Prospectives for heavy-ion physics at LHCb in LHC Run 3-Run 4

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Prospectives QGP France - Orsay - 11 Dec. 2019

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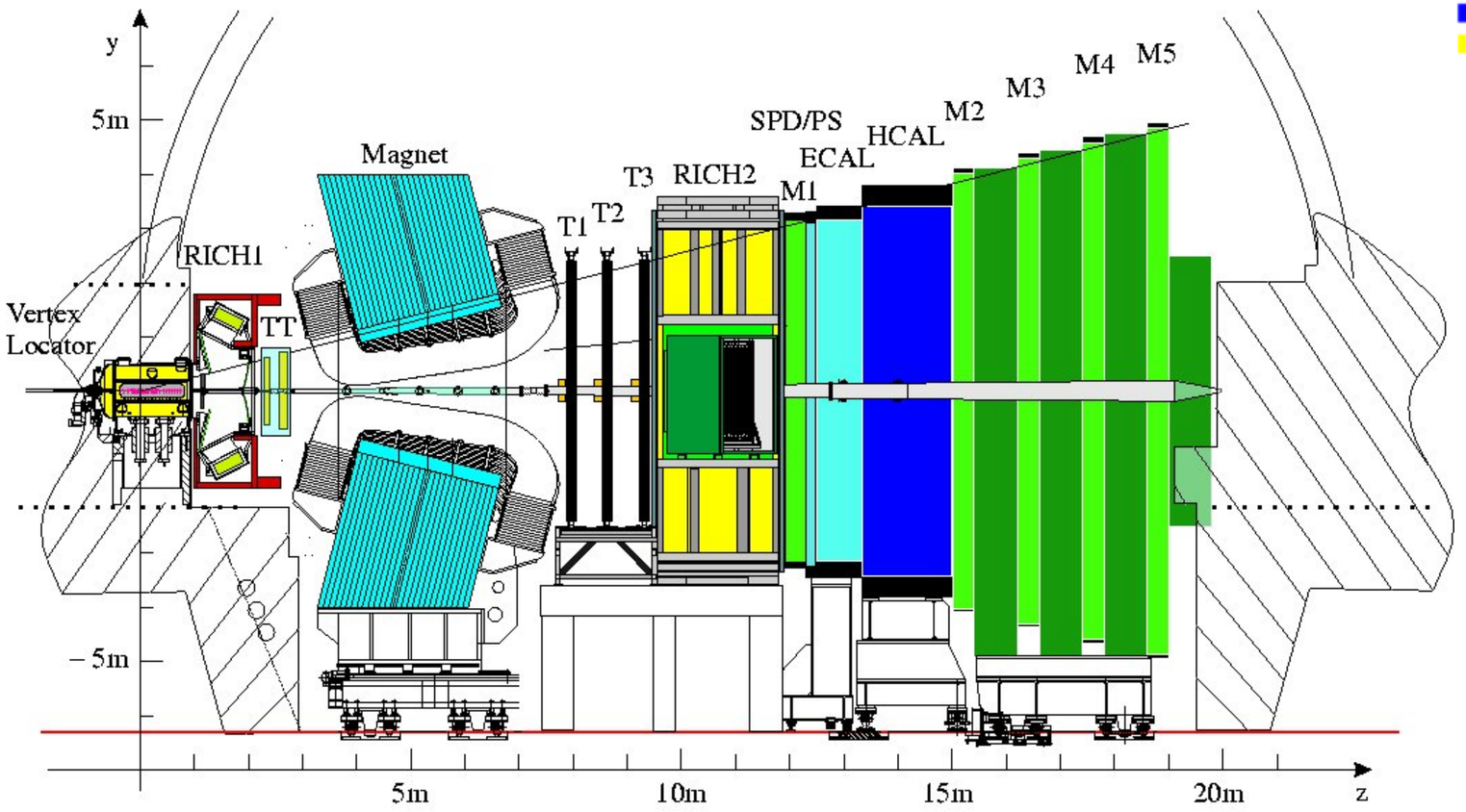
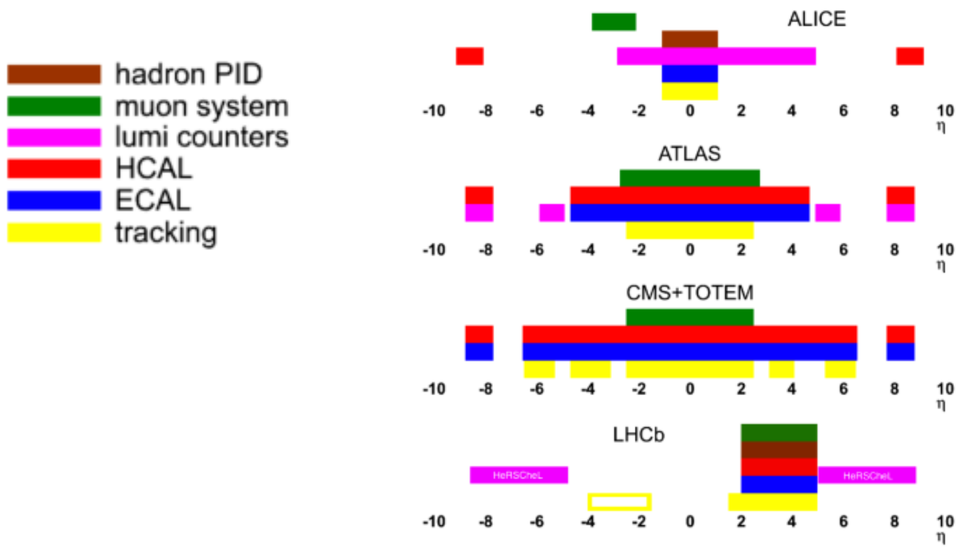
The LHCb detector

10.1142/S0217751X15300227

LHCb : **single arm spectrometer fully instrumented** in pseudo-rapidity range **2 < η < 5**



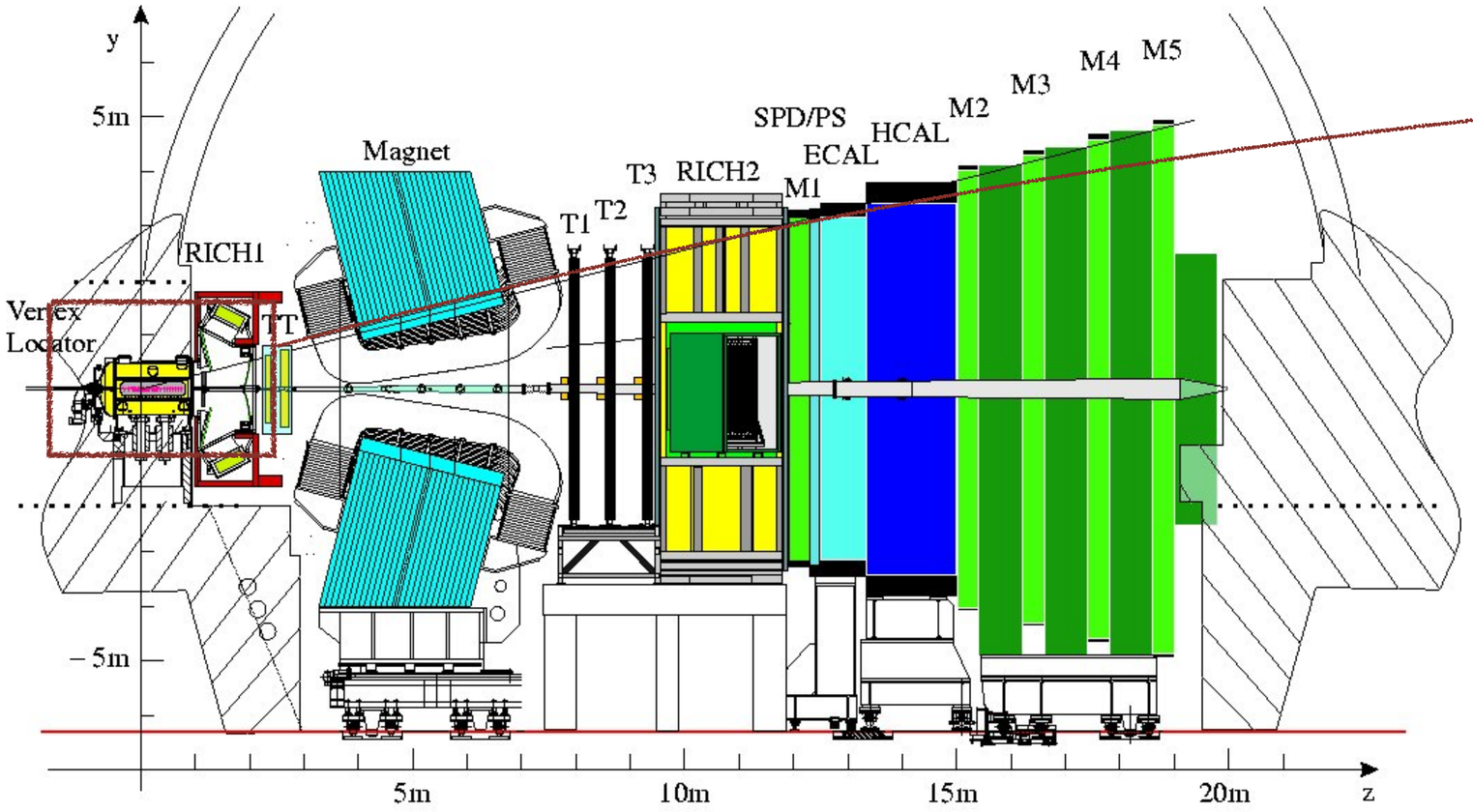


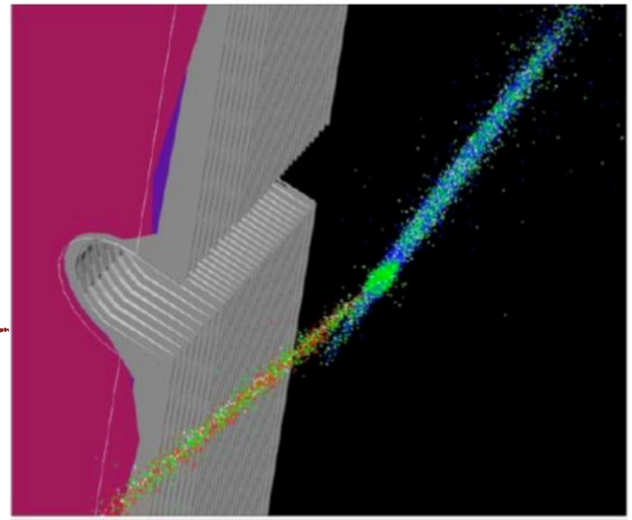
- Track reconstruction **down to $p_T = 0$.**
- Excellent **p_T and mass resolution.**
- Excellent **particle identification.**
- Precision **vertex reconstruction.**

The LHCb detector

10.1142/S0217751X15300227

Can operate both in pp/pPb/PbPb and 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.

Fixed-target mode: **unique at LHC !**

- Injecting gas in the LHCb VErtex LOcator (VELO) tank.
- **Noble gas only** : He, Ne, Ar
- Gas pressure : 10^{-7} to 10^{-6} mbar.

List of publications

Published papers

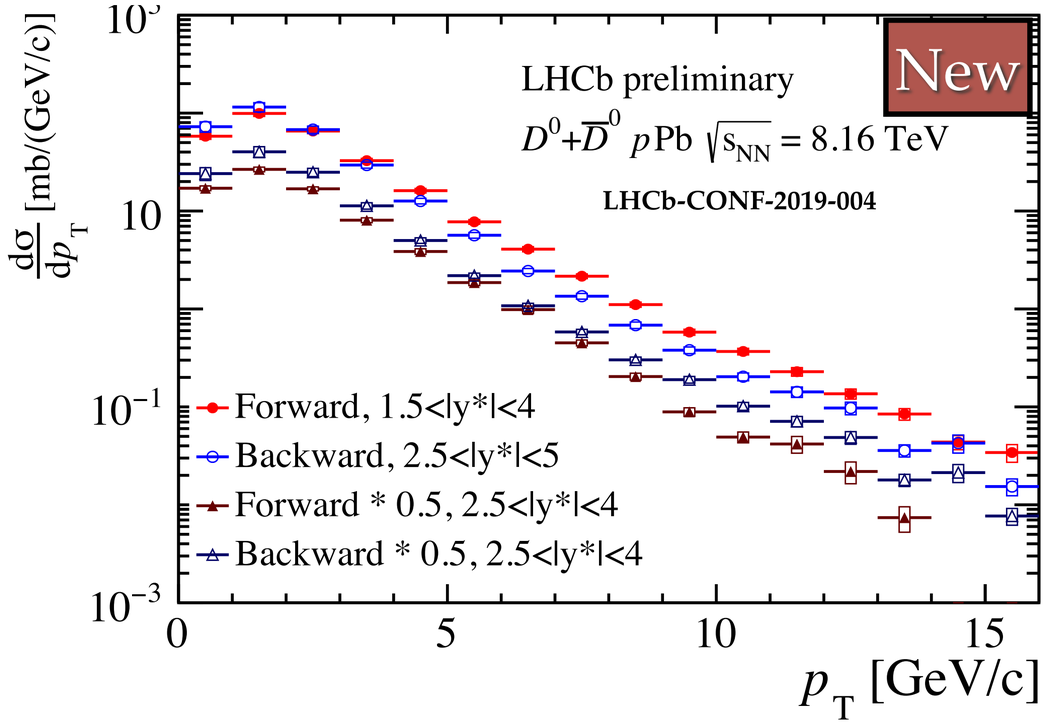
TITLE	DOCUMENT NUMBER	JOURNAL	SUBMITTED ON	CITED
Measurement of B^+, B^0 and Λ_b^0 production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV	PAPER-2018-048 arXiv:1902.05599 [PDF]	Phys. Rev. D99 052011 (2019)	14 Feb 2019	12 [plot]
First measurement of charm production in fixed-target configuration at the LHC	PAPER-2018-023 arXiv:1810.07907 [PDF]	Phys. Rev. Lett. 122 (2019) 132002	18 Oct 2018	27 [plot]
Study of Υ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV	PAPER-2018-035 arXiv:1810.07655 [PDF]	JHEP 11 (2018) 194	17 Oct 2018	16 [plot]
Prompt Λ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV	PAPER-2018-021 arXiv:1809.01404 [PDF]	JHEP 02 (2019) 102	05 Sep 2018	27 [plot]
Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV	PAPER-2018-031 arXiv:1808.06127 [PDF]	Phys. Rev. Lett. 121 (2018) 222001	18 Aug 2018	32 [plot]
Study of prompt D^0 meson production in pPb collisions at $\sqrt{s}$=5 TeV	PAPER-2017-015 arXiv:1707.02750 [PDF]	JHEP 10 (2017) 090	10 Jul 2017	59 [plot]
Prompt and nonprompt J/ψ production and nuclear modification in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV	PAPER-2017-014 arXiv:1706.07122 [PDF]	Phys. Lett. B774 (2017) 159	21 Jun 2017	43 [plot]
Study of $\psi(2S)$ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV	PAPER-2015-058 arXiv:1601.07878 [PDF]	JHEP 03 (2016) 133	28 Jan 2016	43 [plot]
Measurements of long-range near-side angular correlations in $\sqrt{s_{NN}} = 5$TeV proton-lead collisions in the forward region	PAPER-2015-040 arXiv:1512.00439 [PDF]	Phys. Lett. B762 (2016) 473	01 Dec 2015	66 [plot]
Observation of Z production in proton-lead collisions at LHCb	PAPER-2014-022 arXiv:1406.2885 [PDF]	JHEP 09 (2014) 030	11 Jun 2014	45 [plot]
Study of Υ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5$TeV	PAPER-2014-015 arXiv:1405.5152 [PDF]	JHEP 07 (2014) 094	20 May 2014	72 [plot]
Study of J/ψ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}}$ = 5 TeV	PAPER-2013-052 arXiv:1308.6729 [PDF]	JHEP 02 (2014) 72	30 Aug 2013	159 [plot]

