Heavy-ion perspectives with LHCb

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04.12.2017

QCD opportunities with heavy-ion beams with LHCb

LHCb will contribute to many aspects in the future in Run 3/4

QCD matter

- unique heavy-flavour measurements
- potential for low-mass dileptons for medium characterisation, net-charge fluctuations with contact to LQCD
- complementary forward rapidity measurements with PID

QCD phenomena at low-x and high-x in pA
$\rightarrow$ required for precision on QCD matter

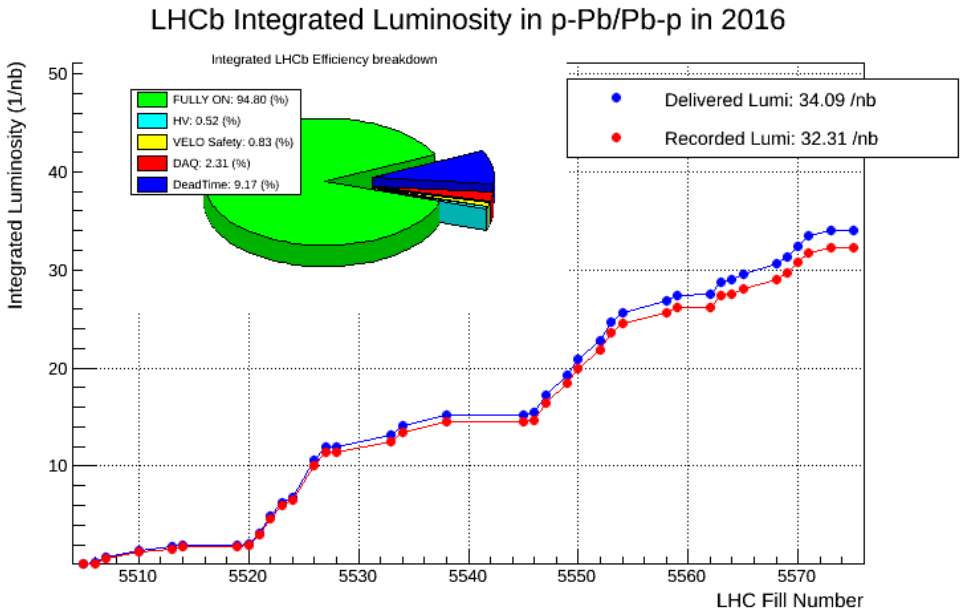
- forward rapidity, low-Q^2 capabilities: low-x
  $\rightarrow$ the place to look for saturation
- emergent phenomena: best acceptance to test dilute-dense regime calculations
- (anti)-shadowing and/or intrinsic charm in fixed target

Unique service for cosmic ray community

Already available pPb LHCb data: a unique treasure for low-x and much more

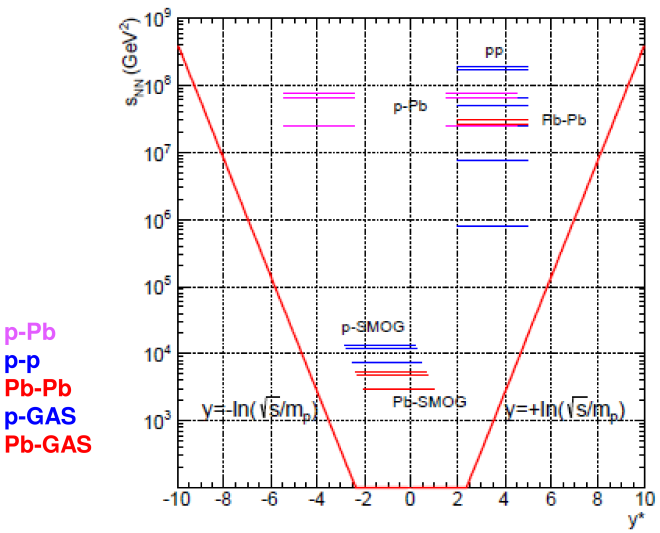
request 10 nb^{-1} per beam direction at 8 TeV:
Hadron PID and precision tracking/vertexing down to low-p_T

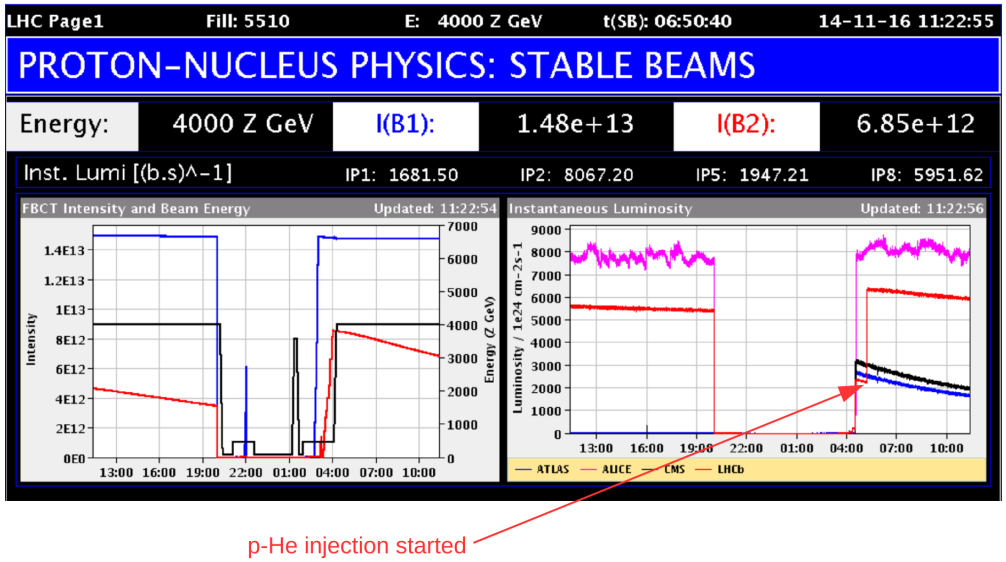
- ψ(2S) precision close to the one of J/ψ in 2013 by 10-40 times higher statistics
- comparison with Drell-Yan
- double charm production and $c\bar{c}(c)$- correlations
- fully reconstructed open beauty and Υ family



13.6±0.3 nb^{-1} in pPb
20.8±0.5 nb^{-1} in Pbp
≈10^9 minimum events in both configurations

Already available fixed-target data: large variety of data samples with large physics potential



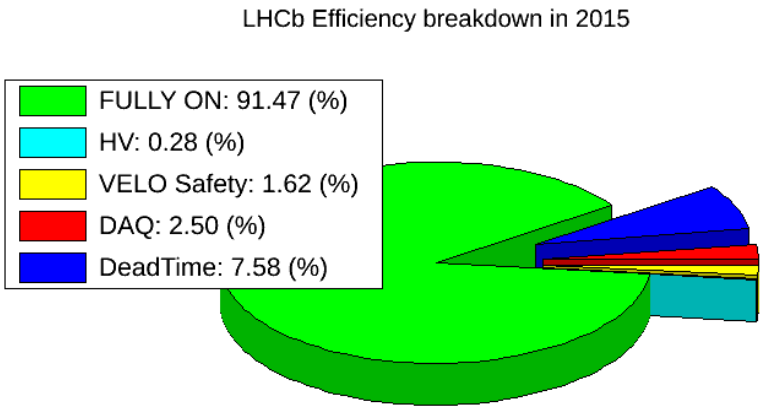


p-He injection started

- noble gas injected in interaction region

  improve luminosity measurement by beam imaging J. Instrum. 9 (2014) P12005
- residual gas pressure in beam pipe increased by 2 orders of magnitude: $O(10^{-7})$ mbar
- used for fixed target with proton and Pb beams: LHCb $\approx$ midrapidity rapidity coverage at lower collision energies
- ***p*He, *p*Ar, *p*Ne**, *p*Ne, *Pb*Ne and *Pb***Ar** data samples available
- *p*Ar and *p*He $O(\text{nb}^{-1})$ integrated luminosities
- *p*Ne about 5×10^{23} protons on target: about 10 times more protons than *p*Ar sample used for charm studies

