Anisotropic Jet Broadening and the $R_{AA} \times v_2$ Puzzle

Supported in part by DoE Grant (DE-SC0024560)
Supported in part by a start-up grand from NMSU

ECT*
14th February, 2024

J. Bahder

NM STATE

In collaboration with Hasan Rahman, Dr. Matthew Sievert, and Dr. Ivan Vitev

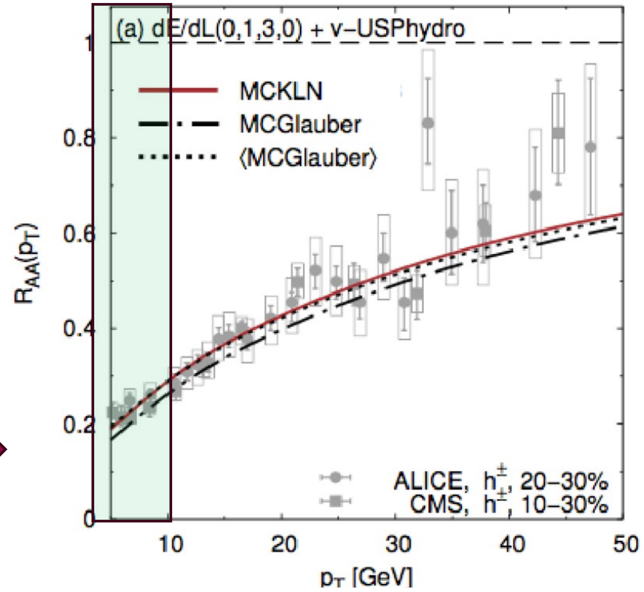
NM STATE

Coupled Observables & the R_{AA} x v_2 Puzzle

- Coupled descriptions are more discriminating
  - a simultaneous description of the observables with a single model
- pQCD models of R_{AA} x v_2
  - Enduring challenge…
  - Success: $p_T > 10$ GeV
  - Failure: 1 GeV < p_T < 10 GeV
    - Underpredicted anisotropic flow for well-behaved R_{AA}
  - Something is missing!

R_{AA} Good!

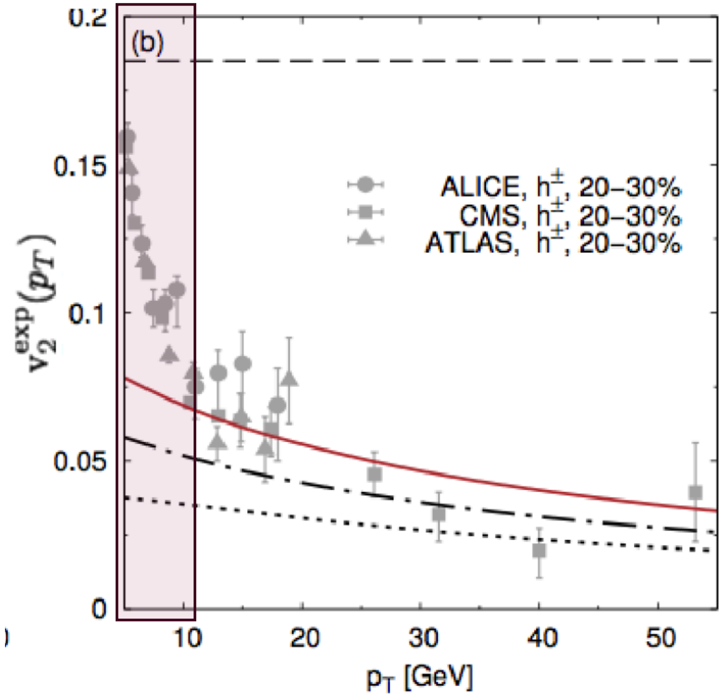
Down to p_T > 5 GeV



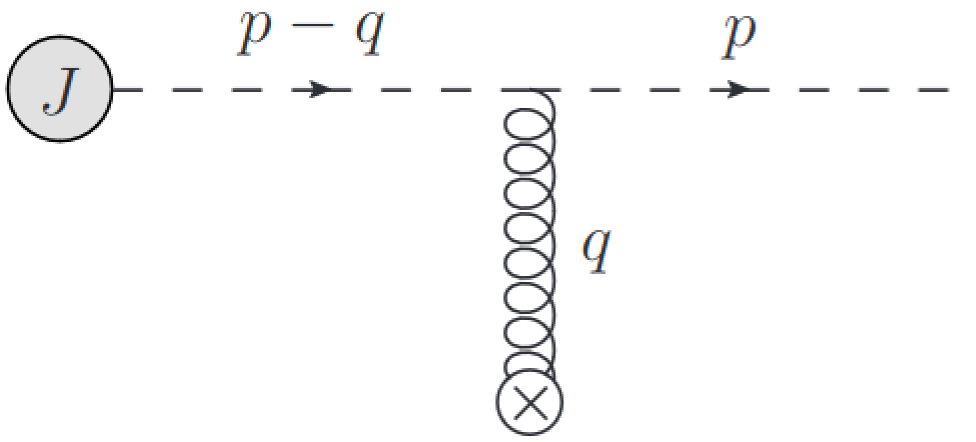
Noronha-Hostler et al:
(arXiv: 1602.03788)

