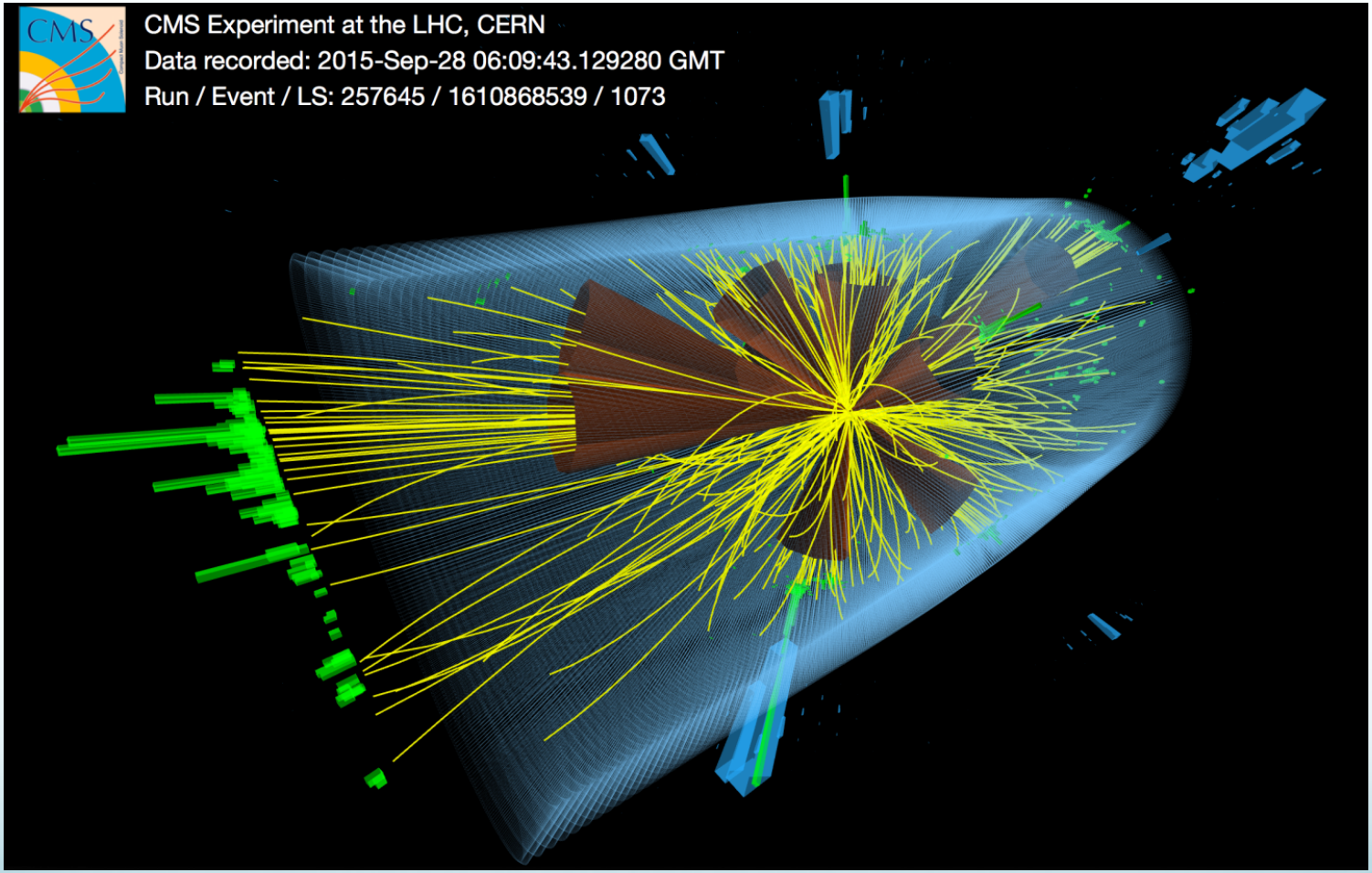
Overview: jet production in p+p and A+A collisions

Zhongbo Kang
UCLA

RHIC & AGS Annual Users' Meeting: Jets
June 20, 2017

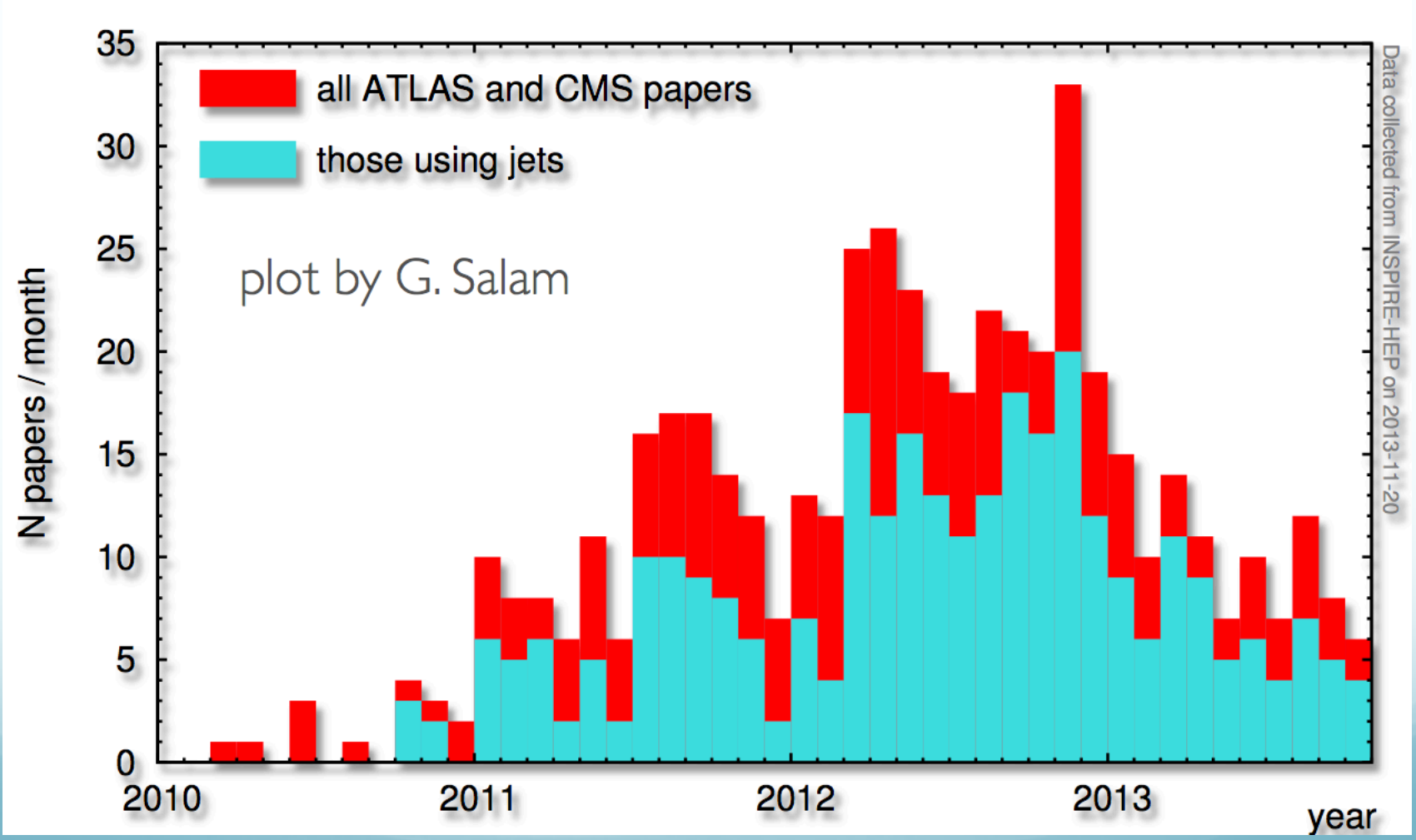
Jets are abundantly produced at the LHC

- They are most common at the LHC



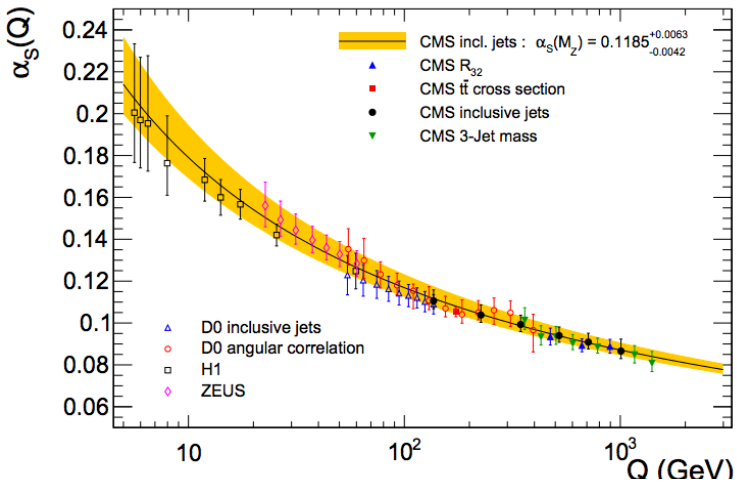
Jets are everywhere

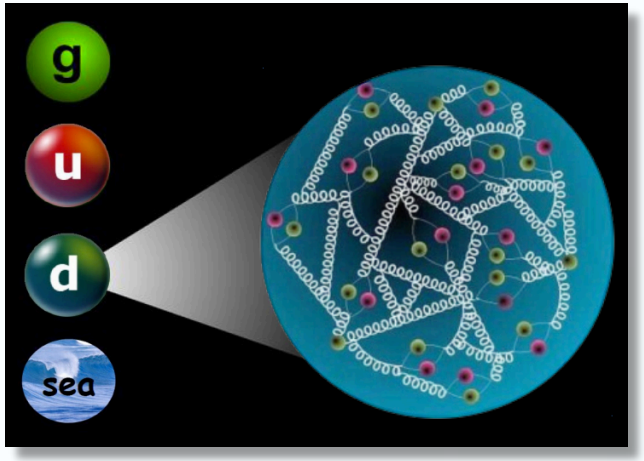
- At the LHC, 60 – 70% of ATLAS & CMS papers using jets in their analysis!



Jets as a precision probe of QCD

- Extraction of strong coupling constant



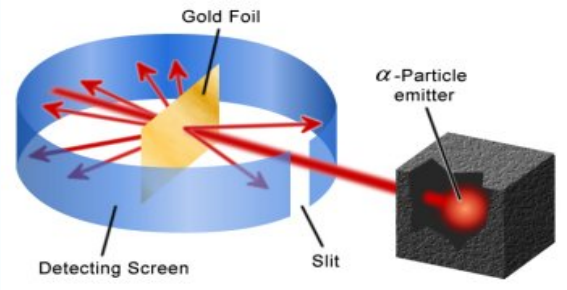


- PDFs are c
distributio

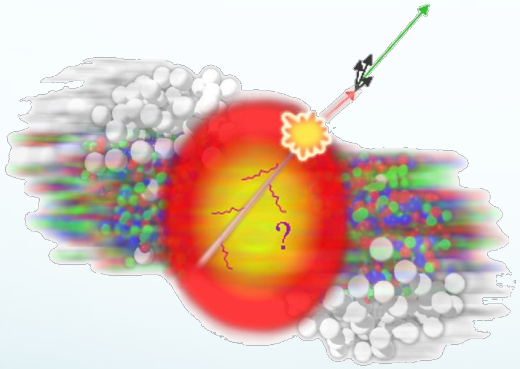
process		sensitivity to PDFs
W asymmetry	→	quark flavour separation
W and Z production (differential)	→	valence quarks
W+c production	→	strange quark
Drell-Yan (DY): high invariant mass	→	sea quarks, high-x
Drell-Yan (DY): low invariant mass	→	low-x
W,Z +jets	→	gluon medium-x
Inclusive jet and di-jet production	→	gluon and $\alpha_s(M_Z)$
Direct photon	→	gluon medium, high-x
ttbar, single top	→	gluon and $\alpha_s(M_Z)$

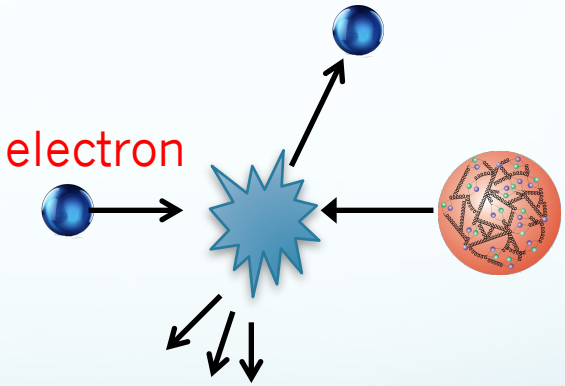
Probing the structure of matter

- Rutherfold's experiment



- Heavy ion physics vs. high energy QCD





- ✓ Properties of QGP
  - ➢ Space-time evolution of the medium: hydrodynamics, AdS/CFT, …
  - ➢ Jet transport parameter, …
- ✓ QCD dynamics in extreme condition

- ✓ Structure of proton
  - ➢ Quark and gluon distributions: global analysis, …
  - ➢ Dynamical correlations
- ✓ QCD dynamics in vacuum

Precision frontier: we are still far away

Charting the Territory Phase

Smoking Gun Phase

Tourist Attraction Phase

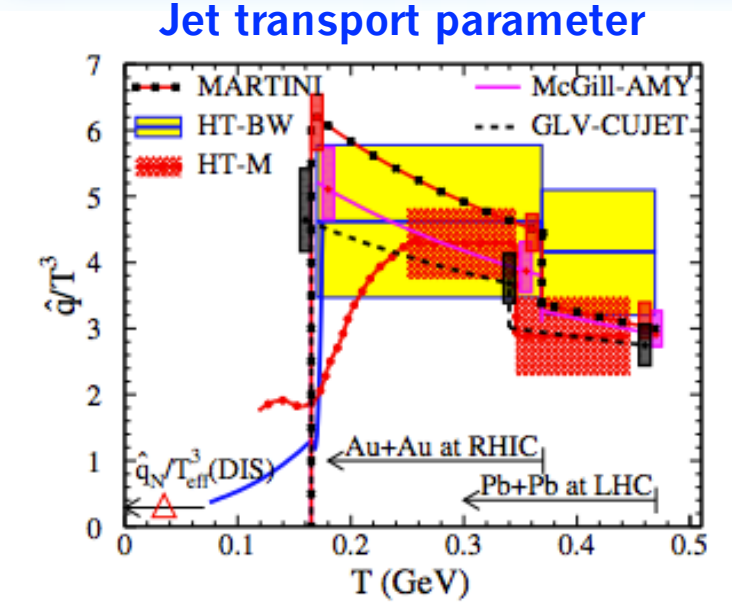
Precision Measurement Phase

3

B. Muller, RHIC/AGS 2011

Heavy ion physics vs high energy QCD

Jet transport parameter



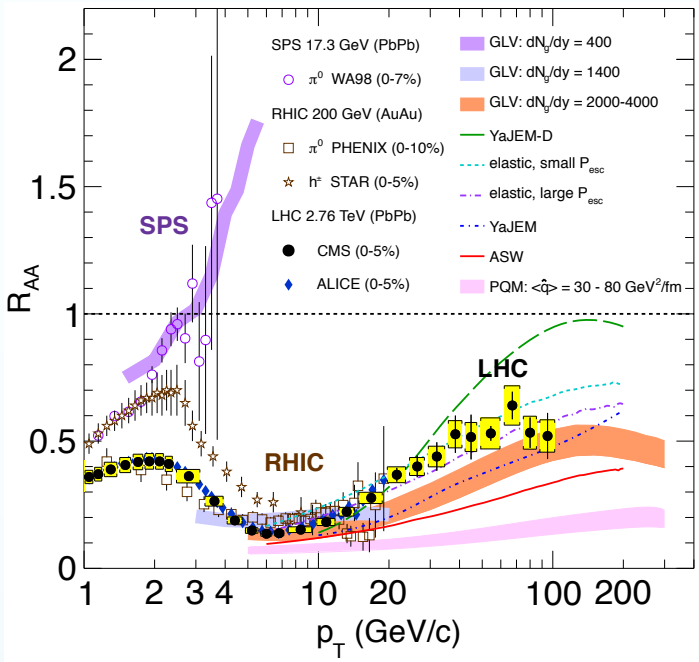
- ✓ process: $A + A \to h + X$
- ✓ # of data: ~70
- ✓ $\hat{q} = 3.5 - 5.5\ T^3$

