Workshop on Hard-Soft Correlations in High-Energy Hadronic Collisions

Clermont-Ferrand • July 23-25, 2018

HARD-SOFT CORRELATIONS with the ALICE-MFT
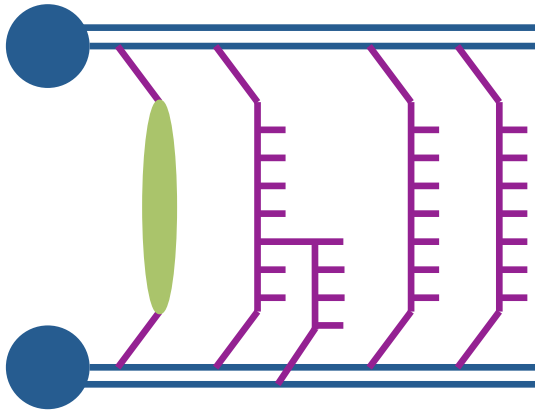
Antonio URAS, *Institut de Physique Nucléaire de Lyon*

ALICE

cnrs
advancing the frontiers

The ALICE detector already allows for a large variety of measurements testing the interaction between hard component and soft component in high-energy hadronic collisions (see dedicated contributions on current results)

❖ The foreseen ALICE upgrade program is mainly motivated by the precision study of heavy-flavor probes down to zero-p_T in Pb-Pb collisions at the top LHC energies

❖ **Hard-soft correlation studies involving forward-rapidity measurements will largely profit from the ALICE upgrade:**

➢ More precise and complete description of the underlying event

➢ **Improved precision in the measurement of hard and electro-weak probes** (charm/beauty separation at forward rapidity, HF baryons at mid-rapidity, extended coverage towards zero-p_T, more differential analyses…)

❖ **The ALICE Upgrade Program**

❖ **Selected items from the available MFT physics performance studies (benchmark: 0-5% most central Pb-Pb collisions)**

➢ Open Heavy Flavors

➢ Quarkonia

➢ Low-Mass Dimuons

➢ Long-range correlations, azimuthal anisotropies, Drell-Yan…

TPC: new GEM readout chambers, pipelined readout

TRD, TOF, PHOS, EMCAL, MUON: new readout electronics

Muon Forward Tracker

V0+, T0+

New beam pipe: smaller diameter

New ITS:
high resolution, low material budget
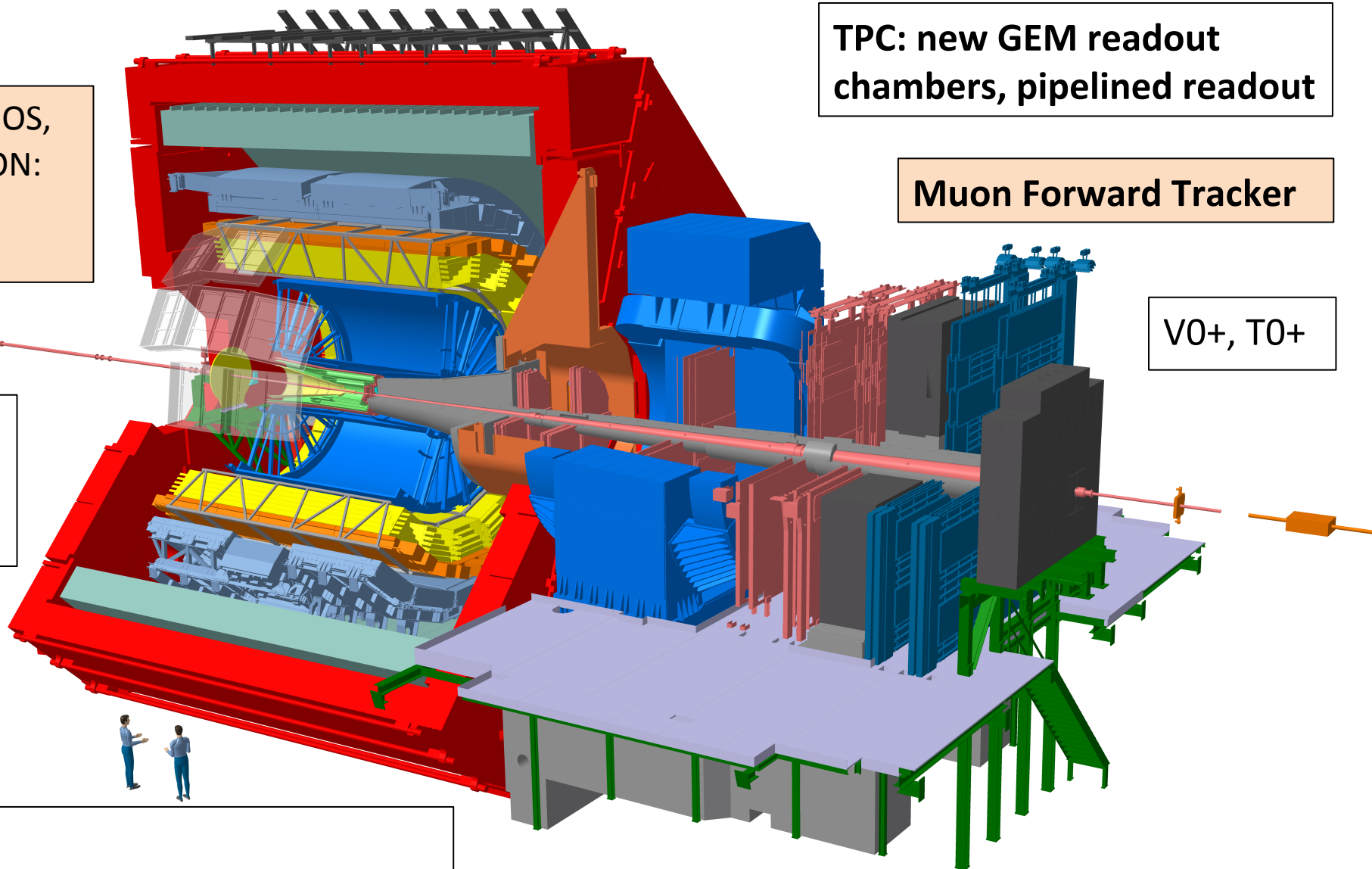
ALICE Upgrade Strategy

- ➢ **ALICE will run at 50 kHz in Pb-Pb** (i.e. L = 6×10^{27} cm^{-1} s^{-1}) with minimum bias (pipeline) readout (max readout with present ALICE set-up: ≈ 0.5 kHz)

  - ❖ Gain a factor of 100 in statistics over current program: **×10** from the integrated luminosity (1 nb^{-1} → 10 nb^{-1}) and **×10** from the pipelined readout allowing inspection of all collisions. Inspect $o(10^{10})$ central collisions instead of $o(10^8)$

- ➢ **Improve vertexing and tracking at low p_T:** better spatial resolution is needed on track reconstruction to improve secondary vertex reconstruction

- ➢ **This entails a major upgrade of the whole apparatus:**

  - ❖ New, smaller radius beam pipe

  - ❖ New inner tracking system: upgraded ITS + MFT

  - ❖ High-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ/HLT, Muons and Trigger detectors

Antonio Uras   Hard-Soft Correlations with the ALICE-MFT

MFT: vertex tracker for the Muon Spectrometer, to be installed between the interaction point and the hadron absorber

➤ **Nominal acceptance:** $2.5 < \eta < 3.6$

   Full azimuth

➤ **920 silicon pixel sensors (0.4 m²)** in 280 ladders of 2 to 5 sensors each

➤ **10 half-disks, 0.7% x/X_0 and 2 detection planes each**
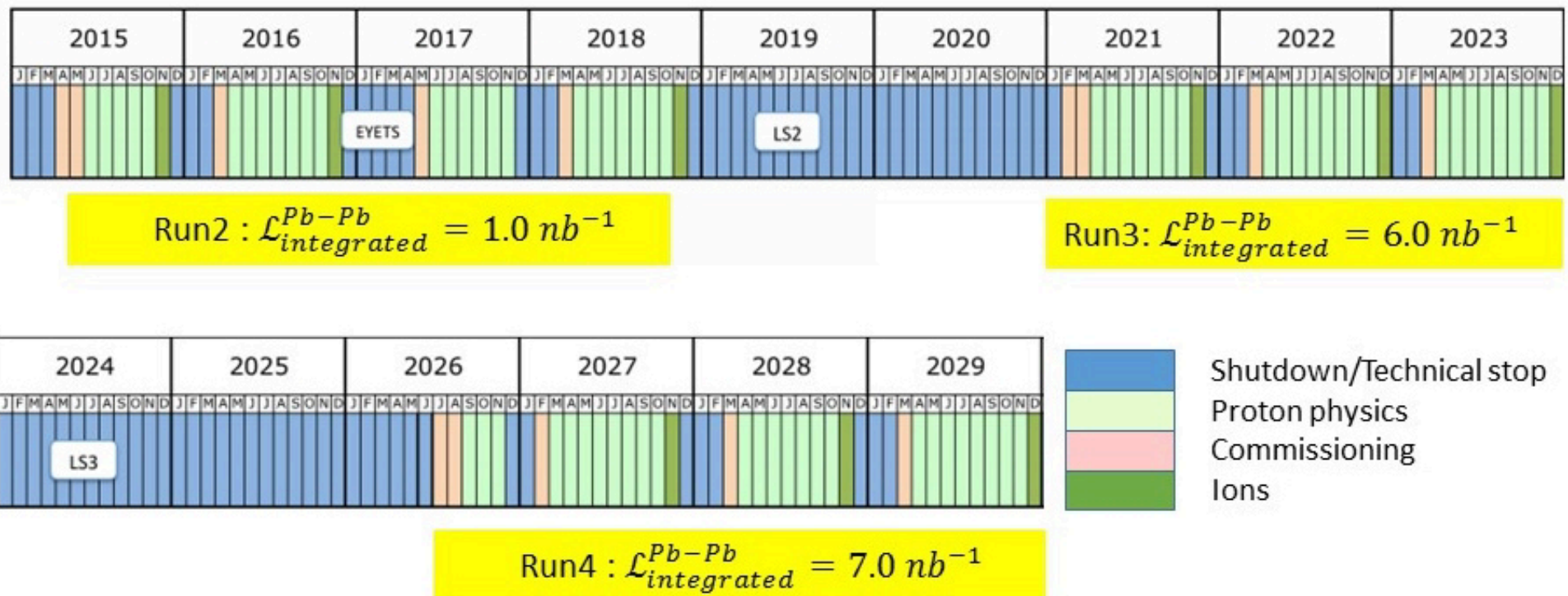
➤ **5% of the ITS surface, twice the ITS inner barrel**
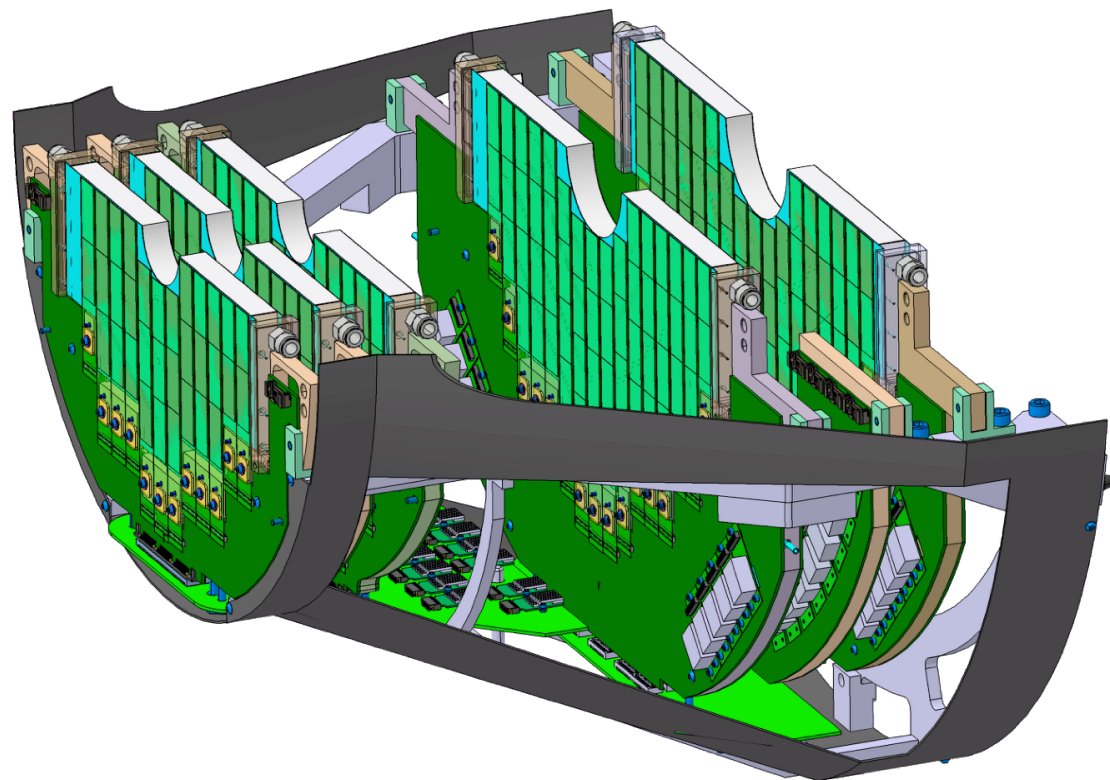
❖ **Experiments request for Pb-Pb:** $L_{int} > 10$ nb^{-1} (ALICE LoI: 10 nb^{-1} with nominal solenoidal field + 3 nb^{-1} with reduced solenoidal field)

    ✧ ×100 larger min. bias sample for ALICE w.r.t. Run 2

    ✧ ×10 larger rare trigger sample for ATLAS/CMS w.r.t. Run 2

❖ **pp reference, p-A.** Investigating feasibility for lighter nuclei collisions

Run2 : $\mathcal{L}_{integrated}^{Pb-Pb} = 1.0 \ nb^{-1}$

Run3: $\mathcal{L}_{integrated}^{Pb-Pb} = 6.0 \ nb^{-1}$

Run4 : $\mathcal{L}_{integrated}^{Pb-Pb} = 7.0 \ nb^{-1}$

➢ **Open heavy flavors**

    ❖ Charm measurement down to $p_T = 1$ GeV/c in the single muon channel

    ❖ Beauty measurement down to $p_T = 0$ in the non-prompt J/ψ channel
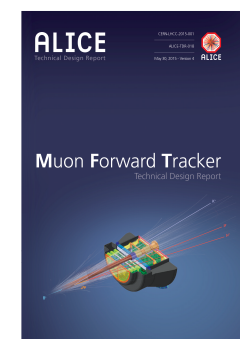
➢ **Prompt Charmonium production**