Already available data: large soft trigger samples for PbPb and XeXe data

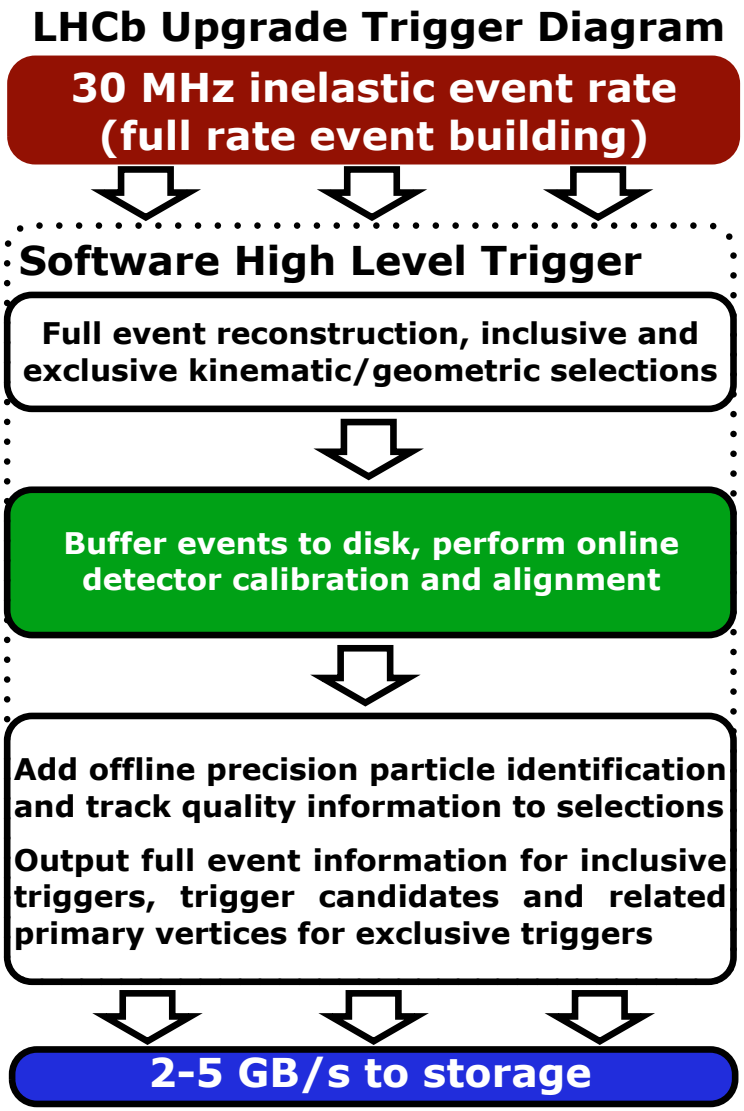


Experiment	2015 PbPb
ALICE central	150 mio MB evts. (0.02 nb^{-1})
ALICE muon	0.225 nb^{-1} analysed
CMS	0.464 nb^{-1} analysed
ATLAS	0.515 nb^{-1} analysed
LHCb	50 mio MB evts., 50-100% tracking

modified version in arXiv:1609.01135, references therein.

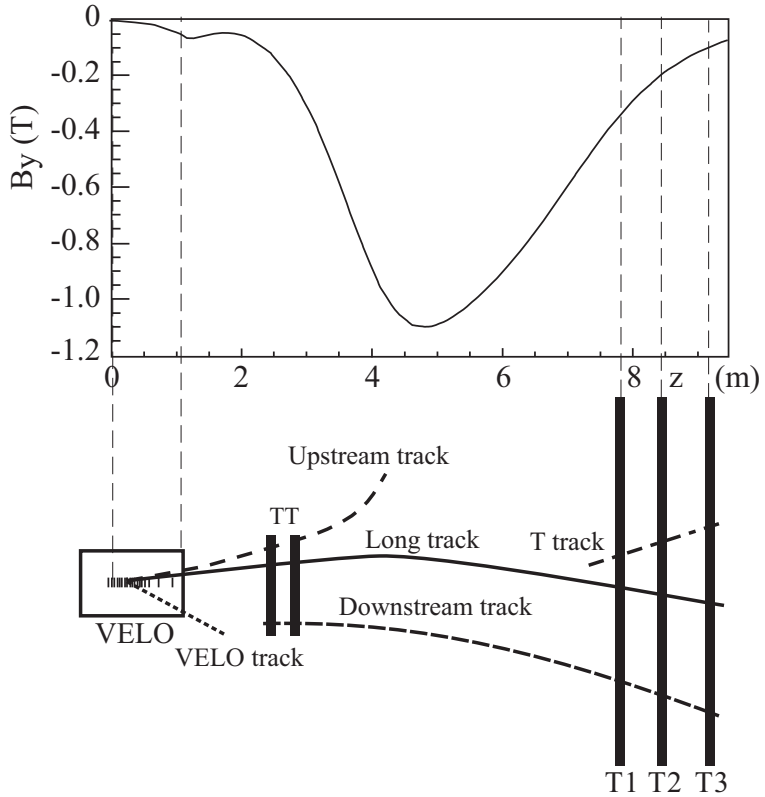
- 2015 first data taking in most challenging environment for LHCb
- competitive data sample for soft probes and charm in terms of event statistics in unique acceptance
- very soft trigger requirement:
  Equivalent amount of QED & photo-induced for dimuons events written on tape!
- XeXe in 2016: about 0.4 μb^{-1} with improved triggers for photo-induced processes

LHCb upgrade



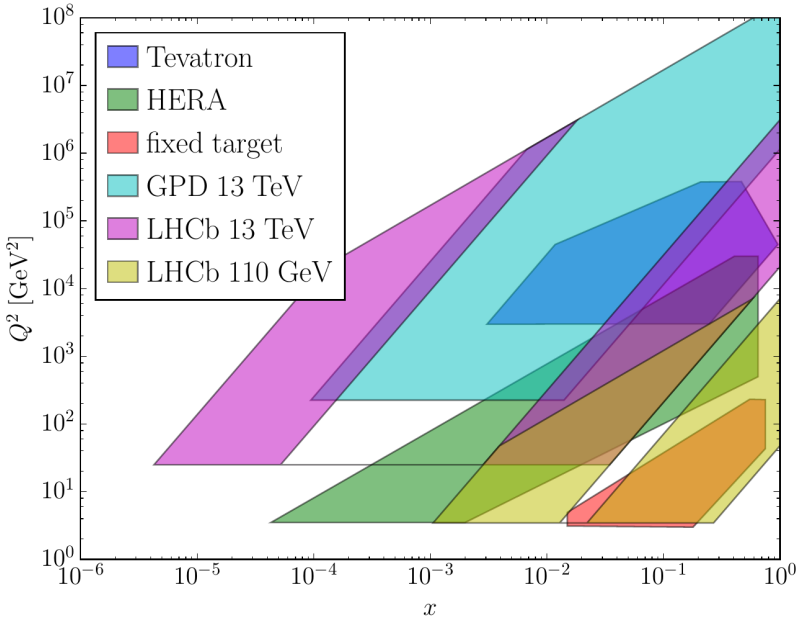
- $L = 2 \times 10^{33}$ cm$^{-2}s^{-1}$: ≈ 5 collisions on average per beam crossing instead of 1 now
- triggerless readout and full software trigger at 30 MHz
- p–Pb and p–A fixed target multiplicities below pp average conditions
- tracker with larger granularity