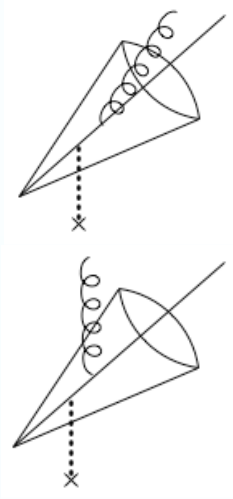
Global analysis of PDFs

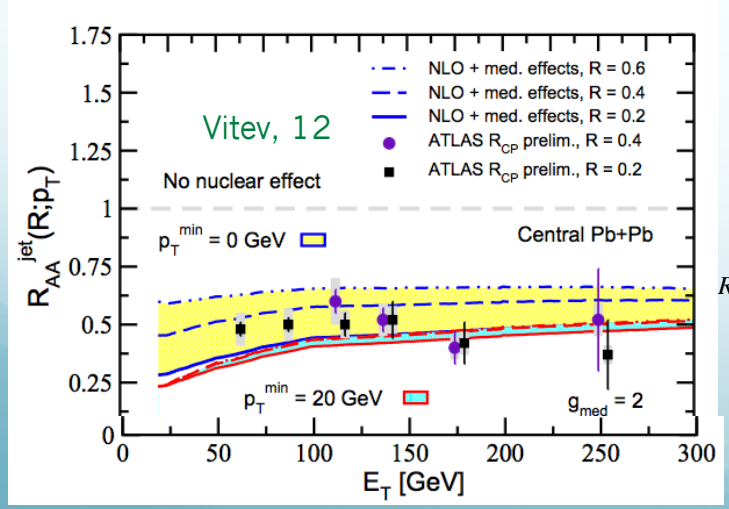
	NNPDF3.0	MMHT14	CT14
SLAC P,D DIS	✓	✓	✗
BCDMS P,D DIS	✓	✓	✓
NMC P,D DIS	✓	✓	✓
E665 P,D DIS	✗	✓	✗
CDHSW NU-DIS	✗	✗	✓
CCFR NU-DIS	✗	✓	✓
CHORUS NU-DIS	✓	✓	✗
CCFR DIMUON	✗	✓	✓
NUTEV DIMUON	✓	✓	✓
HERA I NC,CC	✓	✓	✓
HERA I CHARM	✓	✓	✓
H1,ZEUS JETS	✗	✓	✗
H1 HERA II	✓	✗	✗
ZEUS HERA II	✓	✗	✗
E605 & E866 FT DY	✓	✓	✓
CDF & D0 W ASYM	✗	✓	✓
CDF & D0 Z RAP	✓	✓	✓
CDF RUN-II JETS	✓	✓	✓
D0 RUN-II JETS	✗	✓	✓
D0 RUN-II W ASYM	✗	✗	✓
ATLAS HIGH-MASS DY	✓	✓	✓
CMS 2D DY	✓	✓	✗
ATLAS W,Z RAP	✓	✓	✓
ATLAS W p_T	✓	✗	✗
CMS W ASY	✓	✓	✓
CMS W +C	✓	✗	✗
LHCB W,Z RAP	✓	✓	✓
ATLAS JETS	✓	✓	✓
CMS JETS	✓	✓	✓
TTBAR TOT XSEC	✓	✓	✗
TOTAL NLO	4276	2996	3248
TOTAL NNLO	4078	2663	3045

pQCD advances in heavy ion physics
need to understand all other processes (jet, jet substructure, heavy flavor jets/meson, dijet/dihadron correlation, gamma/Z-jet/hadron, ...)

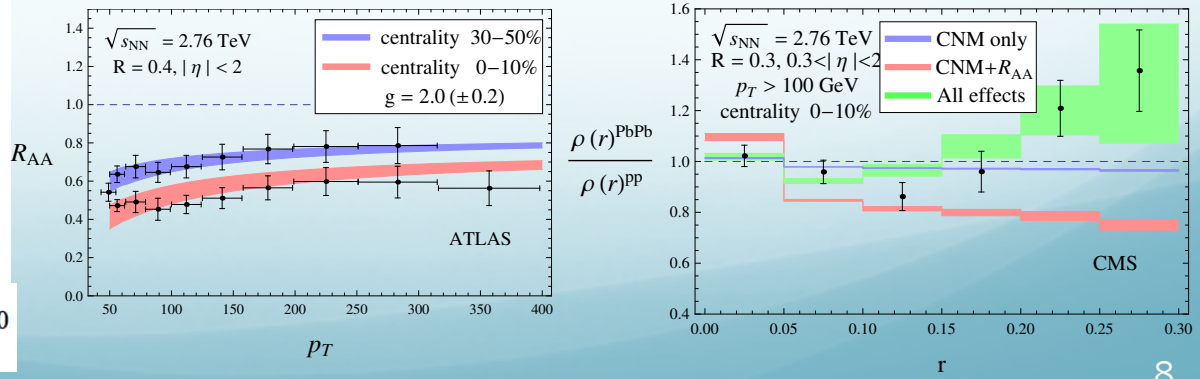
We come a long way







Chien, Vitev, 16



Soft-Collinear Effective Theory (SCET)

- SCET: an effective field theory of QCD

Bauer et al. 01, Pirjol et al. 04

  - Suitable for processes where there are energetic, nearly light-like (collinear) degrees of freedom interacting with one another via soft radiation

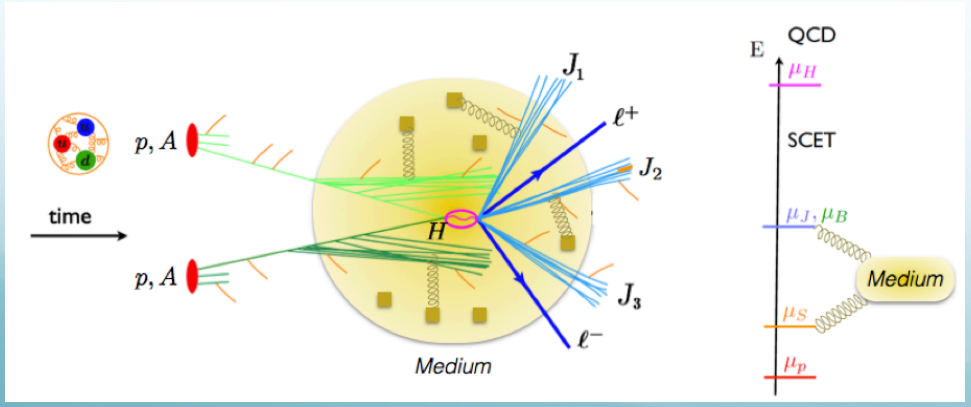
- Modes in SCET

Collinear quarks, antiquarks	$\xi_n,\ \bar{\xi}_n$
Collinear gluons, soft gluons	$A_n,\ A_s$

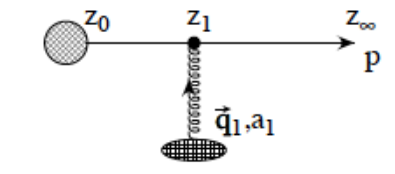
modes	$p^\mu = (+,-,\perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$

$$\sigma = H \otimes S \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j$$

- Especially suited for jet physics



- Glauber mode to describe the interaction between energetic jet/parton with the medium

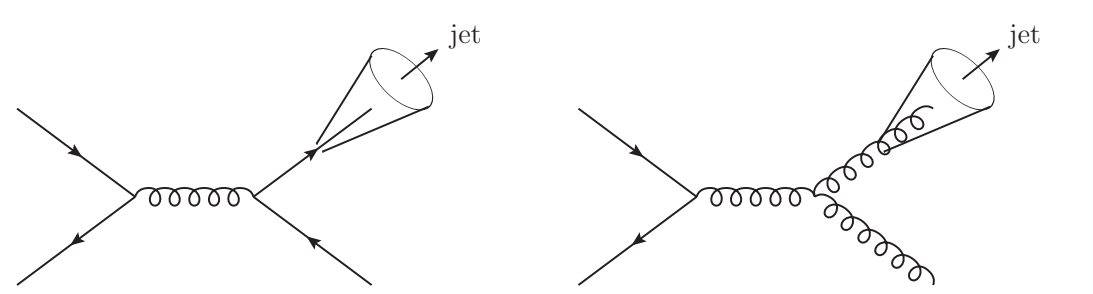


$$q = (\lambda^2, \lambda^2, \lambda)Q$$

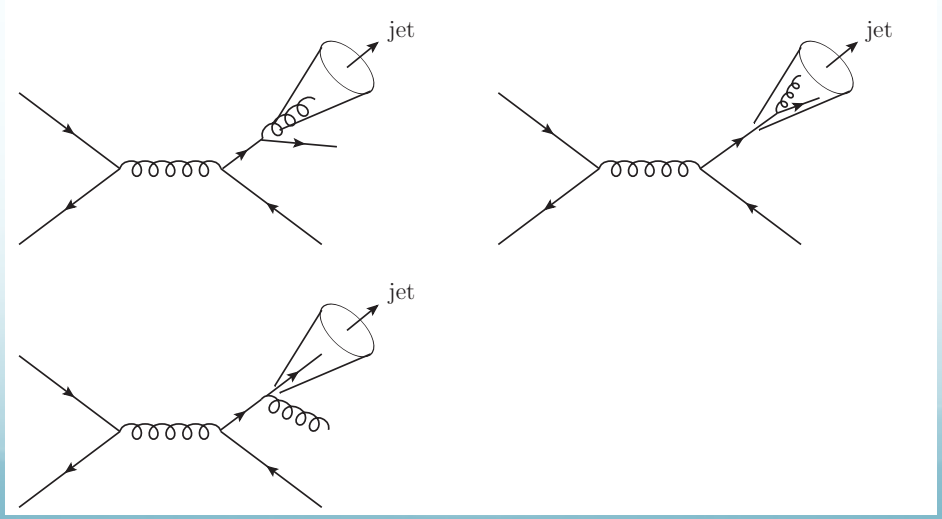
Gyulassy, Levai, Vitev, 02, Idilbi, Majumder 08, D'Eramo, Liu, Rajagopal, 10, Ovanesyan, Vitev, 11, ...

Quark and gluon jet still LO

- Quark and gluon lose different energy, and thus we need the **separate** contribution from quark and gluon jets
  - At LO, there is no ambiguity: one parton goes into the jet

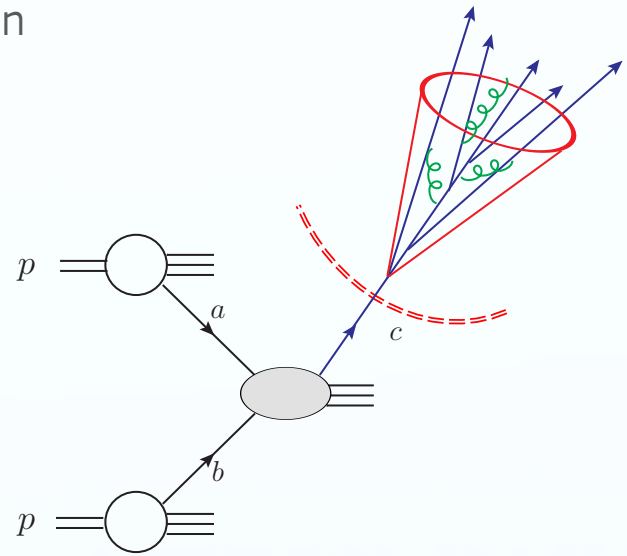


  - At NLO, one needs a consistent way to define what one calls quark/gluon jets



QCD factorization makes things simple

- When R << 1, the relevant scales for single jet production
  - Two momenta: (1) hard collision: pT (2) jet radius can build one: pT*R
  - A further factorization



$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(\mu \sim p_T R)$$

  - Good thing: semi-inclusive jet function $J_{q,g}(z, R)$ are purely perturbative

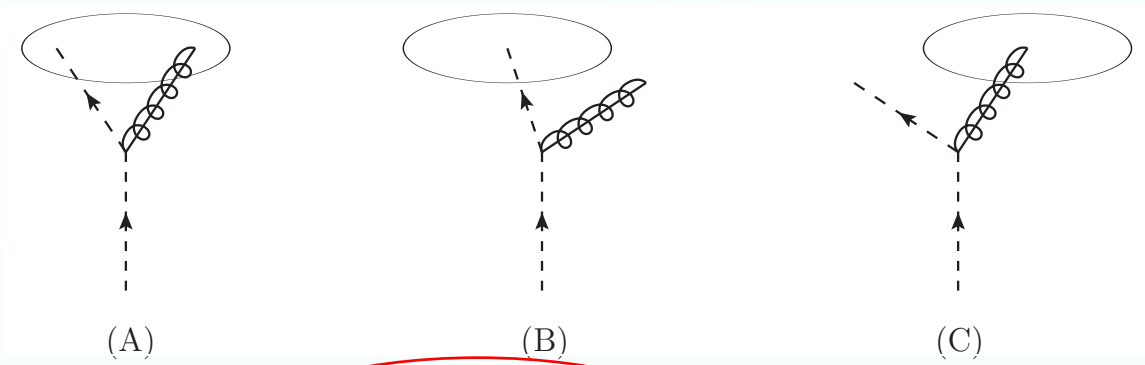
Kang, Ringer, Vitev, arXiv:1606.06732, Dai, Kim, Leibovich, 1606.07411, see also, Kaufmann, Mukherjee, Vogelsang, 1506.01415

Semi-inclusive jet functions

- At LO: only one parton becomes the jet Kang, Ringer, Vitev, arXiv:1606.06732, JHEP

$$J_q^{(0)}(z,\omega_J) = \delta(1-z),$$
$$J_g^{(0)}(z,\omega_J) = \delta(1-z),$$

- At NLO: e.g., for quark-initiated jets



$$J_q^{(1)}(z,\omega_J) = \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon}+L\right)\left[P_{qq}(z)+P_{gq}(z)\right]$$
$$-\frac{\alpha_s}{2\pi}\left\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z)d_J^{q,\mathrm{alg}}\right.$$
$$\left. + P_{gq}(z)2\ln(1-z) + C_F z\right\},$$

