Probing nucleon properties with Z boson and $Z + J/\psi$ production at LHCb

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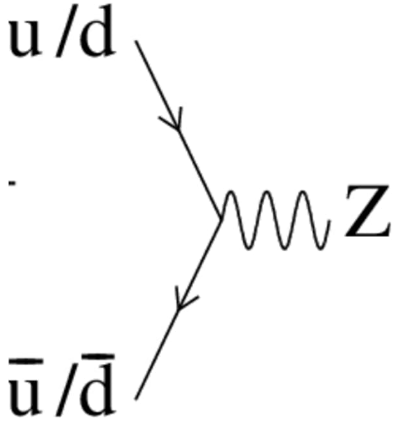
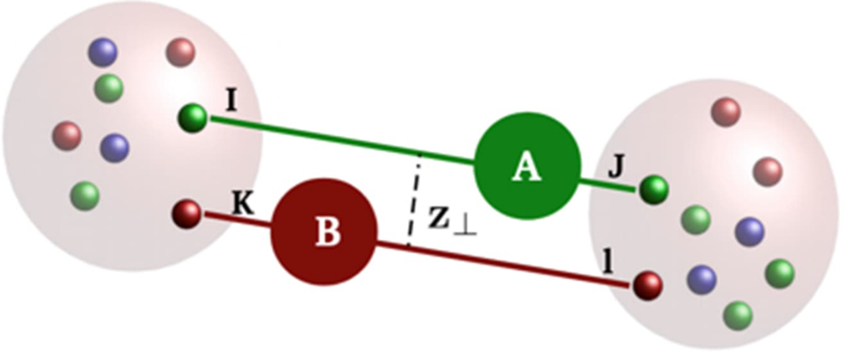
Outline

- Research motivation
- The LHCb Detector
- Part I : Z boson production in pPb collisions
- Part II : Associated $Z + J/\psi$ production in pp collisions
- Summary and outlook

Research motivation

- Understanding the internal structure of nucleons and nuclei is a fundamental goal in high-energy physics.
- Z bosons, produced via electroweak interactions, provide clean access to the parton distribution functions (PDFs) due to their minimal interaction with the strong force.
- In pPb collisions: Z production probes cold nuclear matter effects and nuclear modifications of PDFs (nPDFs).
- In pp collisions:
  - Associated $Z + J/\psi$ production gives access to multi-parton interactions, especially double parton scattering (DPS).
- The LHCb detector, with its unique forward acceptance ($2 < \eta < 5$), provides studies in previously unexplored kinematic regions.



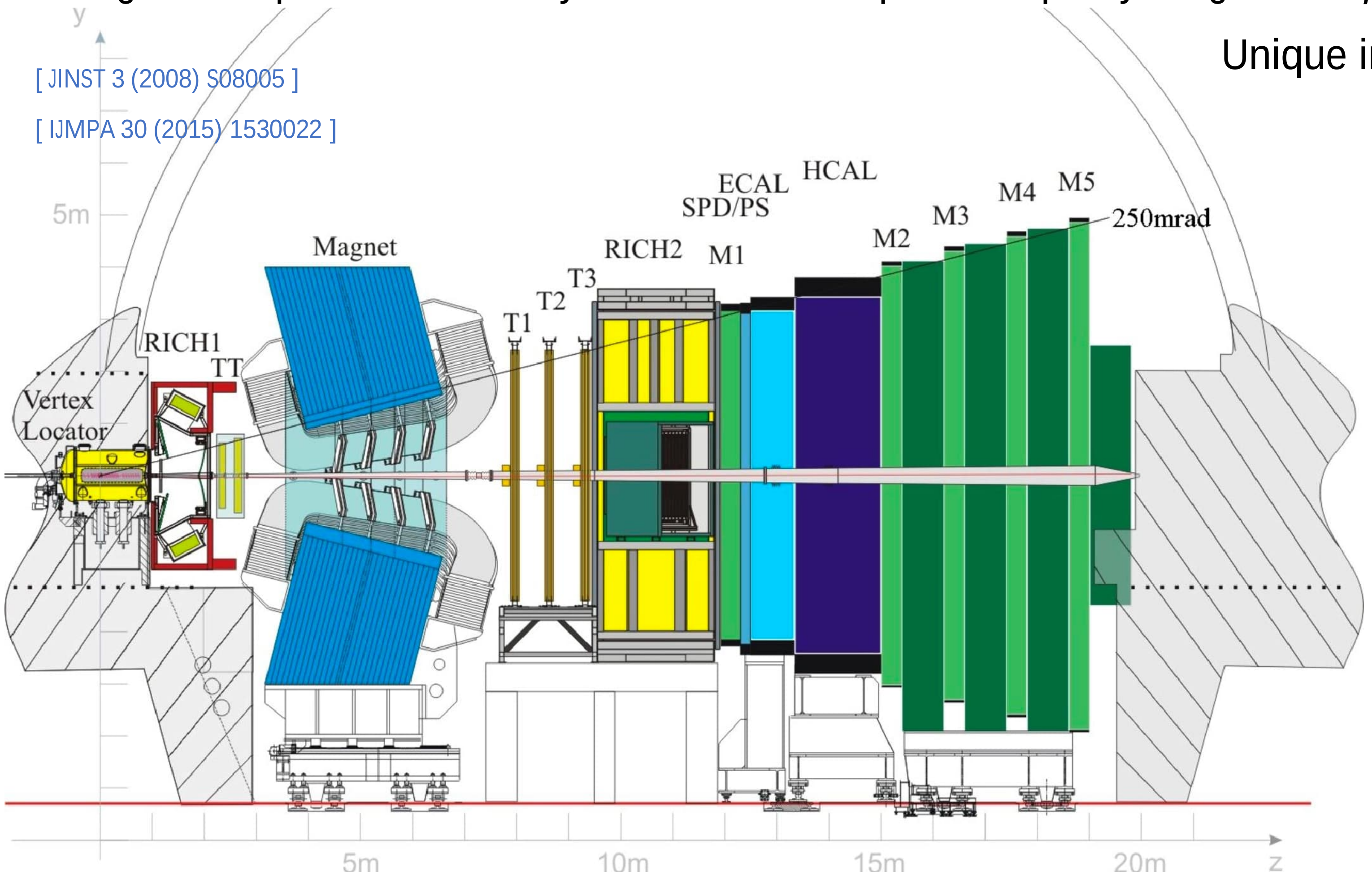


The LHCb detector

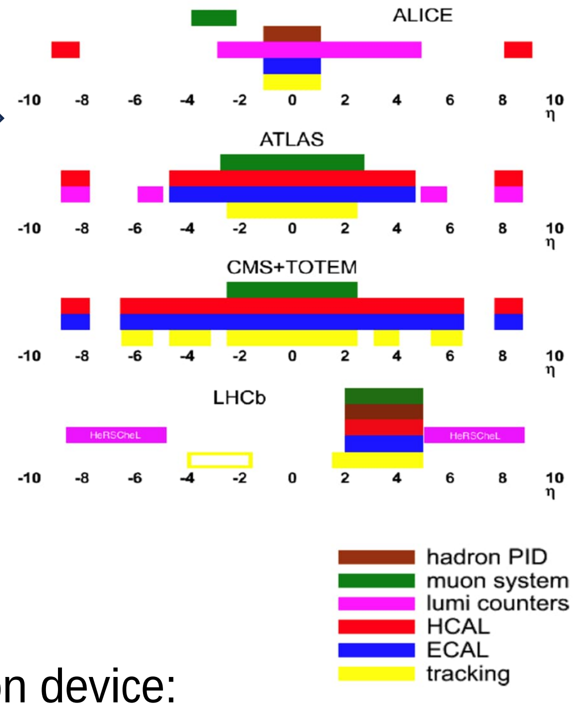
- Single arm spectrometer fully instrumented in pseudorapidity range: $2 < \eta < 5$

[JINST 3 (2008) S08005]

[IJMPA 30 (2015) 1530022]



Unique in this range



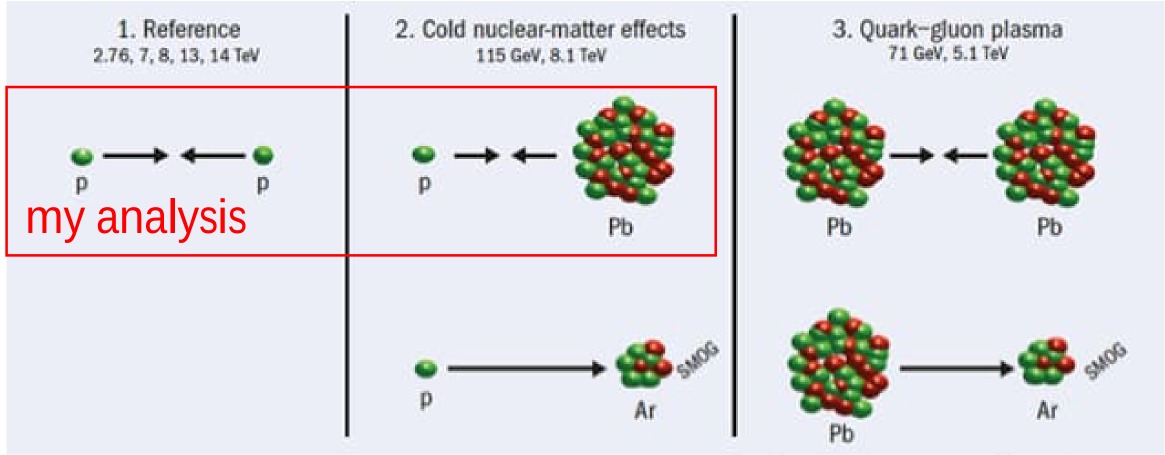
- High precision device:
  - Vertex, Impact parameter and decay time resolution
  - Momentum resolution
  - Particle identification

