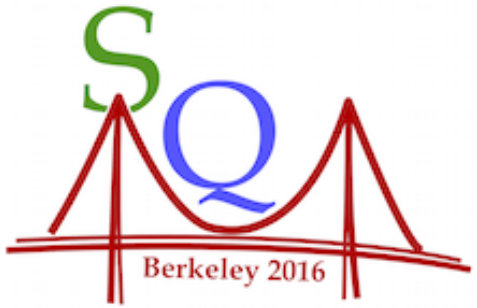
Highlights from the LHCb Ion Physics Program

Michael Schmelling – MPI for Nuclear Physics

– on behalf of the LHCb collaboration –

Outline

- *Introduction*
- *LHCb Detector and Physics Reach*
- *Proton-Lead Collisions*
- *Lead-Lead Collisions*
- *Fixed-Target Physics*
- *Summary and Outlook*



Strangeness in Quark Matter 2016

UC Berkeley, 27 June to 1 July

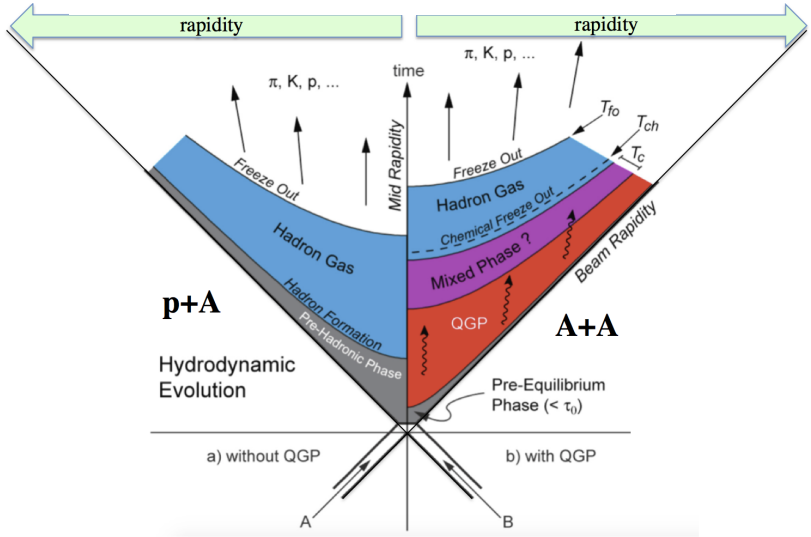
1. Introduction

➜ *theoretical understanding of strong interactions:*

- the QCD Lagrangian is well known and tested
- many open questions in the non-perturbative regime
  - ➜ soft processes, bound states and high densities and temperatures

❖ an incomplete list of things to explore. . .

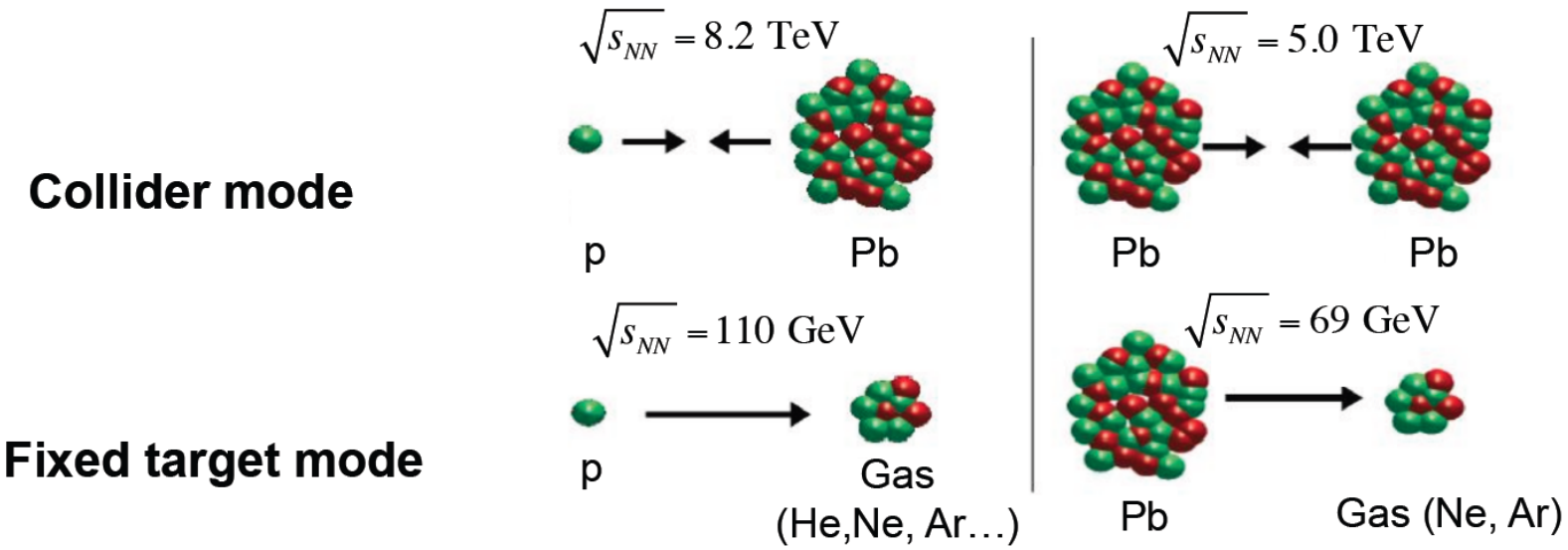
- ➜ quark gluon plasma
- ➜ cold nuclear matter effects
- ➜ nucleon structure at large x
- ➜ intrinsic charm in the nucleon
- ➜ spin-structure of the nucleon
- ➜ hadronization
- ➜ diffractive scattering



Experimental approach

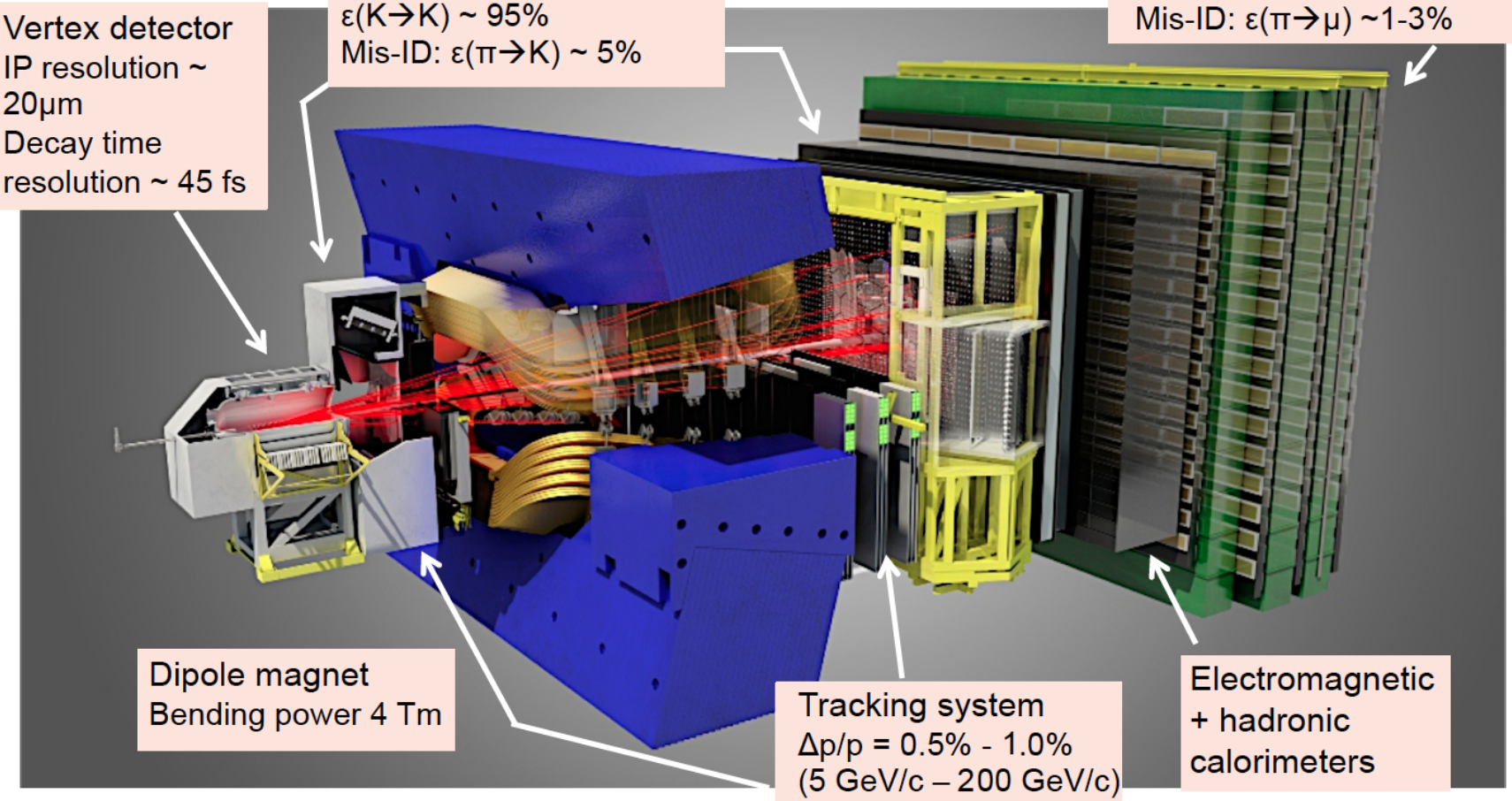
➜ *study hadronic collisions*

- as a function of the centre-of-mass energy
- for different beam-target combinations
- reference given by pp collisions



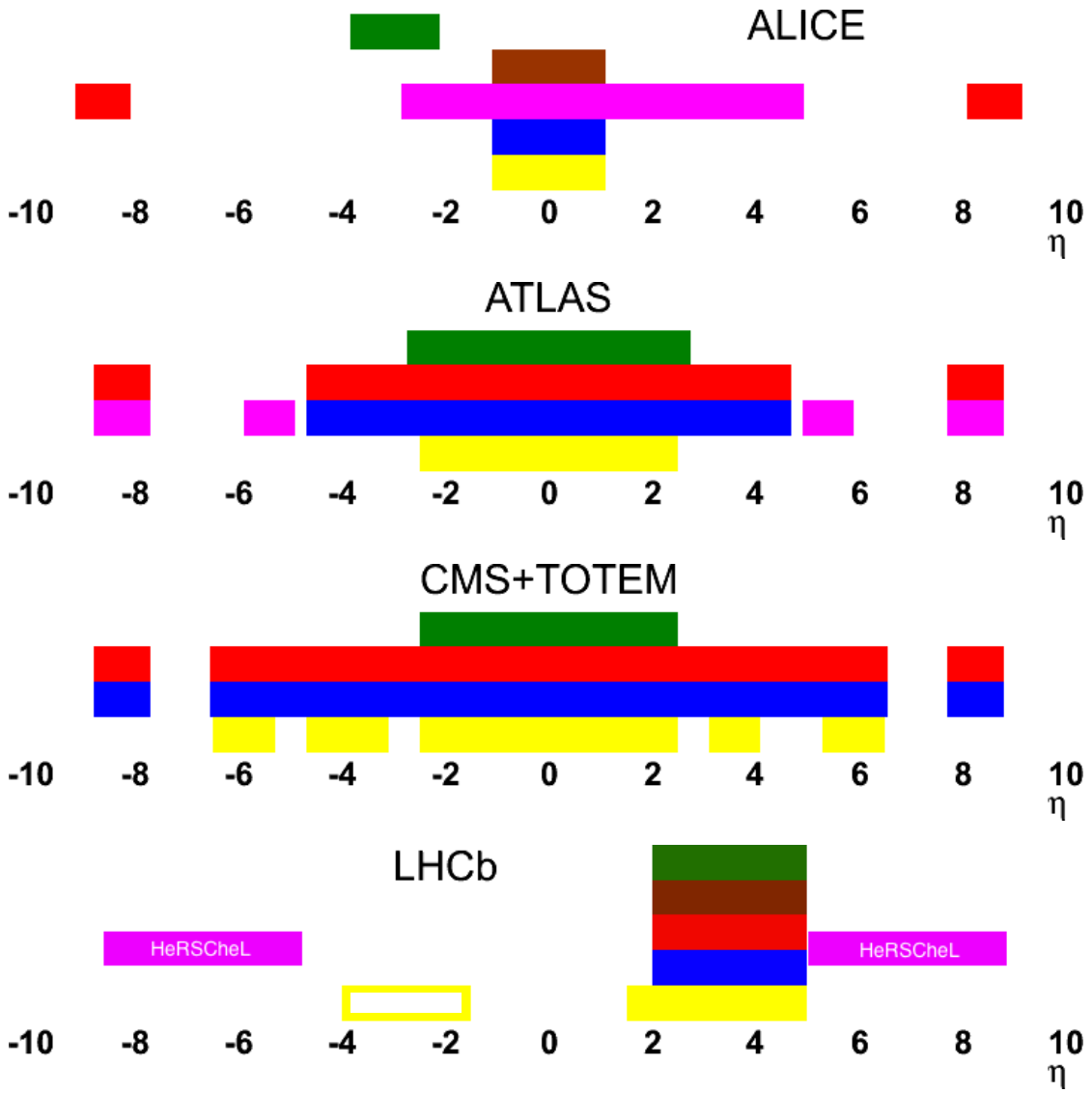
2. LHCb Detector and Physics Reach

Vertexing, tracking, particle-ID and calorimetry in the forward region down to low p_T

