Separating prompt and non-prompt J/ψ : The emancipation of quarkonias in ALICE run 3 and other stuff

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GDR QCD - 25th of May 2022

Outline

From theoretical to experimental physics

Epidemiology

Renormalisation group approach inspired model to describe epidemiology data

$\longleftrightarrow$

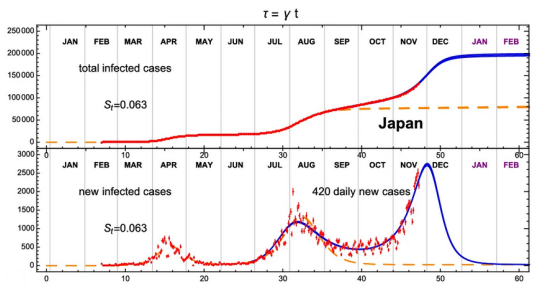
Theoretical physics

New model of Grand Unification : Compactified extra-dimensions + copy of SM particles

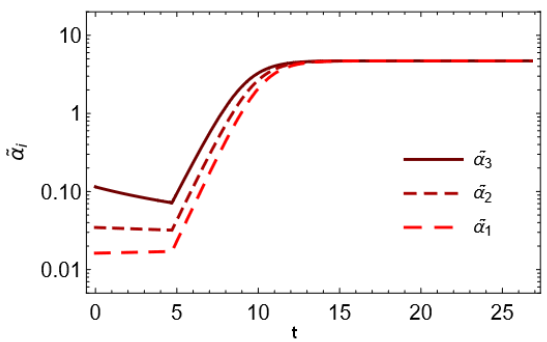
$\longleftrightarrow$

Phenomenology

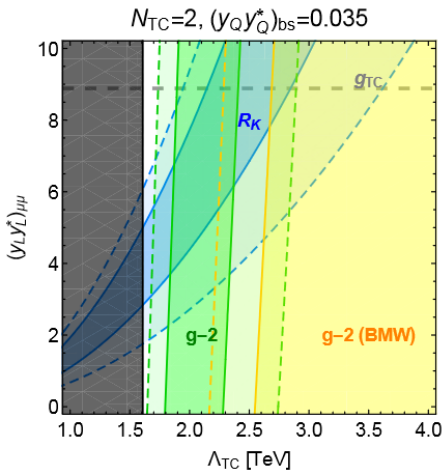
Use of experimental results to constrain BSM theories



$\longleftrightarrow$



$\longleftrightarrow$



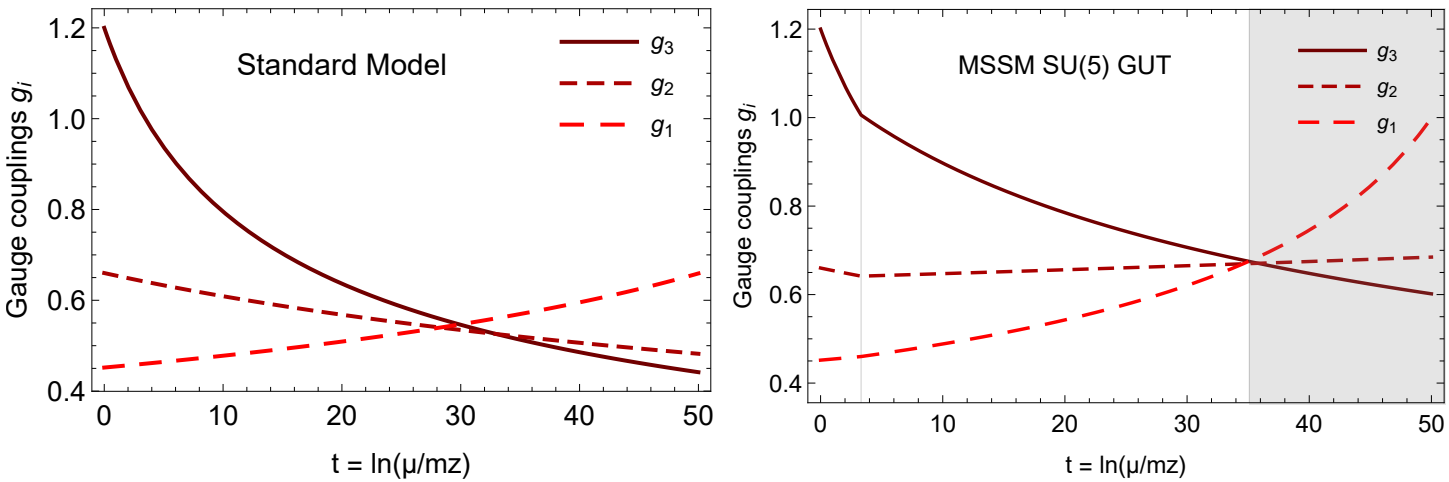
Applications of the renormalisation group equations : From Grand Unification to epidemiology.

Beta function and running couplings

- The theory of renormalisation implies that it exists a scale-invariant function β such that for any coupling g (or any lagrangian parameter) :

$$\frac{\partial g}{\partial \mathrm{Ln}\mu} = \beta(g)$$

$$G_{SM} = SU(3)_c \times SU(2)_W \times U(1)_Y \subset SU(5)$$



- Standard unification = Intersection point. Exact unification possible by adding a SuperSymmetric sector.
- Problems : Proton decay phenomenology and SUSY not found at LHC.

aGUT $SU(5)$ model

- Compactified extra-dimension on a $S^1/(Z_2 \times Z_2')$ orbifold + Copy of SM particles embedded in $SU(5)$ multiplets.
- Scalar and Fermion content in $\mathbf{1}$, $\mathbf{5}$, $\bar{\mathbf{5}}$, $\mathbf{10}$ and $\overline{\mathbf{10}}$ representations :

$$\phi_5 = \begin{pmatrix} H \\ \phi_h \end{pmatrix}, \quad \psi_{5_{L/R}} = \begin{pmatrix} b \\ L^c \end{pmatrix}_{L/R}, \quad \psi_{\bar{5}_{L/R}} = \begin{pmatrix} B^c \\ l \end{pmatrix}_{L/R}, \quad \psi_1 = N,$$

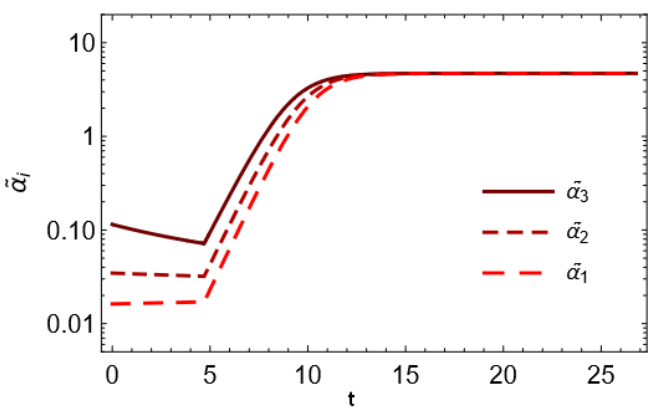
$$\psi_{10_{L/R}} = \frac{1}{\sqrt{2}} \begin{pmatrix} T^c & q \\ & \mathcal{T}^c \end{pmatrix}_{L/R}, \quad \psi_{\overline{10}_{L/R}} = \frac{1}{\sqrt{2}} \begin{pmatrix} t & Q^c \\ & \tau \end{pmatrix}_{L/R},$$

- SM fields and new fields called Indalo ("creation" in Zulu) fields (noted 🧍).
- Conserved baryon and lepton number → No proton decay !

