Associated Z Boson Production in the Forward Region

第4届LHCb前沿物理研讨会

中国 烟台

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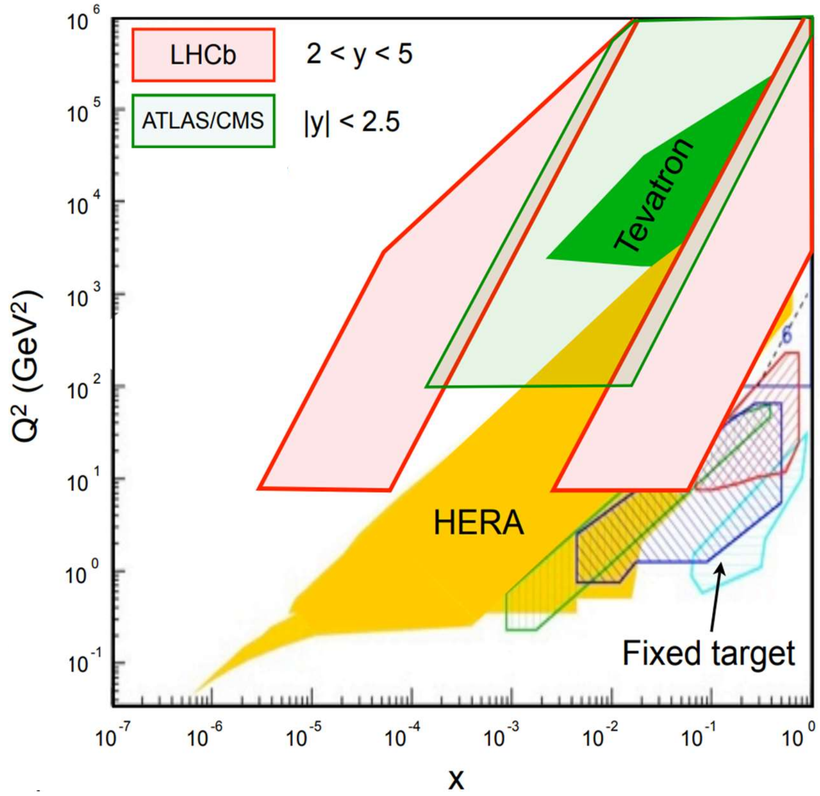
Z boson measurements at LHCb

Ref. [PoS (QCDEV2017) 058]

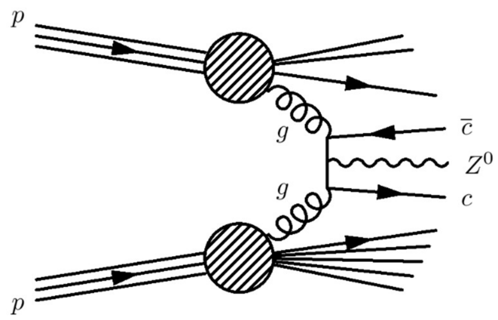
- Electroweak measurements in the forward region probe pQCD and electroweak theory in a novel region of (x, Q^2) phase space.
- Z boson production can be used to constrain PDFs at $Q^2 = 91^2 \mathrm{GeV}^2$.
  - sensitive to effects at low and high values of Bjorken-x
- Z boson do not participate strong interaction - clearly probe initial state, can be used to differentiate between initial and final state effects.
- LHCb results are complementary to other LHC experiments

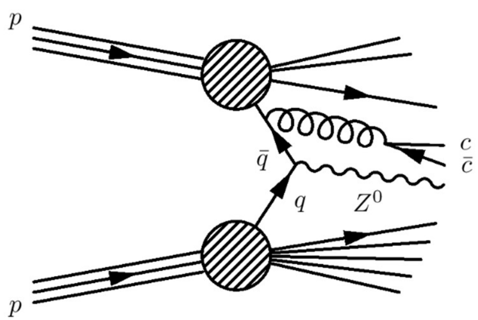


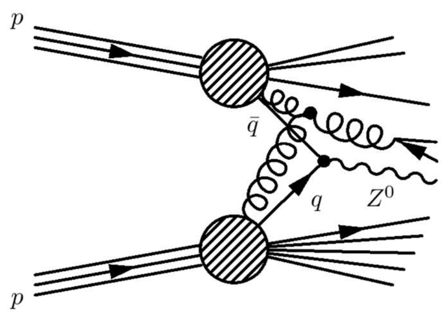
$\mathbf{Z + J/\psi}$ production in pp collisions at 13TeV

Motivation

- $Z + J/\psi$ in pp collisions probes the production mechanisms of quarkonium in association with vector bosons, allows studies of multiple partonic Interactions (MPI).
- 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.
  - DPS in particle physics serves multiple purposes. It helps estimate background noise in searches for rare signals, provides insights into strongly interacting matter in nuclear collisions, tests Quantum Chromodynamics (QCD), and aids in understanding multi-parton processes.







Analysis Strategy

- Efficiency corrected yield:

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

Each event's weight (ω_i) is divided by the total efficiency (ε_i^{tot}) for that event.

- The sPlot technique is used, and the weights (ω_i) are typically based on the mass fit result.
- 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