- Divergent: needs renormalization

Gluon-initiated jets

- For gluon jets

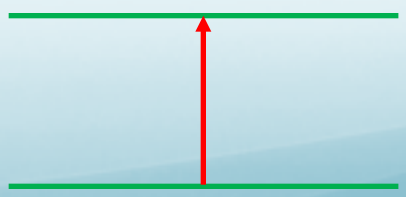
$$J_g^{(1)}(z,\omega_J) = \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon}+L\right)\left[P_{gg}(z)+2n_f P_{qg}(z)\right]$$
$$-\frac{\alpha_s}{2\pi}\left[\frac{4C_A(1-z+z^2)^2}{z}\left(\frac{\ln(1-z)}{1-z}\right)_+ - \delta(1-z)d_J^{g,\mathrm{alg}}\right.$$
$$\left.+4n_f\Big(P_{qg}(z)\ln(1-z)+T_F z(1-z)\Big)\right],$$

- Natural scale for quark/gluon jet functions: $L=\ln\frac{\mu^2}{\omega_J^2\tan^2\frac{\mathcal{R}}{2}} \to \mu=\omega_J\tan\frac{\mathcal{R}}{2}=p_T\cdot R$

After renormalization, one will find: semi-inclusive quark/gluon jets follow DGLAP evolution equation, just like hadron fragmentation functions

$$\mu\frac{d}{d\mu}J_i(z,\omega_J,\mu)=\frac{\alpha_s(\mu)}{\pi}\sum_j\int_z^1\frac{dz'}{z'}P_{ji}\left(\frac{z}{z'},\mu\right)J_j(z',\omega_J,\mu)$$

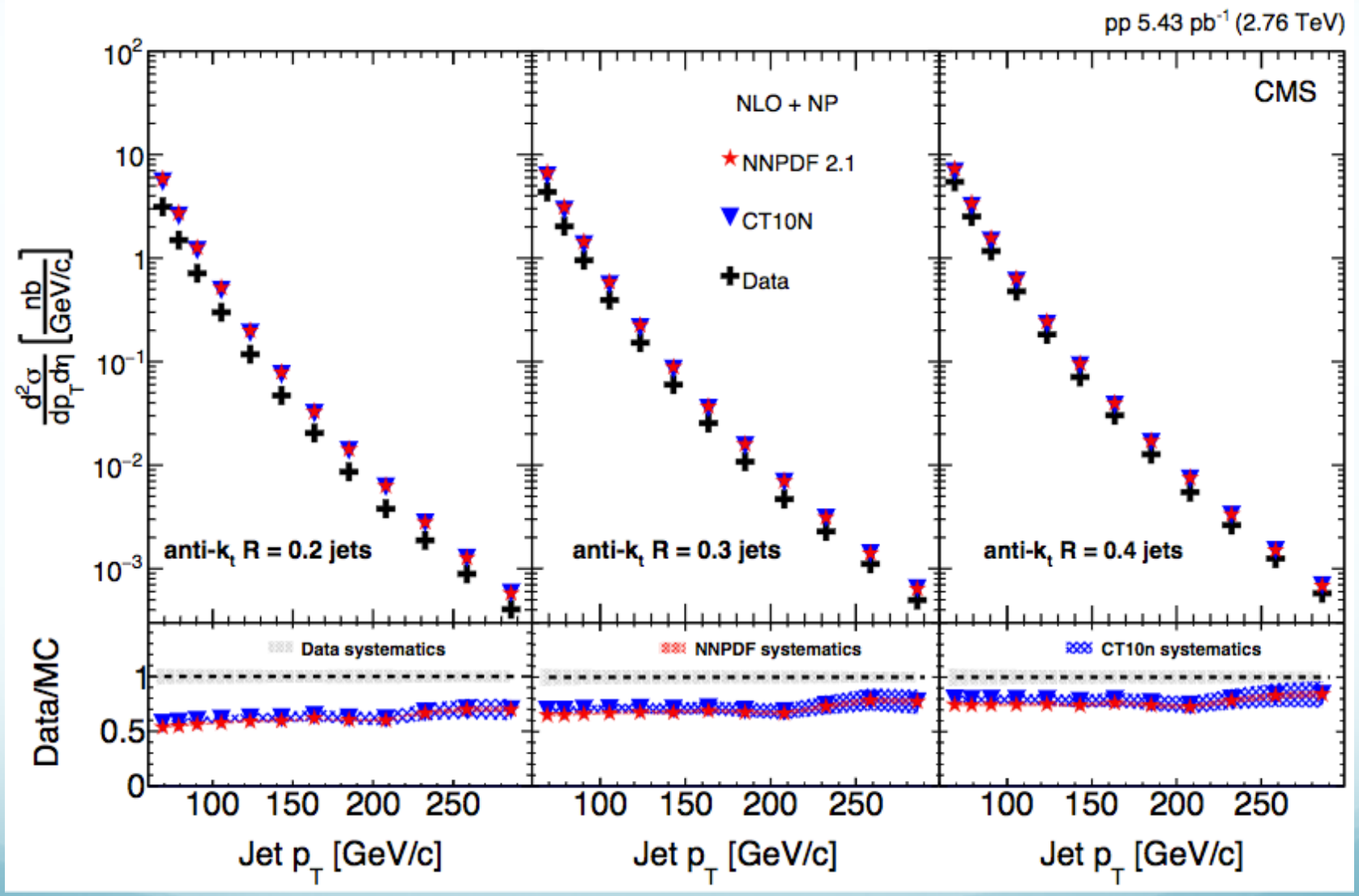
- Jet radius resummation: $(\alpha_s\ln R)^n$



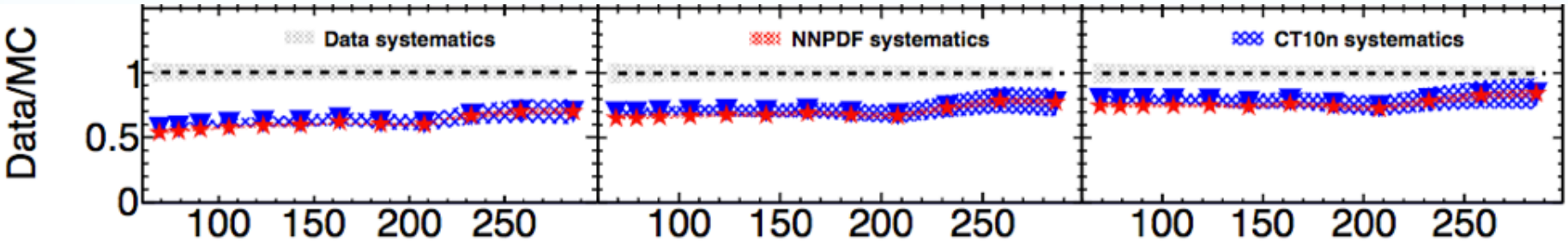
$\mu\sim p_T$

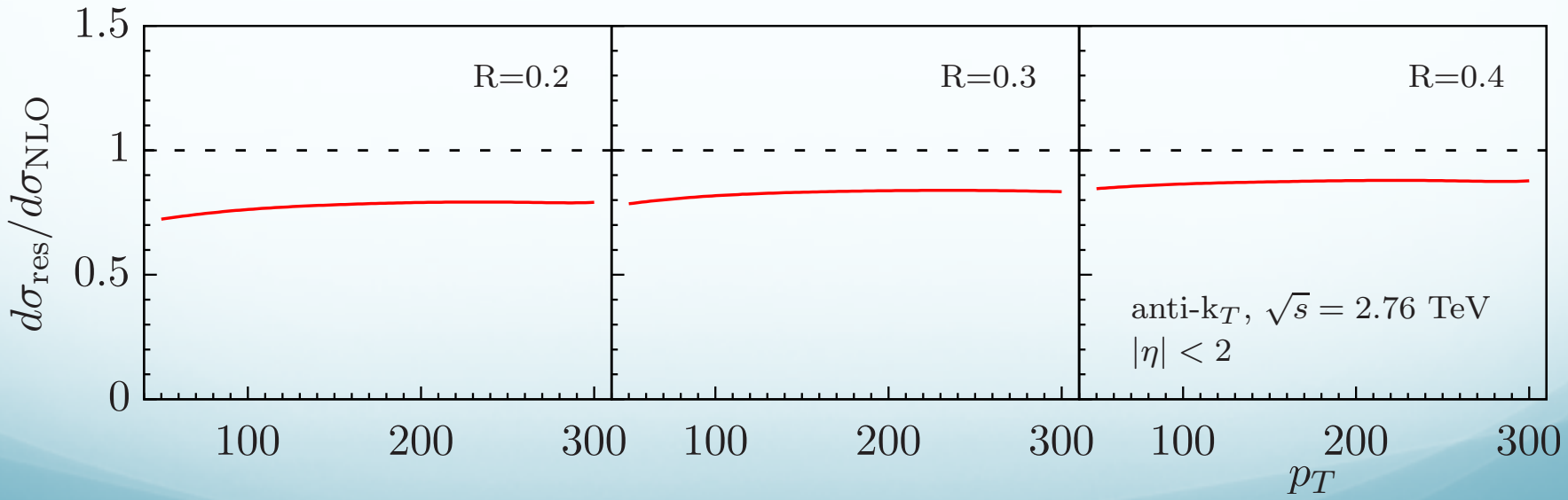
$\mu_J\sim p_T\times R$

Is it relevant?



Effect of ln(R) resummation

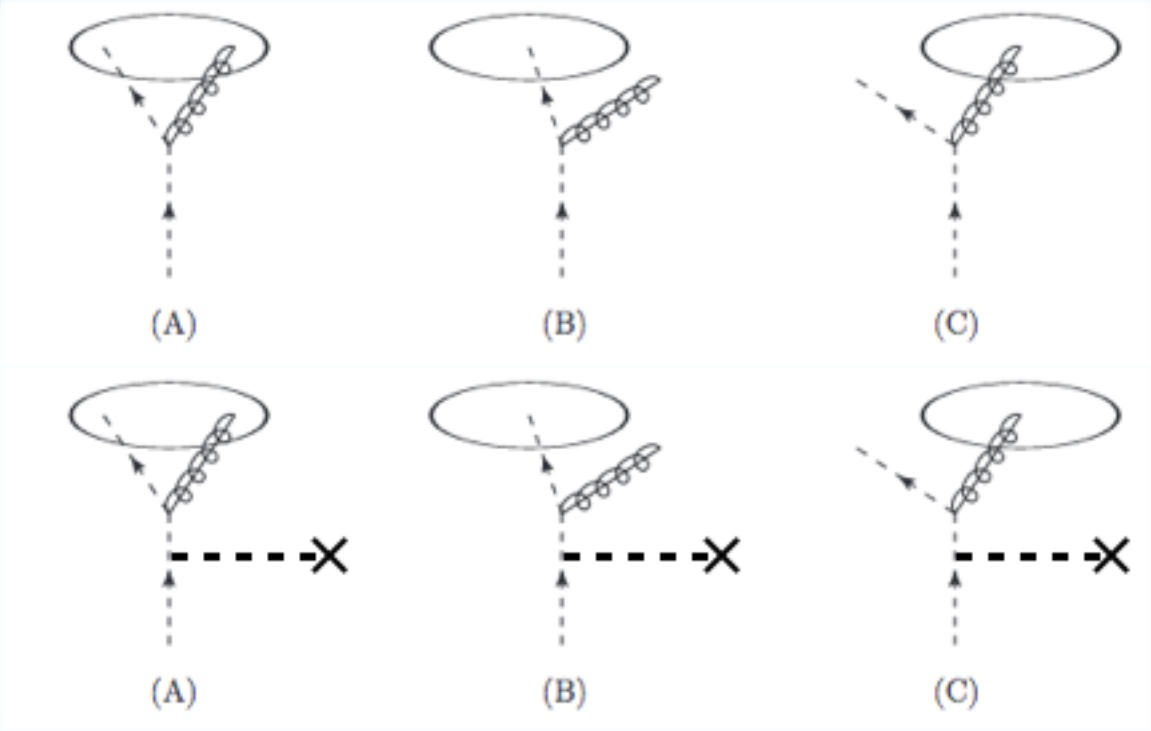




Now ready to do jet modification at NLO

vacuum

medium

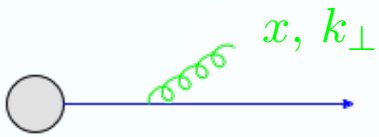


$$J_c(z,\omega_J) = J_c^{\rm vac}(z,\omega_J) + J_c^{\rm med}(z,\omega_J)$$

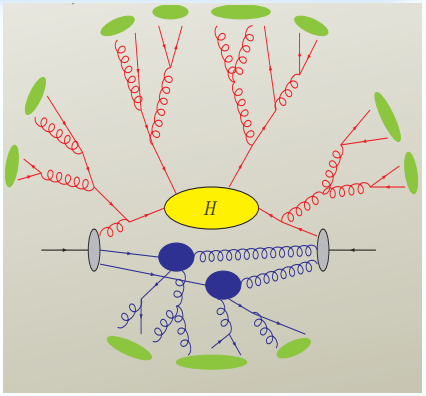
$$J_q^{\rm med,(1)}(z,\omega_J) = \left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}^{med}(z,q_\perp)\right]_+ + \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{gq}^{med}(z,q_\perp)$$

What happens in medium?