    ❖ Prompt/non-prompt J/ψ separation down to $p_T = 0$

    ❖ ψ(2S) measurement in central Pb-Pb collisions, down to $p_T = 0$

➢ **Low-mass dimuons**

    ❖ Improved mass resolution for resonances

    ❖ Sensitivity to prompt continuum

➢ **And also:**
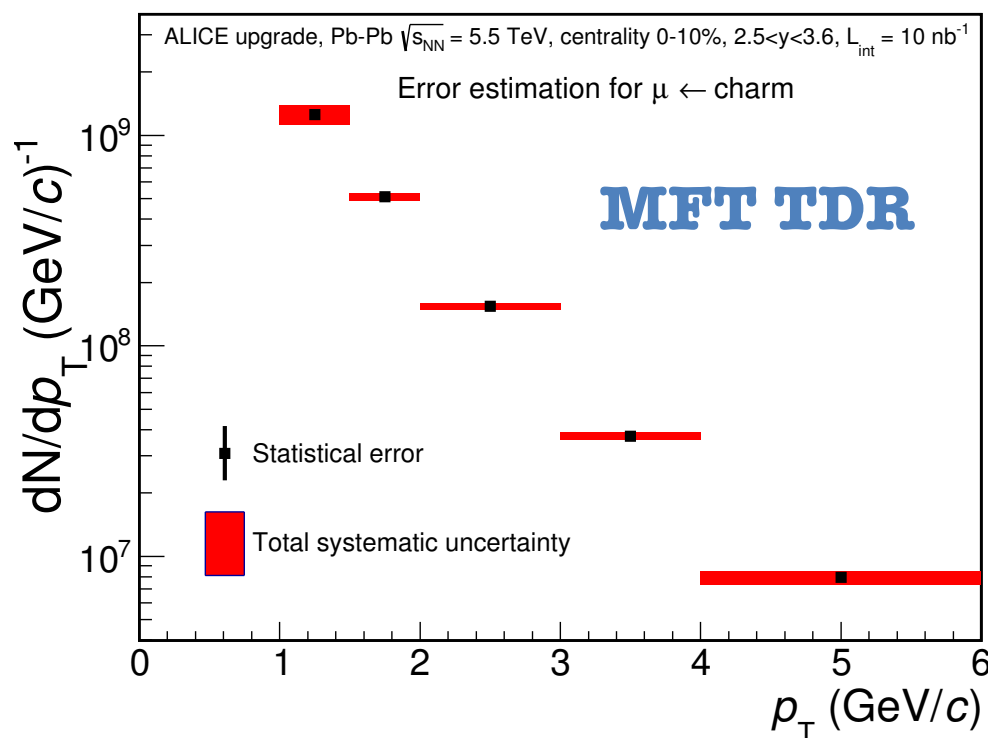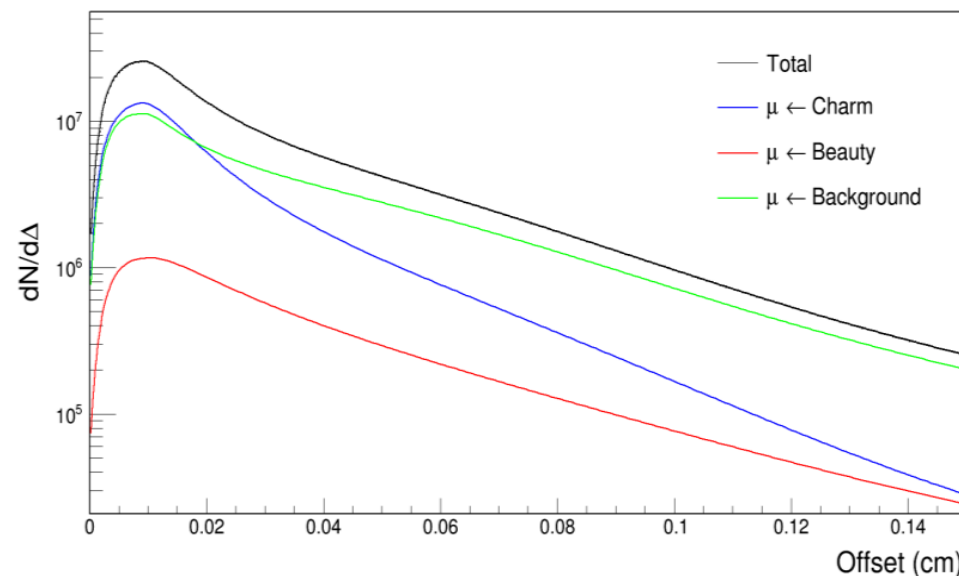
    ❖ Long-range correlation with the combined ITS+MFT coverage

    ❖ Event plane measurement and azimuthal correlations at forward rapidity

   ❖ Isolation of any prompt signal involving $p_T > 1$ GeV/c (Drell-Yan, limits on light BSM bosons?)

- ➤ **Charm clearly distinguishable for $p_T > 1$ GeV/c**

- ➤ At low p_T background mimics beauty template: large uncertainties in beauty extraction

- ➤ **Charm yield** accessible starting from $p_T(\mu) = 1$ GeV/c (at least)

- ➤ **Important baseline** for charmonium measurements

➢ **Prompt/displaced J/ψ discriminating variable:** longitudinal projection of the primary-secondary vertex distance considered for the analysis (not possible with the current ALICE Muon Spectrometer)
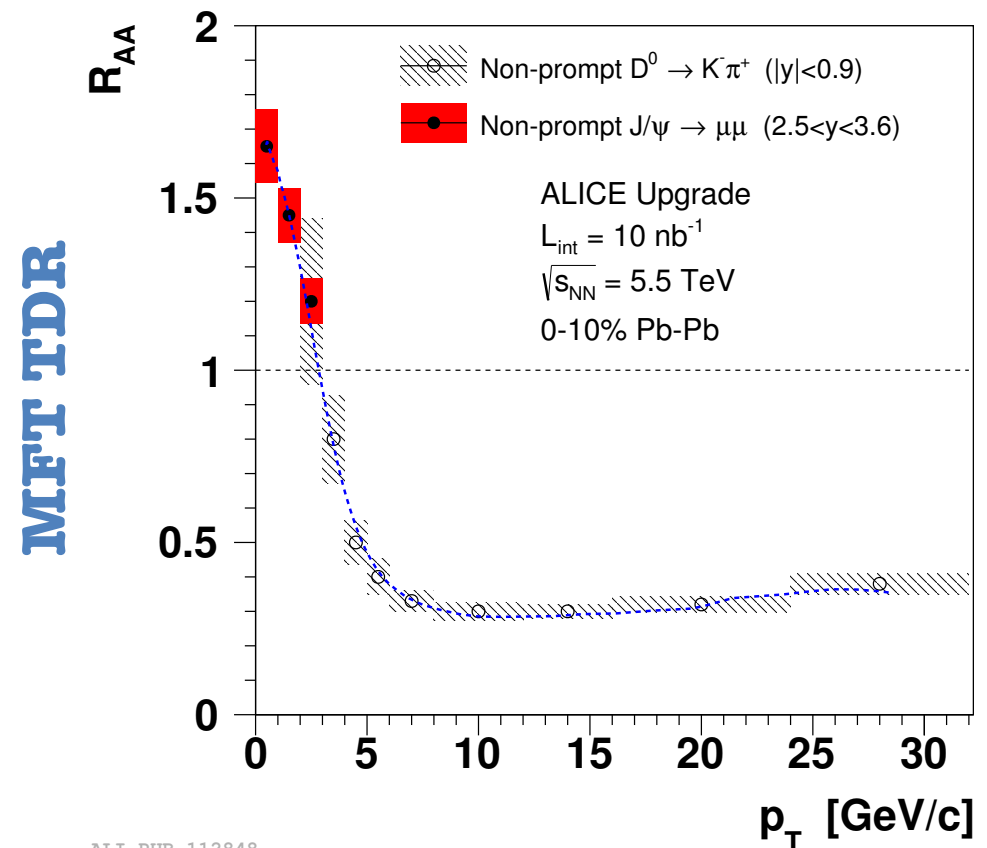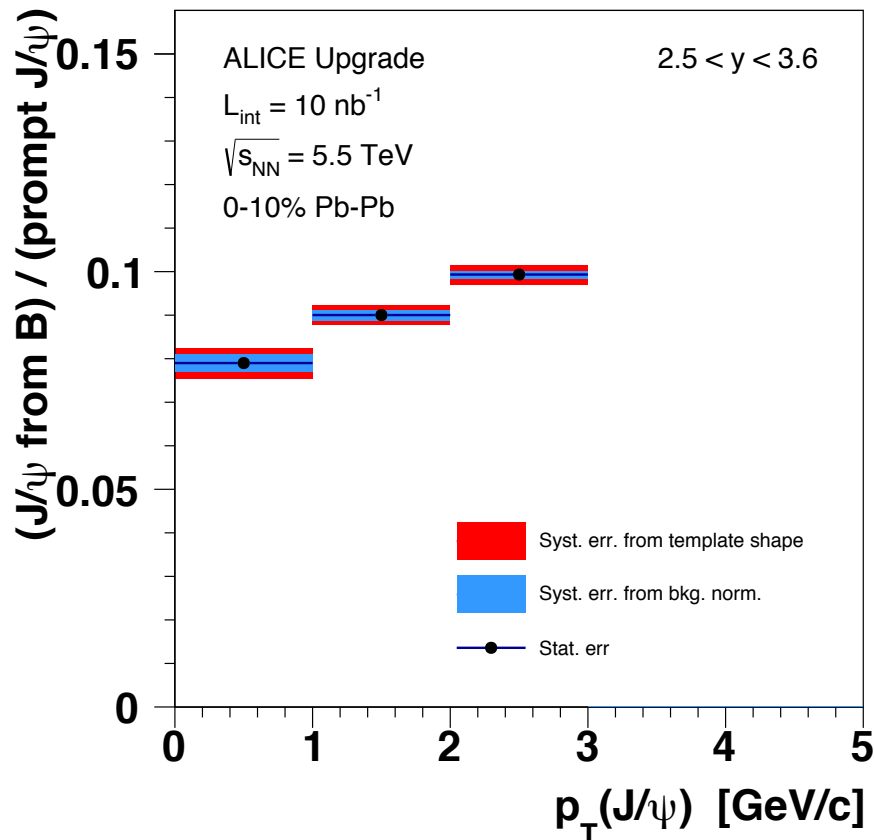
$$t_z = \frac{\left(z_{J/\psi} - z_{\mathrm{vtx}}\right) \cdot M_{J/\psi}}{p_z}$$
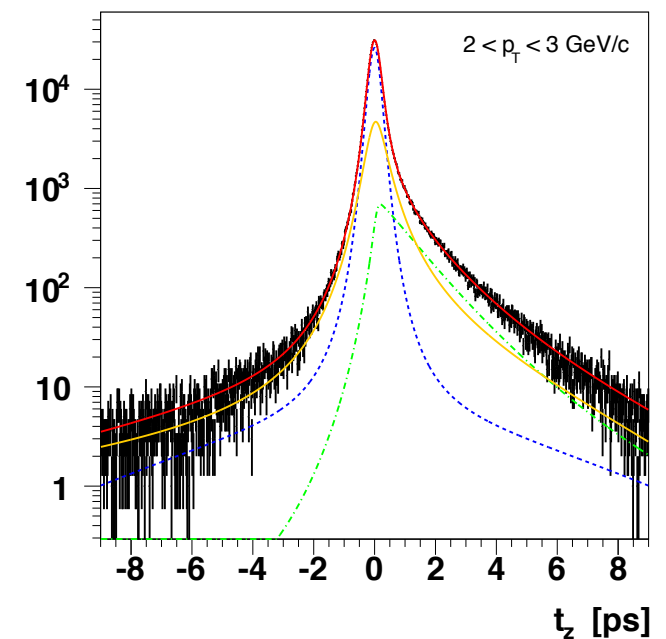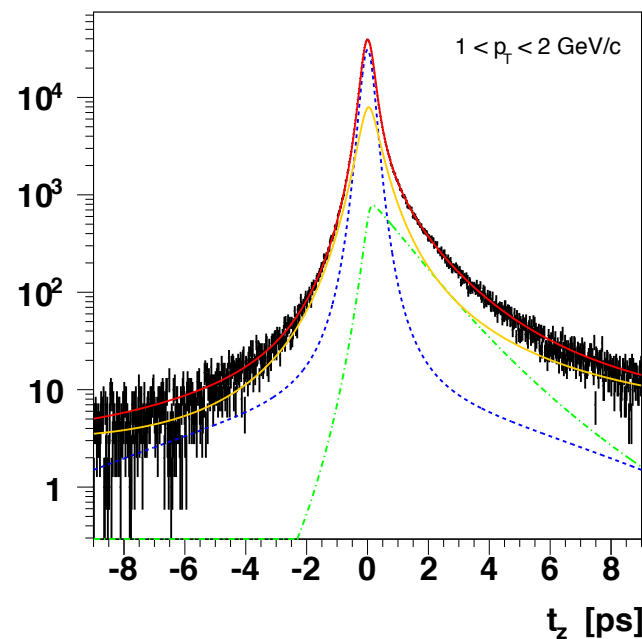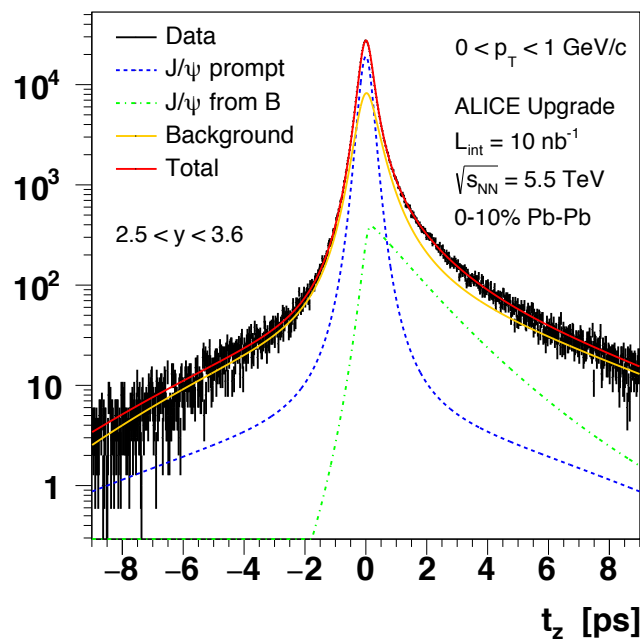
> **Displaced/prompt separation** possible down to zero $p_T(J/\psi)$ within 5% stat + syst uncertainties