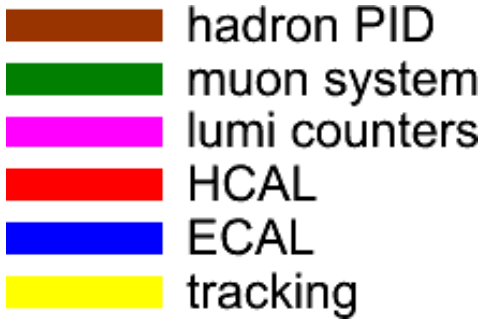


JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

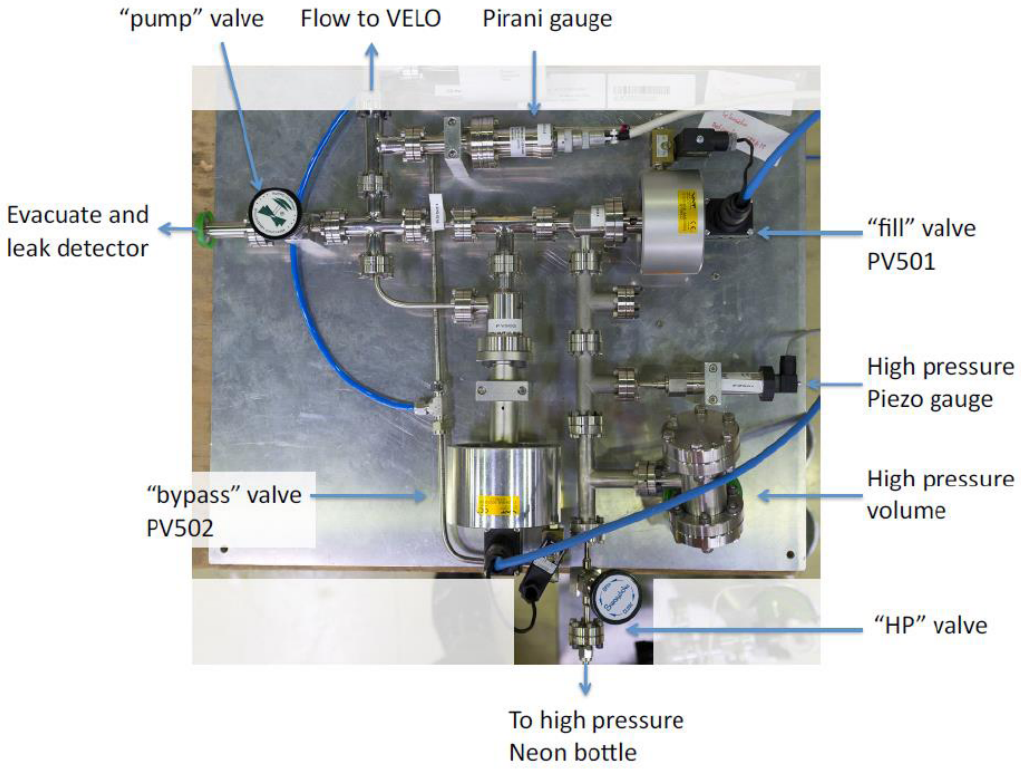
Angular coverage of the LHC experiments



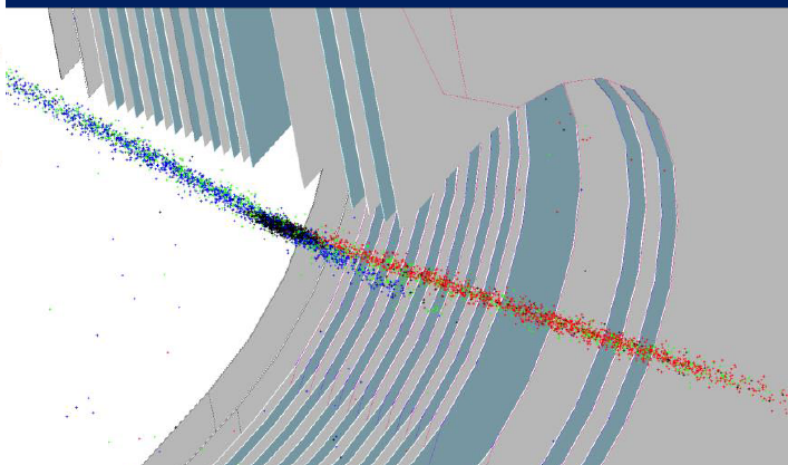
- ALICE
  - ➜ central
  - ➜ forward muon coverage
- ATLAS & CMS
  - ➜ central detectors
- LHCb
  - ➜ forward detector
  - ➜ tracking, particle-ID and calorimetry in full acceptance



➜ SMOG: System for Measuring Overlap with Gas



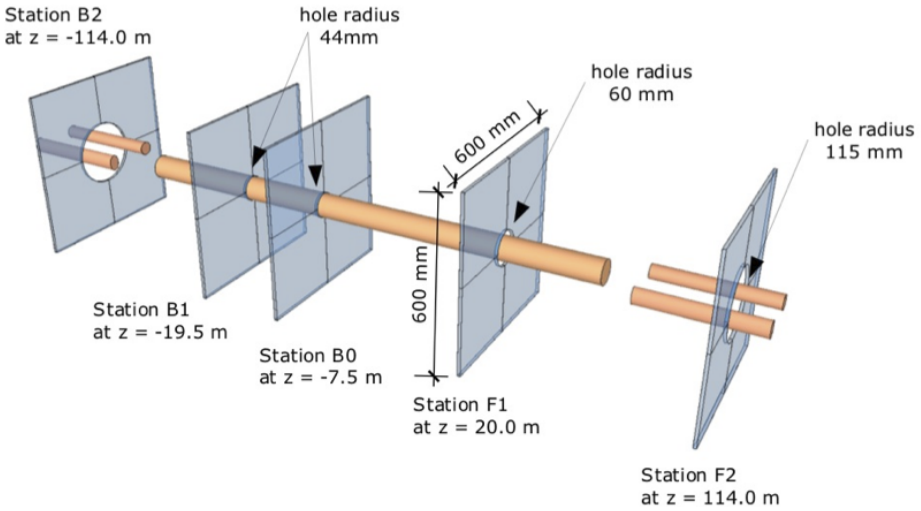
- injection of gas into interaction region
- very simple robust system
- used for a precise luminosity determination

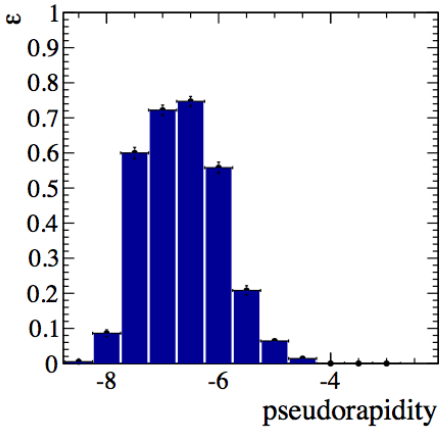


- possibility to inject (noble) gases: He, Ne, Ar (maybe Kr)
- fixed-target physics in pA and PbA configuration

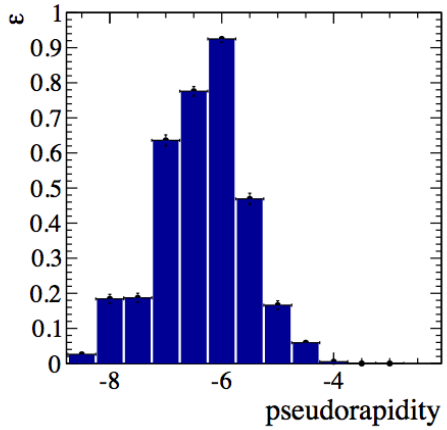
Forward extension of the detector

➜ HeRSCheL: High Rapidity Shower Counters for LHCb





$p_T > 0.5\,\text{GeV}/c$



$p_T > 1.5\,\text{GeV}/c$

- scintillators at large rapidities
- up to ± 114 m from IP
- central region not covered
- coverage $5 < |\eta| < 9$
  - ➜ huge gain for diffractive physics and central exclusive production

LHCb simulation results for the efficiency to see charged pions

LHCb running modes

➜ *available/upcoming LHCb running modes and* $\sqrt{s_{NN}}$

E_{beam}(p)	pp	p-Gas	p-Pb/Pb-p	Pb-Gas	Pb-Pb
450 GeV	0.90 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV(1)			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV(2)	5 TeV	54 GeV(3)	
6.5 TeV	13 TeV	110 GeV(4)	8.2 TeV	69 GeV(5)	∼5 TeV

(1) SMOG with ^{40}Ar few h (2015)

(2) SMOG with ^{20}Ne 2.5 h (2012)

(3) SMOG with ^{20}Ne 30 min (2013)

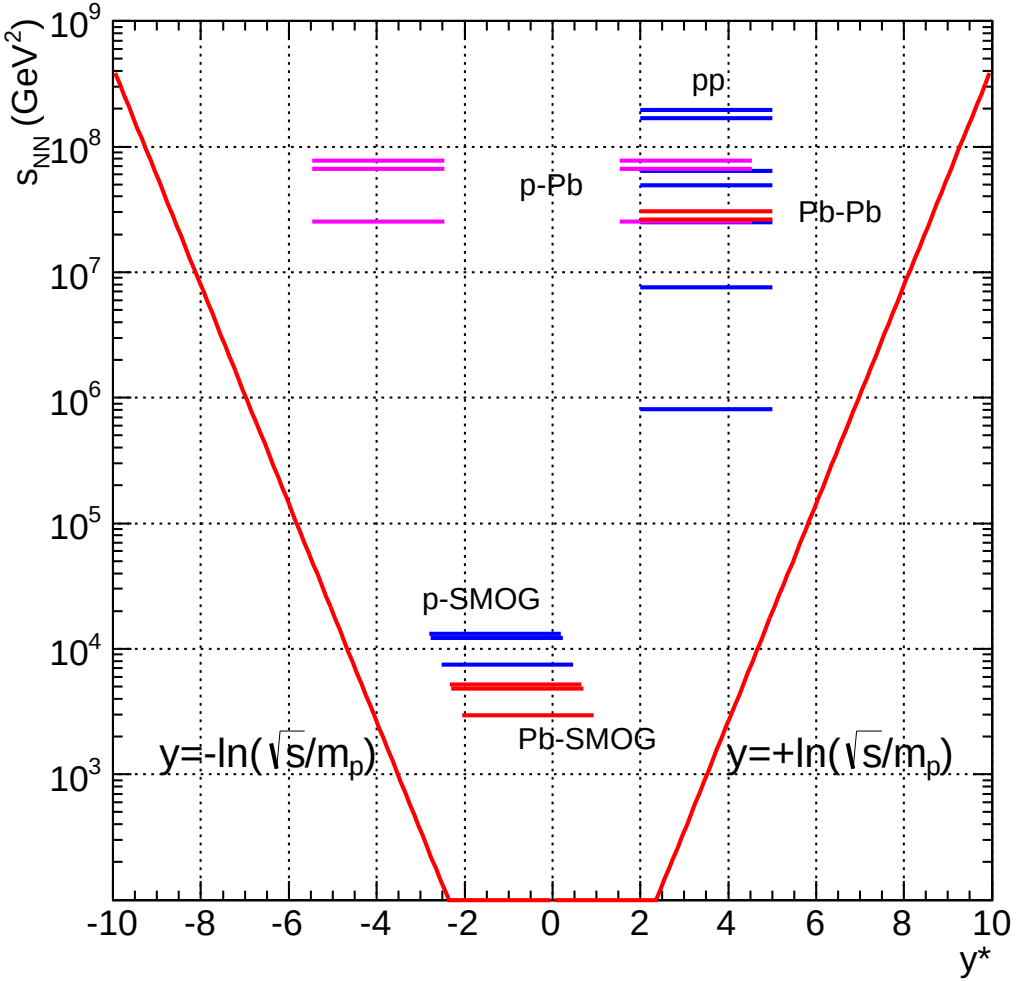
(4) SMOG with ^{4}He 8 h (2015) + 2 d (2016), ^{20}Ne 12 h (2015), ^{40}Ar 3 d (2015)

