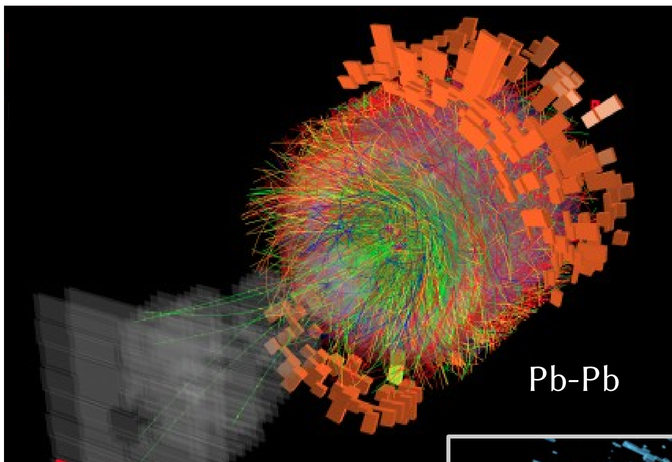
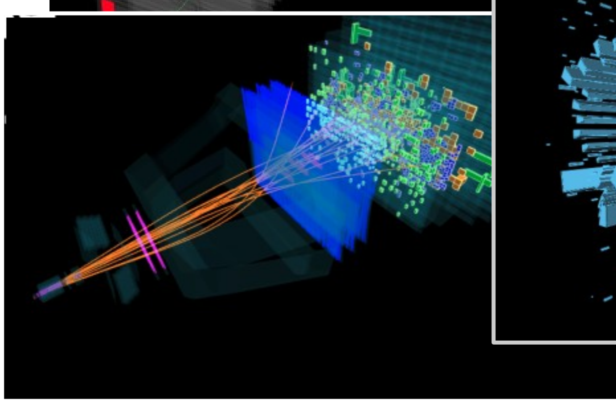
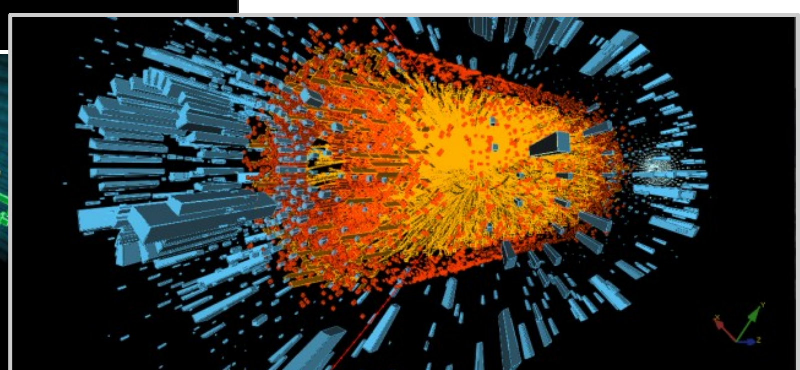
Antonin MAIRE – IPHC Strasbourg
Tues 03 March 2020 – **Prospectives GT03 In2p3**

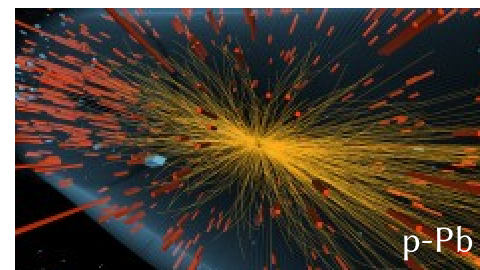
Experimental prospectives of LHC runs III+IV

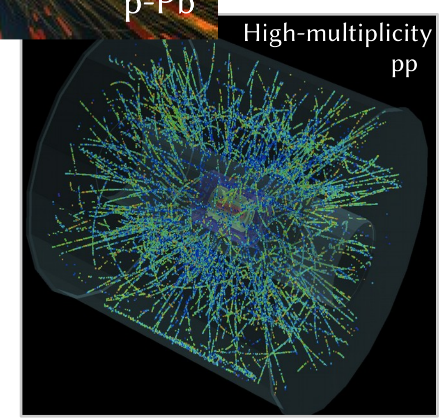
ALICE, CMS, LHCb … in France











Foreword : contributions falling into this summary...

<u>Focus</u> : LHC context, QCD(AA, pA, pp) + QGP (high temperature + low μ_B)

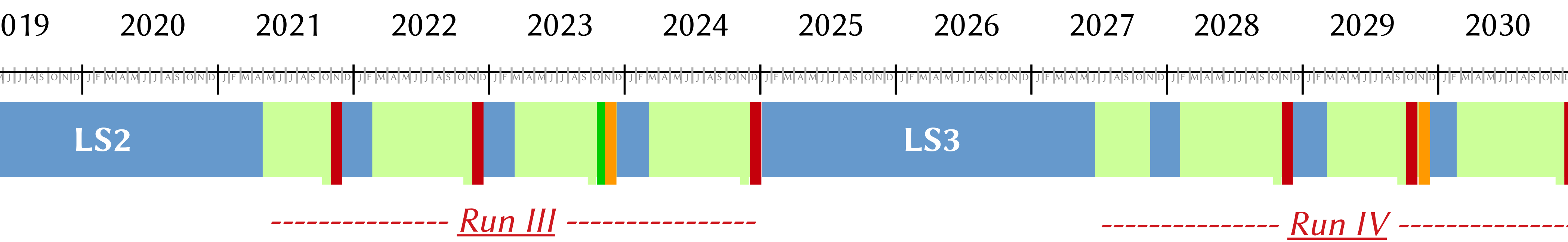
ipnshare.in2p3.fr : 05 out of 14 contributions

- Generic / QGP (= the poll...) : *Prospects on Quark-Gluon Plasma characterization and heavy-ion collisions*
- Generic / Small systems : *Unravelling the hadronic collision structure with Large-Scale System and Energy Scan*
- Multi-Experiment / Fixed target : *French Community Support for A Fixed-Target Programme for the LHC*
- ALICE /
  - ITS-3 + ANGHIE : *Une expérience de nouvelle génération pour la QCD au HL-LHC*
  - FoCal : *The ALICE FoCal proposal and small-x physics at the LHC*
- CMS : *Heavy-ion physics with the Compact Muon Solenoid*
- LHCb : *Heavy-ion physics at LHCb*

+ See presentations : QGP France prospectives meeting 10-12 Dec 2019, https://indico.cern.ch/event/862727/

next slides = mix between summary (*I have tried...*)
and my own ± objective biases (*quite possible...*)

Outline



A. Template for experimental cases at (HL-)LHC

B. *Some* (HL-)LHC physics case (*runs III + IV*)

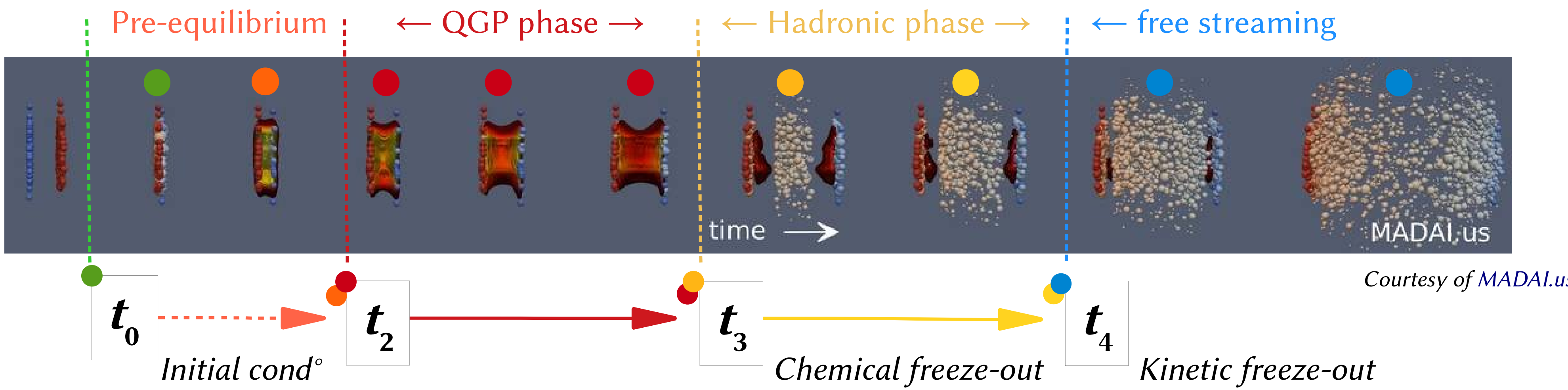
C. 2020, where are we ?

D. ≥2021, Run III (*ALICE major upgrades, LHCb upgrade I*)

E. ≥2027, Run IV (*ALICE upgrade, CMS phase 2, LHCb upgrade Ib*)

Part A – template for physics cases

I.1 – Observables : Layer 1 / as a function of the collision time



Courtesy of MADAI.us

0.
- Coherent E_{loss}
- nPDF
- shadowing
- CGC
+ fluctuations
…

1.
- Level of :
 . Hydrodynamisation
 . Chemical equilibration
 . Thermalisation

via

Multi-Parton Interactions
 + Colour Reconnections
 + Multiple parton scatterings
 + Rope shoving
 + Glasma

…

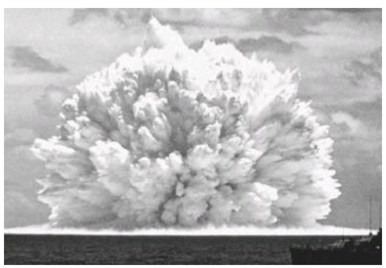
2.
- Degrees of freedom
- Phase transitions :
 . Chiral symm. restoration
 . Deconfinement
- Eq° of State
- Transport coefficients
- Radiative/Collisional E_{loss}

…

3+4.
. Sudden freeze-out
. HBT/Femtoscopy
. Recombination/ coalescence
. Hadronic re-interactions
…

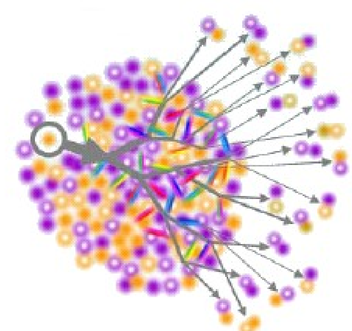
I.2 – Observables : Layer 2 / as a function of *momentum*

A. low-p_T "collectivity" ($p_T \leq$ 2-3 GeV/c)



≈ relativistic hydrodynamics

B. high-p_T "collectivity" ($p_T \geq$ 6-8 GeV/c)

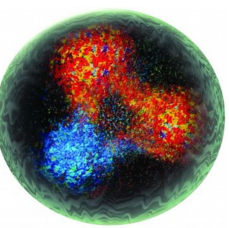


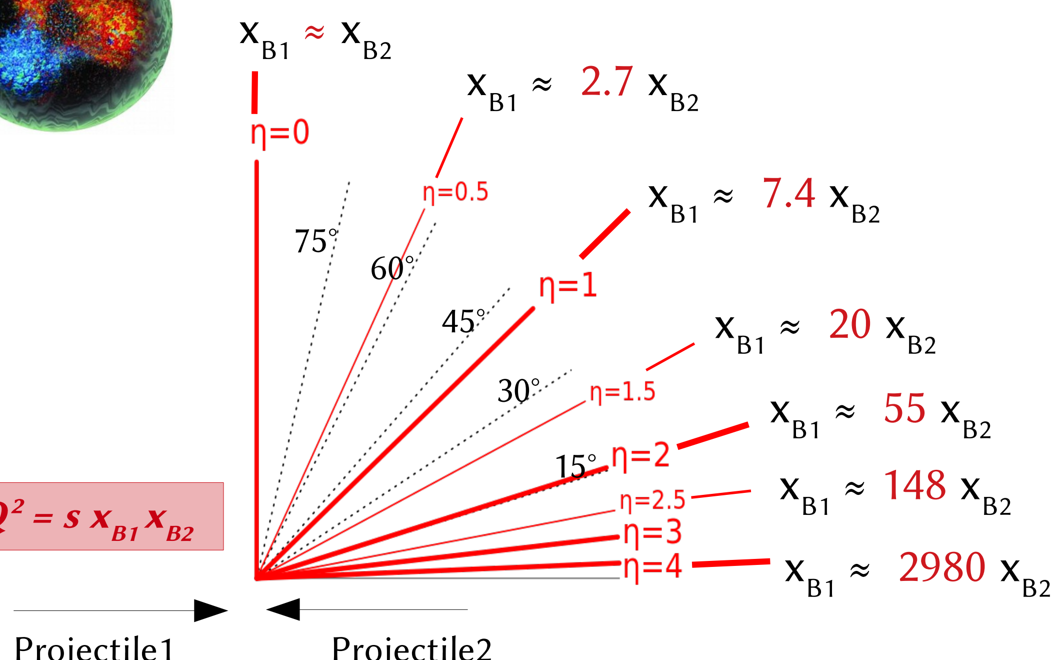
≈ in-medium energy losses for energetic particles

I.3 – Observables : Layer 3 / as a function of *y* (twice)

Initial state			*Longitudinal dynamics*		
I.	ultra-low x_B	$(x_B \leq 10^{-5})$	I'.	$\lvert y\rvert < 2$	: max = rapidity plateau in $dN_{ch}/d\eta$
II.	low x_B	$(x_B \in [10^{-5} ; 10^{-3}])$	II'.	$\lvert y\rvert \approx 3.5$	: 75% $(dN_{ch}/d\eta)_{max}$
III.	moderate x_B	$(x_B \in [10^{-3} ; 10^{-1}])$	III'.	$\lvert y\rvert \approx 5.0$	: 45% $(dN_{ch}/d\eta)_{max}$

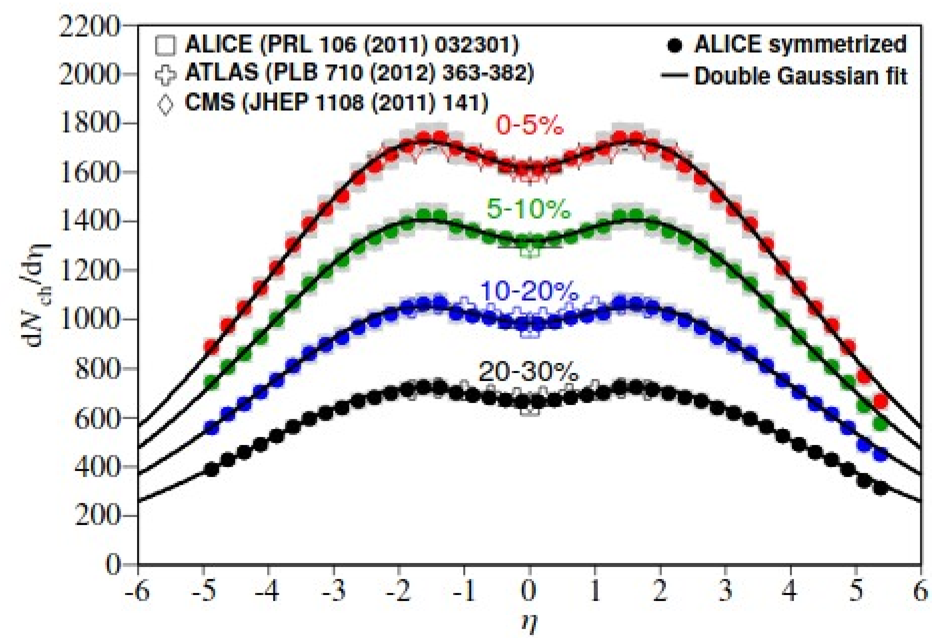
JLab





$Q^2 = s\, x_{B1} x_{B2}$

ALICE, arXiv:1304.0347



* if y ≈ η (m << p)
+ same type of beams (A_i/Z_i)

I.4 – Observables : Layer 4 / as a function of flavours

« hadron-quark duality »

g + u,d,s,c,b (t) <=>

- $\pi^{\pm}$ π^{0} $K^{\pm}$ K^{0}_{S} … p Λ Ξ^{-} Ω^{-} …
  $\eta(547)$ $\omega(782)$ … $K^{0}(892)$ $\phi(1020)$ $\Sigma^{\pm}(1385)$ $\Lambda(1520)$ $\Xi^{0}(1530)$
  + d t ^{3}He ^{4}He …
  + $^{3}_{\Lambda}H$ …
  } *u,d,s*
- D^{0} $D^{\pm}$ $D^{*\pm}$ D_{S}^{+} … η_{c} J/ψ χ_{Ci} $\psi(2S)$ … Λ_{C}^{+} Ξ_{C}^{0} … } *c*
- B^{0} $B^{\pm}$ B^{0}_{S} … $\Upsilon(1S,2S,3S)$ … Λ_{b}^{0} … } *b*

\+

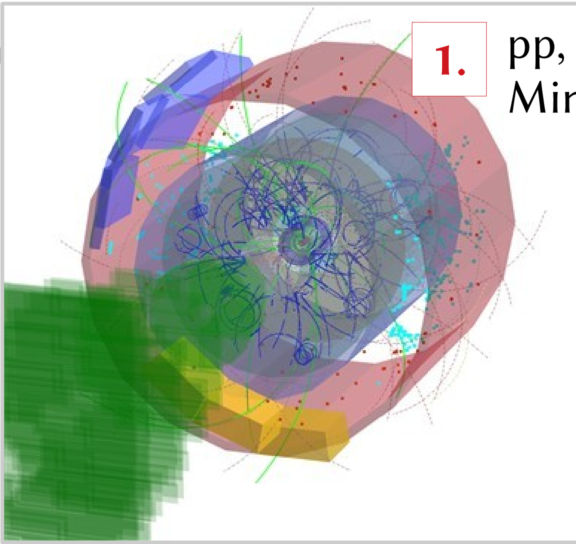
(• $e^{\pm}$ γ)
(• $W^{\pm}$ γ/Z°)

NB :

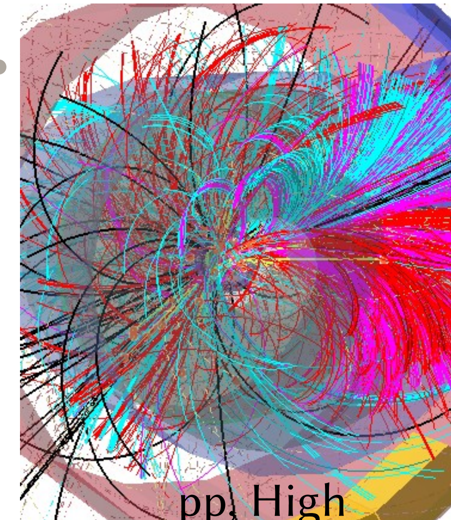
baryons Vs mesons
mixed flavours (s+c, s+b, … c+b …)