> **Beauty R_{AA} measurement** possible down to zero $p_T(J/\psi)$ within 7% stat + syst uncertainties even in central Pb-Pb
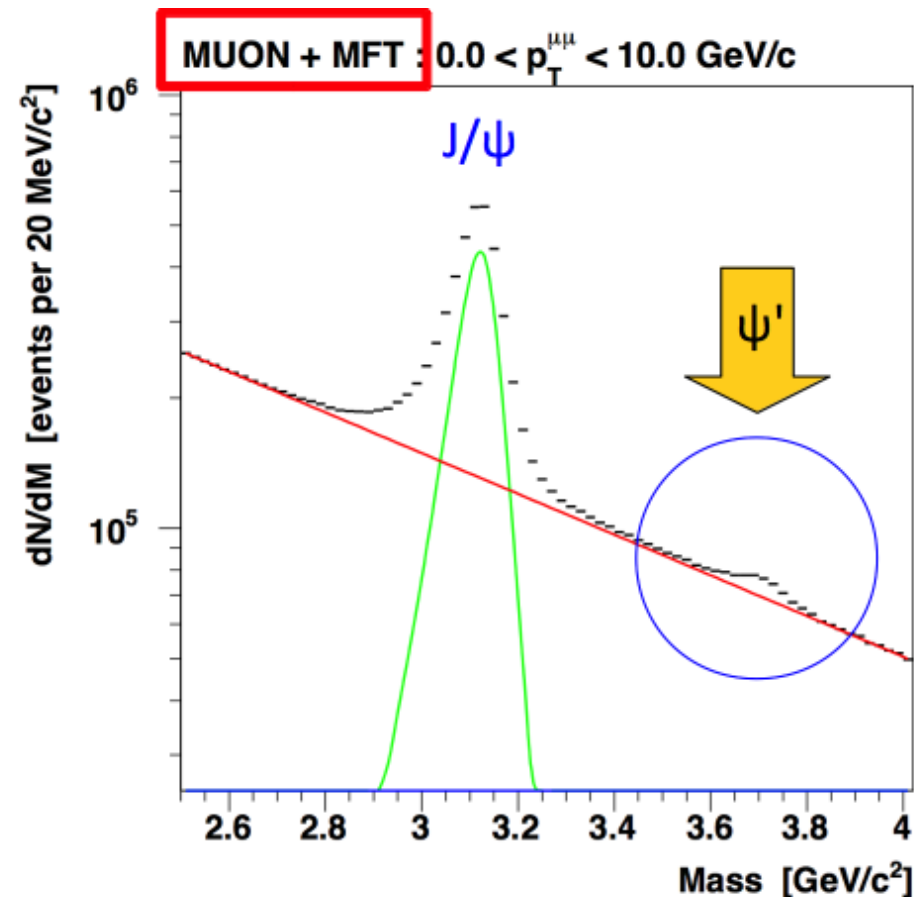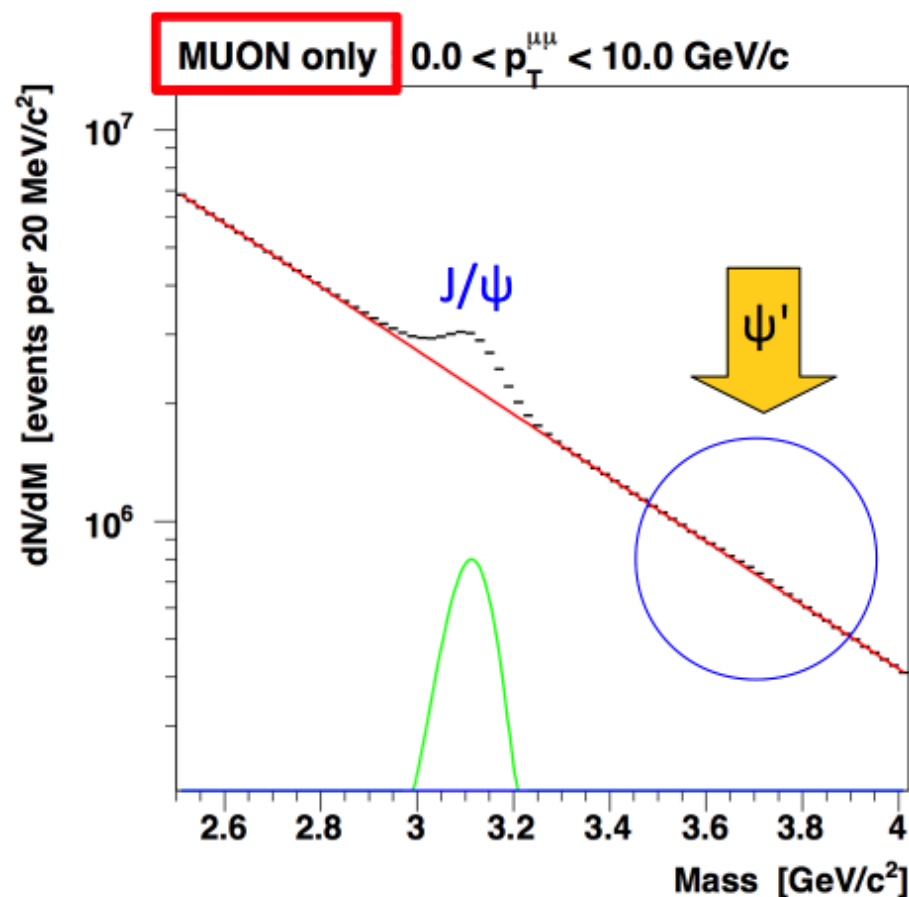
Left plot:

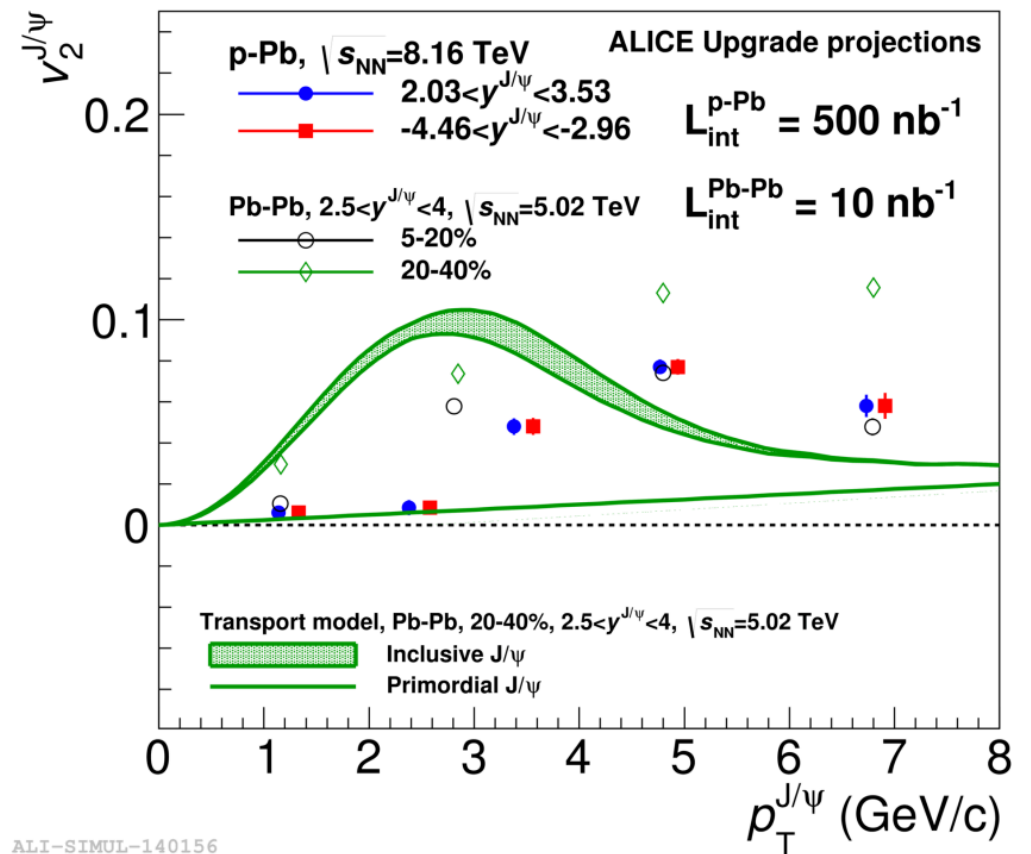(J/ψ from B) / (prompt J/ψ) vs $p_T(J/\psi)$ [GeV/c]

ALICE Upgrade
$L_{int} = 10\ nb^{-1}$
$\sqrt{s_{NN}} = 5.5$ TeV
0-10% Pb-Pb

$2.5 < y < 3.6$

Syst. err. from template shape
Syst. err. from bkg. norm.
Stat. err

Right plot:

R_{AA} vs p_T [GeV/c]

Non-prompt $D^0 \rightarrow K^-\pi^+$ ($|y|<0.9$)
Non-prompt $J/\psi \rightarrow \mu\mu$ ($2.5<y<3.6$)

ALICE Upgrade
$L_{int} = 10\ nb^{-1}$
$\sqrt{s_{NN}} = 5.5$ TeV
0-10% Pb-Pb

MFT TDR

ALI-PUB-112848
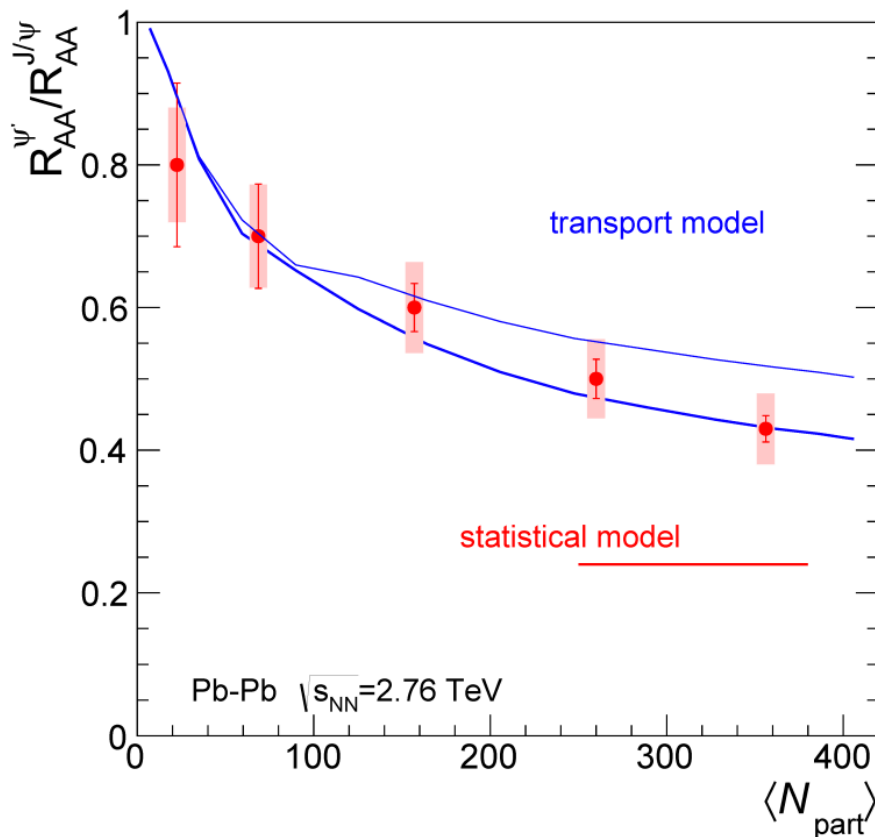
❖ **S/B improved by a factor 6-7**, significance improved by a factor up to 1.5

