Jets for precision QCD and spin dynamics

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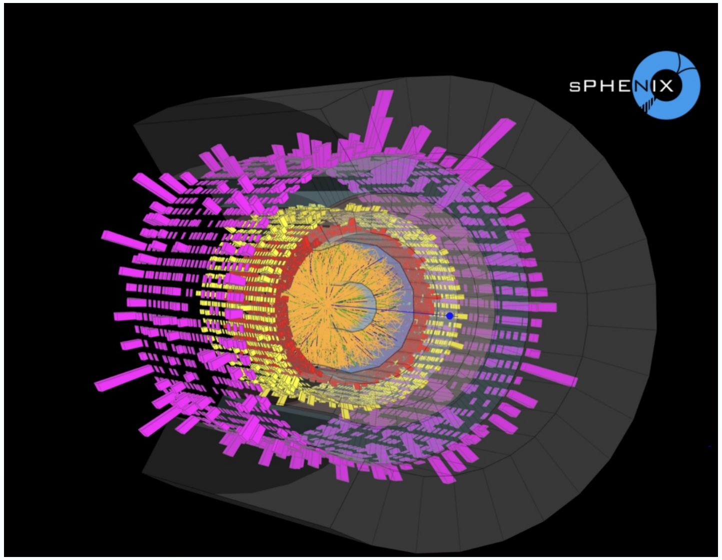
RBRC Workshop: Predictions for sPHENIX
July 20 – 22, 2022

sPHENIX beam use

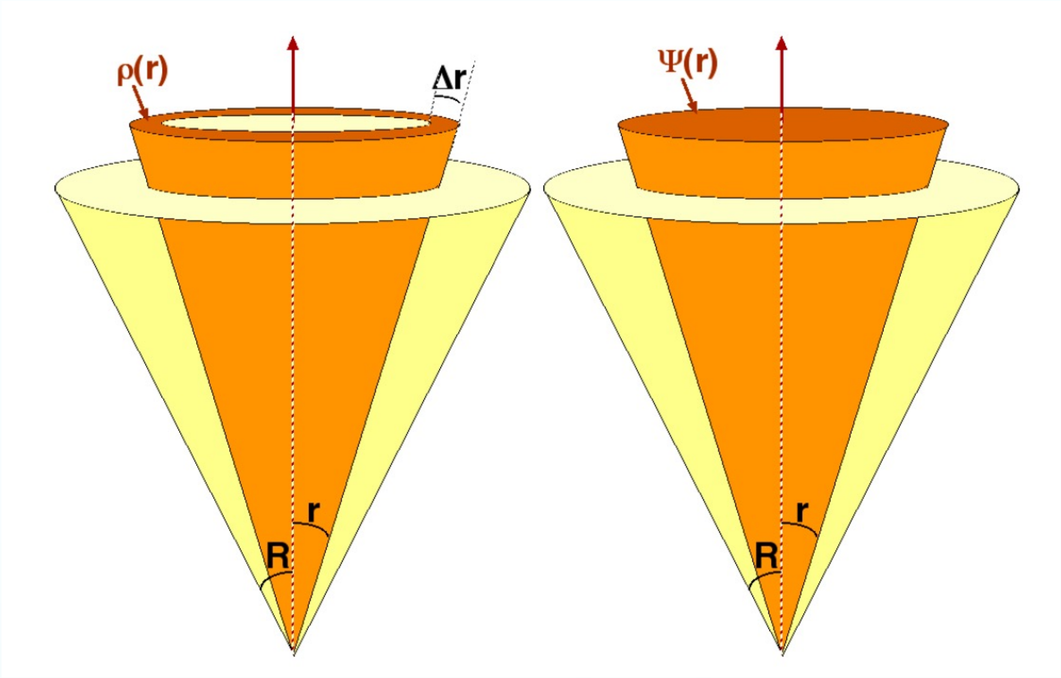
- Jet and heavy flavor machine



Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| < 10$ cm	Samp. Lum. $\|z\| < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Jet shape

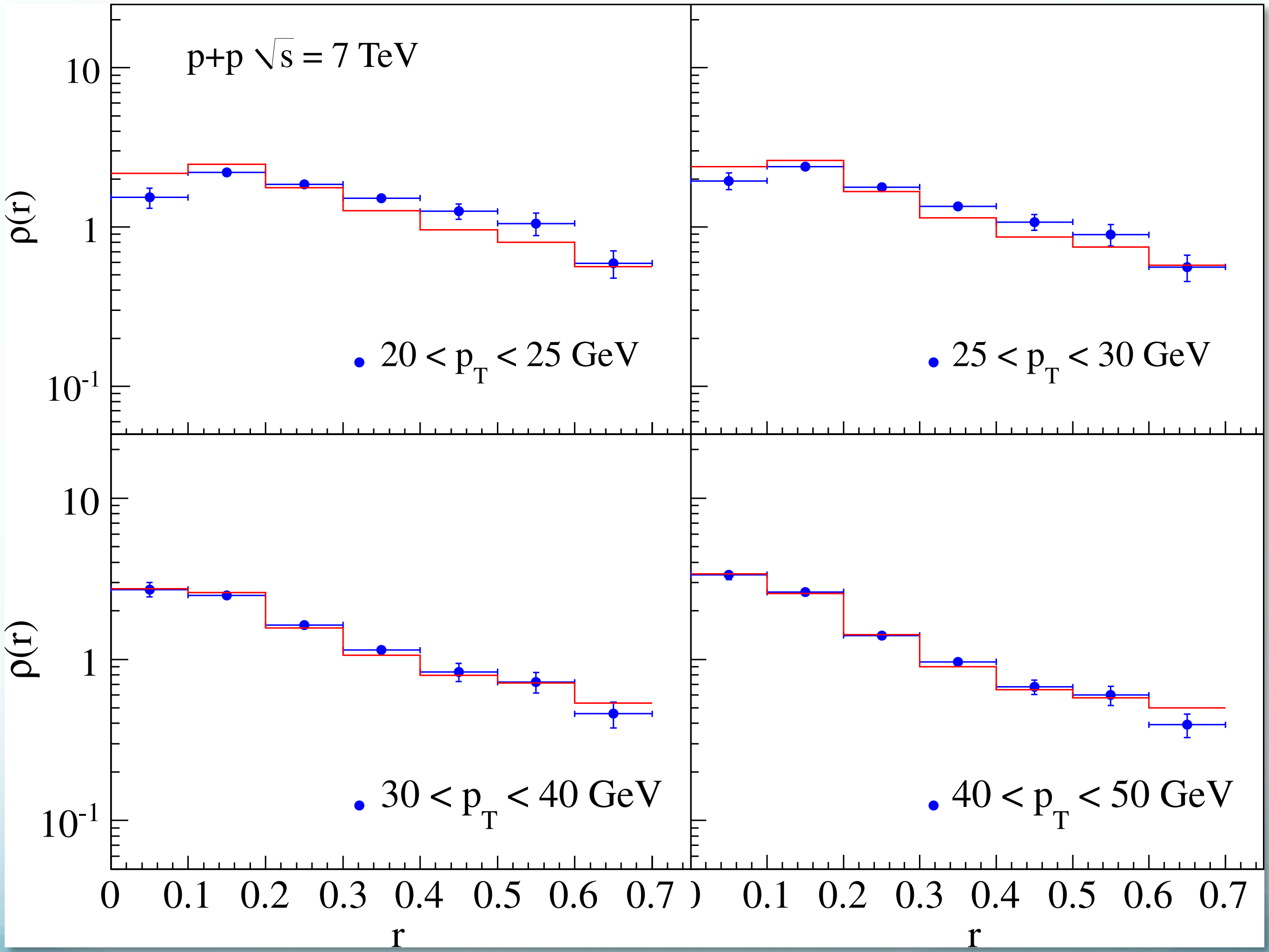
- Differential and integrated jet shape



$$\psi(r) = \frac{\sum_{r_i<r} p_{Ti}}{\sum_{r_i<R} p_{Ti}} \qquad \rho(r) = \frac{\mathrm{d}\psi(r)}{\mathrm{d}r}$$

