Hard Probes in Heavy-ion Collisions

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Outline

- Introduction
- Leading hadron productions
- Full jet observables

1） Gauge boson tagged jets （Z, W, H)

2） Double b-jet

3） Z + b-jet

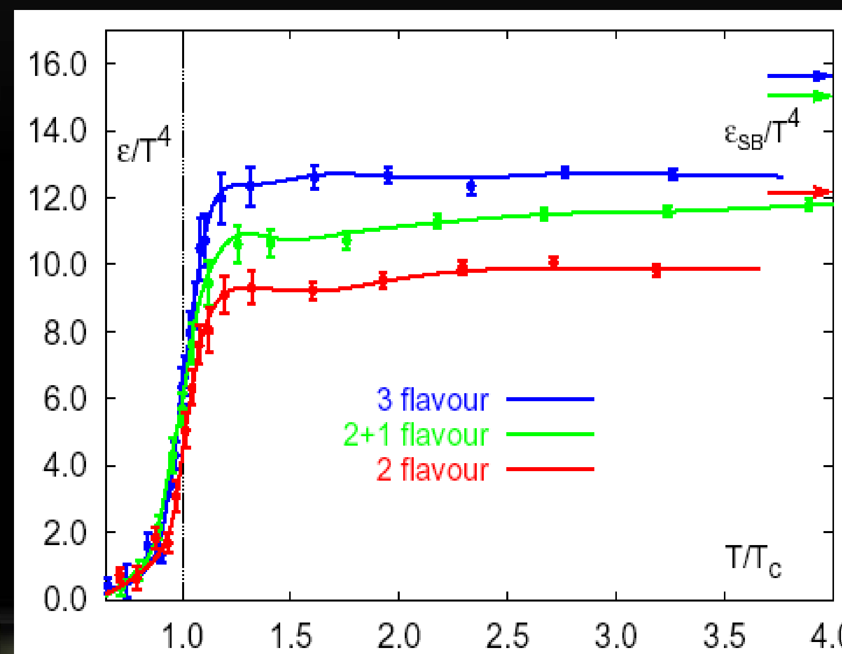
- Summary

Deconfinement and QGP

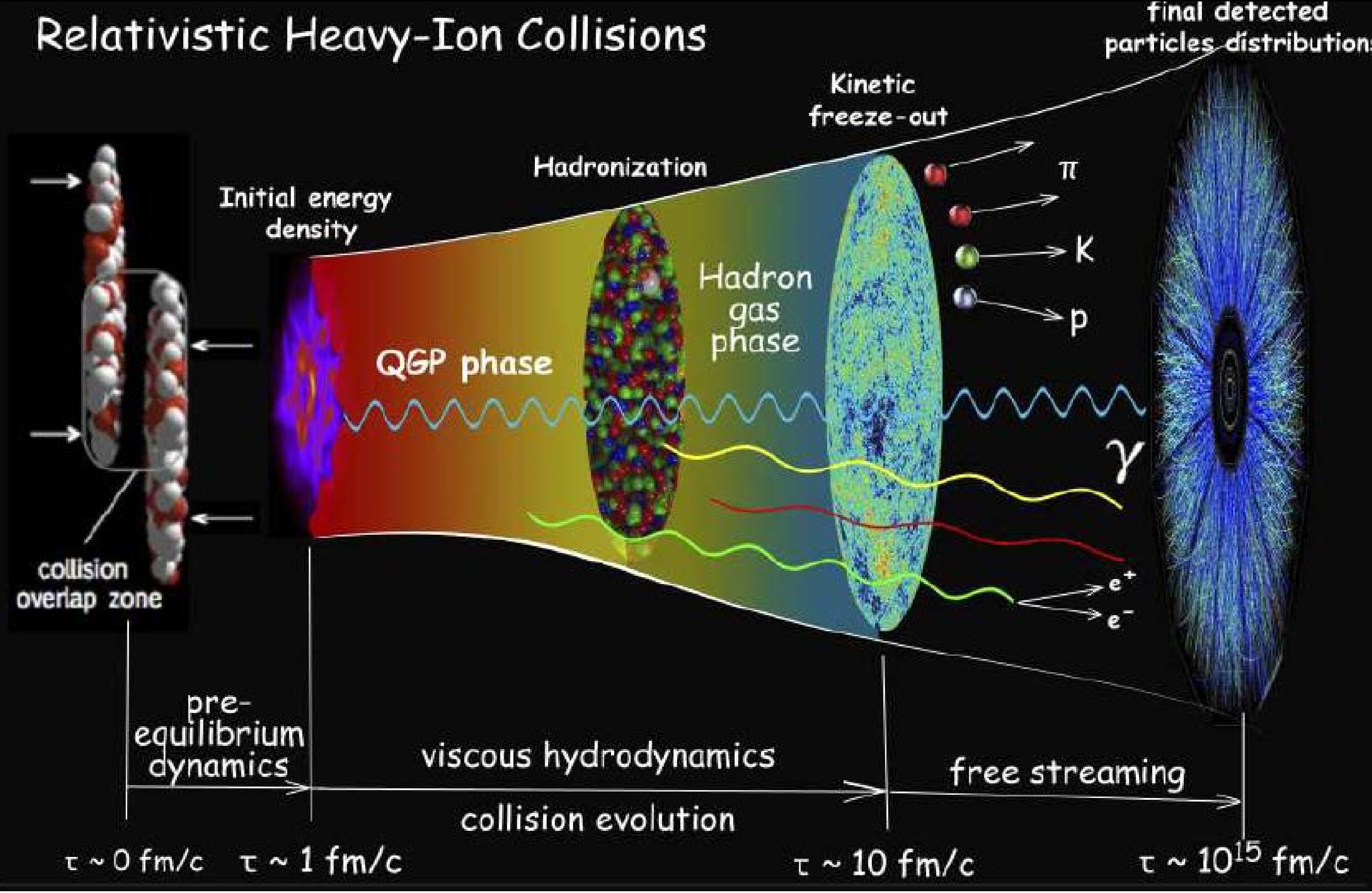
It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.

T. D. Lee (1978)

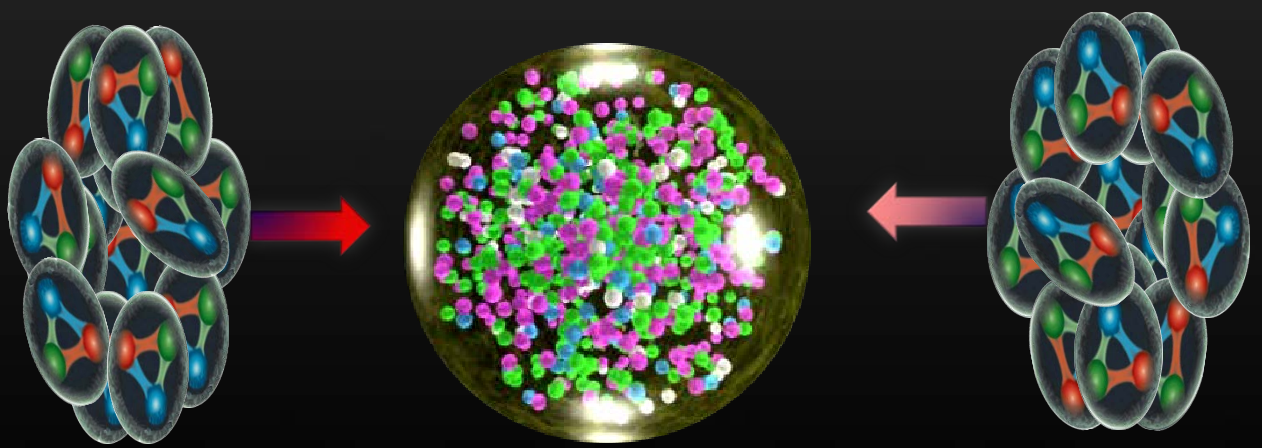
Lattice QCD predicts phase of thermal QCD matter with sharp rise in number of degrees of freedom near T_c=170MeV.