LHCb upgrade



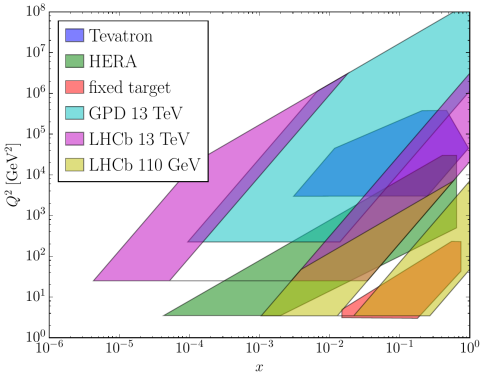
- Velo: from strip to pixel ($55 \times 55\ \mu m^2$): Velo TDR
- T1-T3: Outer/Inner Tracker $\rightarrow$ Scintillating Fibre Tracker
- 200 μm(InnerTracker)/5.25 mm (OuterTracker) $\rightarrow$ 270μm pitch, fibres extend from innermost to outermost radius Tracker TDR
- TT $\rightarrow$ UT: 10cm$\times$183μm $\rightarrow$ 10/5cm$\times$190/95μm Tracker TDR
- evaluation with **full simulation ongoing**: to be released in course of workshop series $\rightarrow$ will define priority collider vs. fixed target
- improved tracking efficiency below $p < 4$ GeV$/c$ via magnet stations on the side of dipole under study

pPb with LHCb

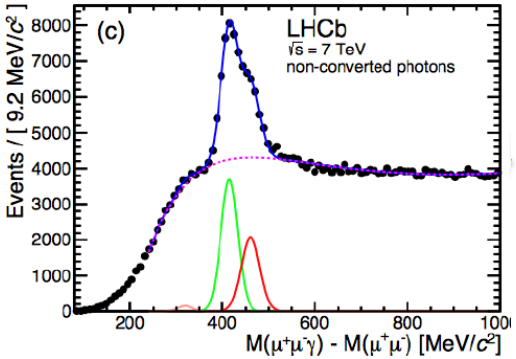


- at HL-LHC workshop: J. Jowett 500-1000 nb^{-1} for ATLAS/CMS at full energy possible within one heavy-ion run
- unique chance with LHCb to explore down to $x = 10^{-6}$ thanks to forward acceptance
  $\rightarrow$ best place to look for **saturation**
  $\rightarrow$ lower x-reach than planned electron-ion collider
- required to **understand** nuclear effects in **charm/beauty** observables in pPb and in PbPb $\rightarrow$ needed to lift ambiguity in model comparisons
- *In addition: best tool to bridge low multiplicity pp towards PbPb*

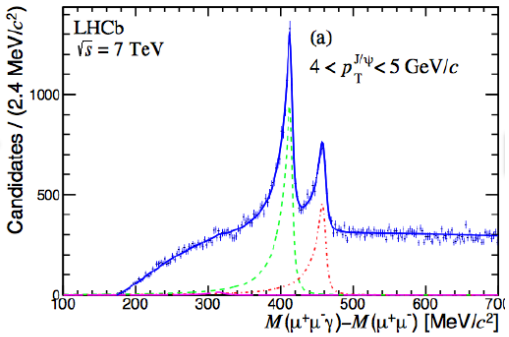
pPb: new probes for low-x



LHCb-PAPER-2011-030
(unconverted γ)

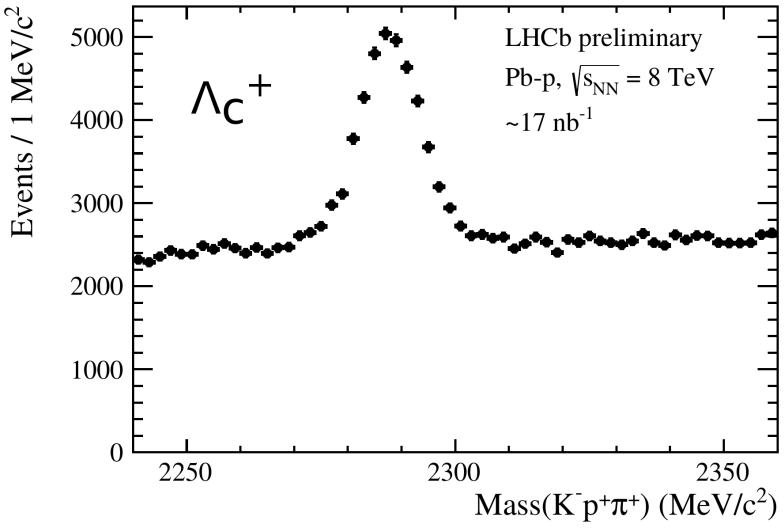


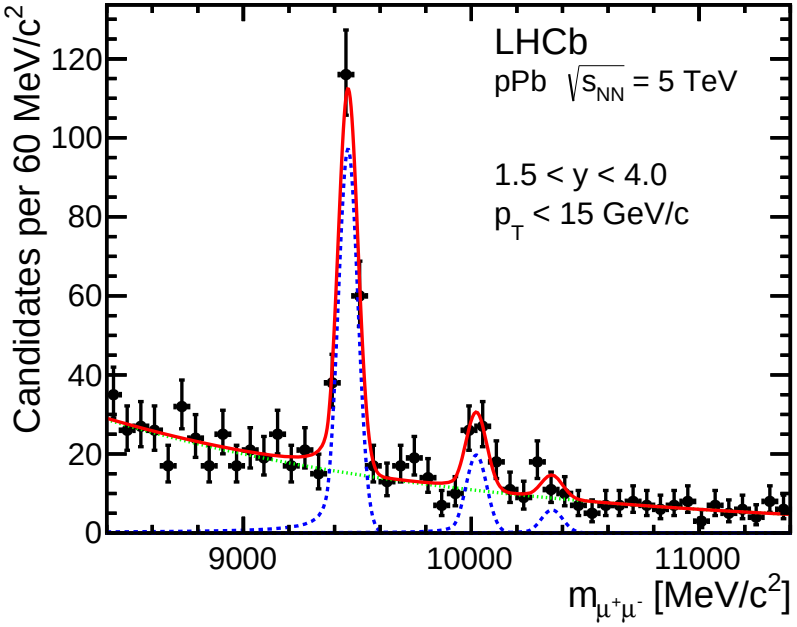
LHCb-PAPER-2013-028
(converted γ)



- Drell-Yan from Z down to J/ψ:
  $\rightarrow$ theoretically clean, experimentally cleanest in LHCb due to precision vertex detector and displacement of heavy-flavour background due to boost
- other observables under investigation $\gamma + jet$, at leading order directly sensitive to gluons
- larger luminosity required: currently statistically limited measurements as χ_C, η_c and beauty measurements will help to understand PbPb
- would require about 450 nb^{-1} for DY-measurement à la pp

