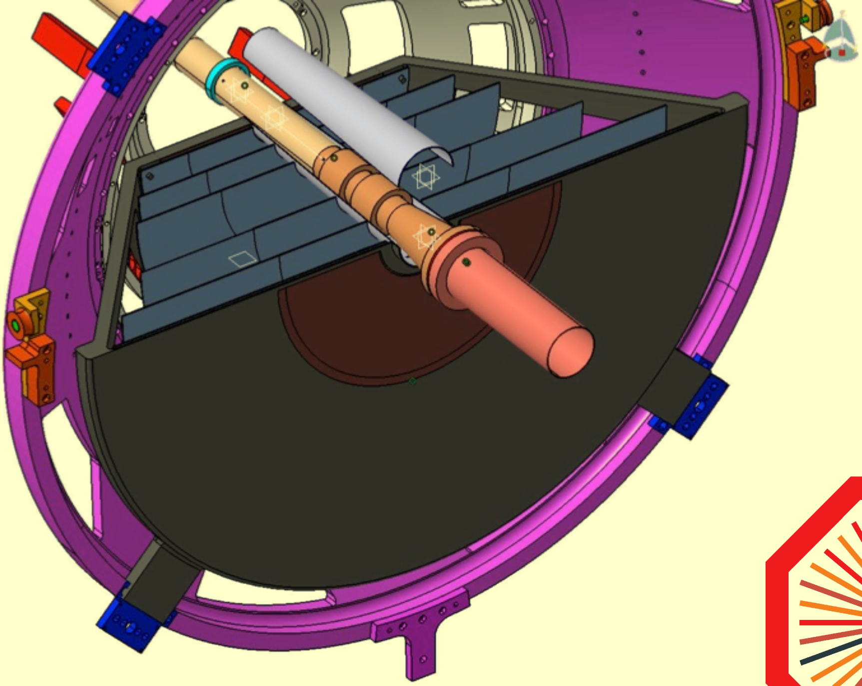
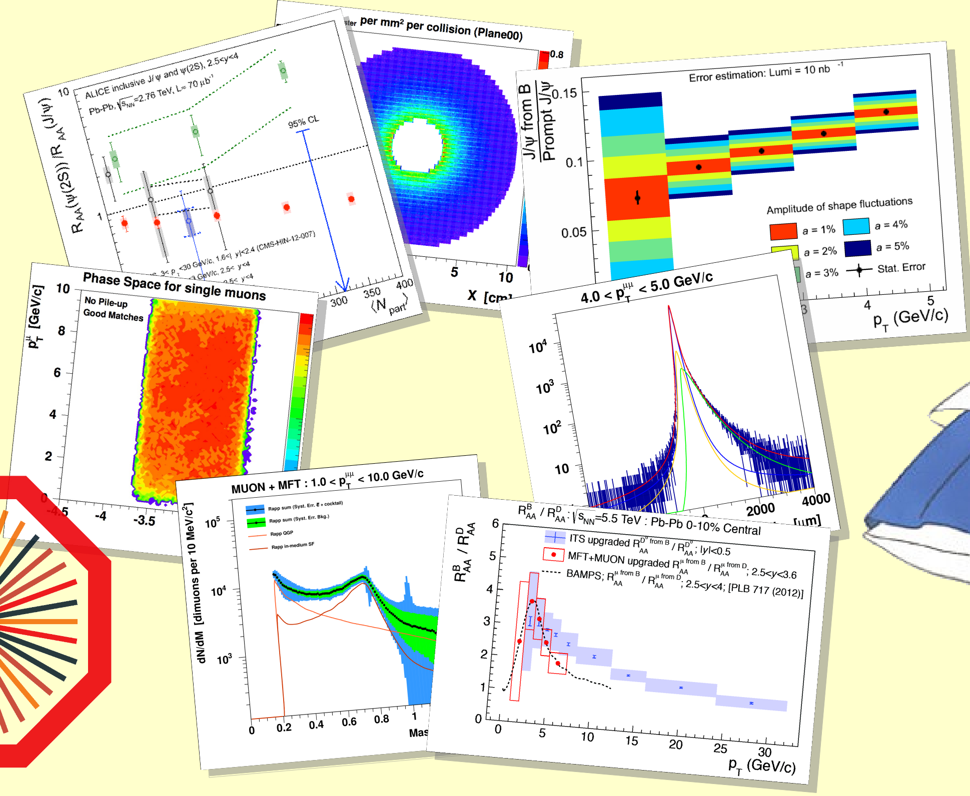




Muon Physics in ALICE

Performances after the LS2 Upgrades

Antonio URAS

for the ALICE MFT Working Group

ALICE Lyon group @ IPNL

9-12 September 2013

Rencontres QGP-France
Étretat, Haute Normandie

Outline

- The MFT Concept

- Prompt Charmonia ($\rightarrow \psi'$ measurement)
- J/ψ from Beauty
- Open Heavy Flavor measurements
- Low Mass Dimuons

} 0-10% Pb-Pb @ 5.5 TeV

For more details: http://cds.cern.ch/record/1592659 NEW!

ALICE Muon Physics: Motivations

- **Main stream of the ALICE Muon Physics:** study the behavior of the hadronic matter at extreme temperature and energy density conditions

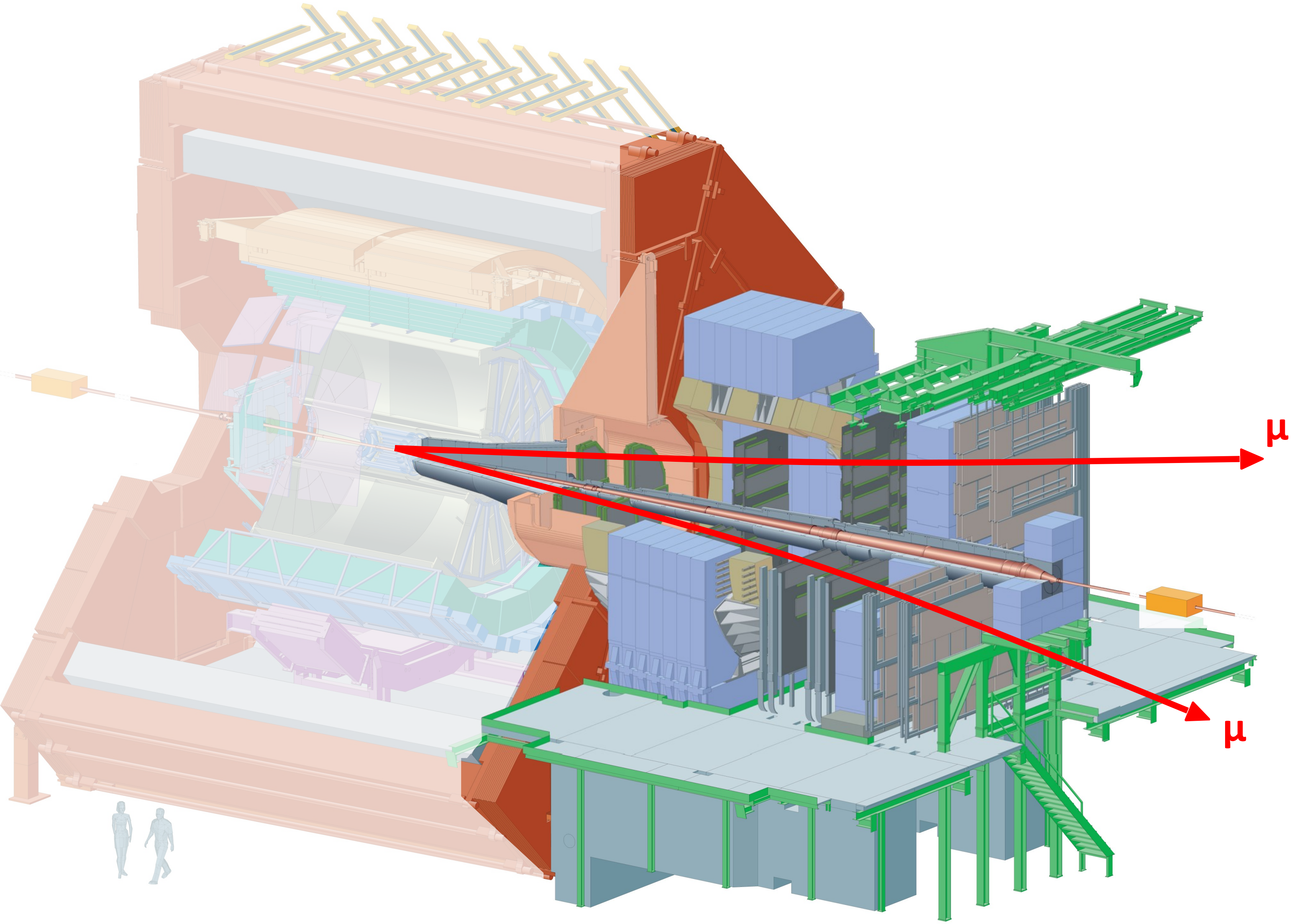
- Unique tool to study QGP at forward rapidities of the Bjorken plateau at LHC energies. Complementary to the studies of ALICE central barrel, ATLAS and CMS at mid rapidity. Powerful tool to constrain the theoretical models

- **ALICE Muon Physics motivations still valid after the LHC Long Shutdown 2**, but: wider range of observables, more precise observations, more powerful tools to constrain models

Muon Measurement with the ALICE Detector

Designed to detect muons in the **polar angular range 2 – 9°, i.e. – 4.0 < η < – 2.5** and in the full azimuthal range

- Hadron Absorber
- Dipole Magnet
- 10 tracking chambers
- Iron wall
- 4 trigger chambers



Main Design Limitations of the Current Muon Arm

- **High level of background from π/K decays**
  - High systematic uncertainties induced by background subtraction for all physics topics. Open HF analysis in single muons cannot access below p_T = 4 GeV/c. ψ' cannot be easily observed

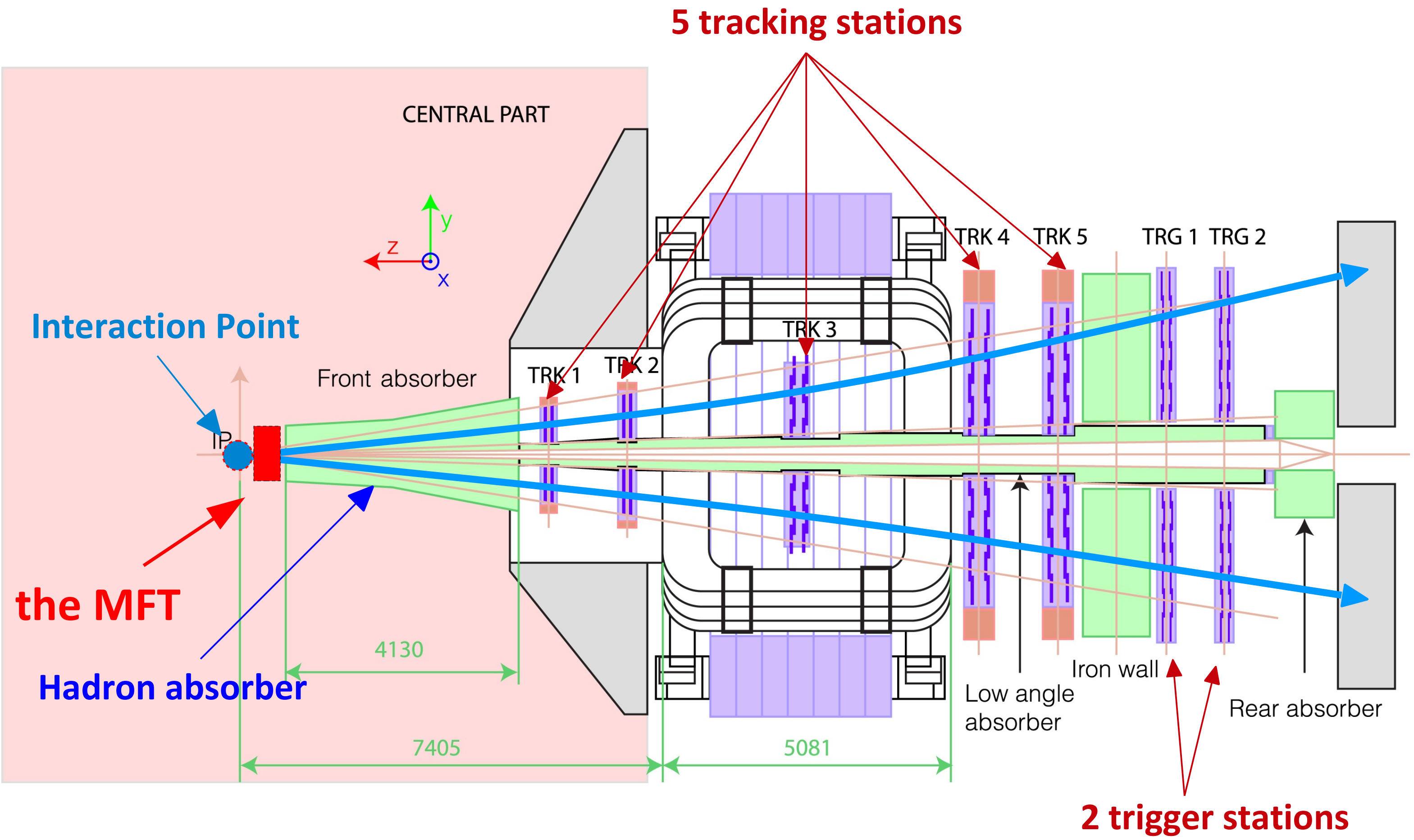
- **Impossibility to determine muon production vertex**
  - No charm/beauty separation in single muon
  - No J/ψ from B measurement. We miss an important source of information for the study of beauty

- **Limited mass resolution, having a non-negligible impact at low mass**

The MFT in the Muon Arm Framework

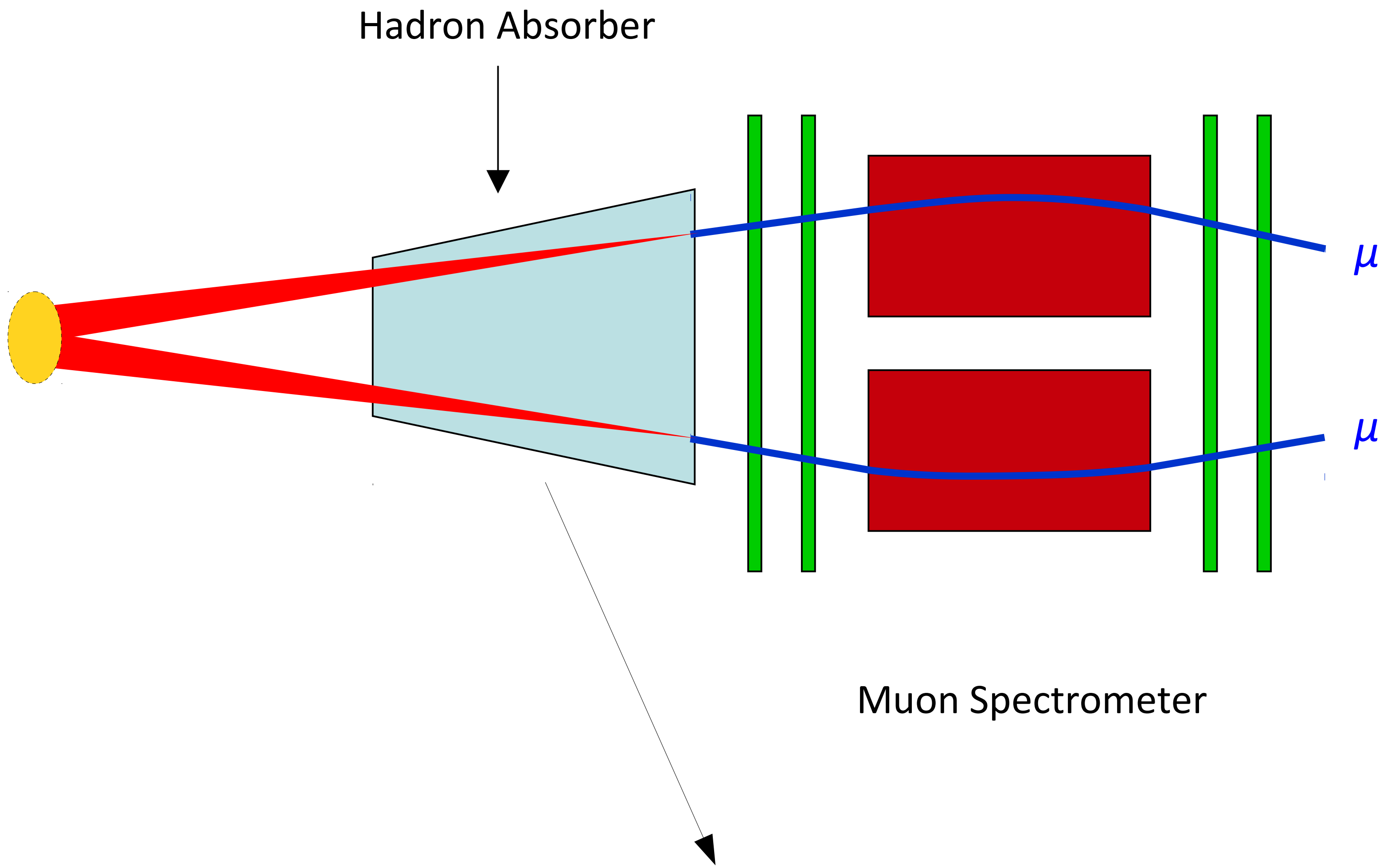
Silicon pixel tracker in the acceptance of the Muon Spectrometer

To be placed between the Interaction Point and the Hadron Absorber



Non-trivial integration challenges: constraints from the upgraded ITS, the future beam pipe, the existing hadron absorber, . . . → **See talk by G. Batigne**

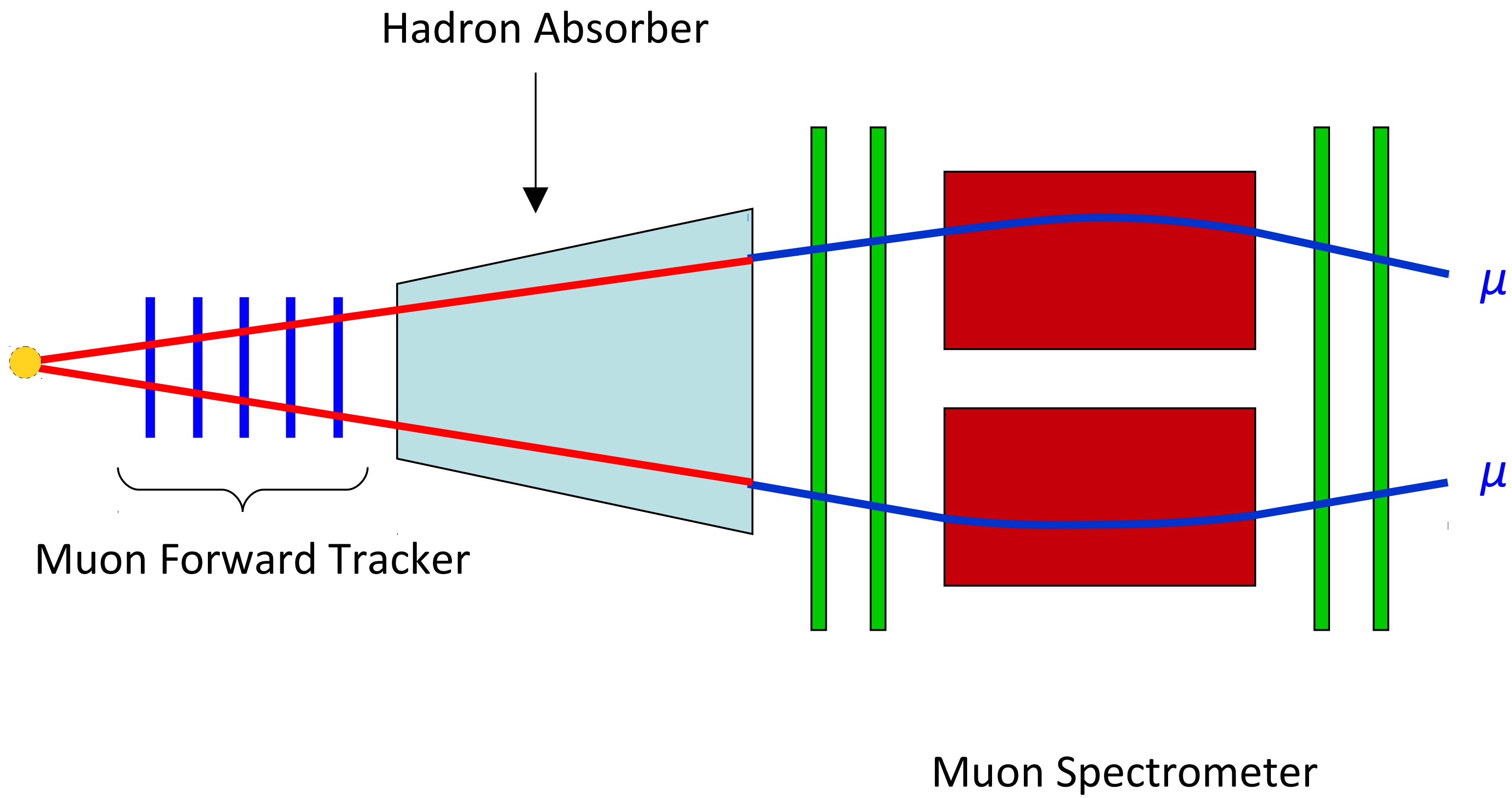
The MFT Concept



Extrapolating back to the vertex region **degrades the information** on the kinematics

The MFT Concept

Muon tracks are extrapolated and **matched to the MFT clusters** before the absorber



High pointing accuracy gained by the muon tracks after matching with the MFT clusters

Prompt Charmonia Physics

- Evaluation of the contribution of c-cbar recombination to the production of charmonium at LHC energies
- Direct observation of the deconfined phase of matter

Charmonia: Finding the Point of Closest Approach

- **PCA:** Point of Closest Approach between two muon tracks
- **PCA Quality:** Estimates the probability that both muons are coming from the PCA
- **Powerful tool to improve the S/B when the tracks have p_T > 1 GeV/c**

$$f_i(\vec{v}) = \exp\left[-0.5(\vec{v}-\vec{r_i})^T V_i^{-1}(\vec{v}-\vec{r_i})\right]$$

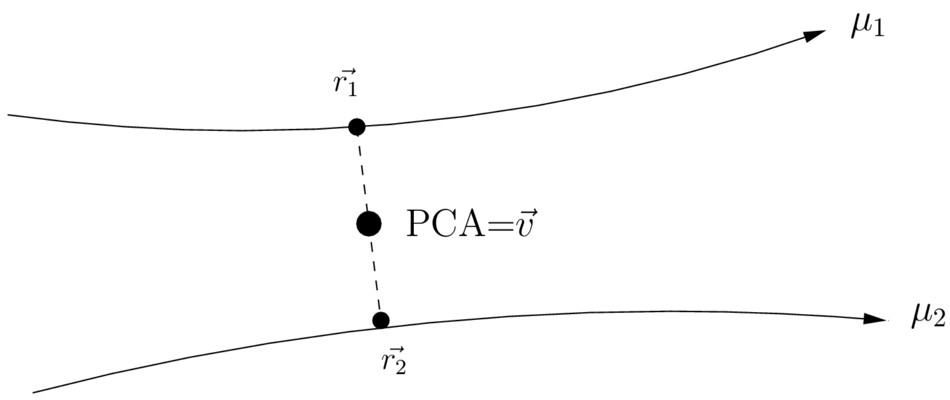
where $\vec{r_i}$ is the point of closest approach of track *i* to the point $\vec{v}$. V_i is the covariance matrix of the track *i* at $\vec{r_i}$

$$P(\vec{v}) = \sum_{i=0}^{n} f_i(\vec{v}) - \frac{\sum_i f_i^2(\vec{v})}{\sum_i f_i(\vec{v})}$$

is then the probability that *n* tracks all come from the same, common origin $\vec{v}$