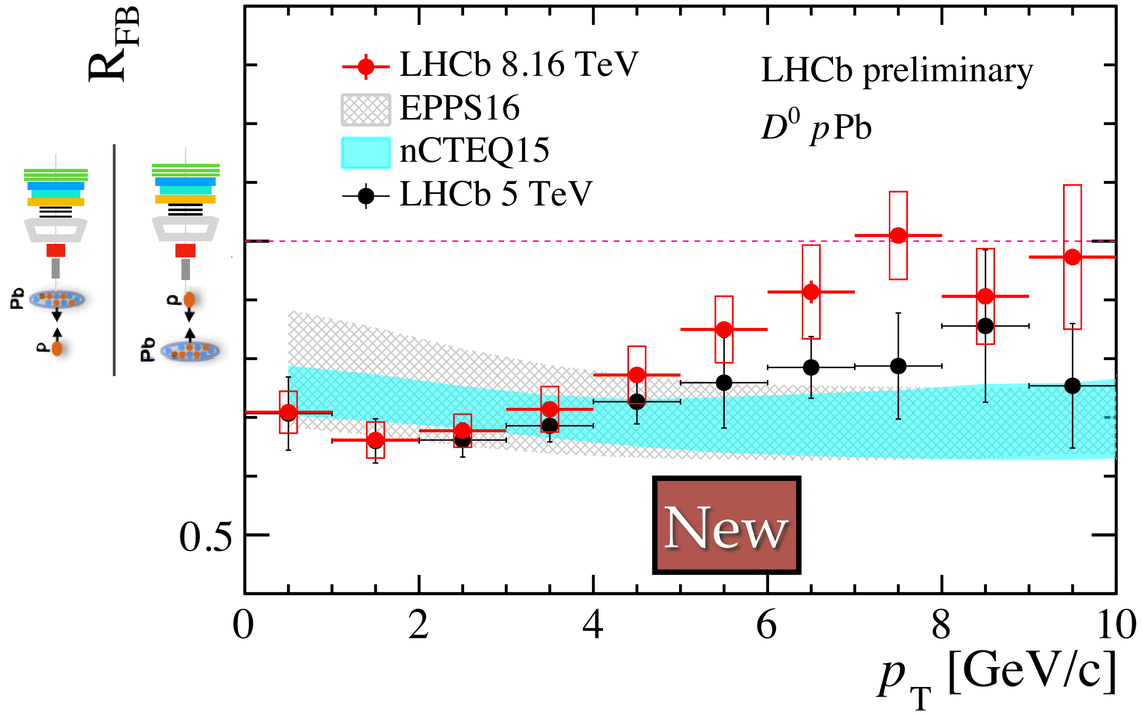
Conference notes

TITLE	DOCUMENT NUMBER	SUBMITTED ON	CITED
Multiplicity-dependent modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pp collisions at $\sqrt{s}$= 8 TeV	CONF-2019-005	14 Nov 2019	
Study of prompt D^0 meson production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV at LHCb	CONF-2019-004	12 Nov 2019	
Measurement of Z production cross-sections in proton-lead collisions at $\sqrt{s_{NN}} = 8.16$ TeV	CONF-2019-003	12 Nov 2019	
LHCb projections for proton-lead collisions during LHC Runs 3 and 4	CONF-2018-005	22 Nov 2018	1
Study of coherent J/ψ production in lead-lead collisions at $\sqrt{s_{NN}} = 5$ TeV with the LHCb experiment	CONF-2018-003	25 May 2018	16 [plot]
Prompt Λ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$TeV	CONF-2017-005	01 Sep 2017	7 [plot]
LHCb dimuon and charm mass distributions	CONF-2016-005	19 Jul 2016	2 [plot]
Reference pp cross-sections for $\Upsilon(1S)$ studies in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV and comparisons between ALICE and LHCb results	CONF-2014-003	08 Aug 2014	5 [plot]
Reference pp cross-sections for J/ψ studies in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV and comparisons between ALICE and LHCb results	CONF-2013-013	22 Dec 2013	20 [plot]
First analysis of the pPb pilot run data with LHCb	CONF-2012-034	03 Dec 2012	8 [plot]

- 12 papers
- 10 notes
- Link to all documents

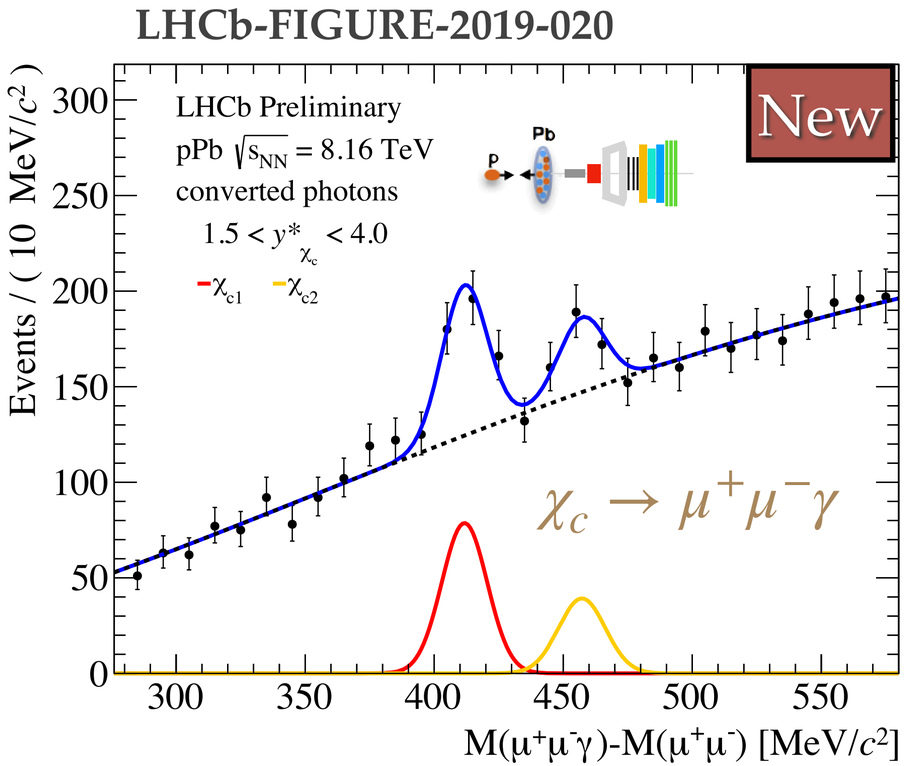
Open and hidden charm production in pPb collisions

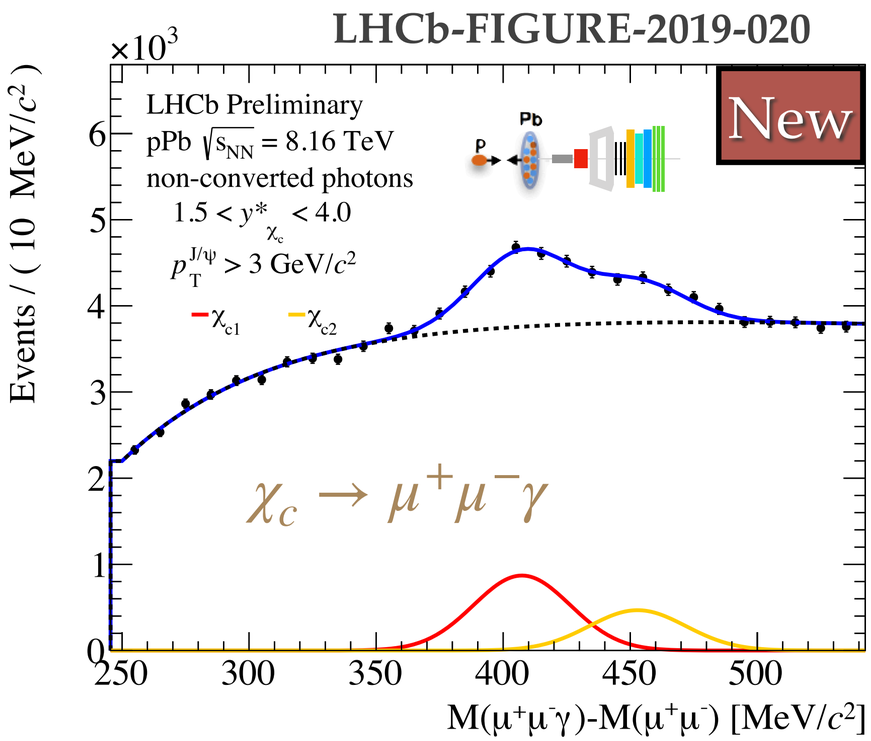




- **Preliminary results for D^0 cross-section** in pPb / Pbp collisions at $\sqrt{s_{NN}}$ = 8 TeV **up to p_T = 16 GeV/*c***.
- **Improved statistics** by factor 20 compared to previous LHCb results.
- **Tension between data and nPDFs predictions. Additional effects required.**

Highlights of ongoing analysis …



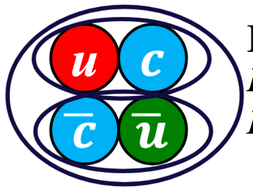


- χ_{c1} and χ_{c2} peaks **observed** in pPb / Pbp collisions with converted and non-converted photons.

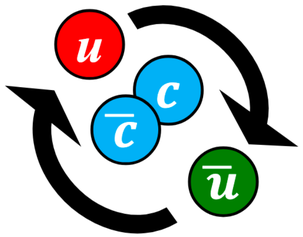
Analysis ongoing, stay tuned !

Highlights of ongoing analysis …

Compact tetraquark/pentaquark

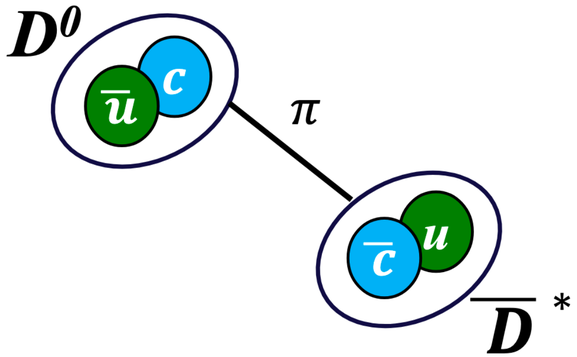


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



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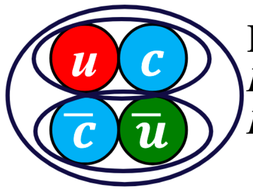
- X(3872) : exotic state still not understood.
  - Tetraquark / hadronic molecule / something else ?

Compact tetraquark/pentaquark



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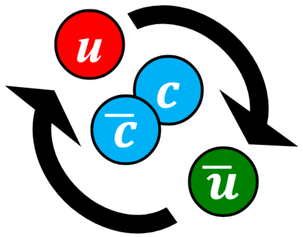

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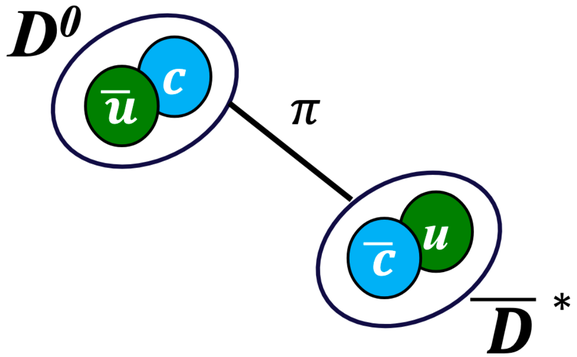
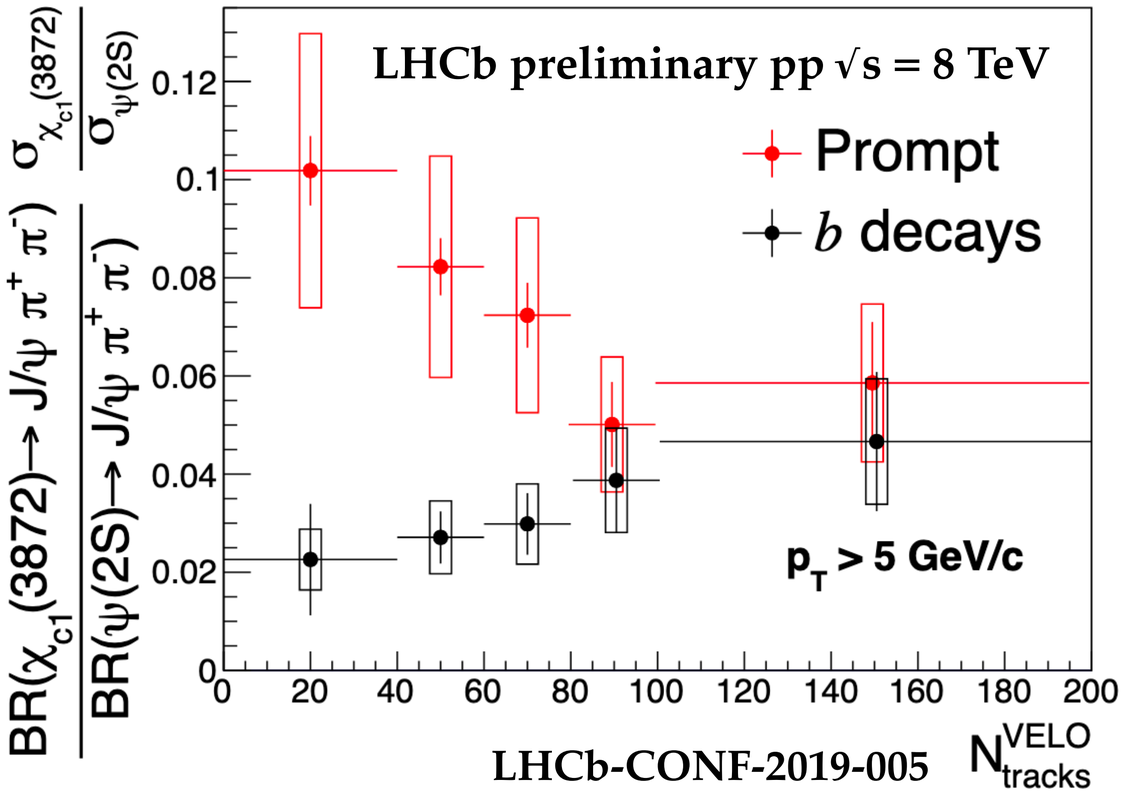


Highlights of ongoing analysis …

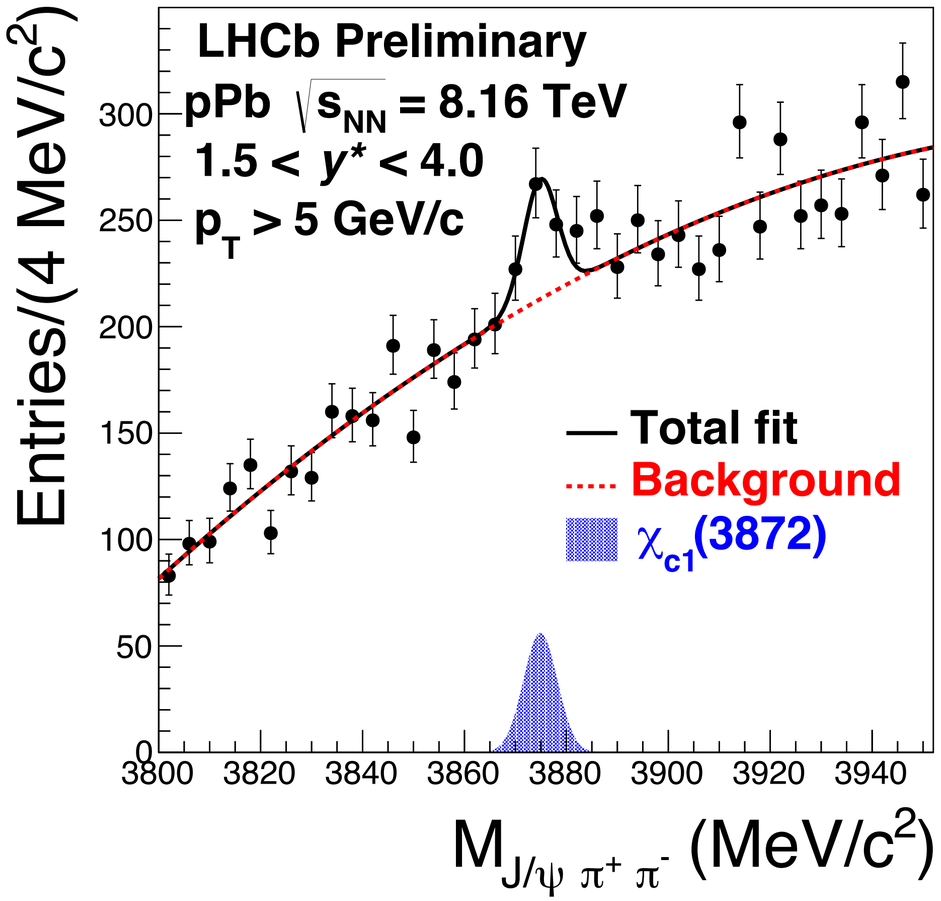
- X(3872) : exotic state still not understood.
  - Tetraquark / hadronic molecule / something else ?
- X(3872) / ψ(2S) ratio versus N_{tracks} measured in pp collisions at √s = 8 TeV.
  - No significant **variation is observed** for the **non-prompt** component.
  - **Hint of a relative suppression with event activity for prompt component.**