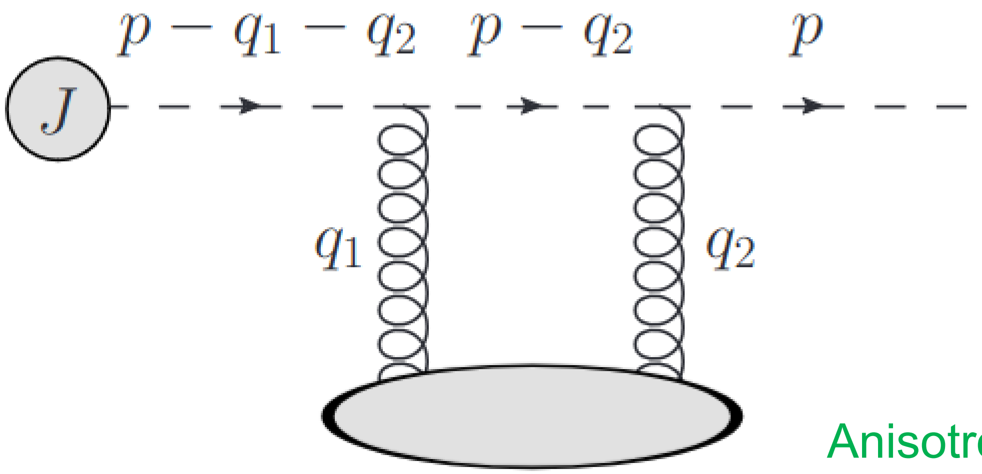
Missing v_2!!!

Suspiciously only around
p_T < 10 GeV

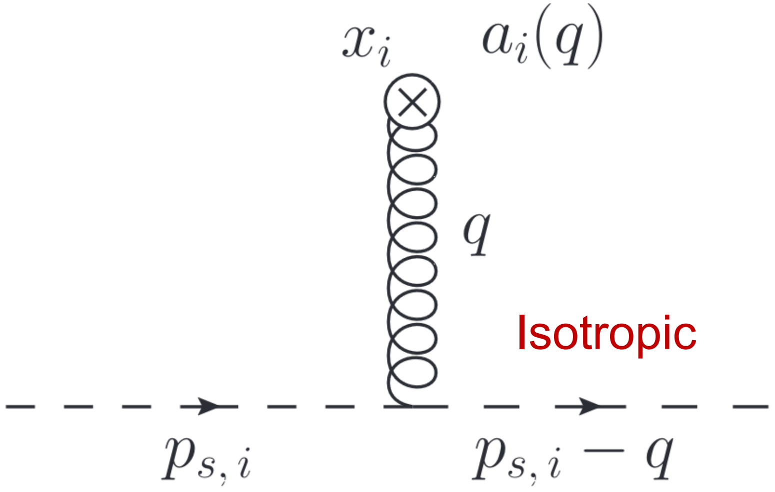


Jet Broadening – Isotropic vs Anisotropic





A. V. Sadofyev, I. Vitev, & M. D. Sievert
Phys.Rev.D 104 (2021)
(arXiv:2104.09513)



Isotropic

$$a_i^{\mu\, a}(q) = g^{\mu +}(t^a)_i \left[2\pi \delta(q^+)\right] \left[\frac{-g_{eff}}{q_T^2}\right]$$