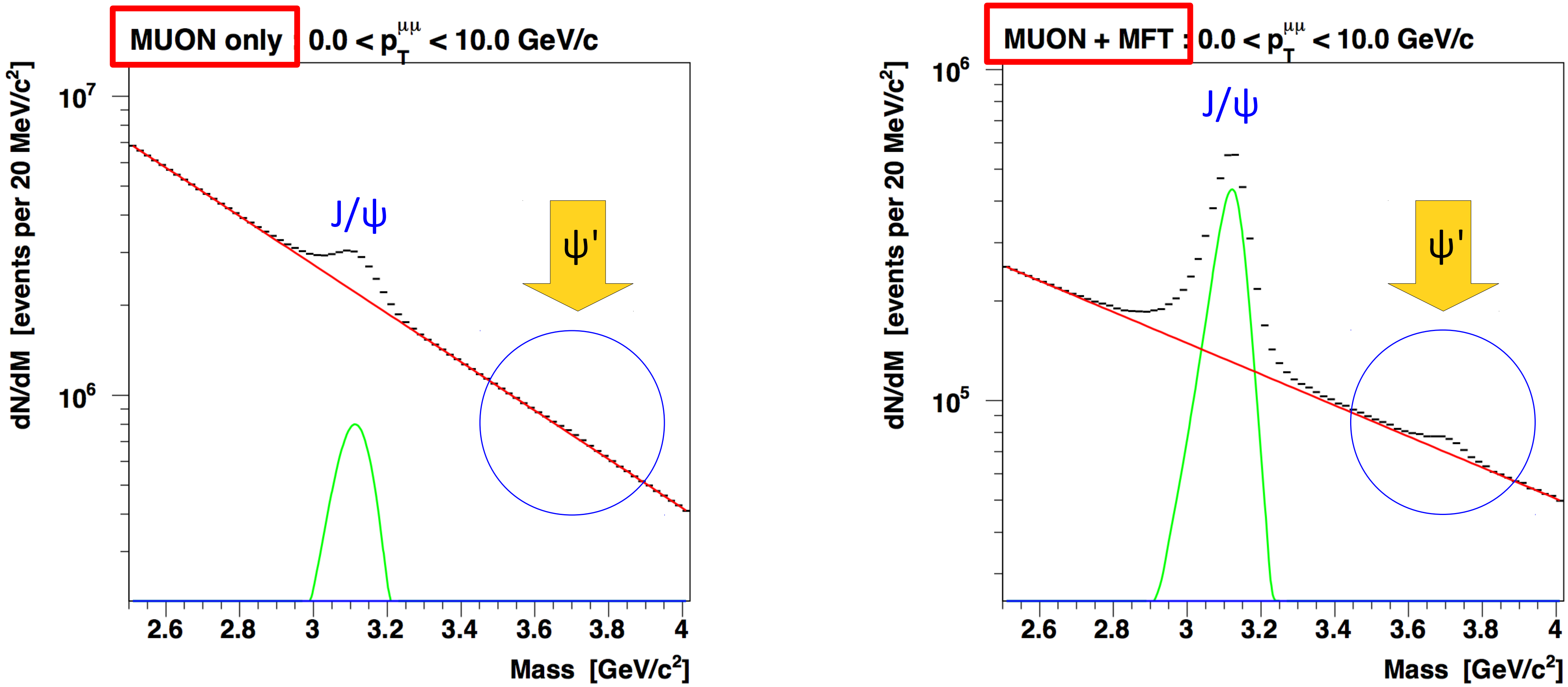
In the case of two tracks only:

$$P(\vec{v}) = \frac{2 f_1(\vec{v}) f_2(\vec{v})}{f_1(\vec{v}) + f_2(\vec{v})}$$



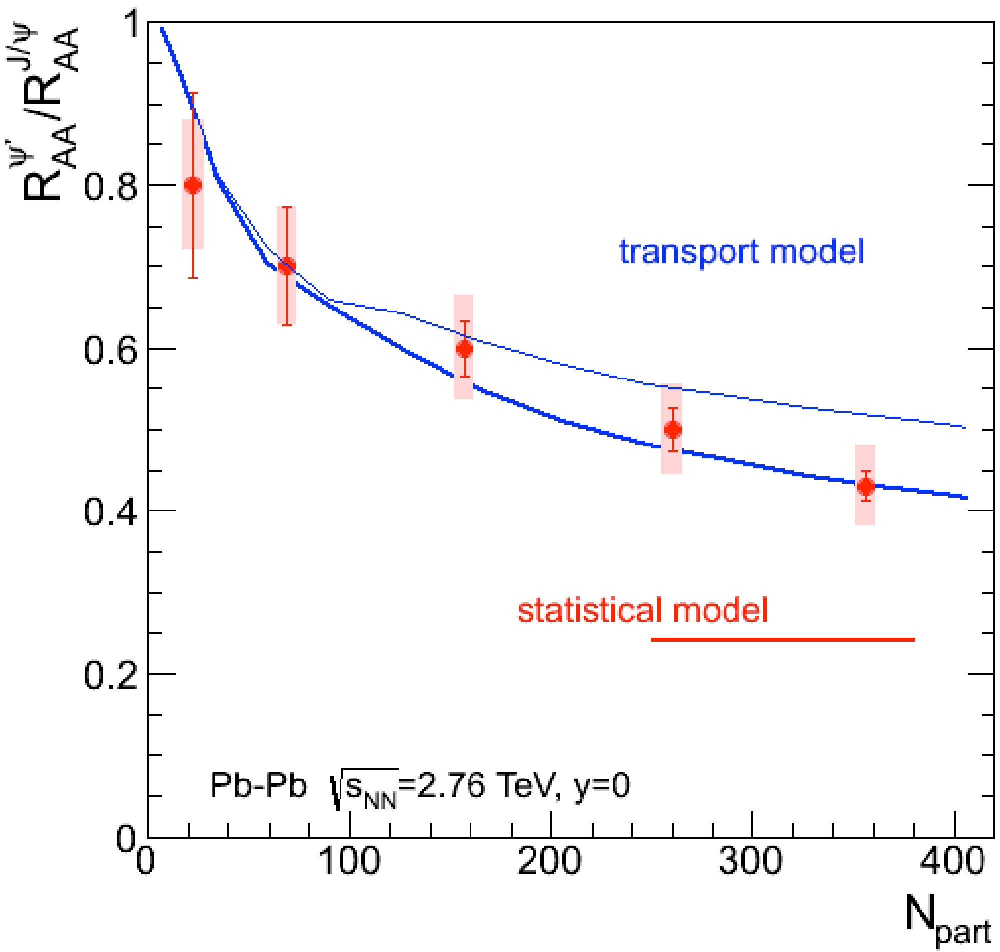
Charmonia: Inclusive J/ψ and ψ' Measurement

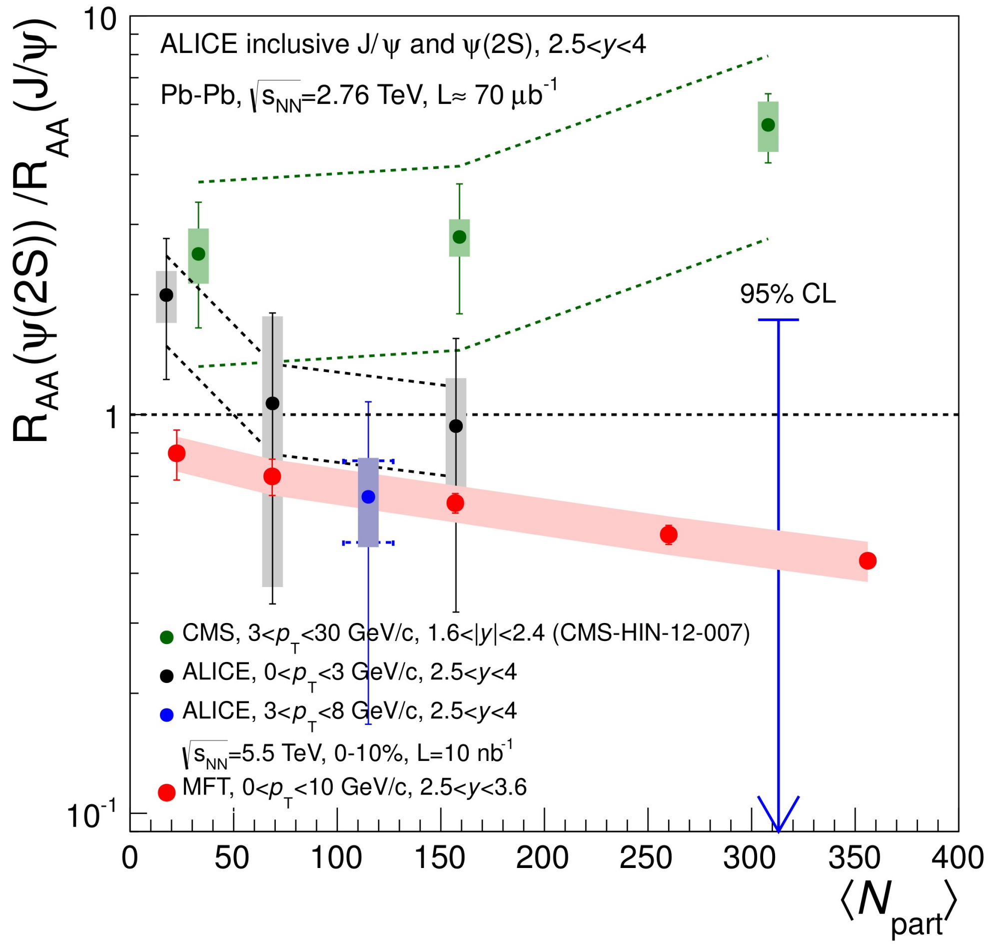
- S/B improved by a factor **~6-7, significance improved by a factor up to ~1.5**
- The ψ' is visible even in central Pb-Pb collisions: signal extraction more robust, systematic uncertainties significantly reduced



Charmonia: Inclusive J/ψ and ψ' Measurement

- Via the measurement of the "double ratio" $R_{AA}(\psi') / R_{AA}(J/\psi)$ the MFT allows discrimination between statistical and transport models



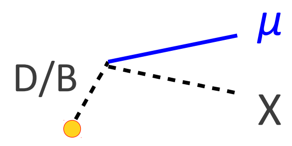


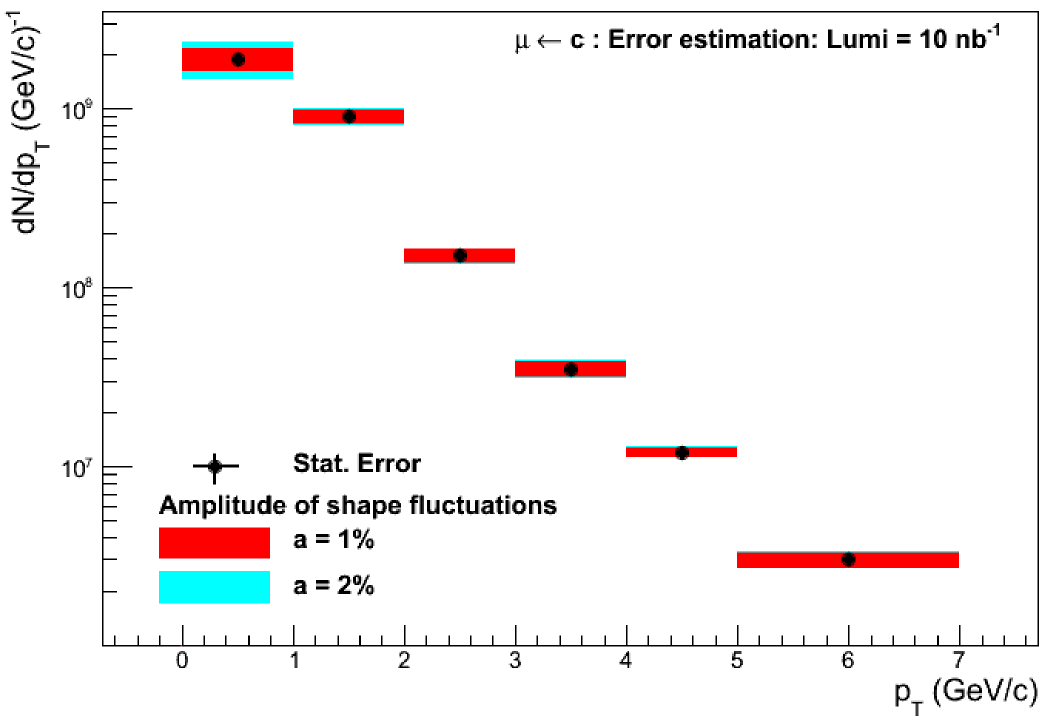
Heavy Flavor Physics (single μ, J/ψ from B)

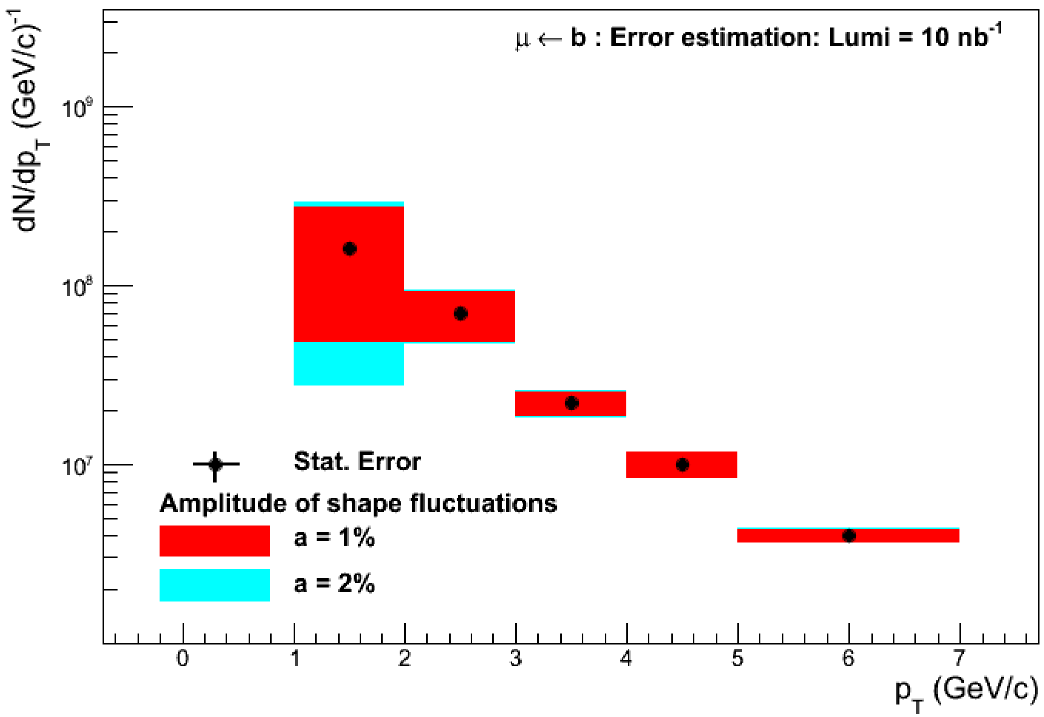
- Probing QCD medium by measuring the energy loss of quarks c and b
- Measuring total beauty production cross-section: gold reference for upsilon suppression studies

Open Heavy Flavors in Single Muons

- **Combined fit of the Offset distribution** of single muons, to separate Charm, Beauty and Background
- Extraction of **Charm** possible down to $\mathbf{p_T = 1}$ **GeV/c**
- Extraction of **Beauty** possible down to $\mathbf{p_T = 2}$ **GeV/c**

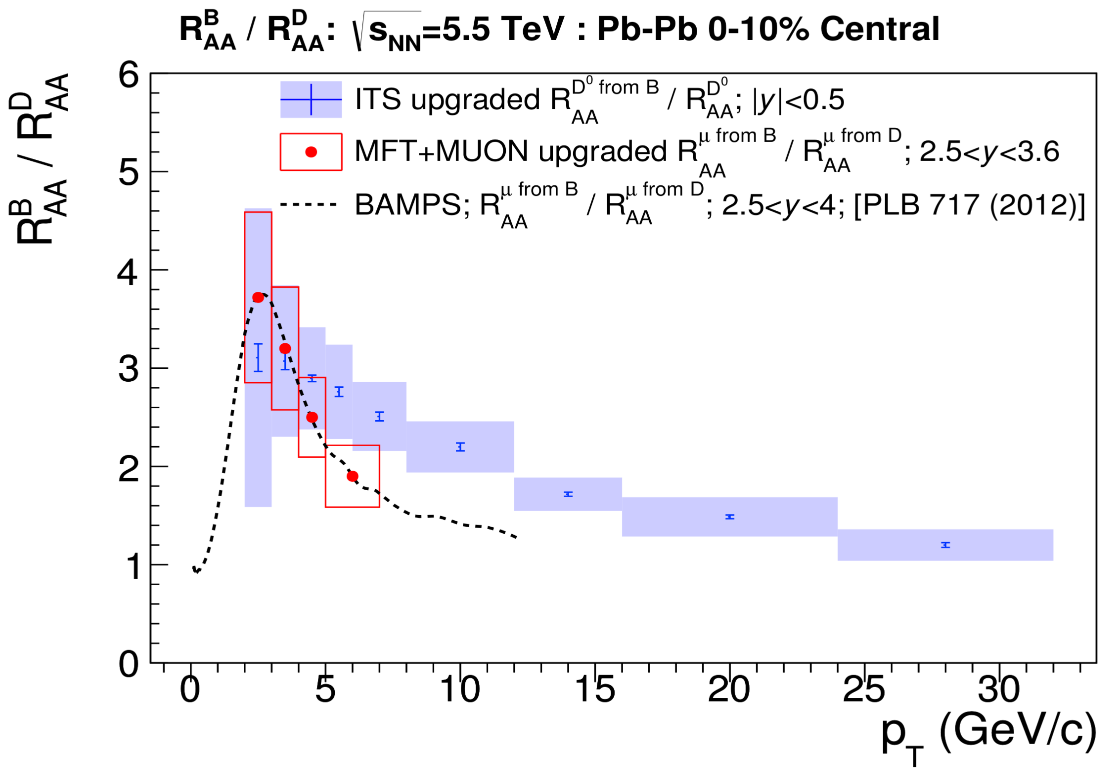






Open Heavy Flavors in Single Muons

- Compare **R_{AA}(μ from B) / R_{AA}(μ from D)** with **R_{AA}(D0 from B) / R_{AA}(D0 prompt)**
- For MFT assume Error(pp) = Error(Pb-Pb)
- MFT+MUON performances are equivalent to those of the new ITS in a complementary rapidity domain



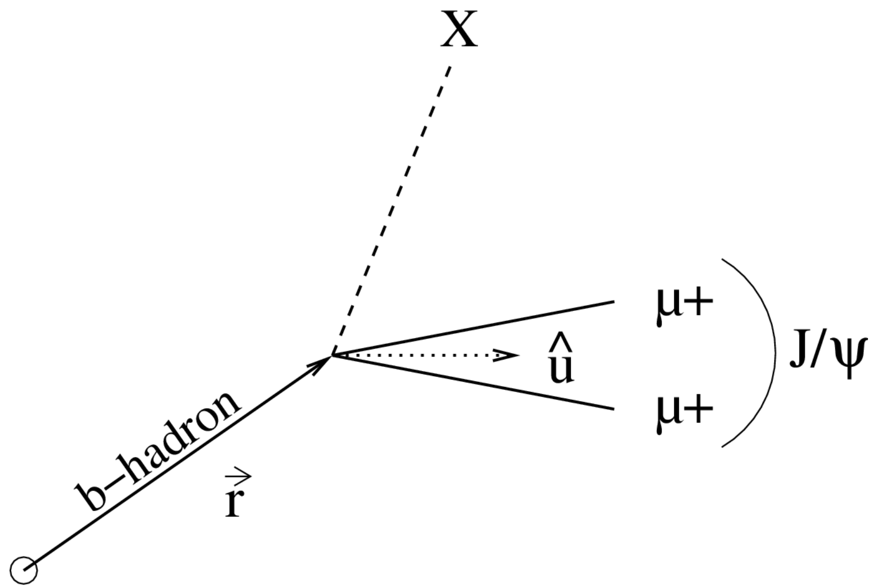
Displaced J/ψ: the Pseudo-Proper Decay Length

We take e.g. the definition given in CMS analysis: Eur.Phys.J. C71 (2011) 157

$$L_{xy} = \frac{\hat{u}^T S^{-1} \vec{r}}{\hat{u}^T S^{-1} \hat{u}} \approx \frac{\hat{u}^T \cdot \vec{r}}{\hat{u}^T \cdot \hat{u}}$$

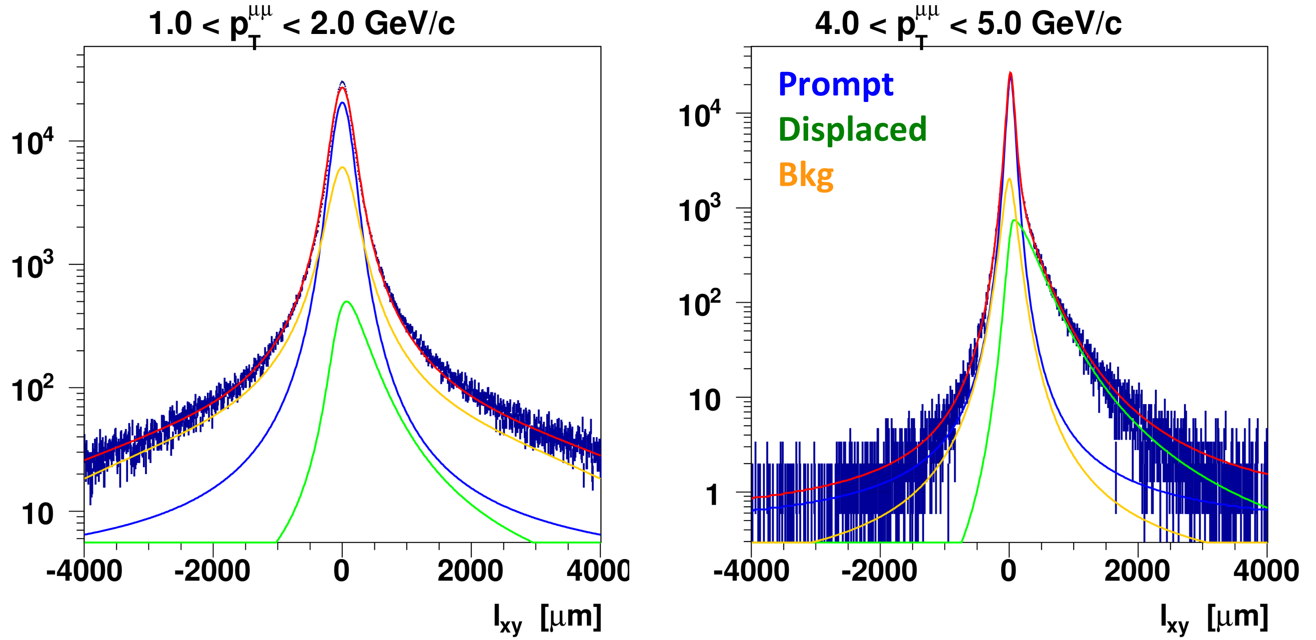
- $\vec{r}$: vector joining the secondary and the primary vertex
- $\hat{u}$: unit vector in J/ψ p_T direction
- S : sum of primary and secondary vertex covariance matrices

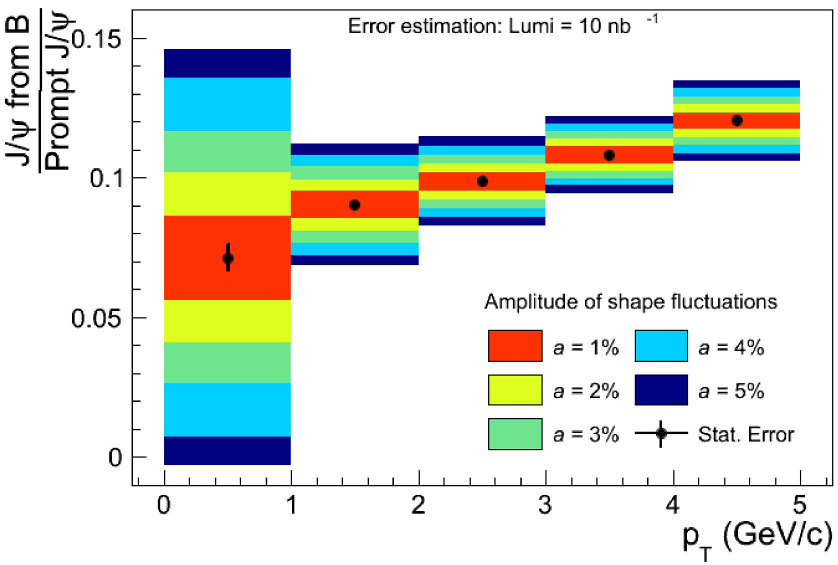
➡ Pseudo-proper decay length distributions expected to be significantly different between prompt J/ψ and J/ψ coming from decays of B mesons