❖ The ψ' is visible even in central Pb-Pb collisions: **signal extraction more robust, systematic uncertainties significantly reduced**
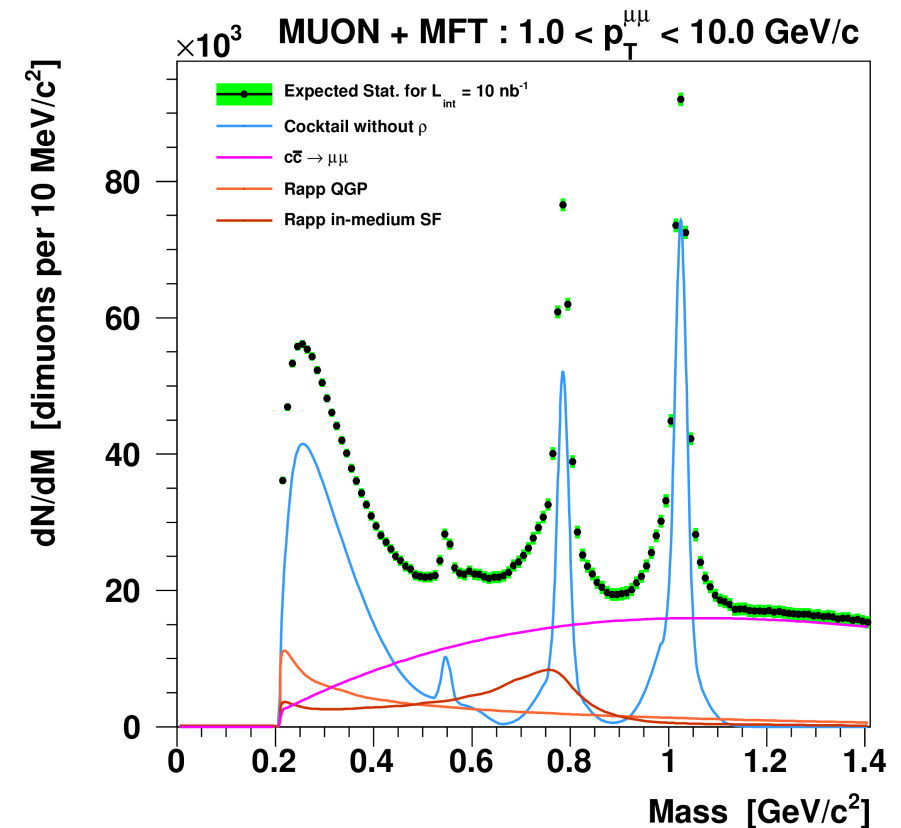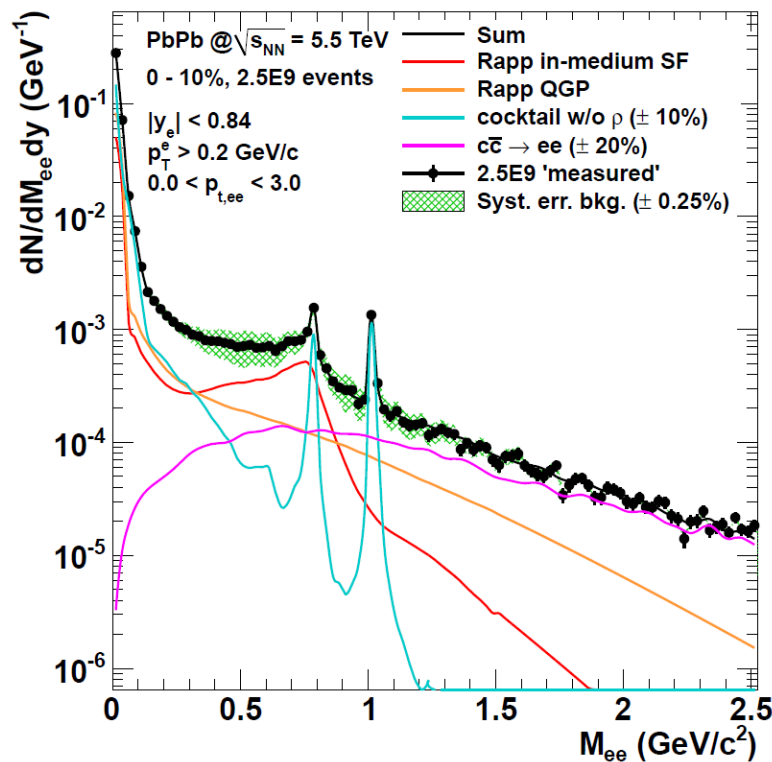
❖ **Dissociation/recombination** models for charmonia can be tested by comparing the nuclear modification factors of J/ψ and ψ(2S) down to zero p_T

❖ **Precision measurement for J/ψ (elliptic) flow in all collision systems**

❖ **Low and intermediate mass dileptons** both in the dielectron (mid rapidity) and dimuon (forward rapidity) channels

❖ Isolation of prompt sources needs **precise measurement of dilepton offset**

❖ In addition, **MFT will improve the mass resolution** for light resonances in dimuons

❖ **Precise measurement of dilepton offset** to remove charm and π/K continuum

❖ **Dielectron channel advantaged** thanks to the excellent offset resolution of the upgraded ITS, but dedicated low magnetic field needed for low p_T acceptance

❖ Charm rejection strategy for the MFT must e optimized for the intermediate masses
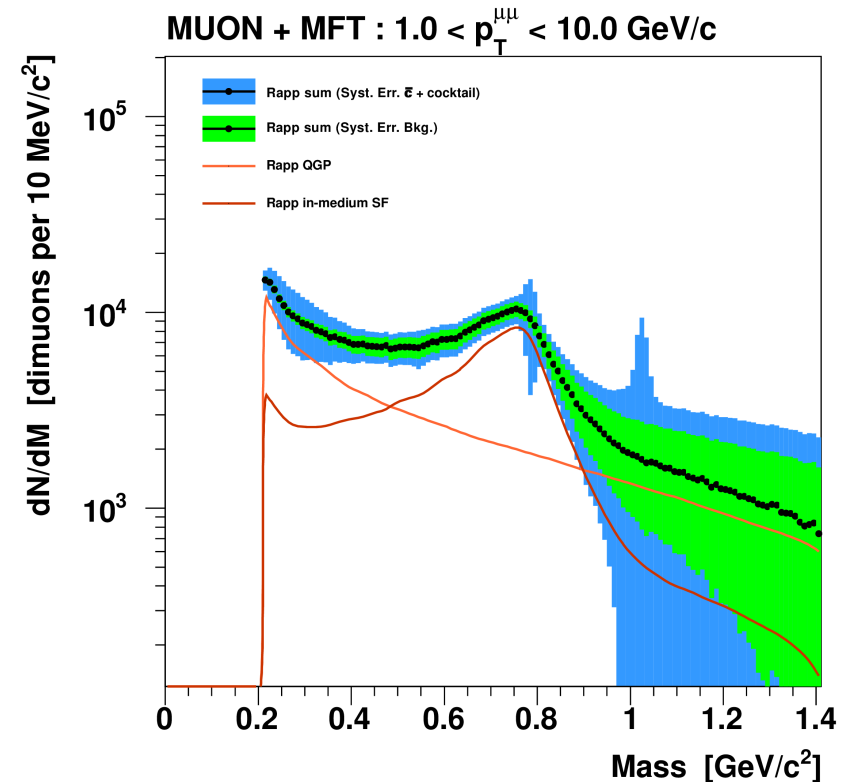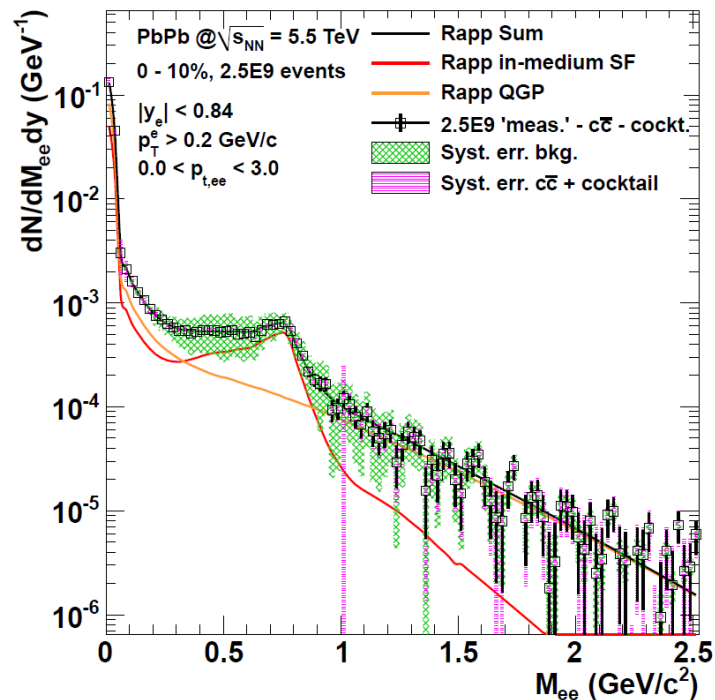
η-coverage vs vertex z:

❖ MFT tracks with hits in ≥ 4 disks

❖ ITS tracks with ≥ 4 layers (with ≥1 hits in IB)

❖ ITS coverage for tracks with 3 inner layers

(dashed lines – geometrical acceptances; shaded areas – acceptance from simulations)
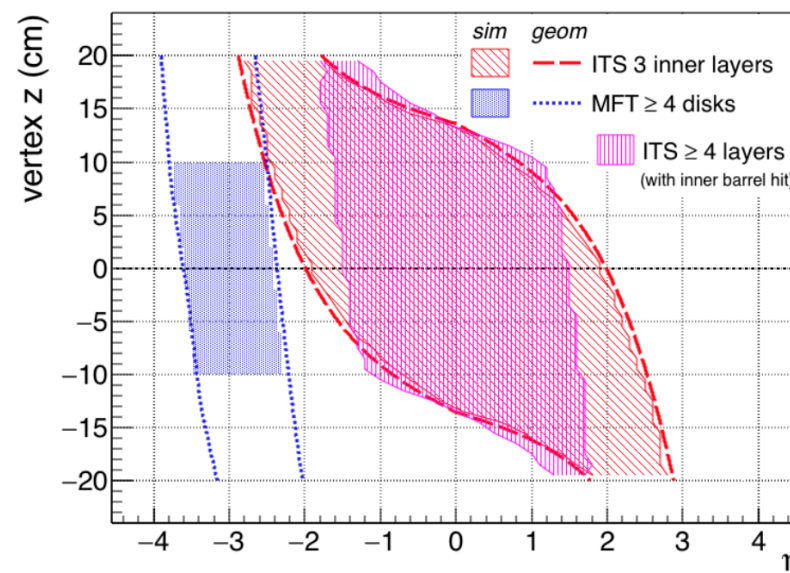
Maximum η-separation of particles VS vertex z

❖ With ≥ 4 ITS layers and ≥ 4 MFT disks:

➢ η-separation up to 5 units in |z| < 10 cm

➢ With a minimum a η gap of 1 unit

❖ If only 3 inner ITS layers, η-separation can be up to 6 units

credits: Igor Altsybeev,

❖ **Example phenomenon:** overlapping strings push each other and generate transverse pressure

❖ **Implementation in PYTHIA8:** "string shoving" → near-side "ridge"

credits: Igor Altsybeev,

min.bias

$1 < p_T < 3$ GeV/c

high mult

$1 < p_T < 3$ GeV/c
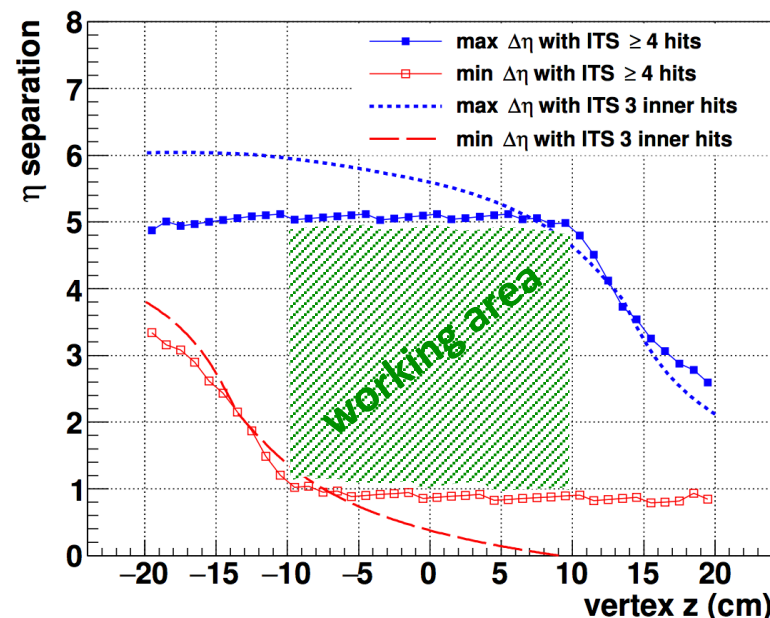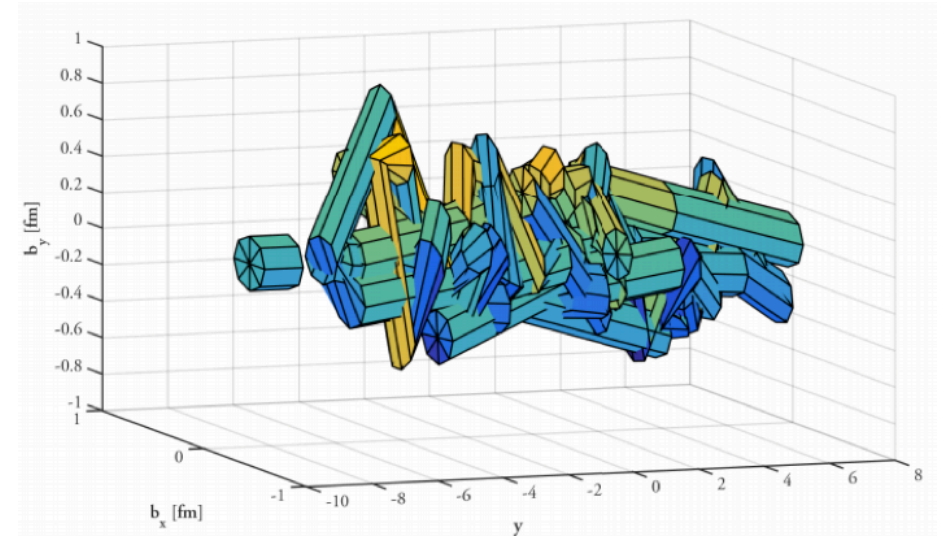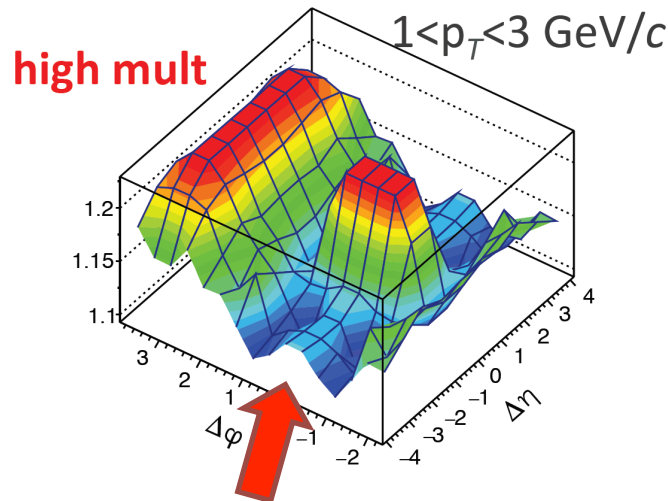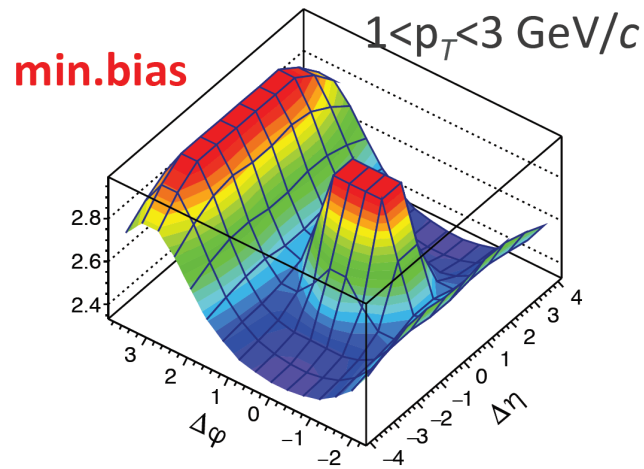
❖ We'll be able to study long-range 2-Particle Correlations between **unidentified tracks from MFT** and **identified tracks in central barrel**

