J/ψ Production by Jet Fragmentation

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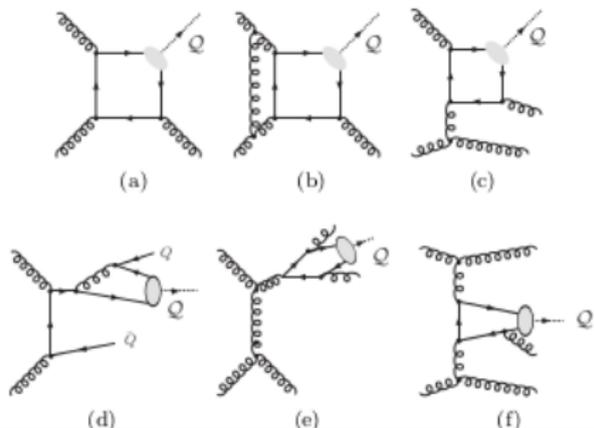for the CMS Collaboration

May 3, 2019

- Introduction: Inclusive prompt J/ψ production
- These Data: Are prompt J/ψ Mesons correlated with jets?
- Correlations predicted by Fragmenting Jet Function analysis
- FJF/Data Comparison: Unique determination of dominant NRQCD long distance matrix element in jet+J/ψ fragmentation.
- Further outcome: Almost all J/ψ with energy > 15 GeV and $|y| < 1$ are fragments of jets with $|\eta| < 1$.

Early J/ψ History - the Color Singlet Model

- Fundamental Question: how does colored $Q\overline{Q}$ system make colorless J/ψ?
- Color singlet model (CSM): Q line radiates soft gluon to compensate color but leaves T polarization of parent massless gluon
- Problem: CSM underestimated Tevatron J/ψ and ψ(2S) production cross section by factors of 10-50.
- Later CSM efforts (Stirling, *et al.*, Artoisenet, *et al.*): keep adding gluons and build CSM amplitude coherently at larger p_T
- Feature: in all CSM diagrams, J/ψ remains isolated.

(a) (b) (c)

(d) (e) (f)

Production Solution: NRQCD and Color Octet Amplitudes

- NRQCD: colored diquark has production-independent hadronization parameters: non-perturbative long-distance matrix elements (LDMEs). Probability to make J/ψ depends on L, J, and color state. Adjusting LDMEs fits p_T-dependent J/ψ and $\psi(2S)$ differential cross sections from different data sets.

- Choice of *which* production data to fit leads to different LDME parameters sets and different physics consequences.

- Initial Cho and Leibovich (CL) model: Heavy $Q\overline{Q}$ system is color octet with L=J=1 $\Rightarrow$ J/ψ polarization

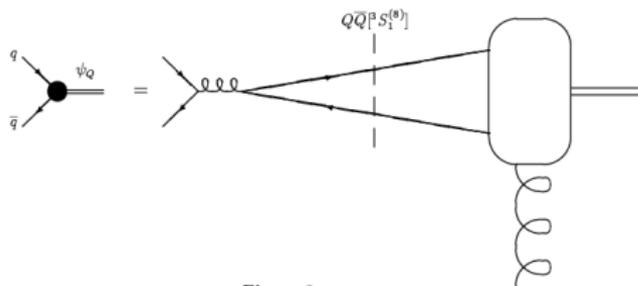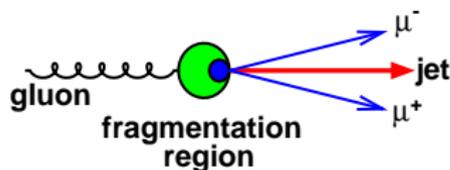- CL recoil gluon can form jet, but again, J/ψ is isolated