Displaced J/ψ: Signal Extraction

- **Combined fit** on the pseudo-proper decay length distribution
- Background normalization fixed from mass spectrum (error at 1% level)





- Uncertainty on MC pseudo-proper decay length templates: both in shape and normalization
- Uncertainty on the cuts and selections included in the final errors

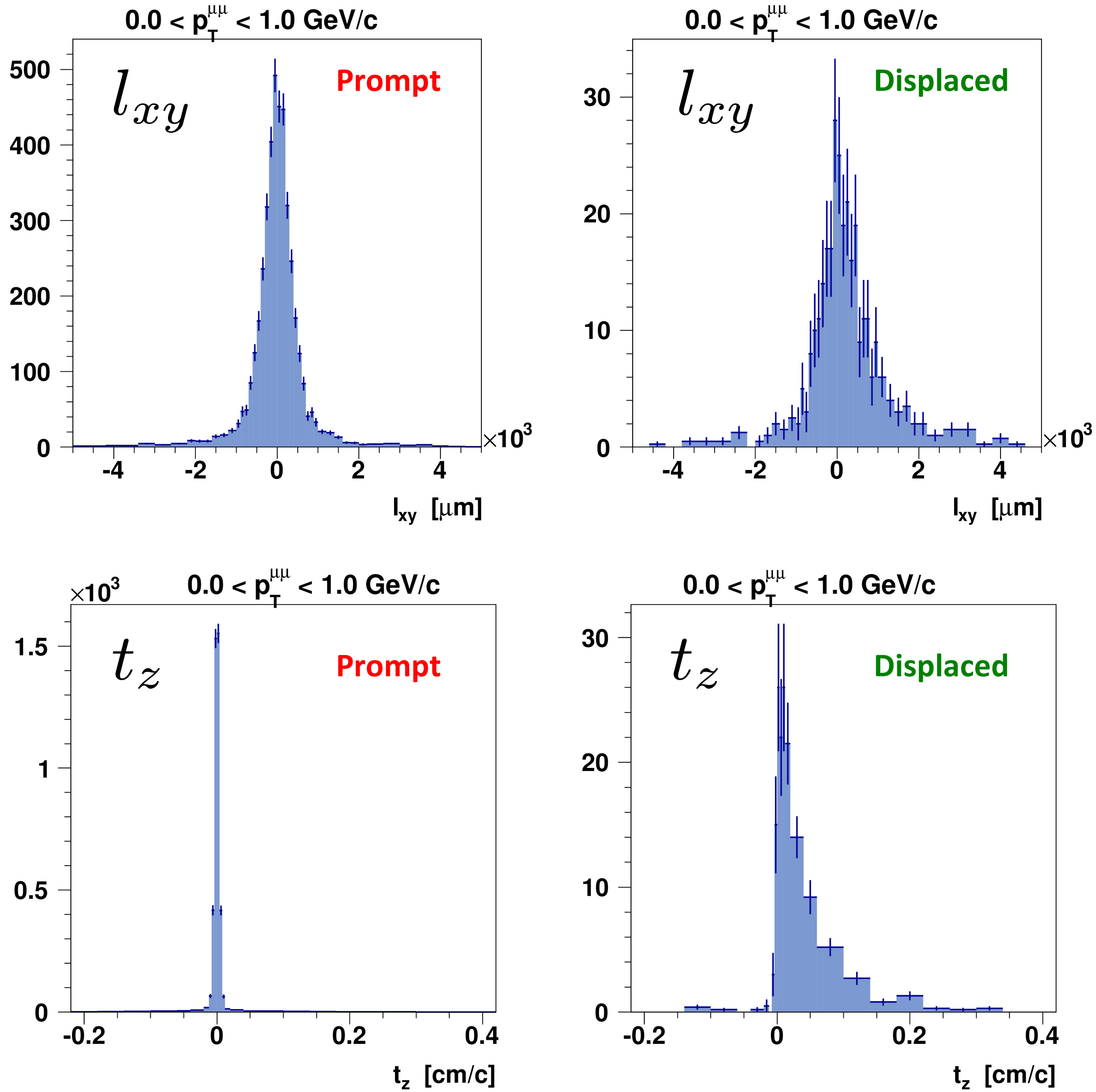
Displaced J/ψ: Transverse vs Longitudinal Approach

- Going to zero p_T, at forward rapidity, the secondary vertex will be essentially displaced **along the longitudinal direction!**

- The variable adopted by LHCb seems to be definitely well suited for the ALICE muon arm:

$$t_z = \frac{(z_0 - z_{J/\psi}) \cdot m_{J/\psi}}{p_z^{J/\psi}}$$

- MFT performances for J/ψ from B will be re-evaluated in the next simulation run

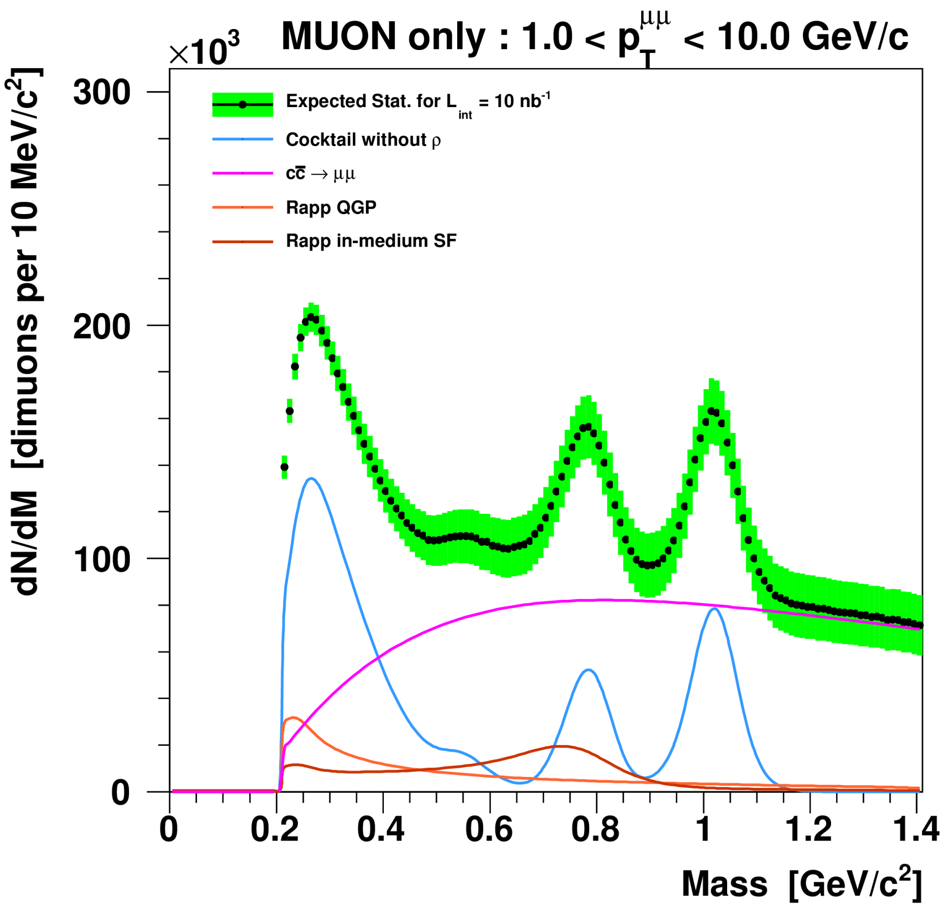


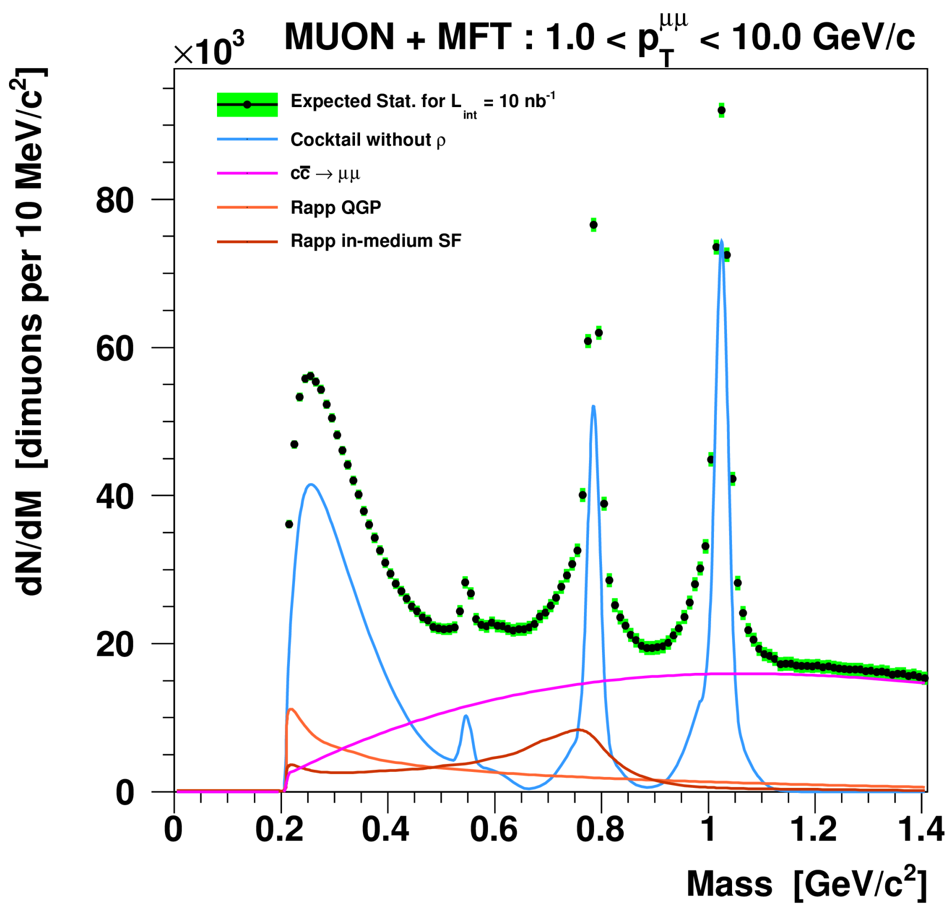
Low Mass Dimuon Physics

- Modification of spectral functions of vector mesons in the medium, linked to the chiral symmetry restoration
- Strangeness production and other aspects of the soft QCD

Low Mass Dimuons

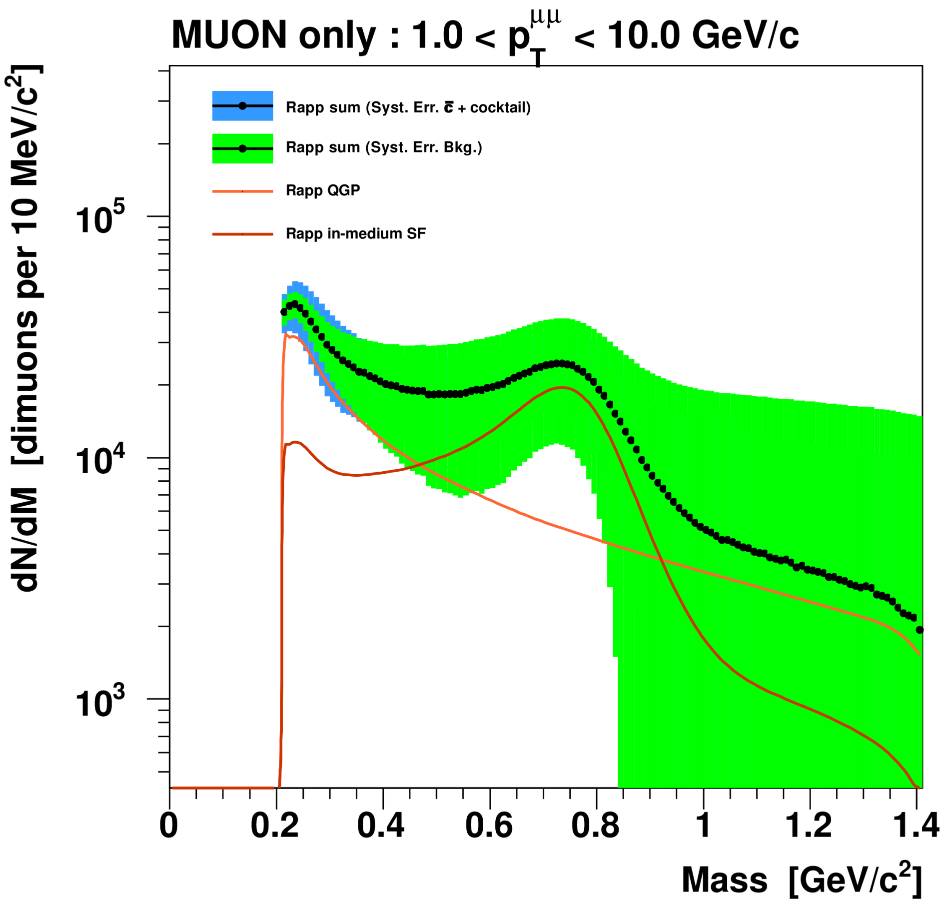
- **S/B ratio improved by a factor 3 to 7** thanks to the offset measurement
- **Improved mass resolution** thanks to the improved measurement of opening angle
- **Predictions for QGP radiation and in-medium line shapes** by R. Rapp

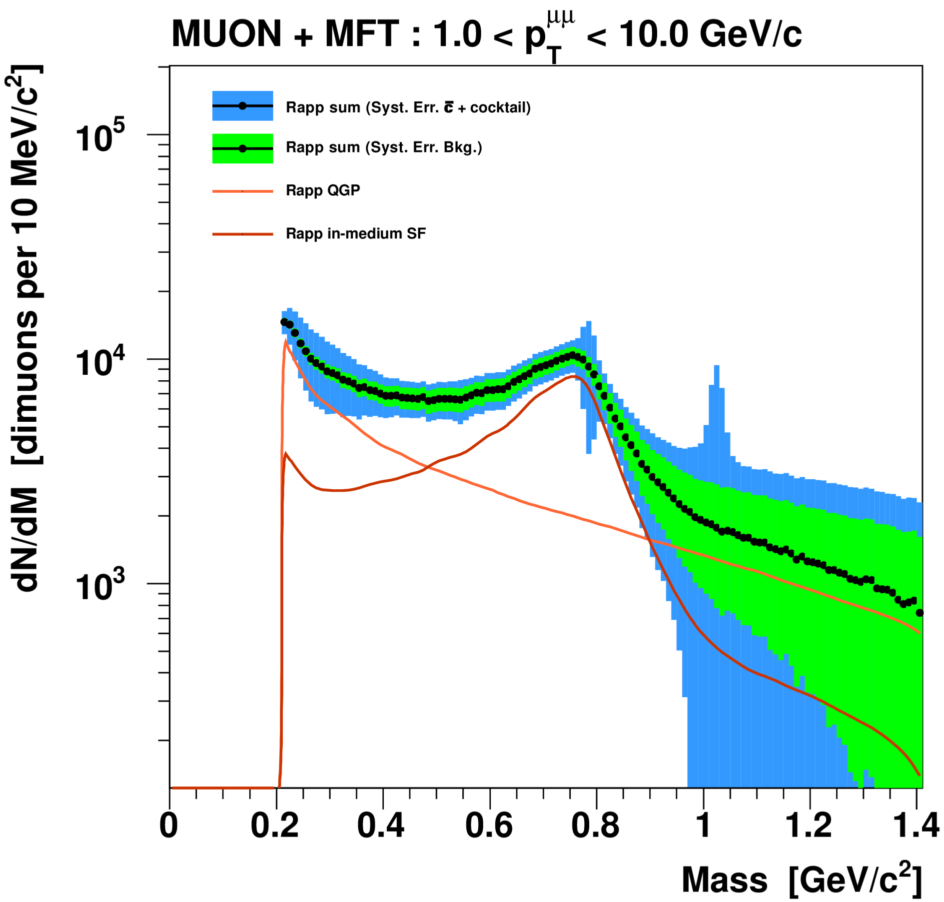




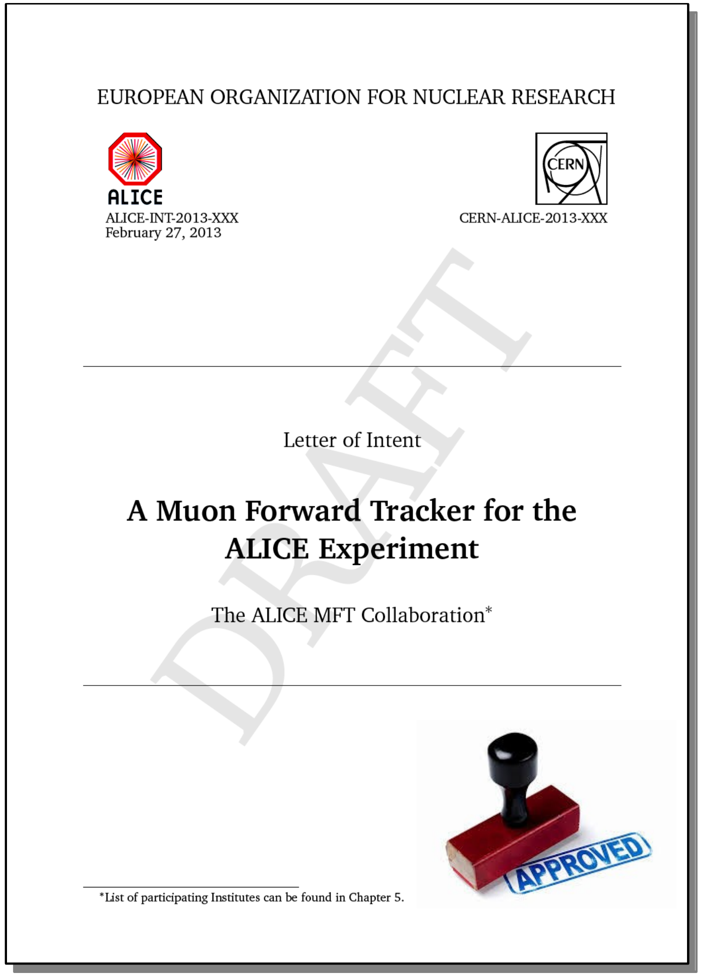
Low Mass Dimuons

- @ 0.5 GeV/c² : ~ **70 %** total systematic uncertainty **w/o MFT**
- @ 0.5 GeV/c² : ~ **22 %** total systematic uncertainty **w/ MFT**





From the MFT LoI to the ALICE LoI Addendum


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE
ALICE-INT-2013-XXX
February 27, 2013

CERN-ALICE-2013-XXX

Letter of Intent

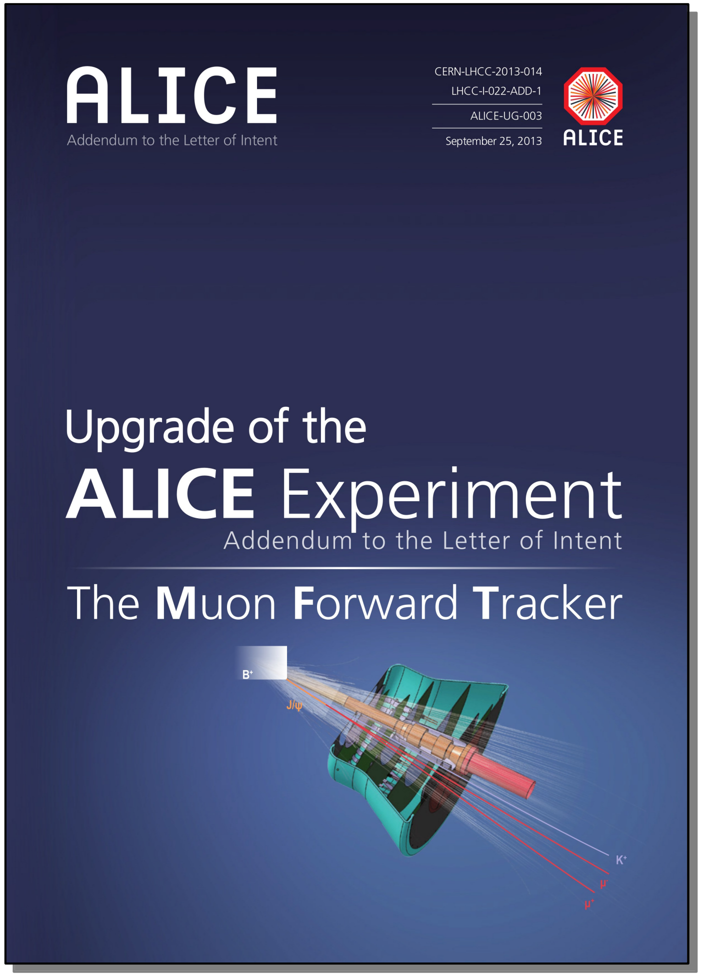
A Muon Forward Tracker for the ALICE Experiment

The ALICE MFT Collaboration*

DRAFT

APPROVED

*List of participating Institutes can be found in Chapter 5.


ALICE
Addendum to the Letter of Intent

CERN-LHCC-2013-014
LHCC-I-022-ADD-1
ALICE-UG-003
September 25, 2013

ALICE

Upgrade of the
ALICE Experiment
Addendum to the Letter of Intent

The **M**uon **F**orward **T**racker

Approved by ALICE Collaboration (Mar. 2013)

Submitted to LHCC (Decision on 25 September)

Conclusions

The ALICE experiment has already a rich and successful physics program with the present Muon Arm

The MFT will significantly boost the interest of the ALICE muon physics (the upgrade of the Muon Spectrometer electronics is mandatory!)