(5) SMOG with ^{40}Ar 1.5 weeks (2015)

❖ *bridge the gap from SPS to LHC in a single experiment*

Phase space coverage of LHCb

➜ *kinematic acceptance for $E_{\mathrm{beam}}(p)$ between 450 GeV and 7 TeV*



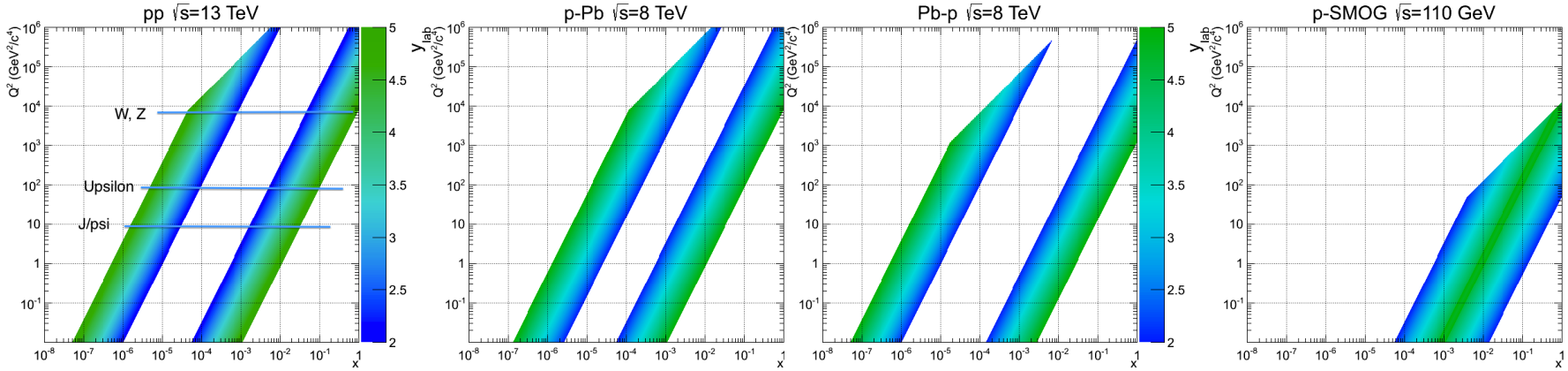
y^*: rapidity in nucleon-nucleon centre-of-mass system, with forward direction (+ values) in direction of the proton/beam

Access to parton densities

➜ *probe x by inclusive particle production*

mass M, rapidity y: $\quad x_{1,2} \approx e^{\pm y} \frac{M}{\sqrt{s}}$

- two x-values from nucleon/nuclear PDF for given y and $Q^2 = M^2$



➜ boost between lab and nucleon-nucleon centre-of-mass system

p on Pb	$\Delta y \approx 0.465$
p on gas	$\Delta y \approx 4.8$
Pb on gas	$\Delta y \approx 4.3$

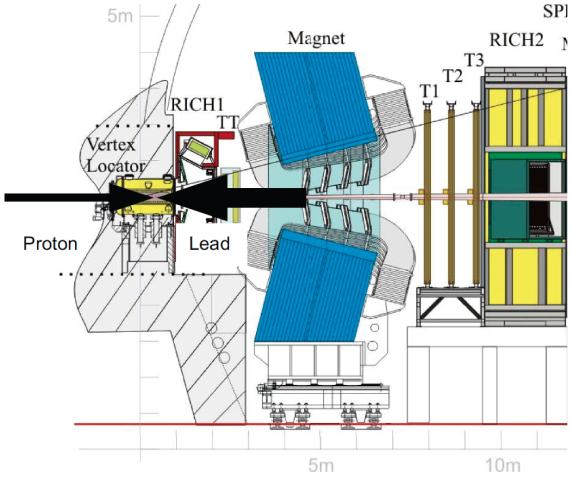
➜ *study nuclear effects:*

nuclear modification factor: $R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}/dy}{d\sigma_{pp}/dy}$

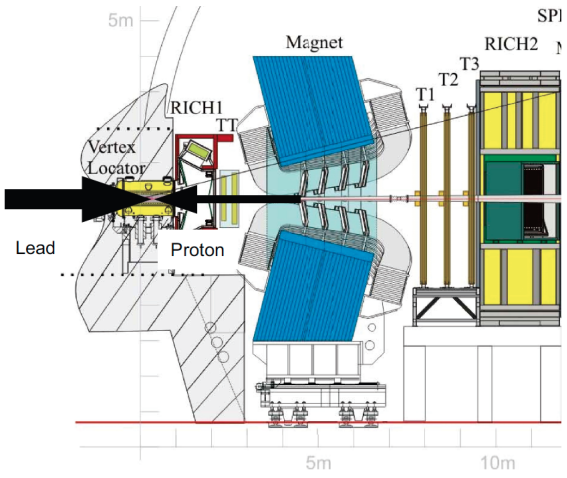
forward-backward asymmetry: $R_{FB}(y) = \frac{\sigma_{pA}(+|y|)}{\sigma_{pA}(-|y|)}$

- pp cross-section and experimental systematics cancel in R_{FB}
- flip beam directions to measure both hemispheres

p



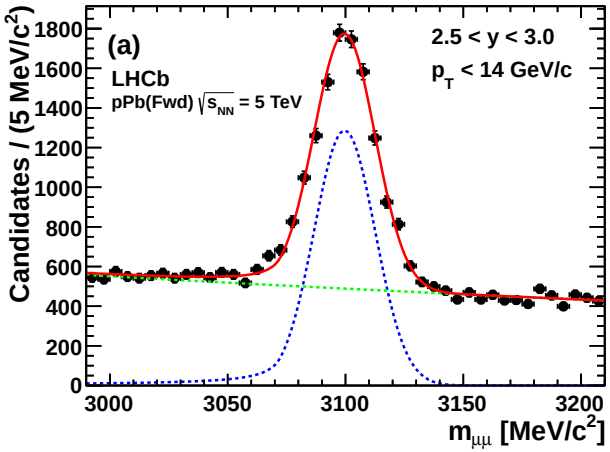
Pb

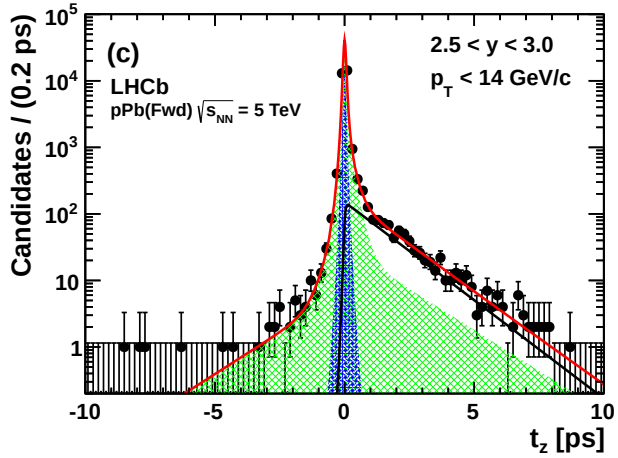


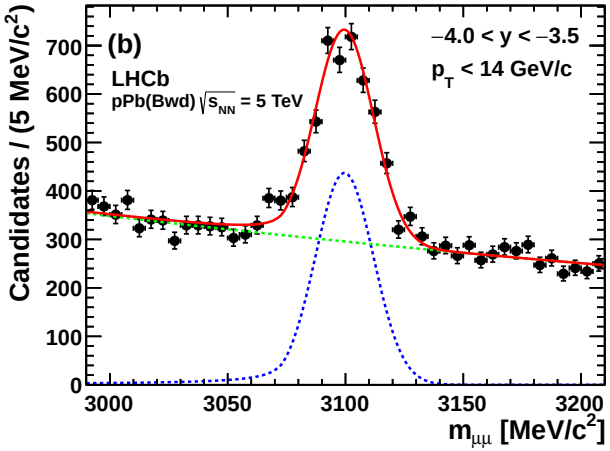
results from $1.6\,\text{nb}^{-1}$ pPb-data recorded in 2013 ➜

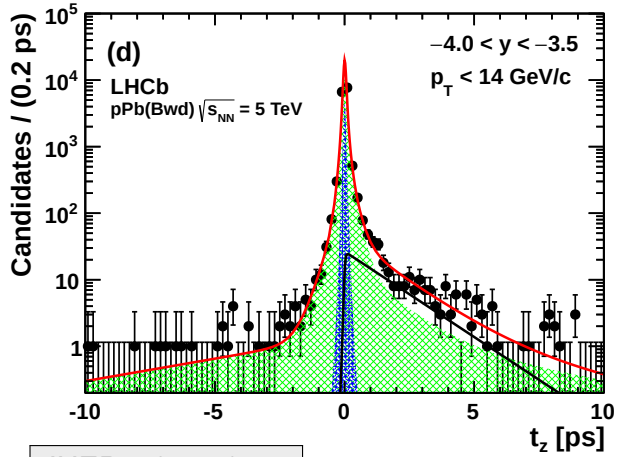
J/ψ and $\psi(2S)$ production in pPb collisions

➜ *separate prompt and delayed components by a simultaneous fit of mass and pseudo-proper-time* $t_z = (z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}/p_z^{J/\psi}$









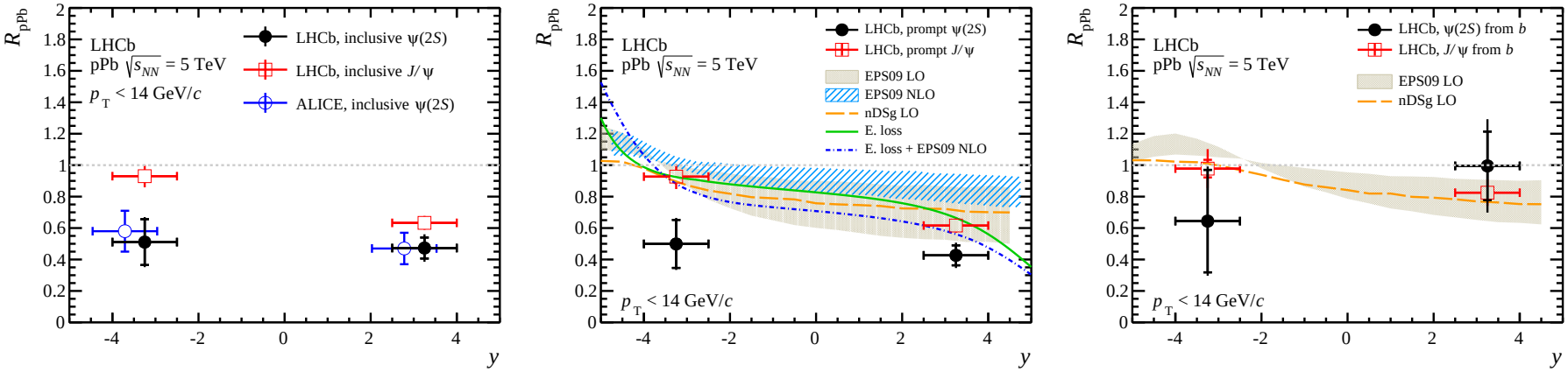
pA collisions:
forward hemisphere
$1.5 < y < 4.0$
$p_T < 14\,\text{GeV}/c$

