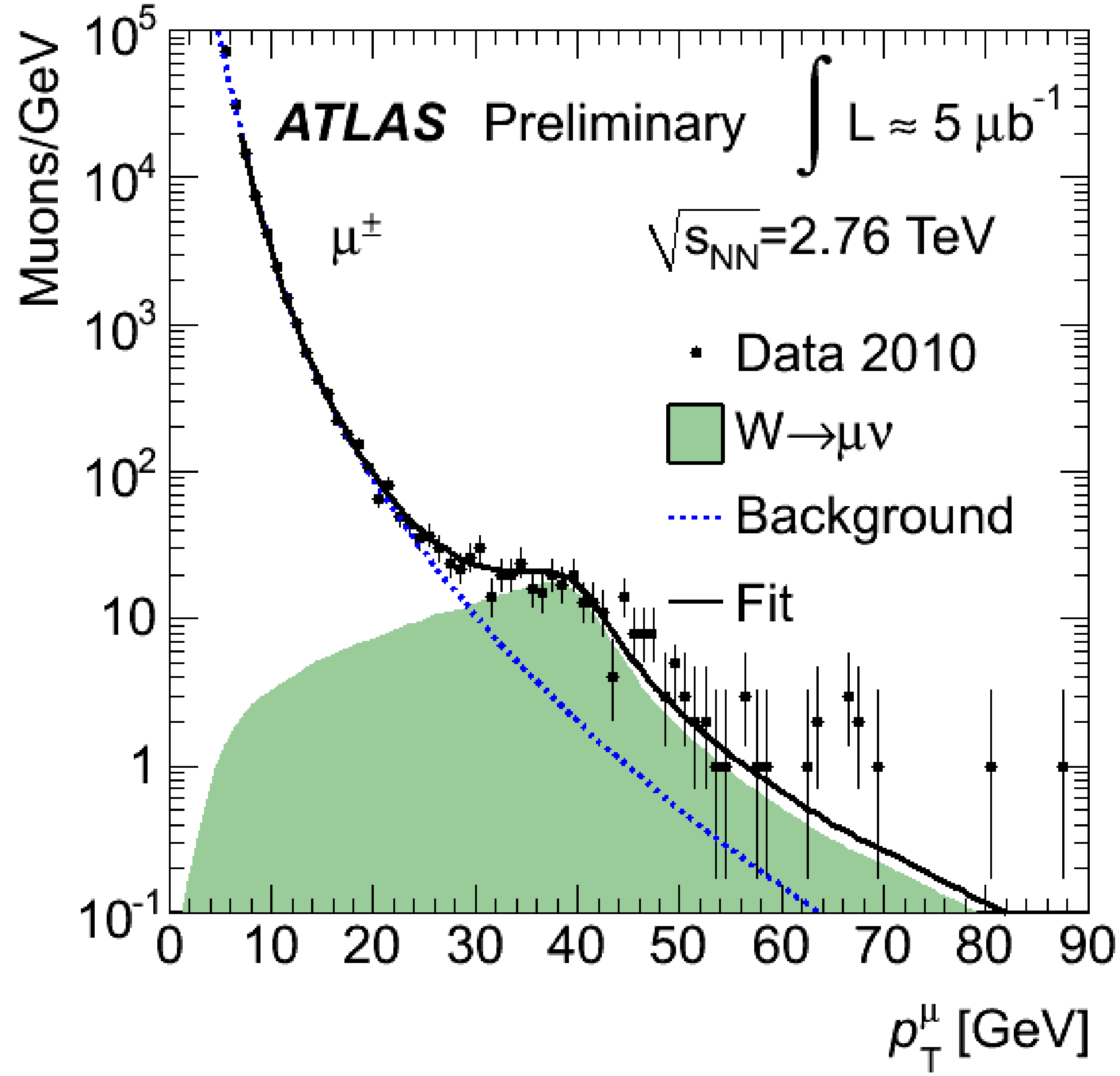


Electroweak boson detection in the ALICE muon spectrometer
Z. Conesa del Valle for the ALICE Collaboration
Eur. Phys J. C 49, 149-154 (2007)