LHCb upgrade and AA collider

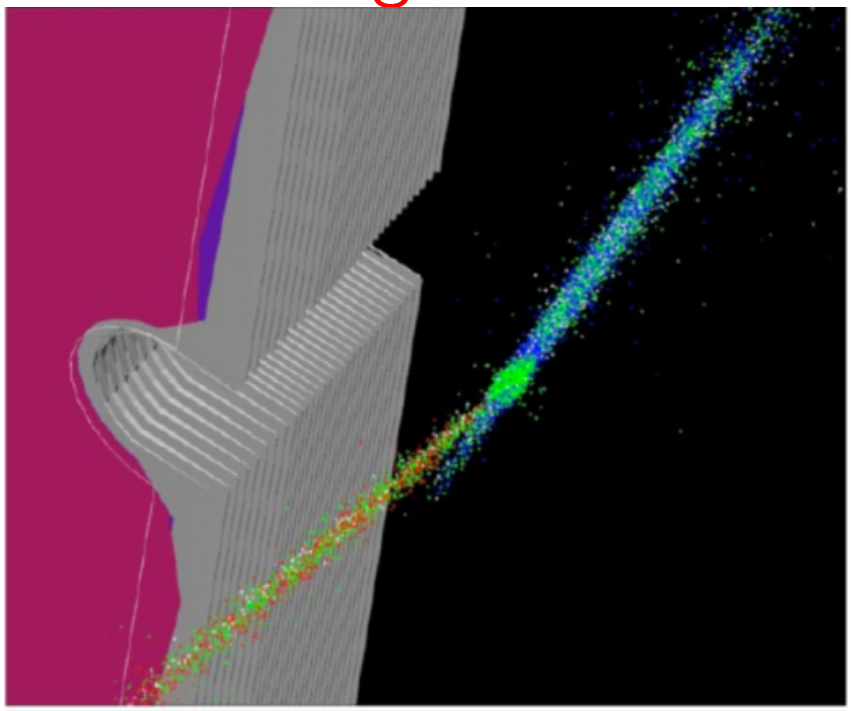




right: JHEP 07 (2014) 094

- considerations depending on ongoing simulation studies with upgraded detector
- studies ongoing for Λ_C, Υ

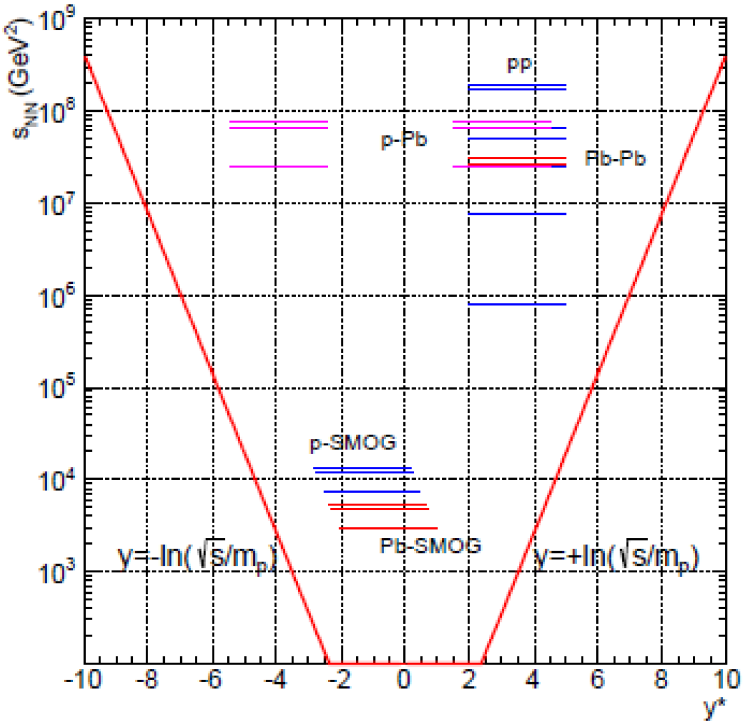
LHCb fixed target



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

p-Pb
p-p
Pb-Pb
p-GAS
Pb-GAS



- noble gas injections with pressures 10^{-6}-10^{-7} mbar introduced for improved luminosity measurements
- used as internal gas target for p-gas and ion-gas collisions: He(A=4), Ne(A=20), Ar(A=40) used so far
- LHCb acceptance reaches close to midrapidity
- first preliminary measurements in pAr and in pHe collisions from Run2

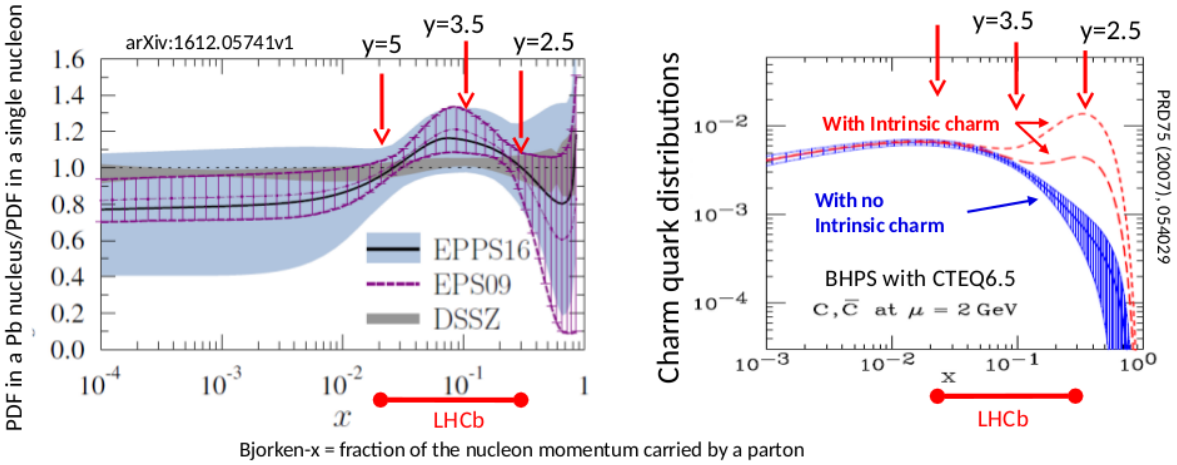
LHCb fixed target: nucleus-nucleus in Run3/4

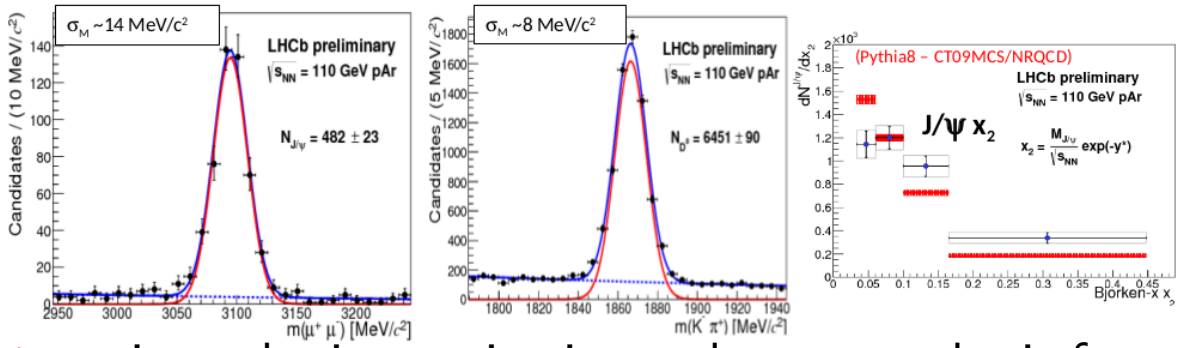
	System \ centrality	60 – 100%	50 – 60%	40 – 50%	30 – 40%	20 – 30%	10 – 20 %	0 – 10%
LHC	PbNe – 71 GeV	108.6	254.4	392.5	588.0	814.5	1086.0	1494.9
LHC	PbAr – 71 GeV	123.6	308.8	496.5	806.6	1228.3	1711.9	2372.7
SPS	PbKr – 71 GeV	196.9	533.6	919.1	1451.2	2205.5	2986.6	4084.3
SPS	PbPb – 17 GeV	124.2	331.6	605.9	919.6	1338.7	2035.8	2980.5

(based on EPOS-LHC-v3400)