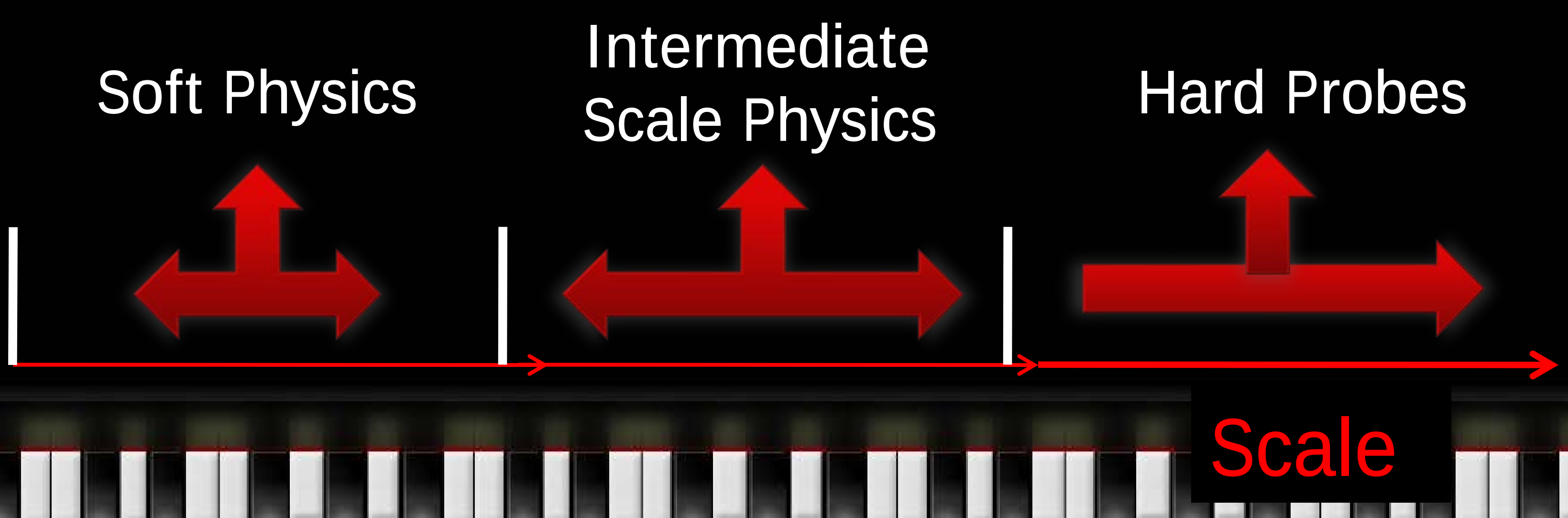


The Little Bang

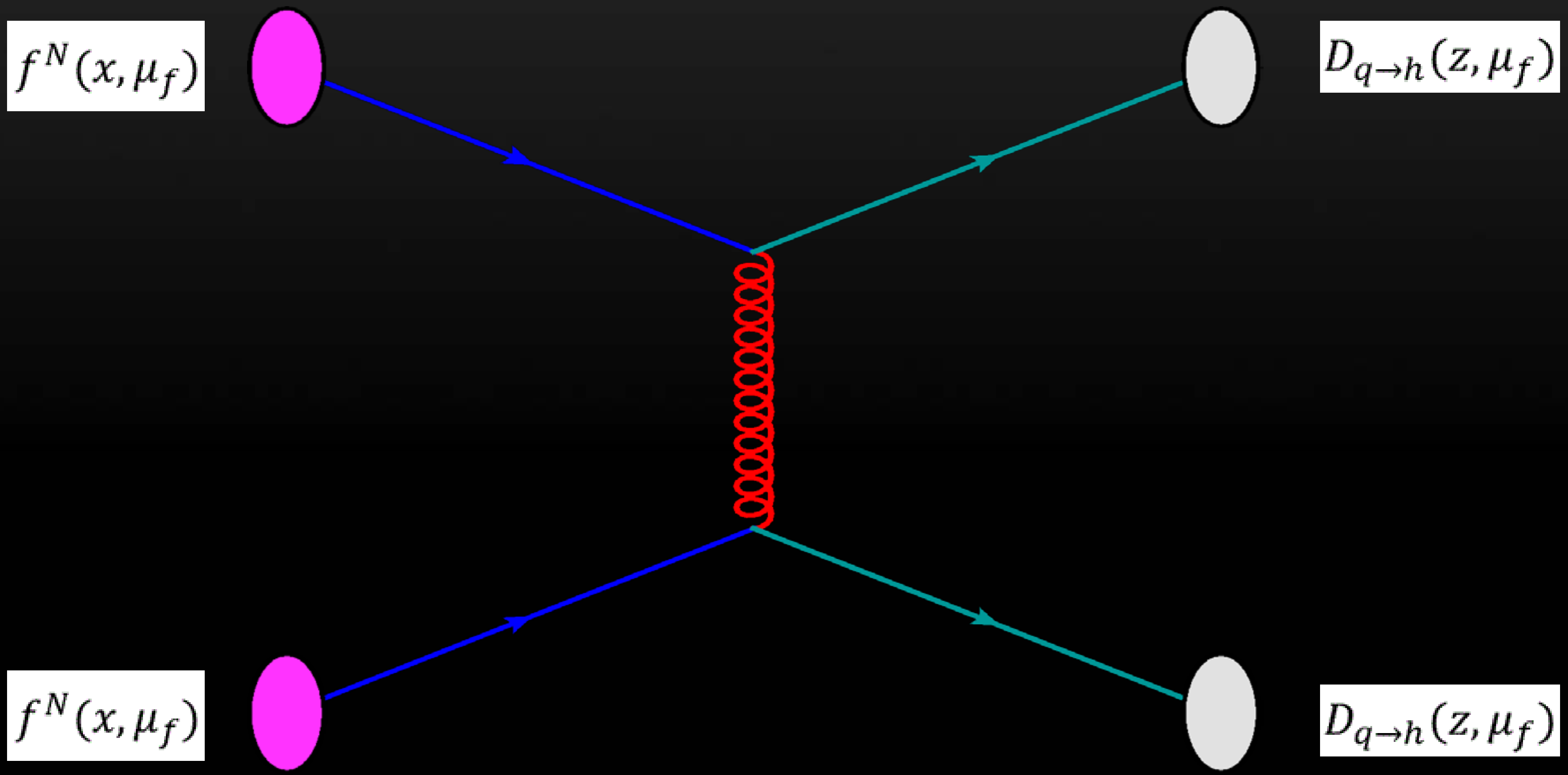


QGP

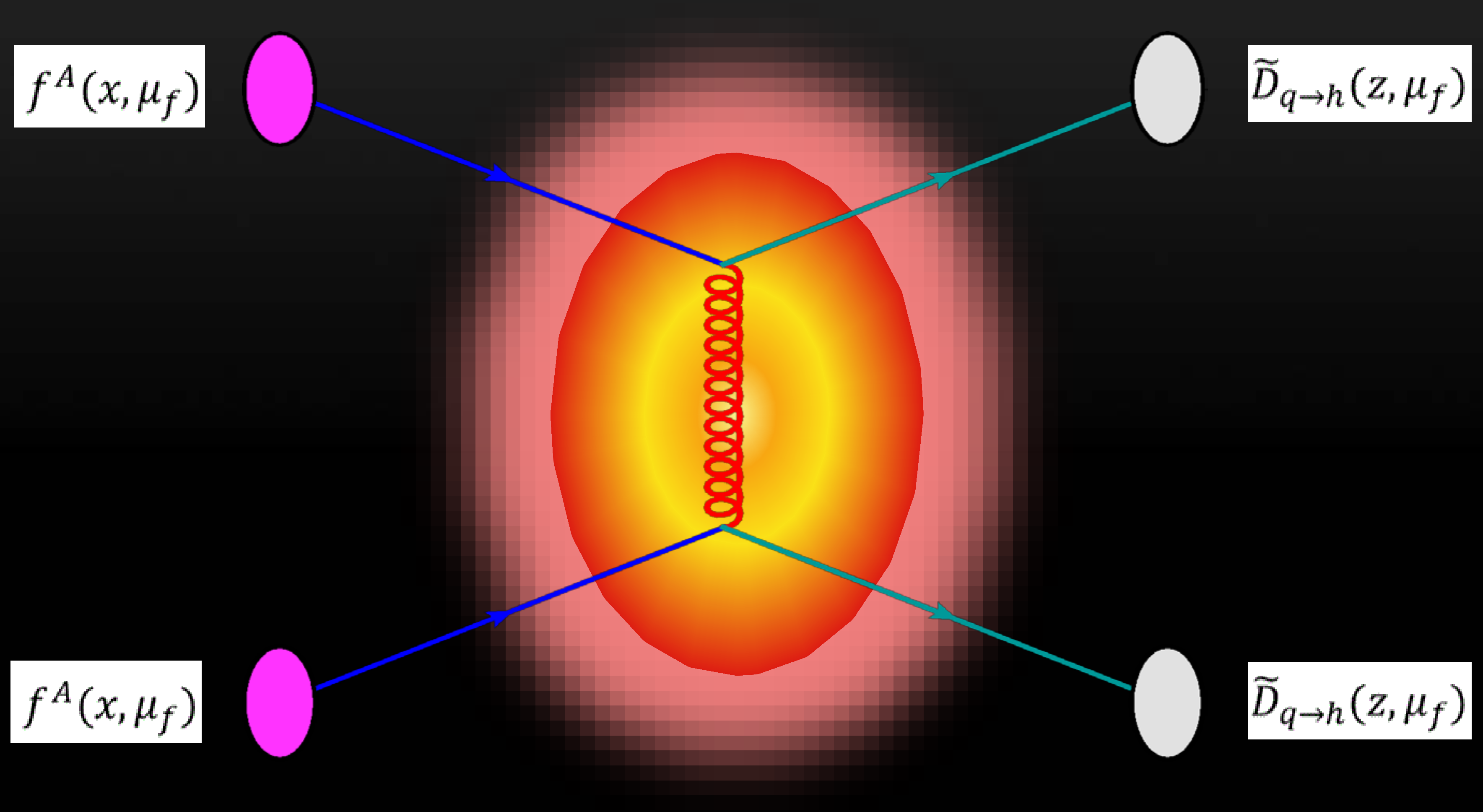



Soft Physics
Intermediate Scale Physics
Hard Probes
Scale

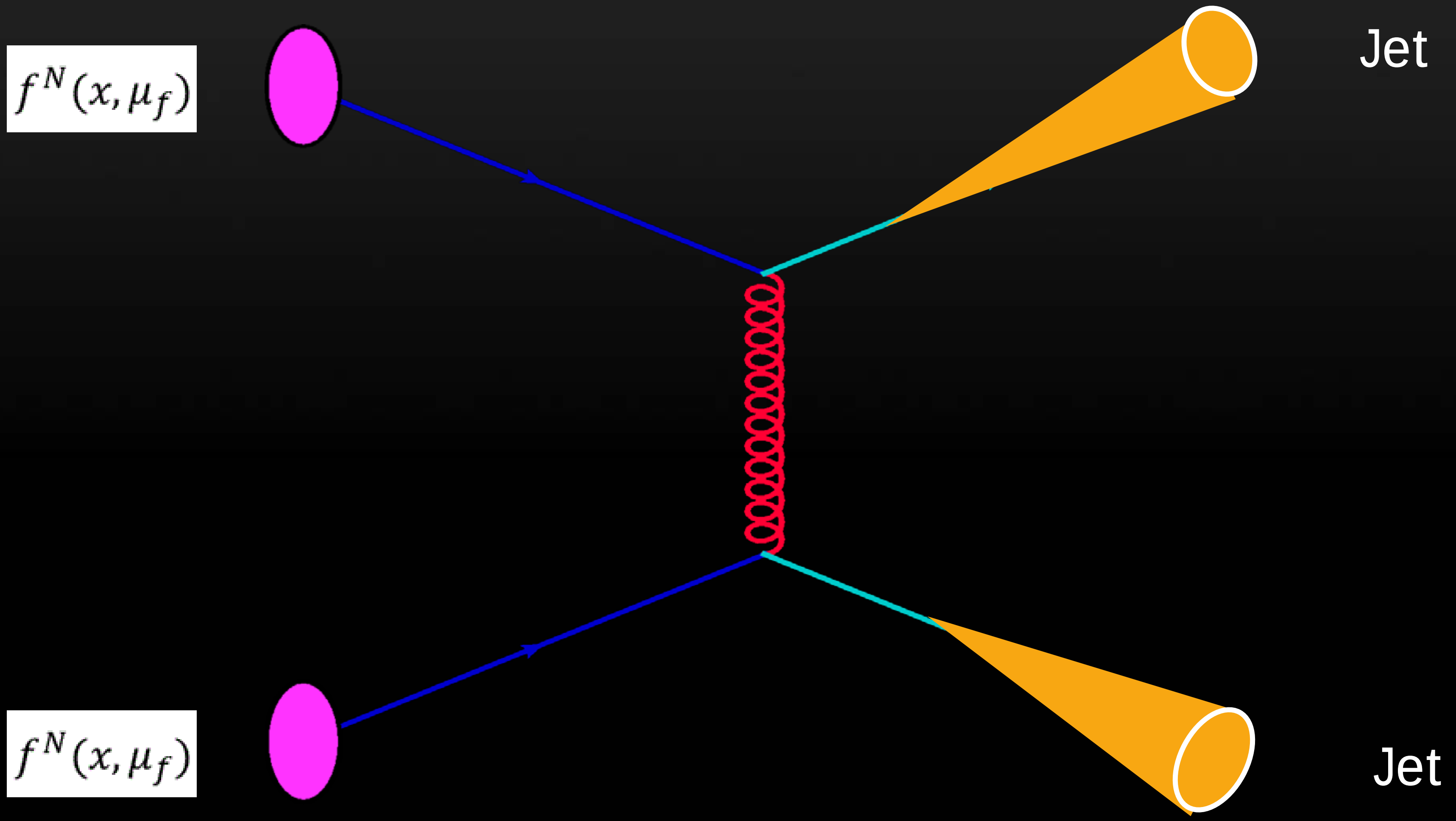
Hard Probes: leading hadrons



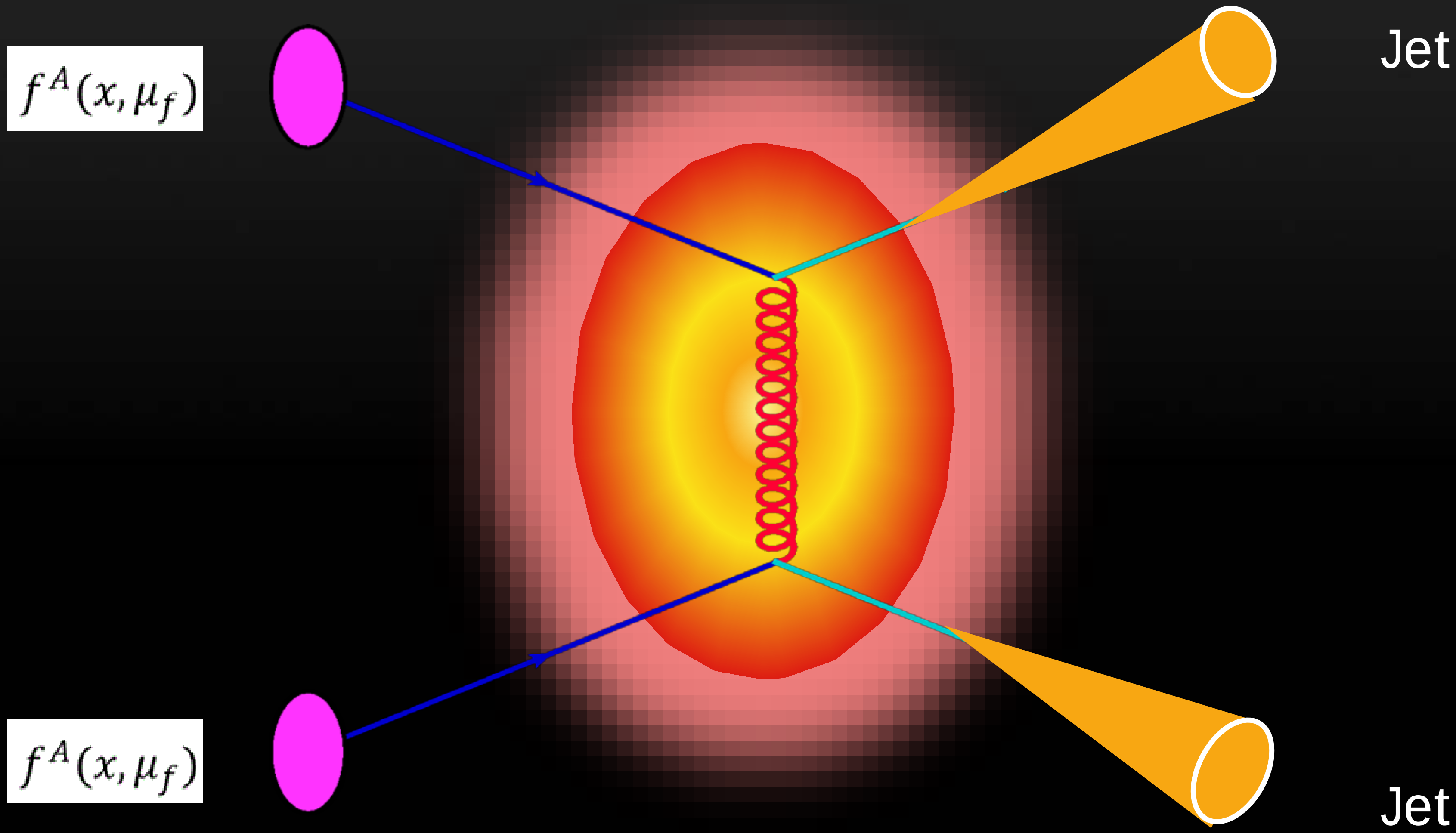
Hard Probes: leading hadrons



Hard Probes: full jets



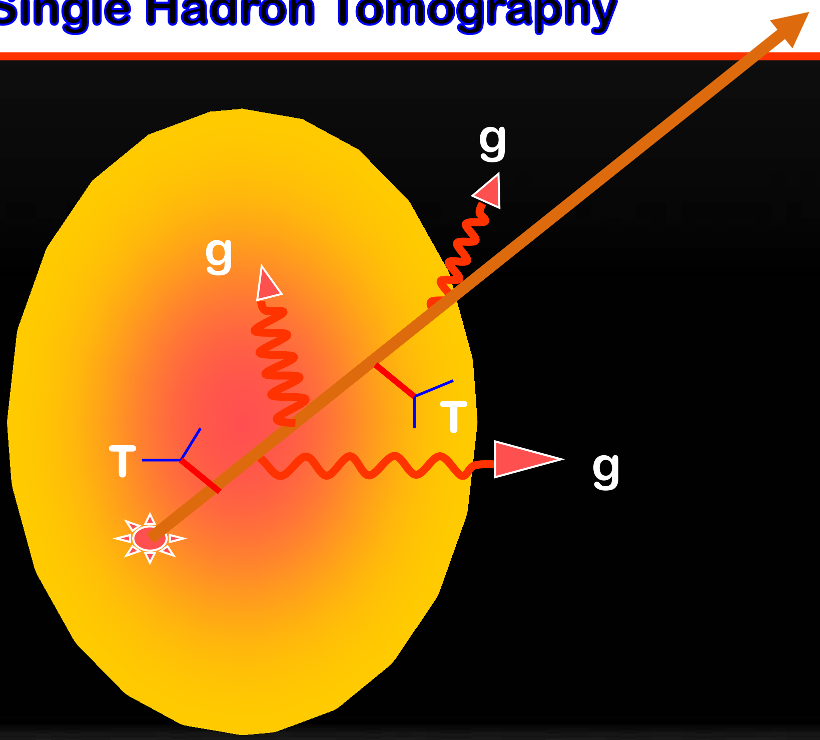
Hard Probes: full jets

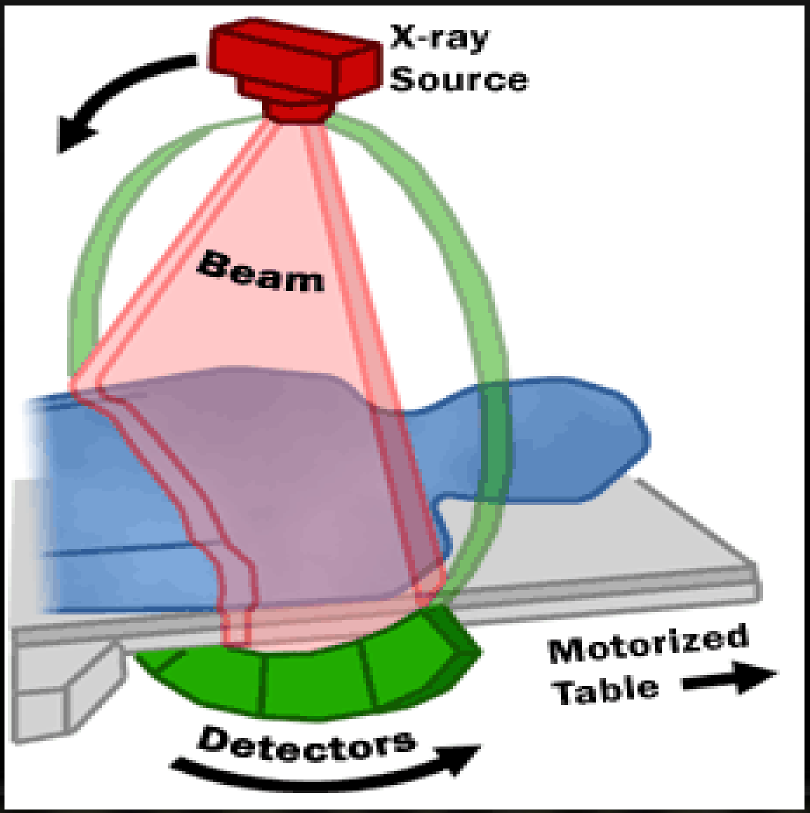


Jet quenching

Parton energy has been proposed as an excellent probe of the hot/dense matter created at HIC.

Single Hadron Tomography

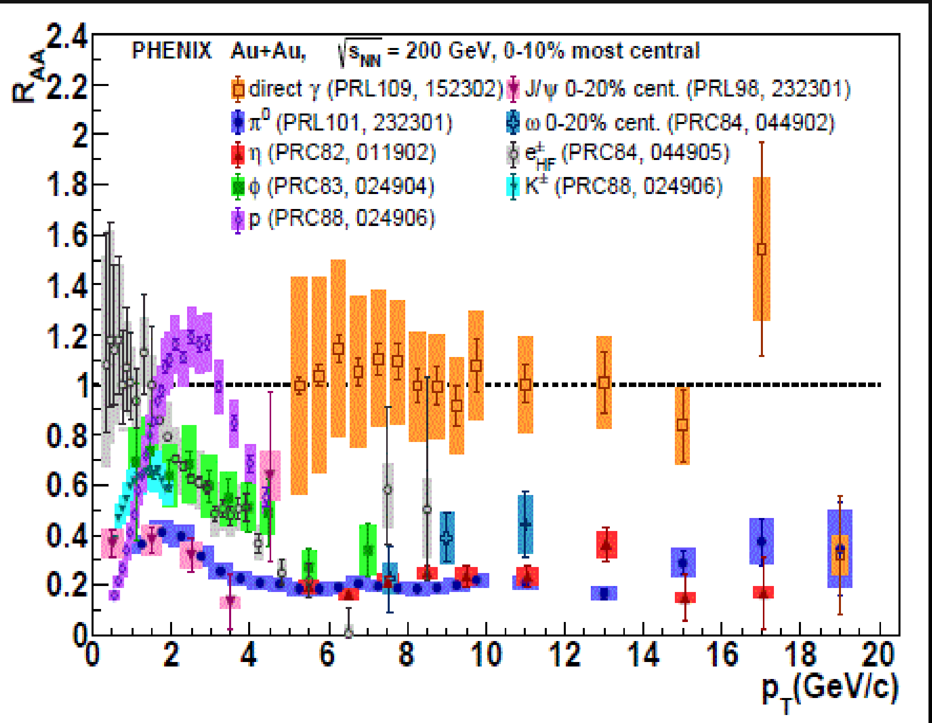


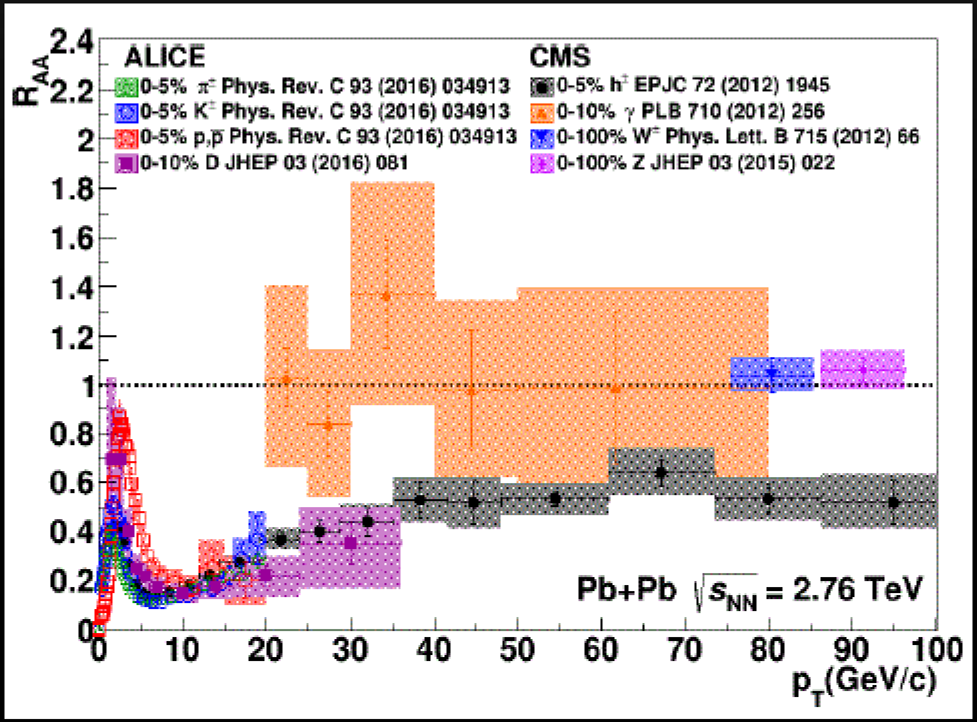


Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC and LHC

$$R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\text{Yield}_{pp}}$$

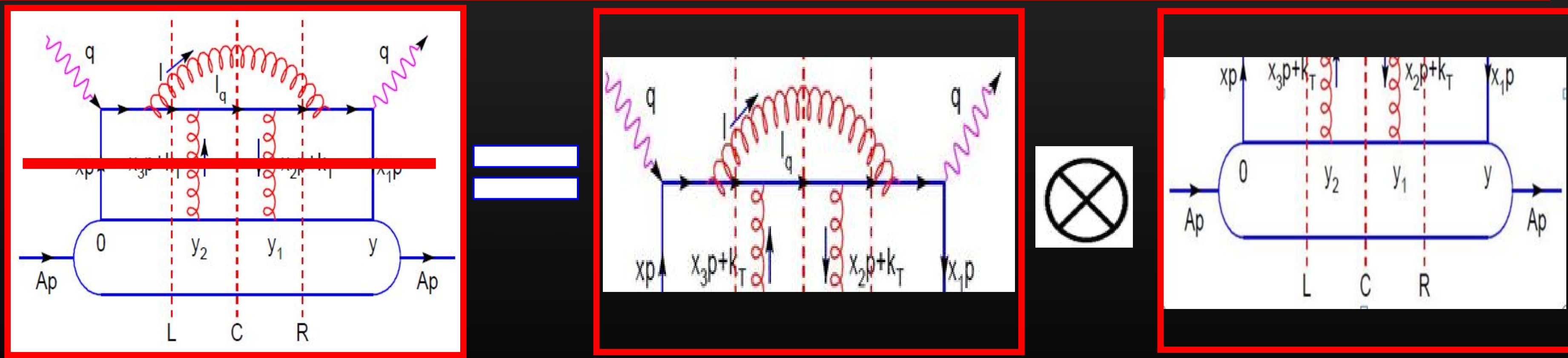




Large p_T hadrons in HIC

Jet quenching with higher twist approach

The parton energy loss due to medium-induced gluon radiation has been calculated with higher twist approach.



$$\widetilde{D}_{q\to h}(z_h,\mu^2) \equiv D_{q\to h}(z_h,\mu^2) + \int_0^{\mu^2} \frac{d\ell_T^2}{\ell_T^2}\frac{\alpha_s}{2\pi}\int_{z_h}^1 \frac{dz}{z}\Big[\Delta\gamma_{q\to qg}(z,x,x_L,\ell_T^2)D_{q\to h}(z_h/z) + \Delta\gamma_{q\to gq}(z,x,x_L,\ell_T^2)D_{g\to h}(z_h/z)\Big] ,$$

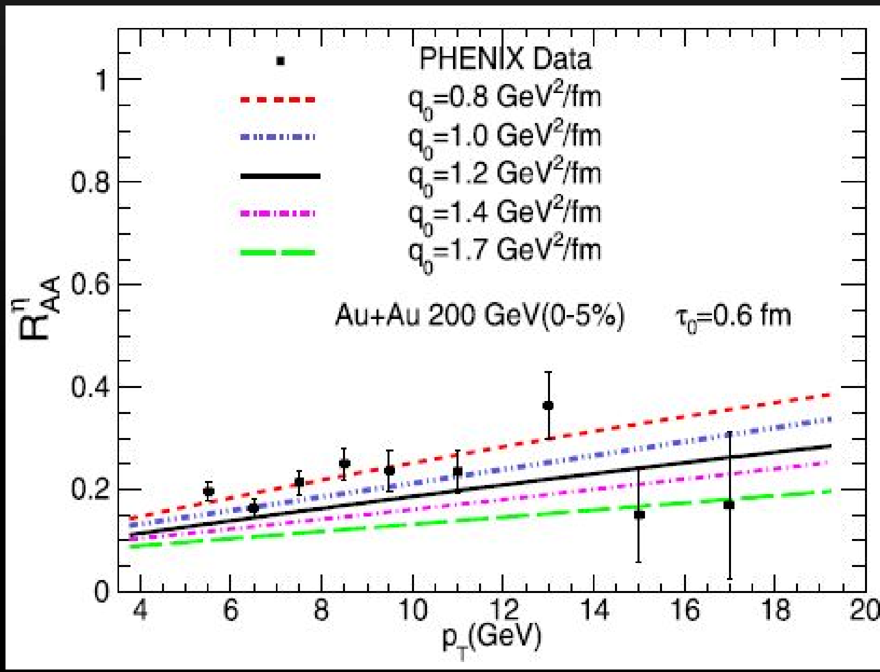
$$\frac{1}{N_{\rm bin}^{AB}(b)}\frac{d\sigma_{AB}^h}{dyd^2p_T} = \sum_{abcd}\int dx_a dx_b f_{a/A}(x_a,\mu^2) f_{b/B}(x_b,\mu^2) \times \frac{d\sigma}{d\hat{t}}(ab\to cd)\frac{\langle \tilde{D}_c^h(z_h,Q^2,E,b)\rangle}{\pi z_c} + \mathcal{O}(\alpha_s^3).$$