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

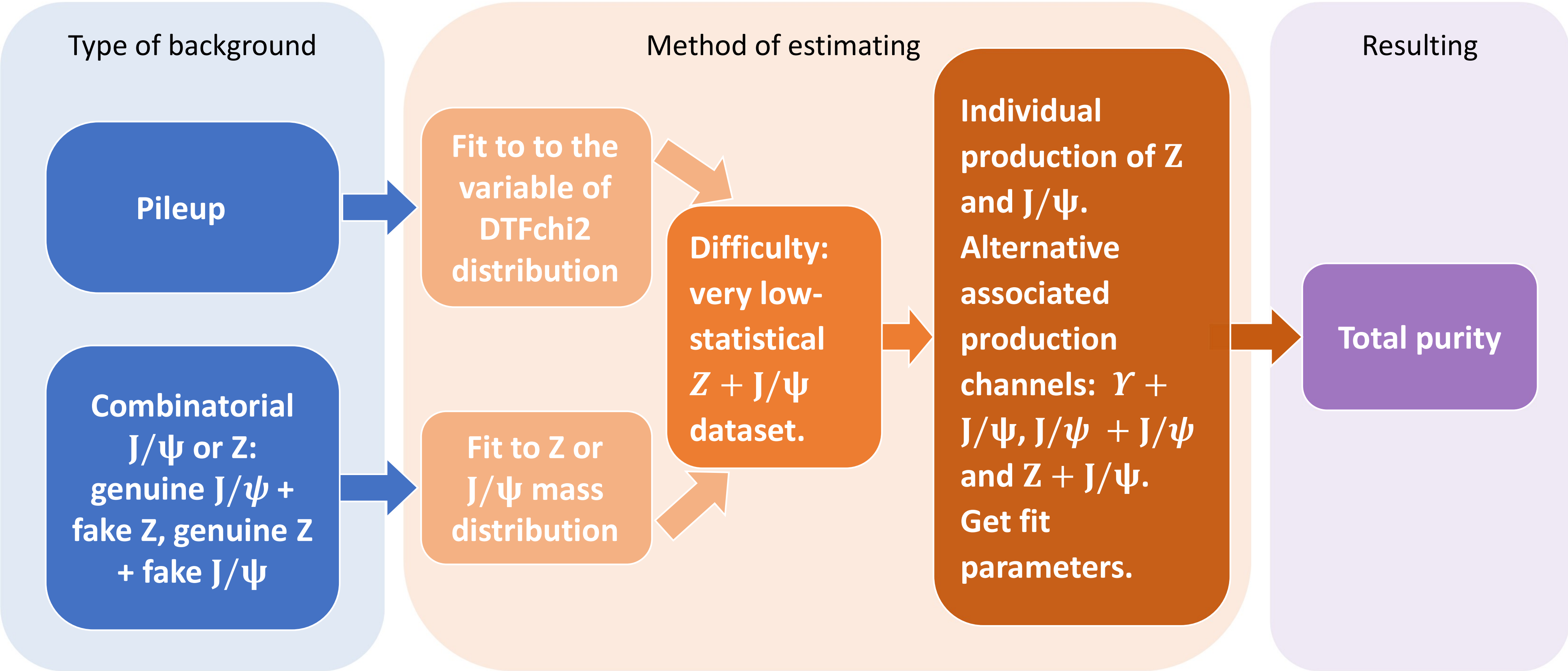
the branching ratio of the Z boson decay to a certain state (B_1), and B_2 for J/ψ meson.

- Fiducial range:
  - Z0: $2.0 < \eta^{\mu} < 4.5$, $p_T^{\mu} > 20 GeV/c$, $60 < M_{\mu^+\mu^-} < 120 \ GeV/c^2$;
  - Jpsi: $0 < p_T^{J/\psi} < 14 \ GeV/c$, $2.0 < y^{J/\psi} < 4.5$.
- 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.
  - It is a measure of the double PDFs inside a proton.

Signal yields/ background estimation



Efficiency estimation

- Total efficiency:

$$\epsilon_{tot}^{Z+J/\psi} = \epsilon_{acc}^{Z+J/\psi} \times \epsilon_{rec\&sel}^{Z+J/\psi} \times \epsilon_{PID}^{Z+J/\psi} \times \epsilon_{trg}^{Z+J/\psi}$$

multiplying

Both Z0 and J/ψ are independently the selection requirements, just multiplying

$$\epsilon_{i}^{Z-J/\psi} = \epsilon_{i}^{Z} \times \epsilon_{i}^{J/\psi}, \qquad i = rec\&sel, PID$$

$$\epsilon_{trg}^{Z-J/\psi} = 1 - (1 - \epsilon_{trg}^{Z}) \times (1 - \epsilon_{trg}^{J/\psi})$$

Efficiency estimation for Z boson

Using the pp Z → μ+ μ− MC events to get cut-and-count efficiency as the first step. Then use the tag-and-probe method to correct the difference between MC and collider data.

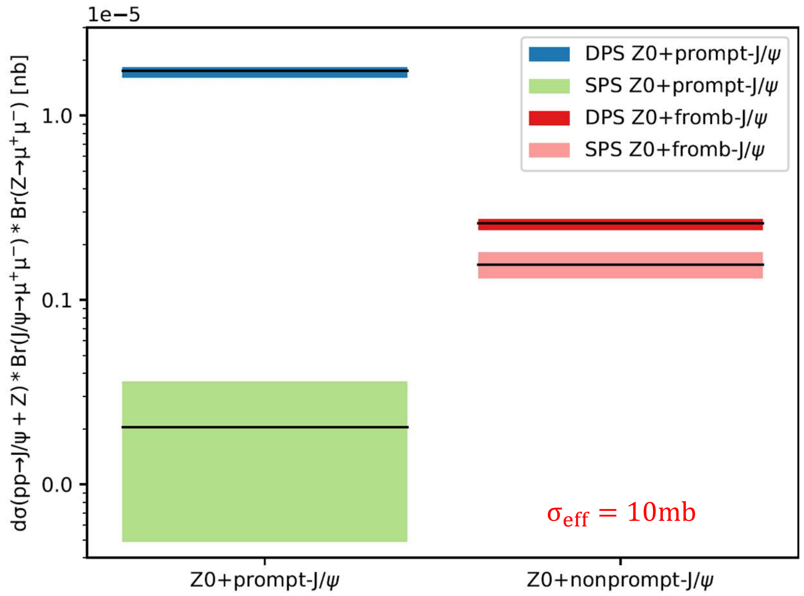
Efficiency estimation for J/ψ

Tracking Efficiency, using TrackCalib method. PID Efficiency, PIDCalib2 method.
Using the pp Z → μ+ μ− MC events to get cut-and-count efficiency for acc and trg.