LHCb experimental set-up

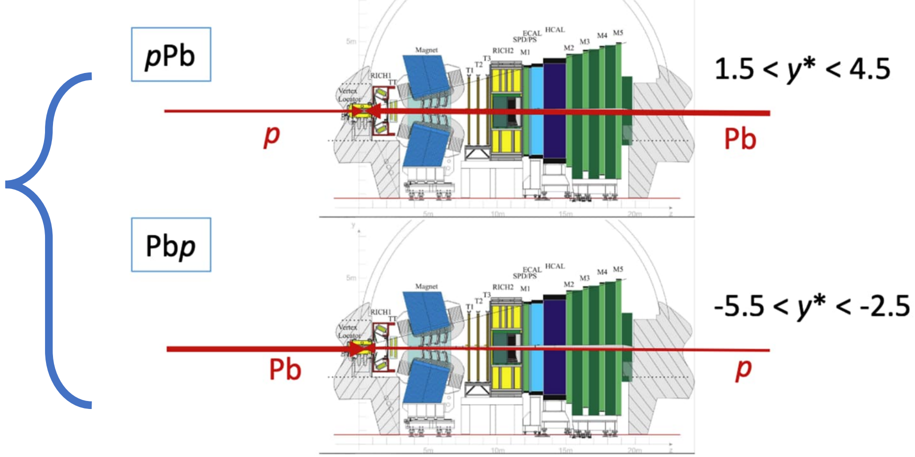
- LHCb provides a unique opportunity to study nuclear structure in the forward region using different beam configurations.
- Experimental approach:

Collider mode

Fixed-target mode



- In pPb collisions, the rapidity forward/backward region is covered
  - Due to the asymmetric beam energies per nucleon, rapidity in center of mass frame, y^*, required a rapidity shift of about 0.47 w.r.t. the lab frame coverage.

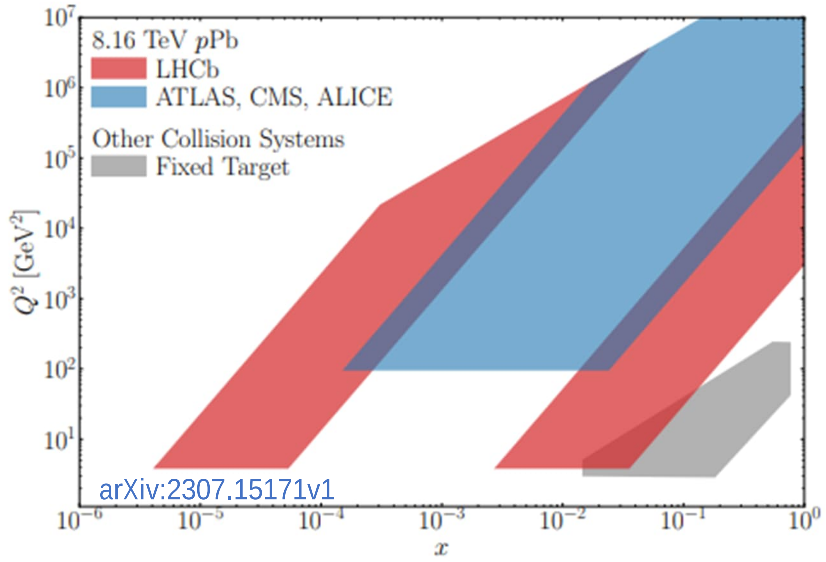


Z production in pPb collisions at 8.16 TeV

Physics motivation

- Z bosons are produced in the initial stage of pPb collisions and do not interact via the strong force, making them clean probes of the nuclear initial state.
- Parton distribution functions (PDFs) inside nuclei differ from those in free protons. These modifications are known as nuclear PDFs (nPDFs).
- The nuclear modification factor: $R_i^A(x,Q^2) = f_i^{p/A}(x,Q^2)/f_i^p(x,Q^2)$ quantifies deviations due to cold nuclear matter effects.
- LHCb's forward and backward configurations provide access to both small-x and large-x regions, complementing central detectors.
- These results help constrain nPDFs at $Q^2 = 91^2\mathrm{GeV}^2$

- $\boldsymbol{Q^2}$: the squared momentum exchanged between interacting partons.
- $\boldsymbol{x}$: momentum fraction of the parton with respect to nucleus.

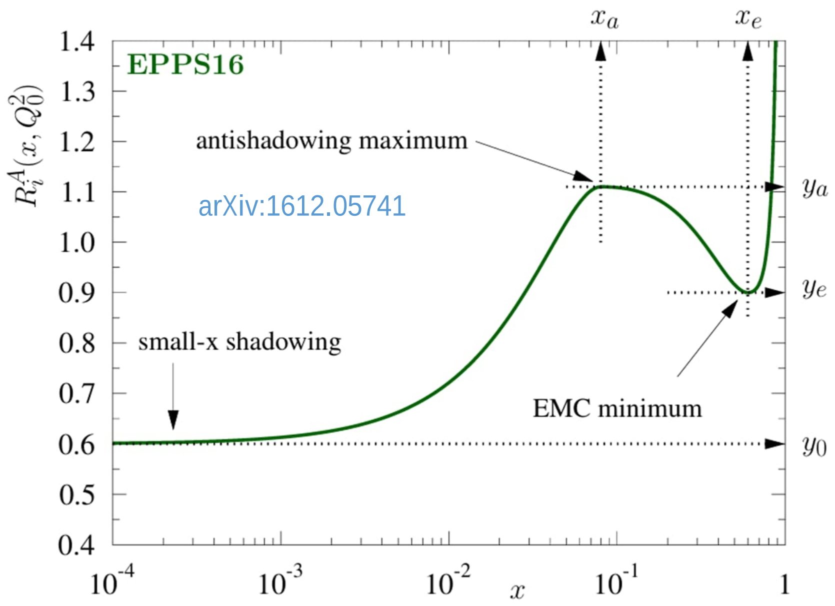


Cold nuclear matter effects

- Cold nuclear matter (CNM) effects: modifications to particle production arising from nuclear environment, distinct from quark-gluon plasma (QGP) effects.
- Nuclear modification factor (R_{pA}):
  - Quantifies CNM effects by comparing proton–nucleus (pA) to proton–proton (pp) collisions:

$$R_{pA} = \frac{\sigma_{pA}}{A \cdot \sigma_{pp}}$$

- Three characteristic regions:
  - Nuclear shadowing ($R_{pA} < 1$):
    Reduced parton densities at small x,
    suppression at forward rapidities.
  - No modification ($R_{pA} \approx 1$):
    Nuclear environment has negligible impact on particle yields.
  - Enhancement ($R_{pA} > 1$):
    Anti-shadowing enhance particle yields
    at intermediate to large x.



A is mass number of nuclei
EMC: European Muon Collaboration effect

Analysis strategy

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- Cross-section:

$$\sigma^{\text{fid}}_{Z\to\mu^+\mu^-,\ p\text{Pb}/\text{Pb}p} = \frac{N_{\text{cand}}\cdot\rho\cdot f_{\text{FSR}}}{\mathcal{L}\cdot\epsilon^{\text{reco\&sele}}\cdot\epsilon^{\text{muon-id}}\cdot\epsilon^{\text{trig}}}$$

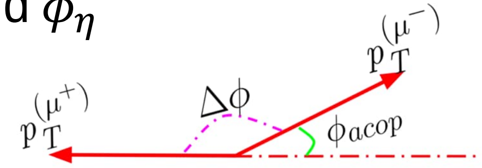
  - N_{cand} is the number of selected Z candidates
  - $\mathcal{L}$ is the integrated luminosity
  - ρ is the purity (the fraction of actual signal events)
  - f_{FSR} is final state radiation correction
  - $\epsilon^{\text{reco\&sele}}$ is the reconstruction and selection efficiency
  - $\epsilon^{\text{muon-id}}$ is the muon-identification efficiency for selected candidates
  - ϵ^{trig} is the trigger efficiency

- Fiducial volume:

$$p_{\text{T}}(\mu^{\pm}) > 20\text{GeV}/c,$$
$$2.0 < \eta_{\mu^{\pm}}(\text{lab}) < 4.5,$$
$$60 < m_{\mu^+\mu^-} < 120\text{GeV}/c^2$$

- Differential cross-section results are estimated separately in bins of the y^*_{Z}, p^{Z}_{T} and ϕ^*_{η}

$$\phi^*_{\eta} = \frac{\tan(\phi_{acop}/2)}{\cosh(\Delta\eta/2)}$$



- ϕ^*_{η} is defined as $\phi_{\text{acop}} \equiv \pi - |\Delta\phi|$, where the acoplanarity angle
- $\Delta\phi$ the difference in azimuthal angle of the two leptons
- $\Delta\eta$ the difference in pseudo-rapidity of the two leptons

Analysis strategy

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- Forward-Backward ratio at the common $2.5 < |y_Z^*| < 4.0$

$$R_{\mathrm{FB}} = \frac{\sigma(p\mathrm{Pb})}{\sigma(\mathrm{Pb}p)}$$

- Nuclear modification factor

$$R_{p\mathrm{Pb}}^{\mathrm{fw.}} = \frac{1}{208} \times \frac{\sigma(p\mathrm{Pb})}{\sigma(pp)}$$

$$R_{p\mathrm{Pb}}^{\mathrm{bw.}} = \frac{1}{208} \times \frac{\sigma(\mathrm{Pb}p)}{\sigma(pp)}$$

  - where 208 is the mass number of the Pb nucleus
  - The resulting $\sigma_{Z\to\mu^+\mu^-,\,pp}$ given by LHCb public results [ARXIV:1511.08039]

- Results are estimated separately in bins of the y_Z^*, p_{T}^Z and ϕ_η^*.

- The pPb (forward) and Pbp (backward) data sets are collected separately, the integrated luminosity is different for them.

$$\mathcal{L}_{\mathrm{pPb}} = 12.18 \pm 0.32 \mathrm{nb}^{-1}$$
$$\mathcal{L}_{\mathrm{Pbp}} = 18.58 \pm 0.46 \mathrm{nb}^{-1}$$

- Yields of the $Z \to \mu^+\mu^-$ candidates after offline selection are $N(p\mathrm{Pb}) = 268$ and $N(\mathrm{Pb}p) = 167$

Table: Selection criteria for Z candidates in pPb/Pbp collisions.