Figure 2

NRQCD and Fragmenting Jet Function (FJF) Approach

- theoretical interest in jet sources of heavy quarks from SCET.
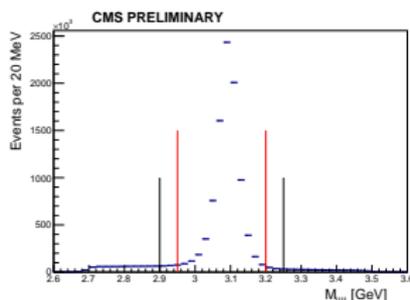- FJF: form J/ψ from non-perturbative fragmentation of jet

$$\frac{d\sigma(E_{jet}, z)}{dE_{jet}dz} = H \times \Sigma_{a,b} f_{a/p} \otimes f_{b/p} \Sigma_i J_i \otimes \; \mathcal{G}^{\psi}(E_{jet}, z | R, \mu). \quad (1)$$

- Baumgart, Leibovich, Mehen and Rothstein: decompose fragmentation function $\mathcal{G}$ for gluon jets in terms of NRQCD amplitudes and long-distance matrix elements
- for gluons, four LDME terms: $^1S_0^{(8)}$, $^3S_1^{(8)}$, $^3P_J^{(8)}$, $^3S_1^{(1)}$. Small central charm fragmentation mixed into $^3S_1^{(1)}$ term.
- expect non-isolated J/ψ

J/ψ Data

- analysis starts with $J/\psi \to \mu^+\mu^-$ trigger
- LHCb has published quark jet fragmentation (large rapidity) to J/ψ
- We are interested in high-p_T gluon-dominated production region
- select $E_{J/\psi} > 15$ GeV, $|y_{J/\psi}| < 1 \to p_T|_{J/\psi} > 10$ GeV
- excellent CMS dimuon mass resolution gives clean J/ψ signal
- remove combinatoric background by sideband subtraction and non-prompt events by transverse miss distance selection
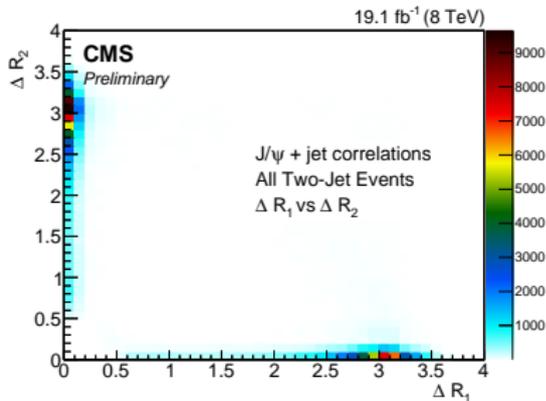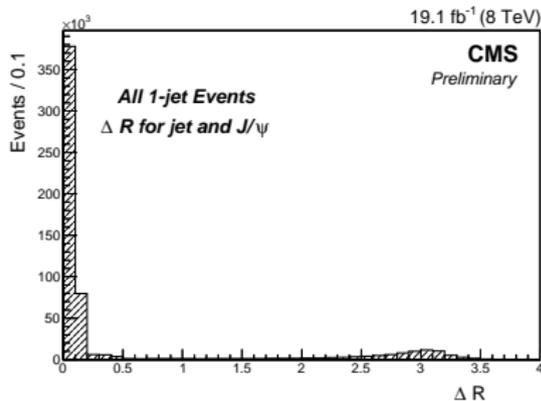
And add jets

- event selection depends only on J/ψ and is independent of jet observation
- CMS jet-finding is well understood. Use standard anti-k_T jets with selection radius $R < 0.5$.
- use CMS jet energy corrections and pileup correction
- For pileup background control, require jet $p_T > 25$ GeV
- For central region physics, require $|\eta_{jet}| < 1$
- there is no muon requirement on jet-finding
- Monte Carlo simulation of jet-finding efficiency shows plateau at $> 98.5\%$ for jet energy above 44 GeV.

Is there a J/ψ + jet correlation? - YES!