- Precise ψ(2s) measurement even in central Pb-Pb
- Prompt and non-prompt J/ψ separation
- Separation of charm/beauty down to very low p_T
- Improve S/B ratio and mass resolution for Low Mass dimuons

➡ **The MFT project has been approved by the ALICE Collaboration to be part of the ALICE upgrade planned for the LHC LS2 (2018)**

➡ **Final discussion to get the LHCC endorsement: next 24 September**

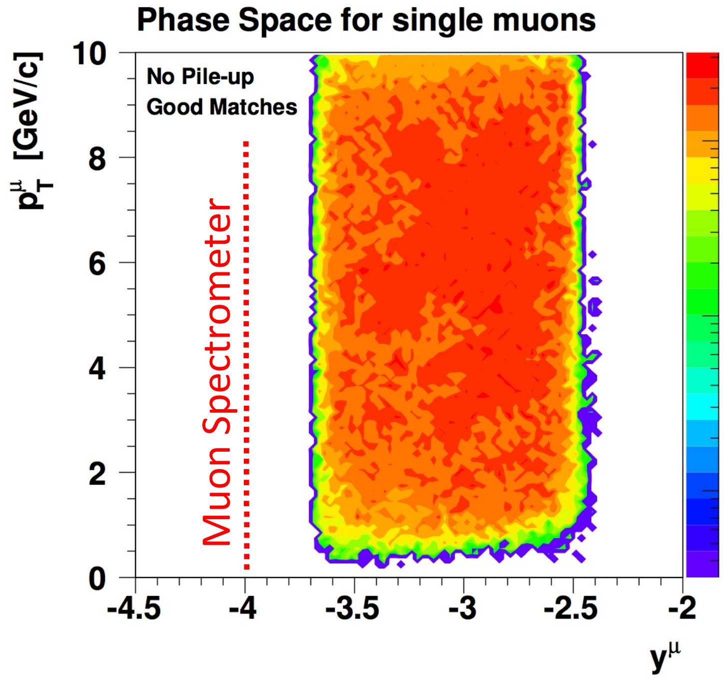
Backup Slides

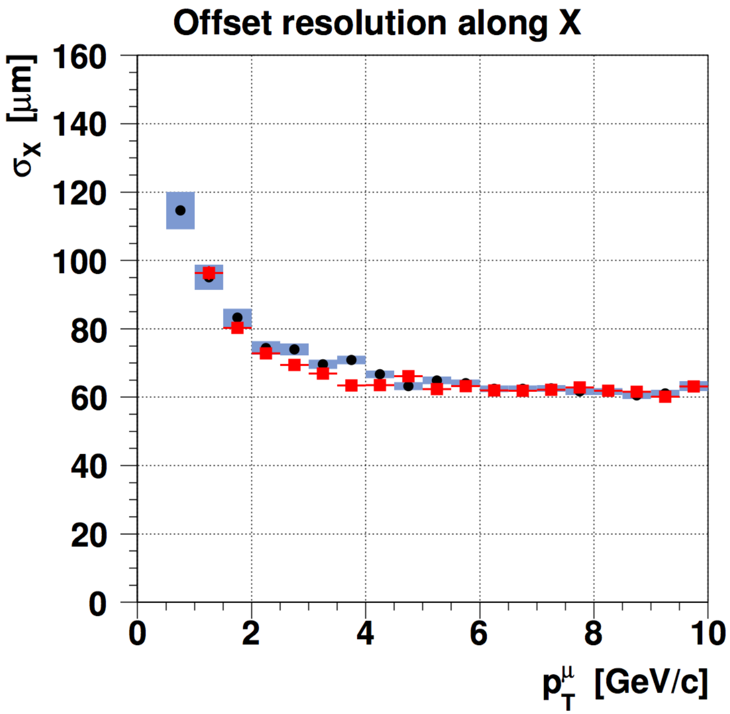
Backup Slides

Geometrical Acceptance and Pointing Resolution

- **Coverage: $-3.6 < \eta < -2.5$**
- **Limited by the inner radius of the MFT planes**

  → In discussion with ALICE TC to be as close as possible from the beam pipe, as the first layer of the ITS





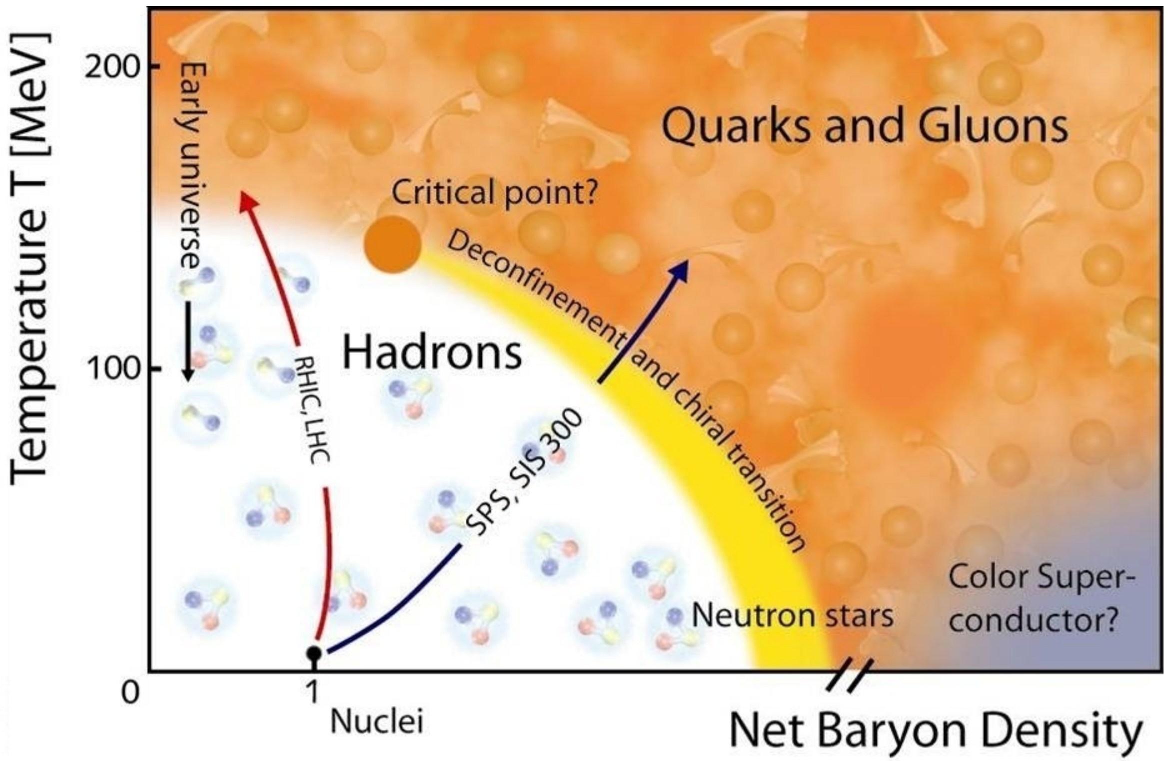
- With 15 μm misalignment → **60 μm pointing resolution at high p_T**
- Allows reliable **charm/beauty separation**
- Allows **non-prompt J/ψ identification**

- Still rather pessimistic scenario: 50 μm uncertainty on the primary vertex position is included!

The Quark Gluon Plasma

Ordinary hadronic matter : quarks and gluons confined within the hadrons (asymptotic freedom)

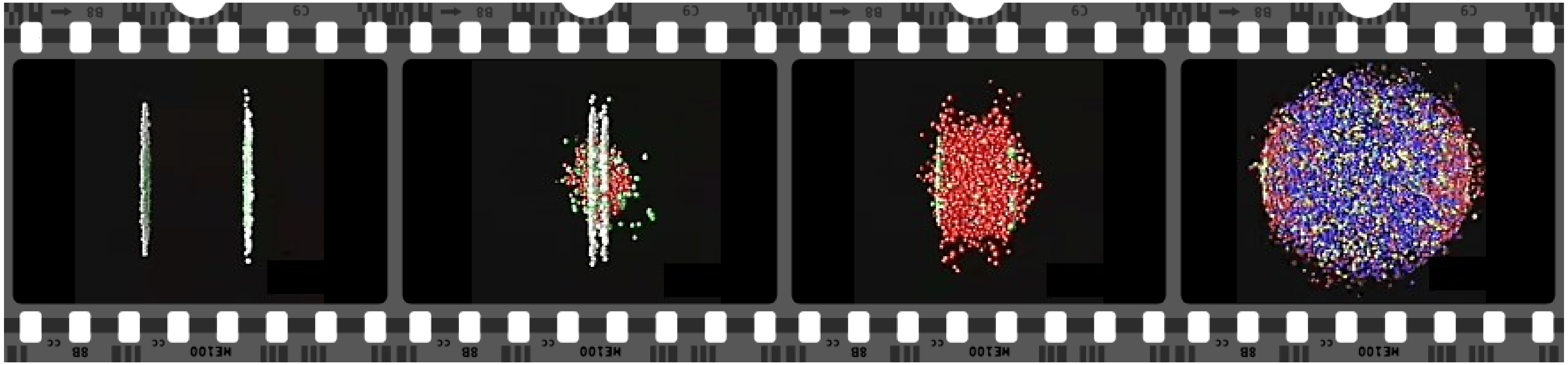
Quark Gluon Plasma : quarks and gluons deconfined in a plasma because of the charge color density (Debye screening)



Which conditions are needed ?

- Deconfinement temperature predicted by the (non-perturbative) lattice QCD : ≈ 175 MeV
- Energy density required to be larger than ≈ 3 GeV/fm^3
- Such conditions can be obtained in laboratory by colliding heavy nuclei at high energies

Probing the QGP via Single Muons and Dimuon

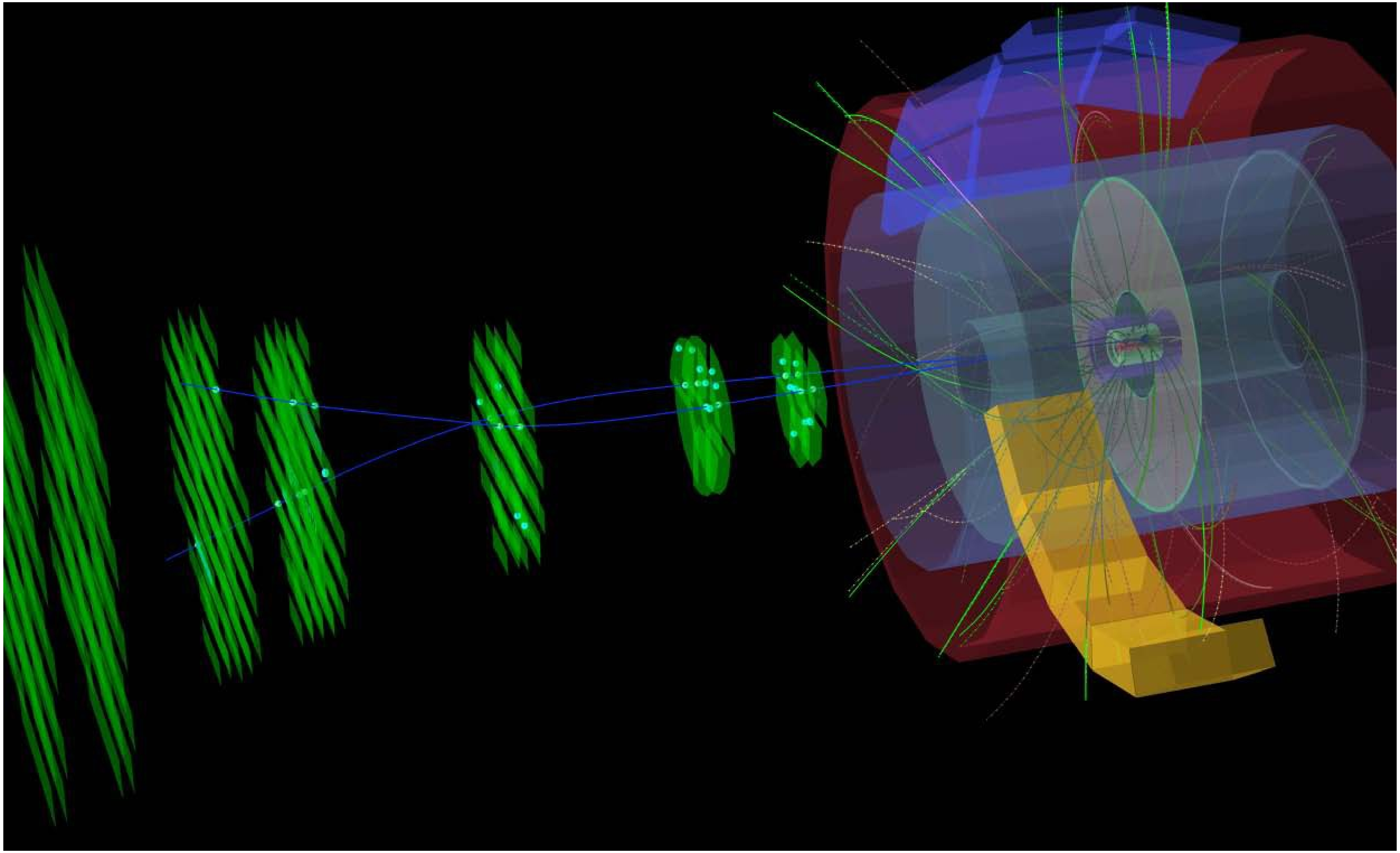


t = 0 t ≈ 0.3 fm/c t ≈ 3 fm/c

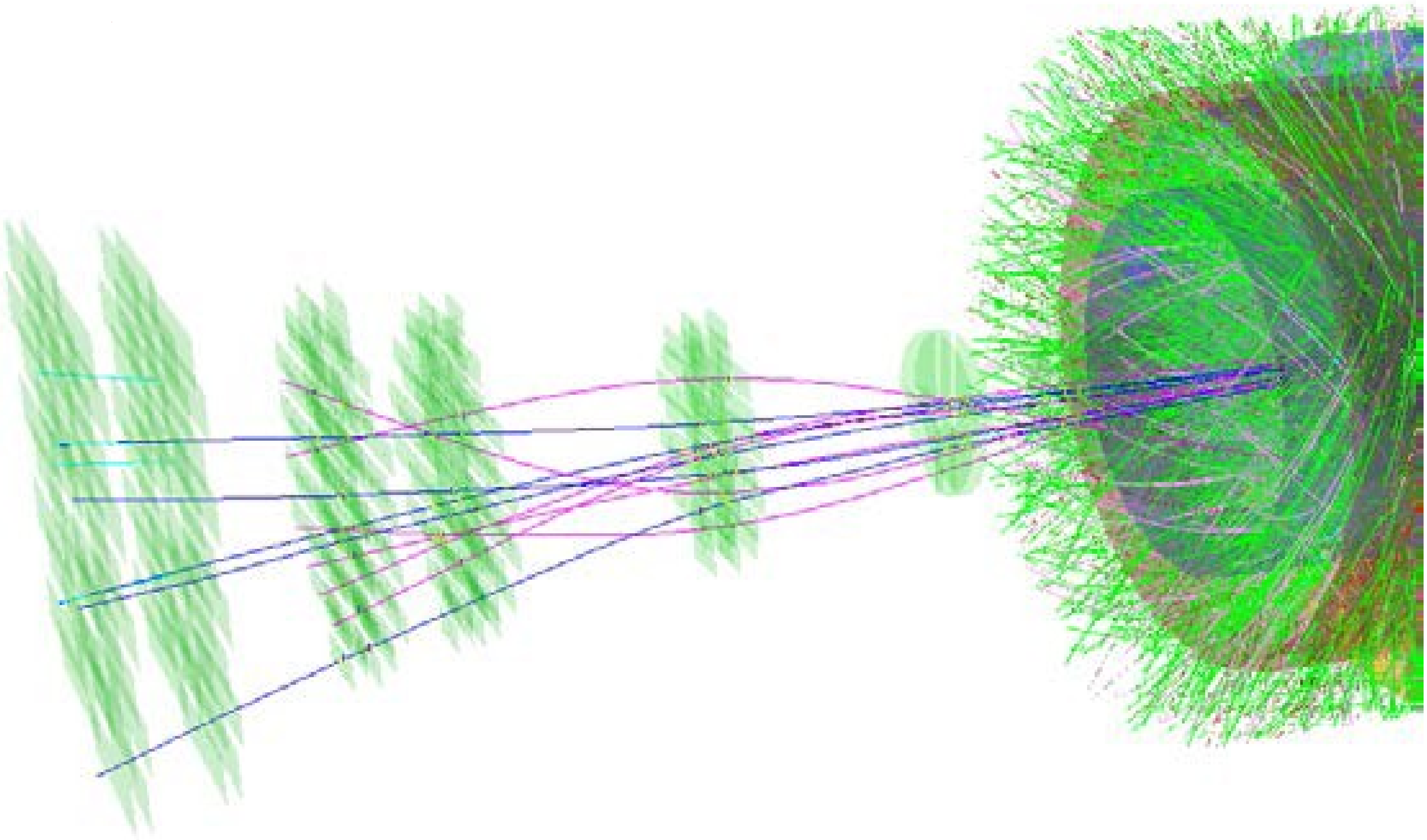
- Pb-Pb collisions at the LHC create the largest, longest-living and hottest QGP ever produced in laboratory. Current energy: 2.76 TeV per nucleon pair. Designed energy is 5.5 TeV

- Single muons and dimuons: clean probe to investigate the QGP. Among the observables:
  - Heavy flavor (c and b) production via the semi-muonic decay of D and B
  - Quarkonia production via dimuon decays
  - Thermal radiation from QGP via low and intermediate mass dimuons

pp Event in the Muon Spectrometer

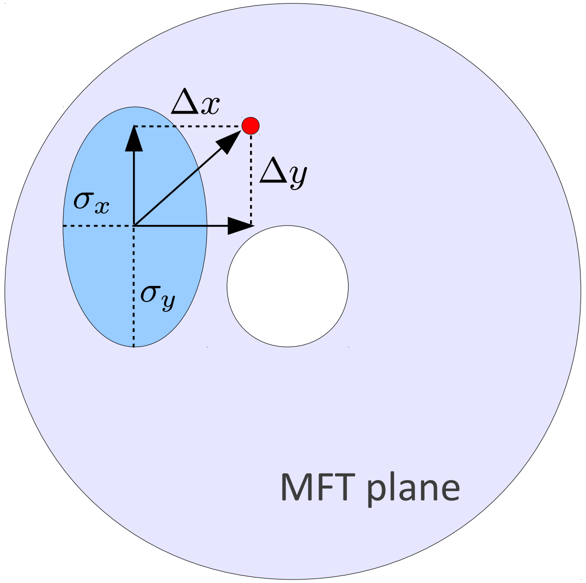


Pb-Pb Event in the Muon Spectrometer



Matching between MUON Tracks and MFT Clusters

For each **cluster** in the plane, its compatibility with the parameters of the **extrapolated MUON track** is checked, in terms of the quantity:



$$\chi^2_{\mathrm{clust}} = \frac{\Delta x^2 \cdot \sigma_y^2 + \Delta y^2 \cdot \sigma_x^2 - 2 \cdot \Delta x \Delta y \cdot \mathrm{cov}(x,y)}{\sigma_x^2 \cdot \sigma_y^2 - \mathrm{cov}^2(x,y)}$$

Distance between the cluster and the track at the plane along X and Y

Covariance matrix elements of the track parameters after extrapolation (+ cluster size along X and Y)

If the X and Y coordinate parameters of the track are not correlated, we simply have:

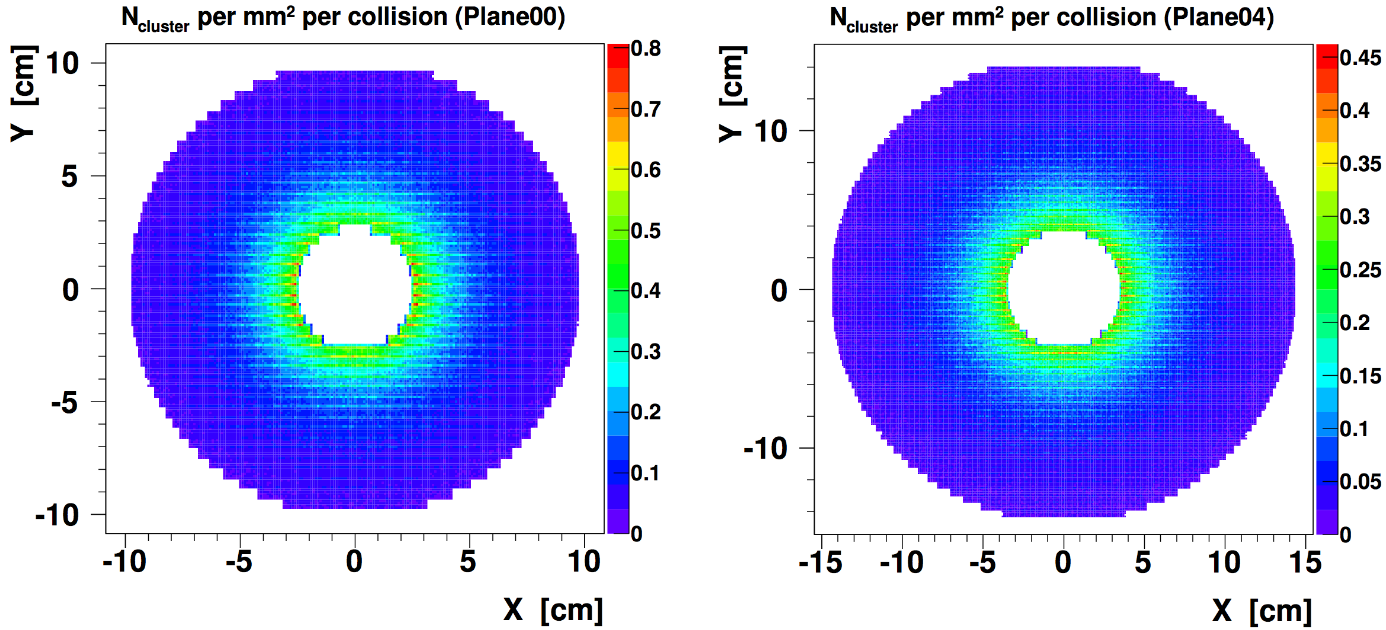
$$\chi^2_{\mathrm{clust}} = \frac{\Delta x^2}{\sigma_x^2} + \frac{\Delta y^2}{\sigma_y^2}$$

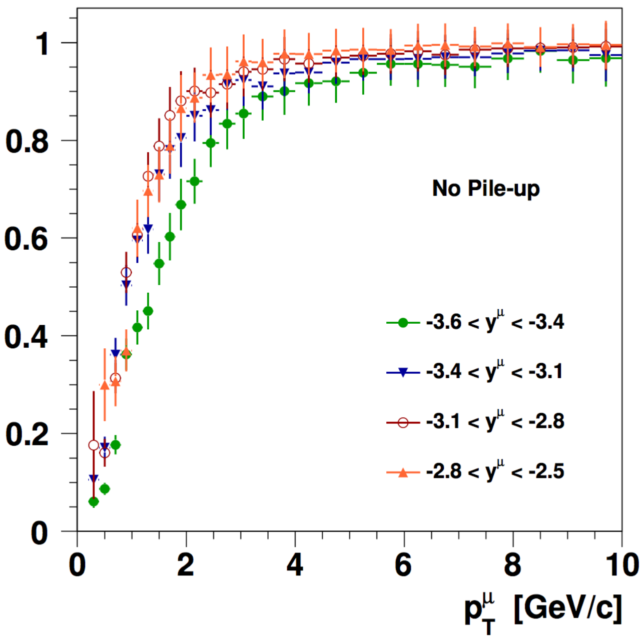
The cut is expressed as: $\chi^2_{\mathrm{clust}} < 2 \cdot n_\sigma^2$

Currently used: $n_\sigma = 4$

Plane Occupancy and Correct Matching Rate

- **0-10% central Pb-Pb**
- Max 0.5 cluster/mm^2
- Reduc. by factor 2 from 1st to 5th plane



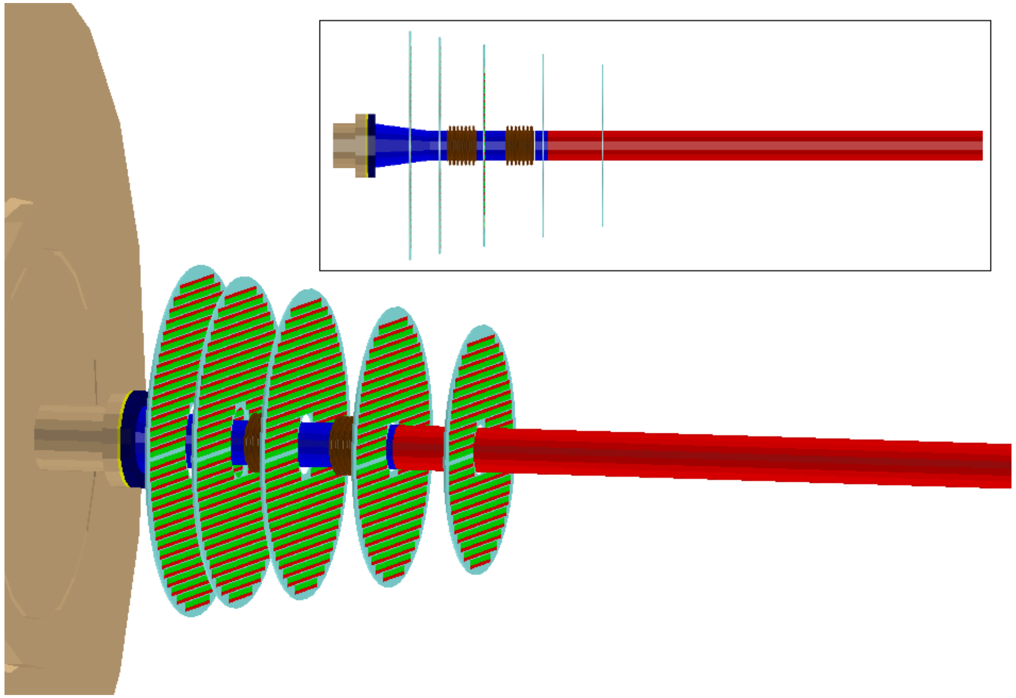


- 90% correct matching down to $p_T \sim 2$ GeV/c
- 50% correct matching rate for $p_T \sim 1$ GeV/c
- Fake matches can be reduced by means of appropriate selections. Residual fakes treated as a component of the signal

The MFT in AliRoot

The **$ALICE_ROOT/MFT** directory already contains the code to perform simulations:

- MFT geometry and structure (volumes, materials)
- Creation of Hits and SDigits
- Conversion SDigits → Digits (Digitization) → Clusters (Clusterization)
- ✯ Matching between MUON tracks and MFT clusters