	Condition
Turbo line:	Hlt2DiMuonBTurbo
Fiducial region:	$60 < M(\mu^+\mu^-) < 120\,\mathrm{GeV}/c^2$
	$2 < \eta < 4.5$, $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$,
Offline selection:	Both muon reconstracted as LongTrack
	$\Delta p/p < 0.1$,
	track χ^2 probability > 0.01
Muon ID:	isMuon (muonID)
L0 Trigger:	at least one $\mu^\pm$ pass L0Muon_TOS,
HLT1 trigger:	at least one $\mu^\pm$ pass Hlt1SingleMuonHighPT_TOS.

Systematic uncertainty

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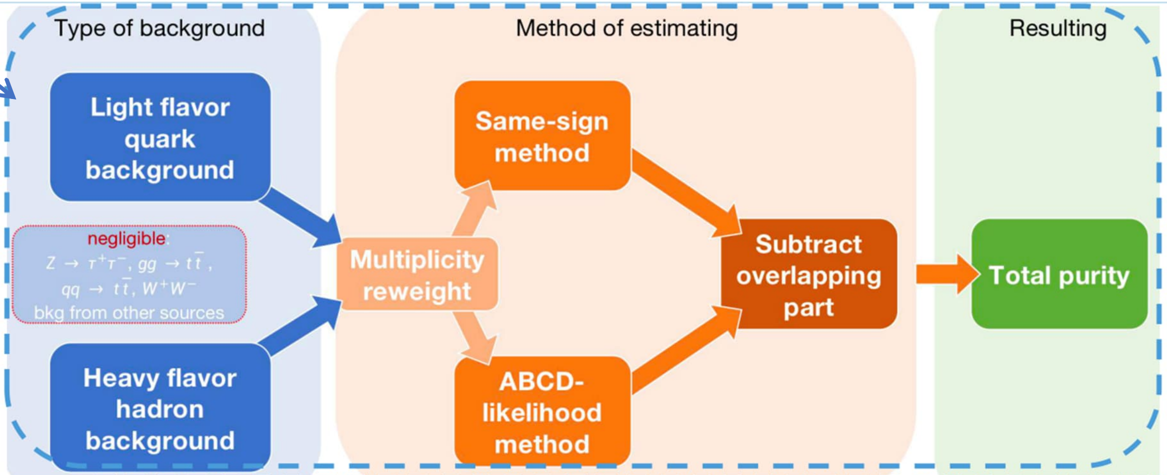
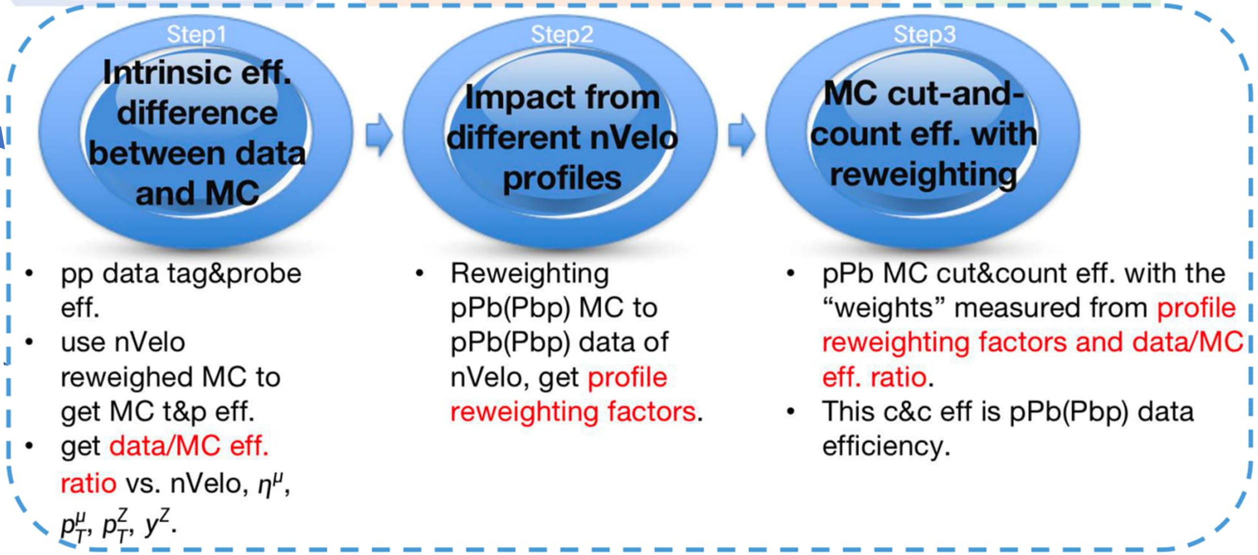
- Major systematic uncertainties
  - Uncertainties from background modeling (purity)
  - Uncertainties from efficiency: reco&select (tracking, largest), muon-id, and trigger efficiencies
  - Uncertainties from fsr corrections
  - Luminosity: directly propagated
- Rapidity coverage is different for xsec, R_{FB} and R_{pA} measurements, uncertainties are shown in table.

Quantity	Forward	Backward
$N_{\rm cand}$ (for $\sigma^{\rm fid}$)	268	166
$N_{\rm cand}$ (for $R_{\rm FB}$)	160	166
$N_{\rm cand}$ (for $R_{p\rm Pb}$)	241	166
ρ [%]	99.69 ± 0.07	99.75 ± 0.08
$\epsilon^{\rm reco\&sel}$ [%]	87.2 ± 2.9	72.0 ± 2.5
$\epsilon^{\rm muon\text{-}id}$ [%]	97.3 ± 0.3	97.3 ± 0.3
$\epsilon^{\rm trig}$ [%]	98.3 ± 0.6	97.1 ± 0.6
$\mathcal{L}$ [nb^{-1}]	12.2 ± 0.3	18.6 ± 0.5
$f_{\rm FSR}$	1.02 ± 0.01	1.02 ± 0.01
$k_{\rm FB}$ (for $R_{\rm FB}$)	0.65 ± 0.02	–
$k_{p\rm Pb}$ (for $R_{p\rm Pb}$)	0.706 ± 0.002	1.518 ± 0.003





Fiducial cross-section results

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- Total fiducial cross-section

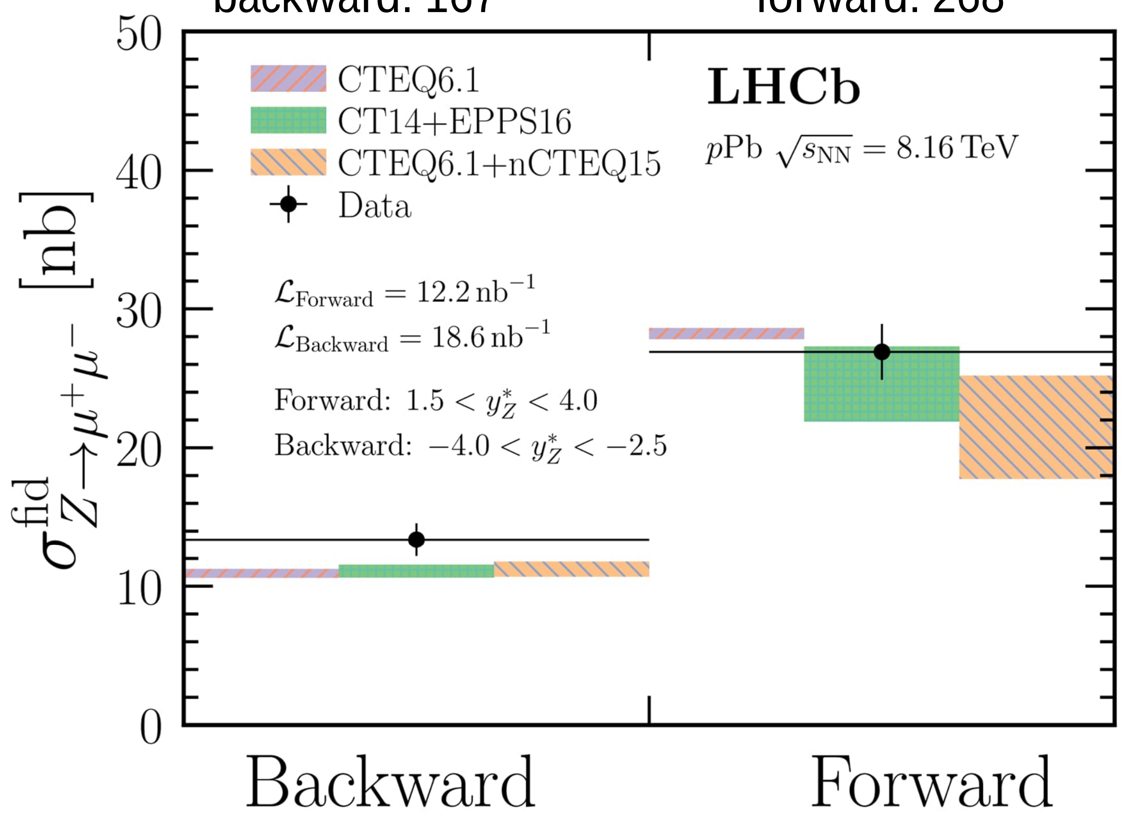
$$\sigma^{\text{fid}}_{Z\to\mu^+\mu^-,\text{pPb}} = 26.9 \pm 1.6(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.7(\text{lumi.}) \quad \text{nb}$$

$$\sigma^{\text{fid}}_{Z\to\mu^+\mu^-,\text{Pbp}} = 13.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.3(\text{lumi.}) \quad \text{nb}$$

- Measured results compatible with the theoretical calculations within current uncertainties:
  - CTEQ61(PDF) for both p and Pb
  - CT14(PDF) for p and EPPS16(nPDF) for Pb
  - CTEQ61 for p and nCTEQ15(nPDF) for Pb
- Forward result (at small Bjorken-x) shows strong constraining power on the nPDF.

