# LHC prospects: Quarkonia in pp collisions

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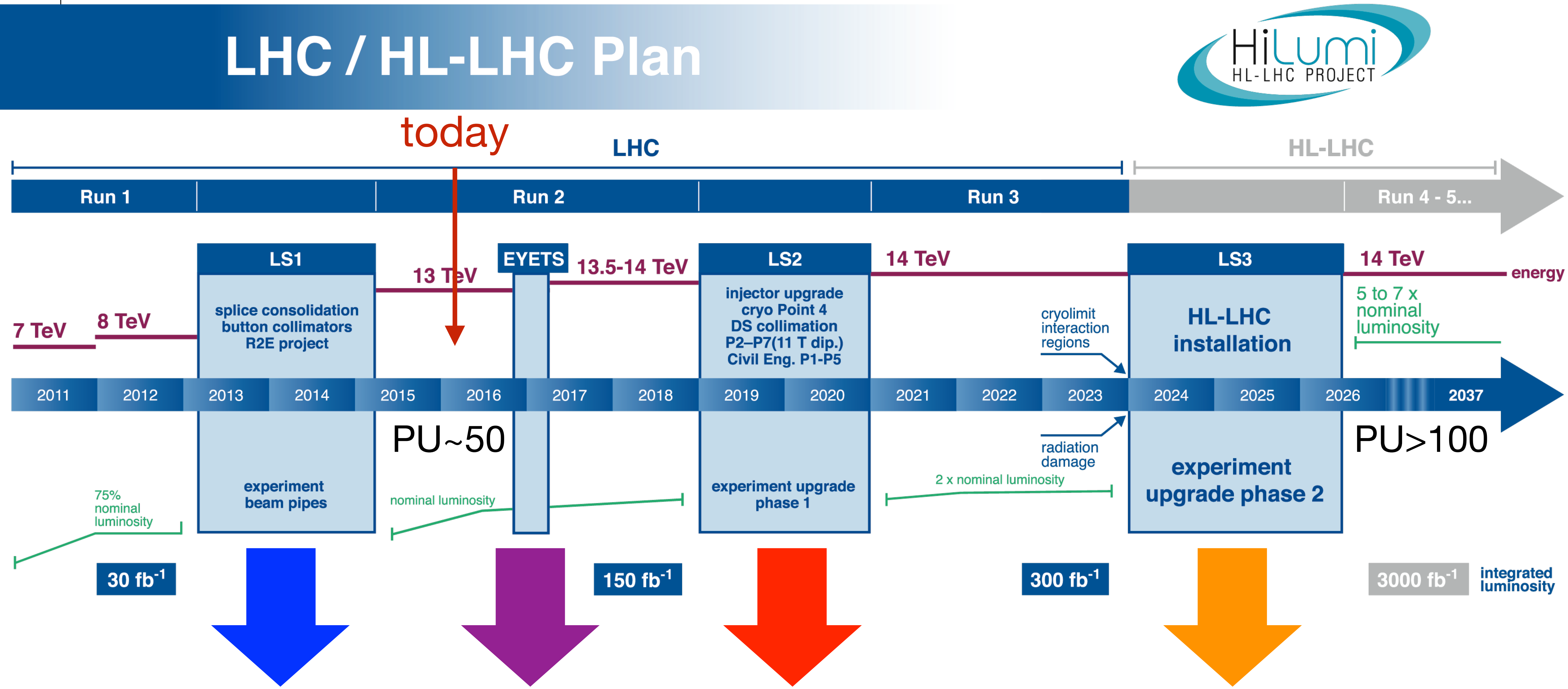
Excellence Cluster Universe - TU München

ECT* Workshop: Quarkonium 2016
March 4th, 2016

Excellence Cluster Universe

Technische Universität München

# Schedule




ATLAS:
- Insertable B-Layer
- Topological trigger

CMS:
- Muon endcaps

CMS:
- Pixel upgrade

ALICE:
- GEM-TPC
- ITS upgrade
- MFT

ATLAS:
- New small muon wheel

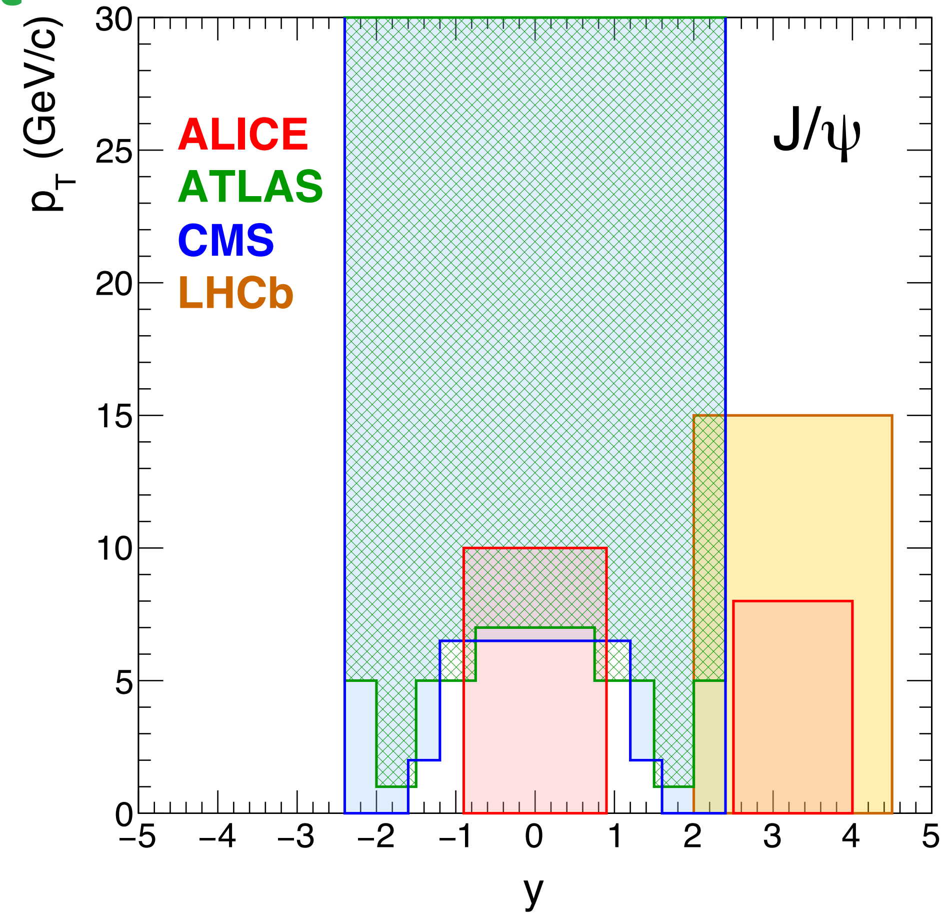
CMS:
- L1 muon and calo trigger
- Muon system

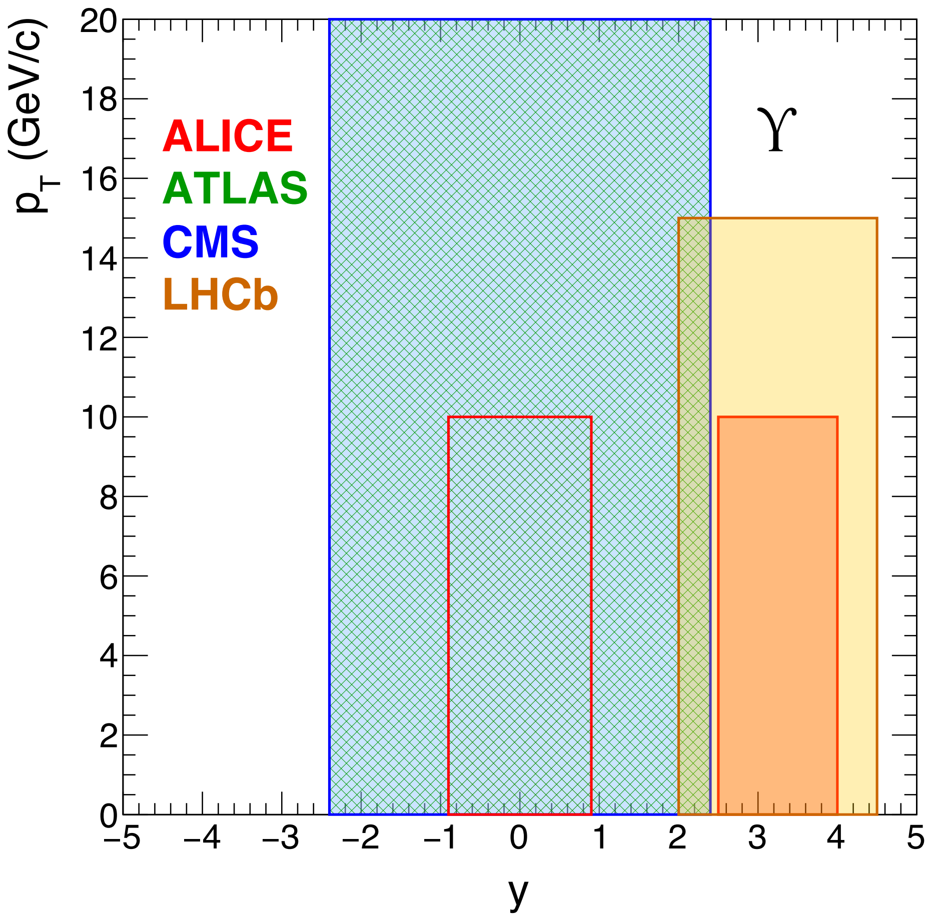
ATLAS:
- HI-LHC Tracker

CMS:
- New tracker out to |η|<4
- Additional muon redundancy possibly out to |η|<4

LHC/ HL-LHC Plan (last update February 22, 2016)

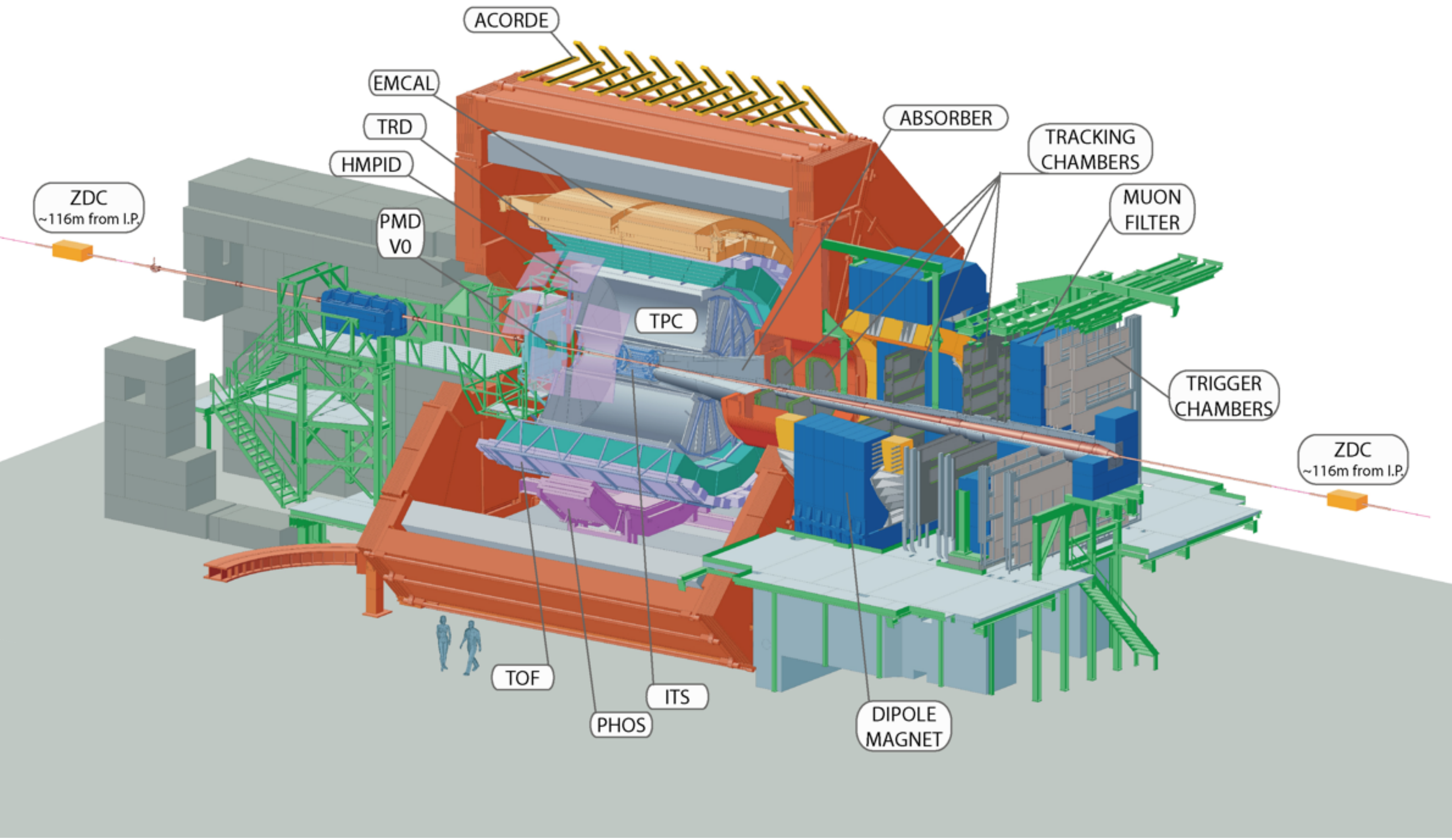
# Quarkonia Acceptance in pp



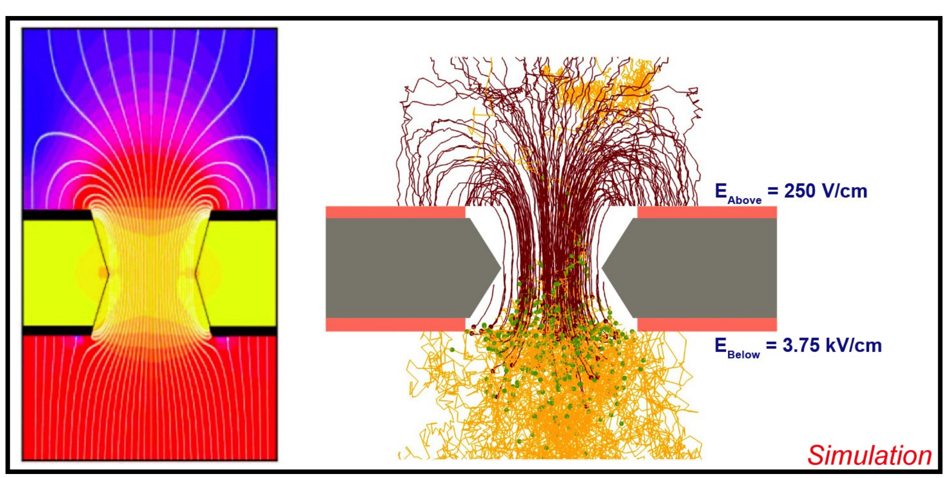

- ALICE: acceptance for $p_T > 0$
  - midrapidity: no absorber and low B field
  - forward rapidity: longitudinal boost
- ATLAS and CMS: Muons need to overcome strong magnetic field and energy loss in the absorber
  - minimum total momentum p~3–5 GeV/c to reach the muon stations
  - Limits J/ψ acceptance:
    - mid-rapidity: $p_T > 6.5$ GeV/c
    - forward rapidity: $p_T > 0$ GeV/c
    - (slightly higher thresholds for for ATLAS)
  - ϒ acceptance:
    - $p_T > 0$ GeV/c for all rapidity
- LHCb: acceptance for $p_T>0$
  - forward rapidity: longitudinal boost
  - occupancy limited

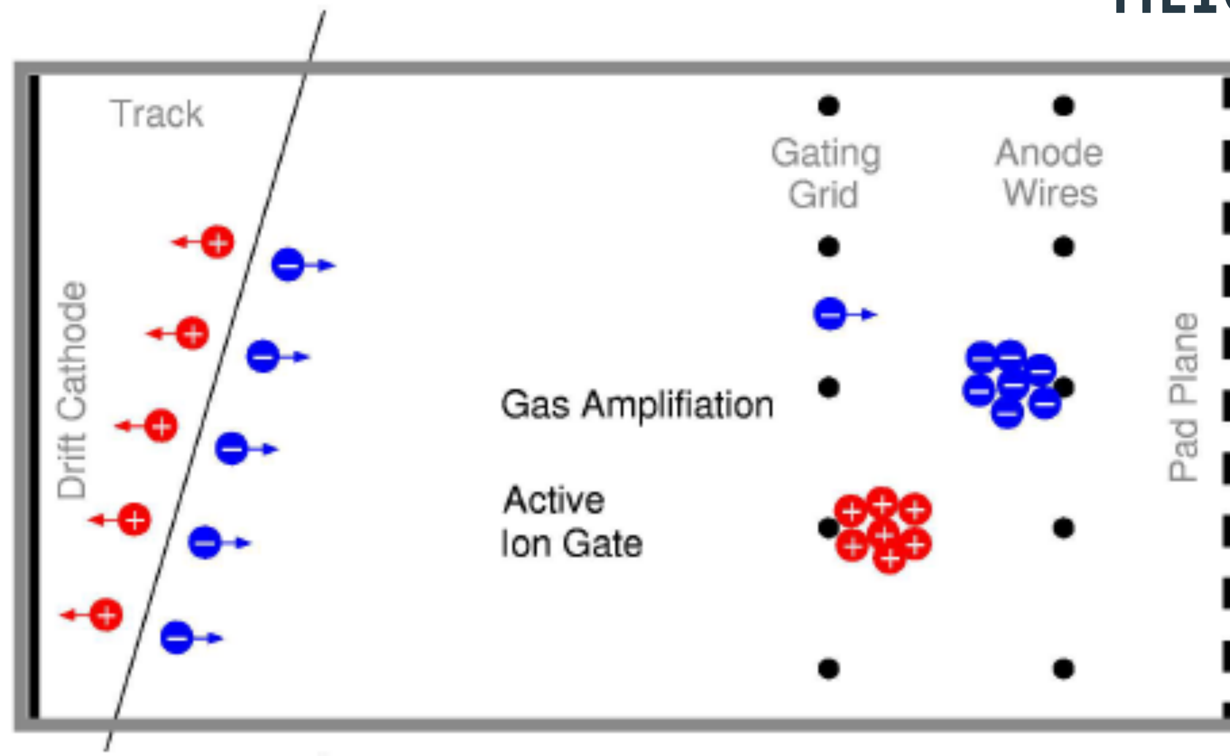
# ALICE

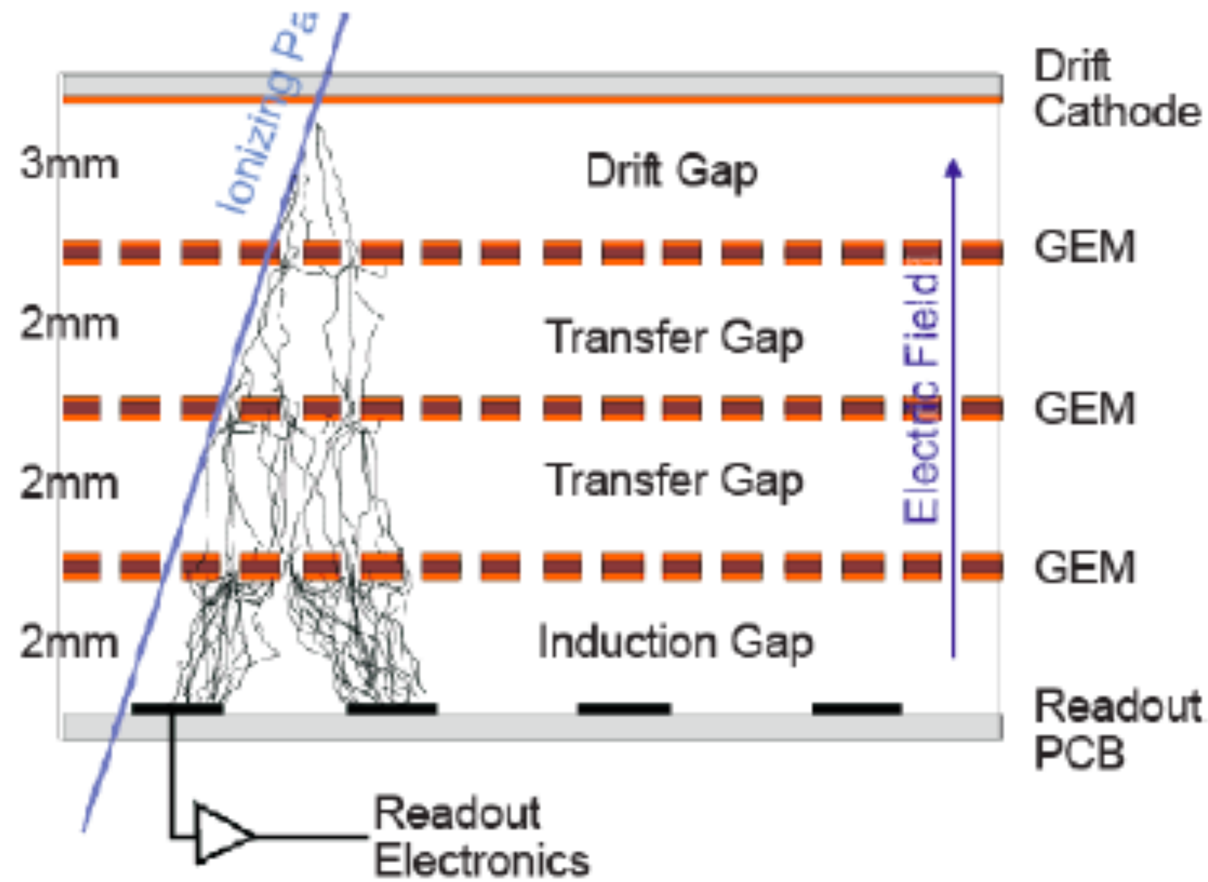

ACORDE
EMCAL
TRD
HMPID
ZDC
~116m from I.P.
PMD
V0
TPC
ABSORBER
TRACKING CHAMBERS
MUON FILTER
TRIGGER CHAMBERS
ZDC
~116m from I.P.
TOF
ITS
PHOS
DIPOLE MAGNET