Ap collisions:
backward hemisphere
$-5.0 < y < -2.5$
$p_T < 14\,\text{GeV}/c$

JHEP02(2014)072

J/ψ and $\psi(2S)$ production in pPb collisions

➜ *nuclear modification factors*

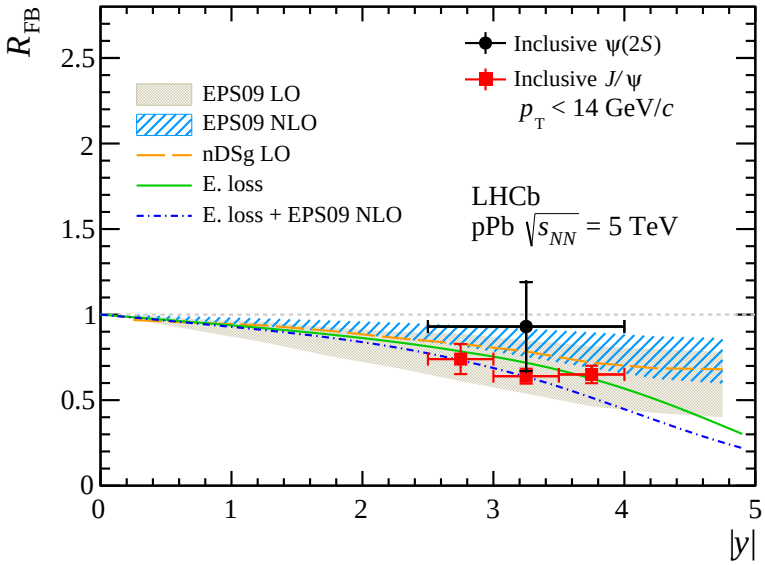


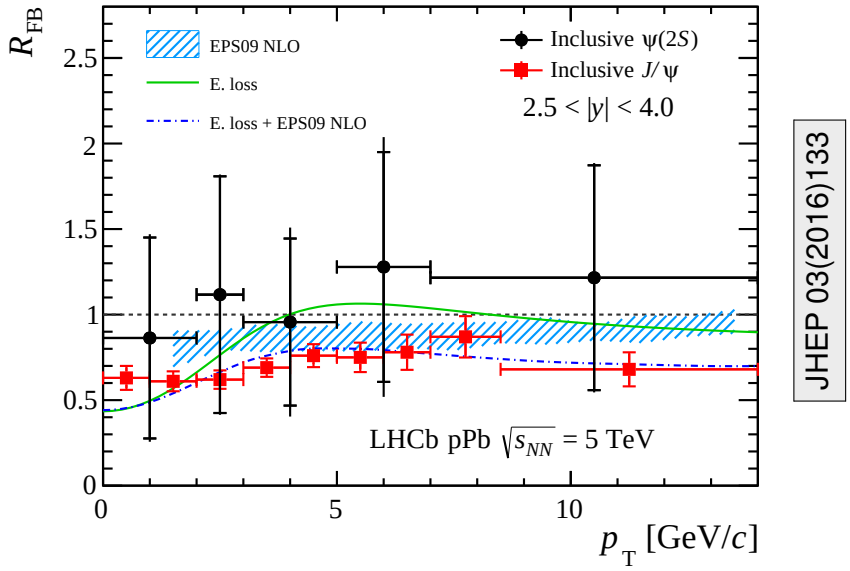
JHEP 03(2016)133

- results require interpolation of pp cross-section to $\sqrt{s} = 5\,\text{TeV}$
- $R_{pPb} \neq 1$: the nucleus is not a loose collection of independent nucleons
- tighter bound B-mesons less affected than prompt J/ψ
- J/ψ data agree with "energy loss + NLO shadowing"
- consistent results from ALICE and LHCb for stronger $\psi(2S)$ suppression
- J/ψ from b and $\psi(2S)$ from b expected to be consistent

J/ψ and $\psi(2S)$ production in pPb collisions

➜ *forward-backward asymmetries of $\psi(2S)$ versus J/ψ*





- $\psi(2S)$ ratios closer to unity than J/ψ ratios
  - ➜ J/ψ and $\psi(2S)$ consistent within uncertainties
  - ➜ consistency expected by theoretical models
- resolve with 2016 pPb data (10x more than 2013)

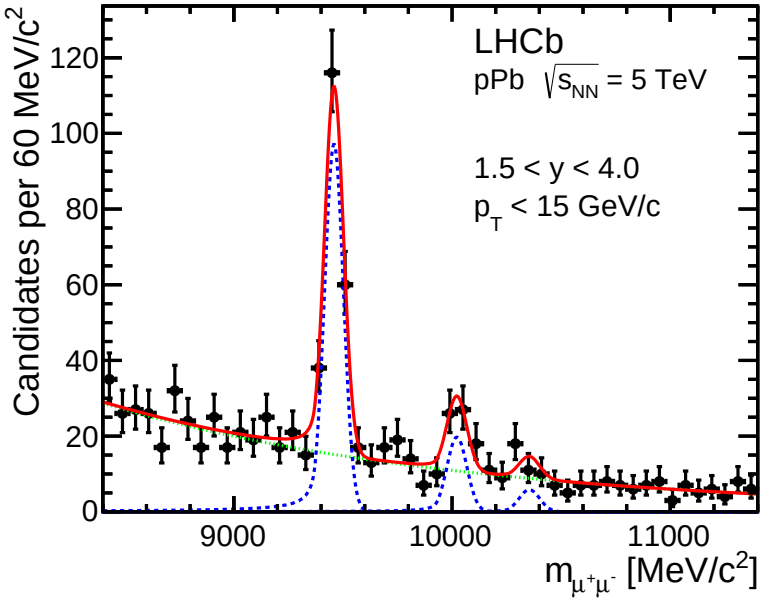
Ferreiro et al. PRC88(2013)04791

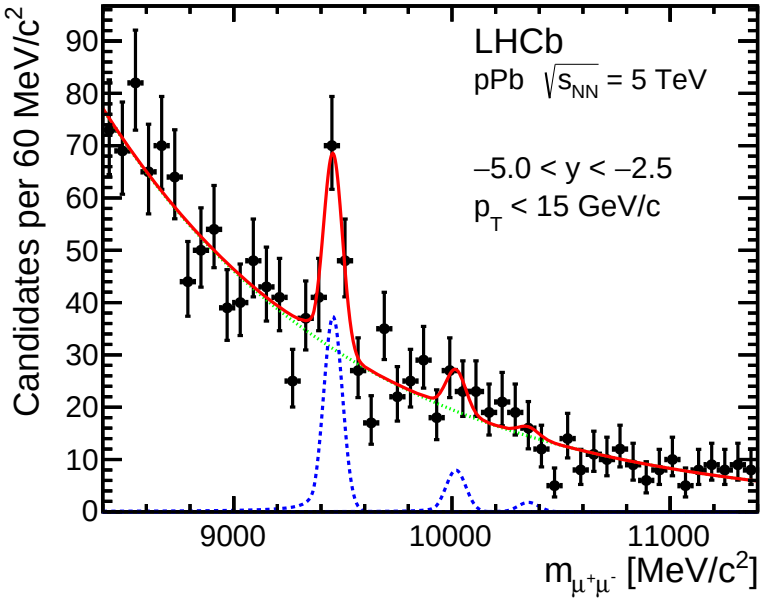
Arleo, Peigne JHEP03(2013)122

Albacete et al. IJMPE22(2013)133007

Upsilon production in pPb collisions

➜ *statistics limited measurement*



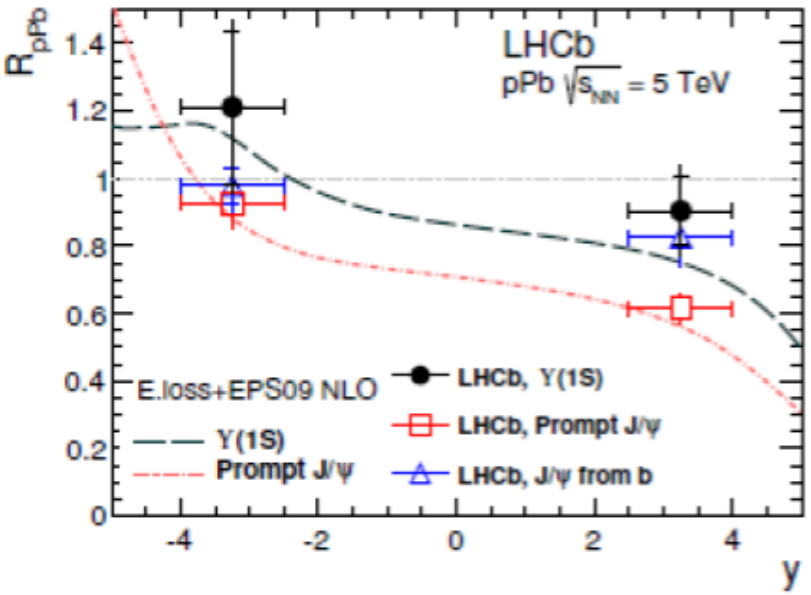


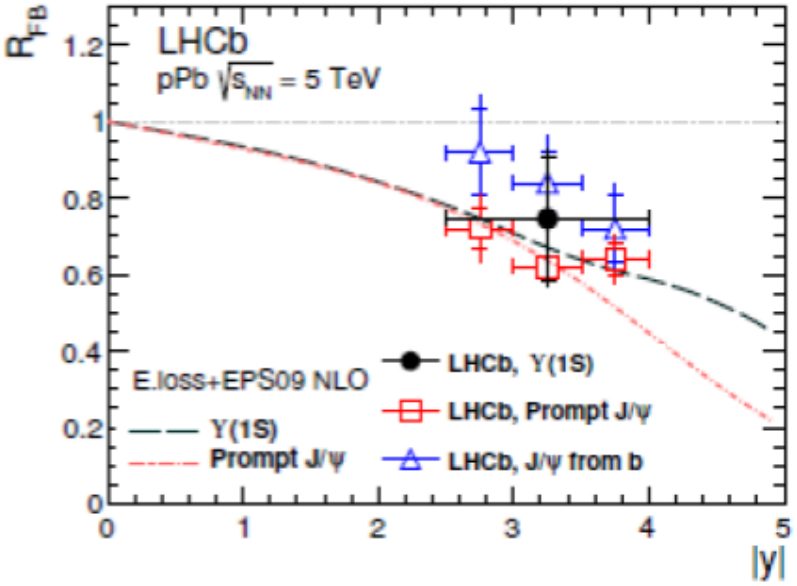
JHEP07(2014)094

- kinematic range: $p_T < 15\,\text{GeV}/c$, $1.5 < y < 4.0$ and $-5.0 < y < -2.5$
- no differential measurements possible
- evidence for strong suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$
  - ➜ 2016 data will allow a measurement
- study $\Upsilon(1S)$ nuclear effects in common rapidity range $2.5 < |y| < 4.0$

Upsilon production in pPb collisions

➜ $\Upsilon(1S)$ *nuclear modification factor and forward-backward asymmetry*





JHEP07(2014)094

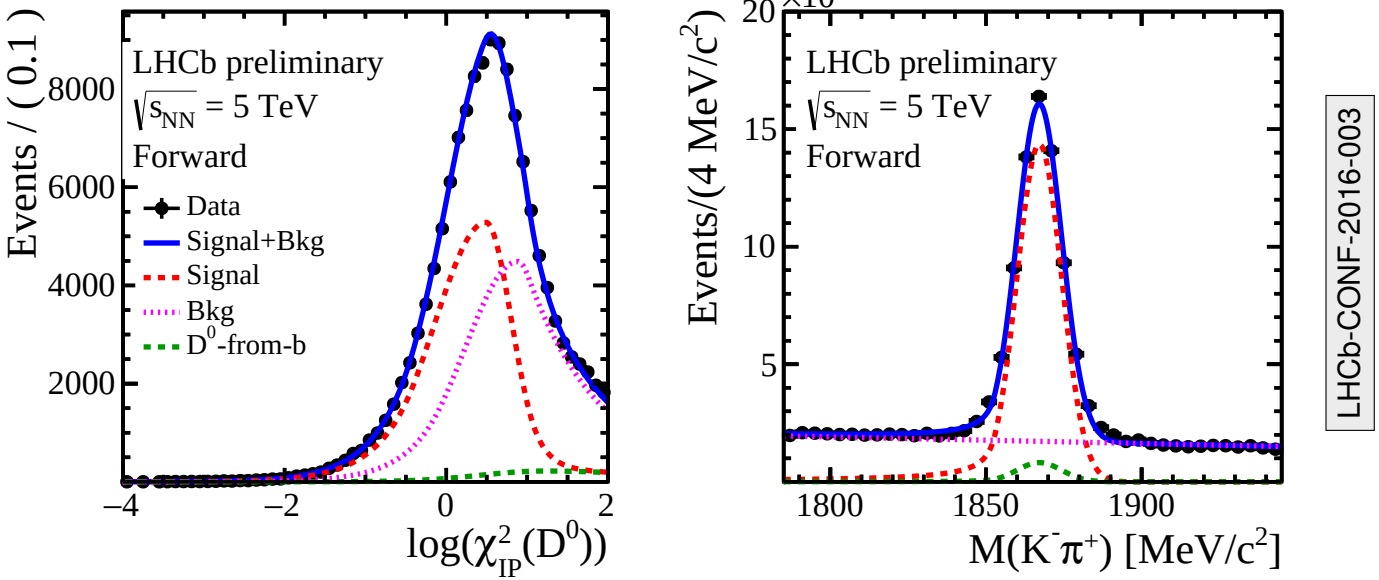
- large uncertainties
- Upsilon consistent with J/ψ from b
- backward data consistent with expectations of “anti-shadowing”