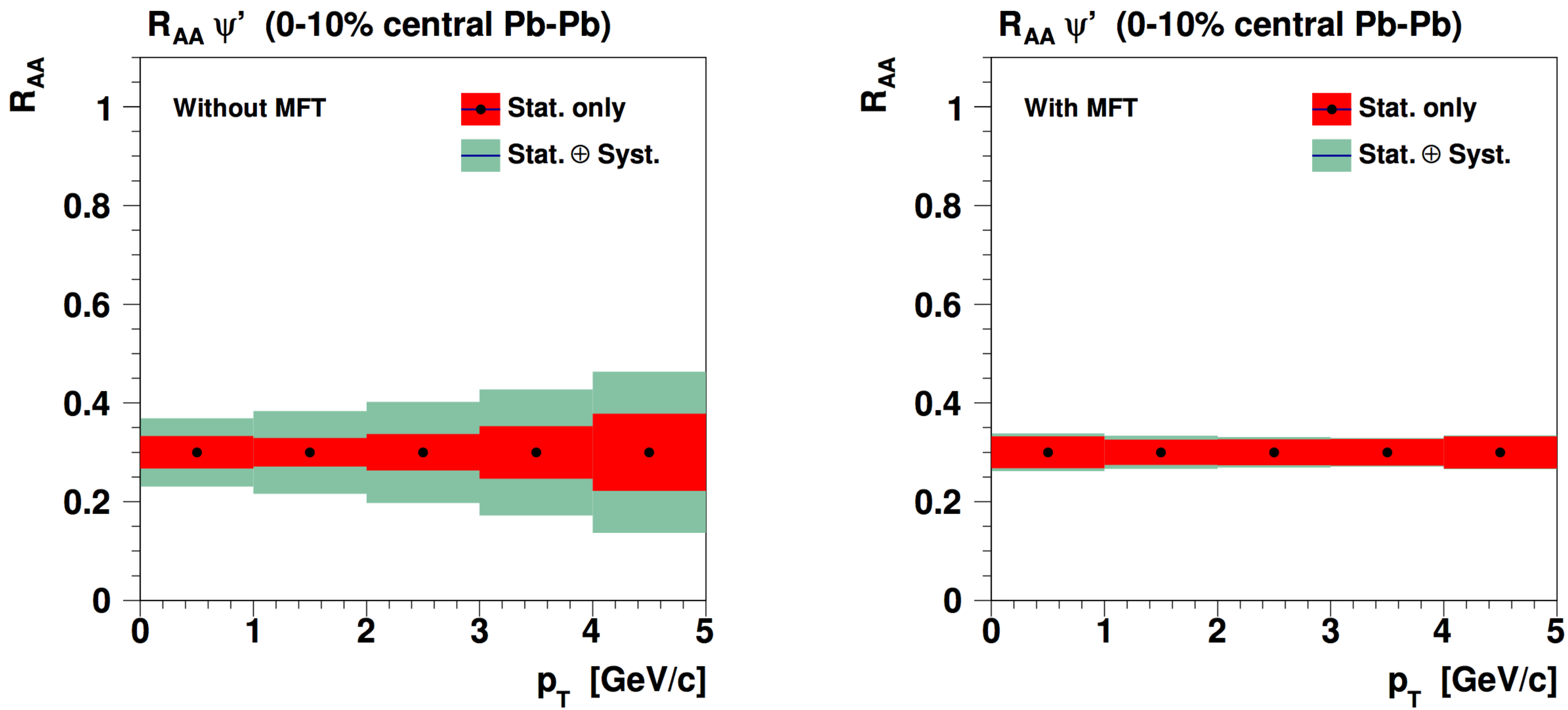


Current simulation scenario:

- 5 MFT planes
- 25×25 μm² pixel size
- 0.4 % x/X_0 per plane
- 15 μm residual misalignment
- Pile-up scenario for a 25 μs readout time: 1 Pb-Pb central collision + 1 Pb-Pb central collision (with different prim. Vertex)

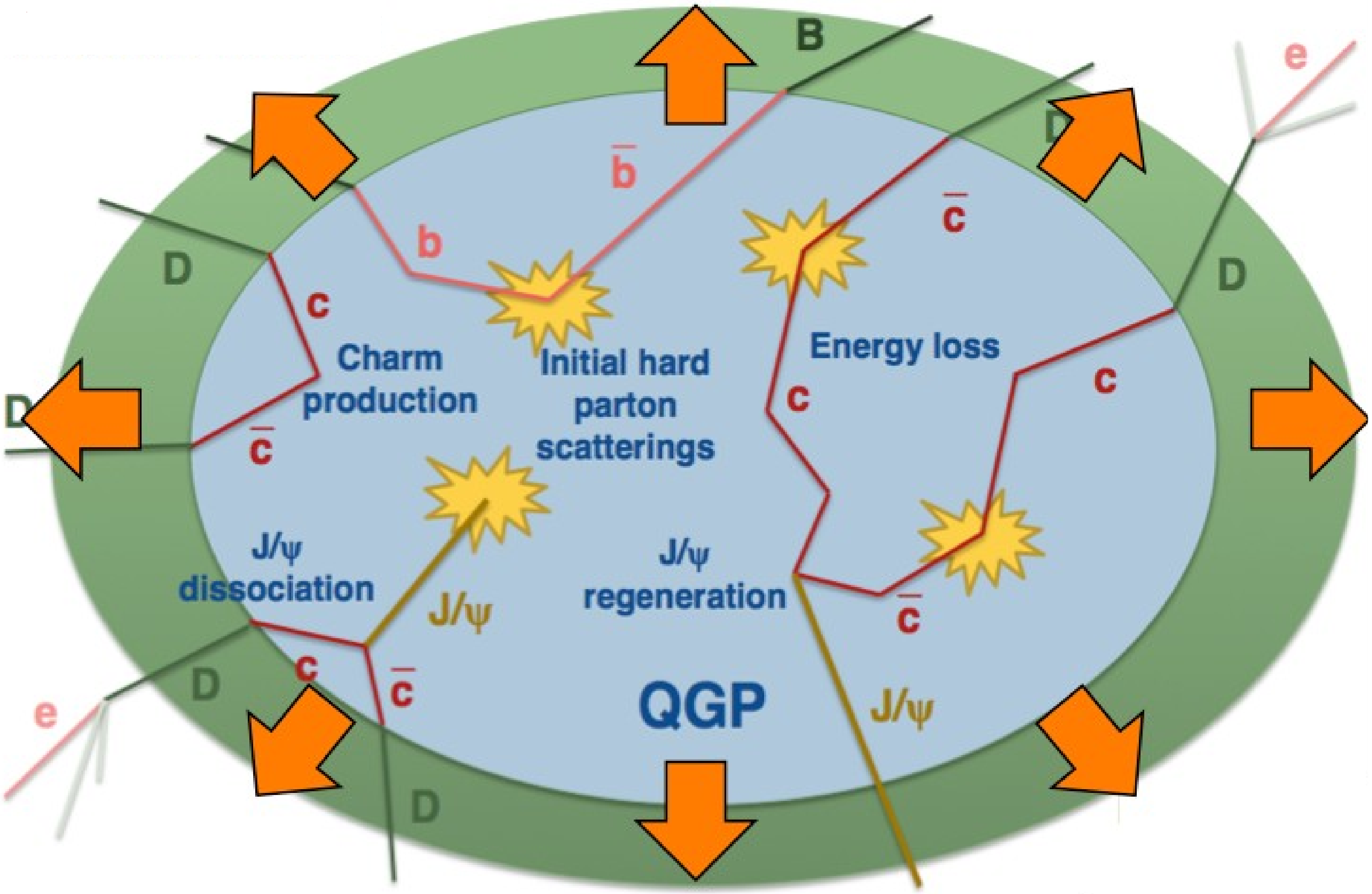
Charmonia: Inclusive J/ψ and ψ' Measurement

- Reduction of main systematic contribution (the background subtraction) thanks to highly improved S/B ratio. ψ' measurement down to zero p_T would be a unique case at the LHC



Selected items from the current ALICE Muon Physics

Heavy Quarks in QGP



graphics courtesy J. Uphoff

Heavy Quarks in QGP

- **Large mass** ($m_c \sim 1.5$ GeV, $m_b \sim 5$ GeV) $\rightarrow$ produced in large virtuality Q^2 processes at the initial stage of the collision with **short formation time** $\Delta t > 1/2m \sim 0.1$ fm $<< \tau(QGP) \sim 5\text{-}10$ fm/c. Insight on the short time scale of the collision

- **Charmed and beauty hadrons have a long life time** ($c\tau \sim 150$ µm and $c\tau \sim 500$ µm): information on the evolution of the deconfined medium

- **Sensitivity to the density of the medium** is provided by the mechanism of in-medium energy loss of heavy quarks (**"Dead-cone" effect**)

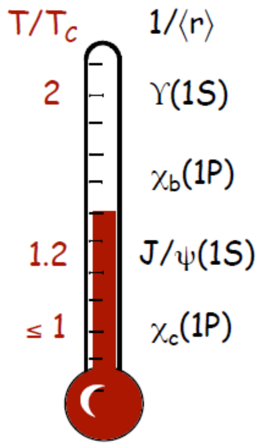
- **Sensitivity to the temperature of the medium** is provided by the sequential melting of bound quarkonium states (charmonia and bottomonia)

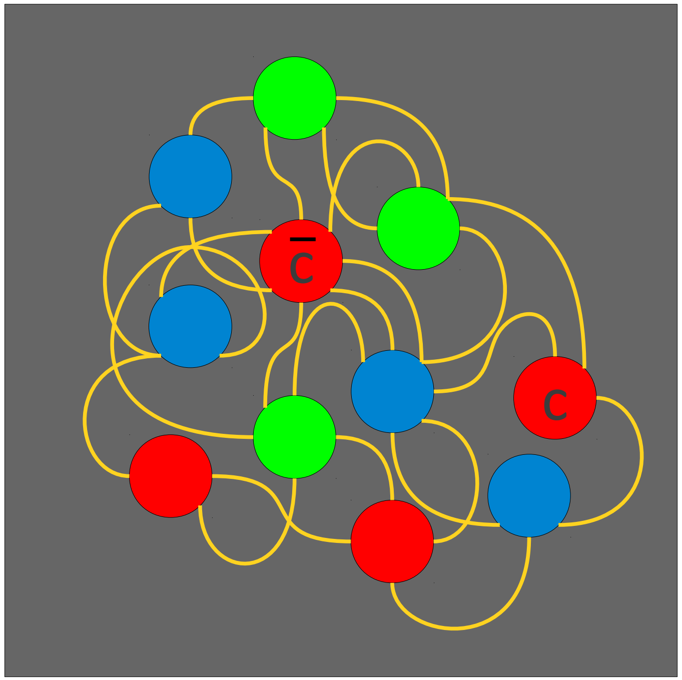
graphics courtesy J. Uphoff

The Two "Historical" Pillars

- **Dissociation of $Q\bar{Q}$ states via color-screening**

  Matsui and Satz, 1986

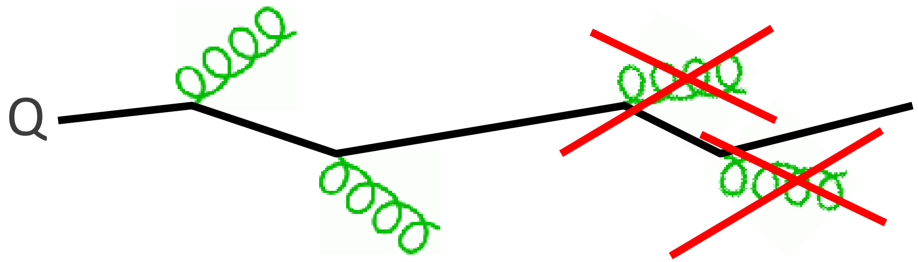




Direct probe of medium deconfinement and temperature

- **Mass dependence of parton energy loss (dead cone)**

  Dokshitzer and Kharzeev, 2001



In-medium gluon radiation is expected to increase with the color-charge of the emitting particle, and to decrease with its mass

Direct probe of QCD interaction dynamics over extended systems

Open HF: ALICE μ Measurement in pp

Heavy flavors in pp collisions:

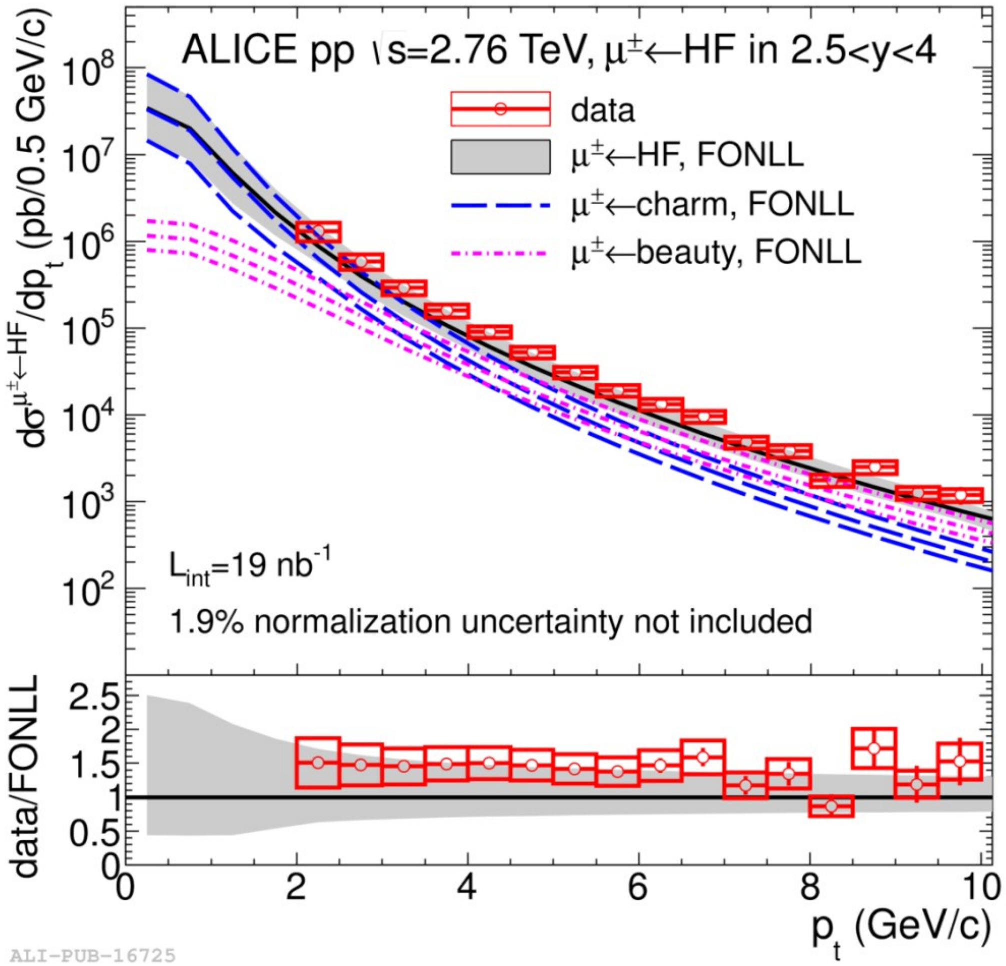
- Reference for pA and AA collisions
- Test pQCD in a new energy domain

Data well described by FONLL calculations within uncertainties in pp collisions at $\sqrt{s}$ = 2.76 and 7 TeV

FONLL predicts that muons from beauty decays dominate at $p_T \geq 6$ GeV/c

➡ **Data cannot distinguish between open charm and open beauty production**

[Phys. Rev. Lett. 109 (2012) 112301]



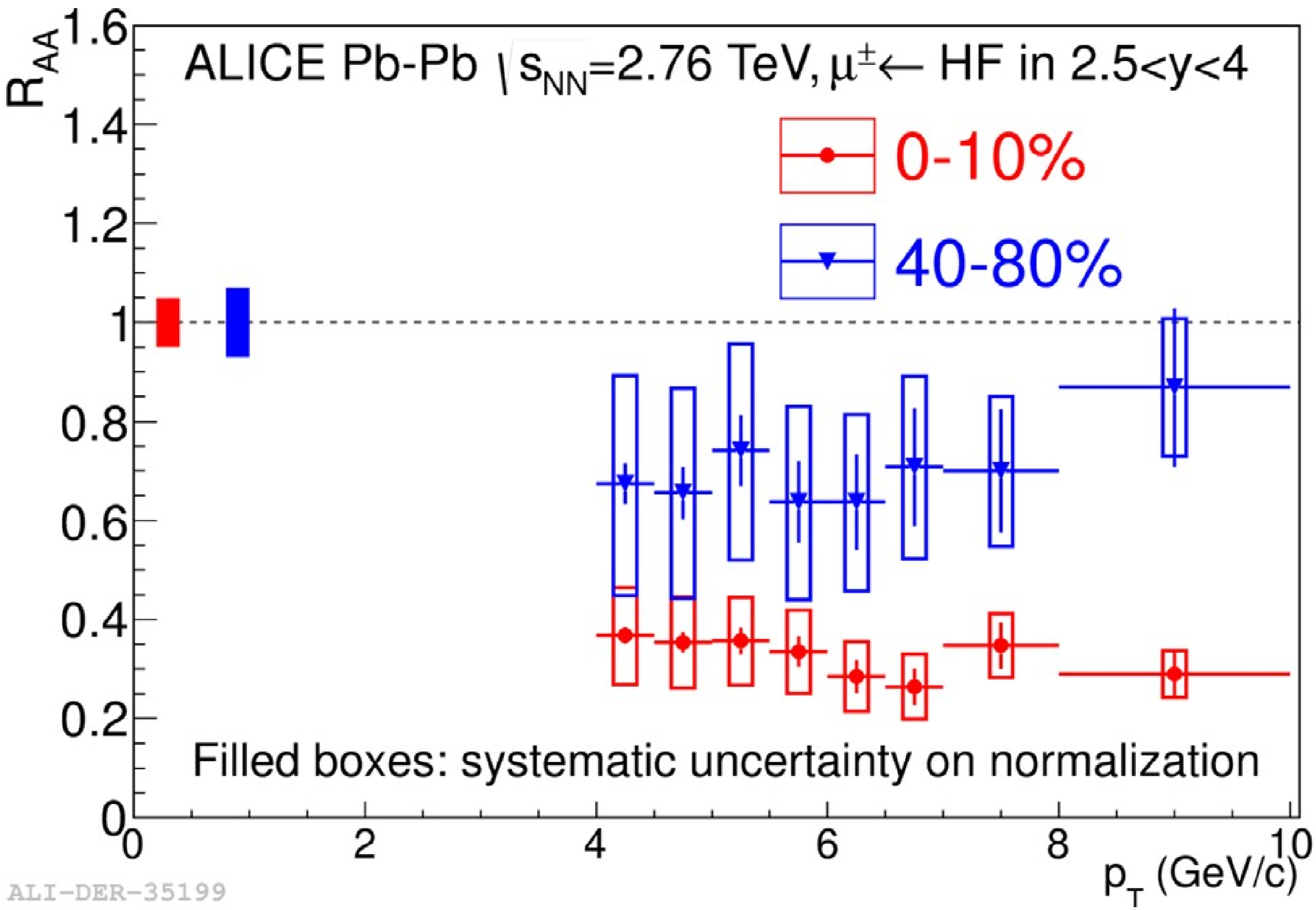
FONLL calculation from M. Cacciari et. al., arXiv:1205.6344

Open HF: ALICE μ Measurement in Pb-Pb

[Phys. Rev. Lett. 109 (2012) 112301]

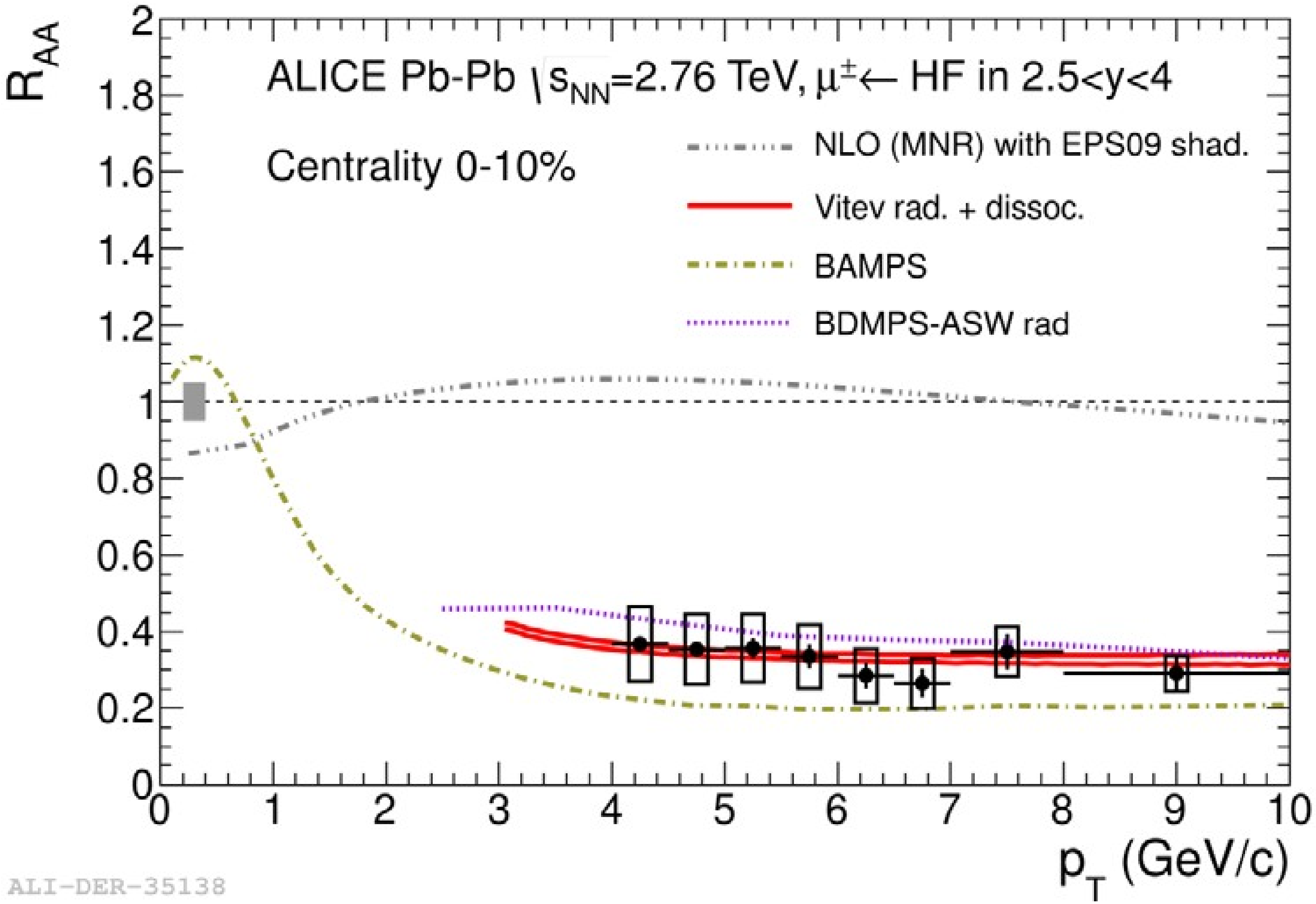
Heavy flavors in Pb-Pb at 2.76 TeV per nucleon pair

- Suppression is observed and shows a weak p_T dependence in the measured p_T range
- Stronger suppression in central collisions than in peripheral collisions
- p_T range limited by the large contamination from background (muons from light flavors) at lower p_T



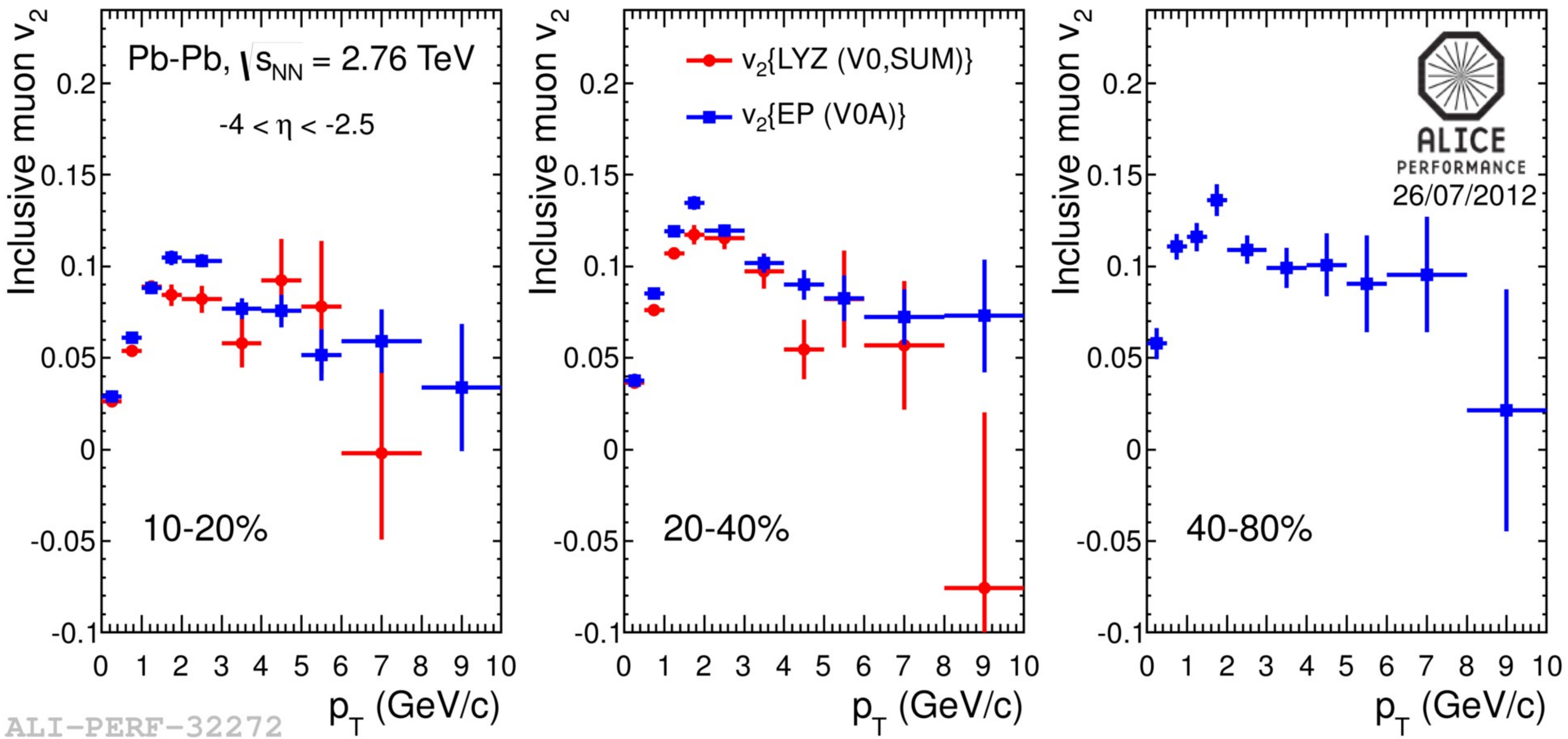
Open HF: ALICE μ Measurement in Pb-Pb

Suppression in 0-10% central Pb-Pb: comparison with models in the available p_T range