Events for backward: 167

Events for forward: 268



Forward-backward ratio R_{FB}

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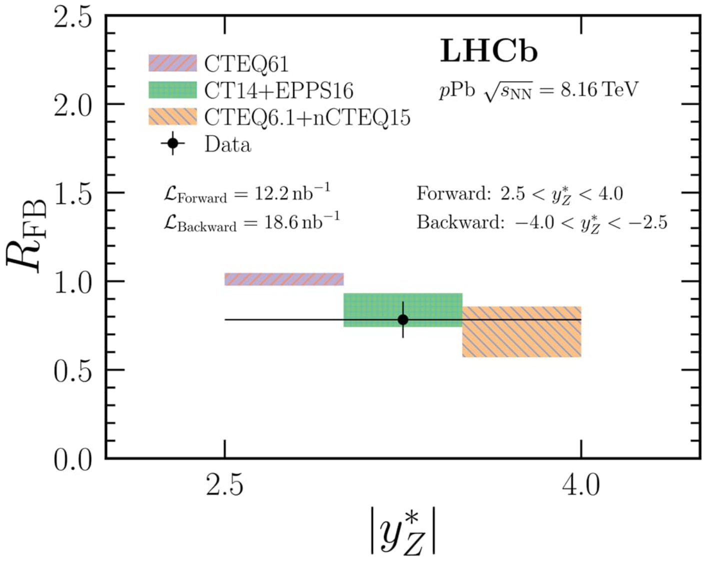
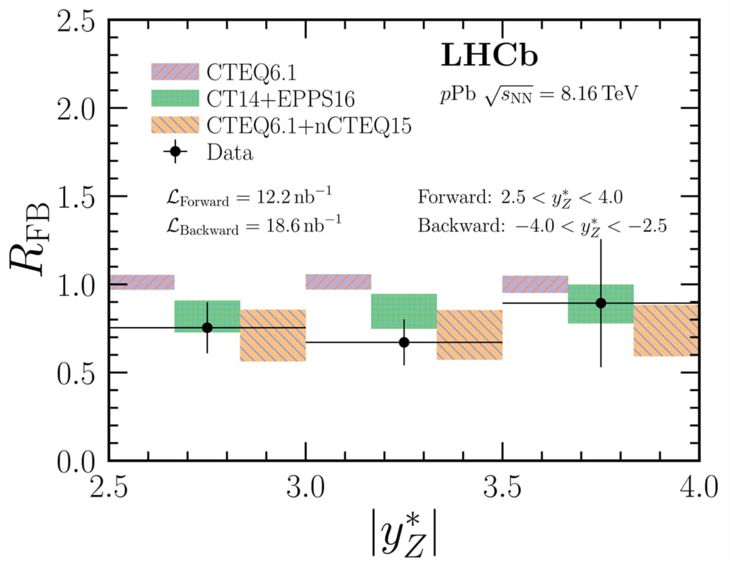
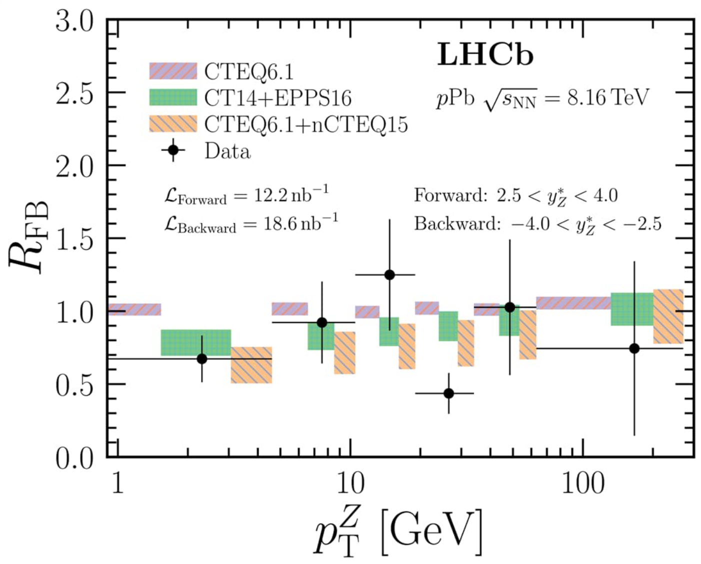
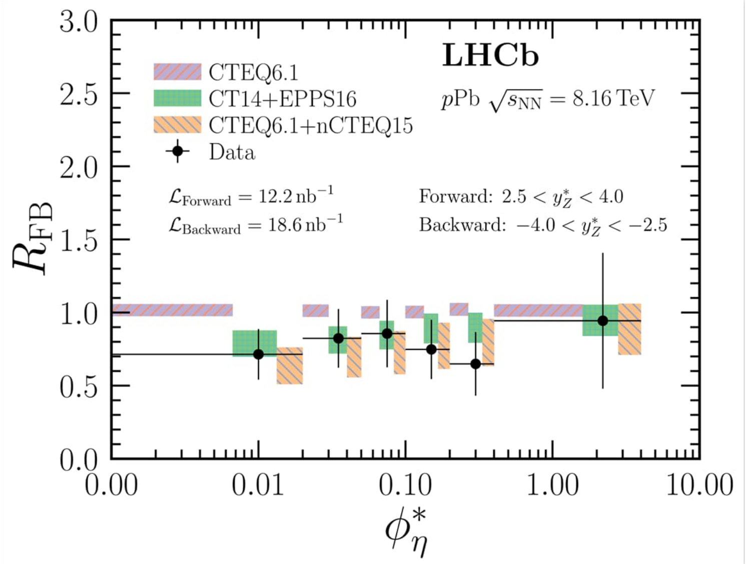
- Forward and backward ratio is sensitive to nuclear effects in the Z production, probe the nuclear matter effects
- The measurement shows a general suppression below one, is consistent with theoretical predictions, smaller uncertainty provide constraining power on the nPDFs.
- The measurements show a good agreement with the theoretical predictions









Nuclear modification $R_{p\mathrm{Pb}}$: overall

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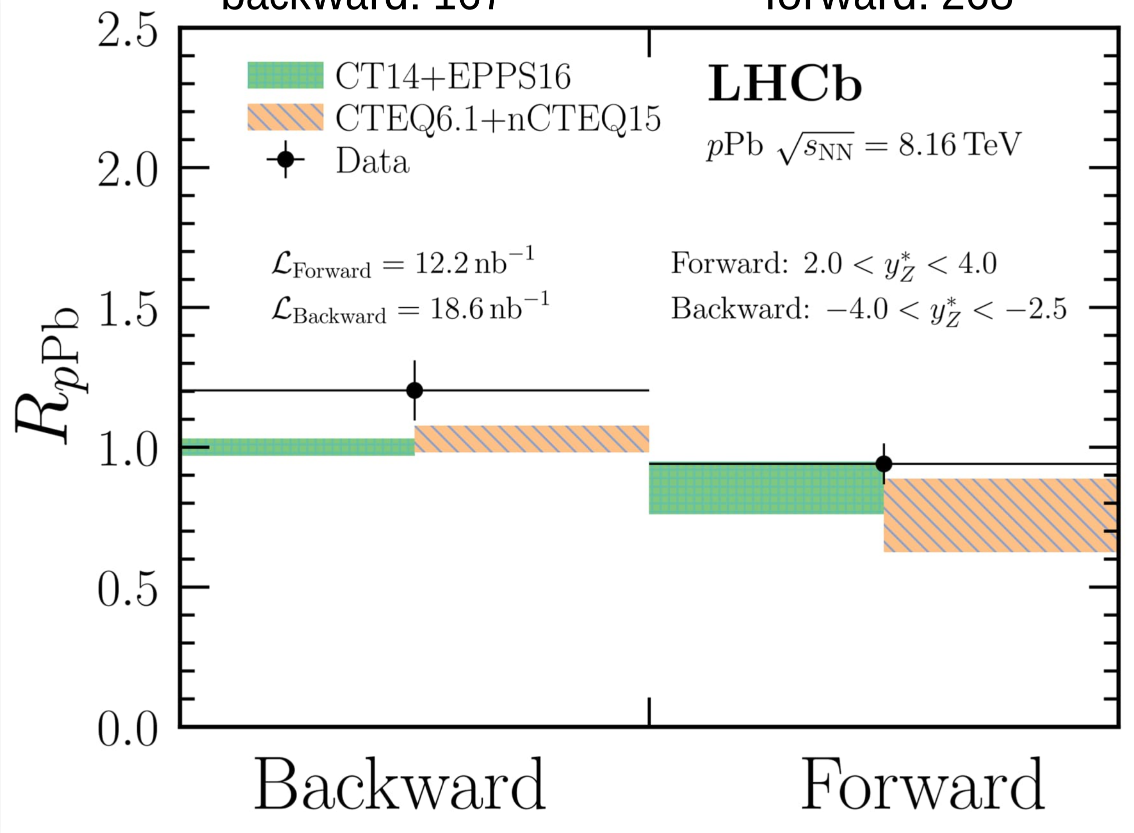
- Nuclear modification factor $R_{p\mathrm{Pb}}$ directly probes the cold nuclear matter effects.
- The measured results:

$$\mathrm{R}^{\mathrm{fw.}}_{pPb} = 0.94 \pm 0.07$$
$$\mathrm{R}^{\mathrm{bw.}}_{pPb} = 1.21 \pm 0.11$$

- The measurements are compatible with theoretical predictions; Results in forward region(small Bjorken-x, nuclear shadowing suppression part) give higher precision, constrain on the current nPDF sets.

