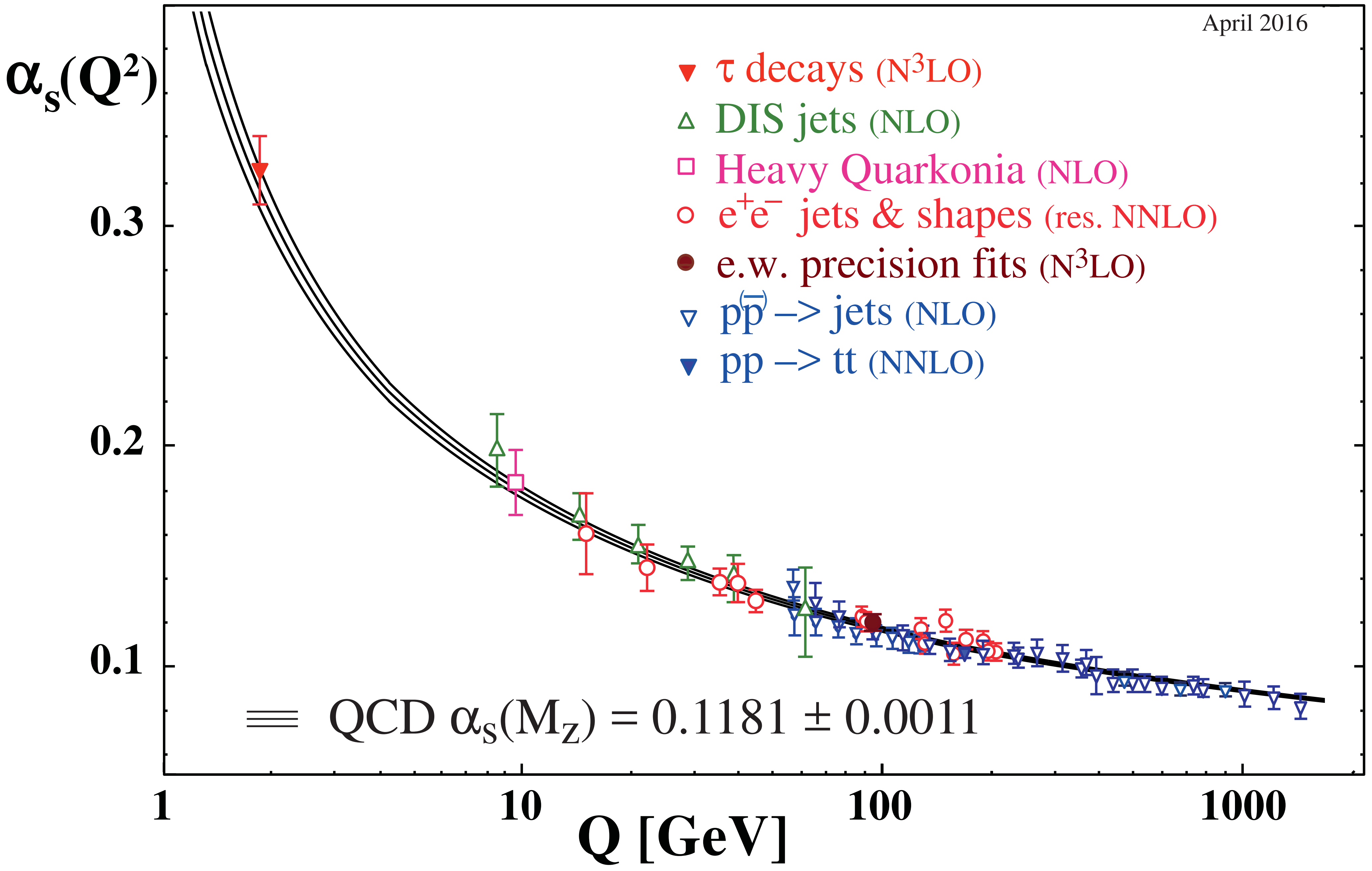
Heavy-ion physics with LHCb detector

Samuel Belin on behalf of the LHCb-IFT-IGFAE group

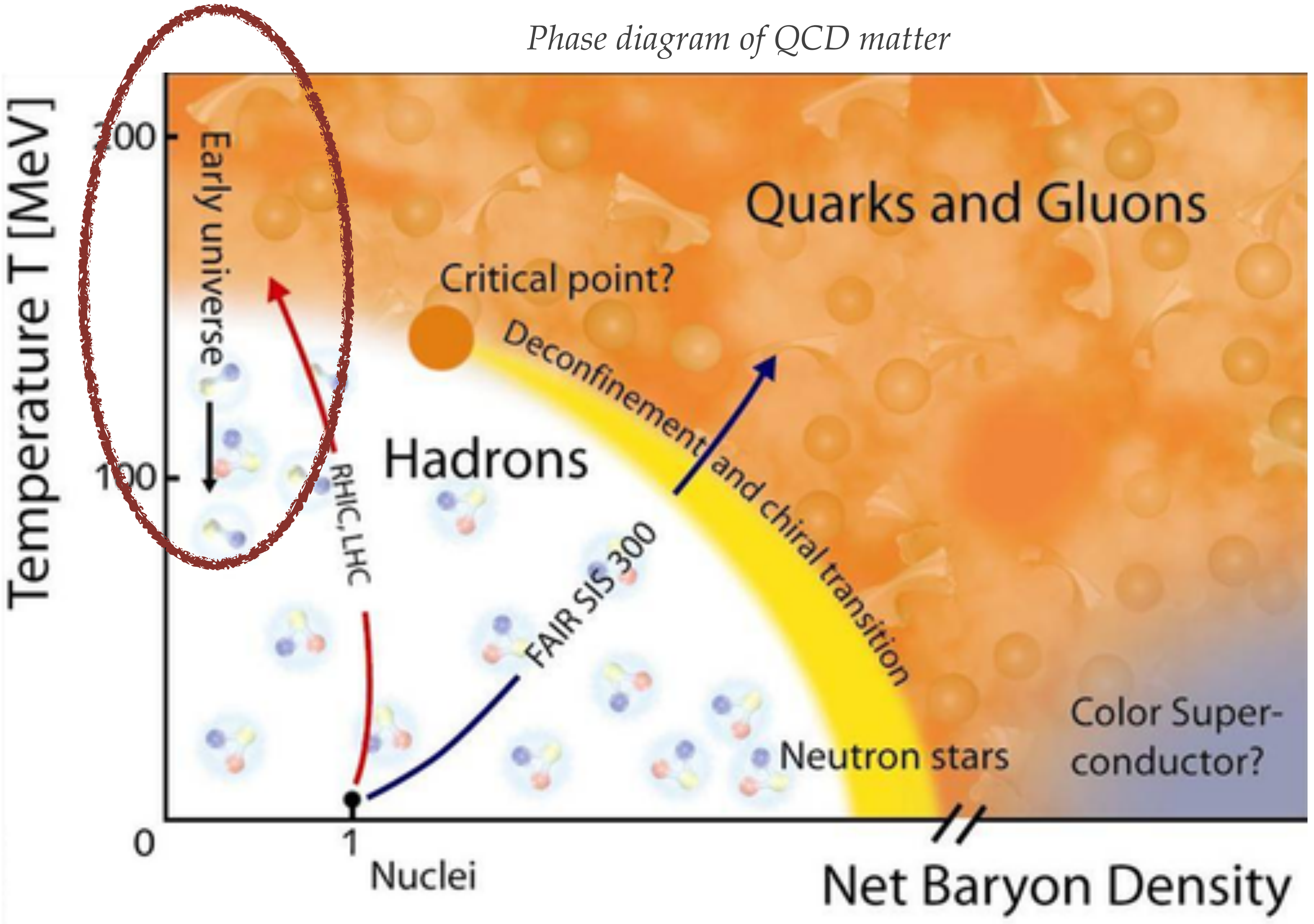
Samuel Belin
samuel.belin@cern.ch

Extreme states of nuclear matter

Coupling constant of Quantum Chromodynamic (QCD)



Phase diagram of QCD matter



At high temperature and/or density, Quark Gluon Plasma formation.

Objectif of « heavy-ion physics »: Understand QCD and study the Quark Gluon Plasma (QGP)

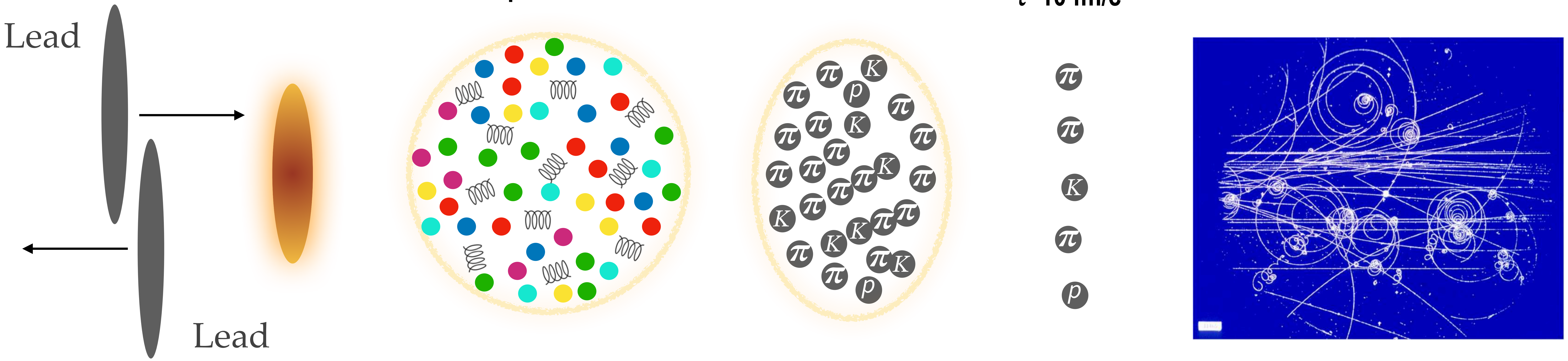
Produce the QGP in the laboratory

Large Hadron Collider

Initial state
τ~0 fm/c

QGP formation and hydrodynamic expansion

Hadrons cinematic fixed
τ~10 fm/c



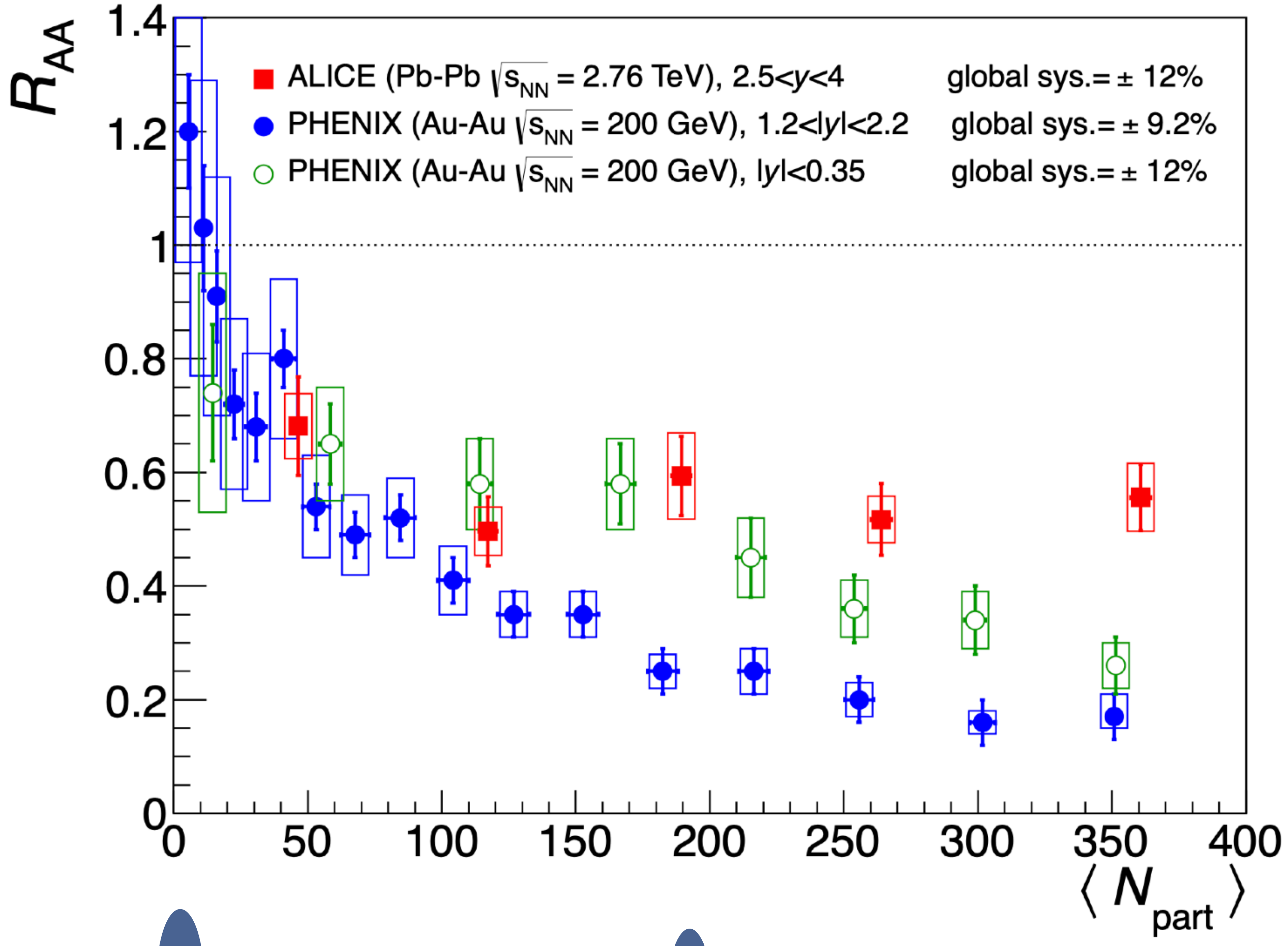
Initial state density
τ~1 fm/c

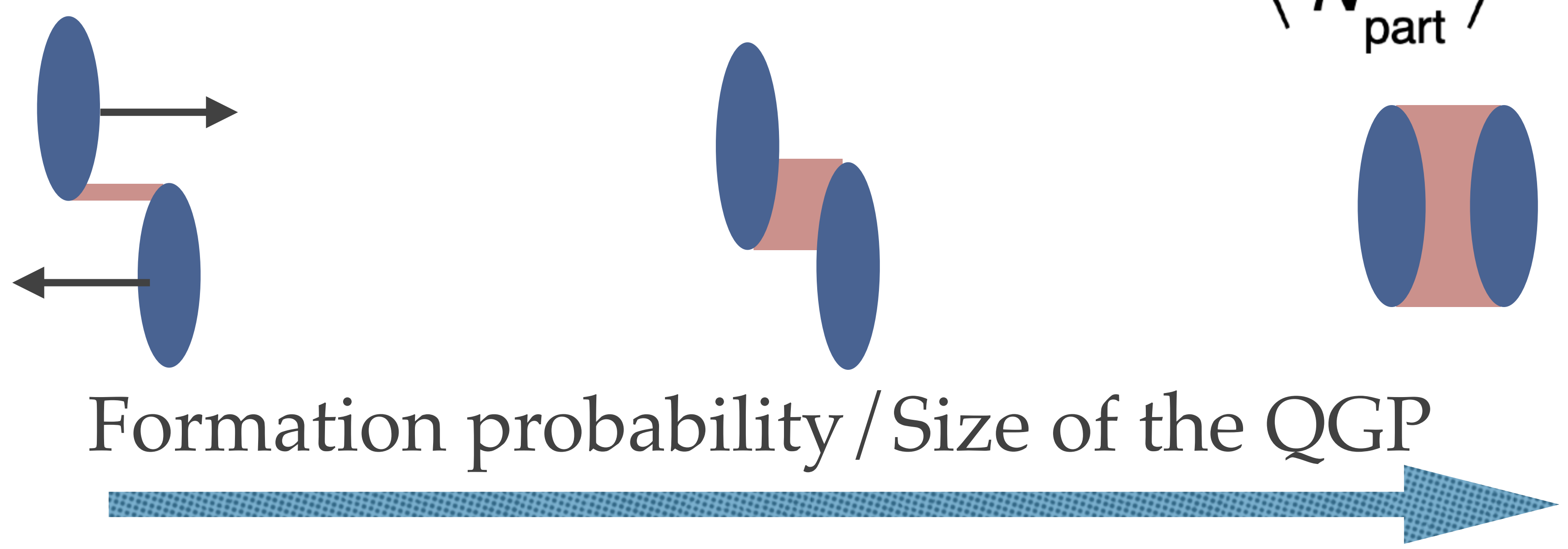
Hadronisation and hadron gaz formation

Particles detection
τ~10^{15} fm/c

Detect QGP ?