- Compare J/ψ with every observed jet in event using ΔR test:
  $\Delta R = \sqrt{(\eta_{J/\psi} - \eta_{jet})^2 + (\phi_{J/\psi} - \phi_{jet})^2}$.
- Left Figure: events with one observed jet: sharp correlation peak for $\Delta R < 0.5$ with 84% of events. If the jet contains the decay muons, jet is identified as fragmentation source of J/ψ
- Right Figure: two observed jets: 94% of J/ψ are jet fragments.
- For two observed jets: fragmenting jets: $<n> = 25 \pm 6$; recoil jets: $<n> = 29 \pm 7$; global jet properties are same for fragmenting and recoil jets

Moving toward testing FJF Predictions

- theory uses E_{jet} and $z = E_{J/\psi}/E_{jet}$ as independent variables;
- Experimental test using dijet events: fragmenting jet energy scale is not affected by $z \Rightarrow$ independent experimental variables are $E_{J/\psi}$ and E_{jet}.
- FJF normalized differential cross section for each LDME term j:

$$d\tilde{\sigma}_j(E; z_1) = \frac{d\sigma_j}{dE}|_{z_1} / \Sigma_{j=1}^4 \int_{.3}^{.8} \frac{d\sigma_j(E; \zeta)}{dE} \, d\zeta$$

- Theory cuts off at $z > 0.8$ and sets lower limit $z = 0.3$.
- experiment makes ratio function $\Xi(E_{jet}; z_1)$:

$$\Xi(E; z_1) = \mathcal{N}_{corr}(E; z_1) / (\mathcal{N}_{corr} + \mathcal{R}_{corr}(E; .3 - .8))$$

- $\mathcal{N}_{corr}(E; z_1)$ is the number of events in $\pm \Delta z = 0.25$ about z_1.
- $\mathcal{R}_{corr}(E; .3 - .8)$ is the number of events in .3-.8 excluding $\mathcal{N}_{corr}(E; z_1)$.

Effects of experimental resolution

- Constructing experimental $\Xi(E_{jet}; z)$ functions requires unfolding jet energy resolution for E_{jet} and z measurements

- Unfolding done using RooUnfold d'Agostino method with 4 iterations, tested extensively with MC simulation of different distributions

- To compute Ξ, $\mathcal{N}_{corr}(E; z_1)$ and $\mathcal{R}_{corr}(E; .3 - .8)$ are unfolded separately.

- Test z unfolding with 1D and 2D unfolding; $|z_{unf} - z_{meas}| < .01$ for all z $\Rightarrow$ use z_{meas}.

- Energy unfolding correlates data statistical uncertainties in adjoining energy bins. Use MC method to determine independent uncertainties.

- Unfolding studies: analysis energy range 56–120 GeV

- use three z_1 ranges: 0.40–0.45; 0.50–0.55; 0.60–0.65 to study jet energy distribution of $\Xi(E_{jet}; z_1)$ functions
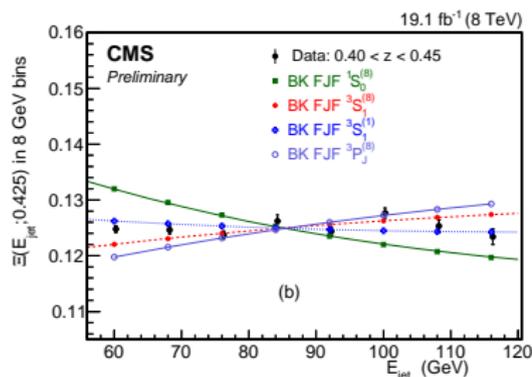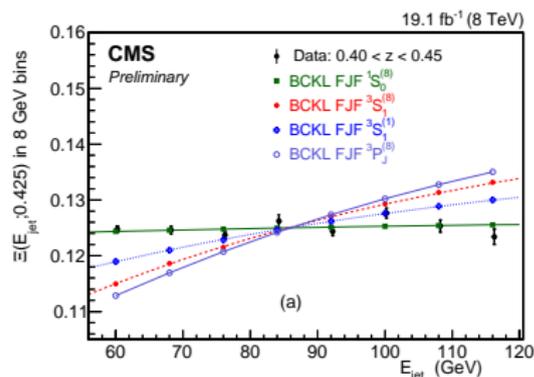
Data evaluation of LDME terms