# ALICE GEM-TPC

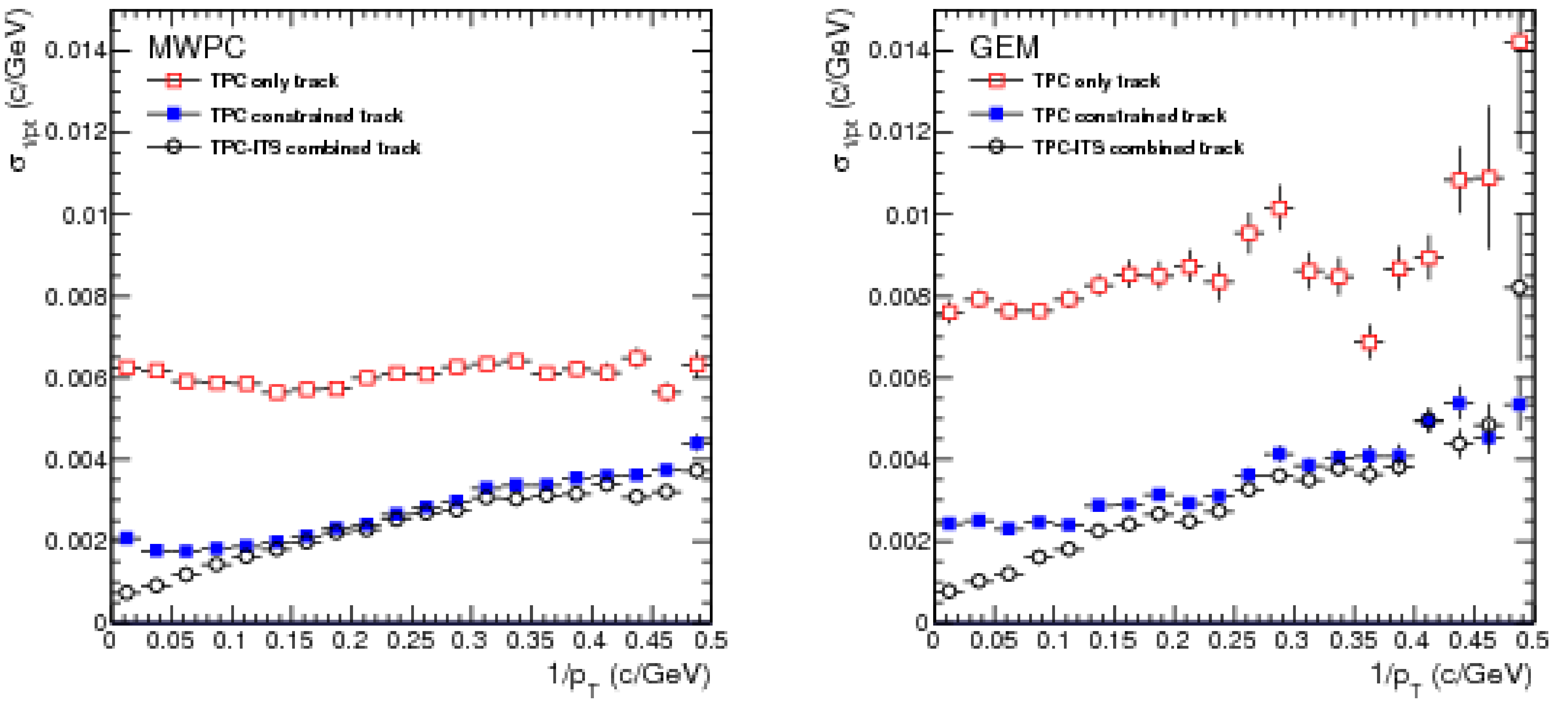
- Current TPC operation
  - 100 μs drift time + 280 μs gating
  - max. rate: 3.5 kHz!
- Expect PbPb rates of 50 kHz!
  - corresponds to 2 MHz pp
- Remove gating:
  - significant space charge distortion
  - incompatible with MWPC operation
- Answer: GEM readout
  - ~~triple~~ quadruple GEM stack
  - E-field configuration reduces ion back flow



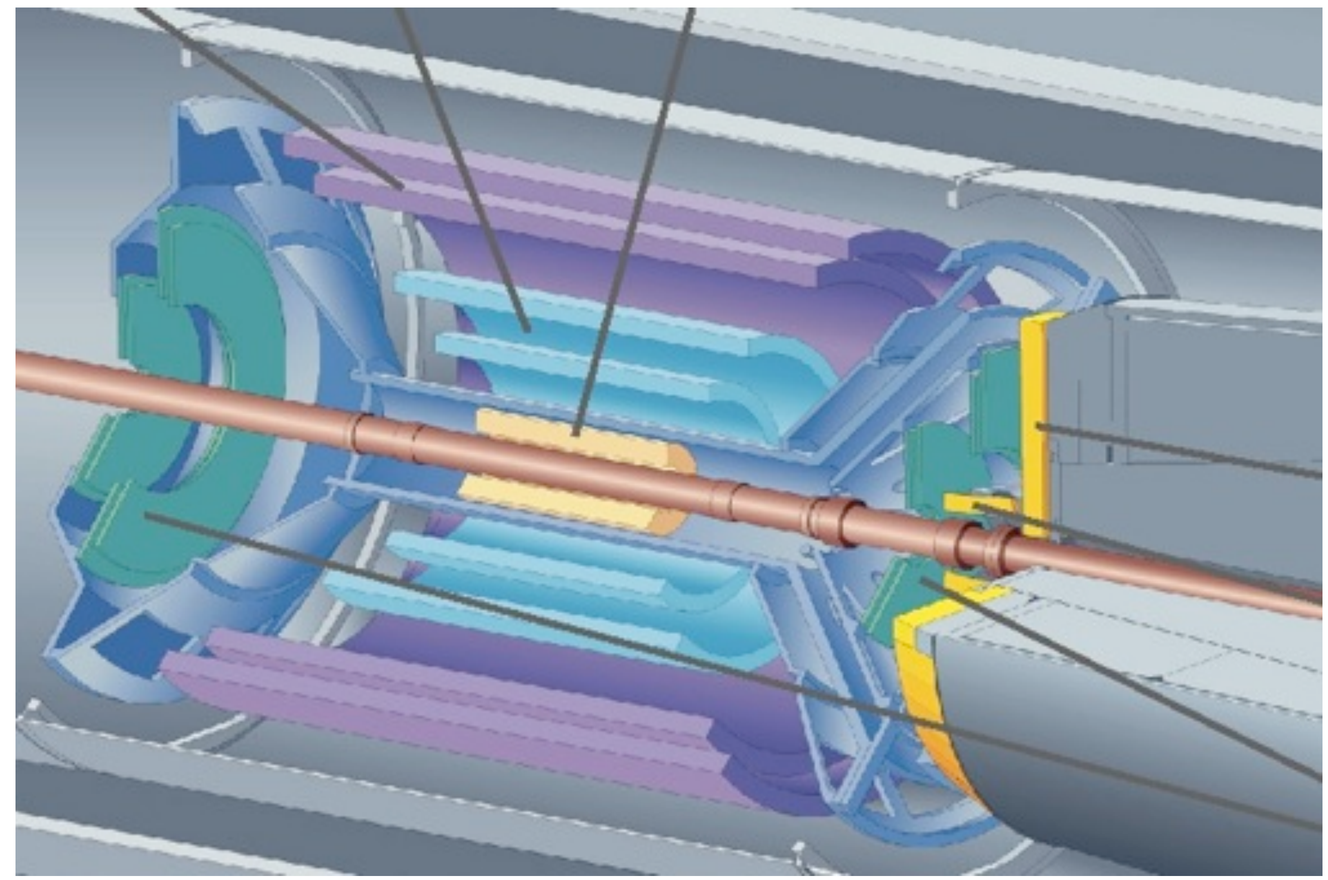
# Momentum Resolution




- Intrinsic momentum resolution worse with GEMs than MWPC
- Combination of ITS+TPC: no sizeable difference
- Also: preserve PID capability via dE/dx

# ALICE: Current ITS

- 6 concentric barrels, 3 different technologies
  - 2 layers of silicon pixel (SPD)
  - 2 layers of silicon drift (SDD)
  - 2 layers of silicon strips (SSD)
- Max. readout rate of ~1 kHz
  - limited by SDD



# ALICE: New ITS

1. Improve impact parameter resolution by ×3

- Get closer to IP (position of first layer): 39 mm → 22 mm
- Reduce material budget $X/X_0$ / layer: ~1.14% → ~ 0.3% (for inner layers)

2. Reduce pixel size
   currently 50 μm x 425 μm
   monolithic pixels → O(30 μm x 30 μm)

3. Improve tracking efficiency and $p_T$ resolution at low $p_T$

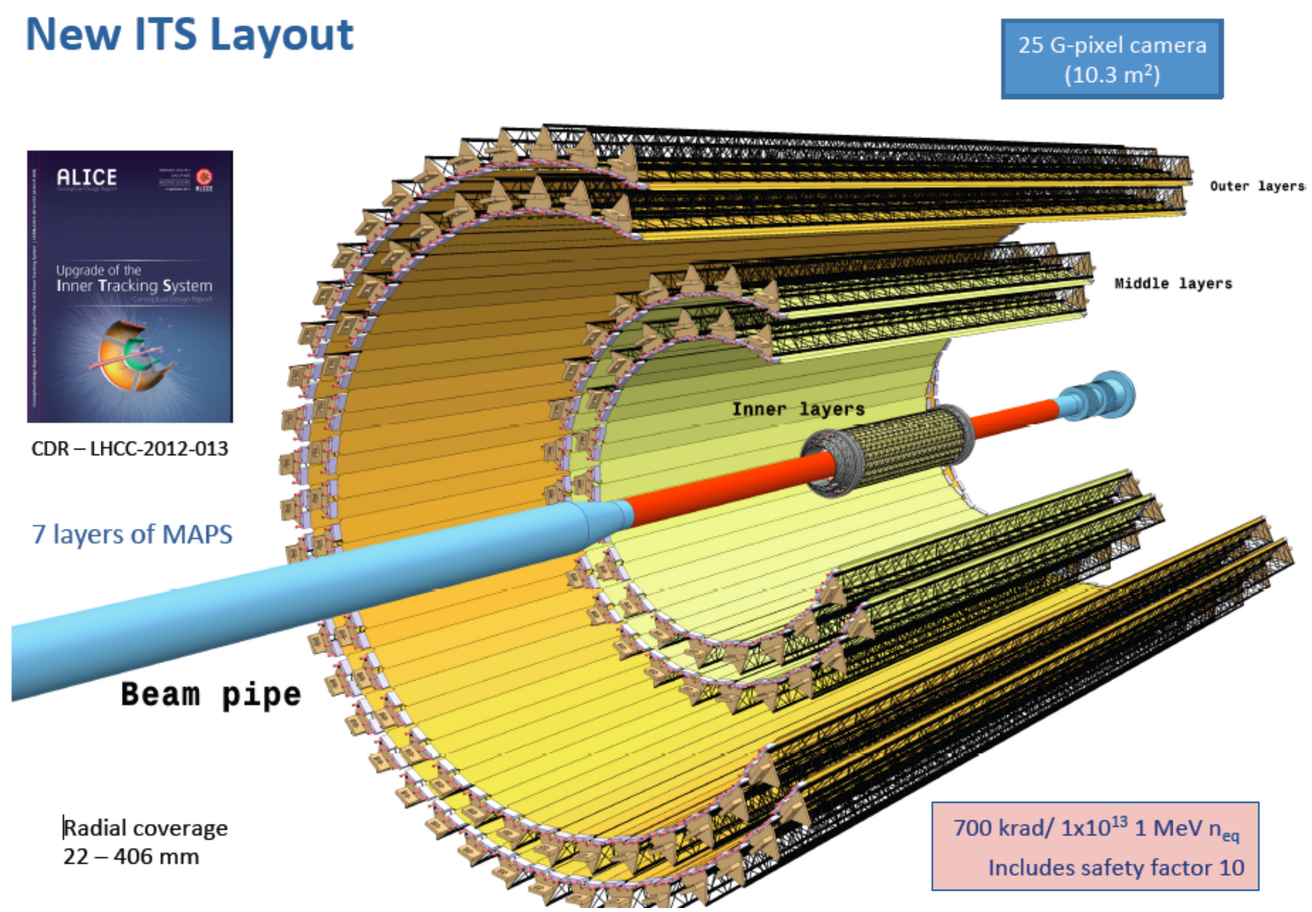
- Increase granularity: 6 layers → 7 layers, reduce pixel size

4. Fast readout

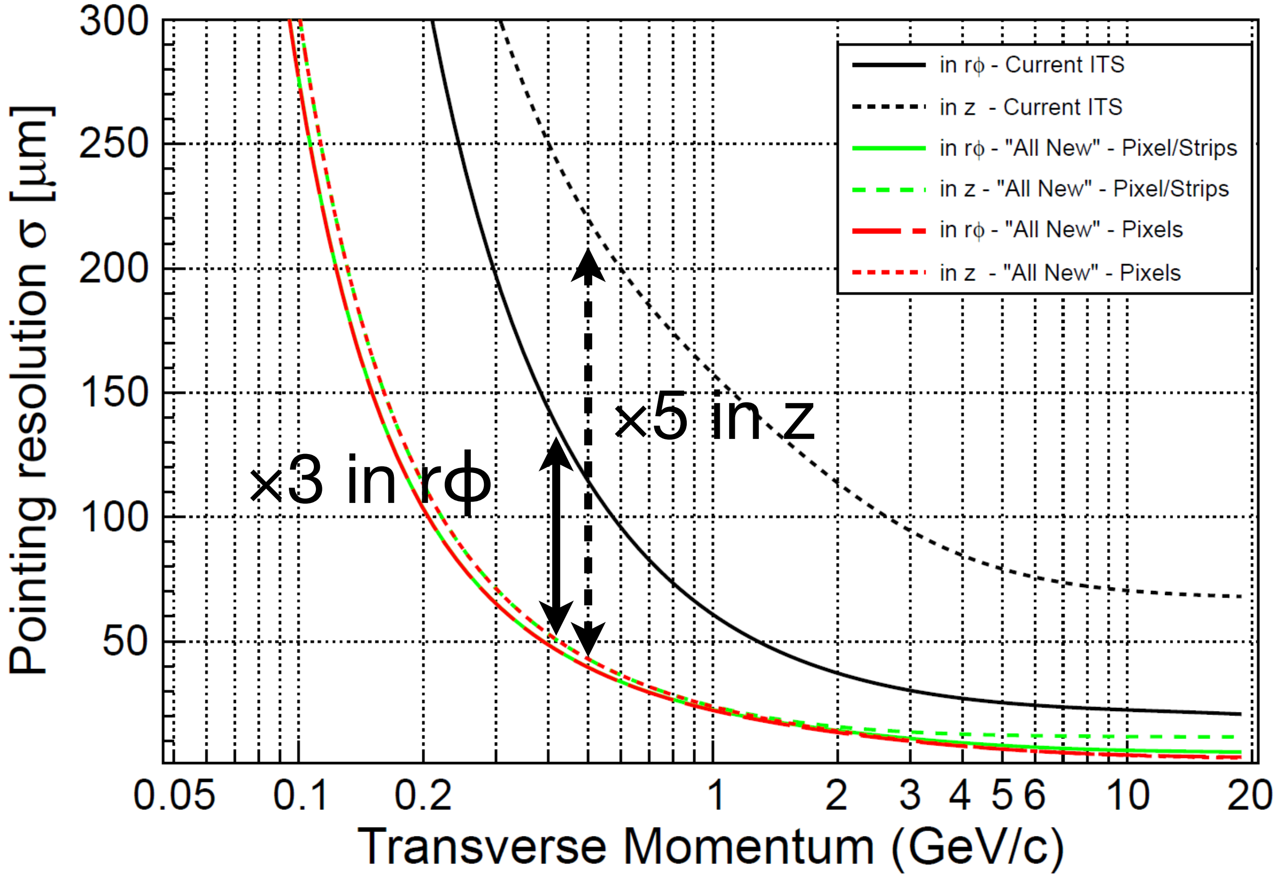
- readout of PbPb interactions at > 50 kHz and pp interactions at ~ 1 MHz

