QUARKONIUM PRODUCTION STUDIES AT CMS

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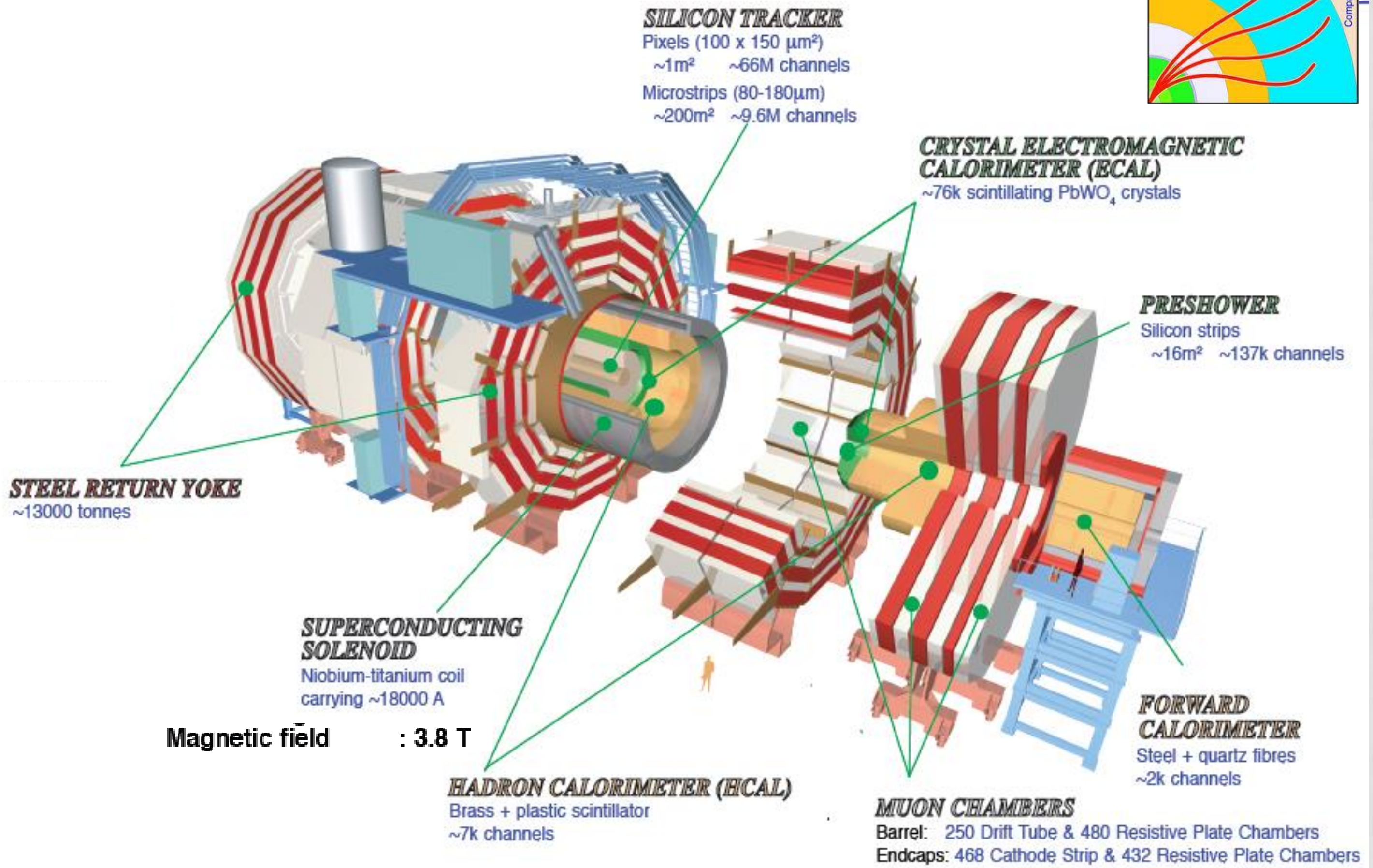
ON BEHALF OF THE CMS COLLABORATION