❖ **Strongly-intensive quantity Σ** (independent of volume and volume fluctuations) encoding the correlation between particle multiplicity at the ends of a pseudo-rapidity gap:

$$\Sigma(n_F, n_B) \equiv \frac{1}{\langle n_F \rangle + \langle n_B \rangle}[\langle n_F \rangle \omega_{n_B} + \langle n_B \rangle \omega_{n_F} - 2\,\mathrm{cov}(n_F\,n_B)]$$

➡ **Significant differences between the predictions from different generators!**

credits: Igor Altsybeev,
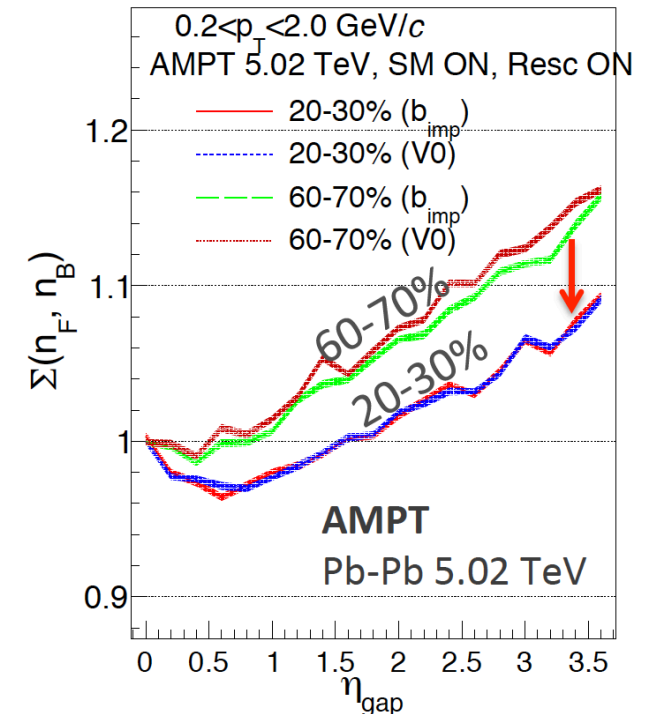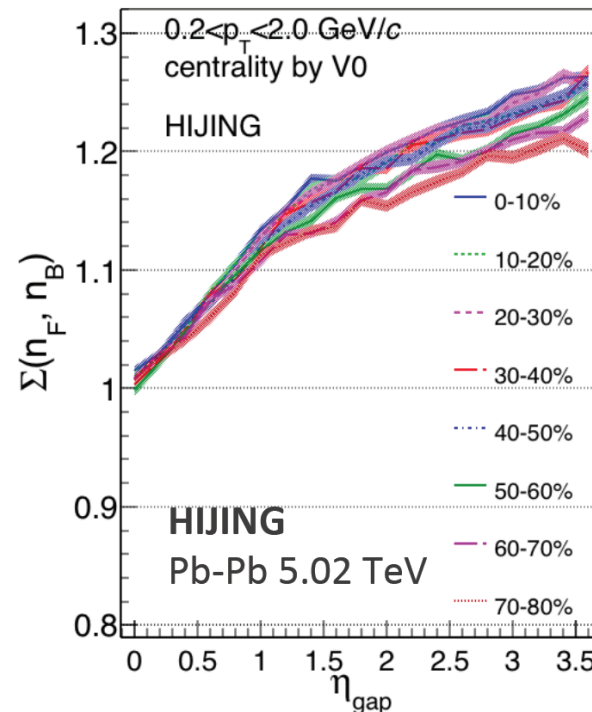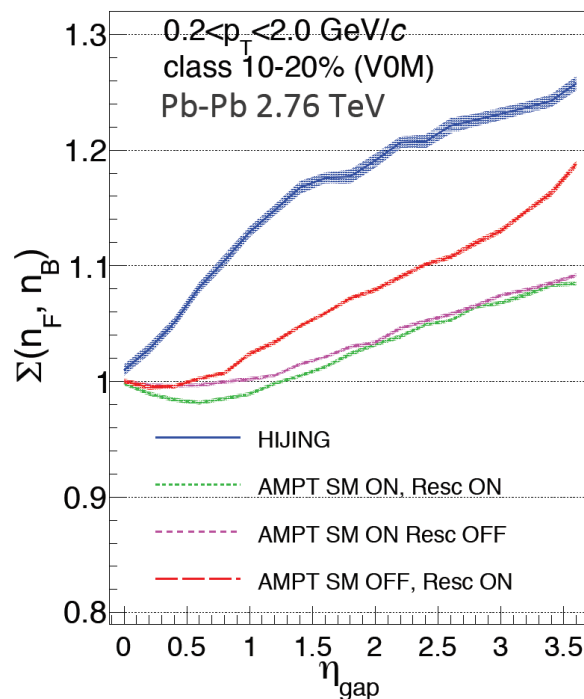
Reaction Plane Measurement
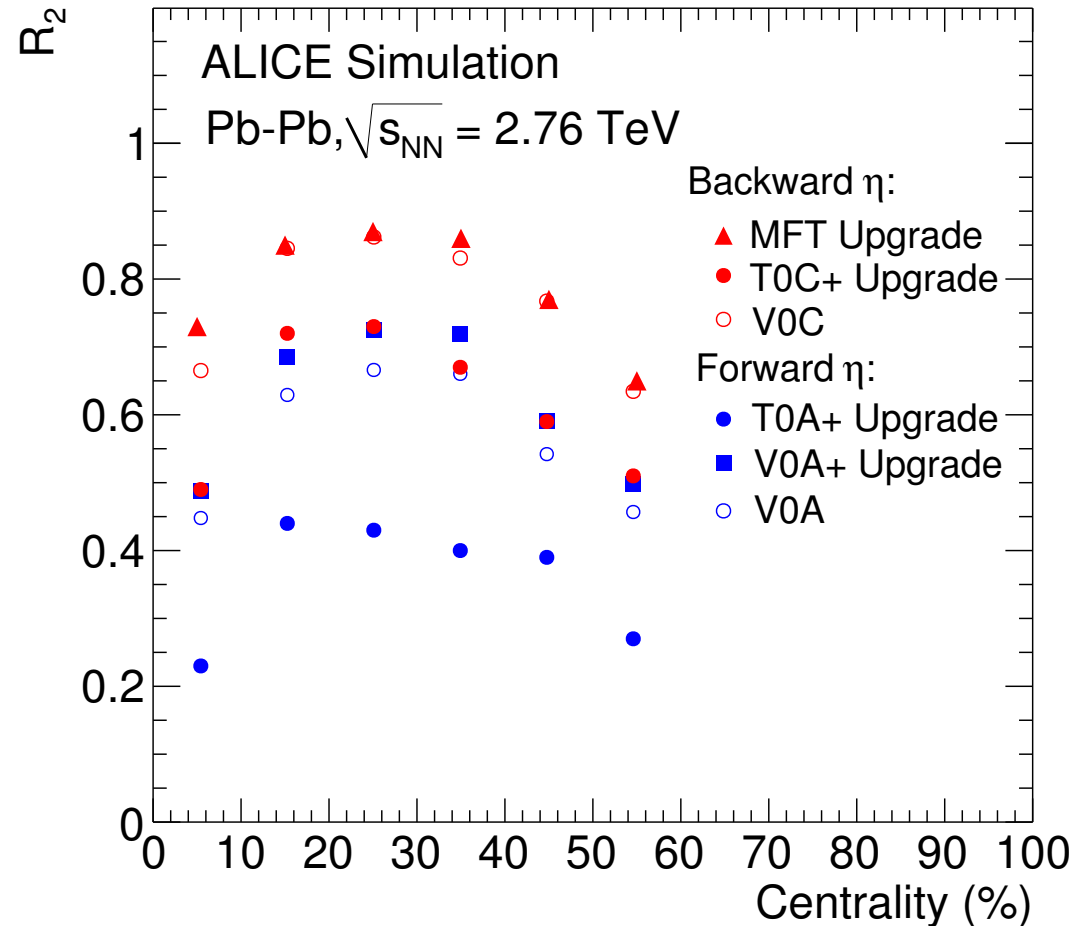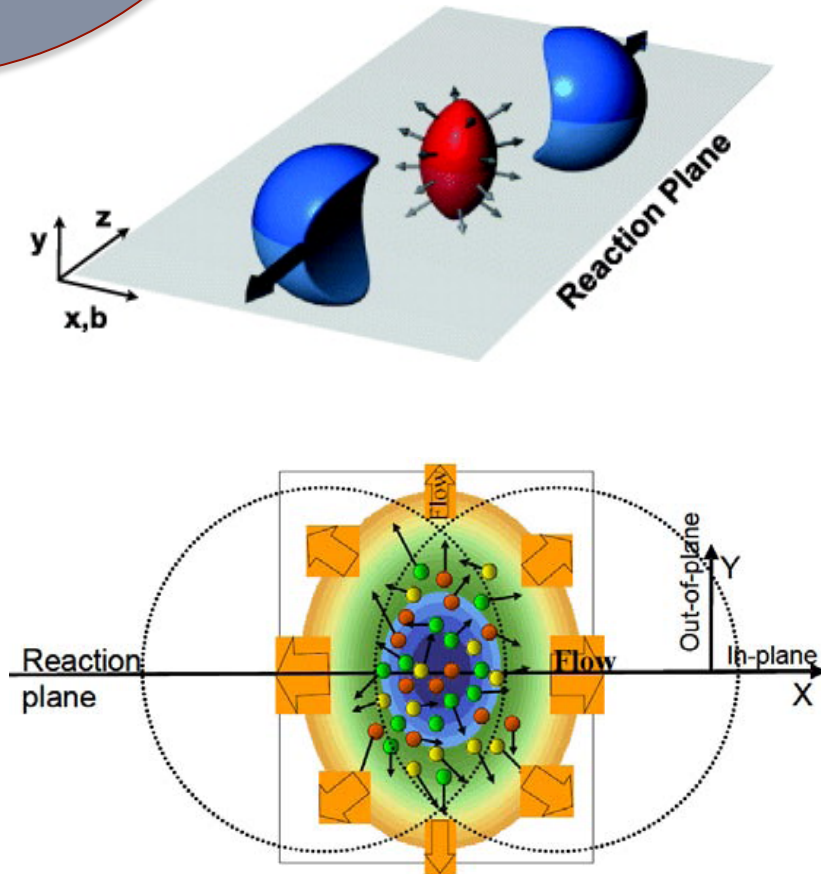
ALI-SIMUL-96184

❖ **Excellent reaction plane resolution**, thanks to the high-granularity and the possibility to perform a standalone tracking (excluding contaminations from noisy clusters)

Low-mass (< 10 GeV/c²) Drell-Yan lepton-pair production at forward rapidity: important source of information on the partonic structure of protons

❖ Constraints on the gluon distribution and its nuclear dependence through the transverse momentum distributions

❖ Information about the onset of (gluon) saturation at small-x

Drell-Yan: main source of prompt dimuons between J/ψ and Υ at the LHC

➢ Easily identifiable with a mass-offset combined fit on MFT-matched dimuons

➢ Due to the relatively large mass, a strong single-μ p_T cut (p_T > 2 GeV/c) can be imposed to improve the quality of the sample

ALICE

Courtesy of P. Bartalini

Disclaimer:
MPI = Multiple parton interactions
within a single collision.
(i.e. it is not referring to the pile-up)

Scale of secondary scatter(s)

Double parton scattering (DPS)

pp, pA, AA

DPS 2 high scales

W+W, W+Z, Z+Z

High Luminosity LHC

Soft MPI

DPS 2 low scales

4 (mini)jets
γ + 3 (mini) jets
Multiple HF

DPS 1 high scale

W/Z + (mini)jets
W/Z Multiple HF

CMS, ATLAS, LHCb
have pp results

MB

High Multiplicity

pp. pA. AA results
RUN 2 → higher
energy. More Stat

UE Measurements
pp results from all LHC
experiments

Scale of primary scatter

❖ All the relevant channels for the DPS studies will profit from the high luminosity available in the Run3-4 program

❖ The continuous, untriggered data taking strategy will largely enhance the possibility of performing measurements **combining high-p_T muons and electrons**
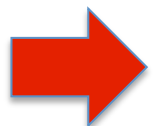
➡ **The MFT will specifically improve the signal/background for channels where the signal is composed of prompt muons: J/ψ + third high-p_T muon**

Conclusions

Hard-Soft correlation studies in ALICE will largely profit from the ALICE-MFT upgrade: new observables, improvement of the already available ones