X Guo, X N Wang, PRL(2001); X Guo, X N Wang, NPA (2001);
BWZ, X N Wang, NPA(2003) ; BWZ, E Wang, X N Wang, PRL (2004)

η in heavy-ion collisions at NLO

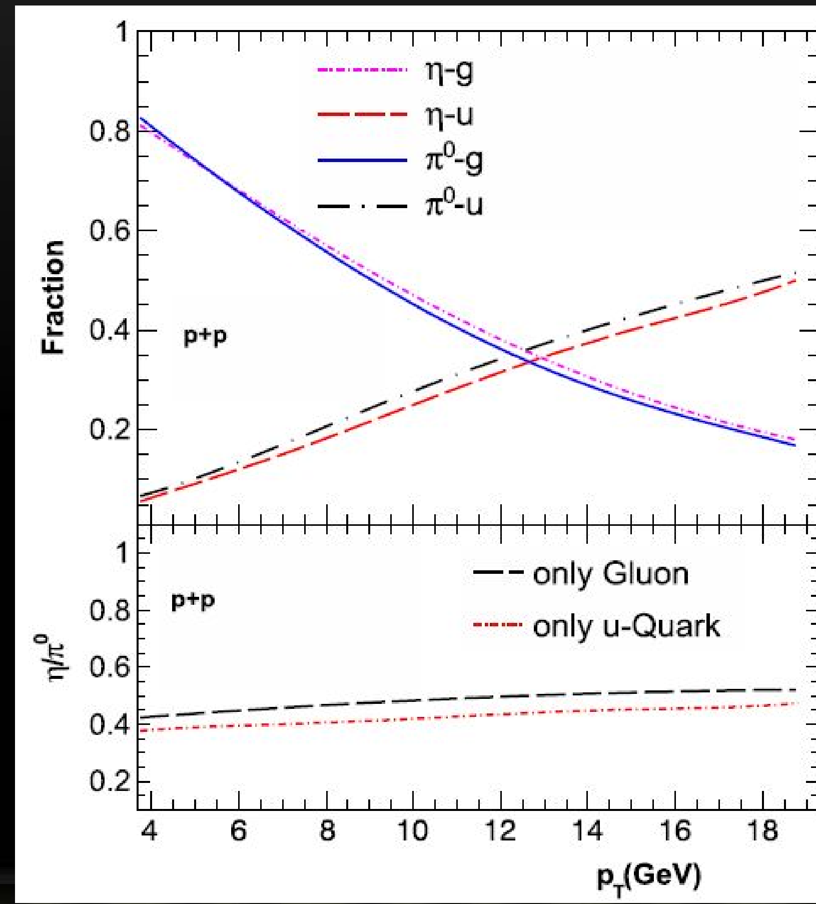
- Production of eta meson in HIC has been calculated;
- Flavor composition has very small effect on the ratio η/π^0 .

$$(dE/dx)_{\rm rad} = -C_2 \hat{q} L$$



$$G^{\eta,\pi^0}(p_T) = \frac{\int f_g(\frac{p_T}{z_h}) \cdot D_{g\to\eta,\pi^0}(z_h, p_T) \frac{dz_h}{z_h^2}}{\frac{1}{p_T}\frac{d\sigma_{\pi^0,\eta}}{dp_T}}$$

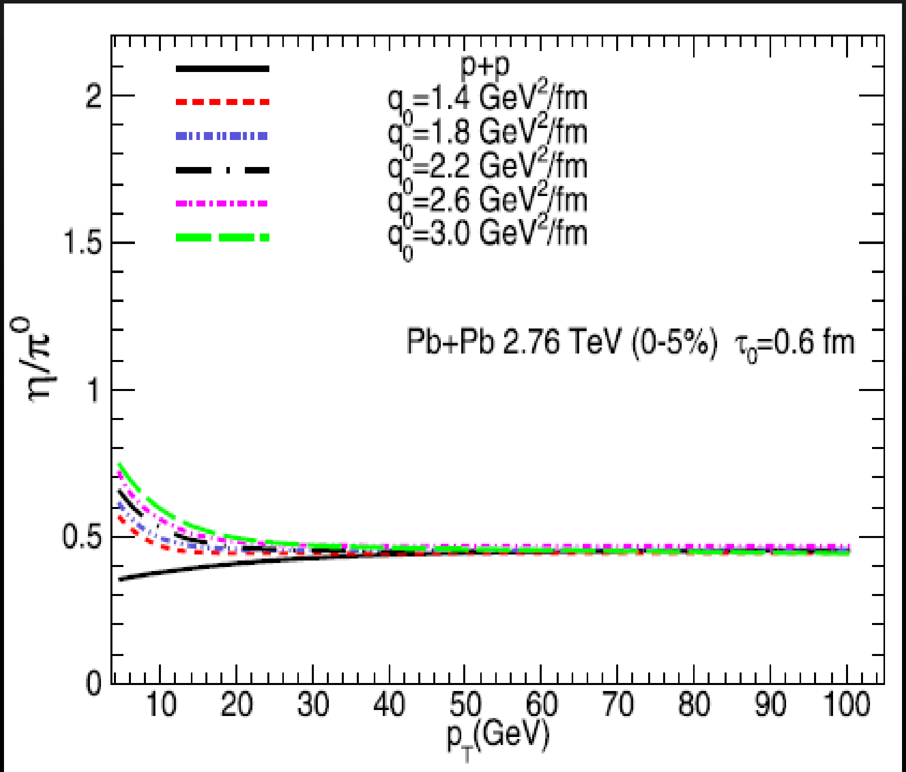
$$G^{\pi^0}(p_T) \approx G^{\eta}(p_T)$$

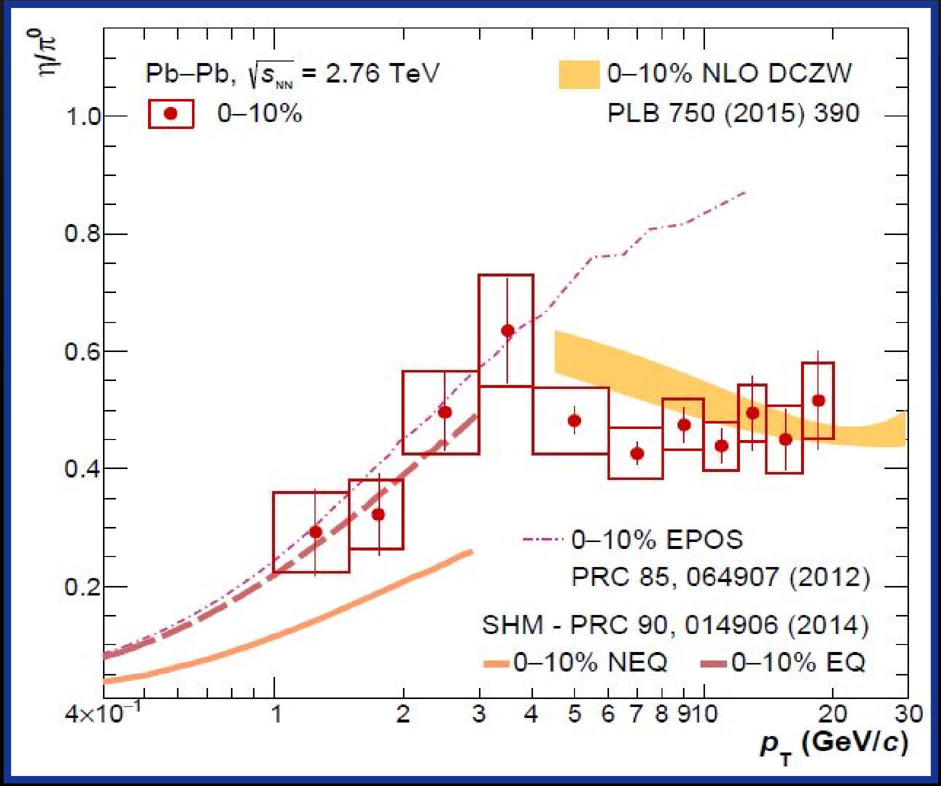


W Dai, X Chen, BWZ, E Wang， Phys. Lett. B 750 (2015) 390

η/π^0 in HIC at NLO

- η/π^0 ratio is almost same (~0.5) for p+p, Au+Au and Pb+Pb collision.
- Prediction on η/π^0 ratio has been confirmed by ALICE.



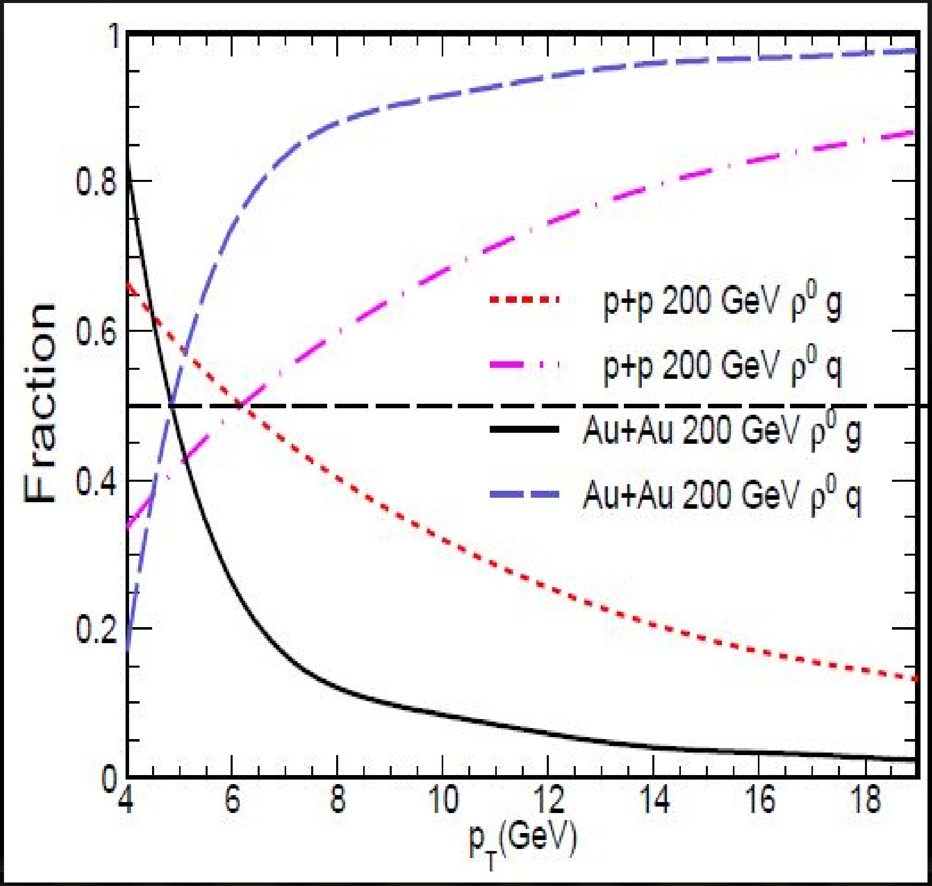


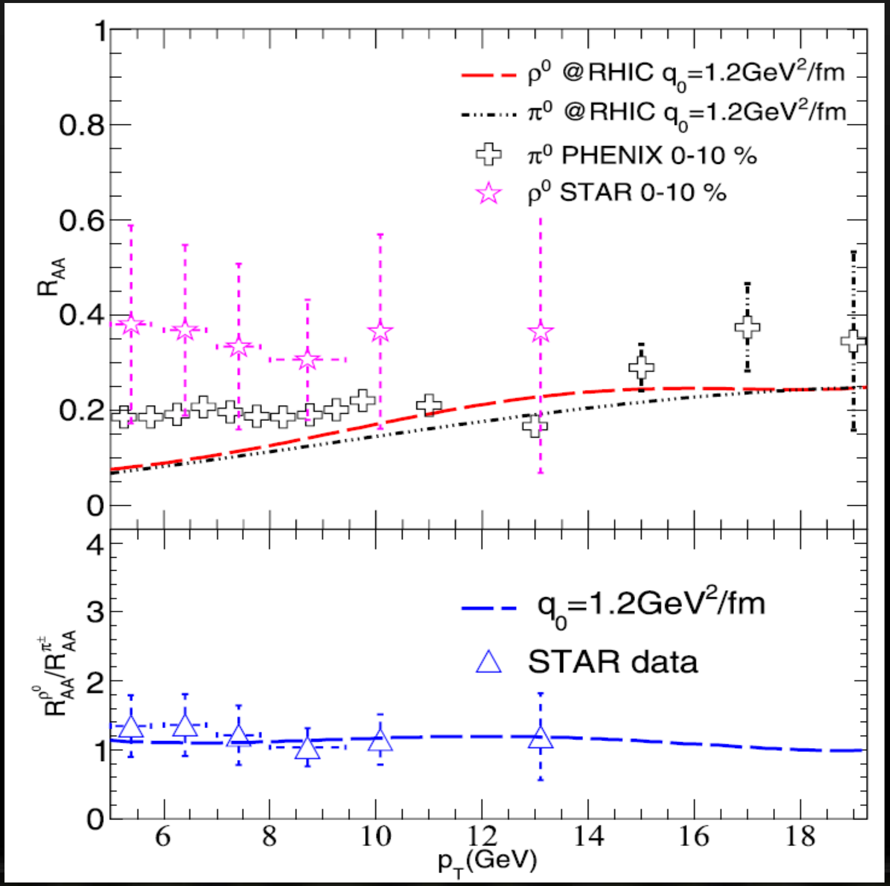
ALICE, arXiv: 1803.05490

W Dai, X Chen, BWZ, E Wang， Phys. Lett. B 750 (2015) 390

ρ production in A+A at NLO

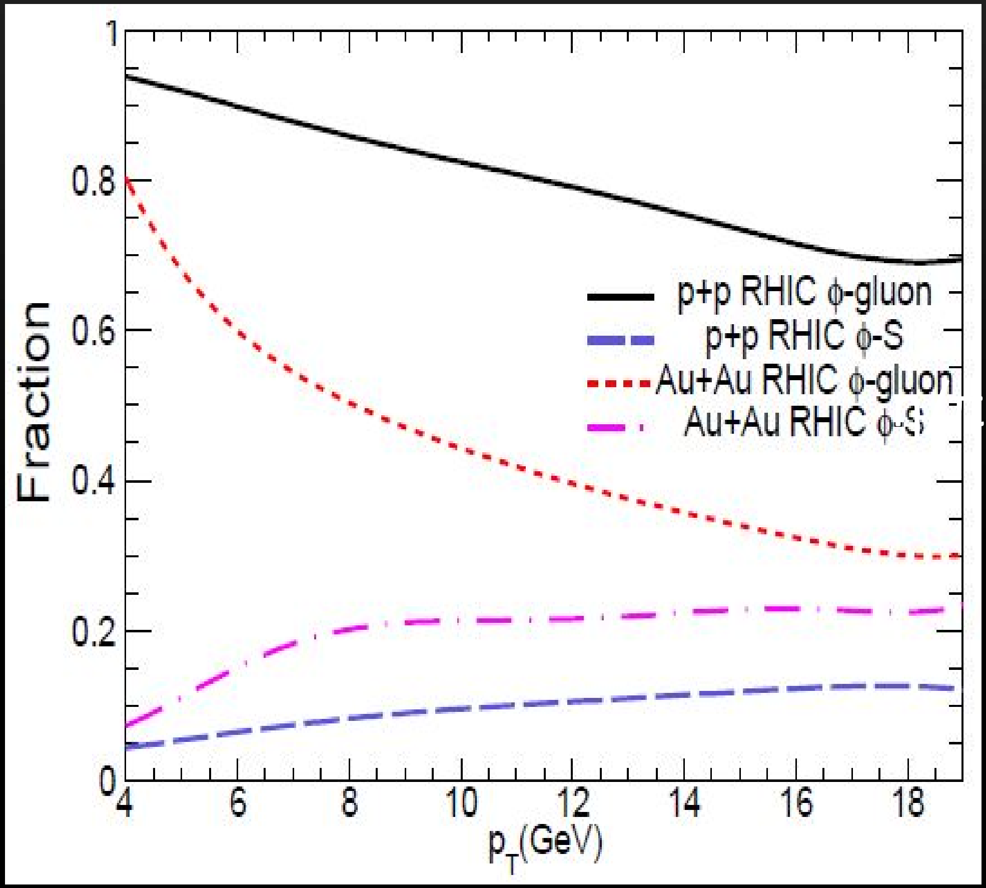
- A broken SU(3) model has been utilized to get ρ FFs in p+p.
- Dominant contributions of quark fragmentations both in p+p and in A+A.

