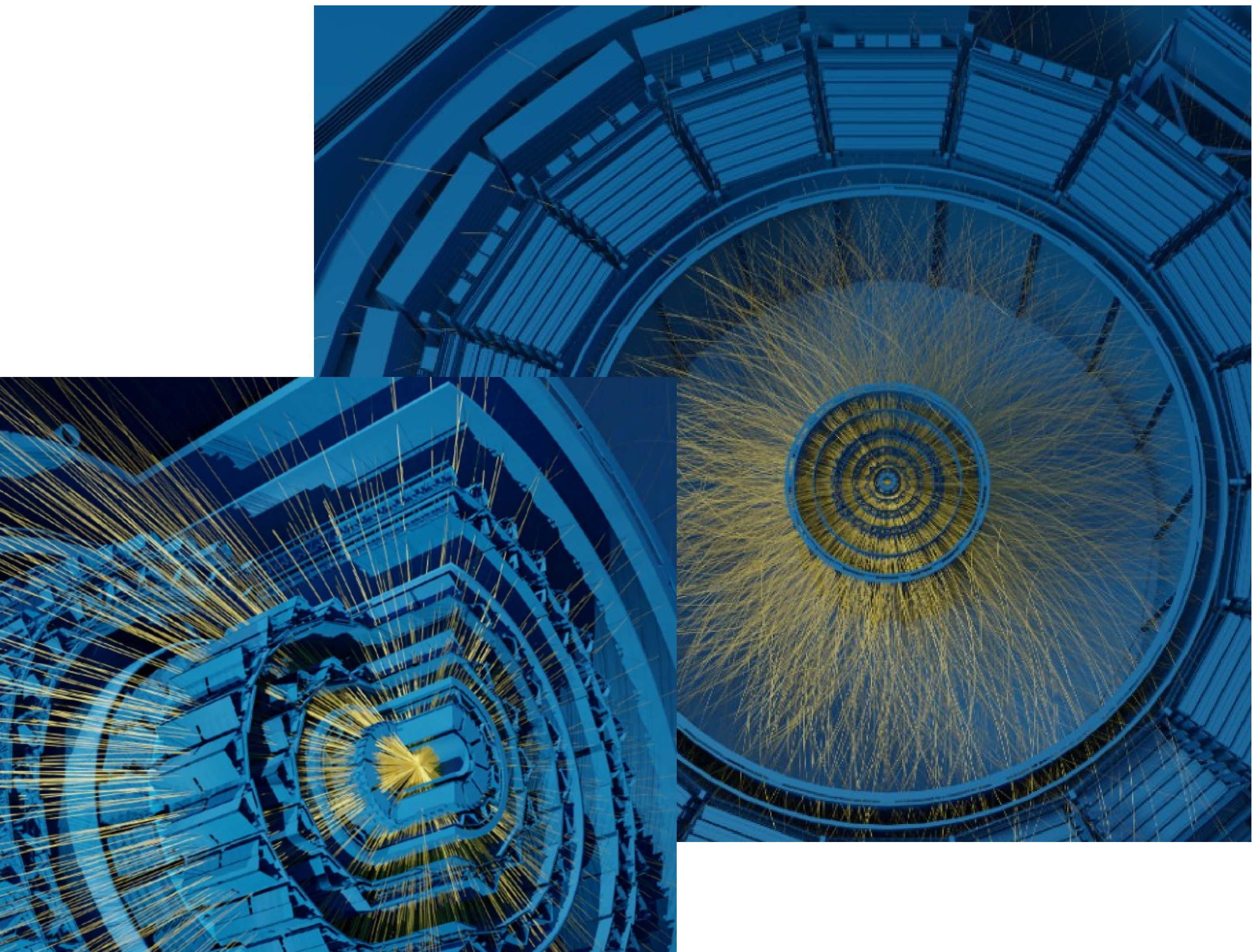
Antonin MAIRE, for the ALICE collaboration

Thursday, 25 Jan. 2024 – **Tuning hadron interaction model for cosmics**

https://indico.uni-wuppertal.de/event/284

ALICE bridging towards cosmic ray physics

identified-particle production



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Outline

A. ALICE$_1$ sub-detectors & data ...

B. .Selected results ...

C. Event activity estimators ..

D. Rivetisation effort ...

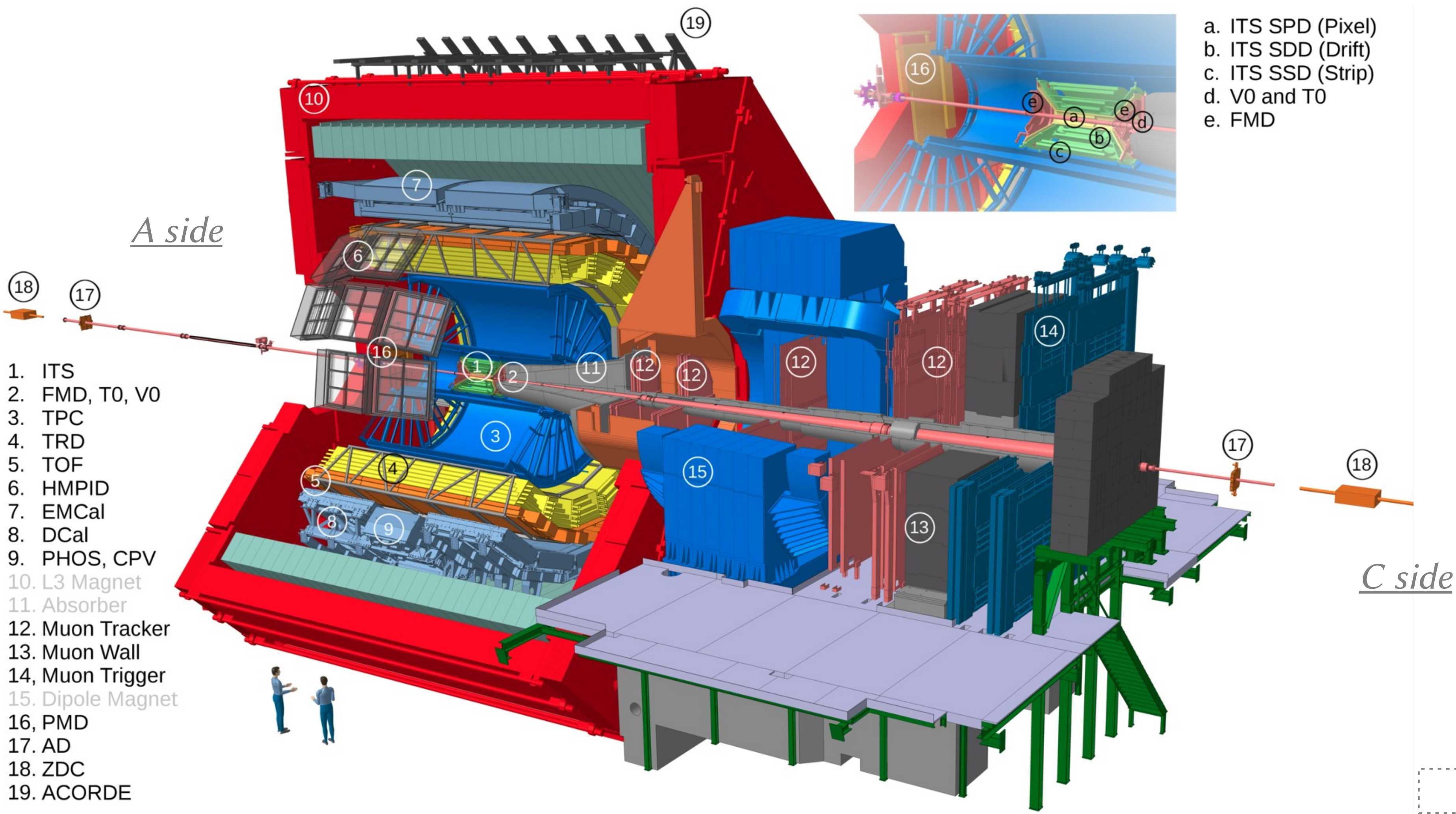
Disclaimer :

- I am not a calorimeter experimentalist...
  - ⟶ I may miss key ingredients in the air shower step
  - ⟶ will only address potential input for parts of the problem that may relate to MC event generators
- biased towards measurements of production rates :
  - identified particles : (u,d,s) + c quark sectors
  - y ≈ 0, rather than forward rapidities
  - low p_{T} : $0.1 < p_{\mathrm{T}} < 2\text{-}10$ GeV/c

Part A – ALICE detectors & data

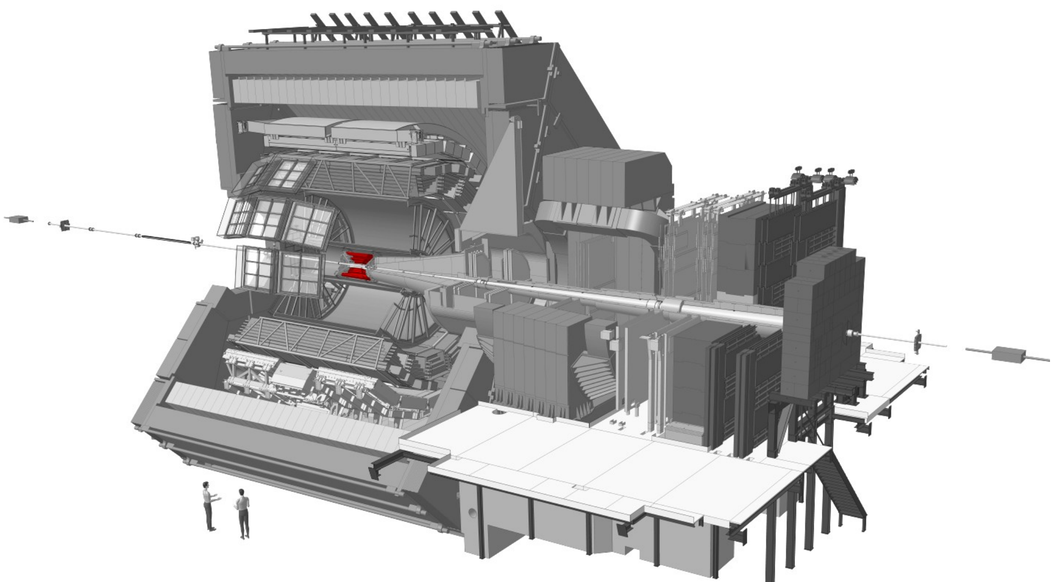
I.1 – ALICE[1] : detector layout

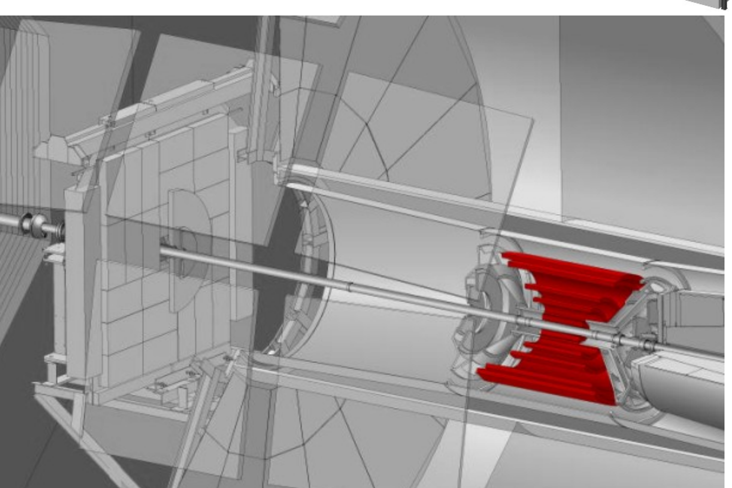
ALICE in run 2 = 20 active sub-detectors of various kinds
⟶ 2 main parts : i) forward y + ii) y ≈ 0



I.2.a – ALICE$_1$: central barrel, ITS

ALICE-PHO-SKE-2017-002





- **Inner Tracking System, ITS**

$|\eta_{ITS}| < 0.9$ at least / $p_T^{threshold} \sim 50$ MeV/c

2 layers = silicon pixels, SPD

(hybrid pixels : 50 x 425 μm^2)

2 layers = silicon drift, SDD

2 layers = silicon strips, SSD

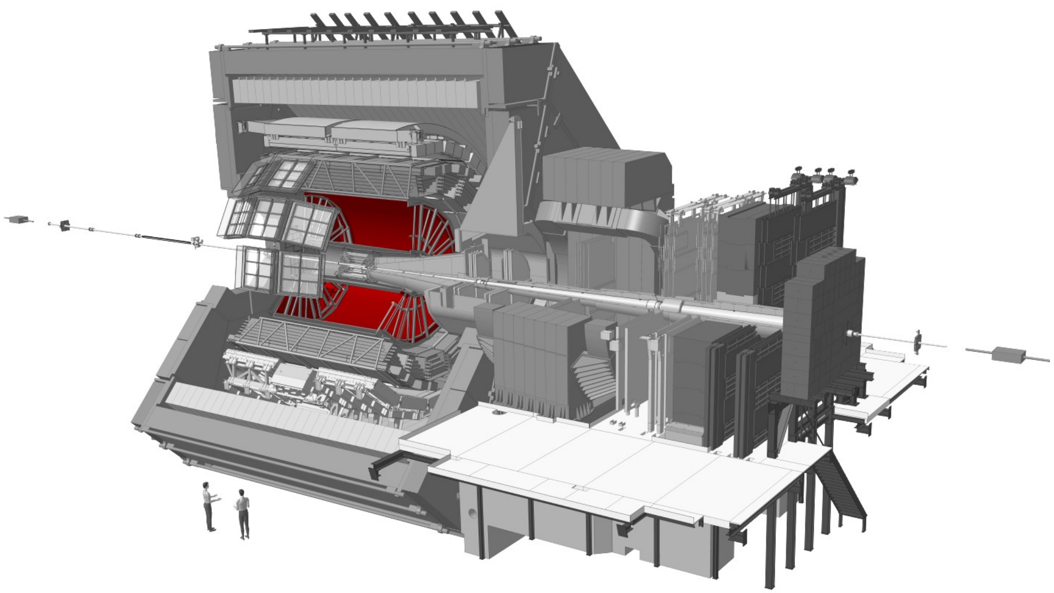
→ **trigger** (SPD)

→ **vertexing, tracking** (SPD, SDD, SSD)

→ **PID (d*E*/d*x*)** (SDD, SSD)

I.2.b – ALICE$_1$: central barrel, TPC

ALICE-PHO-SKE-2017-002



- **Time Projection Chamber, TPC**

$|\eta_{TPC}| < 0.9$

$p_T^{threshold} \sim 150$ MeV/c

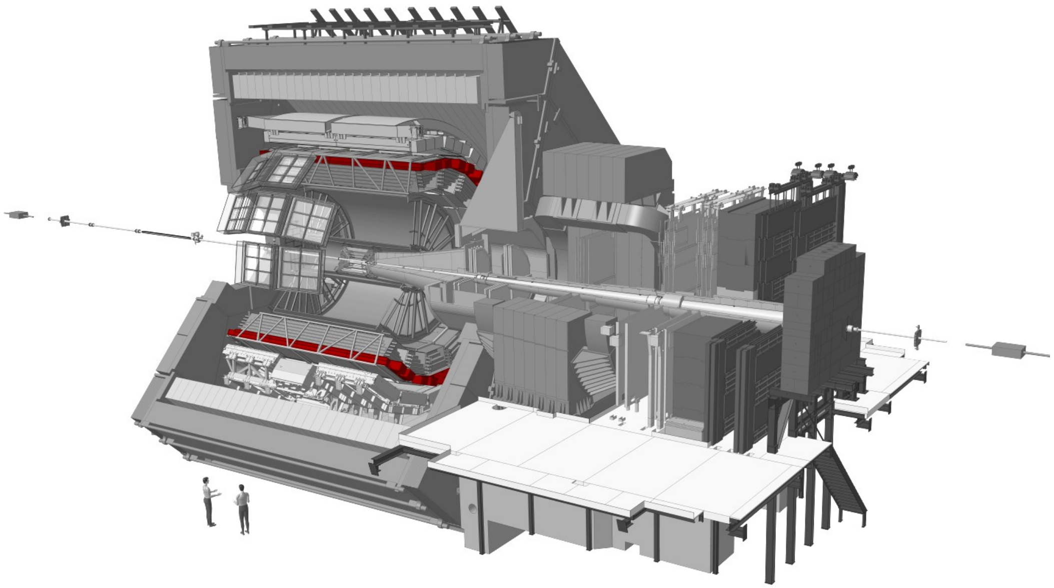
Ne-CO_2-N_2 or Ar-CO_2 gas in active volume