❖ more data needed for firm conclusions

D^0 production in pPb collisions

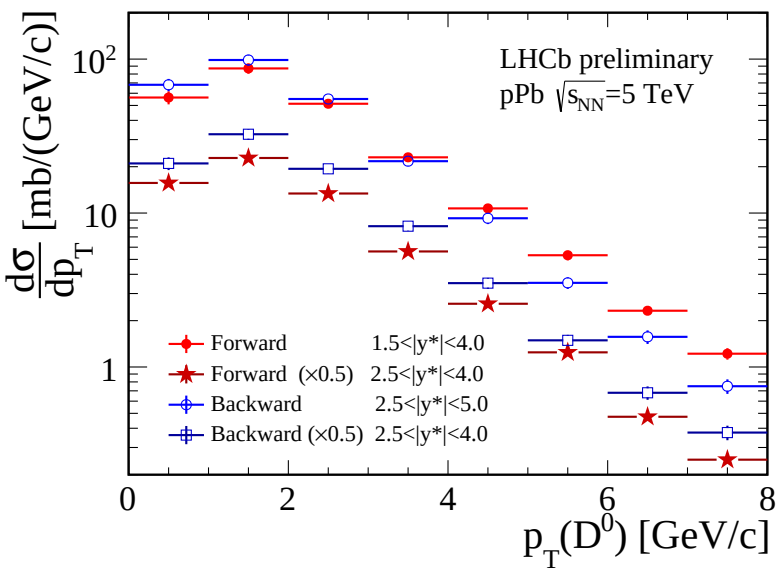
➜ *forward production of prompt open charm in pA collisions*

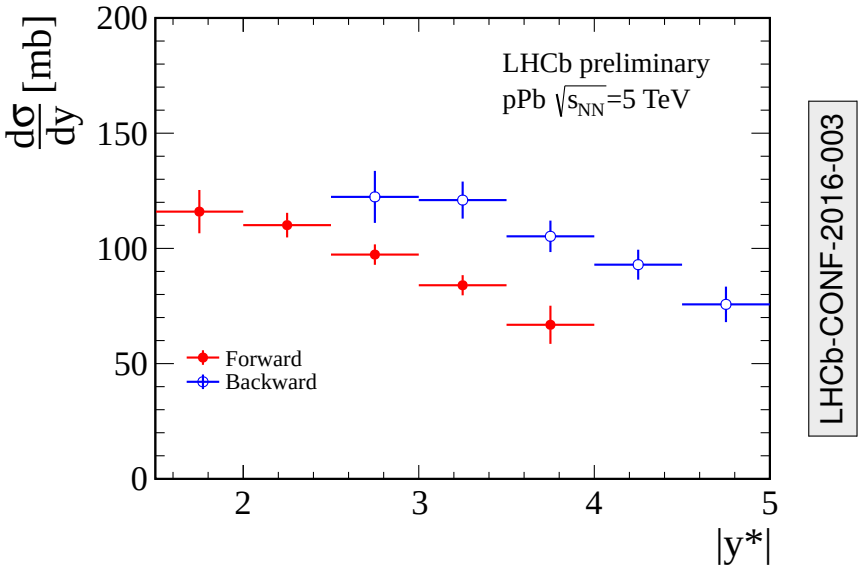
- $L = 0.11\,\text{nb}^{-1}$ (forward) and $L = 0.05\,\text{nb}^{-1}$ (backward)
- reconstruction in $D^0 \to K^-\pi^+$ + CC decays
  - ➜ kinematic range: $p_T < 8\,\text{GeV}/c$, $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$
  - ➜ simultaneous fit of impact parameter and invariant mass
  - ➜ extraction of prompt yields down to $p_T \to 0$



D^0 production in pPb collisions

➜ *differential cross-sections*

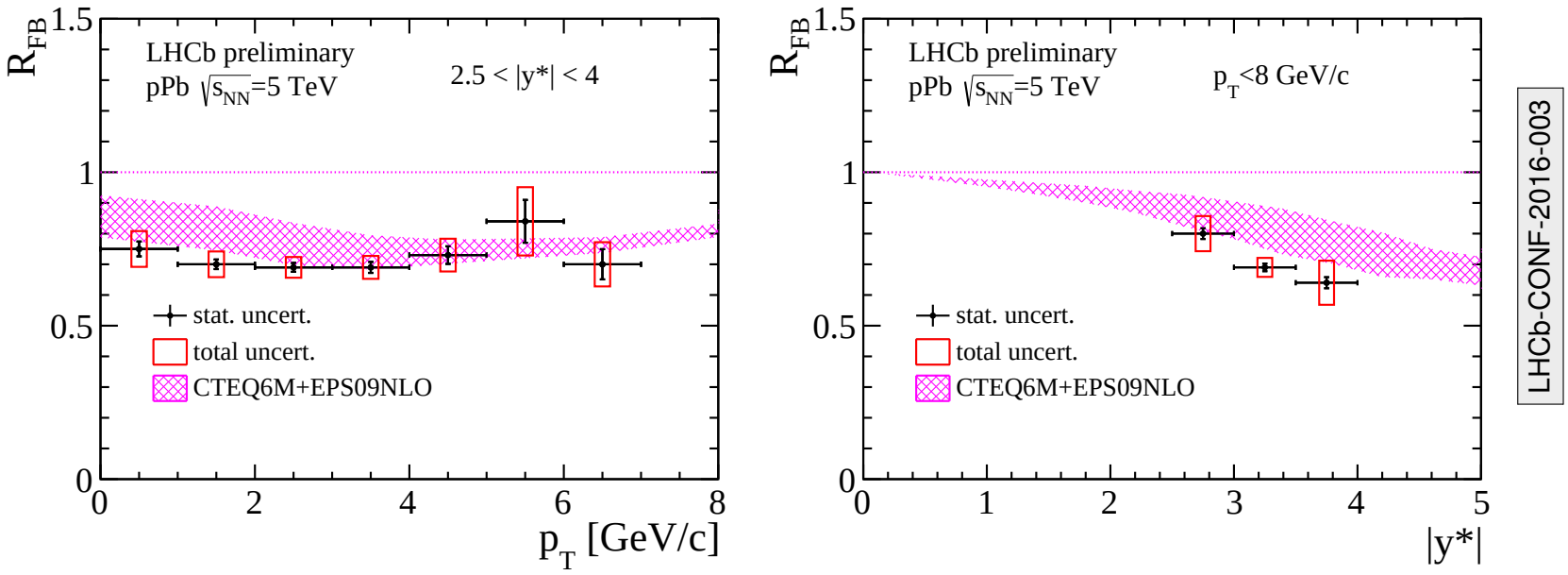




- similar p_T slopes in beam and target hemispheres
- more forward production in target hemisphere

D^0 production in pPb collisions

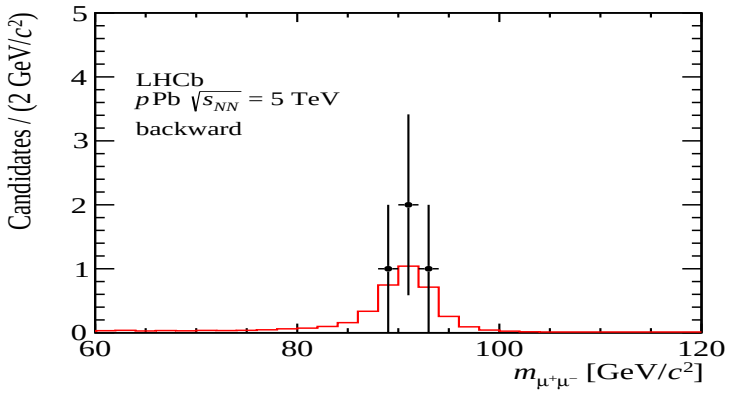
➜ *forward-backward asymmetries*

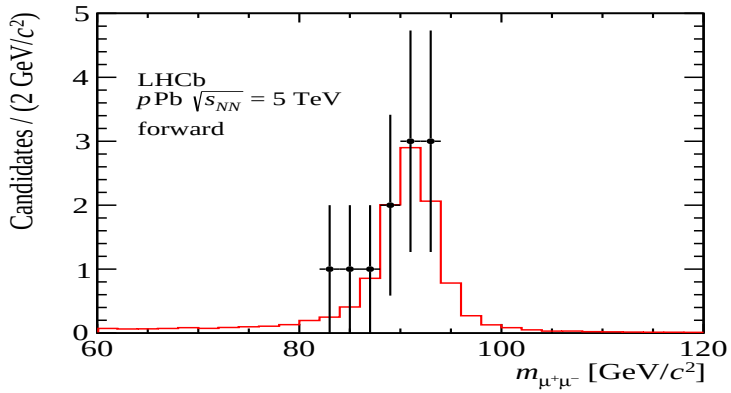


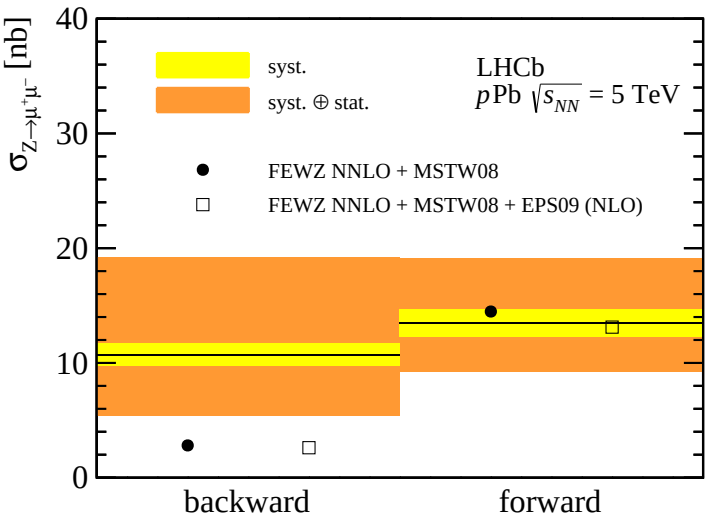
- significant deviations from unity, consistent with expectations
- theoretical uncertainties larger than experimental ones
- analysis is being updated to include full statistics
- measurement of nuclear modification factor will use 5 TeV pp data

Z production in pPb collisions

➜ *clean signals: 4 backward-candidates, 11 forward-candidates*







➜ *muon selection*

- $p_T > 20\,\text{GeV}/c$, $2.0 < \eta < 4.5$
- $60 < M(\mu^+\mu^-) < 120\,\text{GeV}/c^2$

➜ *cross-section results*

$$\sigma_{\text{fwd}} = 13.5 \pm^{5.4}_{4.0}\,(\text{stat}) \pm 1.2(\text{syst})\,\text{nb}$$

$$\sigma_{\text{bwd}} = 10.7 \pm^{8.4}_{5.1}\,(\text{stat}) \pm 1.0(\text{syst})\,\text{nb}$$

(expect ~ 250 $Z \to \mu^+\mu^-$ in 2016)

Two-particle correlations in pPb collisions

➜ *measure "per trigger-particle associated yield"*

- 2-dim correlation functions of prompt particles in $(\Delta\eta, \Delta\phi)$
- select particles in fixed p_T-range as "trigger"
- study all pairs of particles with the "trigger"
- compare associated yields per trigger
  - ➜ within an event ($S(\Delta\eta, \Delta\phi)$)
  - ➜ with random combinations ($B(\Delta\eta, \Delta\phi)$) from mixed events

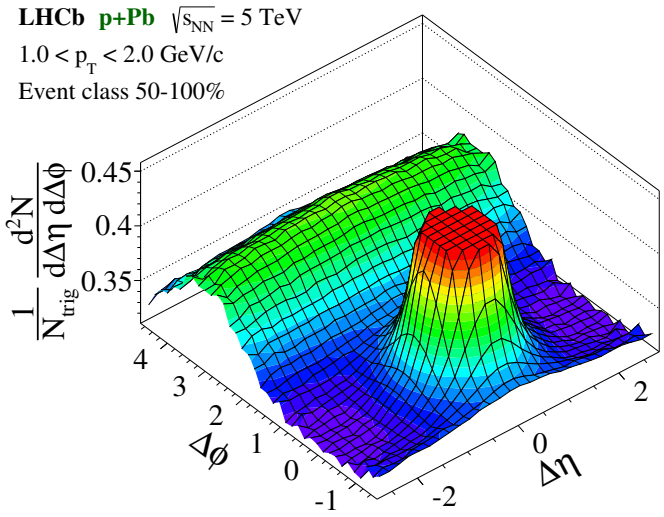
❖ definition of the experimental observable

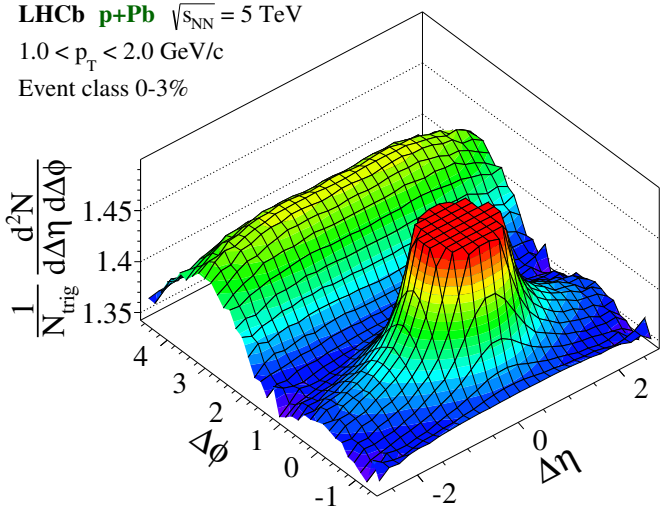
$$\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta\, d\Delta\phi} = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} \times B(0,0)$$