- similar charged particle multiplicity as at SPS: similar energy densities
- measurements will profit from upgraded detector
- maximal occupancy in central PbAr about factor 5 below central PbPb $\rightarrow$ preferred running strategy during ion beams to be defined after detailed simulations inputs
- unique chance for open charm and yet missing hidden charm (χ_c) in that energy regime and density regime at $\approx$ midrapidity
- work ongoing for storage cell: larger areal density by up to 2 orders of magnitude in Run 3/4, not limited to noble gases $\rightarrow$ targeting LS2

LHCb fixed target: proton-nucleus in Run3/4

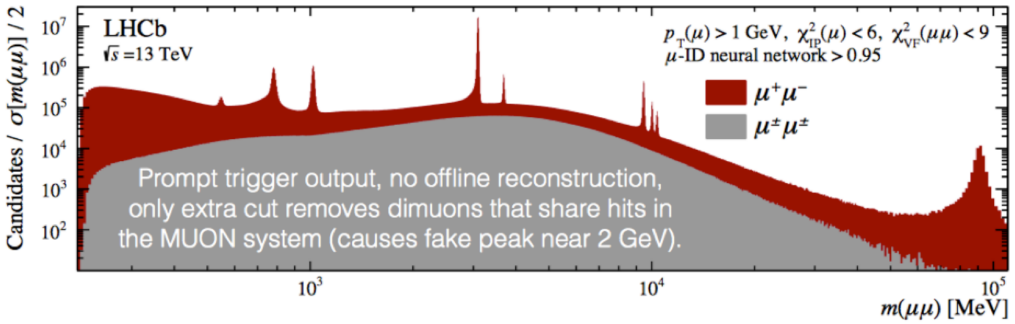


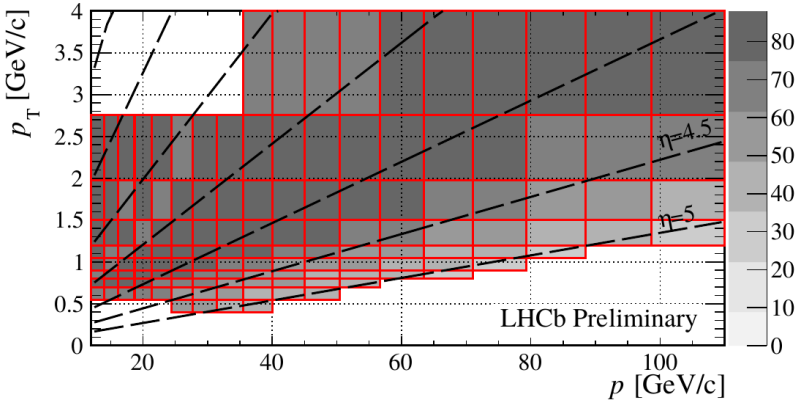


- unique physics motivation and necessary basis for nucleus-nucleus

  first preliminary measurements now LHCb-CONF-2017-001; *p*Ar collisions with 685 non-colliding bunches: $4{\cdot}10^{22}$ protons on target, overall data (17h) : 500 J/ψ, 6500 D^0
- unique chance for open charm and yet hidden charm including χ_C in that energy regime: clarify break-up mechanisms limiting precise understanding
- physics programme profitting from internal unpolarised gas target upgrade via storage cell

Yet uncharted major potentials





Right: LHCb-CONF-2017-002

- intermediate-mass dileptons: precision temperature measurement above the ϕ-mass via thermal radiation to be checked also in high-multiplicity pPb, pp

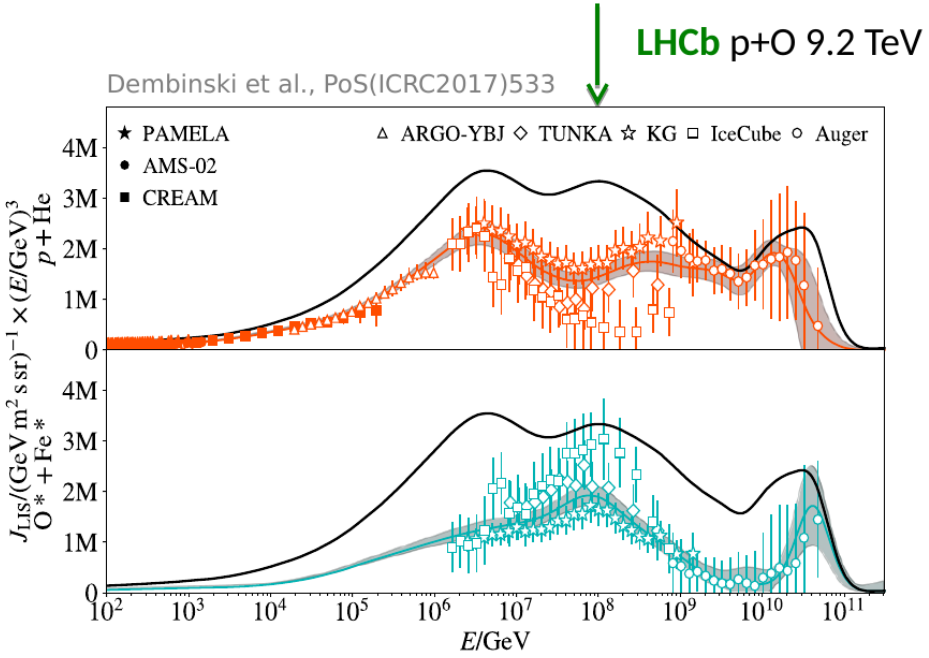
  masses below to be seen, current minimal p_μ with ID 3GeV/c: $p_T = 200, 400$ (η =4.0,2.5)

- net-baryon fluctuations: contact to LQCD and trace remnants of chiral phase transition with low-p_T at moderate p and solid state detectors

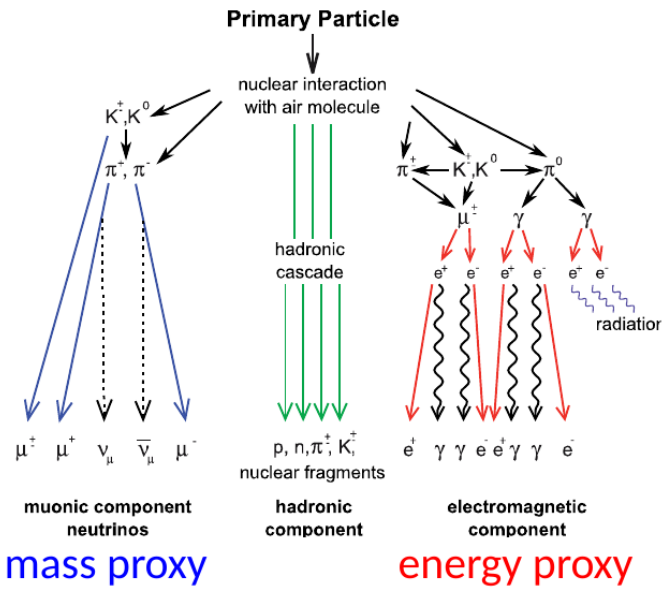
  currently $p > 10$ GeV/c via RICH-veto K,π, active from 17 GeV/c on

- for LS3 addition of TOF (TORCH) option in discussion
- interesting both for fixed-target and collider

Cosmic ray physics: motivation for a *p*O run



Haungs et al., JoP Conf. Ser. 632 (2015) 012011



(other mass proxies exist, but muons are used in **most** experiments)

- High-energy cosmic rays are measured through induced extensive air showers
  - **Energy** inferred from number of electrons and gammas
  - **Mass** inferred from number of muons (tracers of hadronic cascade)
- Air shower development shaped by forward hadron production
  - Phenomenological hadronic interaction models (EPOS, ...) need **collider data** for refinement
  - Inferred cosmic-ray mass composition limited by **model accuracy**
- **p+O runs:** lab measurement of first interaction in a **10^8 GeV air shower**