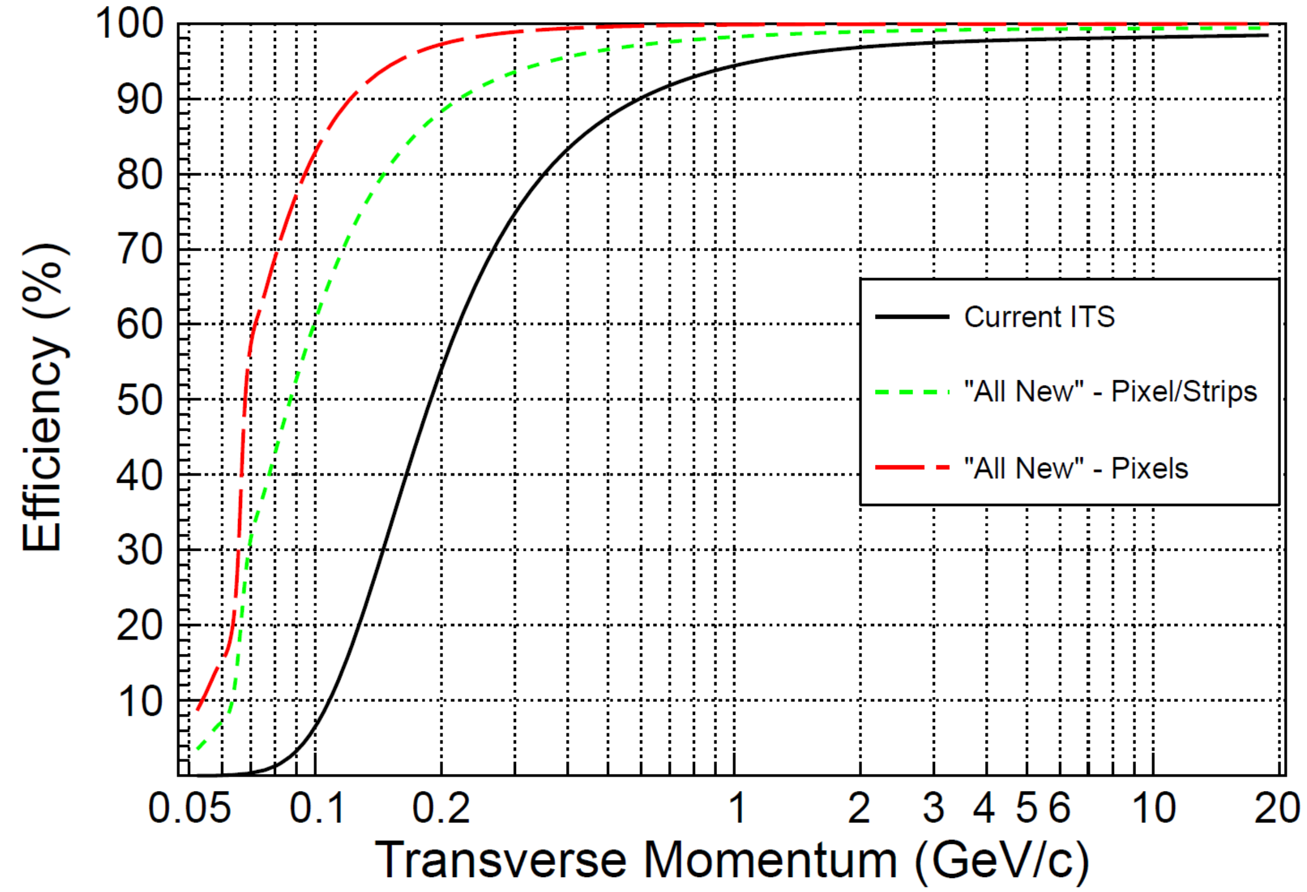
5. Fast insertion/removal for yearly maintenance

- possibility to replace non functioning modules during yearly shutdown



# New ITS: Resolution

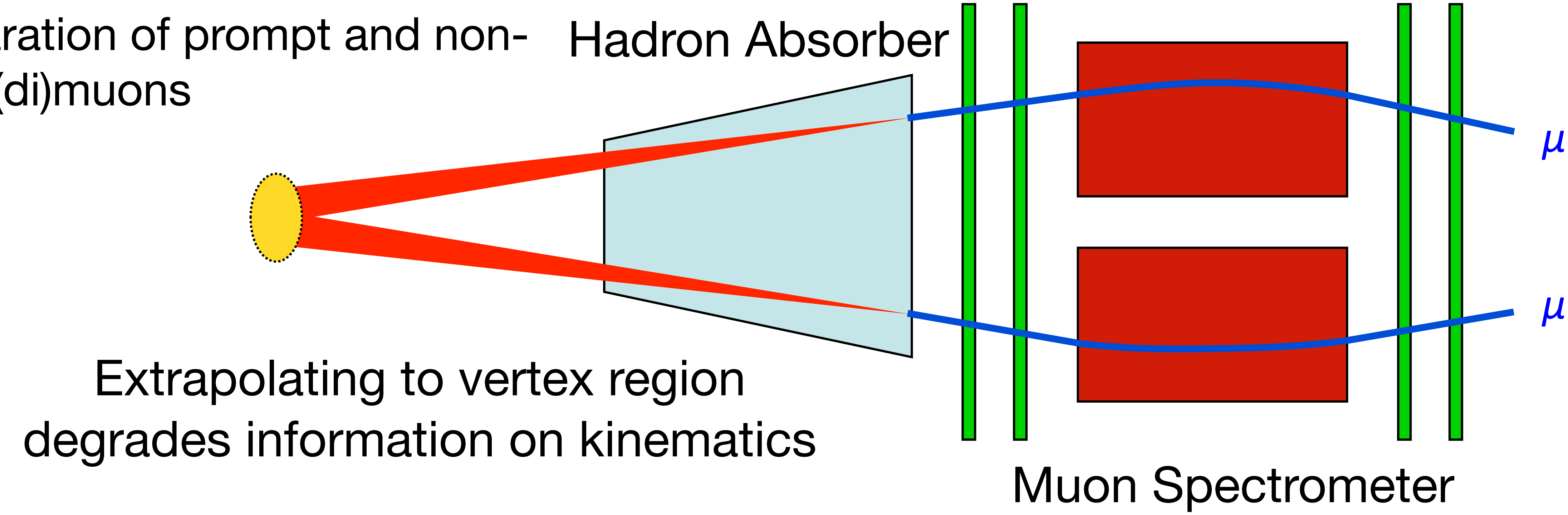



- 7 pixel layers
  - Resolutions: $\sigma_{r\phi}$ = 5 μm, $\sigma_z$ = 5 μm for all layers
  - Material budget: $X/X_0$ = 0.3% for 3 innermost layers and 0.8% for remaining 4
- no PID via dEd/x anymore (binary readout)

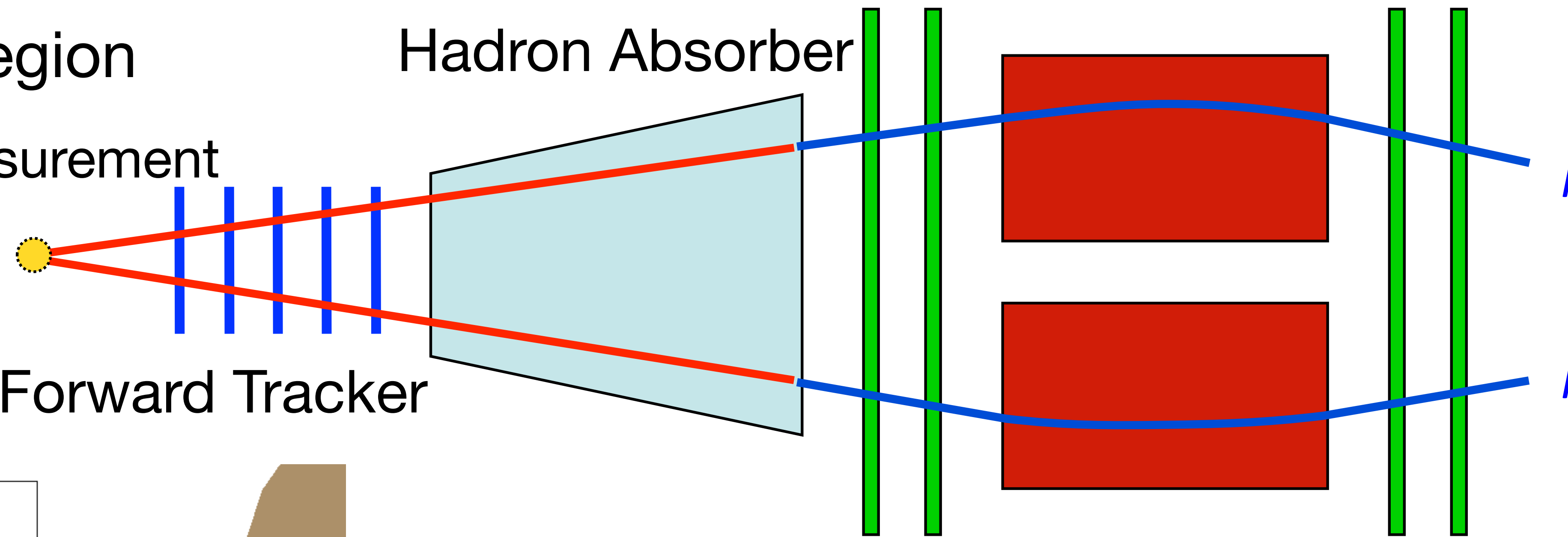
# Current Muon Arm

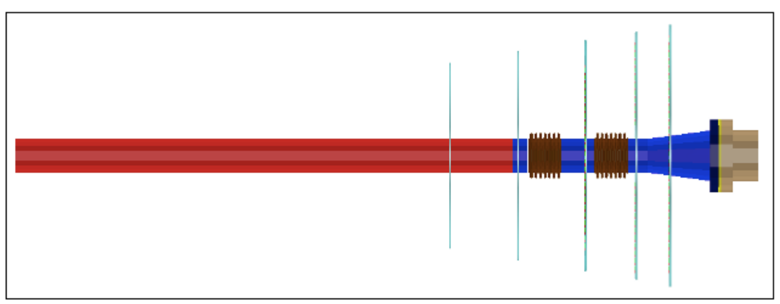
- Muons only measured after hadron absorber
  - No track constrains in vertex region
  - No separation of prompt and non-prompt (di)muons

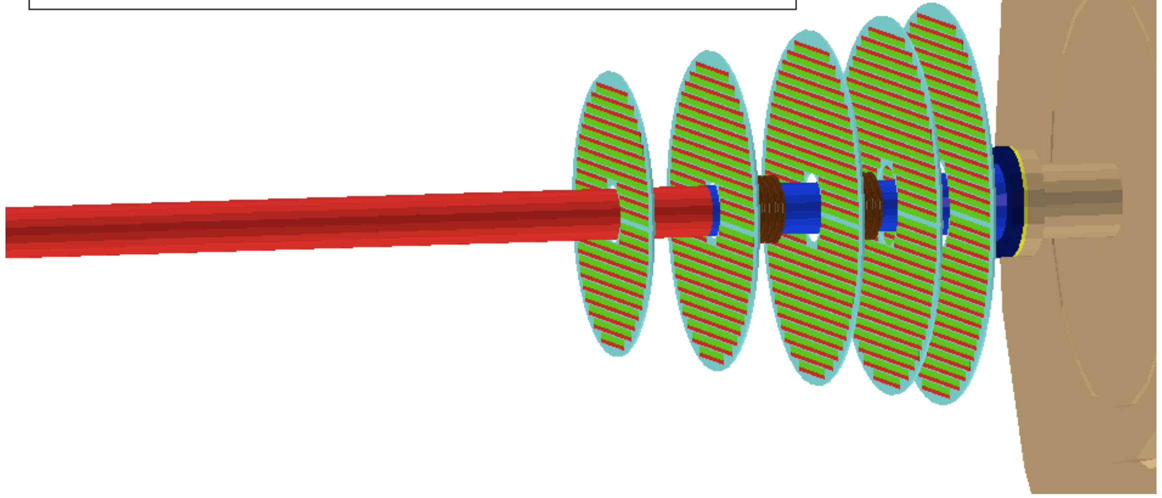


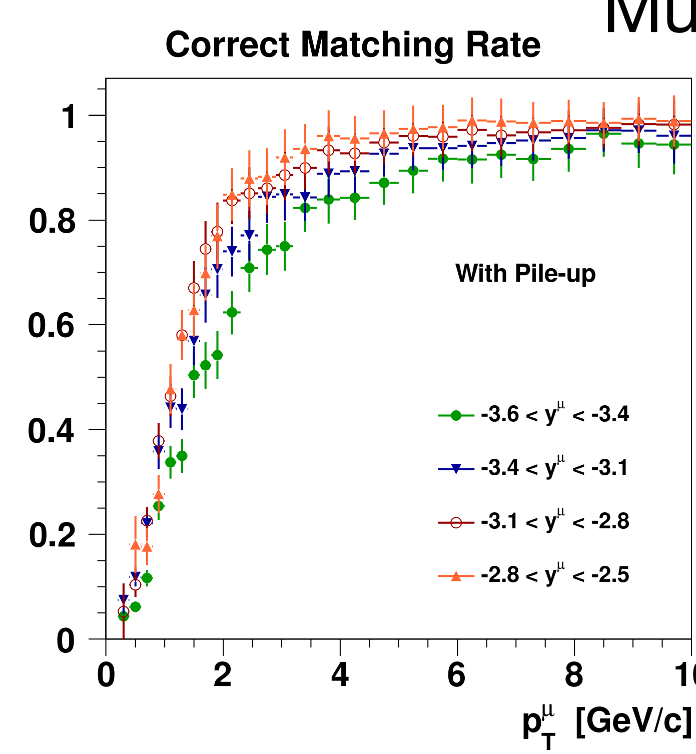
# MFT Upgrade

- Match tracks in MFT and Muon spectrometer
  - improve pointing accuracy in vertex region
- No B-field in MFT region
  - no momentum measurement



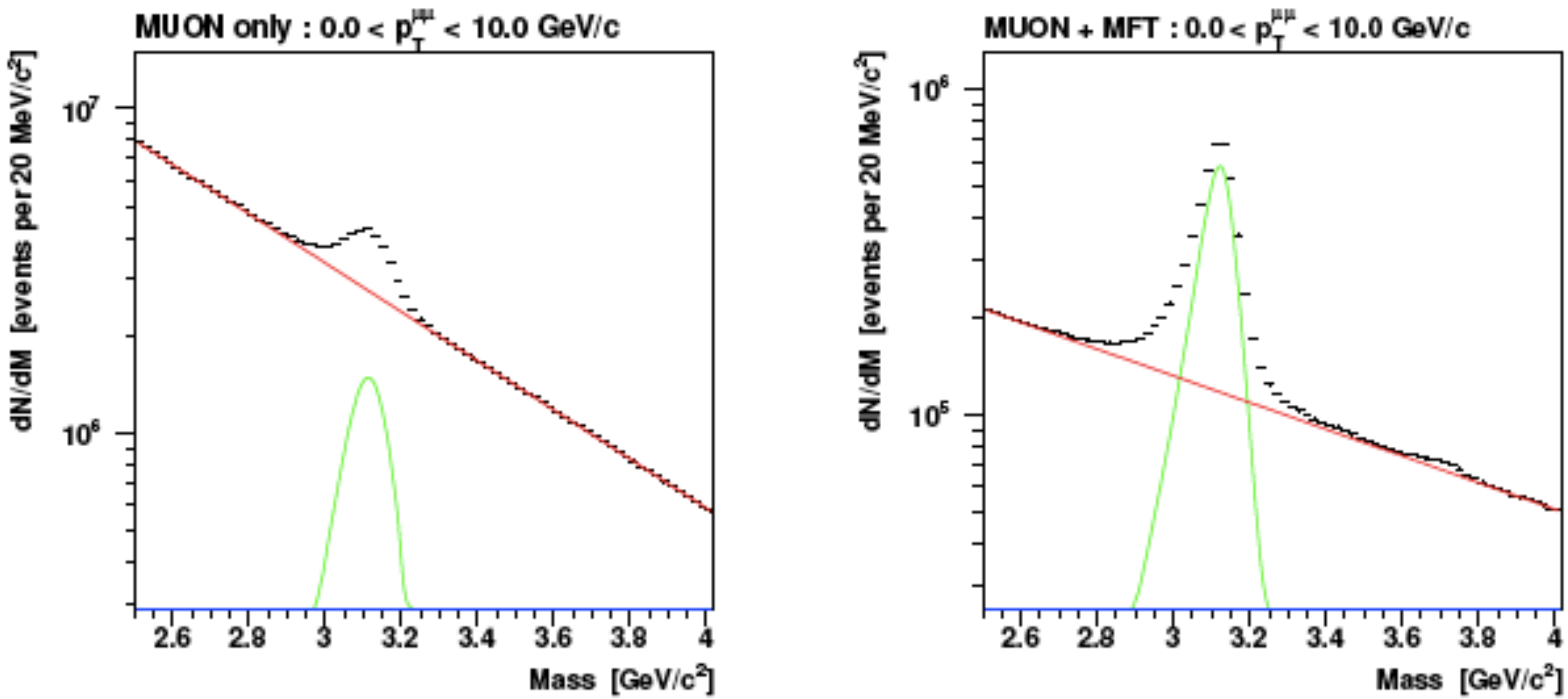







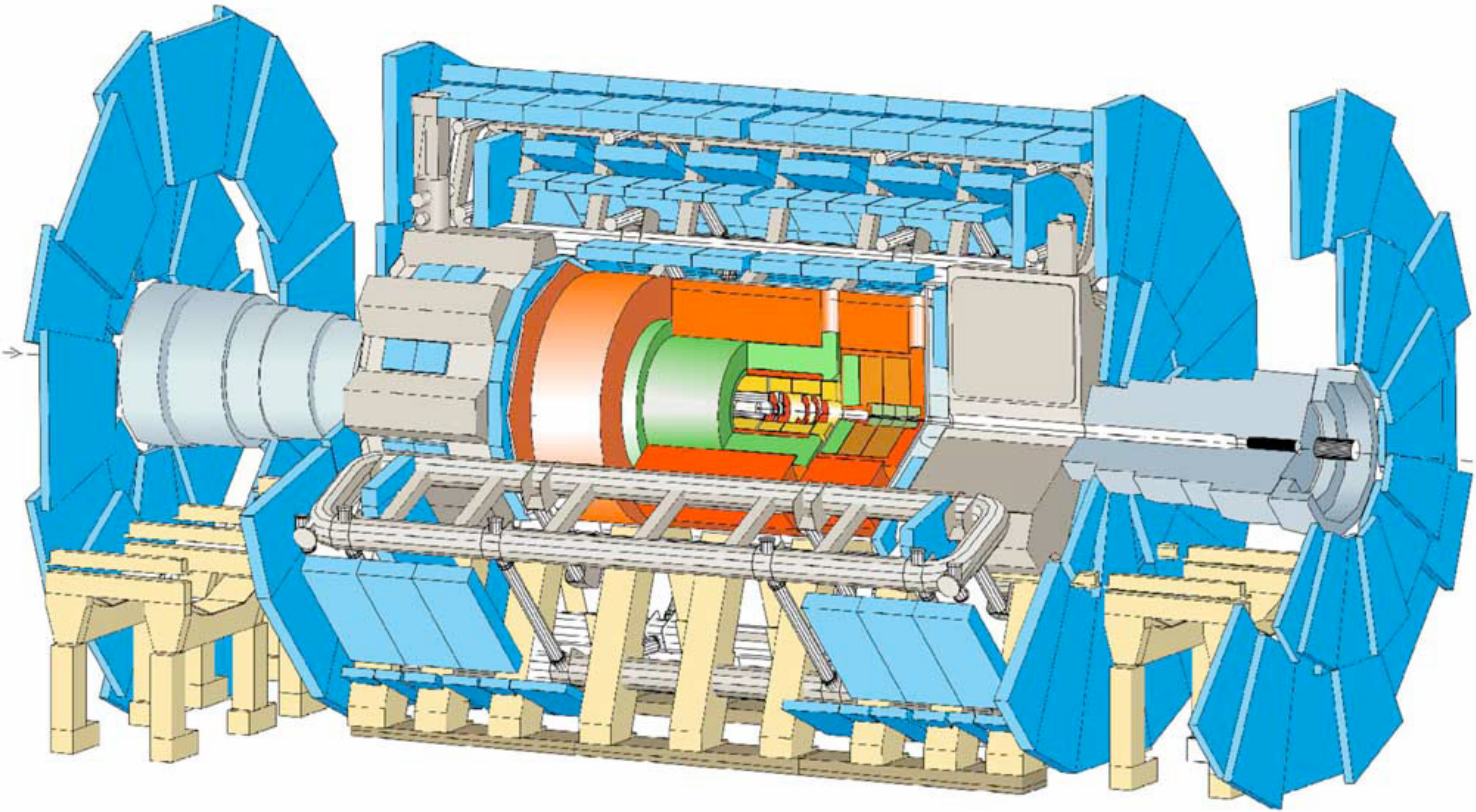

Matching inefficient for $p_T(\mu) < 1$ GeV/c

# Charmonia + MFT




- MFT matching
  - loss in signal (×3 after all cuts)
  - gain in S/B
    - relevant for systematic uncertainty
  - S/√(S+B) improves only at high $p_T$
    - relevant for statistical uncertainty