LHCb-CONF-2019-005

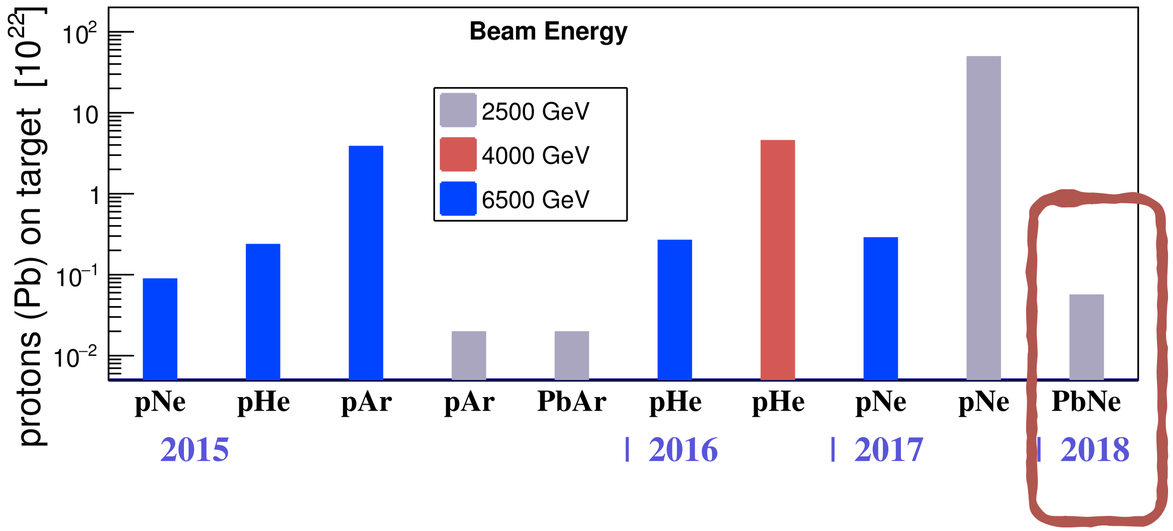
Highlights of ongoing analysis …

- X(3872) : exotic state still not understood.
  - Tetraquark / hadronic molecule / something else ?
- X(3872) / ψ(2S) ratio versus N_{tracks} measured in pp collisions at √s = 8 TeV.
  - No significant **variation is observed** for the **non-prompt** component.
  - **Hint of a relative suppression with event activity for prompt component.**
- **Baseline for a future pPb analysis !**

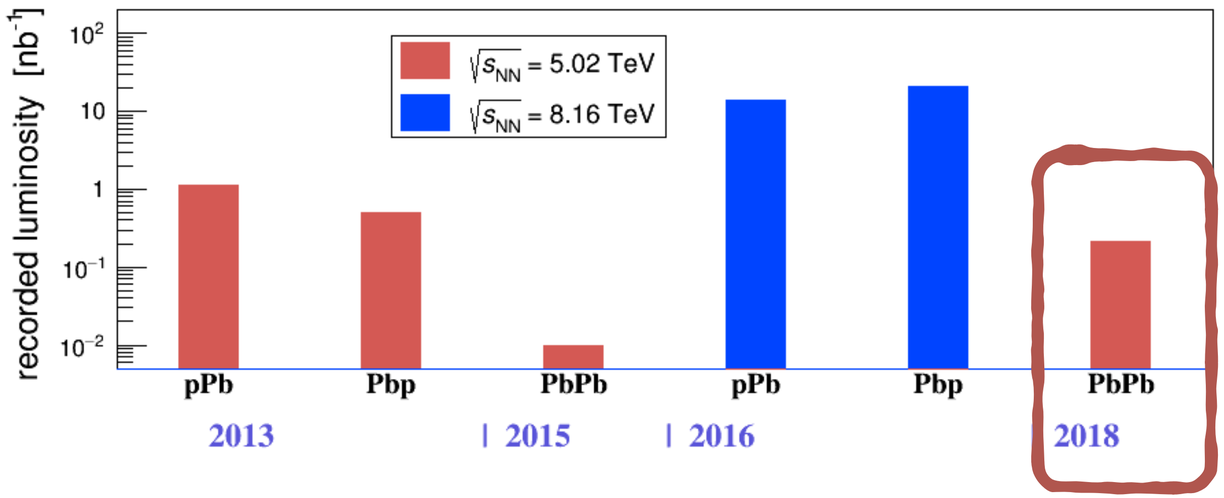


LHCb physics program

Fixed-target mode samples



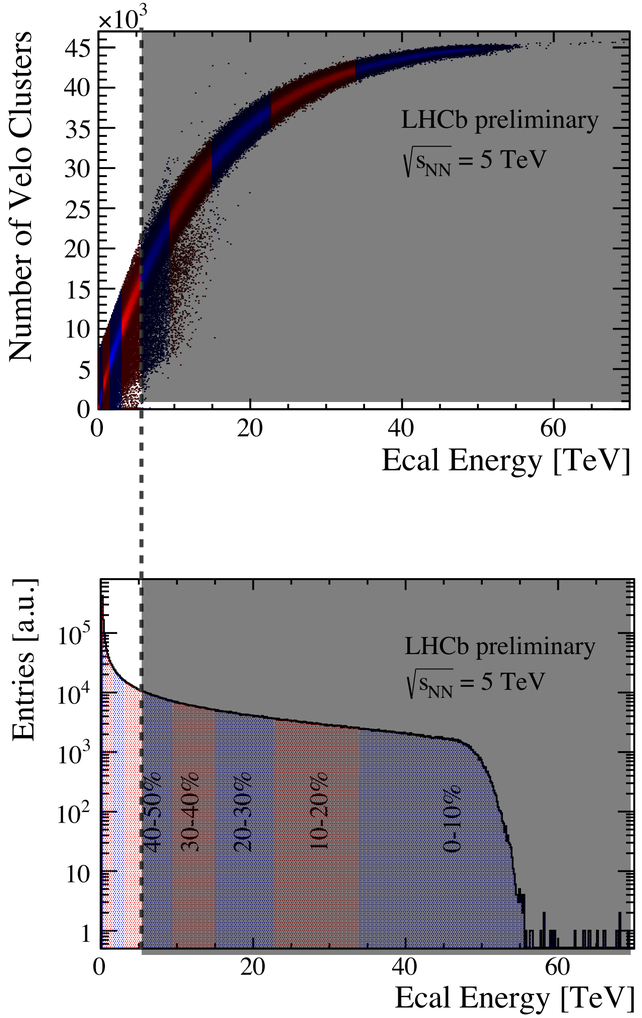
Collider mode samples



~ 20 times 2015 luminosity

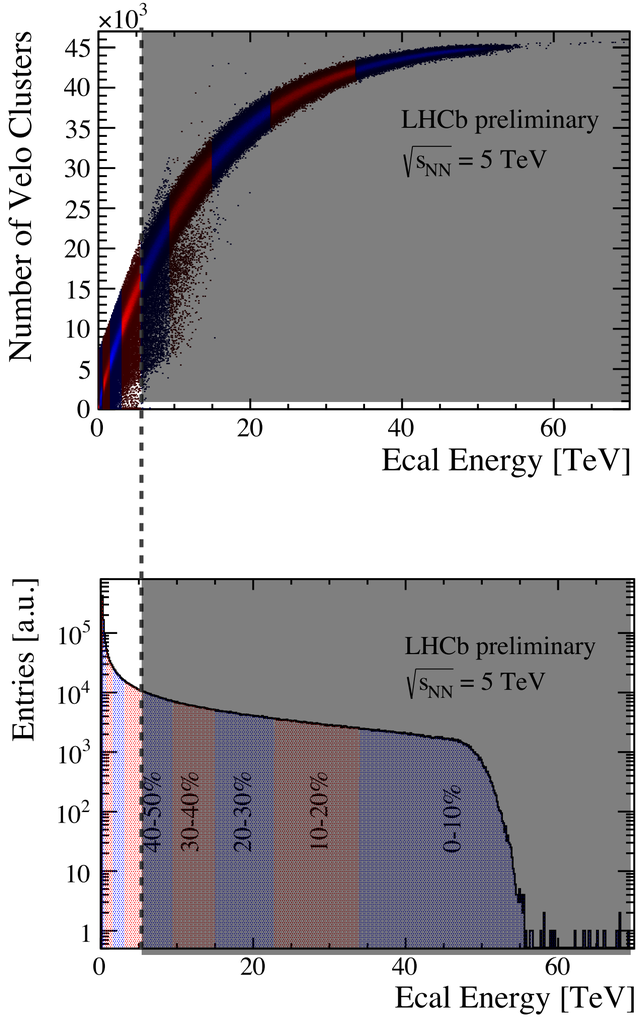
- Large variety of samples to study !
- **Two new samples** : PbNe at $\sqrt{s_{NN}}$ = 68.6 GeV and PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV.

Status in nucleus-nucleus collisions



Status in nucleus-nucleus collisions

Studies in PbPb limited to 60% less central collisions.



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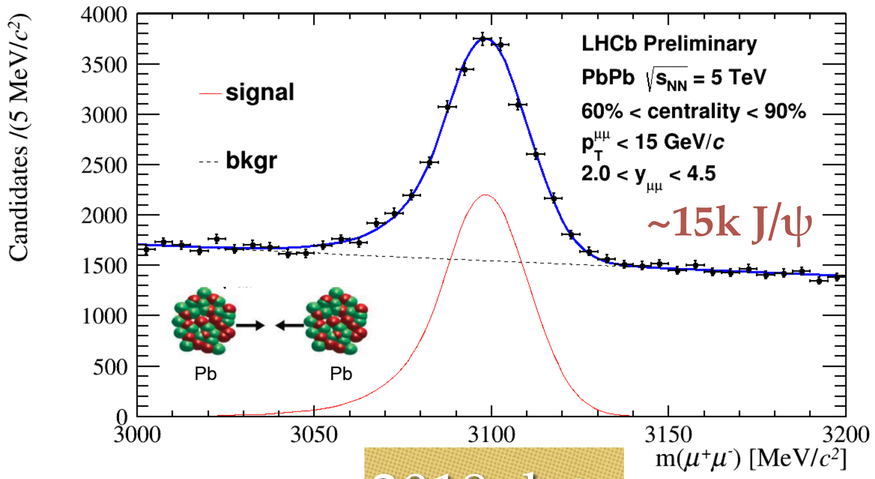
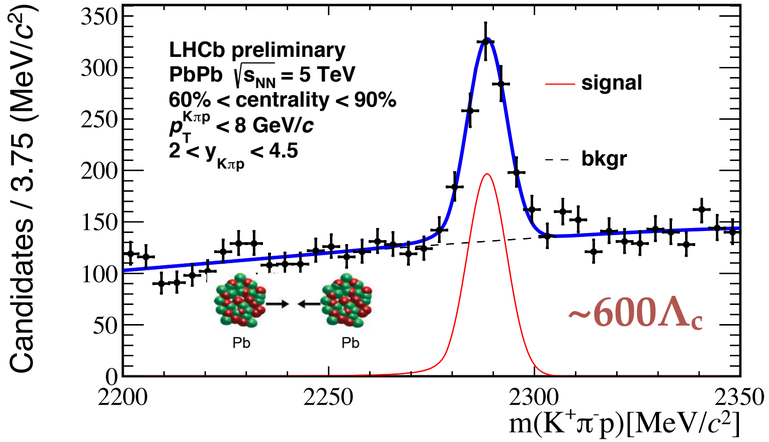


2018 data



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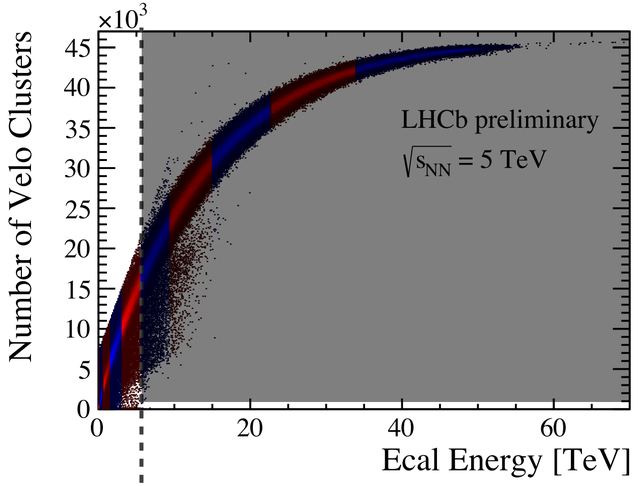

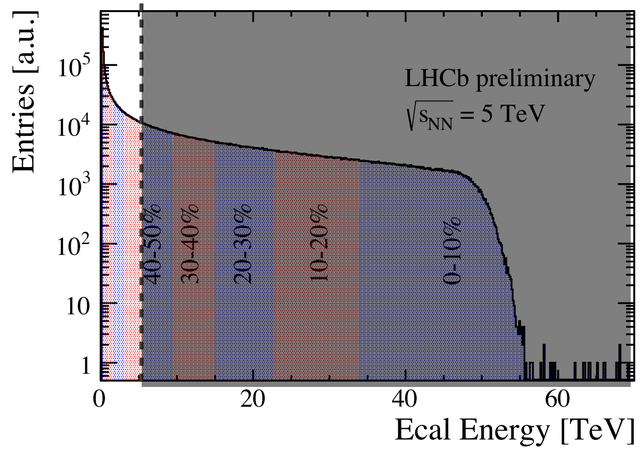

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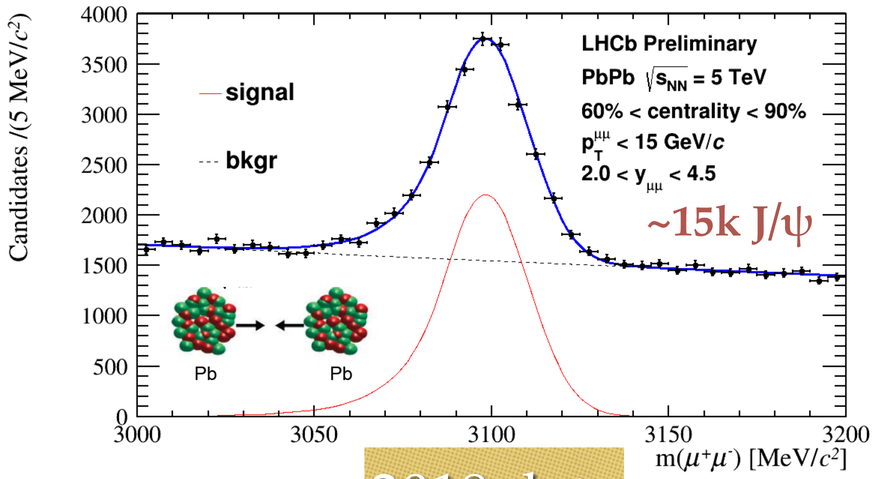

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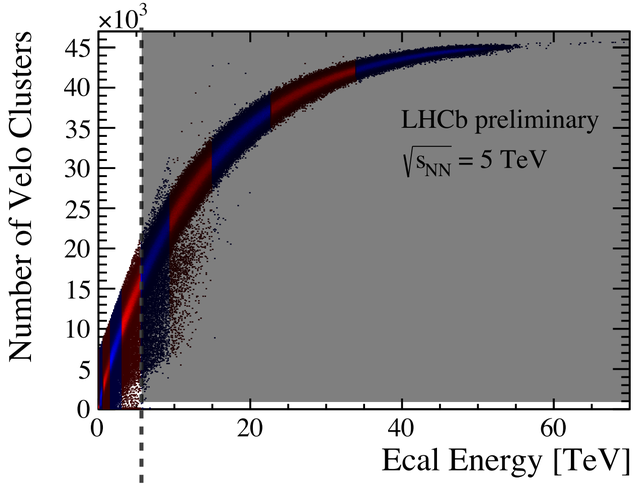
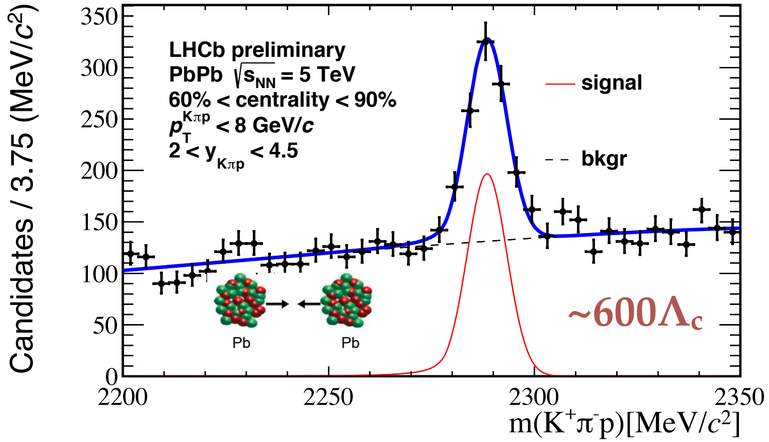
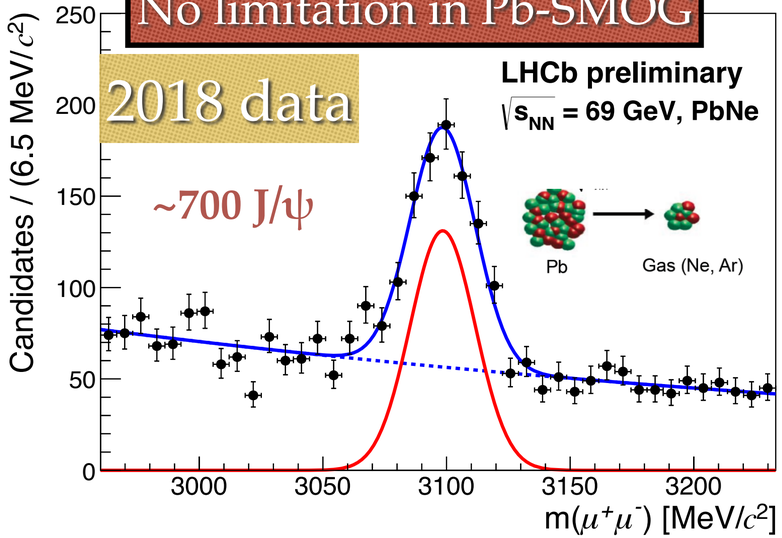
Analysis ongoing, stay tuned !