- Different LDME sets (Bodwin, Chung, Kim and Lee (BCKL) or Butenschoen and Kniehl (BK)) produce different FJF distributions for each of the four LDME terms

- If one LDME j dominates in a given z region, then the FJF prediction is controlled by the restricted z-region behavior and can be compared to the Ξ E_{jet} variation in that z slice of the data:

$$d\tilde{\sigma}_j(E; z_1) = \frac{d\sigma_j}{dE}|_{z_1} / \Sigma_{j=1}^4 \int_{.3}^{.8} \frac{d\sigma_j(E; \zeta)}{dE} \, d\zeta$$

- To look for dominance, compare each LDME term to data shape for the three z slices. If no single LDME term dominates, data will not match any of the four FJF shapes.

- FJF shapes for BCKL $^1S_0^{(8)}$ and BK $^3S_1^{(1)}$ terms are too similar to distinguish for $z > 0.5$.
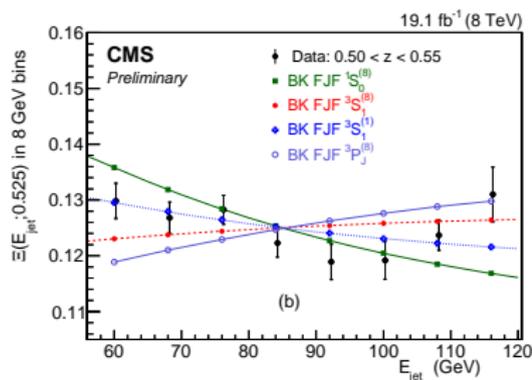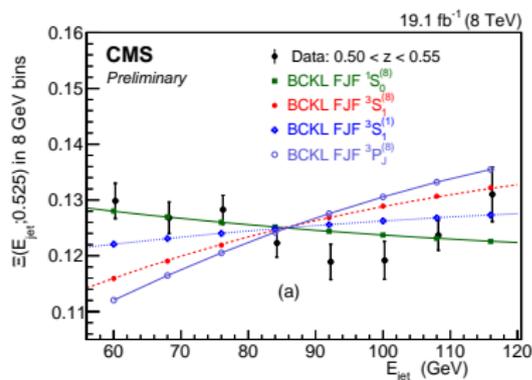
$z_1 = 0.425$ distributions

- Comparison of data (black dots with error bars) with FJF curves for the four LDME terms using (a) BCKL LDME set and (b) the BK LDME set.
- Match χ^2 and probabilities are tabulated. BCKL $^1S_0^{(8)}$ term is only acceptable match to data for $z_1 = 0.425$.
- results show that jet fragmentation data is powerful discriminator between LDME terms and parameter sets.

	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^3S_1^{(1)}$	$^3P_J^{(8)}$
BCKL	14.2 (.048)	810 (10^{-170})	163(10^{-32})	675 (10^{-141})
BK	278 (10^{-55})	42 (10^{-6})	29 (.00014)	122 (10^{-23})

$z_1 = 0.525$ distributions

- Comparison of data (black dots with error bars) with FJF curves for the four LDME terms using (a) BCKL LDME set and (b) the BK LDME set.
- Match χ^2 and probabilities are tabulated. BCKL $^1S_0^{(8)}$ and similar BK $^3S_1^{(1)}$ terms are only acceptable matches to data for $z_1 = 0.525$.