- Renormalisation group equation for the one-loop factor gauge coupling constants :

$$2\pi \frac{d\alpha_i}{dt} = b_i^{SM} \alpha_i^2 + \left(m_Z R e^t - 1\right) b_5 \alpha_i^2$$

- All gauge couplings run to the same non-zero UV fixed point asymptotically (If $n_g \leqslant 3$) → Asymptotic Grand Unification Theory.



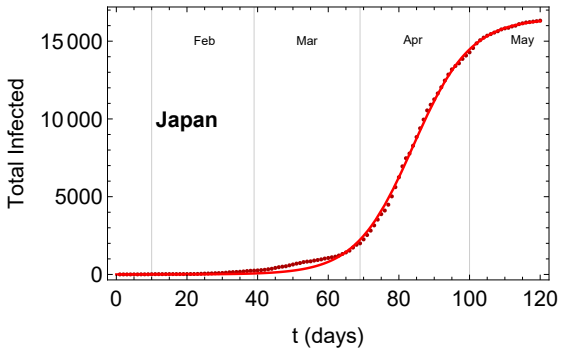
Phys. Rev. D 104, 075012

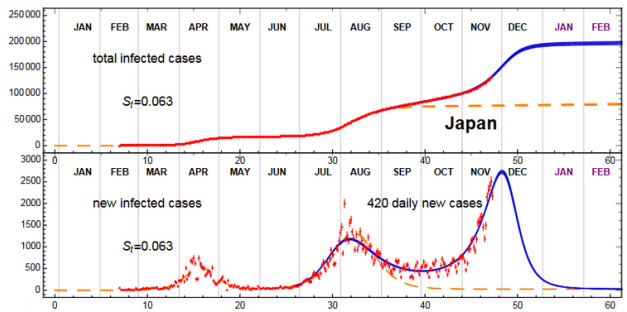
The framework basis

- Basis equation on the cumulative number of infected I(t) :

$$\frac{dI}{dt} = \gamma I(t)\left(1 - \frac{I(t)}{a}\right),$$

$$I(t) = \frac{a e^{\gamma t}}{b + e^{\gamma t}}$$





eRG fit with $\gamma = 0.123\ day^{-1}$ and $a = 16479$.

- Two parameters needed to reproduce a wave : γ the "infection rate per time unit" and a the total number of cases.

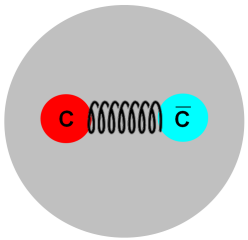
$$\frac{dI_i}{dt} = \gamma_i I_i(t)\left[\left(1 - \frac{I_i(t)}{a_i}\right)^2 - \delta_0\right]^{p_0} \prod_{\rho=1}^{w}\left[\left(1 - \zeta_\rho \frac{I_i(t)}{a_i}\right)^2 - \delta_\rho\right]^{p_\rho} + \sum_j k_{ij}\left(I_j(t) - I_i(t)\right)$$

- Simplest eRG equation : one-wave behavior.
- Interactive eRG : k_{ij} number of travellers from region i to region j.
- Endemic phase : $\delta < 0$, complex fixed points → constant number of cases.
- Multiwave eRG : Multiples waves with different parameters (ζ_ρ).

Sci Rep 10, 15514 (2020), Sci Rep 11, 4150 (2021), Sci Rep 11, 6638 (2021)

Outline

J/ψ particles and QGP

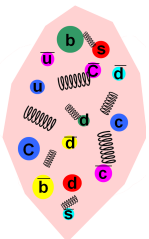


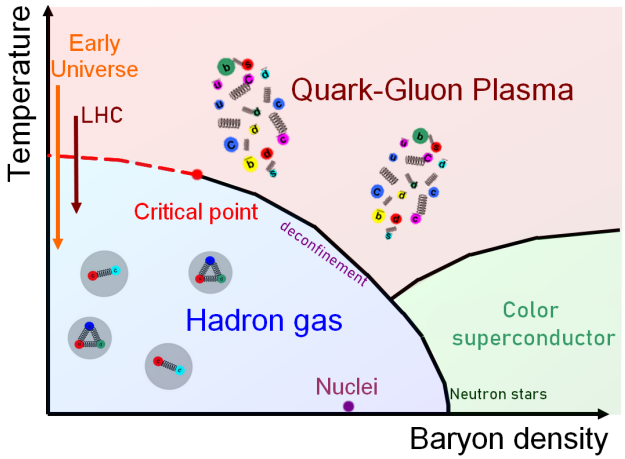
What is the J/ψ ? :

- $c - \overline{c}$ meson (charmonia)
- Discovered independently at SLAC (Richter) and BNL (Ting) in 1974.

Why the J/ψ is so important ?

- Lightest spin 1 charmonium : 3.0969 GeV → High statistics in hadron collisions.
- Relatively long lifetime : 7.2×10^{-21} s
- Produced early → Allows to probe hot QCD medium from collisions → Ideal to study Quark-Gluon Plasma (QGP).





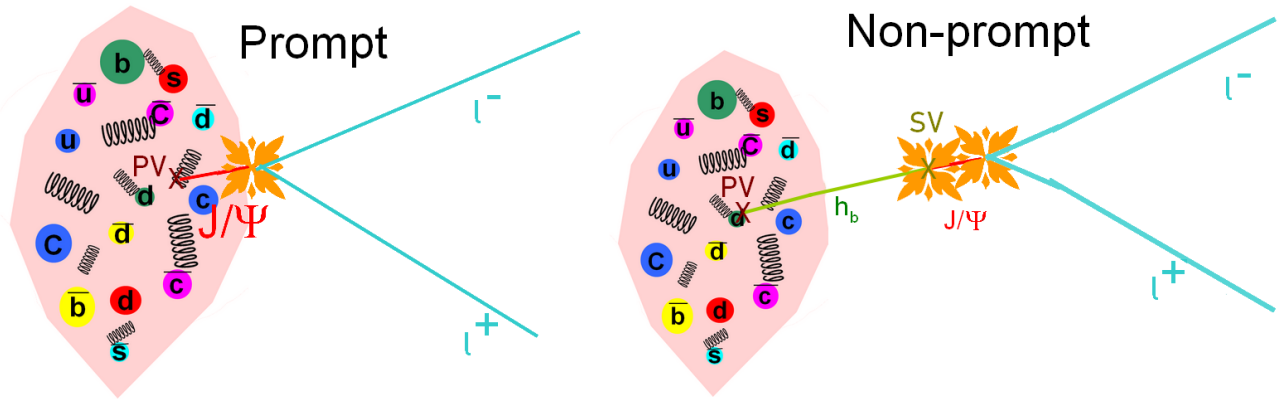
What is the Quark-Gluon Plasma ? :

- Deconfined state where gluons and quarks behave freely (local color charges).
- Behaves like a perfect fluid.

Why the QGP is so important ?

- Hints on the early state of the Universe.
- Allows to study phenomena like jet quenching, color-screening, recombination ...