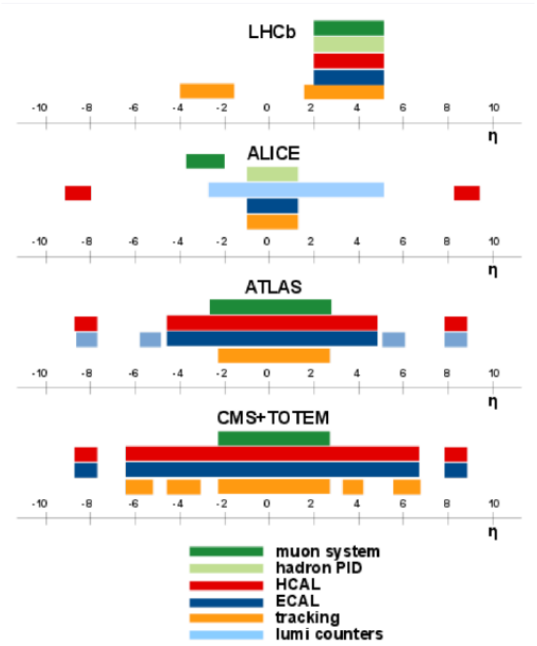
Cosmic ray physics: required statistics

- Why pO?
  - pO collisions reproduce **first interaction** in 10^8 GeV air showers
  - All models tune to pp, use Glauber theory to compute pO and pN
  - **Test Glauber theory** by comparing pO with pp
  - Why oxygen, not nitrogen? oxygen already used as support gas for lead

- What to measure?
  - **π, K, p**
    - Inclusive production, double-differential X-section (eta, pT)
    - Multiplicity distribution
  - Open and hidden charm
    - Decays produce high-energy muons (IceCube background)

- Required luminosity
  - **100M events,** about **Lint = 0.2 nb^{-1}**

- Forward detectors especially important
  - **LHCb: full hadron PID for 2 < eta < 5**
  - LHCf: gamma and neutrons at eta > 8.4
  - CASTOR: EM calorimeter at 5.2 < eta < 6.5



Summary

- Very rich opportunities
- **low**-x physics very strong LHCb point: requires large pPb luminosity
- nucleus-nucleus fixed-target and collider for **QCD matter**: unique heavy-flavour opportunities addressing deconfinement at forward rapidity and much more
  $\rightarrow$ estimate Run 3/Run 4 occupancy limits in PbPb and Pb-Ar/Ne ongoing, will define running strategy
- **cosmic ray physics**: unique opportunity to clarify with soft particle production in pO collider mode longstanding key problem

Bottleneck for a field: Inferring the mass

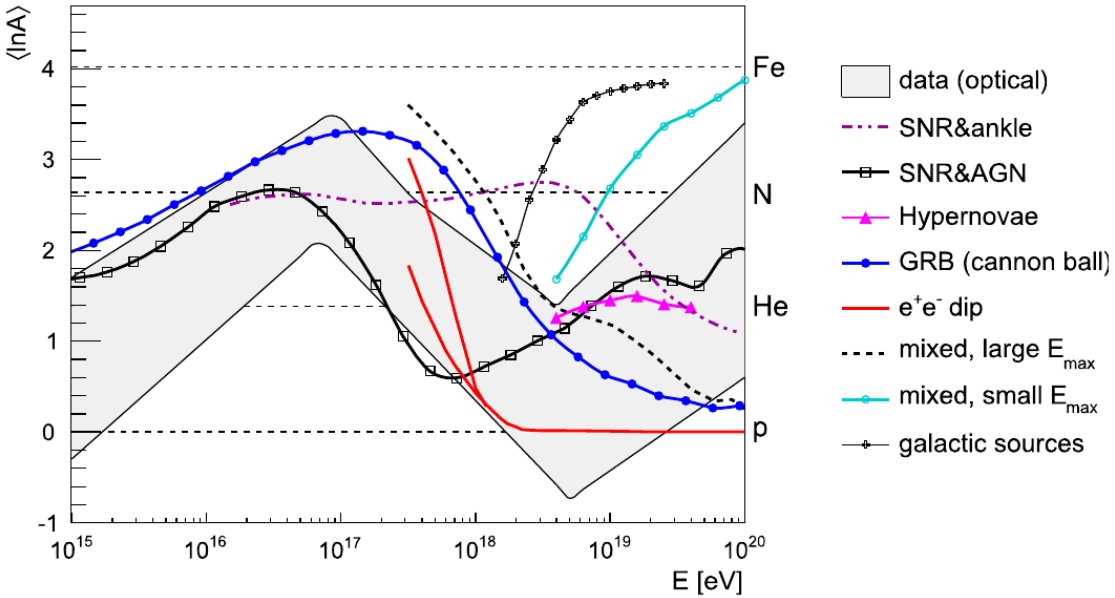
Cosmic ray observables
to test astrophysical theories

Directions
- No point sources found
- Weakly discriminating

Energy spectrum
- Small uncertainties
- Weakly discriminating

Mass composition
- **Large uncertainties (so far)**
- **Strongly discriminating**

Kampert & Unger, Astropart. Phys. 35 (2012) 660–678



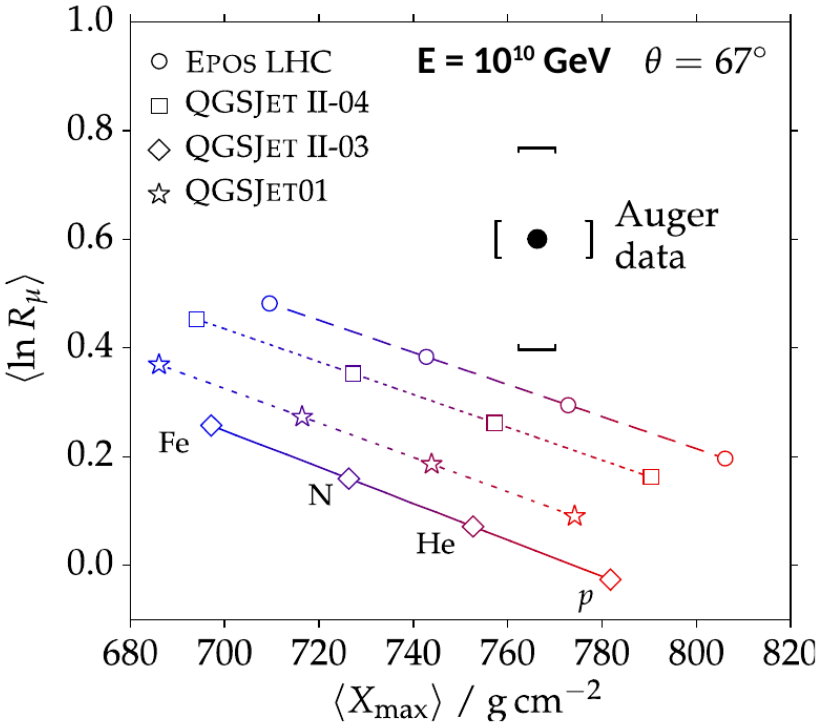
Mass composition differs **greatly** in astrophysical theories of CR origin,
but accuracy of measurement poor because of **uncertainties in air shower models**

Example: Two leading experiments differ above the knee, likely because of model
- IceTop/IceCube: μ-measurement interpreted with SIBYLL 2.1, QGSJet01
- KASCADE-Grande: μ-measurement interpreted with EPOS-LHC, SIBYLL 2.3, QGSJet-II.04