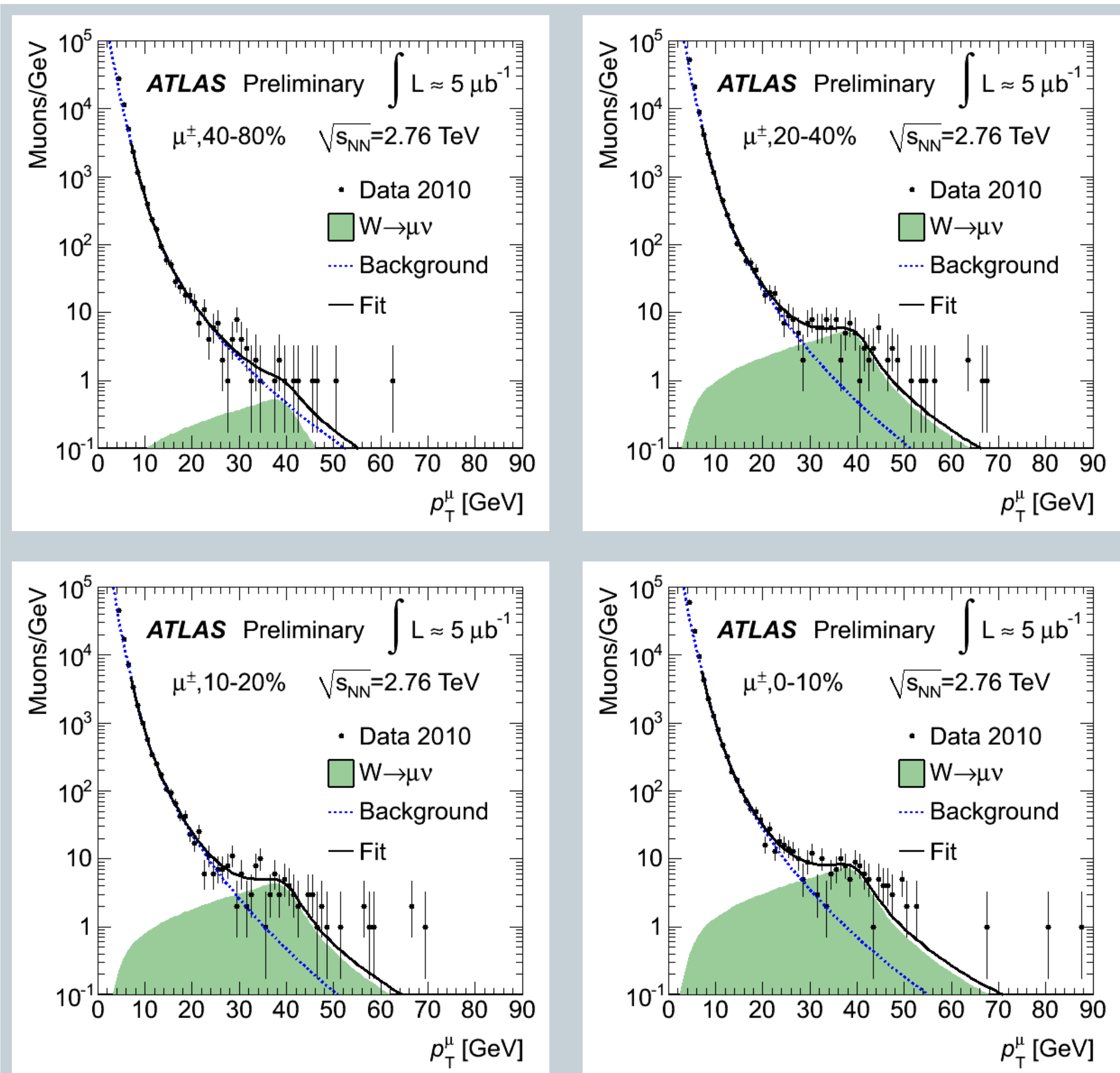
- Muons from W are on average more energetic than muons from QCD background
- At high momenta the dominating source of muons are W and b-quark decays
- The muons from W create a shoulder in the p_T spectrum

Extracting W→μν From Data

- Veto on dimuons with $m_{\mu\mu}$ > 66 GeV (Z/DY)
- Veto on decays in flight → efficiency loss on W on MC is < 0.3%
- Build a template for W→μν from pp MC @2.76 TeV
- Use a parametric model to describe background
- Fit data with signal+background and extract number of W candidates → unbinned maximum likelihood fit
- Cross-check using cut and count procedure