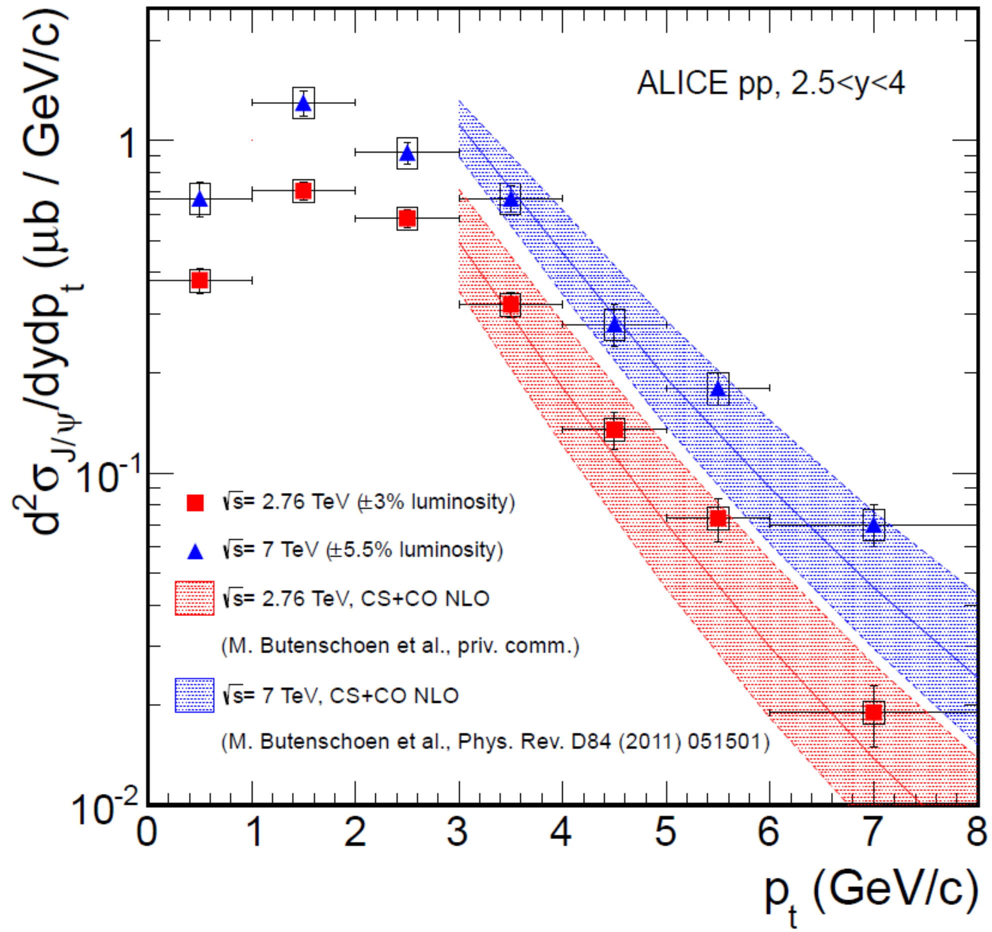
Open HF: ALICE μ Measurement in Pb-Pb

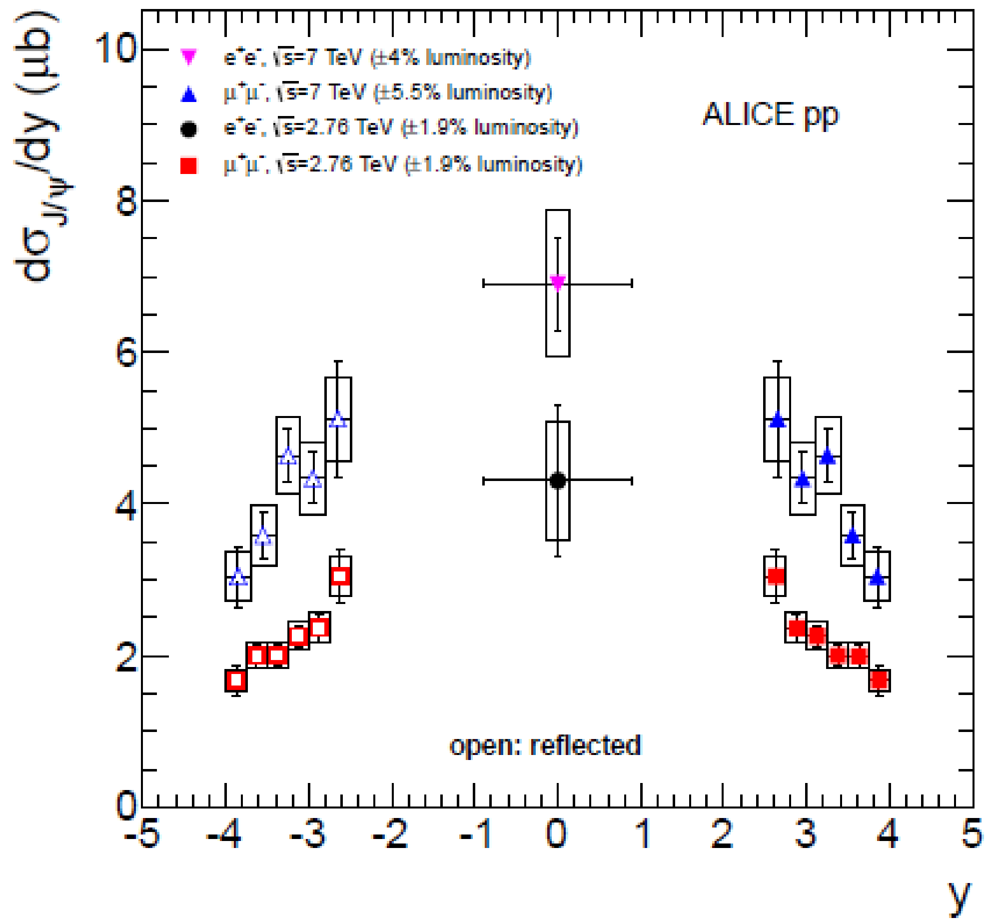
- **Inclusive muon v_2** is measured up to 10 GeV/c (background not subtracted)
- Indication for larger v_2 in semi-central collisions than in central collisions



Charmonia: ALICE μμ Measurement in pp

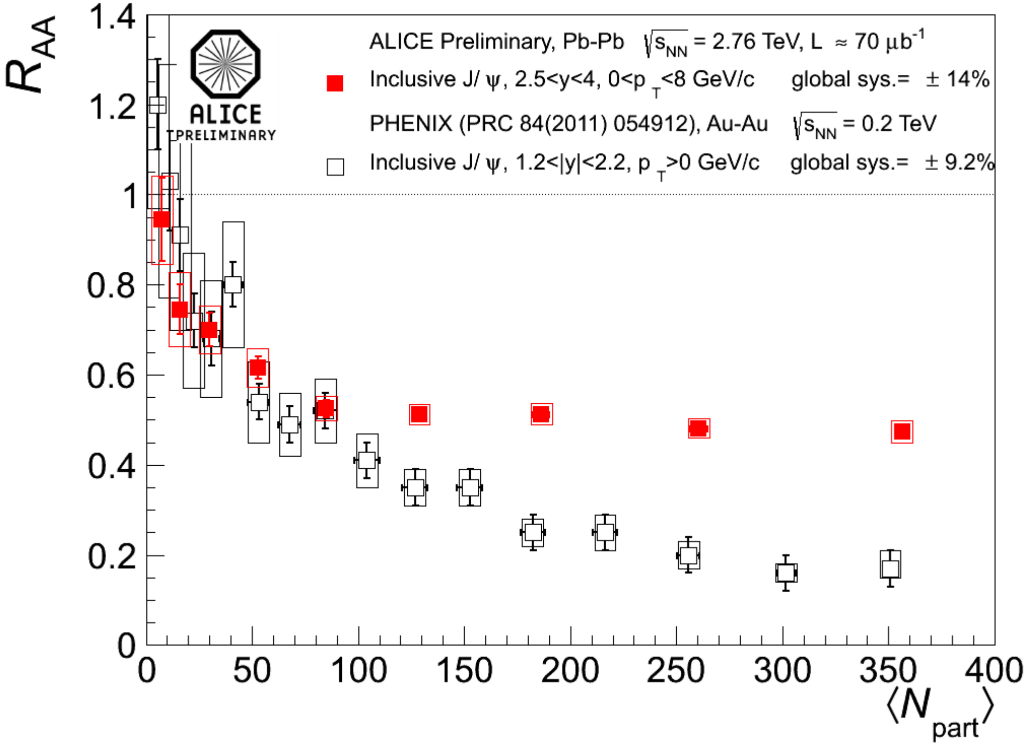
- Data taking at Vs = 2.76 TeV essential to build the R_{AA} reference
- Results in agreement with NLO NRQCD calculations

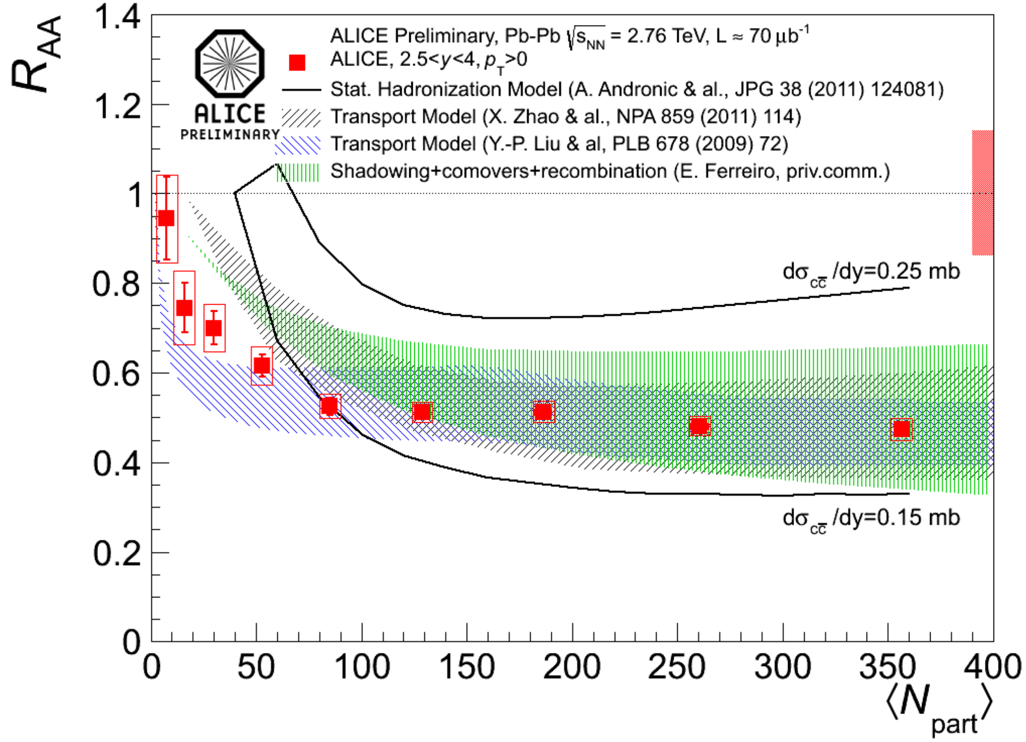




R_{AA} vs $\langle N_{part} \rangle$:

- Comparison with PHENIX: **Stronger centrality dependence at lower energy**
- Behavior of ALICE data is qualitatively expected in a **(re)generation scenario**

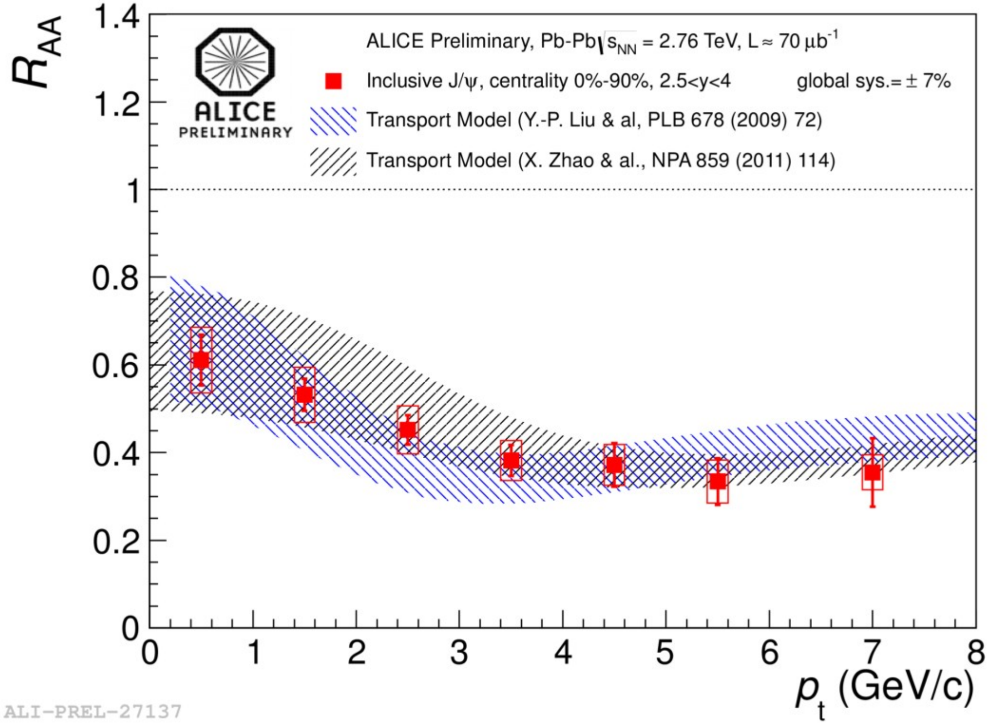


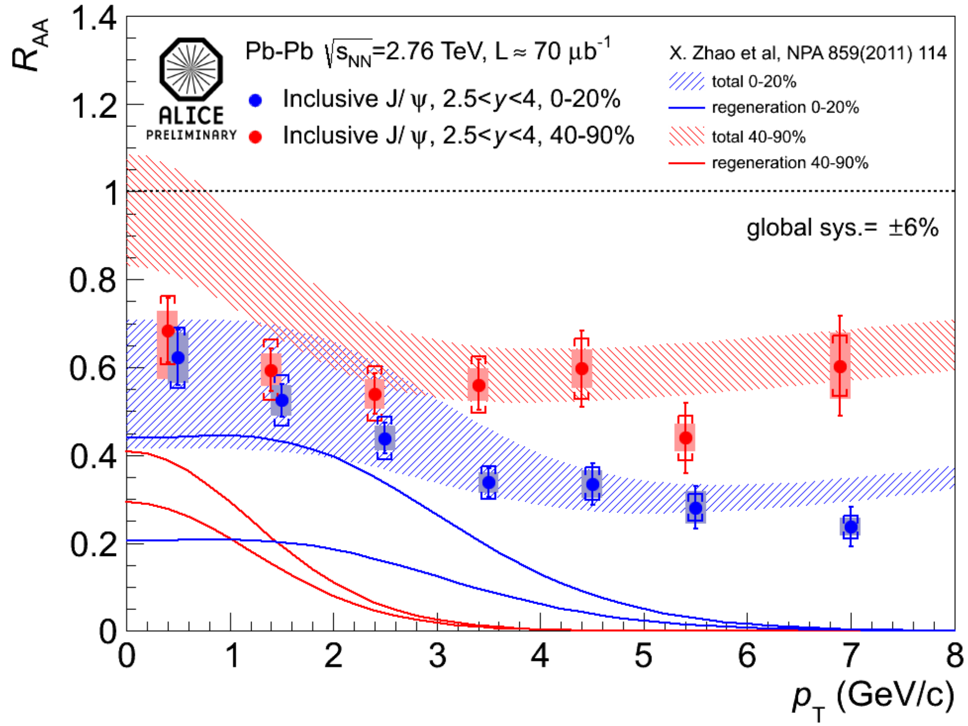


Charmonia: ALICE μμ Measurement in Pb-Pb

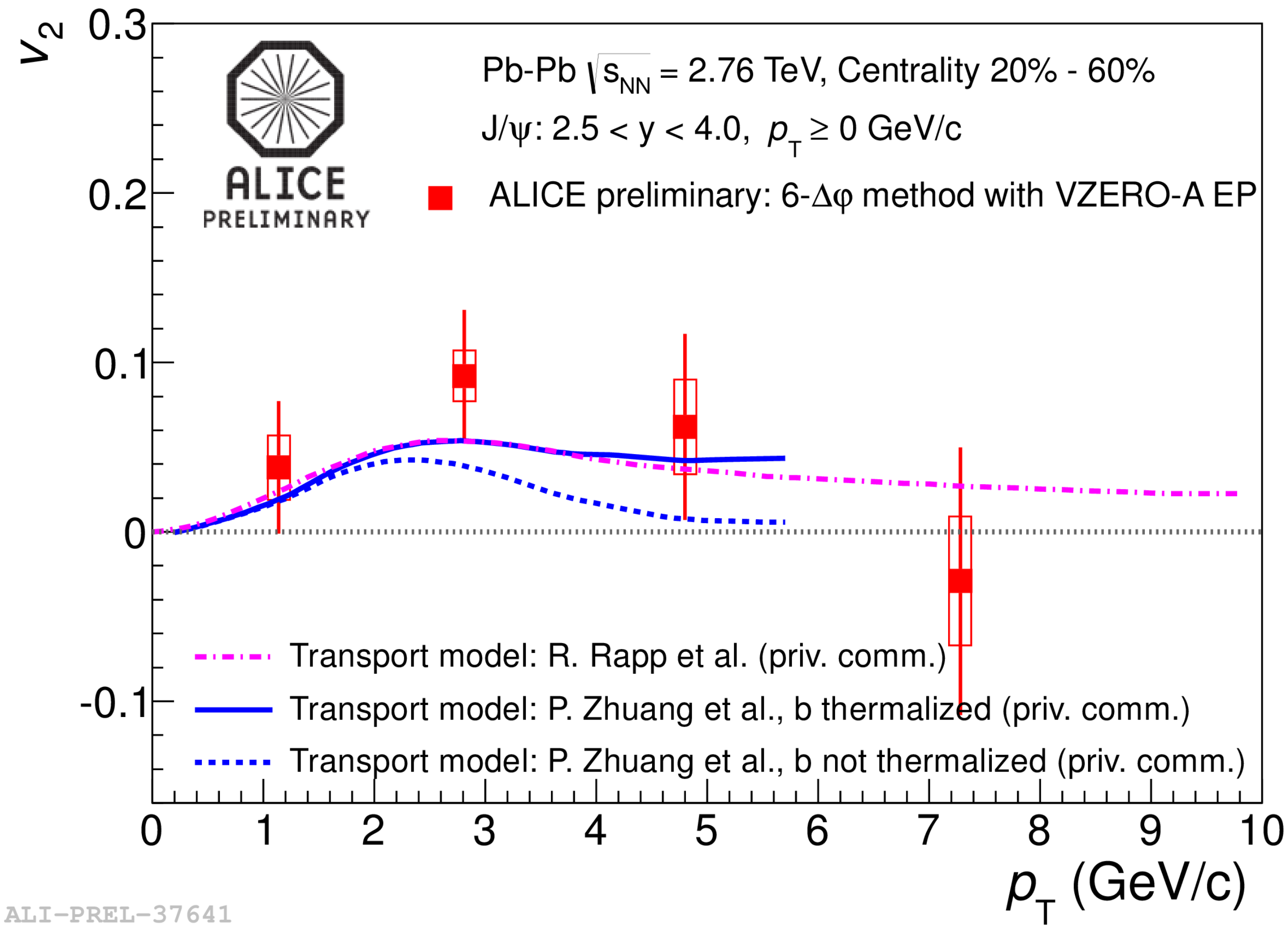
R_{AA} vs p_T (for all centralities and in different centrality bins)

- Suppression is stronger for high-p_T J/ψ: regeneration at low p_T?
- Splitting in centrality bins we observe that the difference low vs high-p_T suppression is more important for central collisions

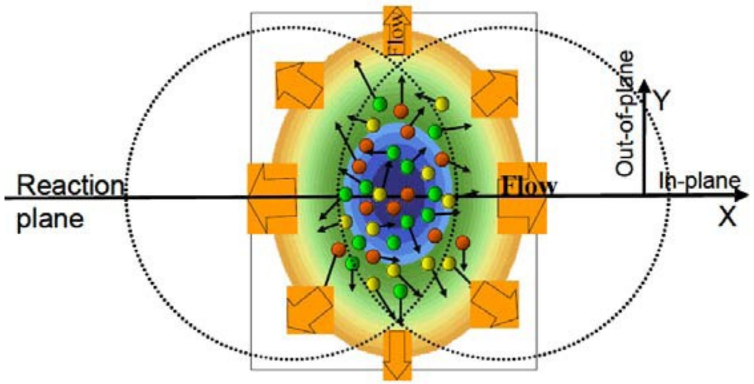




Measurement of J/ψ elliptic flow may answer the question: are charm quarks in equilibrium with the QGP?