No vector info

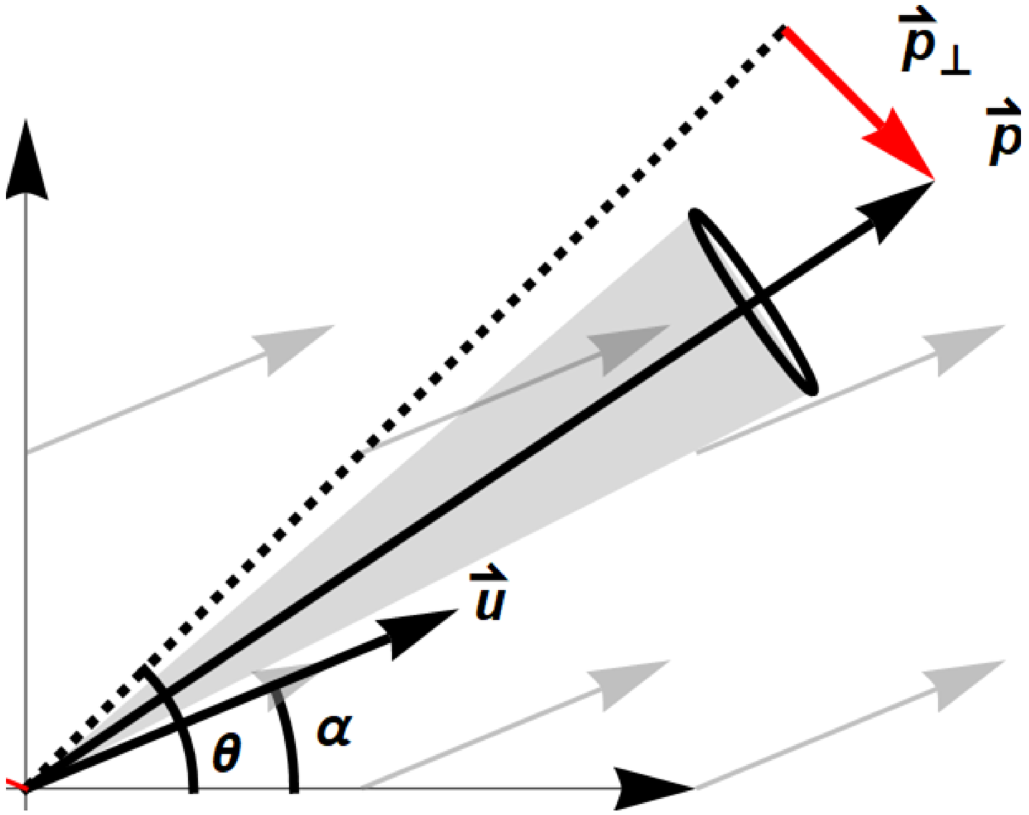
- Difference in setup – constraints on external gluon field
- Isotropic
  - Jet quark moves lightcone (+), medium quark moves lightcone (-)
- Anisotropic
  - Jet quark moves lightcone (+), medium quark moves with medium flow
- Two vector directions associated with the medium
  - Flow
  - Gradients

Anisotropic

$$g\, a_i^{\mu a}(q) = t_i^a\, u_i^\mu\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \boldsymbol{u}_i \cdot \boldsymbol{q}\right)$$

Preferred direction!

Anisotropic Jet Broadening: “Jet Drift”



$$\langle \vec{q}_{drift} \rangle = \hat{e}_\perp \int d\tau \frac{3}{E(\tau)} \frac{\mu^2(\tau)}{\lambda(\tau)} \ln \frac{E(\tau)}{\mu(\tau)} \frac{u_\perp(\tau)}{1 - u_\parallel(\tau)}$$

Energy suppressed

Temperature Enhanced

Flow enhanced and flow direction controlled

$$\frac{1}{\lambda} = \sigma\rho$$
$$\rho \propto T^3$$
$$\mu \propto T$$

- "New" class of pQCD effects: asymmetric / anisotropic
- Flow-Mediated Drift
  - Preferential broadening in direction of medium flow
- Can use analytic approximation to discuss “trajectory of the average”
- L. Antiporda, J. Bahder, H. Rahman & M. D. Sievert
  - Jet Drift Analytic Phenomenology
  - Phys.Rev.D 105 (2022) (arXiv: 2110.03590)