W Candidates vs Centrality



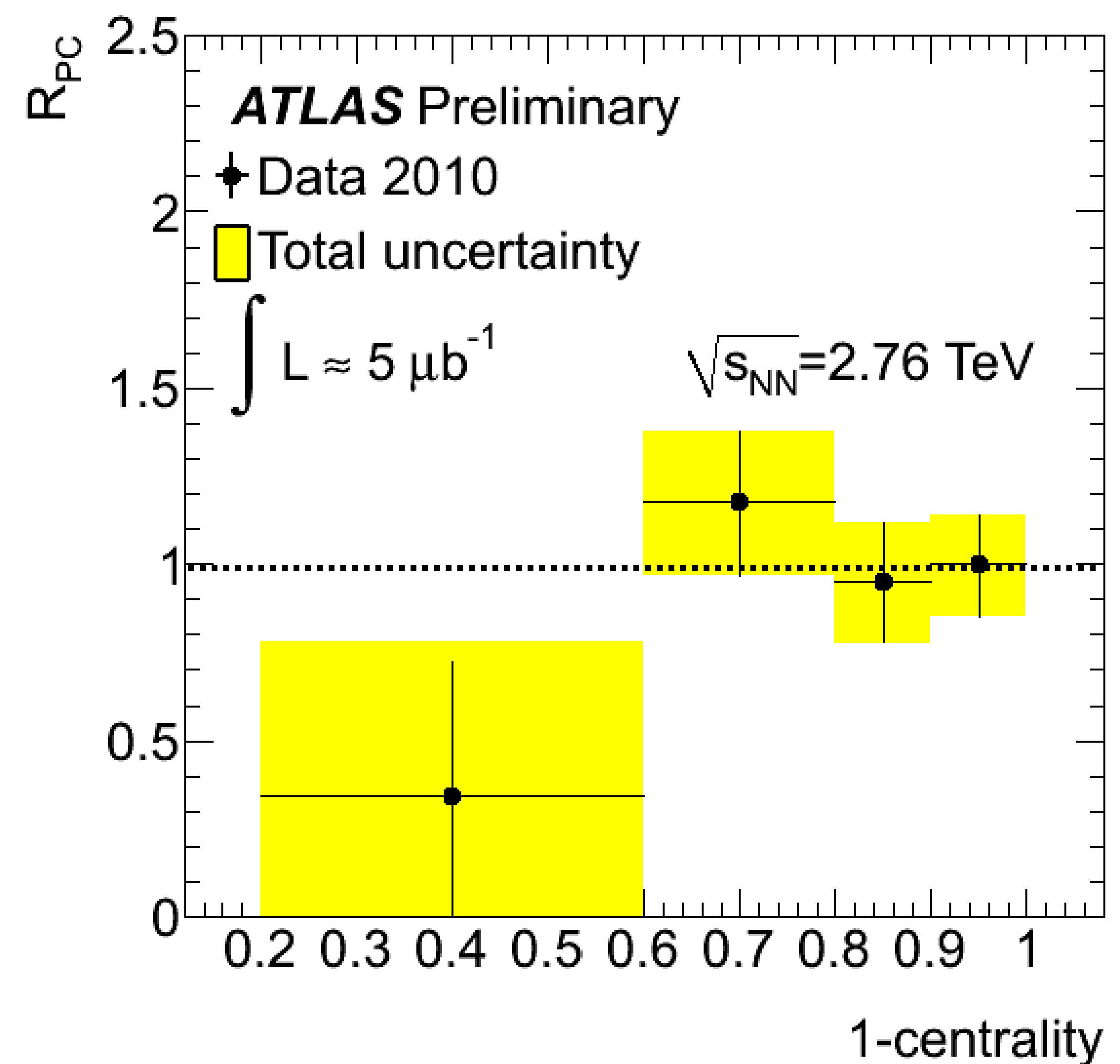
- Centrality bins definition analogous to J/ψ analysis
- Small statistic in first most peripheral bin, but higher than Z for the three others

Centrality	N_W^{fit}
40-80%	12^{+13}_{-12}
20-40%	118^{+17}_{-24}
10-20%	97^{+16}_{-18}
0-10%	165^{+23}_{-25}
W (all)	399^{+36}_{-38}

W Yield Ratio Measurement

- Same ratio calculation as for J/ψ and Z
- Here normalization wrt to most central bin instead of most peripheral
- No suppression hypothesis is fitted on data with

$$\chi^2/\text{NDoF} = 3.02/3$$



the result is consistent with absence of suppression of the W boson for central events