- ❖ Charm/beauty single-muon separation

- ❖ Prompt/diplaced charmonium separation

- ❖ EM probes from low- and intermediate-mass dimuons

- ❖ Large η-acceptance and low-p_T reach in ITS+MFT correlation studies

- ❖ Better understanding of the underlying event at forward rapidity

Run3+Run4: focus on multiplicity-dependent studies
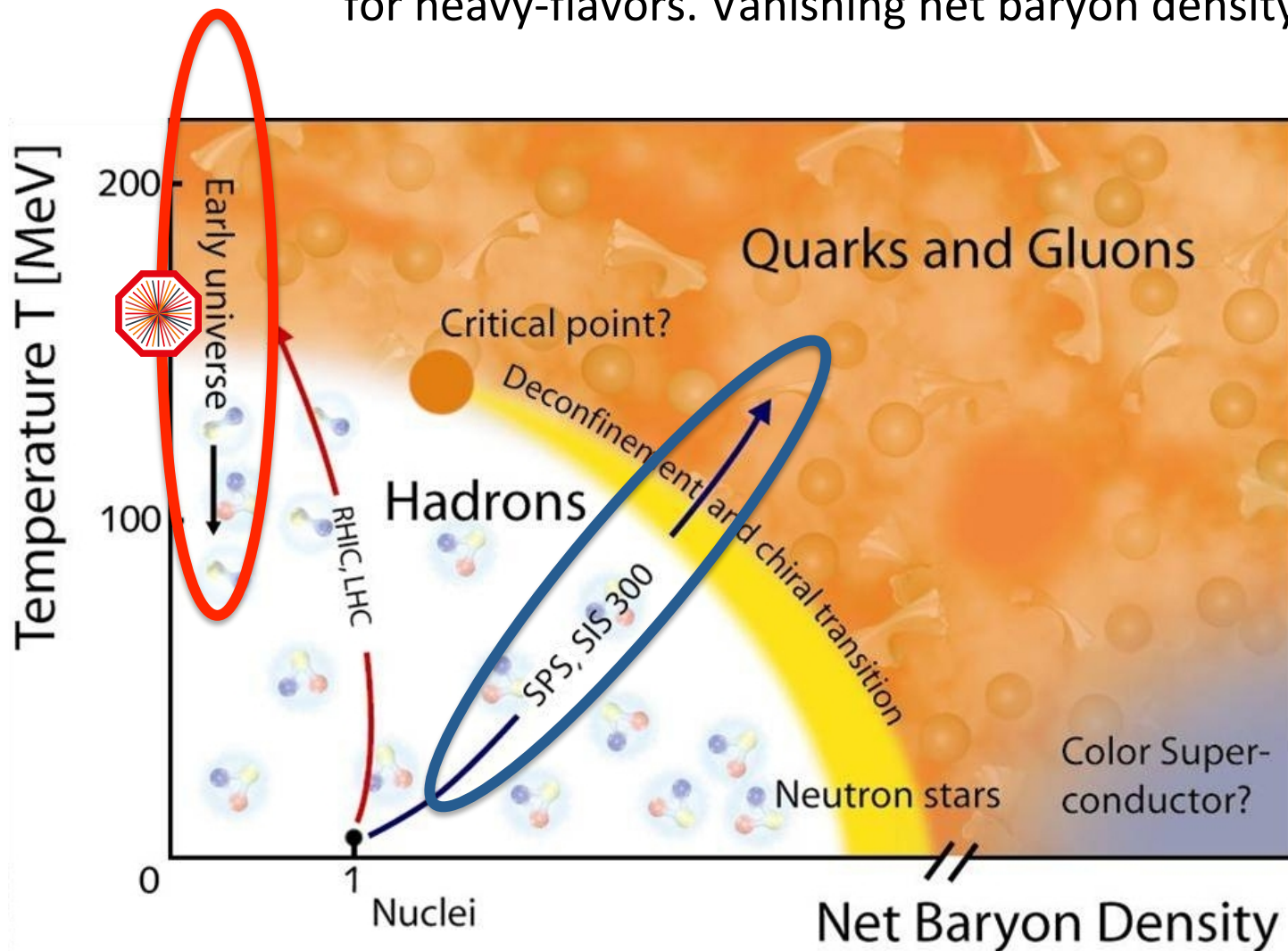
Stay tuned for more details!

Backup Slides

❖ **The high-energy frontier:** large and long-living QGP, large cross-sections for heavy-flavors. Vanishing net baryon density: Early Universe conditions

❖ **The low-energy frontier:** focus on light-flavor observables. **Energy scan:** search of the critical point and characterization of the phase transition

credits: G. Martinez
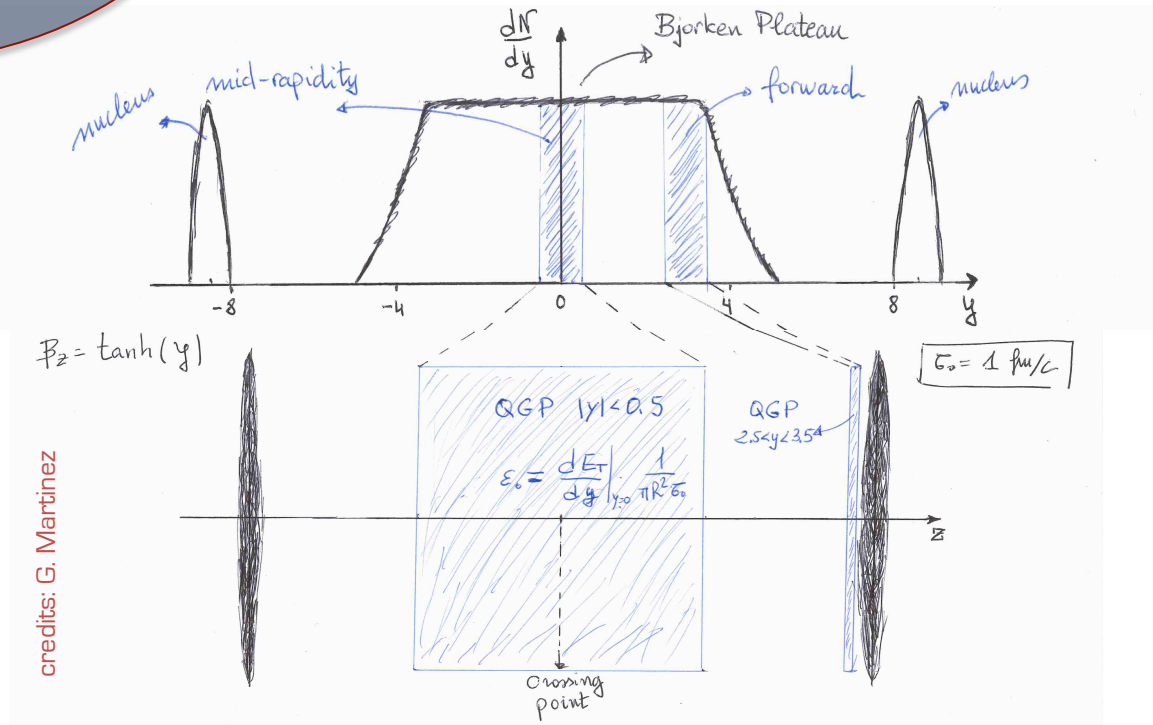
➤ **Main stream of the ALICE Muon Physics:** study the behavior of the hadronic matter at extreme temperature and energy density conditions

➤ **Motivations still valid** after the LHC LS2, but: wider range of observables, more precise observations

➤ **Forward Physics in ALICE:** unique tool to study QGP at the limits 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

- **Low-mass dimuons.** Non-perturbative aspects of QCD through Dalitz and 2-body decays of light narrow resonances close to freeze-out. (Hidden) strangeness production. Thermal emission mediated by the broad vector meson ρ in the form $\pi^+\pi^- \longrightarrow \rho \longrightarrow \mu^+\mu^-$

- **Quarkonium states.** Dissociation/recombination in the QGP phase (and in smaller systems?). Thermal charm production at low p_T. Test of perturbative QCD hadro-production mechanisms in pp collisions. Photo-production in ultra-peripheral heavy-ion "collisions"

- **Heavy-flavor single muons.** Energy loss and coupling of charm and beauty quarks with the deconfined medium

- **Single muons and dimuons from W/Z bosons.** Standard candle reference for in-medium effects. Probes of nucleons and nuclei parton structure

➢ **High level of background from π/K decays**

  ❖ Large systematic uncertainties induced by background subtraction for all physics topics. Open HF analysis in single muons cannot go below p_T = 4 GeV/c. ψ(2S) cannot be easily observed

➢ **Impossibility to determine muon production vertex**

  ❖ No charm/beauty separation in single muons

  ❖ No beauty measurement from non-prompt J/ψ: we miss an important source of information for the study of beauty

➢ **Limited mass resolution for light neutral resonances**

MFT

➢ **Readout not designed for the interaction rates expected after LS2**
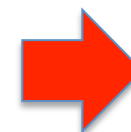
Muon Spectrometer Electronics upgrade

Hadron absorber

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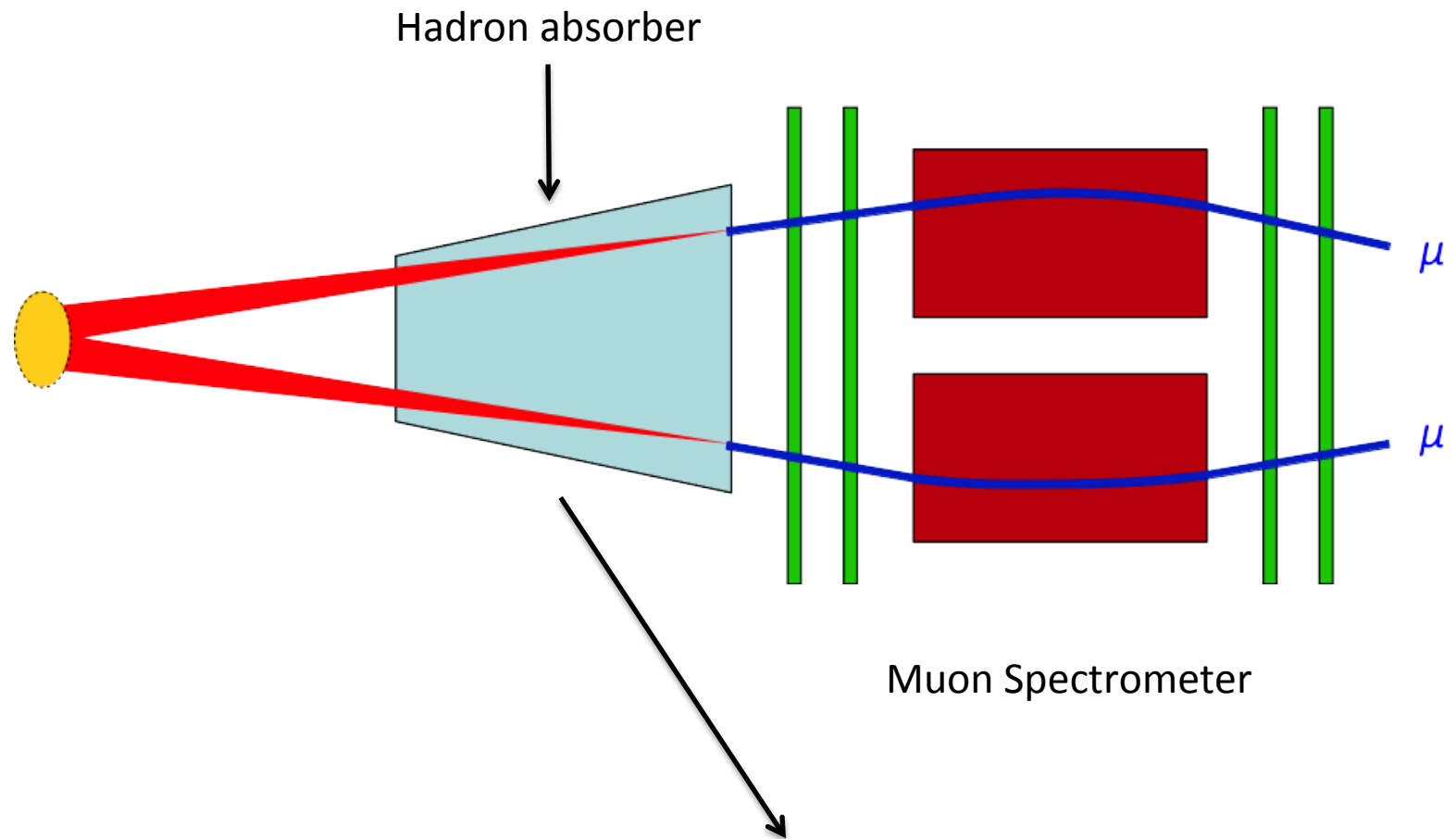
Extrapolating back to the vertex region **degrades the information** on the kinematics

Hadron absorber

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

Muon Forward Tracker

Muon Spectrometer

μ

μ
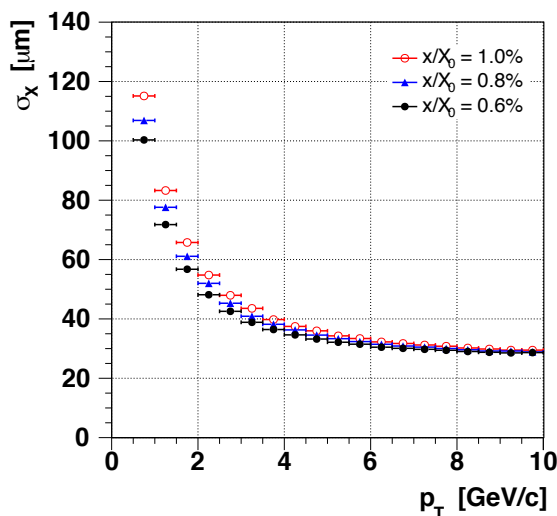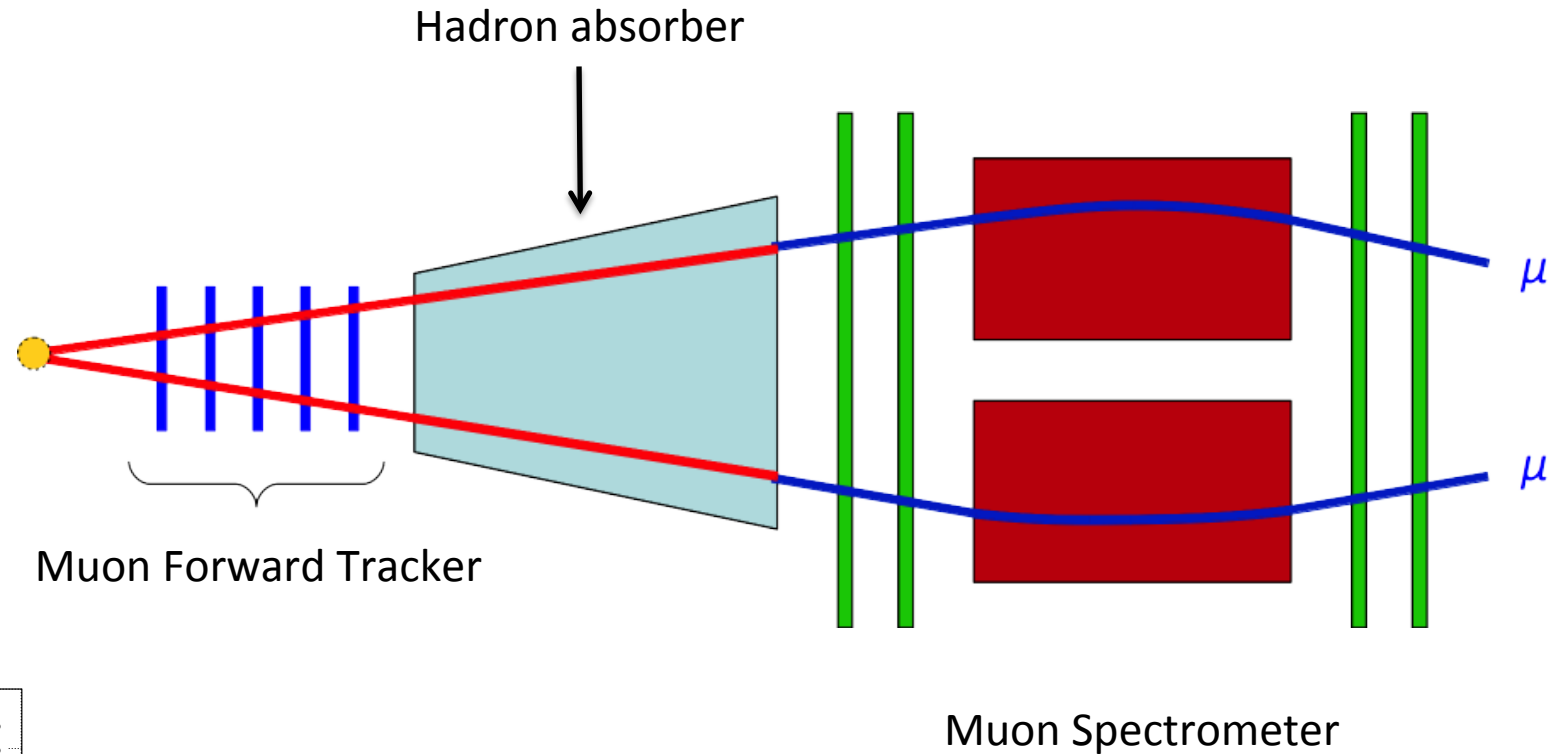
High pointing accuracy gained by the muon tracks after matching with the MFT clusters. Rapidity window reduces to 2.5 < y < 3.6