I.5 – Observables : Layer 5 / as a funct° of the collision system

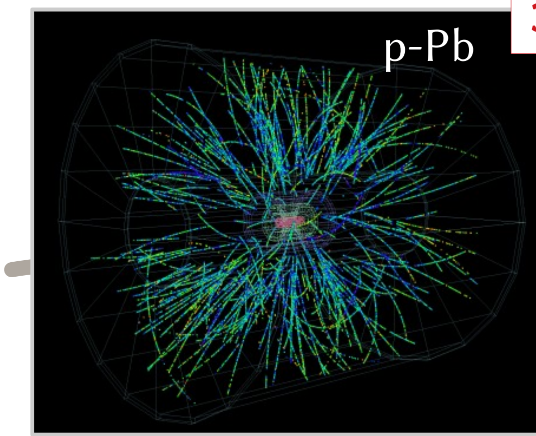
1. pp, Min. Bias



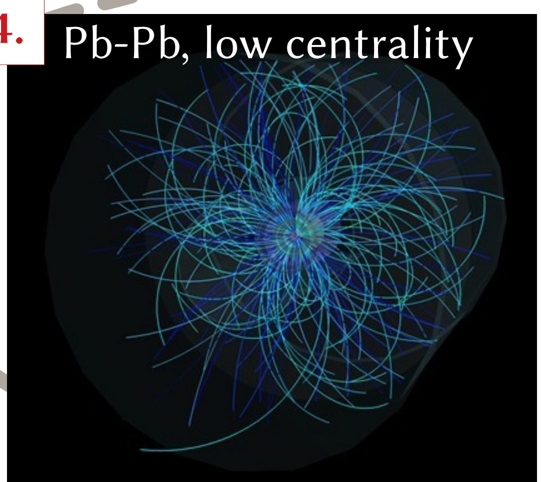
2. pp, High Multiplicity



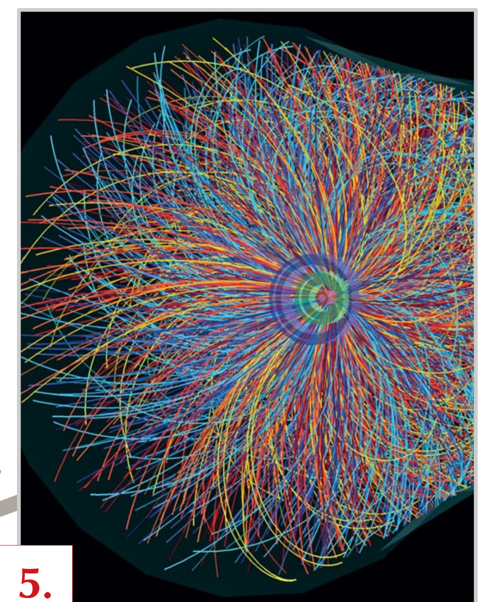
3. p-Pb



4. Pb-Pb, low centrality



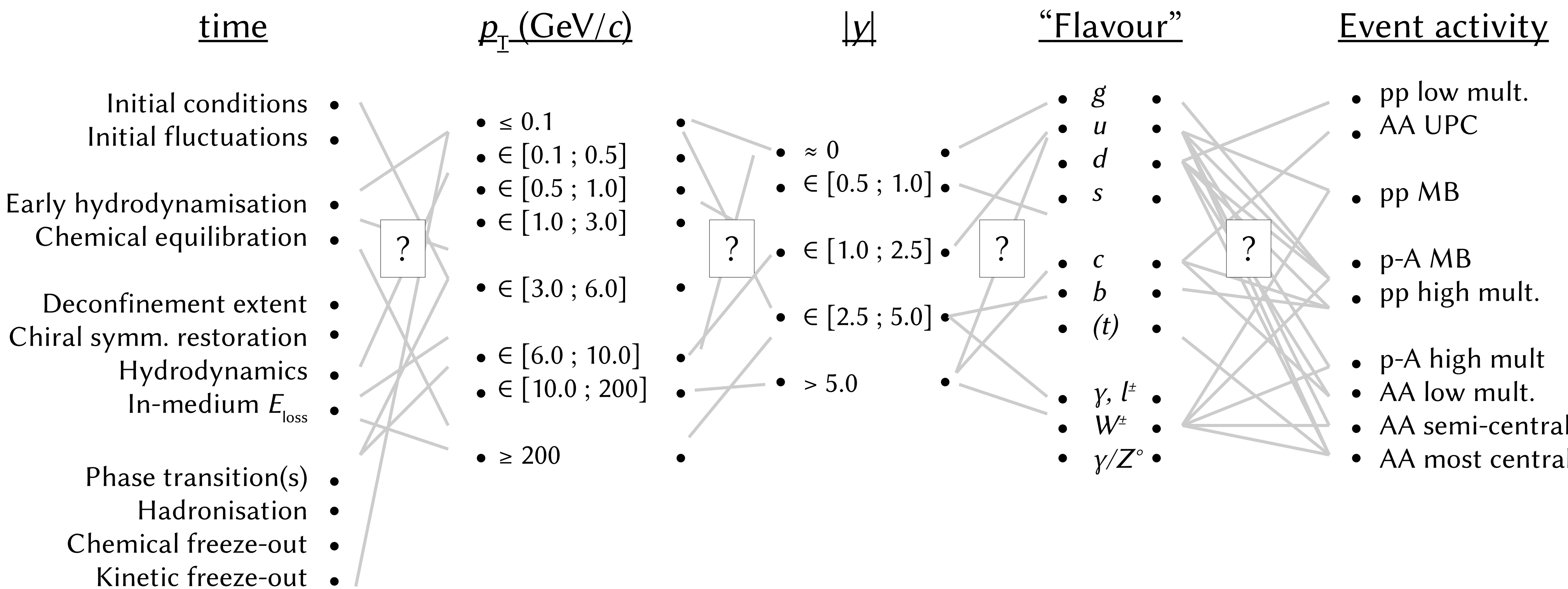
5. Pb-Pb, most central events



CDS/record-1305398

I.6 – Observables : paths through the multi-layer mesh

The multi-variate and interleaved families of QCD+QGP observables :



(HL-)LHC watchword for (≥Run III) : "precision era" pushed on many fronts

i.e. fight for (σ_{stat} ≈ negligible) ⊗ (σ_{syst} ≤ 1-5%) as much as possible

Note : QCD+QGP physics is both i) a bulk physics + ii) a rare-probe physics
⟶ Nowadays, precision then implies extreme cases on both fronts … (*i.e.* also for abundant observables)
(e.g. *multi-differential, multi-correlated probes, ≤ 1 High-Mult. evt every [10^6-10^9] MB pp evts …*)

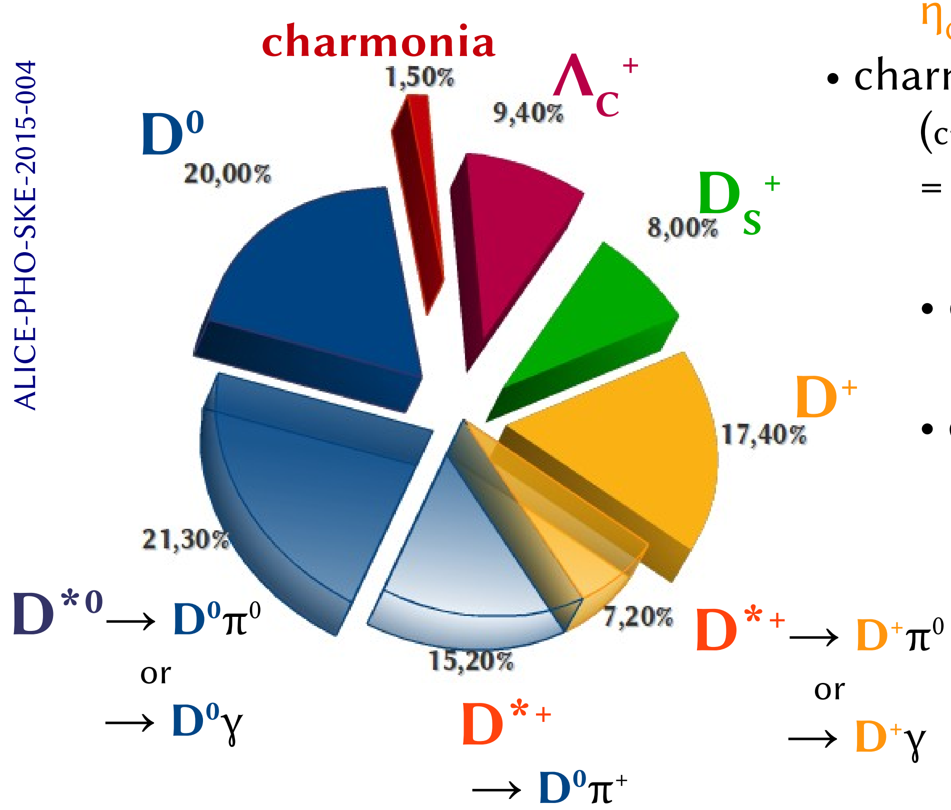
Part B – *Selected* physics cases for LHC and HL-LHC

1. Heavy flavours
2. Jets
3. Net quantum fluctuations

III.1 – Phys. case : example 1 – heavy-flavours facing collectivity

→ hydrodynamization / diffusion coefficient / in-medium energy loss / hadronisation

ALICE-PHO-SKE-2015-004



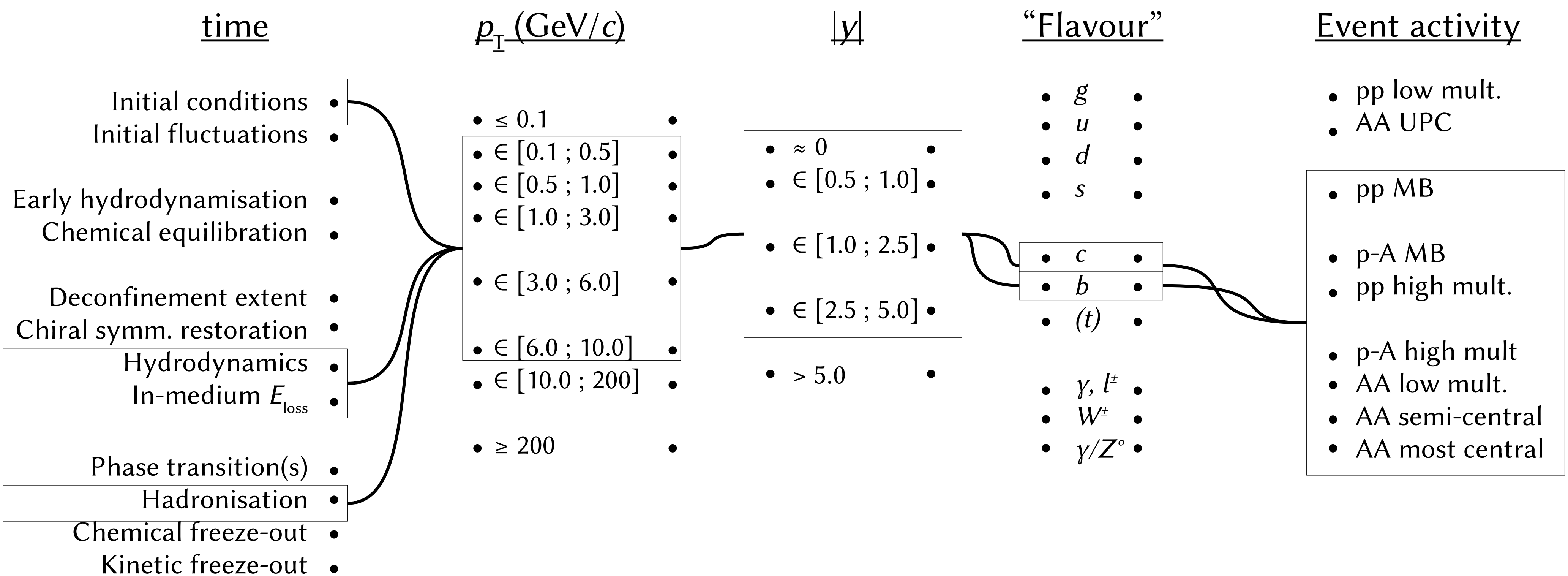
1. *Charm sector (Runs III+IV)*

- total charm cross-section $c\bar{c}$:
  $\eta_c(1S)$, J/ψ, $\psi(2S)$, χ_{Cj} + D^0, D^+, D_s^+, $D(2010)^\pm$ + Λ_c^+
- charm baryons
  ($c\tau$ ~ 30-130 µm + 2-to-6 final states cascade decays) :
  = $\Lambda_c^+(udc)$, $\Xi_c^+(usc)$, $\Xi_c^0(dsc)$, $\Omega_c^0(ssc)$, $\Xi_{cc}^{2+}(ucc)$, … , $\Omega_{ccc}^{2+}(ccc)$
  - quark recombination :
    $p/\pi^+ \to \Lambda/K^0_s \to \Lambda_c^+/D^+ \to \Lambda_b^0/B^0$
  - charm hypernuclei, *c*-deuteron = $\Lambda_c n$ bound state

2. *Beauty sector (Runs III+IV)*

mesons : $B^0 \to D^-\pi^+$,
$B^\pm \to D^0\pi^\pm$,
$B_s^0 \to$ non-prompt D_s^+
+ bottomonia : $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
baryons : $\Lambda_b^0 \to \Lambda_c^+ \pi^-$, …

III.1 – Phys. case : ex. 1 – charm and beauty sectors

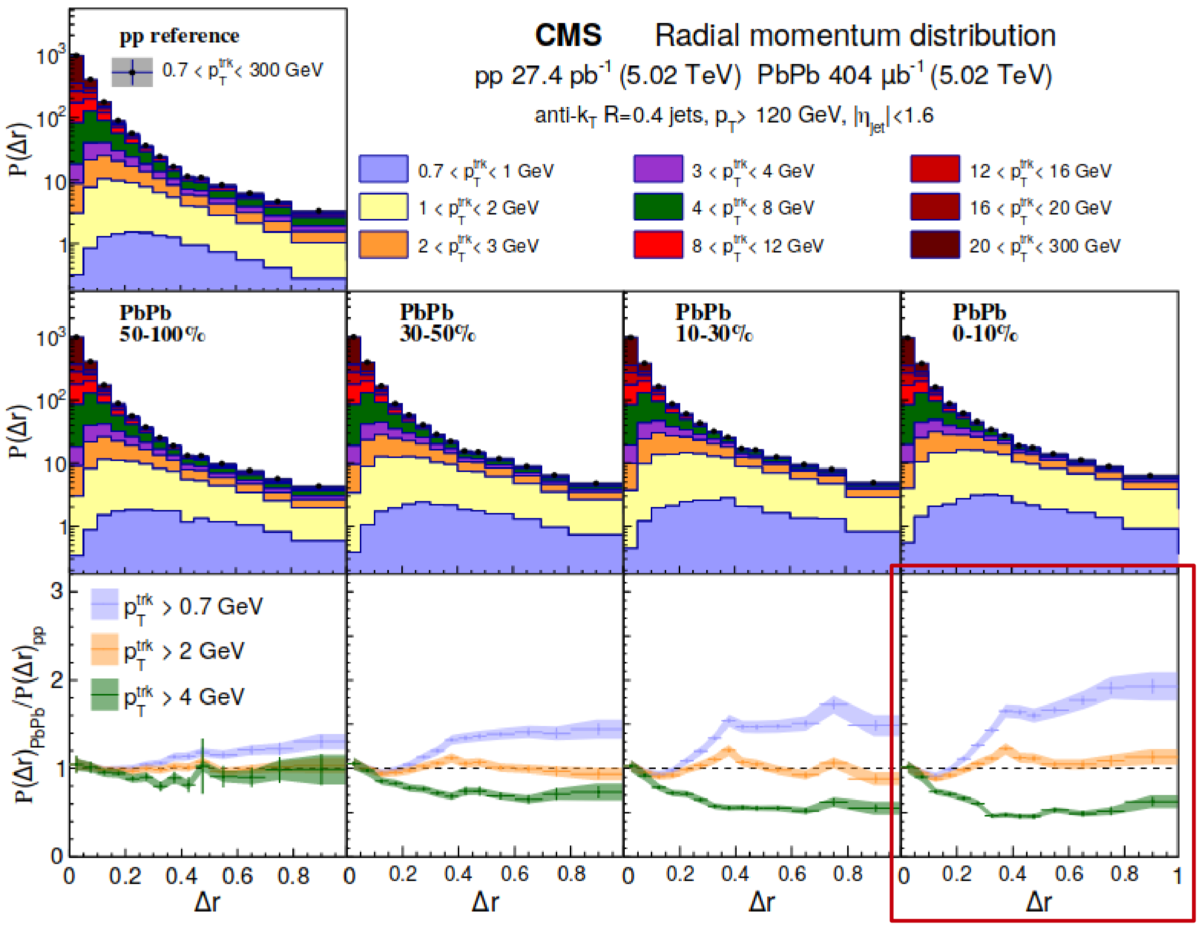


Pros : charm/beauty quarks produced from early primary hard-scatterings in collision

Difficulties :
- low B.R.
- significant invariant mass background
- need excellent pointing resolution for 2^{dry} vertices

III.2 – Phys. case : ex. 2 – in-medium modification on jets

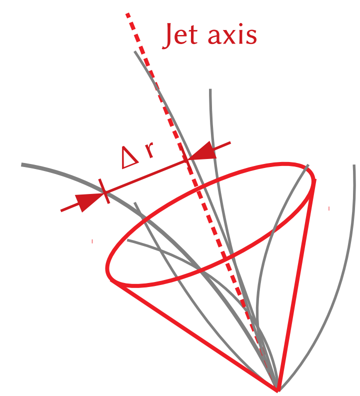
CMS Pb-Pb 5.02 TeV arXiv:1803.00042



- Where does the quenched energy go ?
- How is the vacuum picture altered ?

  - Modification of parton shower ?
  - Modification of fragmentation ?