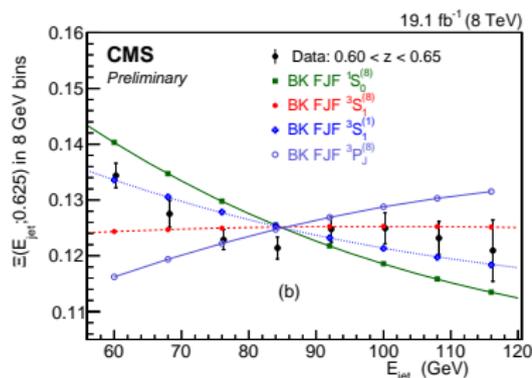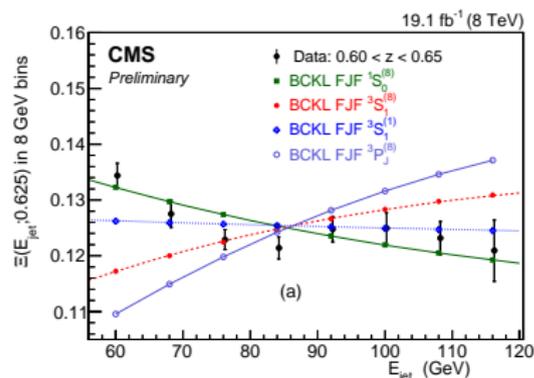|	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^3S_1^{(1)}$	$^3P_J^{(8)}$
BCKL	10.2 (.18)	54 (10^{-9})	22 (.0024)	88 (10^{-16})
BK	22 (.0024)	19 (.0082)	10 (.19)	36 (10^{-5})

$z_1 = 0.625$ distributions

- Comparison of data (black dots with error bars) with FJF curves for the four LDME terms using (a) BCKL LDME set and (b) the BK LDME set.
- Match χ^2 and probabilities are tabulated. BCKL $^1S_0^{(8)}$ and similar BK $^3S_1^{(1)}$ terms are only acceptable matches to data for $z_1 = 0.625$.

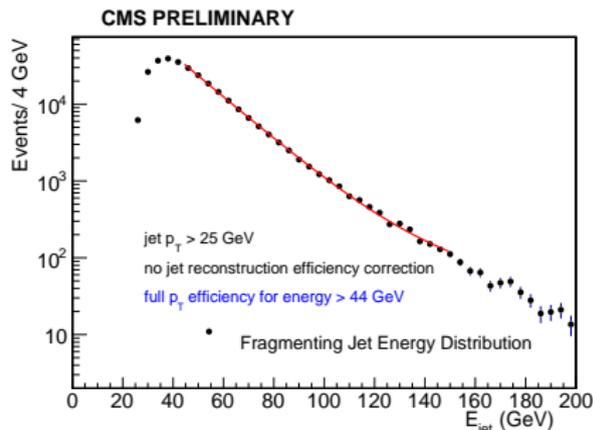|	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^3S_1^{(1)}$	$^3P_J^{(8)}$
BCKL	14.3 (.046)	83 (10^{-15})	21 (.0038)	501 (10^{-104})
BK	50(10^{-8})	28 (.0002)	17 (.017)	328 (10^{-66})

FJF Summary

- This first comparison of gluonic FJF predictions and jet fragmentation data agree *even though* these data are independent of information used to derive the two LDME parameter sets

- Conclusion: gluon jet fragmentation is described by FJF model and dominates high-energy central J/ψ production in events with observed jets.

- Fragmenting jet data discriminate between different LDME terms and different LDME parameter sets.

- Only BCKL $^1S_0^{(8)}$ LDME term describes data for all three z_1 regions, with consequence of small J/ψ polarization for $|y_{J/psi}| < 1$ and $E_{J/\psi} > 15$ GeV.

- BK $^3S_1^{(1)}$ is shape-degenerate with BCKL $^1S_0^{(8)}$ term for $z > 0.5$ and could play a role at large z, but with the consequence of large J/ψ polarization for $E_{J/\psi} > 30$ GeV, in disagreement with CMS polarization measurement.