W/Z Yield Ratio

- Ratio of the cross-sections of W and Z bosons is an important test of the Standard Model
- To compute it we need to correct for geometrical acceptance and muon reconstruction efficiency → from MC sample
  - Systematic is 3-4% extracted from data-MC comparisons
- Theory @2.76 TeV
  - With or without nuclear modification to PDF:

  Pb-Pb → $R_{W/Z} = 11.5 \pm 0.7$
  - NNLO QCD with MSTW2008 PDF

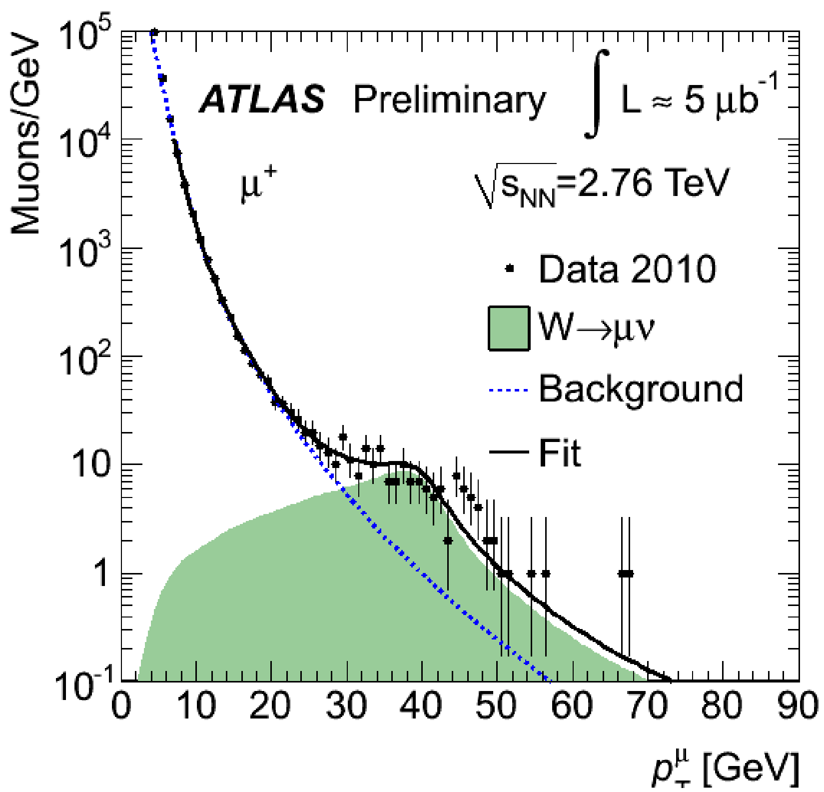
  pp → $R_{W/Z} = 11.3 \pm 0.6$

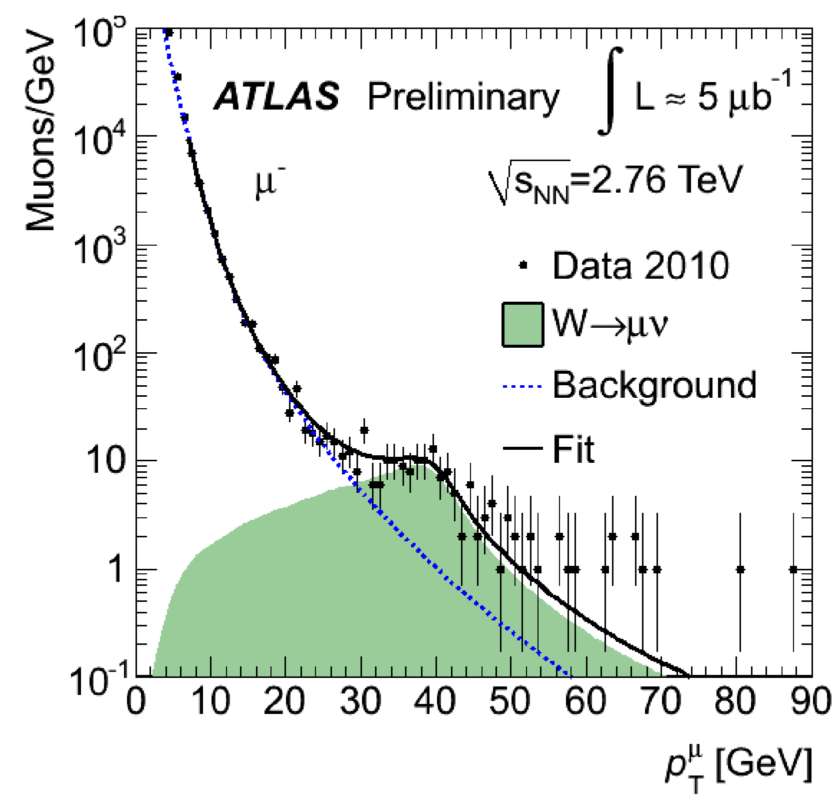
  nn → $R_{W/Z} = 10.8 \pm 0.6$
- ATLAS Result: $R_{W/Z} = 10.5 \pm 2.3$