= f(p_T, jet mass, quark flavour, ...)



Now known with Runs I+II :

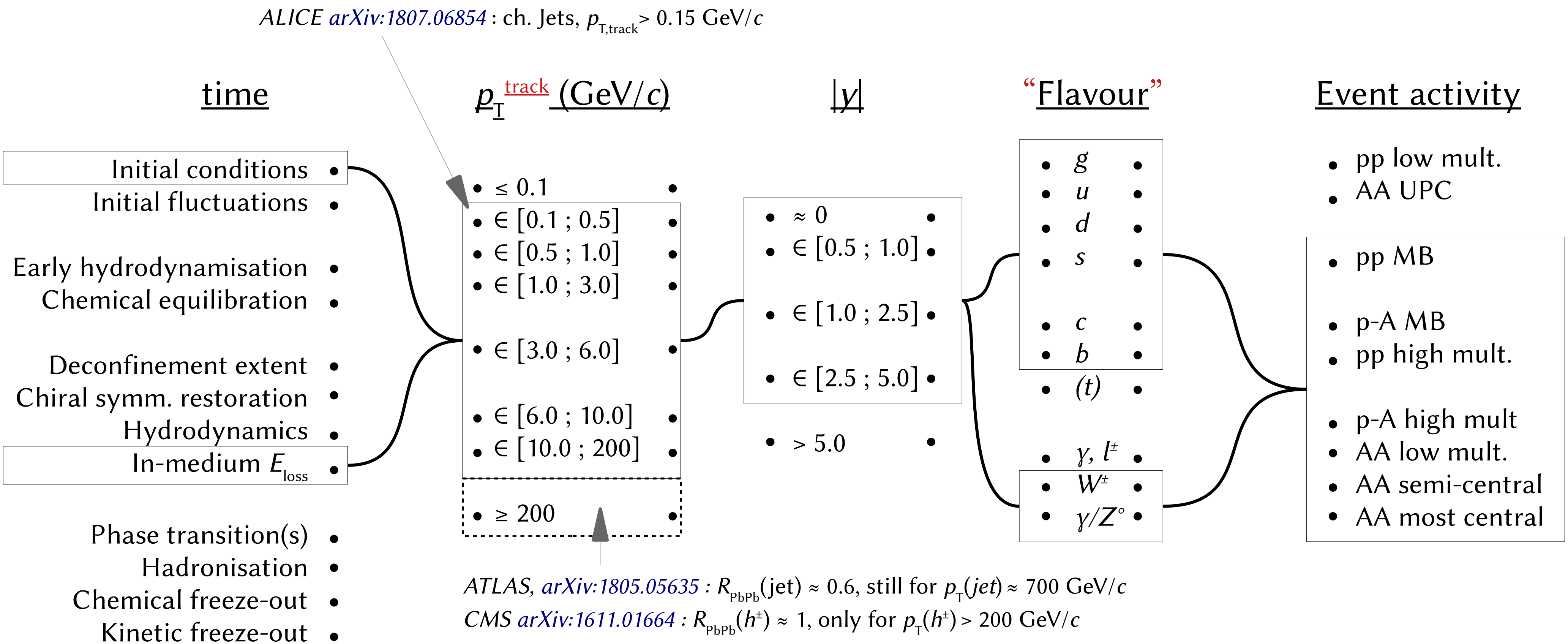
(0-10% AA)/pp diff = important at :

- large Δr (Δr >0.4)

← - low $p_{T,track}$ (p_T < 1 GeV/c)

⟶ (hyper)fine structure/shape jets (N_{ch}, Δr, $\xi = ln(z^{-1})$, z_G, N-subjettiness, ...) with flavour tagging (g Vs. q, c Vs. b, ...) and PID content

III.2 – Phys. case : ex. 2 – in-medium modification on jets



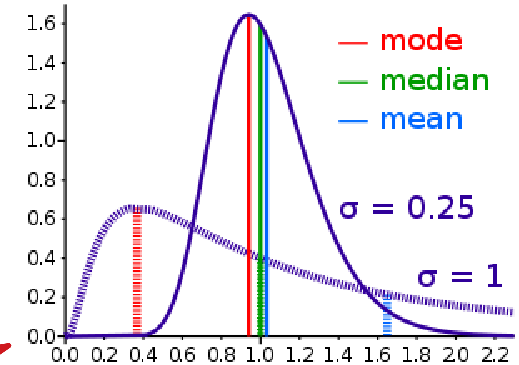
Pros : triggerable hard probes

Difficulties : - subtraction of underlying event
- multiple-energy-scale problem, from hard to soft

III.3 – Phys. case : ex. 3 – net quantum fluctuations

Net quantum number fluctuations at ($\mu_B = 0$)

Q : net charge ($h^+ - h^-$),
B : net baryon ($p - \bar{p}$, $\Lambda - \bar{\Lambda}$, ...)
S : net strangeness ($K^+ - K^-$, $\Lambda - \bar{\Lambda}$, ...)

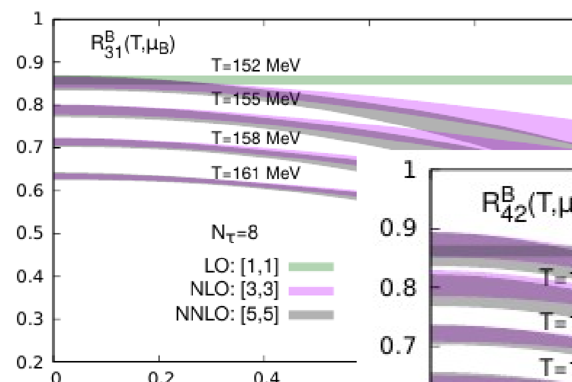


Wikipedia:Skewness

Measure event-by-event fluctuations into distributions with $p_T > 0$ GeV/c + over large y

(i.e. p_T-integrated quantities)

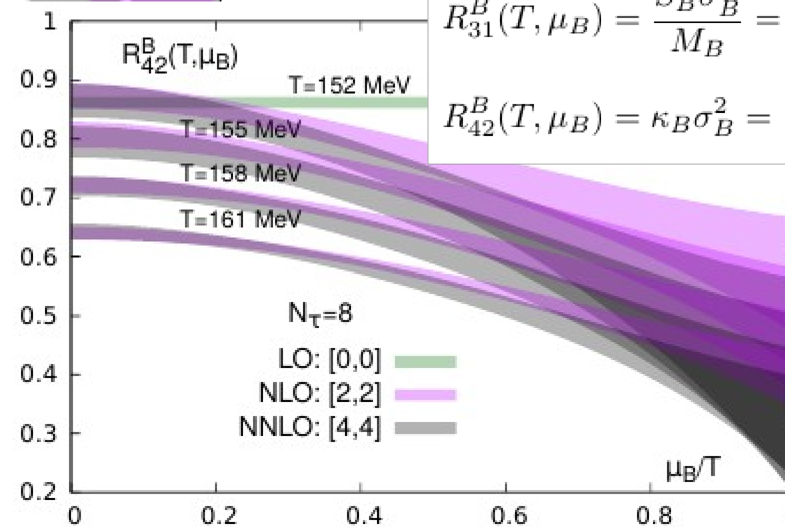
1st moment, m_1 : mean M
2nd moment, m_2 : variance σ^2
3rd moment, m_3 : ∝ skewness S
4th moment, m_4 : ∝ kurtosis κ
5th moment, m_5 : *no name*
6th moment, m_6 : ...
7th moment, m_7 : ...



HotQCD, arXiv:2001.08530

$$R^B_{31}(T,\mu_B) = \frac{S_B \sigma^3_B}{M_B} = \frac{\chi^B_3(T,\mu_B)}{\chi^B_1(T,\mu_B)}$$

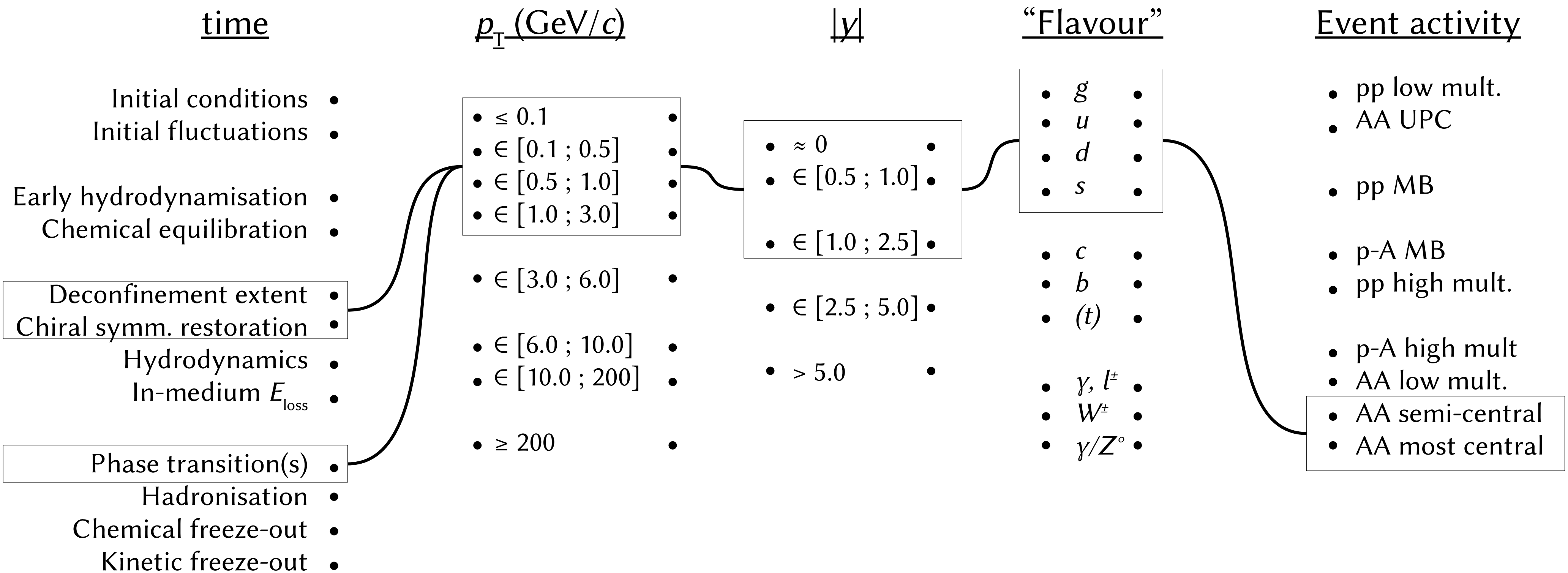
$$R^B_{42}(T,\mu_B) = \kappa_B \sigma^2_B = \frac{\chi^B_4(T,\mu_B)}{\chi^B_2(T,\mu_B)}$$



→ *key* : ratios m_j/m_i (e.g. m_4^B/m_2^B)
to access direct comparison to LQCD for
(deconfinement d.o.f.
+ chiral restoration
+ nature of transitions)

See also EMMI, arXiv:2001.08831

III.3 – Phys. case : ex. 3 – net quantum fluctuations



Pros : challenge and/or test ~directly to LQCD

Difficulties : event-by-event measurement, calling for high efficiency (tracking + PID) over large acceptance

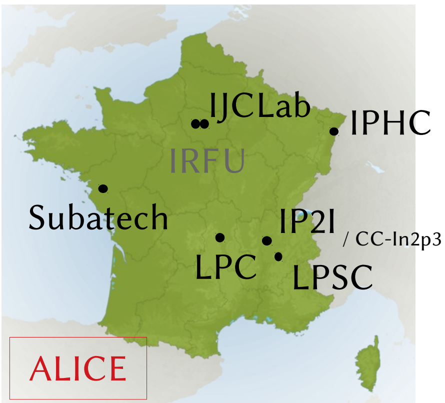
e.g : net baryon fluctuations via ($\bar{p}$-p) :

- $m_4/m_2 \approx$ ok for Runs III+IV (need > 0.2 .10^9 0-5% Pb-Pb evts ↔ > 0.5 nb^{-1}),
- $m_6/m_4 \not\approx$ ok for Runs III+IV (need > 5.0 .10^9 0-5% Pb-Pb evts ↔ > 13.5 nb^{-1})

(⟶ *HL-LHC Yellow Report arXiv:1812.06772, Ch.3 p.35*)

Part C – Where we are, 2020

II.1 – 2020 picture : Human Ressources



	ALICE France		CMS France (*Heavy ions*)	LHCb France (*Heavy Ions*)
	CNRS + Ens. Sup	CEA	CNRS + Ens. Sup	CNRS + Ens. Sup
Chercheurs	**25**	**8**	**2+1**	**2.5**
Ens.-Ch.	**11**	-	-	1
Post-docs	$\mathcal{O}(2)$	$\mathcal{O}(1)$	1	1
PhD students	$\mathcal{O}(10)$	$\mathcal{O}(4)$	2	2
ITA	**61**	**11**	0 *HI*, but *n* in common with pp (GT01)	0 *HI*, but *m* in common wit pp (GT01)
PWG / sub-PWG responsabilities	✓(past) and/or ✓(currently)			
Construct°/ Operat°	• MFT (c project leader) • µTrk+µID (c project leader) • ITS2 • (Em/DCal) • Data Preparation Group DPG (calibrat°, Quality Assu.) • Computing		• ECal & HGCal • Computing	• SMOG2
			Synergies with the respective "pp" communities	

II.2 – 2020 picture : LHC runs I+II experiment config.

→ systematism of the measurements : ∀ y ? ∀ p_T ? ∀ system ? ∀ event activity ?

1.

	$p_T(h^{\pm})$ (GeV/c)						PID	y			system			
	0 - 0.08	0.08 - 0.15	0.15 - 0.5	0.5 - 1	1 - 10	10 - 200	Det.	≤1	≤ 2	fwd	pp, MB + HighMult	p-Pb MB + HighMult	Pb-Pb 101-70%	Pb-Pb 0.5-0%
ALICE	✗	≡	✓	✓	✓	≡	✓	✓	✗	≡	✓	✓	✓	✓
ATLAS	✗	✗	≡	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
CMS	✗	✗	≡	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
LHCb	≡	✓	✓	✓	✓	≡	✓	✗	✗	✓	✓	✓	✓	✗
								✓ SMOG		✗ SMOG				

γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p
(+ topological identifications) •

2.

delivered Vs.
inspected Vs.
recorded luminosity

(*acc-stats.cern.ch/LHC*)	CMS (≈ ATLAS)	LHCb	ALICE
2018, pp $\sqrt{s}$ = 13 TeV : $\mathcal{L}_{int}$	66 830 pb^{-1}	2460 pb^{-1}	27.4 pb^{-1}
pp *in-bunch* pile-up (2015-2018)	μ_{CMS} $\mathcal{O}$(30-40)	μ_{LHCb} $\mathcal{O}$(1)	μ_{ALICE} ≤ 0.02
2018, Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV : $\mathcal{L}_{int}$	≈ 1800 μb^{-1}	≈ 225 μb^{-1}	≈ 900 μb^{-1}

Key = data taking strategy for physics at the event level (campaign planning + $\mathcal{L}_{instantaneous}$ levelling)
→ Particle in its (QCD) context ≠ physics ~independently of the event

II.3 – 2020 picture : after LHC *runs I+II*, done Vs. tbd

(phenomena of interest)

1. **Initial state,** its fundamental nature

2. **“hydrodynamization” / Equilibration:**
   AA-like signs at high $\sqrt{s}$ in **small systems**
   - Which mechanisms drive a (quantic QCD system) into a (high-T ~equilibrated medium) ?
   - such an equilibration, possible in small systems ? or are there elementary QCD mechanisms that mimic, initiate the observed collectivity ?