→ **tracking**

→ **PID (dE/dx + relativistic rise dE/dx)**

I.2.c – ALICE$_1$: central barrel, TOF

ALICE-PHO-SKE-2017-002



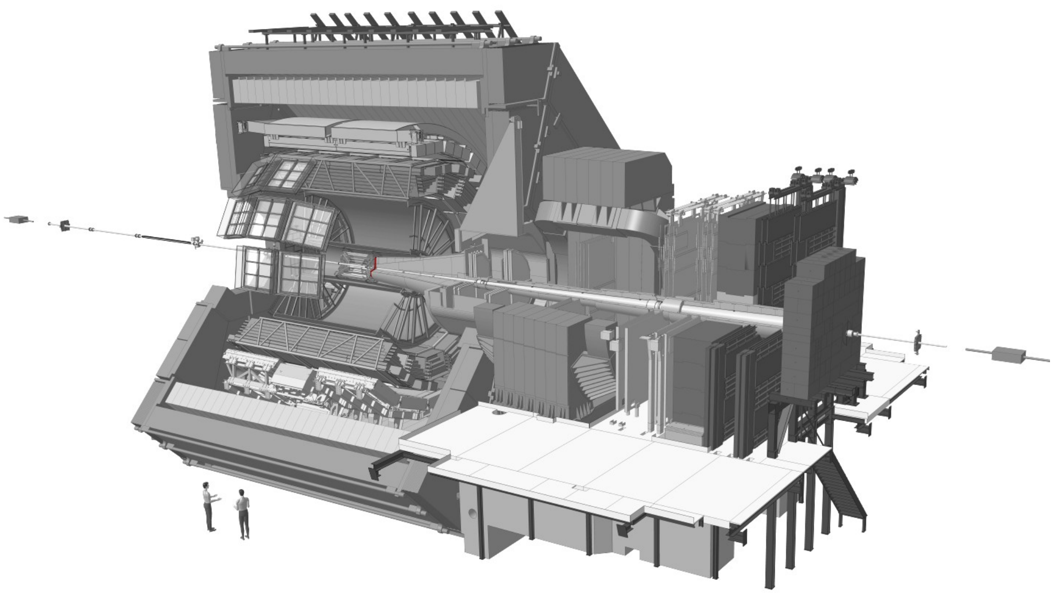
- **Time Of Flight, TOF**

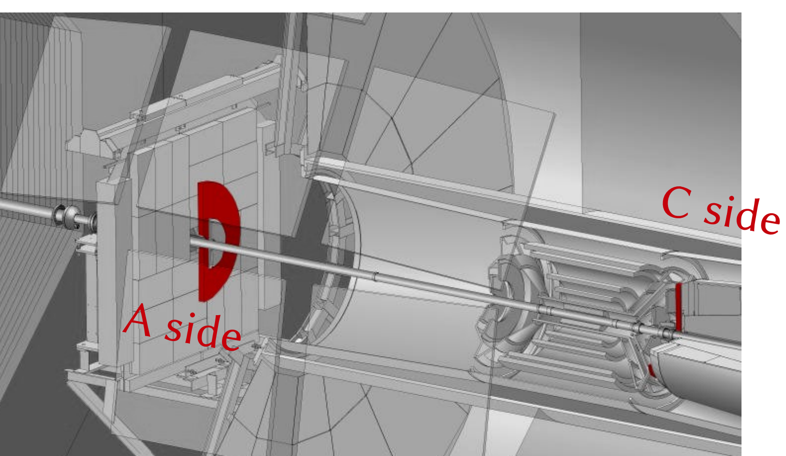
$|\eta_{TPC}| < 0.9$
$p_T^{threshold} \sim 300$ MeV/c
Resistive Plate Chamber

→ $\boldsymbol{t^0}$ of the event
→ **pile-up** rejection (offline)
→ **PID (ToF)**

I.2.d – ALICE$_1$: forward, VZERO

ALICE-PHO-SKE-2017-002





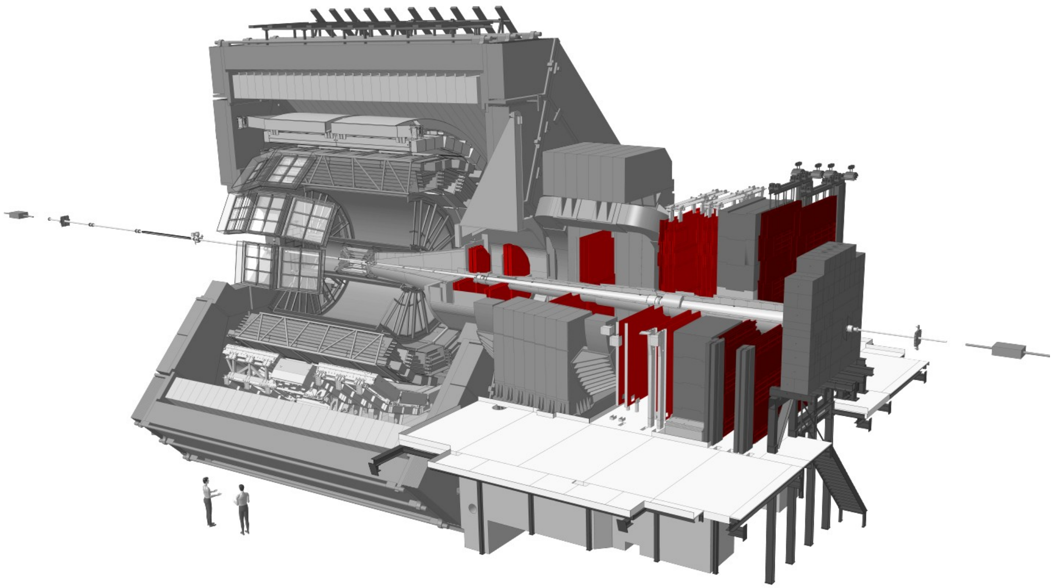
- **VZERO or V0**

V0C = -3.7 < η < -1.7
V0A = +2.8 < η < +5.1
forward arrays of scintillators

→ **event activity :**
Online trigger
(Min Bias + Pb-Pb centrality + high-mult. pp)
Offline use
(activity in Pb-Pb, p-Pb, pp)
→ **event selection :**
physics vs beam-gas identification
→ **event charac. :**
event plane + ref. flow vector (Pb-Pb)

I.2.e – ALICE$_1$: forward, muon chambers

ALICE-PHO-SKE-2017-002



- **μCH and μID**

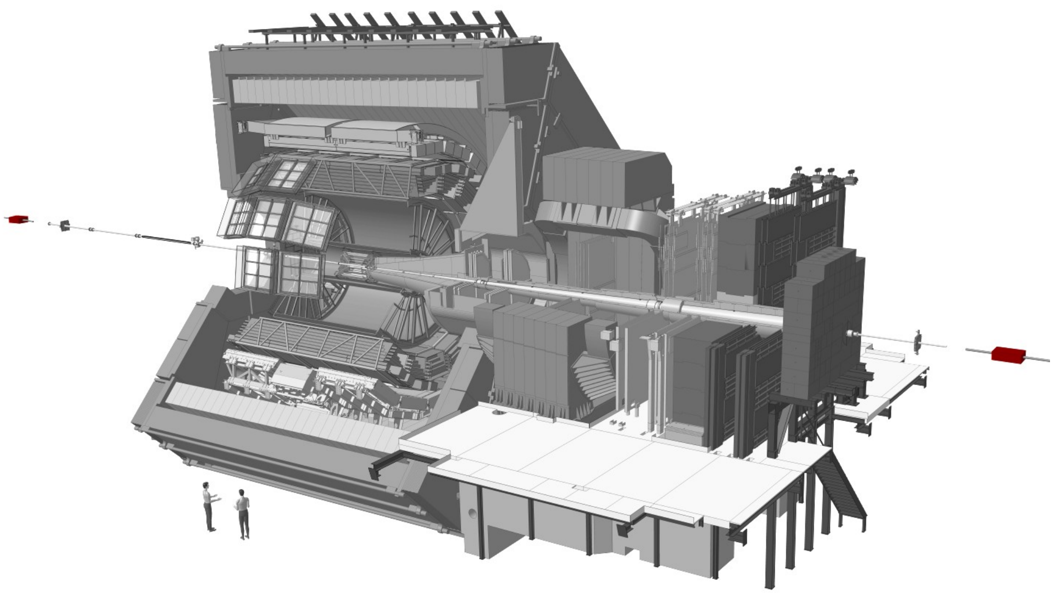
-4.0 < η < -2.5
Muon Chambers = MWPC for tracking
Muon ID = RPC for triggering

→ **single- or multiple-muon identification**
beyond :
i) a hadron absorber, μCh
ii) an iron wall, μID

I.2.f – ALICE$_1$: forward, ZDC

ALICE-PHO-SKE-2017-002

ALICE JInst, doi:10.1088/1748-0221/3/08/S08002



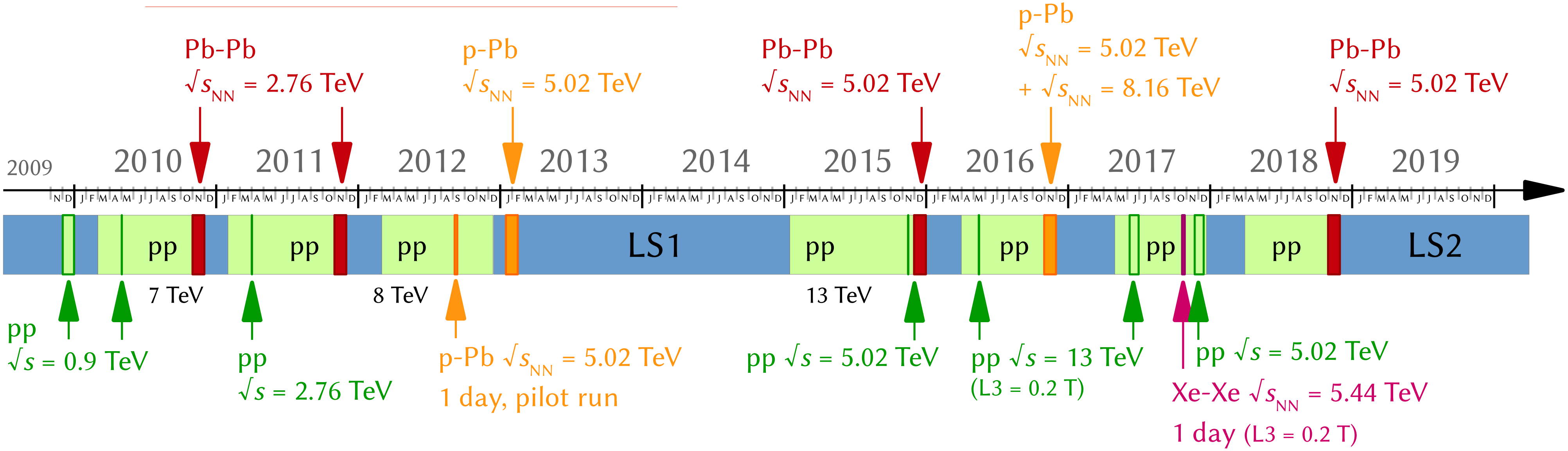
- **ZERO Degree Calorimeters, ZDC**

$z \approx +7.3$ m ($+4.8 < \eta < +5.7$)
ZEM = Pb+quartz for photons
(for distinction between UPC
and low peripheral collisions)

$z \approx \pm 113$m
ZN ($|\eta| > 8.7$, full azimuth)
= tungsten+quartz for neutrons
ZP ($7.8 < |\eta| < 12.9$ in pp 13 TeV)
= brass-quartz for protons

⟶ used in Pb-Pb, Xe-Xe, p-Pb, Pb-p...
but also in some periods of pp 13 TeV
2015, 2017, 2018
(pp ≈ 130.10^6 pp evts in total)

II.1 – ALICE : ALICE$_1$ campaigns in LHC runs 1+2



ALICE objectives for Runs 1+2 :
- 1 nb^{-1} in Pb-Pb + "track-equivalent" $\mathscr{L}_{int}$ in pp
- pp campaigns at reference $\sqrt{s}$
- p-Pb campaigns

Remark (~for pp) : delivered Vs. inspected Vs. recorded luminosity

e.g. LHC-delivered $\mathscr{L}_{int}$ pp for 2018 (*bpt.web.cern.ch/statistics*) :

CMS (ATLAS) ≈ 66 440 (64 771) pb^{-1} Vs. LHCb ≈ 2446 pb^{-1} Vs. ALICE ≈ 27,19 pb^{-1}

⟶ ALICE = [physics at the event level] ≠ [physics for particles ~independently of the event]

⟶ specific data taking strategy (campaign planning + $\mathscr{L}_{instantaneous}$ leveled at ≈ 2.6 10^{30} cm^{-2}s^{-1}) ...

ex : pp pile-up (2015-2018) $\mu_{ALICE} \leq 0.02$ // μ_{CMS} (40-60)

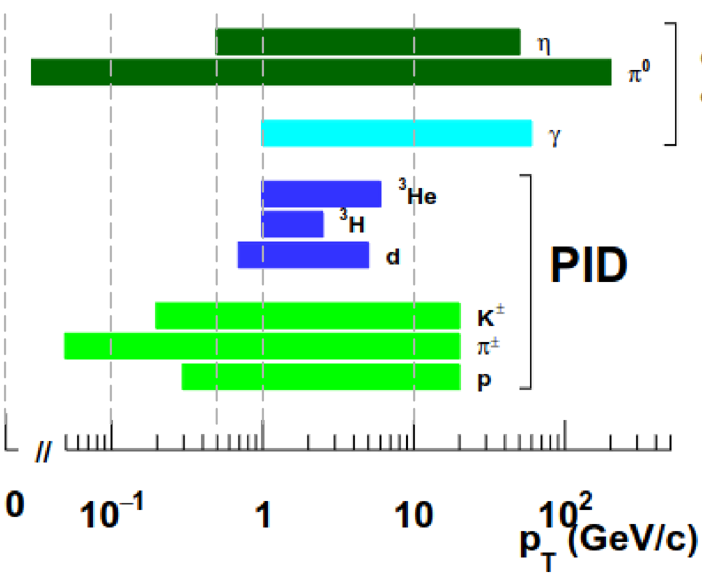
Part B – Selected set of results

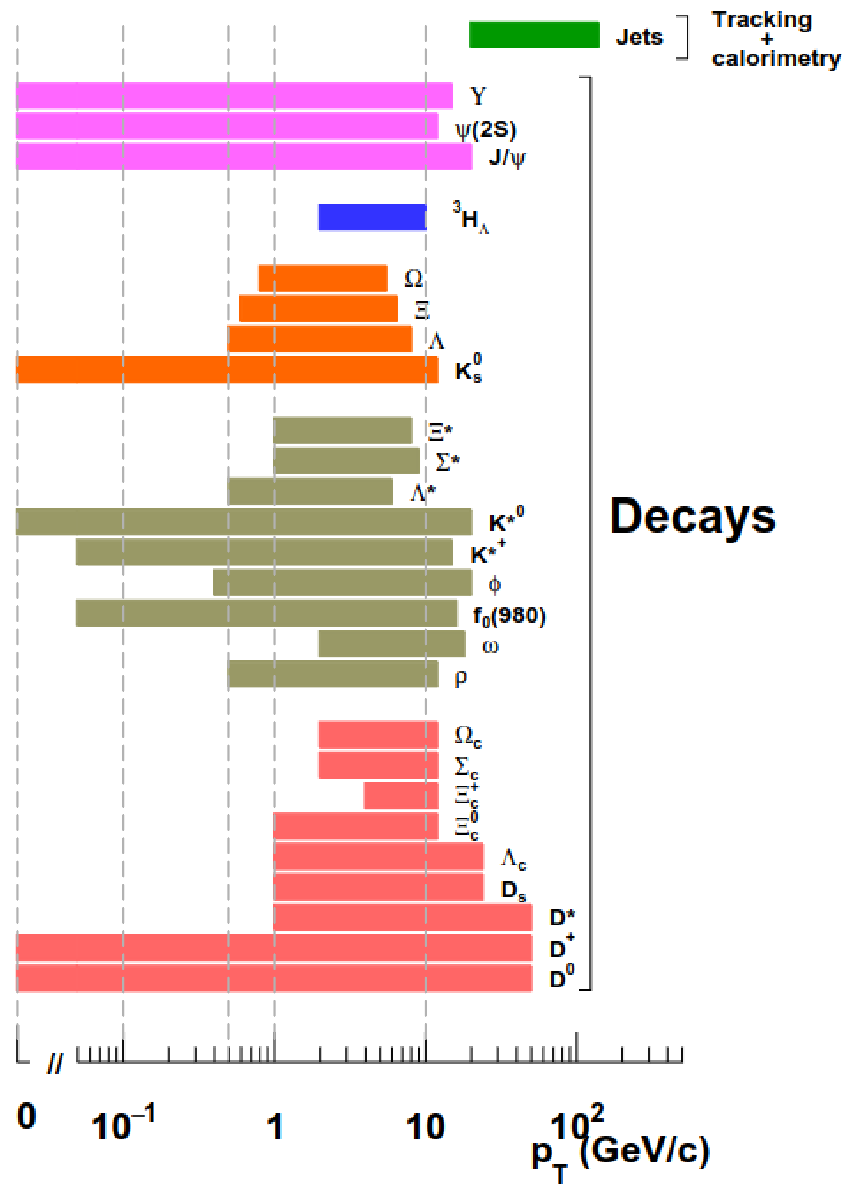
III.1 – Landscape : particle identif° via detector + via inv.-mass

pp, p-Pb, Pb-p, Xe-Xe, Pb-Pb ($^{129}Xe^{54+}$, $^{208}Pb^{82+}$) …

- Barrel $|\eta| < 0.9$
  → Rapidity coverage ? **$|y| < 0.5$** chosen
  for mostly any identified particle here in the table