INTERNATIONAL WORKSHOP ON HEAVY QUARKONIUM (QWG)
TORINO, 13 MAY 2019

COMMON EXPERIMENTAL ASPECTS

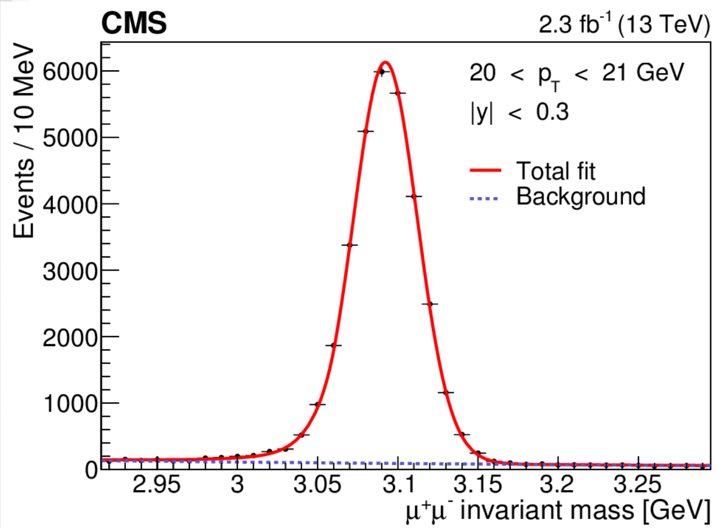
THE CMS DETECTOR

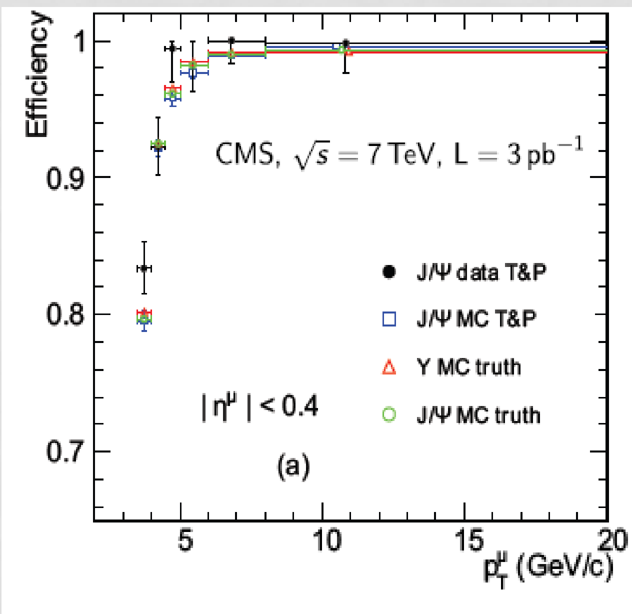
Muon reconstruction from combined information of silicon tracker and muon detectors (DT, CSC, RPC)



- Di-muon triggers:
  - segments found in muon detectors (Level-1) + fast regional track reconstruction (HLT)
  - At 13 TeV, higher rate compensated with cuts on vertex quality, invariant mass etc.

MUON EFFICIENCY MEASUREMENTS





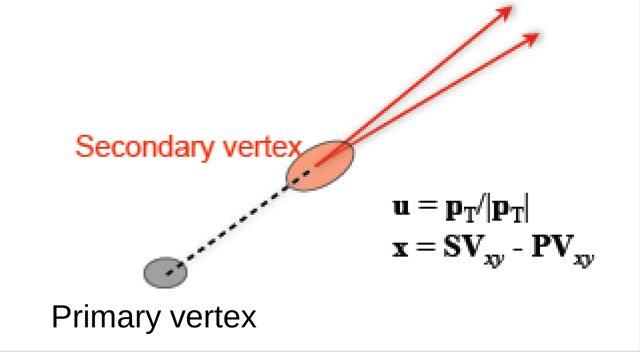
- Use data-driven measurements of the muon efficiency ("tag-and-probe" method)
  - In events with a J/ψ candidate, ask for one well-identified muon ("tag"): the other muon ("probe") can pass or not pass a given selection *S*
  - Invariant mass plots separated for the two cases: the fitted $N_{pass\text{-}S}/N_{all}$ gives an unbiased estimate of the efficiency ε_S

- Limitation of the method: assumes efficiency factorization, MC corrections required (dominant systematic uncertainty)

PROMPT CHARMONIUM FRACTION

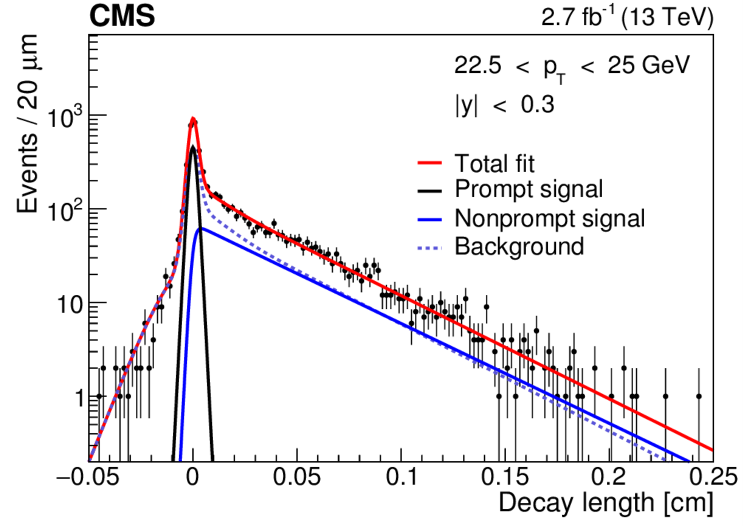
- Use estimate of proper decay length

$$\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T$$



- Event-by-event upper cut (remaining non-prompt contamination ~ 5%) or fit:
  - Prompt: δ-function
  - Non-prompt: exponential (with an effective smearing due to J/ψ motion in the B frame)
  - Continuum background: determined from mass side-bands