3. **In-medium dynamics** (low and high p_T)
   - hydrodynamics, already entered into precision era…
   - in-medium energy loss, on the verge to do so

4. **Hadronisation,** processes to create hadrons, flavour by flavour

(particles of interest)

π^+ π^0 K^+ K^0_S … p Λ Ξ^- Ω^- …

$\eta(547)$ $\omega(782)$ $K^0(892)$ **$\phi(1020)$**

$\Sigma^{\pm}(1385)$ $\Lambda(1520)$ $\Xi^0(1530)$

d t ^3He ^4He … $^3_\Lambda H$ …

(D^0 D^+ D^{*+} D_s)… η_c J/ψ χ_{ci} $\psi(2S)$ … Λ_c^+ Ξ_c

heavy-flavour ($\mu^{\pm}$, $e^{\pm}$)

B^0 $B^{\pm}$ B^0_s … $\Upsilon(1S,2S,3S)$ … Λ_b^0

γ l^+l^-

jets

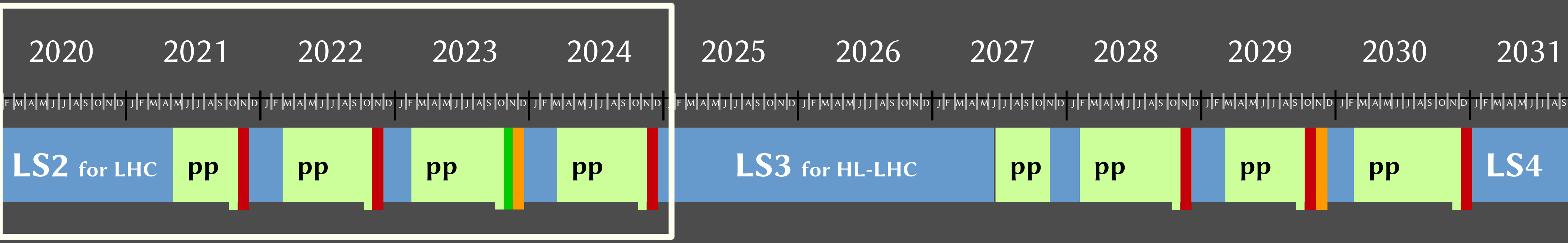
$W^{\pm}$ Z

Colour conventions :

- ■ : physics for large parts already explored or in full swing
- ■ : tackled but further precision needed/expected
- ■ : missing so far (limited by statistics or detector capabilities)

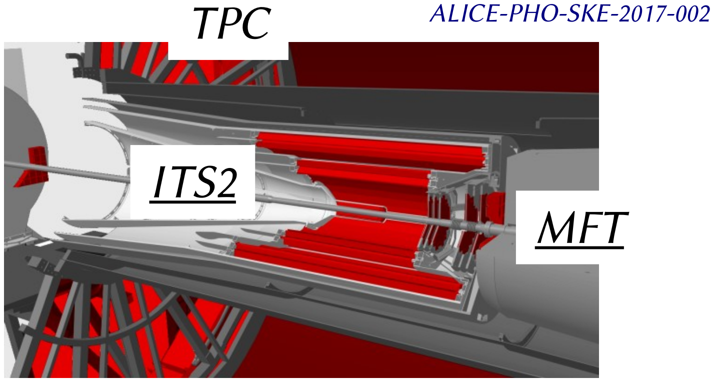
Underlined : with French contributions

Part D – Run III, after LS2 (≥2021)



LHC running plan

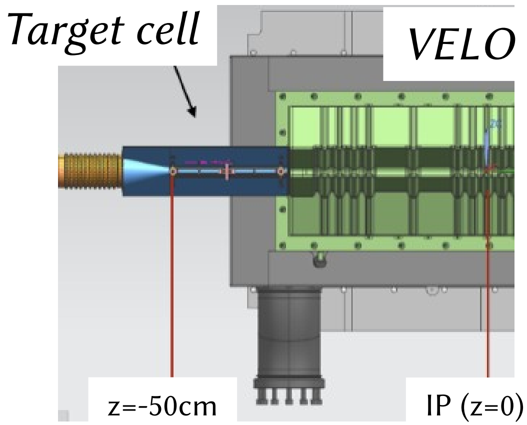
IV.1 – Run III : LHC projects approved and on rail



ALICE : major upgrade (ITS2, MFT, TPC GEM, …
+ readout electronics µTrk, µID)

- Continuous readout = MB (triggerless)
- low material budget, "maintained" y≈0
- PID, maintained y≈0
- tracking, improved (AxEff + space resol°) y≈0 + fwd

CMS : config Run III ≈ Runs I+II



LHCb : major upgrade (SMOG²; Pixel VELO + UT = µStrips + DT = SciFi)

- Continuous readout + software trigger
- SMOG² : Fixed Target higher luminosity
  ([p,Pb]+noble gas = He, Ne, Ar, … or light gas : H_2, N_2, O_2 …)
- PID, "maintained"
- tracking, improved

	$p_T(h^\pm)$ (GeV/c)						PID	y			system			
	0 - 0.08	0.08 - 0.15	0.15 - 0.5	0.5 - 1	1 - 10	10 - 200	Det.	≤1	≤ 2	fwd	pp, MB + HighMult	p-Pb MB + HighMult	Pb-Pb 101-70%	Pb-Pb 0.5-0%
ALICE	✗	=	✓	✓	✓	=	✓	✓	✗	=	✓	✓	✓	✓
ATLAS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
CMS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
LHCb	=	✓	✓	✓	✓	=	✓	✗	✗	✓	✓	✓	✓	✗
								✓ SMOG		✗ SMOG				

with $\mathcal{L}_{\text{instantaneous}}$ ++

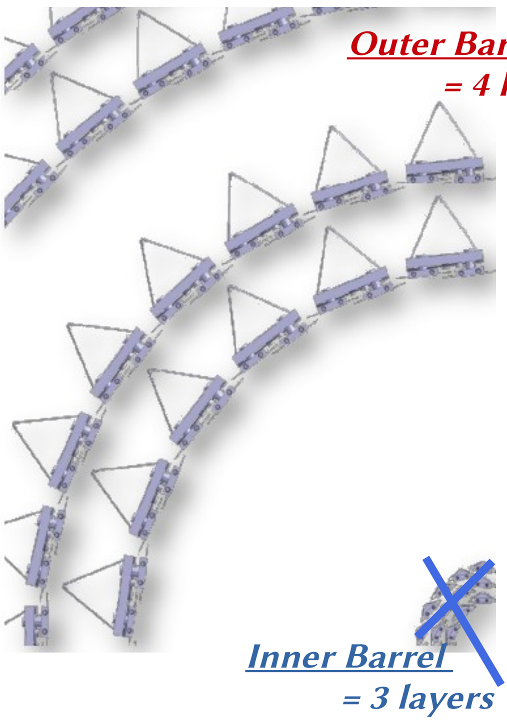
> 30% most central Pb-Pb

Underlined

Part E – Run IV, after LS3 (≥2027)

LHC running plan

V.1 – ALICE : ITS-3



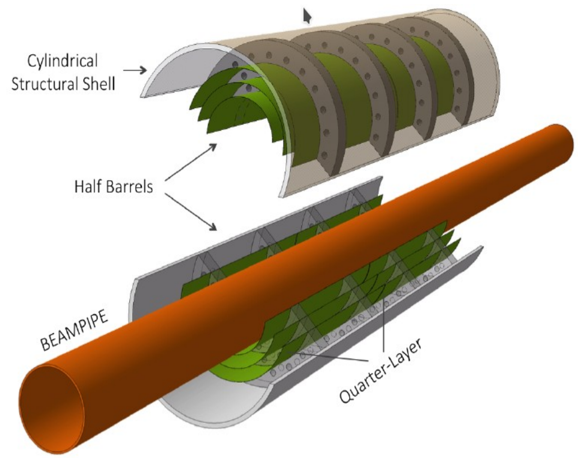


Fig.7 EoI ITS3
ALICE-PUBLIC-2018-013

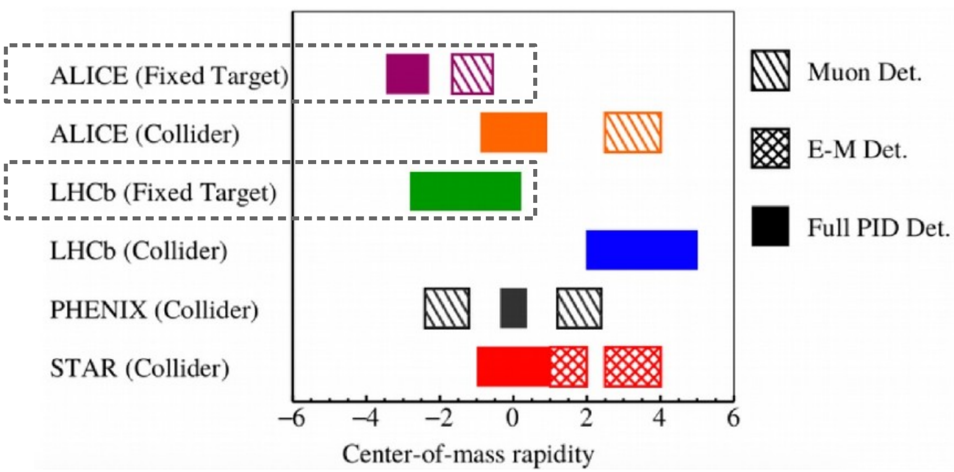
<u>Keys</u> :
|η| < 2.0
$\mathcal{O}$(15x15) μm²
ultra-low material budget
(0.05% x/X° per layer)

- improve track pointing resolution
  (Heavy-flavour vertexing at low p_T)
  prompt/non-pr Λ_C^+, D_s^+, Ξ_C ...
  + Λ_b ? $\Lambda_c n$?
- strangeness tracker

	$p_T(h^{\pm})$ (GeV/c)						PID	y			system			
	0 - 0.08	0.08 - 0.15	0.15 - 0.5	0.5 - 1	1 - 10	10 - 200	Det.	≤1	≤ 2	fwd	pp, MB + HighMult	p-Pb MB + HighMult	Pb-Pb 101-70%	Pb-Pb 0.5-0%
ALICE	✗	=	✓	✓	✓	=	✓	✓	✗	=	✓	✓	✓	✓
ATLAS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
CMS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
LHCb	=	✓	✓	✓	✓	=	✓	✗	✗	✓	✓	✓	✓	✗
								✓ SMOG		✗ SMOG				

<u>Project milestones</u> :
. EoI *ALICE-PUBLIC-2018-013*
. 2019 : LHCc blessing for R&D
. TDR by 2022

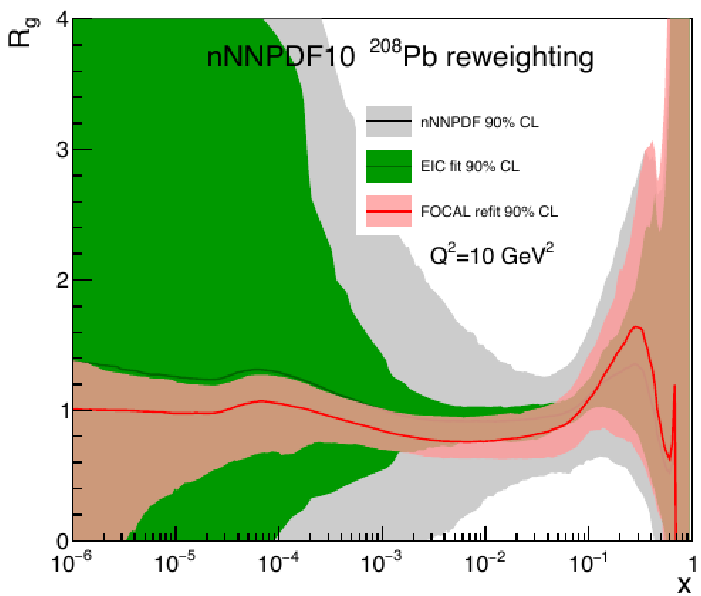
V.2 – ALICE : FoCal + Fixed target



Keys :
$\sqrt{s_{NN}}$ = 72-115 GeV, solid targets at z = +4.8m
(bent crystal and solid target, target versatility)

- Physics cases similar to SMOG2
  (QGP physics at $\sqrt{s_{NN}}$ between RHIC top energy and BES, high *x* in nPDF (x > 0.1), ...) but ++ bckwd *y*

Project milestones :
. ESPP *CERN-PBC-Notes-2019-004*
. Ongoing UA9 R&D + performance studies



Keys :
Si+W EmCal + Pb-Sci HCal, 3.2 < η < 5.8 at z = +7m

- forward π^0 , isolated γ
- correlations forward Vs mid-y
- ultra-low x in nPDF

Project milestones :
. LoI *arXiv:1708.05164* + CDR *ALICE-PUBLIC-2019-005*
⟶ LHCc final review : June 2020

V.3 – CMS : tracker + MTD + HGCal

Keys :
In Run 4, after LS3, new CMS opportunities...

a) tracking on very large η coverage as well ($|\eta| < 4$)
CMS tracker, CERN-LHCC-2017-009

b) mid-y + fwd calorimetry ($|\eta| < 3$) : $PbW0_4$ EmCal + HGCal SiPM sampling
CMS HGCal, CERN-LHCC-2017-023

c) MTD = pile-up tagger + TOF ...
CMS MTD = "pile-up tagger", *Fig 1.5 + Fig 5.23 - TDR CERN-LHCC-2019-003*
(LGAD in endcap or SiPM in barrel ⟶ $\sigma_{\text{time stamp}} \approx 30$ ps),

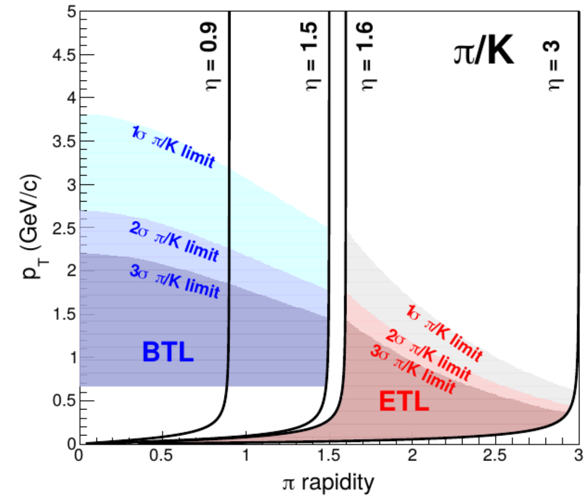
- Jet, onia, open charm, long range correlations

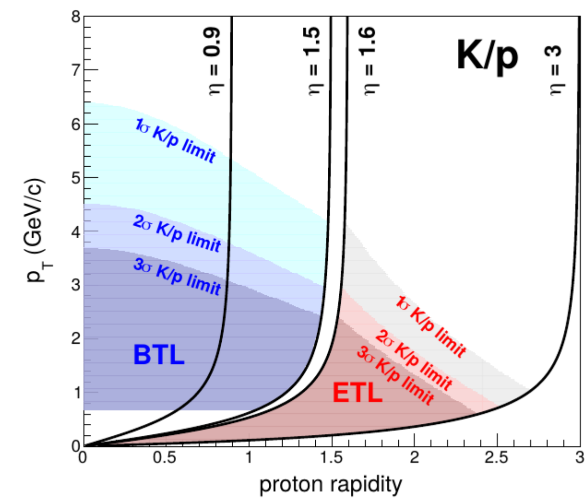
Project milestones : all approved, towards production

	$p_T(h^{\pm})$ (GeV/c)						PID	y			system			
	0 - 0.08	0.08 - 0.15	0.15 - 0.5	0.5 - 1	1 - 10	10 - 200	Det.	≤1	≤ 2	fwd	pp, MB + HighMult	p-Pb MB + HighMult	Pb-Pb 101-70%	Pb-Pb 0.5-0%
ALICE	✗	=	✓	✓	✓	=	✓	✓	✗	=	✓	✓	✓	✓
ATLAS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
CMS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
LHCb	=	✓	✓	✓	✓	=	✓	✗	✗	✓	✓	✓	✓	✗
								✓ SMOG		✗ SMOG				

with $\mathcal{L}_{\text{instantaneous}}$ ++

Fig 1.5 - TDR CERN-LHCC-2019-003





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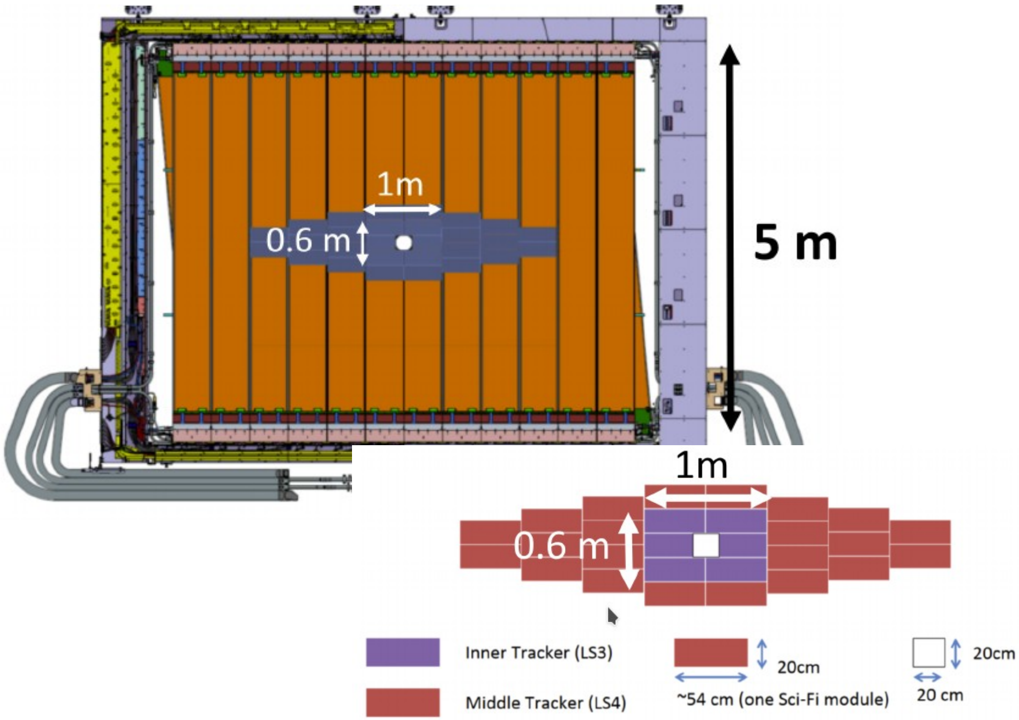
V.4 – LHCb : early Mighty Tracker

DT = SciFi + Mighty Tracker



	$p_T(h^{\pm})$ (GeV/c)						PID	y			system			
	0 - 0.08	0.08 - 0.15	0.15 - 0.5	0.5 - 1	1 - 10	10 - 200	Det.	≤1	≤ 2	fwd	pp, MB + HighMult	p-Pb MB + HighMult	Pb-Pb 101-70%	Pb-Pb 0.5-0%
ALICE	✗	=	✓	✓	✓	=	✓	✓	✗	=	✓	✓	✓	✓
ATLAS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
CMS	✗	✗	=	✓	✓	✓	~	✓	✓	✗	✓	✓	✓	✓
LHCb	=	✓	✓	✓	✓	=	✓	✗	✗	✓	✓	✓	✓	✗
								✓ SMOG		✗ SMOG				

with $\mathcal{L}_{\text{instantaneous}}$ ++

> 10% most central Pb-Pb

Keys :

Collider mode : pp, pA, AA

+ (polarised) fixed target mode :

Run IV = SMOG2 ⟶ LHCspin

First elements (6 to 10) of the Mighty Tracker in DT likely $\mathcal{O}$(100x500) μm² HV-CMOS pixels

- HF (*c*,*b*, open/hiden, mesons/baryons)
- em probes (γ, Drell-Yan $\mu^+\mu^-$, ...)
- towards more and more central AA

- FT LHCspin : nucleon-spin physics (Sivers asymm. between DY and SIDIS)

Project milestones :

. LoI *CERN-LHCb-INT-2019-007*

. TDR Mighty-tracker by 2020-21

. TDR LHCspin ... ?

Conclusion

Conclusion : food for thoughts / discussion

To In2p3 :

- Feedback : what are the trends after Bad Honnef meeting in January ?
  LHeC on the table ? Long-term = FCC-ee then FCC-hh ?