- Forward particles that decay into ($\mu^{\pm}$)
  - some light flavour resonances [ω, ϕ(1020)]
  - quarkonia [J/ψ, ψ(2S), Υ(nS)]
  - single μ decay from open charm/beauty, HFμ

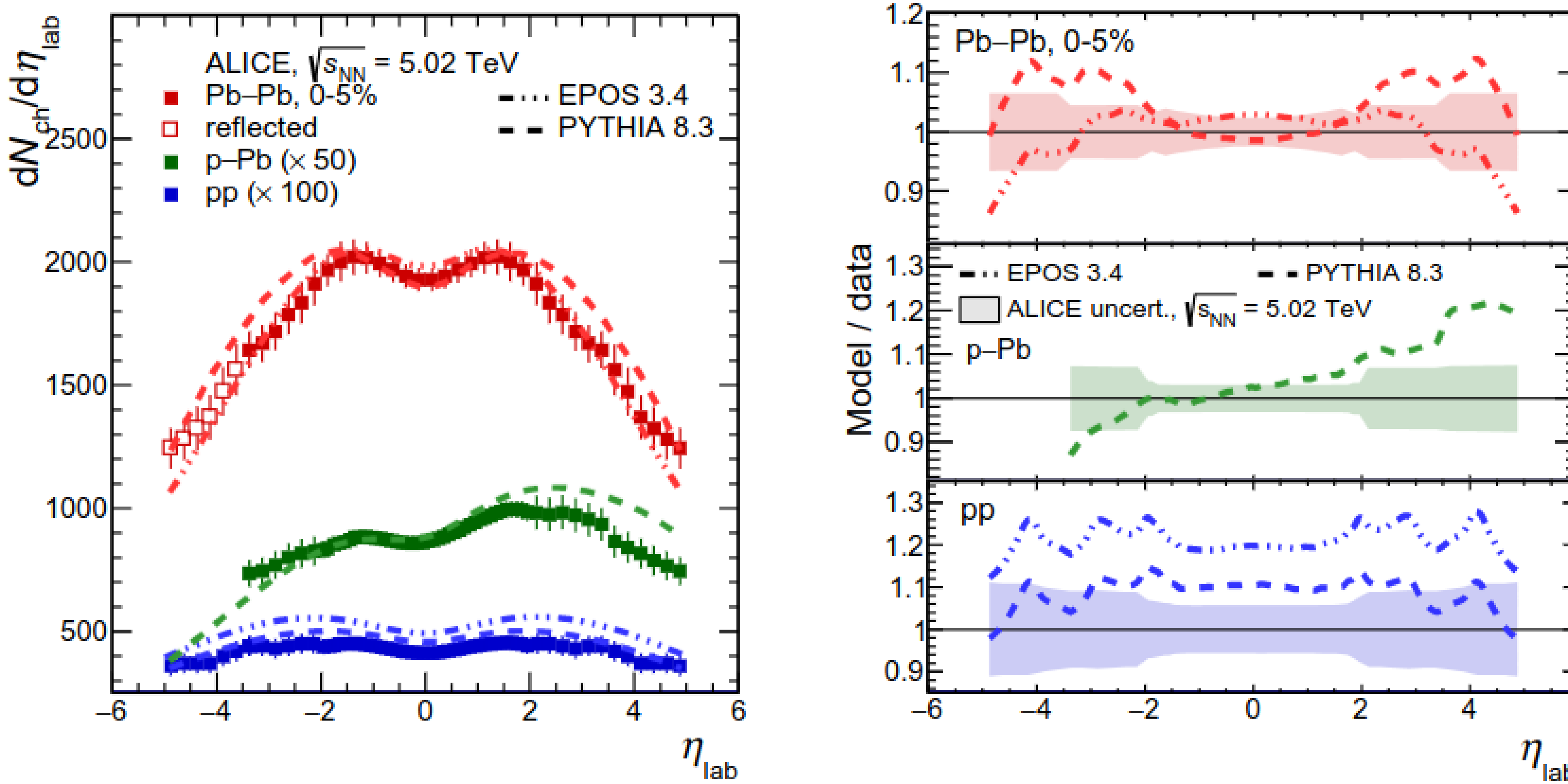




ALICE White paper, Fig.9, arXiv:2211.04384

III.2 – Landscape : $dN_{ch}/d\eta = f(\eta)$, over "large" η range

ALICE White paper, Fig.12, arXiv:2211.04384



NB: **Pb-Pb curve**

- $dN_{ch}/d\eta$ (0-5%, $\eta \in [0.0;0.25]$) = 1929 ± 46
- Integration over (p_T, $|\eta| < 8.6$) : N_{ch} (0-5%) = 21490 ± 1460

  (30% extrapolated in the $|\eta|>5$ tails, without beam remnants)

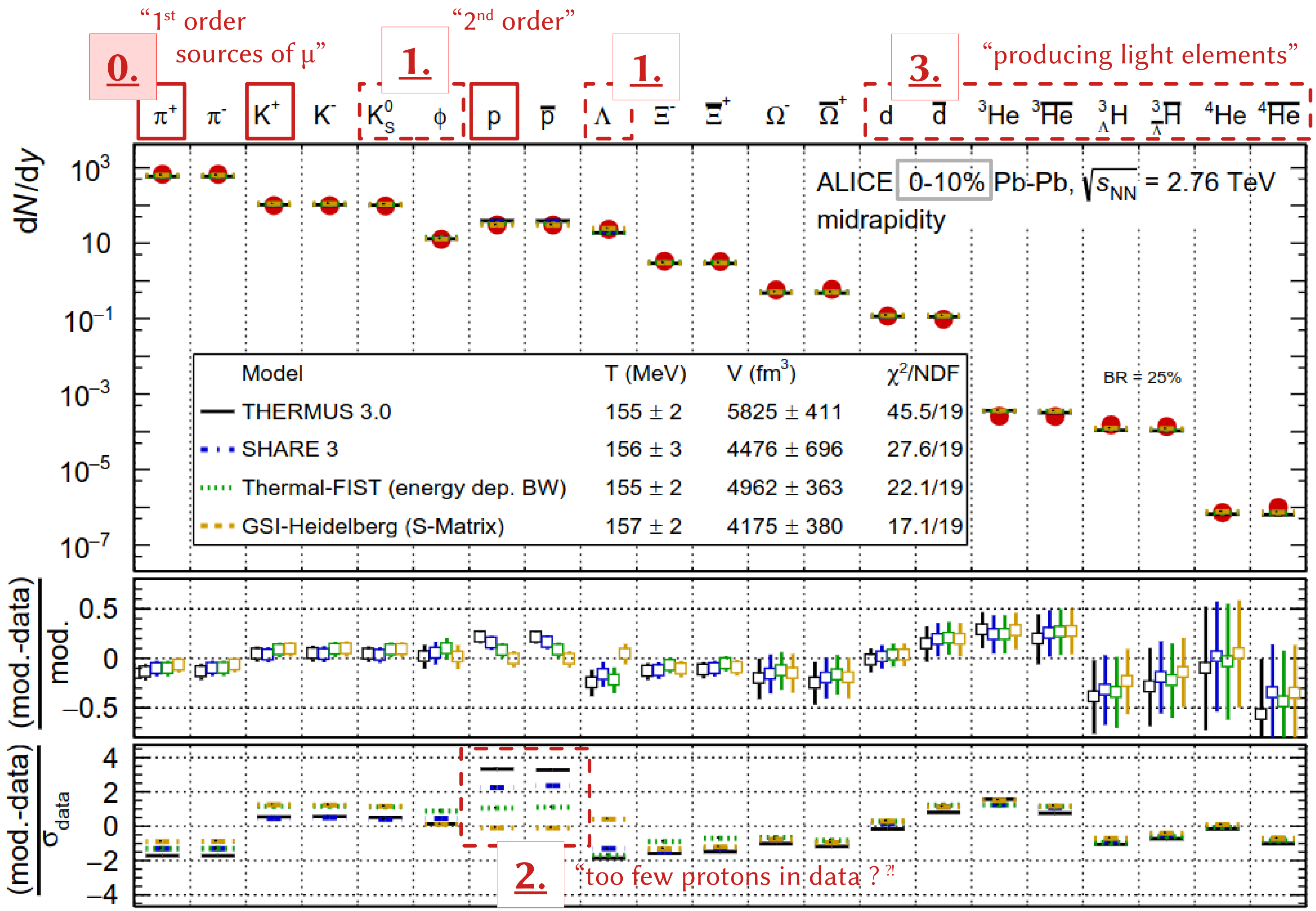
(→ Numbers from *arXiv:1612.08966*)

III.3 – Landscape : p_T-integrated overview at mid-rapidity …

$\int_{p_T=0}^{\infty} d^2N/dp_T dy$ = *corrected* dN/dy per Pb-Pb event

⟶ Very good agreement [*prompt* species] Vs [Statistical Hadronisation Model (SHM)]

SHM assumes *chemical* equilibration at hadronic chemical *freeze-out*, in a *(grand-)canonical* ensemble



ALICE White paper, Fig.33 arXiv:2211.04384

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV (0-5%)

arXiv:1303.0737

$dN_{ch}/d\eta$ = 1601 ± 60

Vs identified *prompt* pop°

π^+	733	±	54
π^-	732	±	52
K^+	109	±	9
K^-	109	±	9
p	34	±	3
p̄	33	±	3
	1750	±	130

0. "1st order"

i.e. $\pi^\pm$, $K^\pm$, $p^\pm$ ≈ already 100% of the N_{ch} picture

arXiv:1307.5530

K^0_s	110	±	10
Λ	26	±	3

arXiv:1404.0495

φ(1020) 13.8 ± 1.8

1. "2nd order"

III.3 – Landscape : p_T-integrated overview at mid-rapidity …

$\int_{p_T=0}^{\infty} d^2N/dp_T dy = dN/dy$ per pp event

Same picture desired in pp 2.76 TeV, 5.02 TeV, 7 TeV and/or 13 TeV …

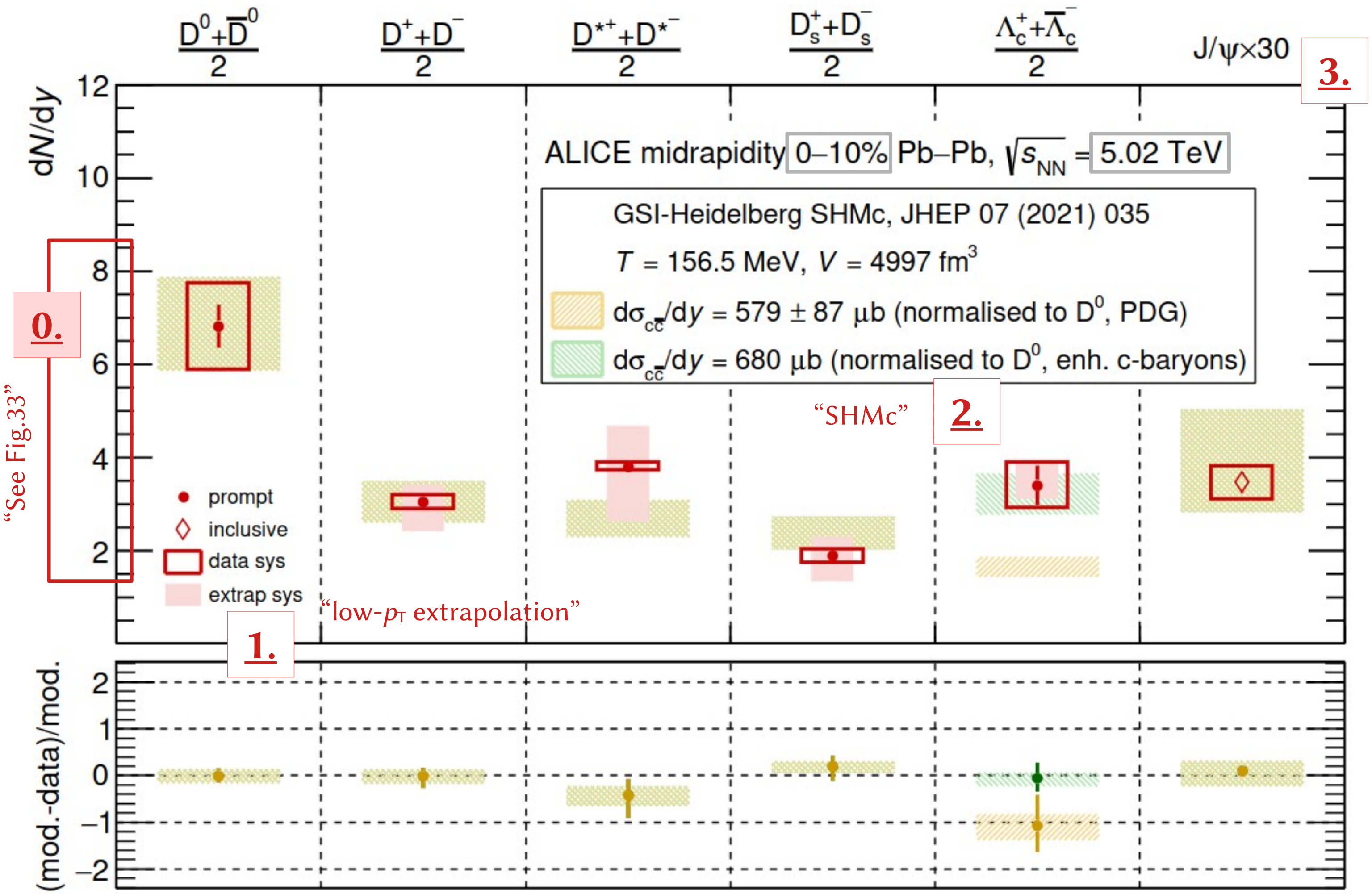
1. ALICE data dN/dy are measured and there, still to be plotted
   - dN/dy orders of magnitude will of course change dramatically
   - but the relative abundancies π,K,p will remain in the same ballpark

     i.e. $\pi^{\pm}/N_{ch} \approx$ 84-85%
     $K^{\pm}/N_{ch} \approx$ 12-15%
     $p^{\pm}/N_{ch} \approx$ 4-5%