Cross-section Determination

- Using splot method to calculate weighted signal yield, from mass fit to subtract background
- Efficiency corrected signal yield is determined by event-by-event correction to be
  - $N_{corr}^{Z+J/\psi} = \sum_{i=1}^{n} \frac{w_i}{\varepsilon_{tot,\,i}^{(Z+J/\psi)}}$
- Cross-section is measured to be
  - $\sigma^{Z+J/\psi} = \frac{N_{corr}^{Z+J/\psi}}{\mathcal{L} \times \mathcal{B}_{Z0\to\mu^+\mu^-} \times \mathcal{B}_{J/\psi\to\mu^+\mu^-}}$
  - $\mathcal{L} = (5.09E3 \pm 0.10E3)\ \mathrm{pb}^{-1}$
  - $\mathcal{B}_{Z0\to\mu^+\mu^-} = (3.366 \pm 0.007)\ \%$
  - $\mathcal{B}_{J/\psi\to\mu^+\mu^-} = (5.961 \pm 0.033)\ \%$

- Theoretical predictions ($\sigma_{eff} = 10\mathrm{mb}$): [Huasheng Shao]
  - $\sigma_{SPS}^{Z+prompt-J/\psi} = (0.10 \pm 0.08)\mathrm{pb}$
  - $\sigma_{DPS}^{Z+prompt-J/\psi} = (8.68^{+0.41}_{-0.68})\mathrm{pb}$



PhysRevLett.128.082001

$\boldsymbol{Zc}$ production in pp collisions at 13TeV

Motivation

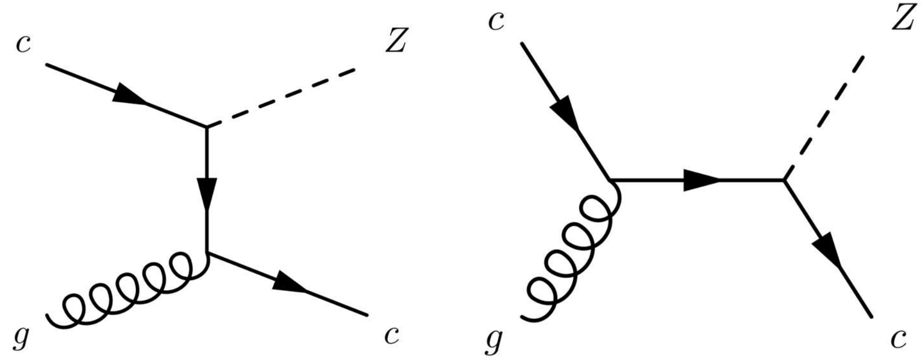
PhysRevLett.128.082001

- Zc production at electroweak scale, hadronic effects are small
- Use the ratio of cross section between Zc and Zj (events of a Z boson and any type jet) to manifest:

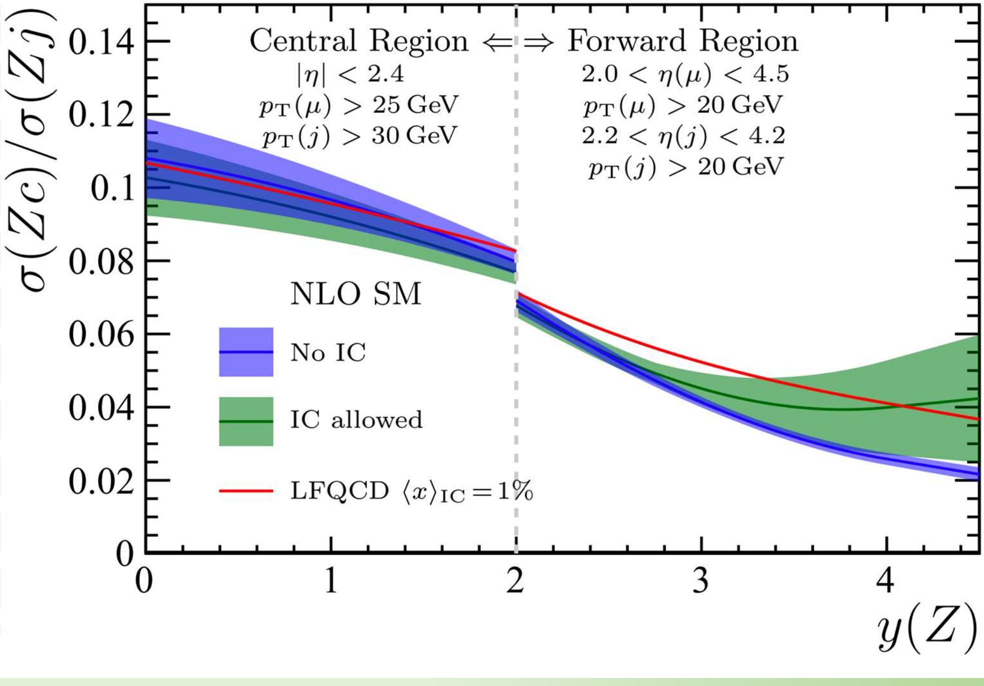
$$R_j^c = \frac{\sigma(Zc)}{\sigma(Zj)}$$

  - cancel some experimental and theoretical uncertanties
- The leading-order Zc production mechanism is

$$gc \to Zc$$



- Use NLO standard model calculate the ratio as a function of Z rapidity
- Intrinsic charm (IC) contribution enhance c-jet production at large Z rapidity



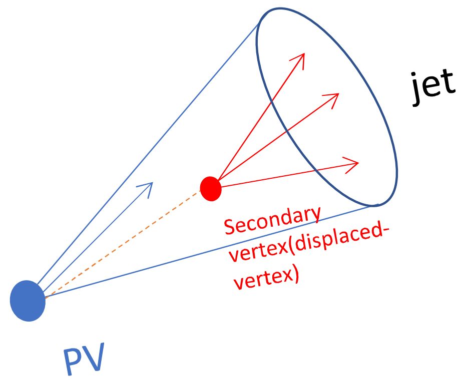
Analysis Strategy

PhysRevLett.128.082001

- Data sample: integrated luminosity of $6fb^{-1}$, pp collisions at a center-of-mass energy of 13 TeV
  - Z bosons: reconstructed using the $Z \to \mu^+\mu^-$ decay
  - The c-jet as a jet containing a c-hadron, identified by tagging secondary vertices
- Measurement strategy:

$$R_j^c = \frac{N(c-\mathrm{tag})}{N(j)\epsilon(c-\mathrm{tag})}$$

  - N(c-tag) is observed Zc yield
  - c-tag efficiency, calculated by using dijet data
  - N(j) is total Zj yield, reconstructed in the fiducial region