- Support strategy for HR by In2p3 in the coming 10 years (PhD, Post-doc, Permanent positions)

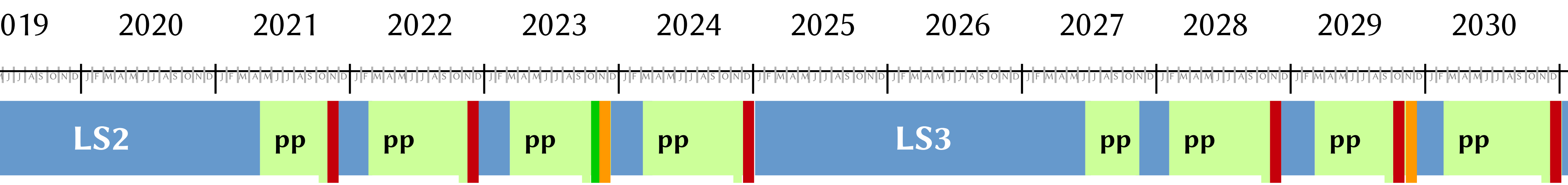
- Difference (+ or -) to be made between projects with/without hardware contributions ?

To In2p3 <u>and</u> to the audience :

- How to manage and steer the community ?
  . top-down ("some sharp decisions from In2p3 direction" = "cut and focus") ?
  . bottom-up ("let the community get self-organised along the way") ?

- ...

Wrap-up.1 : campaigns in (LHC run III) + (HL-LHC run IV)



1. Already very enthousiasming and rich programme in Runs III+IV

2. We will know in ~June 2020 the favoured LHC running plan for Run III
   (“AA in 2022 ?”, “p-O as well as O-O pilot runs ?”, “When p-Pb ?”)

3. Runs III and, even more, the key Run IV = channelled entry point for what to come next ?
   e.g. . involved into ALICE ITS3 Run IV ? ⟶ tracker ANGHIE ≥Run V ?
   . CMS HGCal ? ALICE FoCal Run IV ? ⟶ pre-shower calorimetry ANGHIE ≥Run V ?
   . CEA’s interests for Heavy Flavours + e.m. probes at forward *y*, gradually moving to LHCb ≥Run V

Wrap-up.2 : 2030 picture after *runs III+IV*, done Vs tbd ?

(phenomena of interest)

1. Initial state, 1st grasp on its nature

2. Equilibration / "hydrodynamization" :
- Clearer picture with small system "scan"
(pp high mult + small campaigns p-O, O-O, Ar-Ar)

3. In-medium dynamics (low and high p_T)
- low p_T: hydrodynamics = precise view
  . ultra-low pT (≤0.1 GeV/c) in good part missing
  . light (hyper-)nuclei still not fully explored
- in-medium energy loss :
  clear progress will be made,
  but wil they be decisive ?

4. Hadronisation, flavour by flavour
- Quite some view on the charm meson sector
- Charm baryons still with large uncharted territories
- Exploration started into beauty sector

(particles of interest)

π^+ π^0 K^+ K^0_S … p Λ Ξ^- Ω^- …

$\eta(547)$ $\omega(782)$ $K^0(892)$ ϕ**(1020)**

$\Sigma^\pm(1385)$ $\Lambda(1520)$ $\Xi^0(1530)$

d t ^3He ^4He … $^3_\Lambda H$ …

(D^0 D^+ D^{*+} D_S)… η_C J/ψ χ_{Ci} $\psi(2S)$ … Λ_C^+ Ξ_C

heavy-flavour ($\mu^\pm$, $e^\pm$)

B^0 $B^\pm$ B^0_S … Υ(1S,2S,3S) … Λ_b^0

γ l^+l^-

jets

$W^\pm$ Z

Colour conventions :
- ■ (green) : investigations for large parts already explored or in full swing
- ■ (orange) : tackled but further precision needed/expected
- ■ (red) : missing so far (limited by statistics or detector capabilities)

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Appendices

Part A – Physics cases

I.1 – HL-LHC QCD+QGP : for which physics cases ?

1. Measuring QGP temperature = f(time) [low mass e^+e^-]

2. Nature of phase transitions (deconfinement + chirality) :
   Connecting to LQCD + asserting Hydrodynamics [ultra low p_T]

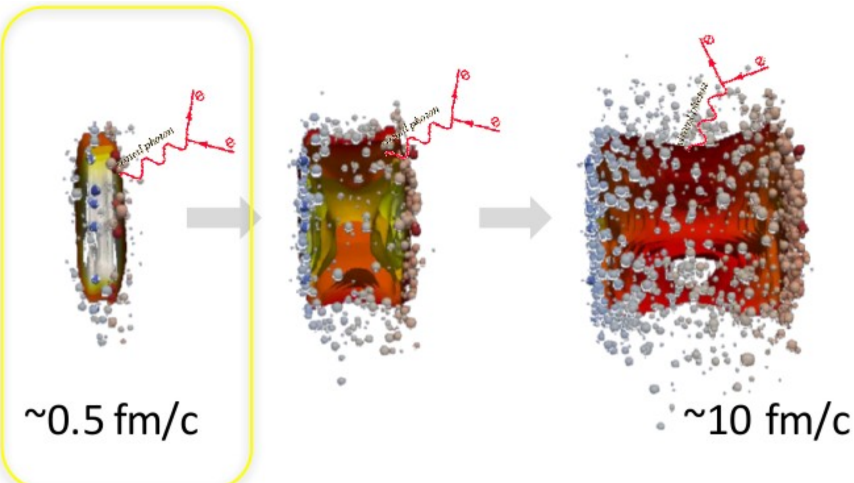
3. Understanding in-medium energy loss [Jets shapes and structures]

4. Challenging the flavour dependence of collectivity [*s*,*c*,*b*]

5. Searching for "SM/BSM" [...]

I.2 – HL-LHC QCD+QGP : low mass (e^+e^-) as virtual γ

1. QGP temperature = f(time) via thermal virtual photons (m_{e+e-} ∈ [0;2.5] GeV/c^2)
   high m_{e+e-} = high T, i.e. early times



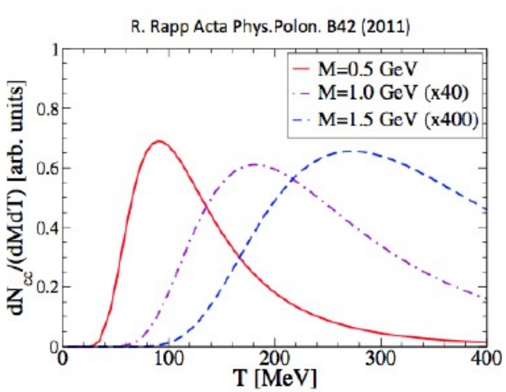
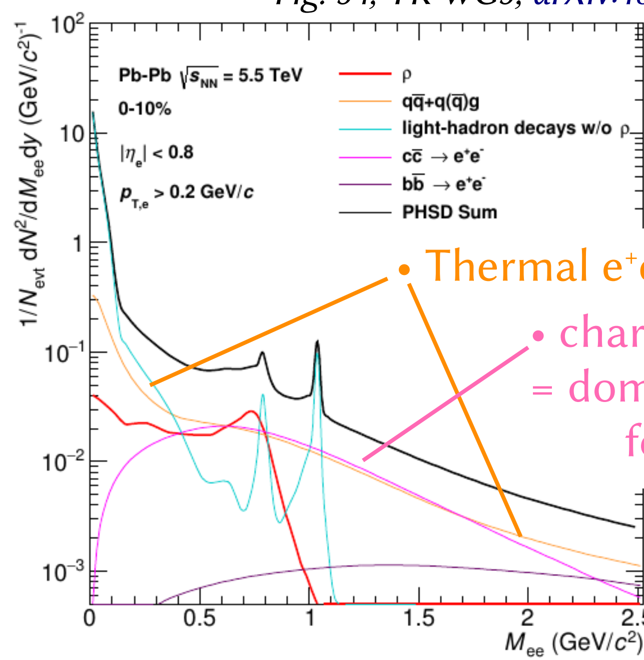


Fig. 54, YR WG5, arXiv:1812.06772



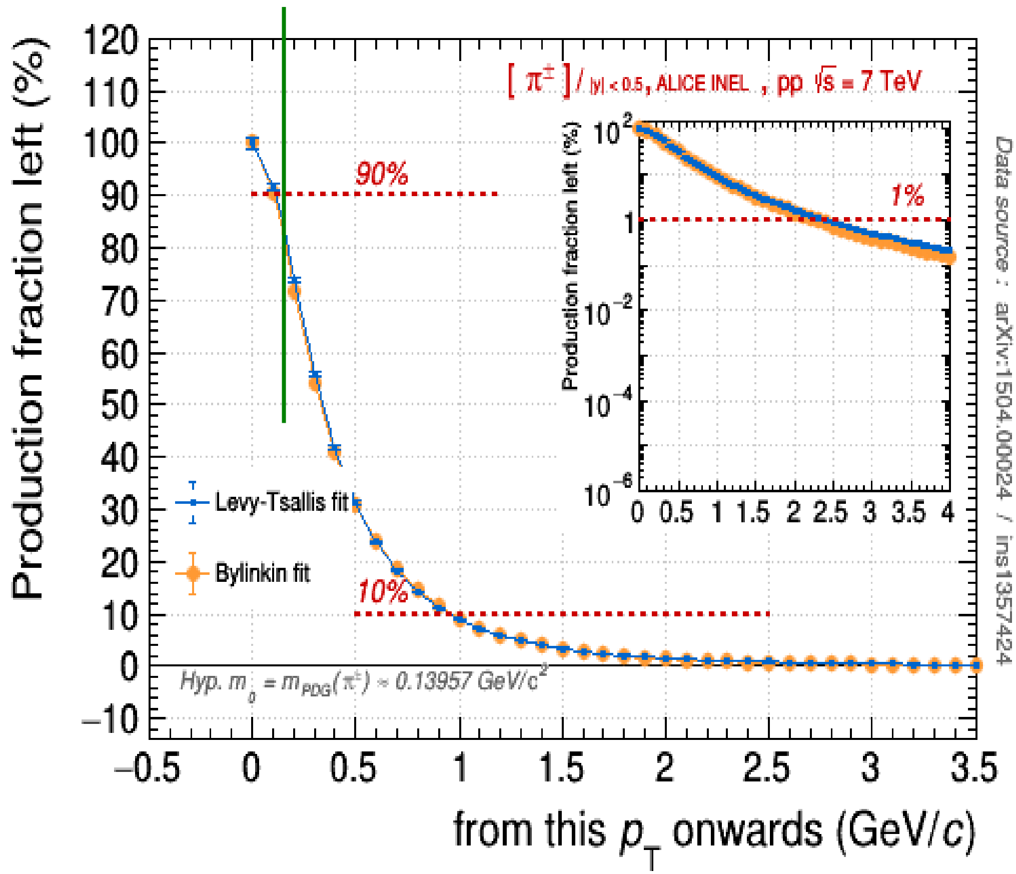
- Thermal e^+e^- signal
- charm semi-leptonic decays = dominant bckgnd for m_{ee} > 1 GeV/c^2

NB :
⟶ so, very good control needed on charm = a must

I.3 – HL-LHC QCD+QGP : low-p_T $\pi^{\pm}$

If your $\pi^+(u\bar{d})$ / $K^+(u\bar{s})$ / p(*uud*) … measurements start above 0.0, 0.1, 0.2 … GeV/c,
how much (*x*%) of the total d*N*/d*y* in pp/in AA do you miss ?

For a given particle type of interest, can you claim a “precision measurement”
if you indeed miss *x*% of production ? → yes or no ? to be decided, case by case…



NB : ALICE pp 7 TeV arXiv:1504.0024
$h^{\pm} > 0.15$ GeV/c → Missed cross-section ≈15%
$\pi^{\pm} > 0.10$ GeV/c → Missed cross-section ≈10%

I.4 – HL-LHC QCD+QGP : the whole AA/pp jets machinery

- Charged-track jets (≈ ALICE), calorimeter jets (≈ ATLAS), calorimeters+charged tracks (≈ CMS)
- Variations in Jet algorithms (Anti-k_T, SIScone, Cambridge-Aachen,...)
- Variations in resolution parameter R (R ∊ [0.1, 0.7])
- Control more or less complex of the event-by-event underlying event subtraction

  ...

→ **Jet (fragmentation, properties, shape)** in the cone and nearby : N_{ch}, dN_{ch}/dr, $d^2N_{ch}/drdp_{T,track}$,

- Pb-Pb 5.02 TeV : ATLAS, arXiv:1805.05424, CMS, arxXiv:1803.00042
- Pb-Pb 2.76 TeV : ATLAS, arXiv:1702.00674, CMS, arXiv:1310.0878
- p-Pb 5.02 TeV : ATLAS, arXiv:1706.02859, CMS, arXiv:1401.4433

→ **PID-tagged and recoiled jets**

- ALICE, arXiv:1712.05603 : ($h^{\pm}$ - jet) correlations, to put limit on jet quenching energy loss in p-Pb
- ALICE arXiv:1608.07201 : (π^0 trigger – associated $h^{\pm}$) correlation for I_{AA} near-side and away-side
- ALICE, QM 18 : D^0-tagged jet
- LHCb, arXiv:1701.05116 : J/ψ-tagged jets in pp 13 TeV, in-cone hadronic activity
- CMS, arxiv:1802.00707 : *b*-tagged dijets for p_T (im)balance
- CMS arXiv:1711.09738 : (isolated γ - jet) azimuthal correlations
- CMS arXiv:1801.04895 (Pb-Pb 5.02 TeV) arXiv:1205.0206 (Pb-Pb 2.76 TeV) : (isolated γ-jet) p_T imbalance
- CMS, arXiv:1702.01060 : (Z^0-jet) correlation, p_T imbalance

→ **Jet mass and jet splitting** (in-medium and in-vacuum parton shower) :

- ALICE, arXiv:1702.00804 : charged-particle jet mass Pb-Pb p-Pb (without soft drop grooming)
- CMS, arXiv:1708.09429 : splitting function with grooming technology
- CMS, arXiv:1805.05145 : grooming for jet mass

Part C – ITS-3 = after LS3 (≥2026, Run 4)

LHC running plan

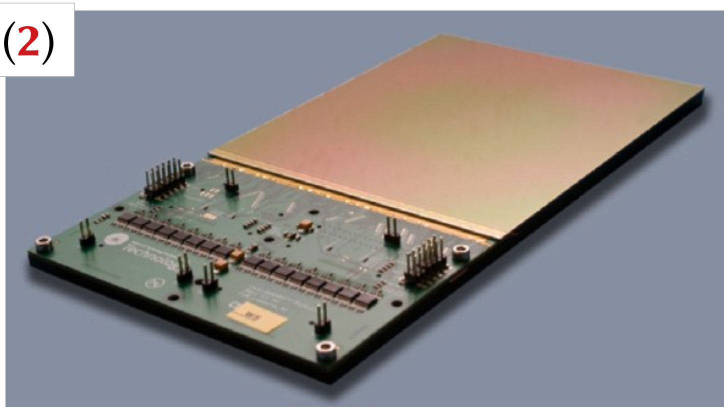
III.1 – ITS-3 : key foreseen features, "closer + lighter"

Keys :

(**1**) - shrinked beam pipe ($r_{\text{beam pipe}}$ = 1.6 cm)
⟶ inner most layer at r_{L0} = 1.8 cm

(**2**) - reticle-size sensor (O[15x10 cm^2])
+ (**3**) - ultra-thin Si CMOS (≤40-μm thick)
⟶ circuitry pushed to periphery (*stitching*), ~no extra services required
⟶ can be curved
⟶ homogeneous 0.05% X/X° per layer

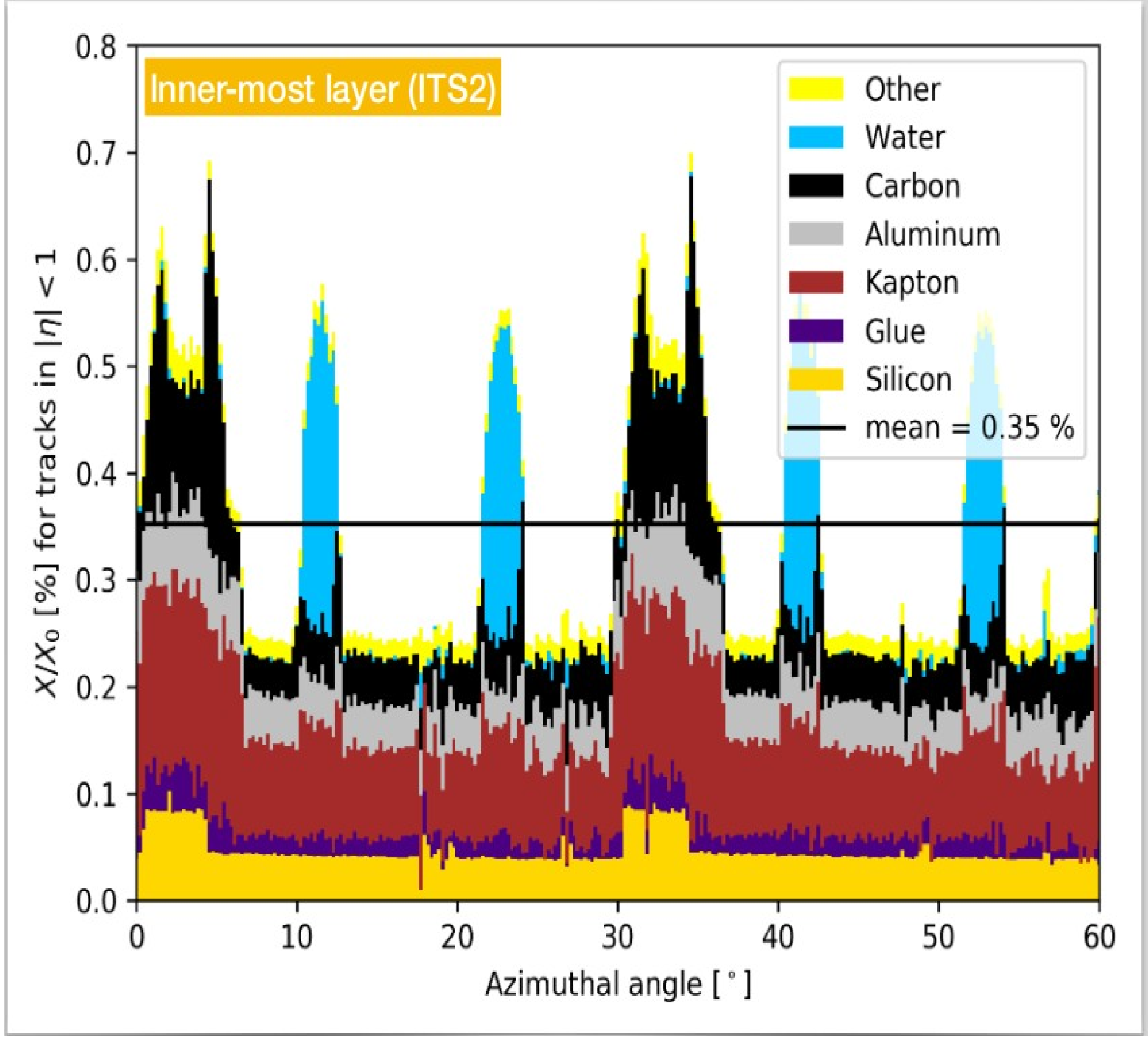
(**2**)