$$R^{AA} = \frac{\sigma_{Jpsi}^{PbPb}}{T_{AA}\sigma_{J/\psi}^{pp}}$$

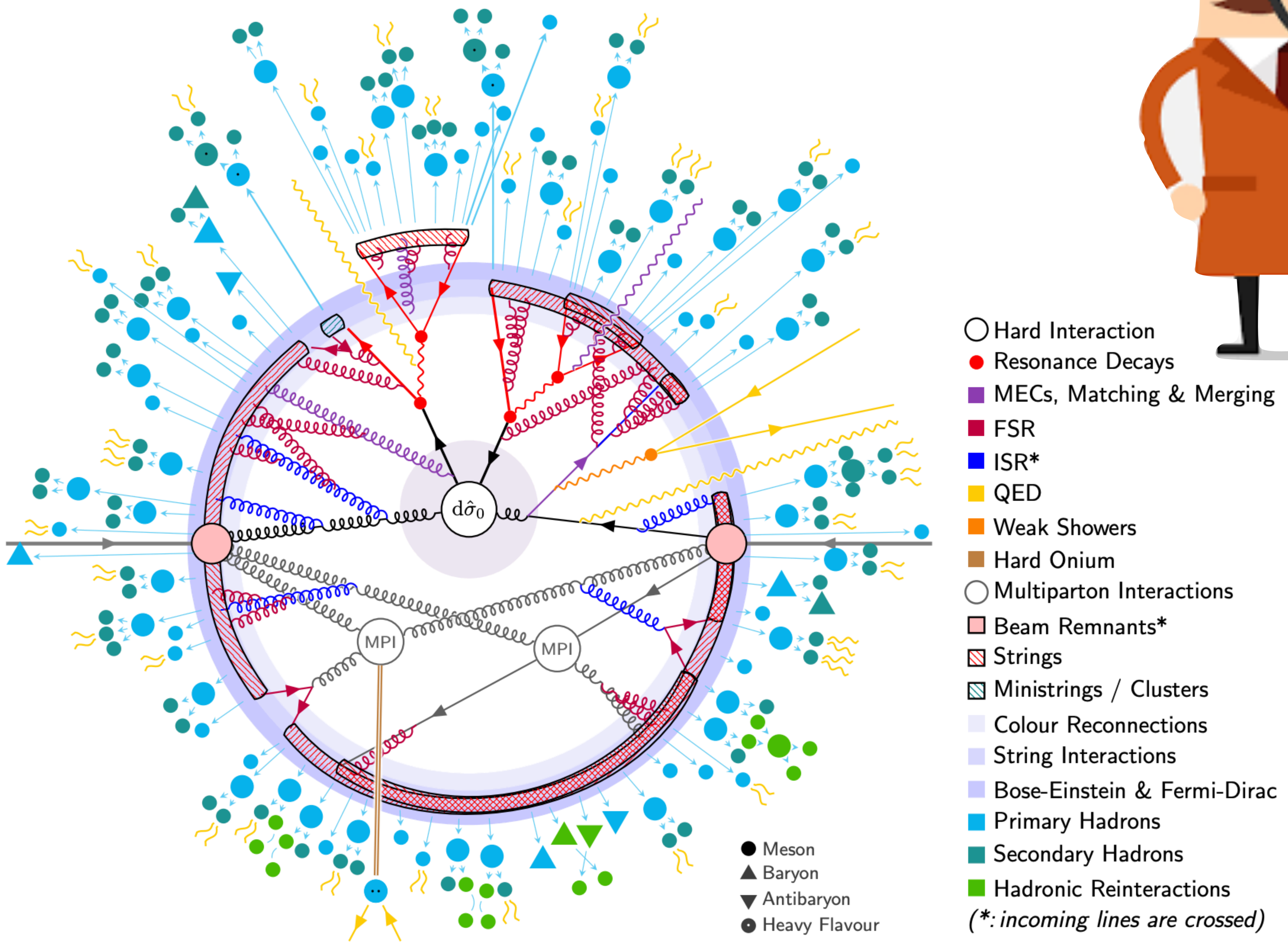




- A classic method is to compare the production of a certain particle (J/ψ for example) in PbPb and scaled *pp* collisions.
  - If $R^{AA} = 1$, no effect. PbPb is a superposition of independent pp collisions
  - If $R^{AA} \neq 1$, additional effects
  - This effects can come from the hot medium (plasma) of the cold medium (confined medium)

Complexity of a hadronic collision

*Effects taken into account by the collision generator **PYTHIA***



proton-proton collision

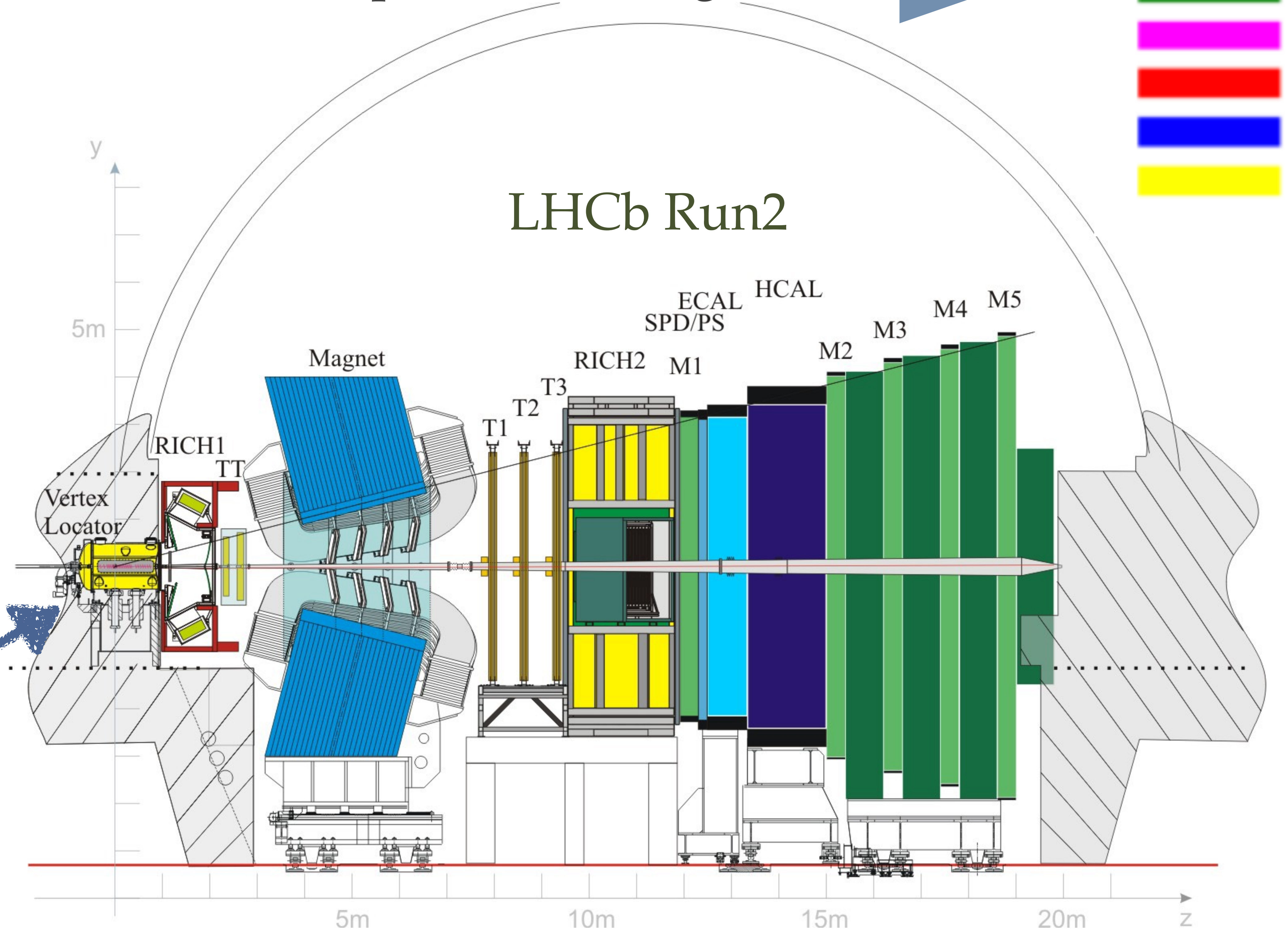
- Important to study QCD in confined and unconfined medium (QGP)
- *proton-proton* and *proton*-Plomb collisions → confined QCD
- Plomb-Plomb collisions → QGP

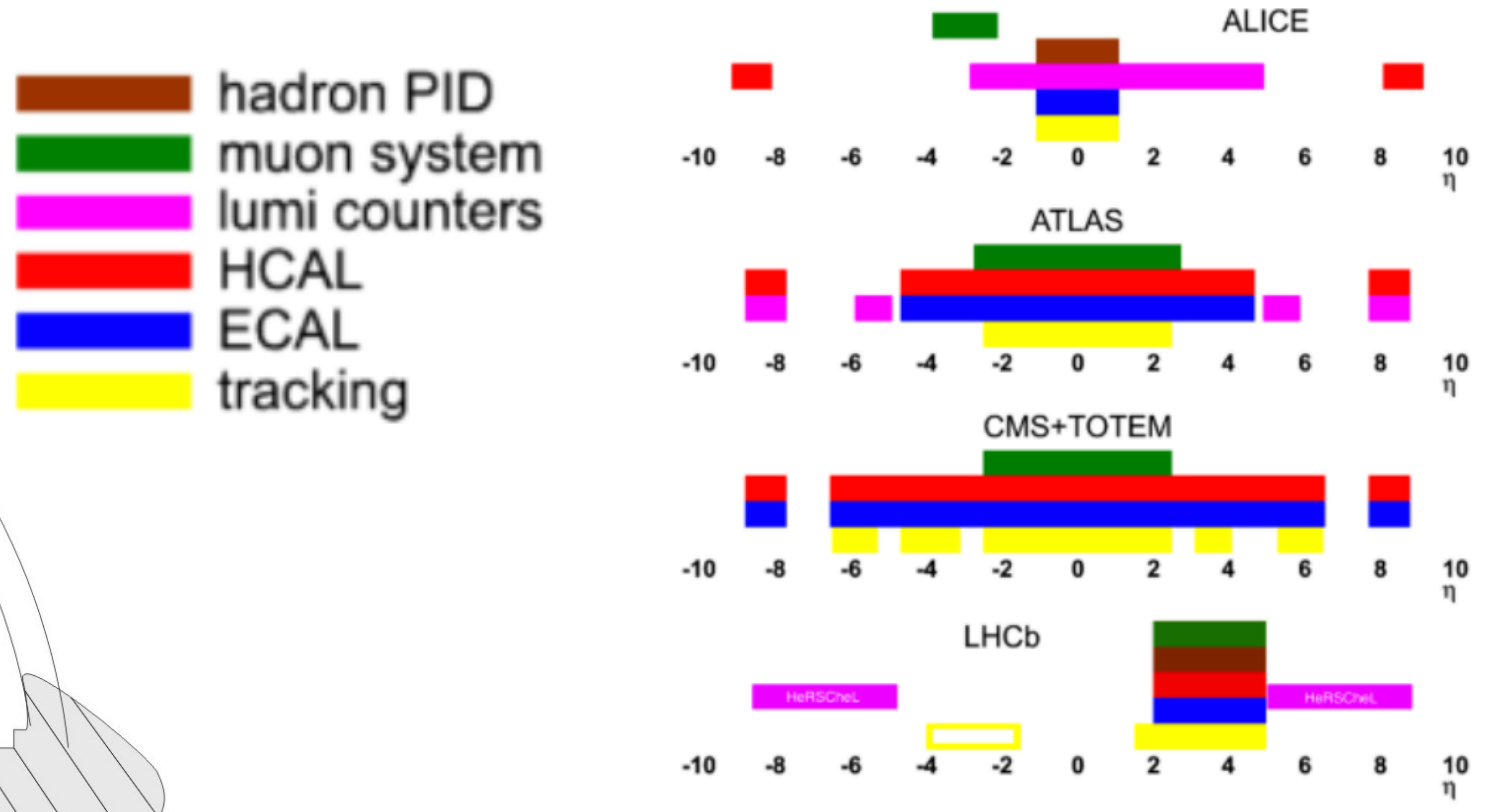
LHCb is the ideal detector for confined QCD

The LHCb detector

Single arm spectrometer fully instrumented in pseudorapidity range $2 < \eta < 5$

Unique in this range





SMOG

- Excellent tracking down to p_T=0.
- Excellent particle identification.
- Excellent primary vertex determination.