- ➜ $L = 0.46\,\text{nb}^{-1}$ (forward) and $L = 0.30\,\text{nb}^{-1}$ (backward)
- ➜ measurement in $1.5 < y^* < 4.4$ and $-5.4 < y^* < -2.5$
- ➜ as function of relative and absolute activity in the acceptance

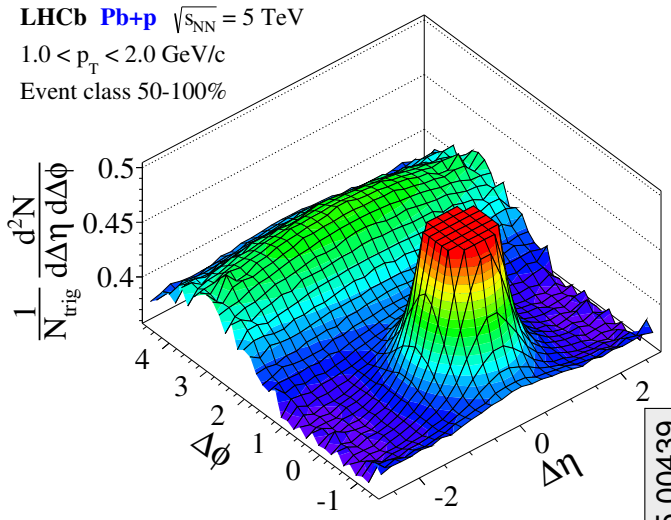
Two-particle correlations in pPb collisions

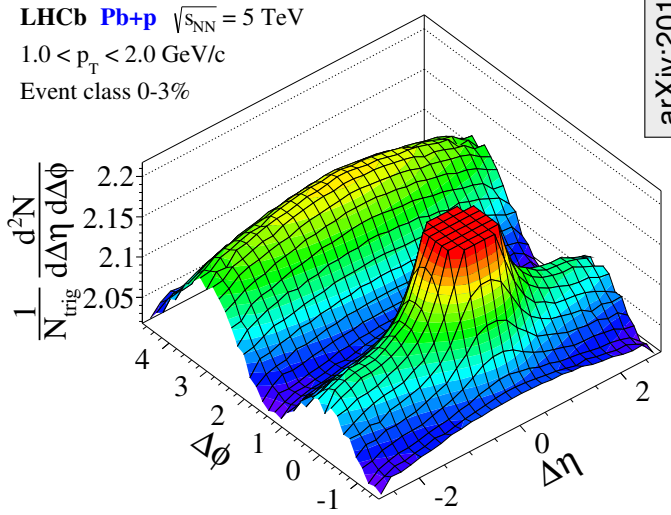
forward





backward





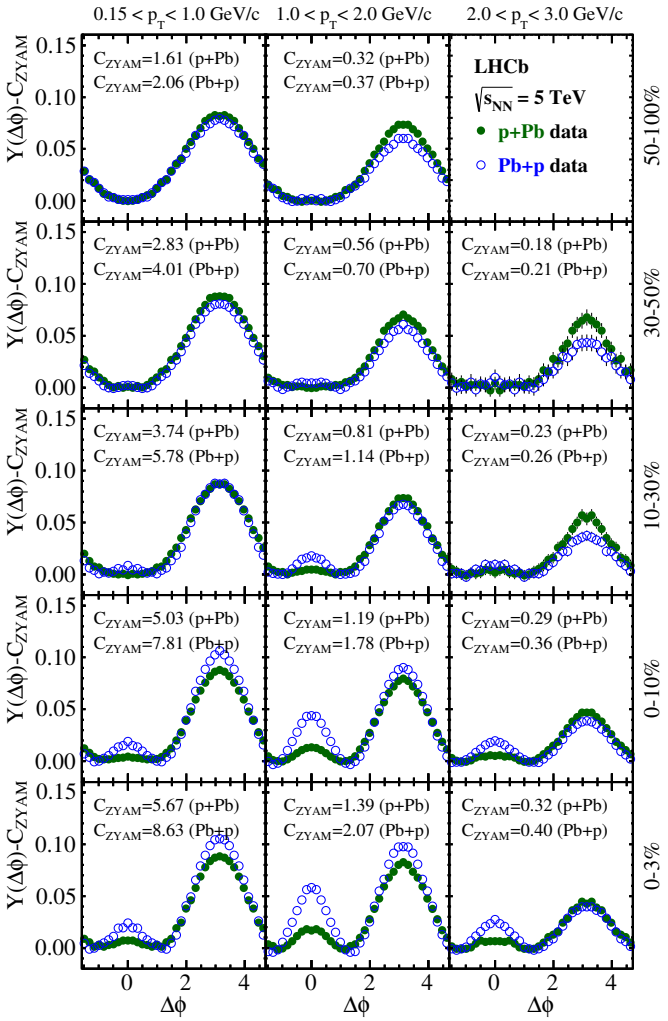
low activity

high activity

arXiv:2015.00439

Two-particle correlations in pPb collisions

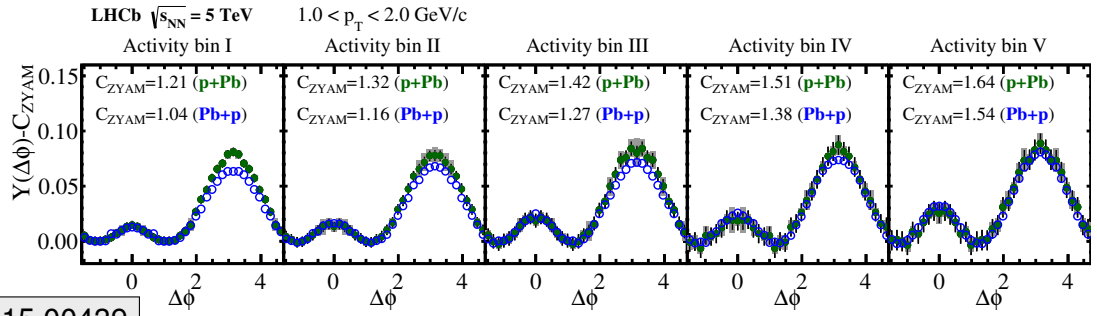
➜ *quantitative results: growing near-side ridge with activity*



- integrated yields vs $\Delta\phi$ outside jet peak

$$Y(\Delta\phi) = \frac{1}{0.9}\int_{2.0}^{2.9} d\Delta\eta \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta\, d\Delta\phi}$$

- subtract offset (Zero-Yield-At-Minimum)
  - ➜ near-side ridge largest at $1 < p_T < 2\,\text{GeV}/c$
  - ➜ equal relative activity: stronger correlation in Pb-hemisphere
  - ➜ equal absolute activity: similar correlation in both hemispheres

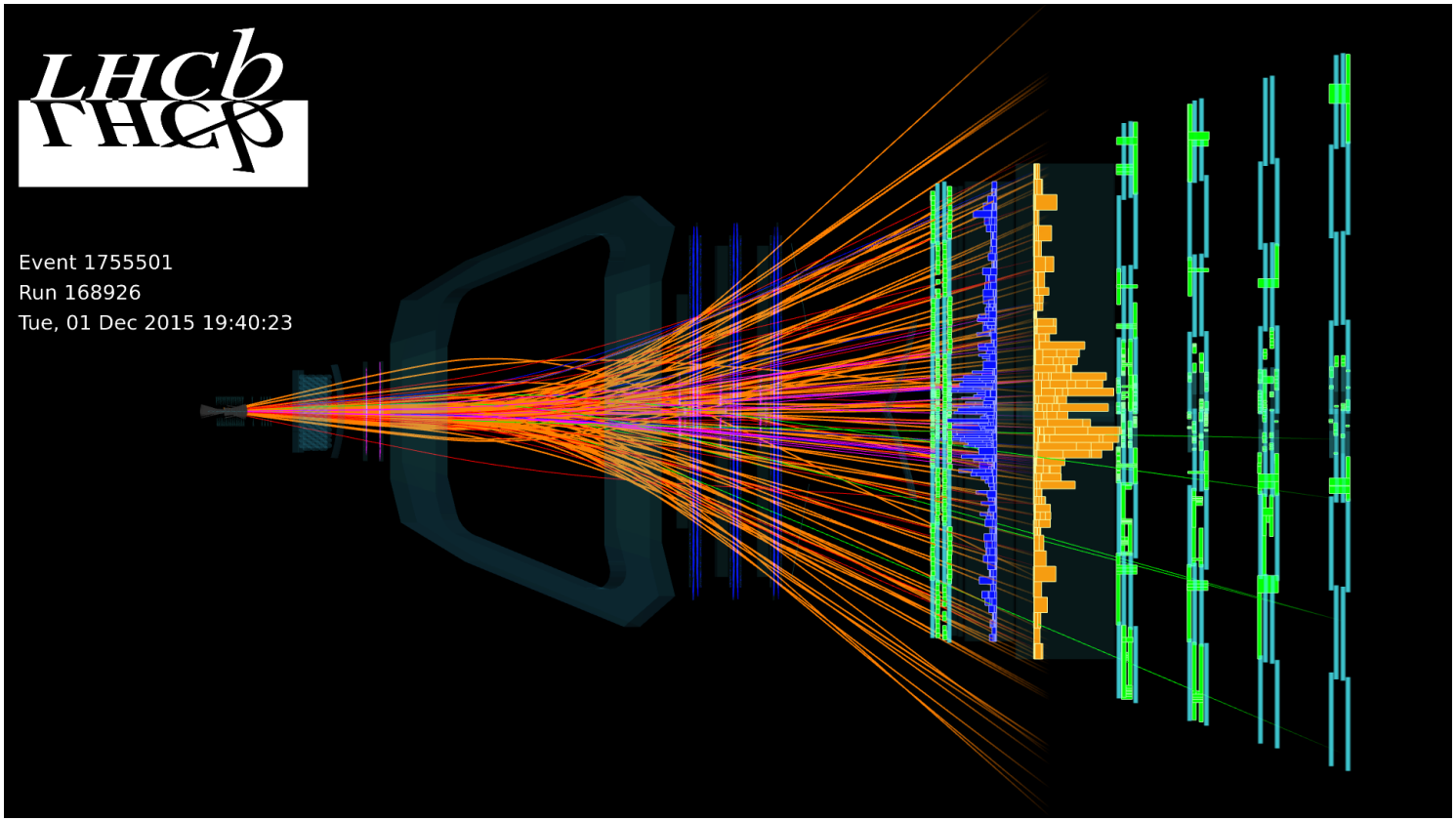


arXiv:2015.00439

4. Lead-Lead Collisions

➜ *first participation in Pb-Pb running by LHCb in December 2015*

- 24 colliding bunches, $L = 3 - 5\,\mu\text{b}^{-1}$,
- minimum bias trigger - i.e. all inelastic interactions recorded

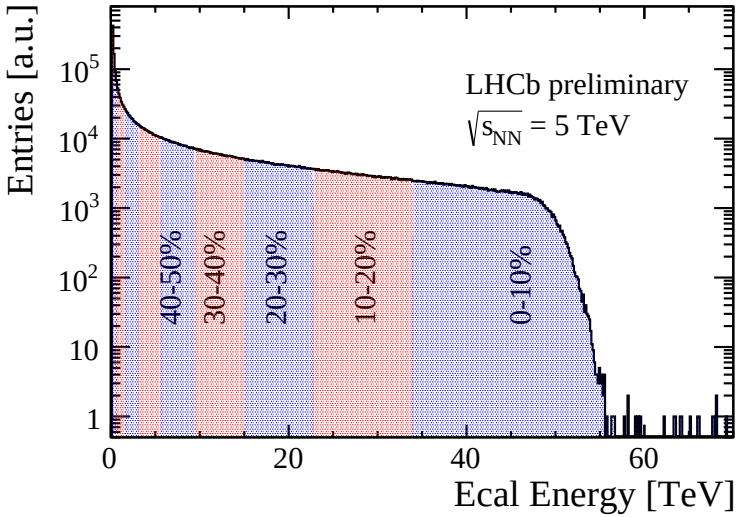


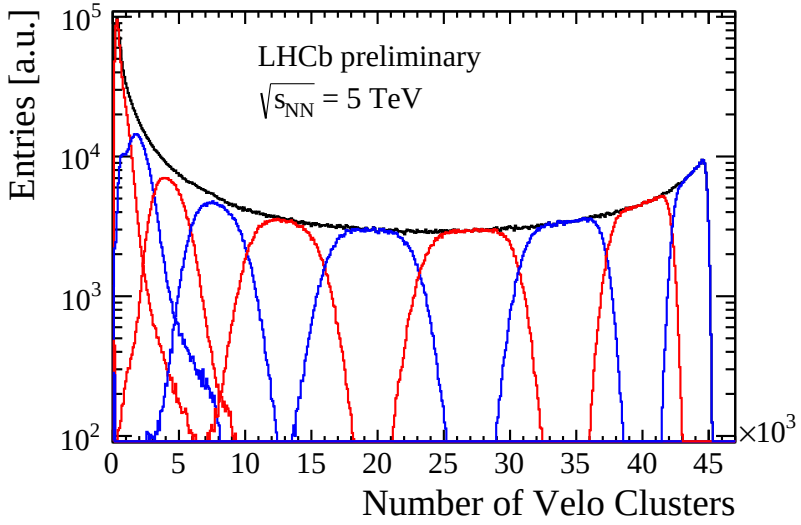
PbPb collision with a J/ψ candidate in 1130 reconstructed tracks