dominated by Z low statistics

W^+ vs W^-

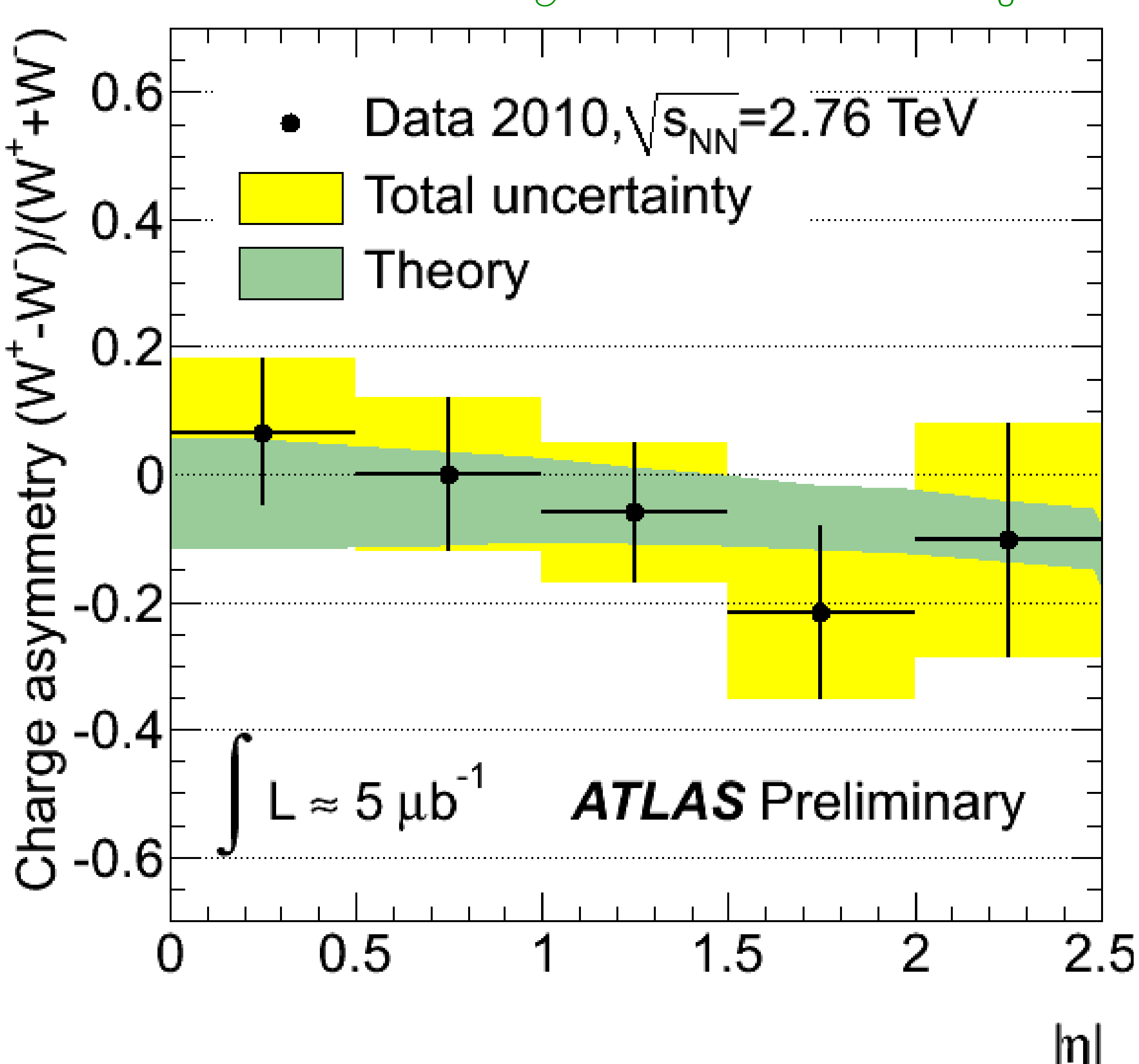
- We expect to see slightly more W^- than W^+ due to the larger number of d-valence than u-valence quarks in a lead nucleus
- From theory:
  - $R_{W+/W-} = 0.90 \pm 0.04$
- Observed at ATLAS:
  - $R_{W+/W-} = (198\ (+25\ -26))/(204\ (+27\ -\ 31)) = 0.97\ (+0.18\ -0.19)$