JINST 3 (2008) S08005

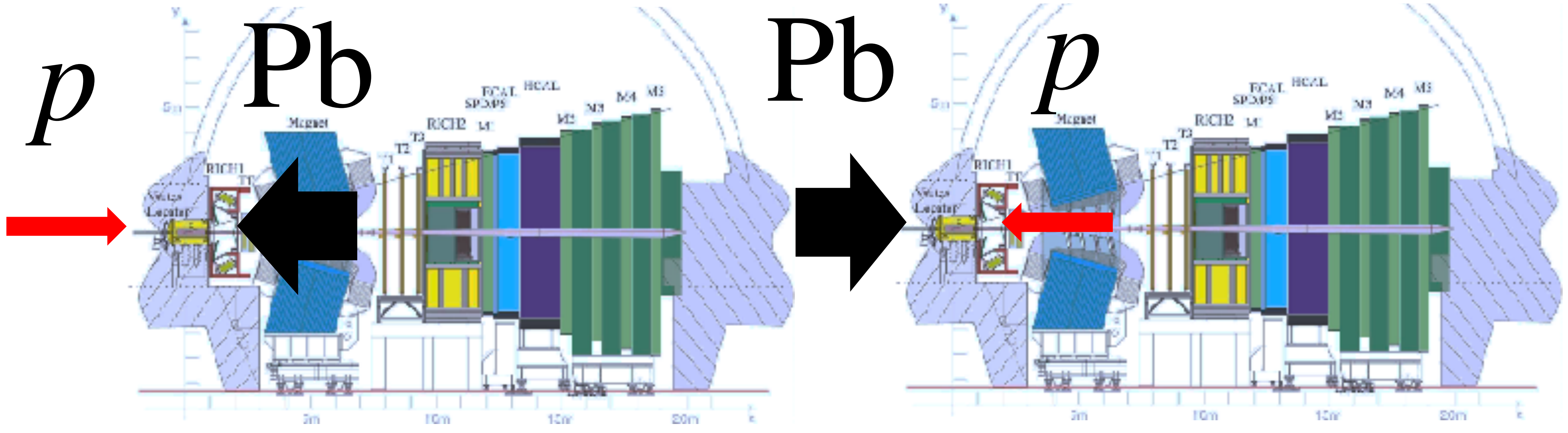
Int. J. Mod. Phys. 734 A30 (2015) 1530022

Samuel Belin samuel.belin@cern.ch

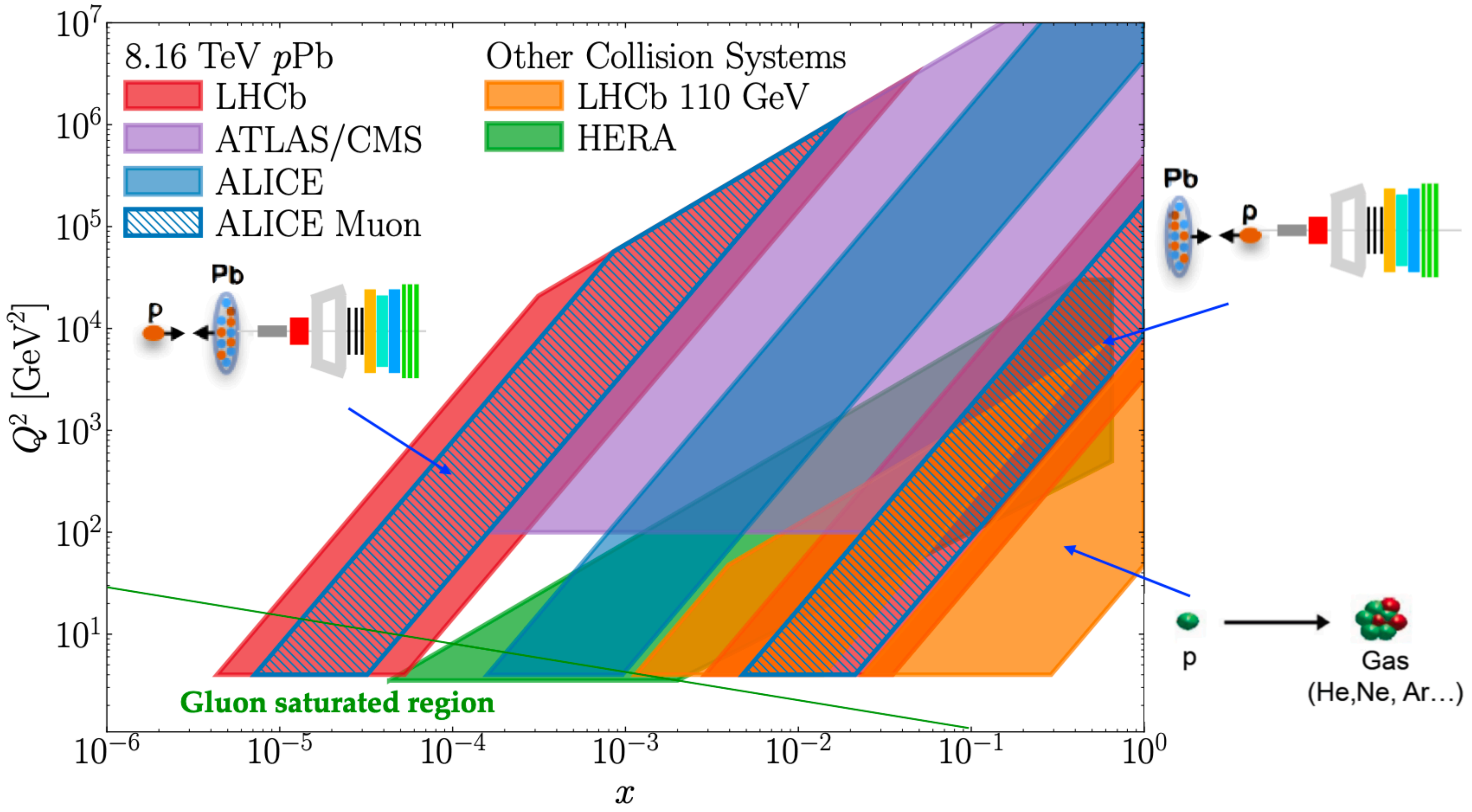
The ultimate nPDF explorer

Excellent possibilities for nuclear physics with pPb and fixed target system

Different energy of the Pb and p beams: boost of nucleon-nucleon cms system $y = y_{lab} \pm 0.465$



Forward $\eta > 0$ Backward $\eta < 0$



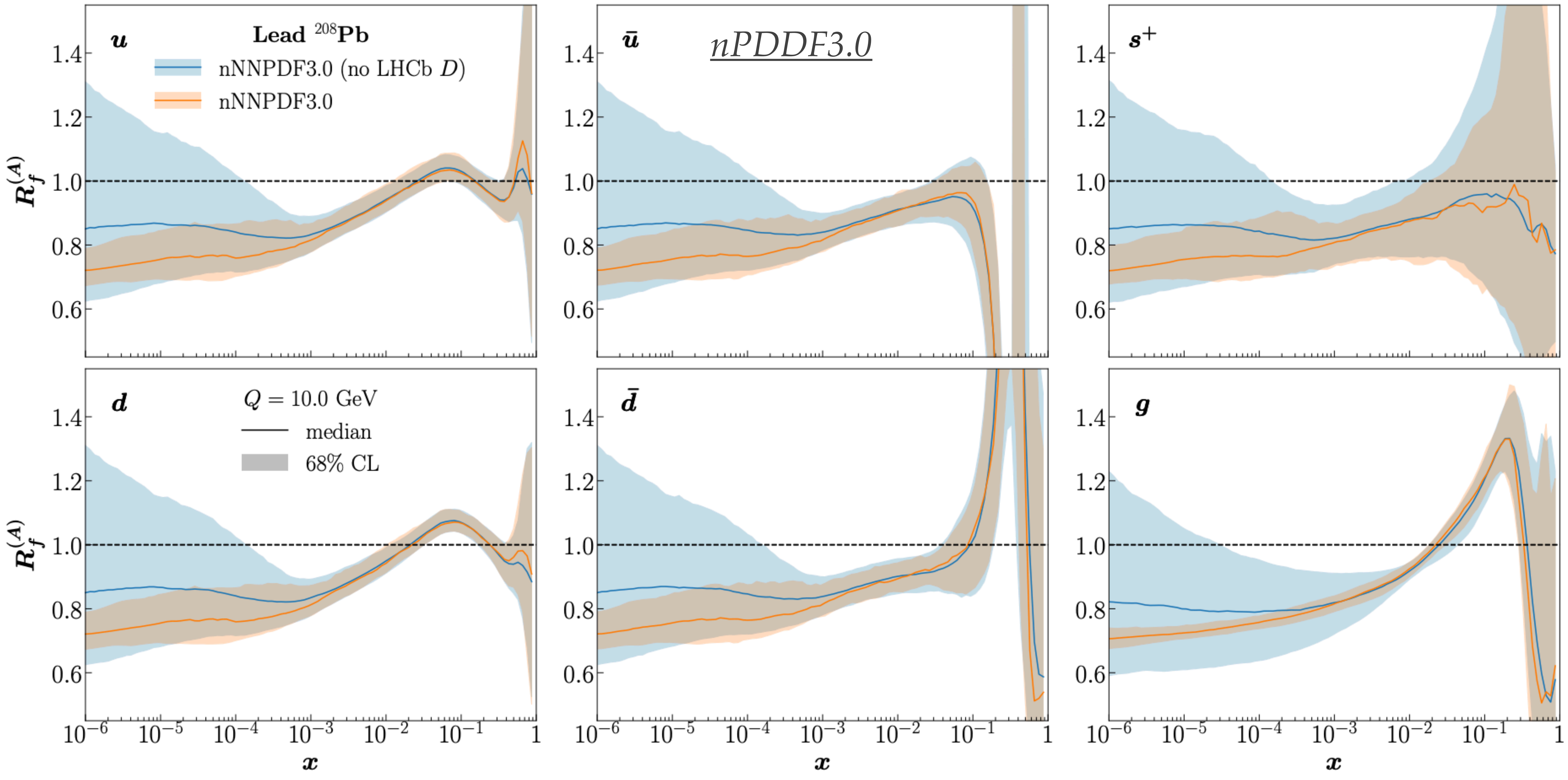
Series of Nuclear modification factor measurement to gives input to nPDFs fits

Probes: charged particles, $\pi^{\pm}$, $K^{\pm}$, p, D^0, $D^{\pm}$ etc…

$$R_{pPb}^{Probe} = \frac{N_{pPb}^{Probe}}{A_{Pb} N_{pp}^{Probe}}$$

The ultimate nPDF explorer

Impact of the our results at 5TeV *LINK*



Phys.Rev.Lett. 128 (2022), 142004

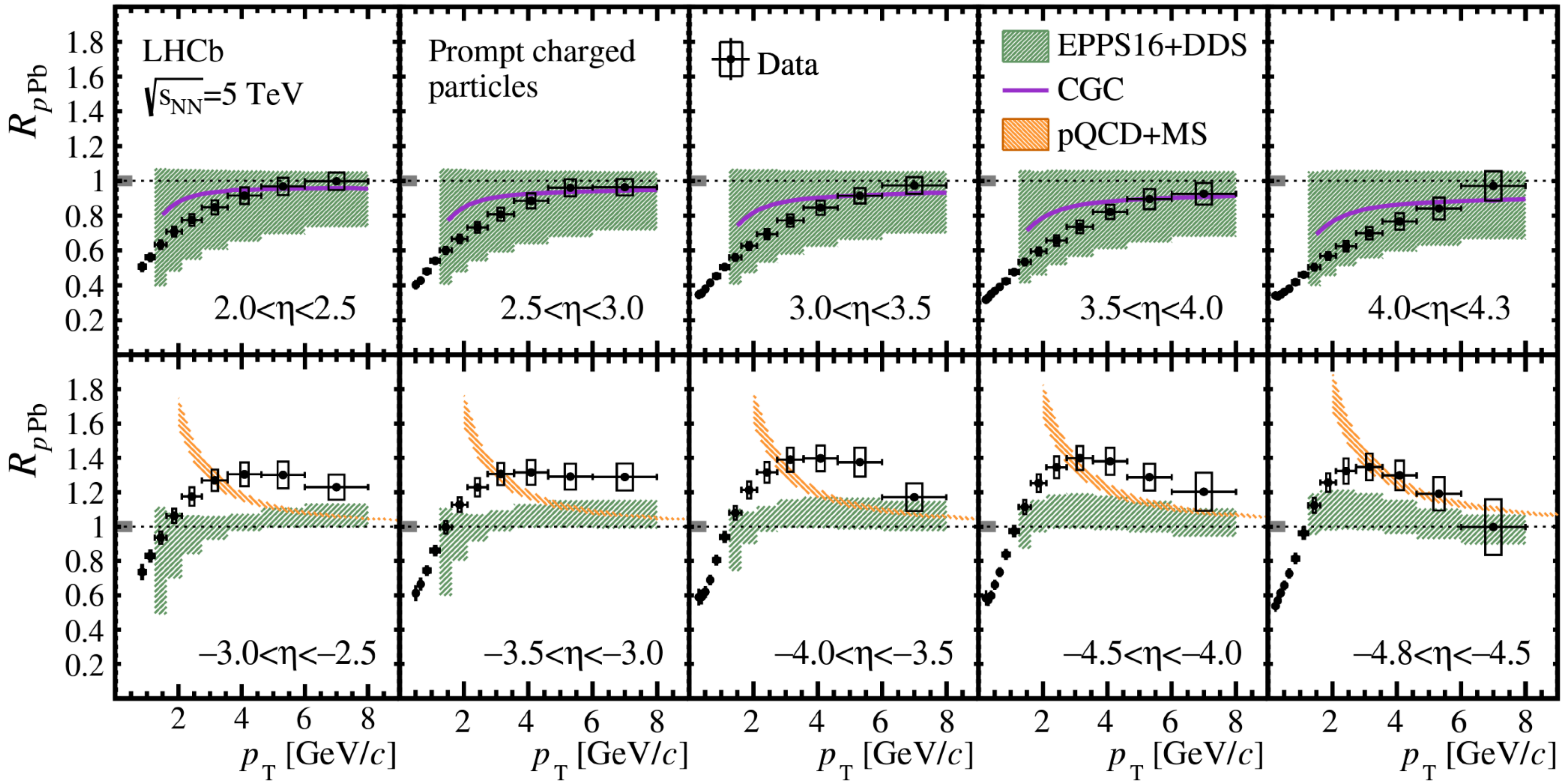
Nuclear modification factor of charged particle in pp, pPb @5TeV

$$\frac{d^2\sigma^{ch}(\eta, p_T)}{dp_T d\eta} = \frac{1}{L}\frac{N^{ch}(\eta, p_T)}{\Delta p_T \Delta\eta}$$

$$R_{pPb}(\eta, p_T) = \frac{1}{A}\frac{d^2\sigma^{ch}_{pPb}(\eta, p_T)/dp_T d\eta}{d^2\sigma^{ch}_{pp}(\eta, p_T)/dp_T d\eta}$$