2. SHM in pp ? "Any expectation ?" :
   - "SHM assumes *chemical* equilibration at hadronic chemical *freeze-out*, in a ~~(grand-~~)*canonical* ensemble"
   - SHM canonical ensemble is a must
   - SHM will perform less well (χ^2/NDF will rise)
     but will likely catch the orders of magnitude
     with $T_{pp} \approx T_{PbPb} \pm$ 2-4 MeV

III.4 – Landscape : SHMc and Heavy flavours

“J/ψ ≈ recombination/~~suppression~~”

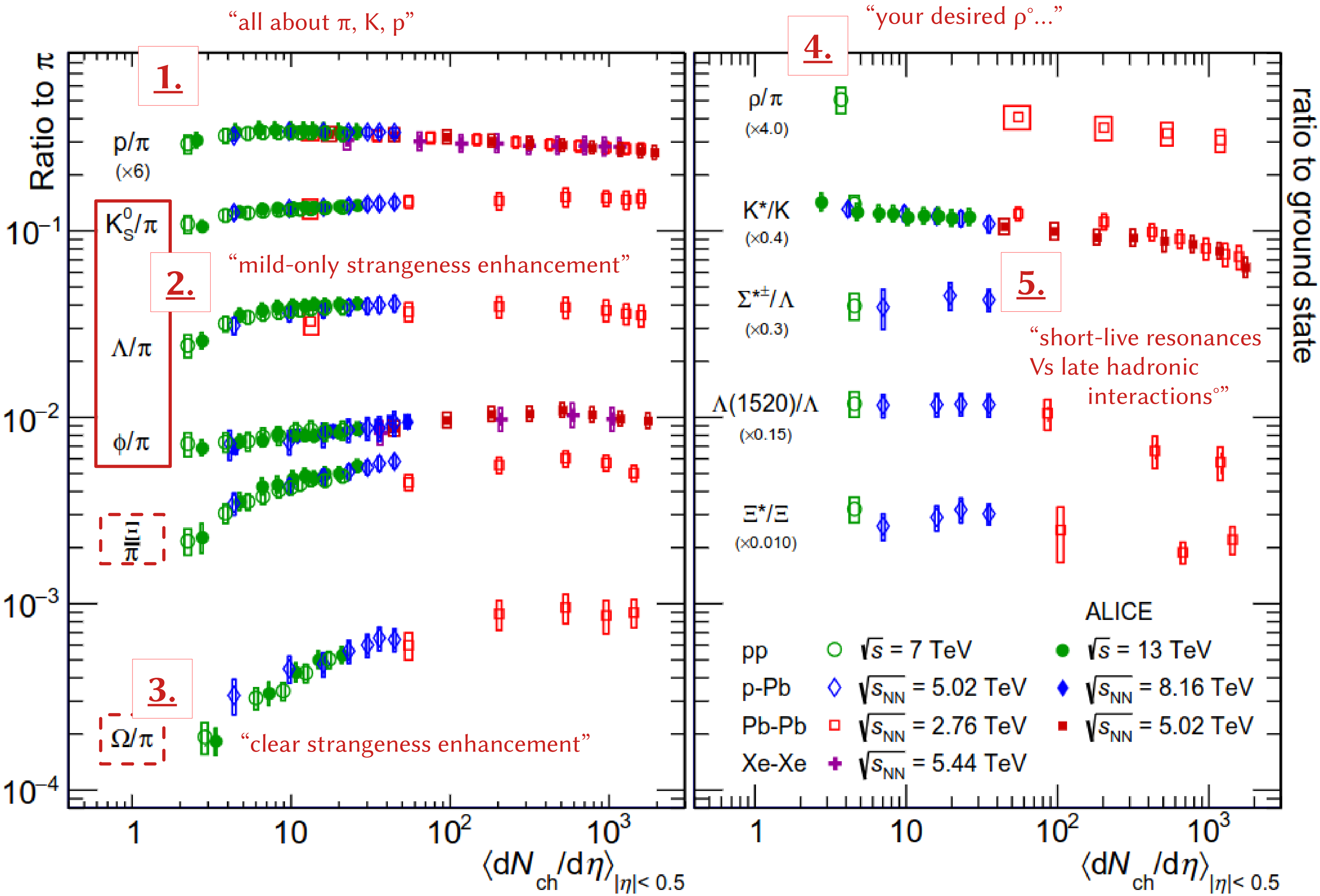


$c+\bar{c}$ produced
before QCD medium,
in the initial
hard scatterings
(T_{medium} too low
to create on-shell $c+\bar{c}$)

But $c+\bar{c}$ may see
each other /
u,d,s quarks around
and
hadronise statistically…

ALICE White paper, Fig.34, arXiv:2211.04384

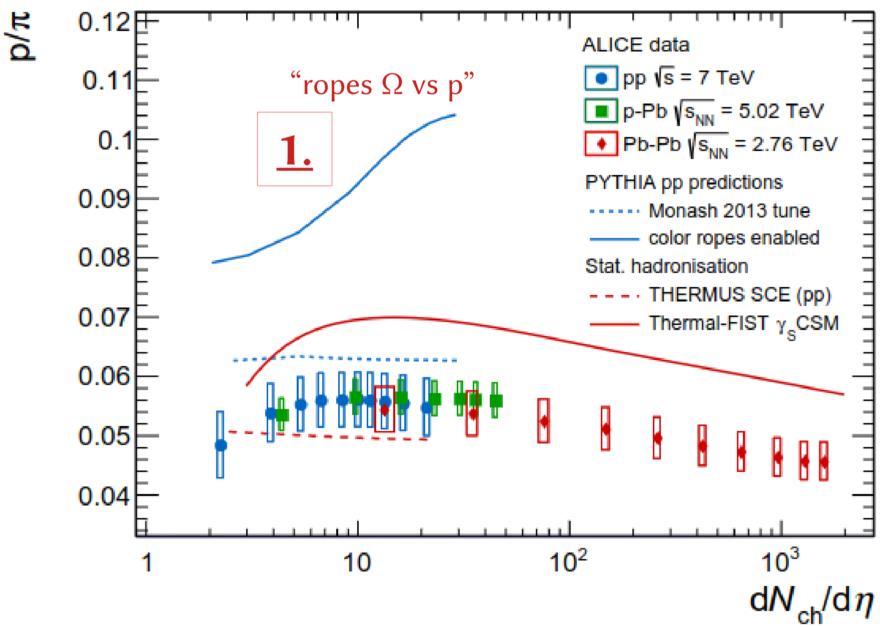
IV.1 – N_{ch} dependence : ratio to $\pi^{\pm}$, ratio resonance/gnd state .

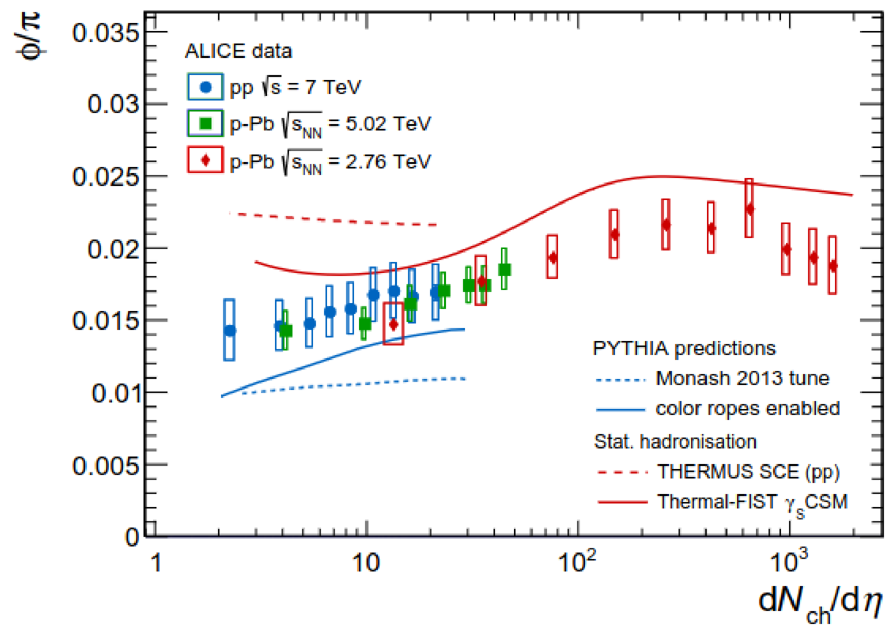


$\rho(770)^0$ (τ = 1.3 fm/c)
$K*(892)^0$ (τ = 4.16 fm/c)
$\Lambda(1520)$ (τ = 12.6 fm/c)
...
$\phi(1020)$ (τ = 46.3 fm/c)

ALICE White paper, Fig.79, arXiv:2211.04384

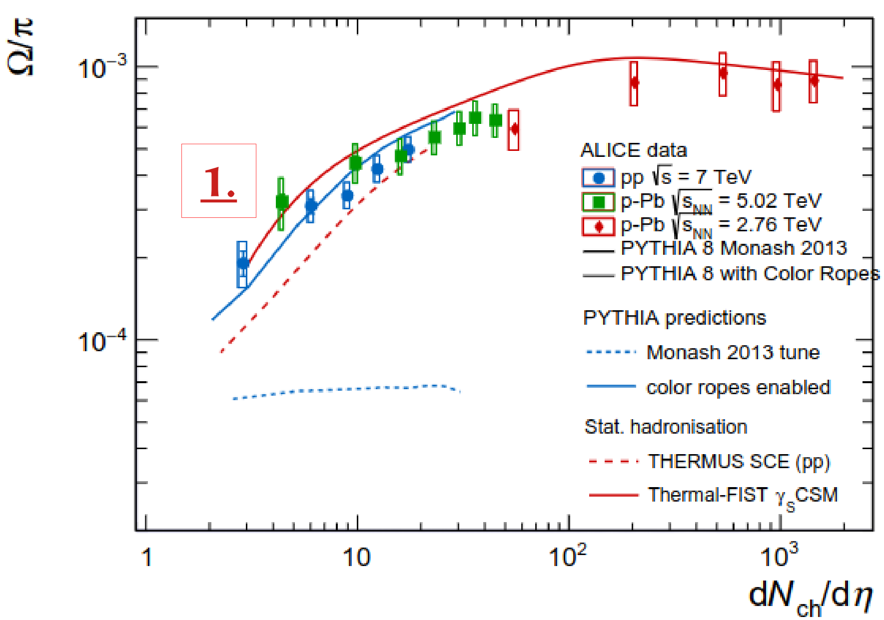
IV.3 – N_{ch} dependence : some comparison to MC generators

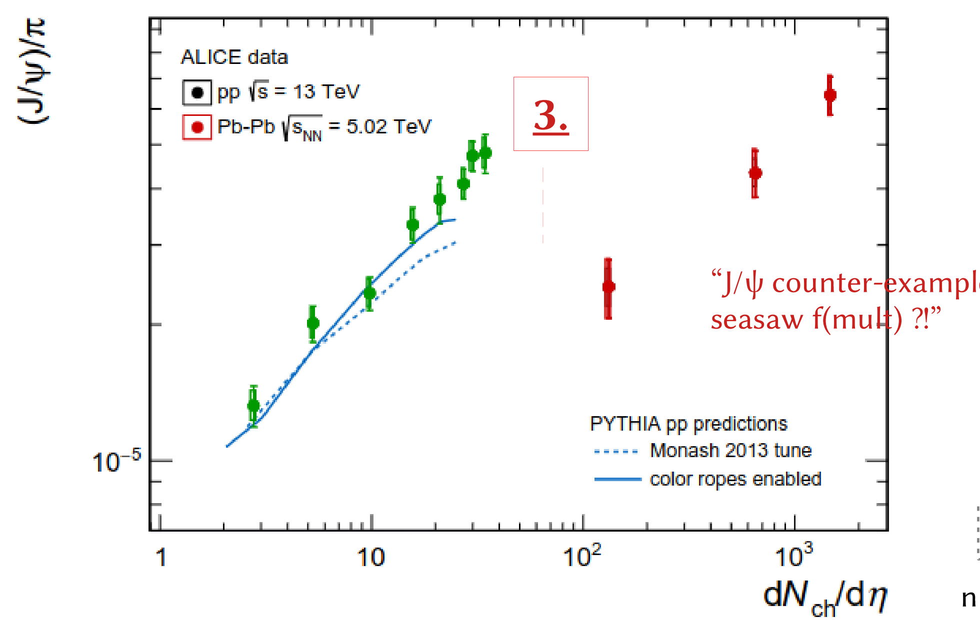




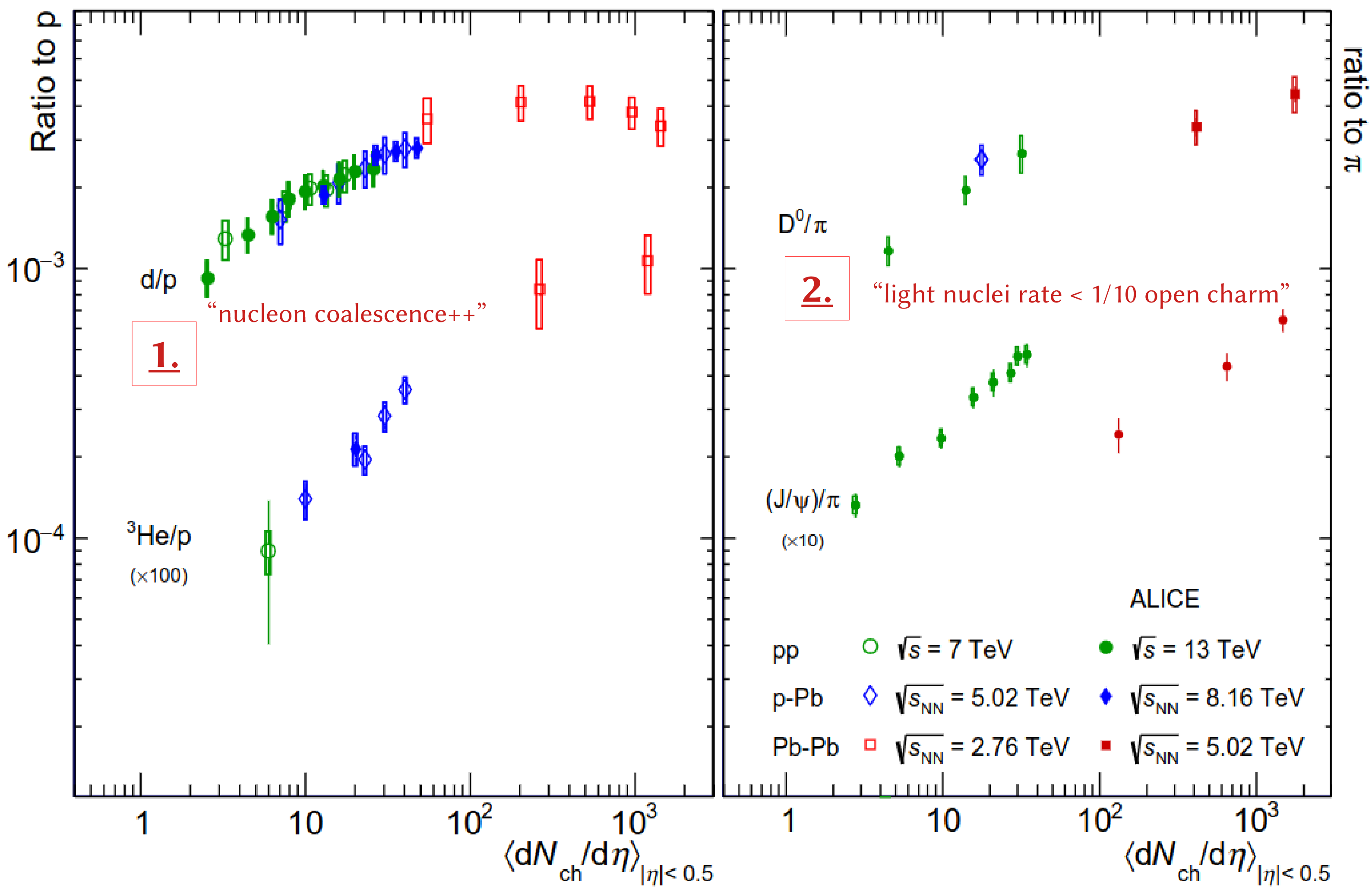
2.