X-ray detector 13.9 x 12 cm^2 TowerJazz 0.18-μm

(**3**)

III.2 – ITS-3 : skimming material budget of ITS-2

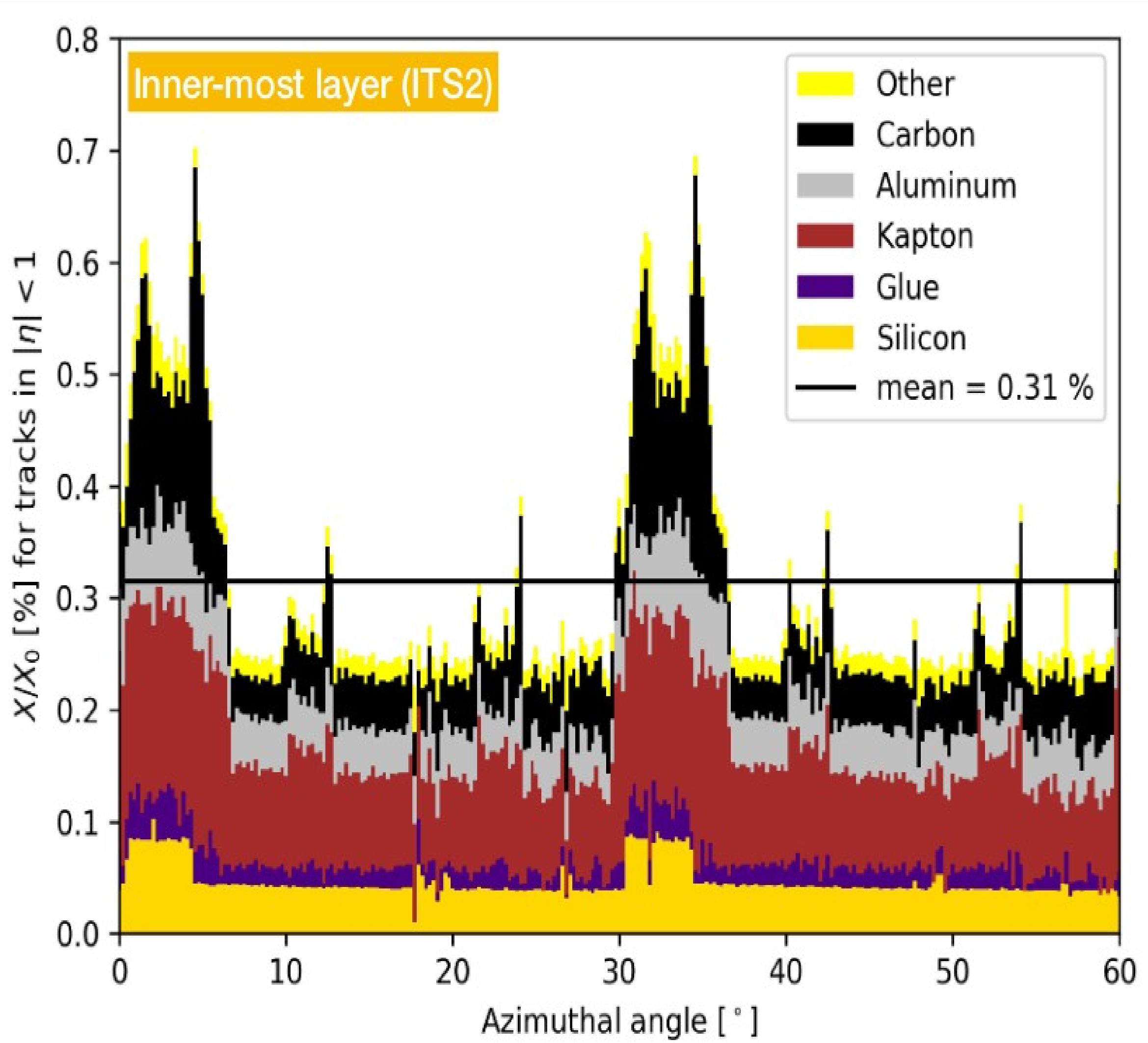


➡ Si only 1/7th of total material

➡ irregularities due to overlaps + support/cooling

LHCc 2019-06 ALICE, M.Mager ITS3

III.2 – ITS-3 : skimming ITS-2



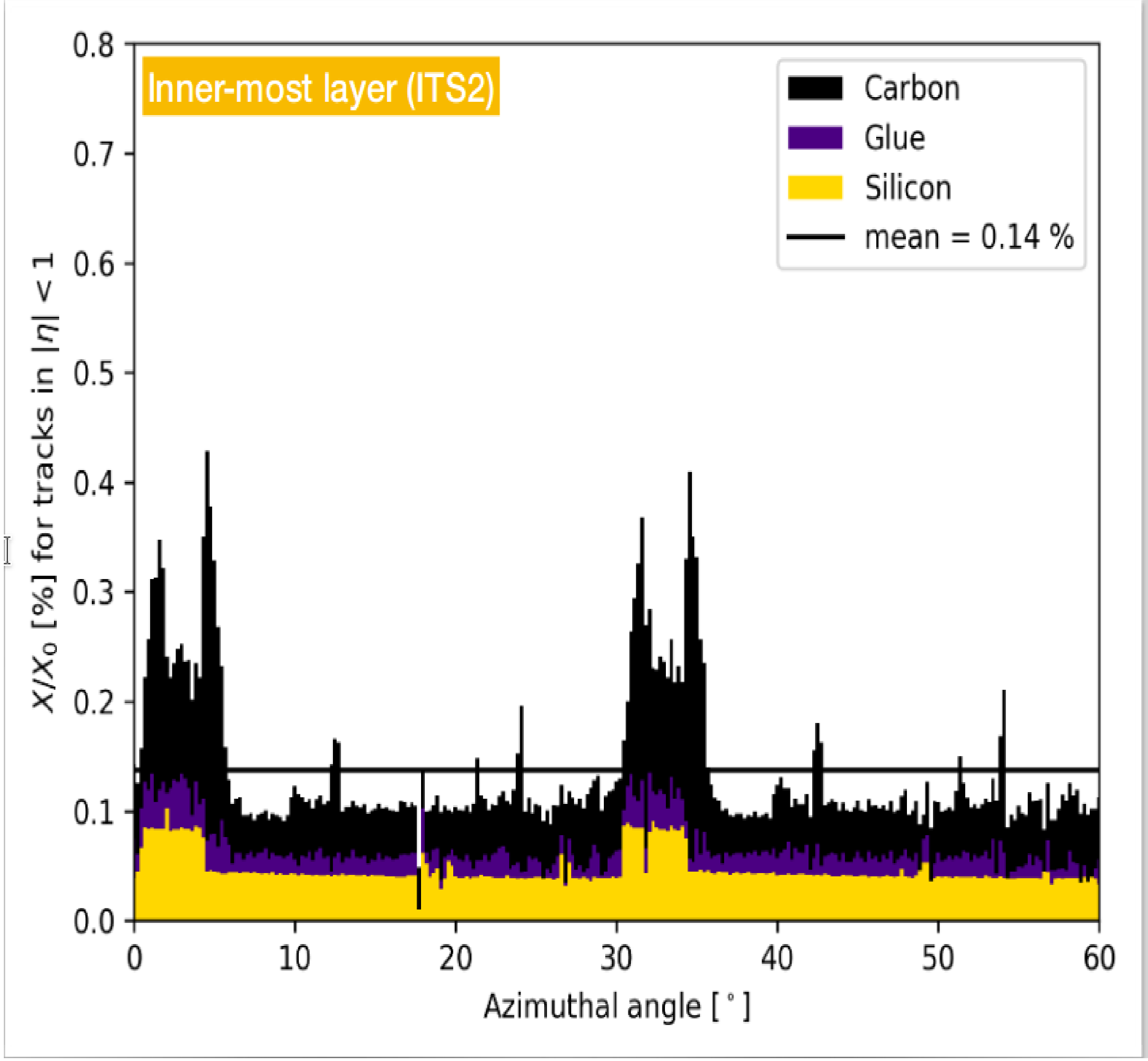
- ➡ Si only 1/7th of total material
- ➡ irregularities due to overlaps + support/cooling

➡ remove water cooling **1.**

➡ possible by reducing power consumption in fiducial volume to <20 mW/cm²

LHCc 2019-06 ALICE, M.Mager ITS3

III.2 – ITS-3 : skimming ITS-2



➡ Si only 1/7th of total material

➡ irregularities due to overlaps + support/cooling

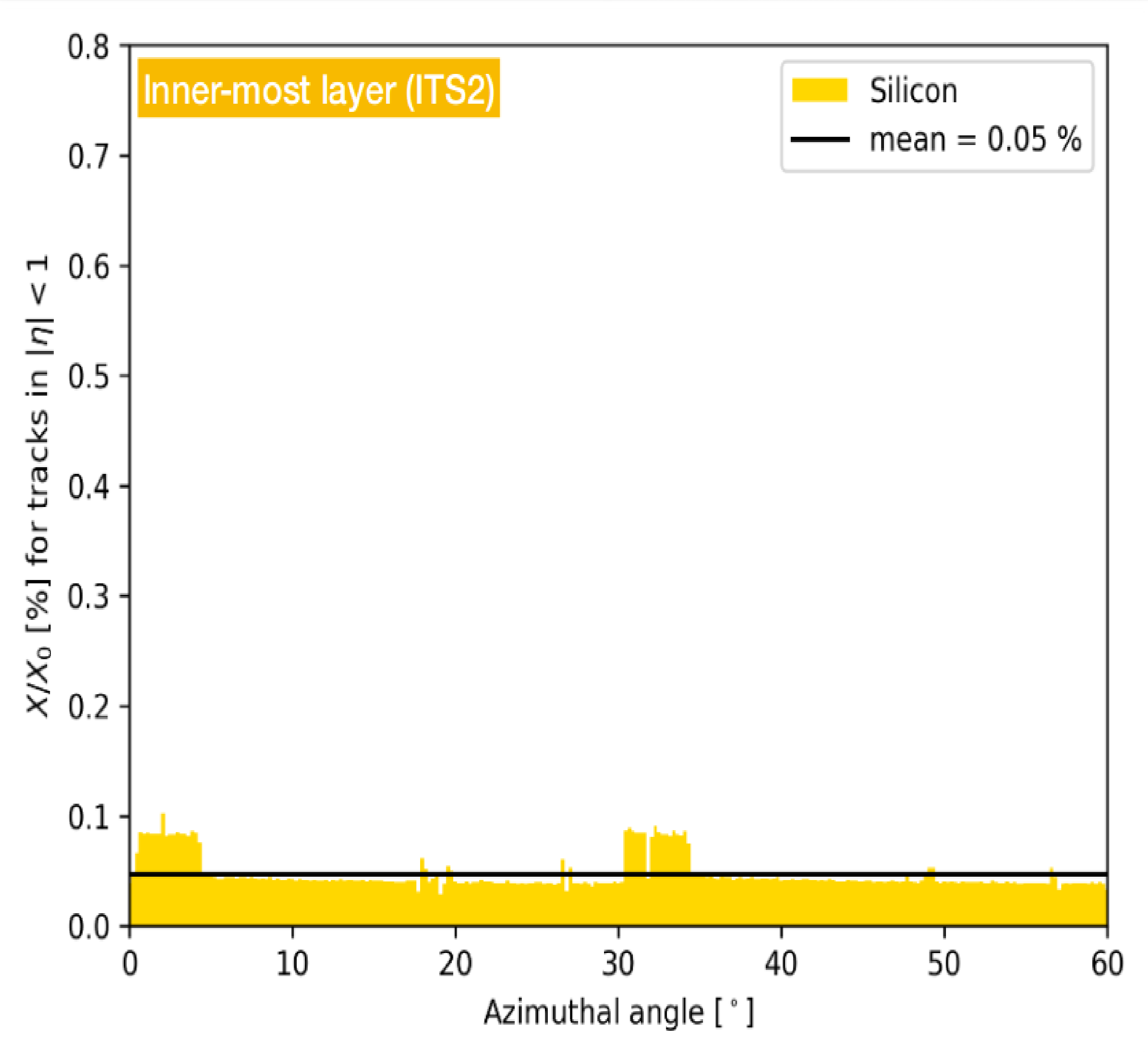
➡ remove water cooling **1.**

➡ possible by reducing power consumption in fiducial volume to <20 mW/cm²

➡ remove external data lines + power distribution **2.**

➡ possible by making a single large chip and that for distribution

III.2 – ITS-3 : skimming ITS-2



➡ Si only 1/7th of total material

➡ irregularities due to overlaps + support/cooling

1. ➡ remove water cooling

➡ possible by reducing power consumption in fiducial volume to <20 mW/cm²

2. ➡ remove external data lines + power distribution

➡ possible by making a single large chip and that for distribution

3. ➡ move mechanical support outside acceptance

➡ benefit from increased stiffness by rolling Si wafers

LHCc 2019-06 ALICE, M.Mager ITS3

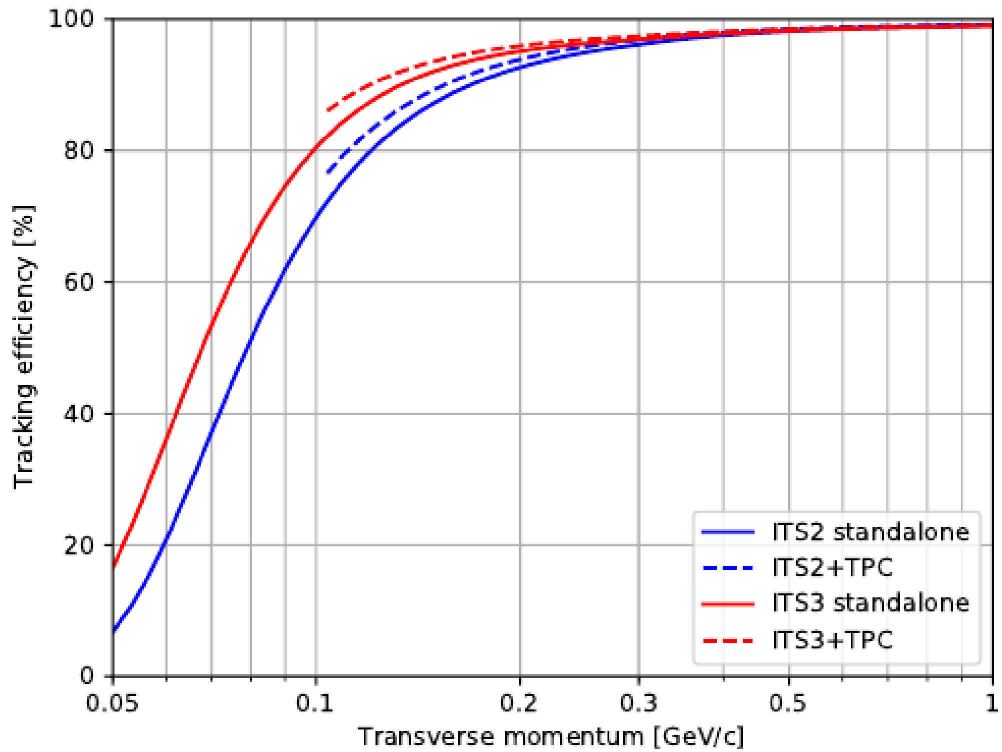
III.2 – ITS-3 : synoptic table

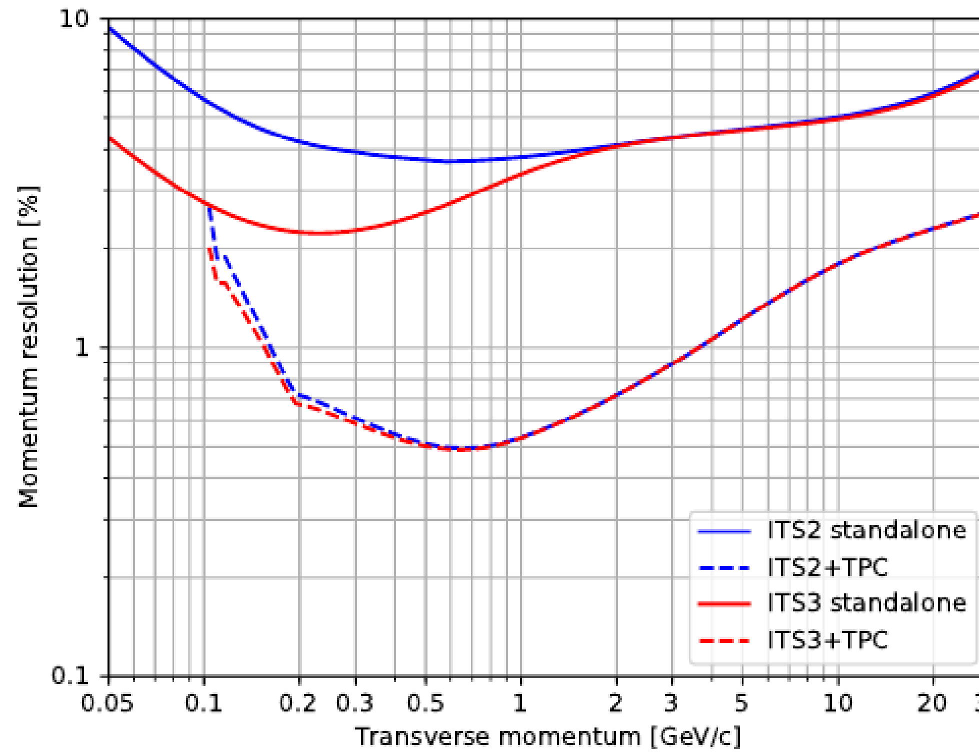
	ITS1 (SPD = 2 inner)	ITS2 (3 inner)	ITS3 (3 inner)
Beam pipe inner radius/thickness	3.0 cm/0.09 cm	1.82/0.08 cm	1.6/0.05 cm
First-layer radius	3.9 cm	2.3 cm	1.8 cm
X/X° per layer	1.1 %	0.35 %	0.05%
|η| coverage	> 1.4	> 2.0	> 2.0
Number of Sensors per layer	80+160	108+144+180	2* to 4
Technology	Hybrid pixels	CMOS	CMOS
Trigger ?	yes	no	not foreseen
Pixel size rφ x z	≈ 50x425 μm²	≈ 30x30 μm²	*≈ 15x15 μm²
Intrinsic resolution rφ / z	12 μm / 100 μm	5 μm / 5 μm	≤ 5 μm / 5 μm
Readout frequency Pb-Pb	< 3 MHz > 300 ns (SPD)	< 50-100 kHz > 20-10 μs	≈ ≥ 1 MHz* ≈ ≤ 1 μs*
Power dissipation in the pixel *matrix*	≈ 550-736 mW/cm² i.e. liquid cooled	~40 mW/cm², i.e. liquid cooled	~7 mW/cm², i.e. air flow

* *if CMOS with the 0.065-μm technology, instead of the current (=ITS-2) 0.180-μm*

III.3 – ITS-3 : why would you invest into it ?