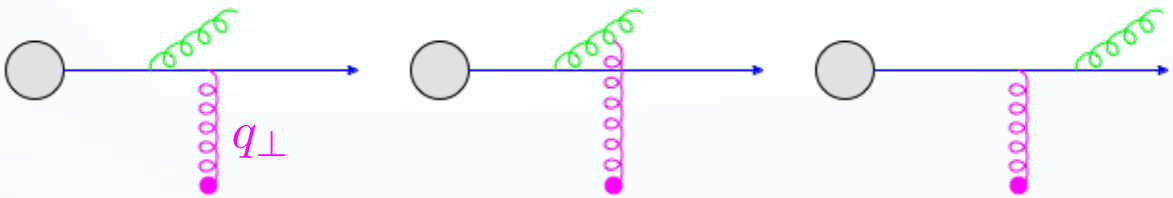
- Vacuum splitting



$$\frac{dN^{\rm vac}}{dx d^2k_\perp} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \frac{1}{k_\perp^2}$$



- Medium splitting ($SCET_G$)
  - transverse momentum kick through Glauber gluons $q \sim (\lambda^2, \lambda^2, \lambda)$



$$\frac{dN^{\rm med}}{dx d^2k_\perp} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2q_\perp} \left[\frac{B_\perp}{B_\perp^2} \cdot \left(\frac{B_\perp}{B_\perp^2} - \frac{C_\perp}{C_\perp^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \cdots \right]$$

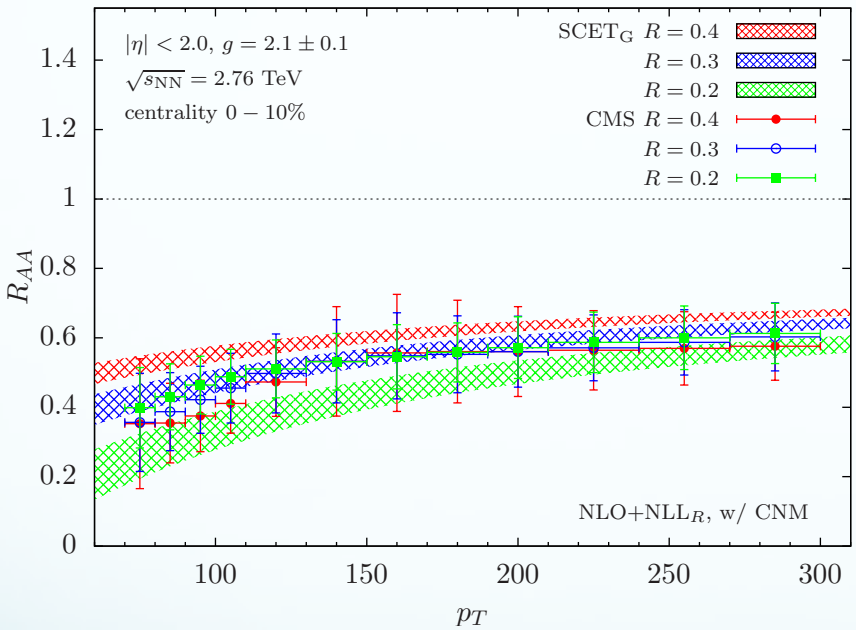
GLV formalism

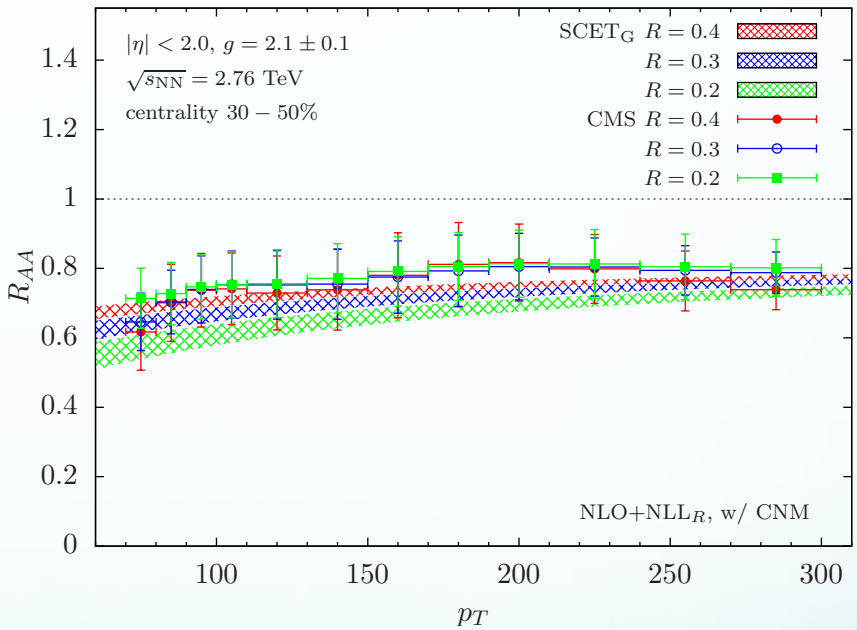
Gyulassy, Levai, Vitev, 02, Idilbi, Majumder 08,
D'Eramo, Liu, Rajagopal, 10, Ovanesyan, Vitev, 11, ...

- Leads to additional contribution to the fragmenting jet function, as well as modifies the jet function

Comparison with the LHC data

Kang, Ringer, Vitev, 1701.05839, PLB



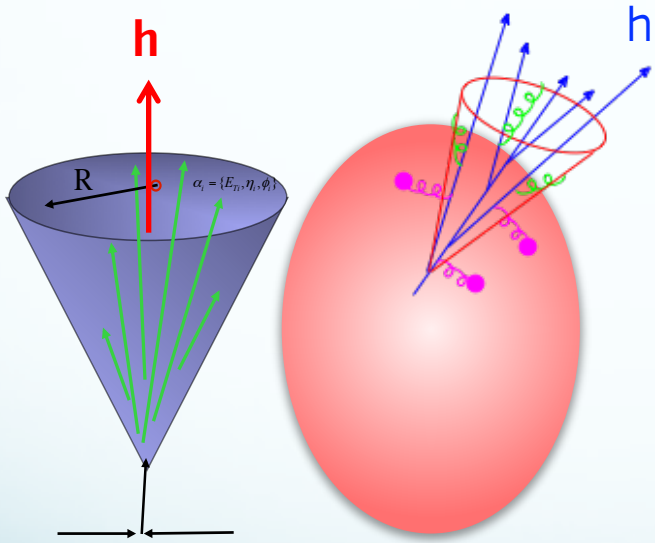


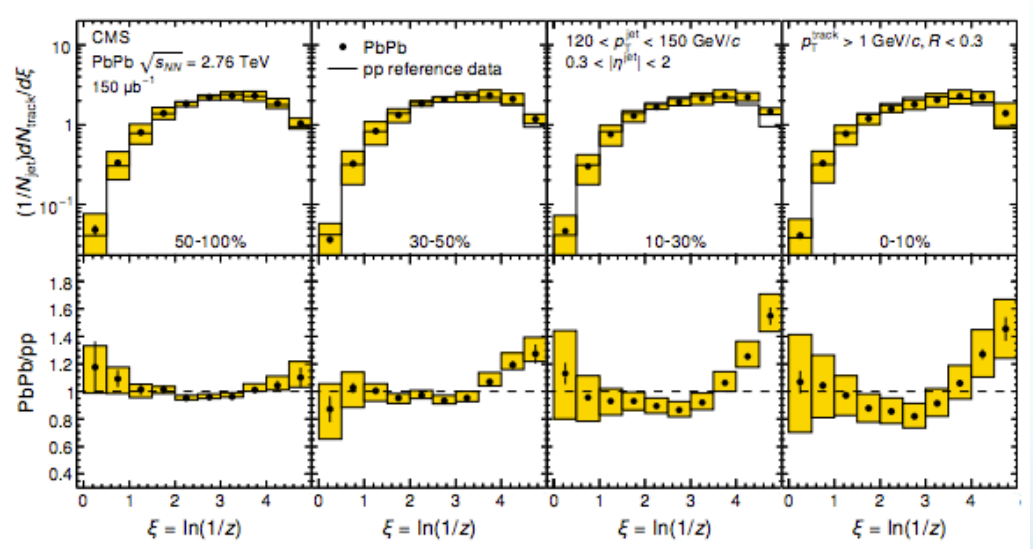
Jet substructure: hadron distribution inside the jet

- Jet fragmentation function
  - Modification pattern reveals detailed information on inner-jet interaction
  - So far jet fragmentation function modification is not explained

$$z_h = p_\perp^{\mathrm{h}} / p_\perp^{\mathrm{jet}}$$

$$F(z_h, p_T) = \frac{d\sigma^h}{dy dp_T dz_h} \Big/ \frac{d\sigma}{dy dp_T}$$



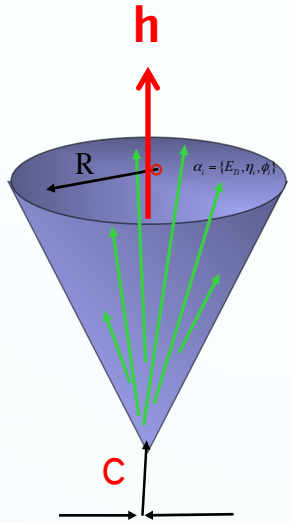


A+A collisions
with medium interactions

- ✓ **Top:** CMS jet fragmentation function measurements in pp and PbPb collisions with different centralities
- ✓ **Bottom:** ratio of medium and vacuum jet fragmentation function

Jet fragmentation function

- First produce a jet, and then further look for a hadron inside the jet



$$F(z_h, p_T) = \frac{d\sigma^h}{dy dp_T dz_h} \Big/ \frac{d\sigma}{dy dp_T}$$

$$z_h = p_T^h / p_T$$

$$z = p_T / p_T^c$$

Kang, Ringer, Vitev, arXiv:1606.07063, JHEP

- Just like the single inclusive jet production, we have
  - Semi-inclusive fragmenting jet function

$$\frac{d\sigma}{dy dp_T dz_h} \propto \sum_{a,b,c} \int \frac{dz}{z^2} \mathcal{G}_c^h(z, z_h, \mu) \int \frac{dx'}{x'} f_{a/p}(x') \int \frac{dx}{x} f_{b/A}(x) \hat{\sigma}_{ab\to c}$$

Two DGLAPs

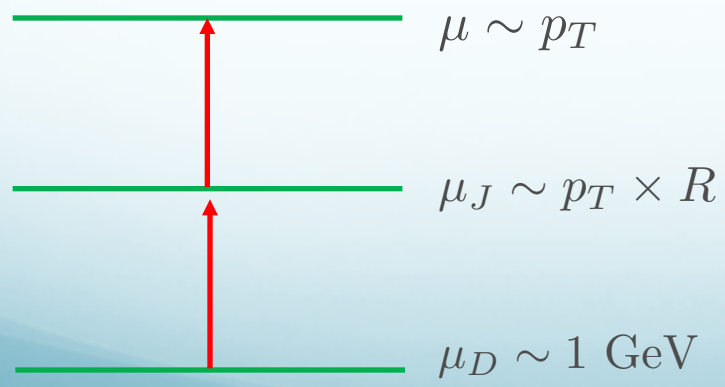
- Again DGLAP evolution: evolution is for variable z

$$\mu \frac{d}{d\mu} \mathcal{G}_i^h(z, z_h, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}\right) \mathcal{G}_j^h(z', z_h, \mu)$$

- Relation to standard FFs: relevant to variable z_h

$$\mathcal{G}_i^h(z, z_h, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}\left(z, z_h', \mu\right) D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$

Kang, Ringer, Vitev, arXiv:1606.07063

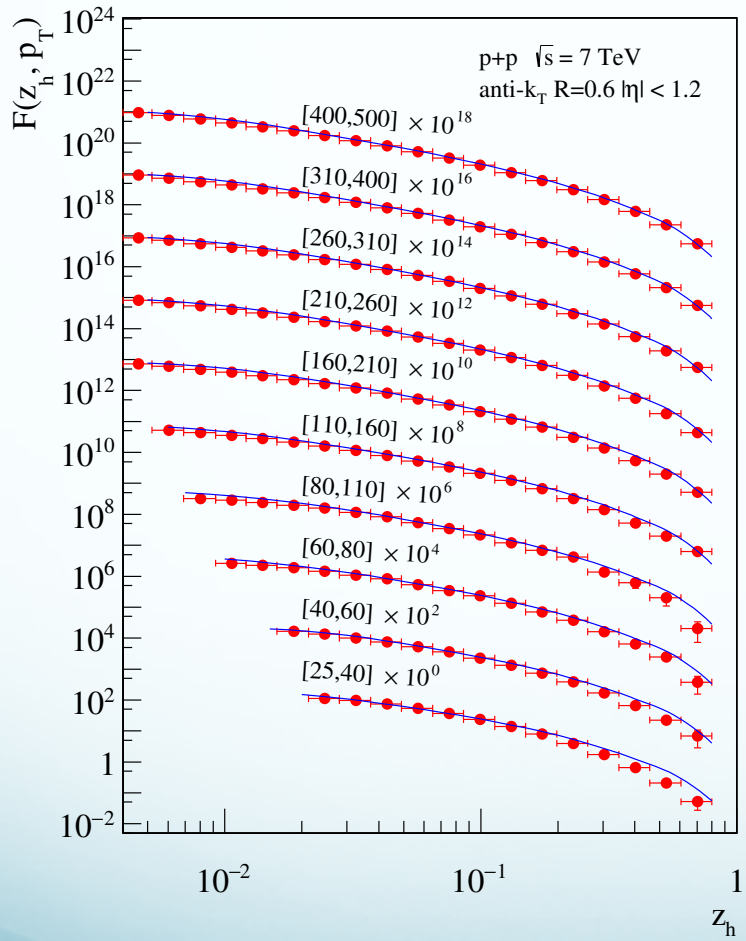


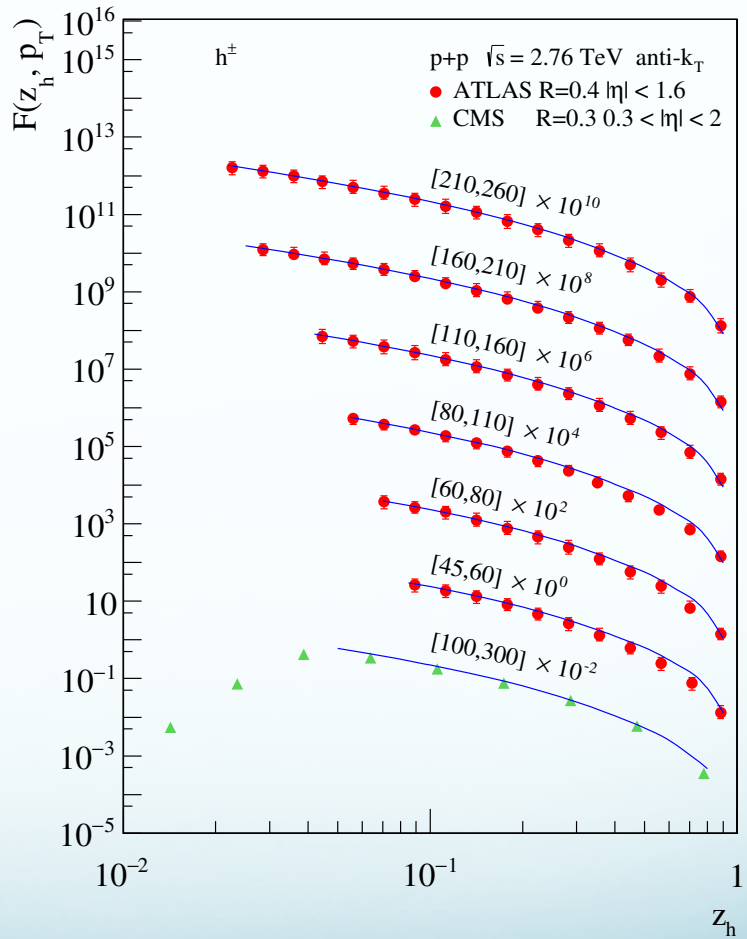
Resum ln(R)