Centrality determination

➜ *ongoing work . . .*

- experimental observable: ECAL or HCAL energy sum
  - ➜ no saturation even for most central collisions
  - ➜ minimal correlation with particle production measurements





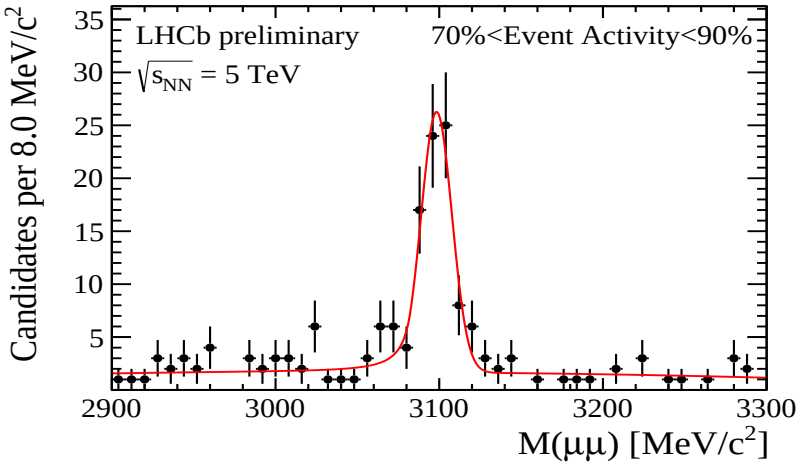
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

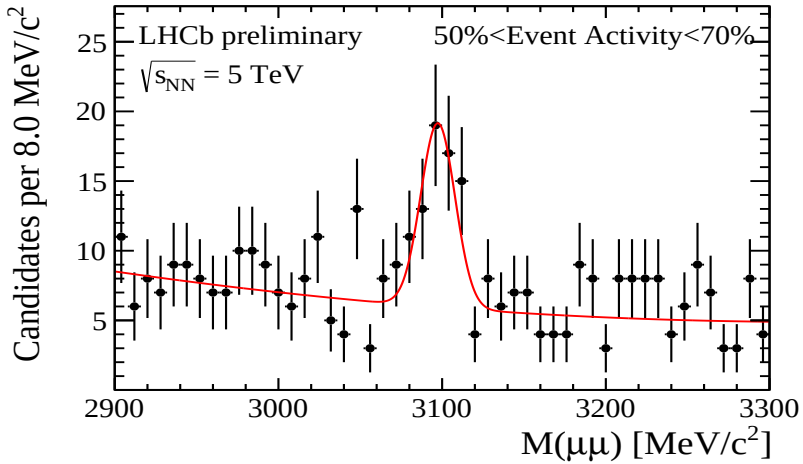
- first step: event classification in terms of ECAL activity
  - ➜ tracking may be possible up to ∼15k VELO hits
  - ➜ corresponding activity range: 100% - 50%

➜ first look at the data

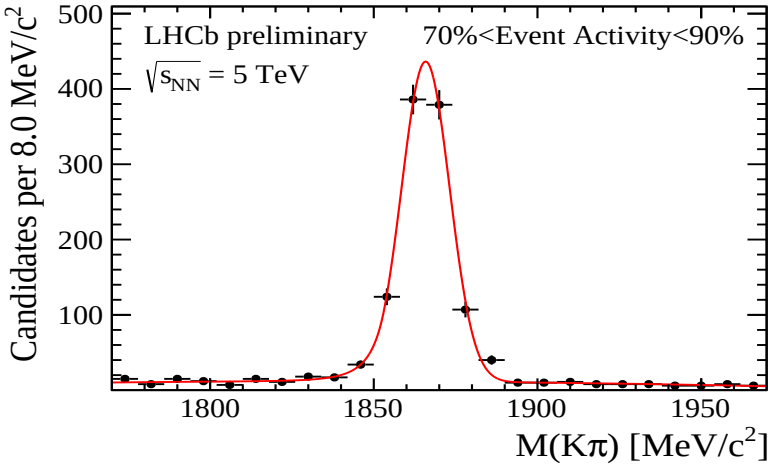
J/ψ and open charm in PbPb collisions

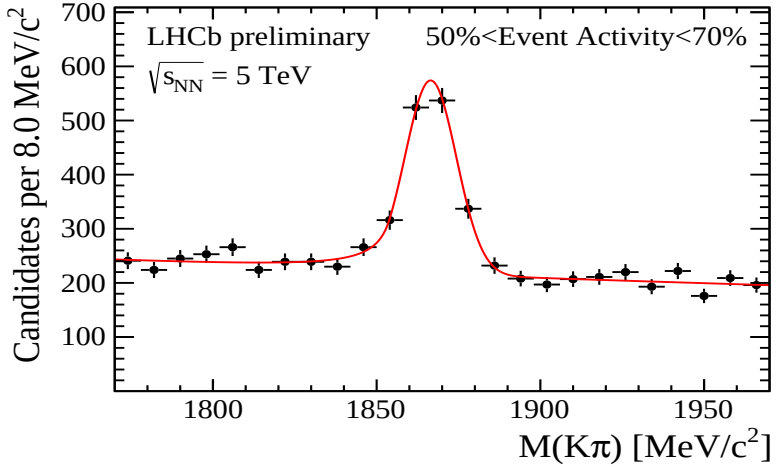
➜ $J/\psi \to \mu^+\mu^-$ decays





➜ $D^0 \to K^-\pi^+$ + CC decays

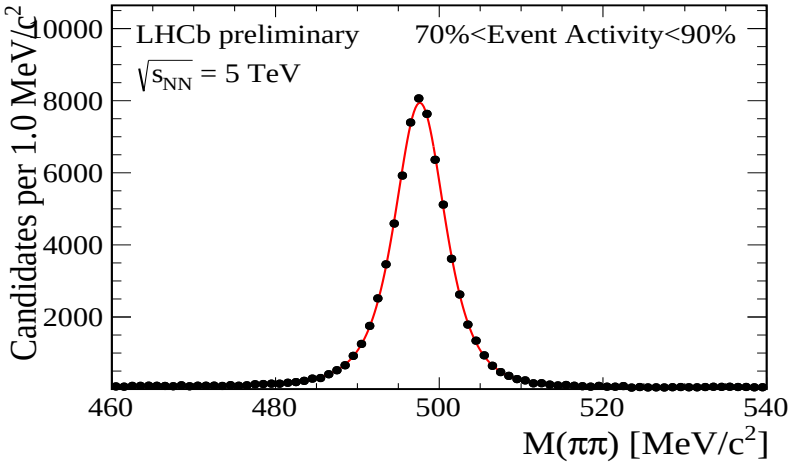


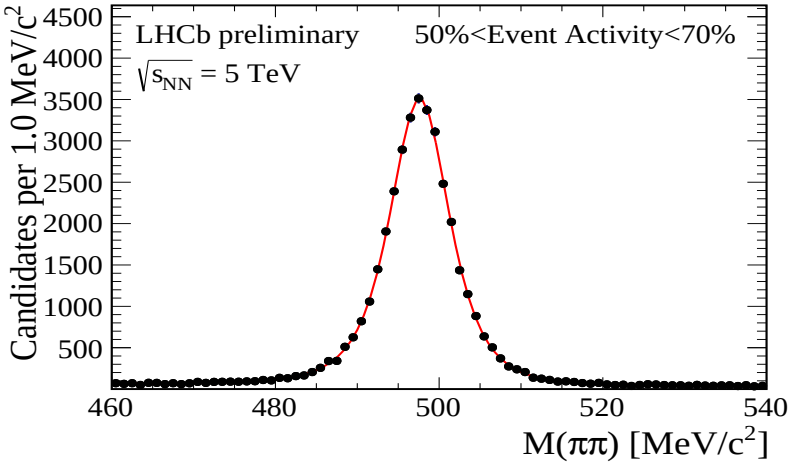


https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

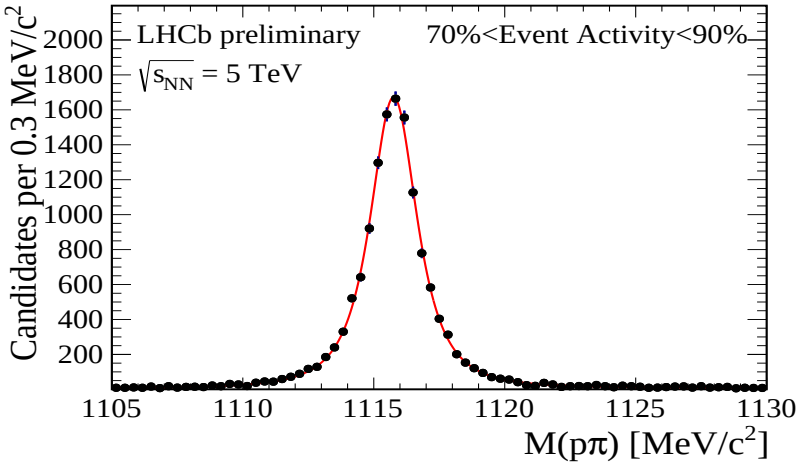
Strangeness production in PbPb collisions

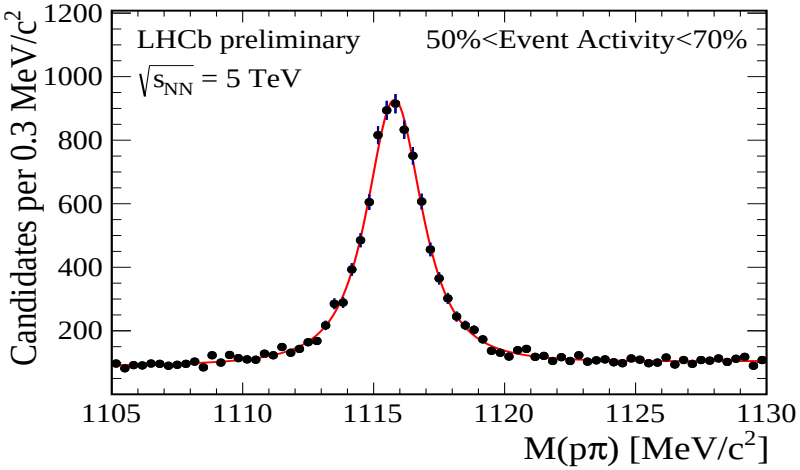
➜ $K^0_S \to \pi^+\pi^-$ decays





➜ $\Lambda \to p\pi^-$ + CC decays



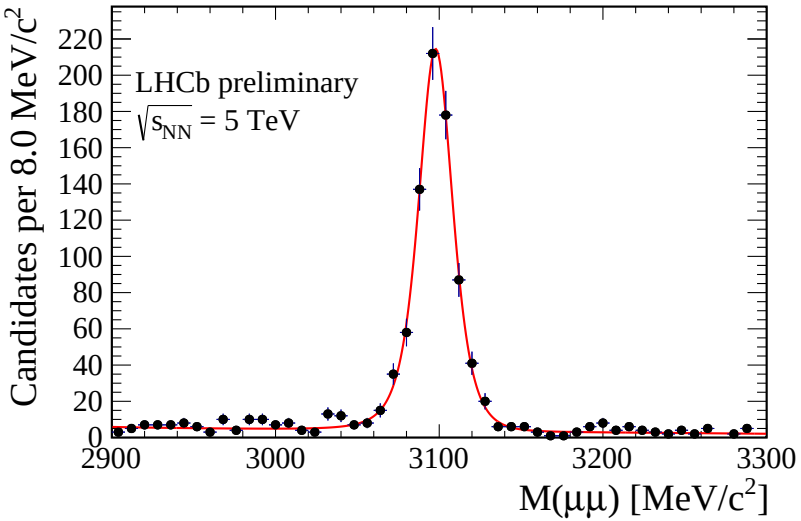


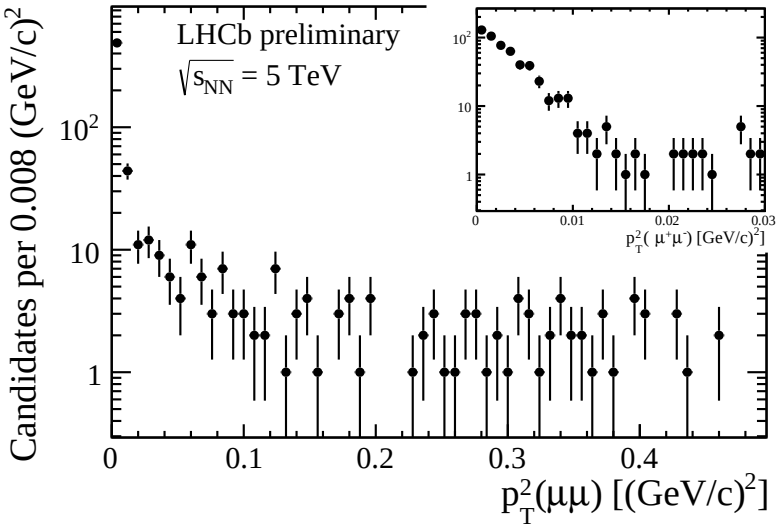
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