Muon Charge Asymmetry from W Decays

Theory curve: CTEQ6.6



$$A_\mu = \frac{d\sigma_{W_{\mu^+}}/d\eta - d\sigma_{W_{\mu^-}}/d\eta}{d\sigma_{W_{\mu^+}}/d\eta + d\sigma_{W_{\mu^-}}/d\eta}$$

- Precision test of W charge asymmetry provides information on parton distribution functions
- We measure the charge asymmetry for all muons with $p_T > 30$ GeV as a function of **η**
- Measurement includes 19% background contamination (mainly b-bbar) → taken into account as a systematic
- No asymmetry is observed within statistical errors → need higher statistics to have a sensitive measurement

Conclusions and Plans

- First heavy ions measurements performed at ATLAS:
  - Observation of J/ψ suppression in Pb-Pb collisions at LHC[9]
  - Z[9] and W[10] observation in Pb-Pb collisions at LHC
  - No suppression observed for W bosons[10]
  - W/Z ratio and W charge asymmetry measurements in agreement with Standard Model predictions[10]
- Future Plans:
  - More Pb-Pb statistics will be available by the end of the year
  - Comparison with runs with p-p collisions @2.76 TeV

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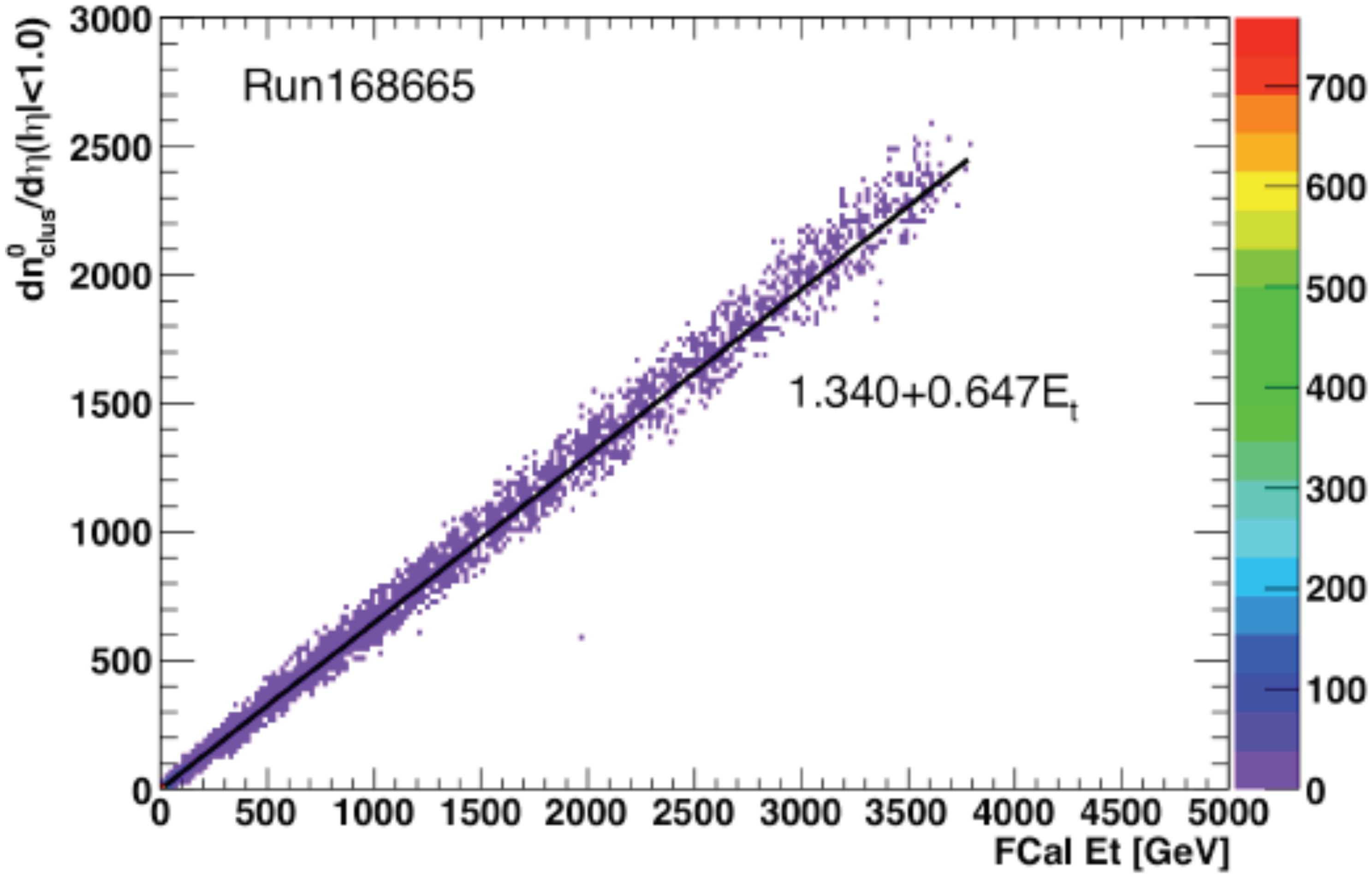
[9] the ATLAS Collaboration, G. Aad *et al.*, "Measurement of the Centrality Dependence of J/ψ Yields and Observation of Z Production in Lead-Lead Collisions with the ATLAS Detector at the LHC", arXiv:1012.5419v1, accepted for publication at Phys. Lett. B