Evolve standard FFs from 1 GeV to pT*R

Some interesting phenomenology

- Works pretty well in comparison with experimental data



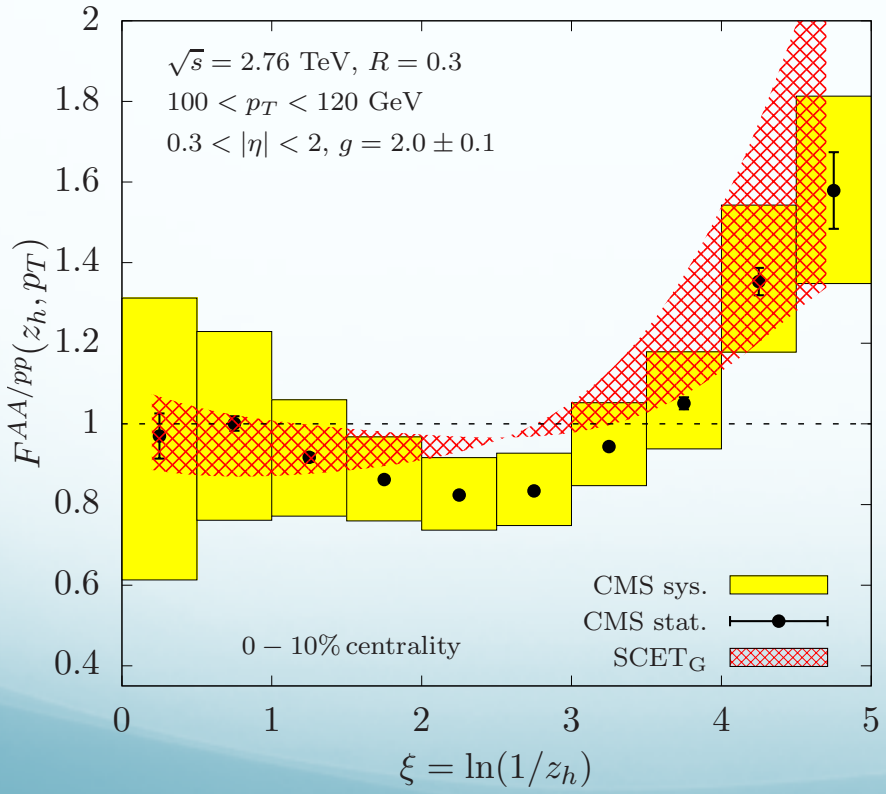


Kang, Ringer, Vitev, arXiv:1606.07063, JHEP

Jet fragmentation function in A+A collisions

- Comparison with CMS data
  - Small z region: jet quenching leads to enhancement for the softer hadrons within the jet
  - Large z region: change of the relative weight of quark and gluons jets leads to modification

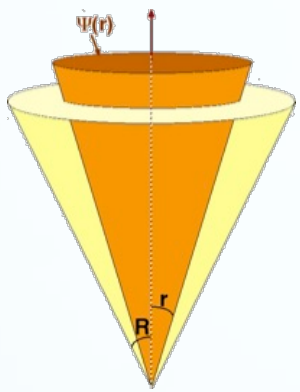
Chien, Kang, Ringer, Vitev, Xing, in preparation

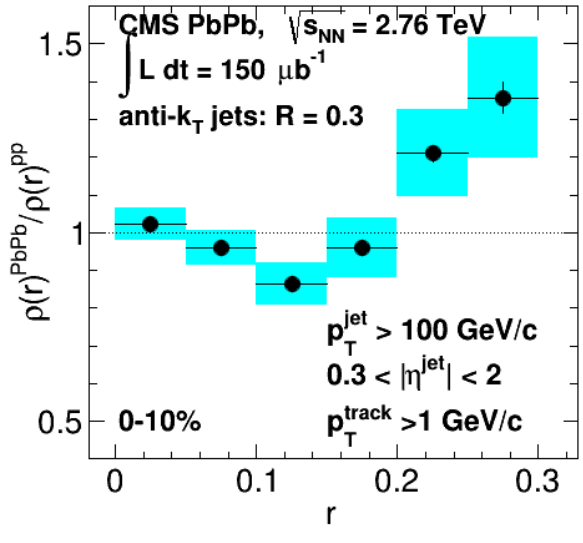


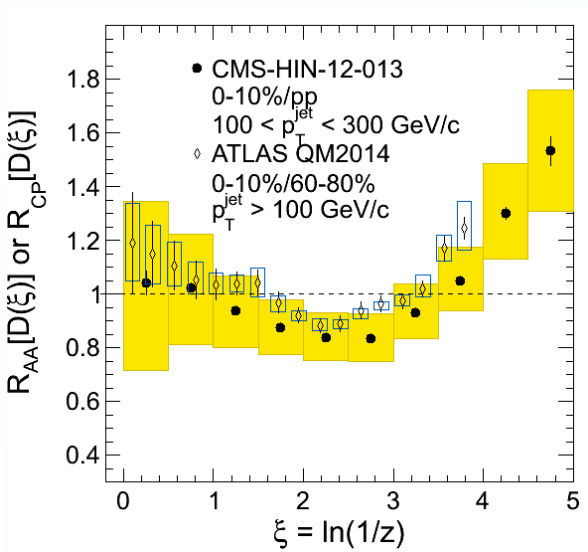
Still in progress of assessing the sensitivity, centrality dependence, etc

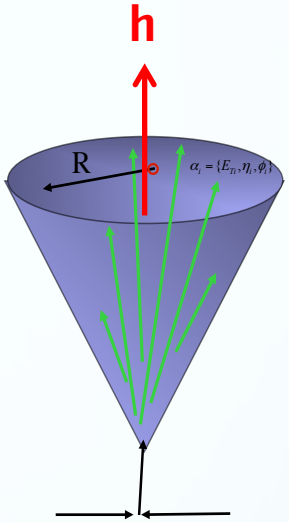
Distribution of subjet inside a fat jet

- Combing jet shape and jet fragmentation function







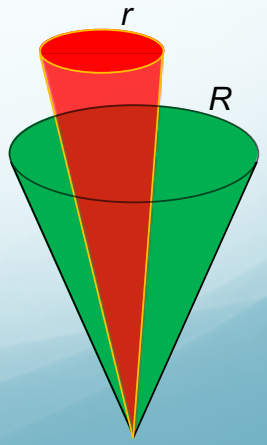


- Subjet distribution inside jets

$$F(z_r, \eta, p_T, r, R) = \frac{\mathrm{d}\sigma}{\mathrm{d}\eta\, \mathrm{d}p_T\, \mathrm{d}z_r} \Big/ \frac{\mathrm{d}\sigma}{\mathrm{d}\eta\, \mathrm{d}p_T}$$

$$z_r = \frac{\omega_r}{\omega_R}$$

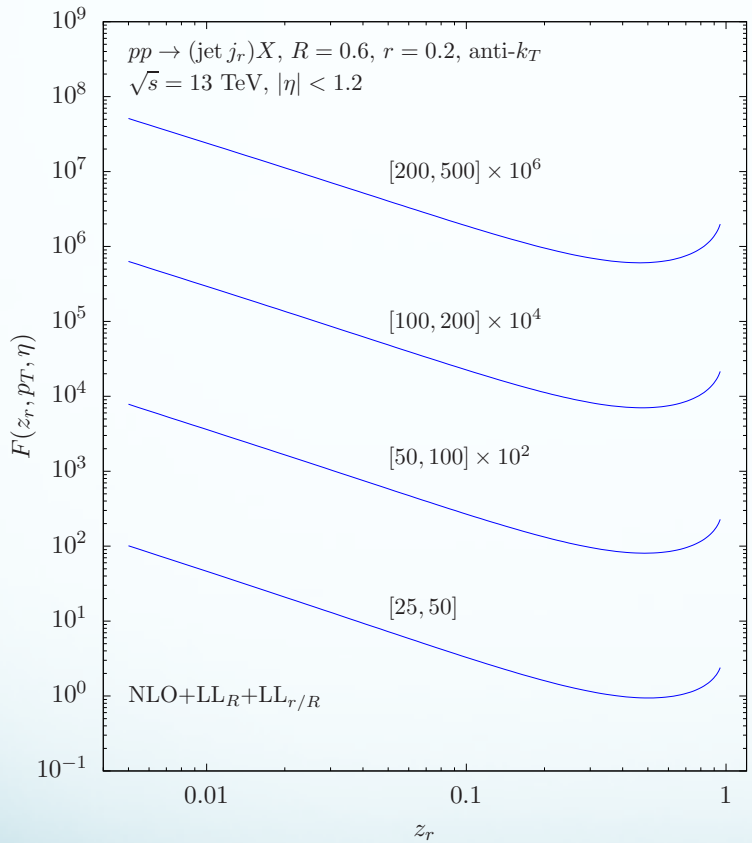
Kang, Ringer, Waalewijn, arXiv:1705.05375

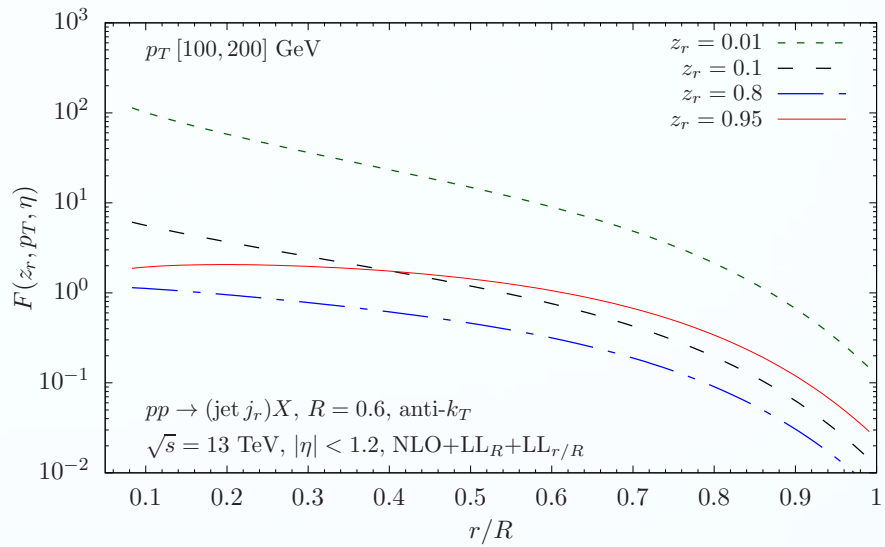


Very preliminary plot

- Subjet distribution inside jets

Kang, Ringer, Waalewijn, arXiv:1705.05375





Shape of Altarelli-Parisi splitting function

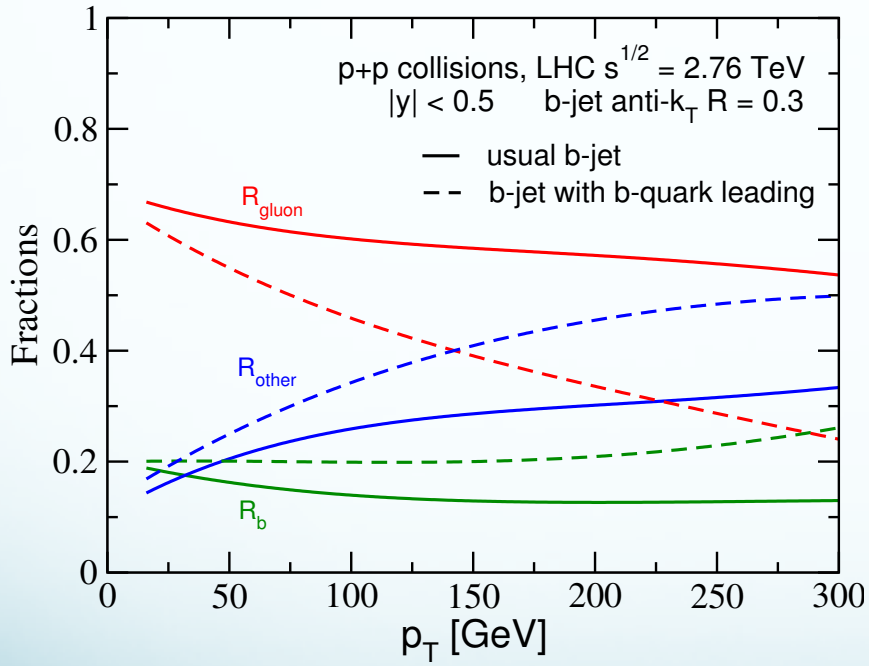
$$\mathcal{G}_q^{\text{jet}}(z, z_r < 1, \omega_R, \mu) = \frac{\alpha_s}{2\pi}\,\delta(1-z) L_{r/R}\left[P_{qq}(z_r) + P_{gq}(z_r)\right]$$

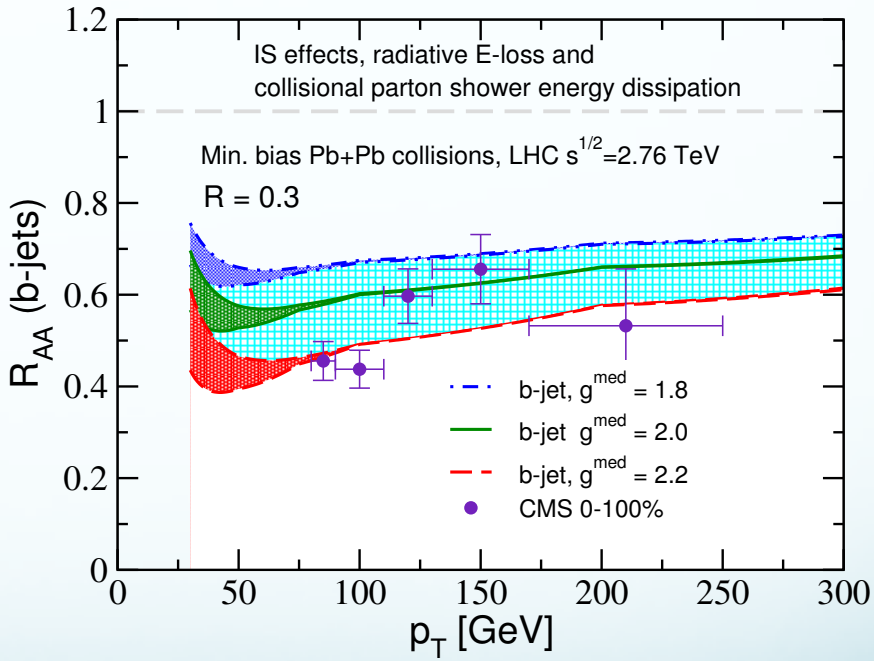
See also: Larkoski, Marzani, Soyez, Thaler, 14