- Determining Zc yields using displaced-vertex(DV) based tagging method
  - Find a displaced-vertex signature from a jet cone
  - Two properties of DV are used: number of tracks in DV (N_{trk}) and corrected mass

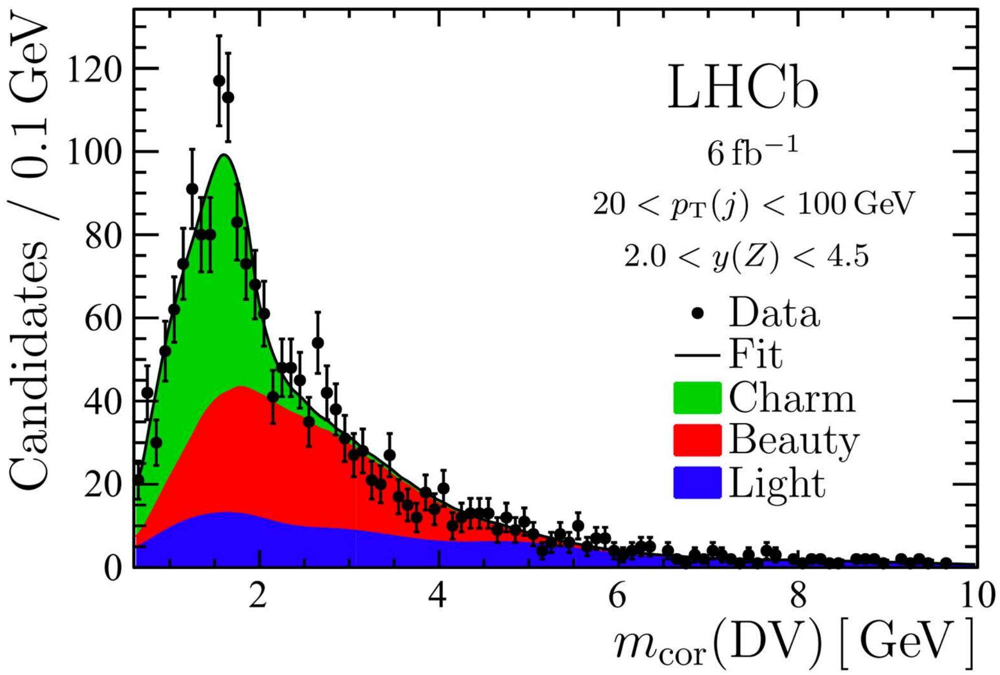
$$m_{\mathrm{cor}}(\mathrm{DV}) = \sqrt{m^2(\mathrm{DV}) + p^2(\mathrm{DV})\sin^2\theta} + p(\mathrm{DV})\sin\theta$$

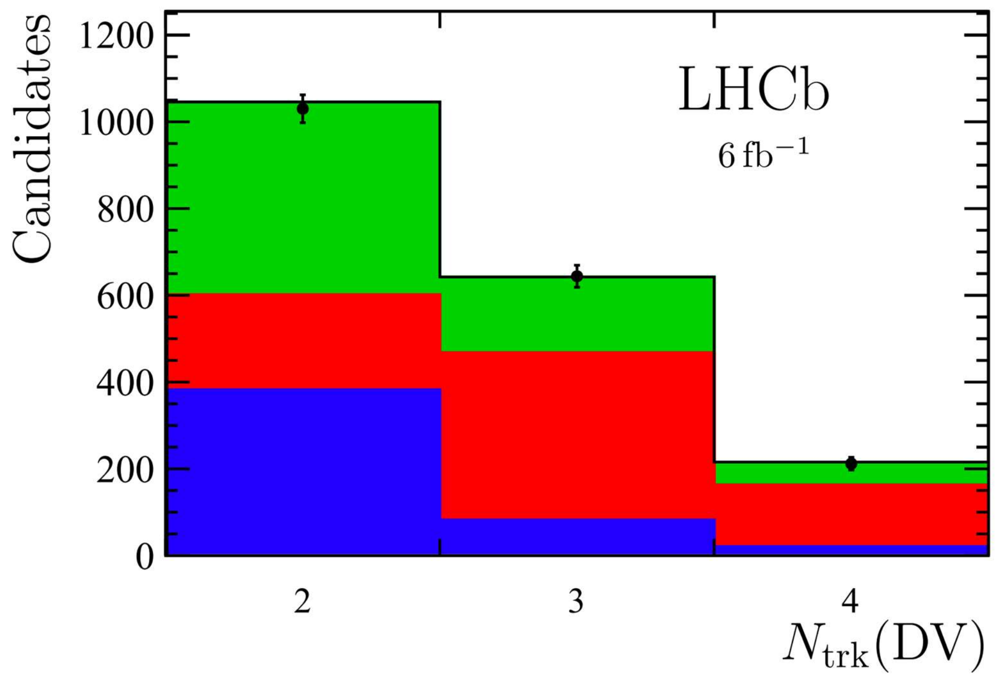
    - θ, angle between the momentum and the flight direction of the DV

c-tagger calibration

PhysRevLett.128.082001

- The $m_{\text{cor}}(\text{DV})$ and $N_{\text{trk}}(\text{DV})$ distributions for DV-tagged candidates of the Zj data sample
- Calculate the reconstructed Zc yields from fit resuts of Zj data