Inclusive (light) jet shape

- Pythia usually describes well the light jet shape



Heavy flavor jet shape

- Standard jet axis

CDF collaboration, A. Lister, thesis

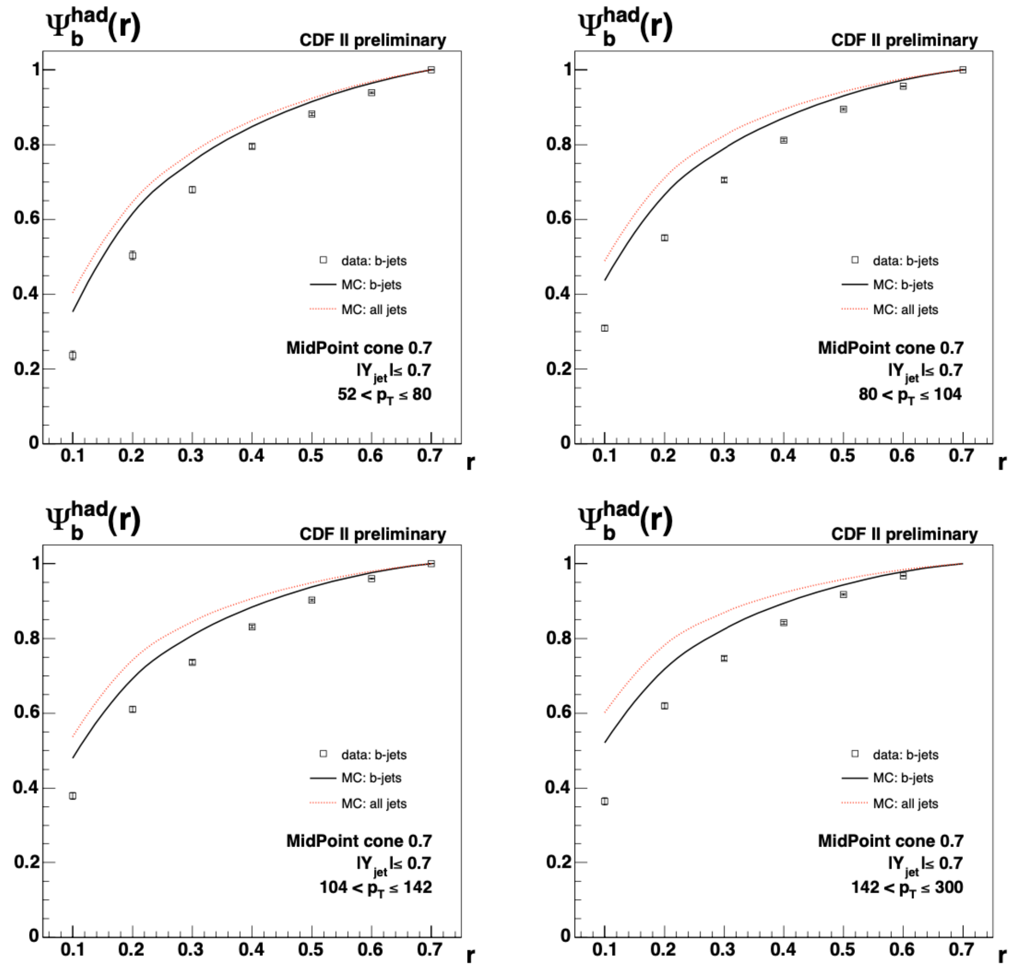
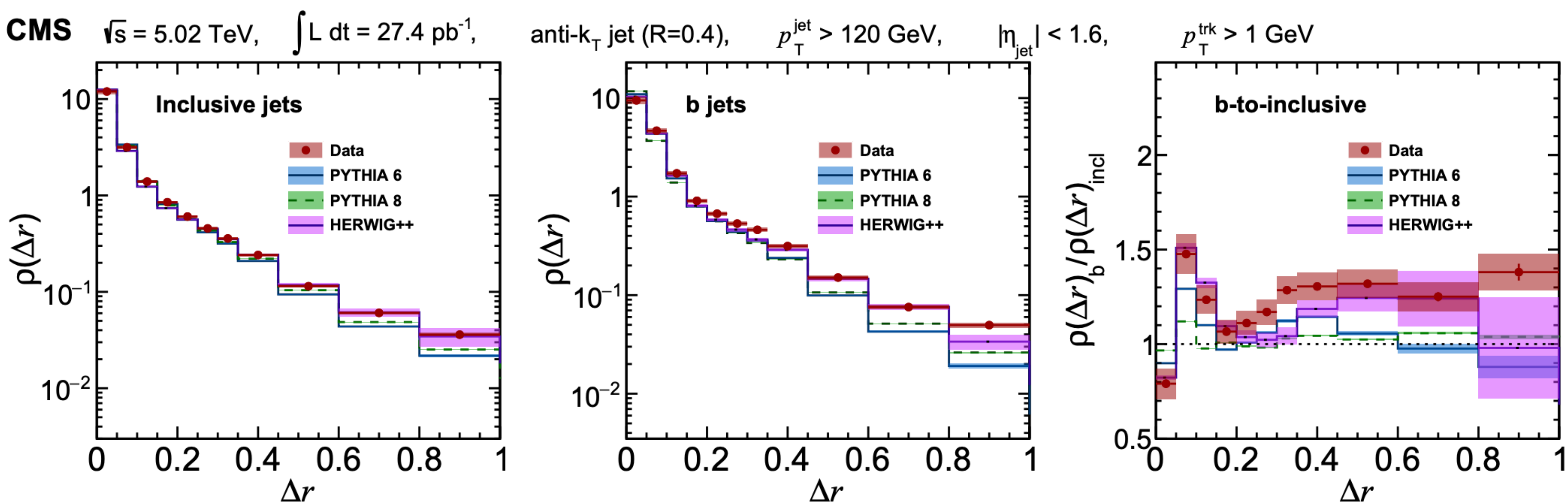


FIGURE 8.12: Hadron level integrated jet shapes in data but using the raw inclusive shapes obtained from Pythia Tune A MC. The results are shown as black points. Only the statistical errors are shown. The MC predictions for inclusive jets and for b-jets are shown as red and black curves, respectively.

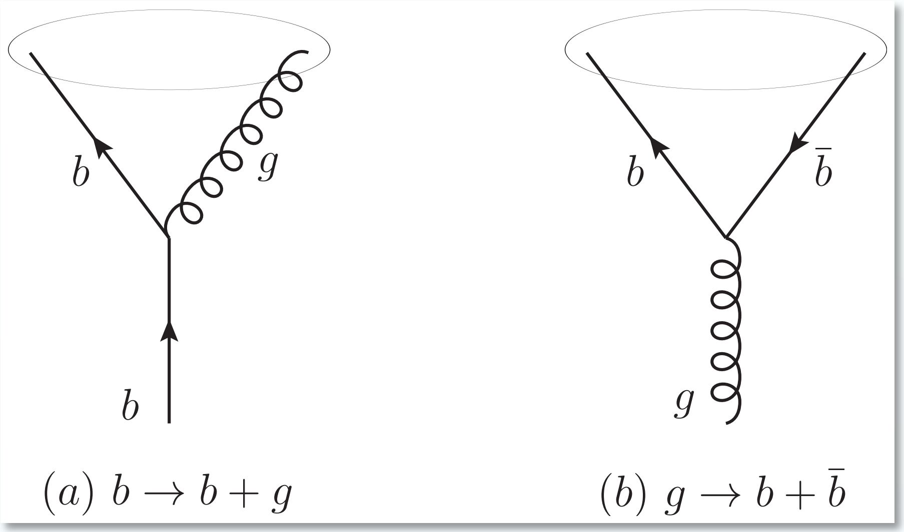
CMS b-jet measurement

- Winner-takes-all (WTA) jet axis



Contributions of b jet substructure

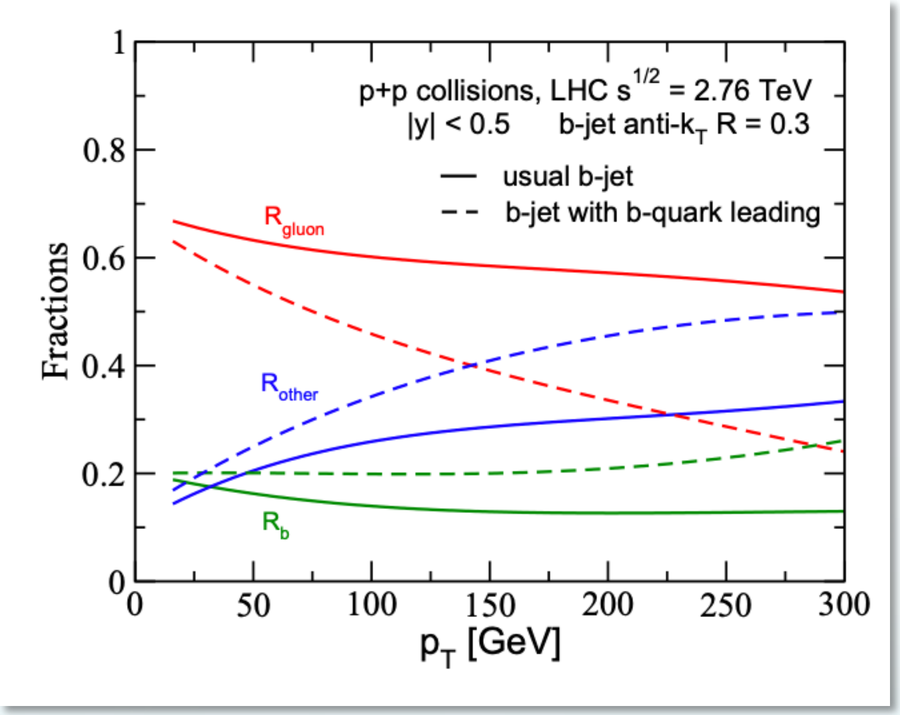
- Two contributions at LO



- It is very important to be able to distinguish these two contributions, to fully understand the true “b-jet” dynamics (such as mass effect, dead-cone)

B jet production

- Various contributions
  - Gluon splitting to b+bbar is significnat



Huang, Kang, Vitev, PLB 2013

Similarly for b jet shape

- Contains 1 b quark, 2 b quark, etc: lots of information

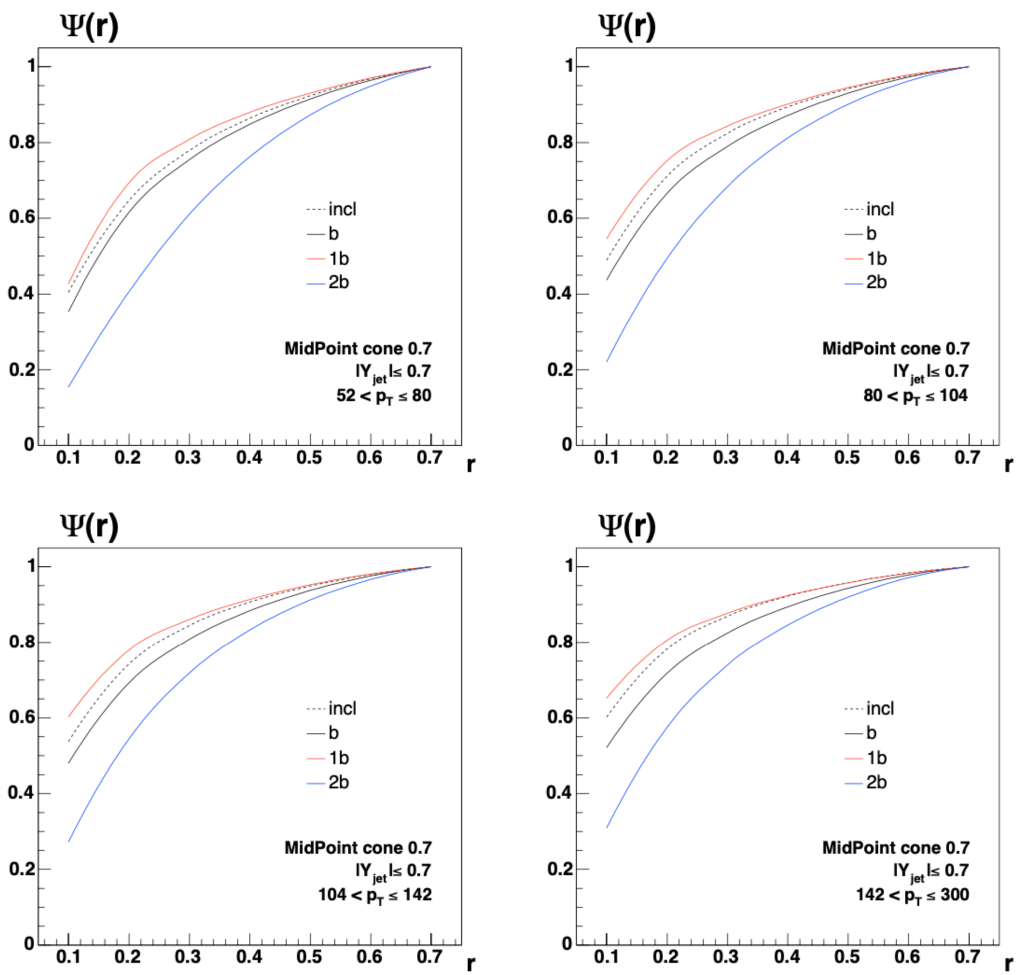


FIGURE 1.8: Hadron level predictions for the integrated jet shapes for b-quark jets and inclusive jets. Also shown are the predictions for single and double b-quark jets.