Forward

Backward



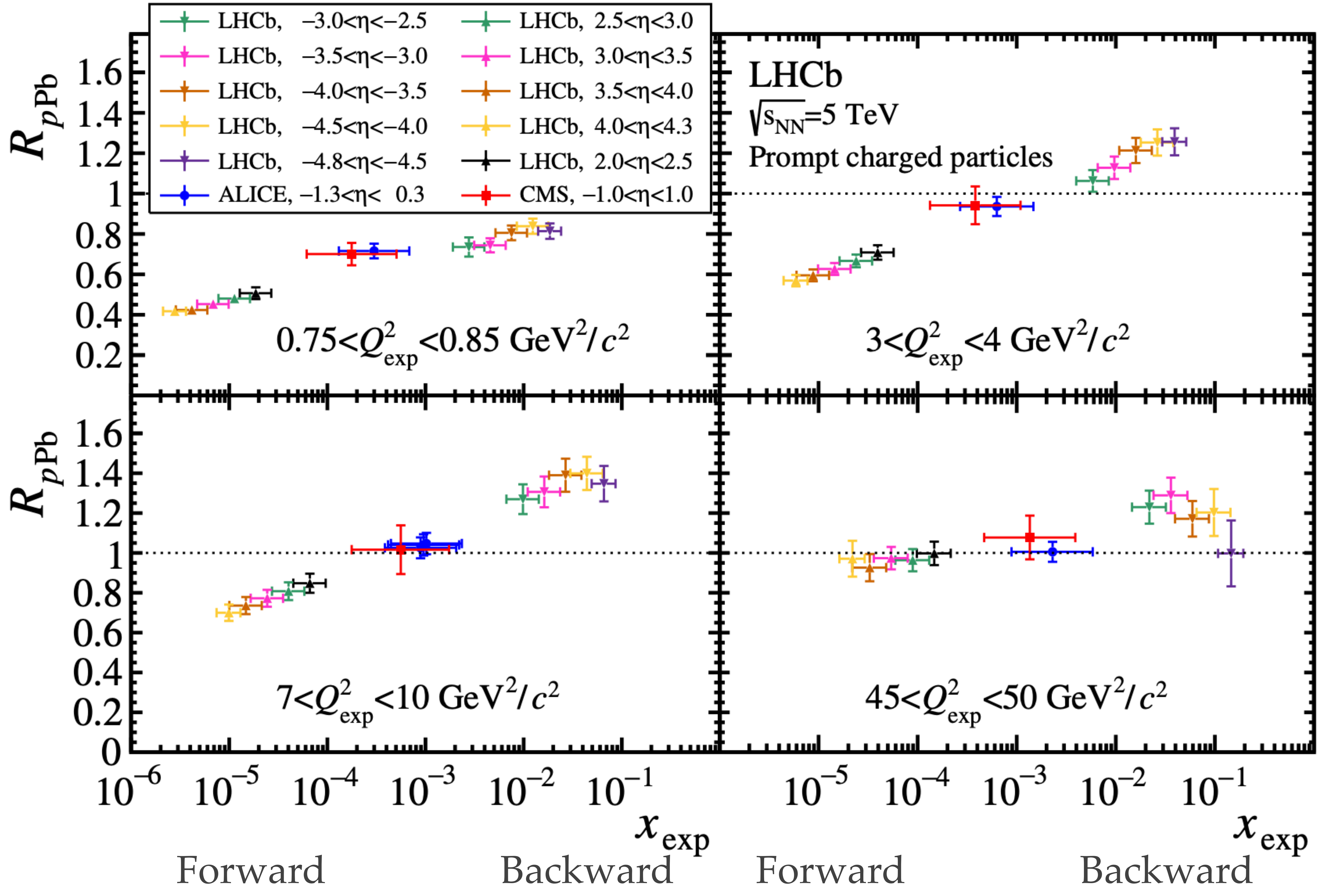
- Constrain nPDF down to x~10^{-6}
- Expected Cronin-like effects in backward and shadowing in forward region
- Tension in the backward region suggesting additional effects, disagreement with CGC calculations in forward
- Greater precision than models !

Phys.Rev.Lett. 128 (2022), 142004

Nuclear modification factor of charged particle in *pp*, *p*Pb @5TeV

$$Q_{exp}^2 = m^2 + p_T^2$$

$$x_{exp} = \frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-\eta}$$



With UB and UAH!

What's next?

- The group increased considerably, with 6 more PhD students!
  - Nuclear modification factor of identified charged particles *pp*, pPb collisions @5TeV
  - Mean-p_T of charged particle versus multiplicity in *pp*, *p*Pb collisions @5TeV.
  - Strangeness enhancement versus multiplicity in *p*Pb collisions @5TeV
  - $J/\psi + \gamma$ production in *pp* collisions at 13 TeV
  - $D^*_{s0}(2317)+$ production analysis versus multiplicity in *pp* collisions at 13 TeV With master students:
    - Study low mass mesons with the dipion and and dimuon decay channel

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QGP in small system ?

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Probing the proton PDF and better understand quarkonium hadronisation

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  - Mean-p_T of charged particle versus multiplicity in *pp*, *p*Pb collisions @5TeV.
  - … multiplicity in *p*Pb collisions @5TeV
  - … s at 13 TeV

Understand final state effects using exotic particle and vice versa

  - $D^*_{s0}(2317)+$ production analysis versus multiplicity in *pp* collisions at 13 TeV
- With master students:
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With UB and UAH!

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  - Strangeness enhancement versus multiplicity in *p*Pb collisions @5TeV
  - $J/\psi + \gamma$ production in *pp* collisions at 13 TeV

Obtaining a reference for PbPb measurement in run 3

versus multiplicity in *pp* collisions at 13 TeV

  - Study low mass mesons with the dipion and dimuon decay channel

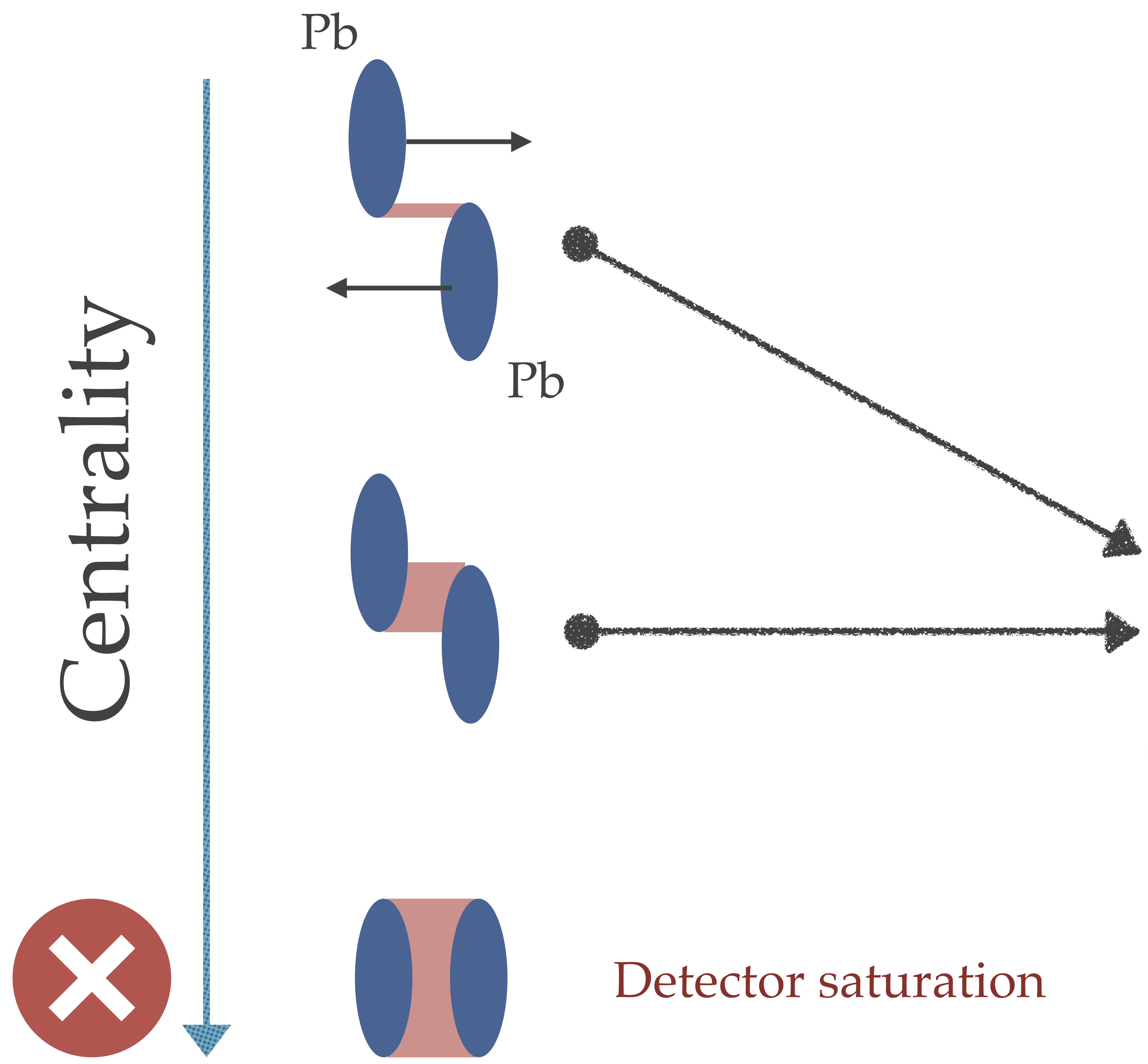
Conclusion

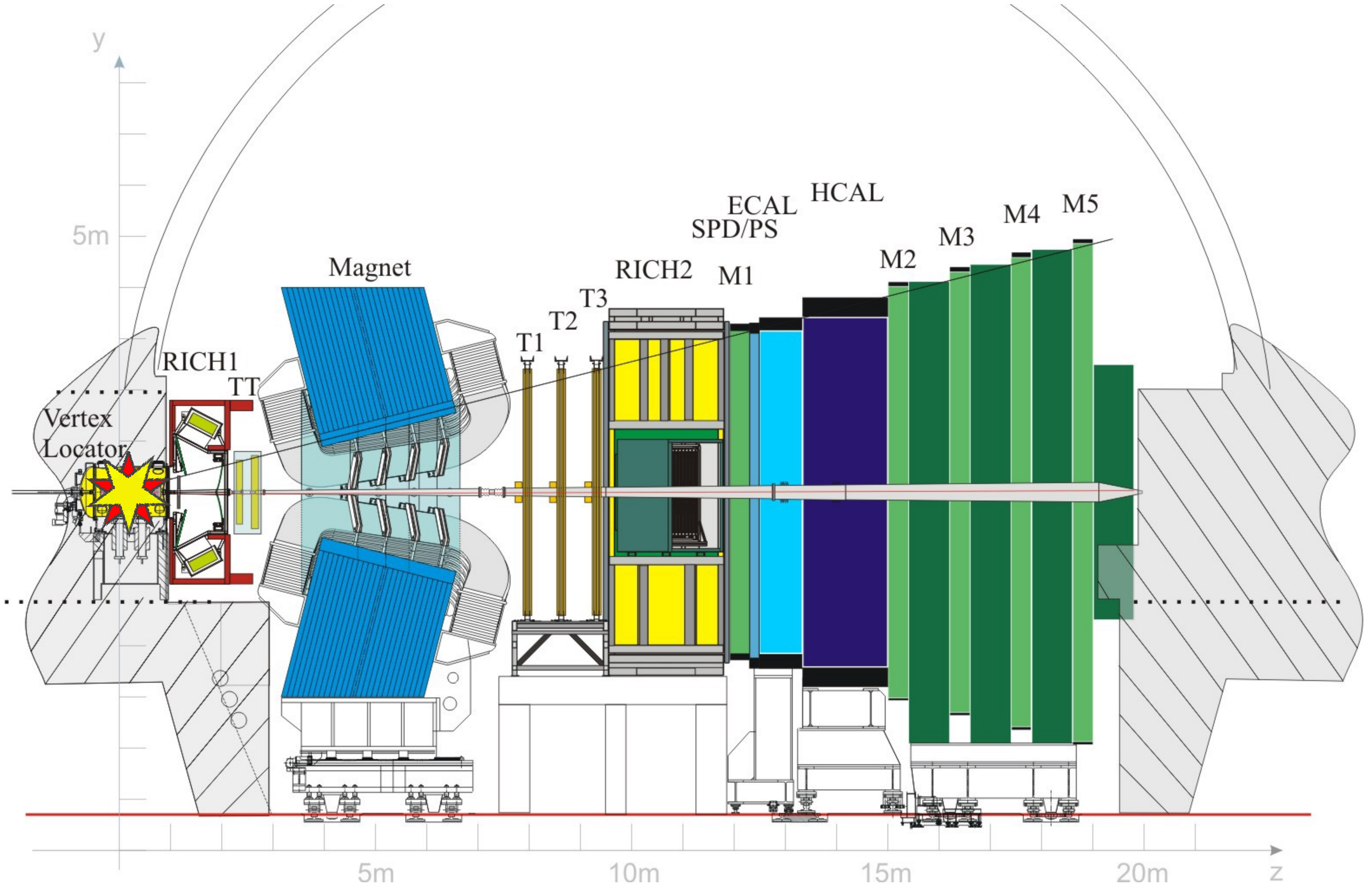
- Santiago (+Barcelona+Alcalá) became one of the biggest heavy-ion group of LHCb!
- Wide research field that will be extended to QGP physics with run 3 PbPb dataset.
- Proximity with the important phenomenology theory group in Santiago.
- Unique research program with the installation of SMOG2, only fixed target experiment of LHC.

Thank you

The LHCb detector

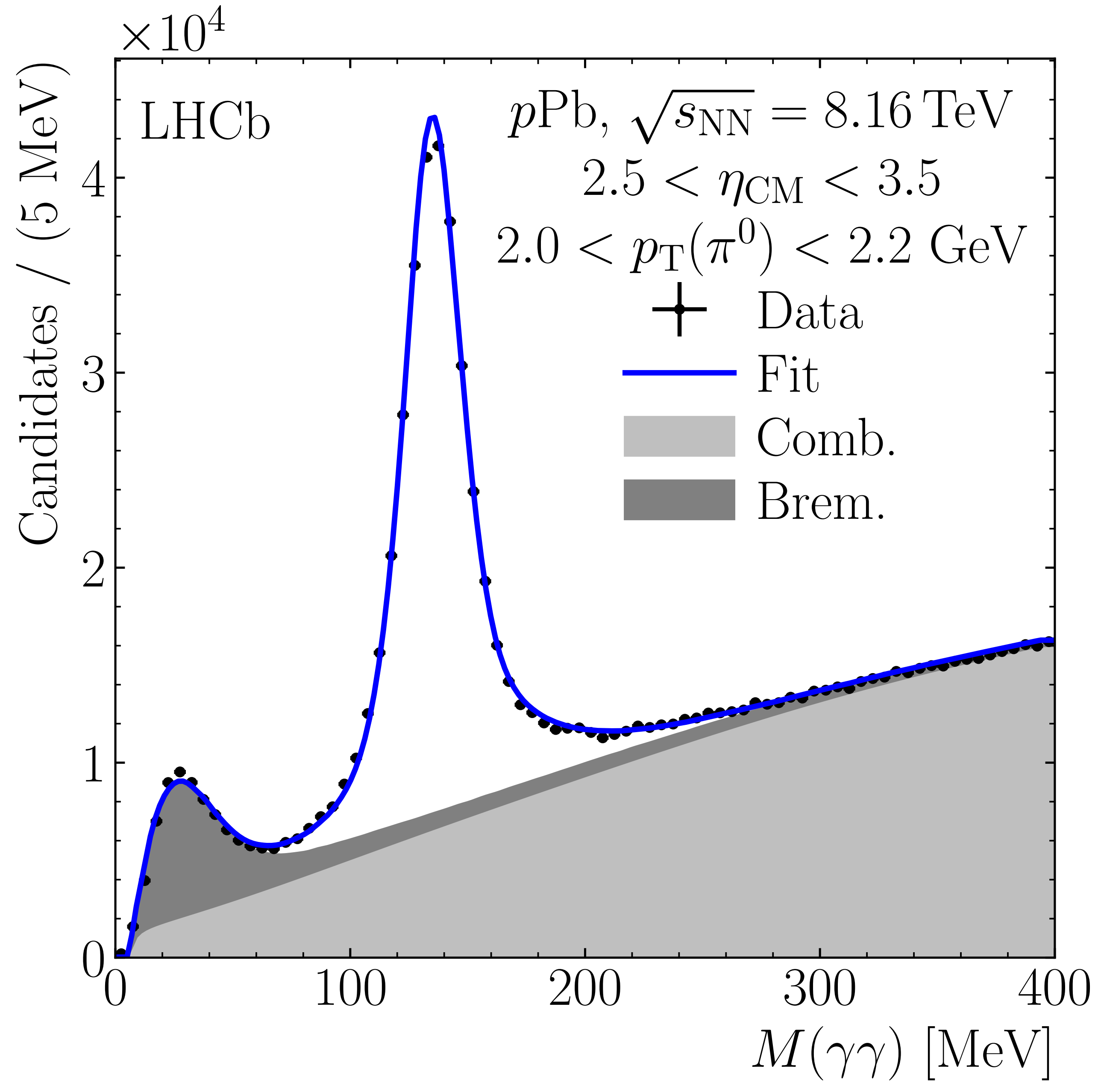
Excellent tracking and PID performance in *pp* and *p*Pb collisions