Different J/ψ production



How J/ψ are created ? :

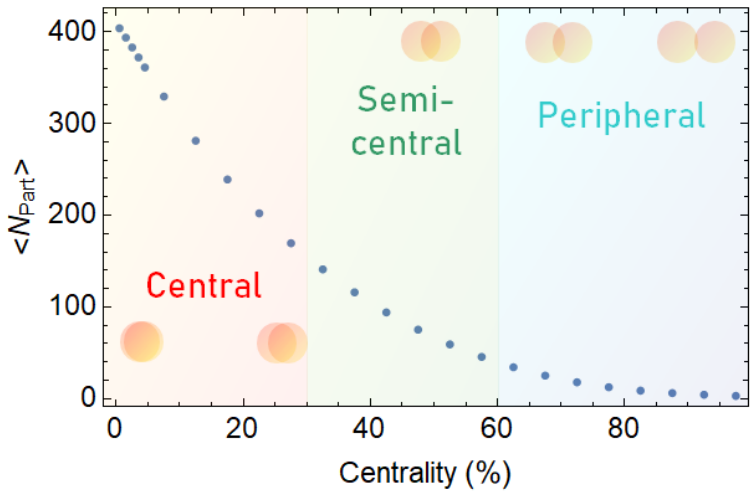
- Directly in the collided medium or decaying from higher mass charmonia states ($\psi(2s)$, χ_c...) : **Prompt** J/ψ.
- Product from the decay of b hadrons → secondary vertex : **Non-prompt** J/ψ.

Why is it important to separate them ?

- Non-prompt J/ψ momentum is close to the one from the b hadron → Information about B mesons.
- Different behavior of *c* and *b* quarks.
- Could allow to constrain theoretical models.

Some variables of interest

- Number of participants/Centrality : $< N_{\text{part}} >$ refers to the number of participants nucleons.
  The Glauber model relates it to the centrality of the collision (in %).
  Glauber, RJ. 1959.



- Nuclear modification factor

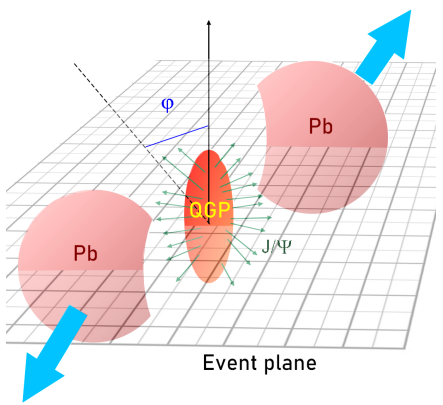
$$R_{AA} = \frac{\frac{d^2\sigma_{PbPb}}{dydp_t}}{\langle N_{coll} \rangle \frac{d^2\sigma_{pp}}{dydp_t}}$$

where $< N_{coll} >$ is the average number of nucleon-nucleon collision in PbPb.

- Elliptic flow :

$$v_2 = \langle \cos [2 (\phi - \Psi_{EP})] \rangle$$

where <> refers to average over the particles, summed over all events, ϕ is the azimuthal angle and Ψ_{EP} is the event plane angle.



How to separate them ?

How it is usually done ? :

- Identification based on the detection of second vertexing.

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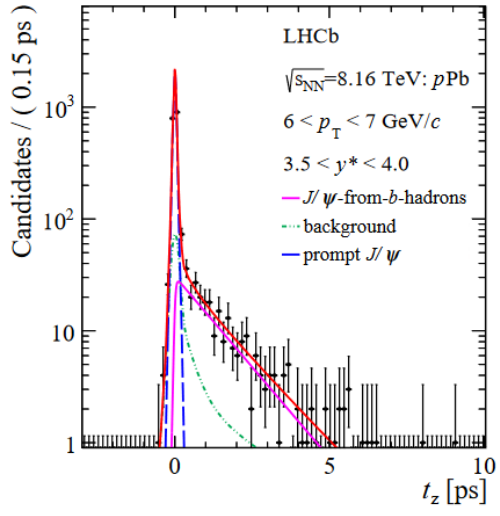


Pseudo proper time :

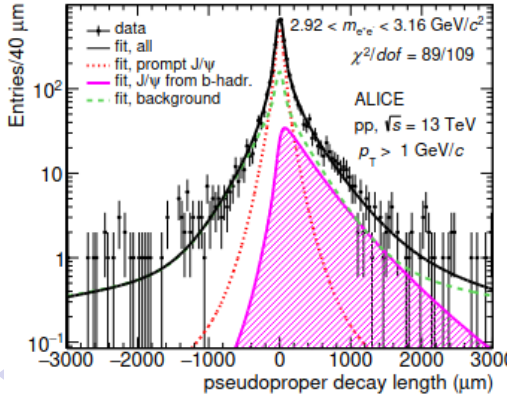
- The pseudo proper time t_z is defined using :

$$t_z = \frac{(z_{SV} - z_{PV})\, M_{J/\psi}}{p_z}$$

where z_{SV} and z_{PV} are respectively the z-coordinates of the primary and secondary vertices and p_z is the momentum along z, where z is the beam axis.

- Prompt : Dirac function / Non-prompt : Exponential function. Both are convoluted with a triple-Gaussian function.

arXiv:2108.02523



Pseudo proper decay length :

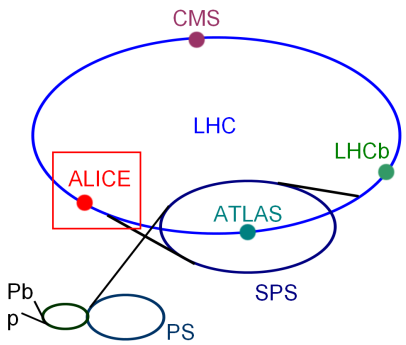
- The pseudo proper decay length x is better designed for central rapidity :

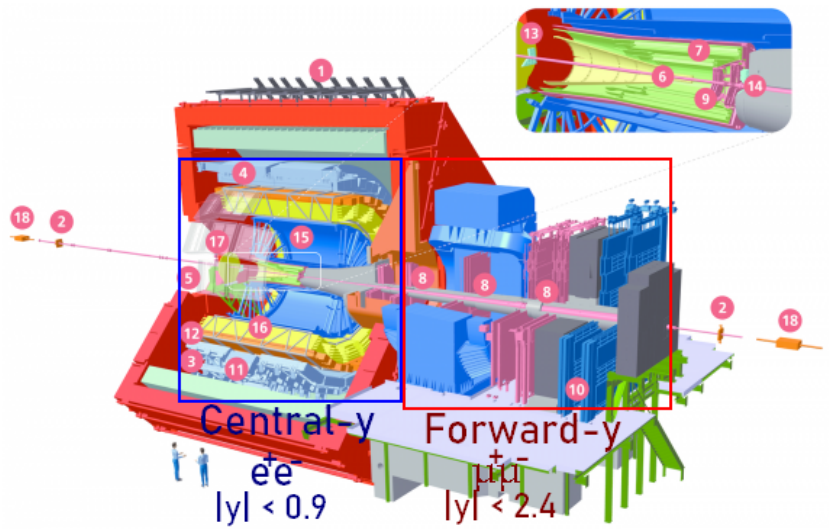
$$x = \frac{\vec{L}.\vec{p_T}\, M_{J/\psi}}{|\vec{p_T}|}$$

where $\vec{L}$ is the vector from the PV to the SV and $\vec{p_T}$ the transverse momentum.