Muon Puzzle

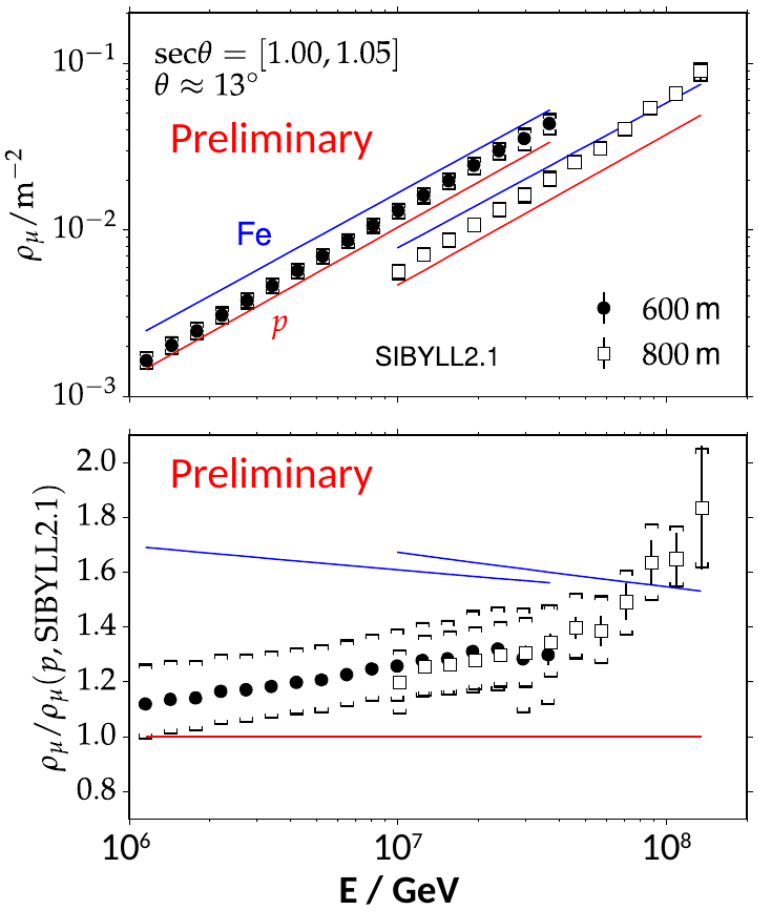
Muon deficit in simulated air showers for cosmic rays above 10^8 GeV
(KASCADE-Grande further finds problems with muon-LDF and muon attenuation)

Pierre Auger Observatory Dembinski et al. (Auger collab.), PRD 91 (2015) 032003



Muon number in data **20 % higher** than closest model (EPOS-LHC)

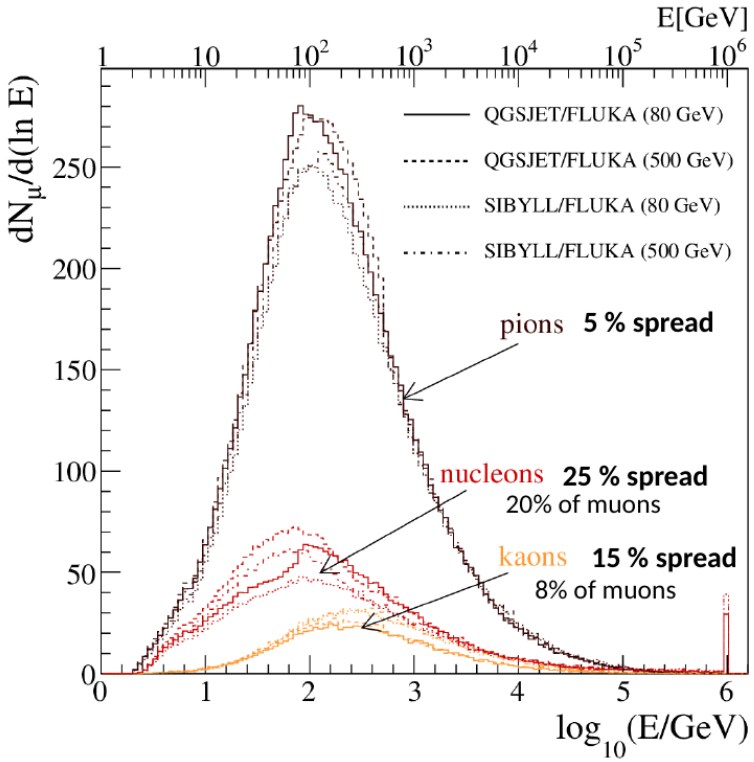
IceCube/IceTop Dembinski et al. (IceCube collab.), EPJ WoC 145 (2017) 01003



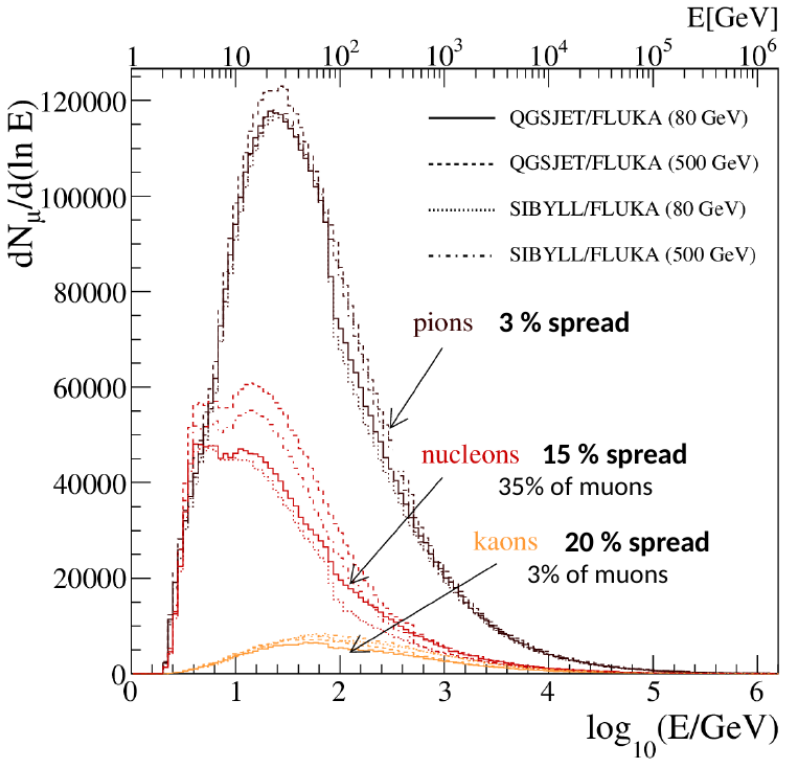
Relevant particles to investigate

Observable muons in air shower experiments Maris et al. (NA61 collab.) Proc. ICRC 2009, 1059

- Are of 10 – 100 GeV energies, not collimated with the shower axis
  - Interesting parent particles: pions, kaons, nucleons
- Direct (prompt) muon production not relevant for Muon Puzzle, but important background for IceCube