Zc production results

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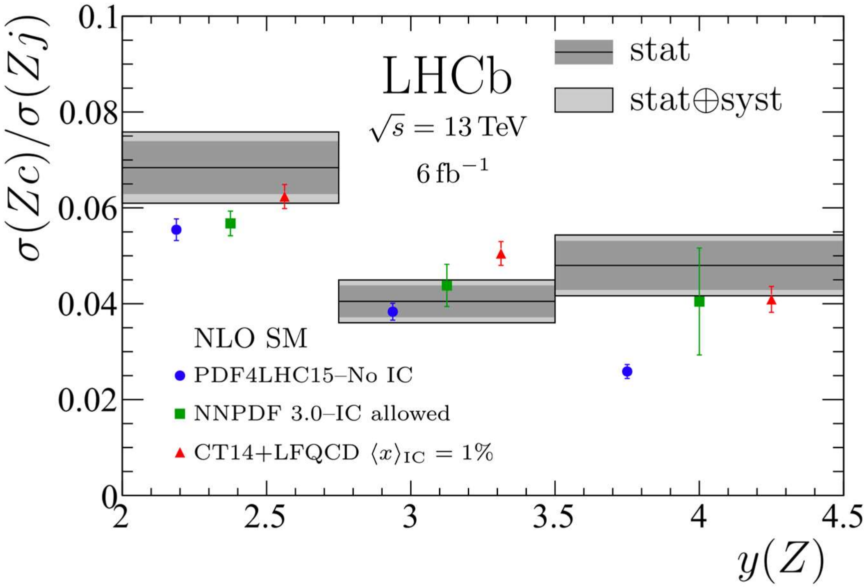

Results for the R_j^c measurements

$y(Z)$	$\mathcal{R}_j^c$ (%)
2.00–2.75	$6.84 \pm 0.54 \pm 0.51$
2.75–3.50	$4.05 \pm 0.32 \pm 0.31$
3.50–4.50	$4.80 \pm 0.50 \pm 0.39$
2.00–4.50	$4.98 \pm 0.25 \pm 0.35$

- The fraction of Zc-jet in Zjet is measured for the first time in the forward region of pp collisions
- R_j^c distributions for three intervals of forward Z rapidity
  - Gray bands show measured R_j^c
  - Theoretical predictions: NLO SM predictions without Intrinsic charm(IC), predictions with IC described by the charm PDF shape, and IC with an average momentum fraction of 1% predicted by light front QCD(LFQCD).
- The observed fraction shows a considerable enhancement at the large forward Z rapidities, consistent with the effect expected if the proton PDF contains the IC component predicted by LFQCD

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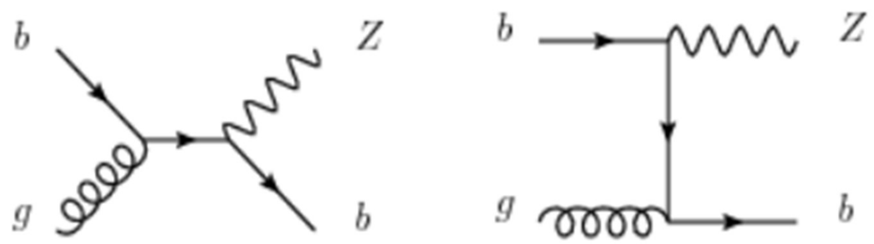
$\boldsymbol{Zb}$ cross-section in pp collisions at 7 TeV

Motivation

- Z+b measurements provide a good way to probe PDF for bottom quarks, NLO QCD effects.
- Z+b is also background for new physics searches.
- Jets from b-quarks is one of the main tools to search new physics at LHCb
- Z+Jet events create an ideal environment to study b-jets, allow for a cleaner and more controlled investigation compared to other QCD processes.

- Ratio $\sigma(\mathrm{Zb})/\sigma(\mathrm{Zj})$ helps in reducing systematic errors. Most uncertainties cancel out, except by dominated b-tag uncertainty
- Feynman diagrams for the production Z+b-jet



Analysis Strategy

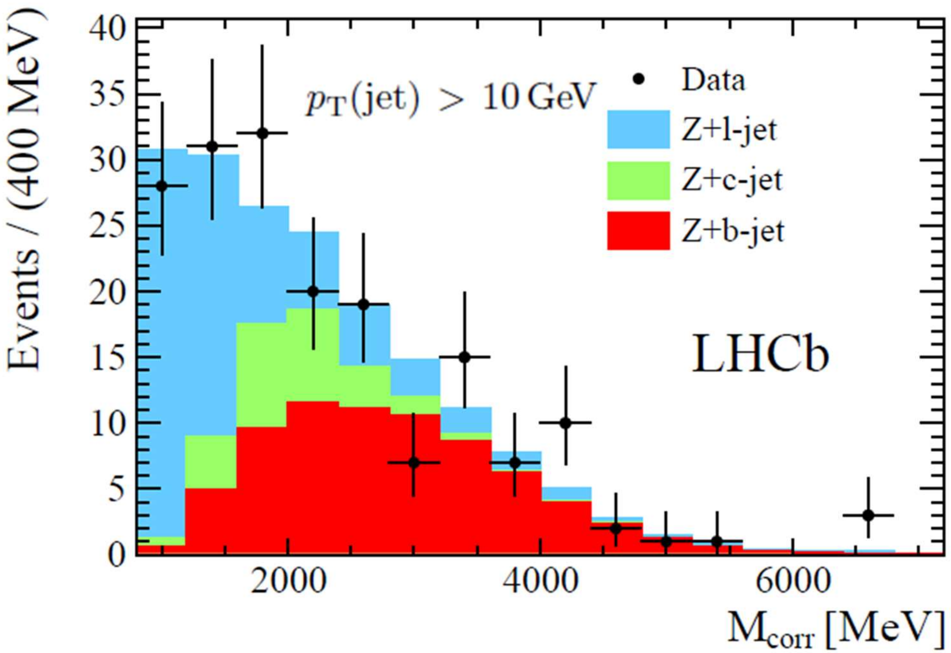
- The cross section for Zb production, $\sigma(\mathrm{Z} + \mathrm{bjet})$, can be expressed as:

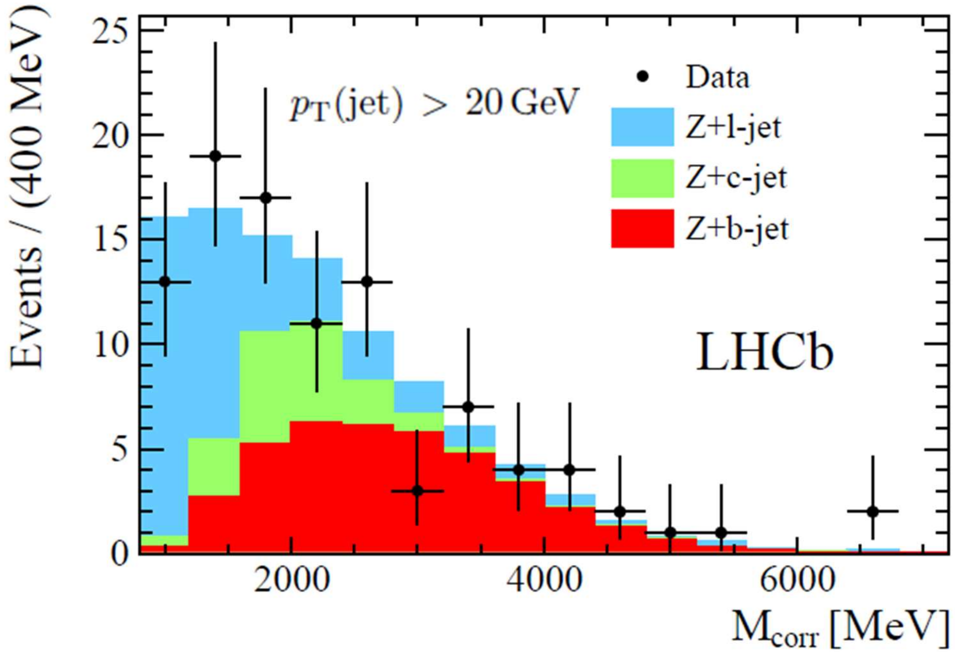
$$\sigma(Z + b\text{-jet}) = \frac{\epsilon(Z + \text{jet})}{\epsilon(Z + b\text{-jet})} \times \frac{1}{\epsilon(b\text{-jet})} \times \frac{N(Z + b\text{-jet})}{N(Z + \text{jet})} \times \sigma(Z + \text{jet})$$

- Apply Z+jet Selection (2011 Data)
- Apply a b-tag method to the leading jet to identify b-jets.
- Perform a template to extract the number of b-jets.
- Verify that the discriminant variables are well simulated.
- Use SPlot to obtain the p_T distribution of b-jets.
- Apply a correction for b-tagging efficiency (1/eff) to extract the number of Zb events.
- Assume detection efficiency is not flavor dependent (less than 2% effect).

Observed $\boldsymbol{Zb}$ events

- Discriminant variable is the $M_{\text{corr}} \equiv \sqrt{M^2 + p^2 \sin^2\theta} + p\sin\theta$
- $N(Z + bjet)$ is estimated by b-tagging (secondary vertex) the jet and fit templates to data.





Results

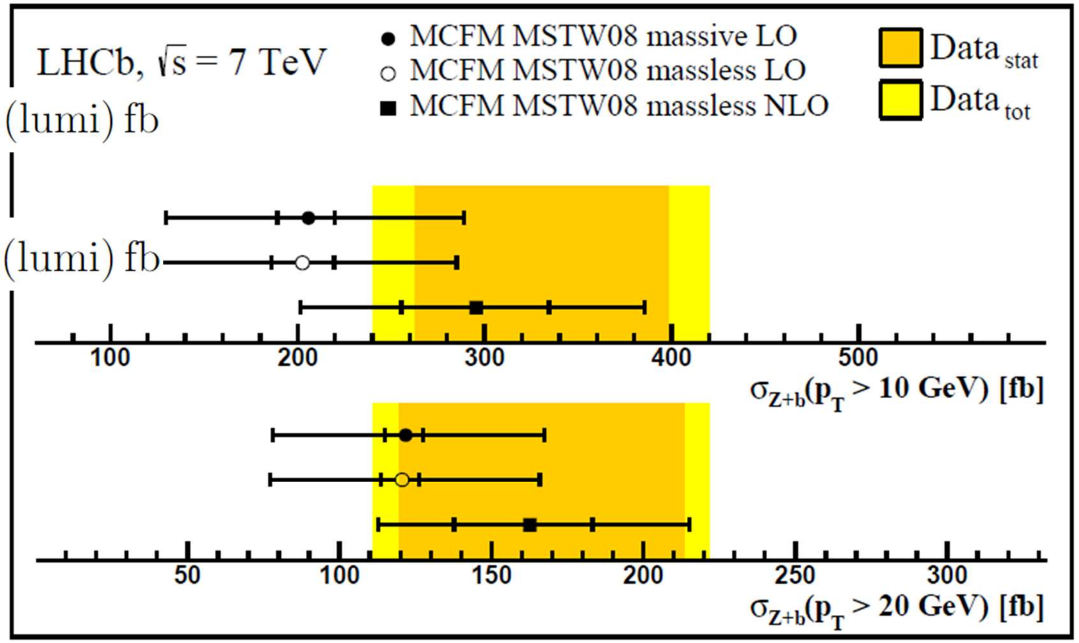
- Using the measurements of Ref. [arXiv:1310.8197], the cross-section of Z+b-jet production is
  - for $p_T(\text{jet}) > 10\text{GeV}$,

$$\sigma(Z/\gamma^*(\mu^+\mu^-)\text{+b-jet}) = 295 \pm 60\ (\text{stat}) \pm 51\ (\text{syst}) \pm 10\ (\text{lumi})\ \text{fb}$$