Outline

The ALICE detector





1 ACORDE | ALICE Cosmic Rays Detector
2 AD | ALICE Diffractive Detector
3 DCal | Di-jet Calorimeter
4 EMCal | Electromagnetic Calorimeter
5 HMPID | High Momentum Particle Identification Detector
6 ITS-IB | Inner Tracking System - Inner Barrel
7 ITS-OB | Inner Tracking System - Outer Barrel
8 MCH | Muon Tracking Chambers
9 MFT | Muon Forward Tracker
10 MID | Muon Identifier
11 PHOS / CPV | Photon Spectrometer
12 TOF | Time Of Flight
13 T0+A | Tzero + A
14 T0+C | Tzero + C
15 TPC | Time Projection Chamber
16 TRD | Transition Radiation Detector
17 V0+ | Vzero + Detector
18 ZDC | Zero Degree Calorimeter

What is ALICE ?

- ALICE is one of the four main experiments on the LHC.
- Composed by multiple sub-detectors (13 for run 3).

What is its purpose ?

- Mainly designed to study heavy ion collisions and QGP through quarkonia mainly.
- Allow to study them down to centrality 0% and to low p_T.

What the run 3 upgrade will bring ?

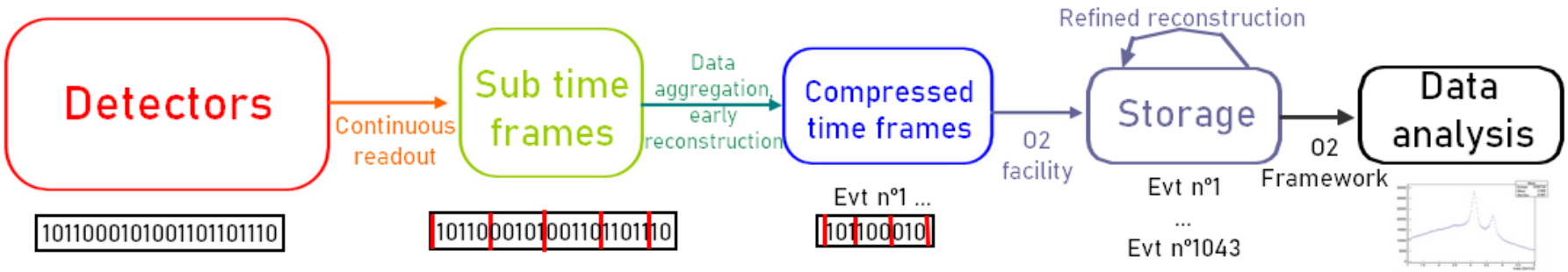
- New detectors : MFT allowing to perform second vertexing for forward rapidity events.
- Improved readout electronics and new framework (O^2) adapted to more luminosity.

The O_2 framework

Why a new framework ?

- PbPb collisions will be collected at up to 50kHz.
- Dataflow estimated to be 1TB/s for Pb–Pb events in Run 3. (10GB/s in Run 1).
- No more Triggering detector → Continuous readout.
- Need to compress the data volume as much as possible.
- Parallelization needed to fasten the analysis.

How O_2 is designed ?



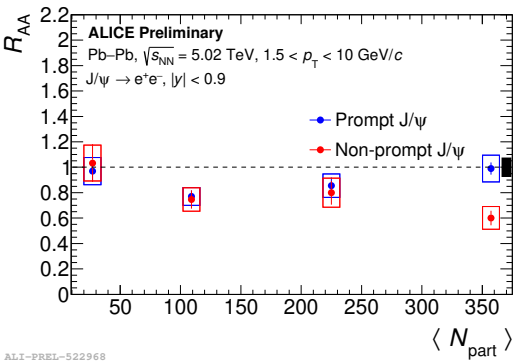
What is its status ?

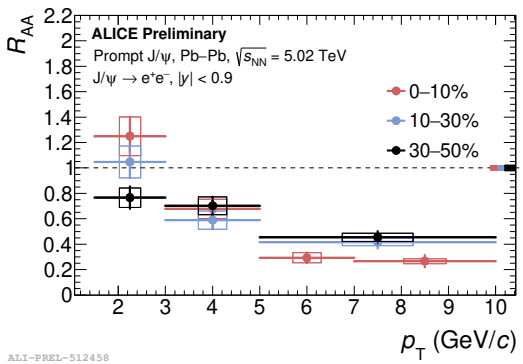
- Most of the framework is ready and heavily tested.
- Some functionalities still not ready (e.g : Embedding).

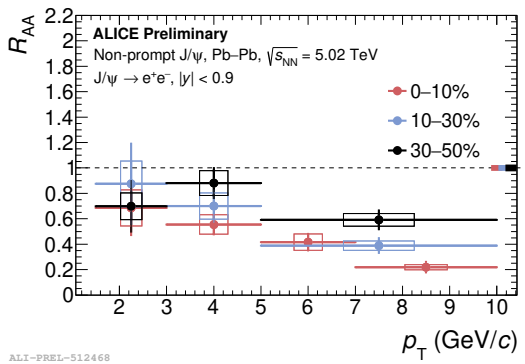
Latest ALICE Run 2 results for PbPb collisions : R_{AA}

- R_{AA} shows suppression of prompt and non-prompt J/ψ in central collisions.
- Recombination creates low p_T prompt J/ψ in central collisions.
- No information about contributions at forward rapidity and low p_T yet.