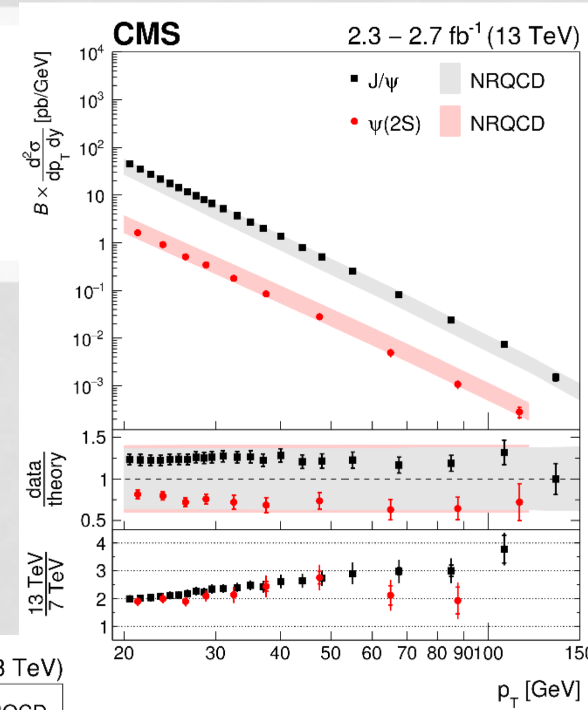
convoluted with $l_{J/\psi}$ resolution factors

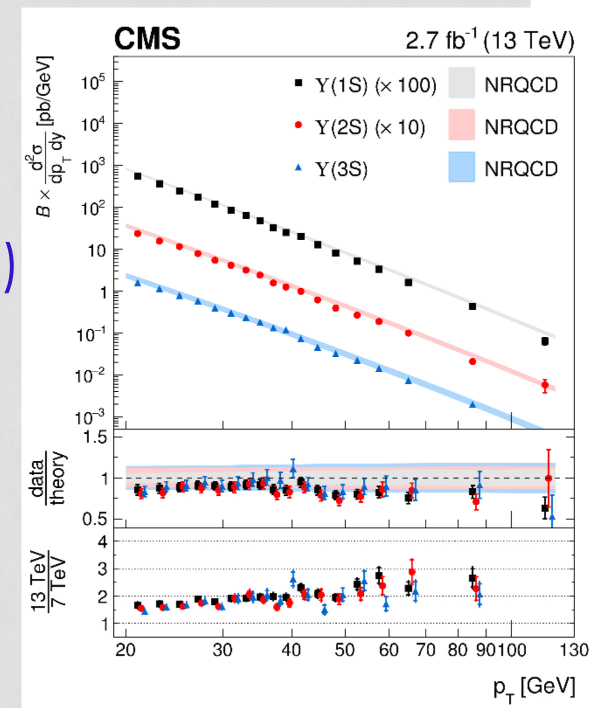


INCLUSIVE PROMPT PRODUCTION

CROSS-SECTIONS

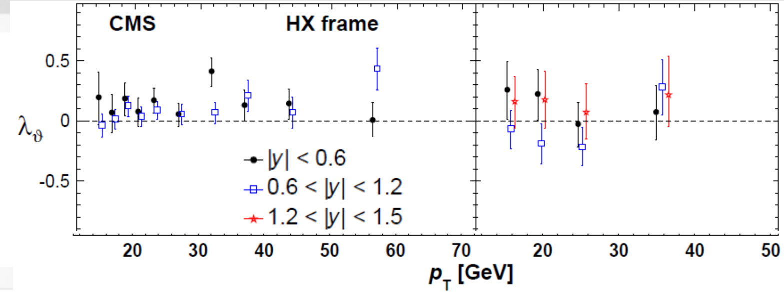
- Prompt production:
  - Includes feed-down for J/ψ (χ_{cJ}, $\psi(2S) \rightarrow J/\psi$) and Υ ($\chi_{bJ} \rightarrow \Upsilon$)
  - Direct only in the $\psi(2S)$ (and $\Upsilon(3S)$?) case: theoretically cleaner
- Differential cross-sections in CMS at both 7 and 13 TeV agree with NLO NRQCD calculations, including color-singlet (CS) and -octet (CO) contributions
  - Result dependent on LDMEs → extracted from TeVatron data





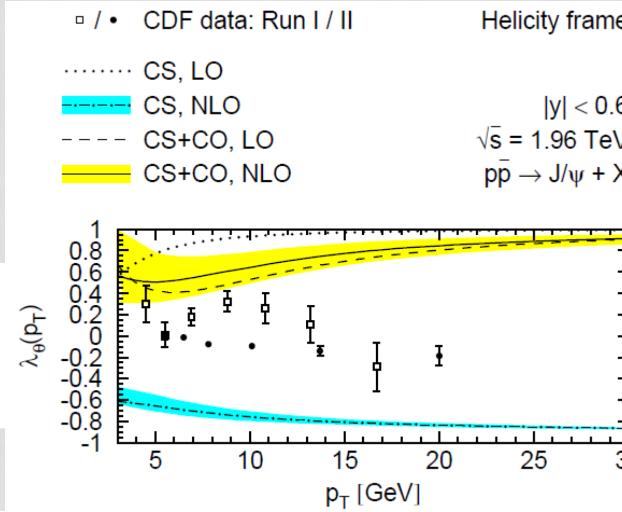
CMS collaboration
Phys. Lett. B780, 251 (2018)