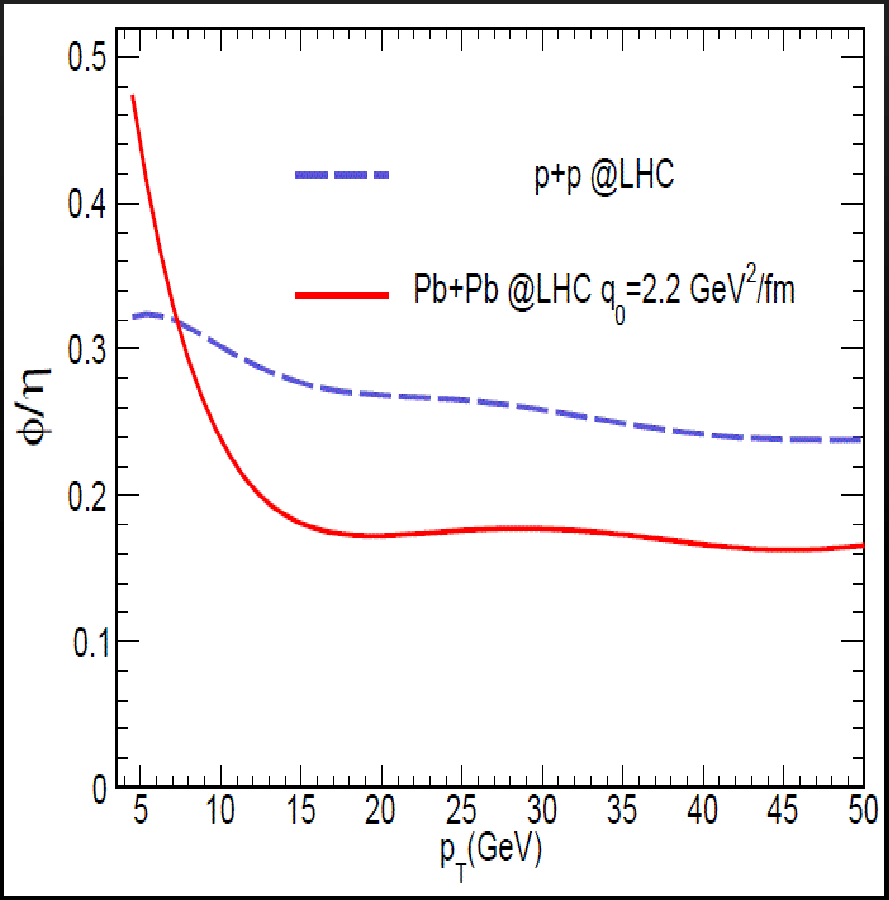




W Dai, BWZ, E Wang, PRC 98 (2018) 024901

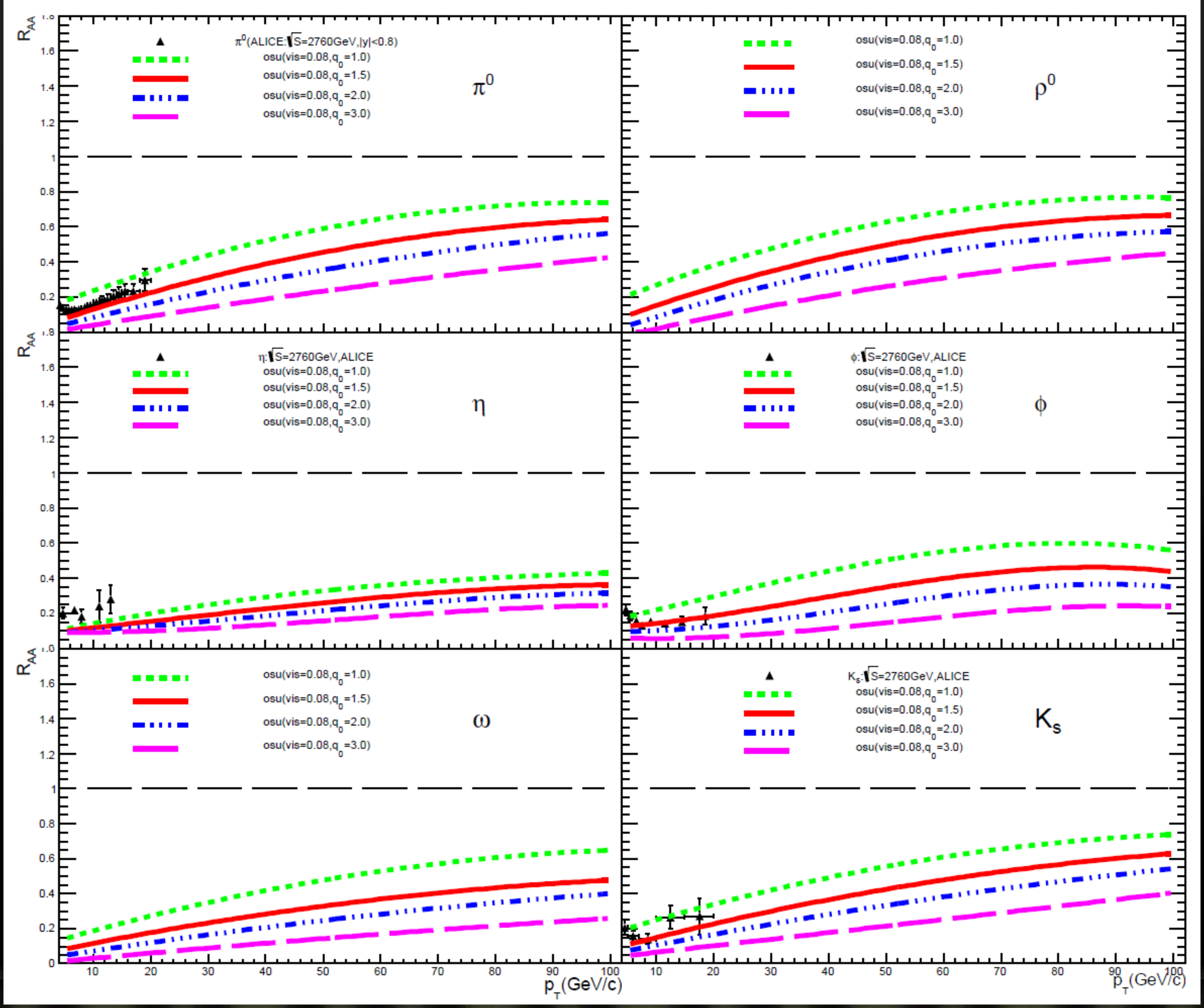
Production of ϕ in HIC at NLO





W Dai, X, Chen, BWZ, H Zhang, E Wang， EPJC 77(2017) 571

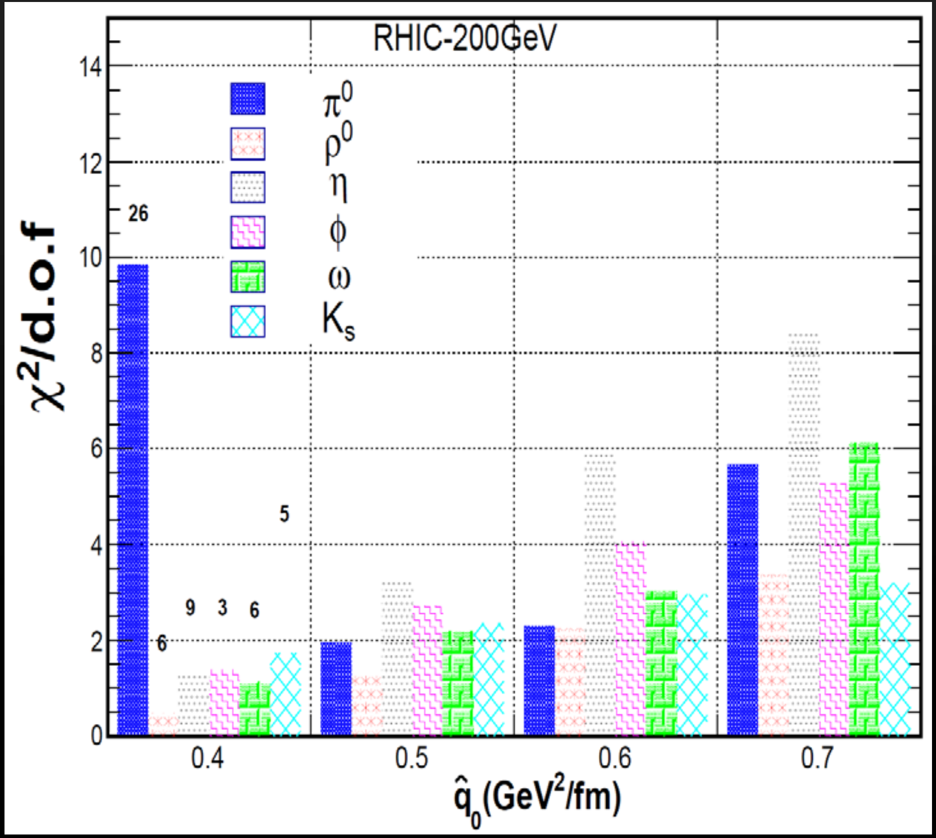
Identified meson in HIC at NLO

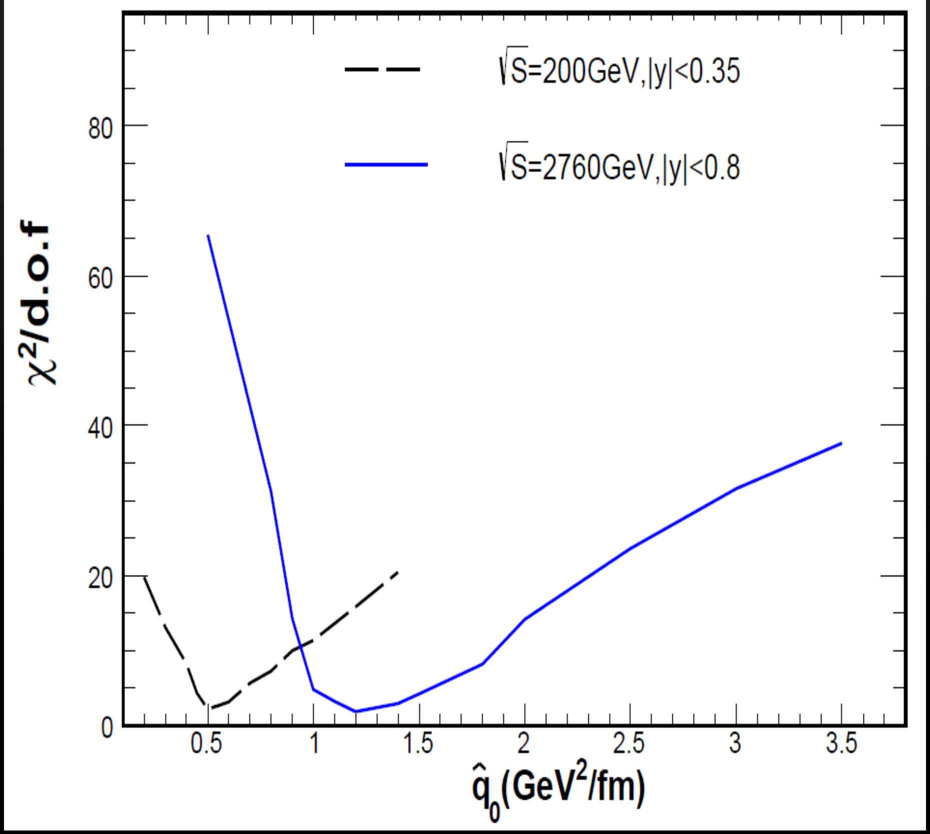


iEBE-VISHNU hydro

G Ma, W Dai, BWZ, E Wang, 1812.02033

Global extraction of qhat



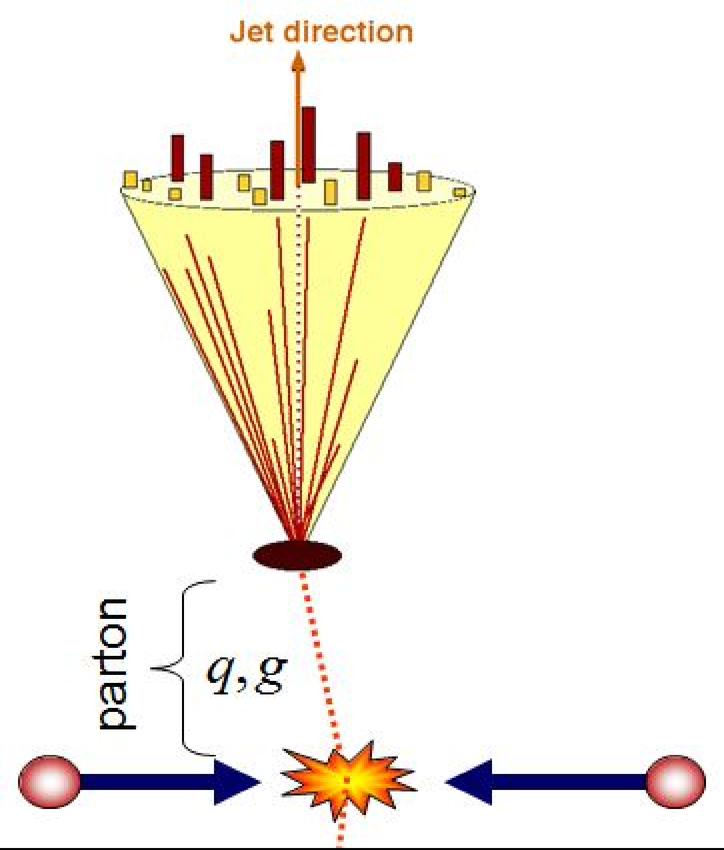


G Ma, W Dai, BWZ, E Wang, 1812.02033

Jets in HIC

What is a jet?

- A jet is a spray of final-state particles roughly moving in the same direction and defined by jet finding algorithms.
- At LO pQCD, jet ≈parton.
- In pQCD local-parton-hadron duality (LPHD) is used
- Jet: more precise and powerful



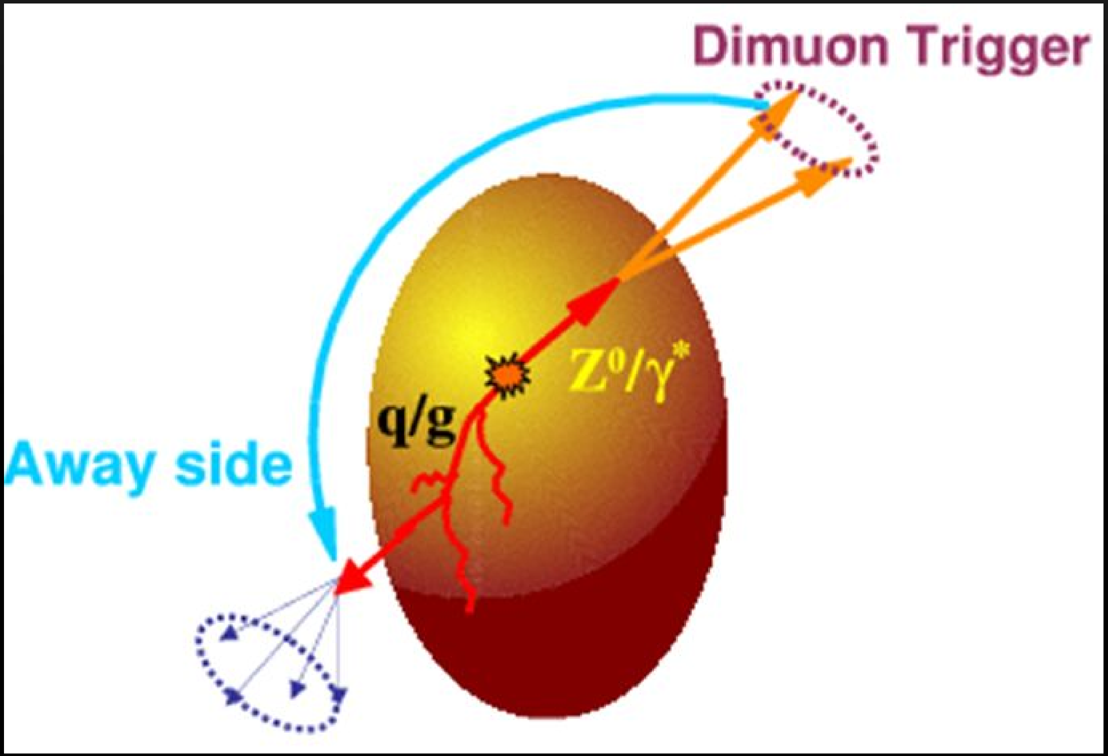
$$E_T = \sum_{i \in jet} E_{T,i}$$

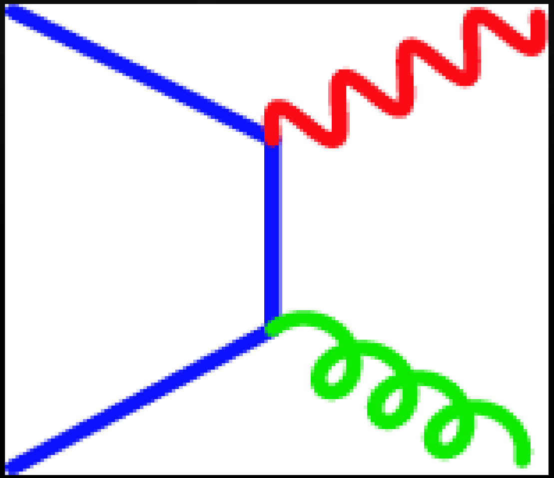
$$y = \sum_{i \in jet} y_i E_{T,i} / E_T$$

$$\phi = \sum_{i \in jet} \phi_i E_{T,i} / E_T$$

$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

Tagged jet production in HIC





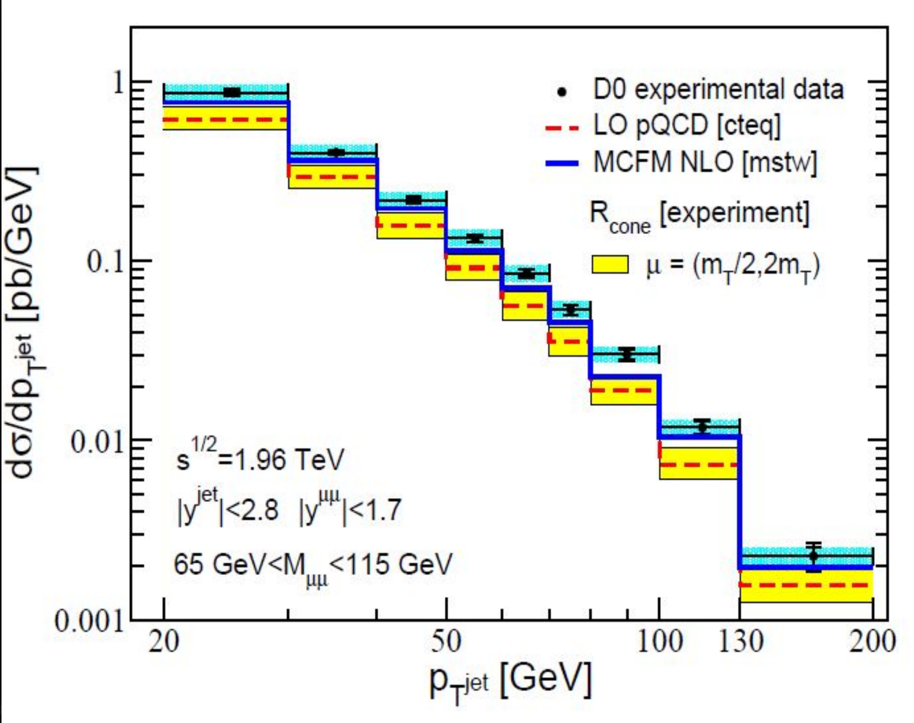
"golden channel"

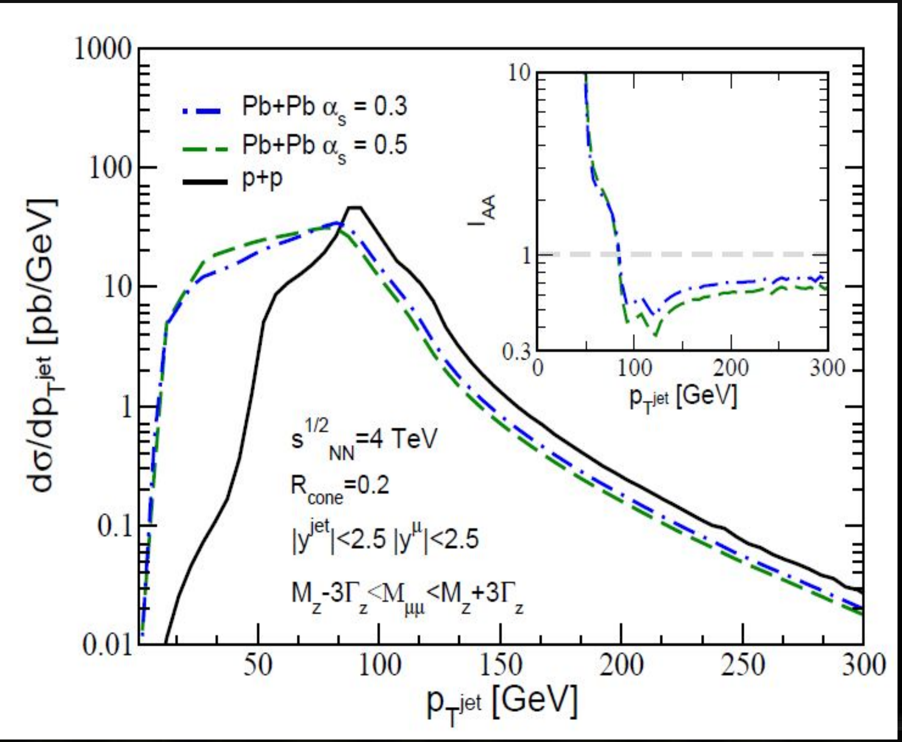
Zº + jet in A+A: Iaa

- A sharp transition from tagged jet suppression above ~pT of Z to tagged jet enhancement below ~pT of Z

$$I_{AA}^{\rm jet}(R,\omega_{\rm min}) = \frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma_{AA}}{dp_{T\,(Z)}dp_{T\,(Q)}} \Bigg/ \frac{d\sigma_{pp}}{dp_{T\,(Z)}dp_{T\,(\rm jet)}}$$