CDF collaboration, A. Lister, thesis

Take advantage of this fact

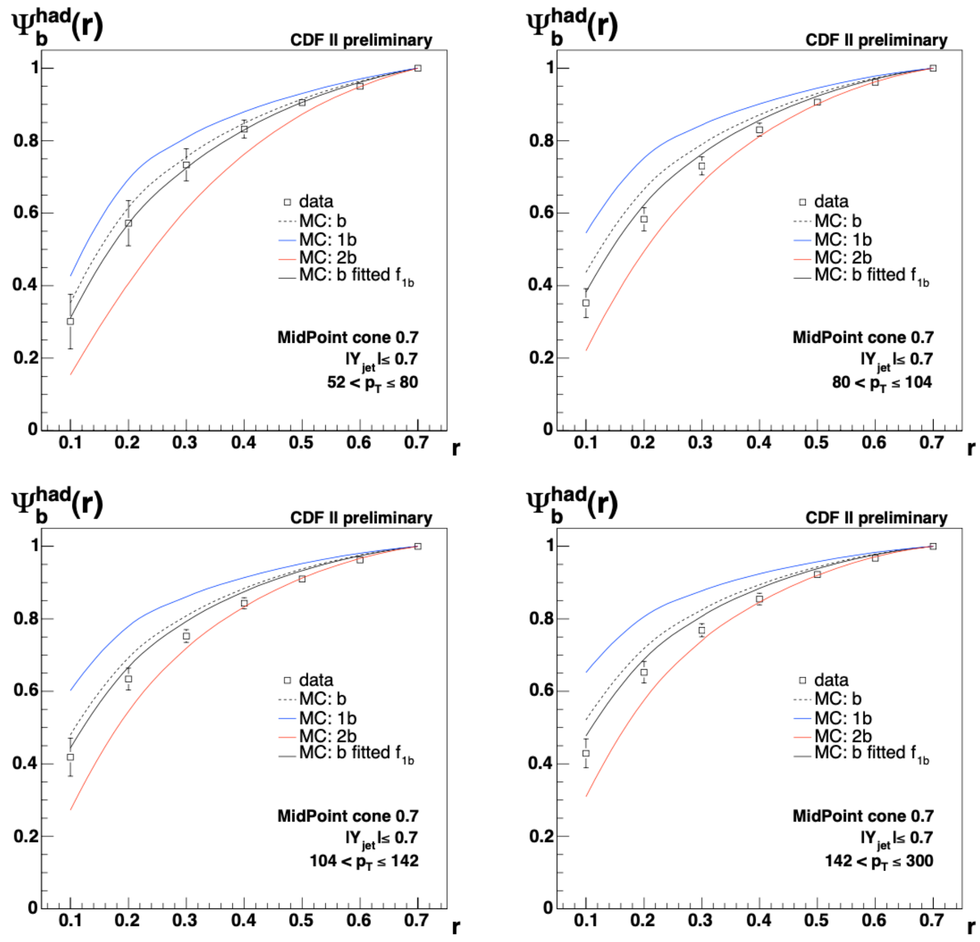


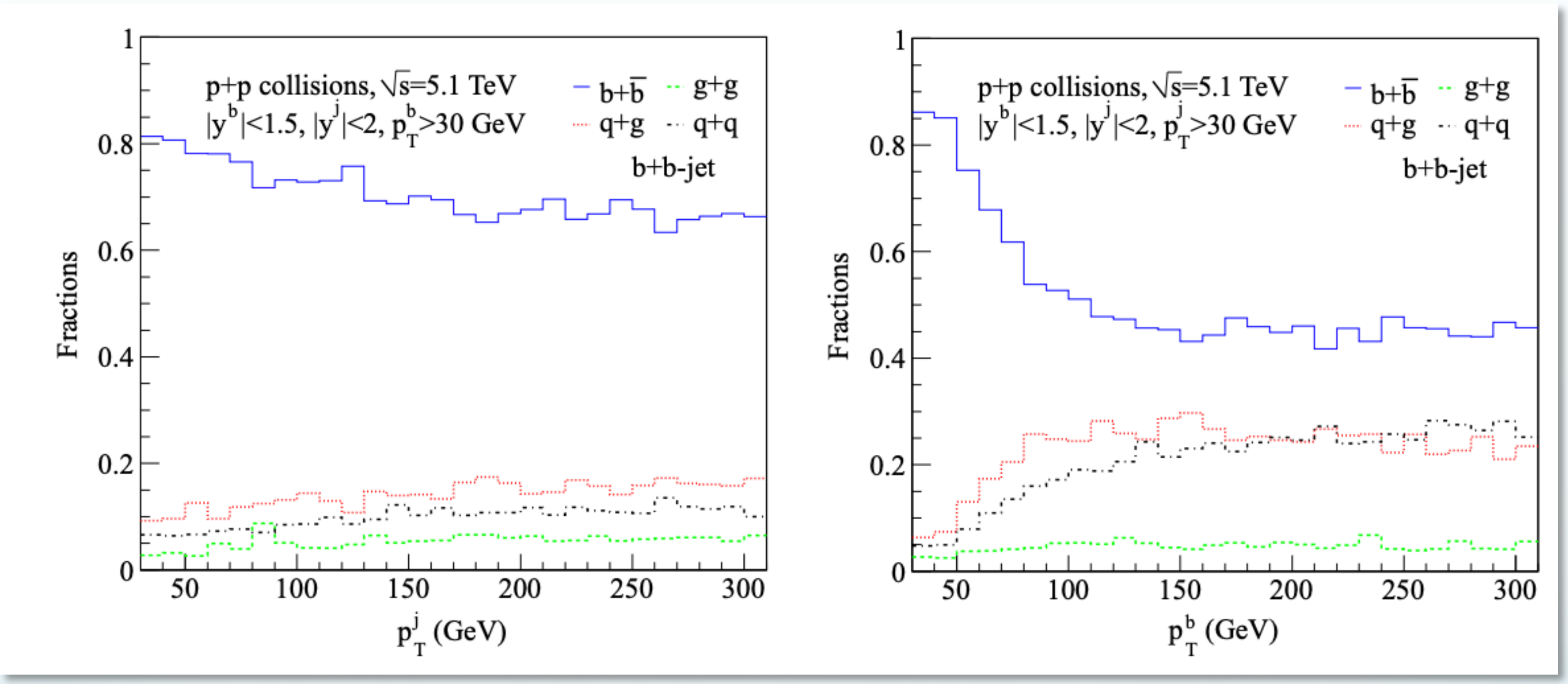
FIGURE 8.17: Hadron level integrated jet shapes for b-quark jets in data (black points). The total errors are shown. The Pythia Tune A MC predictions using the default and the fitted f_{1b} fractions are also shown (dotted and full black lines, respectively) along with the predictions for single and double b-quark jet shapes (red and blue lines, respectively).

B quark-initiated b jet

- sPHENIX: it should be possible to select b-quark initiated b jets by requiring that there is only 1 b quark inside the jet
- The b jets that contain 2+ b quarks inside the jet behave more like a gluon jet
  - This is not what we want to study
  - We should remove these samples from the final b-jet data

Other approaches

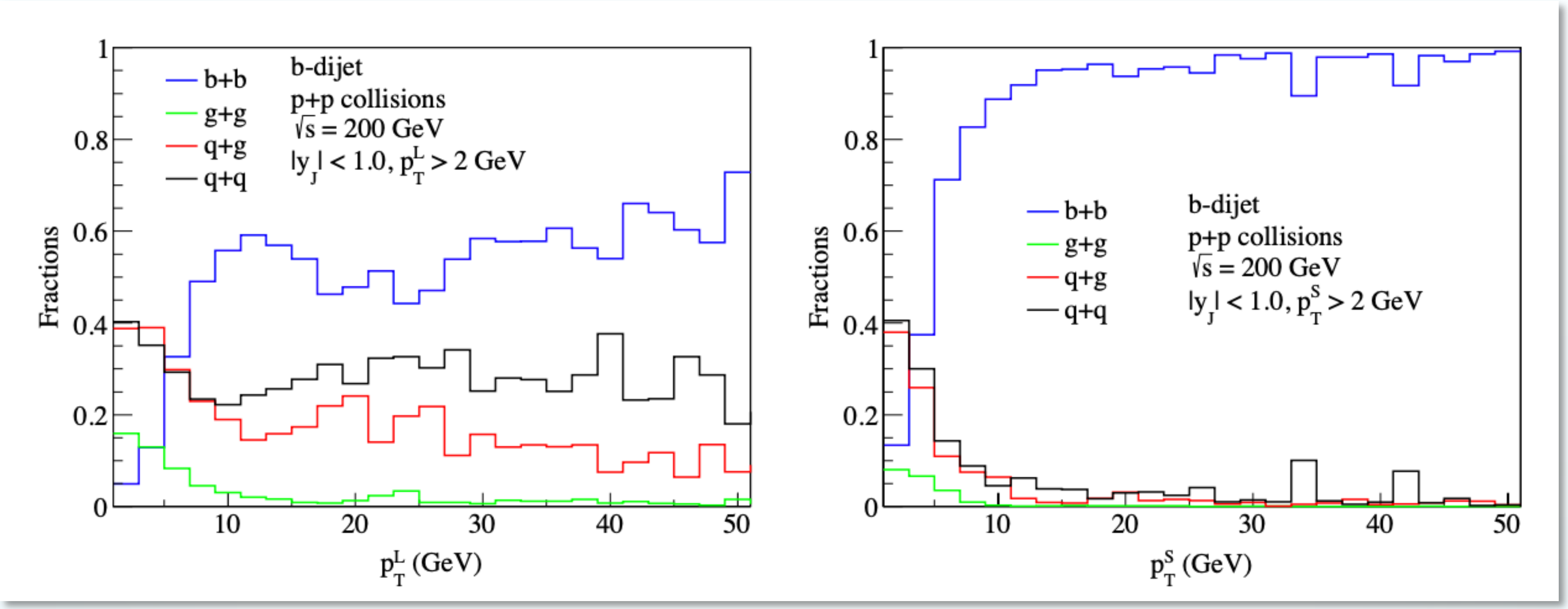
- There are other methods we proposed in the past, that would also allow us to pick up the b-quark initiated b jets