Earlier study on heavy flavor

- Still traditional energy loss formalism

Single inclusive b-jet

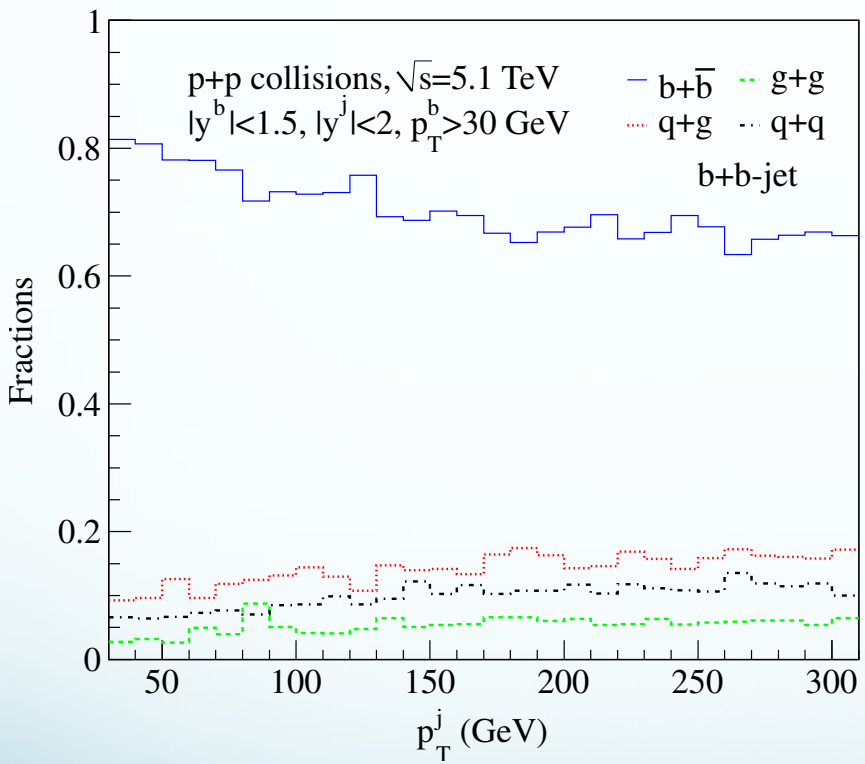


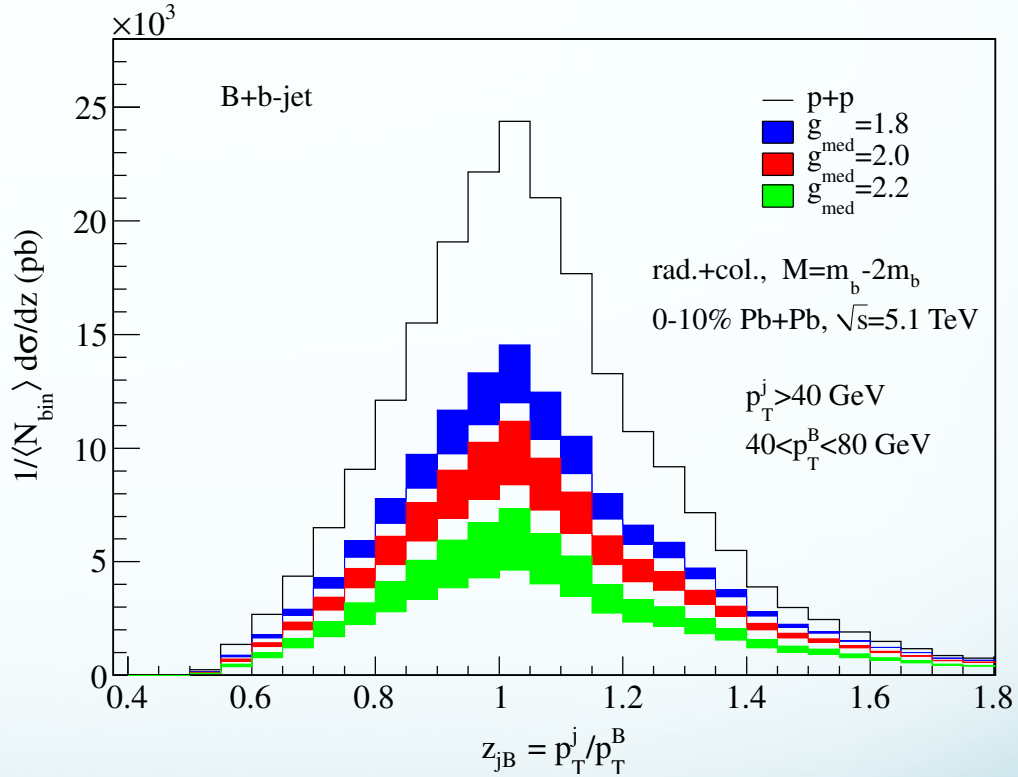


Huang, Kang, Vitev, PLB 13

B meson tagged b-jet

- Heavy quark component is greatly increased





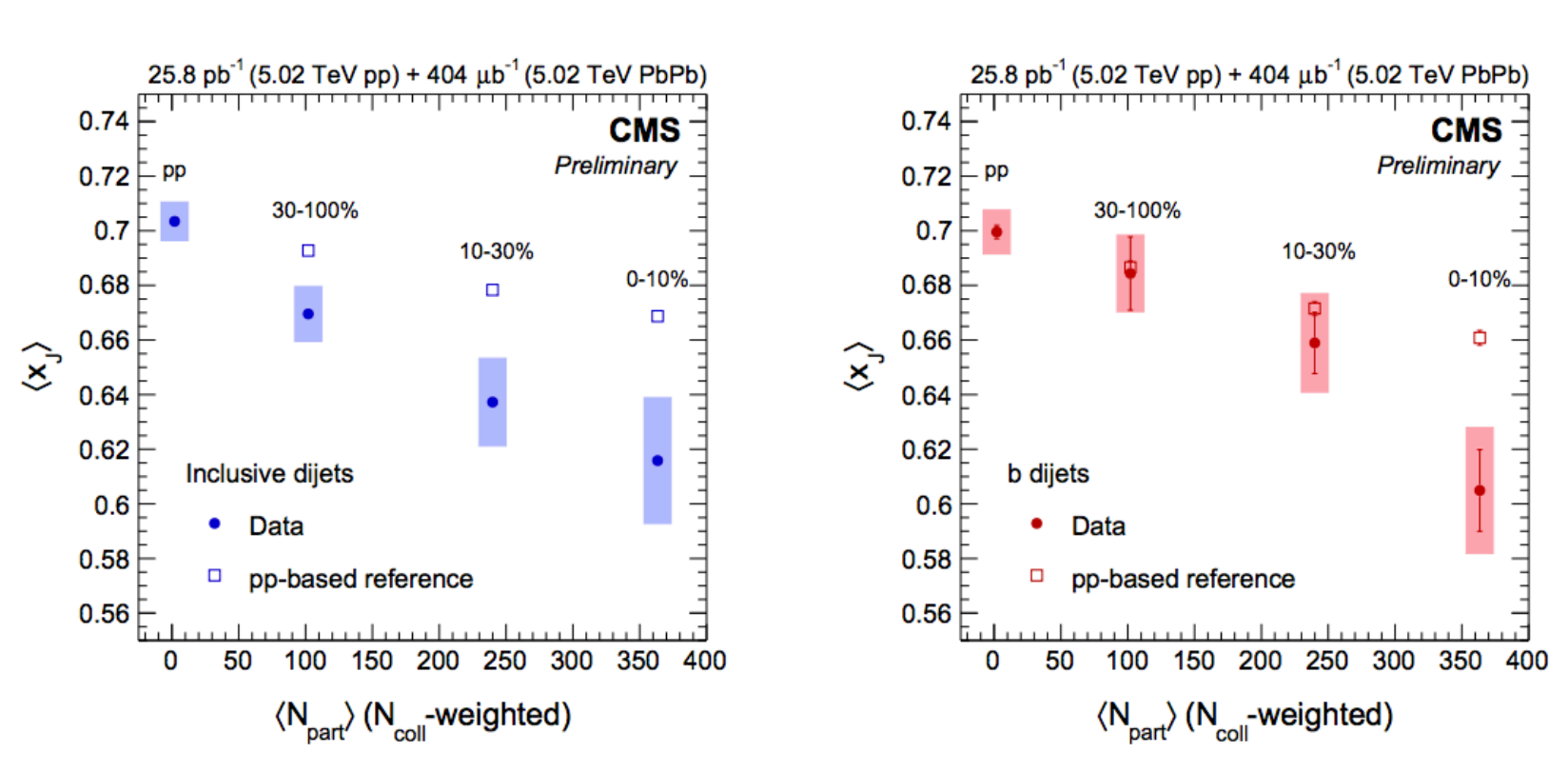
Huang, Kang, Vitev, Xing, PLB 15

- Study bottom di-jet now

Kang, Vitev, Xing, in preparation

Inclusive dijet and bottom dijet

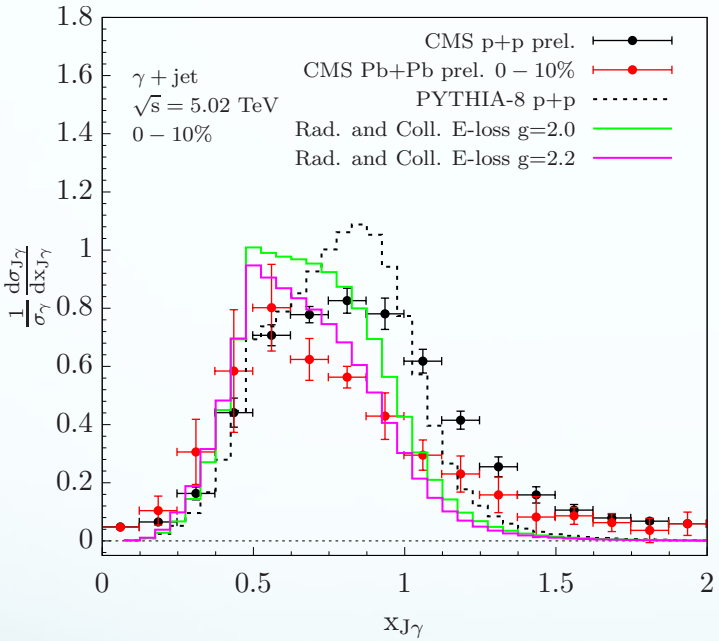
- Similar or different

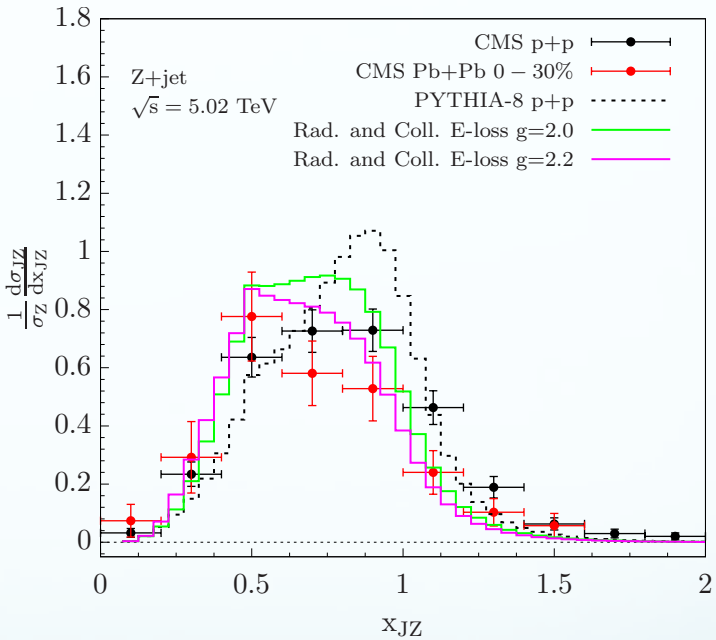


Vector boson tagged jets

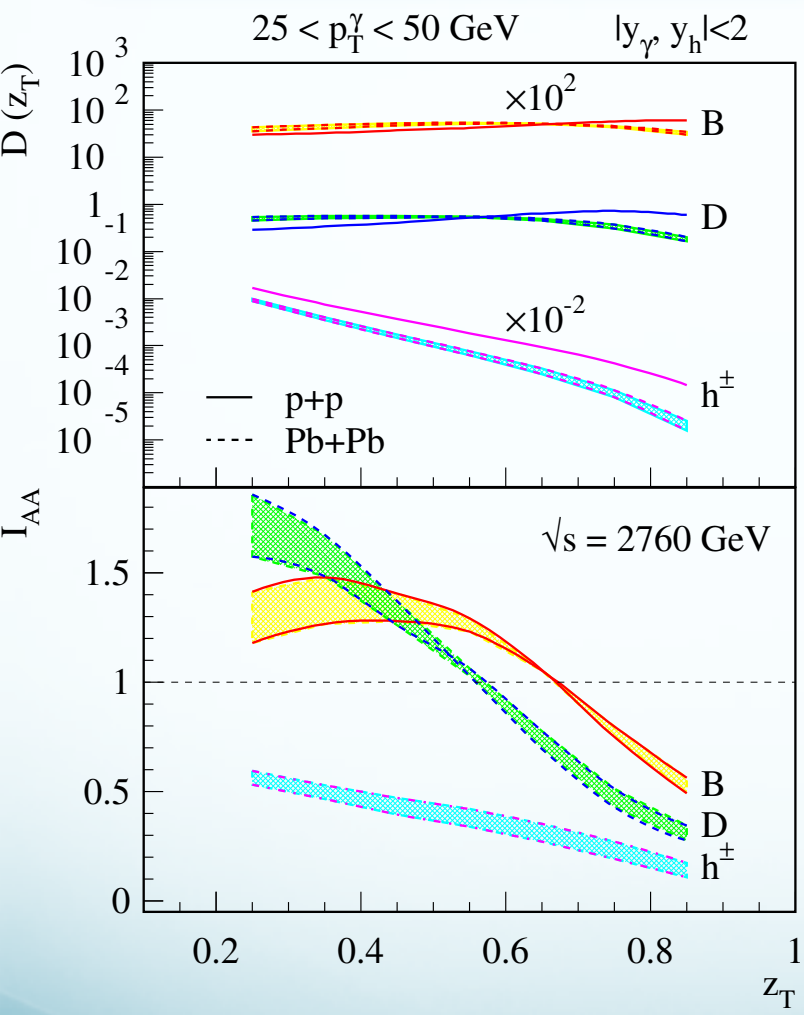
- Photon/Z-boson tagged light jets

Kang, Vitev, Xing, 1702.07276

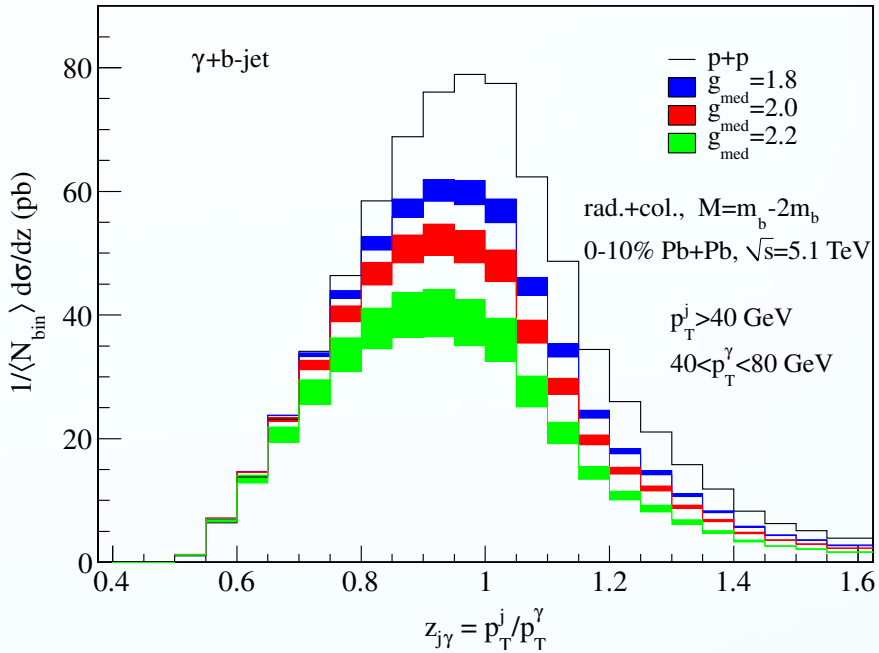




Photon tagged heavy jet and meson



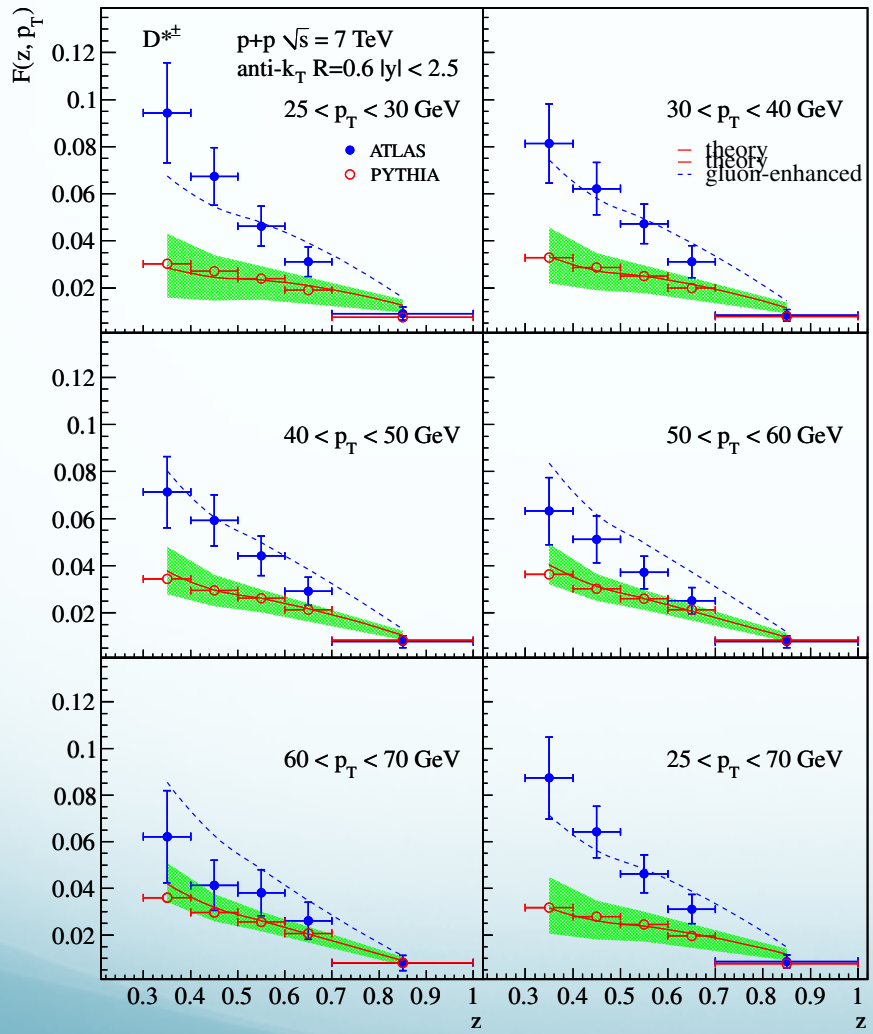
Kang, Vitev, PRD 11



Huang, Kang, Vitev, Xing, PLB 15

Time to do serious QCD computations

- Jet FFs for D meson: use FFs fitted from e+e- data