Jon-Are Sætre - QM 2022

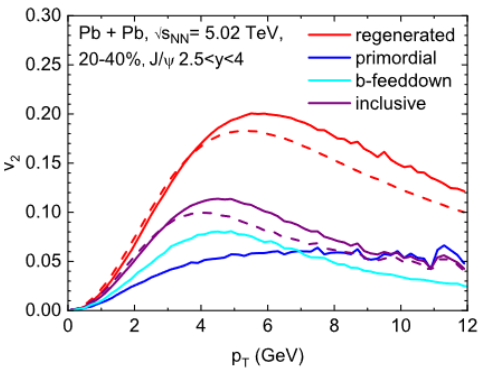


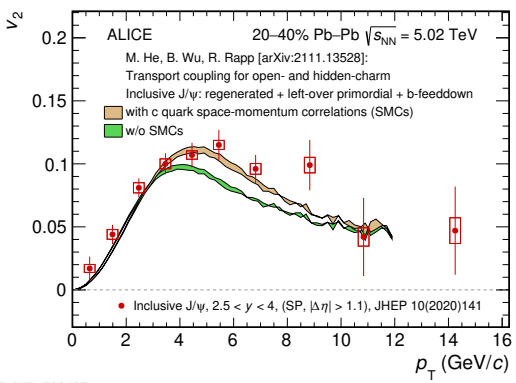




Latest ALICE Run 2 results for PbPb collisions : v_2

JHEP 10 (2020) 141 / arXiv:2005.14518



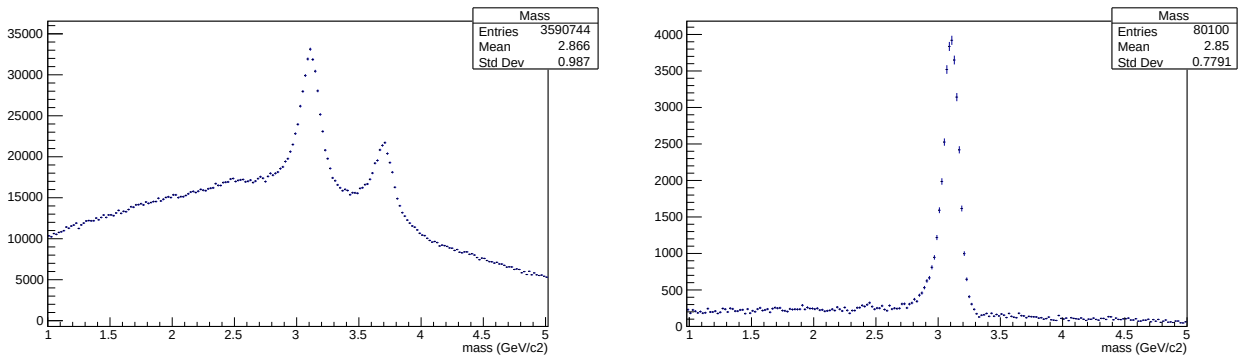


- Small elliptic flow expected for non-prompt J/ψ → No flow for $\Upsilon(1S)$.
- No information about contributions at low p_T yet for prompt/non-prompt.
- Latest TAMU model seem to be in agreement with data.

Run 3 results

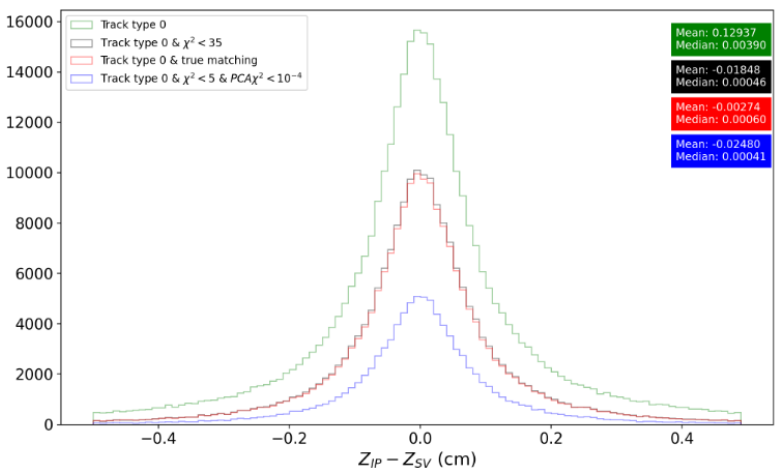
- Simulations analysis ongoing.
- System not fully stable yet.

Prompt and non-prompt simulations through μ channel at forward-y



- Secondary vertexing but matching tracks are not perfect yet.
- Data to come soon. Beam physics will start this week.

Rita Sadek - O2 DQ meeting



Conclusion

We have seen that :

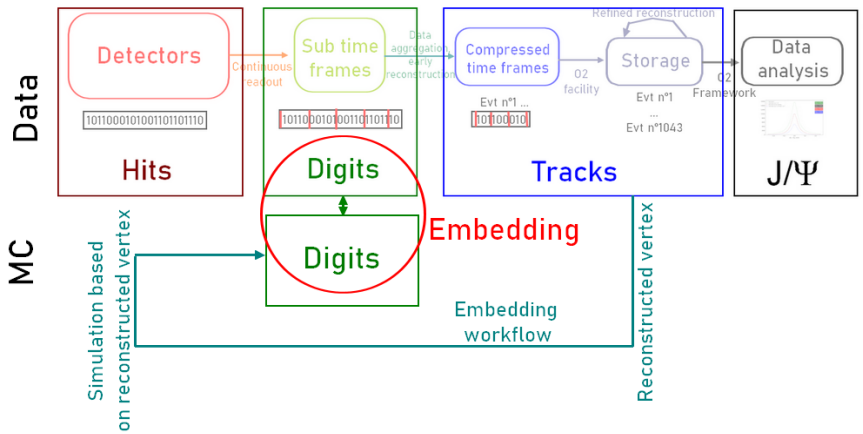
- A new model of Grand Unification involving a different pardigm to understand Unification.
- Physics can give important interdisciplinary insights, especially fields you wouldn't expect to work with.
- Prompt/Non prompt J/ψ separation gives crucial information on nuclear and collective effects.
- Run 3 will bring much more statistics and allow to access to new kinematics regions for the study of J/ψ.
- Particle physics theoreticians-PhD struggles to speak about experimental physics easily (Still in phase transition).

Thanks

Thank you for your attention !

Outline

Embedding Service task



- Embedding is used to add up together simulated signals and real data background
- Embedding expected to be held at the digits level.
- Whole workflow expected to reconstruct real data background vertex, then simulate signals at this vertex, then embed everything together.

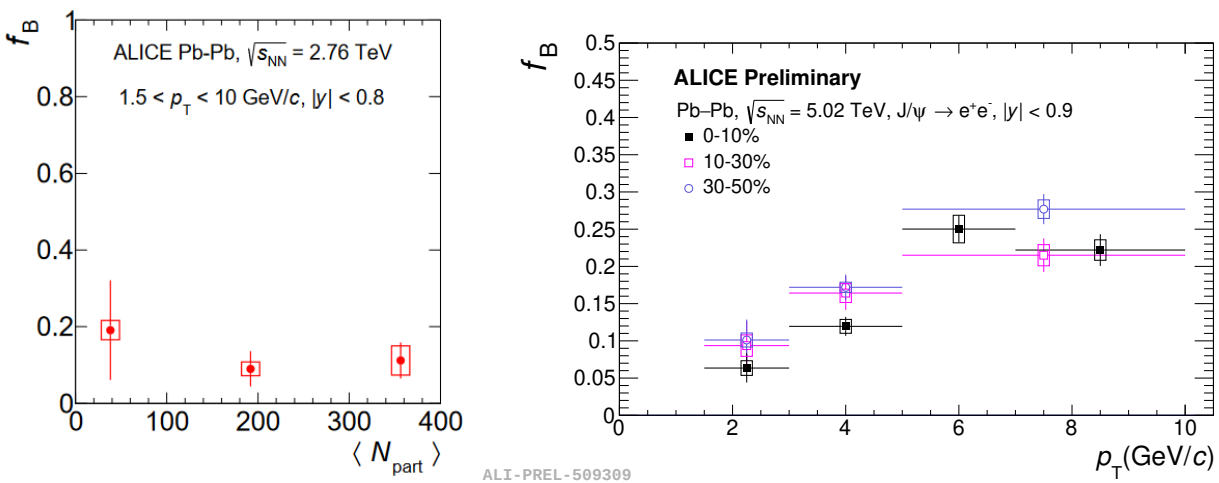
Additional variables

- Non-prompt ratio :

$$f_b = \frac{\frac{d^2\sigma_{np}}{dydp_t}}{\frac{d^2\sigma_{np}}{dydp_t} + \frac{d^2\sigma_{p}}{dydp_t}}$$

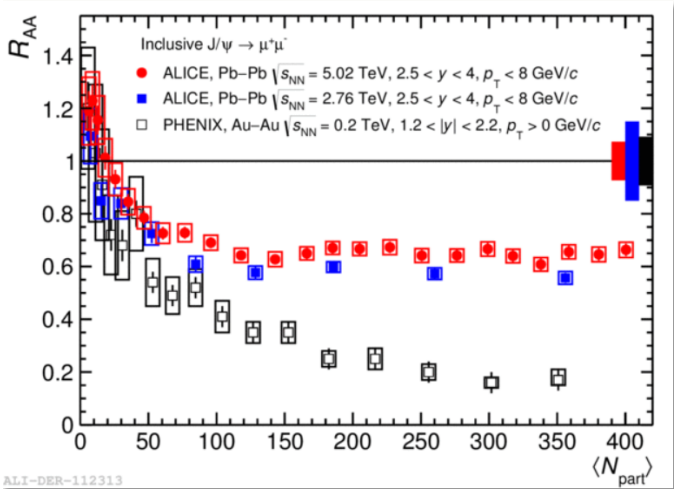
where f_b is the ratio of non-prompt J/ψ yield over inclusive.