NLO

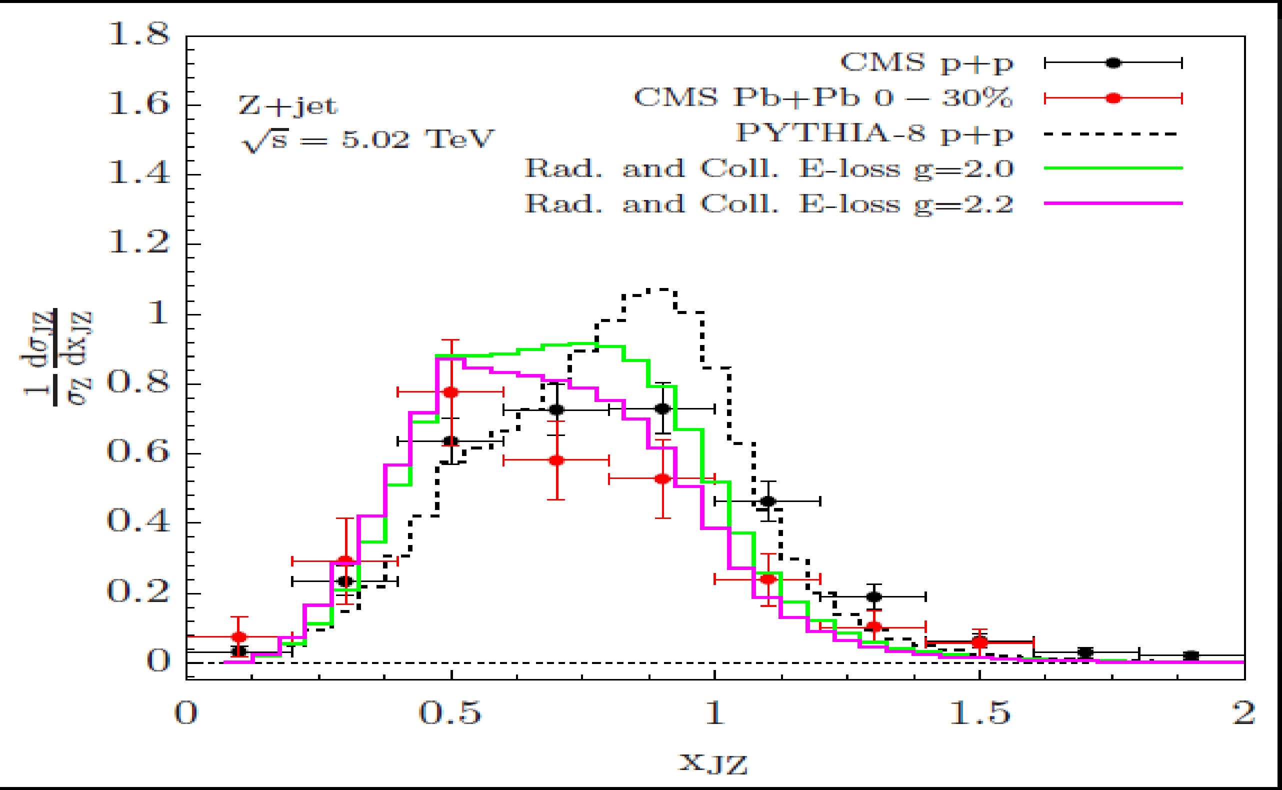




Neufeld, Vitev, BWZ, PRC 83, 034902 (2011).

$p_T \in (92.5\text{GeV}, 112.5\text{GeV})$

Z^o + jet in A+A: asymmetry



LO +PS (parton shower)

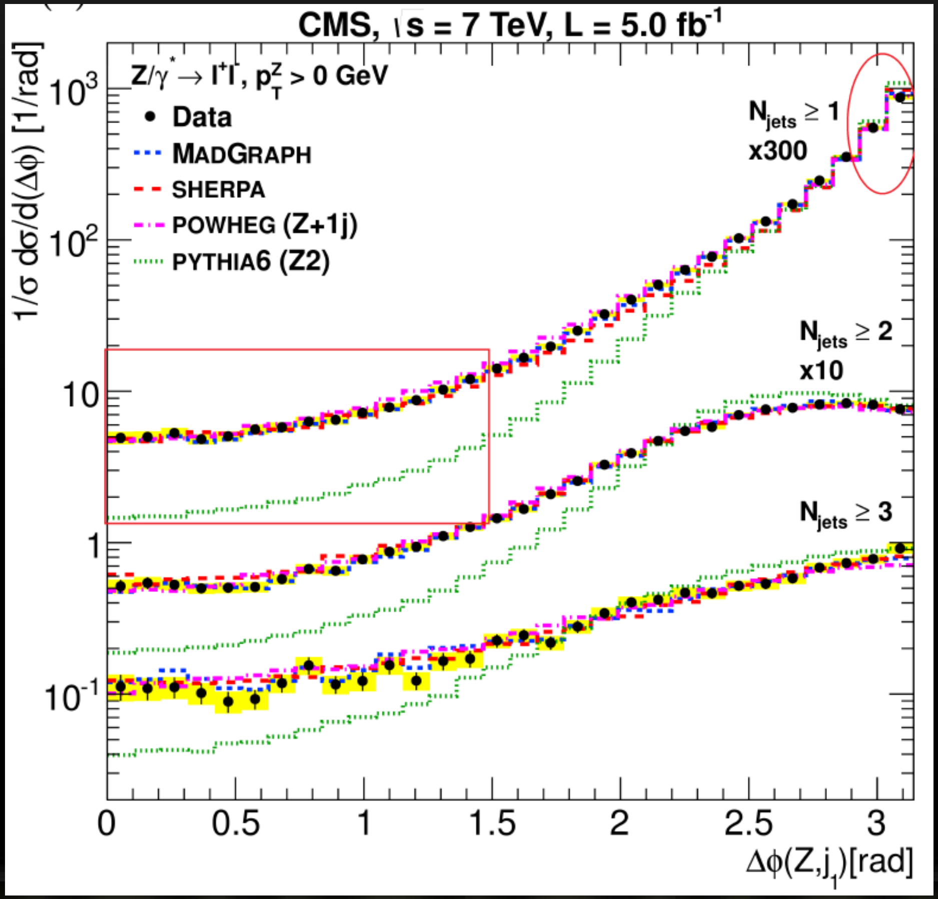
$x_{JV} = p_T^J / p_T^V$

	$\Delta\langle x_{JZ}\rangle$			
p_T^Z (GeV)	40 – 50	50 – 60	60 – 80	80 – 120
CMS [24]	0.061±0.059	0.123±0.051	0.124±0.052	0.068±0.042
Rad. + Coll. $g = 2.0$	0.022	0.050	0.075	0.086
Rad. + Coll. $g = 2.2$	0.024	0.058	0.093	0.119

Z B Kang, Vitev, Hongxi Xing, PRC (2017)

Angular correlation in Z+jet

- NLO calculations fail at angular difference ~π;
- LO+PS calculations fail at small angular difference.
- Z+jet in A+A: NLO+PS+Eloss



CMS, PLB

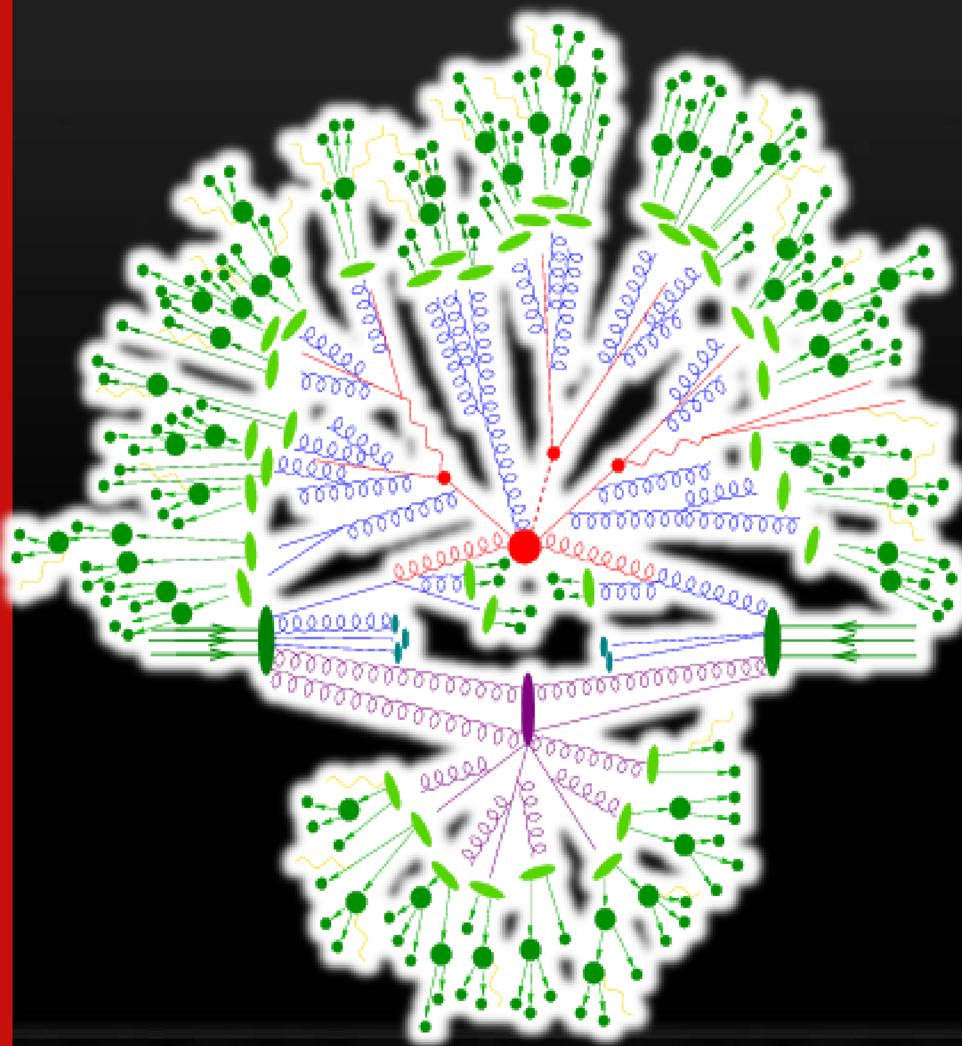
722 (2013) 238

NLO +PS +ELoss

S Zhang, T Luo, X Wang, BWZ, PRC 98 (2018) 021901(R)

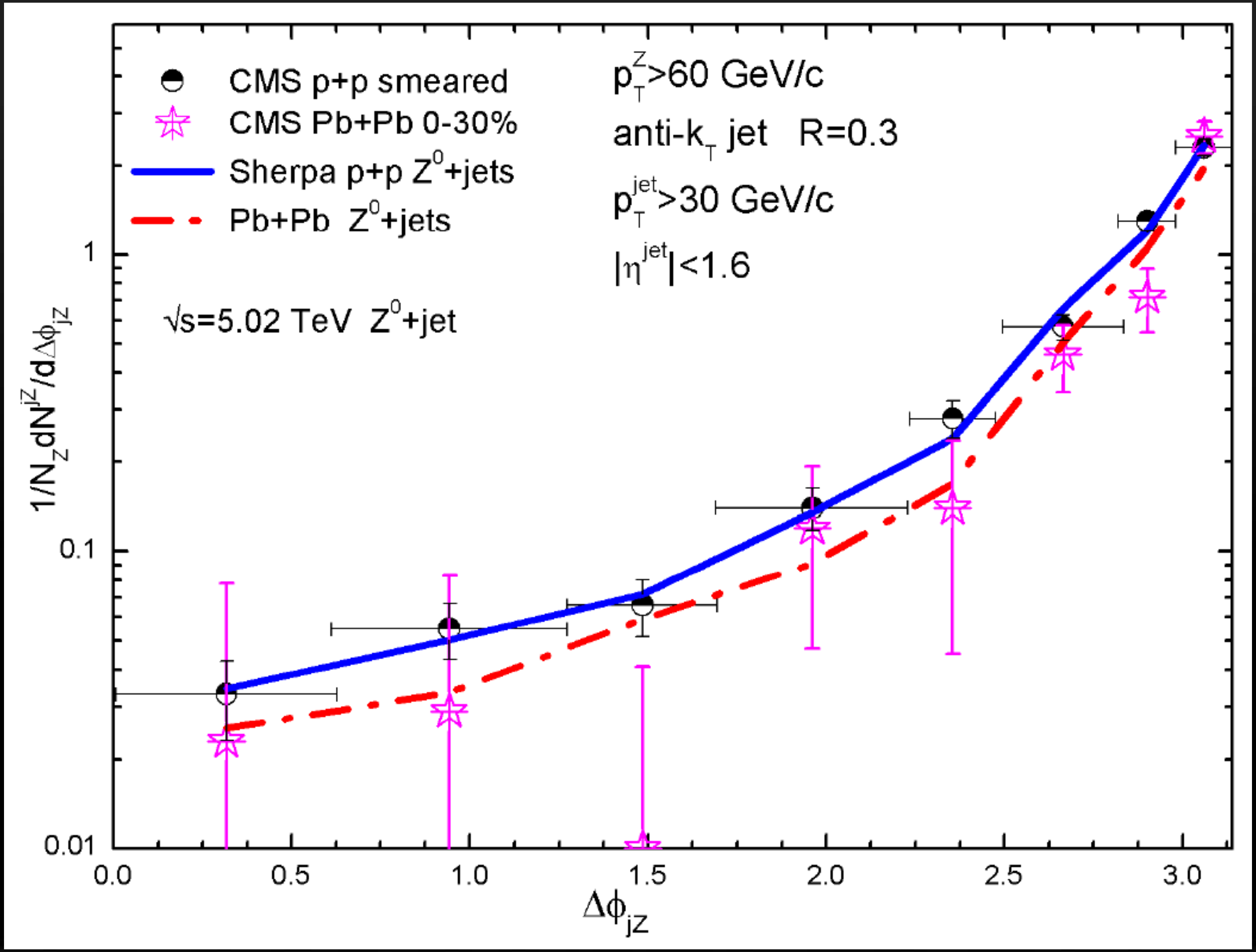
Sherpa: NLO+PS

- Initial state parton shower(PS)
- Final state PS
- NLO matrix elements (ME)
- Signal process
- Fragmentation
- Hadron decays
- Underlying event
- QED radiation



Gleisberg, Hoeche, Krauss, Schumann, Siegert, Winter,

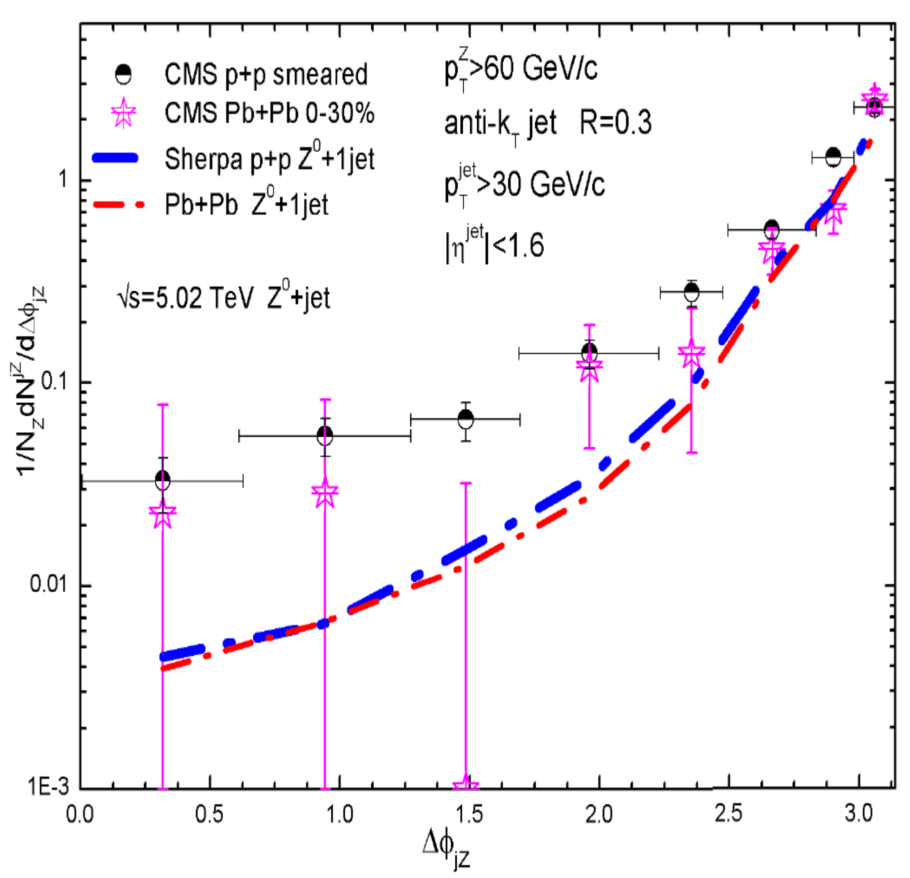
Angular Correlation of Z+jet (I)

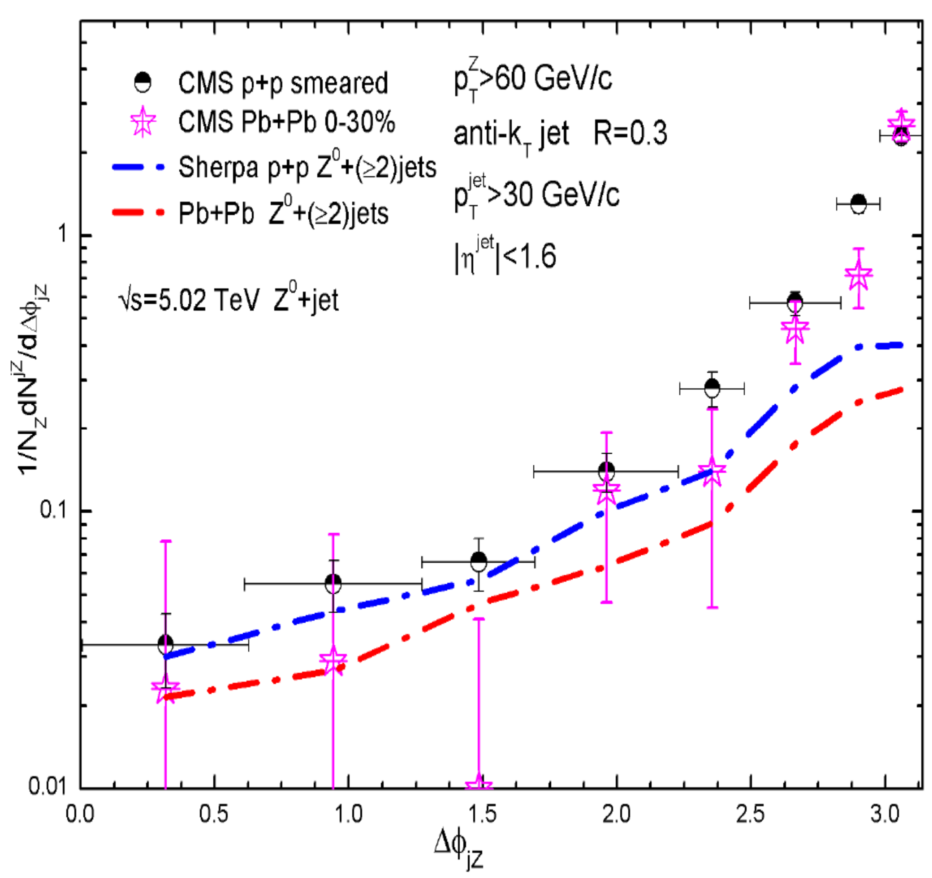


S Zhang, T Luo, X Wang, BWZ, PRC 98 (2018) 021901(R)