σ_x [μm] vs p_T [GeV/c]

x/X$_0$ = 1.0%
x/X$_0$ = 0.8%
x/X$_0$ = 0.6%

Muon Spectrometer 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

μ^+

μ^-
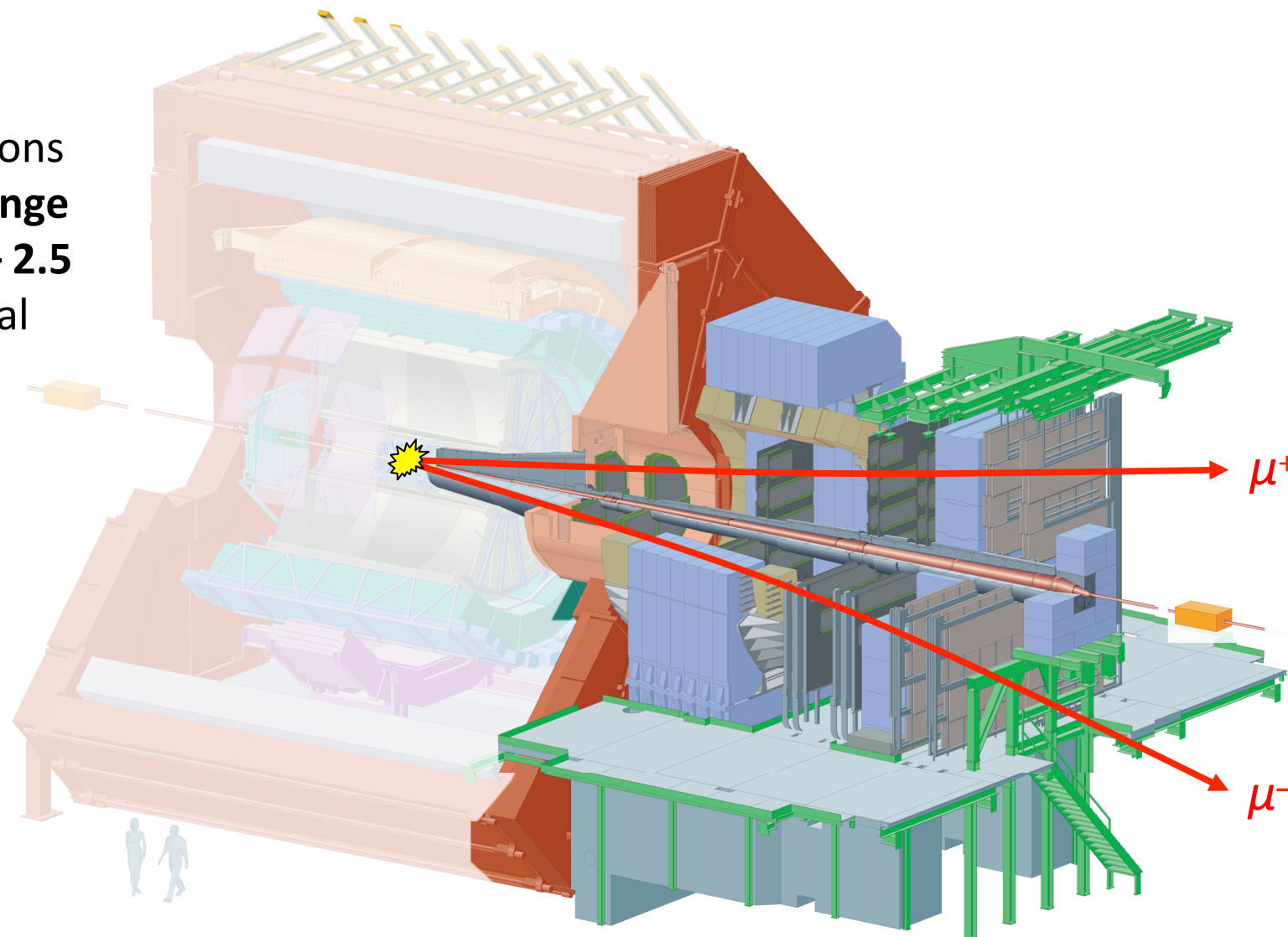
Heavy Flavor and Prompt Charmomium

❖ Probing QCD medium by measuring the energy loss of quarks c and b

❖ Thermalization and hadronization of heavy quarks

❖ Measuring total charm and beauty production cross-section: gold reference for quarkonia studies

❖ Evaluation of the contribution of c-cbar recombination to the production of charmonium at LHC energies

❖ Direct observation of the deconfined phase of matter

❖ **Dissociation of QQ states via color-screening**

Matsui and Satz, 1986
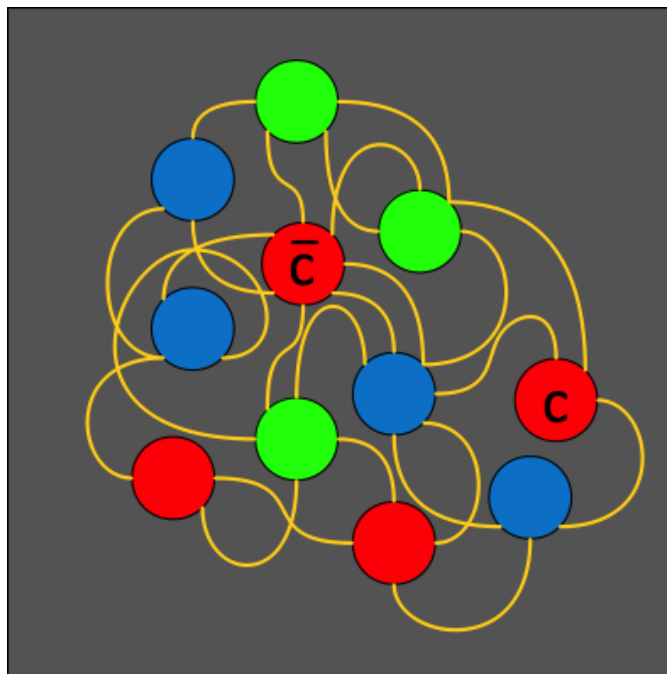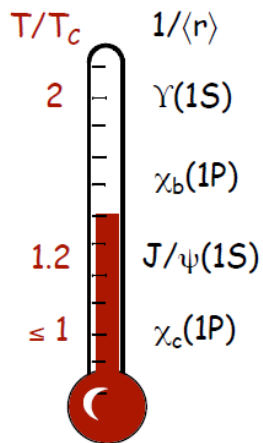
Direct probe of medium deconfinement and temperature

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

Dokshitzer and Kharzeev, 2001
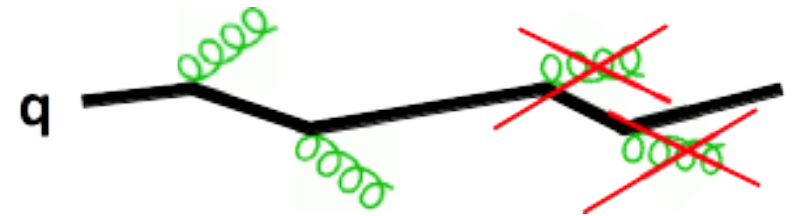
In-medium gluon radiation is expected to increase with the color-charge of the emitting particle, and to decrease with its mass

Direct probe of QCD interaction dynamics over extended systems

➢ **Performance studies only available for p_T < 6 GeV/c** because of the limited MC statistics for the background

➢ **Analysis strategy:** fit of the total transverse offset distribution with the three expected contributions: background, charm and beauty. Templates for each component are extracted from the MC simulations

➢ **Transverse offset:** distance between the primary vertex (measured with the ITS) and the transverse position of the muon tracks extrapolated to the z of the primary vertex

$$\Delta = \sqrt{(x_V - x_{Extrap})^2 + (y_V - y_{Extrap})^2}$$

❖ **Precision measurement for J/ψ at forward rapidity already in LHC Run 2, but:**

➢ No insight on ψ' physics in central Pb-Pb

➢ Only inclusive measurement available at forward rapidity

MFT

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 $\vec{r_i}$
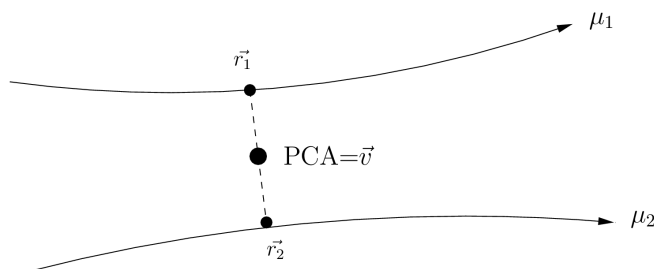
Probability that the two tracks come from the same vertex $\vec{v}$

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

Statistical uncertainties for prompt charmonia: L_{int} = 10 nb^{-1}

J/ψ

❖ **Central Barrel:** between 1% and 5% with the full TPC+TRD PID

❖ **MUON:** below 0.3% independently of the MFT
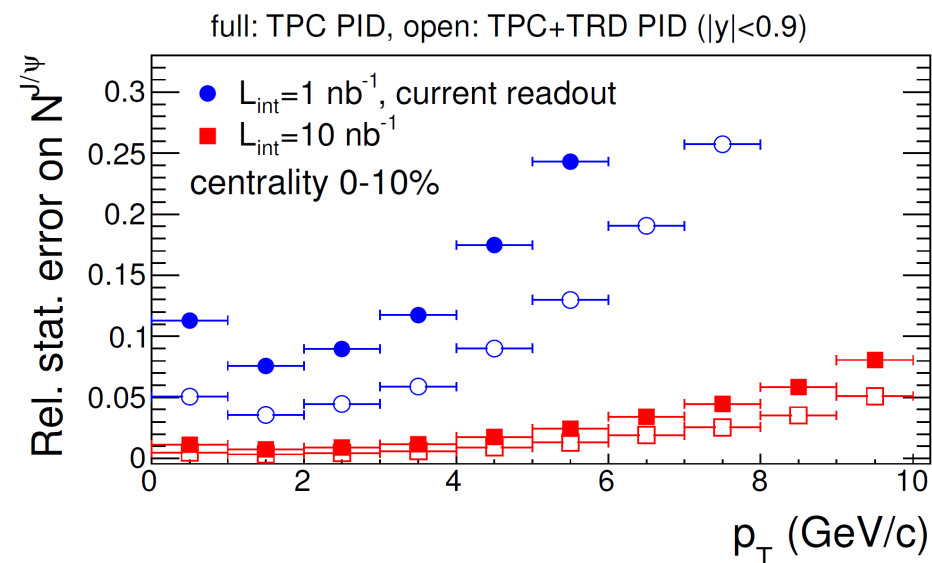

full: TPC PID, open: TPC+TRD PID (|y|<0.9)

- L_{int}=1 nb^{-1}, current readout
- L_{int}=10 nb^{-1}

centrality 0-10%

Rel. stat. error on $N^{J/\psi}$ — p_T (GeV/c)

ψ'

❖ **Central Barrel:** about 20% with the full TPC+TRD PID

❖ **MUON:** about 10% independently of the MFT

L_{int}=10 nb^{-1}, TPC+TRD PID (|y|<0.9)

- statistical model
- pp scaling (N_{coll})

Rel. stat. error on $N^{\psi(2S)}$ — N_{part}

ψ(2S) statistical model scenario
2.5<y<4.0 and p_T>0

- L_{int} = 1 nb^{-1}
- L_{int} = 10 nb^{-1}

Rel. stat. error on $N^{\psi(2S)}$ — Centrality (%)
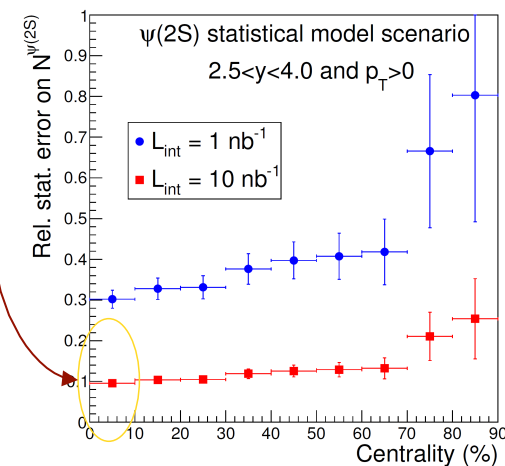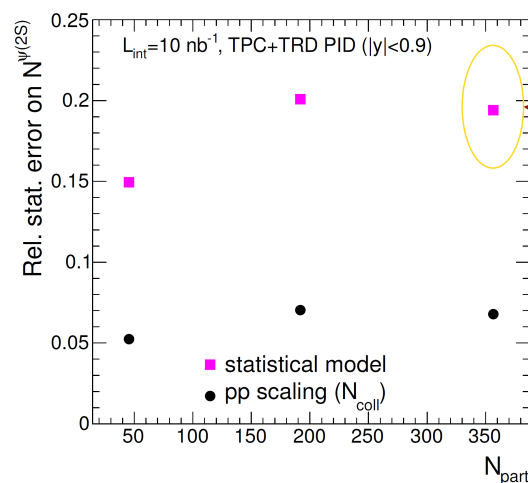
Low Mass & Continuum Dilepton Physics