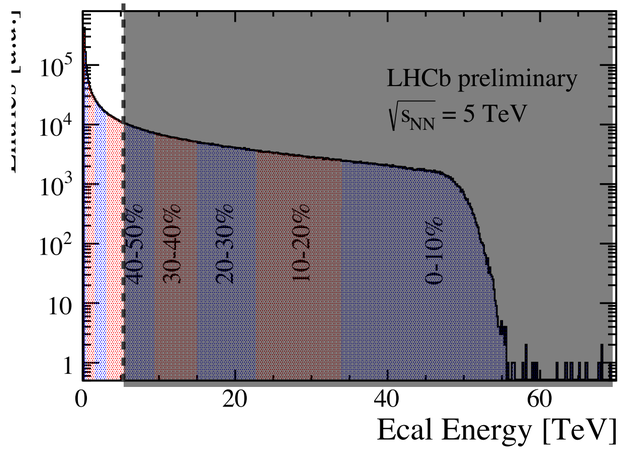




No limitation in Pb-SMOG

2018 data





Benjamin Audurier - benjamin.audurier@cern.ch

The future : Precision era

Physics of HL-LHC WG5: Future physics opportunities for high-density QCD at the LHC arXiv1812.06772 - CERN-LPCC-2018-07

LHC

HL-LHC

Upgrade 1a LS2

Run 3

Upgrade 1b LS3

Run 4

Upgrade 2 LS4

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
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	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

The future : Precision era

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LHC

Upgrade 1a LS2

Run 3

HL-LHC

Upgrade 1b LS3

Run 4

Upgrade 2 LS4

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LHCb is well placed for a **decisive contribution** to Heavy-ion Physics in Run 3 and Run 4

The future : Precision era

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LHC

HL-LHC

Upgrade 1a LS2

Run 3

Upgrade 1b LS3

Run 4

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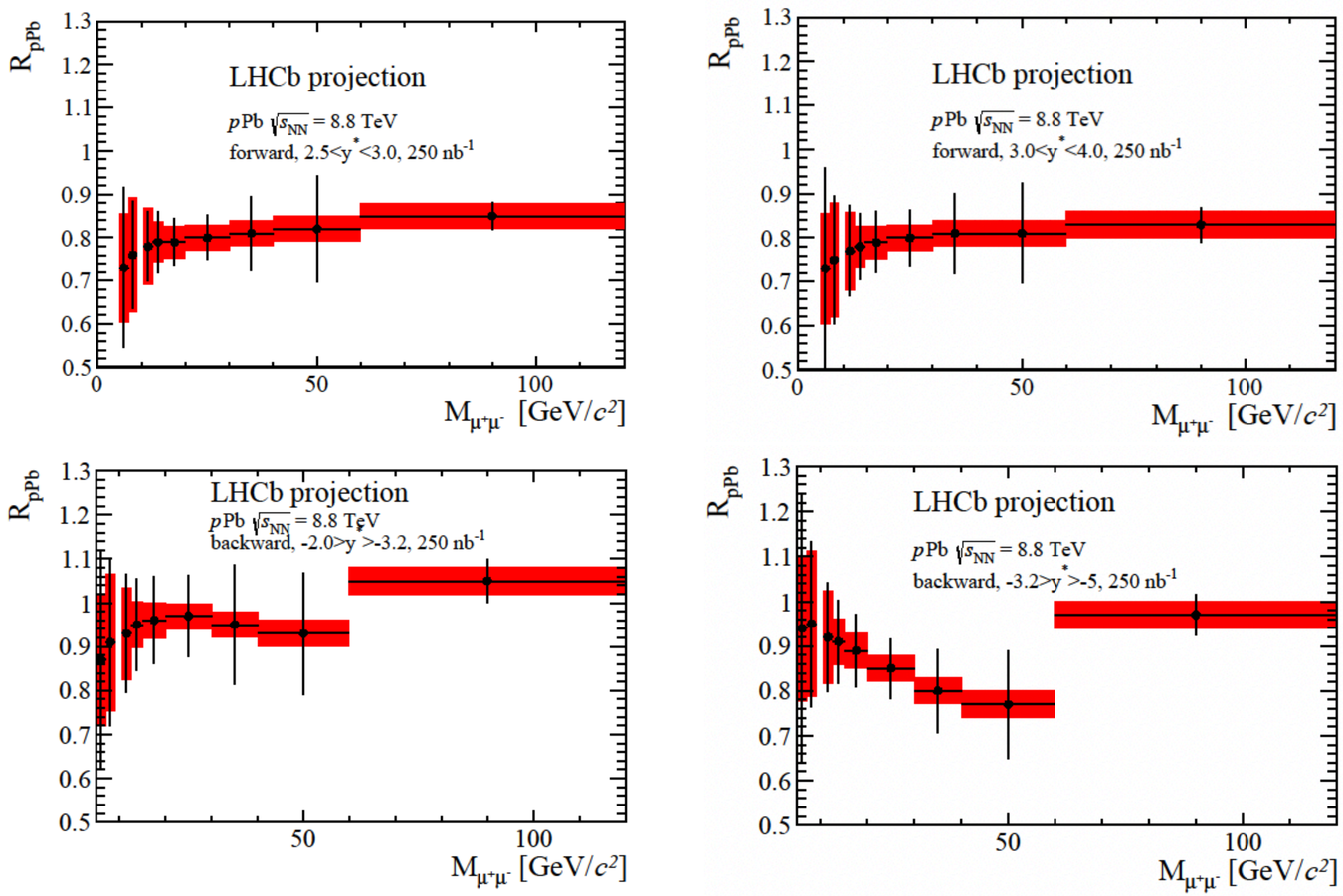
- **Best placed for pp and pPb** collisions at forward rapidity down to low-p_T
  - *In pPb : L_{pPb} ~ 30 nb^{-1} in Run 2 (~1M J/ψ) → L_{pPb} ~ 300 nb^{-1} in Run 3 and ~300 nb^{-1} Run 4*
- **Well placed** (less limited) **in PbPb** collisions at forward
  - *See next slides.*
- **Full physics program in fixed-target.**

Run 3 prospects for heavy-ion physics with LHCb

EPPS16 nPDF prediction at NLO

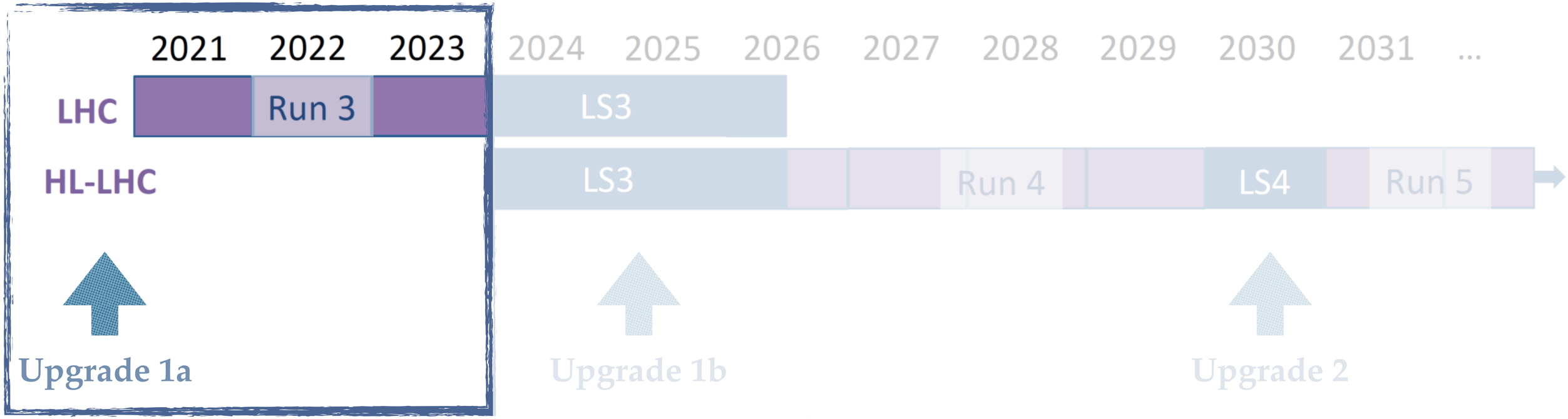
LHCb-CONF-2018-005



Luminosity :
- pPb : 500 nb^{-1} (4 weeks)
- pp : 104 pb^{-1} (much shorter time)

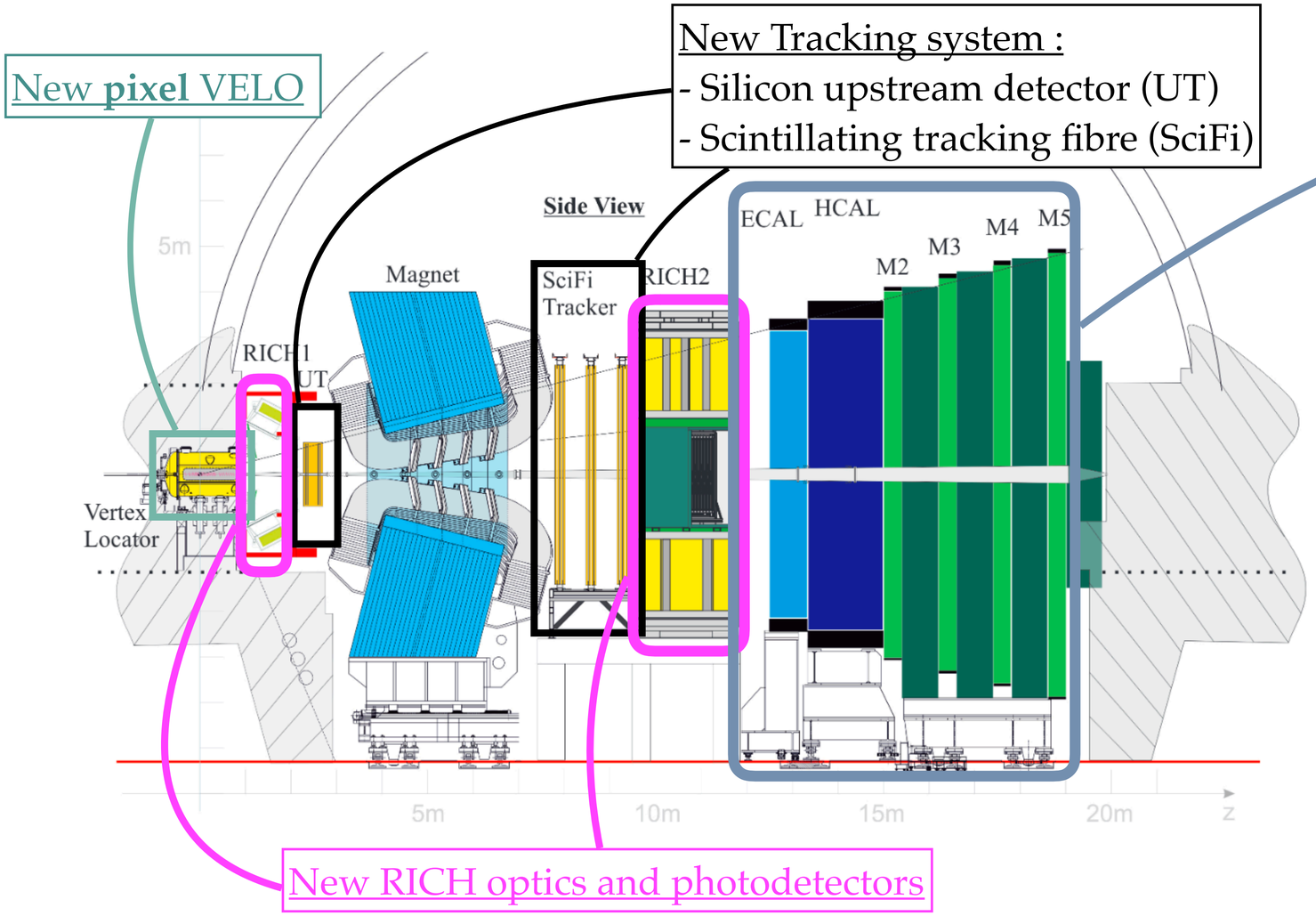
- Drell-Yan production in pPb collisions.
  - Forward rapidity : access shadowing region.
  - Backward rapidity : access to EMC effect.
- Other studies in this document :
  - D_0-$\overline{D_0}$ correlations.
  - B^+ meson productions.
- **Projections show valuable inputs for nPDF fit with limited data taking periods.**

LHCb Upgrade 1a



LHCb detector : season 3 (2021)

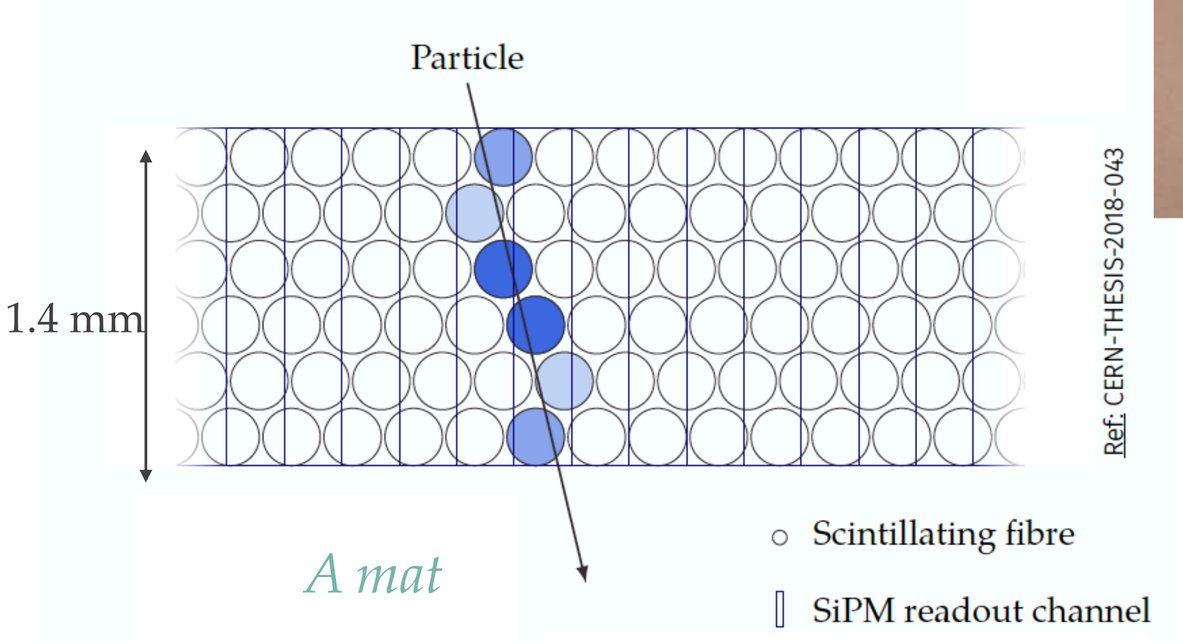
[CERN-LHCC-2012-007]

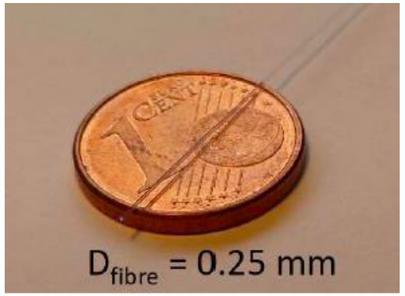


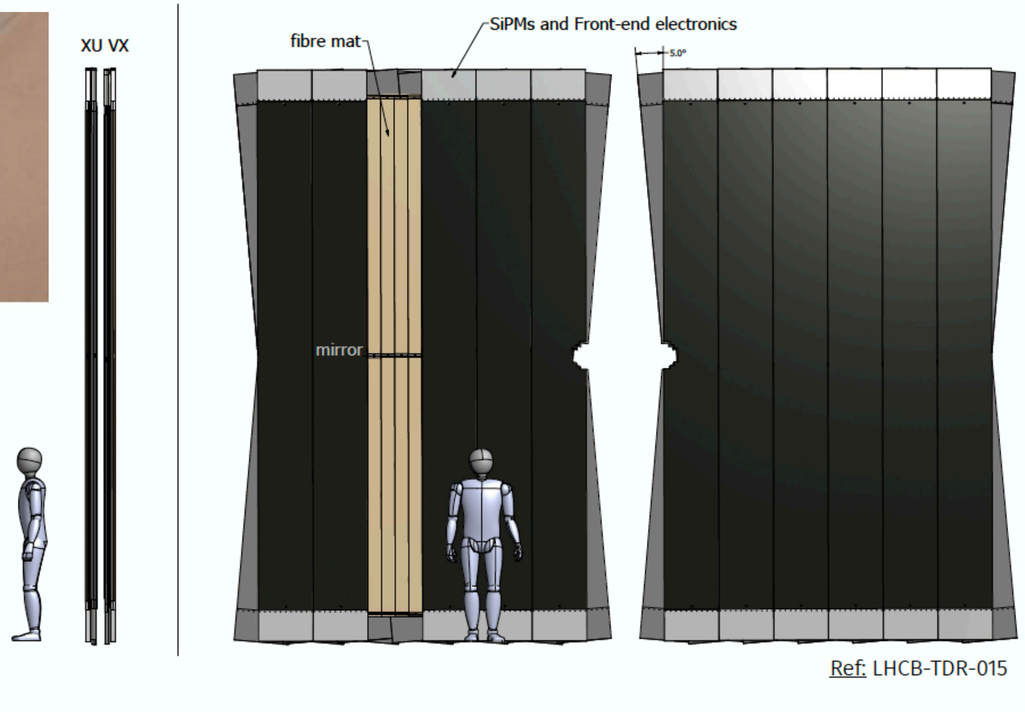
- Upgrade based on pp collision requirements :
  - Collision rate at 40 MHz.
  - Pile-up factor $\mu \approx 5$
- **Replace the entire tracking system.**
- Full **software trigger.**
  - Remove L0 triggers.
  - Read out the full detector at 40 MHz.