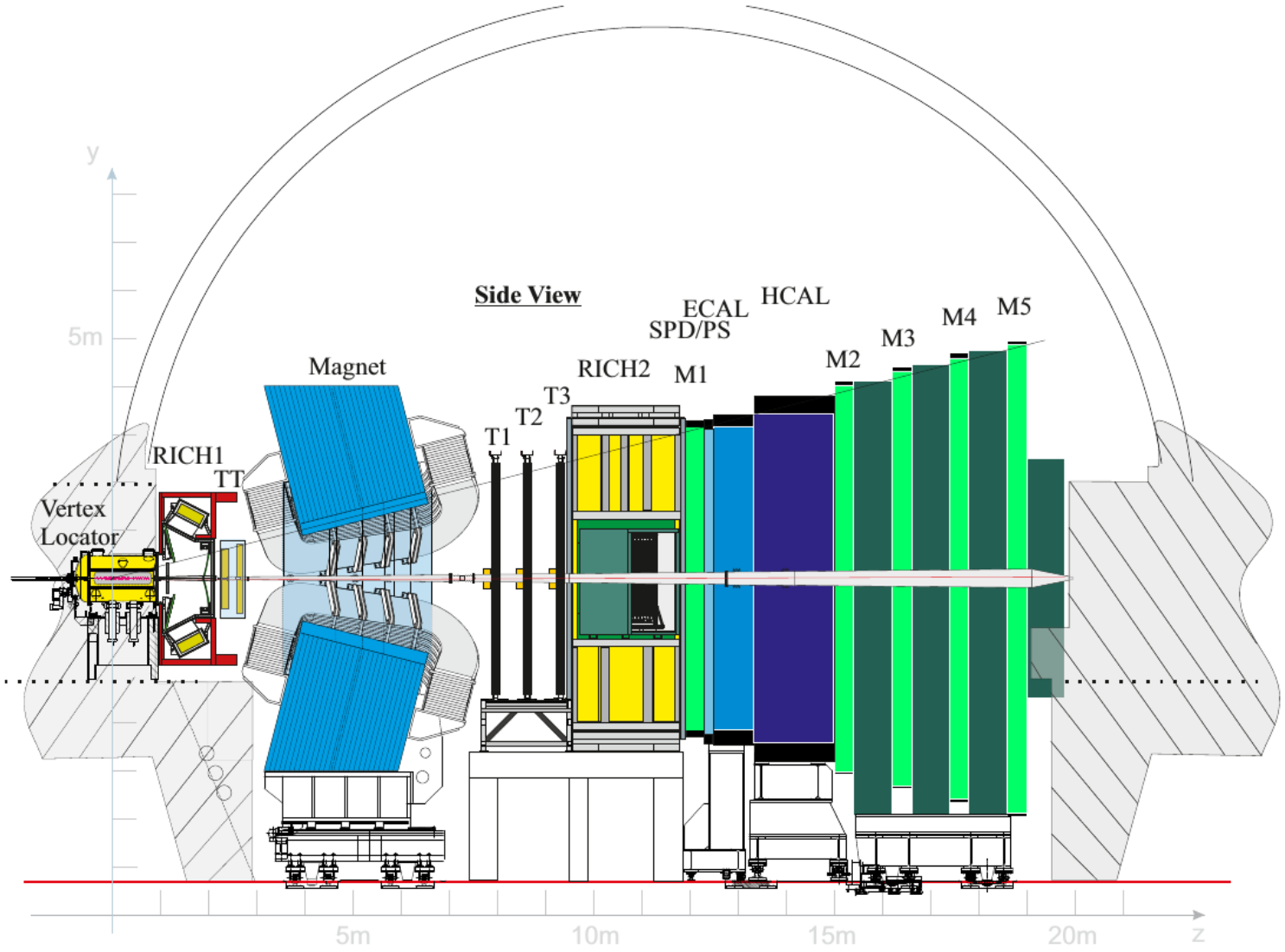


KASCADE: E_0 = 1 PeV, r = 20-200 m



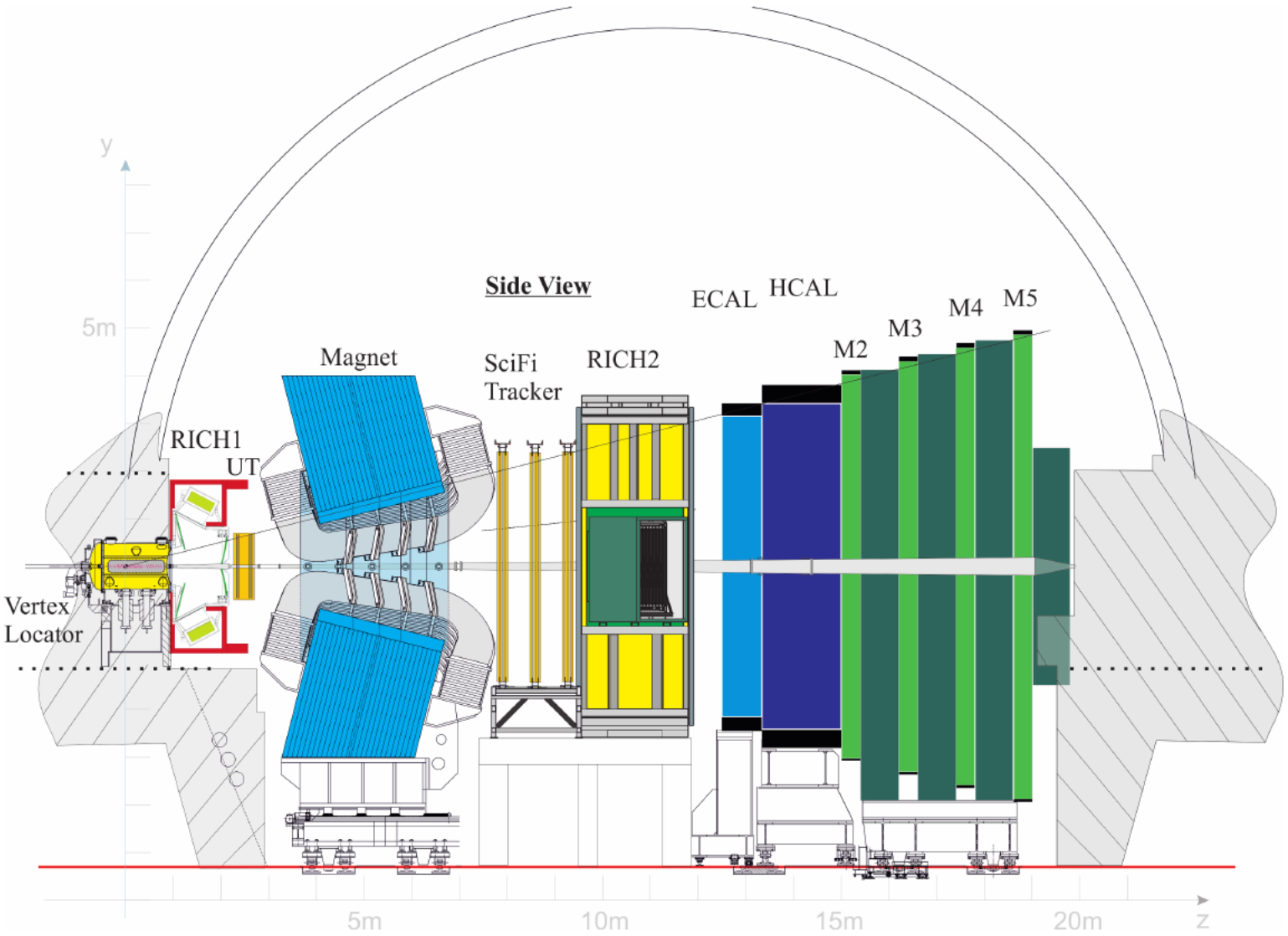
Pierre Auger, E_0 = 10 EeV, r = 1000 m

Current detector



- schematic side view of current detector from Tracker TDR

Upgrade detector



- schematic side view of upgraded detector in Run3/4 Tracker TDR

Fixed-target upgrade

- unpolarised gas target during LS2 under consideration
- discussions with accelerator started and well advancing
- storage cell attached to VELO upstream
- higher areal density and well-defined interaction region of about 20 cm length
- possibility to largely increase the instantaneous luminosity and to choose other than noble gases e.g. hydrogen
- an upgrade study is ongoing