POLARIZATION

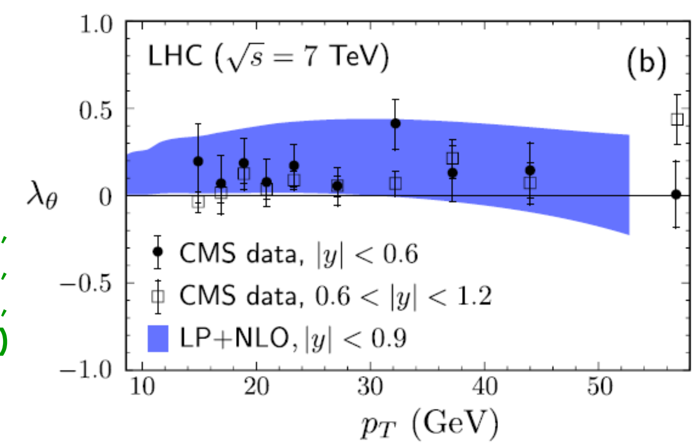


CMS collaboration, Phys. Lett. B727, 381 (2013); B761, 31 (2016)

- Only 7-TeV measurements
  - Inclusive determination for charmonium
  - For bottomonium, also measured as a function of charged-particle multiplicity in the event
- All measurements find polarization compatible with zero, including large p_T region (> 50 GeV)
- Two different approaches to LDME extraction conclude:
  1. Disagreement with CMS data
  2. Agreement within fairly large uncertainties



1. Butesnchoen and Kniehl, Mod. Phys. Lett. A28, 1350027 (2013)



2. Bodwin, Chung, Kim, and Lee, Phys. Rev. Lett. 113, 022001 (2014)

J/Ψ PRODUCTION IN JETS

CMS collaboration, CMS-PAS-BPH-15-003

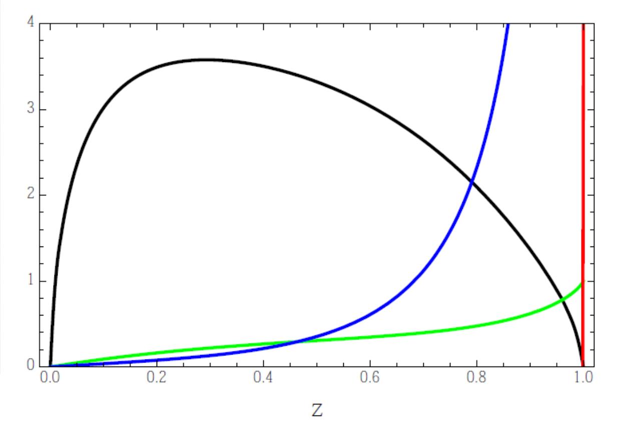
New!

PHYSICS MOTIVATIONS (1)

- Measurement of J/ψ – jet association
  - Testing role of jet fragmentation in quarkonium production
- Theoretically described in Fragmenting-Jet Function (FJF) approach:
  - Differential cross-section in $E = E_{jet}$ and $z = E_{J/\psi}/E$

$$\frac{d^2\sigma}{dE\,dz} = \sum_{a,b,i,j} H_{ab\to ij} \times f_{a/p} \otimes f_{b/p} \otimes J_j \otimes \mathcal{G}_i^{\psi}(E, R, z, \mu)$$

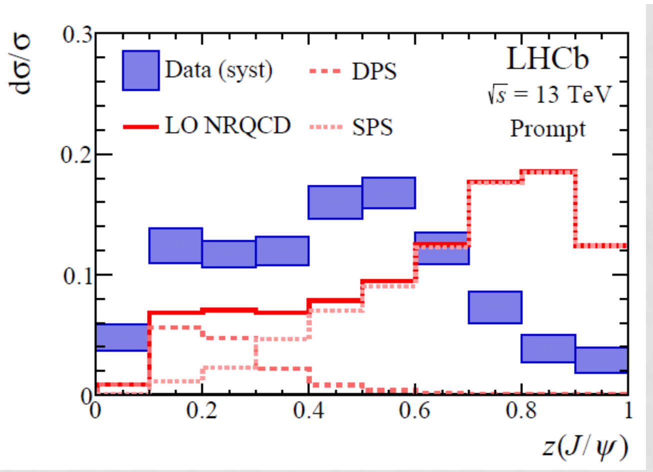
- $\mathcal{G}_i^{\psi}$ (containing all the z dependence) can be decomposed using LDMEs → leading contribution from c and *g* partons
  - CMS: gluon-dominated mid-rapidity region
  - relevant *g* LDMEs: $^3S_1^{(1)}$, $^3S_1^{(8)}$, $^1S_0^{(1)}$, $^3P_J^{(8)}$