Tracking system: Scintillating fibre tracker (SciFi)

- ~10000 km of scintillating fibres arranged in 6 layers with silicon photo-multipliers (SiPM) readout.
  - 3 stations.
  - 4 detection layers per station arranges in x-u-v-x configuration per stations.
  - 10 modules of 2x4 mats.







Run 3 prospects for heavy-ion physics with LHCb

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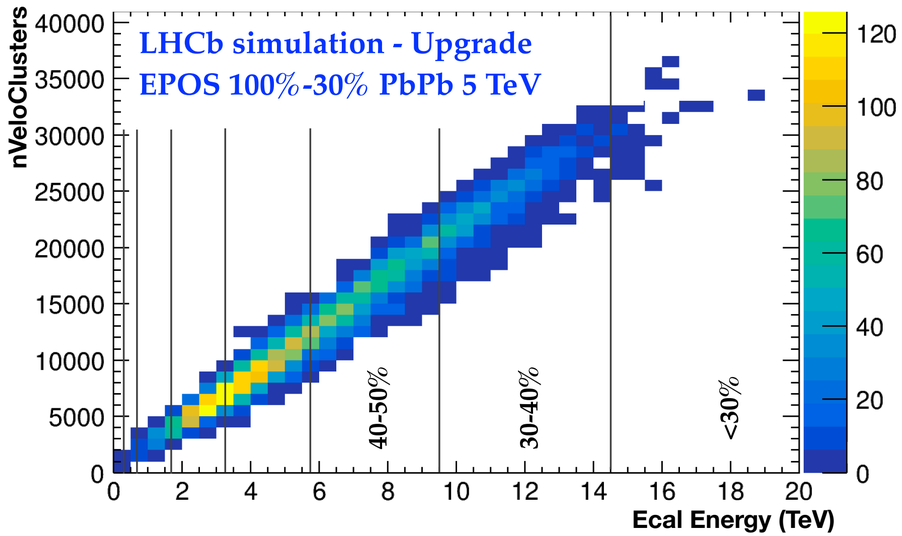
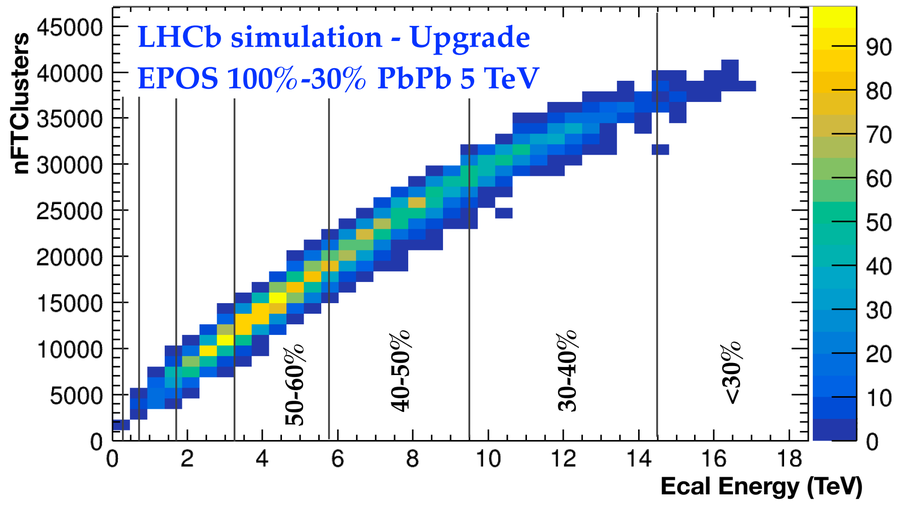
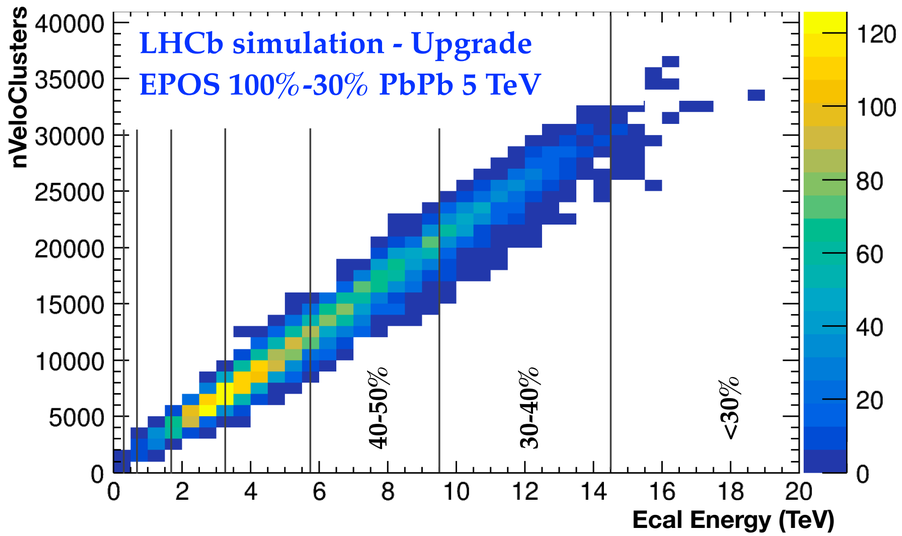
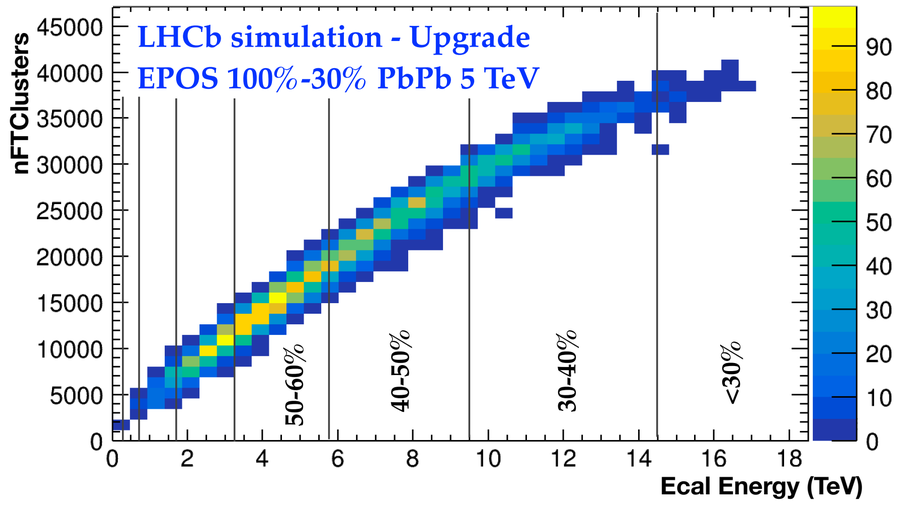




Run 3 prospects for heavy-ion physics with LHCb

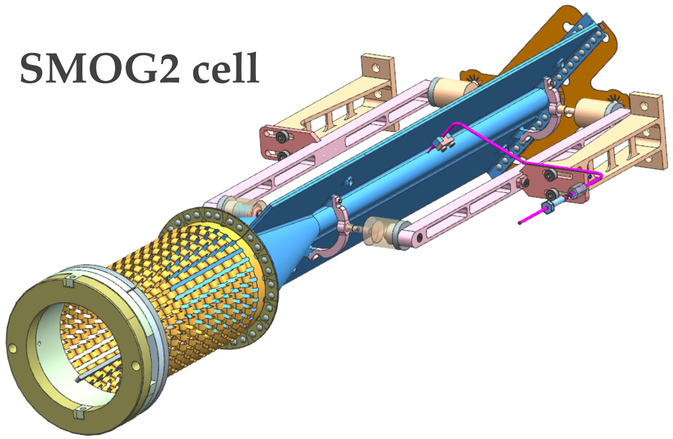
- No significant saturation of the new LHCb detectors **up to 30%!**
- Two proposals for a new tracker (see next slides) :
  - ➡in 2024 → **reach event more central collisions !**
  - ➡In 2030 → **no more limitations !**





LHCb fixed-target program evolution

SMOG2 cell



Projection of ~1 year data taking

Int. Lumi.		80 pb^{-1}
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

- **SMOG 2** (TDR) : Standalone gas storage cell covering z ϵ [-500;-300] mm :
  - **Up to x100 higher gas density** with same gas flow of current SMOG.
  - Gas feed system measures the **gas density with few % accuracy**.
  - **Possibility to run in parallel of pp collisions and inject non noble Gaz .**

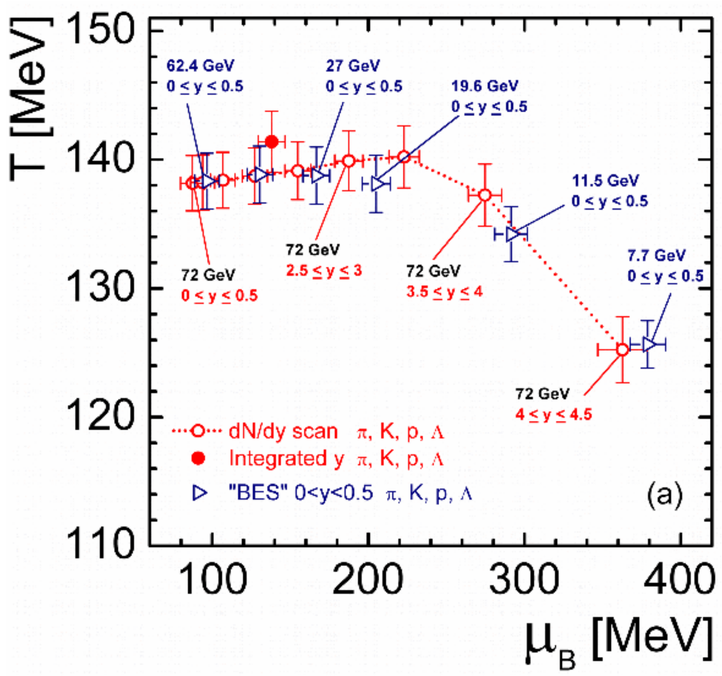
Installation due in December 2019, to be operational from the start of LHC Run 3.

Run 3 prospects for SMOG2 with LHCb

Run 3 prospects for SMOG2 with LHCb

Rapidity scan

Phys. Rev. C98 (2018) 034905



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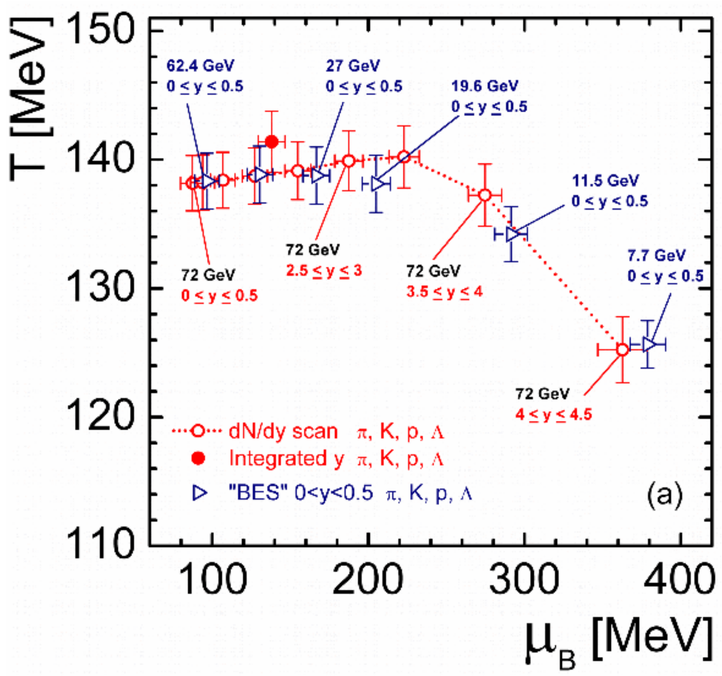

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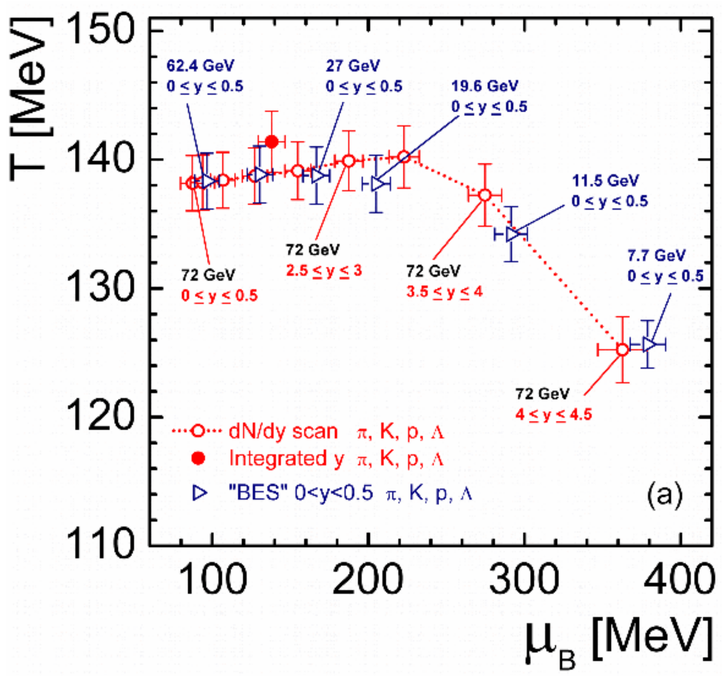

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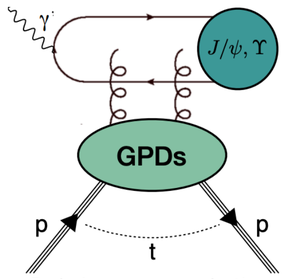
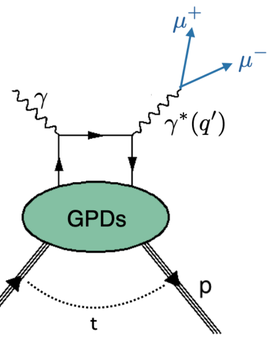
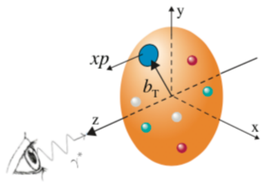
Deep in the hadronic structure



Exclusive meson production



Timelike Compton scattering (TCS)
(access via angular modulation)



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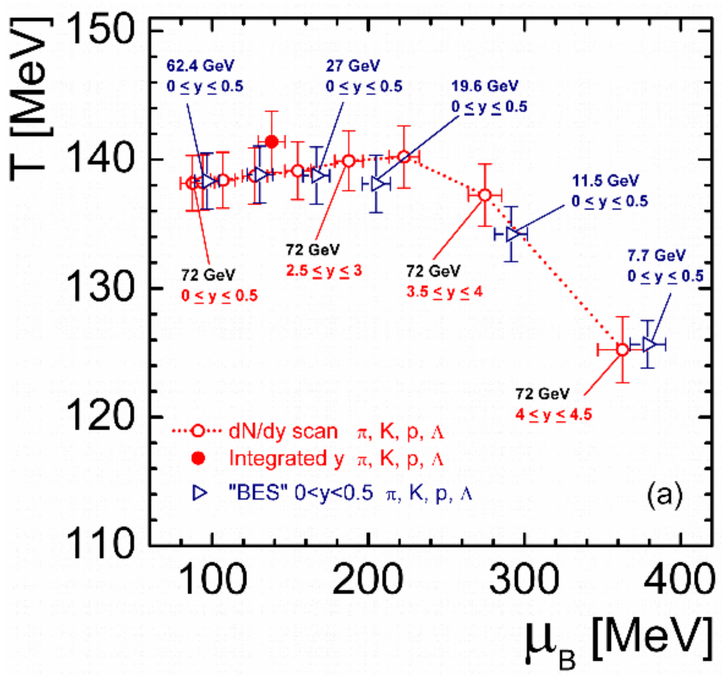

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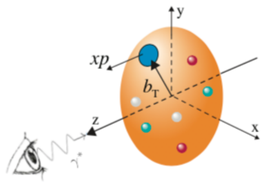

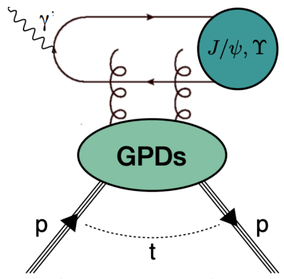

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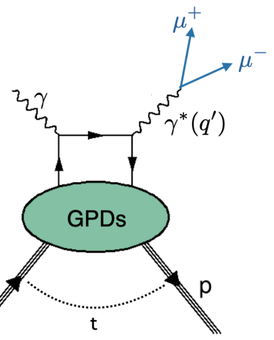