Events for backward: 167

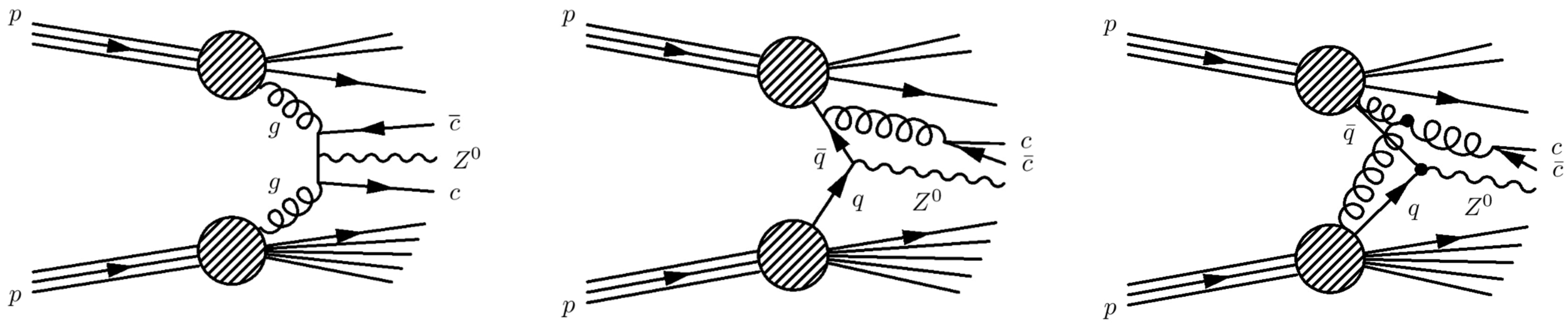
Events for forward: 268



$Z + J/\psi$ production in pp collisions at 13 TeV

Physics motivation

- Two production mechanisms: single parton scattering (SPS) and double parton scattering (DPS).
- DPS: it's a situation where two pairs of quarks or gluons from different protons interact simultaneously.



Double-parton scattering (DPS)

- The cross section of a Single Parton Scattering (SPS) process

$$\sigma = \int dx_1 \int dx_2\, f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, \hat{\sigma}_{ij}(x_1, x_2, Q^2)$$

pdf term

partonic cross section

- DPS can be written in the double parton distribution functions (dPDFs):

pdf term

$$\sigma_{\rm DPS} = \frac{m}{2} \cdot \int dx_1 dx_2 dx_3 dx_4\, d^2b\, f_{i_1 j_1}(x_1, x_3, b, Q_1, Q_2)\, f_{i_2 j_2}(x_2, x_4, b, Q_1, Q_2)$$

distance between partons

$$\times\ \hat{\sigma}_{i_1 i_2}(x_1, x_2, Q_1)\, \hat{\sigma}_{j_1 j_2}(x_3, x_4, Q_2)$$

partonic cross section

- m: symmetry factor, processes A and B are distinct perturbatively described processes -> m is 1, if A=B; else 2.

- Factorization in DPS processes:
- Assume that the PDFs can be factorized in longitudinal versus transverse components:

$$f_{i,j}(x_1, x_3, b) = f_i(x_1) f_j(x_3) T(b)$$

- Integrate over longitudinal momentum fractions:

$$\int dx_1 dx_3 f_{i_1,j_1}(x_1, x_3, b)\hat{\sigma}_{i_1,i_2}(x_1, x_2) = \sigma_A T(b)$$

- Combine and integrate over transverse space:

$$\sigma_{\rm DPS} = \frac{m}{2} \int d^2b\, \sigma_A T(b)\, \sigma_B T(b)$$

- Integral over T(b) gives the effective overlap area $\sigma_{\rm eff}$: T(b) describes the spatial distribution of partons

$$\frac{1}{\sigma_{\rm eff}} = \int d^2b\, T(b)^2$$

Analysis Strategy

- Efficiency corrected yield:

$$N^{corr} = \sum_{i=0}^{n} \frac{\omega_i}{\epsilon_i^{tot}}$$

- The sPlot technique is used, and the weights (ω_i) is the combined weight obtained from the sequential sWeighting in the mass and χ^2_{DTF}/ndf fits.
- ϵ_i^{tot} represents the overall efficiency for each event to be detected within the fiducial range, including any selection criteria or detection efficiencies.

- Cross-section for $Z + J/\psi$ production in the fiducial range

$$\sigma^* = \frac{N^{corr}}{L \times B_1 \times B_2}$$

the branching ratio of the Z boson decay to a certain state B_1, and B_2 for J/ψ meson.

- Fiducial range:
  - Z: $2.0 < \eta^{\mu} < 4.5$, $p_T^{\mu} > 20\text{GeV}/c$, $60 < M_{\mu^+\mu^-} < 120\ \text{GeV}/c^2$;
  - J/ψ: $0 < p_T^{J/\psi} < 14\ \text{GeV}/c$, $2.0 < y^{J/\psi} < 4.5$. (to facilitate comparisons with standalone J/ψ cross-section)
- Effective cross-section:

$$\sigma_{eff}(Z + J/\psi) = \frac{\sigma(J/\psi) \times \sigma(Z)}{\sigma_{DPS}(Z + J/\psi)}$$

  - It characterizes the probability of having more than one parton interaction within a single pp collision.

Uncertainty summary

- The summary of systematic uncertainties on $Z + J/\psi$ cross-section.

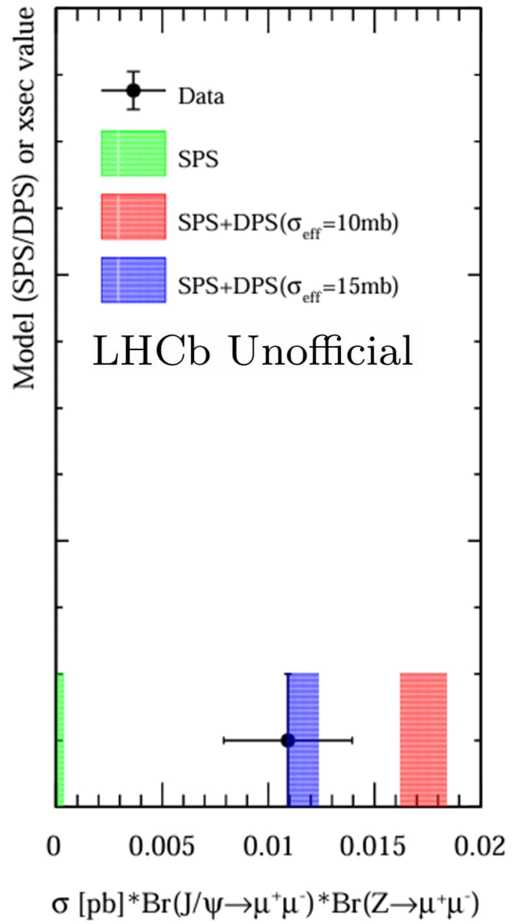
Component	Uncertainty(%)
Signal shape	5.58
sPlot	1.12
Efficiency determination	0.55
Tracking efficiency	3.51
PID efficiency	2.64
Luminosity	2.00
$\mathcal{B}_{J/\psi\to\mu^+\mu^-}$	0.55
$\mathcal{B}_{Z\to\mu^+\mu^-}$	0.21
Total LHCb Unofficial	7.51

- Systematic uncertainties for effective cross-section for $Z + J/\psi$
  - Single $J/\psi \to \mu^+\mu^-$ cross-section: relative systematic uncertainty: 5.49%
  - Single $Z \to \mu^+\mu^-$ cross-section:
    - Relative systematic uncertainty: 2.15%
    - Corrected uncertainty (luminosity cancellation): $\sqrt{2.15^2 - 2^2} = 0.79\%$.
  - Luminosity uncertainty: cancels out when comparing $Z + J/\psi$ to single $Z \to \mu^+\mu^-$ cross-section.
  - Theoretical uncertainty: 1.44%
  - Total systematic uncertainty: quadratic sum of all components → 9.21%

Cross-section Determination

- Cross-section is measured to be
  - $\sigma^{Z+J/\psi} = \frac{N_{corr}^{Z+J/\psi}}{\mathcal{L}\times\mathcal{B}_{Z0\to\mu^+\mu^-}\times\mathcal{B}_{J/\psi\to\mu^+\mu^-}}$ = 5.50 ± 1.46(stat) ± 0.40(syst) ± 0.11(lumi) [pb]
- Theoretical predictions
  - $\sigma_{SPS}^{Z+prompt-J/\psi}$ = (0.10 ± 0.08)pb
  - $\sigma_{DPS}^{Z+prompt-J/\psi} = (8.68^{+0.41}_{-0.68})$pb ($\sigma_{eff}$ = 10mb)
  - $\sigma_{DPS}^{Z+prompt-J/\psi} = (5.79^{+0.27}_{-0.45})$pb ($\sigma_{eff}$ = 15mb)
- Theoretical Cross-sections for DPS:
  - Differential cross-sections for Z+J/ψ calculated using DPS pocket formula.
  - Single J/ψ cross-sections: HELAC-Onia, data-driven (arXiv:1610.05382).
  - Single Z cross-sections: MadGraph5_aMC@NLO at NLO QCD+PS with Pythia8.
- Theoretical Cross-sections for SPS:
  - Differential cross-sections in NRQCD using HELAC-Onia + Pythia8.
  - Includes colour octet, singlet, S-wave, P-wave, and feed-down contributions.
  - Dependent on various colour octet long-distance matrix elements (LDMEs).