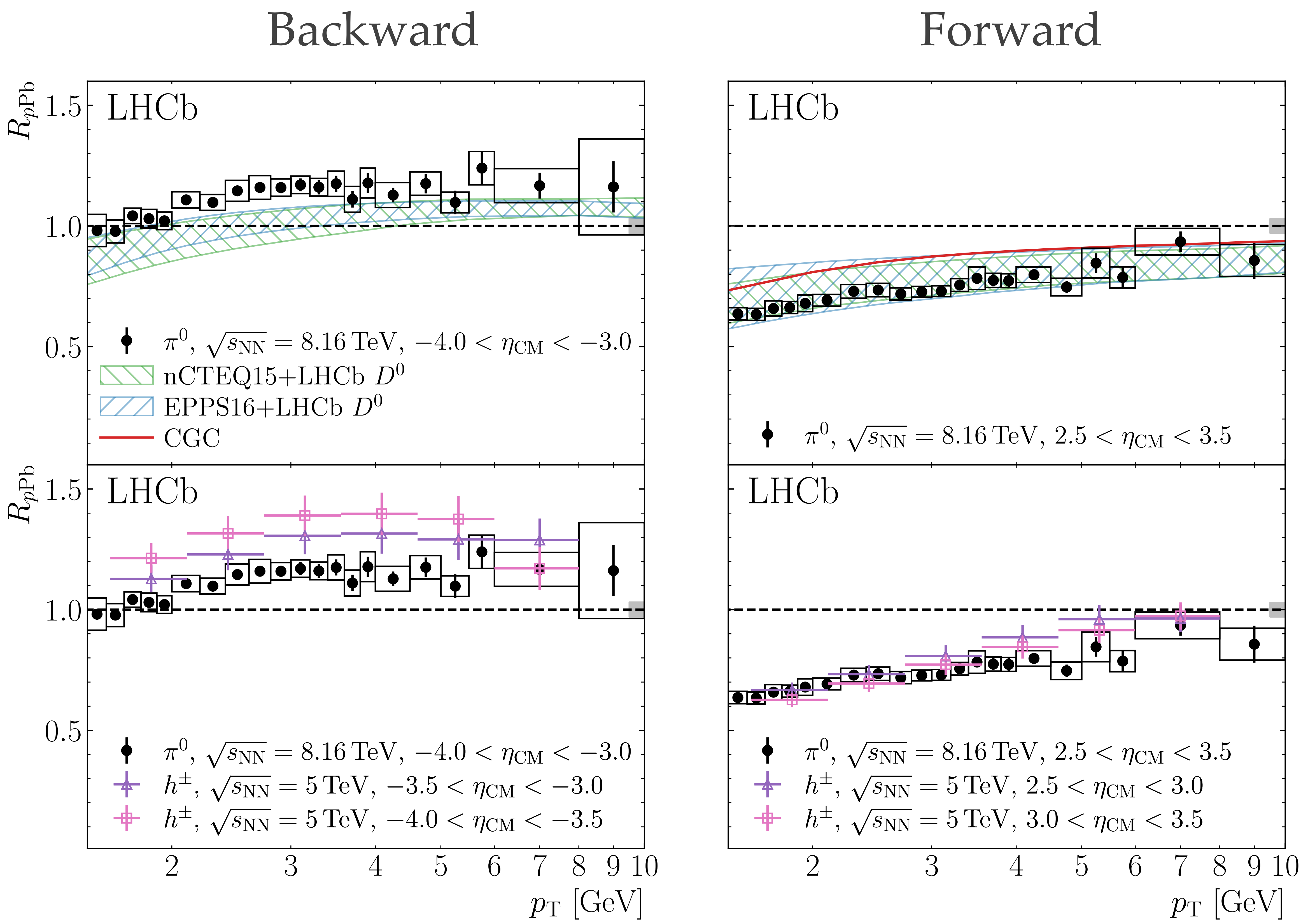


Samuel Belin *samuel.belin@cern.ch*

Nuclear modification factor of $\pi^{0/\pm}$ in pPb @8TeV



$\pi^0 \rightarrow \gamma$(converted)γ(calorimeter)



- Constrain nPDF down to x~10^{-6}
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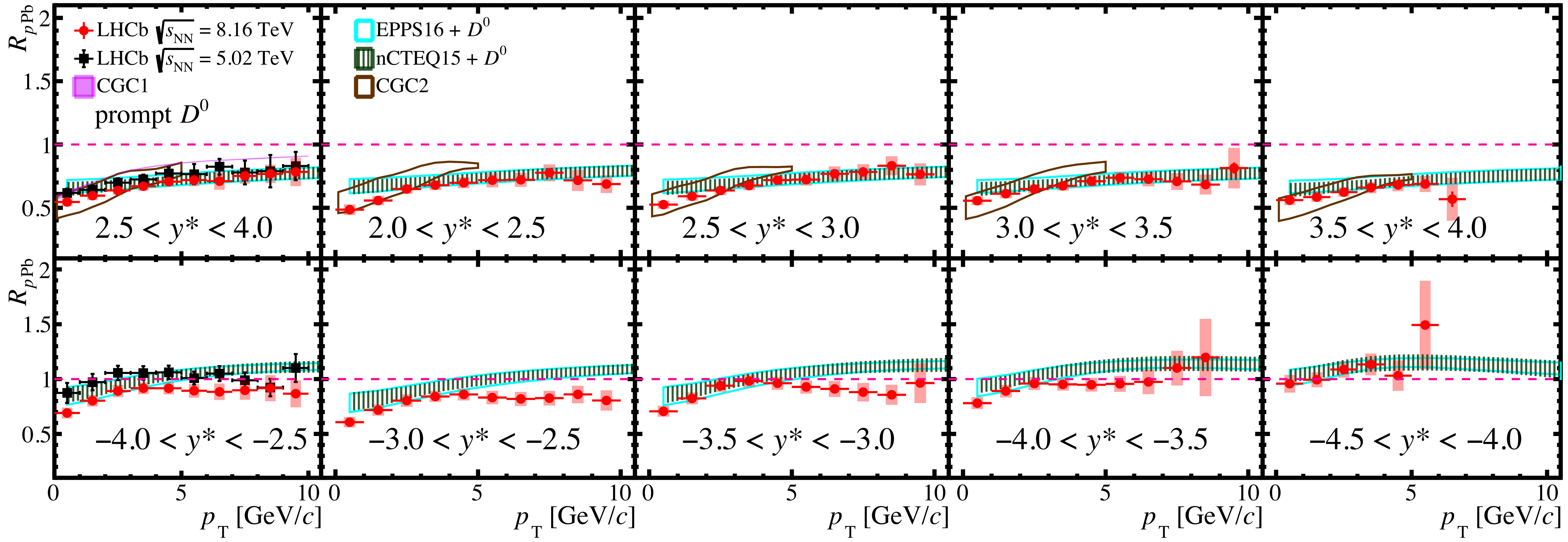
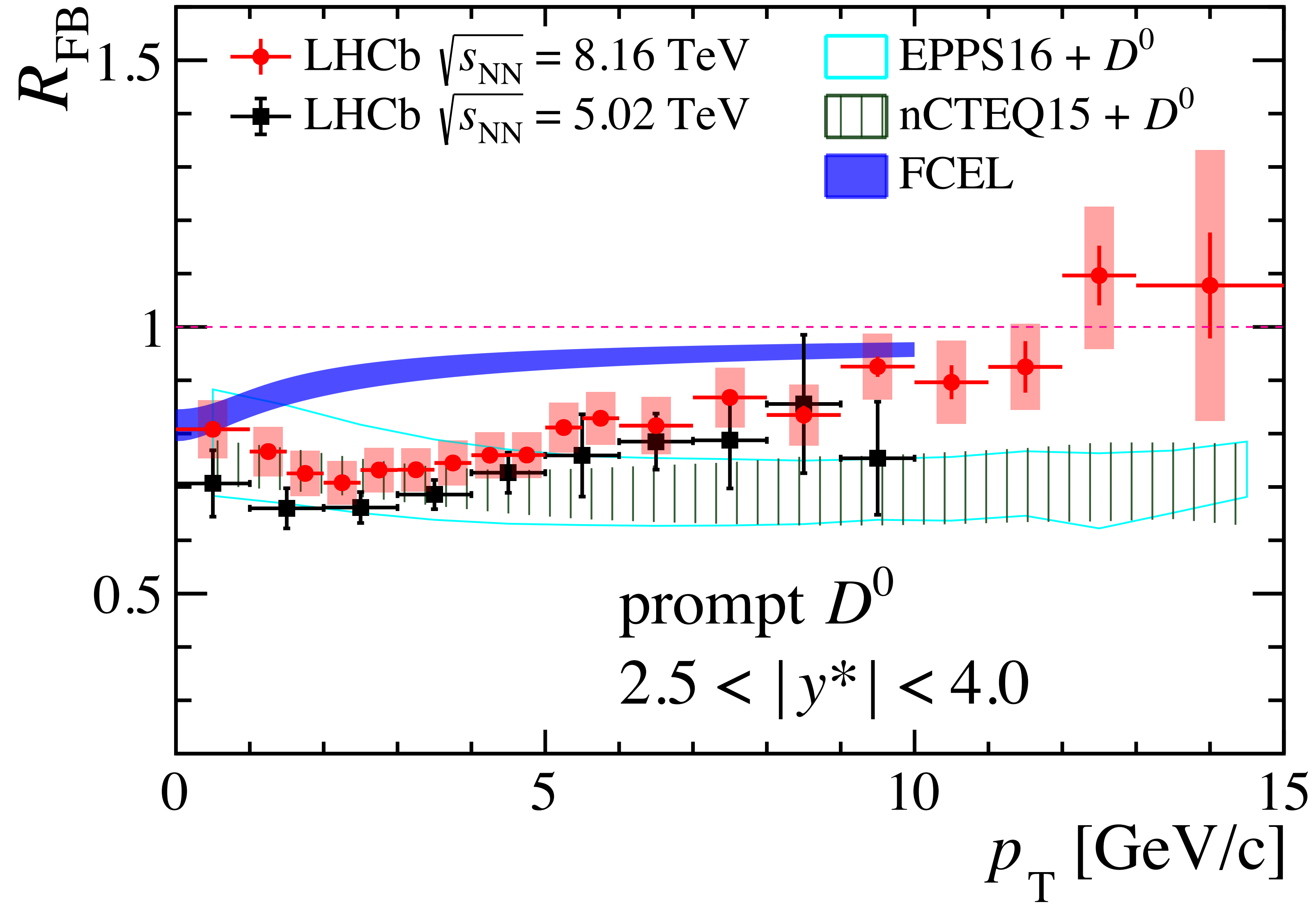
Prompt D^0 mesons in pPb @8TeV