# ATLAS

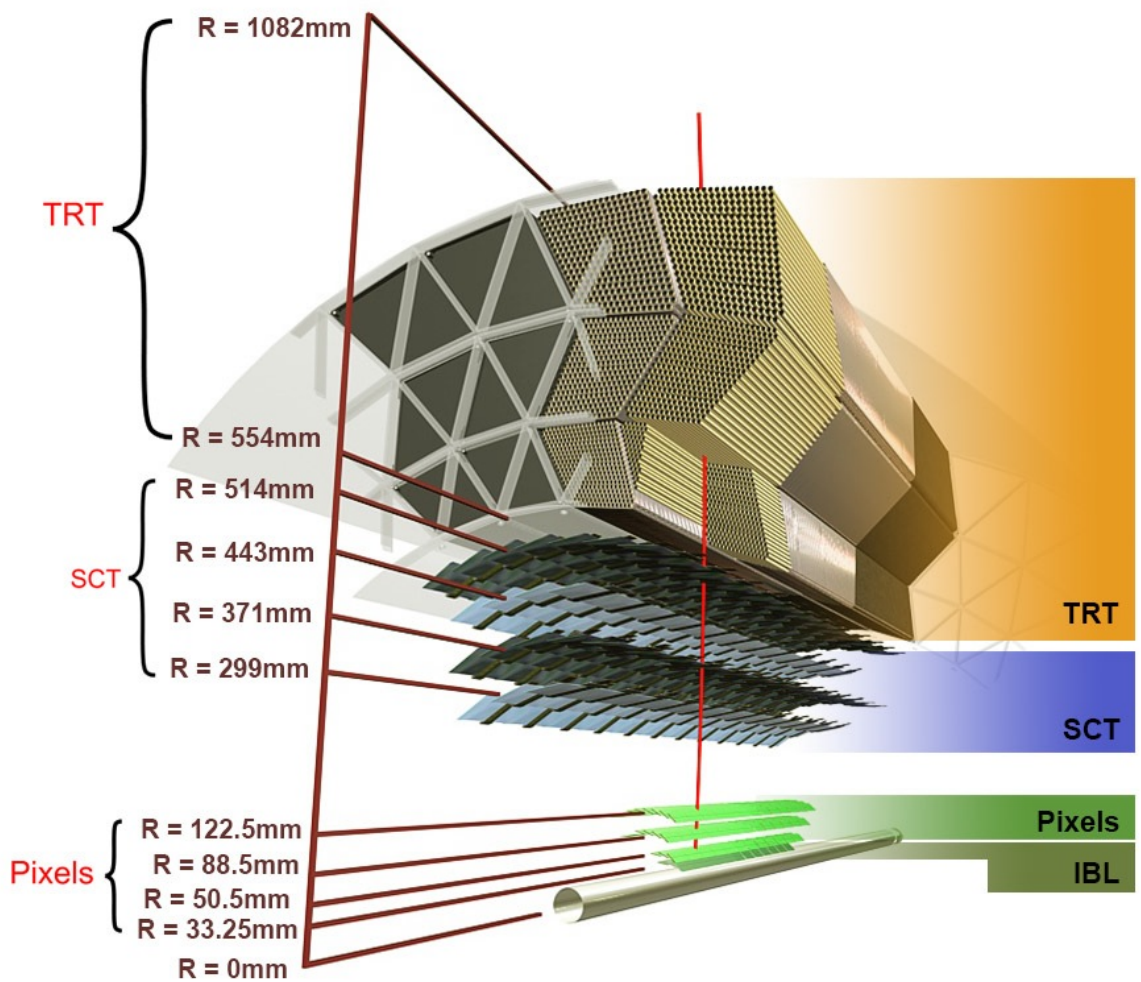


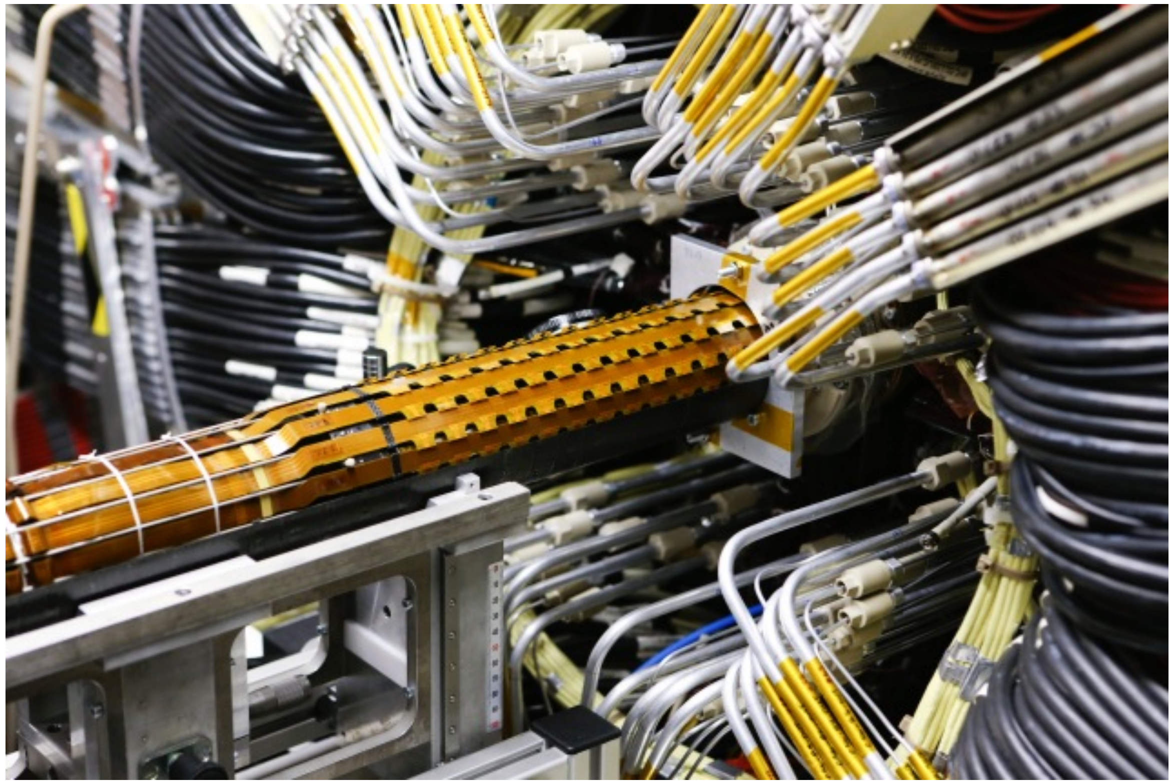
# ATLAS Prospects

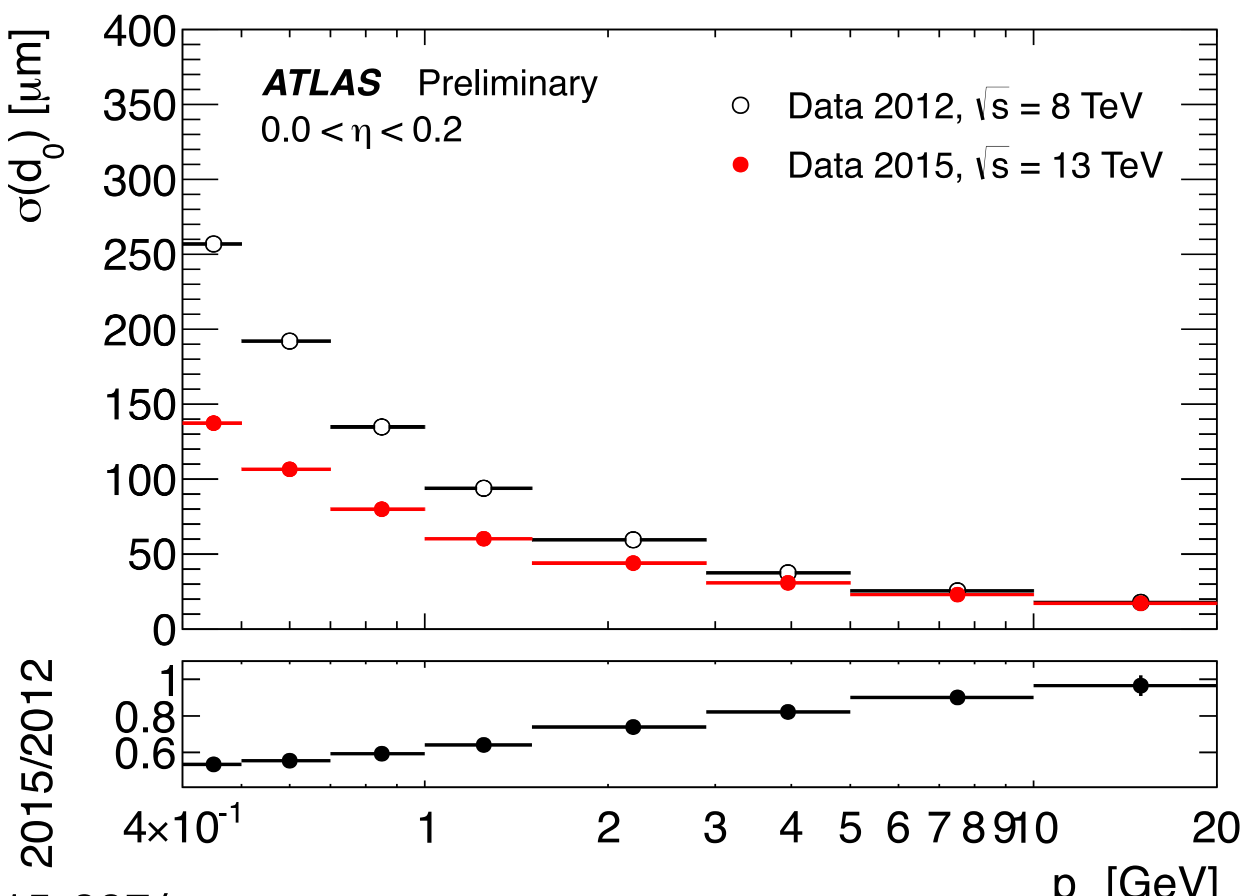
- Inclusive charmonium and bottomonium production
- Exotic quarkonium measurements and searches
- Associated production (quarkonia+quarkonia, quarkonia+open heavy flavour, quarkonia+vector boson)
- Polarisation measurements planned with the 13 TeV data.
- Rare Higgs decays with charmonium and bottomonium final states (search published in Phys. Rev. Lett. 114, 121801 (2015))

# Insertable B-Layer

- Installed during LS1
- Additional fourth Pixel layer
- Improved impact parameter resolution at low $p_T$