“ϕ(1020) to π ≈ 1-2%.... ϕ(1020)/K± ≈ 12-15%”



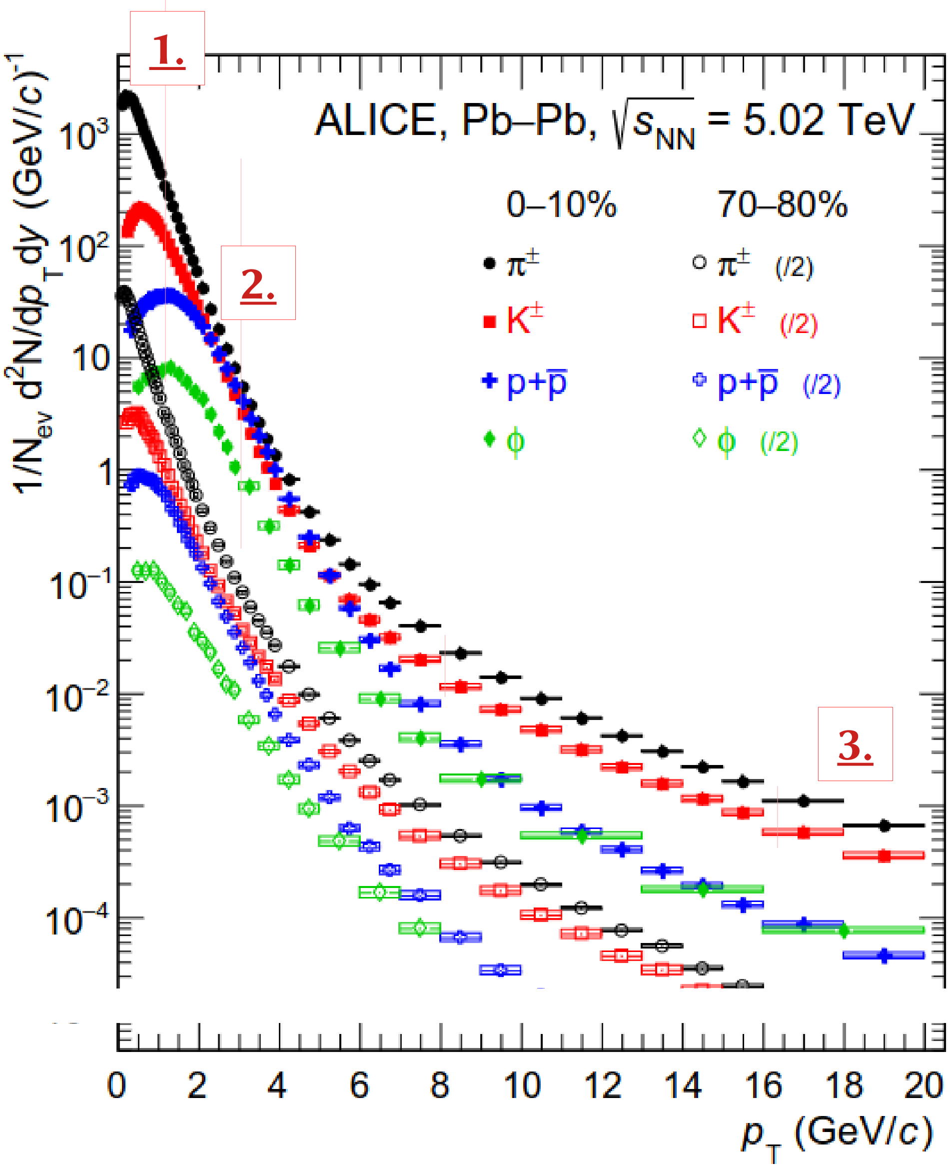


IV.2 – N_{ch} dependence : light nuclei and charm ratios



ALICE White paper, Fig.80, arXiv:2211.04384

V.1 – Remarks : the upheaval with the p_T dependence



ALICE White paper, Fig.35, arXiv:2211.04384

1. • Where does lay most of the production ?
≈ ∀ LF species, 95% of dN/dy sits at $p_T < 2$ GeV/c

• Beware :
the order of magnitude of d^2N/dp_Tdy

the hierarchy among species $f(p_T)$

the reorganisation among p_T domains
for a given species

⟶ behind the "$\int p_T$ scene",
production ratios = $f(p_T)$!

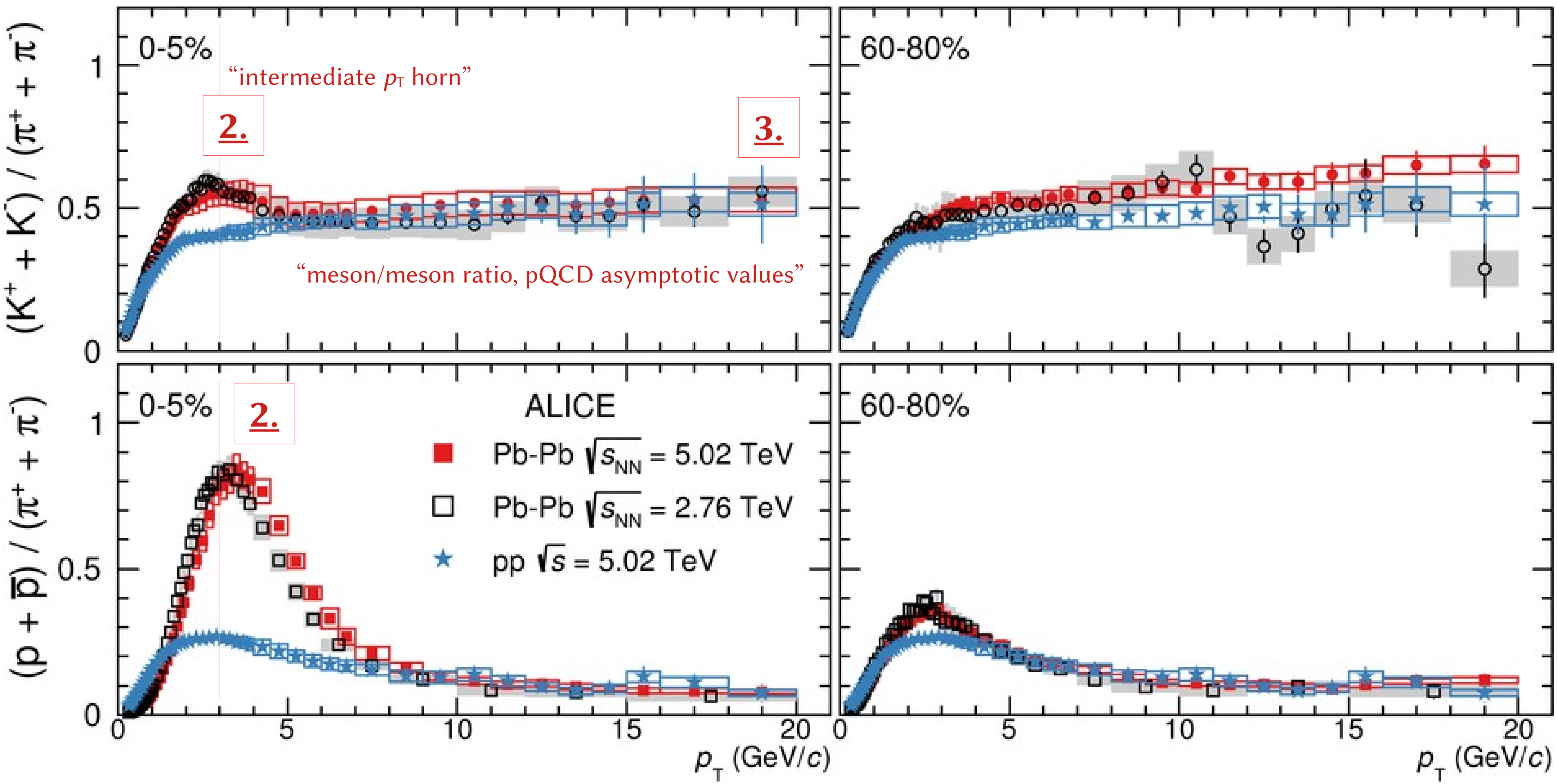
e.g.

2. [p > K] and [p ≈ π], at $p_T \approx 3$ GeV/c

3. K/π ≈ asymptotic value at $p_T > 5$-6 GeV/c
Similarly, ϕ(1020)/K, flatens out ...

V.2 – Remarks : the upheaval with the p_T dependence

arXiv:1910.07678



For $\phi(1020)/K = f(p_T)$ or $\phi(1020)/\pi = f(p_T)$, see Fig.7 in arXiv:1702.00555

V.3 – Remarks : side-note remarks …

• **(superposition of ≠ collision types) = a fact** : Pb-Pb hadronic collision + photoproduction γ-Pb^{82+}
Seen in excess (factor 7 wrt to pp) of low momentum J/ψ ($0 < p_T < 300$ MeV/c)
from coherent photo-production of vector mesons in γ-A "collisions" ⟶ arXiv:1509.08802
⟶ To be considered also for LF sector ? e.g. ALICE ρ° photoproduction in UPC, at y ≈ 0
⟶ ρ° : arXiv:2002.10897 2.76 TeV + arXiv:2002.10897 5.02 TeV

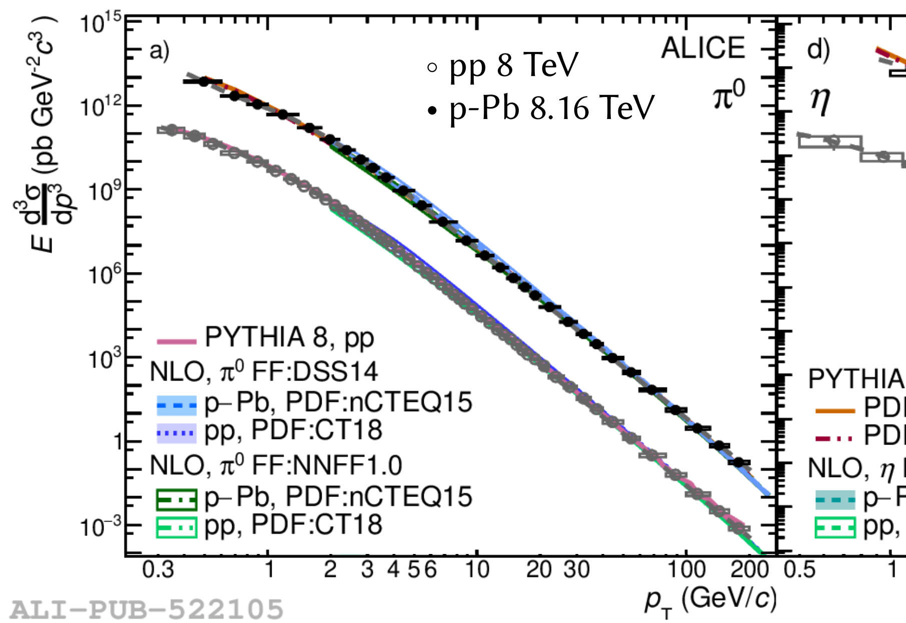
• ∃ [**ϕ(1020)** ⟶ $\mu^+\mu^-$] measurement at forward rapidities ($-4 < y < -2.5$)
⟶ arXiv:1506.09206 p-Pb 5.02 TeV, pp 2.76 TeV
⟶ arXiv:1804.08906 Pb-Pb 2.76 TeV (fwd y + mid y)

• **π° and η** p_T-spectra $|y| < 0.5$ in pp, p-Pb, Pb-Pb
("N_μ sensitive to γ flux in the late air shower", right ?
∃ 11 ALICE articles on such neutral mesons,
(e.g. arXiv:2104.03116)
⟶ Any tension π° Vs π$^\pm$
(isospin symmetry likely preserved in *direct* production,
but may ∃ feed-down difference = f(p_T)
in both *prompt* π° and π$^\pm$ populations) ?

1. Ratio π°/π$^\pm$ = f(p_T)
   to be computed from HEPdata…

2.1 Ratio $K^\pm/K^0$s = f(p_T)
   to be computed from HEPdata…

2.2 Getting in turn a ratio $K^\pm/K^0_L$ = f(p_T)…

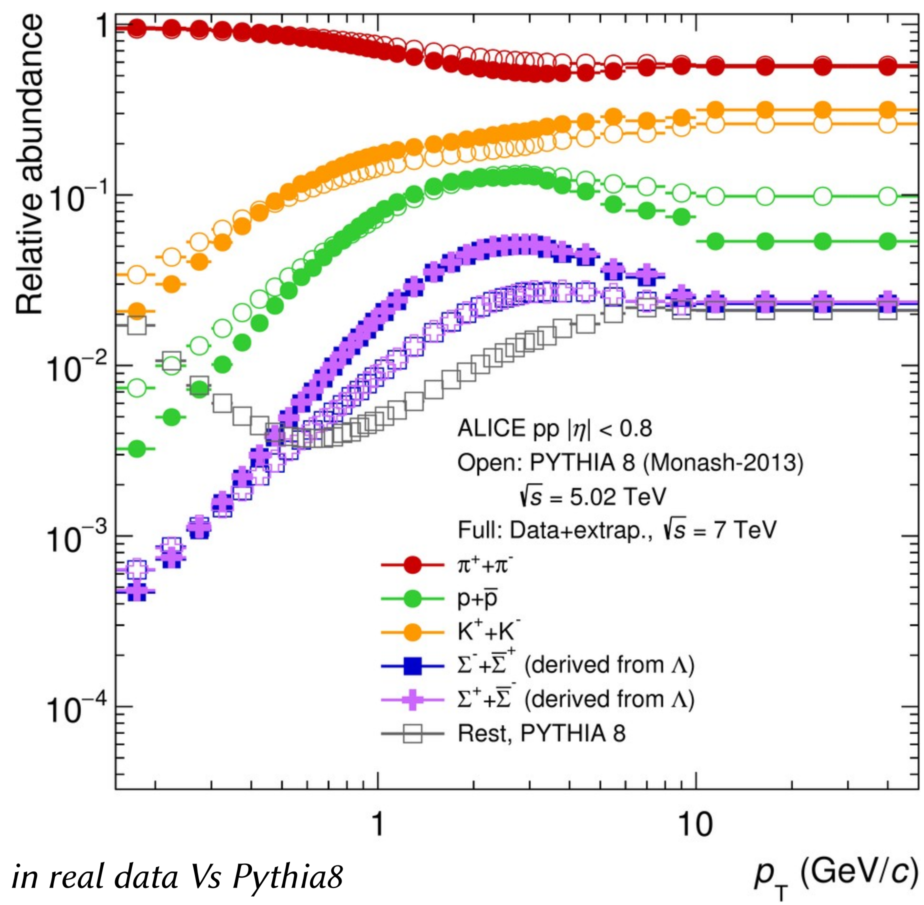


V.4 – Remarks : my parting shot on the cocktail composition ...

The importance of getting the correct cocktail composition of particle species... as function of p_T
⟶ May play decisive role on the various **feed-down** towards

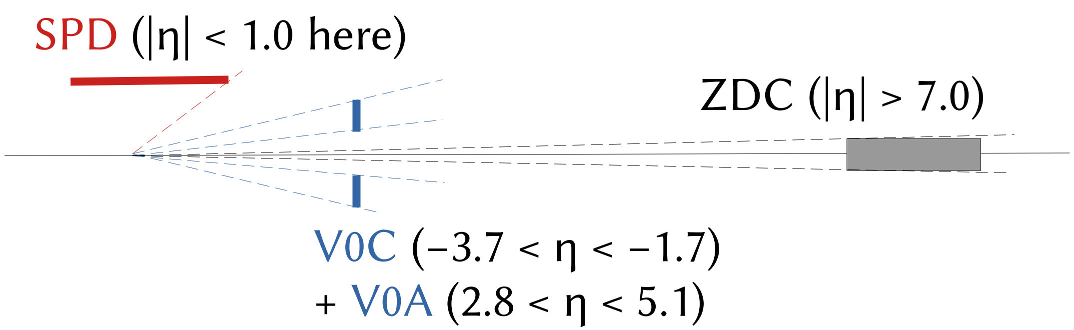
$\pi^{\pm}$, π°, $K^{\pm}$, K^0_S, K^0_L,
($K^*(892)$, $\phi(1020)$, ...)