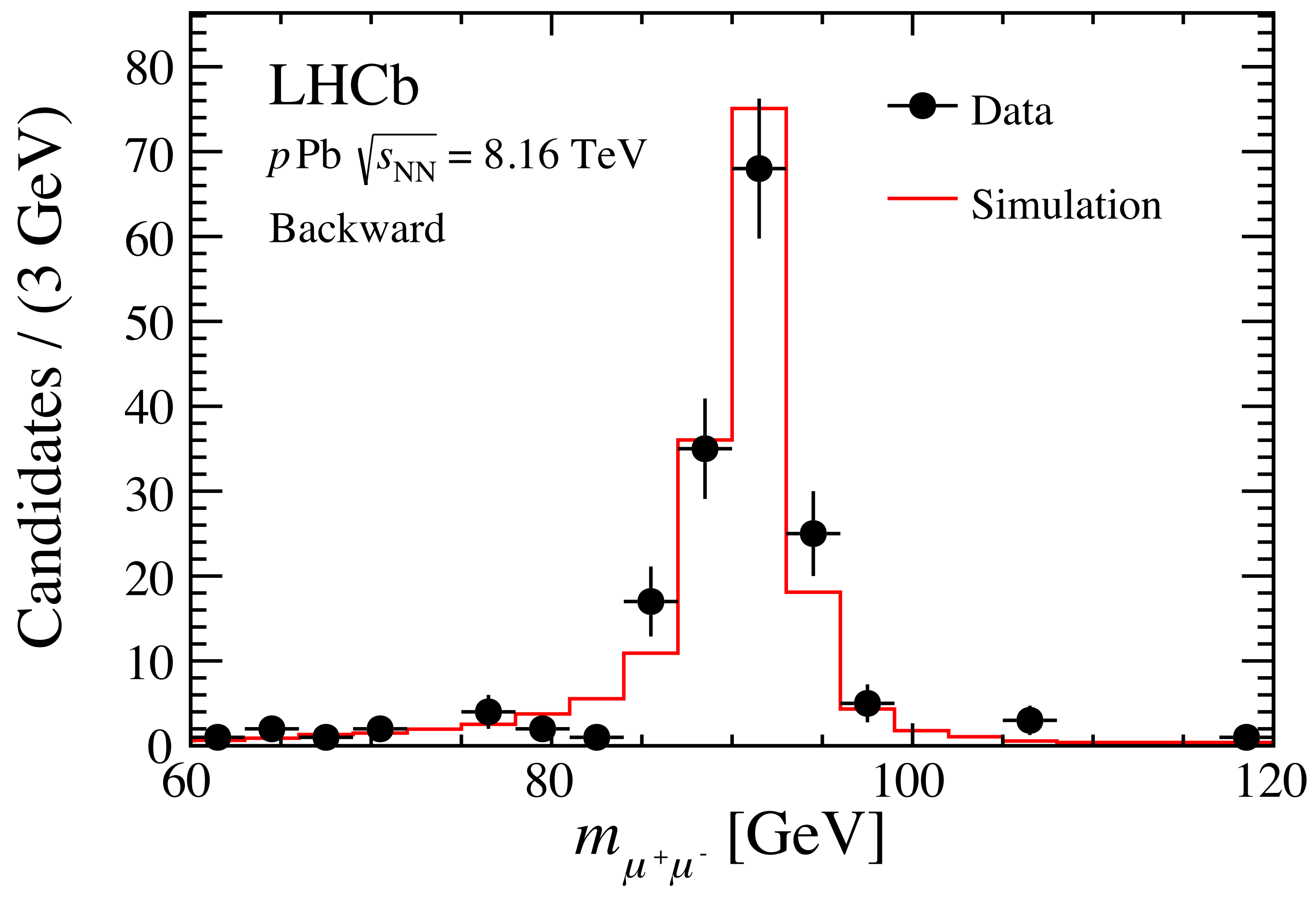


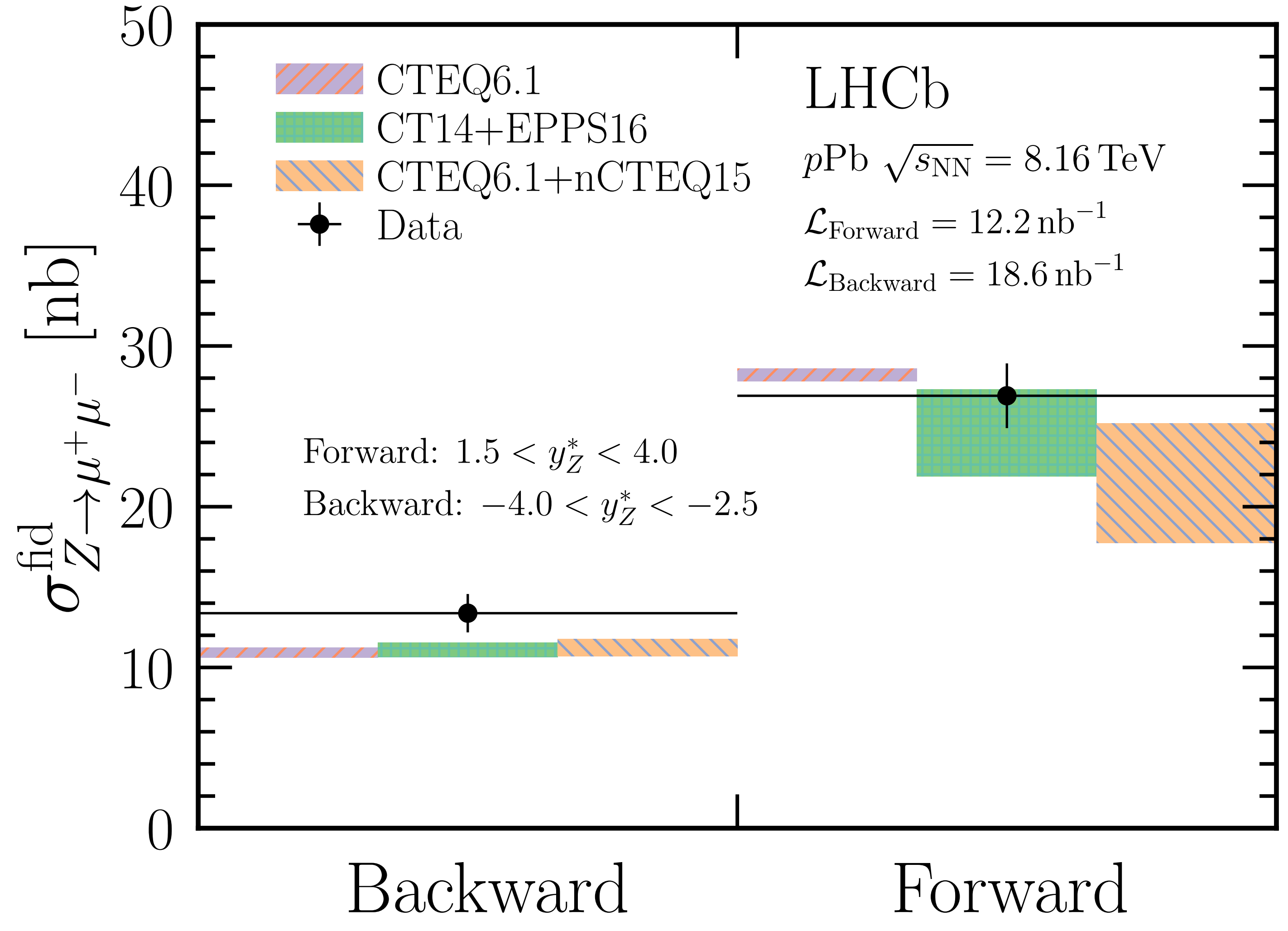


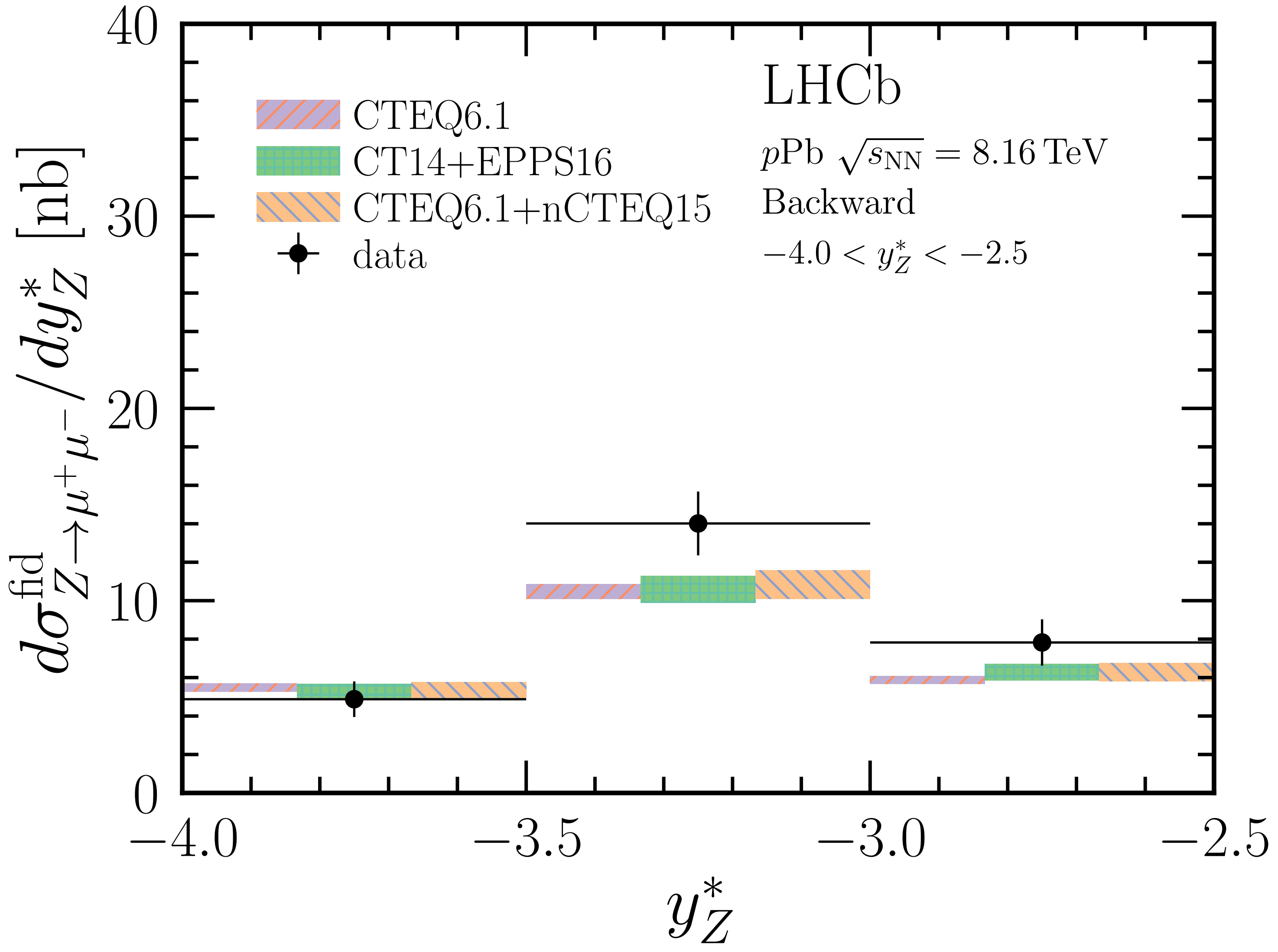
- Results compared with CGC and nPDFs
- Overall good agreement, tension at high-p_T suggests an additional effect like energy loss
- Backward to forward ratio, including medium-induced fully coherent energy loss (FCEL) without nPDFs effects

arXiv:2205.10213 Accepted by JHEP

Z boson in *p*Pb @8TeV







Backward $-4.0 < y^*_Z < -2.5$

$\sigma^{fid}_{Z\to\mu^+\mu^-,\ pPb} = 13.4 \pm 1.0 \pm 0.5 \pm 0.3$ nb

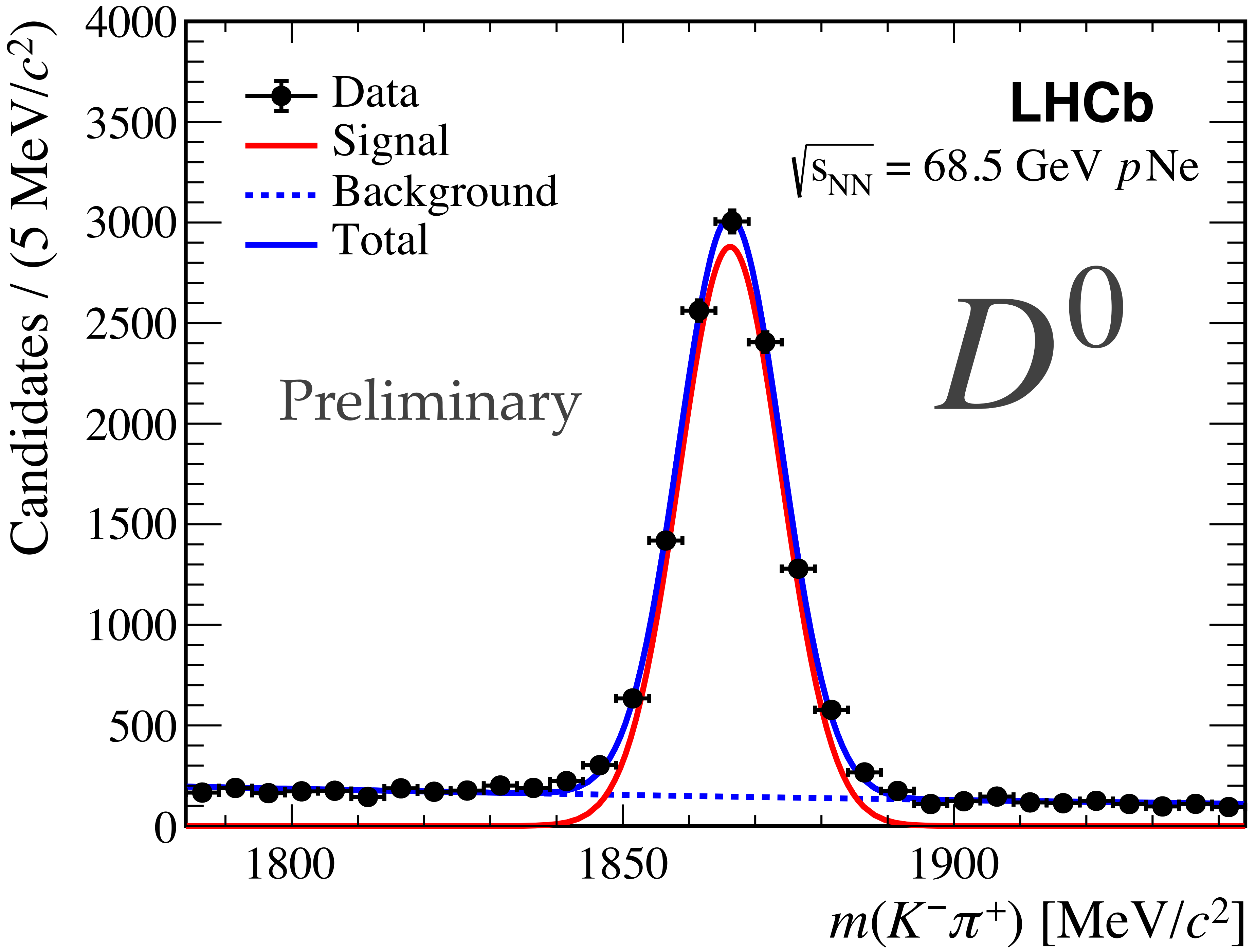
Forward $1.5 < y^*_Z < 4.0$

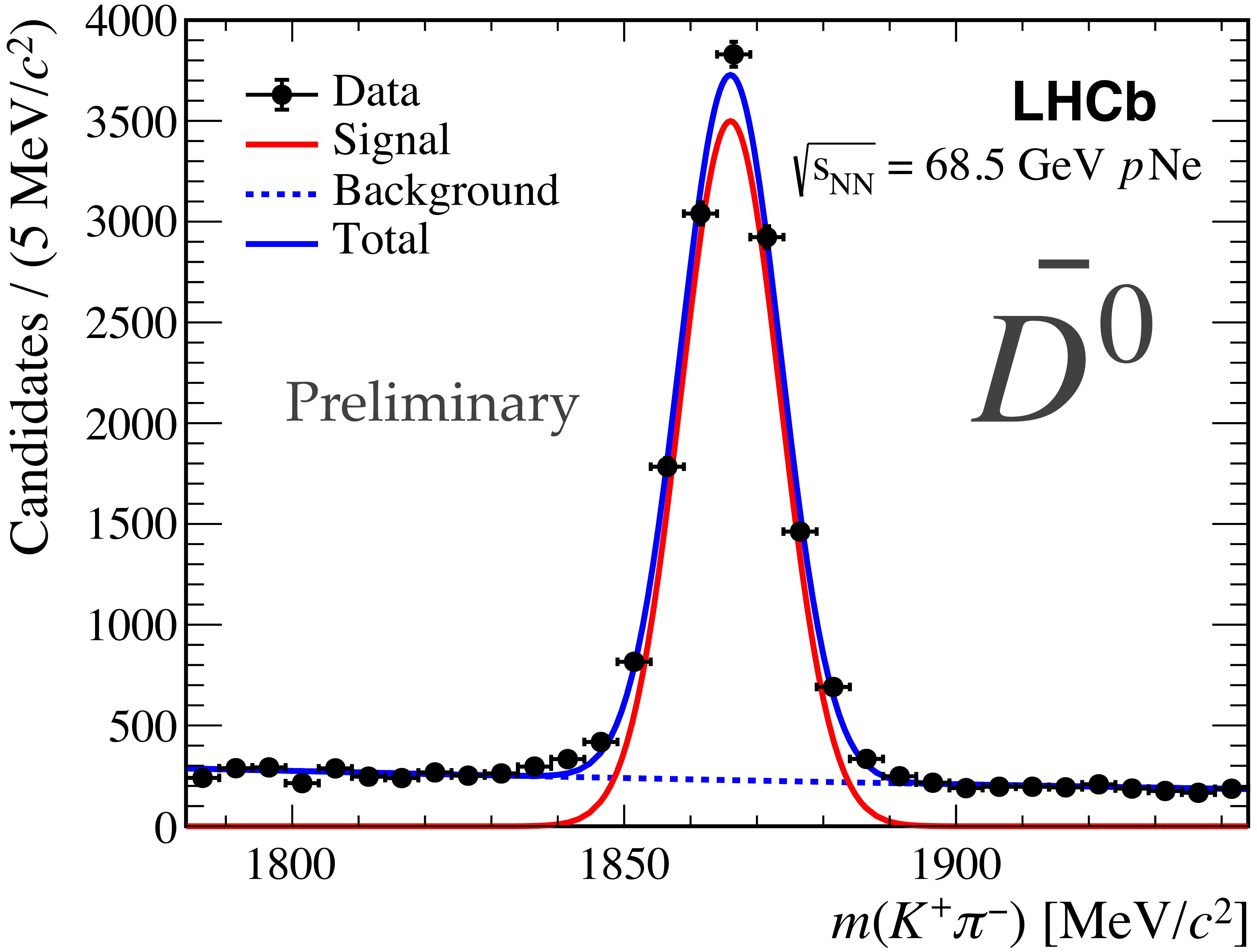
$\sigma^{fid}_{Z\to\mu^+\mu^-,\ pPb} = 26.9 \pm 1.6 \pm 0.9 \pm 0.7$ nb