- Hint of non-zero v_2
- For 20-60% at p_T: $2 \leq p_T < 4$ GeV/c significance = 2.2 sigma, contrary to zero v_2 observed at RHIC



Low Mass Dimuons in ALICE

Low mass vector meson (ρ, ω, ϕ) production provides key information on the hot and dense state of strongly interacting matter which is produced in high-energy heavy-ion collisions. Insights on **non-perturbative QCD** are provided:

- Strangeness enhancement accessed via ϕ meson production
- In-medium modifications of hadron properties accessed through ρ spectral function: possible link to chiral symmetry restoration

Why dimuons (= virtual photons)? They are not affected by in-medium effects: information from the deconfined volume is not distorted

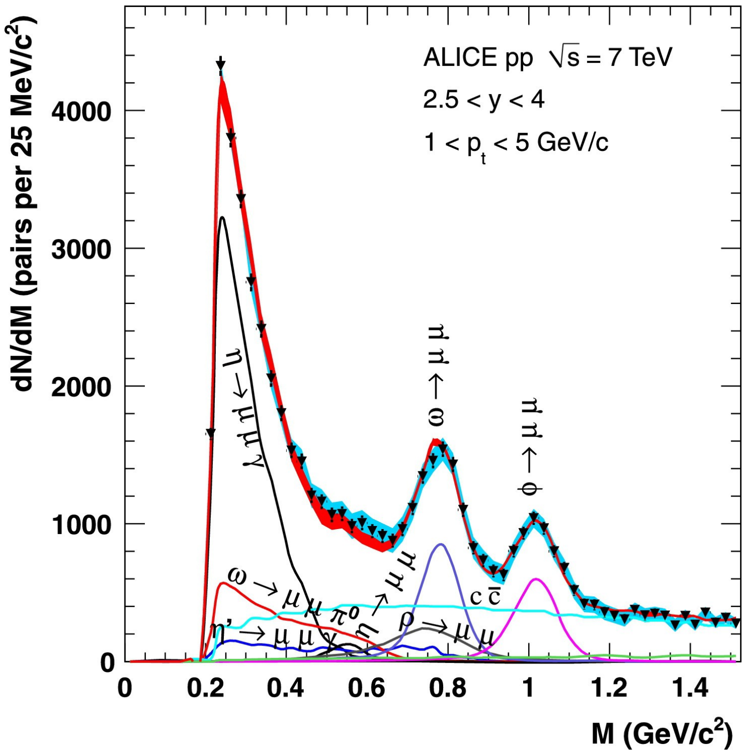
Why measurements in pp (and soon in p-A!) collisions? Needed reference for correctly interpreting in-medium effects

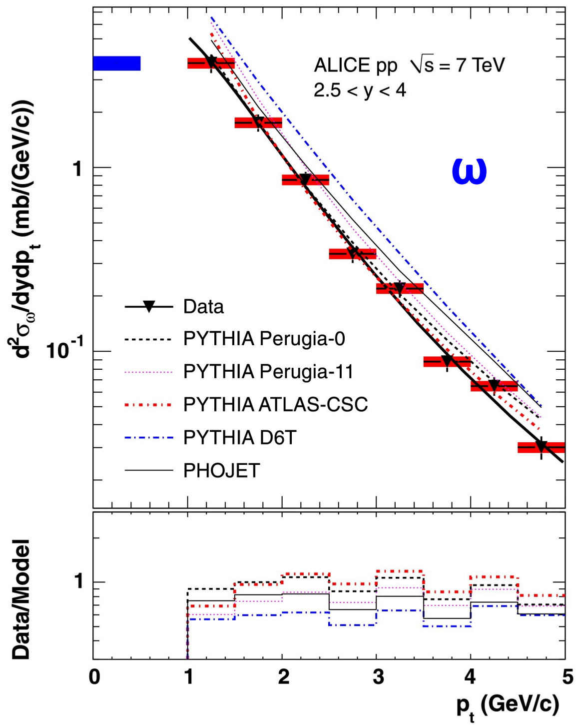
Why measurements at the LHC? Unexplored energy regime, with a hotter and longer living deconfined medium. **Unique physics case for ALICE**

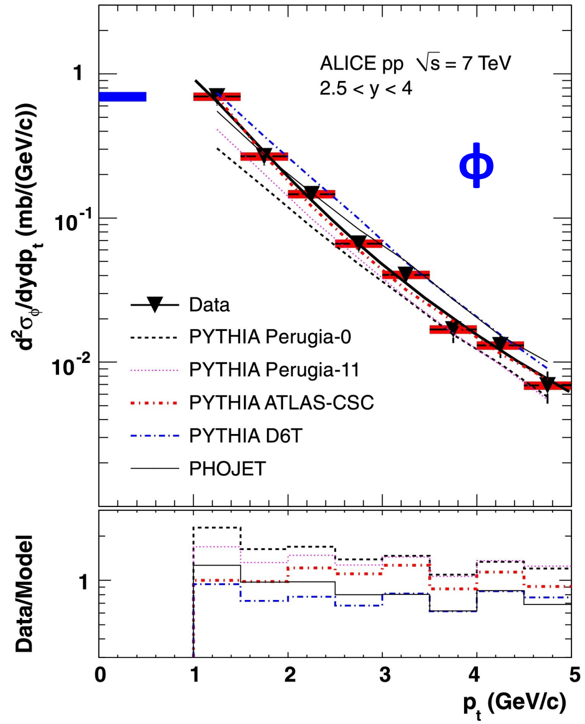
Low Mass Dimuons: ALICE Measurement in pp

A clear signal is obtained after the subtraction of the combinatorial background. **MC sources:** hadronic cocktail + open charm/beauty

- Good agreement between data and MC
- p_T distributions are extracted for the ω and ϕ mesons: comparison is provided with several PYTHIA and PHOJET settings



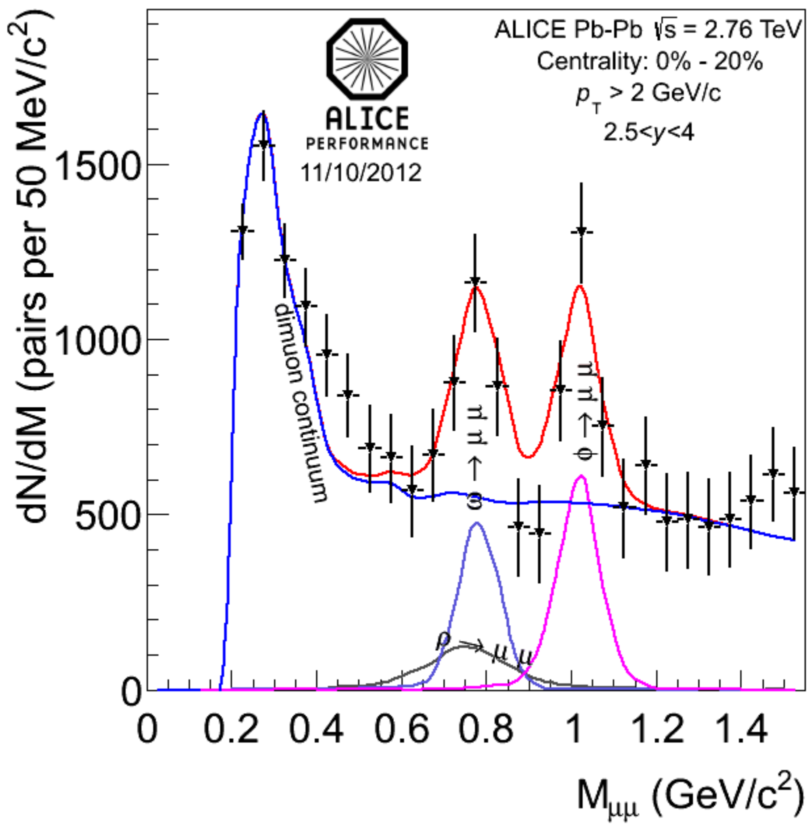


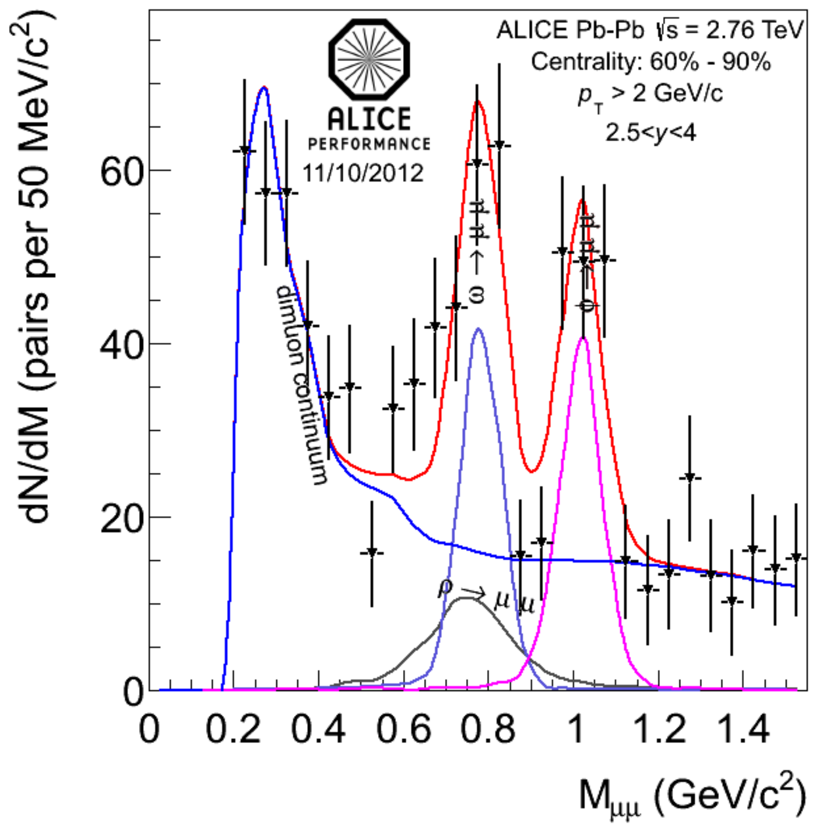


Low Mass Dimuons: ALICE Measurement in Pb-Pb

Subtraction of the combinatorial background is more delicate in Pb-Pb than in p-p

- Analysis limited to $p_T > 2$ GeV/c because of the unfavorable trigger conditions
- Search for unconventional sources (QGP radiation, in-medium spectral functions) is limited by the statistics available





The MFT Working Group

- **MFT Labs**

  France: Clermont-Fd, Lyon, Nantes, Orsay, Saclay

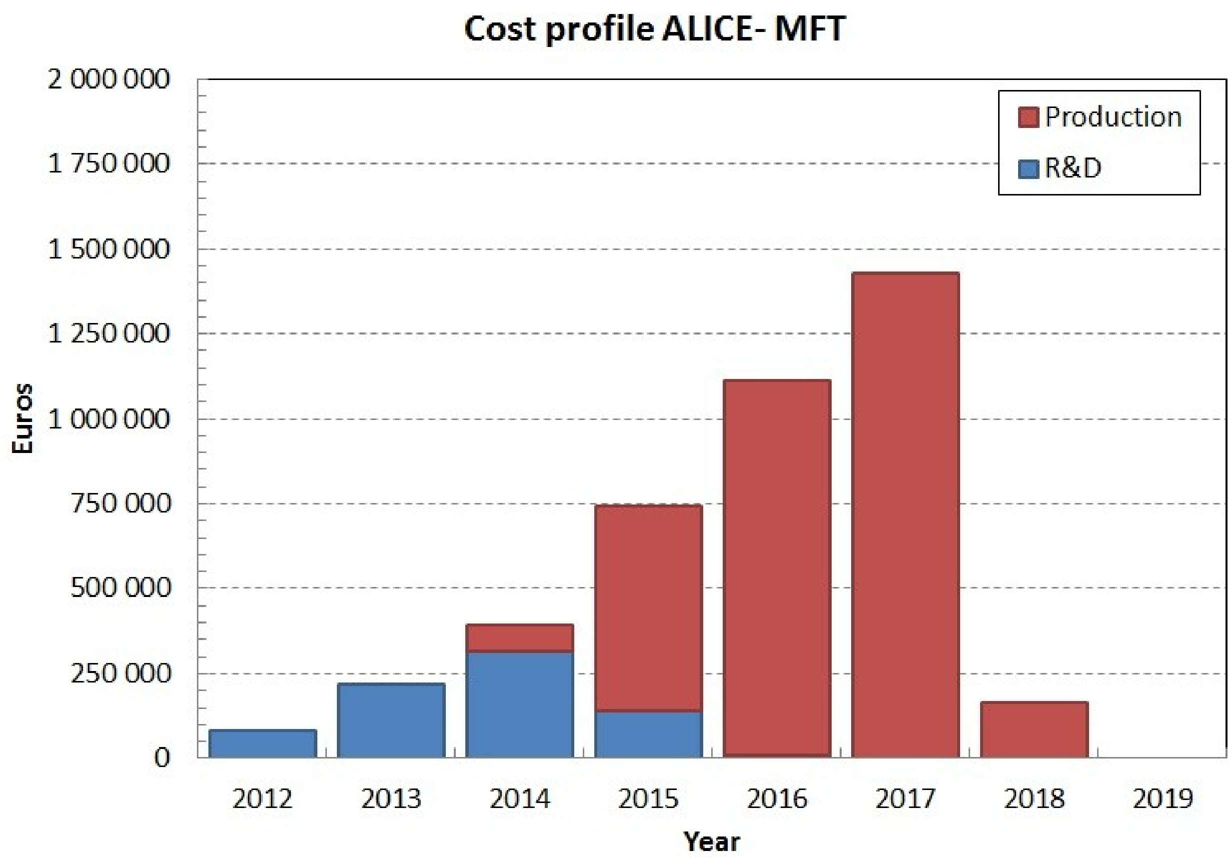
  Russia: Gatchina, **India:** Kolkata, **South Africa:** Cape Town, **Armenia:** Yerevan, **Italy:** Cagliari (simulations only)

- **Contacts with China, Korea**

Cost Estimation

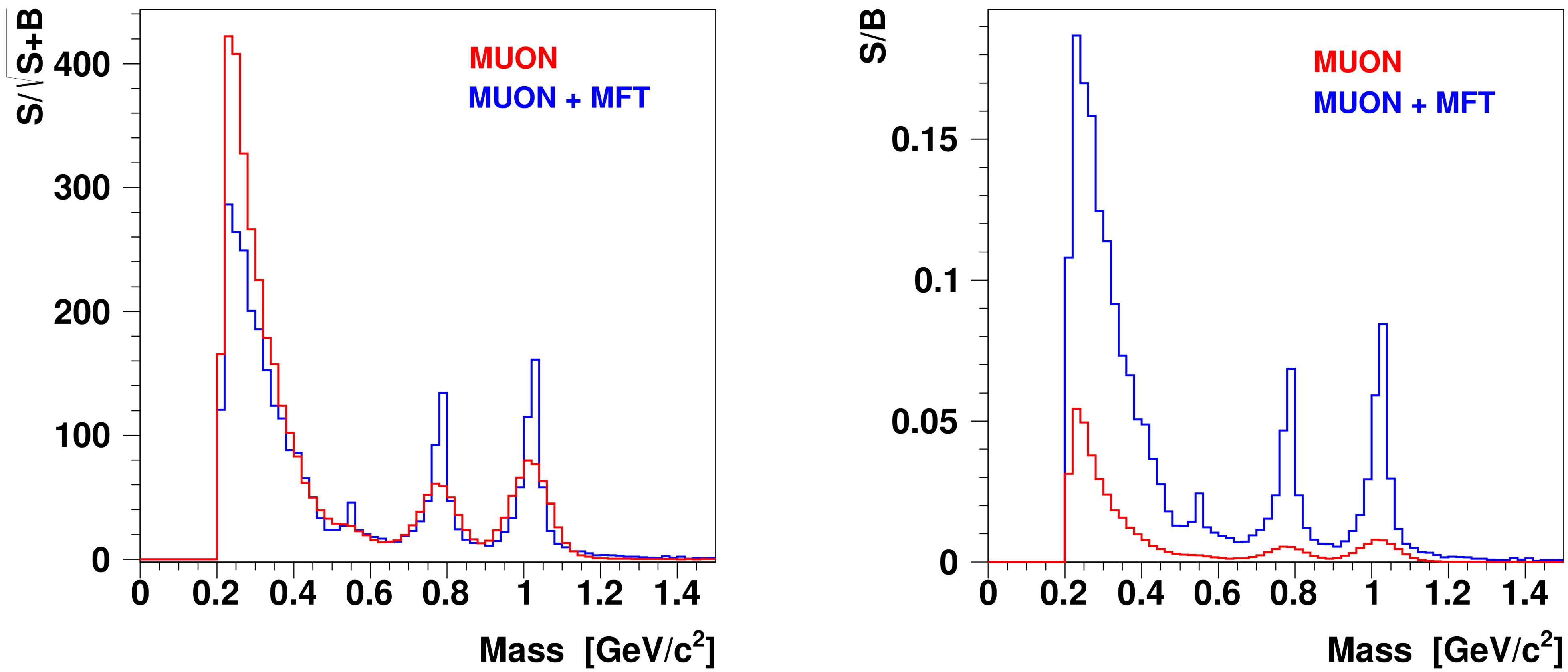
Estimated Cost: 4.1 M€ = 3.3 M€ (production) + 0.8 M€ (R&D)

Cost estimate in adjustment process

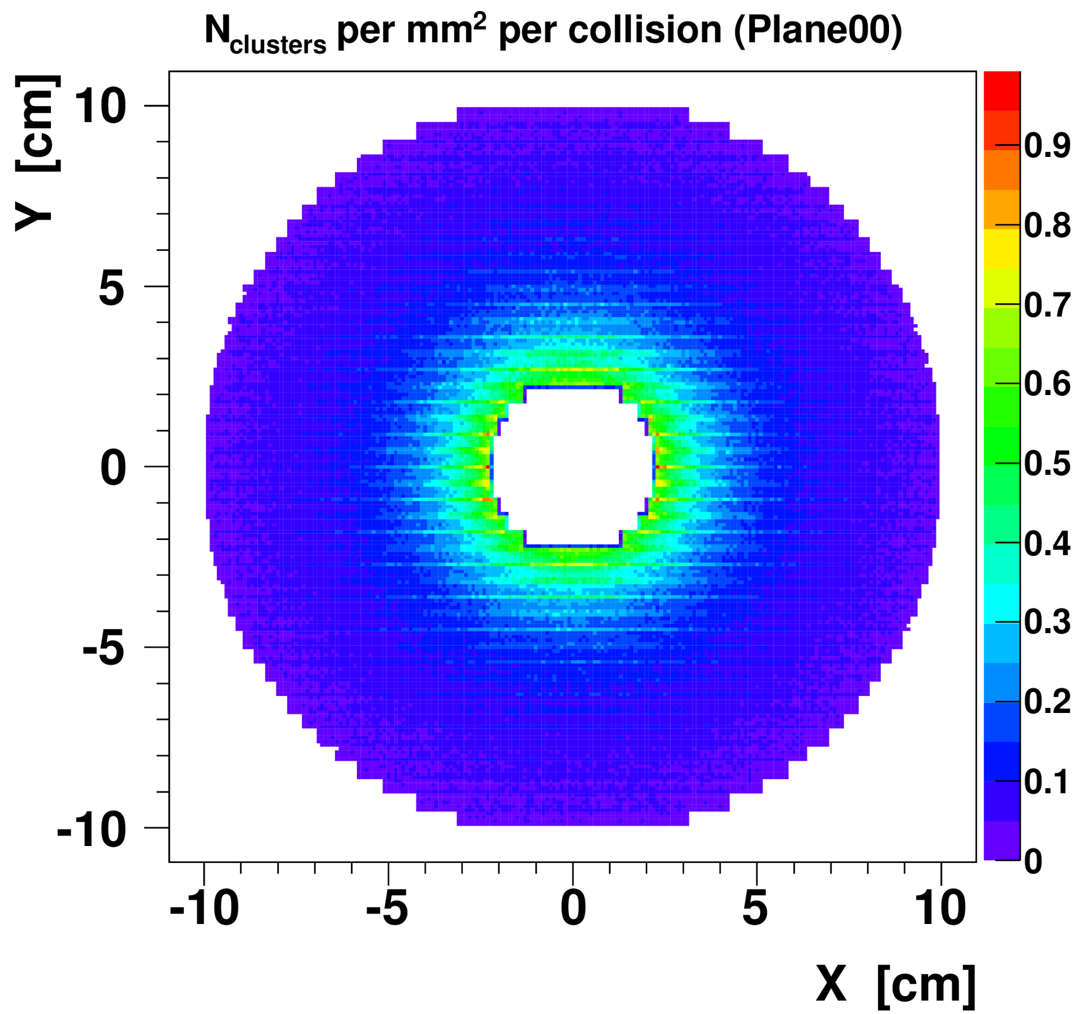


Low Mass Dimuons: S/B and Significance

We gain in S/B (which will limit the systematic uncertainties) without loosing the significance (already sufficient to have low statistical uncertainties)