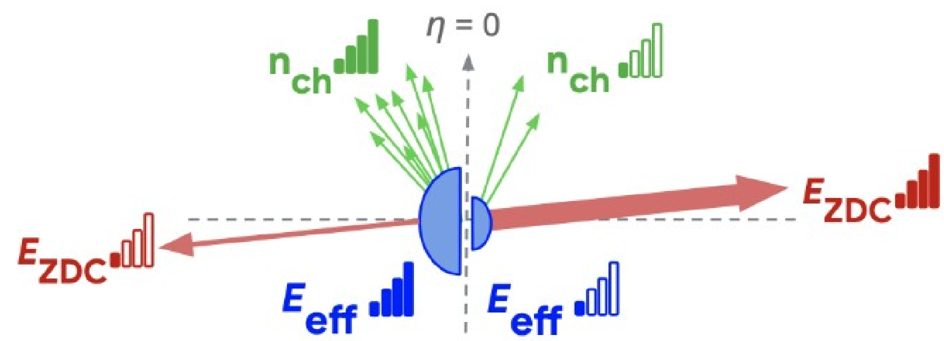
Example:
One tends to overlook $\Sigma^{\pm}$ and $\Sigma^{\mp}$ ...
But they can influence $dN_{ch}/d\eta$,
i.e. there are :
(*i*) ≈ abundant
(*ii*) charged particles
(*iii*) that live long enough,
especially from mid p_T on
⟶ arXiv:1802.09145

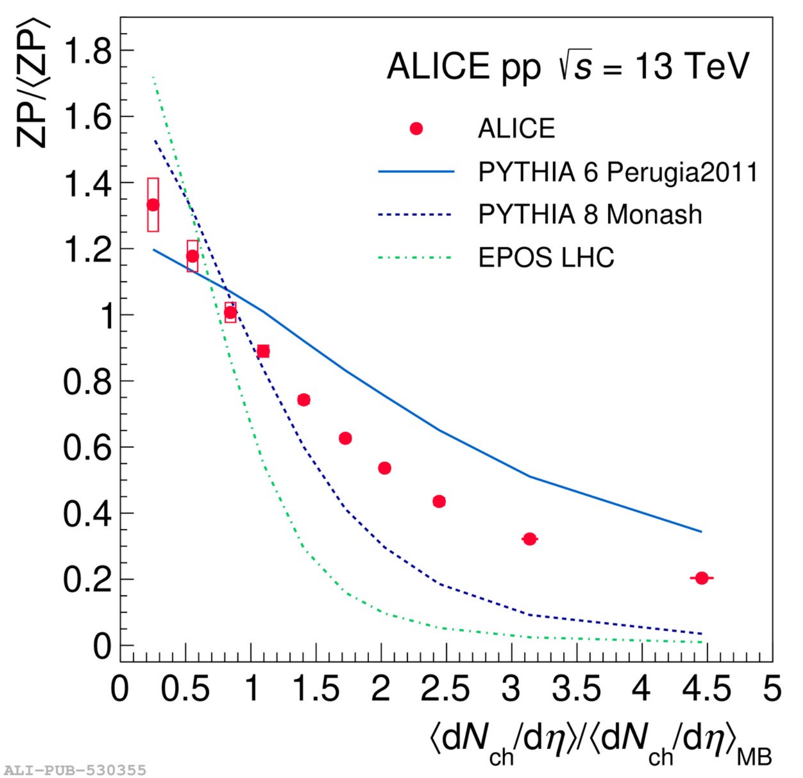


Cocktail composition in real data Vs Pythia8

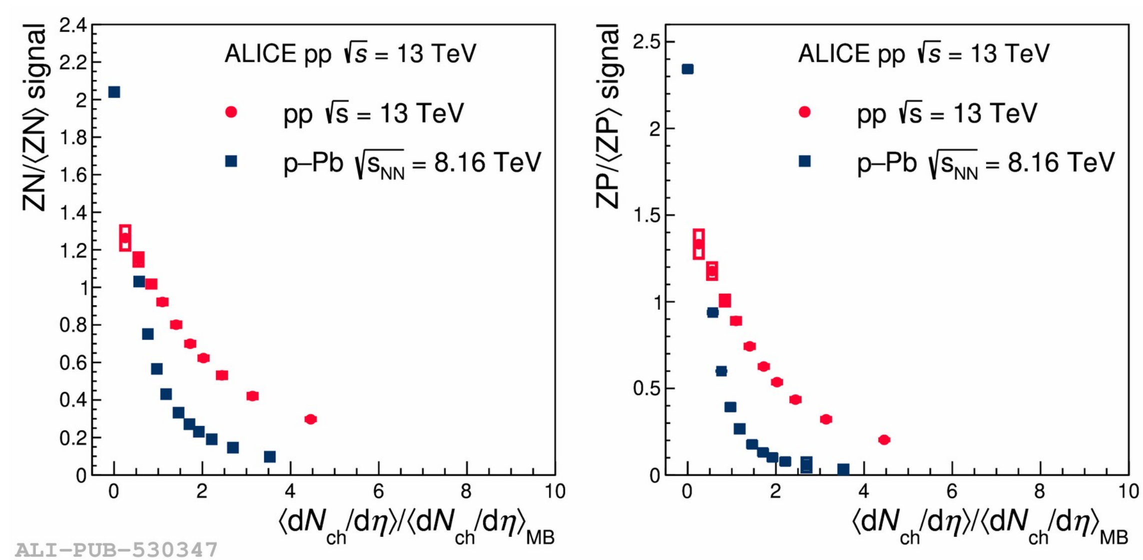
VI.1 – Special glimpse : [mid-rapidity $dN_{ch}/d\eta$] Vs [fwd energy]







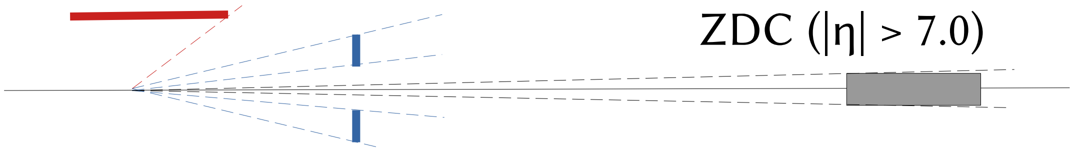
∃ anti-correlation E_{ZDC} Vs $dN_{ch}/d\eta$ | $_{|\eta| < 0.8}$!



= ALICE, arXiv:2107.10757 + C. Oppedisano, Kruger2022

VI.2 – Glimpse : strangeness enhancement Vs forward energy

SPD ($|\eta| < 0.8$ here)

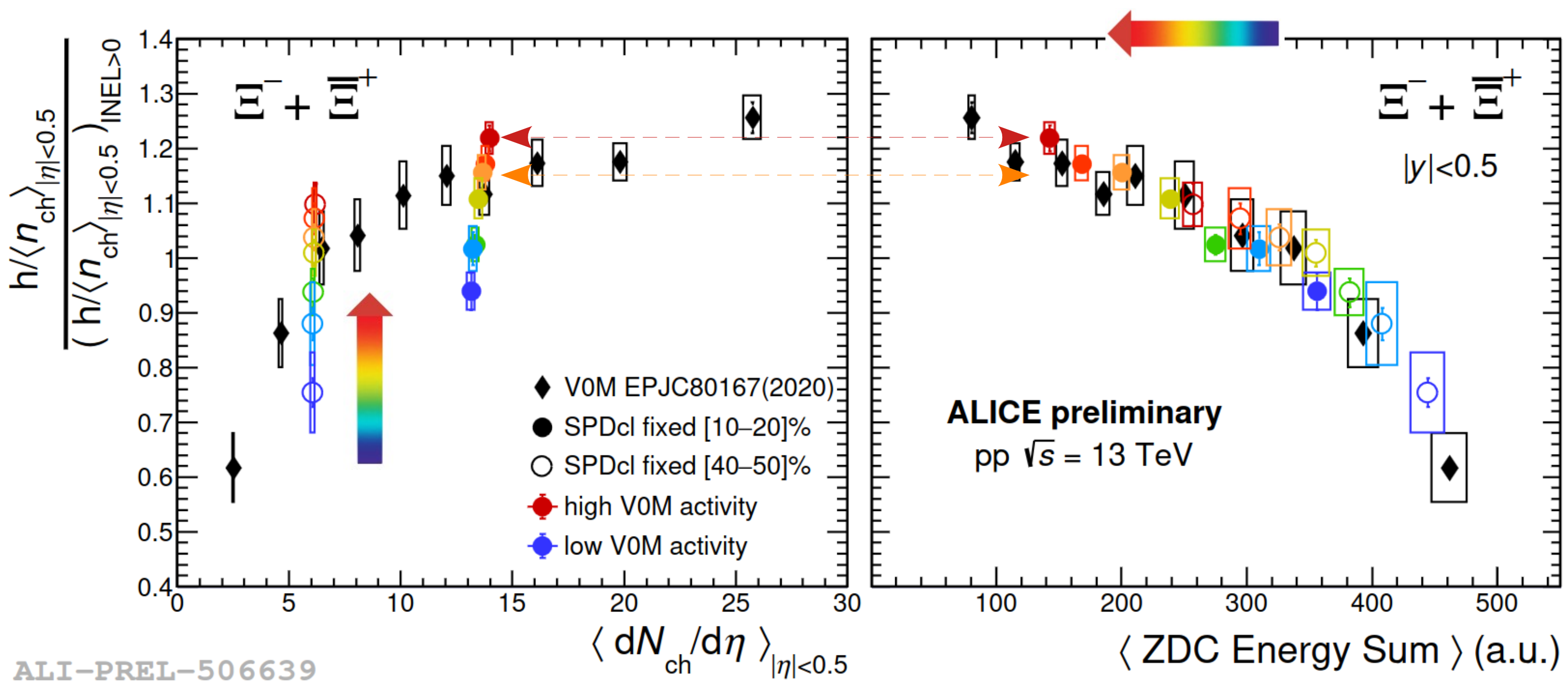


ZDC ($|\eta| > 7.0$)

V0C ($-3.7 < \eta < -1.7$) + V0A ($2.8 < \eta < 5.1$)

"Triple"-differential analysis...

$$E_{\text{effectively available}} = \sqrt{s} - E_{\text{fwd leading baryon}} \approx \sqrt{s} - E_{\text{ZDC}}$$



Strangeness enhancement is **anticorrelated** with forward E_{ZDC}, even if one fixes mid-y multiplicity

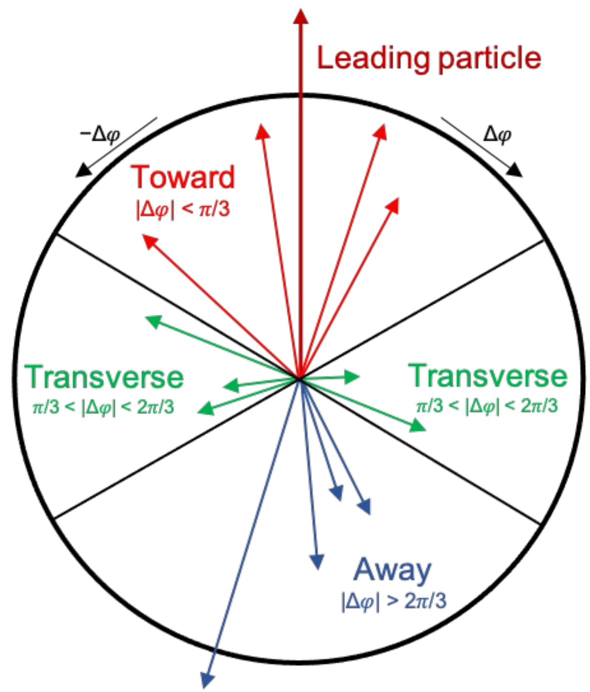
⟶ Early stages (large rapidity gap) matter in strangeness enhancement

F. Ercolessi, *QM 2022 + ICHEP 2022*

Part C – Event activity estimators in ALICE

VII.1 – Event activities : examples

- ***N_{ch}*** in a given η region
  - |η| < 0.5, 0.8, 1.0, 1.2 with SPD tracklets or clusters
  - forward activity with V0A+V0C amplitudes



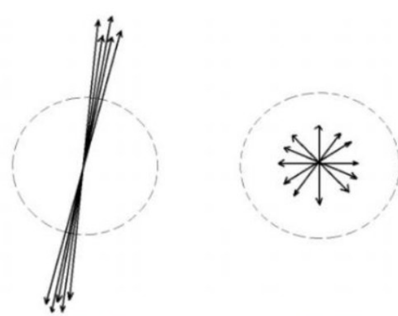
(• ***R_T*** = $N_{ch,transverse}$ / $\langle N_{ch,transverse}\rangle_{MB}$

Nch in the underlying-event region after *Skands, arXiv:1603.05298*
their per-event transverse activity with respect to the mean
e.g.

ALICE, arXiv:2310.07490
ALICE, arXiv:1910.14400

- **Spherocity** = define the unit vector ns that minimise S_0

$$S_0 \equiv \frac{\pi^2}{4} \min_{\hat{\mathbf{n}}_s} \left(\frac{\sum_i |\vec{p}_{T,i} \times \hat{\mathbf{n}}_s|}{\sum_i p_{T,i}} \right)^2$$



ALICE, arXiv:1905.07208
ALICE, arXiv:2310.10236

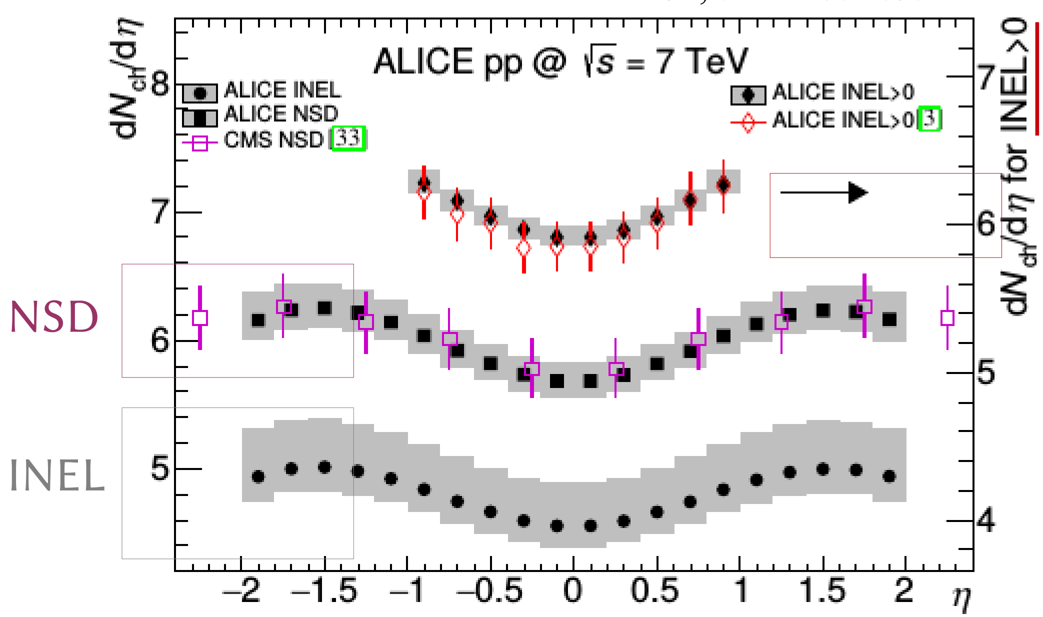
) *not for today…*

VII.2 – Method : retain a global event class, “0-100%”

Possible choices :

- Non-Single diffractive collision sample ?
- Inelastic collision sample ?
- INEL>0 = at least 1 charged track in |η| < 1 ?
- …