- Powerful probe to measure nPDF as the hard process is well described by perturbative QCD
- Results compared to POWHEGBOX predictions using CTEQ6.1, EPPS16 and nCTEQ15 nPDF sets
- Both regions compatible with the prediction, uncertainty in the forward smaller than the predictions, good constrain on the nPDFs

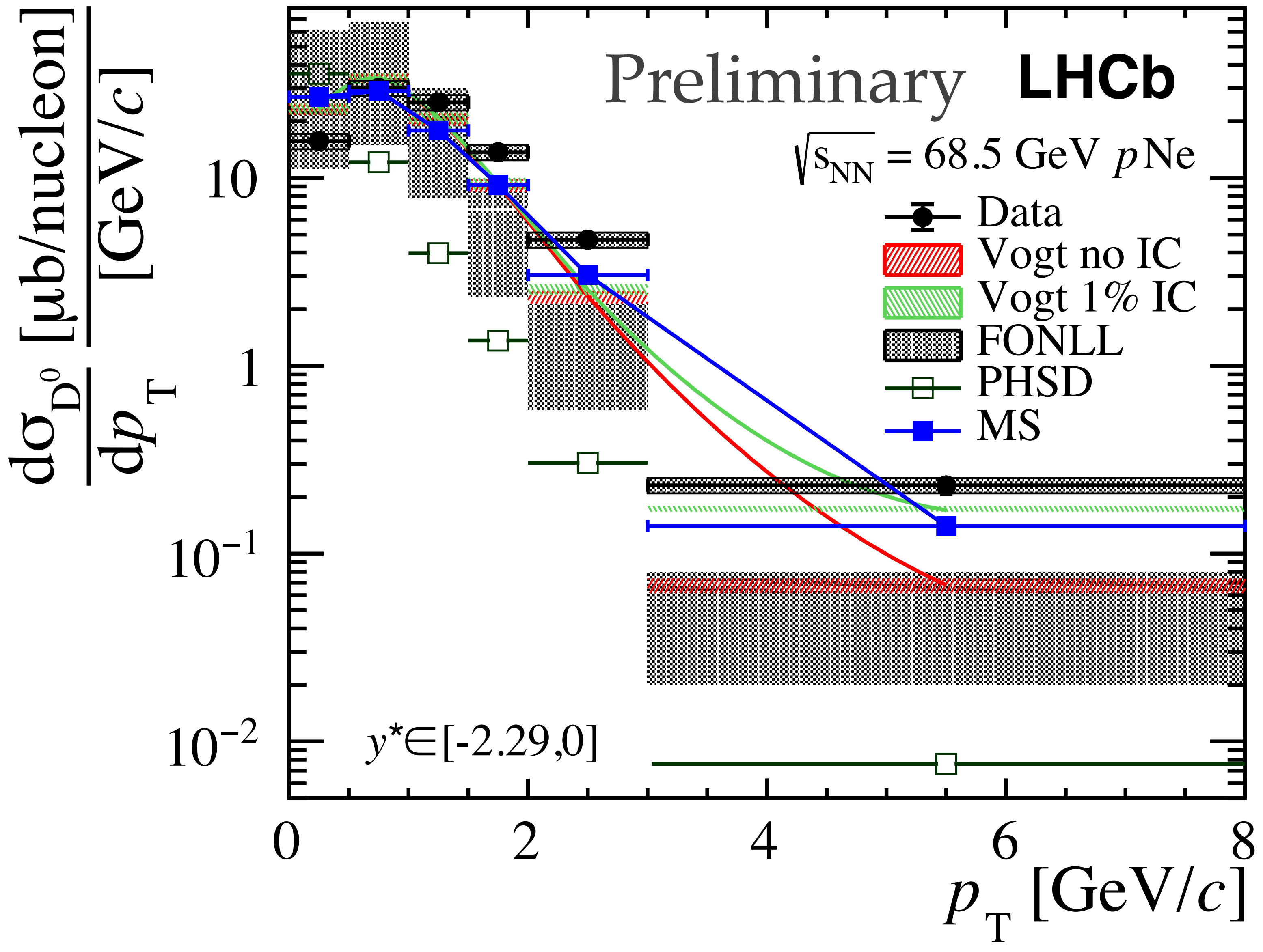
Open charm production in *p*Ne @68 GeV

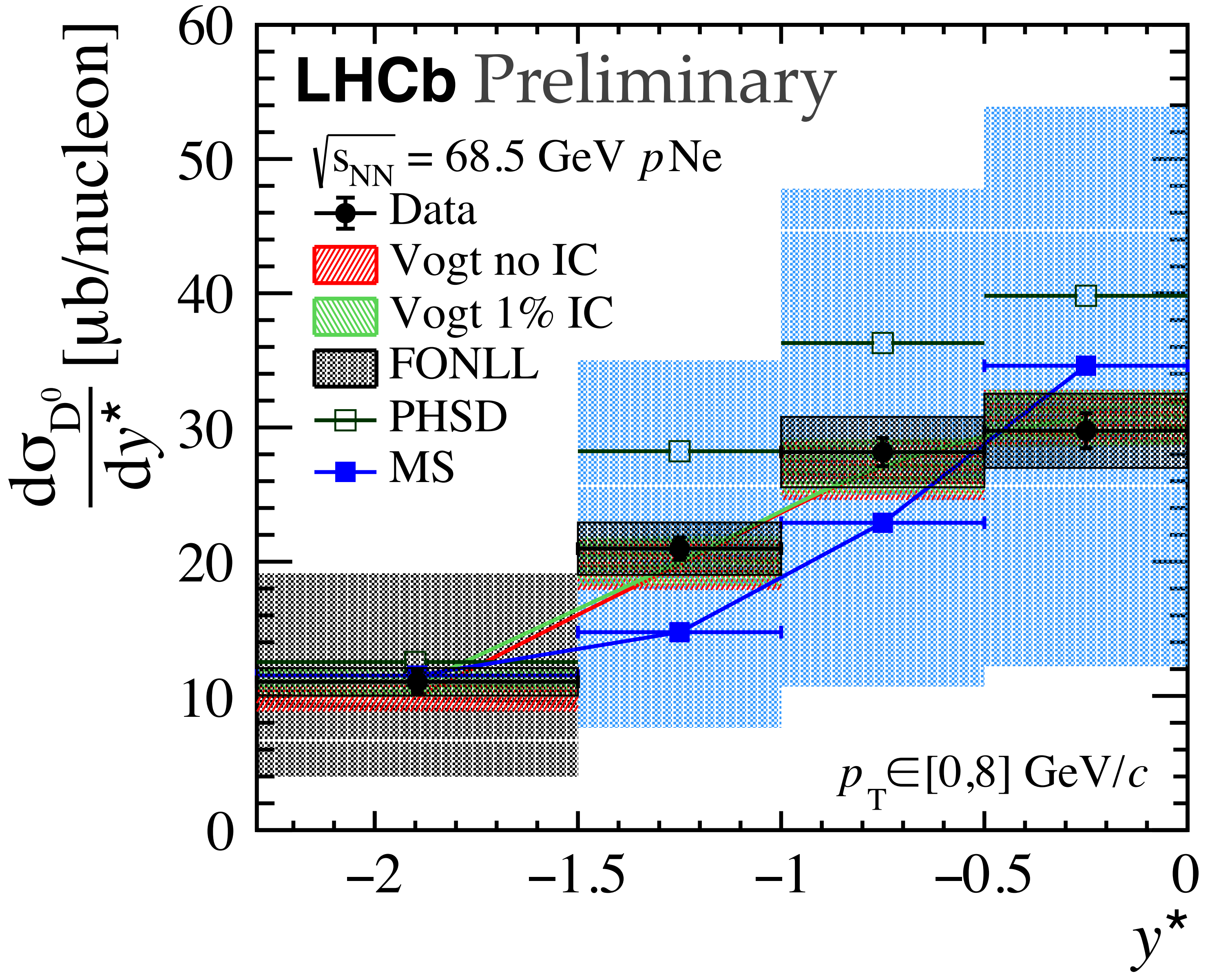
- Fixed target collisions, centre of mass rapidity [-2.29,0] high x-Bjorken
- Cross-section measurements compared to models including or not intrinsic charm
- Largest SMOG sample with $L = 21.7 \pm 1.4\ \text{nb}^{-1}$

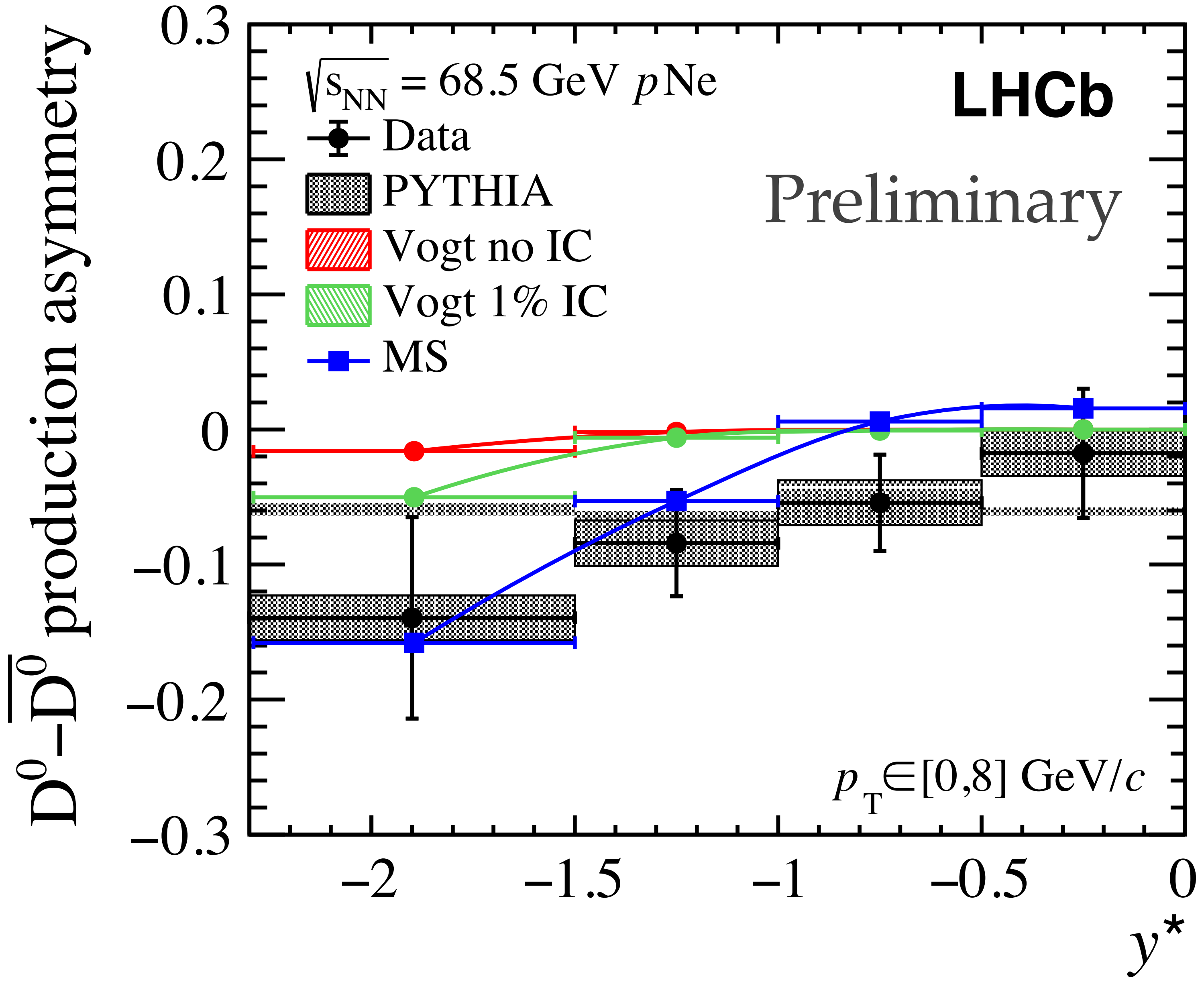




Open charm production in *p*Ne @68 GeV







- Cross-section compared to many models, Vogt and MS model that includes 1% intrinsic charm describe better the data.
- Asymmetry found, down to -15% at $y* = -2.29$, compatible with Pythia8 simulation
- Possible recombination with valence quarks can explain the $D^0 - \bar{D}^0$ asymmetry

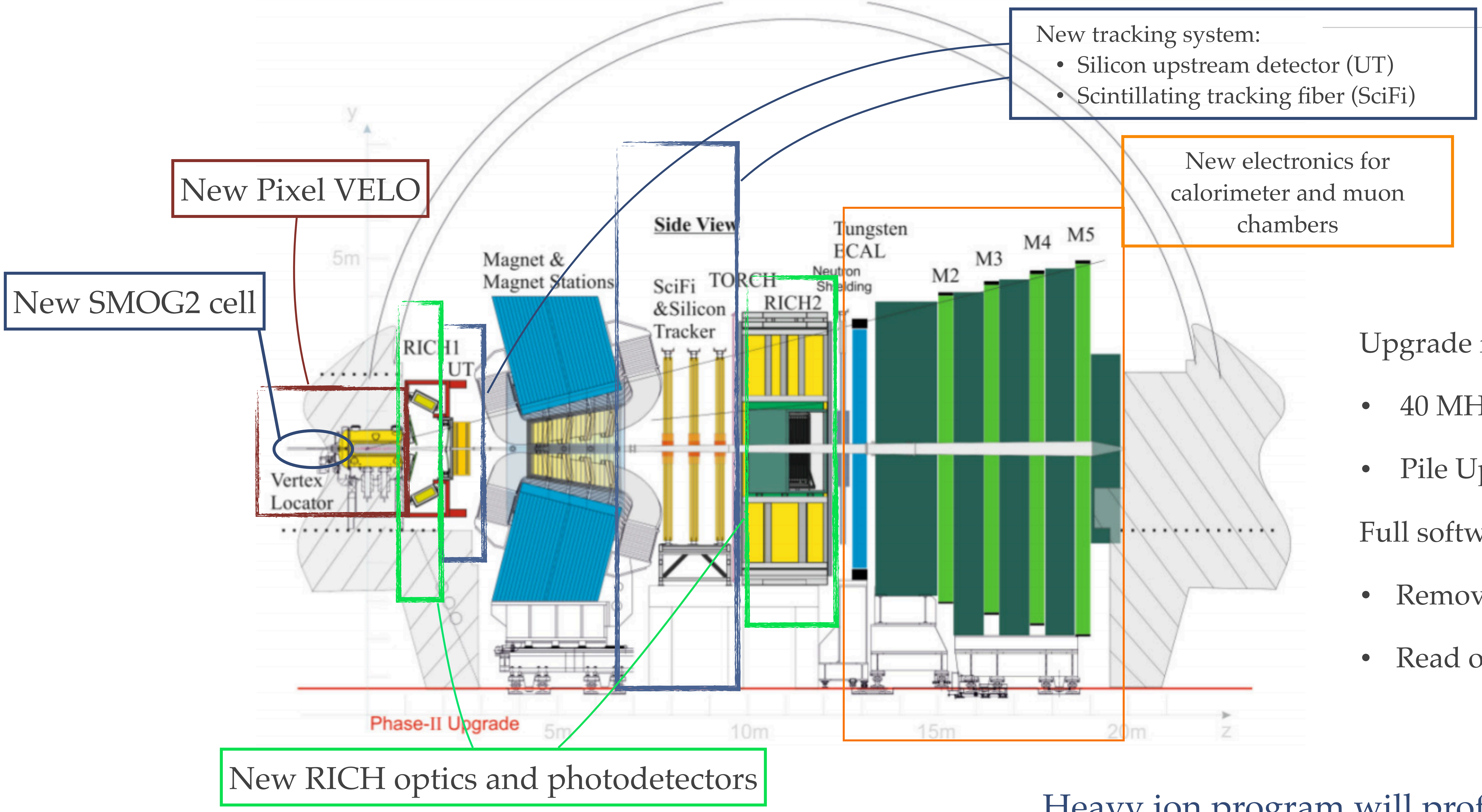
Charmonium production in pNe @68 GeV

- Complete the intrinsic charm measurement with J/ψ
- Again the Vogt model with 1% intrinsic charm seems to better describe the data, but larger samples with the SMOG2 system are needed to draw definitive conclusions