JHEP 05 (2016) 179



Recombination

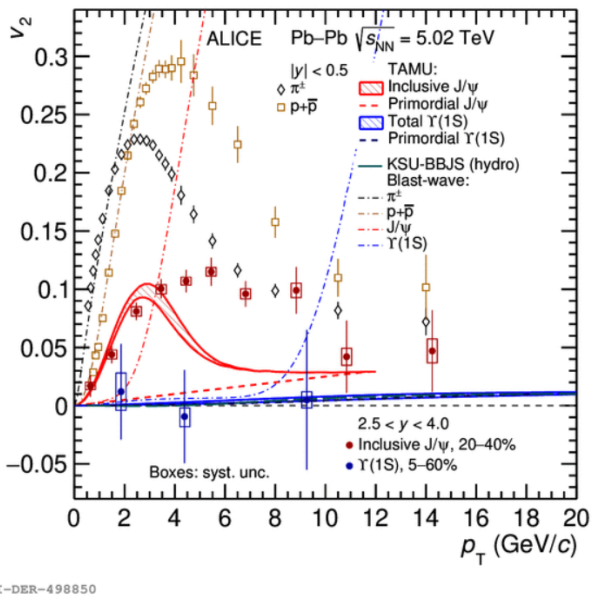
JHEP 05 (2016) 179



- Recombination appears at high energy collisions.
- mostly due to central/semi-central collisions.

b flow

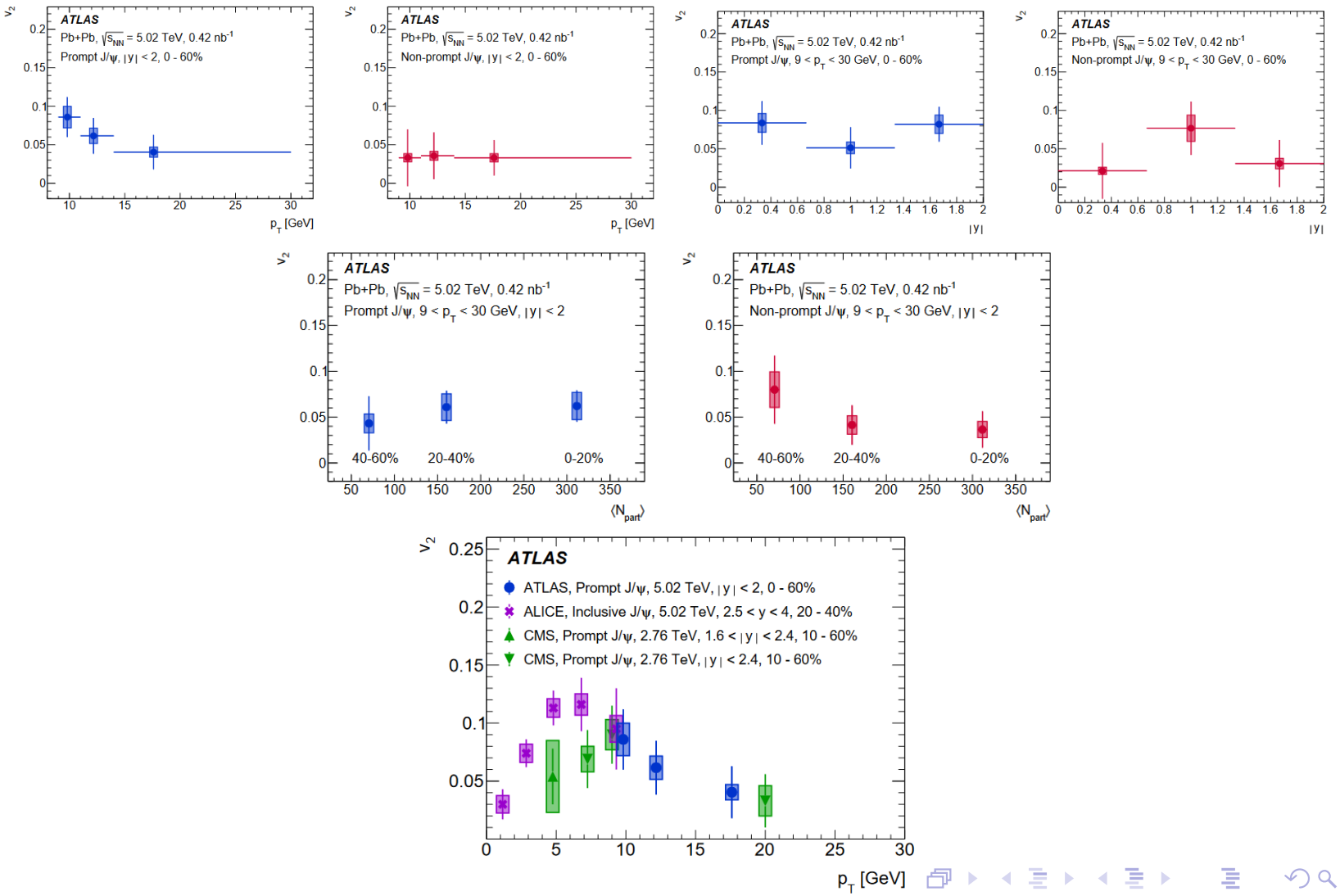
JHEP 05 (2016) 179



- $\Upsilon(1S)$ is not flowing.
- Non-prompt J/ψ seem not to flow as well.