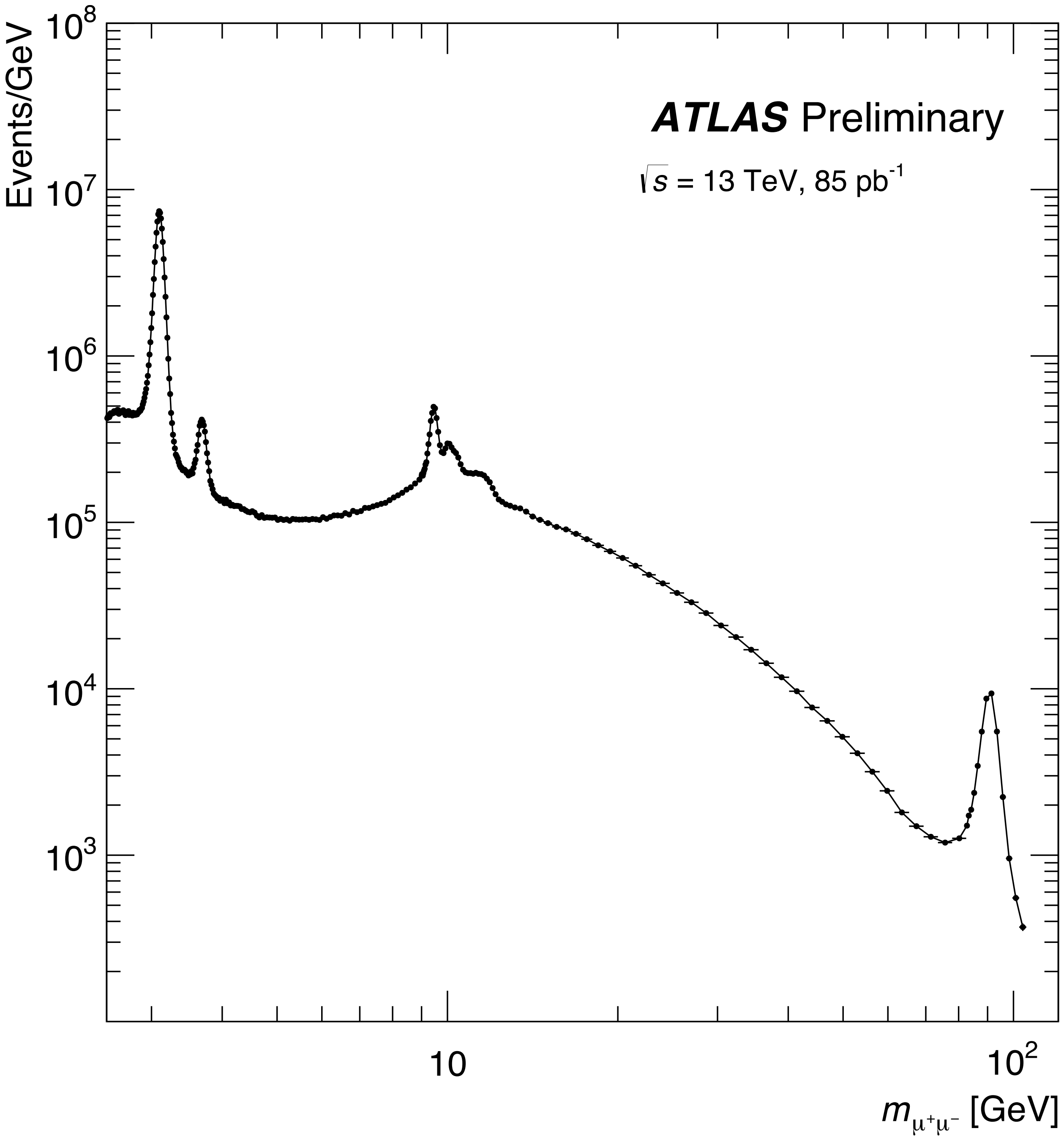


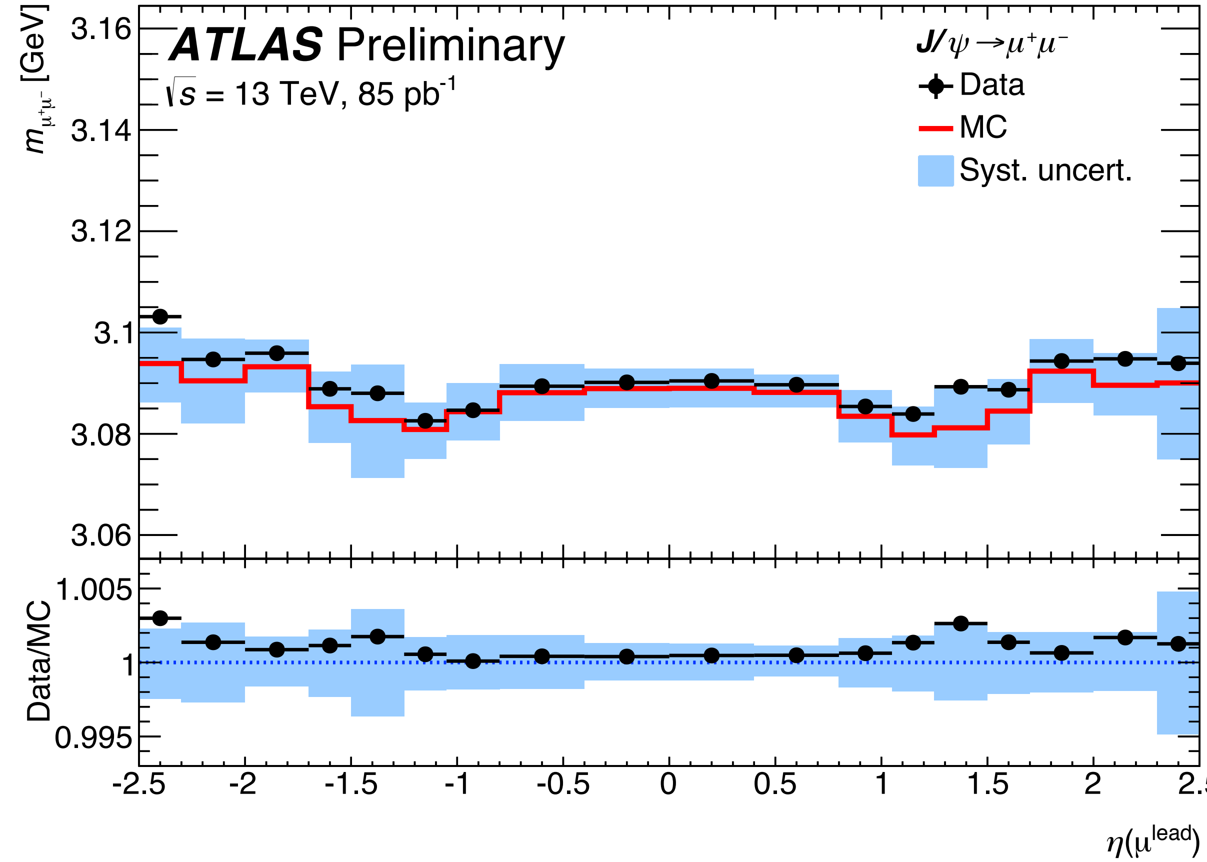

ATLAS-TDR-2010-013

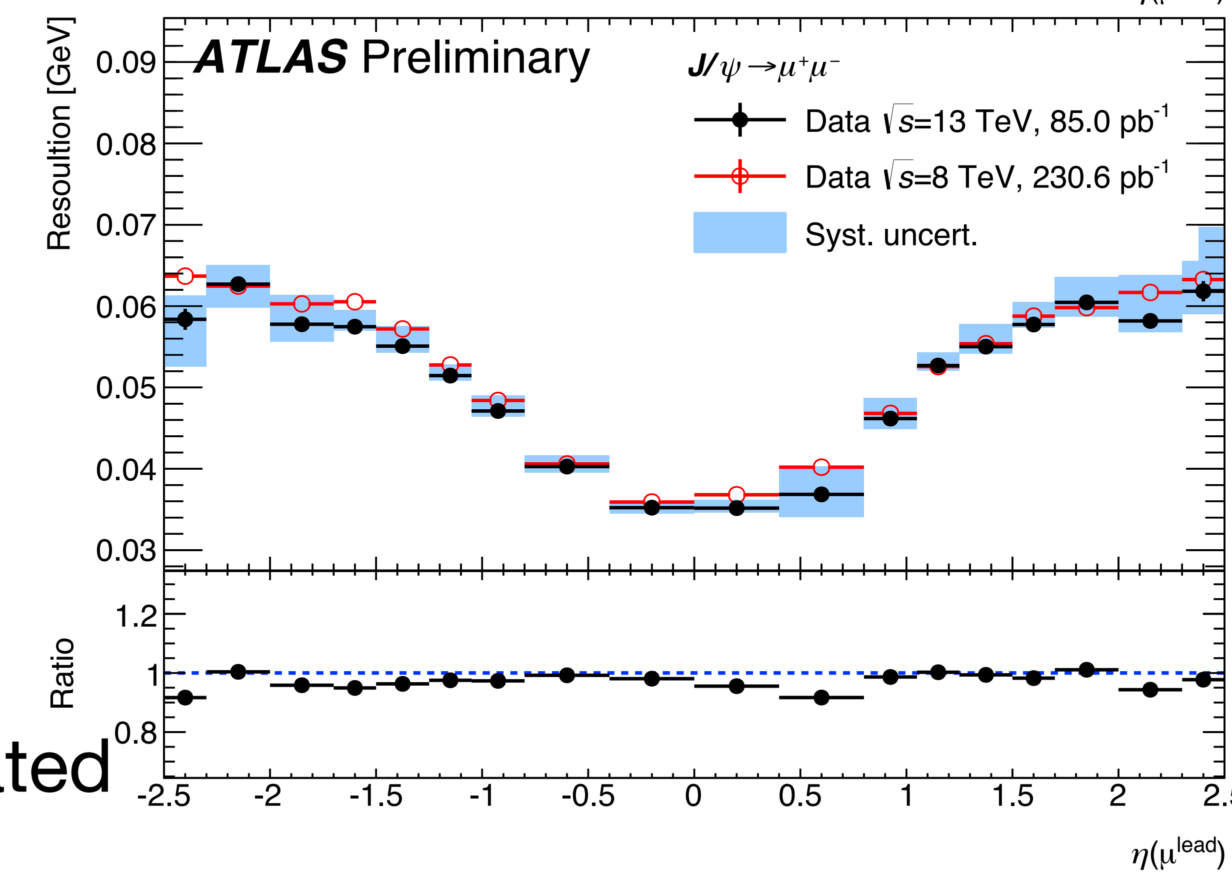
ATL-PHYS-PUB-2015-018

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2015-007/

# First look at Run 2

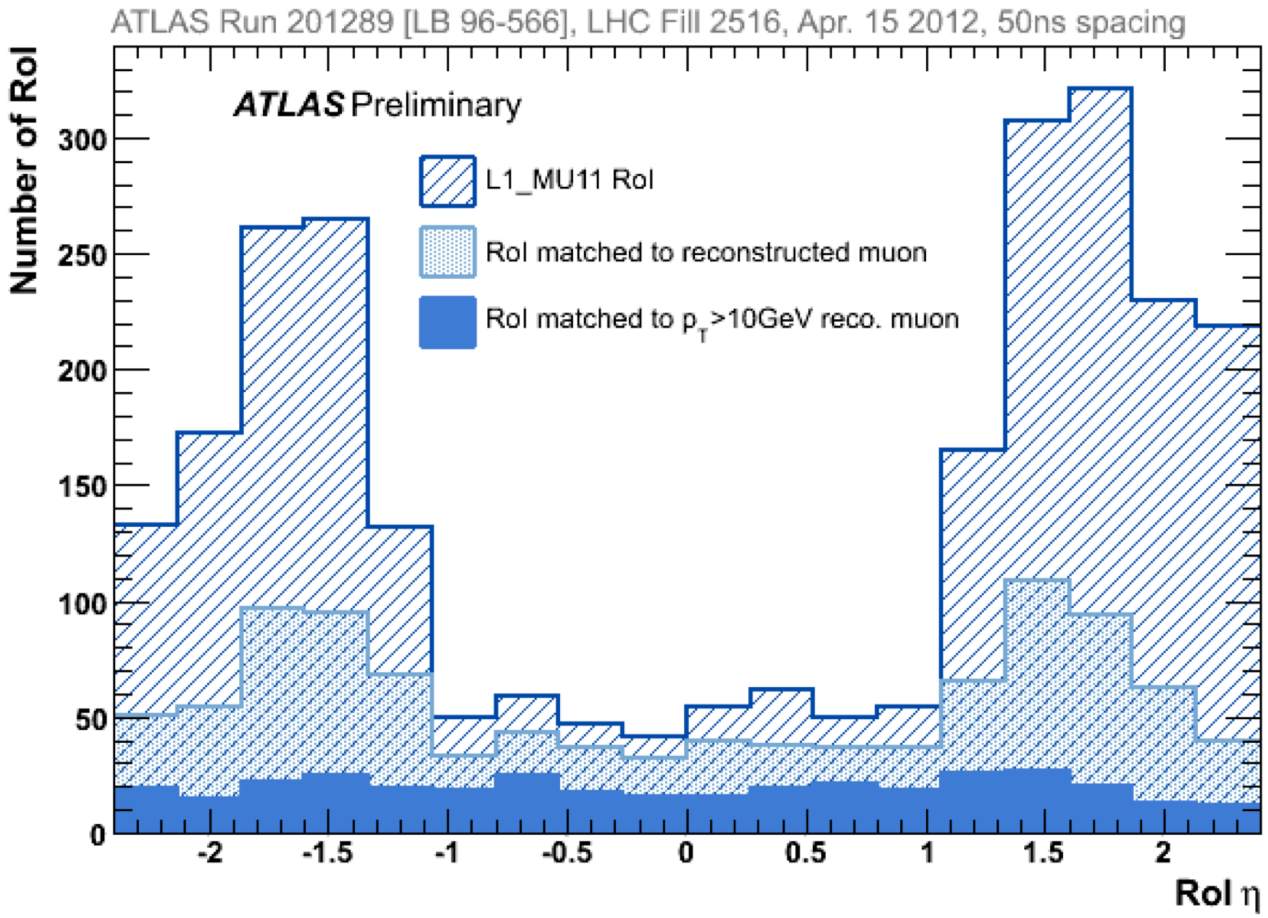


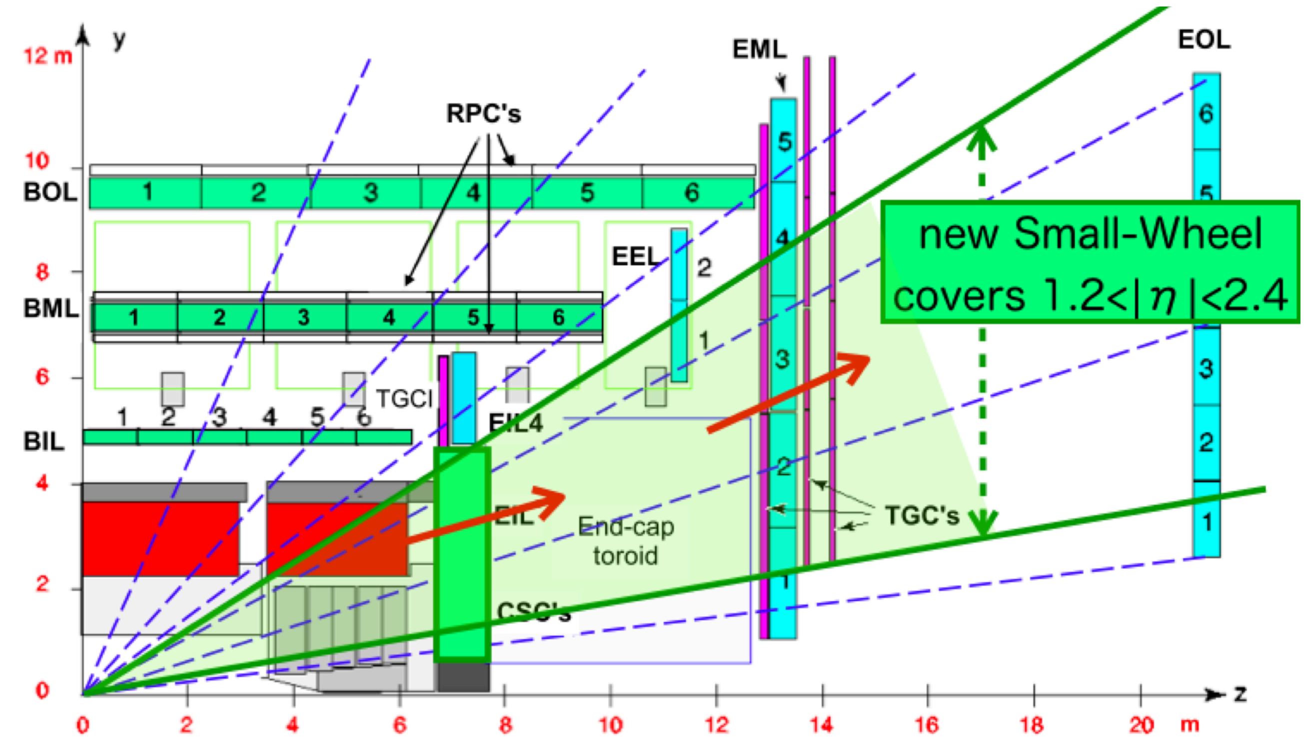




- Performance in early Run-2 well simulated
- Comparable to Run-1

# New Muon Small Wheel: LS2



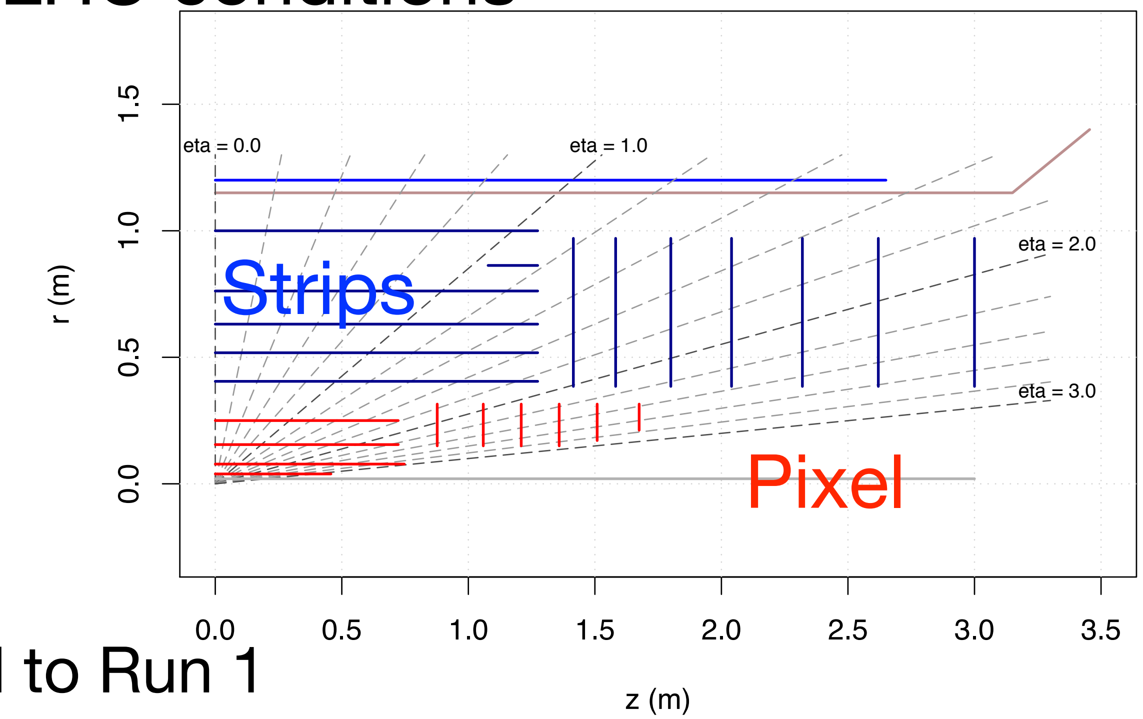



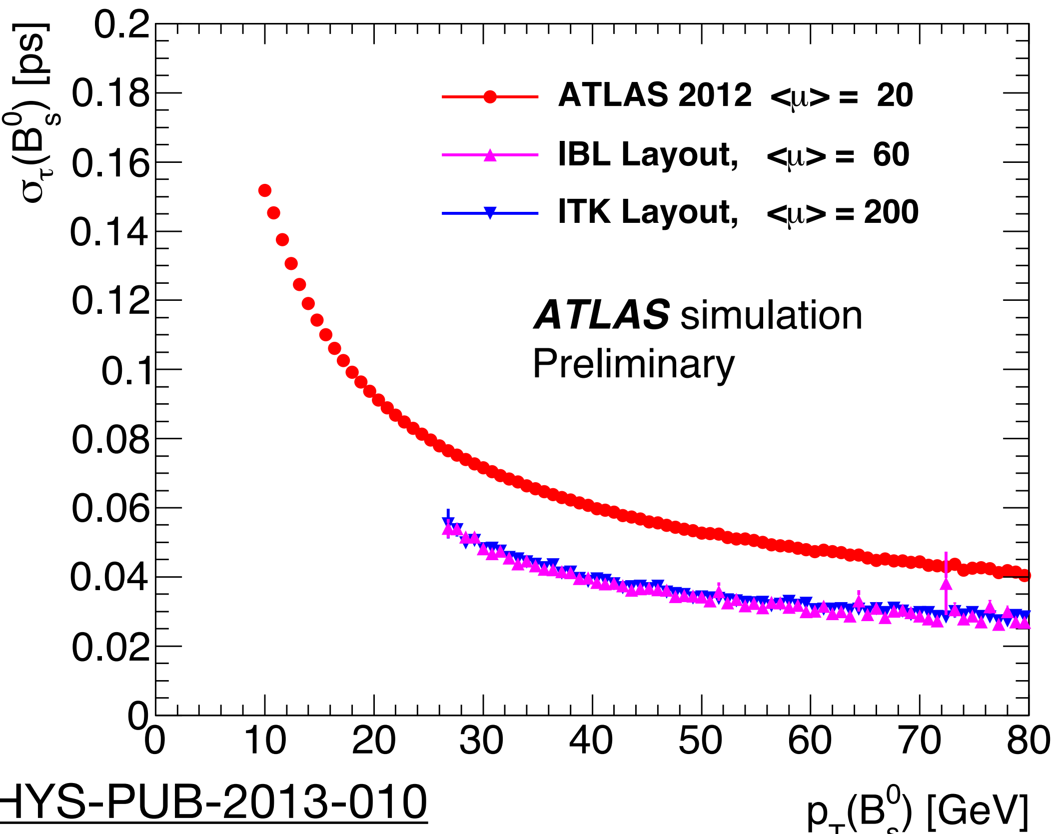

D. Price, Sapore Gravis Workshop 2014

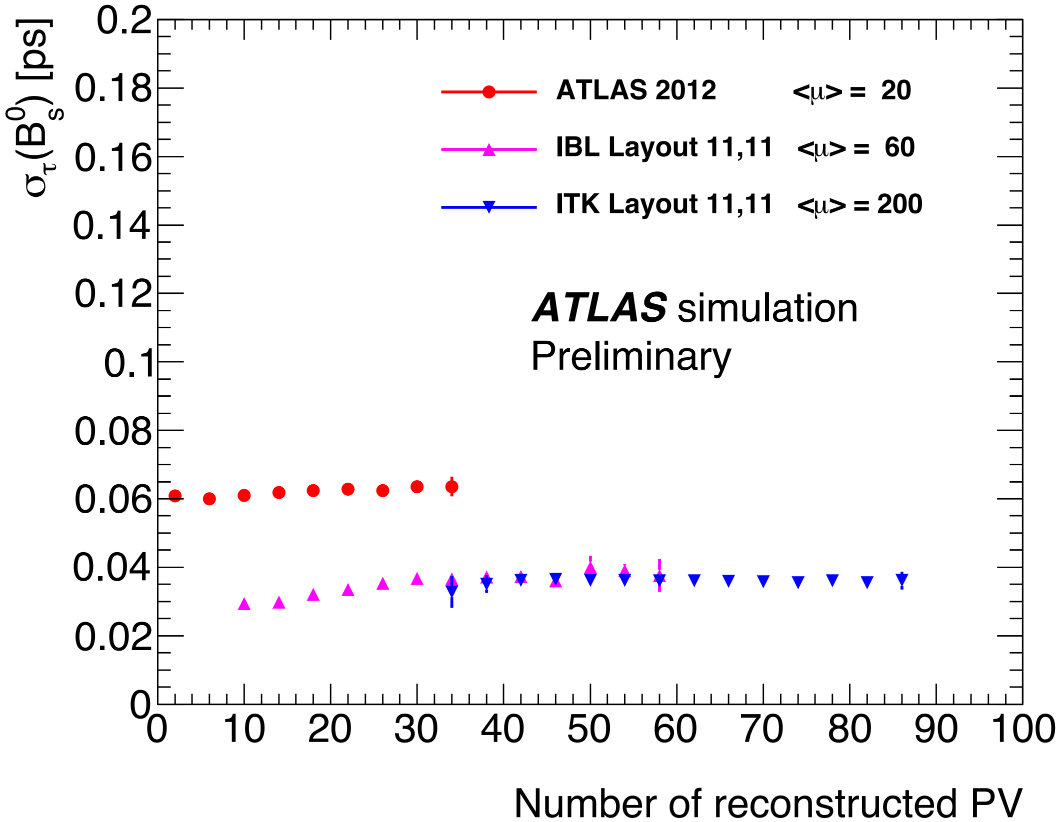
- Forward muon triggers suffer from high fake rate
- Additional trigger segment
- Designed to operate at $5\times10^{34}$ cm$^{-2}$s$^{-1}$
- Can afford more muon triggers with relatively low $p_T$ thresholds

# Inner Detector Upgrades: LS3

- Inner detector designed for $10^{34}$ $cm^{-2}s^{-1}$ and L1 rate of 100 kHz
- Unable to perform under future HL-LHC conditions
  - radiation damage
  - bandwidth saturation
  - occupancy due to high pile up
- ITK upgrade
  - 4x higher granularity
  - improves lifetime resolution compared to Run 1




ATL-PHYS-PUB-2013-010
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## Projections for onia / B-meson production