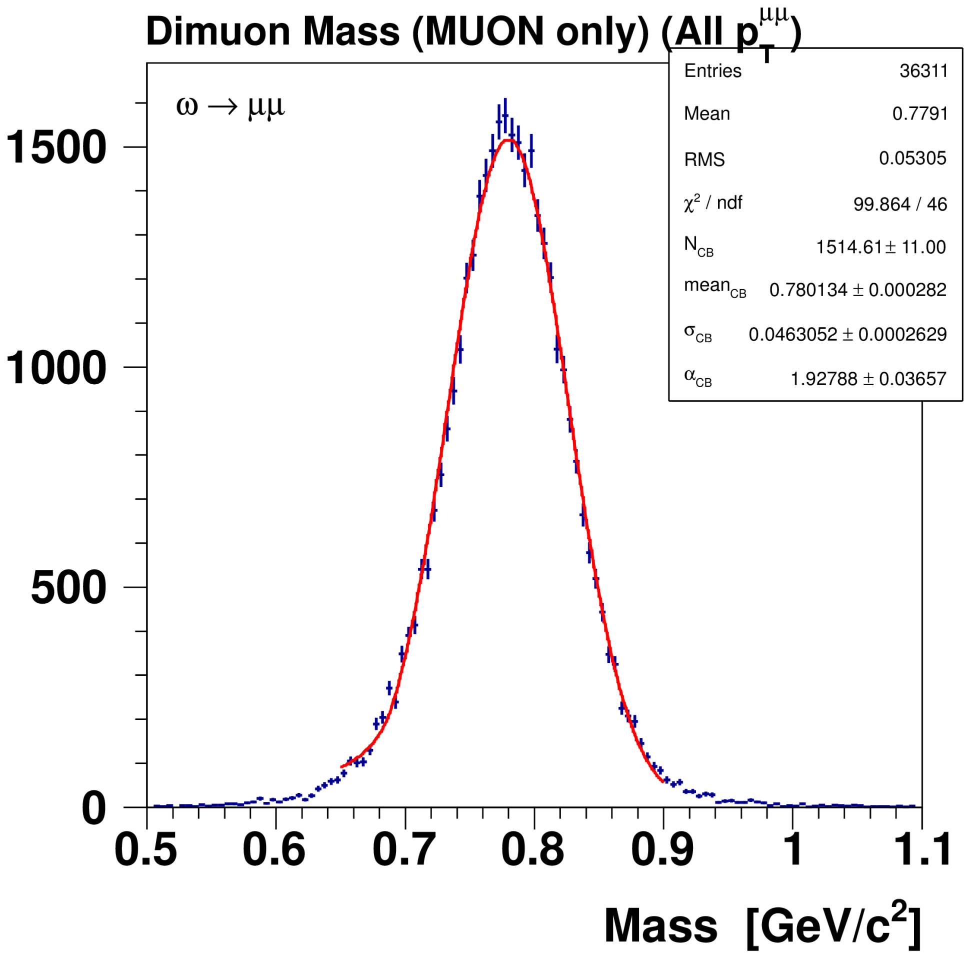


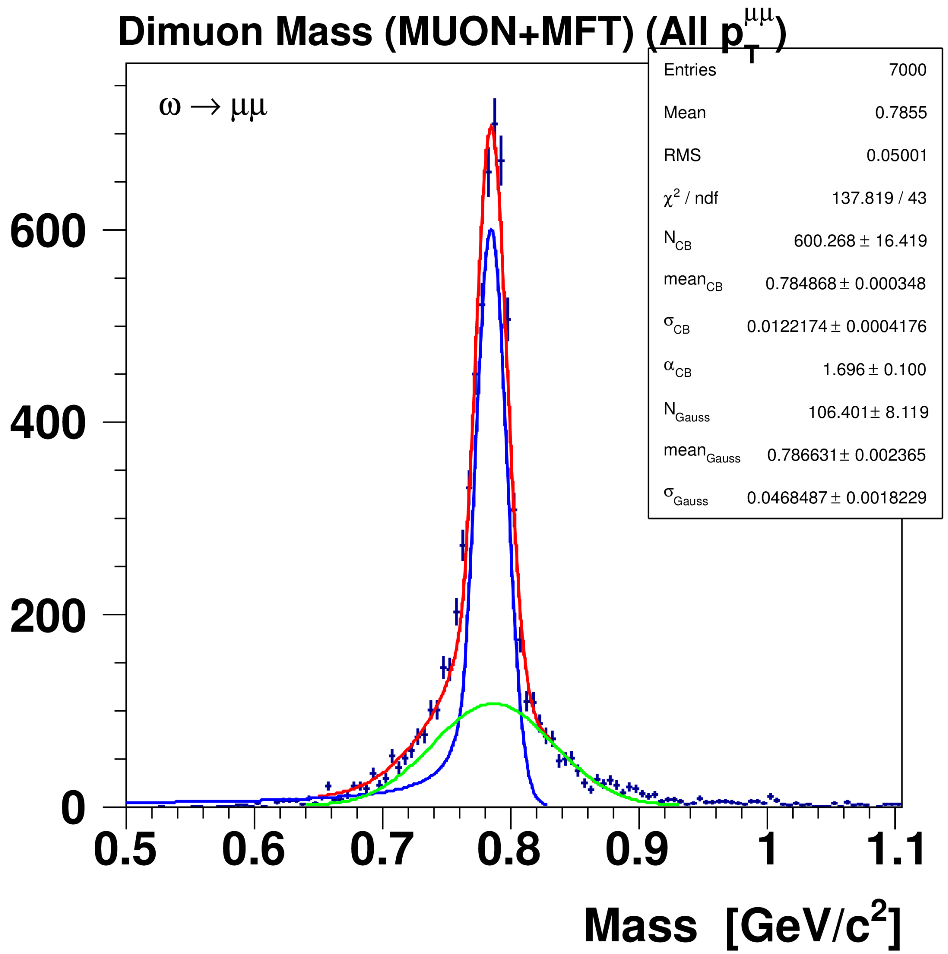
MFT Planes Occupancy



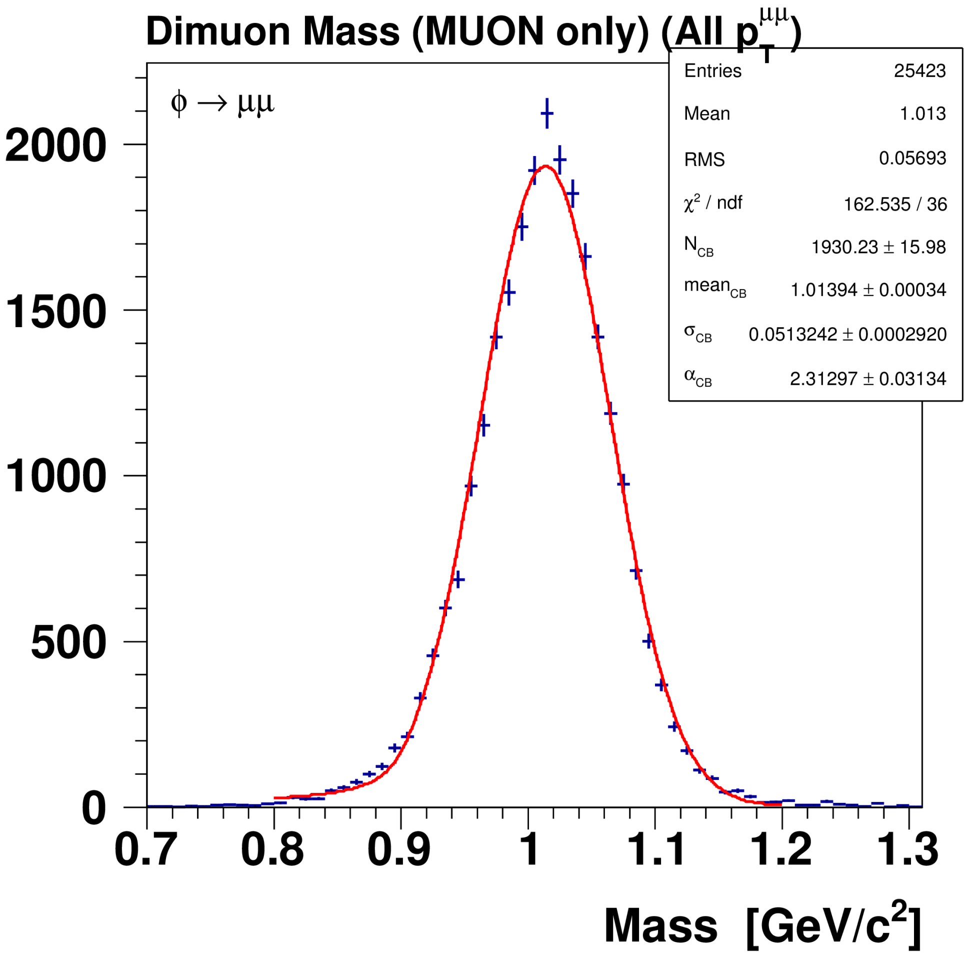
- **Track density below 1 track per mm²** in central Pb-Pb collisions even in the tracking planes closest to the I.P.
- **Residual misalignments to be estimated:** preliminary studies suggest that it should have a negligible impact on the MFT physics. Systematic studies are ongoing

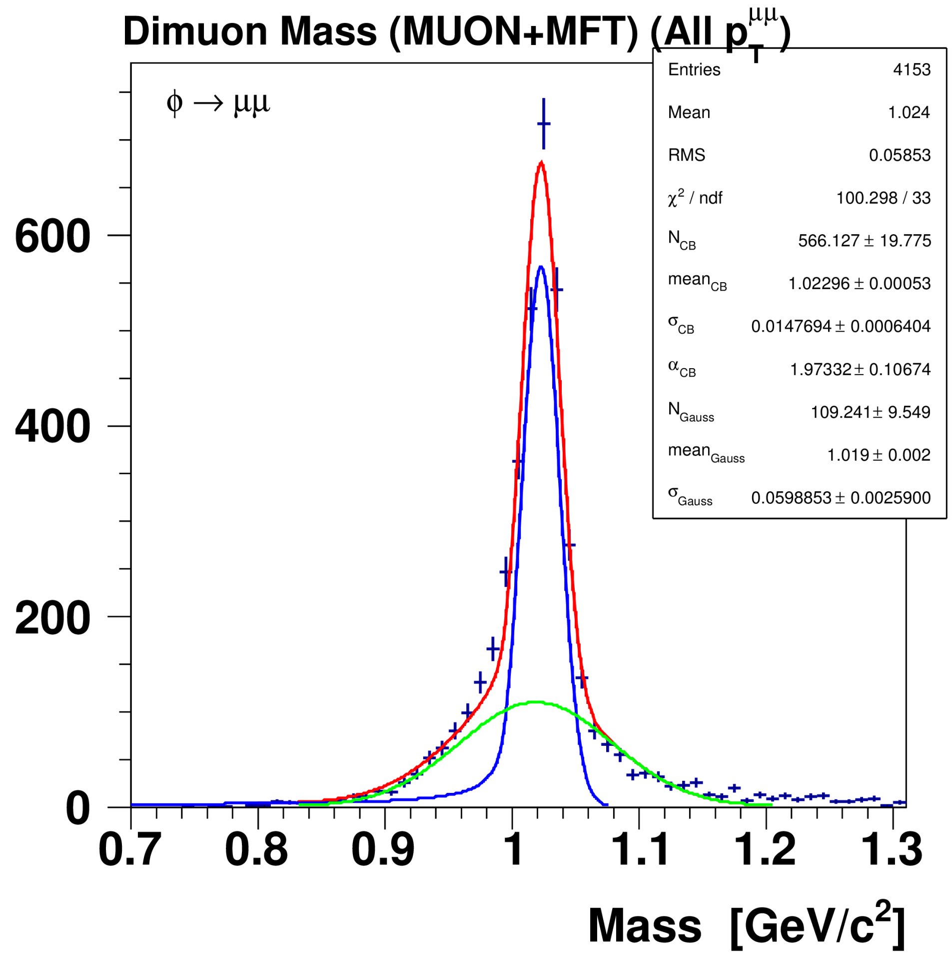
Low Mass Resolution: ω Meson



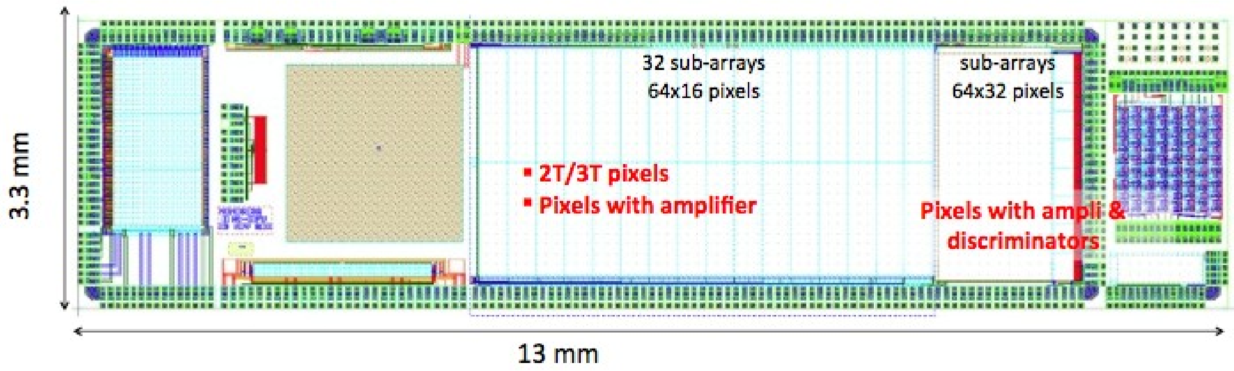


Low Mass Resolution: ϕ Meson





First Pixel Sensor Prototypes

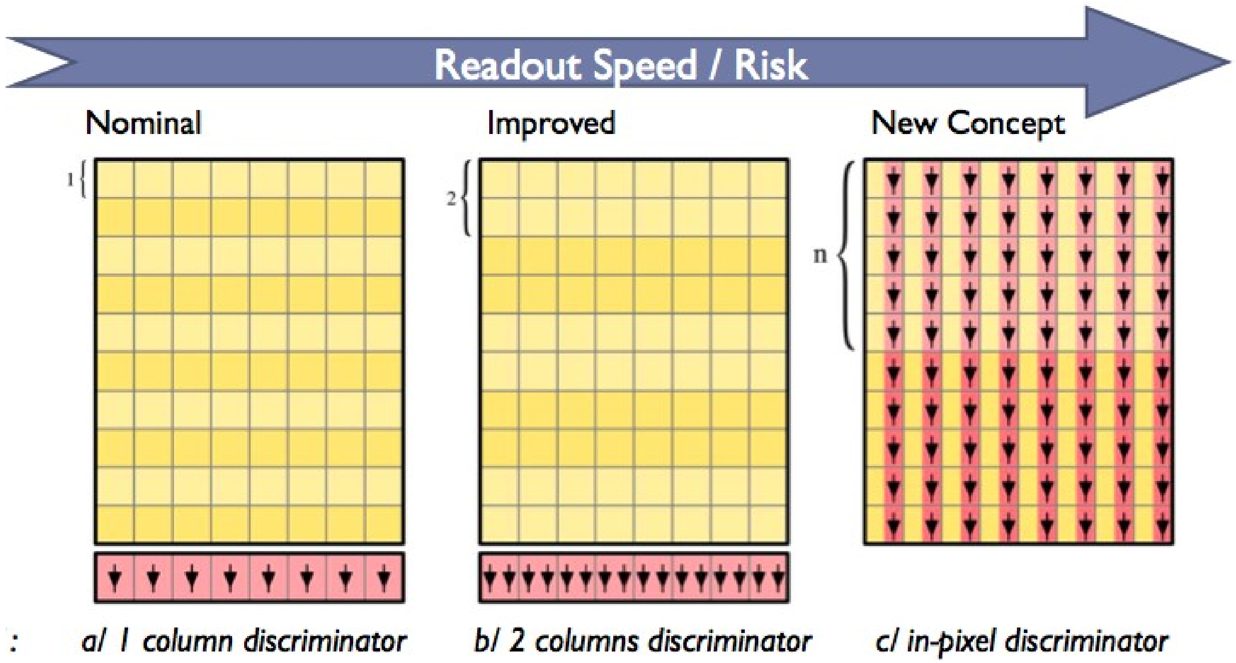


Techno process
Tower Jazz 0.18 μm

Prototype objectives:

- Test different analog architecture
- Improve charge collection efficiency
- Test radiation hardness

Improve readout speed: goal ~10 μs
(no pile-up in Pb-Pb @ 50 kHz)



CMOS Test Results

Laboratory test results:

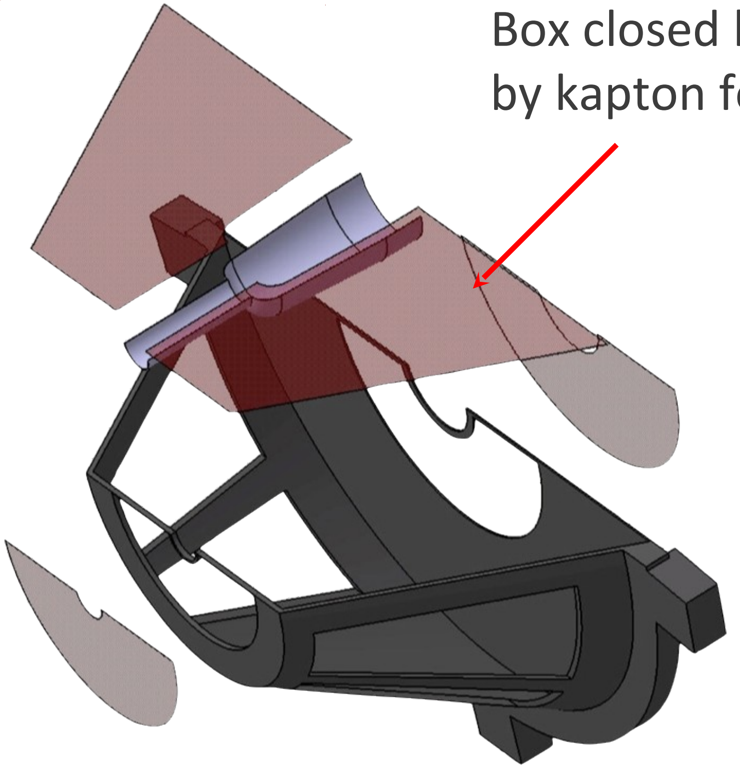
- Noise about 20 e^-
- Charge collection efficiency
  - 30 to 40% in the Seed pixel
  - 70-80% in 4 pix and 100% in 6 pix
  - Efficiency ~ 99.9%
- Radiation Hardness tested up to 1 Mrad and 10^{13} $n_{eq}/cm^2/s$
  - Noise varies from 25 to 31 e^-
  - efficiency from 97.7 to 99.6%

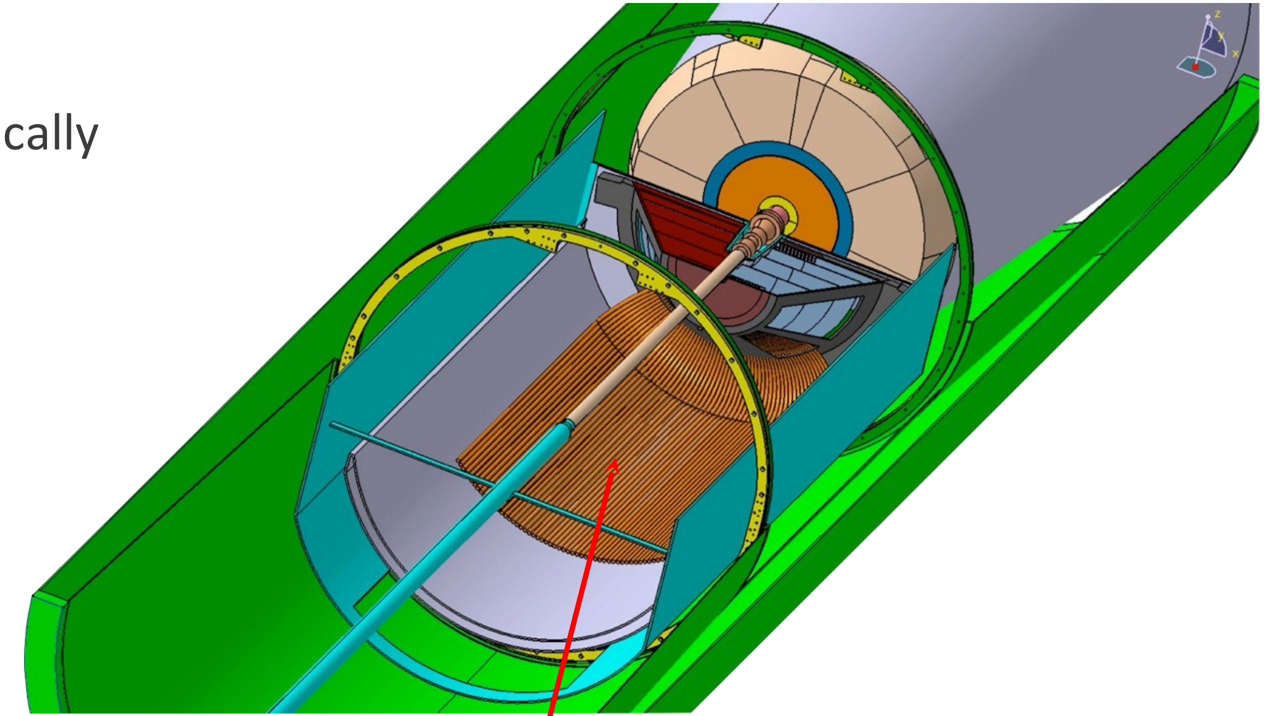
New Prototype to be sent to foundry in February

- New Zero suppression block
- Dual row readout
- In-pixel discriminator with larger matrix

Mechanical Support

Box closed hermetically
by kapton foils



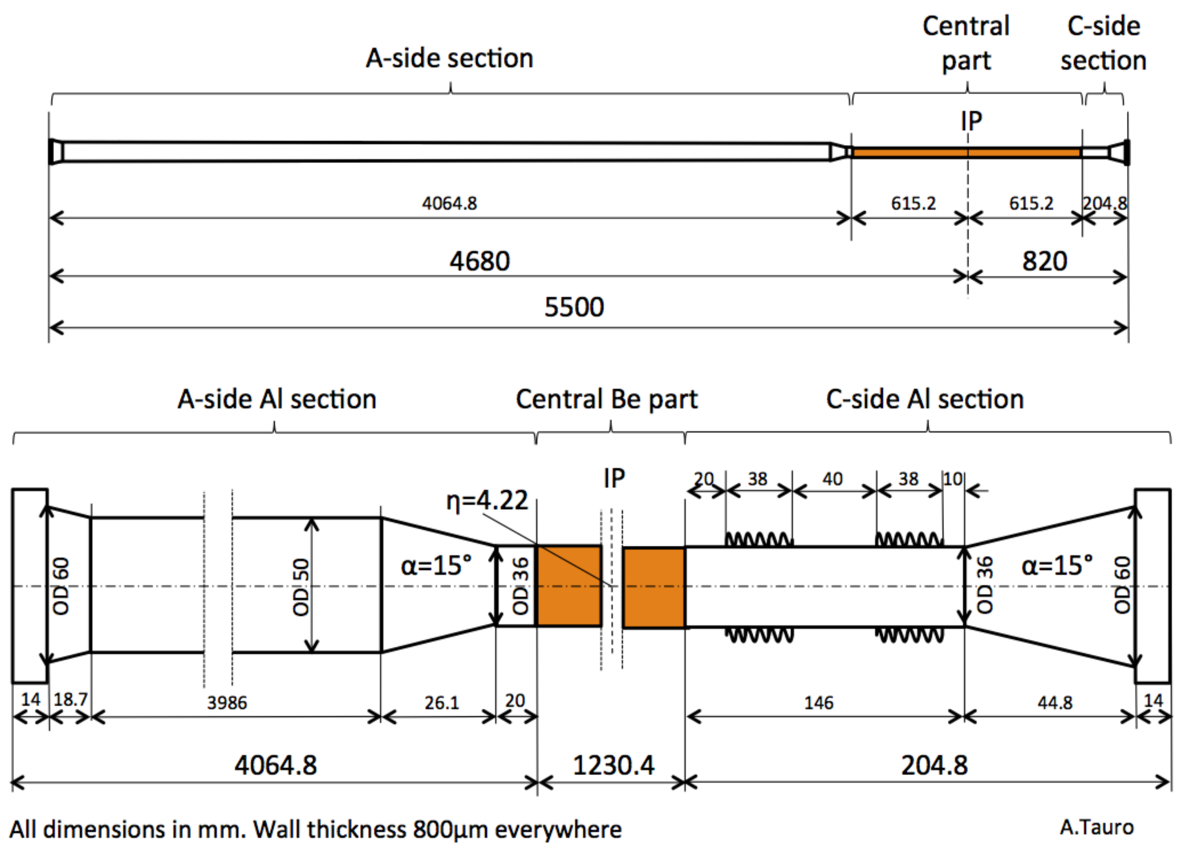


Optical links routed to A side

- MFT separated into **two halves**
- Inserted and fixed thanks to **2 half supporting cages**
- Beam pipe support, installation/maintenances procedures **to be worked-out**

Beam Pipe Constraints

- **New Beam Pipe Design** (in collaboration with the ALICE TC and CERN vacuum group)
  - Longer Beryllium section
  - Use Aluminum for bellows
  - Smaller bellows

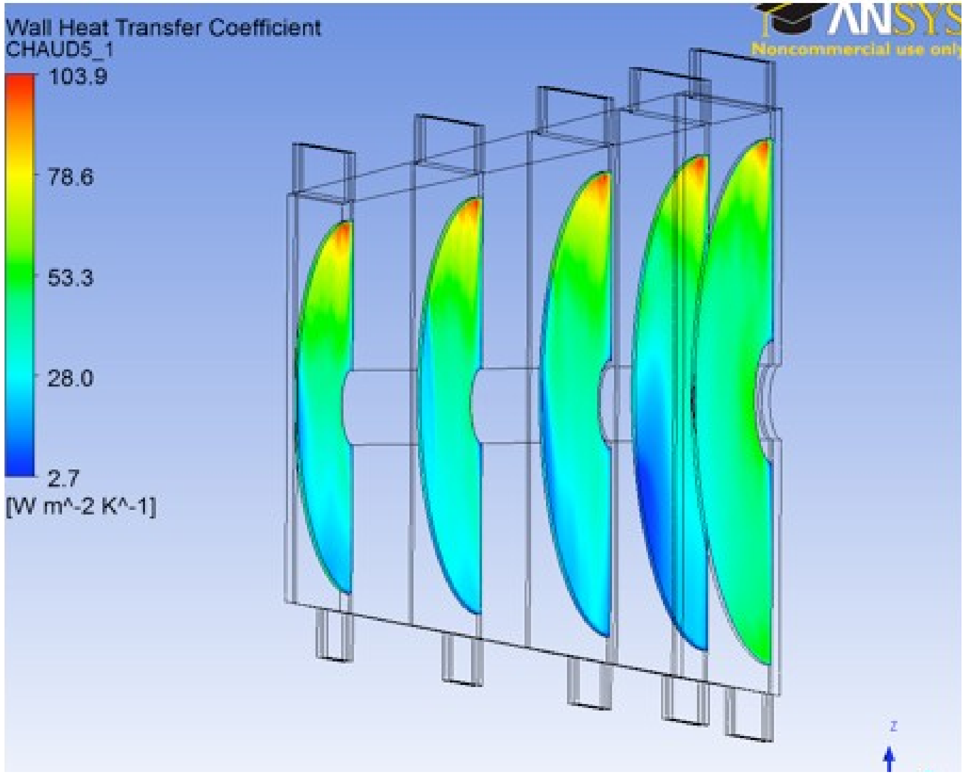


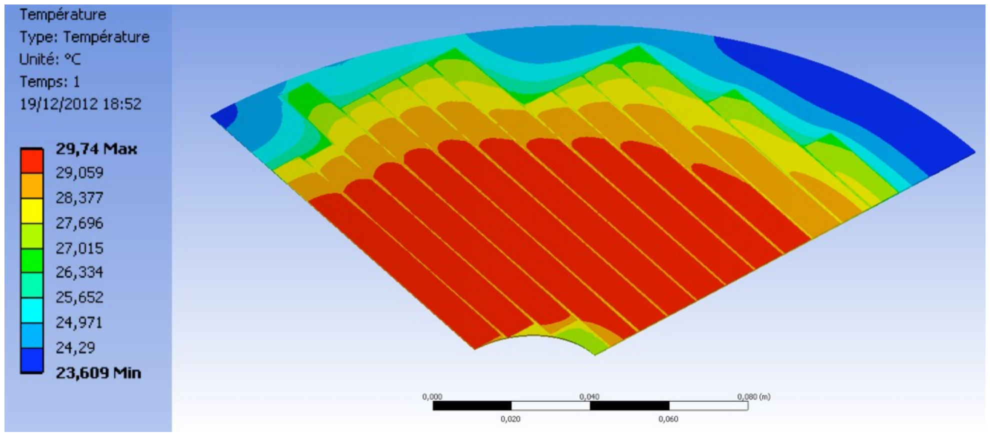
- Optimization still needed to **increase the MFT coverage at small angle**

- Optimization of the **bake-out procedure**

Cooling

- Goal: keep the CMOS sensor at **temperature smaller than 35°C**
- About **1 kW of heat to be extracted**
- **Use Air cooling**
  - 15°C input
  - Blowing air over the sensors + between two sides of the planes





More complete studies + Test benches needed

Data Acquisition

- **Front-End Electronics (on detector, at the end of the ladders)**
  - CMOS sensors Control
  - Raw data transmission
- **«Back-End» Electronics (In counting room – in xTCA crates)**
  - Interface between MFT and the ALICE central systems: CTP DAQ HLT DCS