ATLAS Elliptic flow results

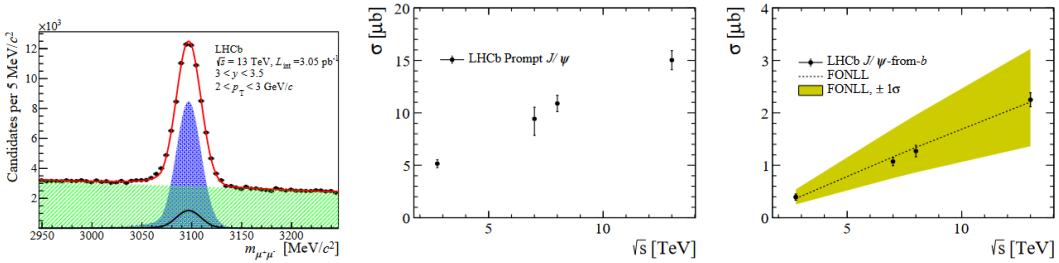
Eur. Phys. J. C 78 (2018) 784



LHCb Run 2 results

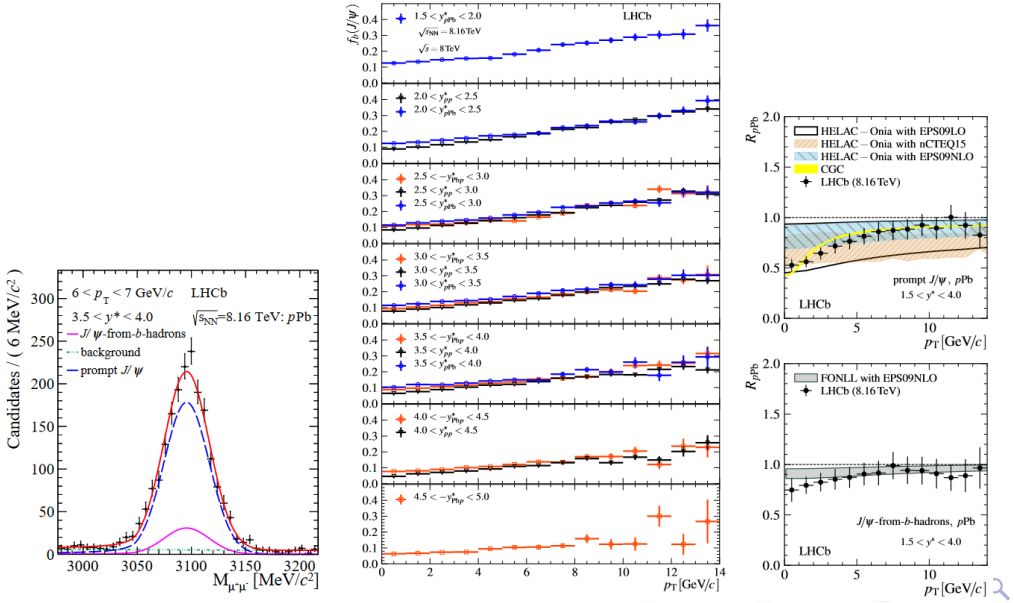
LHCb results for pp collisions :

- JHEP 10 (2016) 172



LHCb results for pPb collisions :

- Phys. Lett. B774 (2017) 159



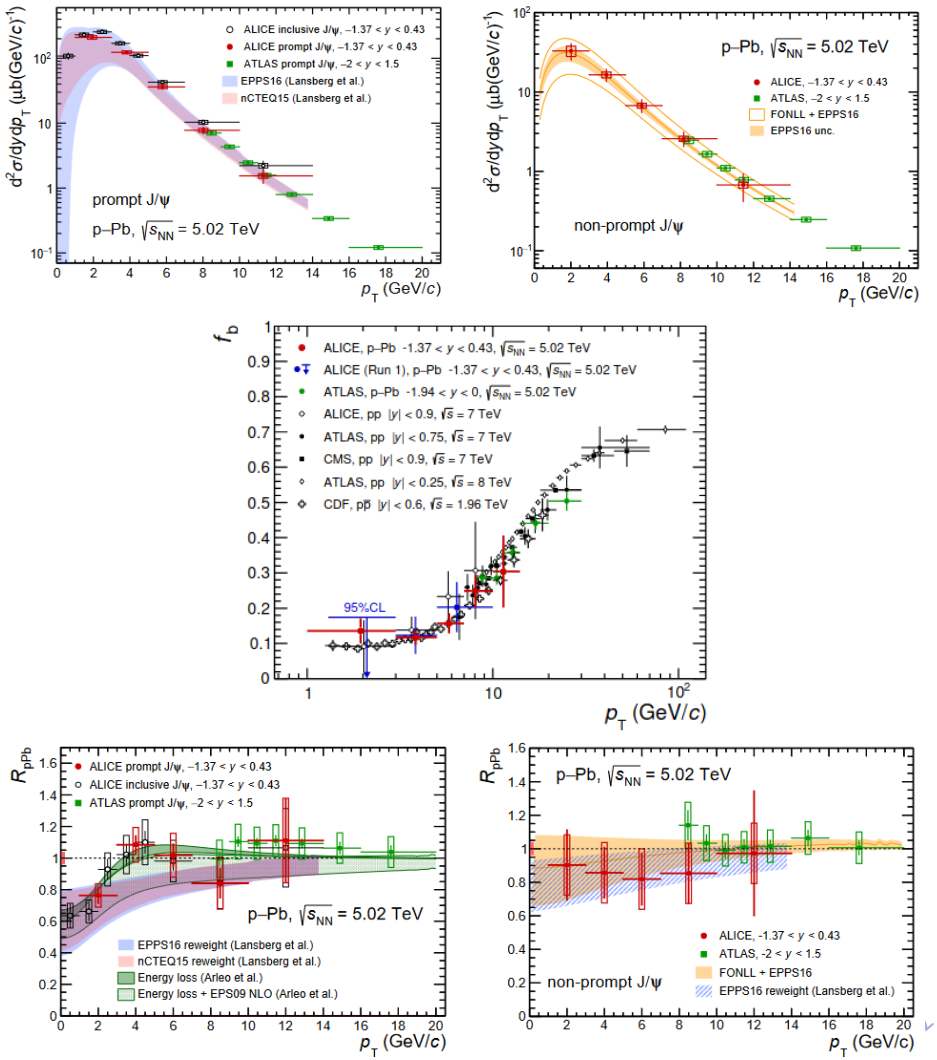
Run 2 analysis status already done

Prompt/Non-prompt Analysis					
Experiment	Collision	Channel	y range	p_T range (GeV/c)	Separation
LHCb	pp	$\mu^+\mu^-$	[2.0,4.5]	[0,14]	t_z
	pPb		[-5.0,-2.5] & [1.5,4.0]	[0,14]	
CMS	pp	$\mu^+\mu^-$	[-2.4,2.4]	[6.5,30]	t_z
	PbPb		[-2.4,2.4]	[6.5,30]	
ATLAS	pp	$\mu^+\mu^-$	[-2.4,2.4]	[1,70]	t_z
	PbPb		[-2.0,2.0]	[9,30]	
ALICE (Run 2)	pp	e^+e^-	[-0.9,0.9]	[1,15]	x
	pPb		[-0.9,0.9]	[0,14]	
	PbPb		[-0.8,0.8]	[1.5,10]	
ALICE (Run 3)	pp	$\mu^+\mu^-$	[-4.5, 4.0]	[0,20]	t_z
	pPb		[-4.5, 4.0]	[0,20]	
	PbPb		[-4.5, 4.0]	[0,20]	