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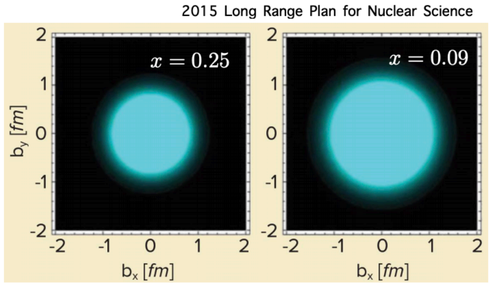

One of the objectives : 3D pictures in impact parameter space

Run 3 prospects for SMOG2 with LHCb

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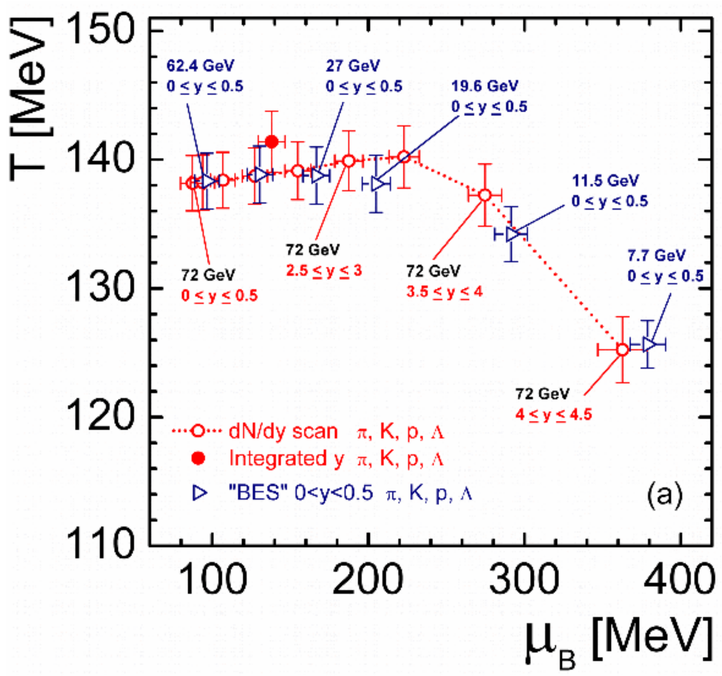

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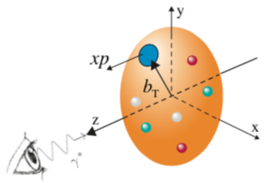

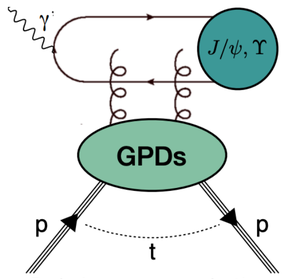

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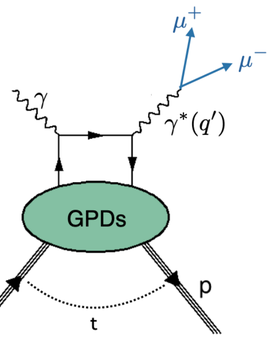

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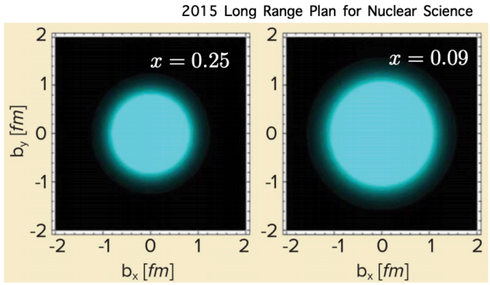
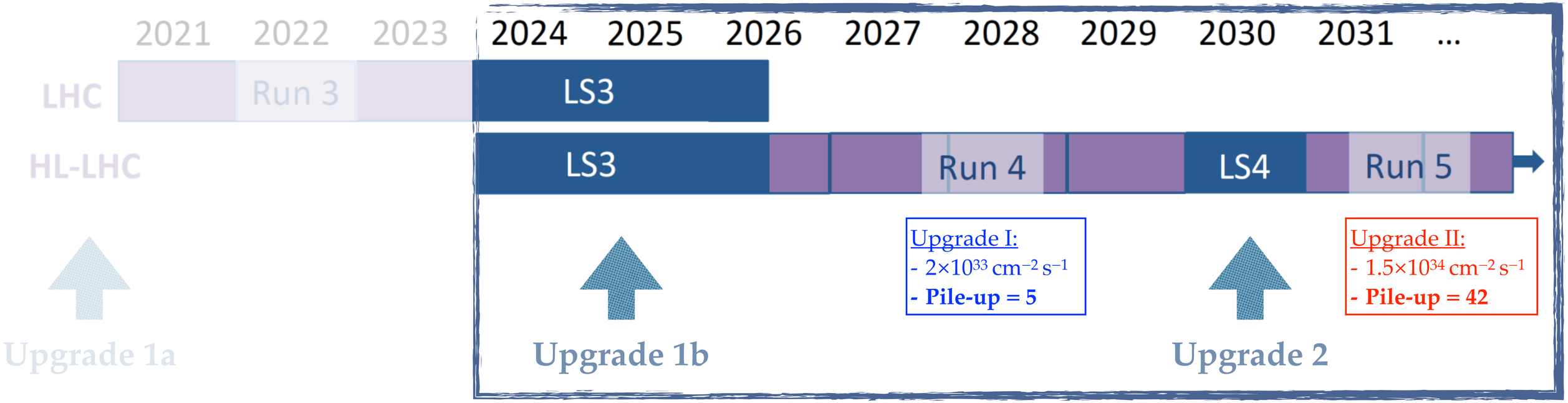


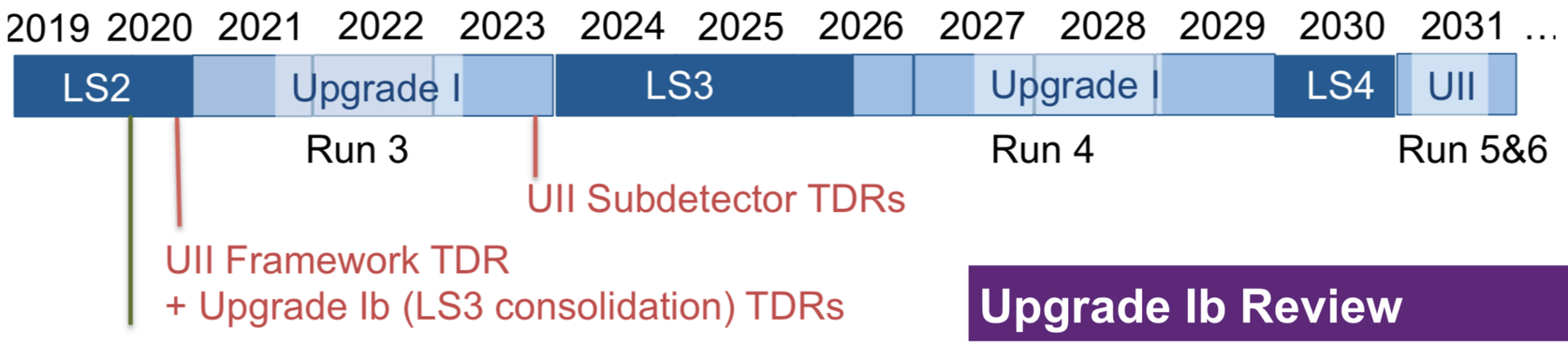
One of the objectives : 3D pictures in impact parameter space

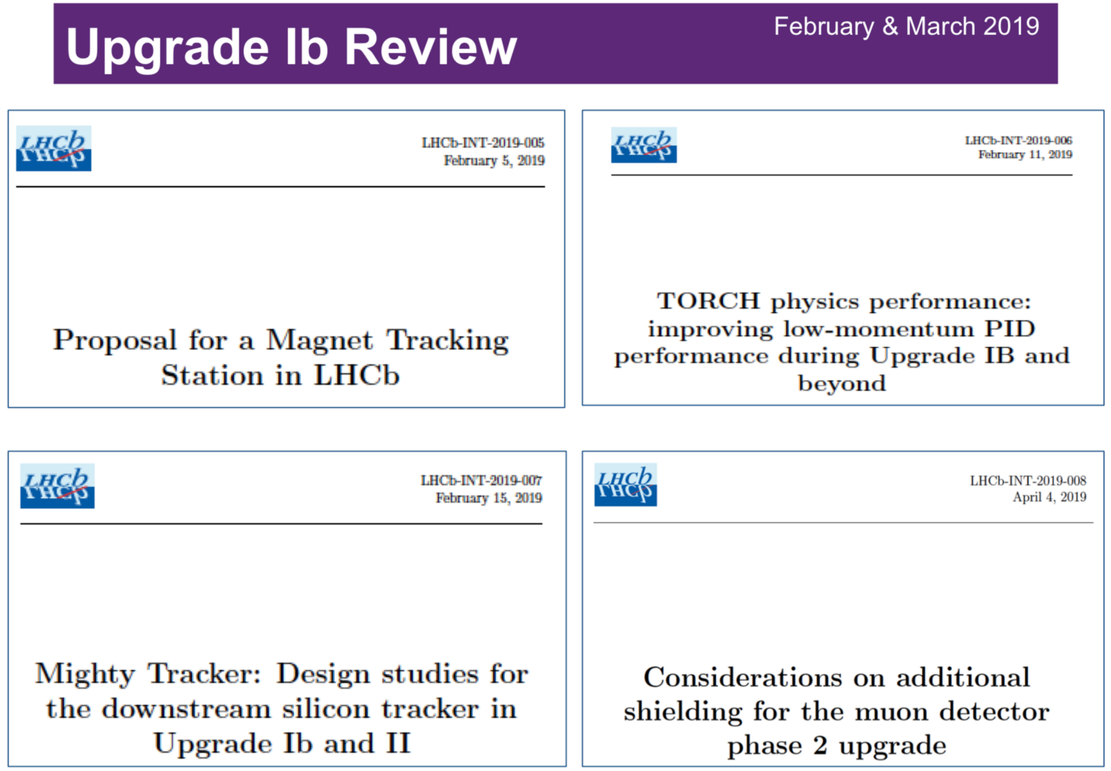
- SMOG2@LHCb could probs **nuclear PDFs, TMDs, GPDs at large Bjorken-x.**

LHCb Upgrade 1b and 2



Phase II in a nutshell

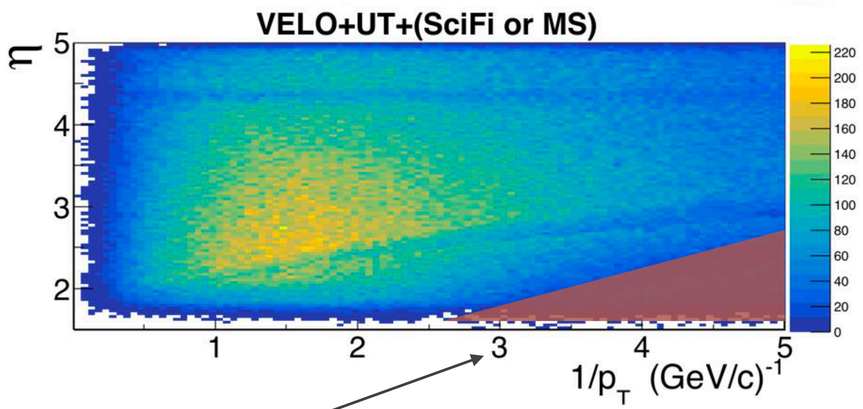




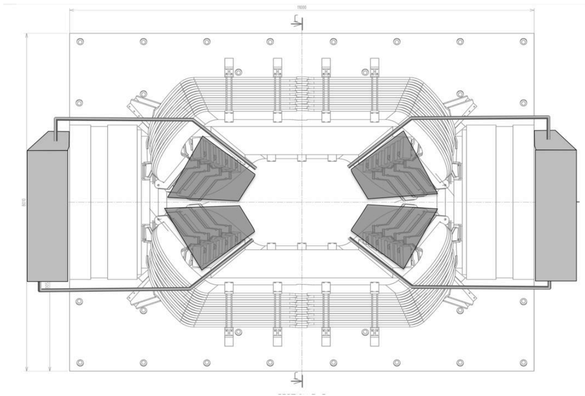
- Sub detectors considering timing :
  - Before the magnet :
    - VELO, RICH1
  - After the magnet :
    - TORCH, RICH2, ECAL

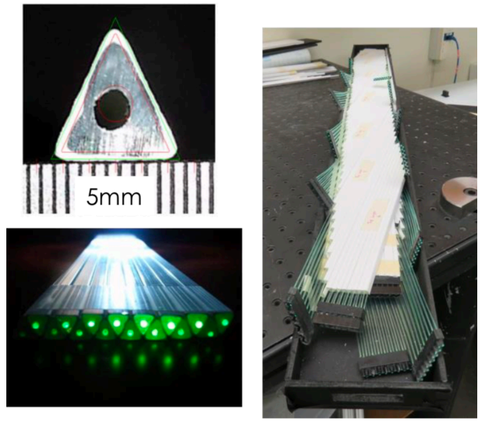
Magnet Tracking Station

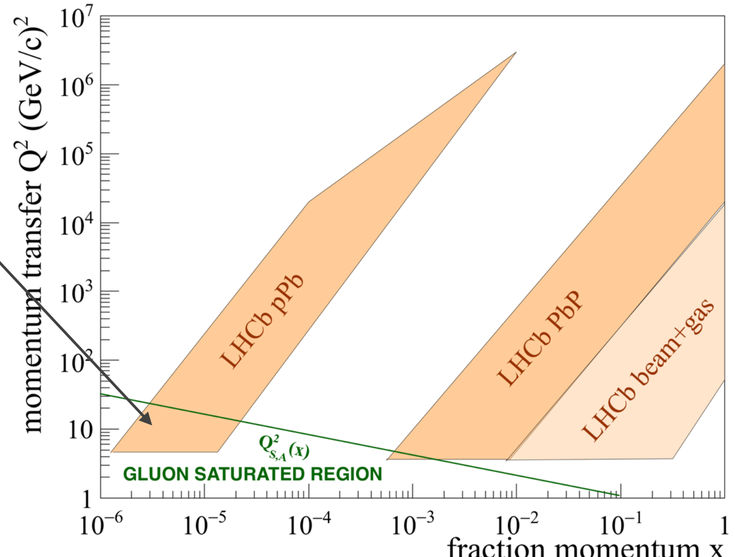
- Proposal for tracking station inside the magnet.
  - Triangular Extruded Scintillating Bars
  - Increase coverage of low-p_T tracks.
  - Physics motivations : access to converted photons.
- **Proposing the installation of a small prototype** inside the magnet during LS3.