Kneesch, Kniehl, Kramer, Schienbein, 08

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

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

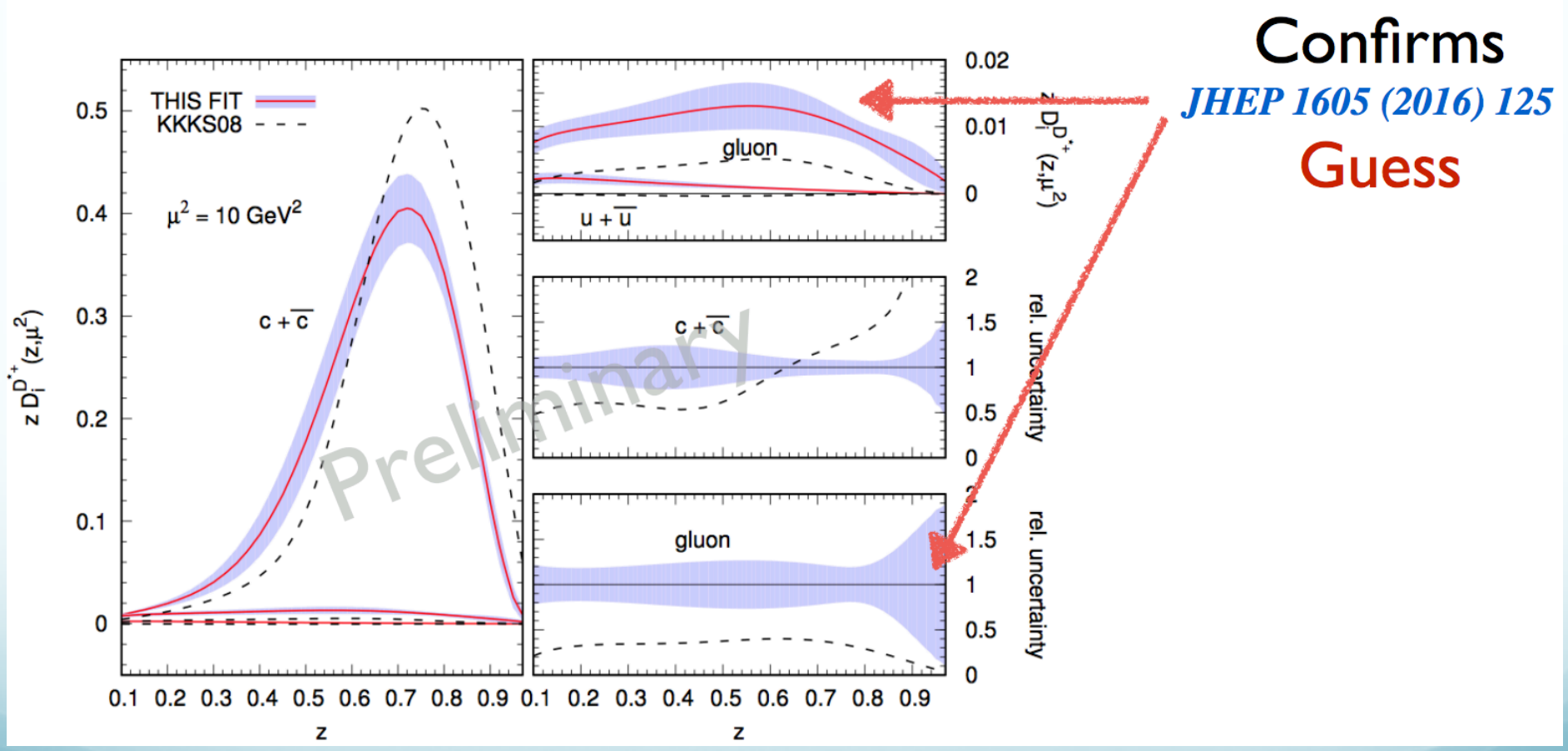
New fit of D-meson FFs:
Anderle, Ringer, Stratmann, Vitev, in progress

MC event generator can NOT completely replace analytical type theory calculations, they are complimentary to each other

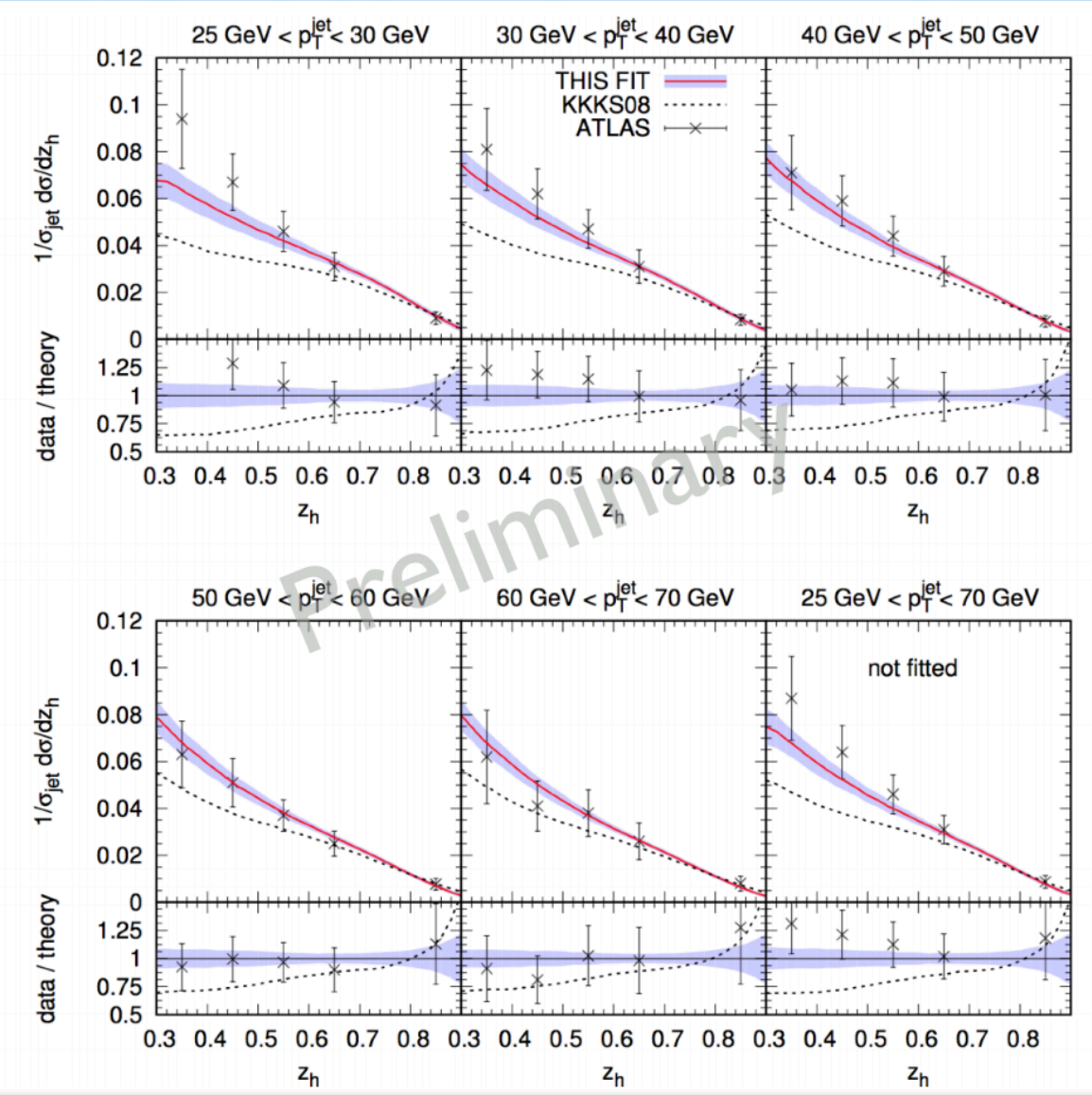
A new global analysis of FFs

- New fit of D-meson FFs

New fit of D-meson FFs:
Anderle, Ringer, Stratmann, Vitev, in progress



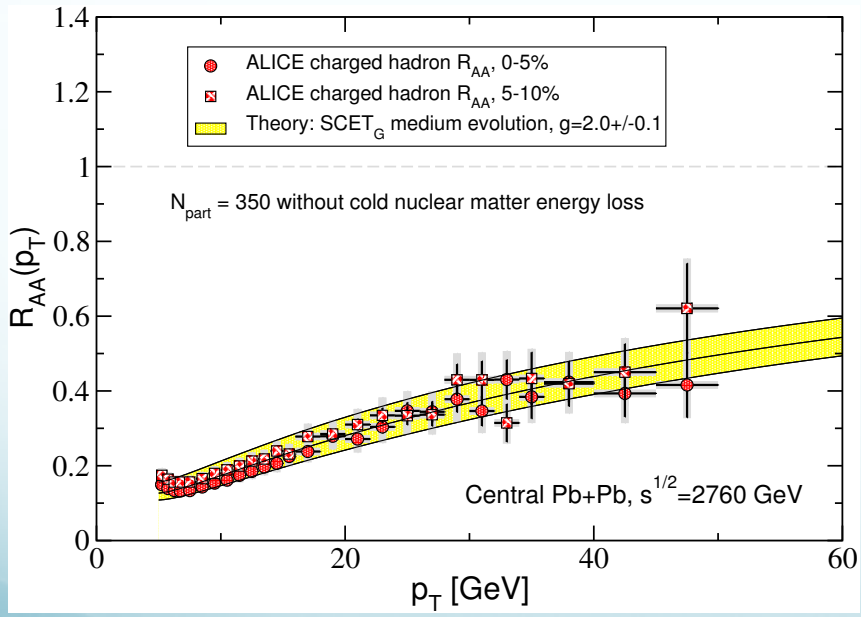
The new fit

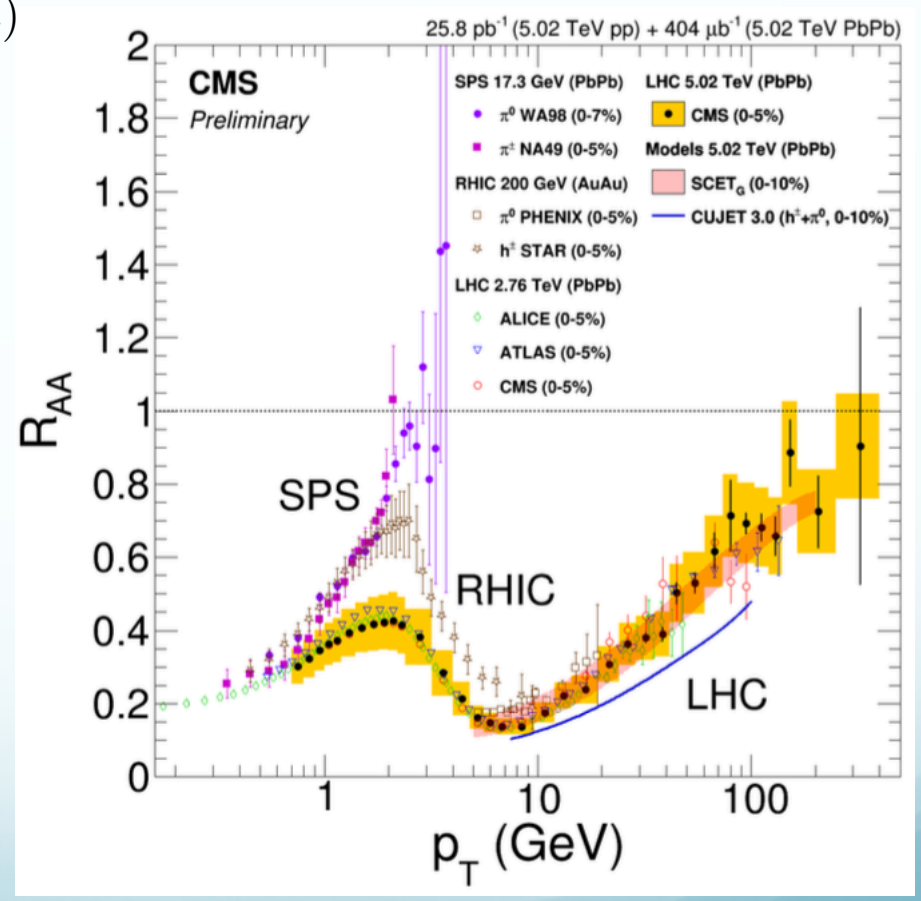

25 GeV < p_T^{jet} < 30 GeV
30 GeV < p_T^{jet} < 40 GeV
40 GeV < p_T^{jet} < 50 GeV
THIS FIT
KKKS08
ATLAS
$1/\sigma_{jet}\, d\sigma/dz_h$
data / theory
z_h
Preliminary
50 GeV < p_T^{jet} < 60 GeV
60 GeV < p_T^{jet} < 70 GeV
25 GeV < p_T^{jet} < 70 GeV
not fitted