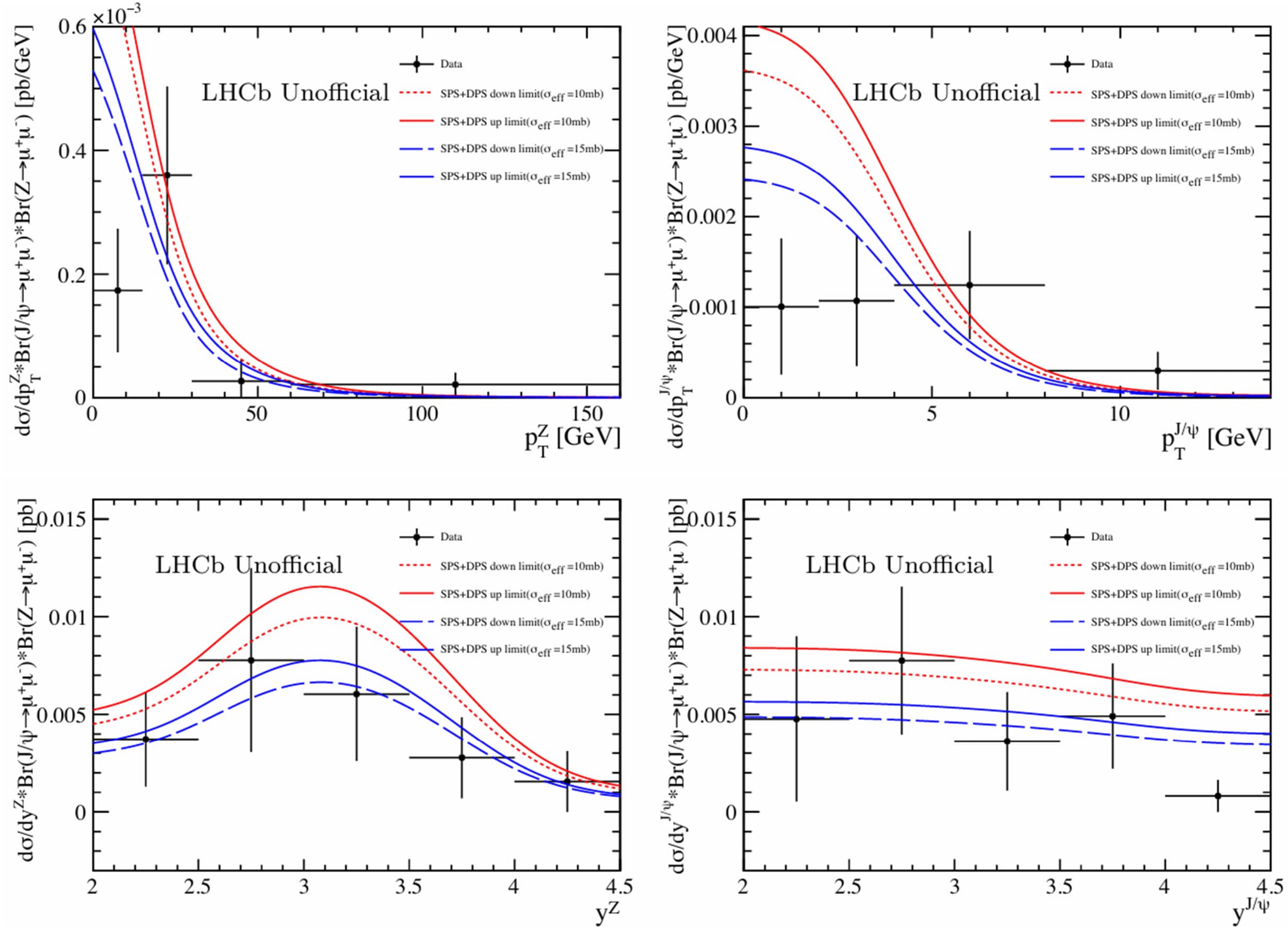
- Compare xsec*br1*br2 between exptl. and theoretical predictions



Comparison between theoretical and exptl. results

- Differential cross-section*br1*br2 for $Z + J/\psi$ scattering as a function of J/ψ transverse momentum (p_T), Z transverse momentum (p_T), J/ψ rapidity, and Z rapidity is illustrated in the accompanying graph.

- Theoretical results, red and blue line, attributed to Huasheng Shao

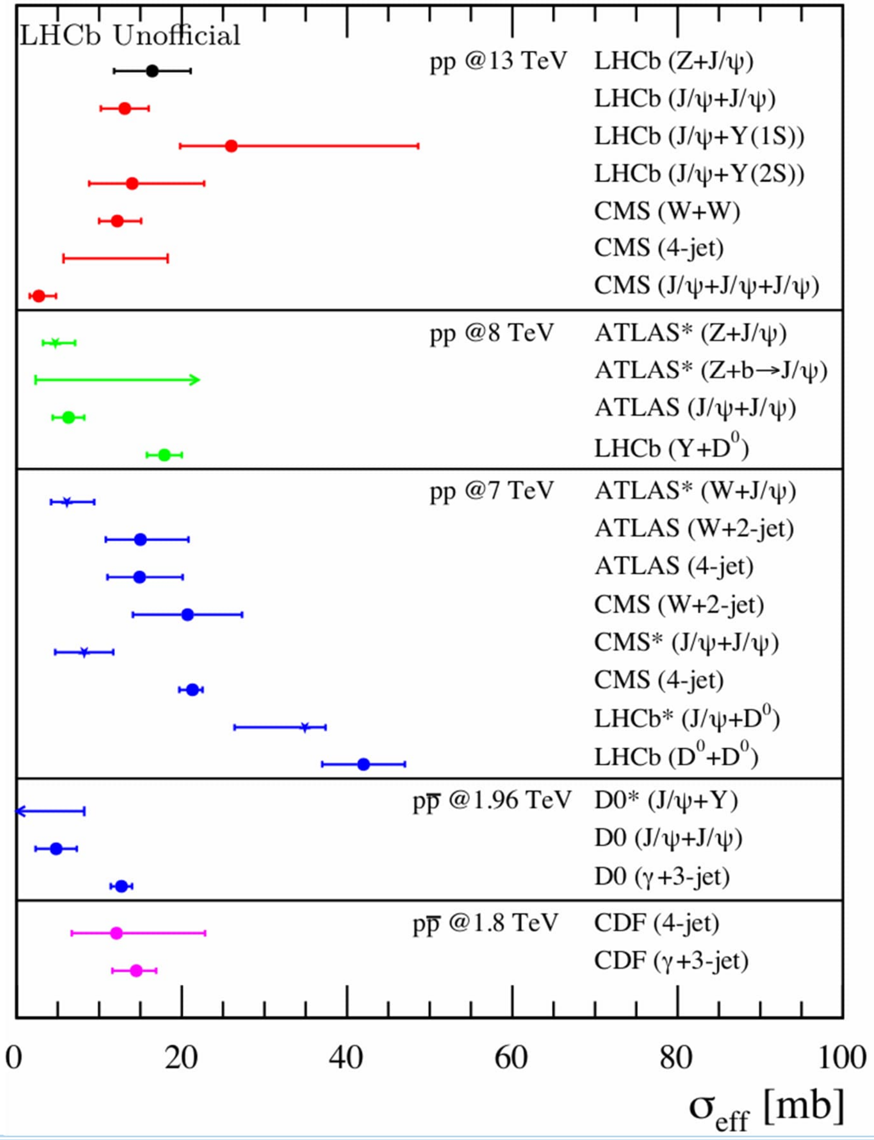


Effective cross-section σ_{eff}

- Effective cross-section:

$$\sigma_{\text{eff}}(Z+J/\psi) = \frac{\sigma(J/\psi)\times\sigma(Z)}{\sigma_{\text{DPS}}(Z+J/\psi)}$$

- $\sigma_{\text{eff}}(Z+J/\psi) =$ 16.55±4.40(stat) ±1.52(syst) [mb]
- Figure:
  - Effective cross-sections measured in various particle production processes by different experiments.
  - The σ_{eff} value for $Z+J/\psi$ from this analysis is represented by the black point.
  - The CMS 4-jet measurement (red line) is shown as a range, encompassing several model-dependent results. Arrows denote lower or upper limits at the 95% (68%) confidence level.



Summary

- A measurement of Z boson production at 8.16 TeV is presented.
  - The new results are in agreement with nCTEQ15 or EPPS16 nPDFs calculations.
  - Differential cross-section (forward-backward ratio or nuclear modification factors) as the function of y_Z^*, p_{T}^Z and ϕ_η^* in pPb (Pbp) collisions are measured and compared with theory models.
  - New results of Z production are consistent with previous measurements at 5 TeV.

- Measurement of $Z + J/\psi$ associated production in pp collisions at 13 TeV.
  - Cross section for associated production ($Z \to \mu\mu$, $J/\psi \to \mu\mu$) measured.
  - Differential cross-sections presented as functions of y and p_{T}.
  - Effective cross-section (σ_{eff}) determined, providing insights into DPS.
  - Theoretical predictions indicate that DPS significantly contributes to Z+prompt J/ψ production.

Outlook

- Z in pPb at 8 TeV
  - Reduce statistical uncertainties significantly with larger datasets from Run 3.
  - Future measurement to complement Z boson results: W in pPb at 8 TeV
- $Z + J/\psi$ in pp at 13 TeV
  - High-statistics data in Run 3 enable:
    - Measurement of Z+non-prompt J/ψ production.
    - Clear experimental separation of SPS and DPS contributions.
    - Significant reduction of statistical uncertainty.
  - Future associated production measurements:
    - $Z + c$-jet, $Z + b$-jet, and $Z + D$ meson processes. Explore heavy flavor dynamics with precision.

Back up

Rapidity shift

1. Because the per-nucleon energy in the proton beam is larger than that in the lead beam, the proton-lead system is not at rest in the laboratory frame($2.0 < y < 4.5$). In case of pPb configuration, the proton-lead system is boosted to the forward direction, while in case of Pbp configuration, the proton-lead system is boosted to the backward direction.

rapidity: $y_{cm} = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ total energy: $E = E_p + E_N = \frac{N_A+N_Z}{N_A} \cdot E_p$

total momentum: $p_z = E_p - E_N = \frac{N_A-N_Z}{N_A} \cdot E_p$ (neglecting the masses)

$E + p_z = 2 \cdot E_p$ $E - p_z = 2 \cdot \frac{N_Z}{N_A} \cdot E_p$

$y_{cm} = \frac{1}{2} \ln \frac{E+p_z}{E-p_z} = \frac{1}{2} \ln \frac{N_A}{N_Z} = \frac{1}{2} \ln \frac{208}{82} = 0.4654 = \Delta y$

$y = y^* + y_{cm}$

2. Hence the rapidity of a particle in the laboratory system is equal to the sum of the rapidity of the particle in the center of mass system and the rapidity of the center of mass in the laboratory system.