Fig.12, EoI ITS-3, ALICE-PUBLIC-2018-013



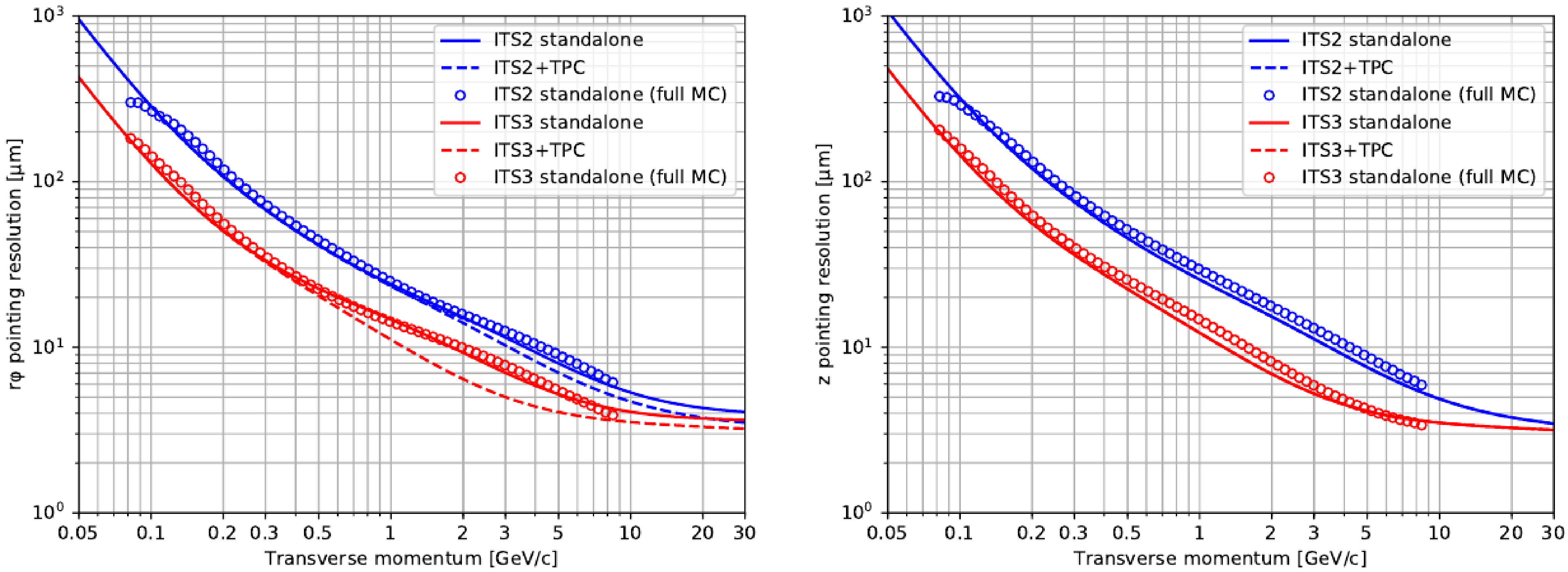


Pb-Pb 0-10% $\sqrt{s_{NN}}$ = 5.5 TeV

(Fast MC tracking tool…)

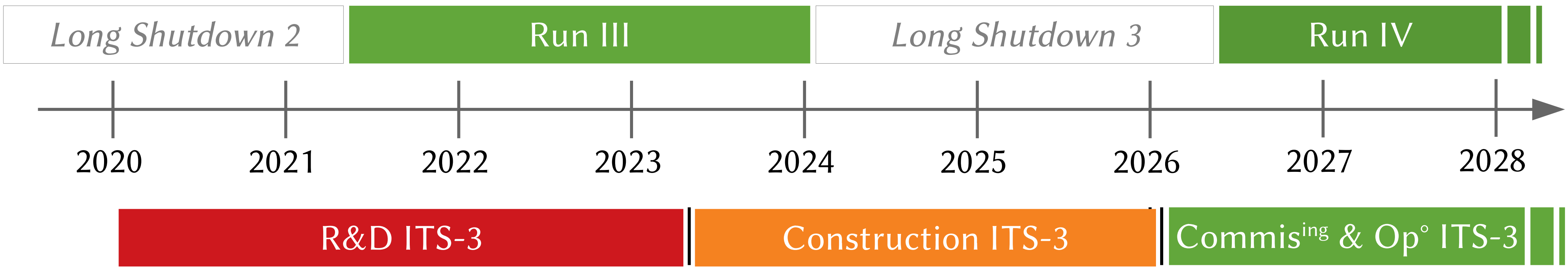
III.3 – ITS-3 : why would you invest into it ?

Fig.11, EoI ITS3, ALICE-PUBLIC-2018-013



Pb-Pb 0-10% $\sqrt{s_{NN}}$ = 5.5 TeV

III.4 – ITS-3 : 5.3 kCHF up to 2025



- **Wafer thinning and bending**
  2019: contact industry
  2019-20 : 1st prototype witj ALPIDE chips + wafers
  >2020 : specific prototype

- **Development of stitched sensor**
  2019-20 : technology test structures
  2020-22 : prototyping chips
  2022-23 : full-scale prototype + final chip

  → *Tech. Design Report + Physics Perf* = 2022

- **Construction** : 2024-25 ≈ 3x2x2 sensors

Table 8: Project cost estimate breakdown (kCHF).

Item	R&D	Construction	Total Cost
Total	≈ 35% 1900	3400	5300
Beampipe	600	900	1500 ≈ 28%
Pixel CMOS sensors	600	800	1400
Sensor test	100	150	250
Thinning & bending	200	300	500
Hybrid printed circuit	100	100	200
Mechanics	150	350	500
Assembly & test	50	200	250
Installation & alignment	0	200	200
Air cooling	100	150	250
Services	0	100	100
Patch panels	0	150	150

LHCc 2019-06 ALICE, M.Mager ITS3

Part D – All-Si = after LS4 (≥2031, Run 5)

B.1 – ANGHIE : In2p3 prospectives, GT03 contribution

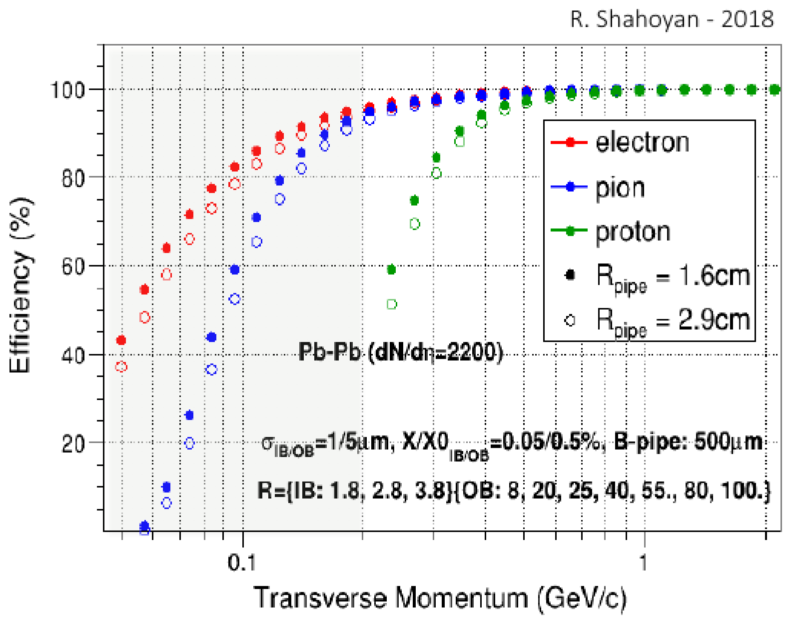
	ITS-2 [3]			ITS-3 [6]			ANGHIE [8]		
Période LHC	Run III + IV (2021-29)			Run IV (2026-29)			≥ Run V (>2030)		
Nombres de couches	3+*4*			3 (*+4 ITS-2*)			*O*(3+*7*)		
R_{tube}	1,82 cm			1,6 cm			1,6 ou 2,9[2]		
r_{L0} / r_{L1} / r_{L2} … r_{Last} (cm)	2,3 / 3,2 / 3,9 … *39,3*			1,8 / 2,4 / 3,0 … *39,3*			1,8 / … ≈ *100*		
Champ magnétique $B_{\text{solénoïde}}$	0,2 ou 0,5 T			0,2 ou 0,5 T			0,2 à 1 T		
Matière par couche (x/X_0)	0,3 % à *0,8 %*			0,07 % à *0,8 %*			0,05 % à *0,5 %*		
Taille d'un pixel (μm²)	≈ 30 x 30			≈15 x 15 (+ *30* x *30*)			≈10 x 10 (+ *30* x *30*)		
Résolution temporelle	≥ 2-5 μs			2-5 μs			≤ 1 μs		
Résolution spatiale	5 μm			5 μm			≈ 3-5 μm		
Couverture en η	|η| < 2,0 à *1,3*			|η| < 2,0 à *1,3*			|η| < 4,0		
$\varepsilon_{tracking}(p_T(h^{\pm})=X\ GeV/c)$	1	0,1	0,05	1	0,1	0,05	1	0,1	0,05
	98 %	60 %	10 %	98 %	75 %	20 %	98 %	75 %	20 %
Coûts totaux (R&D + Constr.)	≈ 10 MCHF			5,3 MCHF			≈ 80-100 MCHF		
Nb d'instituts / Nb de pays	30 / 16			30 / 16			(>399 signataires)		

B.2 – ANGHIE : tracking efficiencies

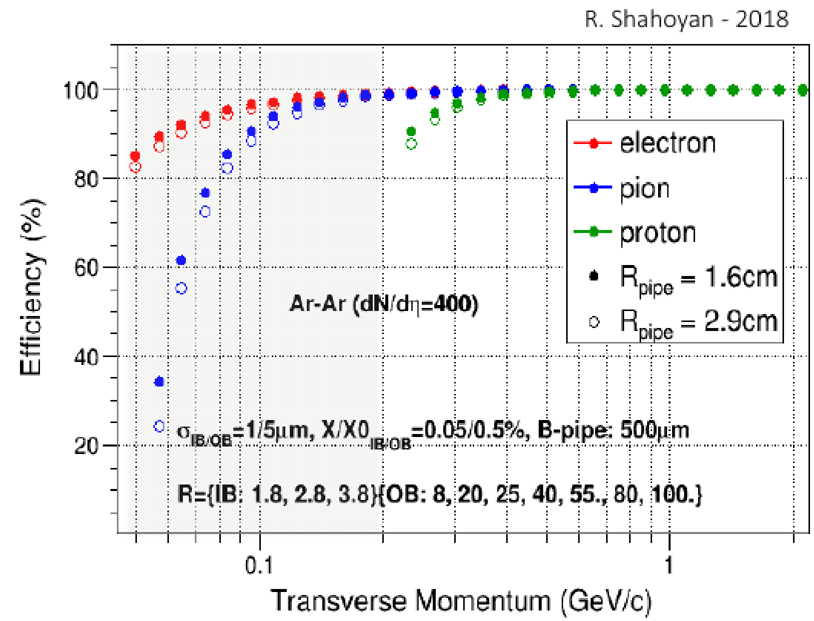
At R = 1m (last layer)

Operation at reduced B field for tracking low p_T particles

Pb-Pb (dN/dη = 2200), B = 0.2 Tesla



dN/dη = 440, B = 0.2 Tesla



Efficiency requiring that all particles reach the outermost layer at 1m (10 layers)

⇨ optimization possible (e.g. using only layers up to 40cm)

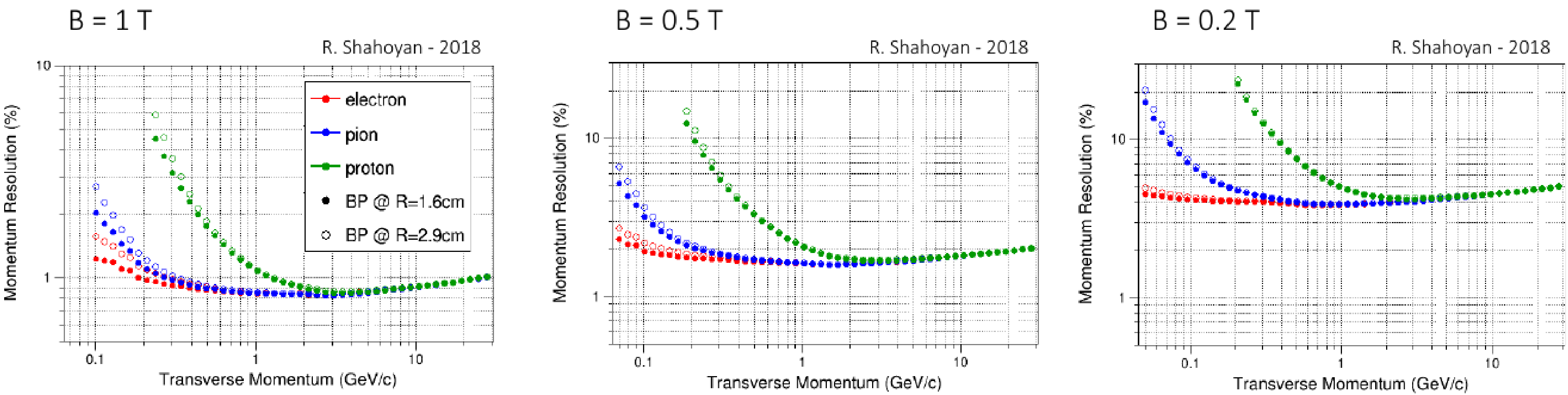
⇨ improvement for lower dN/dη

Further layout optimization possible!

B.3 – ANGHIE : momentum resolution

At R = 1m (last layer)

Compared to ALICE in Run3, same performance at high p_T, some improvement at very low p_T



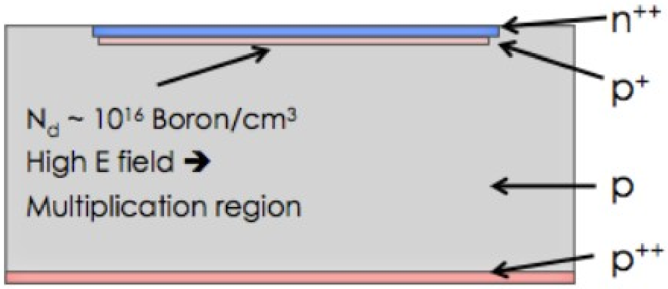
momentum resolution for 1GeV/c pions: ≈ 0.8% (1 T), ≈1.6% (0.5 T), ≈ 4% (0.2 T)

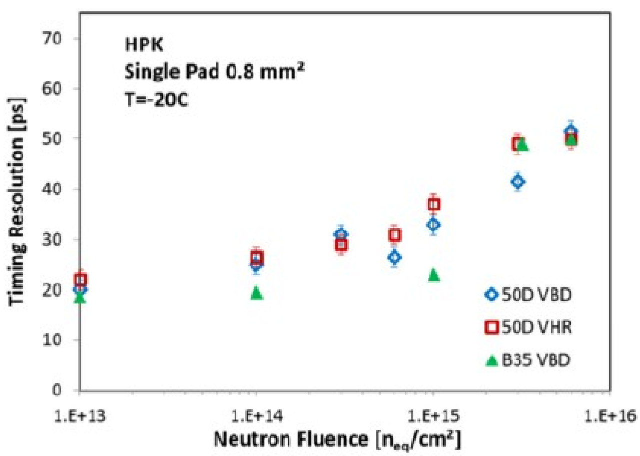
B.4 – ANGHIE : Particle Identification

Electron and hadron ID with TOF

LGAD (Low Gain Avalanche Diode)

- Technology proposed for ATLAS and CMS LS3 upgrades (timing layer)
- Developed for high radiation environment (10^{14} – 10^{15} 1MeV n_{eq}/cm^2)
- Currently low granularity O(1 mm²)
- Add a thin layer of doping to produce low controlled multiplication
- Several vendors: Hammamatsu, FBK, CNN





Time resolution vs. neutron fluence of LGAD produced by HPK with a thickness of 50μm (50D) and 35μm (35D)

Resolution of 20-30ps demonstrated

Cost (CMS estimate) ~ 50 CHF/cm²

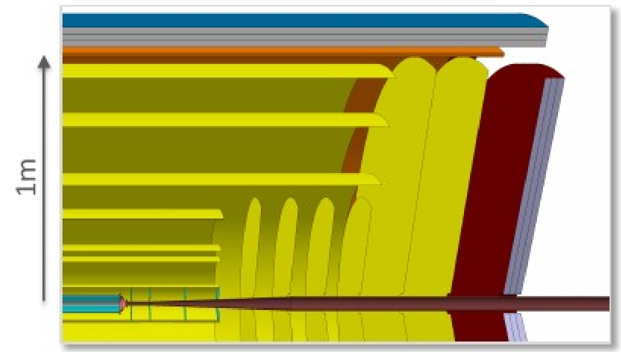
Can such a gain layer be implemented using CMOS? ⇨ large cost saving

⇨ Single Photon Avalanche Diodes (SPADs)

B.5 – ANGHIE : TOF

Electron and hadron ID with TOF

TOF PID – few barrel layers instrumented with LGAD or high-granularity SPAD sensors



SPAD Sensors (Single Photon Avalanche Diode) $\stackrel{\text{def}}{=}$ arrays of avalanche photodiodes reverse-biased above their breakdown voltage

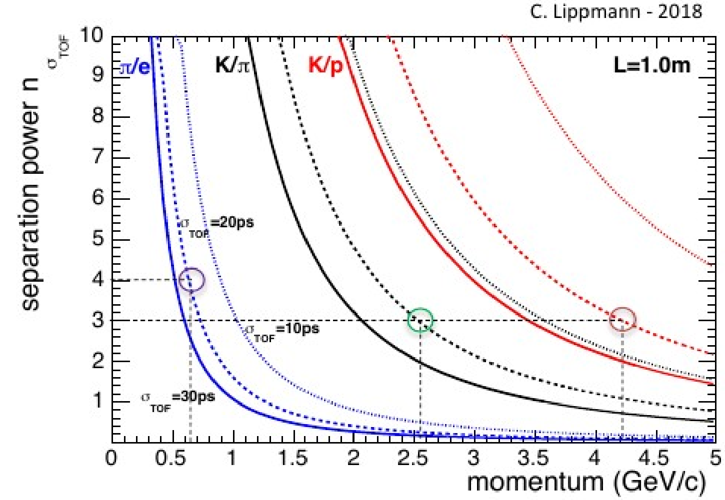
SPAD detectors of recent generation feature a time jitter of tens of picoseconds

Number of layers will depend on time resolution and spatial fill factor achieved in the single layer

Ideal track length and p measurement for 3 scenarios (10ps, 20ps , 30ps) are show in figure

For σ_{TOF} = 20ps

- e/π (4σ) separation ≲ 650 MeV/c
- π /K (3σ) separation ≲ 2.6 GeV/c
- K/p (3σ) separation ≲ 4.2 GeV/c



B.6 – ANGHIE : electron pre-shower, PSD...