Angular Correlation of Z+jet (II)

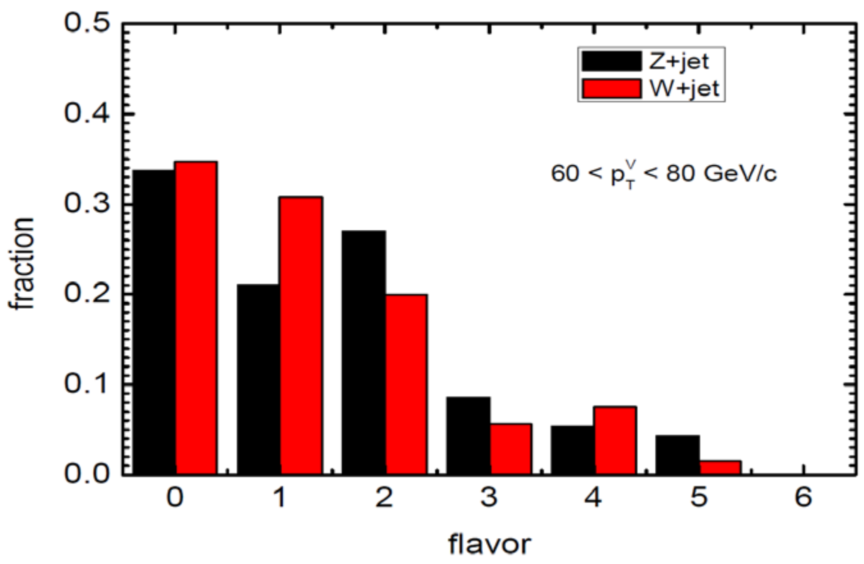
- Suppression to Z+1jet processes is rather small;
- Considerable suppression to Z+ (>2)jets is observed due to jet quenching effect; kinematical cut: pT>30 GeV

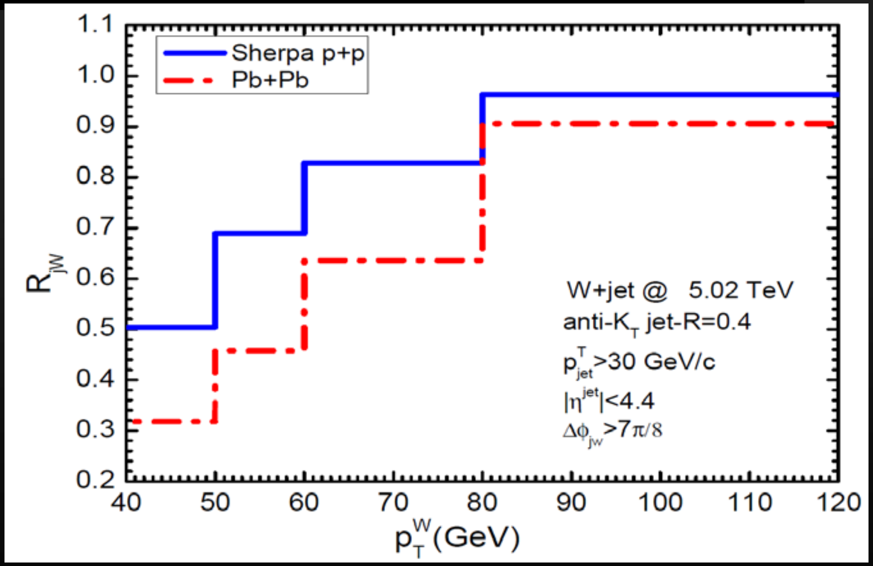


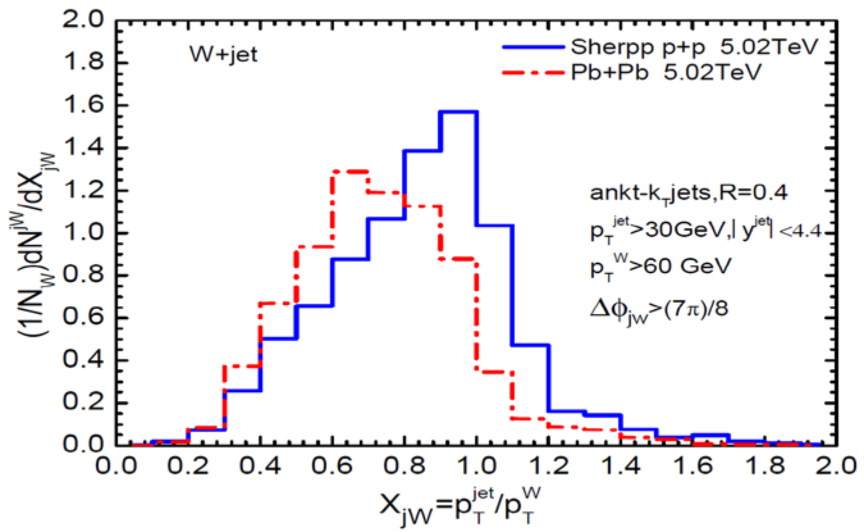


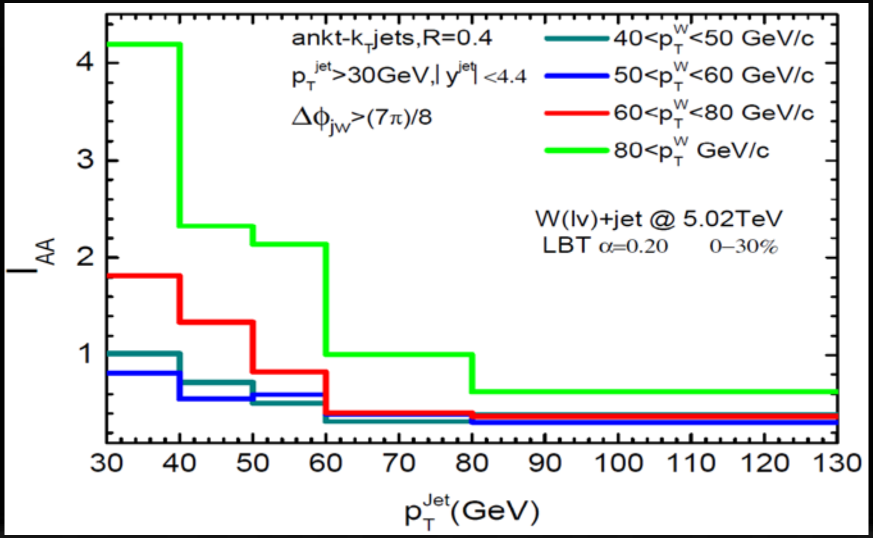
S Zhang, T Luo, X Wang, BWZ, PRC 98 (2018) 021901(R)

W+jet in HIC





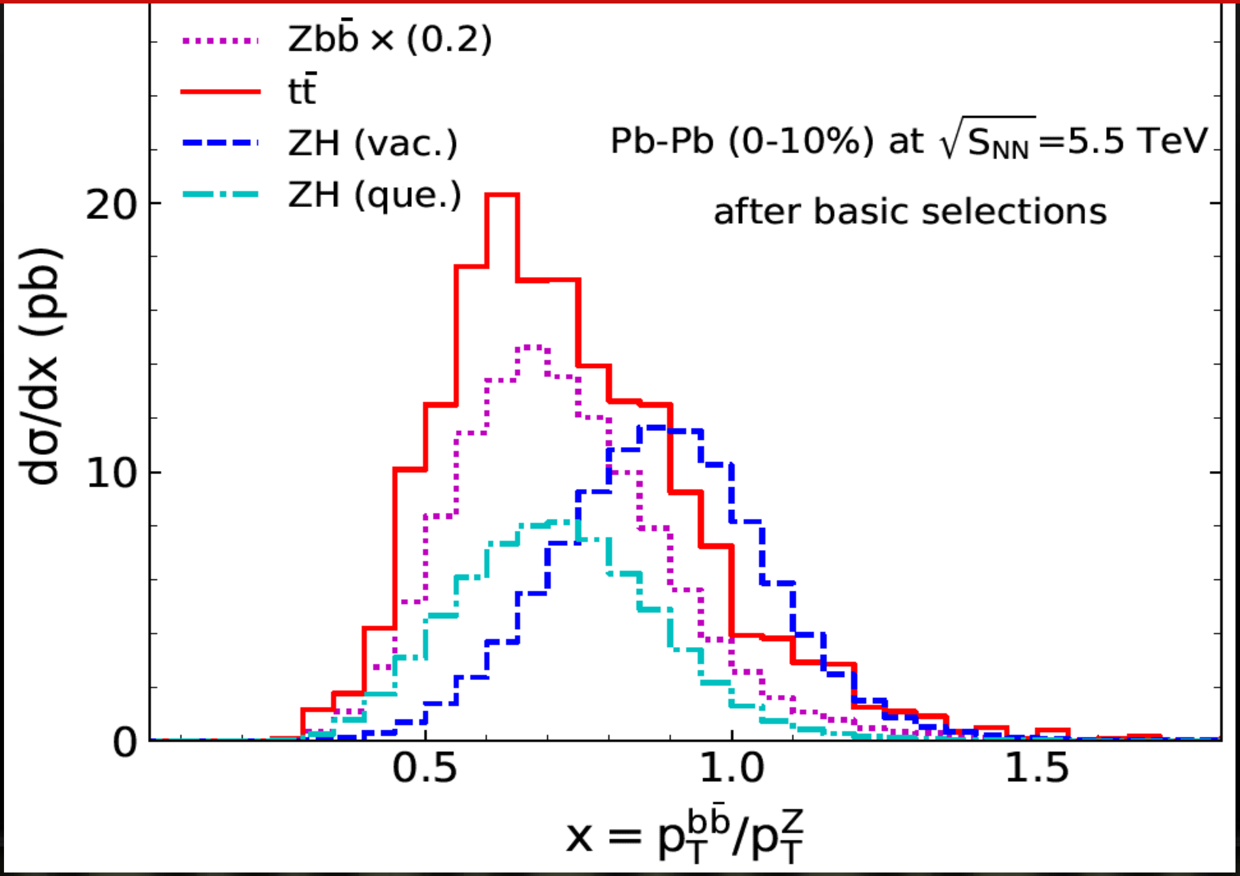




S Zhang, BWZ, X N Wang, to be submitted

Higgs boson in HIC

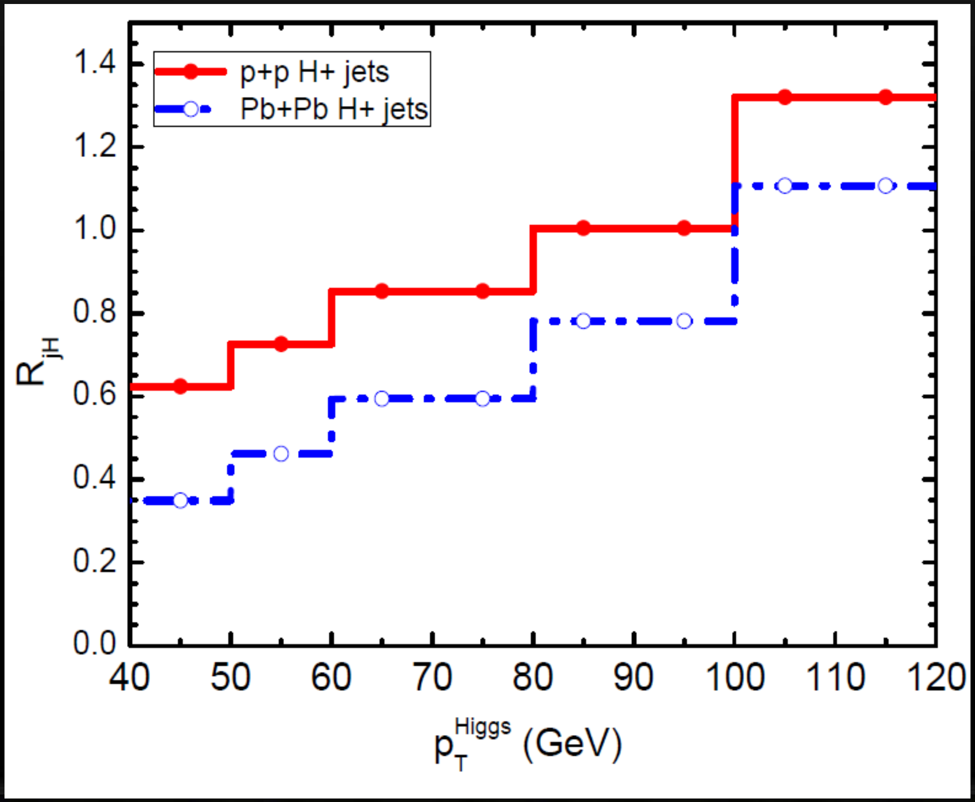
- Higgs boson will not decay in the QGP due to its longer lifetime as compared to that of the QGP
- Signal of Higgs production in HIC should be enhanced relative to the background.

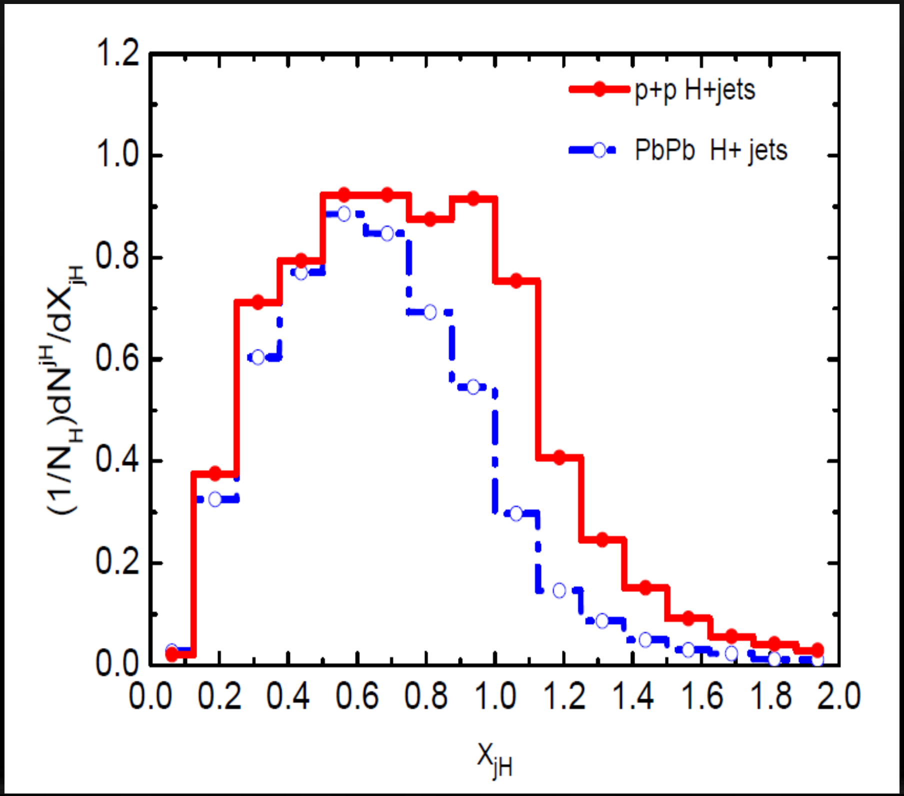


Berger, J Gao, Jueid, H Zhang, PRL 112 (2019) 041803

Higgs + jet in HIC

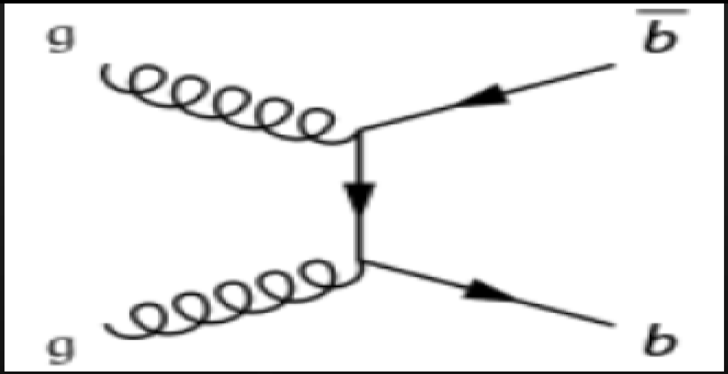
- The number of jets per Higgs boson in Pb+Pb is suppressed considerably as compared to that in p+p collisions.
- The momentum imbalance of Higgs tagged jet production in HIC is reshaped due to jet quenching effect.