JHEP 1409 (2014) 79; arXiv:1407.5532

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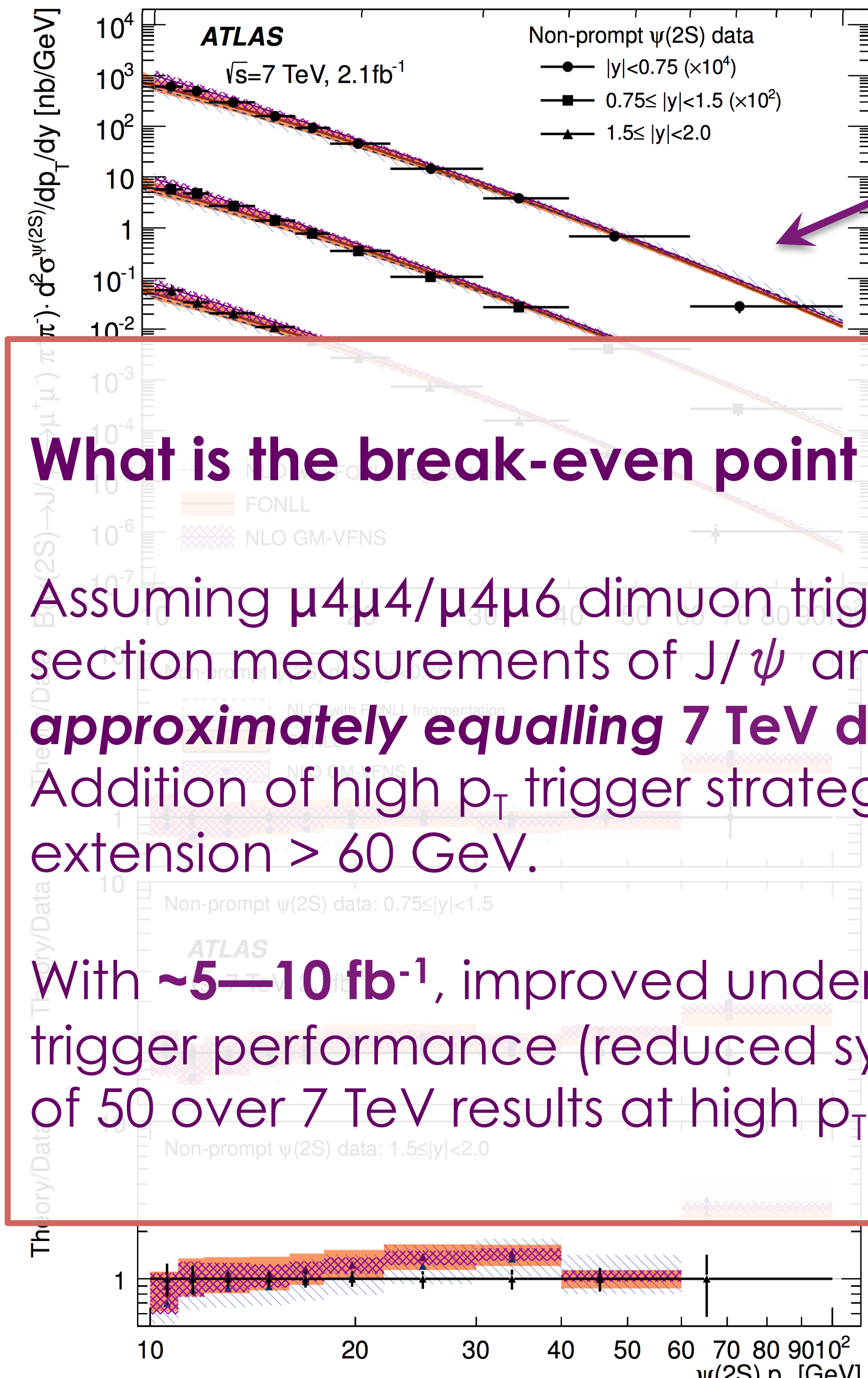
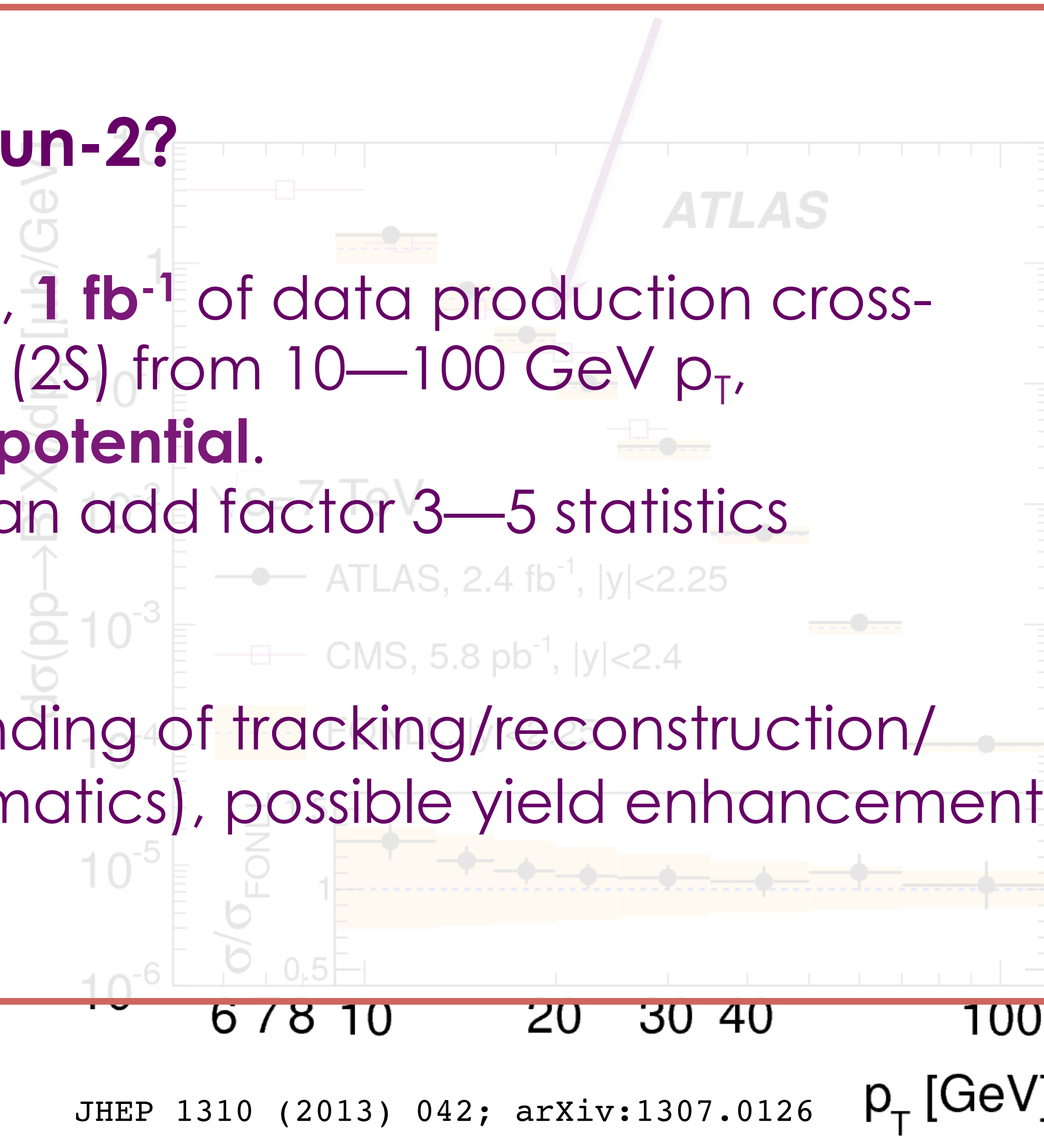



7 TeV $b \rightarrow \psi(2S)\, X$

7 TeV $B^+ \rightarrow J/\psi\ K^+$




JHEP 1310 (2013) 042; arXiv:1307.0126

**What is the break-even point in Run-2?**

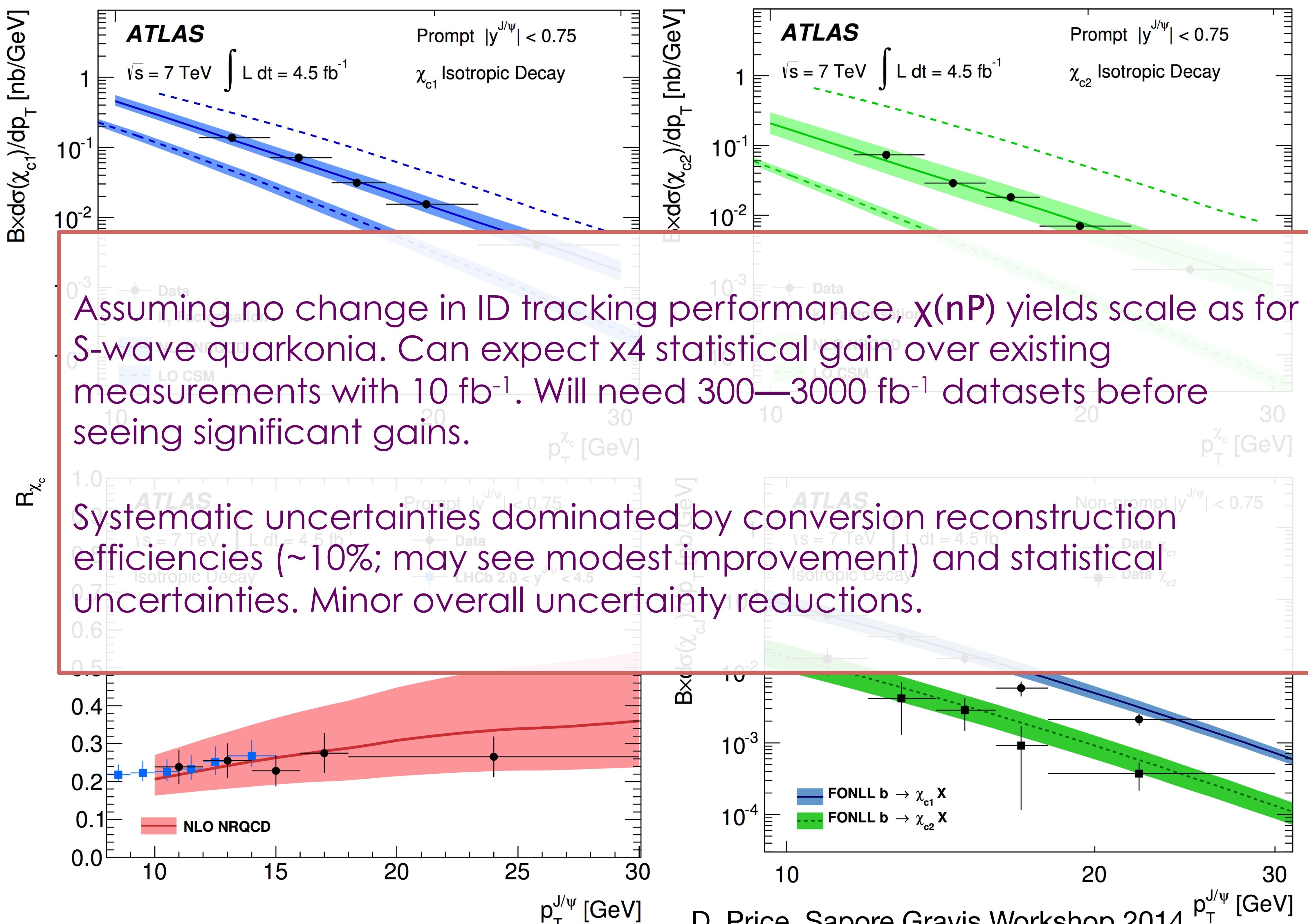
Assuming μ4μ4/μ4μ6 dimuon triggers, **1 fb$^{-1}$** of data production cross-section measurements of $J/\psi$ and $\psi(2S)$ from 10—100 GeV $p_T$, ***approximately equalling 7 TeV data potential***.
Addition of high $p_T$ trigger strategy can add factor 3—5 statistics extension > 60 GeV.

With **~5—10 fb$^{-1}$**, improved understanding of tracking/reconstruction/trigger performance (reduced systematics), possible yield enhancement of 50 over 7 TeV results at high $p_T$.

## $\chi(nP)_{c,b}$ production measurements



JHEP 1407 (2014) 154; arXiv:1404.7035




Assuming no change in ID tracking performance, χ(nP) yields scale as for S-wave quarkonia. Can expect x4 statistical gain over existing measurements with 10 fb$^{-1}$. Will need 300—3000 fb$^{-1}$ datasets before seeing significant gains.

Systematic uncertainties dominated by conversion reconstruction efficiencies (~10%; may see modest improvement) and statistical uncertainties. Minor overall uncertainty reductions.

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# Prospects for $\chi_b(3P)$

## Impact of ID tracking thresholds

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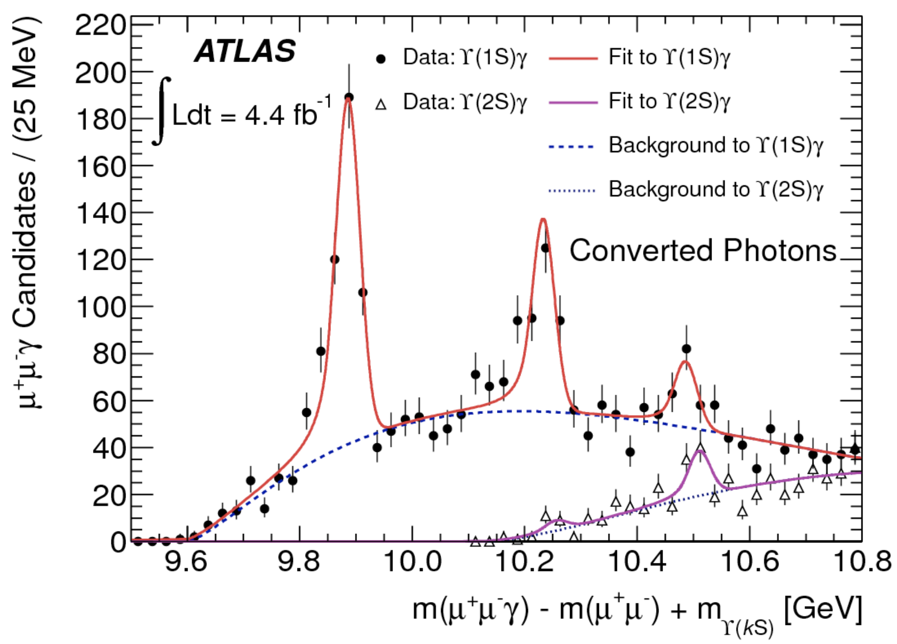
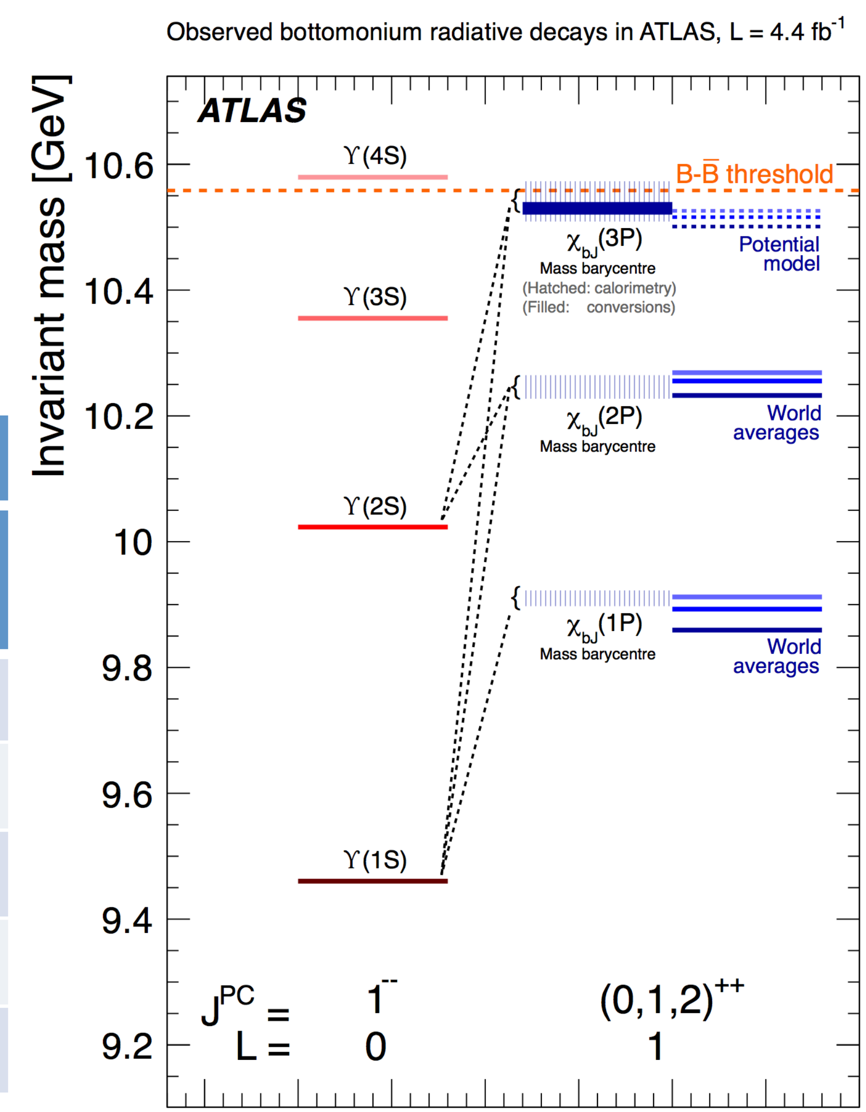
Possibility of lowered tracking thresholds enhances sensitivity to quarkonium states with radiative decays (muon thresholds fixed).



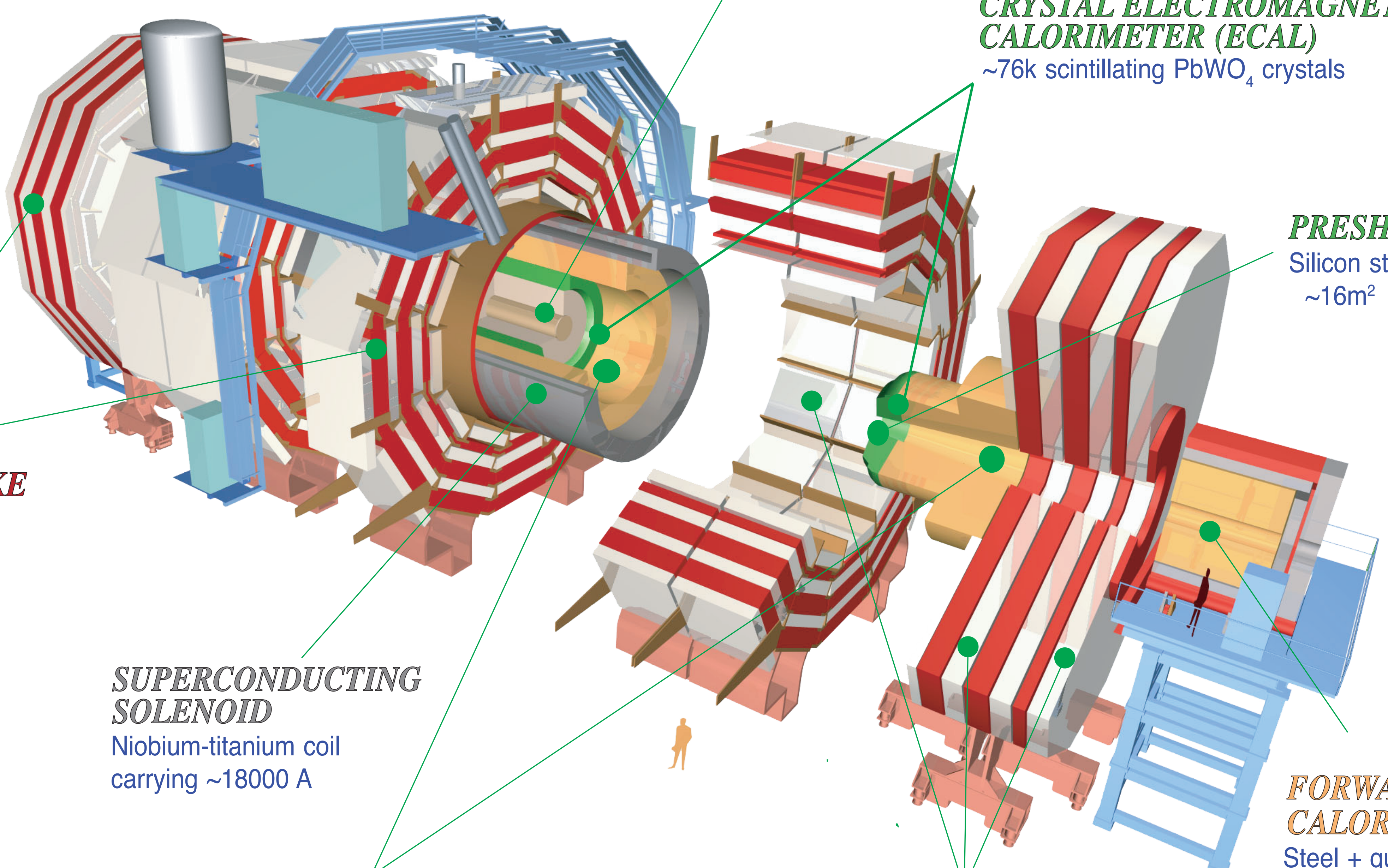

- **Enhancement dependent on mass splitting in decay.**
- **Threshold reduction introduces huge computing overheads! Not possible for all events.**

| Tracking threshold | Estimated signal enhancement | | |
|---|---|---|---|
| | $3P \rightarrow 1S + \gamma$ | $3P \rightarrow 2S + \gamma$ | $3P \rightarrow 3S + \gamma$ |
| 500 MeV | 1.0 | 1.0 | 1.0 |
| 400 MeV | 1.5 | 2 | 5 |
| 300 MeV | 2 | 5 | 30 |
| 200 MeV | 3 | 10 | 200 |
| 100 MeV | 5 | 20 | 1500 |



# CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

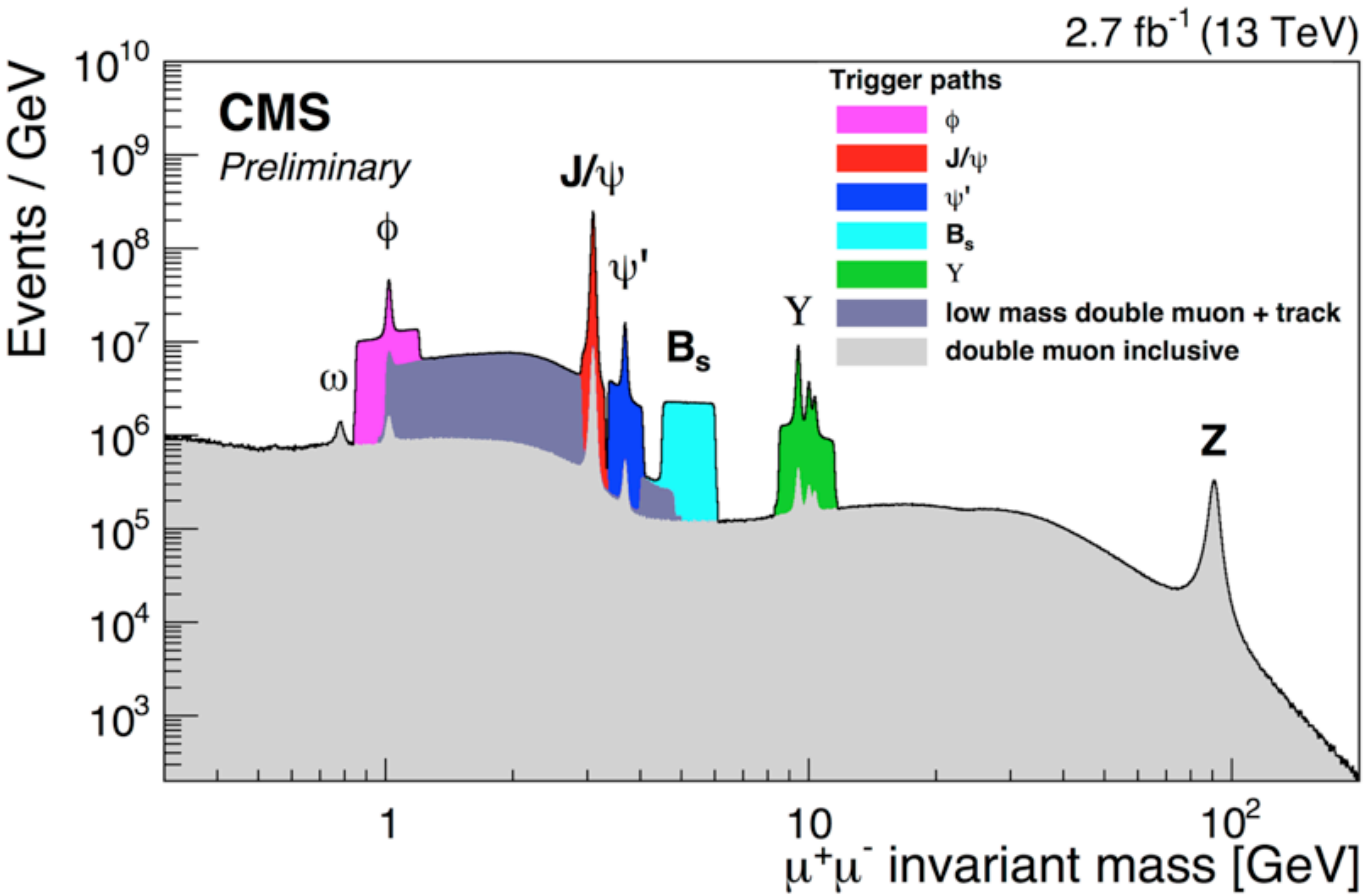



| | |
|---|---|
| **Total weight** | **: 14000 tonnes** |
| **Overall diameter** | **: 15.0 m** |
| **Overall length** | **: 28.7 m** |
| **Magnetic field** | **: 3.8 T** |

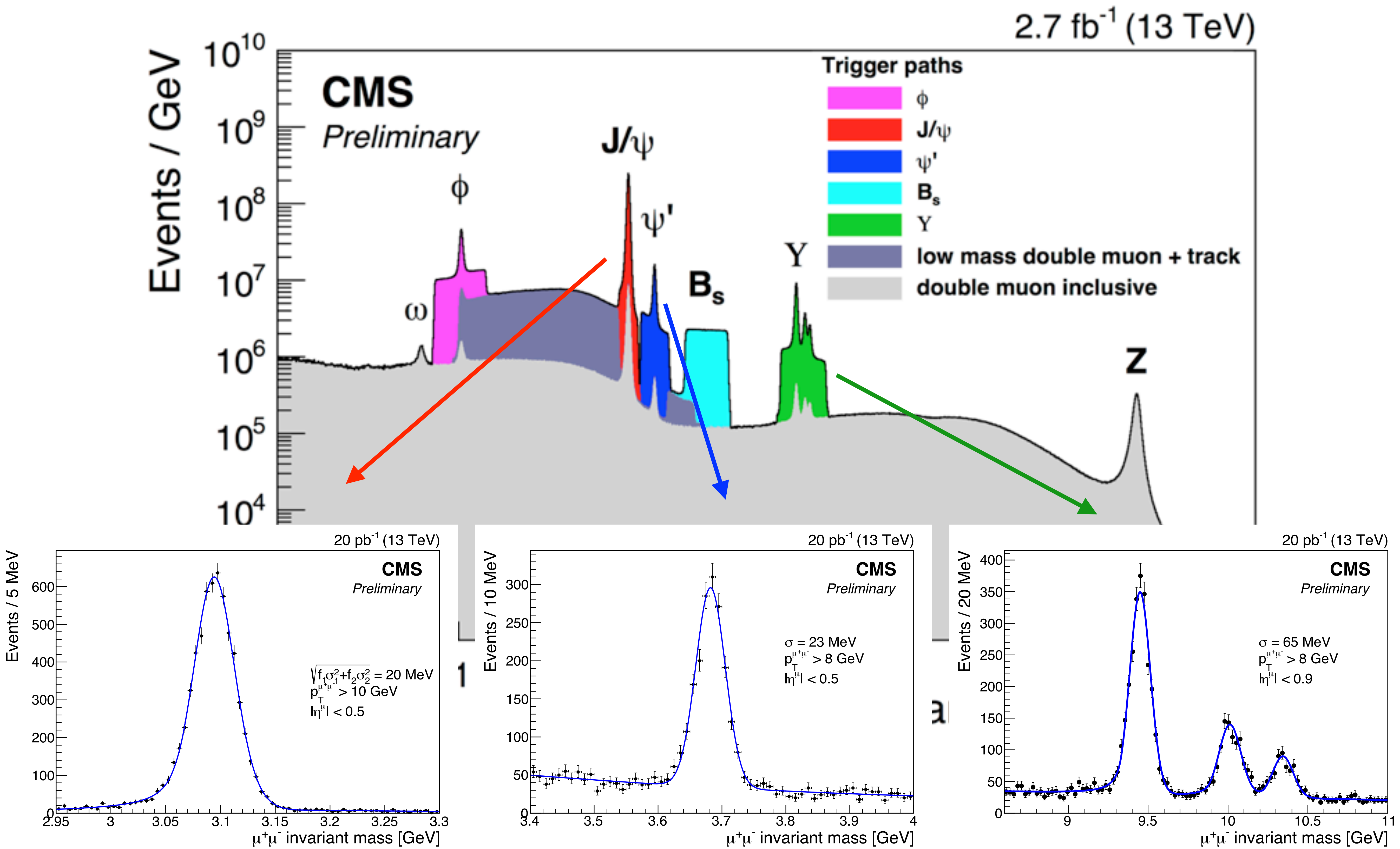
# CMS Prospects

- S-wave states
  - production cross section at the new energies
  - extend (considerably) the $p_T$ reach (high sensitivity regime)
- P-wave states
  - cross sections and polarisations
  - tackle longstanding issue of feed down
- Associated production
  - a more complete characterisation of production mechanisms benefits from measurements of simultaneous production of quarkonia along with other particles
  - further quantify single vs double parton scattering contributions
  - examples: Q+Q, Q+Z/W, Q+hadrons/charged particles, etc.
- extra
  - extend measurements to not-so-heavy quarkonia
  - measurements of exclusive production
  - other heavy flavour states: in addition to quarkonia, explore also exclusive reconstruction of b-hadrons across different collision systems

# The Dimuon Spectrum

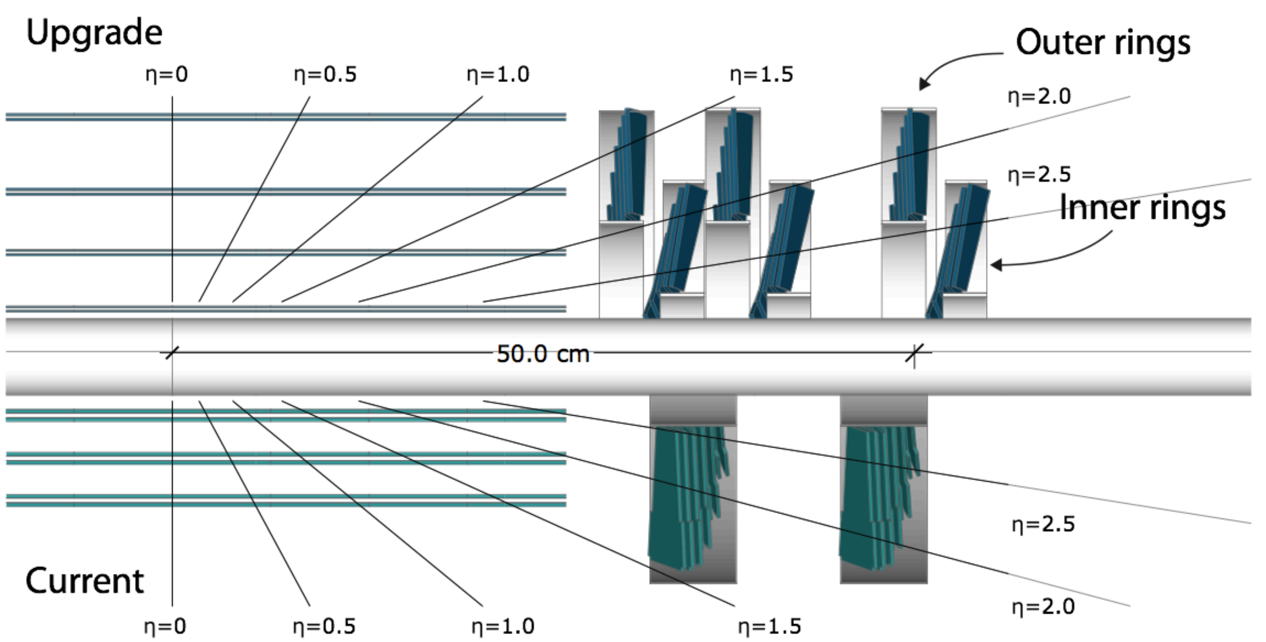


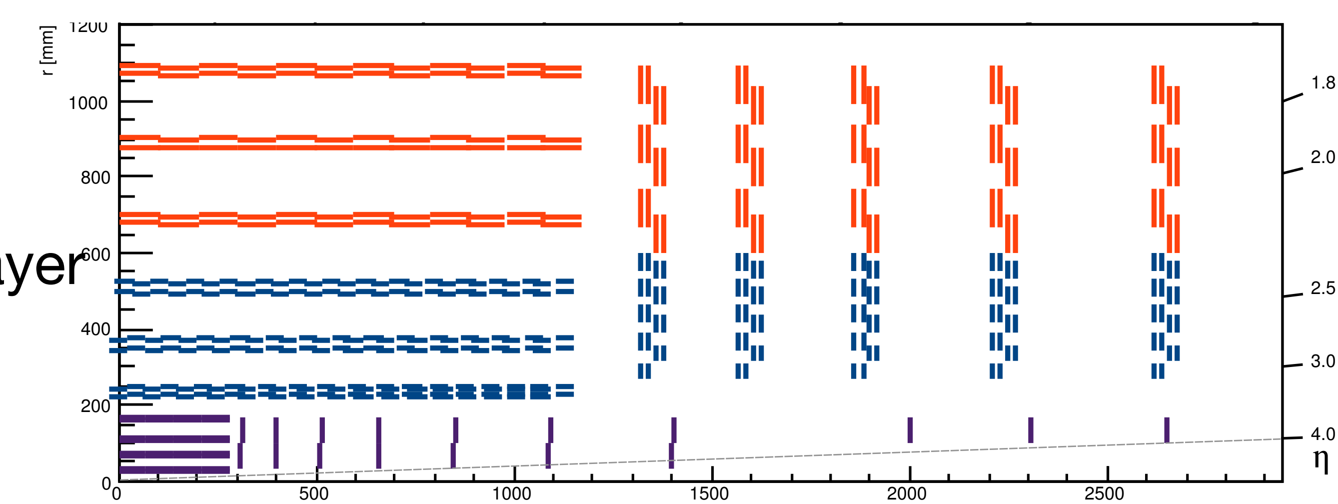
# The Dimuon Spectrum



# CMS: Pixel Upgrade

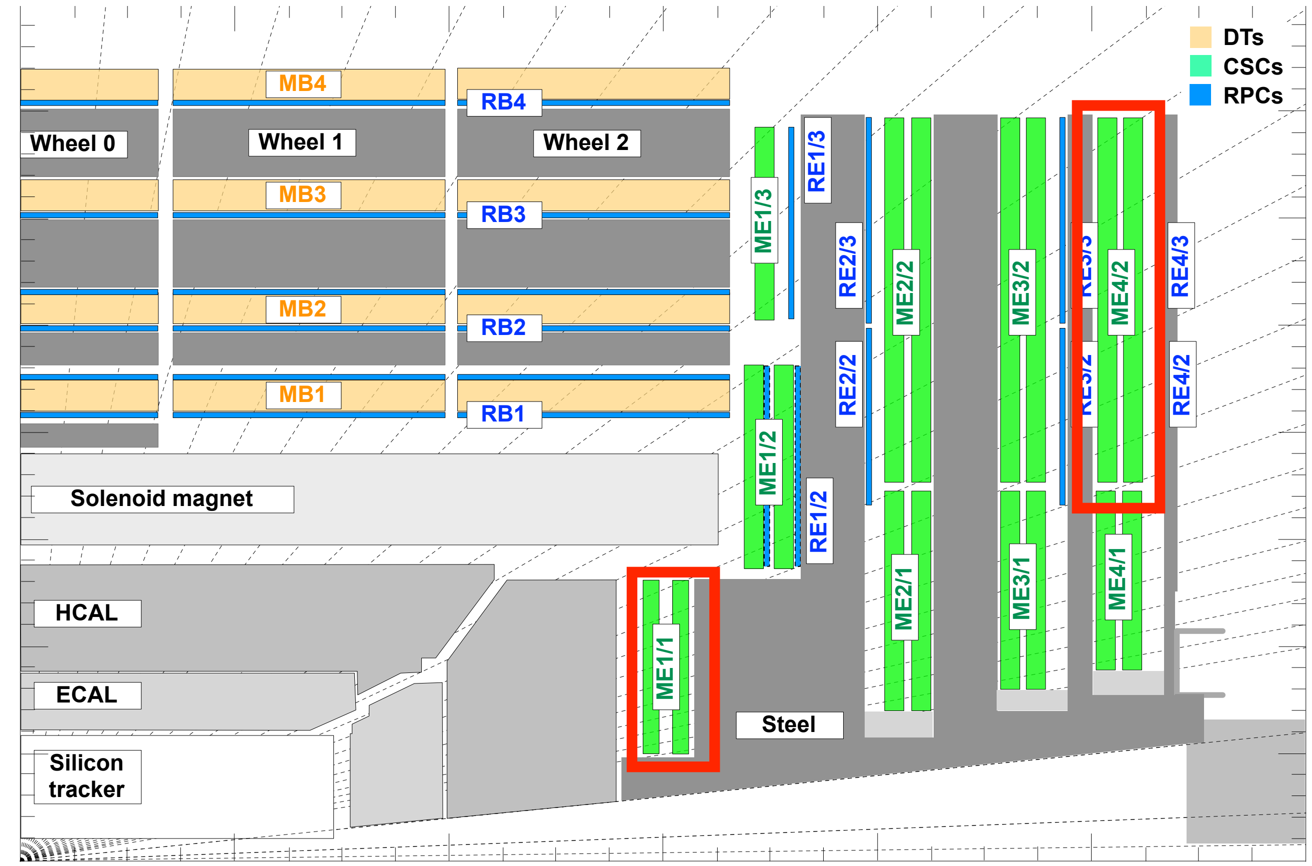
- Upgrade goal: deal with pp environment
  - original tracker design for $10^{34}$ cm$^{-2}$s$^{-1}$
  - upgrade with $2{\times}10^{34}$ cm$^{-2}$s$^{-1}$ in mind (and even beyond after LS3)
- EYETS2016
  - 4 layers / 3 disks
    - 1 more space point, 3 cm inner radius
    - Improved track resolution and efficiency
  - New readout chip
    - Recovers inefficiency at high rate and PU
  - Less material
  - Longevity
    - Tolerate up to 100 PU and survive to 500 fb$^{-1}$, with exchange of innermost layer
- LS3
  - extend rapidity coverage to |η|<4



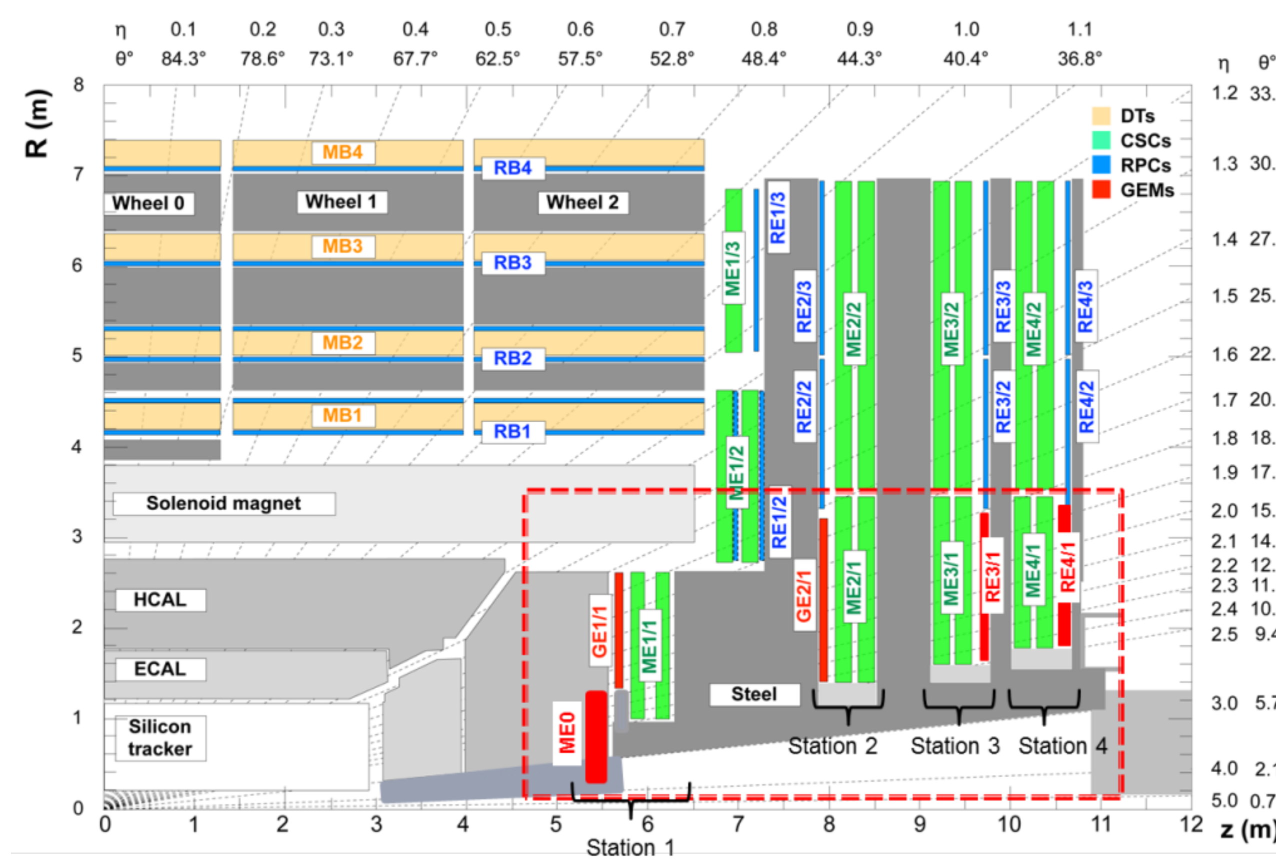



# CMS: Muon Upgrade

- Upgrade goal: deal with pp environment
  - high luminosity and pile up
- LS1: Completed endcaps
  - Add ME4/2 to the endcap
  - Ungang electronics in ME1/1
    - previously: always 3 channels share electronics