Extended acceptance
Extended coverage



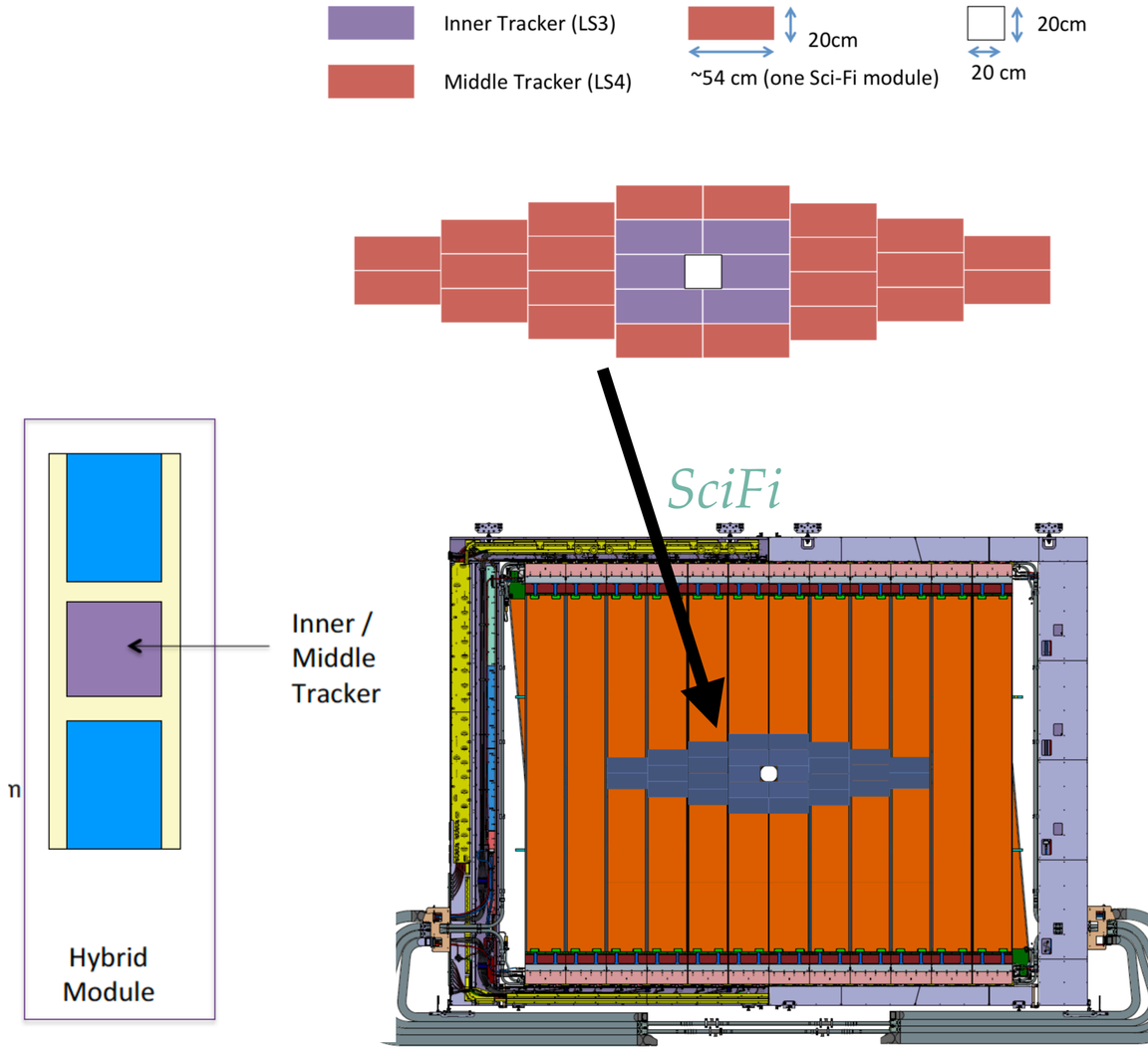




MIGHTY Tracker

LHCb-INT-2019-007

- MIGHTY tracker : biggest silicon tracker built by LHCb.
  - **Upgrade 1b: Inner Tracker + Scifi.**
    - DMAPs technology for silicon sensors.
  - **Upgrade II: New mighty silicon tracker covering larger area.**
    - Rebuild of SciFi + reuse IT.
- Hybrid technology detector, many challenges !
- First estimations show **no limitation in centrality reach with the complete MIGHTY.**



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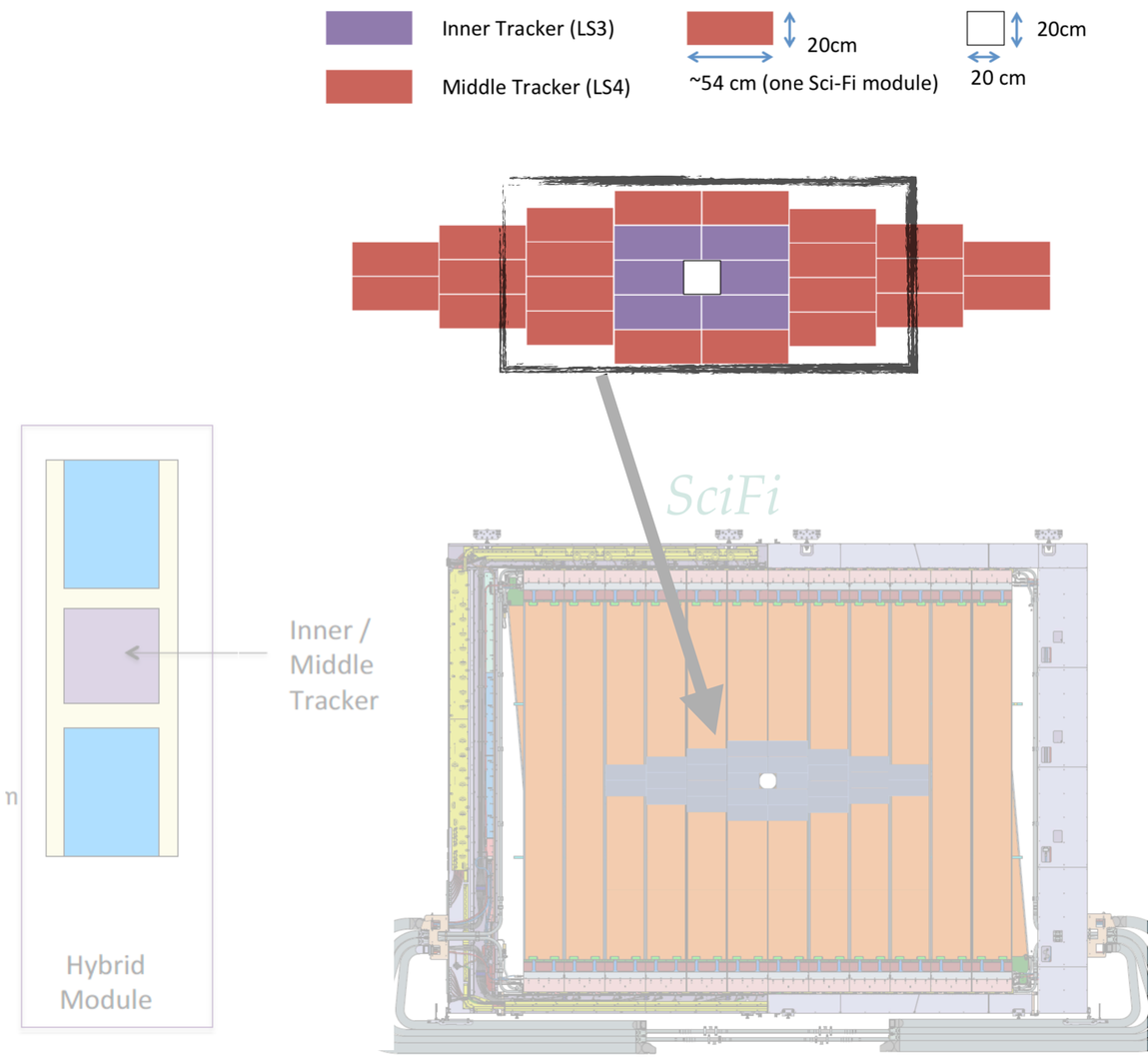

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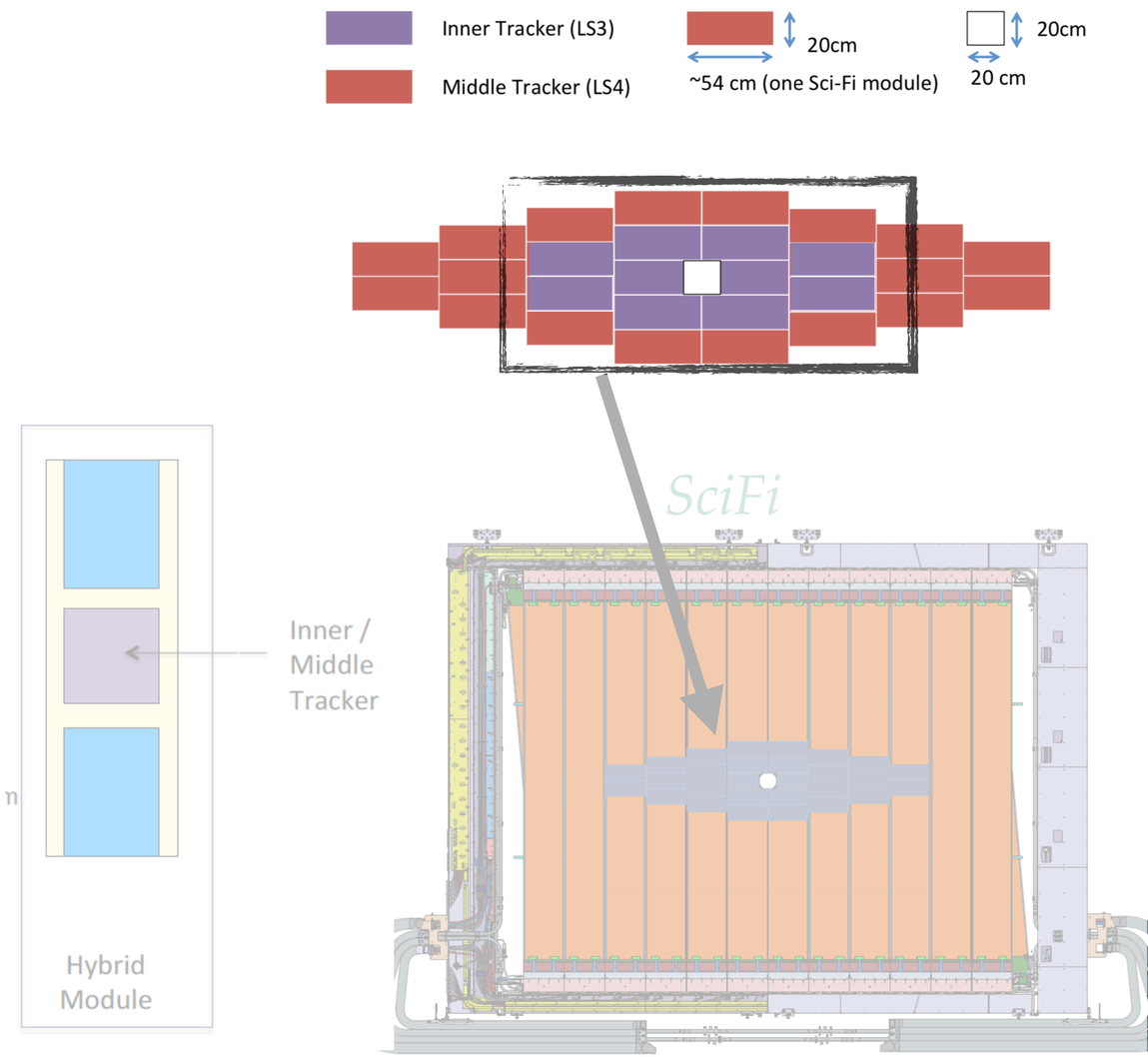

Conclusions

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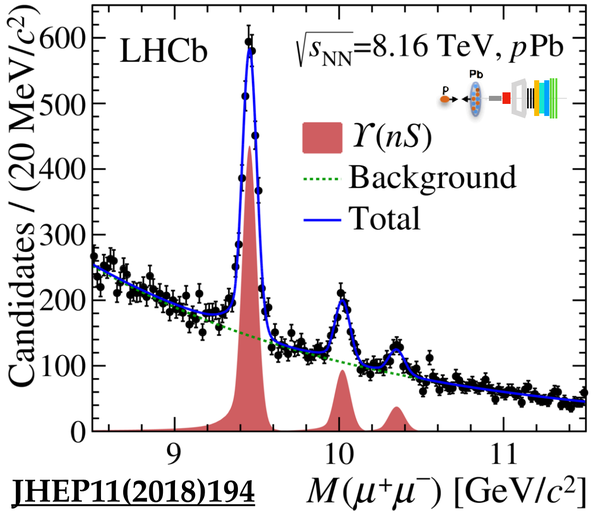
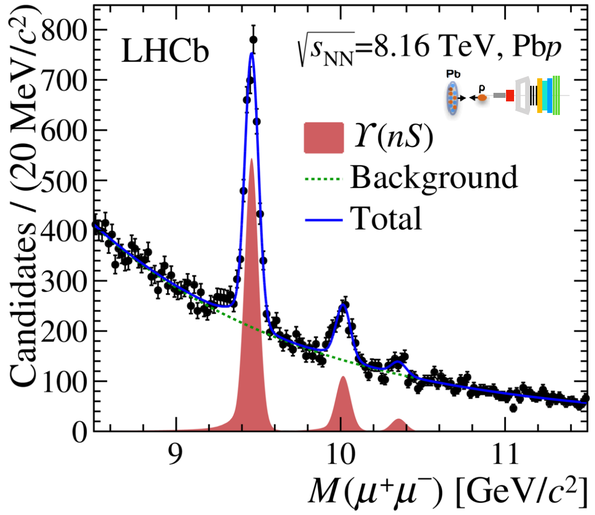
Extended capabilities of the detector = expansion of the physics program !

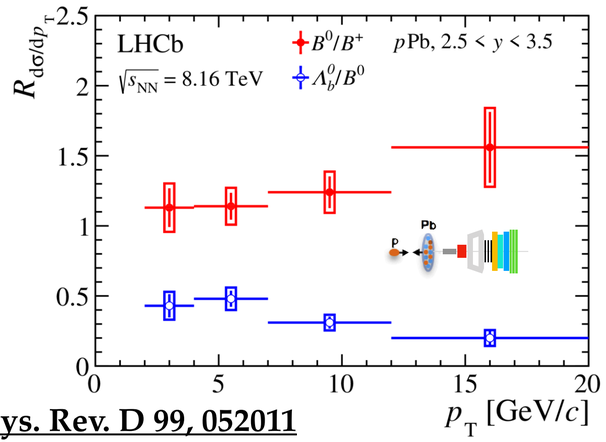
Back-up

Open and hidden beauty production in pPb collisions

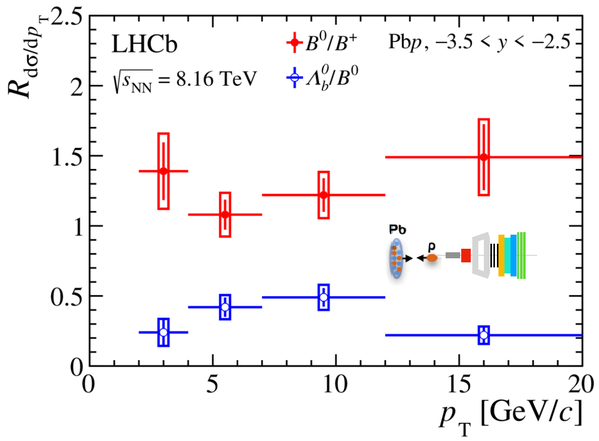


JHEP11(2018)194





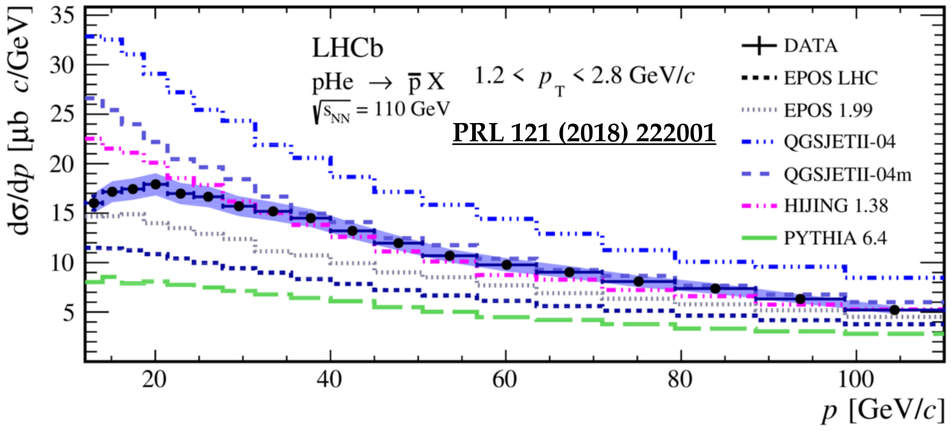
Phys. Rev. D 99, 052011



- Relative production of upsilon states to test cold (hot ?) nuclear matter effects in pPb collisions.
- **Relative Υ(2S)/Υ(1S) and Υ(3S)/Υ(1S) suppression** measured in pPb and Pbp at $\sqrt{s_{NN}}$ = 8 TeV down to zero p_T.
- **Good agreement** between data and predictions when including co-movers effects.
- **Beauty mesons and baryon measured in pPb/Pbp** collisions at $\sqrt{s_{NN}}$ = 8 TeV
- Extensive studies show **good agreement** between data and model predictions

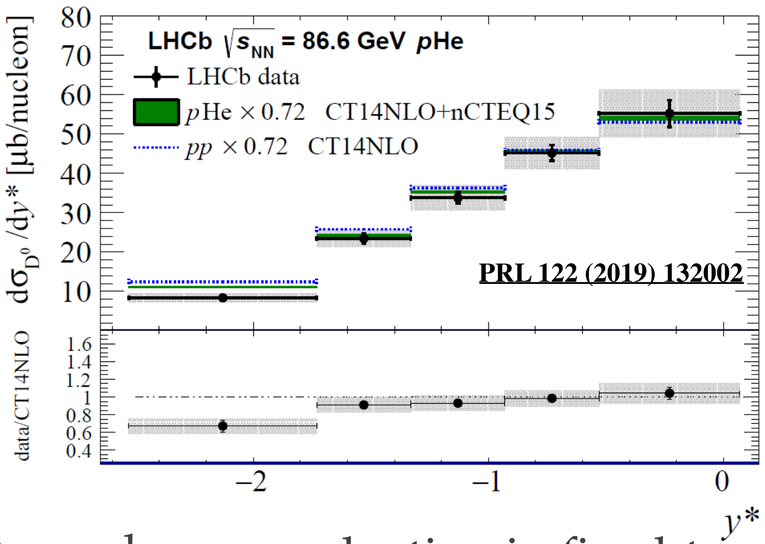
Fixed-target results

Antiproton in pHe at $\sqrt{s_{NN}}$ = 110 GeV



- Antiproton cross-sections in pHe : key to constrain dark matter search in cosmic flux.
  - Data constrain extrapolations from pp to pHe cross-sections.
  - Data constrain empirical parameterization for scaling violation of cross-sections.