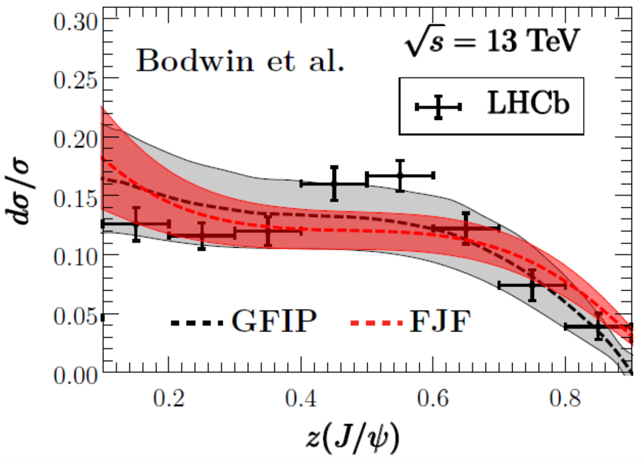
Baumgart, Leibovich, Mehen, and Rothstein, JHEP 11, 003 (2014)

PHYSICS MOTIVATIONS (2)

LHCb collaboration, Phys. Rev. Lett. 118, 192001 (2017)



- LHCb measured z distribution in events with a jet associated to J/ψ in high-rapidity region
  - Pythia8 (implementing CS+CO factorization) does not describe data
  - FJF using LDME extraction by Bodwin et al. gives fairly good agreement
- **CMS:**
  - Measures Ξ(E,z), experimental equivalent of normalized $d^2\sigma/dE\,dz$
  - Estimates acceptance-corrected fraction of J/ψ associated to jets

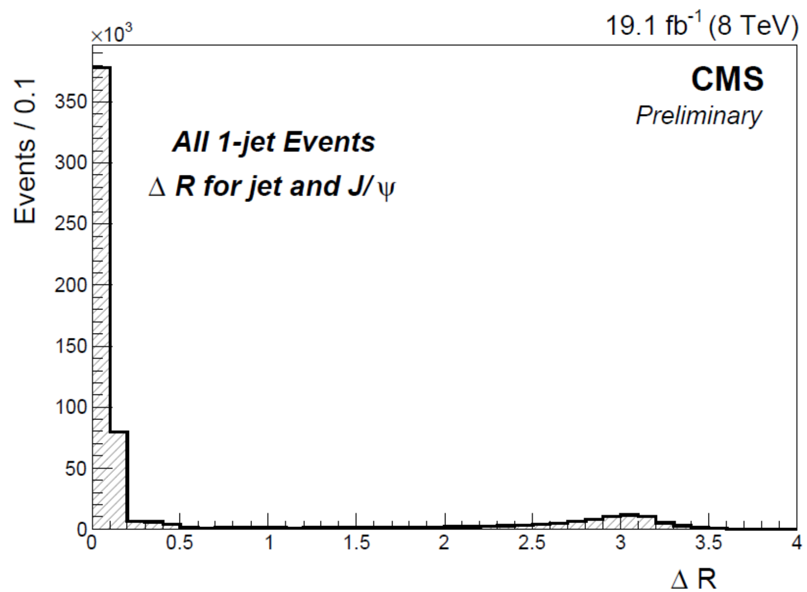


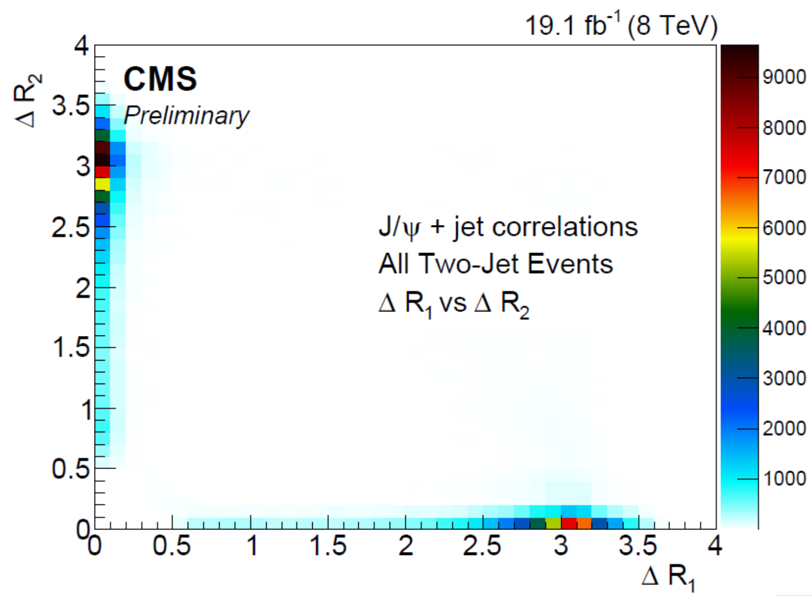
Bain et al., Phys. Rev. Lett. 119, 032002 (2017)