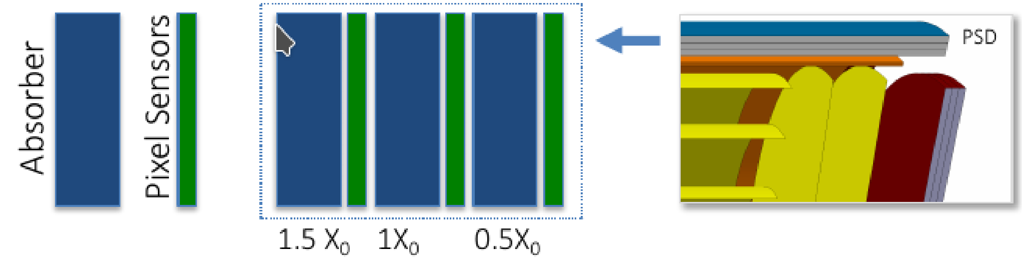
Electron ID with Pixel Shower Detector

Shower Detector (3 X_0) based on high-granularity digital calorimetry (CMOS pixel sensors)

⇨ great potential to identify electrons down to few hundred MeV by detailed imaging of the initial shower (particle counting, geometry)

X_0 (Pb) = 0.56 cm

Pixel Shower Detector



Work in progress – A first look

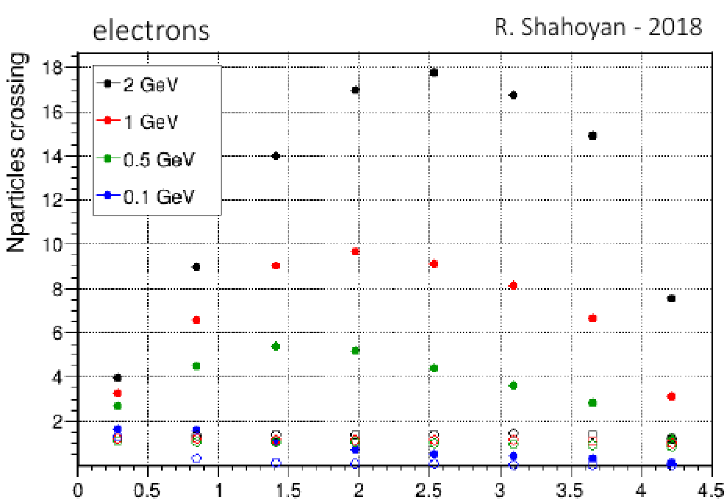


Figure 1

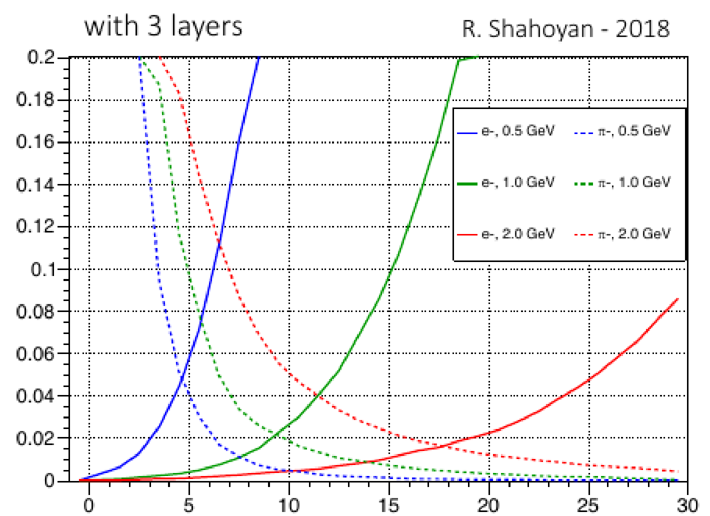


Figure 2

——— e – fraction below N (e-loss) ------- π – fraction above N (contam.)

C.1 – CMS : LHC alternative options possibly on the table

<u>In Run 4+5, after LS3, beware CMS opportunities...</u>

a) tracking on very large η coverage as well ($|\eta| < 4$)

CMS tracker, CERN-LHCC-2017-009

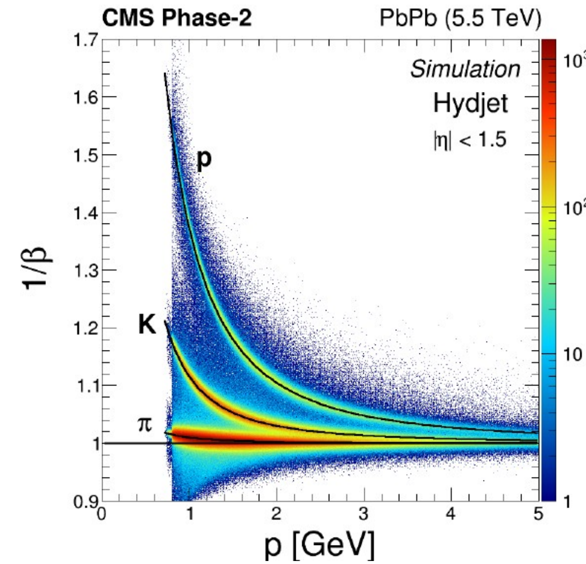
b) unique calorimetry ($PbW0_4$ EmCal + HGCal SiPM sampling)

CMS HGCal, CERN-LHCC-2017-023

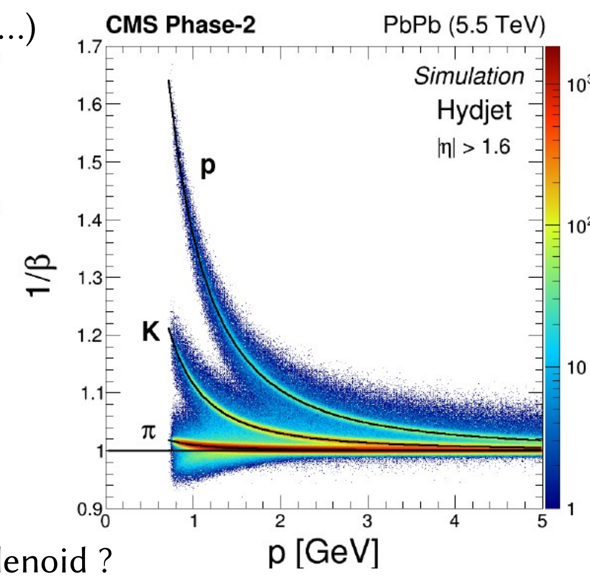
c) MTD = pile-up tagger + TOF ...

CMS MTD = "pile-up tagger", Fig 1.5 + Fig 5.23 - TDR CERN-LHCC-2019-003

(LGAD in endcap or SiPM in barrel ⟶ $\sigma_{\text{time stamp}} \approx 30$ ps),



NB : all this, really expensive (quite more than the All-Si exp...),
but ~funded already (112 MCHF tracker, 67 MCHF HGCal, 21 MCHF MTD, DAQ 12 MCHF ...)



⟶ Could all this be ~bearable (?) for "low-p_T" purpose ?

(*i*) in any (?) or at least low pile-up condition (NB : TOF in Pb-Pb = ok !)

(*ii*) preferentially with moderate B field,

(*iii*) given material budget in the tracker

(phase-2 ≈ 30-40% X/X° as currently at $|\eta| < 1$ + improved at $|\eta| > 1.5$. See Fig 6.2 +12.1)

⟶ Decisive but open questions :

- influence of pile-up (pp) / running time in low pile-up at the end of fill (?)
- running with (B field < 3.8 T) Vs max. number of hysteresis cycles authorised for the solenoid ?

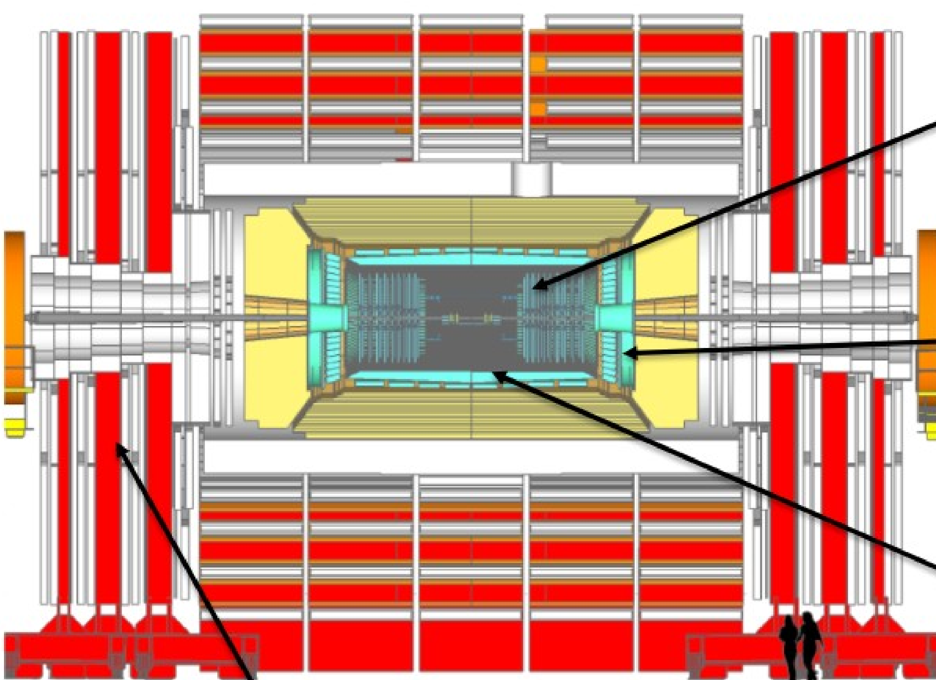
Not really the pb, = rather reconstruction software to be recommisionned + HCal meant to work in B field (?)

C.2 – CMS : LS3 upgrades

Phase II upgrades

Trigger / HLT / DAQ
Track info. in L1
L1/HLT rate x7.5
DAQ: 6 → 60 GB/s

New silicon tracker
Improved granularity
Lighter material budget
$|\eta| < 2.4 \rightarrow |\eta| < 4$



New endcap calorimeters (HGCal)
Unprecedented granularity
$|\eta| < 3$

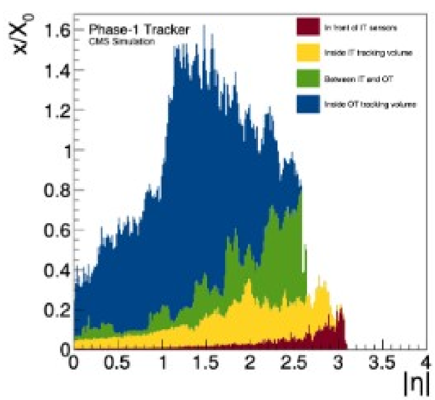
New MIP Timing Detector (MTD)
Precision timing
$|\eta| < 3$

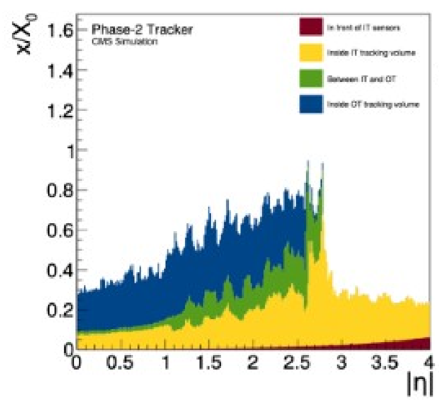
Extended muon coverage
$|\eta| < 2.4 \rightarrow |\eta| < 2.8$

Hermetic coverage at forward rapidity
→ high complementarity with ALICE/LHCb

C.3 – CMS : LS3 tracker characteristics

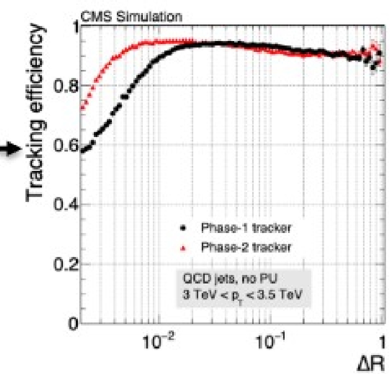
Tracker upgrade

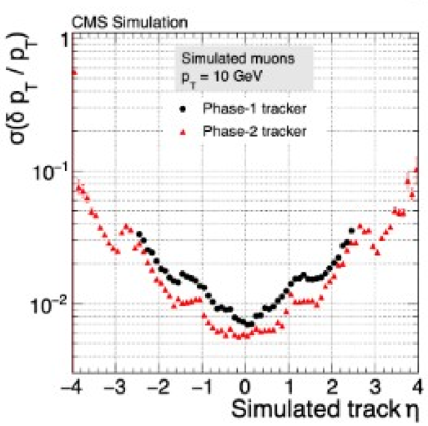


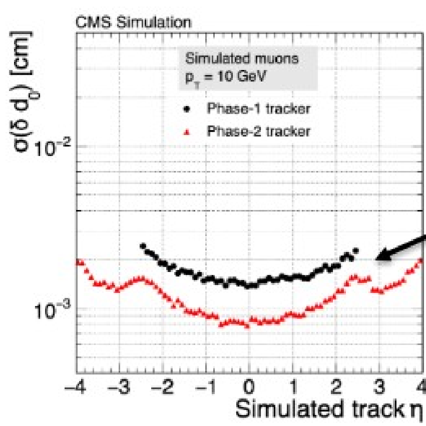


Reduced material budget by up to 2x
→ improved tracking efficiency in AA

… as evidenced by the improved separation of nearby tracks







Improved p_T resolution by about 25%
→ Improved mass resolution for resonances

Impact parameter resolution improved by 40%
→ Improved heavy flavor measurements (B/D hadrons & b/c-jet tagging)

C.4 – CMS : MTD aging

Fig B.10 - TDR CERN-LHCC-2019-003

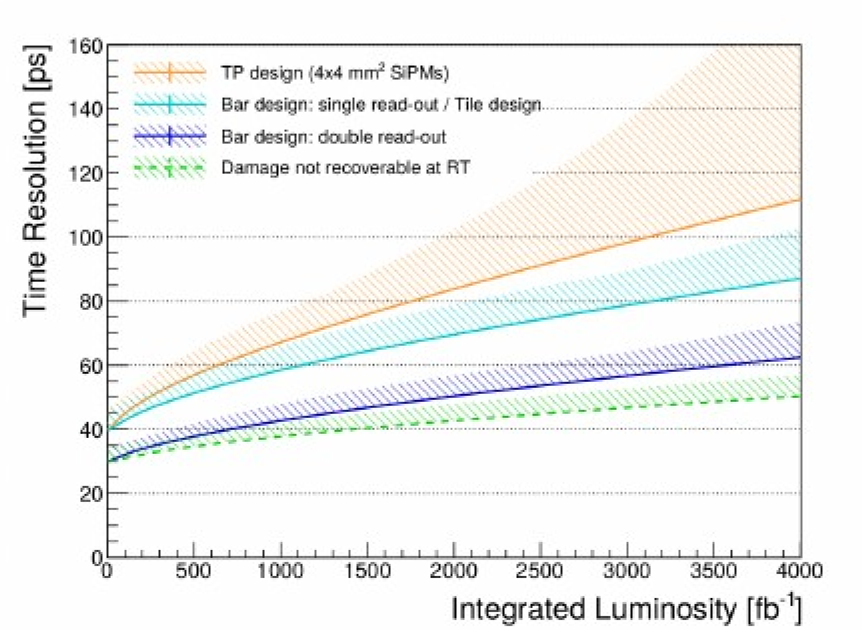


Figure B.10: Expected time resolution as a function of integrated luminosity for the TP reference design (orange); the TDR bar design from single-ended and tile design (light blue); the TDR reference design with crystal bars combining double-ended readout (blue); and the TDR reference design assuming all damage recoverable at room temperature (RT) is annealed. The bands show the expected performance for different sets of SiPM parameters.

D.1 – LHCb : LHC alternative options possibly on the table

In Run 5, beware LHCb opportunities…

LHCb, EoI upgrade LS4, arXiv:1808.08865

a) Profiting from boost for forward geometry,
$\longrightarrow$ LHCb will remain a serial heavy-flavour tagger…
Sitting forward makes life easier than at mid-rapidity in that respect

b) Readout/tracking/PID capabilities likely to work by then
in all systems (pp, p-O, Ar-Ar, Xe-Xe, …)
and under any event activity (Pb-Pb 0-5%)…

D.1 – LHCb : gradual upgrades for Run IV and Run V