  - for $p_T(\text{jet}) > 20\text{GeV}$,

$$\sigma(Z/\gamma^*(\mu^+\mu^-)\text{+b-jet}) = 128 \pm 36\ (\text{stat}) \pm 22\ (\text{syst}) \pm 5\ (\text{lumi})\ \text{fb}$$

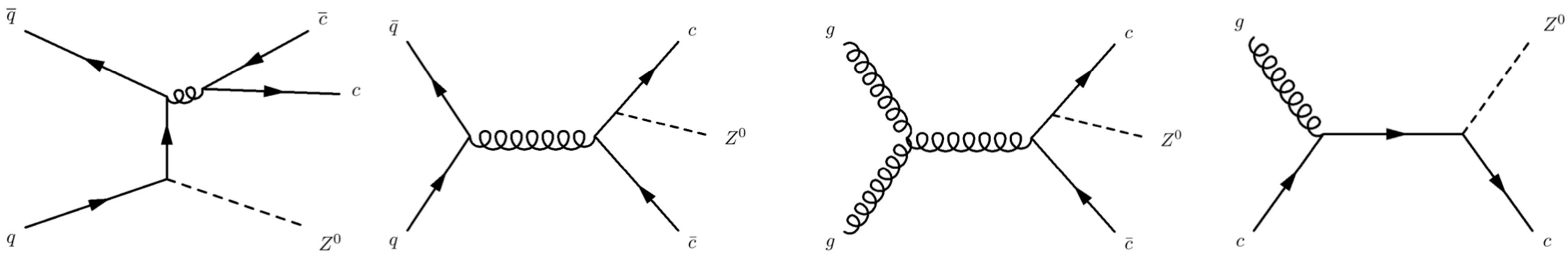
- These cross-sections are evaluated within the fiducial region
  - $p_T(\mu) > 20\text{GeV}$, $60\text{GeV} < M(\mu^+\mu^-) < 120\text{GeV}$, $2.0 < \eta(\text{jet}) < 4.5$, $2.0 < \eta(\mu) < 4.5$ and $\Delta R(\text{jet}, \mu) > 0.4$.



$Z + D$ production in pp collisions

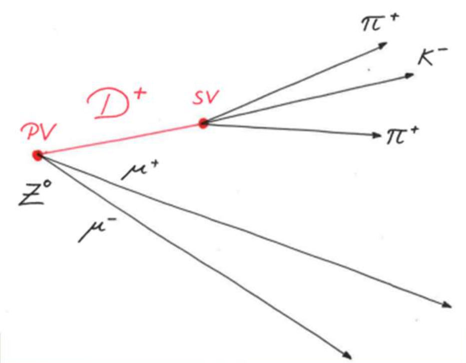
Motivation

- Z+D production in the forward region provides information about
  - charm PDFs;
  - the charm production mechanism;
  - to the understanding of contributions from single- (SPS) and double-parton scattering (DPS).



Analysis Strategy

- Constrain the tracks to follow the topology:
  - Z boson from primary vertex with zero lifetime.
  - D from a secondary vertex but is associated with the same PV as the Z.
- Fit that and check the DTFchi2 for that fit.



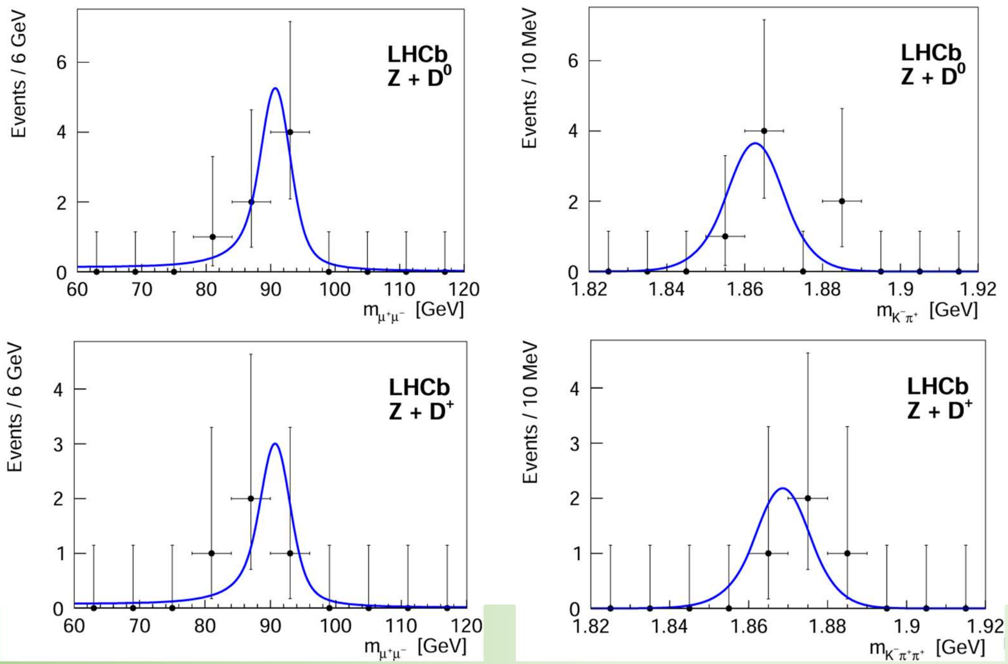
- Cross Section Formula

$$\sigma_{Z,D} = \frac{\rho}{\int \mathcal{L}} \sum_i \frac{1}{\varepsilon_{\text{Trigger}}\varepsilon_{\text{Tracking}}\varepsilon_{\text{PID}}\varepsilon_{\text{Combination}}}$$