Charm in pHe at $\sqrt{s_{NN}}$ = 86.6 GeV

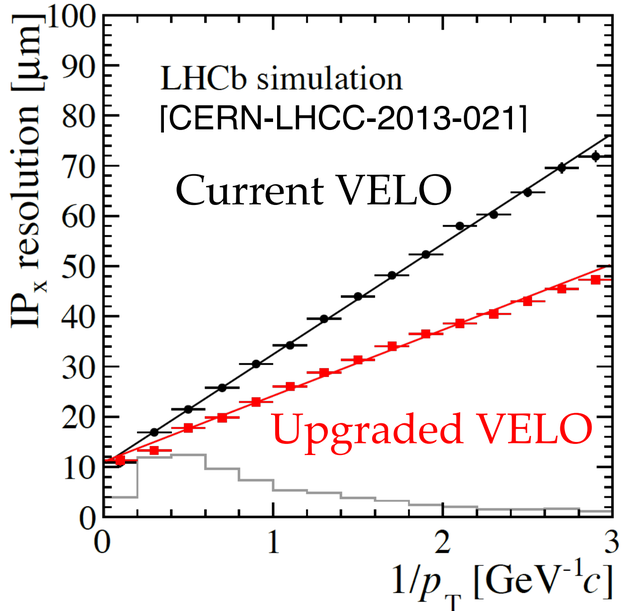


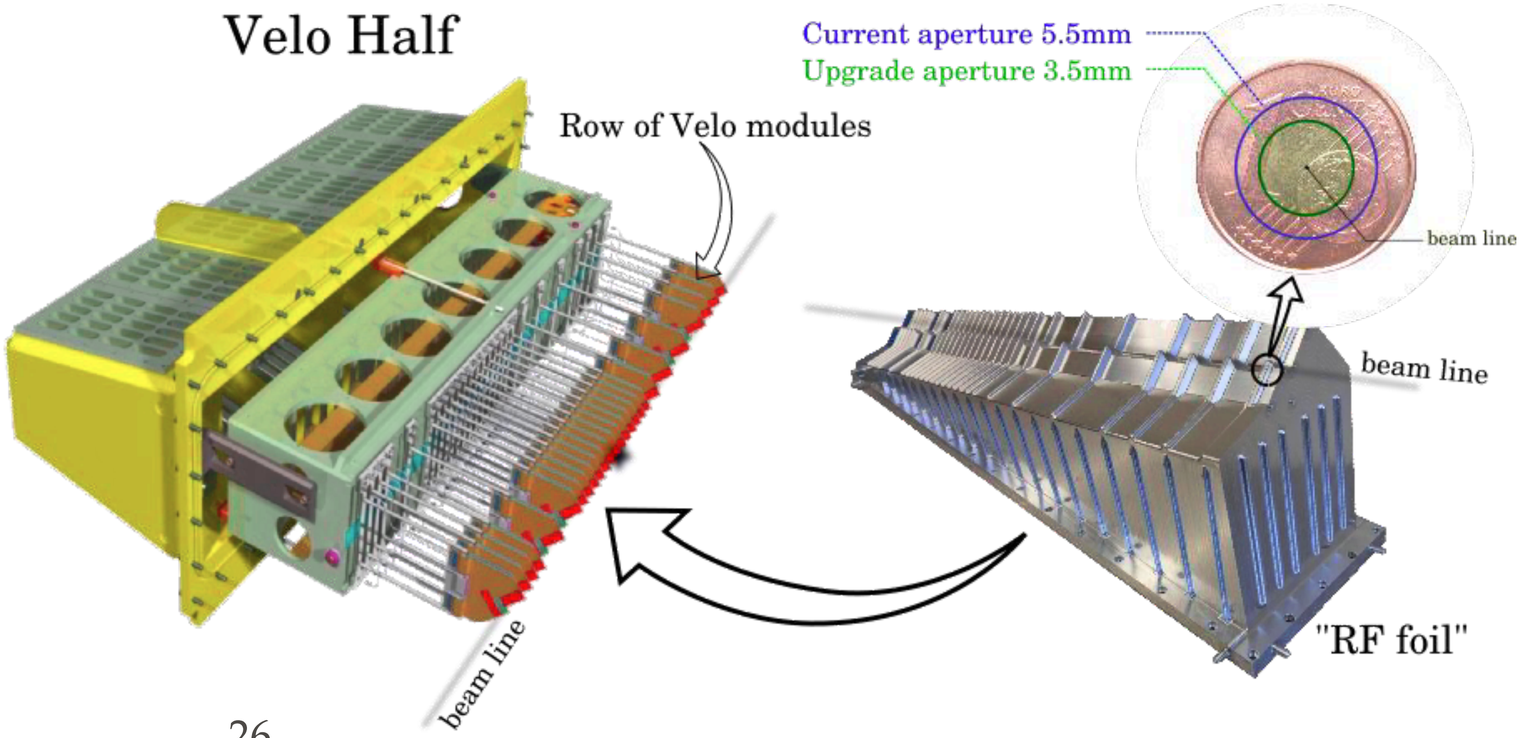
Felipe Garcia - poster

- Open-charm production in fixed-target LHCb acceptance : access to **anti-shadowing** and **intrinsic charm** content in the nucleons.
- **Precise** J/ψ and D^0 measurements in pHe.
- **Good agreement** between data and theory with **no strong intrinsic charm** contribution observed.

Tracking system: Vertex Locator (VELO)

- Silicon pixel detector, **41 M 55 x 55 μm² pixels.**
- Closest pixels at 5.1 mm from the beam line.
- Aluminium foil to protect the Velo without interfering with the beam.
- Sensors to be kept < -20°C
- **Total data rate** : 2.8 Tb/s

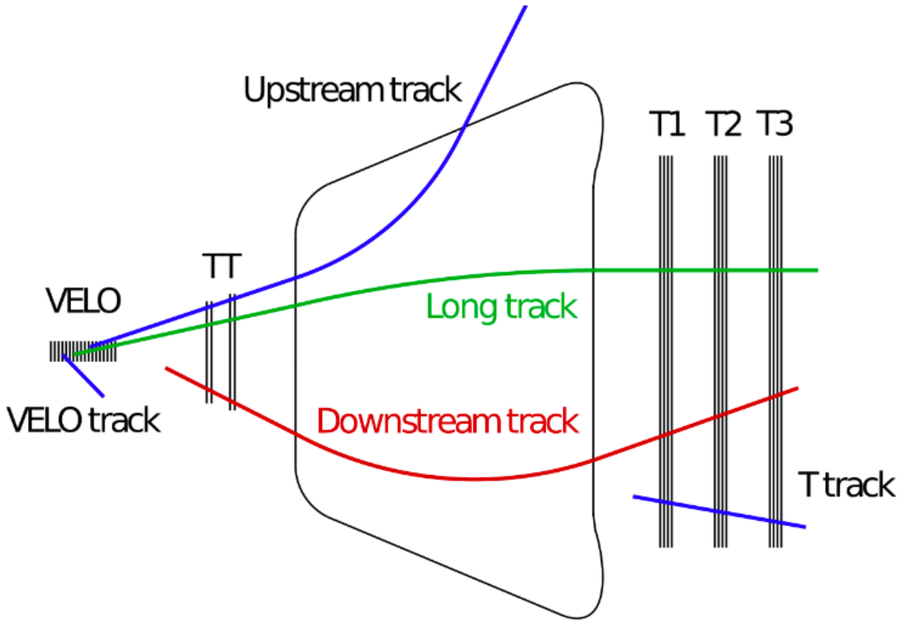




Tracking in LHCb

- Many types of tracks in LHCb, the most important ones are
  - Long tracks.
  - Downstream tracks
- Tracking steps :
  - Finding a track : Forward Tracking algorithm.
    - Combine VELO seeds with hits in the T-stations
    - Match VELO tracks and seeds from T-stations
  - Fitting a track : Kalman filter.

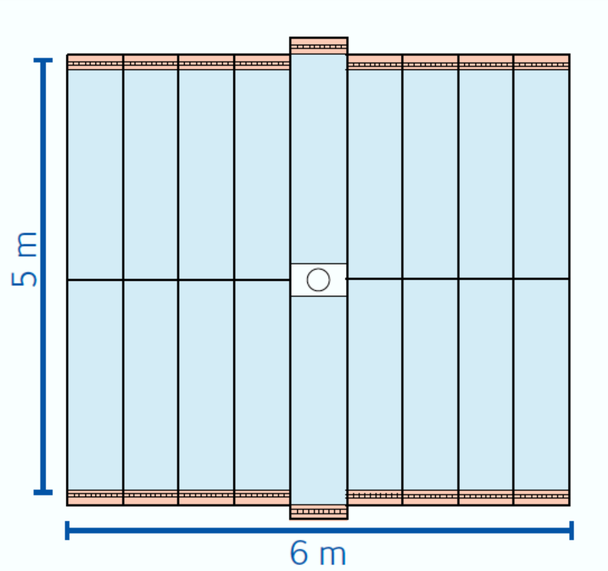
The LHCb tracks

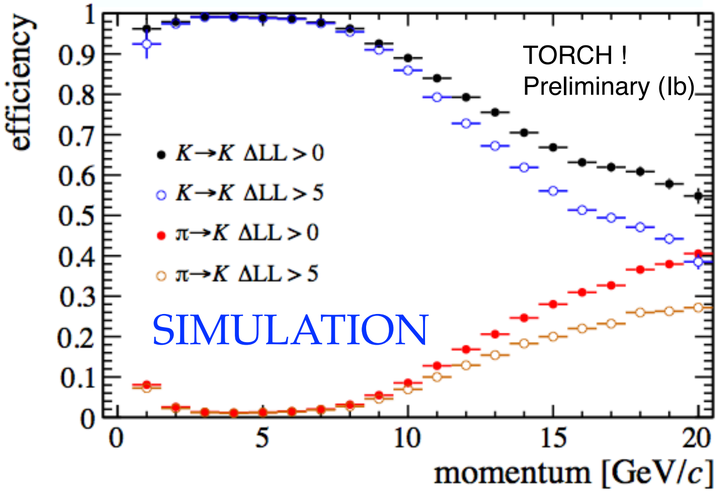


LHCb-INT-2019-006

TORCH - Low momentum PID

- TORCH is a large area time of flight detector that is designed to provide PID in the GeV/c momentum range
  - Considered for use in Upgrade Ib.
  - Exploit prompt production of Cherenkov light in a quartz radiator plate to provide a fast timing signal.
  - Aim for a resolution of 10-15 ps per track
  - A large-scale prototype has been developed.
  - Test-beam ongoing
  - **Good separation between between π/K/p is possible in 2-10 GeV/c range.**

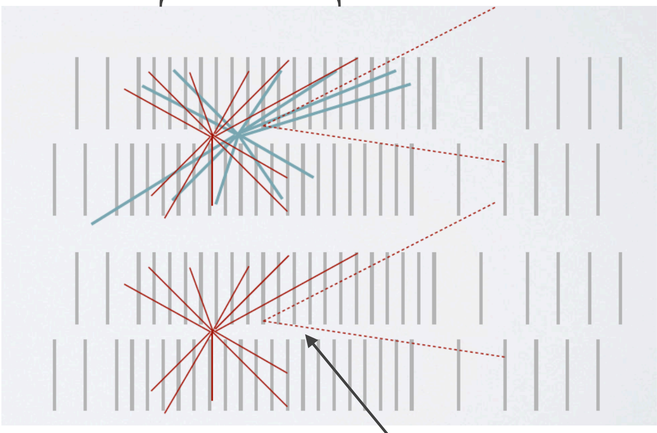




Half-scale demonstrator

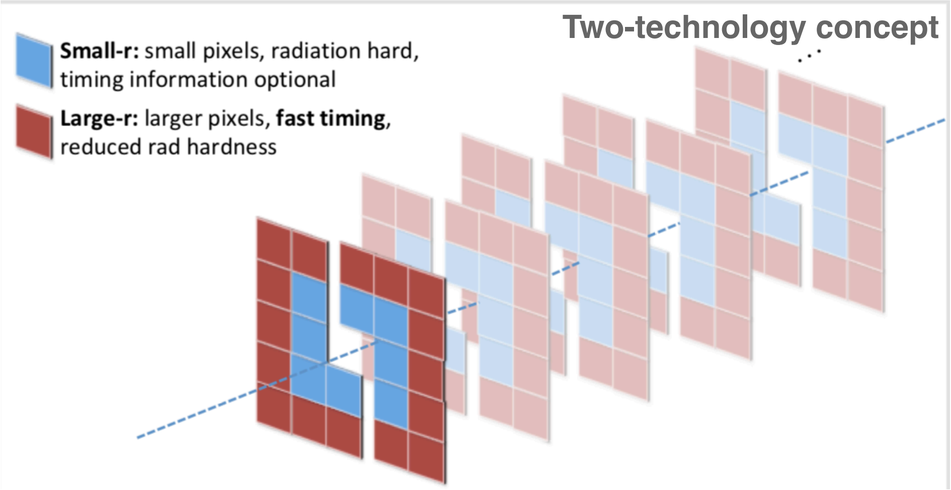
VELO

σ_z(lumi region) ≈ 45 mm
σ_t(lumi region) ≈ 190 ps

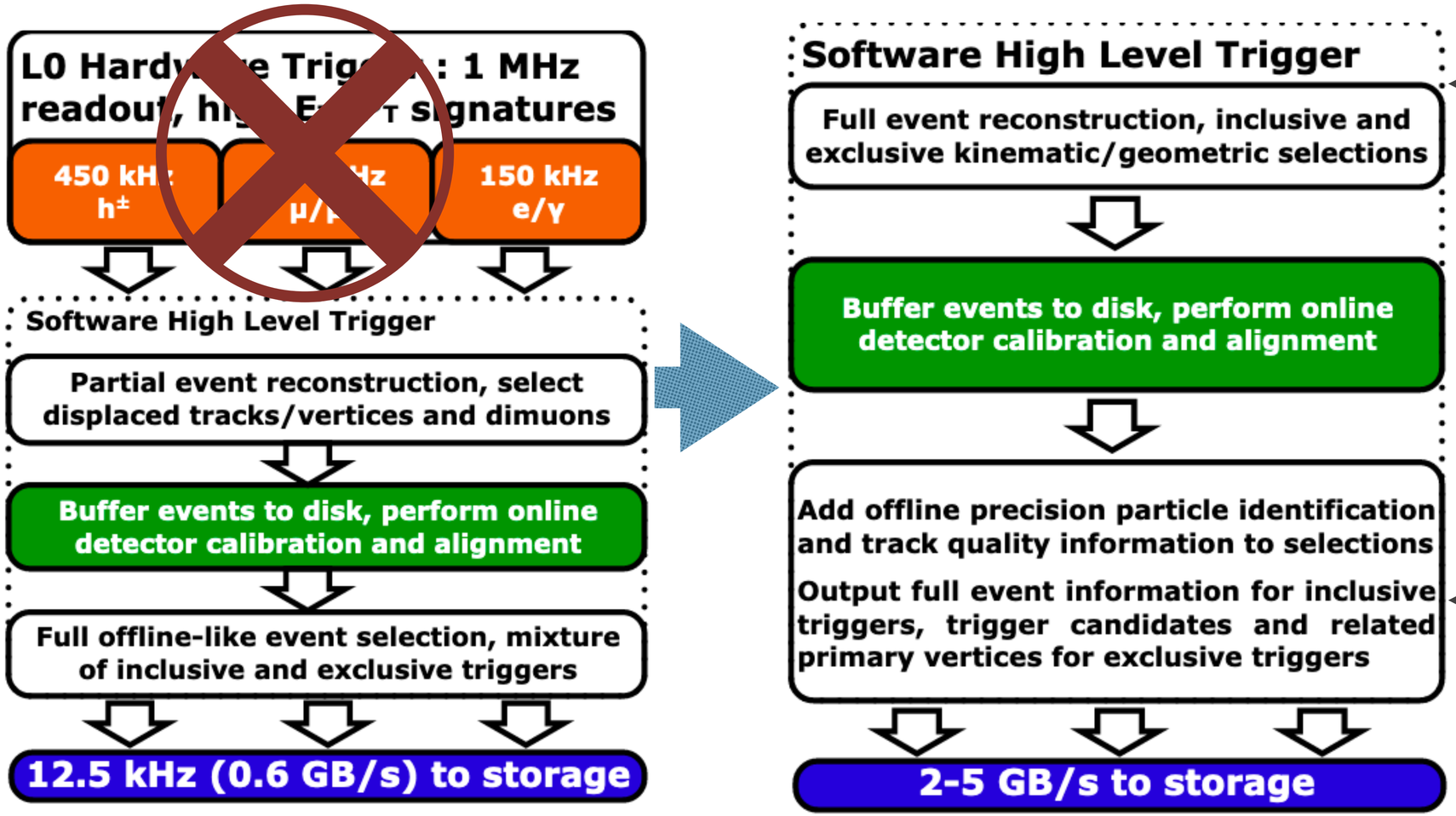


Typical B meson flight time ~15ps

- Upgrade II VELO faces **significant mechanical challenges**
  - huge impact on the design and R&D.
- Track timing will be crucial
  - PV timing and associations, displaced track trigger etc.
  - Difficult question to address that will impact the design.
  - Other issues : cooling, radiations …



Trigger scheme



Partial event reconstruction
- Data preparation for tracking
- Track reconstruction
- Efficient event selection to reduce the rate to between 500 - 1000 kHz

Re use the Run II strategy

Full event reconstruction
- Best tracking performance, add PID information
- Offline quality selections
- Physics analysis on output of the trigger

Real Time Analysis (RTA)