EVENT SELECTION

- 8 TeV data, 19.1 fb^{-1}
- Tight muon identification, $p_{T,\mu}$ and η_μ cuts matching CMS acceptance
- $E_{J/\psi} > 15$ GeV, $|y_{J/\psi}| < 1$
  - remove combinatorial background by sideband subtraction and non-prompt events with $l_{J/\psi}$ selection
  - Inverse «tag-and-probe» efficiencies used as event weights
- Anti-k_T jets with R = 0.5
  - standard jet energy and pileup corrections
  - $p_{T,jet} > 25$ GeV, $|\eta_{jet}| < 1$
- $\Delta R = \sqrt{(\eta_{J/\psi} - \eta_{jet})^2 + (\phi_{J/\psi} - \phi_{jet})^2} < 0.5$ → J/ψ-jet association
- Investigate the $0.3 < z < 0.8$ region, where FJF detailed predictions are available

J/Ψ-JET CORRELATIONS





- At reconstruction level:
  - P(J/ψ associated | 1 jet) ~ 84%
  - P(J/ψ associated | 2 jets) ~ 94%
  - But: P(> 0 jets | J/ψ) ~ 45%

- Indication of a large production of J/ψ from jet fragmentation: extrapolations outside acceptance needed to quantify

Ξ OBSERVABLE IN J/Ψ-JET EVENTS

- In events with observed J/ψ association, construct Ξ(E,z), experimental equivalent of $(1/\sigma)(d^2\sigma/dE_{jet}\,dz)$

$$\Xi(E,z) = \frac{1}{N(z)} \frac{N(E,z)}{\int_{0.3}^{0.8} N(E,z')dz'}$$

- N(E,z) = events in a $[E_{jet},z]$ bin (size: 8 GeV x 0.05)
- Two LDME sets considered:
  - Bodwin, Chung, Kim and Lee (BCKL) or Butenschoen and Kniehl (BK)
  - producing different FJF distributions for each of the four LDME terms
- To look for dominance of a specific LDME in a certain z region, compare each LDME term to data shape for three z slices
  - $0.4 < z < 0.45$, $0.5 < z < 0.55$, $0.6 < z < 0.65$
  - If no single LDME term dominates, no match to any of the four FJF shapes

UNFOLDING AND SYSTEMATICS

- The N(E,z) need to be unfolded, considering jet energy resolution
- Restrict to E_{jet} > 56 GeV (basically constant $A \cdot \varepsilon$)
- Use iterative d'Agostini method with 4 iterations