ALICE, arXiv:1509.07541

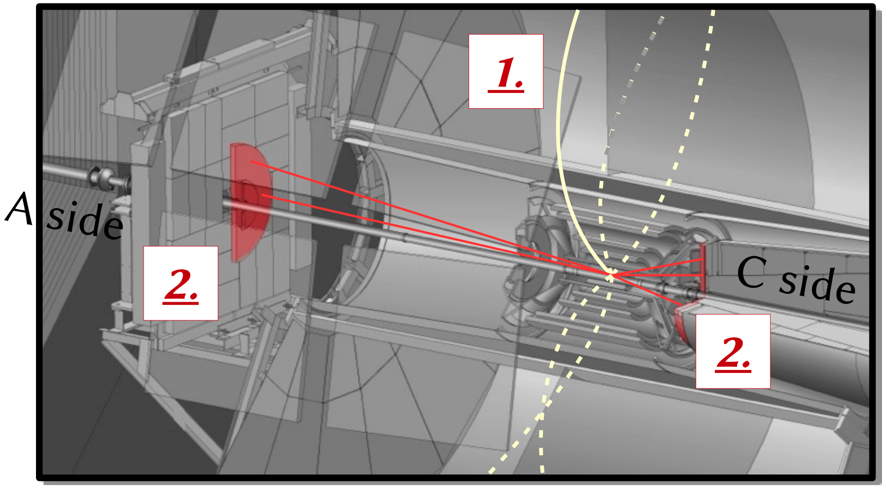


INEL>0 measured in |η |<1 in this figure

Often, choice of the class 0-100% : INEL>0 $|_{|\eta| < 0.5}$

→ purpose : minimising the model dependence

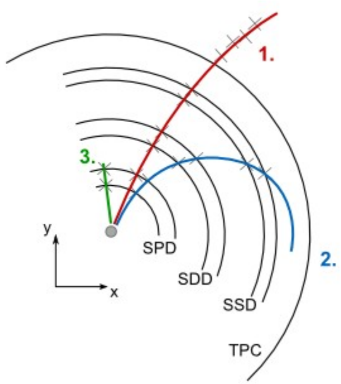
VII.3 – Method : event activity sampling

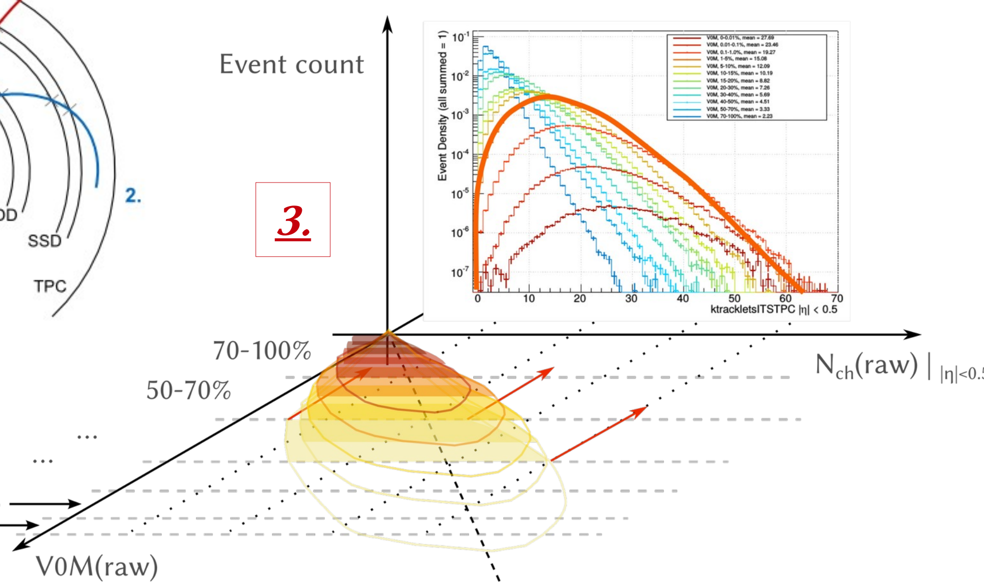


1. For events with at least 1 charged particle (typically above $p_T \approx 50$ MeV/c) in |η| < 0.5
   = INEL>0 $|_{|\eta| < 0.5}$

→ NB : = ***corrected*** quantity
(for tracklet AxEff, ∫p_T, event trigger…)
= what defines "100%" of the event sample

2. sample the event activity with forward det. :
   V0 suM
   i.e. plain addition
   of V0A and V0C ***raw*** signals
   → V0M distrib° further hashed into percentiles





3. For each V0M activity interval,
   → back to y ≈ 0 !
   derive the mean, $\langle dN_{ch}/d\eta \rangle_i$, of the ***corrected*** distrib° of charged tracks in |η| < 0.5

VII.4 – Method : V0M-sampled $\langle dN_{ch}/d\eta \rangle \mid_{|\eta|<0.5}$

pp, √s = 7 TeV
ALICE Nature Phys. = arXiv:1606.07424 + PRC arXiv:1807.11321 + dNch/dη = f(η) in pp arXiv:2009.09434

Reference : $\langle dN_{ch}/d\eta \rangle_{INEL>0}$ ($|\eta| < 0.5$) ≈ 5.96 ± 0.23

≈ **3.5** $\langle dN_{ch}/d\eta \rangle_{INEL>0}$ → class I

Class name	I	II	III	IV	V
$\sigma/\sigma_{INEL>0}$	0–0.95%	0.95–4.7%	4.7–9.5%	9.5–14%	14–19%
$\langle dN_{ch}/d\eta \rangle$	21.3±0.6	16.5±0.5	13.5±0.4	11.5±0.3	10.1±0.3

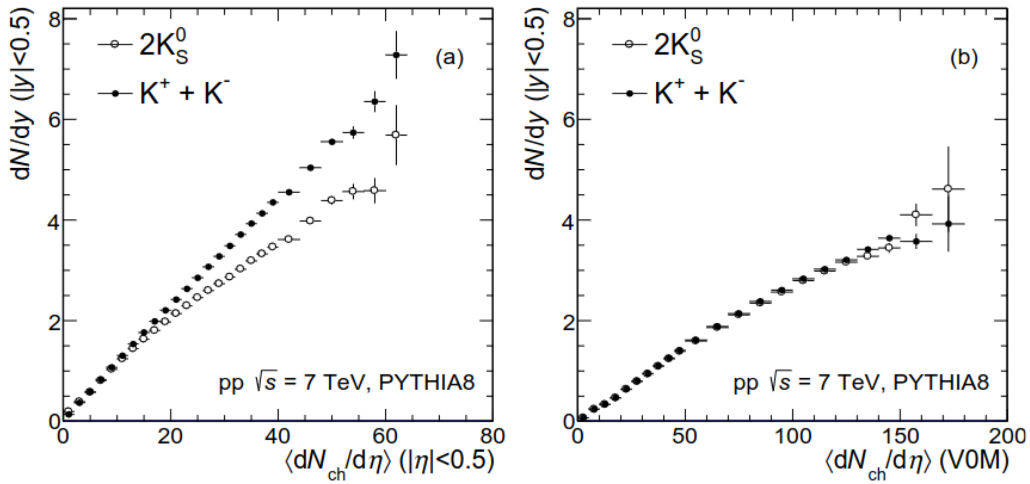
VI	VII	VIII	IX	X
19–28%	28–38%	38–48%	48–68%	68–100%
8.45±0.25	6.72±0.21	5.40±0.17	3.90±0.14	2.26±0.12

≈ **0.4** $\langle dN_{ch}/d\eta \rangle_{INEL>0}$ → class X

Remark : "What is this crazy binning : 0-0.95%, 0.95-4.7 % ?!" …

VII.5 – Method : (mid-mid) self-correlat° and (mid-fwd) correlat°

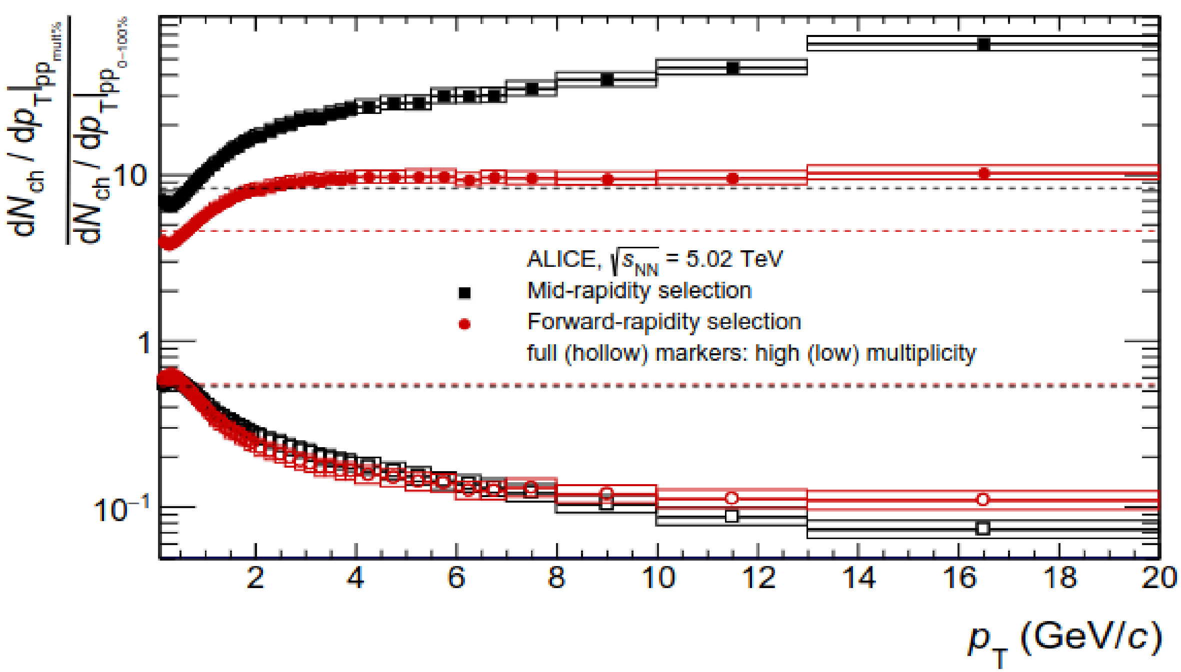
ALICE, arXiv:1807.11321



Example of Pythia8 Monash simulations:

- *Left = Nch estimator = Nch in |η|<0.5 i.e. mid- rapidity*
- *Right = Nch estimator in a V0M acceptance i.e. forward*
- *Particles of interest = kaons, charged or neutral*

→ *left :*
Creating an artificial *isospin asymmetry $K^{\pm}$ K^0s ...*



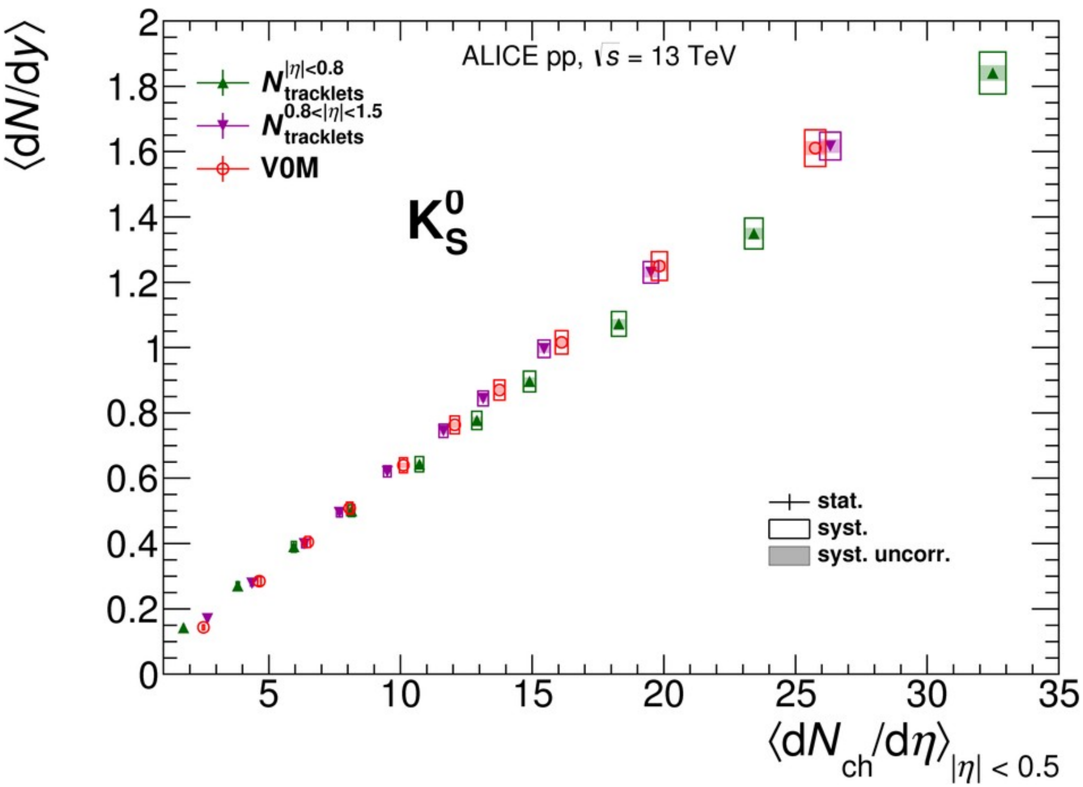
NB:

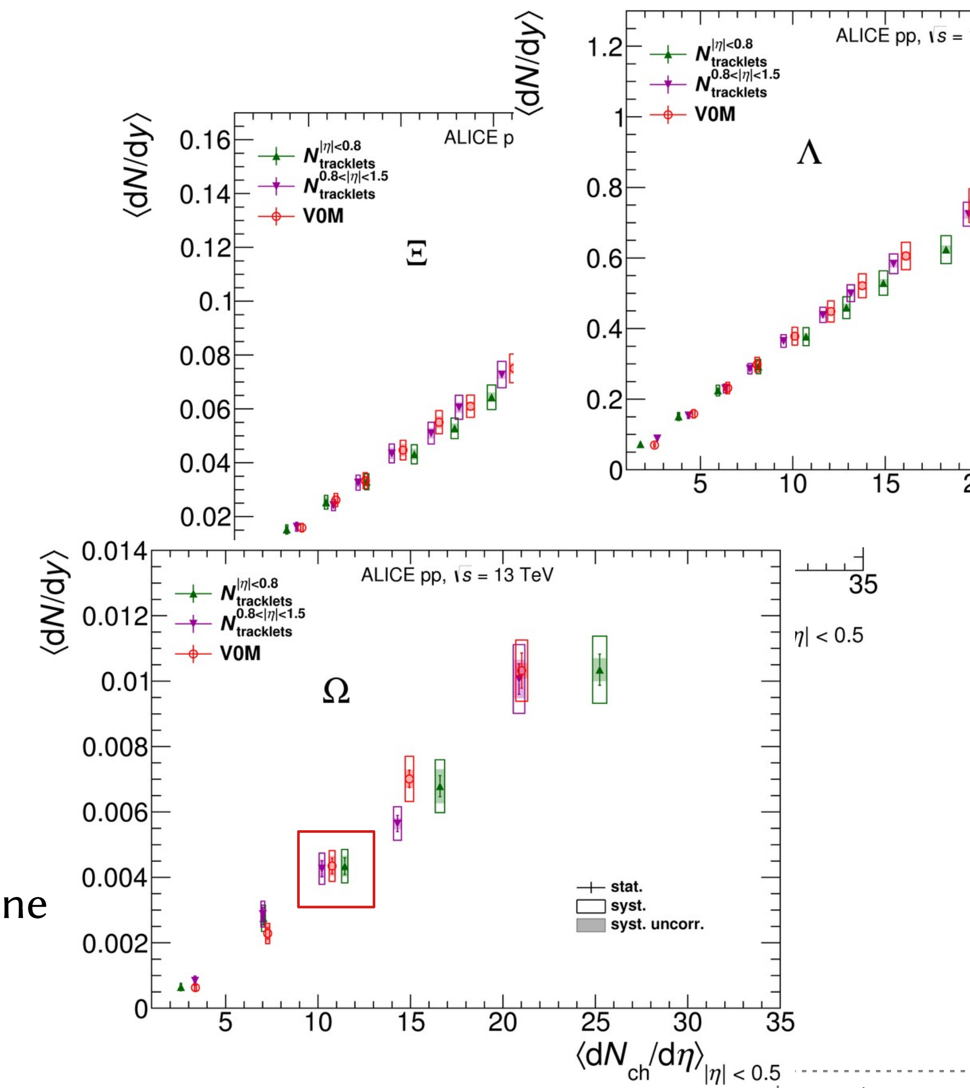
Correlations [mid / fwd] have
their own features...
that MCgen need silently to match...
≠ trivial, = a hidden topic on its own