[10] the ATLAS Collaboration, "Measurements of W Boson Yields in Pb-Pb Collisions at 2.76 TeV/nucleon via Single Muons with the ATLAS Detector", ATLAS-CONF-2011-078

Backup Slides

Centrality In Tracking Efficiency Studies



- For the tracking the relevant quantity is the occupancy vs centrality
- For tracking efficiency studies only we use an occupancy based definition of centrality: number of pixel clusters in the barrel
- We see here that this definition is equivalent to the standard one defined from the ΣE_T^{FCAL}

J/ψ Final Numbers and Systematics

Centrality	$N^{\text{meas}}(J/\psi)$	$\epsilon(J/\psi)_c/\epsilon(J/\psi)_{40-80}$	Systematic Uncertainty		
			Reco. eff.	Sig. extr.	Total
0-10%	190 ± 20	0.93 ± 0.01	6.8 %	5.2 %	8.6 %
10-20%	152 ± 16	0.91 ± 0.02	5.3 %	6.5 %	8.4 %
20-40%	180 ± 16	0.97 ± 0.01	3.3 %	6.8 %	7.5 %
40-80%	91 ± 10	1	2.3 %	5.6 %	6.1 %

Centrality	N(Z)	$\epsilon(Z)_c/\epsilon(Z)_{40-80}$
0-10%	19	0.99 ± 0.01
10-20%	5	0.97 ± 0.01
20-40%	10	0.98 ± 0.01
40-80%	4	1