See LHCb intrinsic charm measurement with Z+jet Phys. Rev. Lett. **128**, 082001

LHCb upgrade run 3

[CERN-LHCC-2012-007]



Upgrade for pp requirement

- 40 MHz collision rate
- Pile Up factor ~ 5

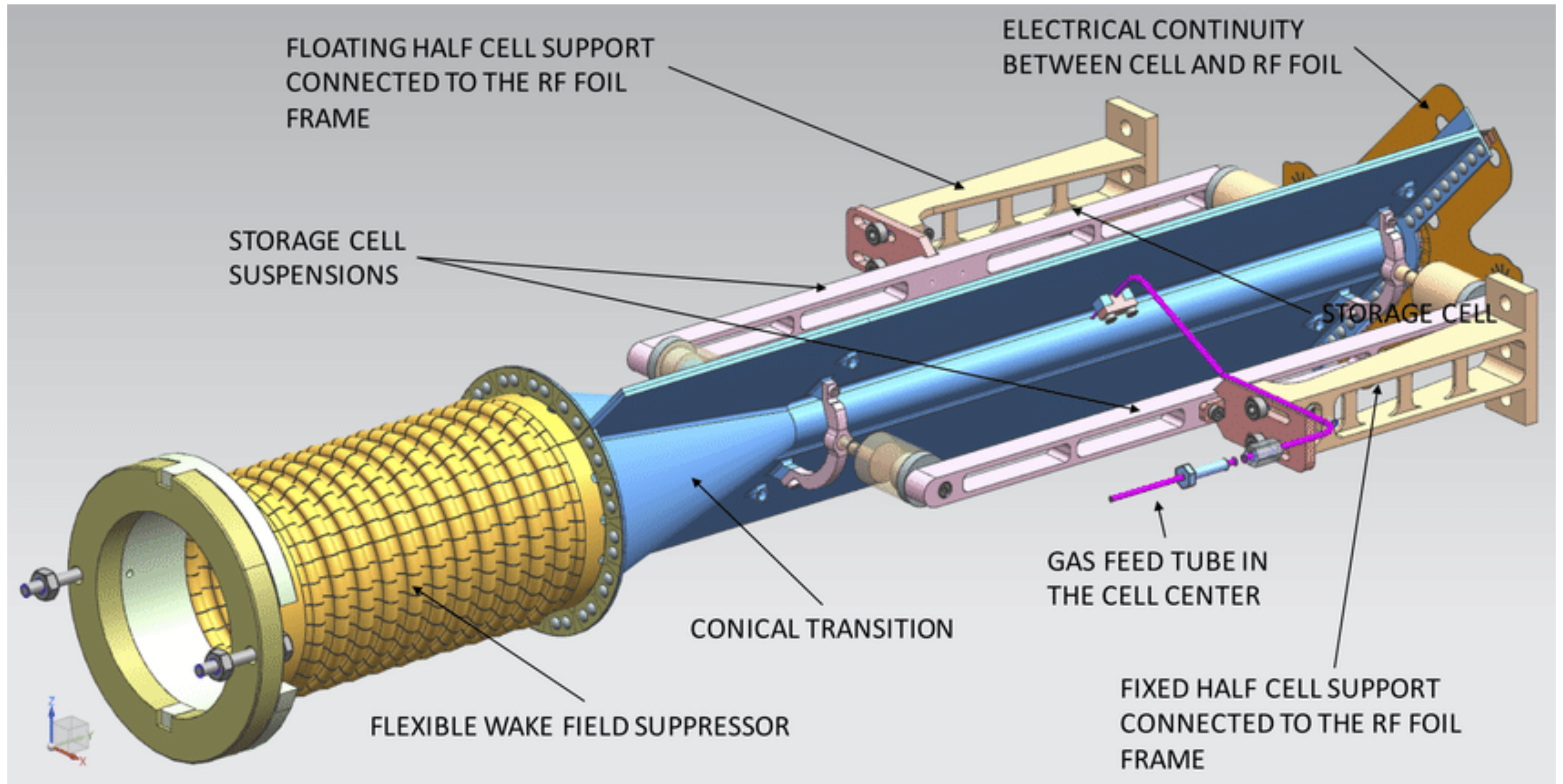
Full software trigger

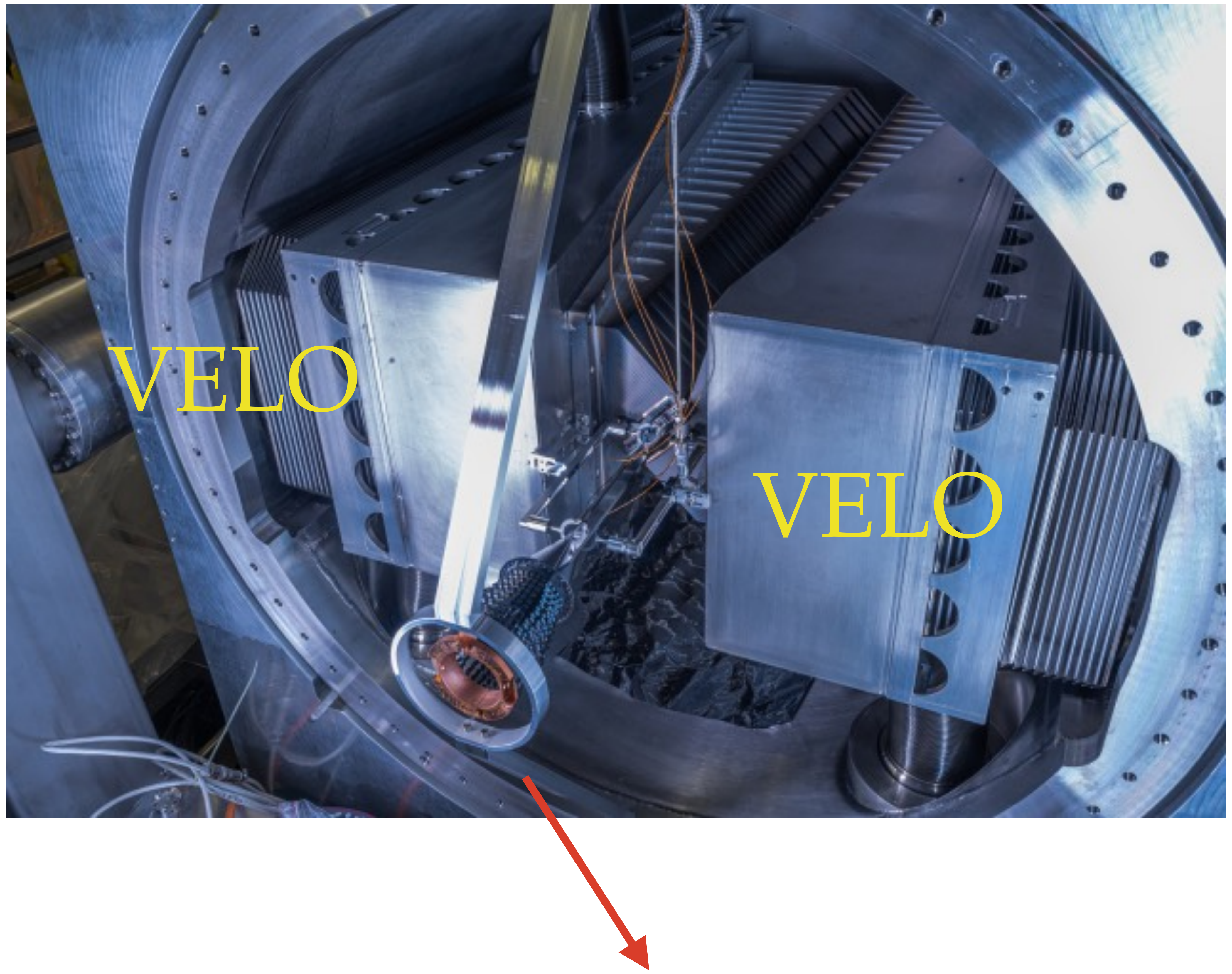
- Remove L0 triggers.
- Read out full detector at 40 MHz.

Heavy ion program will profit from this upgrade !

LHCb upgrade run 3

SMOG2 : A dedicated fixed target system to run simultaneously with normal collisions



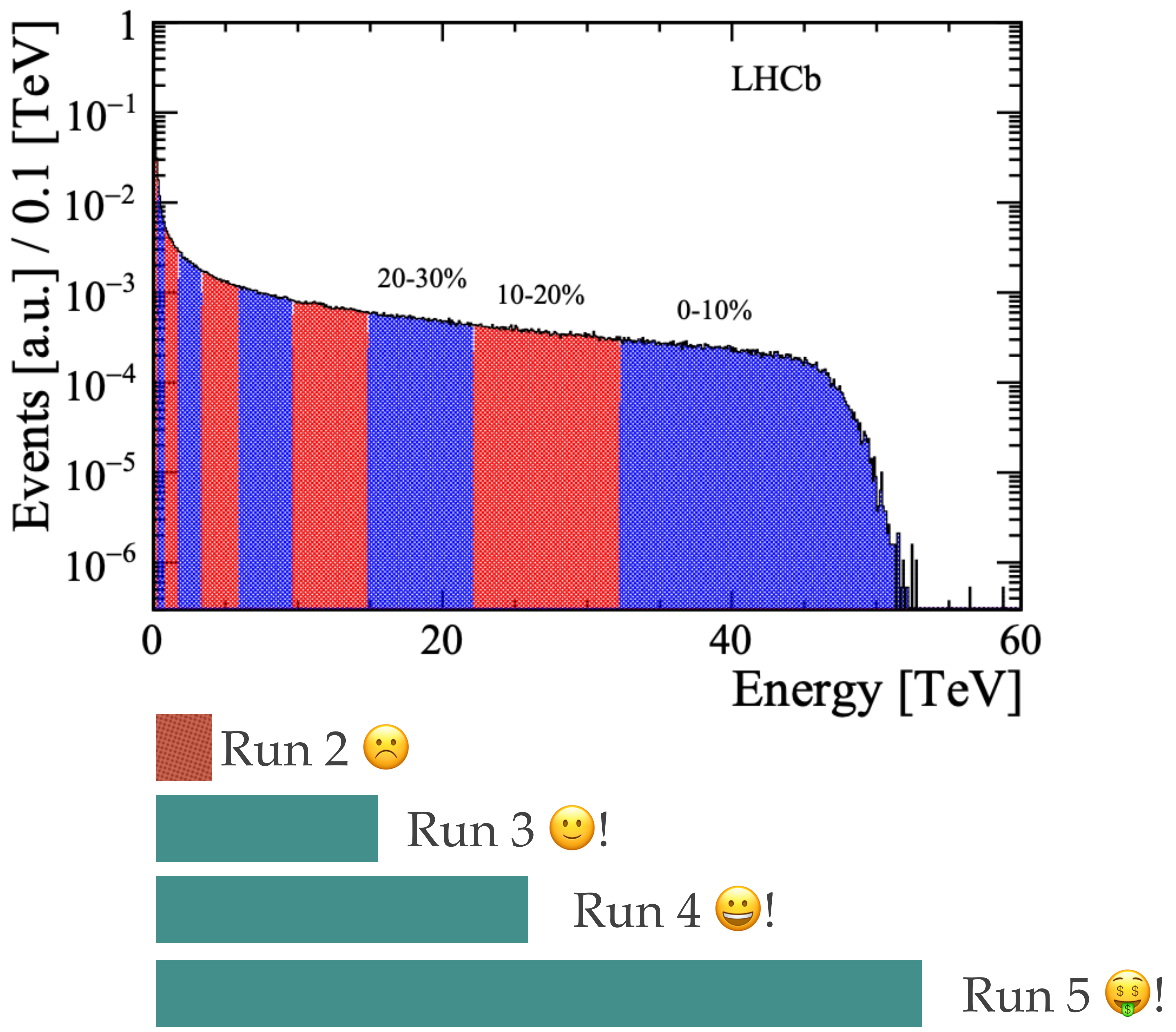


- Higher density of the gas (100 times higher luminosity)
- Better control of the gas density (better luminosity determination)
- New gas H_2, D_2, O_2 in addition to all noble gases

LHCb upgrade run 3

Improved tracking system pushes further the limitation of the detector

Energy deposit in the calorimeter



- Access to more central collisions
- QGP study possible with run3 data!
- Many new study possible (quarkonia suppression, low-mass mesons, flow…)
- Expect higher reach in run 4 and no limitations for run 5
  - Note there is no limitation for the SMOG2 system

Centrality determination

arXiv:2111.01607

Centrality determination using MCGlauber model

Centrality %	$N_{part} \pm \sigma$	$N_{coll} \pm \sigma$	$b \pm \sigma$
100 – 90	2.91 ± 0.54	1.83 ± 0.34	15.41 ± 2.96
90 – 80	7.03 ± 0.78	5.77 ± 0.64	14.56 ± 1.80
80 – 70	15.92 ± 0.64	16.44 ± 0.69	13.59 ± 0.52
70 – 60	31.26 ± 0.67	41.28 ± 0.93	12.61 ± 0.28
60 – 50	54.65 ± 1.13	92.59 ± 2.01	11.59 ± 0.24
50 – 40	87.54 ± 1.01	187.54 ± 2.43	10.47 ± 0.14
40 – 30	131.24 ± 1.15	345.53 ± 3.89	9.23 ± 0.08
30 – 20	188.02 ± 1.49	593.92 ± 6.62	7.80 ± 0.06
20 – 10	261.84 ± 1.83	972.50 ± 10.37	6.02 ± 0.04
10 – 0	357.16 ± 1.70	1570.26 ± 15.56	3.31 ± 0.01