ALICE White paper, Fig.76, arXiv:2211.04384

VII.6 – dN/dy : different mult. estimators, tested

arXiv:1908.01861





Curves look very much alike at first glance ! but...

be careful if you are after a 1-5%-precision MC tune

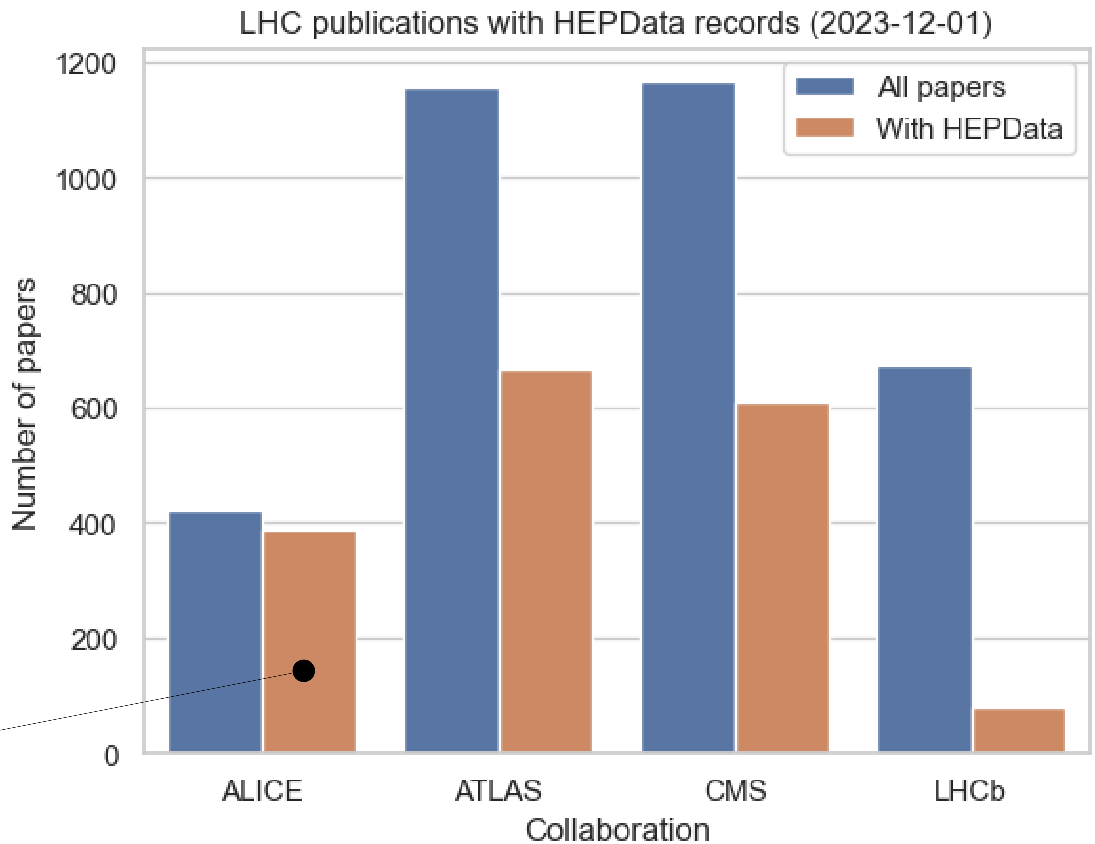
There is a slight degeneracy around !

i.e. one mult estimator $\longrightarrow$ one specific response !

(Keep in mind the effect on the Rivetisation ...)

Part D – Rivetisation efforts

VIII.1 – Rivetisations in ALICE : HEPdata + Rivet plugins



Fraction of ALICE papers with HEPdata > 90%

Graeme Watt, from HEPdata, JupyterNotebook InspireRecordsWiHEPdata

ALICE policy :

- HEPdata archive available internally within the collaboration at the arXiv preprint release
- archive pushed publicly to HEPdata once the paper is accepted by the journal

VIII.2 – Rivetisations in ALICE : HEPdata + Rivet plugins

https://rivet.hepforge.org/rivet-coverage

Key	ALICE	ATLAS	CMS	LHCb	Forward
Rivet wanted (total):	327	401	504	198	16
Rivet REALLY wanted:	55	50	99	16	0
Rivet provided:	**32**/359 = **9%**	**202**/603 = **33%**	**114**/618 = **18%**	**31**/229 = **14%**	**9**/25 = **36%**

Rivet challenges :

1. multiple-run analysis
   (e.g. pp part + Pb-Pb part,
   centrality/event activity calibration)
   ⟶ core features for that available > Rivet 3.1
   ("reentrant finalise")

2. what if post-processing ∈ analysis ?
   (e.g fits often present in analysis)

3. large *MinBias* statistics to simulate,
   large CPU time and/or large disk storage
   (e.g. Pb-Pb event including hydro)

4. Rivetisation objective :
   ≠ match MC points to real data ones, not yet…
   (that is the ultimate goal for the MC generator authors…)
   But
   = mimic as close as possible the logic and the ingredients of the real-data analysis,
   despite everything …

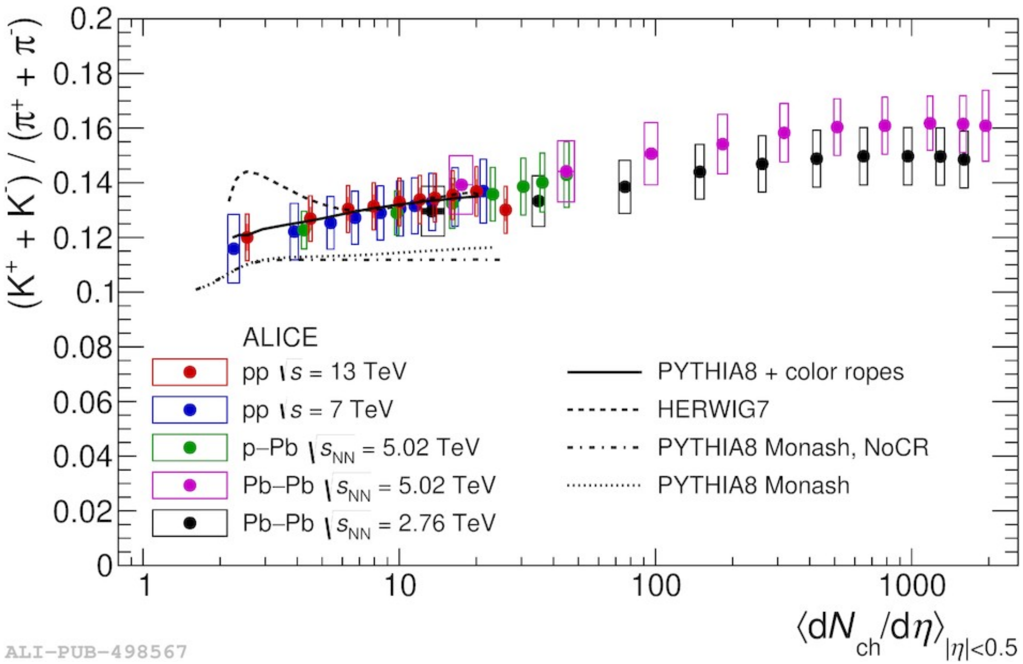
⟶ A *reliable* rivetisation = [~~get the physics, right~~] but [get the MC analysis, alike] !

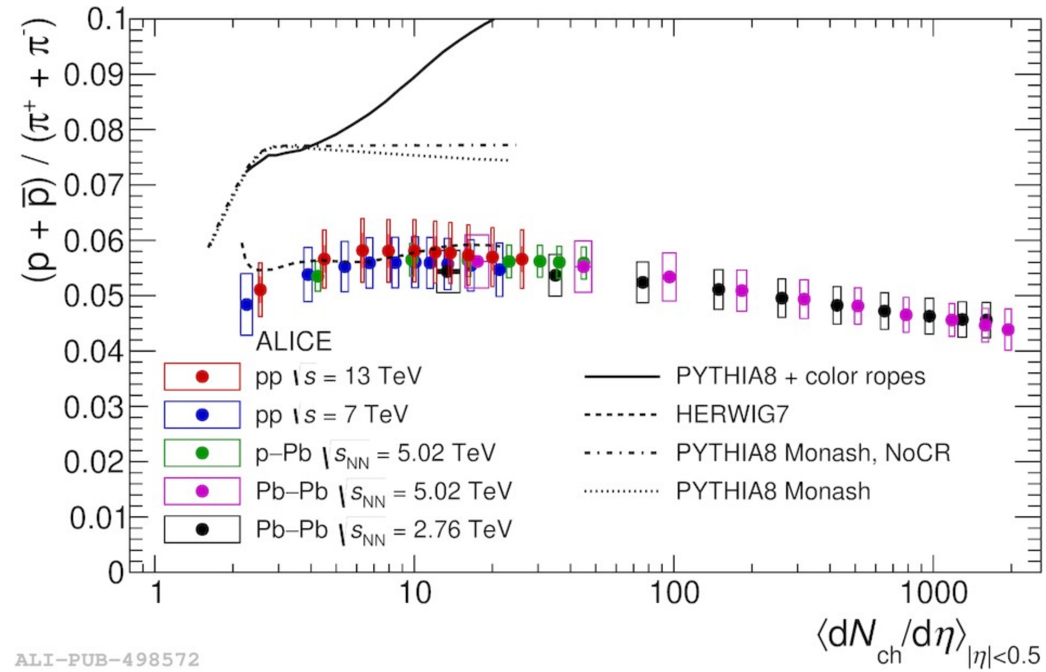
The End…

Part B – Selected set of results

I.1 – Part: ...

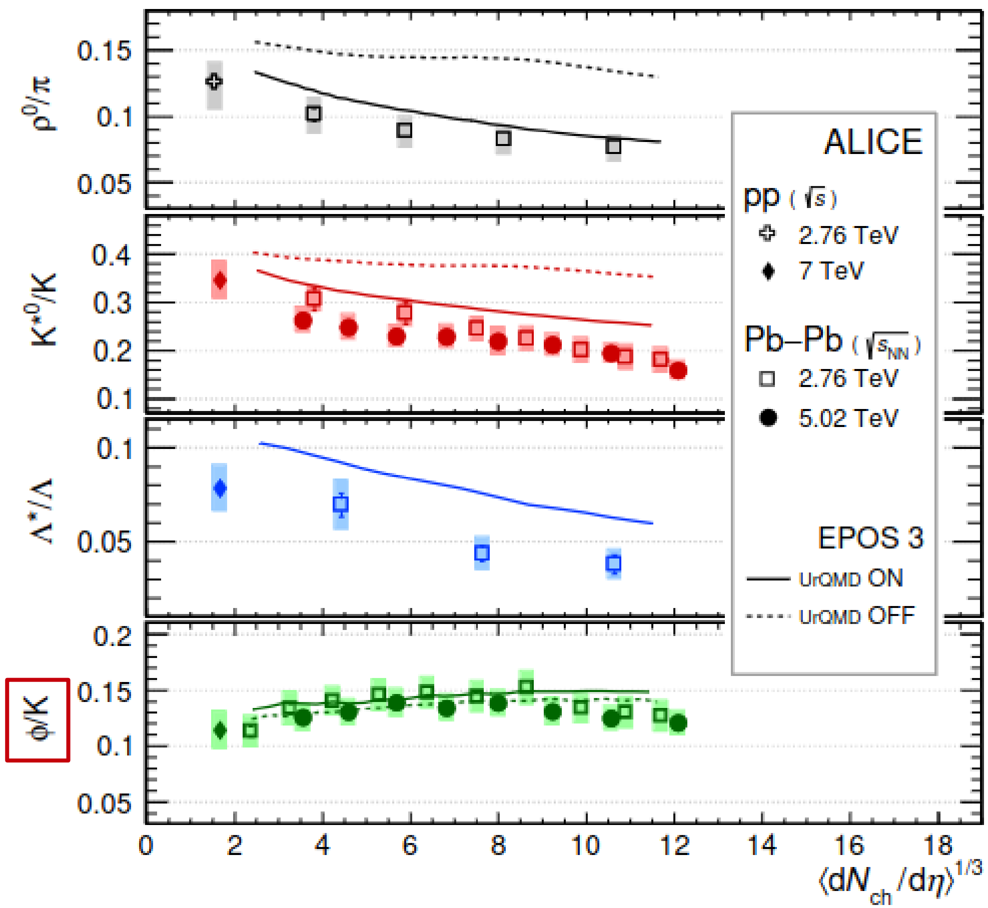
ALICE π,K,p = f(mult) Fig.5 arXiv:2003.02394

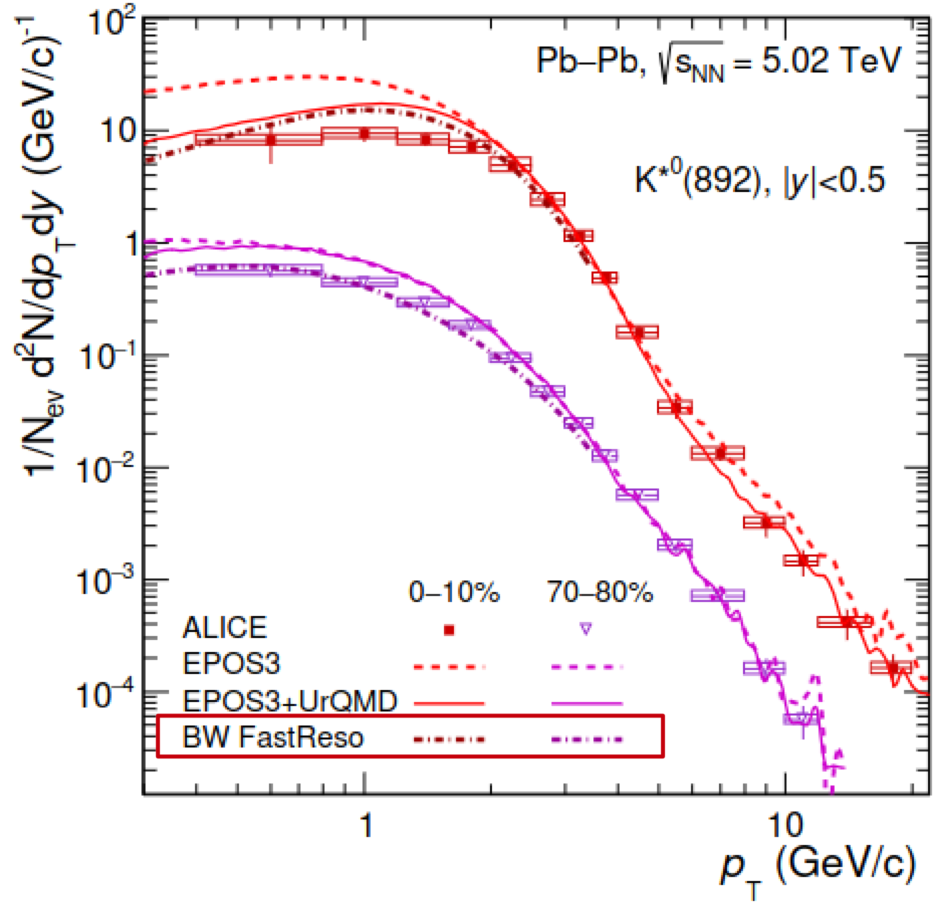




I.1 – Landscape : resonances and hadronic interactions.

ALICE White paper, Fig.41, arXiv:2211.04384





- FastReso by Mazeliauskas, arXiv:1809.11049
- Blast Wave FastReso, arXiv:1909.10485

$\Phi(1020)/K^{\pm} \approx$ stable f(mult) in pp to Pb-Pb

$\rho(770)^0$	(τ = 1.3 fm/c)
$K{*}(892)^0$	(τ = 4.16 fm/c)
$\Lambda(1520)$	(τ = 12.6 fm/c)
$\phi(1020)$	(τ = 46.3 fm/c)