B meson tagged b jet production
Huang, Kang, Vitev, Xing, PLB 2015

Heavy flavor dijet

- Leading, sub-leading b-jets



Kang, Reiten, Vitev, Yoon, PRD 2019

Invariant mass of dijets

- In sPHENIX document

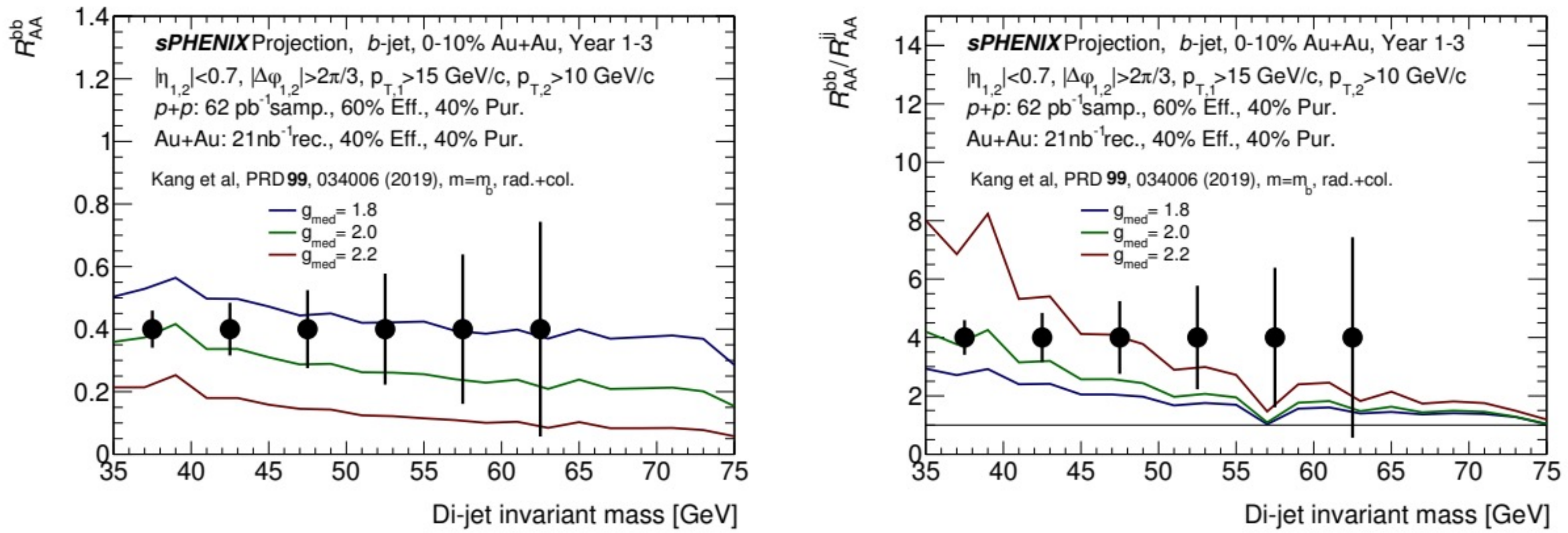
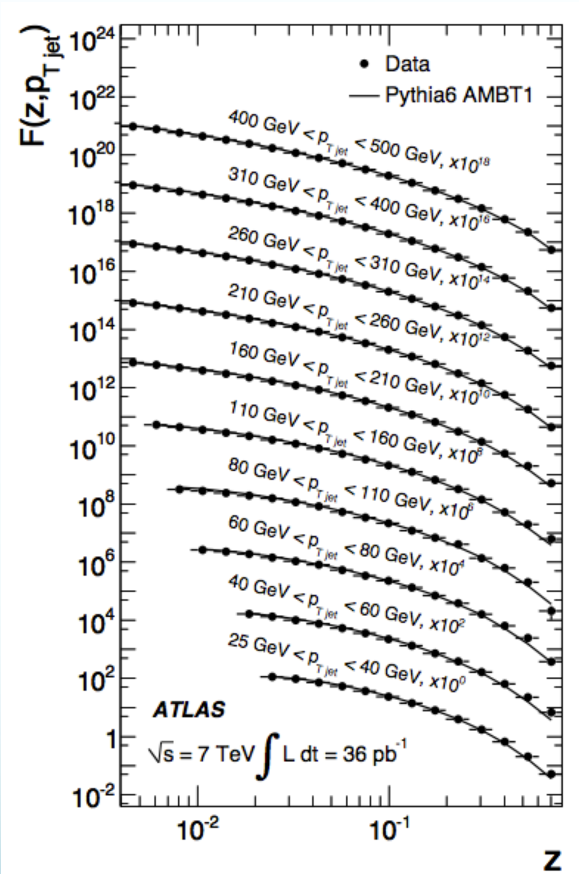


Figure 7.7: Projected statistical uncertainties of nuclear modification for back-to-back *b*-jet pairs (left) and *b*-jet-light-jet super-ratio (right) along with pQCD calculations from Ref. [22]

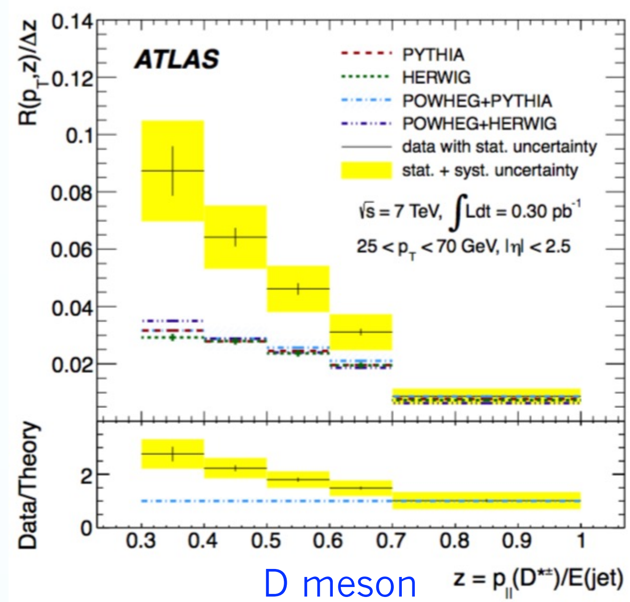
See Vitev's talk at the workshop

Jet fragmentation function: light and heavy

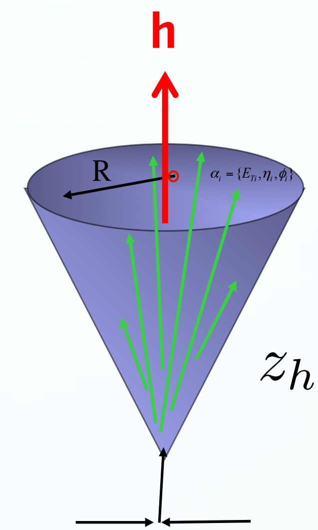
- Hadron distribution inside a jet $p + p \to \text{jet}\,(h) + X$