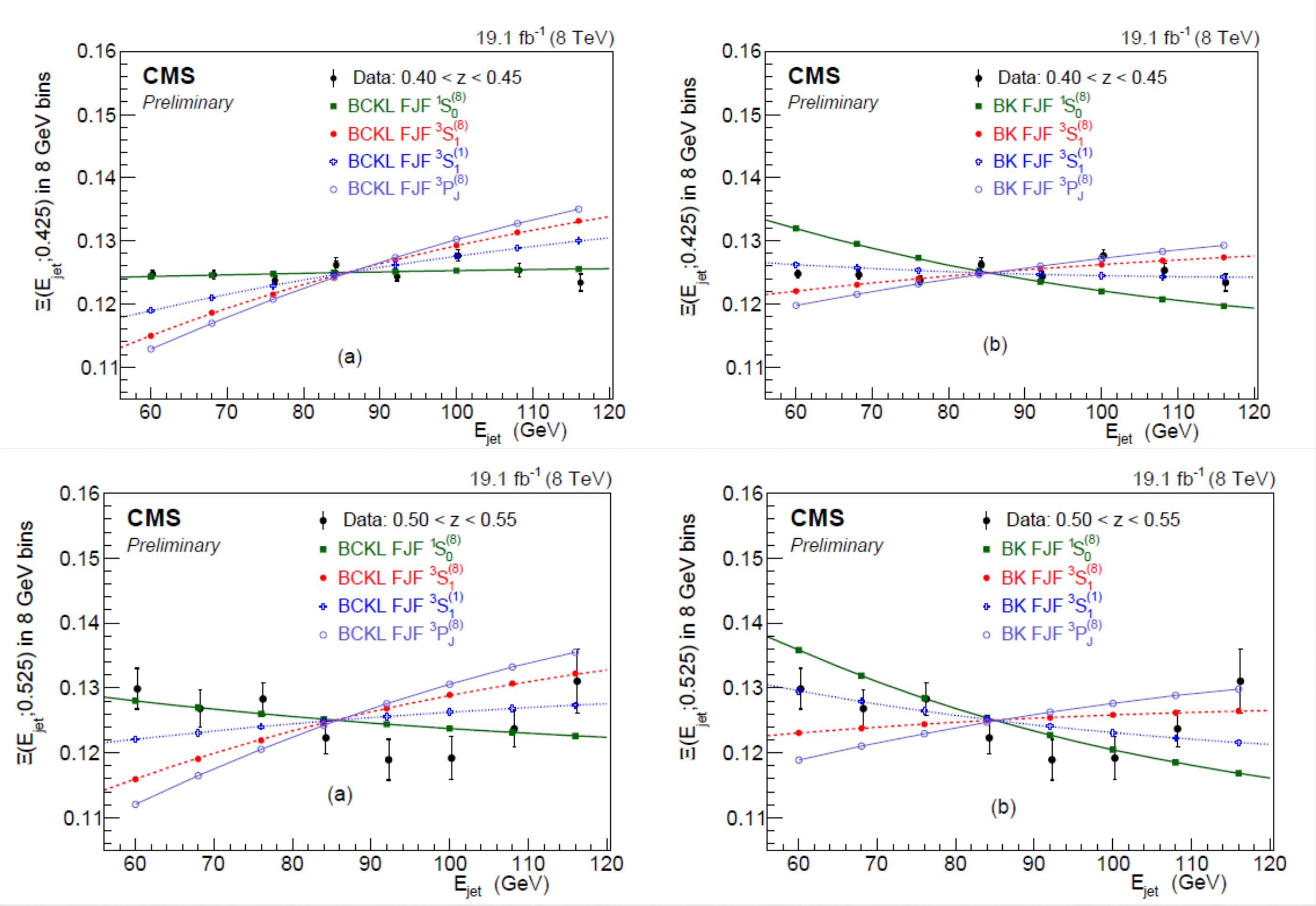
G. d'Agostini, arXiv:1010.0632

  - 2-dimensional unfolding in (E,z) yields small corrections in z → use 1-dimensional
  - Energy unfolding correlates statistical uncertainties in adjoining energy bins. Use MC method to determine independent uncertainties

- Other systematic uncertainties:
  - Muon efficiency uncertainties
  - Correction of bias in ΔR association close to rapidity range limit

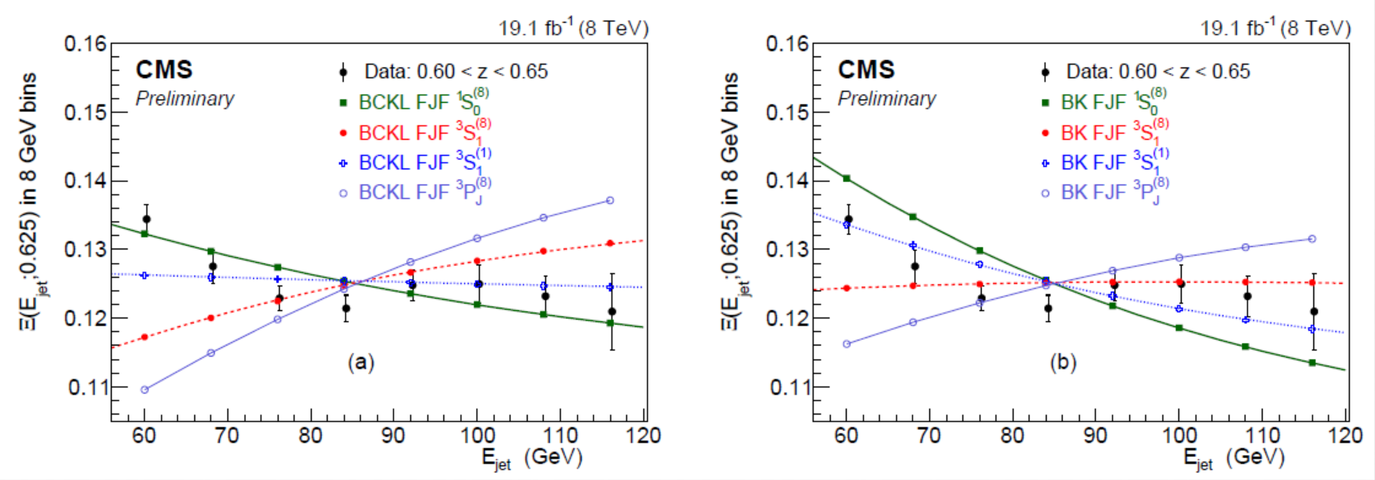
0.4 < Z < 0.45 AND 0.5 < Z < 0.55

- χ^2 tests:
  - Only BCKL $^1S_0^{(8)}$ acceptable
  - Only BCKL $^1S_0^{(8)}$ and BK $^3S_1^{(1)}$ acceptable



0.6 < Z < 0.65 AND SUMMARY

- χ^2 test:
  - Only BCKL $^1S_0^{(8)}$ and BK $^3S_1^{(1)}$ acceptable



- Gluon jet fragmentation is well described by FJF model
- Fragmenting jet data can discriminate between different LDME terms and parameter sets
- BCKL $^1S_0^{(8)}$ LDME term alone describes data for all three z regions
  - Agrees with small J/ψ polarization at large energy and mid-rapidity
- BK $^3S_1^{(1)}$ is shape-degenerate for z > 0.5 and could play a role
  - But would imply transverse J/ψ polarization