Is jet fragmentation source of all high-energy J/ψ mesons?

- 55% of J/ψ events have no observed jet with $p_T|_{jet} > 25$ GeV
- Raise $p_T|_{jet}$ requirement to 30 GeV. Then 65% of J/ψ events have no observed jets (zero-jet events)
- 84% of remaining observed jets for $p_T|_{jet} > 30$ GeV have $\Delta R < 0.5$
- $\Rightarrow$ 84% of the lost jets due to raising the cut were J/ψ fragmentation sources for 25 GeV $p_T|_{jet}$ threshold.
- Implication: some J/ψ mesons in events with no observed jets are fragmentation products of jets with $p_T|_{jet} < 25$ GeV.

Estimating J/ψ fragmentation fraction of zero-jet events

- all jets with actual energy > 42.5 GeV have $p_T|_{jet}$ > 25 GeV
- measured energy resolution smears edge. Choose 44 GeV as 100% $p_T|_{jet}$ efficiency energy
- ASSUME: E_{jet} energy distribution in $p_T|_{jet}$-inefficient region same as that > 44 GeV
- make simple model to count and fragment jets in $p_T|_{jet}$-inefficient region based on fit to efficient region.

Model assumptions, tests and results

- Use fit projection to estimate number of candidate events at jet energy E_i that FAIL the jet p_T selection. Scale up for jet-finding efficiency from MC.
- Use data to get probability p_j of having jet fragment into J/ψ with energy EJ_j.
- Use calculation from FJF paper to get probability that jet fragments with $z_{ij} = EJ_j/E_i$
- sum all possibilities to jet of energy E_i to fragment. This estimates number of fragmenting jets that are NOT observed due to p_T requirement
- make closure test with data by using model to predict number lost in raising jet p_T requirement to 40 GeV. Model prediction matches real data to 3%.
- Model Result: predicted percentage of J/ψ events with no observed jets: MODEL: $(43 \pm 3 \text{ (stat)} \pm 7 \text{ (syst)})\%$; DATA: 55%

Summary for J/ψ production by jet fragmentation

- simple model predicts that most J/ψ events with no observed jets are fragments of jets with $p_T|_{jet} > 25$ GeV
- small peak with $2.4 < \Delta R < 3.4$ for one-jet events (Slide 7, left plot) arises because recoil J/ψ is fragment of unobserved jet (substantiated by p_T balance between J/ψ and jet).
- $\Rightarrow$ both one-jet and two-jet data show that 94% of J/ψ mesons come from jet fragmentation
- total percent of J/ψ due to jet fragmentation: $0.94 \times 45\%$ (observed jets) + 43% (unobserved jets) = 85%
- Allowing for simplicity of model, we can say that $> 80\%$ of J/ψ mesons with $E_{J/\psi} > 15$ GeV and $|y_{J/psi}| < 1$ arise from fragmentation of jets having $E_{jet} > 19$ GeV and $|\eta_{jet}| < 1$

Conclusions

- detailed study of jet fragmentation in central region $|\eta_{jet}| < 1$ shows agreement between data and FJF predictions for gluonic jet fragmentation.
- Only one NRQCD LDME term, the $^1S_0^{(8)}$ term using BCKL parameters, is able to explain the data for the three measured z_1 ranges.
- Jet fragmentation can account for almost all (> 80 %) of J/ψ production in this central region
- the two results combine to indicate that the small J/ψ polarization measured at CDF and CMS is due the dominance of the $^1S_0^{(8)}$ term using BCKL parameters in fragmenting jet production of J/ψ mesons in the central region.
- The BK $^3S_1^{(1)}$ term might play a role for $z > 0.5$, but at the cost of introducing (unobserved) J/ψ polarization.
- on-going jet fragmentation studies for J/ψ and other quarkonia can test FJF and NRQCD predictions in new regions of model space.