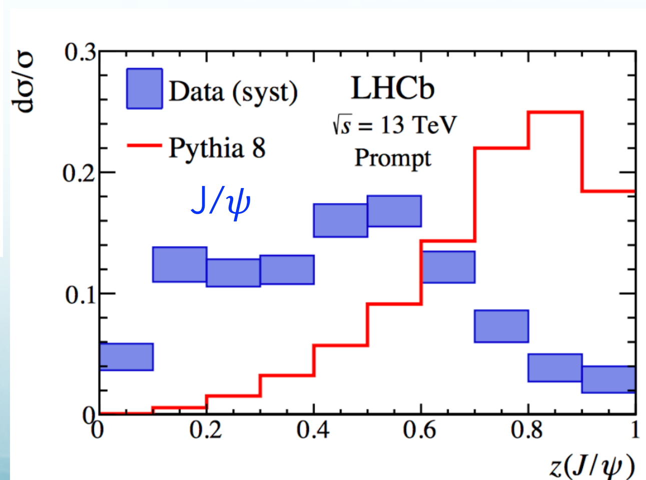
Light charged hadrons

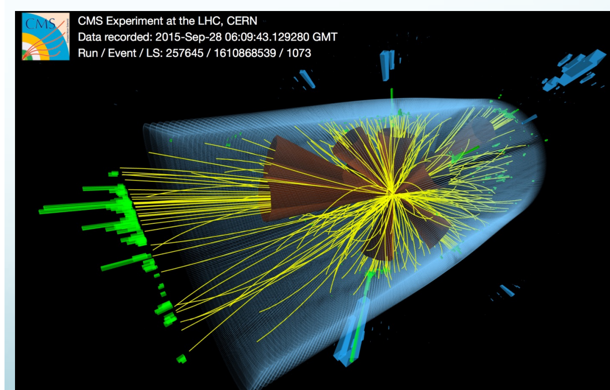


D meson



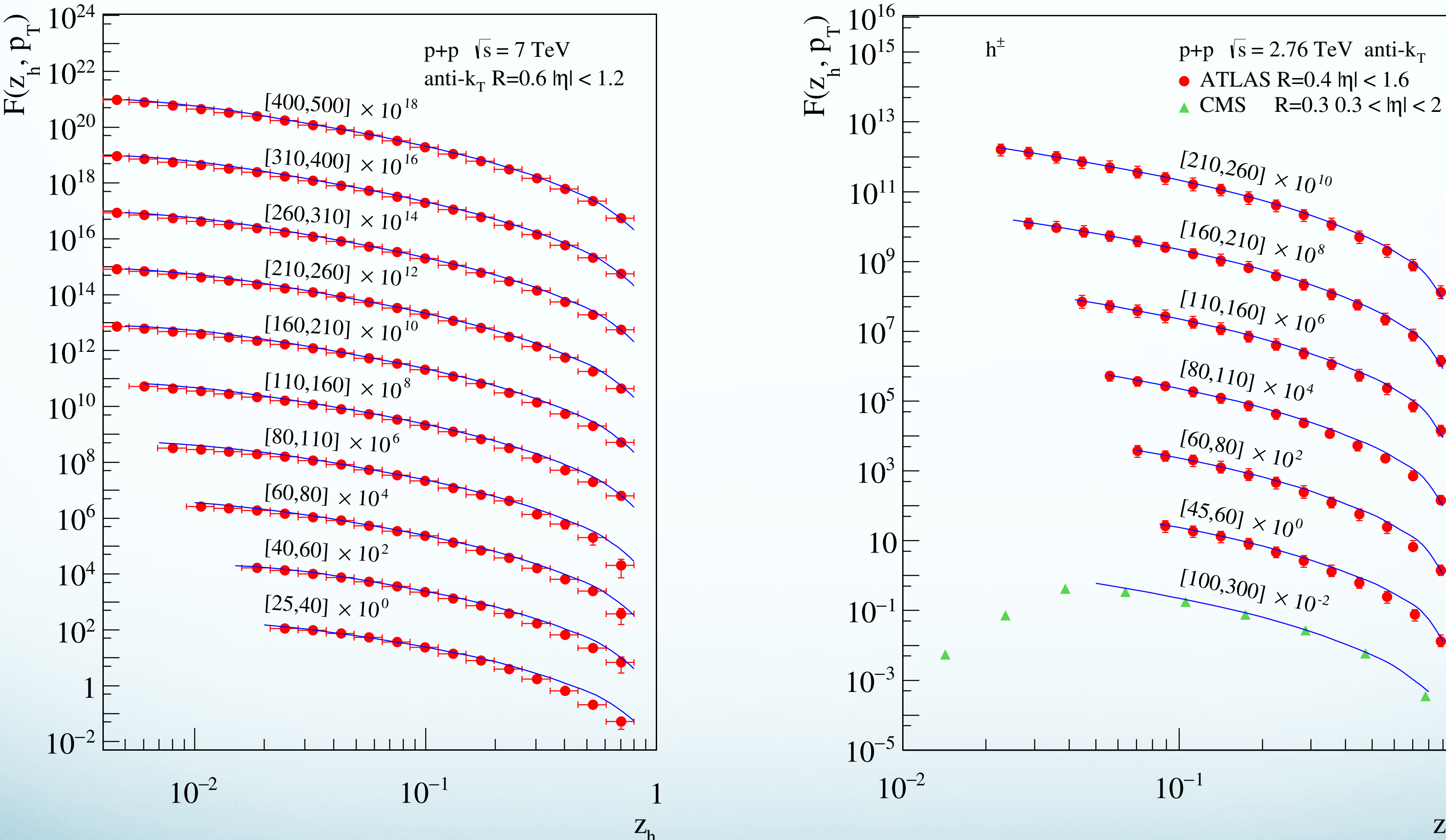
$$z_h = \frac{E_h}{E_{\text{jet}}}$$





Light hadrons: work well

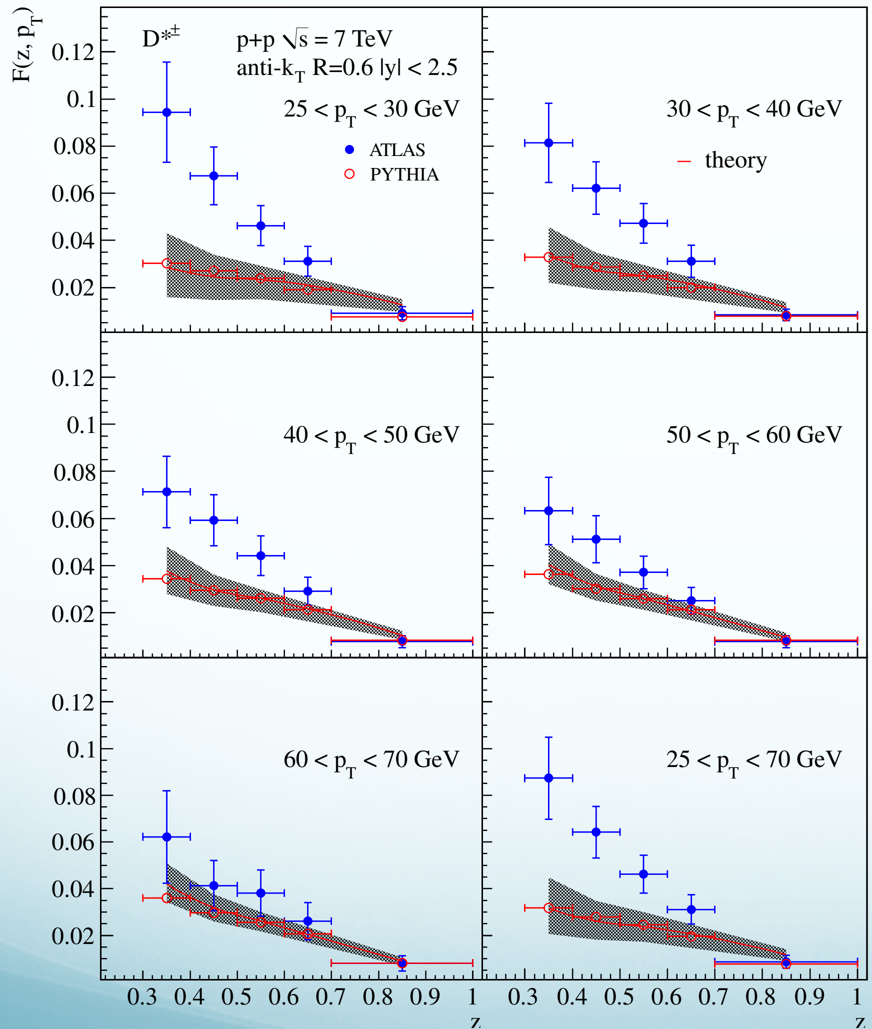
- Light charged hadrons



Kang, Ringer, Vitev, JHEP, 16

Jet fragmentation function for heavy meson

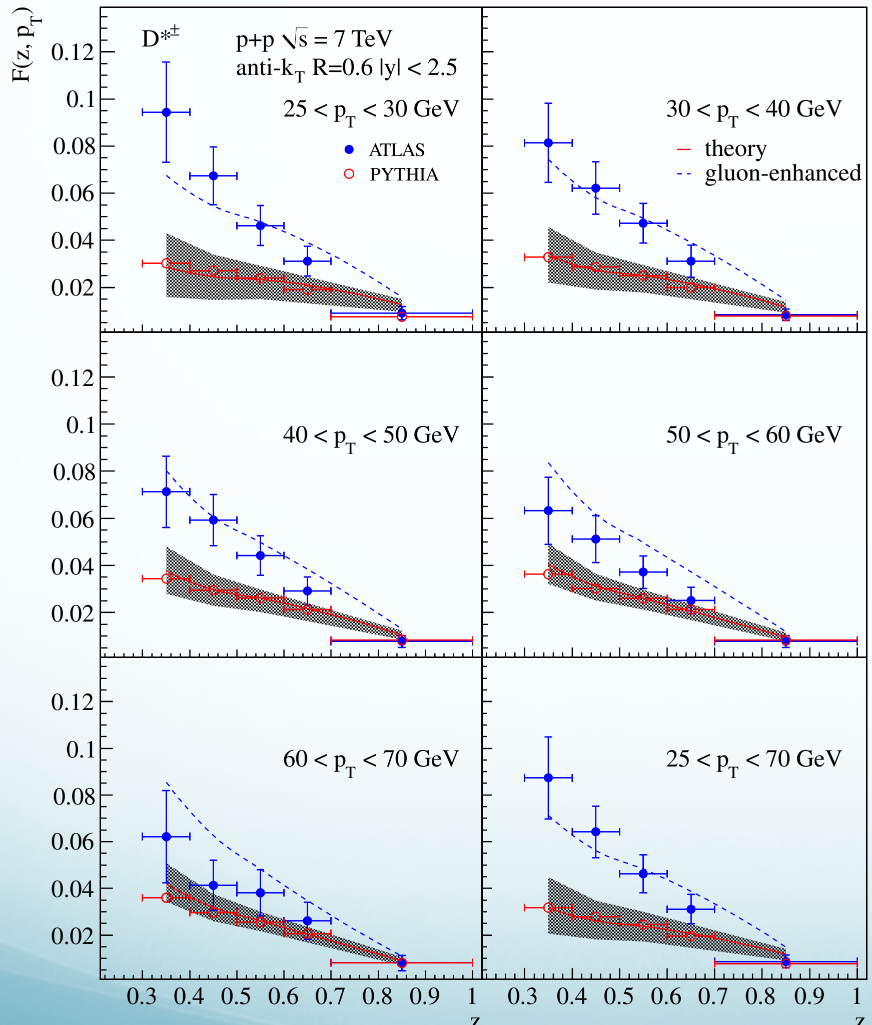
- Using D meson FFs fitted from e+e- data Kneesch, Kniehl, Kramer, Schienbein, 08



Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing, 1512.06851, JHEP 16

Jet fragmentation function for heavy meson

- Using D meson FFs fitted from e+e- data Kneesch, Kniehl, Kramer, Schienbein, 08



Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing, 1512.06851, JHEP 16

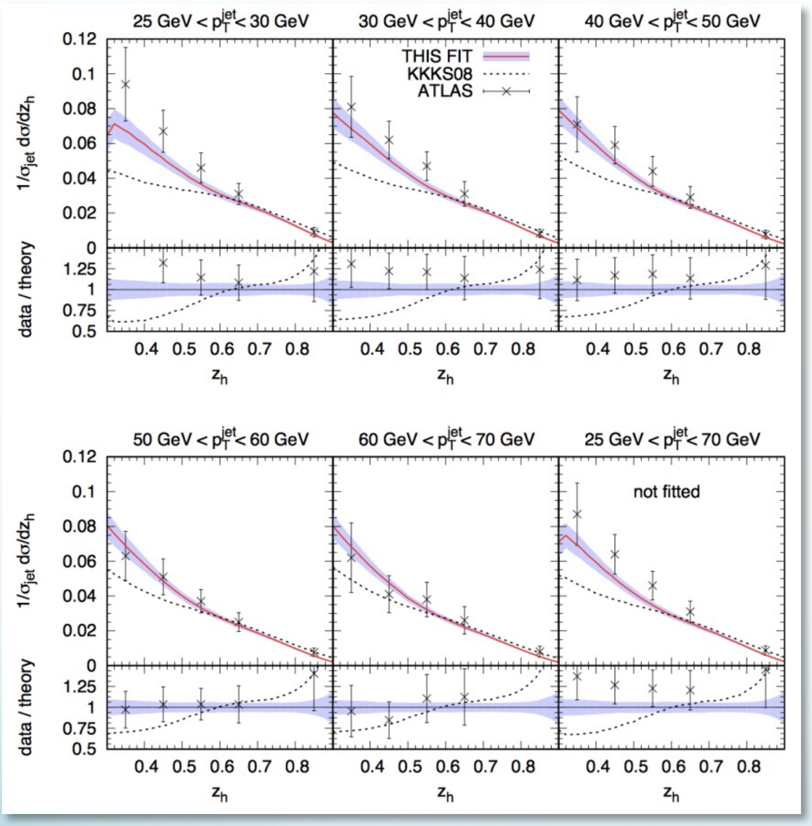
$$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$$

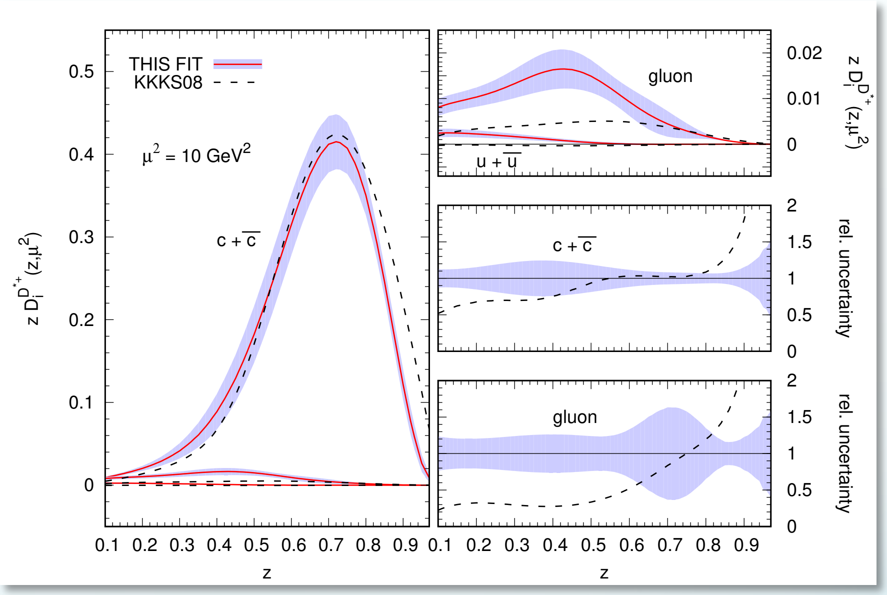
New fit of D-meson FFs needed

A new global analysis of FFs

- New fit of D-meson FFs

New fit of D-meson FFs:
Stratmann, et.al., PRD 2017





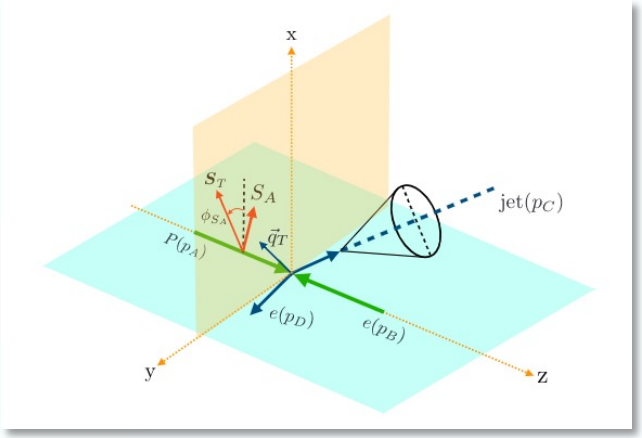
Confirms earlier guess

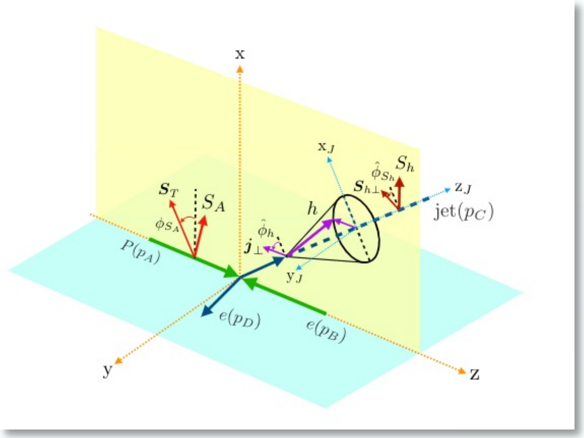
Jet substructure: polarized jet fragmentation function

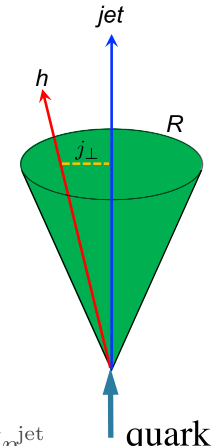
- Imbalance + TMD hadron in jet

  Kang, Lee, Zhao, PLB 20
  Kang, Lee, Shao, Zhao, JHEP 2021

  - Two handles: imbalance qT controls TMD PDFs, while jT of hadron in jet controls TMD FFs







$z_h = p_T^{\rm h}/p_T^{\rm jet}$

$j_\perp$: hadron transverse momentum with respect to the jet

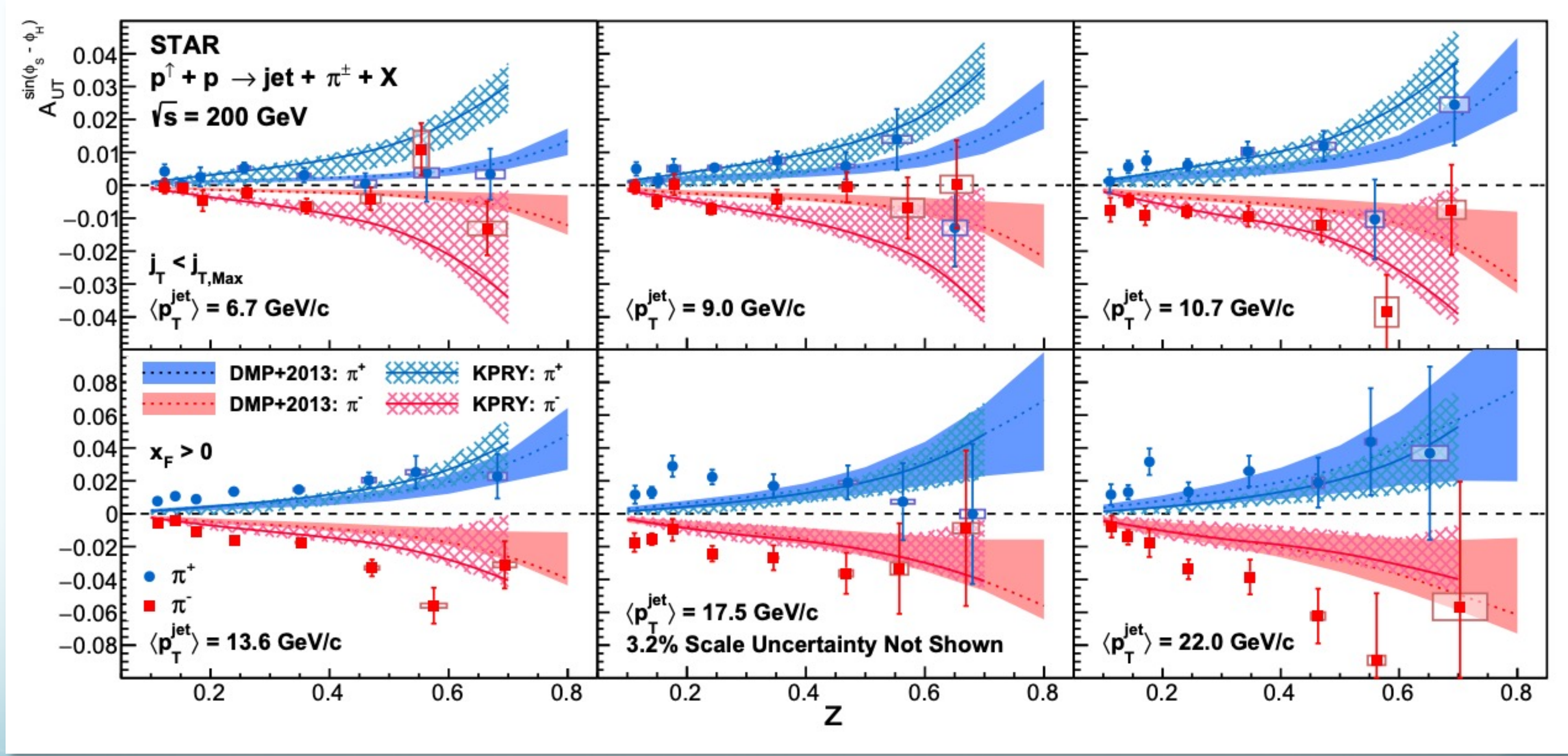
$$
\begin{aligned}
&\frac{d\sigma^{p(S_A)+e(\lambda_e)\to e+(\text{jet}\,h(S_h))+X}}{d^2\boldsymbol{p}_T dy_J d^2\boldsymbol{q}_T dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + \cos(\phi_q - \hat{\phi}_h) F_{UU,U}^{\cos(\phi_q-\hat{\phi}_h)} \\
&+ \Lambda_p \Big\{ \lambda_e F_{LL,U} + \sin(\phi_q - \hat{\phi}_h) F_{LU,U}^{\sin(\phi_q-\hat{\phi}_h)} \Big\} \\
&+ S_T \Big\{ \sin(\phi_q - \phi_{S_A}) F_{TU,U}^{\sin(\phi_q-\phi_{S_A})} + \lambda_e \cos(\phi_q - \phi_{S_A}) F_{TL,U}^{\cos(\phi_q-\phi_{S_A})} \\
&\quad + \sin(\phi_{S_A} - \hat{\phi}_h) F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)} + \sin(2\phi_q - \hat{\phi}_h - \phi_{S_A}) F_{TU,U}^{\sin(2\phi_q-\hat{\phi}_h-\phi_{S_A})} \Big\} \\
&+ \Lambda_h \Big\{ \lambda_e F_{UL,L} + \sin(\hat{\phi}_h - \phi_q) F_{UU,L}^{\sin(\hat{\phi}_h-\phi_q)} + \Lambda_p \Big[F_{LU,L} + \cos(\hat{\phi}_h - \phi_q) F_{LU,L}^{\cos(\hat{\phi}_h-\phi_q)} \Big] \\
&\quad + S_T \Big[\cos(\phi_q - \phi_{S_A}) F_{TU,L}^{\cos(\phi_q-\phi_{S_A})} + \lambda_e \sin(\phi_q - \phi_{S_A}) F_{TL,L}^{\sin(\phi_q-\phi_{S_A})} \\
&\quad + \cos(\phi_{S_A} - \hat{\phi}_h) F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)} + \cos(2\phi_q - \phi_{S_A} - \hat{\phi}_h) F_{TU,L}^{\cos(2\phi_q-\phi_{S_A}-\hat{\phi}_h)} \Big] \Big\} \\
&+ S_{h\perp} \Big\{ \sin(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda_e \cos(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{UL,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})}
\end{aligned}
$$