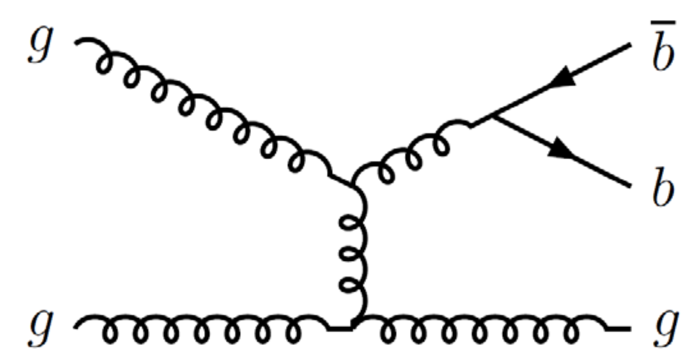


S Zhang, BWZ, X N Wang, in preparation

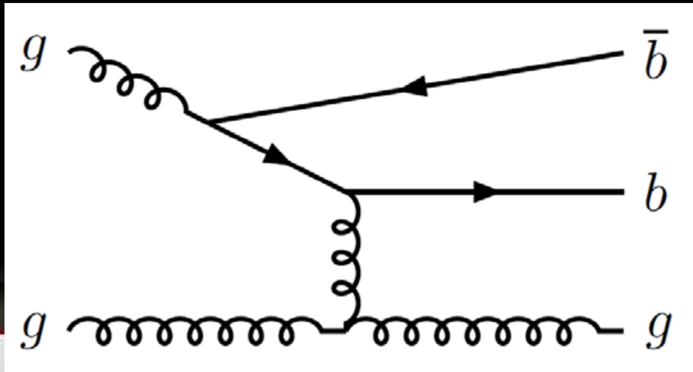
double b-jet production



flavor creation (FCR)



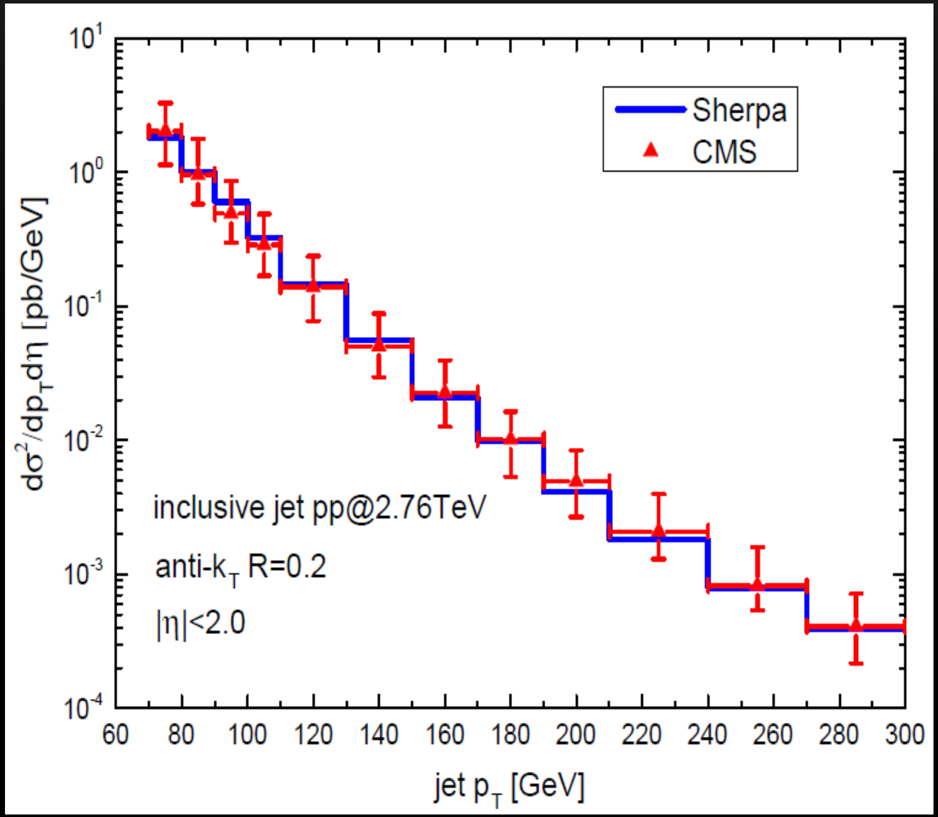
gluon splitting (GSP)

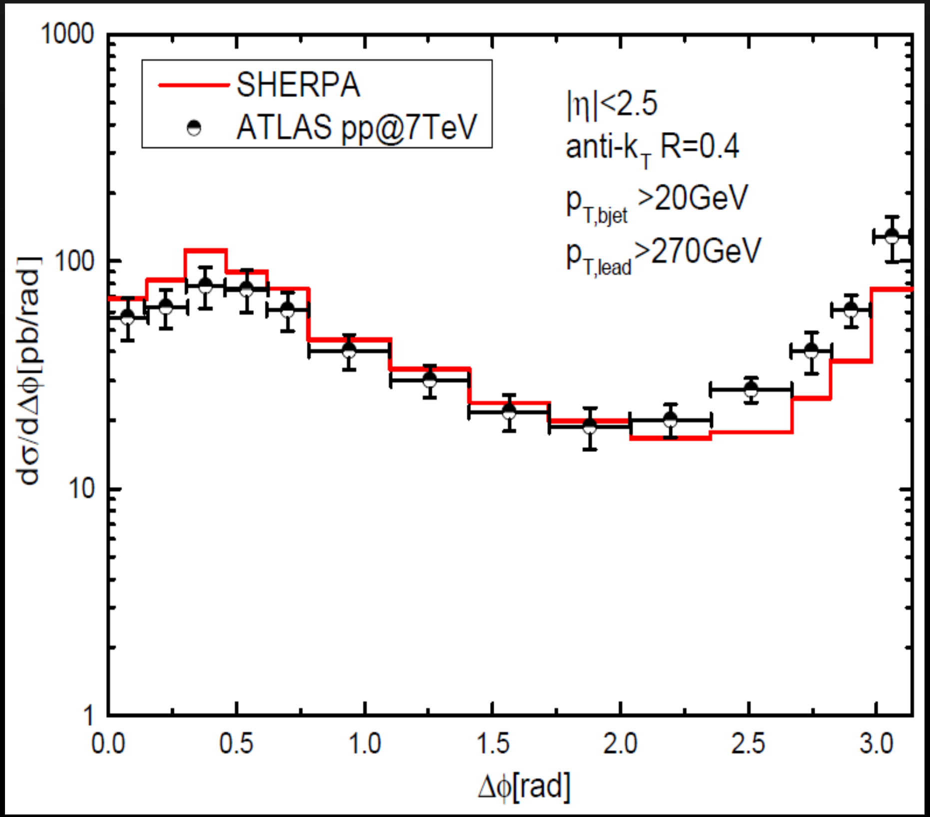


flavor excitation (FEX)

p+p baseline for double b-jet

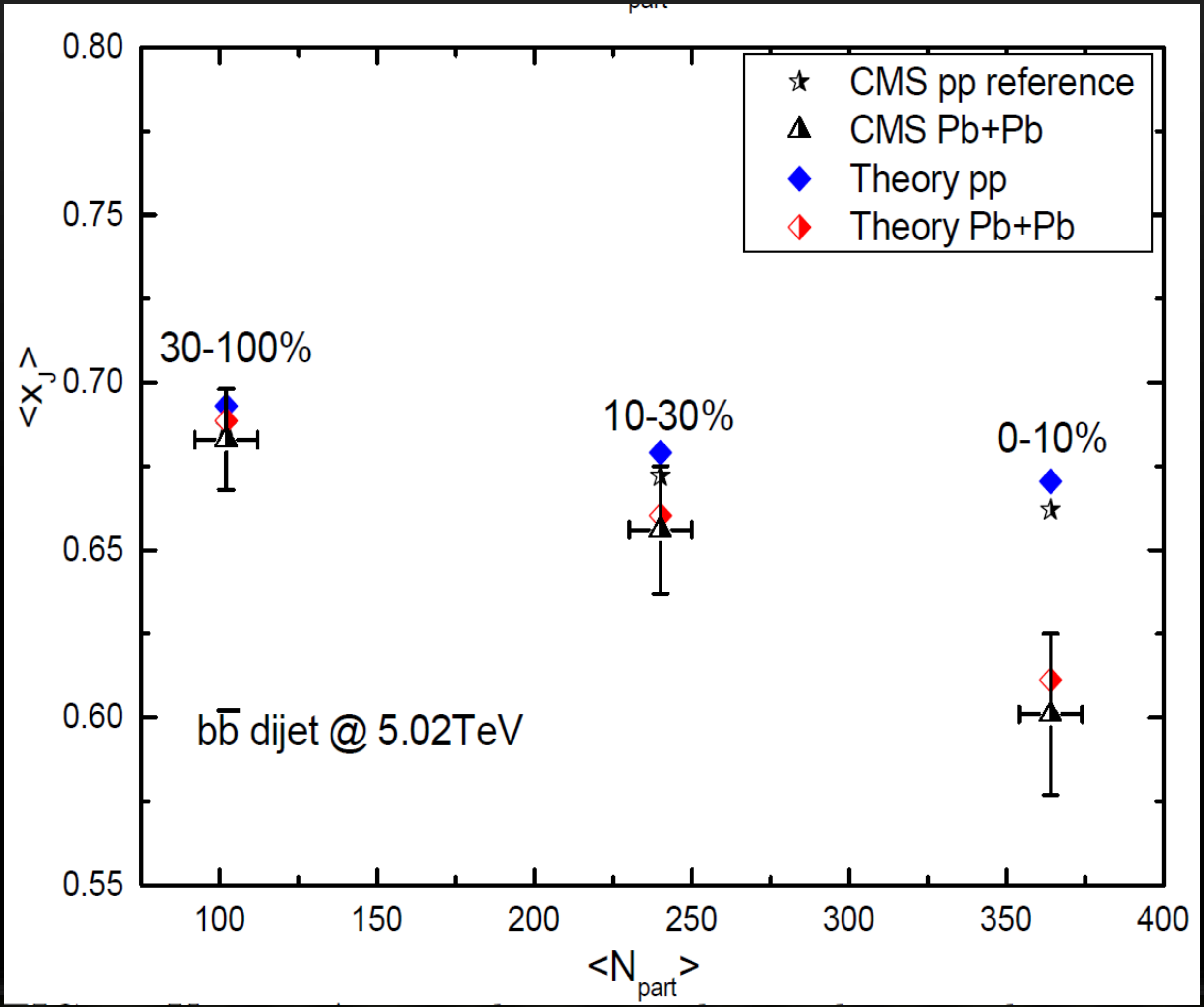
- Simulations with NLP+PS by Sherpa chould give very nice descrptions on inclusive jets, dijets as well as double b-jet.





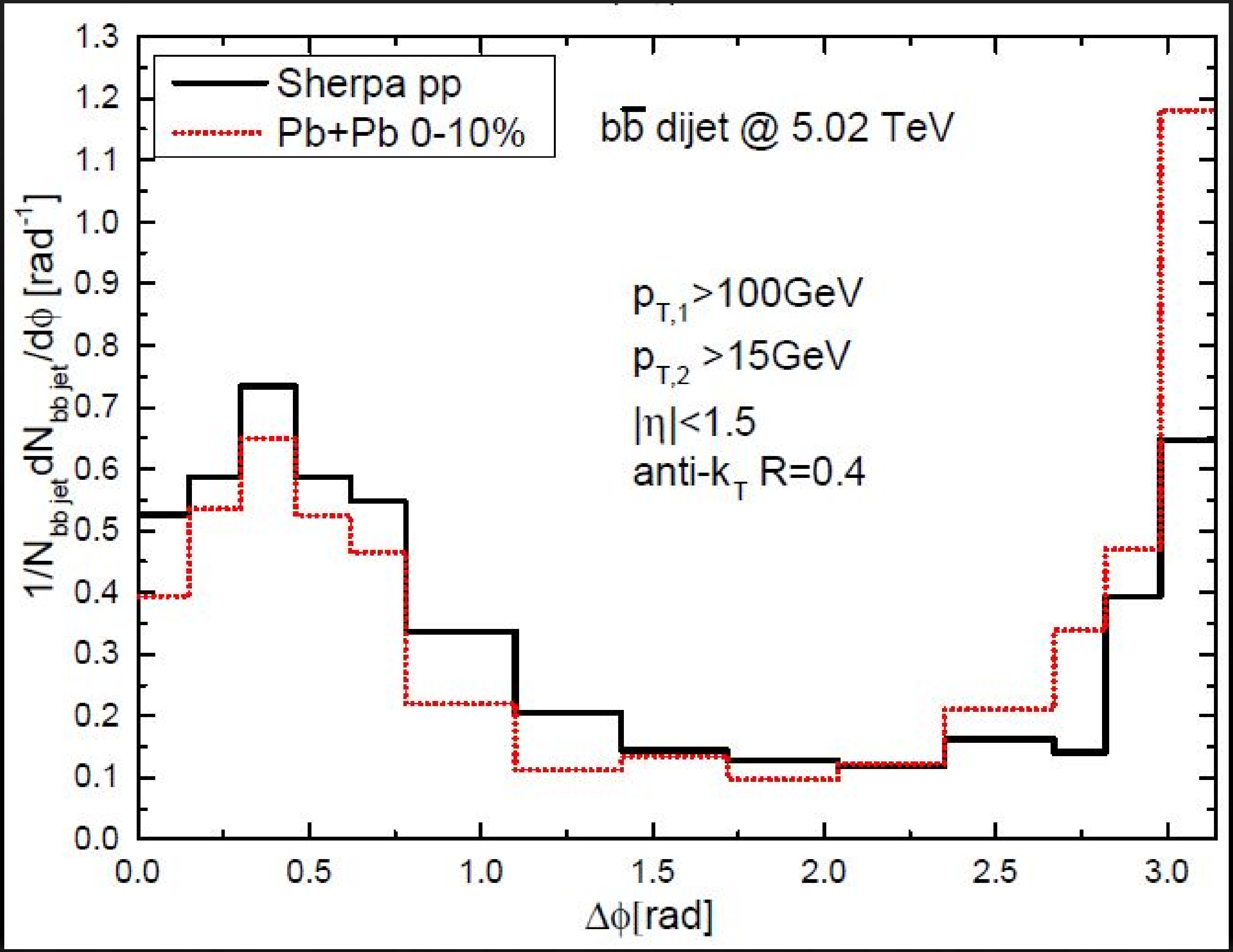
W Dai, S Wang, S Zhang, BWZ, E Wang, arXiv: 1806.06332

Mean values of momentum imbalance



W Dai, S Wang, S Zhang, BWZ, E Wang, arXiv: 1806.06332

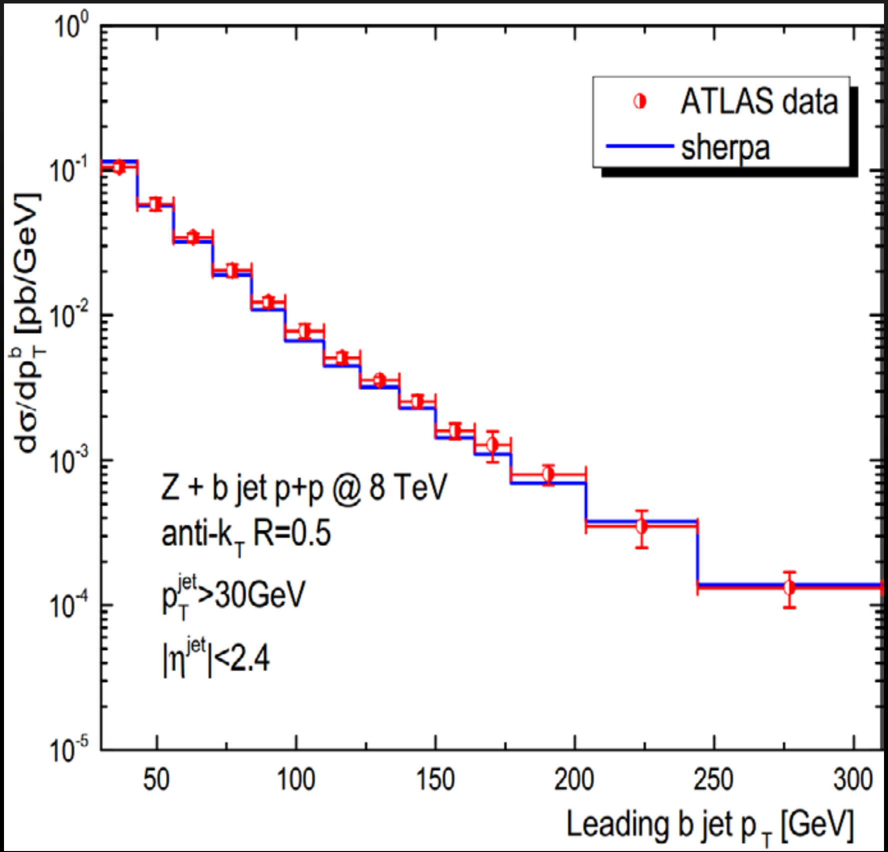
Angle correlation of double b-jet

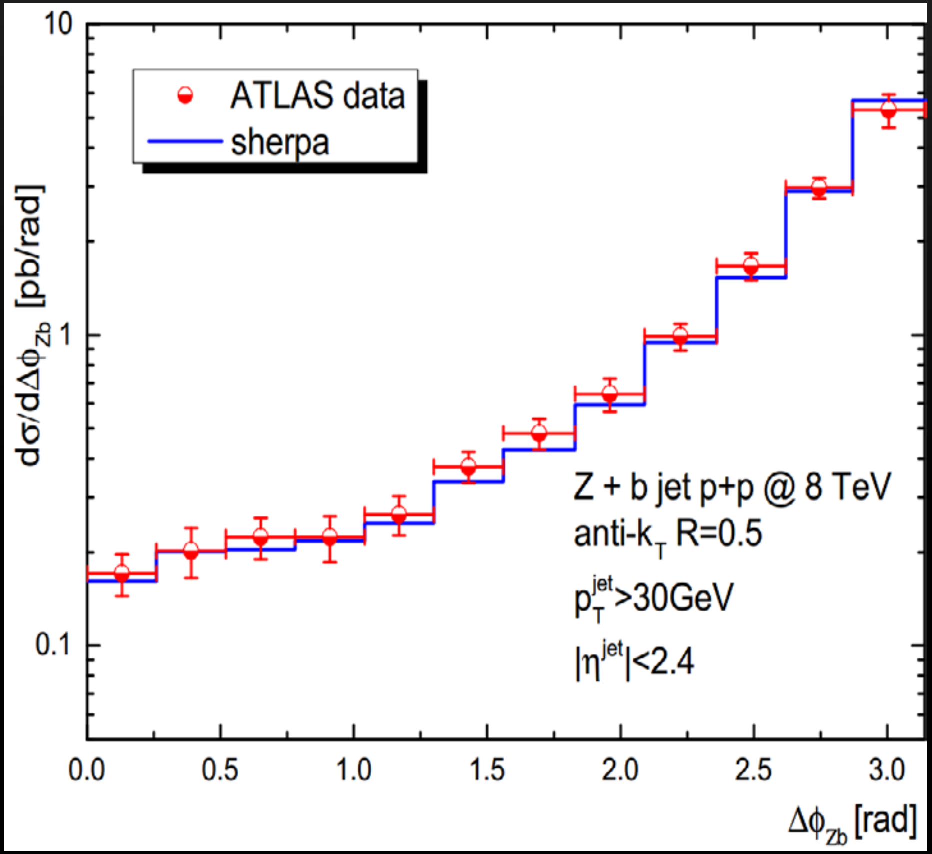


W Dai, S Wang, S Zhang, BWZ, E Wang, arXiv: 1806.06332

Z tagged b-jet production (I)

- B-jet production in association with Z boson in HIC could be calculated in the same formalism (NLO+PS+Eloss)





$$\Delta\phi_{Zb} = |\phi_Z - \phi_{bjet}|$$

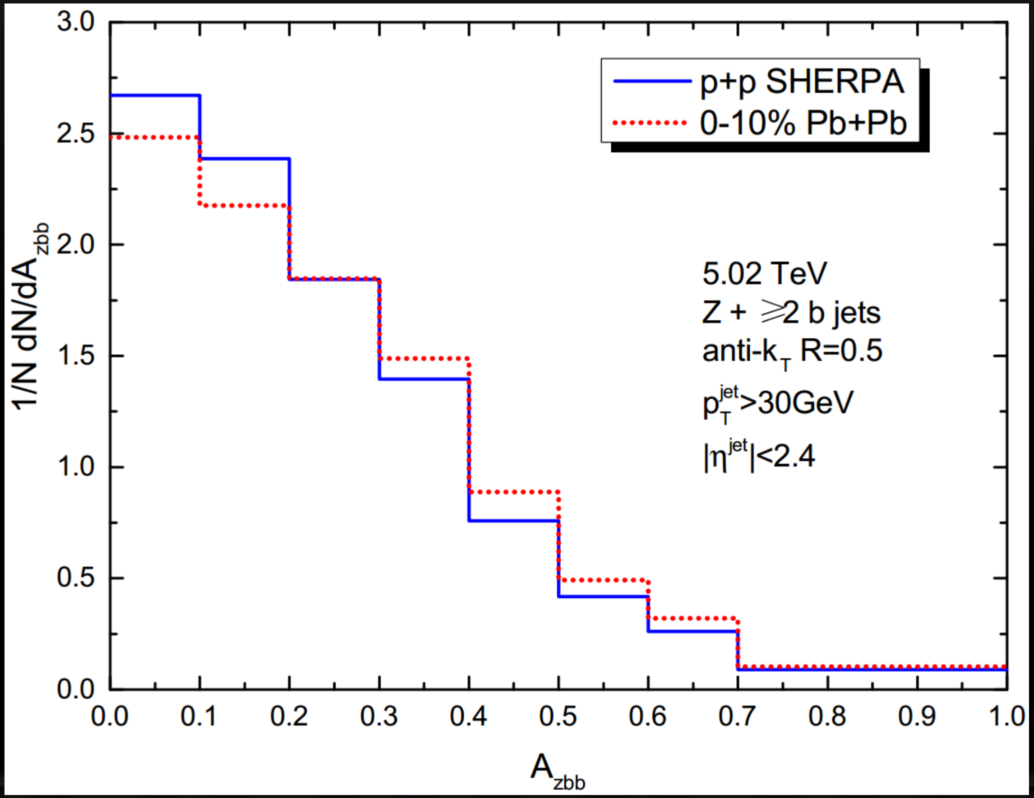
S Wang, W Dai, BWZ, E Wang, in preparation