- LS2:
  - adding GEMs in the first two stations ($p_T$ resolution)
  - and glass RPC in the last two (timing resolution → reduce background)
  - Investigate possibility to extend coverage beyond $|\eta|<2.4$ to utilise extended tracker coverage



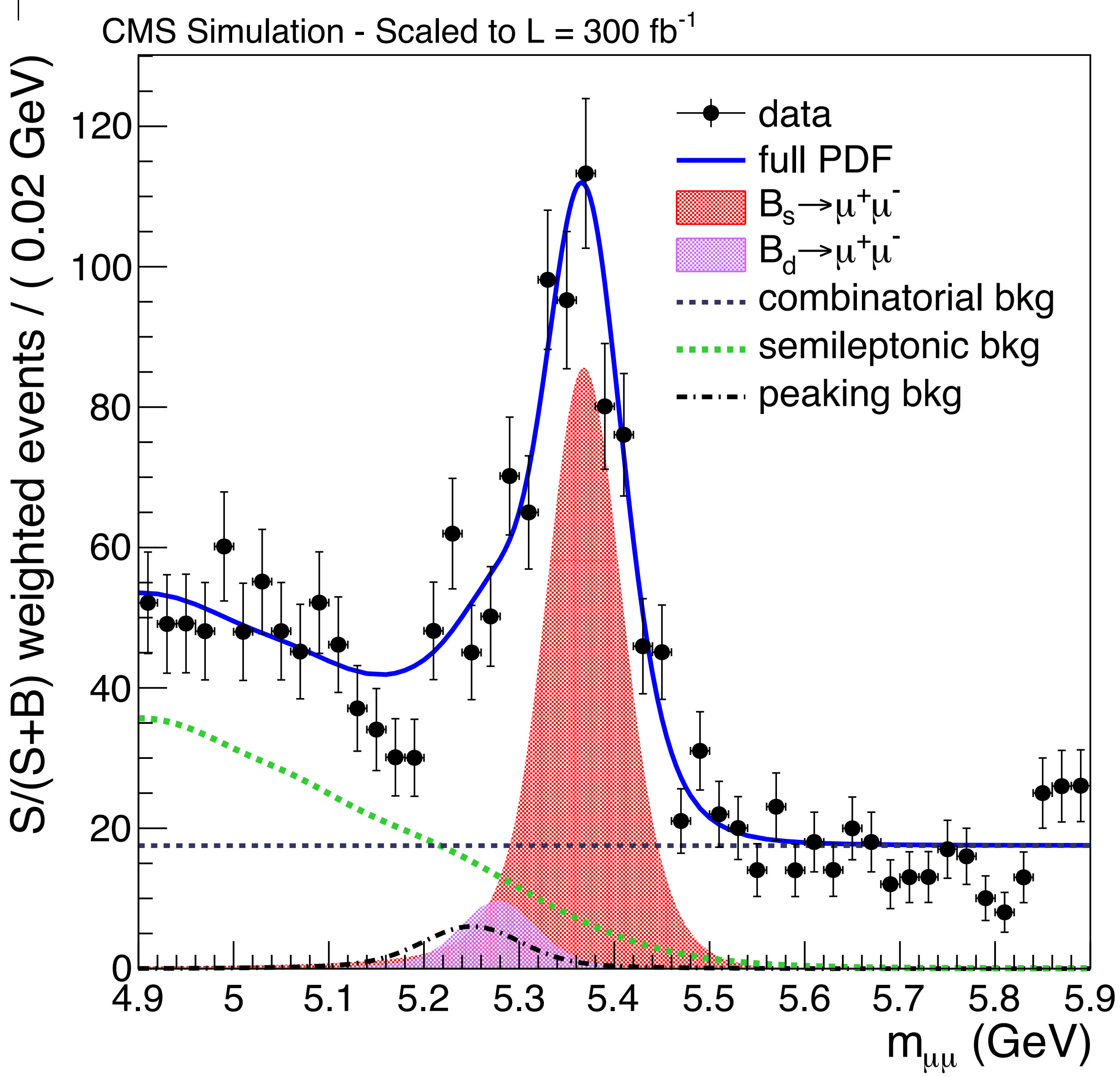
# CMS - L1 Trigger

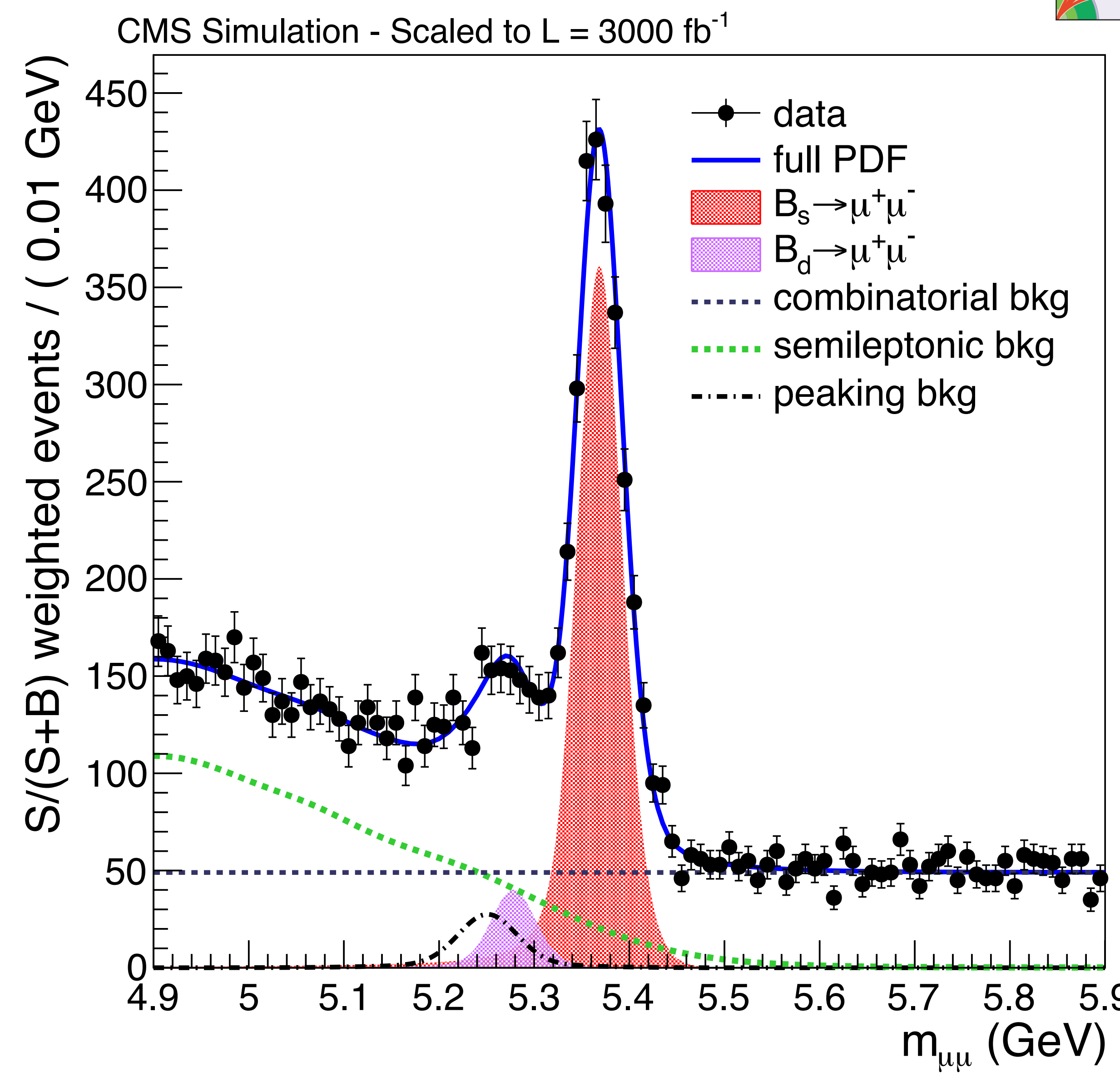
- Design: L1 rate 100 kHz
- Run 2: Expect 6x increase in rate
  - increase trigger thresholds or improve triggers
  - increase L1 rate implies major detector upgrades

- Improvement to muon triggers
  - better $p_T$ resolution in difficult regions
  - muon isolation with calorimeters + pile-up subtraction

- Combine info from DT, CSC, and RPC earlier in the trigger decision
  - common track finder to replace individual track finders

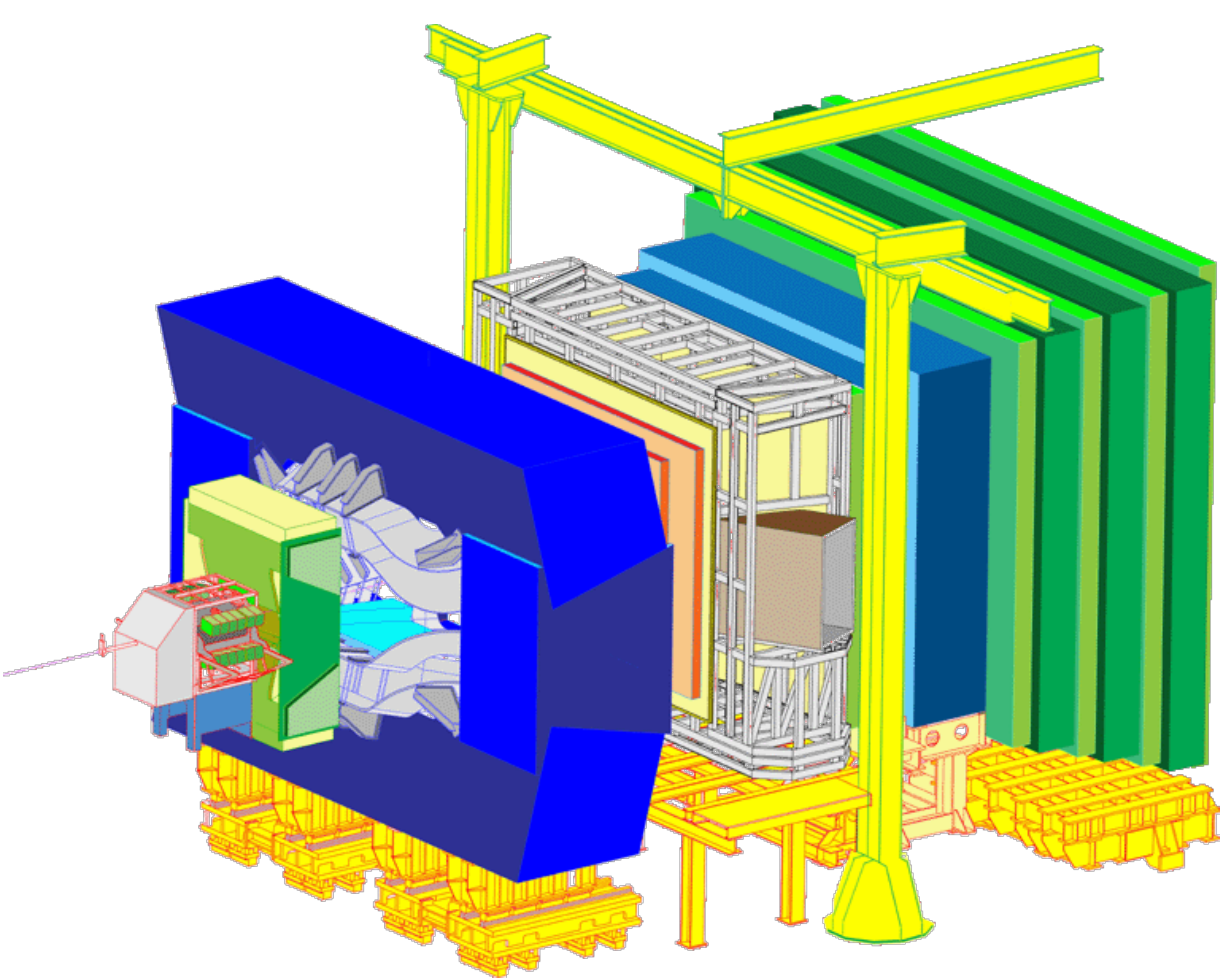
# Dimuon Projections




- Gain factor 1.5 resolution in the barrel, 1.2 in the endcaps
- Tracking at L1
- Improved muon trigger capability

# LHCb

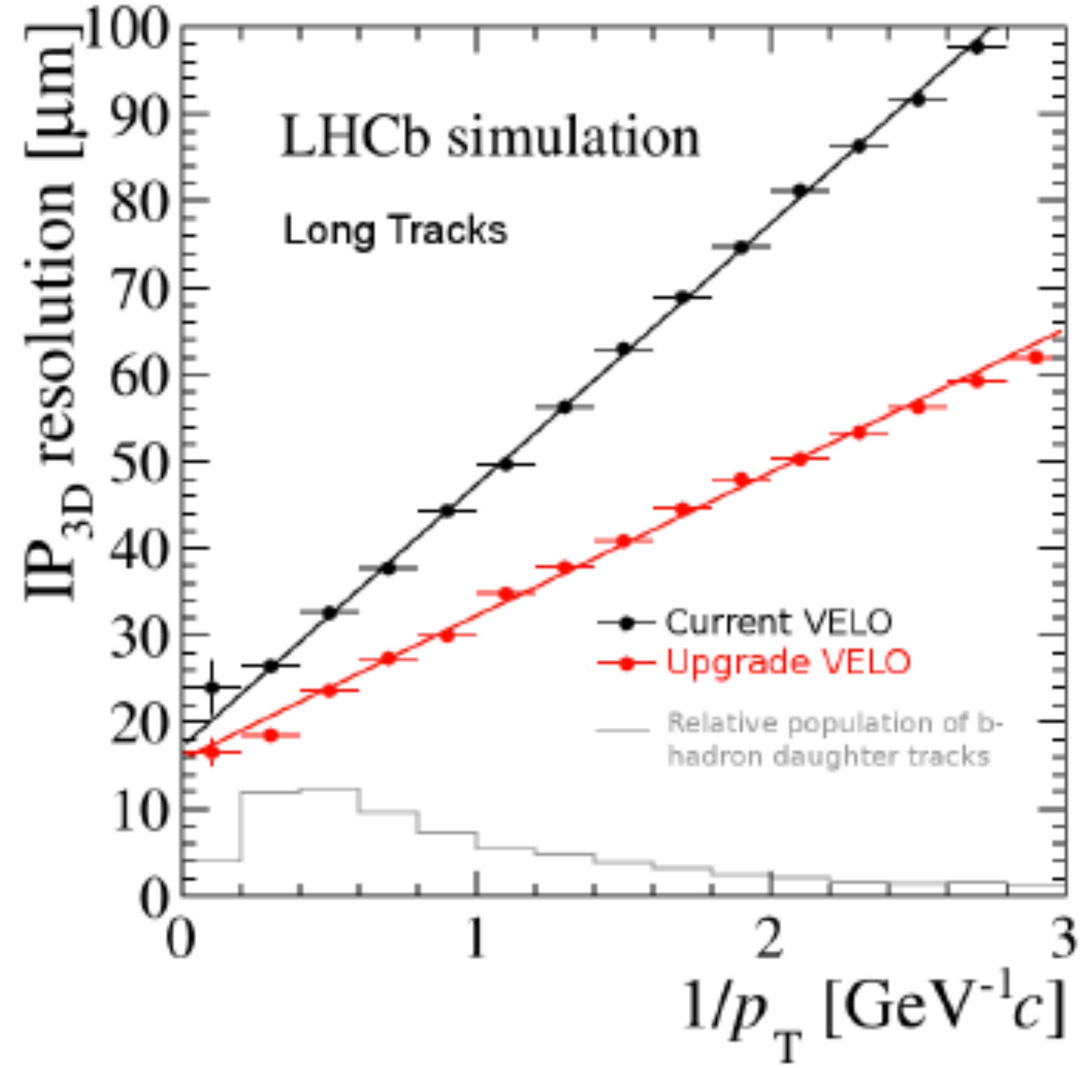


# LHCb Prospects

- 2016: collect $L_{int}$ = 1.5 $fb^{-1}$
- 2017–2018: $L_{int}$ = 2 $fb^{-1}$ per year
- Collect di-muon samples for “standard” quarkonium analyses (J/ψ, ϒ, $\chi_c$, $\chi_b$ production and polarization) with a small bandwidth reserved for the di-muon in the trigger
- Main other analyses that will be pushed are:
  - study of quarkonium production with the proton-antiproton final states (you can look at J/ψ, $\chi_c$, $h_c$, $\eta_c$ with this decay mode, since it is 2-body it is easier to measure polarization, etc…)
  - associated production of J/ψ+D, double J/ψ, double ϒ, ϒ+charm, …
  - the various exotic states: “pentaquark” in various production (prompt or from B) and decay modes, “tetraquarks”
  - study of the $B_c$: excited states ($B_c^* \to B_c \gamma$, $B_c^* \to B_c \pi^+ \pi^-$, …) and various decay modes (but this is more to study the weak decay modes of the $B_c$).
- Excited states are important though for the production mechanisms.

# LHCb upgrades

- VELO will be replaced by a pixel detecter
- replace other tracking devices by fibre based detectors
  - significantly increased granularity
- detector will be readout at 40 MHz.
  - run at higher instantaneous luminosity
  - collision rate: 30 MHz
- perform analysis at trigger level
  - will then help for rare processes
  - For standard quarkonium analyses it will not change a lot, except that you can obtain reduced quantities out of the trigger (for example you keep just the J/psi 4 momentum) and are then not limited by bandwidth



# Summary

- Upgrades aim to maintain performance at high luminosities and pile up
  - does not mean trigger threshold will never be increased
  - certainly, thresholds won't decrease (unless on more exclusive processes)

- Main focus at rare electroweak and/or BSM processes
  - QCD is a background
- Focus of ALICE: Heavy-Ion collisions

- Main prospects in pp collisions:
  - increase integrated luminosity
  - extend $p_T$ reach of cross section and polarisation measurements
  - access to more exclusive processes
  - P-wave states at low $p_T$ out of reach for ATLAS and CMS
    - maybe ALICE, LHCb…?