$$
\begin{aligned}
&+ \sin(\hat{\phi}_{S_h} - \phi_q) F_{UU,T}^{\sin(\hat{\phi}_{S_h}-\phi_q)} + \sin(2\hat{\phi}_h - \hat{\phi}_{S_h} - \phi_q) F_{UU,T}^{\sin(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_q)} \\
&+ \Lambda_p \Big[\cos(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})} + \cos(\phi_q - \hat{\phi}_{S_h}) F_{LU,T}^{\cos(\phi_q-\hat{\phi}_{S_h})} \\
&\qquad + \cos(2\hat{\phi}_h - \hat{\phi}_{S_h} - \phi_q) F_{LU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_q)} + \lambda_e \sin(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{LL,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} \Big] \\
&+ S_T \Big[\cos(\phi_{S_A} - \hat{\phi}_{S_h}) F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})} + \cos(2\hat{\phi}_h - \hat{\phi}_{S_h} - \phi_{S_A}) F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})} \\
&+ \sin(\hat{\phi}_h - \hat{\phi}_{S_h}) \sin(\phi_q - \phi_{S_A}) F_{TU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})\sin(\phi_q-\phi_{S_A})} \\
&+ \cos(\hat{\phi}_h - \hat{\phi}_{S_h}) \cos(\phi_q - \phi_{S_A})) F_{TU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_q-\phi_{S_A})} \\
&+ \cos(2\phi_q - \phi_{S_A} - \hat{\phi}_{S_h}) F_{TU,T}^{\cos(2\phi_q-\phi_{S_A}-\hat{\phi}_{S_h})} \\
&\qquad + \cos(2\hat{\phi}_h - \hat{\phi}_{S_h} + 2\phi_q - \phi_{S_A}) F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}+2\phi_q-\phi_{S_A})} \\
&+ \lambda_e \cos(\hat{\phi}_h - \hat{\phi}_{S_h}) \sin(\phi_{S_A} - \phi_q) F_{TL,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})\sin(\phi_{S_A}-\phi_q)} \\
&+ \lambda_e \sin(\hat{\phi}_h - \hat{\phi}_{S_h}) \cos(\phi_{S_A} - \phi_q)) F_{TL,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_{S_A}-\phi_q)} \Big] \Big\},
\end{aligned}
$$

Collins effect inside the jet

- Earlier measurements: Collins asymmetry for hadron inside the jet in transversely polarized p+p collisions

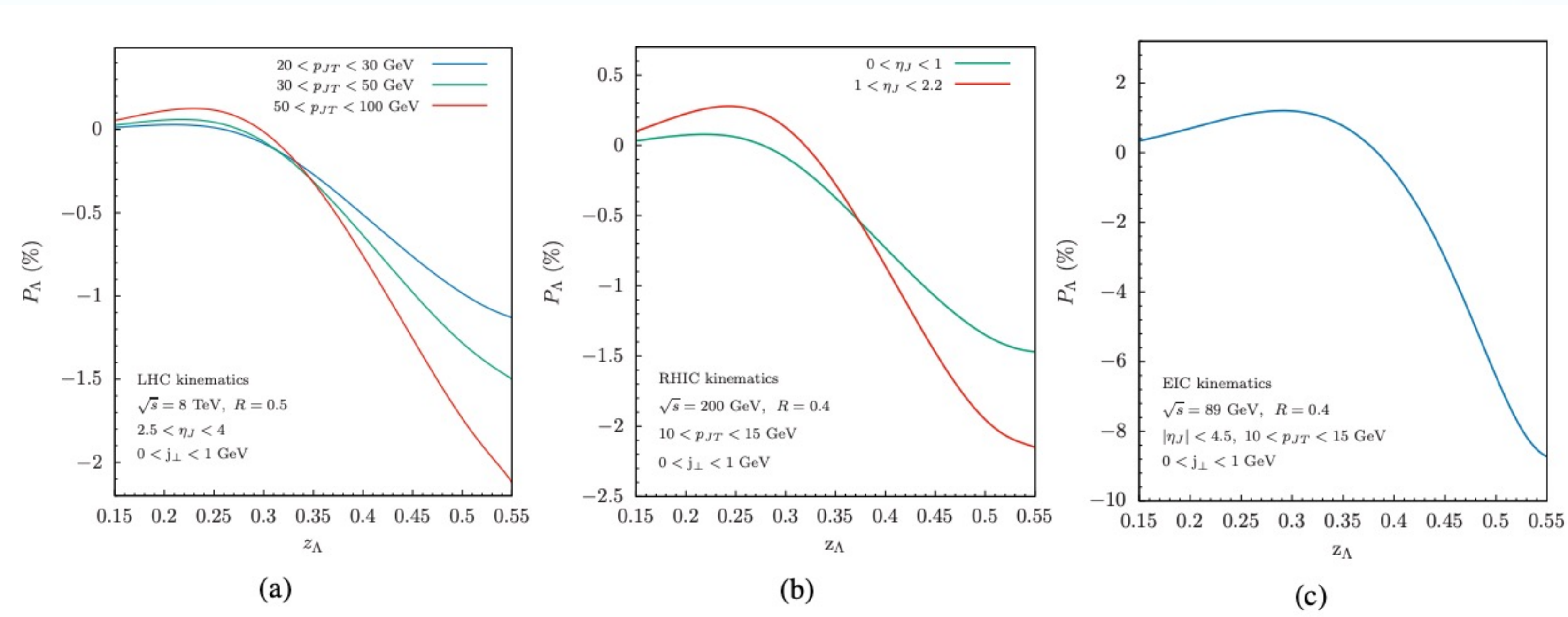
STAR, 2205.11800



Lambda polarization inside the jet

- Earlier prediction
  - Lambda transverse polarization in unpolarized p+p collisions
  - sPHENIX should be able to measure this

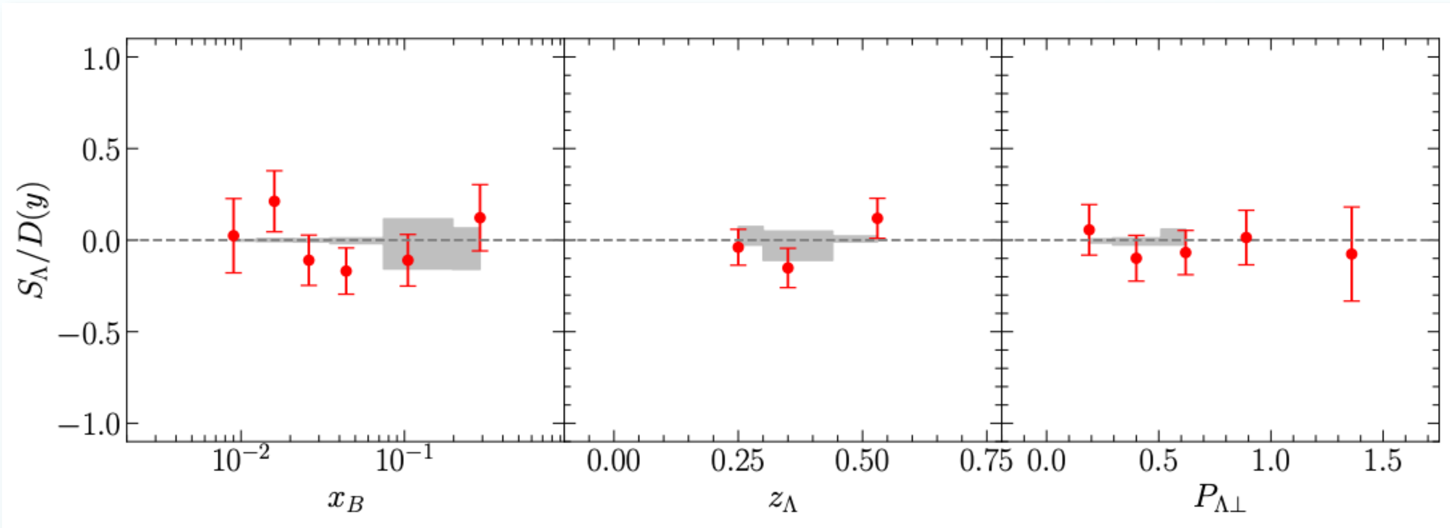
Kang, Lee, Zhao, PLB 20

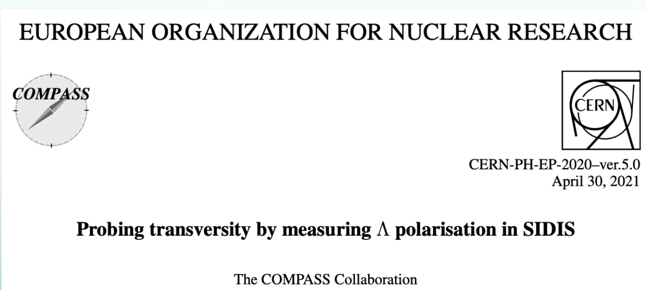


Transverse spin transfer

- sPHENIX: incoming proton (transversely polarized) → transversely polarized Lambda inside the jet
  - Transversity fragmentation function