J/ψ production in ultra-peripheral collisions

➜ *QED with extreme field strengths and large cross-sections*

- events containing only two tracks in the spectrometer
- coherent photoproduction of J/ψ mesons



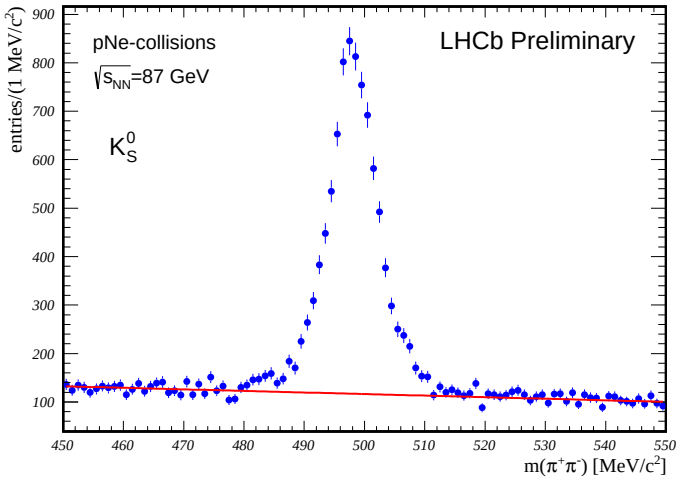


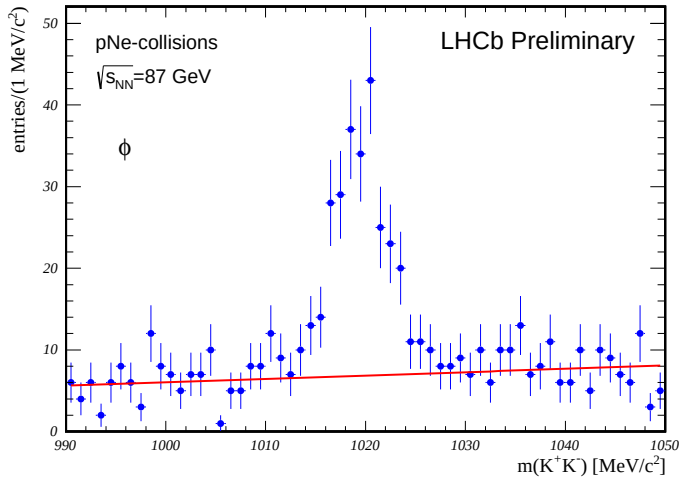
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

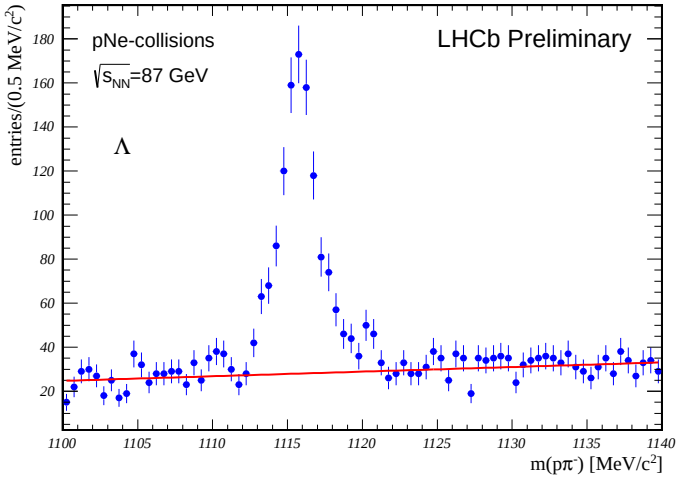
➜ very clean signature

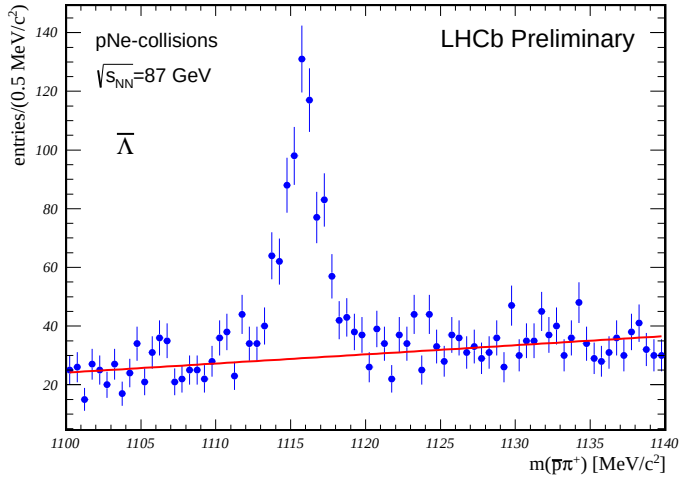
➜ very soft transverse momentum spectrum

➜ *strangeness production in pNe collisions (2012) at* $\sqrt{s_{NN}} = 87$ *GeV*









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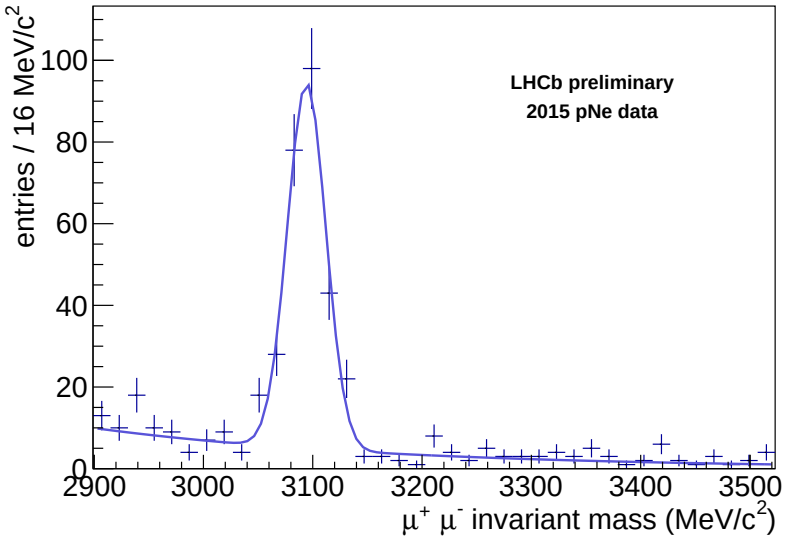
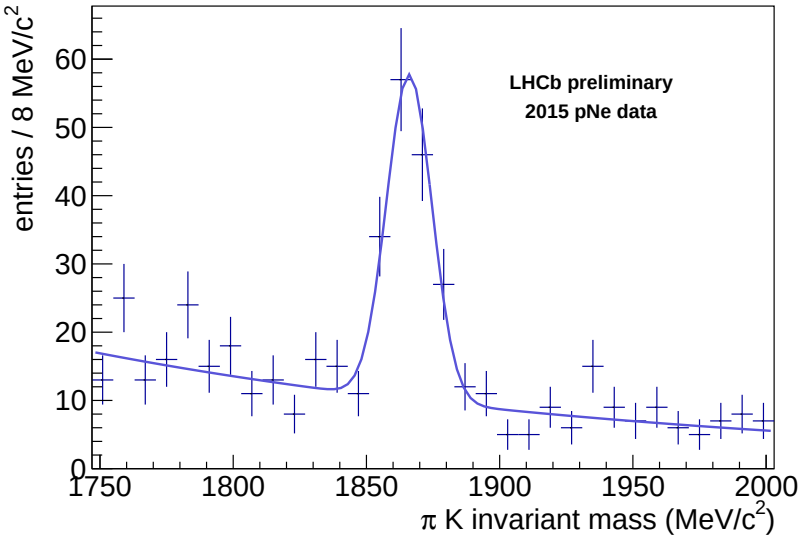
J/ψ and open charm production

➜ *charm production in pNe collisions (2015) at* $\sqrt{s_{NN}} = 110$ *GeV*





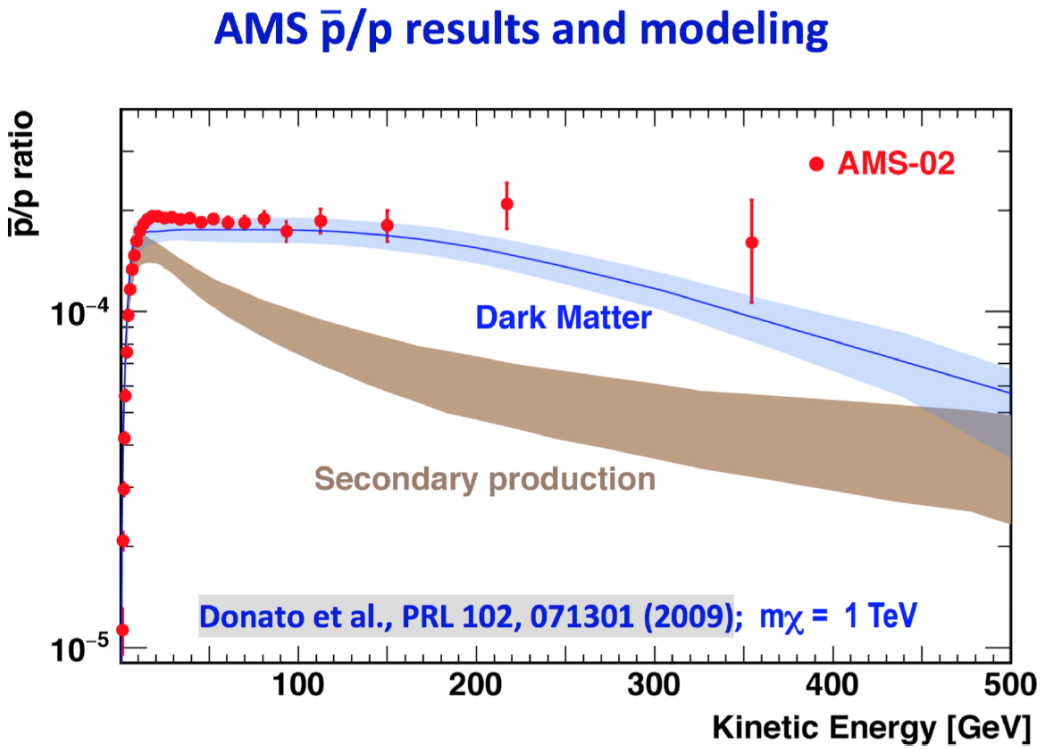
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

- clean signals
- next: luminosity determination based on elastic pe^- scattering
- goal: cross-section measurements for He, Ne and Ar targets

Links to other communities

➜ *cosmic ray physics and cosmology*

- understanding of extensive air showers ➜ MC tuning
- understanding the AMS antiproton/proton ratio



❖ use fixed-target measurements to clarify: QCD or Dark Matter annihilation

6. Summary and Outlook

➜ *LHCb is much more than a pp heavy flavour experiment . . .*

- participation in pp, pPb and since 2015 also PbPb running
- fixed-target physics program with (so far) {p,Pb} on {He,Ne,Ar}
- analyses of pPb collisions
  - ➜ probe nuclear effects with J/ψ, $\psi(2S)$ (prompt & from b), Υ, D^0 and Z
  - ➜ 2-particle near-side ridge correlations vs relative and absolute activity
- analysis of PbPb and fixed-target data starting
  - ➜ PbPb physics results expected up to centralities around 50%
  - ➜ promising signals for large-x fixed-target physics
- significantly enlarged physics reach with 2016 pPb data
  - ➜ 10x more statistics to address open issues
  - ➜ Drell-Yan production to disentangle energy loss and shadowing
  - ➜ associated J/ψ-D^0 production

❖ stay tuned to the LHCb ion physics and fixed-target program!