Light hadron from $SCET_G$

- Compute the medium-induced splitting functions

$$\frac{\partial D_i^h(z,\mu)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi}\left[P_{ji}^{\rm vac} + P_{ji}^{\rm med}\right] \otimes D_j^h(z,\mu)$$





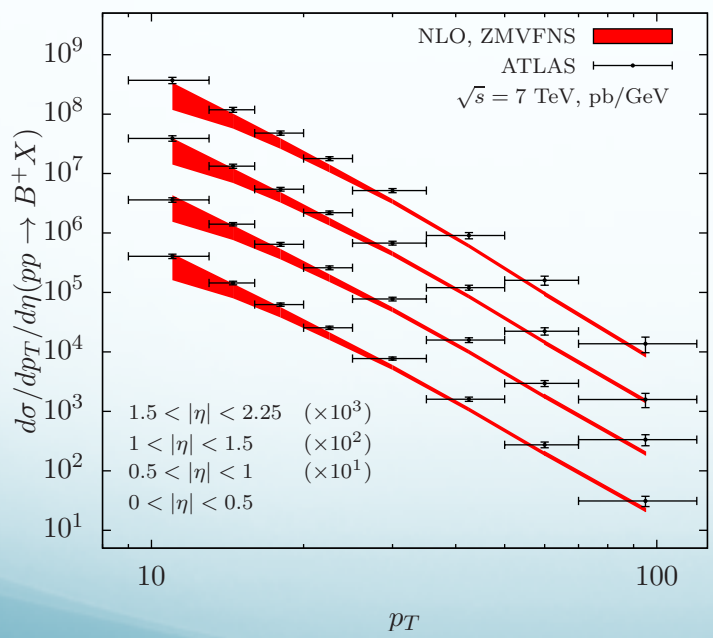
Kang, Ovanesyang, Vitev, et.al., PRL (2015)
Chien, Kang, Ovanesyang, Vitev, et.al., PRD (2016)

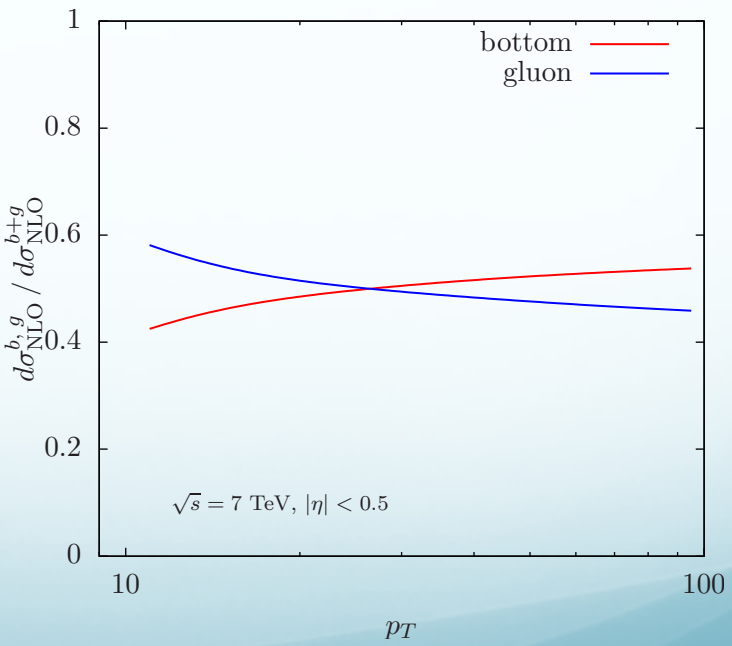
Heavy meson production

- Heavy meson cross section using ZM-VNFS at NLO

$$\frac{d\sigma_{pp}^{H}}{dp_T d\eta} = \frac{2p_T}{s} \sum_{a,b,c} \int_{x_a^{\min}}^{1} \frac{dx_a}{x_a} f_a(x_a,\mu) \int_{x_b^{\min}}^{1} \frac{dx_b}{x_b} f_b(x_b,\mu)$$
$$\times \int_{z_c^{\min}}^{1} \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz} D_c^H(z_c,\mu)$$

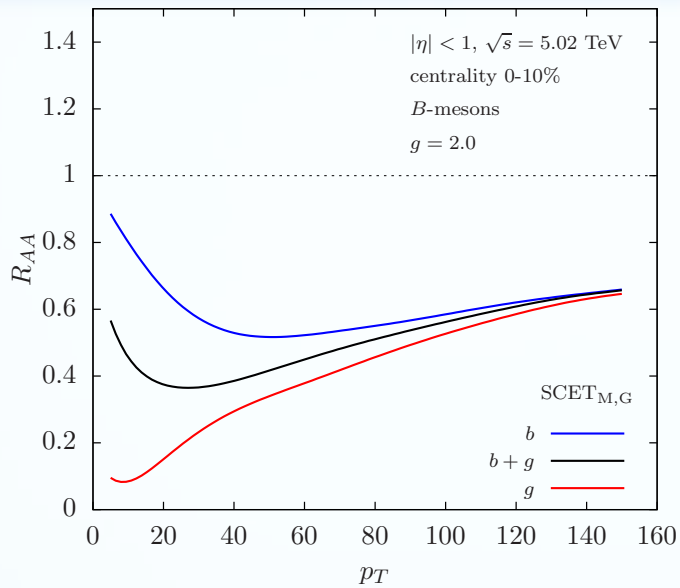
c=light quark, gluon, and heavy quark



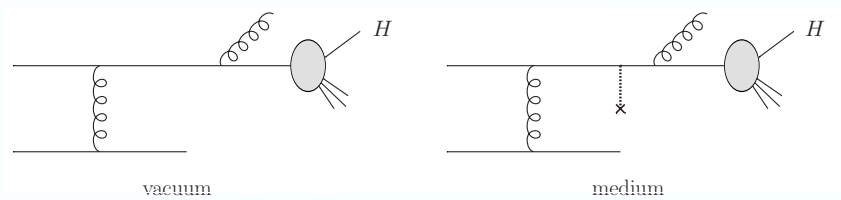


Kang, Ringer, Vitev, 16

Heavy meson in heavy ion collisions

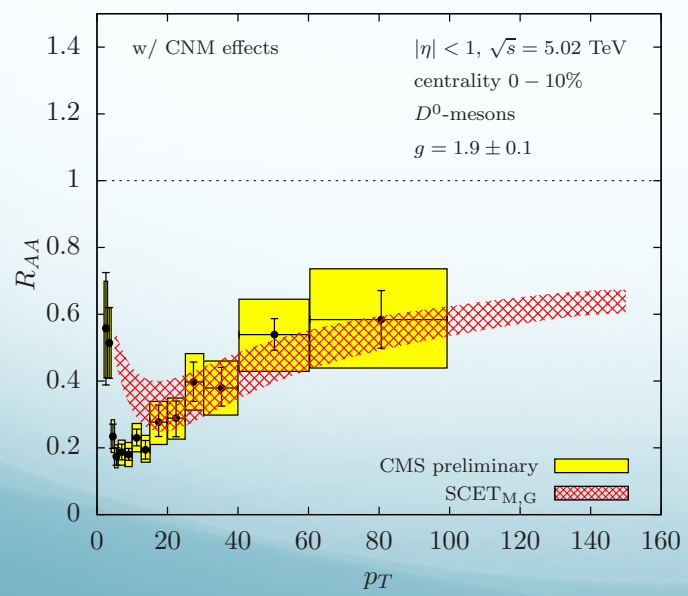


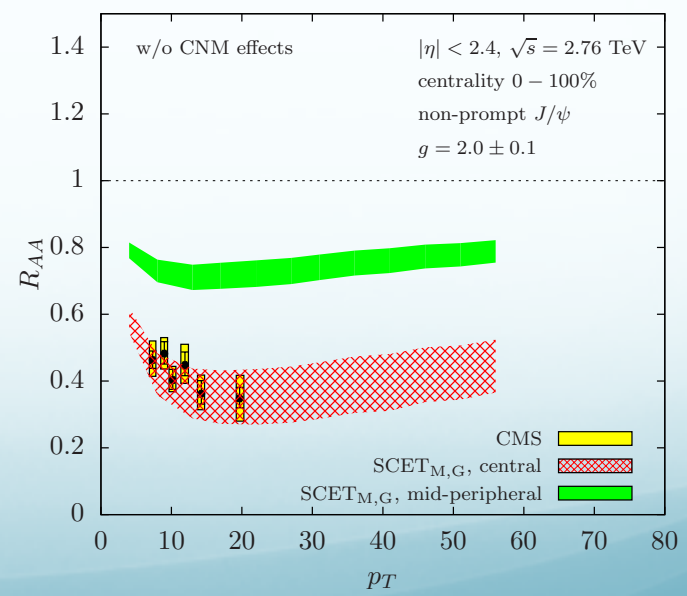
SCET$_{\rm M,G}$



$$d\sigma^{H,\rm med}_{\rm PbPb} = \hat{\sigma}_i^{(0)} \otimes D_i^{H,\rm med} = \sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}^{\rm med}_{i\to jk} \otimes D_j^H$$

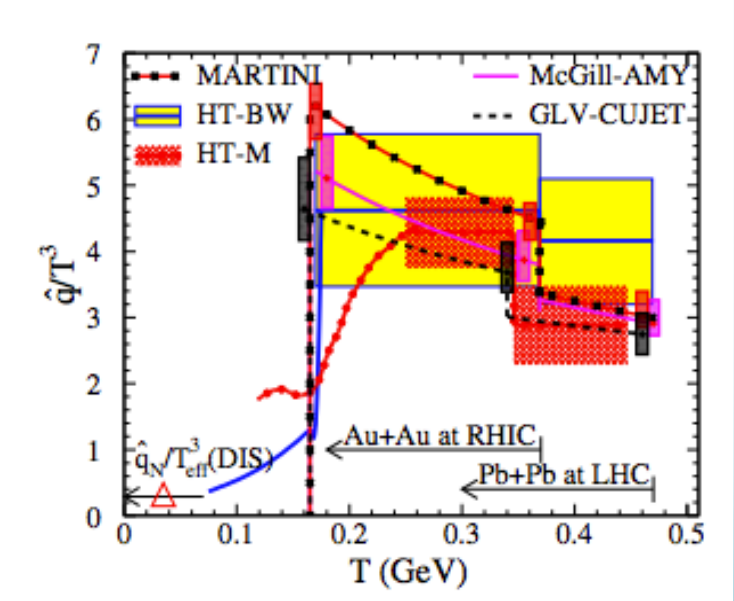
Kang, Ringer, Vitev, 16





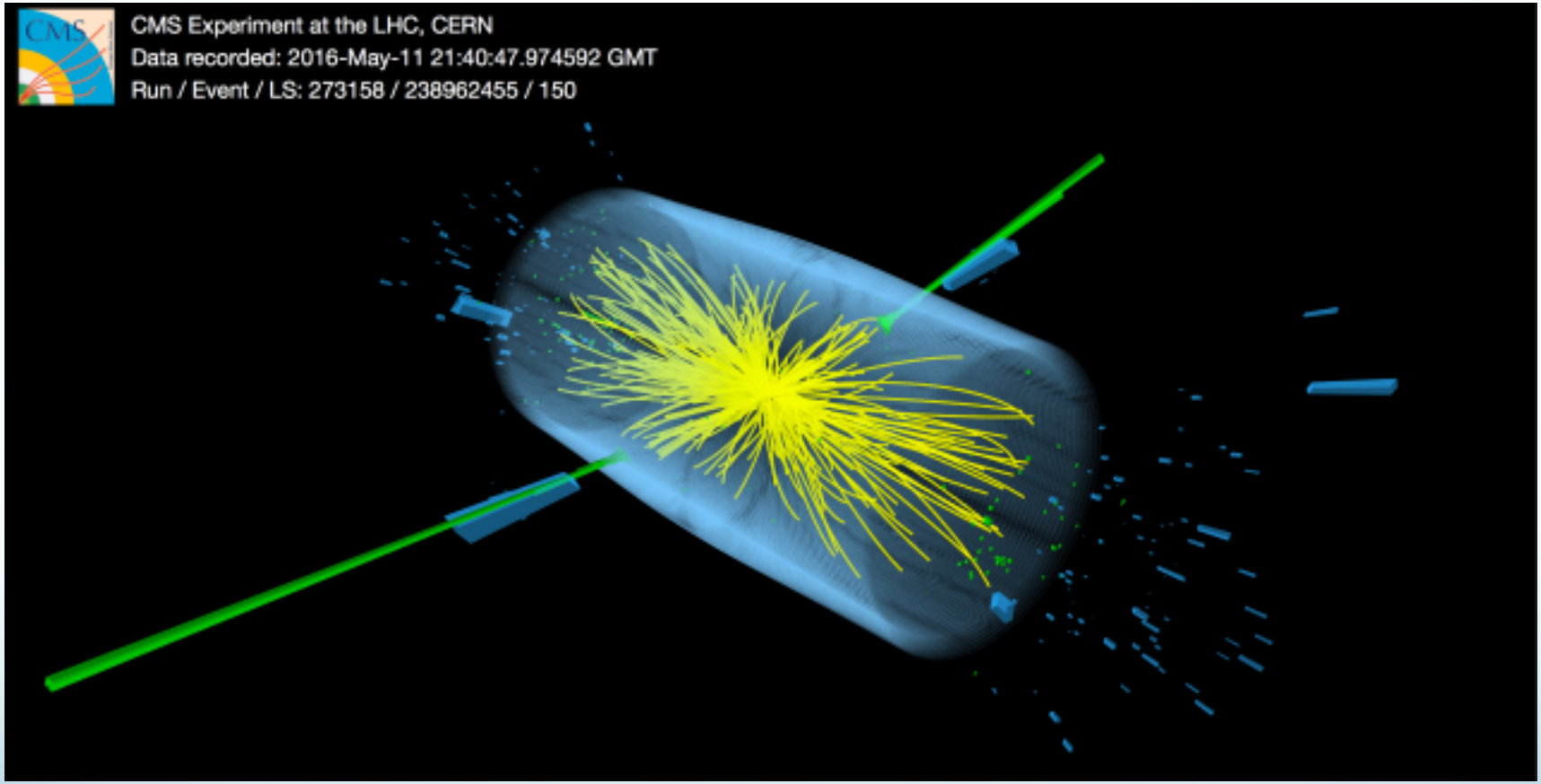
From hadron to jet

- We believe we are on the right track: develop more accurate/consistent QCD framework for jet production in heavy ion collisions
- Still in a exploratory stage, not fully ready for comprehensively extraction of medium properties yet
- Think about the exercise of just single hadron R_{AA}



Exciting era for jet and heavy flavor physics

- RHIC and LHC



Thank you!