Kang, Terry, Vossen, Xu, Zhang, PRD 22




EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

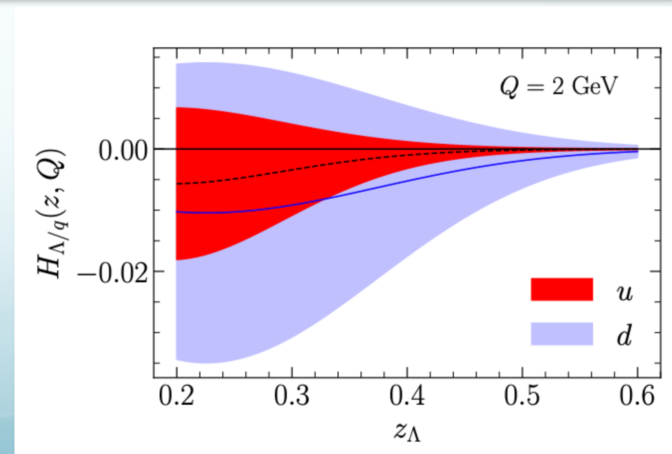
COMPASS

CERN

CERN-PH-EP-2020–ver.5.0
April 30, 2021

Probing transversity by measuring Λ polarisation in SIDIS

The COMPASS Collaboration



Collinear to TMDs: it's time

- These days, it is a standard exercise to quantify the cold nuclear matter effect via collinear nuclear PDFs
  - However, collinear PDFs are only for relatively inclusive process, e.g. pT spectrum of single inclusive hadron or jet production
  - Moving into the future, it is time for us to quantify the modification of 3D structure in the nucleus vs proton

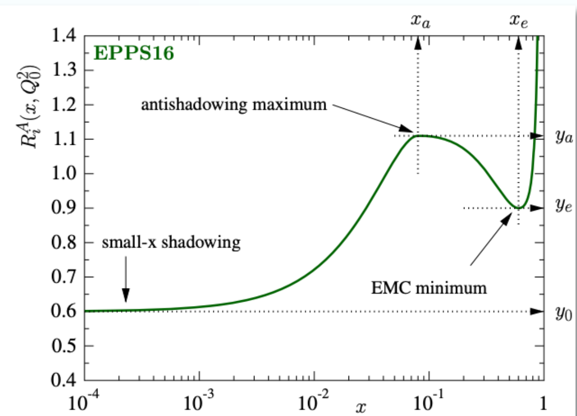
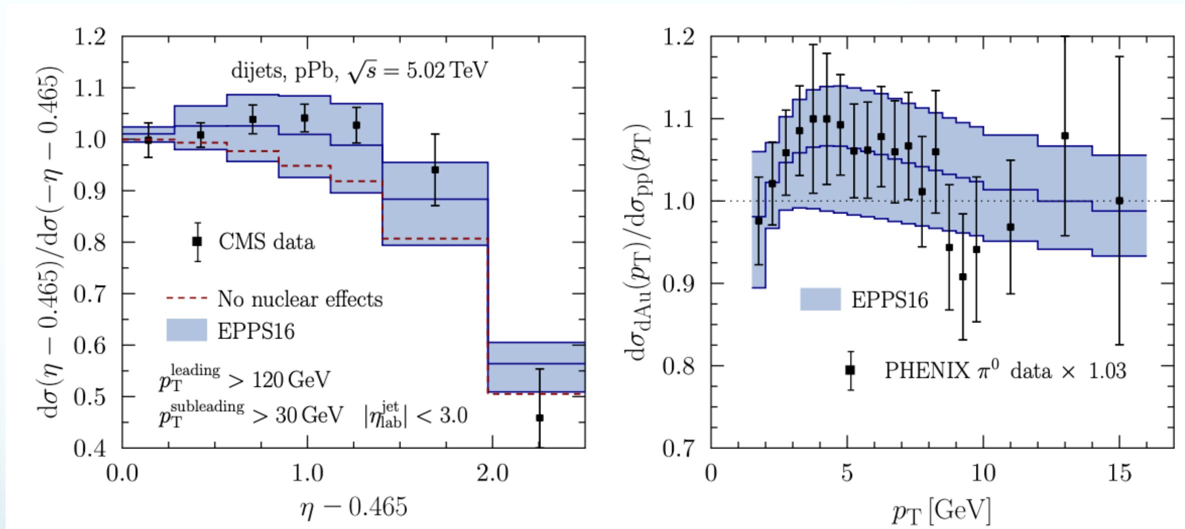
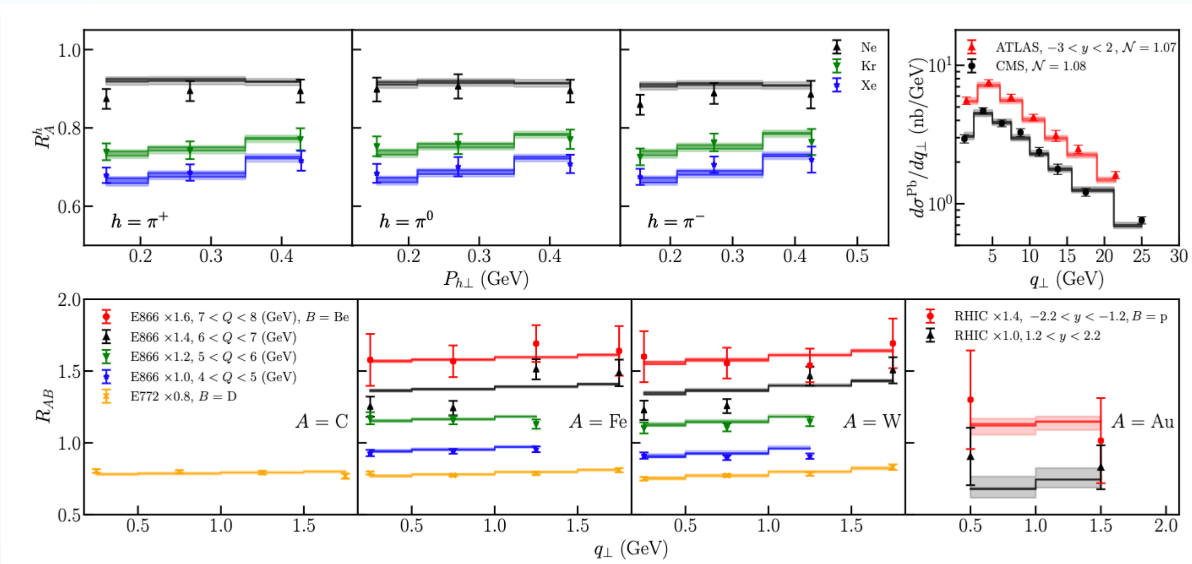


Fig. 1 Illustration of the EPPS16 fit function $R_i^A(x, Q_0^2)$



Global fits of nuclear TMDs

- Nuclear TMD PDFs and TMD FFs



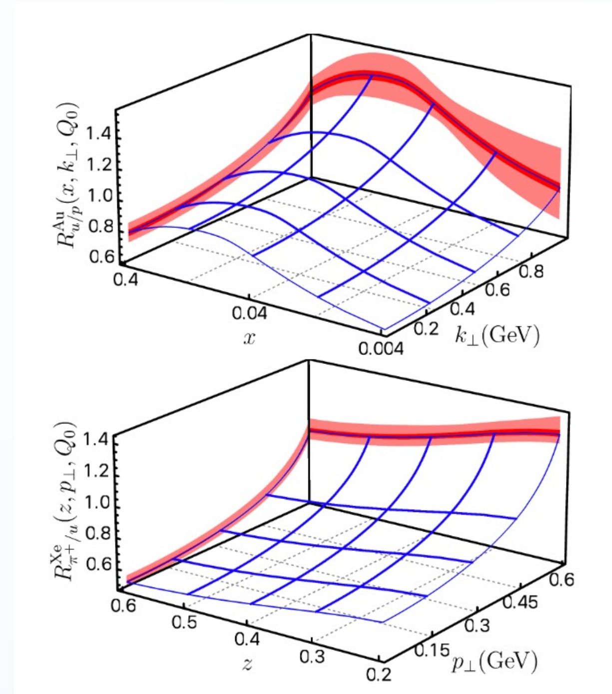


FIG. 3. The extracted nuclear ratio for the TMDPDF (top) and the TMDFF (bottom) at $Q_0=\sqrt{2.4}$ GeV. The light and dark bands are the same as in Fig. 2.

Alrashed, Anderle, Kang, Terry, Xing, 21

sPHENIX: p+A collisions

- The future sPHENIX run in transversely polarized p+p and p+A collisions would allow us
  - Probe hadron distribution inside the jet in p+p: both collinear and TMD distribution, both polarized and unpolarized distributions
  - Modified TMD FFs and TMD PDFs (both spin-independent and spin-dependent ones) in p+A
  - Test universality and evolution of such nuclear TMDs crossing different processes (SIDIS, DY)

Summary

- sPHENIX would open important opportunities for jets and heavy flavor study
- Jet substructure of heavy flavor jet could be a very promising direction at the sPHENIX
  - Heavy flavor jet shape
  - Heavy meson inside the jet
- Substructure of inclusive/light jets would also open new opportunities due to the polarization
  - Polarized jet fragmentation function in p+p
  - Modification and university of nuclear TMD PDFs and TMD FFs in p+A
- Looking forward to the exciting experimental data in the future

Thank you!