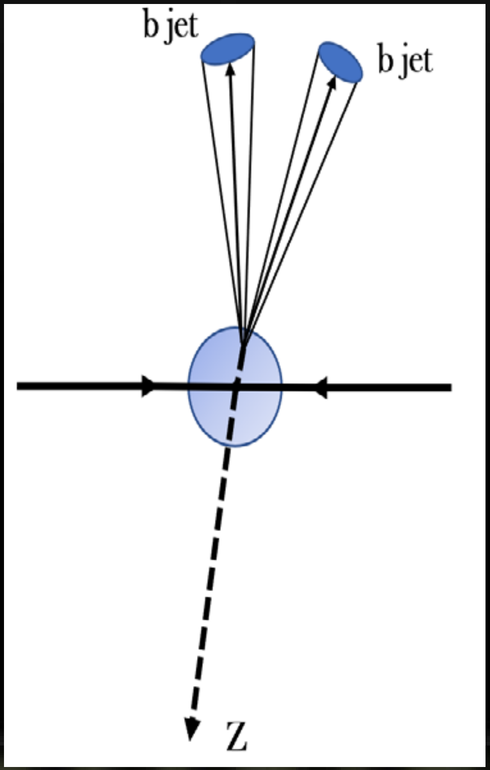
Z tagged b-jet production (II)

- B-jet production in association with Z boson in HIC could be calculated in the same formalism (NLO+PS+Eloss)

$$\Delta R_{zb} = \sqrt{(\Delta\phi_{Zb})^2 + (\Delta\eta_{Zb})^2}$$

$$A_{Zbb} = \frac{\Delta R_{Zb}^{max} - \Delta R_{Zb}^{min}}{\Delta R_{Zb}^{max} + \Delta R_{Zb}^{min}}$$





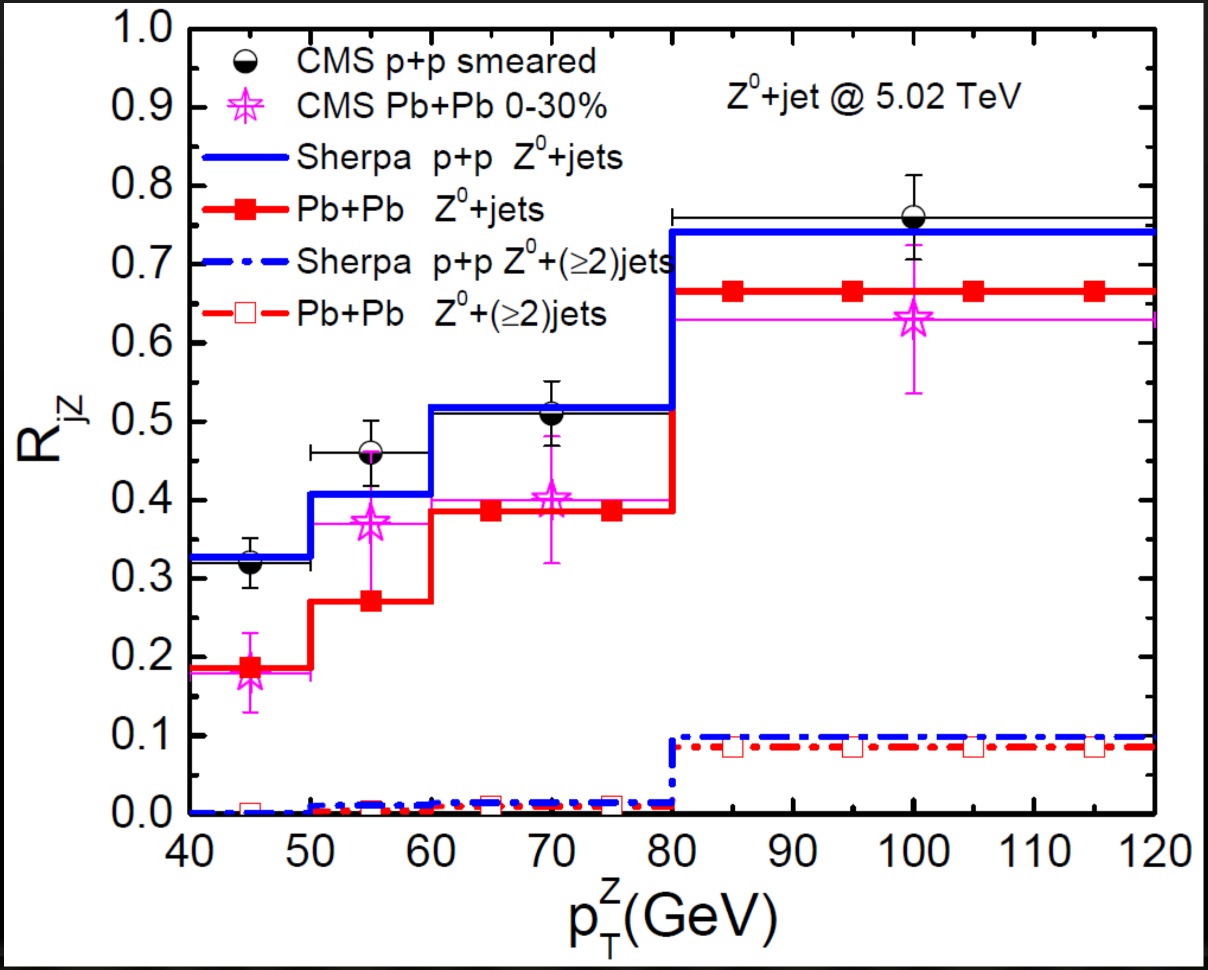
Summary

- A systematic study of identified mesons at NLO in HIC has been discussed.
- A framework of combining NLO+PS for initial hard production with parton energy loss in the QGP has been developed.
- Theoretical models provide nice descriptions of experimental data on tagged jet productions, and predictions on several novel jet observables in HIC.
- Calculations of pQCD with jet quenching can explain a huge amount of data on hard probes with a unified picture. **More studies are needed.**

Backup

Averaged number of tagged jets

$$R_{jZ} = N_{jZ}/N_Z$$



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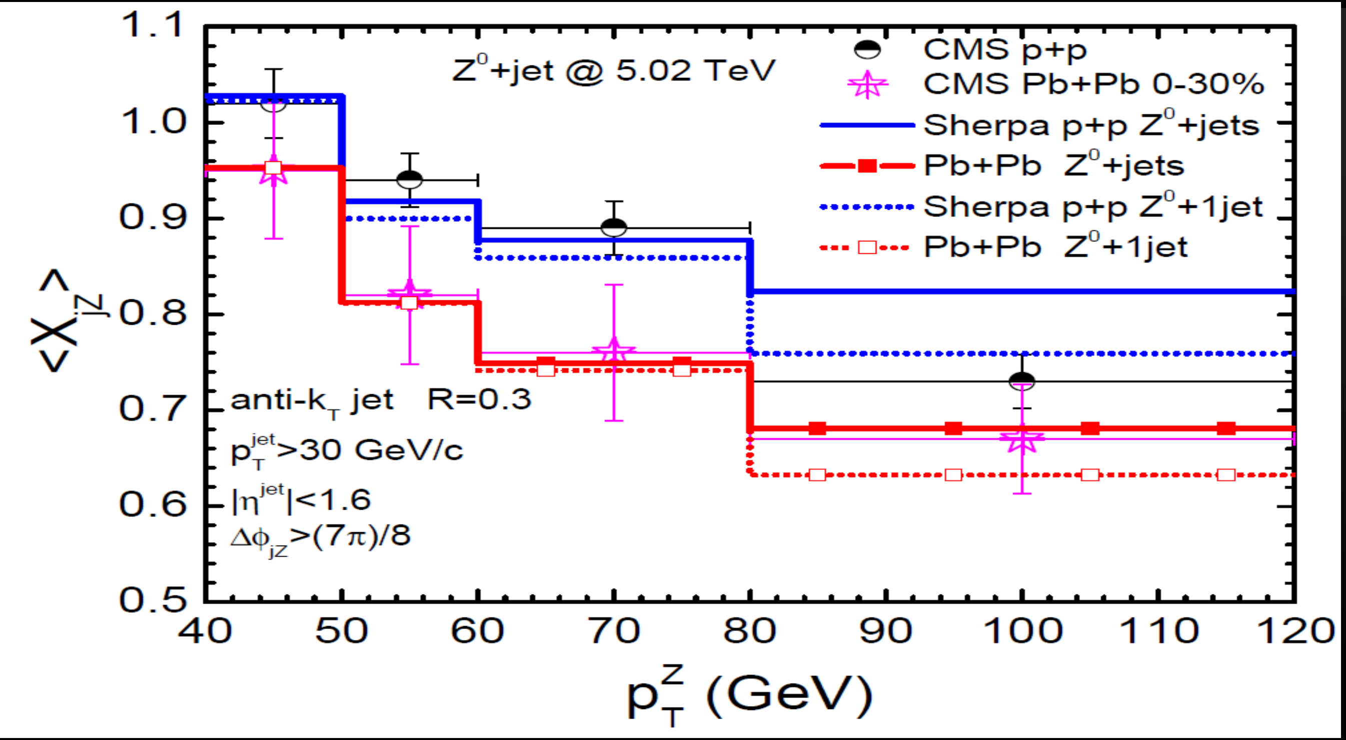
Momentum imbalance



$$\Delta\langle x_{jZ}\rangle = \langle x_{jZ}\rangle_{p+p} - \langle x_{jZ}\rangle_{Pb+Pb}$$

p_T^Z(GeV)	40-50	50-60	60-80	> 80
CMS data	0.07 ± 0.106	0.12±0.148	0.13±0.158	0.06±0.088
$\Delta\langle x_{jZ}\rangle$	0.075	0.106	0.128	0.143

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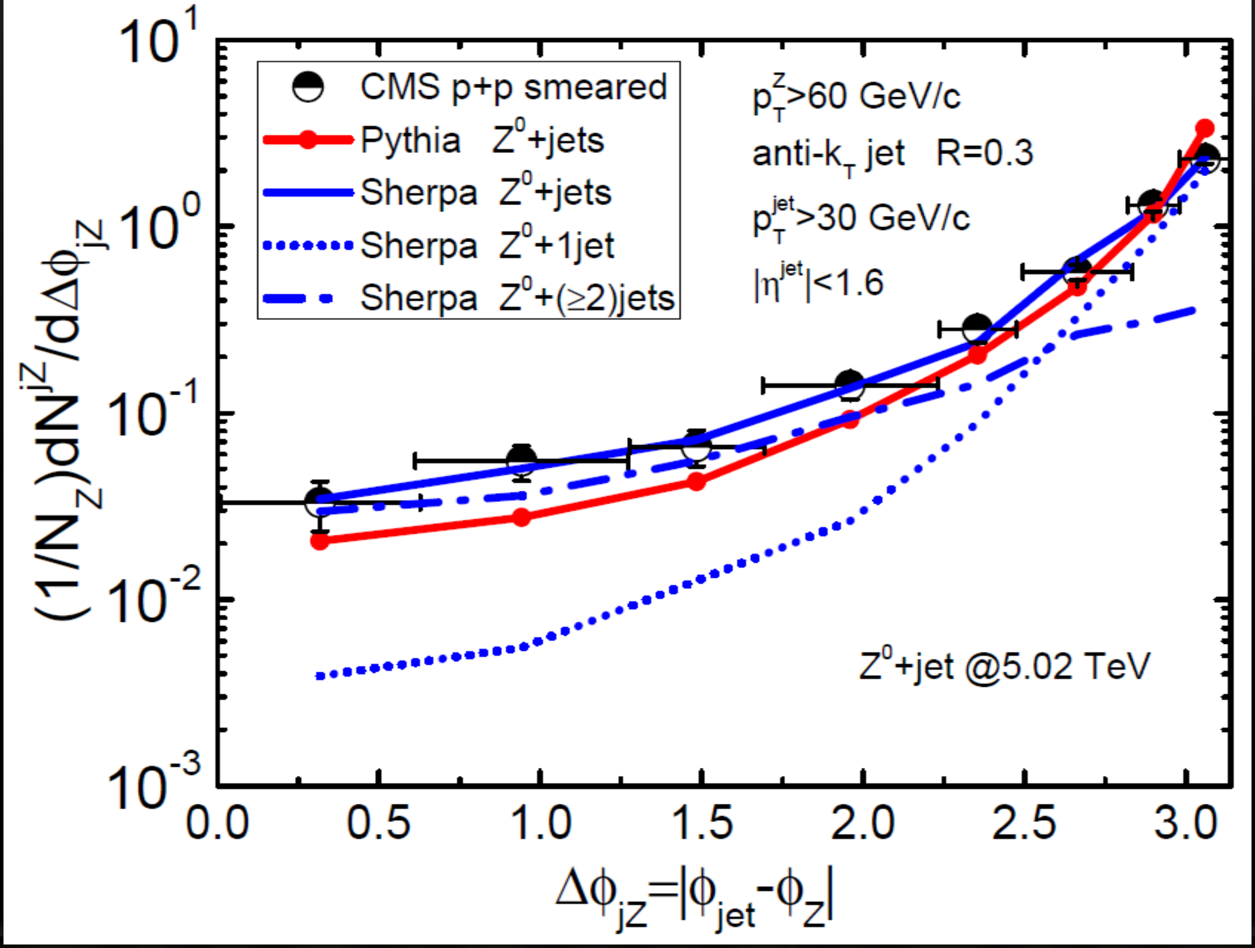
Z+jet in p+p: NLO+PS

- Results with NLO+PS by Sherpa give good descriptions on angular correlation and momentum imbalance of in p+p



S Zhang, T Luo, X Wang, BWZ, PRC 98 (2018) 021901(R)

Linear Boltzmann Transport Model

- Elastic scattering:

$$p_1 \cdot \partial f_1(p_1) = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4)|M_{12\to 34}|^2 \times (2\pi)^4 \delta^4(P_1 + P_2 - P_3 - P_4)$$

$$dp_i \equiv \frac{d^3 p_i}{2E_i(2\pi)^3}, \ |M_{12\to 34}|^2 = Cg^2(s^2 + u^2)/(t + \mu^2)^2$$

$$f_i = 1/(e_i^{p.u/T} \pm 1)(i = 2,4), f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i)\delta^3(\vec{x} - \vec{x}_i)(i = 1,3)$$

X N Wang, Y Zhu, PRL(2013); He, Luo, Wang, Zhu, PRC (2015)

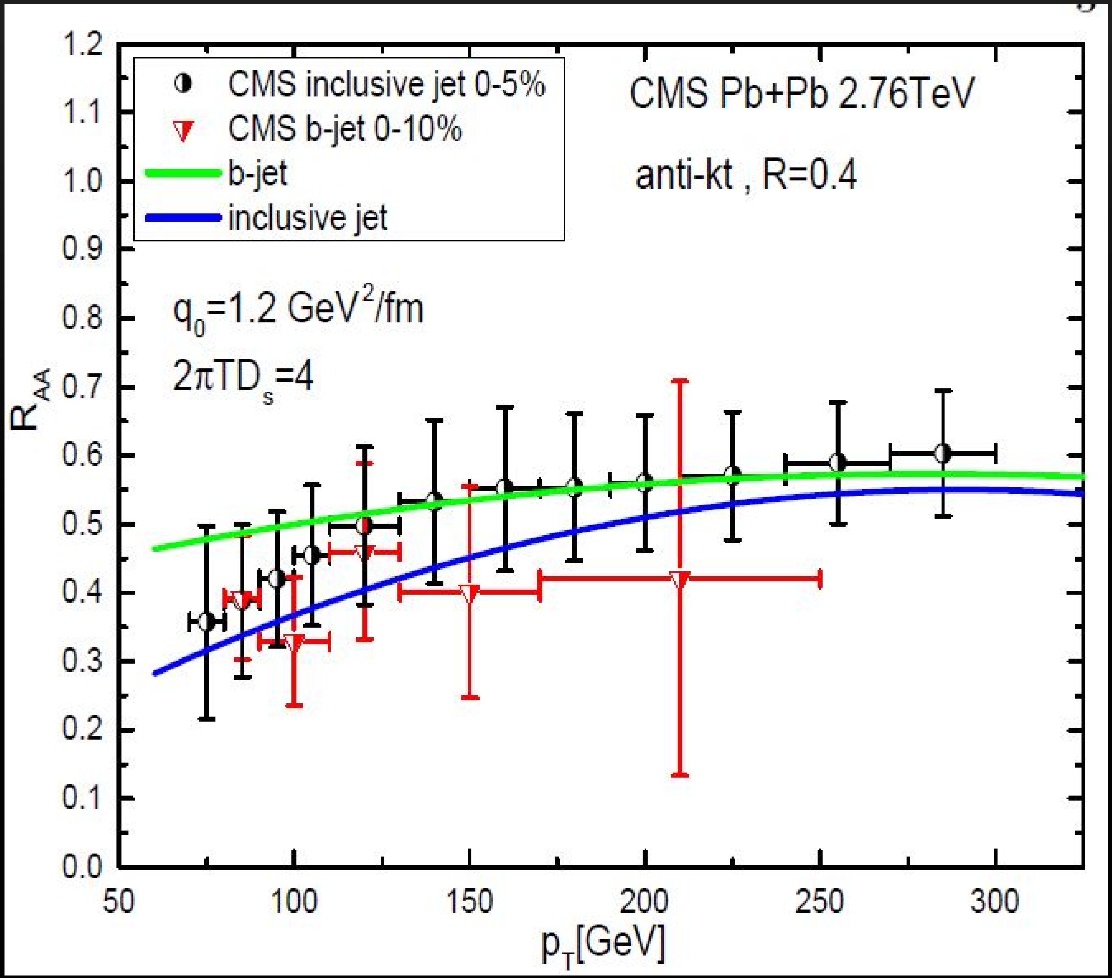
- Inelastic scattering by the higher twist approach:

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{6\alpha_s C_A P(x)\hat{q}}{\pi k_\perp^4}\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^2 \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

Guo, X N Wang, PRL(2002); BWZ, X Wang, NPA(2003);

BWZ, E Wang, X N Wang, PRL (2004); Majumder, PRD(2012)

Inclusive jet and b-jet in HIC



W Dai, S Wang, S Zhang, BWZ, E Wang, arXiv: 1806.06332