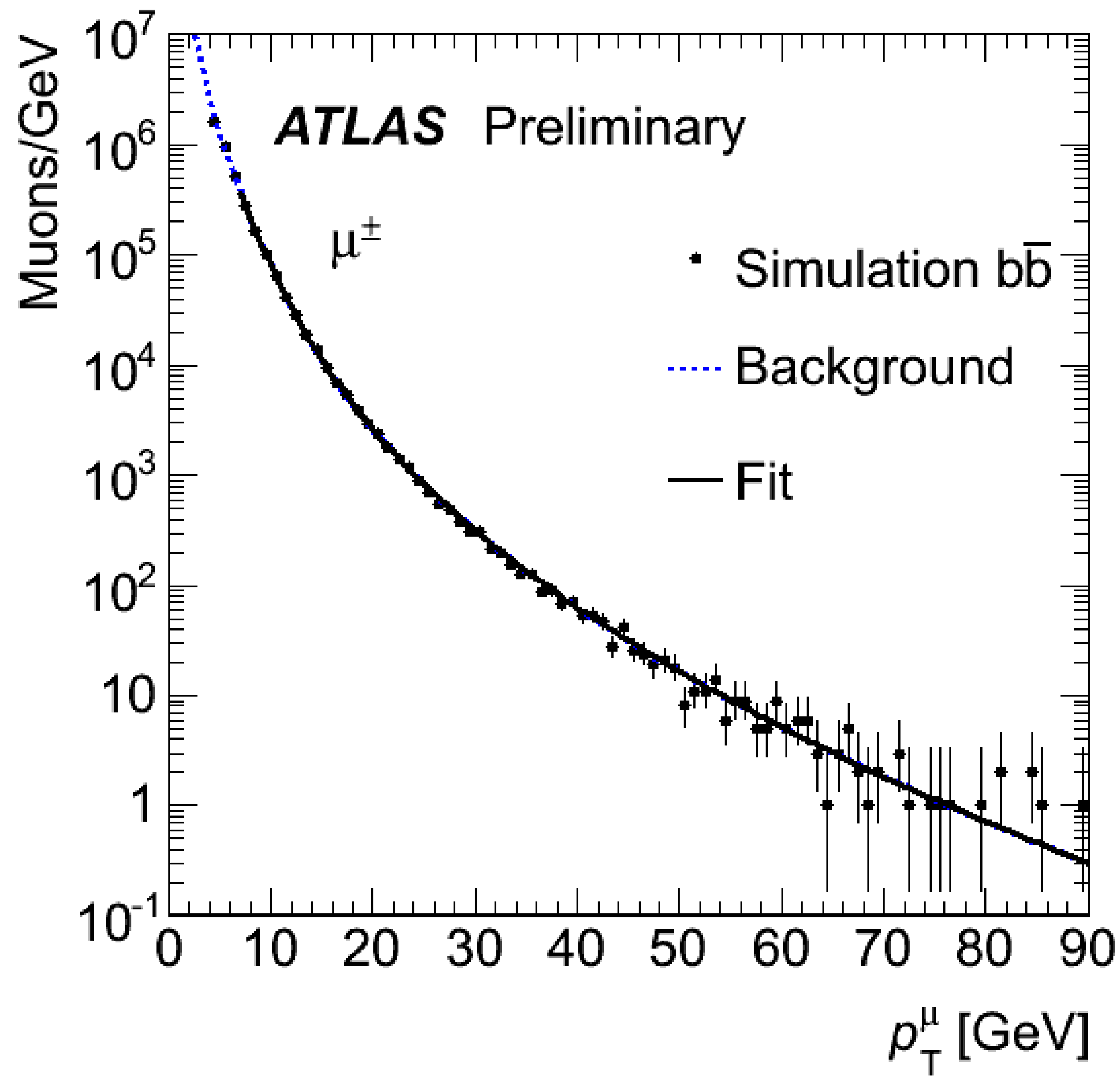
Centrality	R_{coll}	Uncertainty
0-10%	19.5	5.3 %
10-20%	11.9	4.7 %
20-40%	5.7	3.2 %
40-80%	1.0	–

W and Z Events Selection

- W Analysis:
  - Combined muon
  - $|\eta| < 2.5$
  - Track quality: BLayer hits > 0, Pixel hits > 0, SCT hits > 5, (Pixel holes + SCT holes) < 2
  - Two charges from Inner Detector (ID) and Muon Spectrometer (MS) measurements must be identical
  - Momentum in ID must be within 50% equal to momentum in MS
  - π and k rejection: cut on track scattering angles
- Z Initial Analysis:
  - Two combined muons with opposite charge
  - $p_T(\mu_1, \mu_2) > 20$ GeV
  - $|\eta| < 2.5$
  - Cosmics rejection: $|\eta_1 + \eta_2| > 0.01$
  - $66 < m_{\mu\mu} < 116$ GeV
- Z Later Analysis for W/Z Ratio:
  - Same muon quality selection as for W
  - Z selection above
  - Both muons must have a common vertex

Cross-check of W Fitting Technique

- Fit Tested on bb MC sample
  - Estimated number of W is 0 (+11.5 -0)
  - χ2/NDoF = 89.7/75



Muon Pseudo-Rapidity