❖ Modification of spectral functions of vector mesons in the medium, linked to the chiral symmetry restoration

❖ Dilepton (virtual photon) radiation from the partonic phase

❖ Strangeness production

❖ **Systematic uncertainty dominated by background description or subtraction: still, within 10%**

Inclusive ψ' $(3.40 < M_{\mu\mu} < 3.90\ \text{GeV}/c^2)$: $R_{AA} = 0.3$, with the MFT

p_{T} [GeV/c]	Signal [$\times 10^3$]	S/B	$S/\sqrt{S+B}$	Stat. Err. [%]	Sys. Err. [%]
0 − 1	4.47	0.014	7.8	10.7	9.9
1 − 2	8.67	0.014	11	8.5	10.1
2 − 3	6.76	0.018	11	8.7	9.0
3 − 4	4.11	0.027	10	9.0	8.0
4 − 5	2.57	0.030	8.7	10.9	7.8
0 − 10	30.3	0.017	22	4.3	9.2

❖ **Introducing the MFT in the muon HF measurements:**

   ➢ Significant improvement of the physics reach

   ➢ Introduction of new systematic uncertainty sources

❖ **Main systematic sources introduced by the MFT in the HF analyses:**

   ➢ **Control of the MUON-MFT fake match fraction.** Important since key-variables like single muon offset and dimuon t_z depend on the MFT pointing resolution, which is different for correct and fake MUON-MFT matches. It was verified that the effect is included in a 10% uncertainty of the MFT pointing resolution

   ➢ **Assumption of the p_T distribution for the HF hadrons.** Important since it influences the shape of the single muon offset and dimuon t_z templates.
It was verified that a non-negligible impact only exists for the single muon analysis: below 7% for the open charm measurement

See the MFT TDR
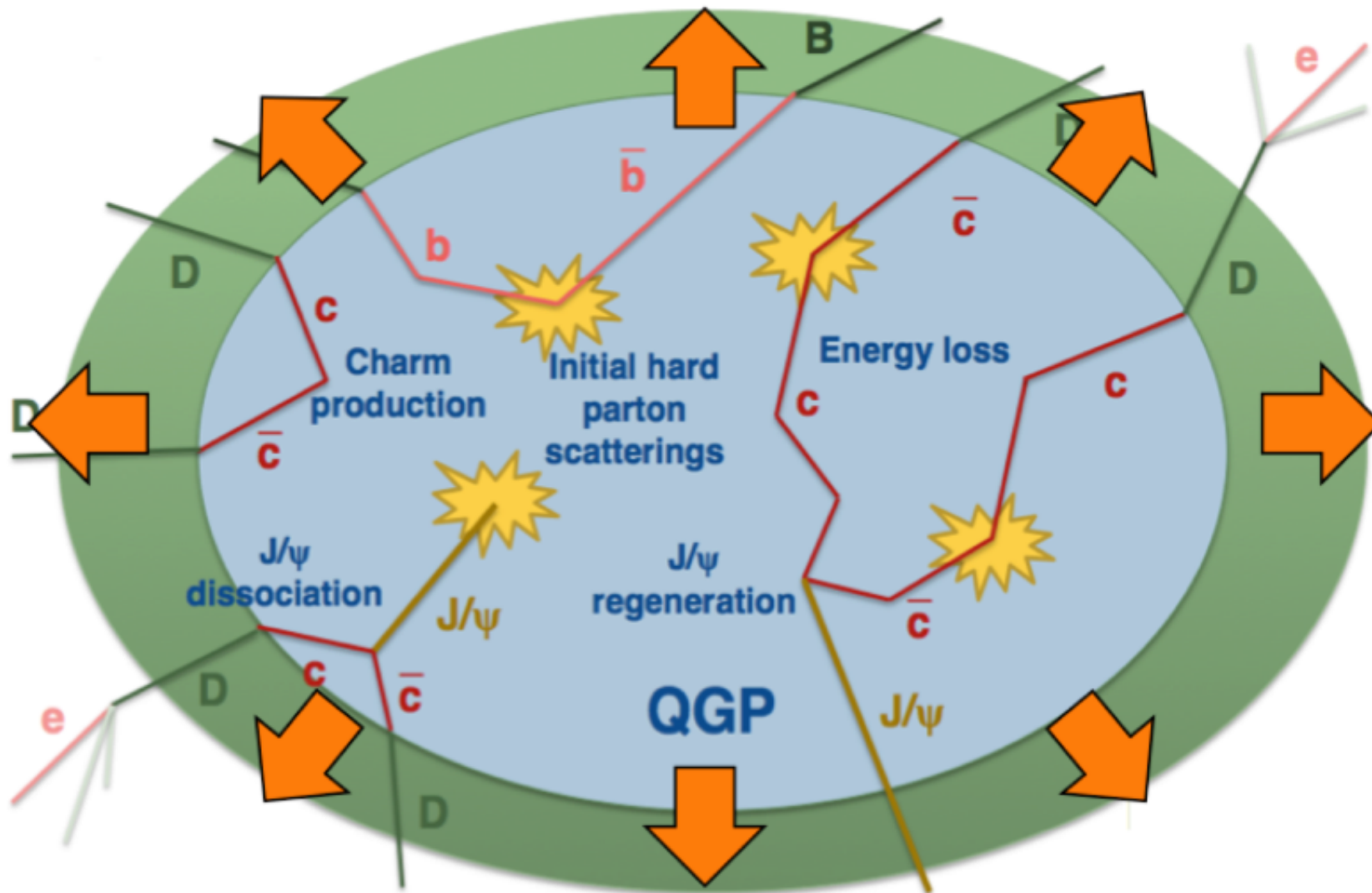
graphics courtesy J. Uphoff

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

❖ **Charmed and beauty hadrons have a long life time** (c$\tau \approx$ 150-300 μm and c$\tau \approx$ 500 μm): information on the evolution of the deconfined medium

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

❖ **Possible charm thermal production?** $\Rrightarrow$ May increase the yield of charm hadrons at low p_T by up to 50-100%. Need to measure charm production **down to p_T = 0**

❖ **Measuring total charm and beauty cross section:** natural normalization for quarkonia production (main uncertainty for J/ψ regeneration models)

Low mass dilepton production in heavy-ion → key information on the hot and dense state of strongly interacting matter produced in high-energy nucleus-nucleus collisions

Insight on **non-perturbative QCD**:

➤ Strangeness production investigated via φ meson production

➤ In-medium modifications of hadron properties accessed through ρ spectral function: possible link to chiral symmetry restoration

Dileptons (dielectrons, dimuons) → Negligible final-state effects
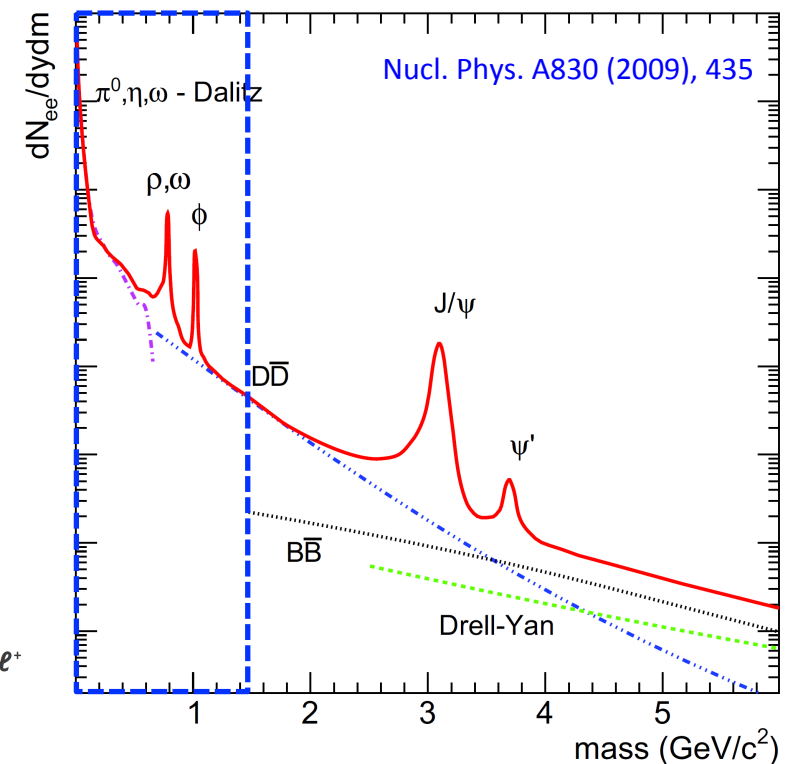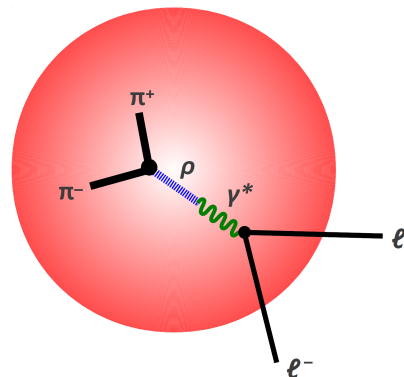
Measurements in pp and p-A collisions → Soft particle production in Cold Nuclear Matter, needed reference for correctly interpreting heavy-ion observations

The ALICE experiment has already a rich and successful physics program based on the performance of the Muon Arm

- ➢ R_{AA} and elliptic flow for muons from open HF: interaction between heavy quarks and deconfined medium
- ➢ Charmonia: R_{AA} and elliptic flow give insight on the suppression/recombination mechanisms predicted by the models
- ➢ Low Mass Dimuons: although limited by the low statistics, no competitor at the LHC
- ➢ Various items not considered here: for instance, J/ψ photoproduction, J/ψ polarization

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

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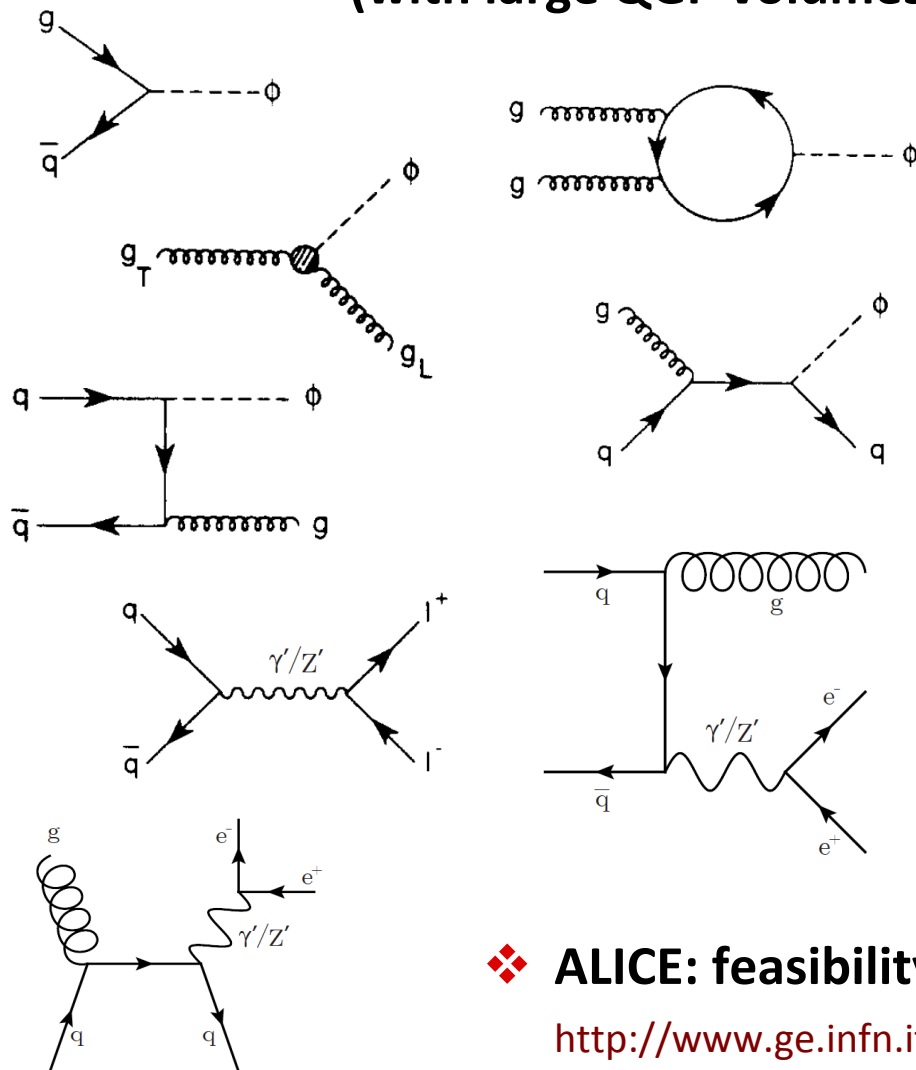- ➢ Improve S/B ratio and mass resolution for Low-mass dimuons

Light scalar or vector BSM bosons could be observed in **high-energy (with large QGP volumes produced), high-luminosity nuclear collisions**

J. Ellis & P. Salati, Nuclear Physics B342 (1990)
J. Davis & C. Böhm, arXiv:1306.3653

❖ **Resonance in the thermal dilepton production from the QGP** for masses up to 3 GeV/c^2: dilepton measurements in ALICE could set limits on quark- and lepton-couplings of light BSM bosons

❖ **Heavier bosons** would mainly decay into multiparticle states involving cc and ττ pairs, and are **no longer detectable in the ee or μμ channels**

❖ **ALICE: feasibility studies on dark photons of mass < 100 MeV/c^2**
http://www.ge.infn.it/~ldma2015/presentations/wednesday-morning/05_gunji.pdf