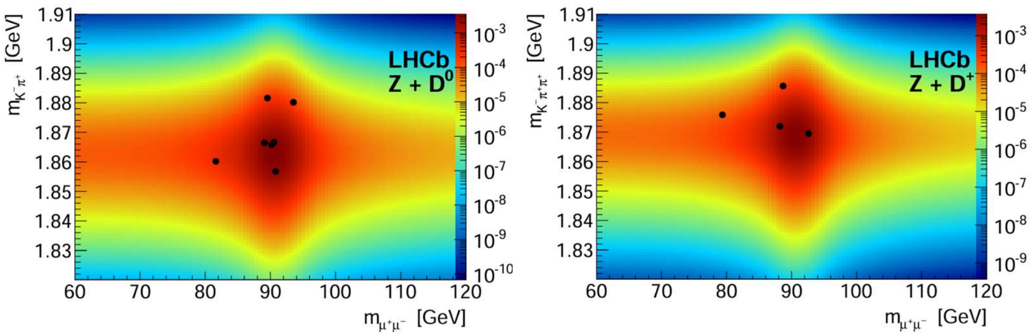
- Efficiencies were taken from LHCb public papers.
- Background considered in purity ρ:
  - good Z and good D but not from the same PV (pileup)
  - good Z and fake D
  - fake Z and good D
  - fake Z and fake D

Signal yields and purity

- 7 candidates for $Z + D^0(K^-\pi^+)$ and 4 candidates for $Z + D^+(K^-\pi^+\pi^+)$
- No observations of $\Lambda_c^+ \to pK\pi$ or $D_s^+ \to \phi\pi^+$
- Both Z and D mesons come from the same PV.



- Charmed hadrons from B decay are considered as background.
- Real Z and D from Different PVs.
- Combinatorial background is estimated from a 2D fit to the mass distributions of the candidates.
- Purity of the selected candidates is: $(95.3 \pm 3.8)\%$ for $Z + D^0$ and $(95.6 \pm 1.2)\%$ for $Z + D^+$.

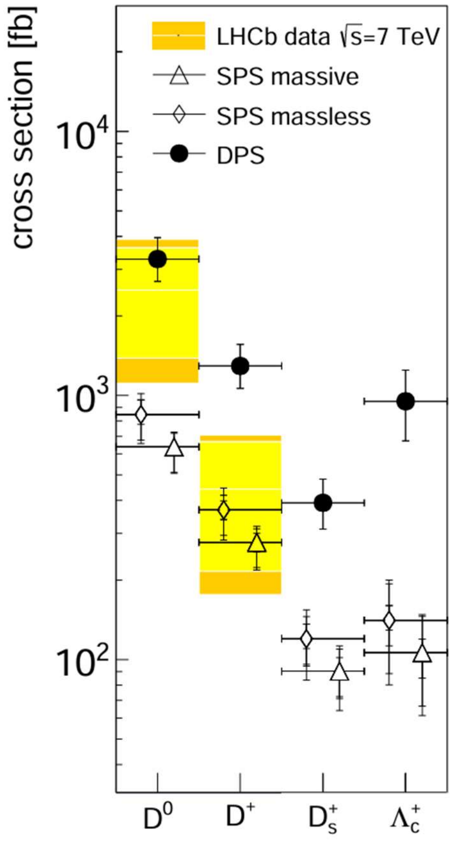


Results

- Comparison of the measured cross-sections [pb] and the theoretical predictions for the associated production of a Z boson with an open charm meson.

	Measured	MCFM massless [1]	MCFM massive [17]	DPS (Eq. (6.1))
$Z+D^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07}\ {}^{+0.11}_{-0.17} \pm 0.05$	$0.64^{+0.01}_{-0.01}\ {}^{+0.08}_{-0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
$Z+D^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03}\ {}^{+0.05}_{-0.07} \pm 0.03$	$0.28^{+0.01}_{-0.01}\ {}^{+0.04}_{-0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

- Theory uncertainty: PDF, scale variations, and c-quark hadronization.
- cross sections are the sum of SPS and DPS.
- for $Z+D^0$, the sum of DPS and SPS contributions is consistent with the measured cross section.
- for $Z+D^+$, the measured cross section lies below the expectation.



Summary

- Z+ J/ψ production:
  - Will give a DPS up limit.
  - Give a comparison between experimental measurements and theoretical predictions.
- Z+c production:
  - Significant enhancement of Z_c^j at forward Z rapidities.
  - Consistent with proton wave function containing | $uudc\bar{c}$ |
- Z+b production:
  - Z+b-jet cross section measured for two different jet p_T thresholds, results agree with MCFM predictions for massless and massive bottom quark calculations.
  - Good agreement with NLO predictions found by all experiments.
- Z+D measurements:
  - Sum of DPS and SPS agrees with measured cross section within uncertainties.
  - No support for large contribution from IC mechanism.

OUTLOOK

Thanks for your attention!

- Some channel:
  - $pp \rightarrow Z + jets$
  - $pp \rightarrow Z + D$ mesons
  - $pp \rightarrow Z + B$ mesons
  - $pp \rightarrow Z + Jpsi$
  - $pp \rightarrow Z + W$
  - $pp \rightarrow Z + Z$
- Measurable Quantities
  - Cross Section: verify the predictions of the Standard Model; momentum, rapidity, angluar distribution compare with theoretical predictions.
  - Ratios: Measuring the ratios of cross-section between Z boson and associated particles.
  - Quark Fragmentation: Studying the fragmentation of charm quarks into D mesons in the presence of a Z boson
  - Flavor Tagging: Identifying and tagging B mesons allows for precise measurements of b-quark production.
- Physical Significance
  - Testing the Standard Model: measuring the cross section of $pp \rightarrow Z + jets$ helps verify the predictions of Quantum Chromodynamics (QCD) and electroweak interactions.
  - Searching for New Physics: Precise measurements and comparisons with theoretical predictions can reveal potential new physics.
  - Understanding Particle Production Mechanisms: Studying Z boson production with other particles (like jets, photons, W bosons, etc.) provides deeper insights into the mechanisms of strong and electroweak interactions.
  - Probing Heavy Quark Dynamics: Studying the production of D mesons with Z bosons provides insights into the dynamics of heavy quarks (charm quarks) and their interactions with the Z boson
  - Understanding Quark Hadronization: Analyzing how charm quarks hadronize into D mesons in the presence of a Z boson