ALICE Run 2 results in pPb for p_t distribution

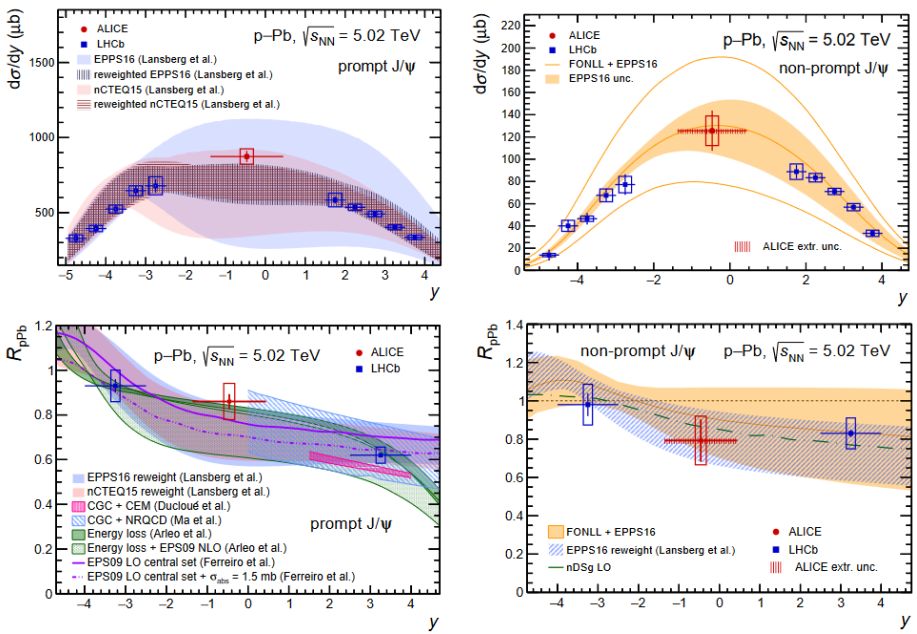
- Non-prompt ratio : All experiments seem to be in accordance. Lack of data for low and high p_t.
- Nuclear modification factor : In agreement with 0 for non-prompt.

arXiv:2105.04957



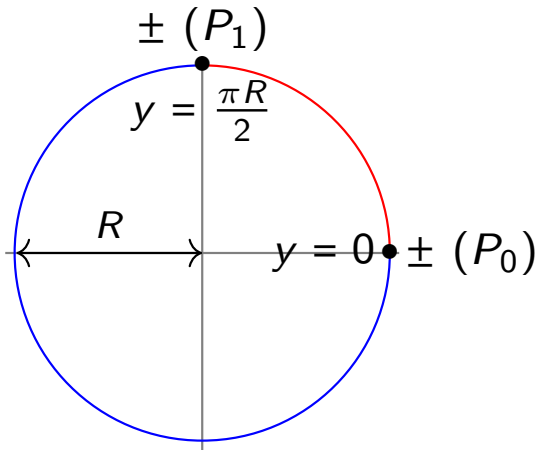
ALICE Run 2 results in pPb for y distribution

arXiv:2105.04957



- Central rapidity not enough bins.
- Could reduce forward rapidity value

Extra-dimension



Orbifold $S^1/\left(Z_2 \times Z_2'\right)$

- Compactification radius R
- 2 parity symmetries P_0 and P_1 at points $y = 0$ and $y = \frac{\pi R}{2}$.
- Boundary conditions $(P_0, P_1) = (\pm, \pm)$.

KK modes (Kaluza 1921 and Klein 1926)

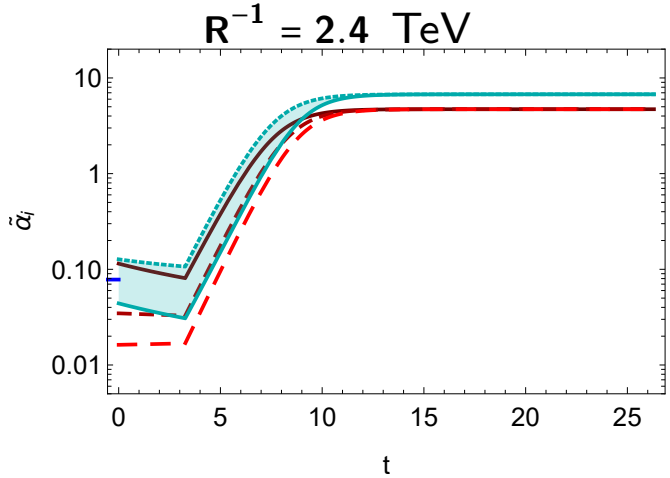
- 5D fields $\overset{Fourier}{\longrightarrow}$ Sum of 4D fields with masses $\frac{n}{R}$.
- Selection rules for vertices conserving the KK number.
- Only zero-modes $(+,+)$ are stable at EW scale → SM fields.

Yukawa sector

Top-Yukawa only scenario

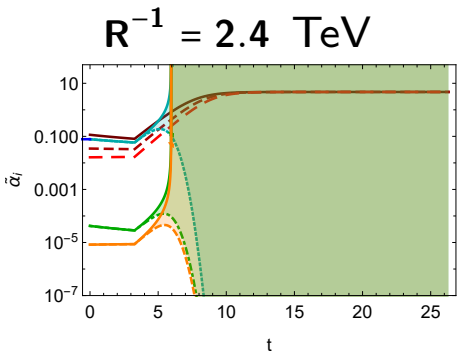
$$2\pi \frac{\mathrm{d}\alpha_t}{\mathrm{d}t} = 2\pi \frac{d\alpha_t}{dt}\bigg|_{\mathrm{SM}} + (S(t)-1)\left(15\alpha_t - \frac{114}{5}\alpha_5\right)\alpha_t$$

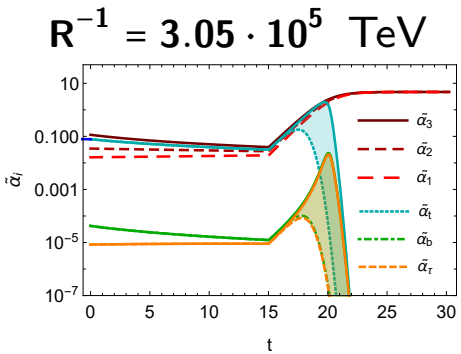
- A non-trivial UV fixed point : $\tilde{\alpha}_t^* = \frac{(41+40n_g)\pi}{75(13-4n_g)}$.



All heavy Yukawa scenario

- No non-trivial UV fixed point for all Yukawa.
- Asymptotically free behavior for $R^{-1} \gtrsim R_c^{-1} = 3 \cdot 10^5$ TeV.





Master eRG equation

$$\frac{dI_i}{dt} = \gamma_i I_i(t)\left[\left(1-\frac{I_i(t)}{a_i}\right)^2+\delta_0\right]^{p_0}\prod_{n=1}^{N}\left[\left(1-\zeta_n\frac{I_i(t)}{a_i}\right)^2-\delta_n\right]^{p_n}+\sum_j k_{ij}\left(I_j(t)-I_i(t)\right)+\delta$$

- Simplest eRG equation (a and γ can be time-dependent).
- Complex eRG : Complex fixed points → constant new cases (endemic phase).
- Multiwave eRG : Multiples waves with additionnal fixed points (a_i/ζ_n).
- Mutation eRG : Multiple independent equations for each mutation.
- Interactive eRG : k_{ij} number of travellers from region i to region j.
- Vaccination eRG : Effect of vaccination on a and γ.

$$\frac{\mathrm{d}a_i(t)}{\mathrm{d}t} = -\frac{\mathrm{d}R_i^v(t)}{\mathrm{d}t}\left(a_i(t)-I_i(t)\right), \quad \frac{\mathrm{d}\gamma_i(t)}{\mathrm{d}t} = -\frac{\mathrm{d}R_i^v(t)}{\mathrm{d}t}\gamma_i(t_0)$$