ϕ_η^*

- The observable ϕ_η^*, which was first measured by the D0 experiment, probes similar physics as the Z boson pT, but is an angular variable that can be measured with better resolution by collider detectors.

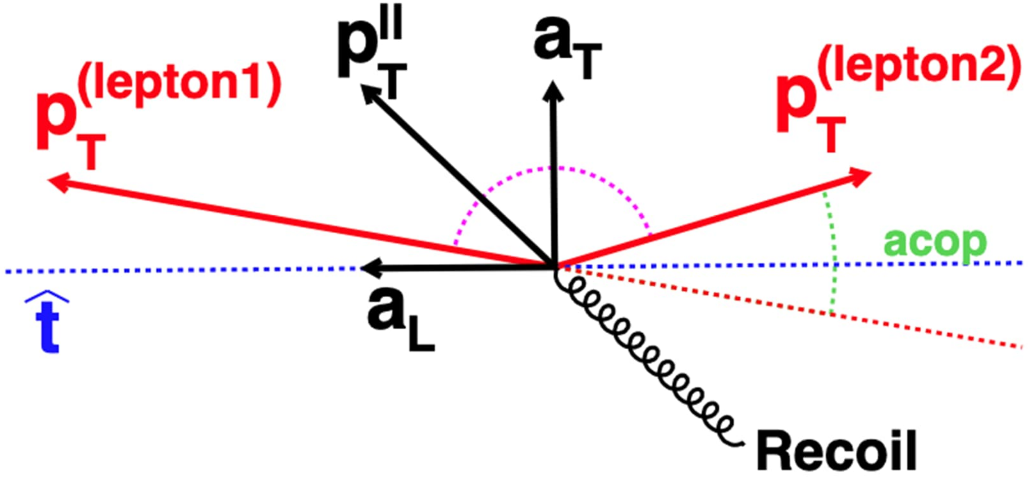
$$\phi_\eta^* = \tan\left(\phi_{\text{acop}}/2\right)\sin(\theta_\eta^*),$$

where ϕ_{acop} is the acoplanarity angle. The variable θ_η^* is a measure of the scattering angle of the leptons with respect to the proton beam direction in the rest frame of the dilepton system. It is defined as: $\cos(\theta_\eta^*) = \tanh[(\eta^- - \eta^+)/2]$, where η^- and η^+ are the pseudorapidities of the negatively and positively
charged lepton, respectively.

- The variable ϕ_η^* is highly correlated with the quantity a_T/m_{ll}, where m_{ll} is the dilepton invariant mass.
  Since ϕ_{acop} and θ_η^* depend exclusively on the directions of the two leptons, which are measured with a precision of a milliradian or better

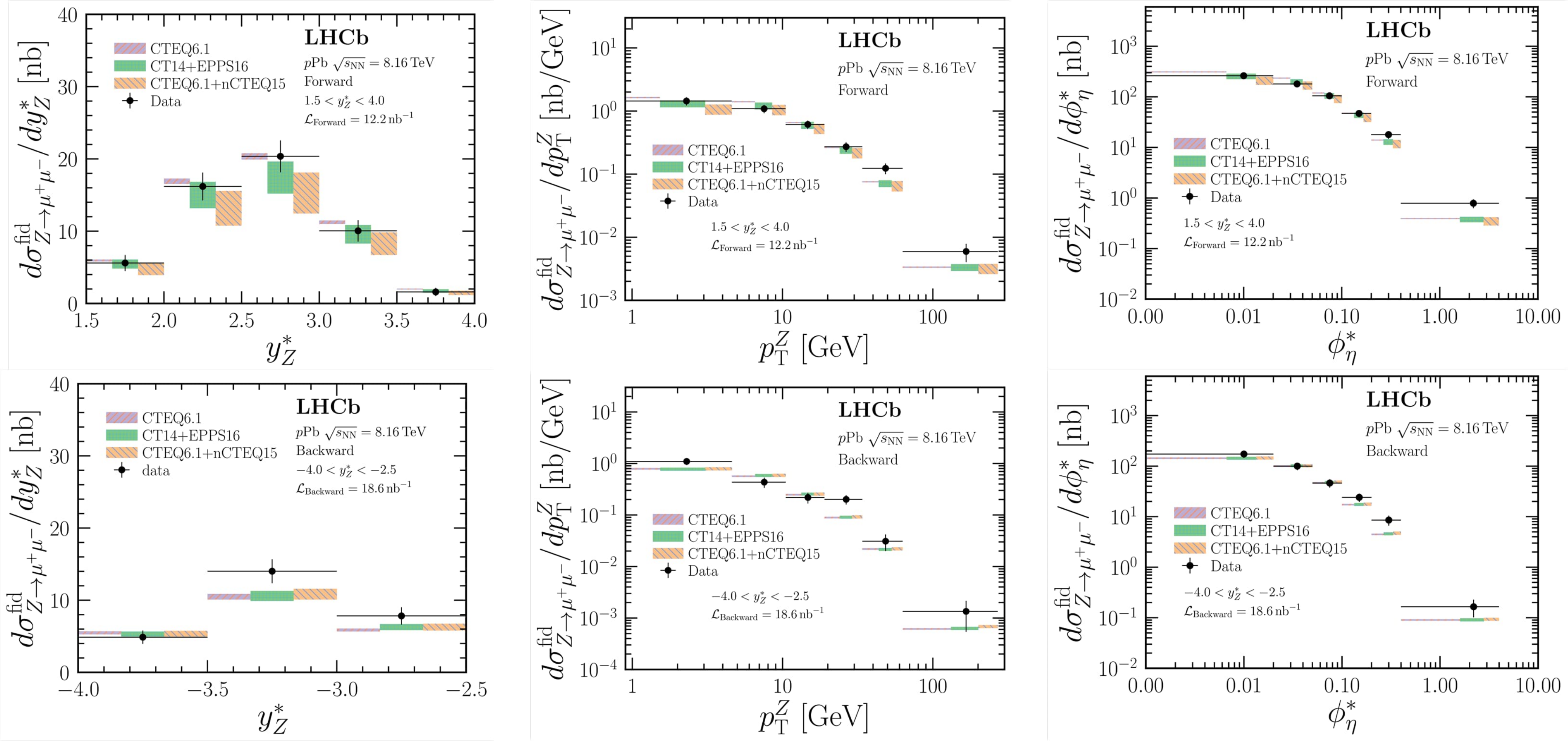
- ϕ_η^* is experimentally very well measured compared to any quantities that rely on the momenta of the leptons.

- The variable a_T, which corresponds to the component of p_T^{ll} that is transverse to the dilepton thrust axis, $\hat{t}$, has been proposed as an alternative analyzing variable.



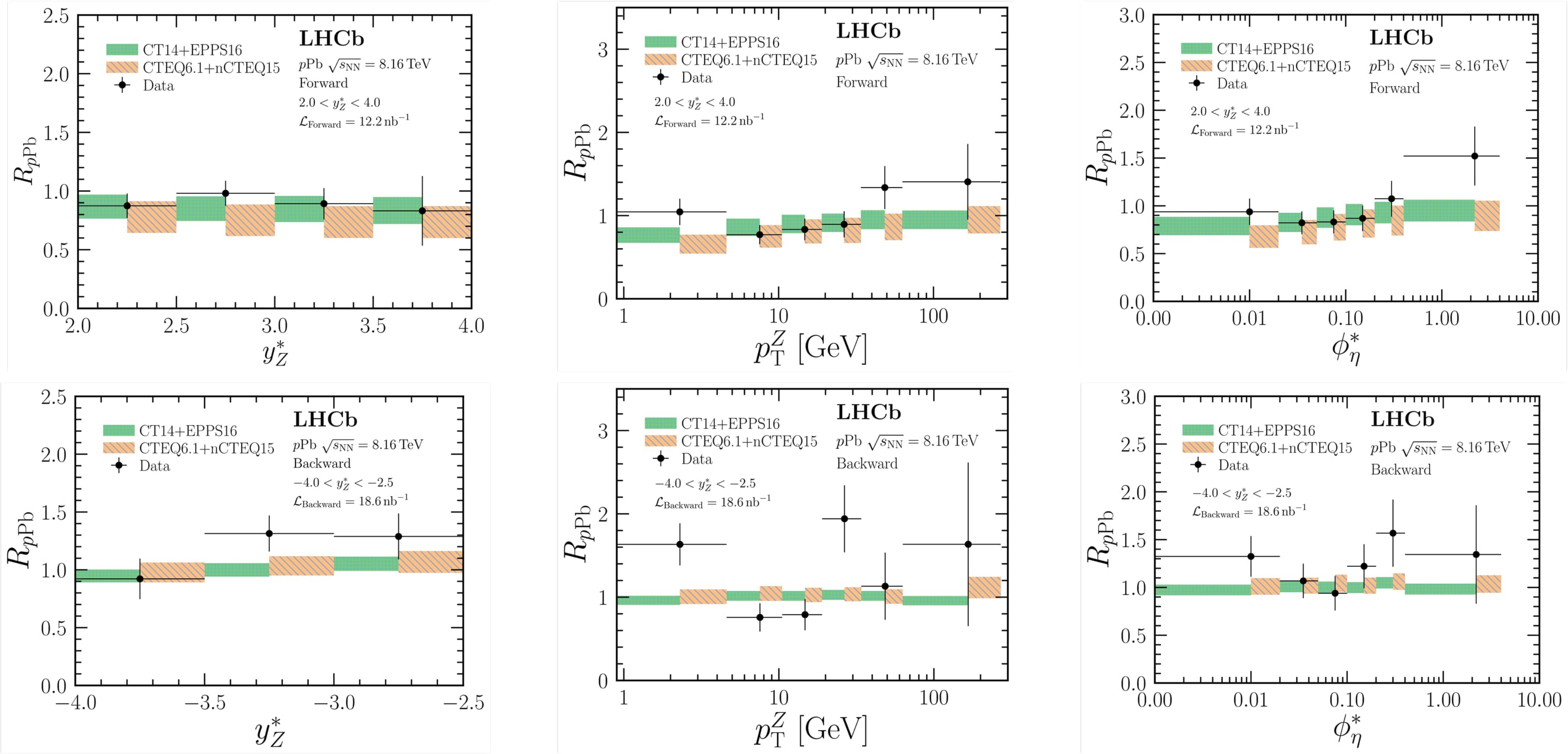
Differential cross-section results

- Differential cross-section as a function of y_Z^*, p_T^Z and ϕ_η^*, compare measured and theoretical results.