ABSOLUTE FRACTION OF J/Ψ IN JETS

- $P(> 0 \text{ jets} \mid J/\psi) \sim 45\%$
  - → other large sources of high-energy J/ψ or just an acceptance effect?
- Raise $p_{T,jet}$ selection from 25 to 30 GeV
  - $P(> 0 \text{ jets} \mid J/\psi) \sim 35\%$
  - $P(J/\psi \text{ associated} \mid 1 \text{ jet}) \sim 84\%$ (unvaried!)
  - Favors latter assumption
- Build a simple model to account for unobserved jets
  - Model assumptions
    1. The jet energy spectrum can be fit with a double-exponential function in the constant $A \cdot \varepsilon$ (high-energy) region and extrapolated to low energies
    2. The J/ψ z-probability, when being a product of an unobserved jet fragmentation, is described by the gluon FJFs calculated in the reference theory paper

MODEL AND RESULTS

$$A_i = N_i \sum_{j=1}^{55} p_j \, w(z_{ij}).$$

- N_i = Extrapolated number of unobserved jets in E_{jet} bin i
- p_j = Probability to fragment into J/ψ in acceptance for each $E_{J/\psi}$ bin j (1-GeV bins from 15 to 70 GeV, taken from data)
- $w(z_{ij})$ = z-probability from theory

⇓

- A_i = Estimated number of unobserved jets in E_{jet} bin i fragmenting into J/ψ

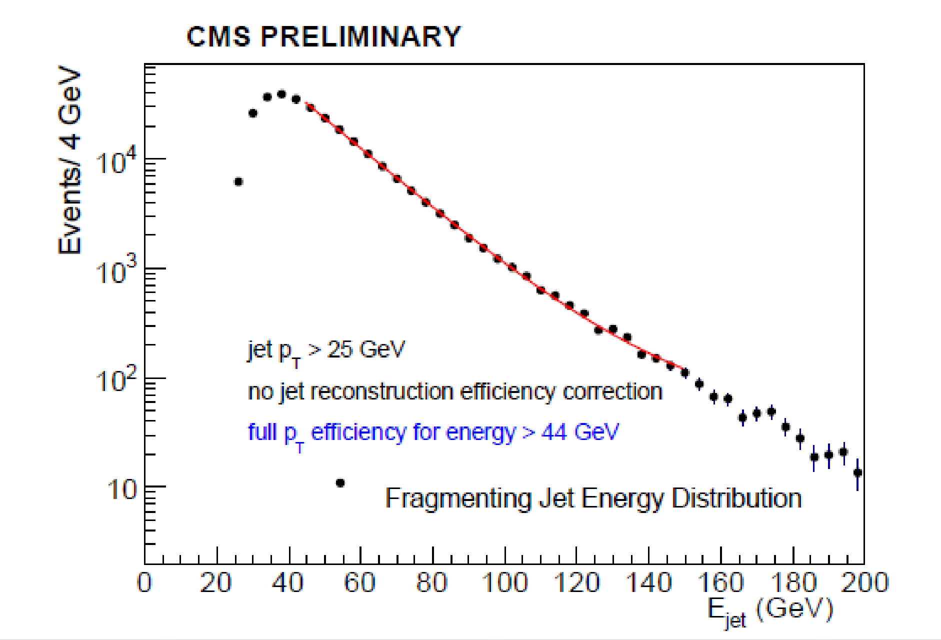
- Closure test performed by raising $p_{T,jet}$ cut, extrapolating and comparing to observed result
- Estimated fraction of J/ψ from unobserved jets: $f_{un} = (43 \pm 3_{stat} \pm 7_{syst})\%$
- Estimated fraction of J/ψ from jet fragmentation: $f_{tot} = f_{obs} \cdot P + f_{un} = $ $\mathbf{(85 \pm 3_{stat} \pm 7_{syst})\%}$

CONCLUSIONS

- Detailed study of jet fragmentation in central region shows agreement between data and FJF predictions for gluon jet fragmentation
- Only one NRQCD LDME, the ${}^1S_0^{(8)}$ term using BCKL parameters, is able to explain the data for the three measured z 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 CMS could be due the dominance of the BCKL ${}^1S_0^{(8)}$ term in fragmenting jet production of J/ψ mesons in the central region.
- The BK ${}^3S_1^{(1)}$ term also shows good agreement for $z > 0.5$, but at the cost of introducing (unobserved) J/ψ polarization.
- Jet fragmentation studies for J/ψ and other quarkonia can test FJF and NRQCD predictions in new regions of model space

BACKUP SLIDES

JET ENERGY SPECTRUM



CHI-SQUARE PROBABILITIES

- 0.4

	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^3S_1^{(1)}$	$^3P_J^{(8)}$
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})

- 0.5

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

- 0.6

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

REAL FORM OF XI

- 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 $\mathcal{N}_{corr}(E; z_1)$.