Nuclear modification factor

- Nuclear modification factor as a function of y_Z^*, p_T^Z and ϕ_η^*



Determine signal shapes (pseudo-proper time for J/ψ)

- Pseudo-proper time defined as

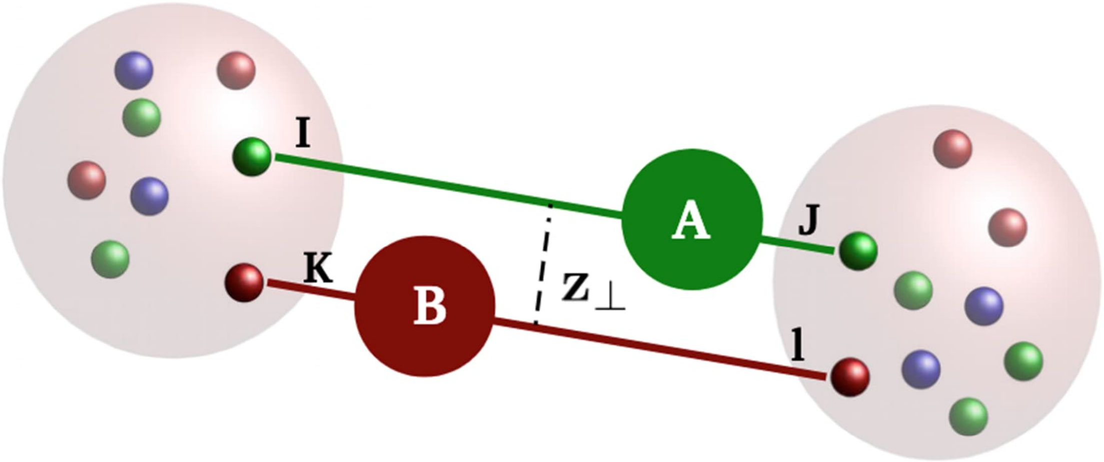
$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$

where $z_{J/\psi}$ and z_{PV} are the positions along the z-axis of the J/ψ decay vertex and of the primary vertex respectively; p_z is the measured J/ψ momentum in the z direction; $M_{J/\psi}$ is the nominal J/ψ mass.

- As shown in the plots on the right, pseudo-proper time shapes are consistent among different control samples:
  - tzsig indicates jpsi events in the mass window $< 100 MeV/c^2$
  - tzbkg indicates jpsi candidates in the mass sidebands, $60 < |m_{\mu^+\mu^-} - m_{J/\psi}| < 150 MeV/c^2$

DPS and dPDFs from multi parton interactions

Multi parton interaction (MPI) can contribute to the, *pp* and *pA,* cross section @ the LHC:



The cross section for a DPS event can be written in the following way:
(N. Paver, D. Treleani, Nuovo Cimento 70A, 215 (1982))

dPDF

Momentum scale

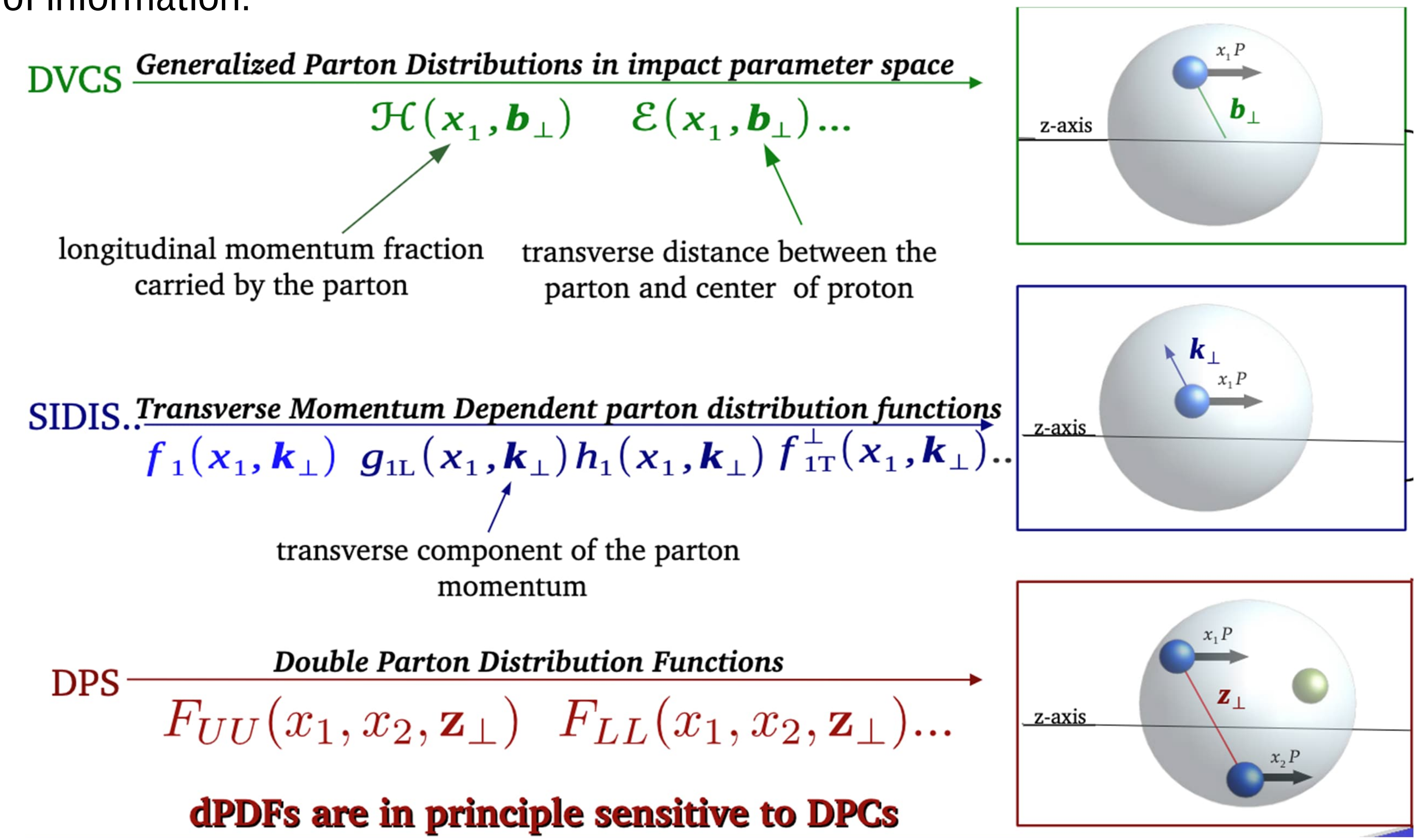
$$d\sigma = \frac{1}{S}\sum_{i,j,k,l}\hat{\sigma}_{ij}(x_1, x_3, \mu_A)\hat{\sigma}_{kl}(x_2, x_4, \mu_B)\int d\tilde{z}_\perp F_{ik}(x_1, x_2, z_\perp, \mu_A, \mu_B) F_{jl}(x_3, x_4, z_\perp, \mu_A, \mu_B)$$

Momentum fraction carried by the parton inside the hadron

Transverse distance between the two partons

3-Dimensional structure of a hadron

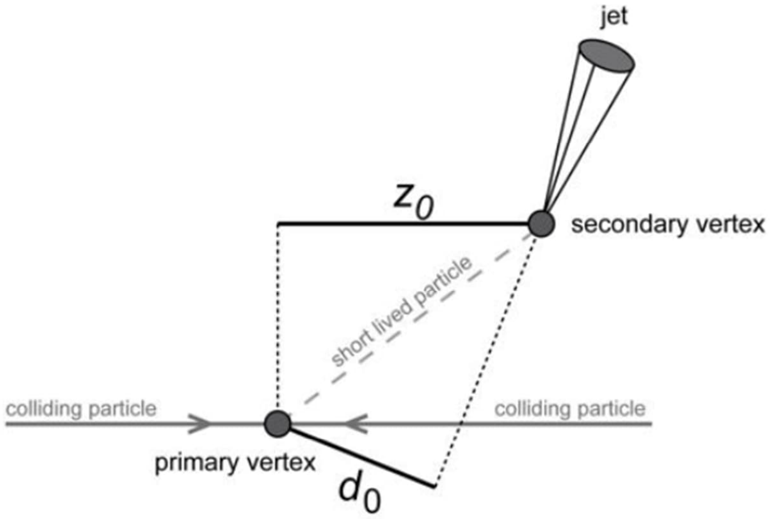
- The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SIDIS, DVCS, double parton scattering ...), measuring different kind of parton distributions, providing different kind of information:



Effective cross-section

Double parton and σ_{eff}

$$\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$



σ_{eff}

- characterizes size of effective interaction region ,
- gives information on the spatial distribution of partons
- Effective cross section σ_{eff} is directly related with parton spatial density

$$\sigma_{\text{eff}} = [\int d^2\beta [F(\beta)]^2]^{-1}$$

$$F(\beta) = \int f(b) f(1-b) d^2 b$$

where f(b) is the density of partons in transverse space.

=> Having σ_{eff} measured we can estimate f(b)

β is impact parameter