Anisotropic Jet Broadening: Flow-Gradient Mediated

Quadratic in Pathlength

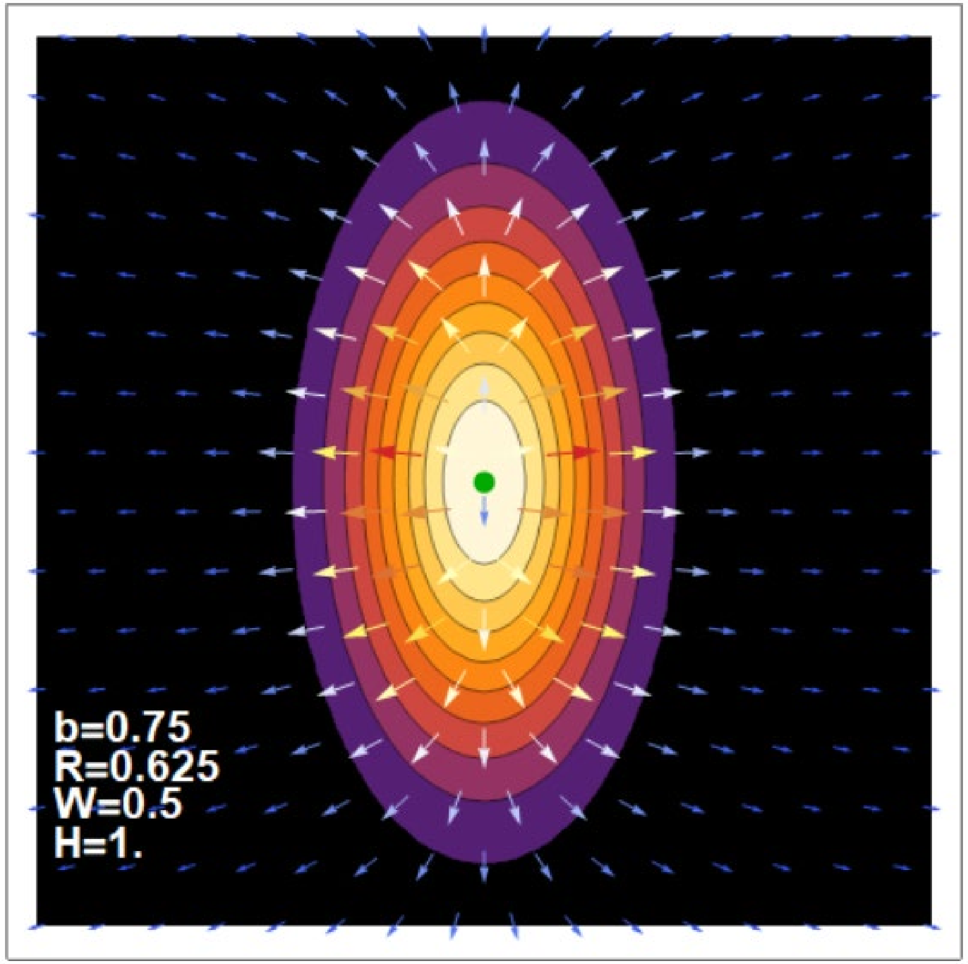
Flow enhanced and flow direction modulated

Energy suppressed

- Mixed Flow-Gradient-Mediated Drift
  - Phenomenology follows flow-mediated drift
  - Small effect in isolation, couples to enhance flow-mediated drift
- A backseat player for now

$$\langle \vec{q}_{fgdrift} \rangle = -\frac{3(2\pi)^2}{2}\frac{g^2}{E}\int_0^L dz\, z \frac{1}{\lambda} \times \Bigg[((\nabla_\perp T) u_\perp) \frac{u_\perp}{(1-u_z)^2} \left(3T \ln\left(\frac{E}{gT}\right) - T \right) + \nabla_\perp u_z \left(\frac{2}{(1-u_z)^3} \right) u_\perp T^2 \ln\left(\frac{E}{gT}\right) + \nabla_\perp u_\perp \frac{2u_\perp}{(1-u_z)^2} T^2 \ln\left(\frac{E}{gT}\right) \Bigg]$$

Elliptical Media =?= Elliptic Modulation



$$T(x,y) = T_0 \exp\left[-\frac{x^2}{2\sigma_x^2}\right] \exp\left[-\frac{y^2}{2\sigma_y^2}\right]$$

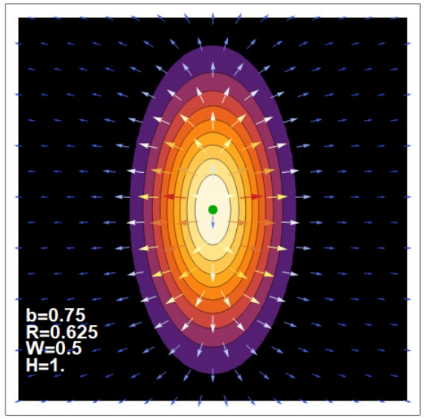
$$\vec{u}(x,y) = u_0\sqrt{\sigma_y\sigma_x}\left(\frac{x}{\sigma_x^2}\hat{i} + \frac{y}{\sigma_y^2}\hat{j}\right) \exp\left[-\frac{x^2}{2\sigma_x^2}\right] \exp\left[-\frac{y^2}{2\sigma_y^2}\right]$$

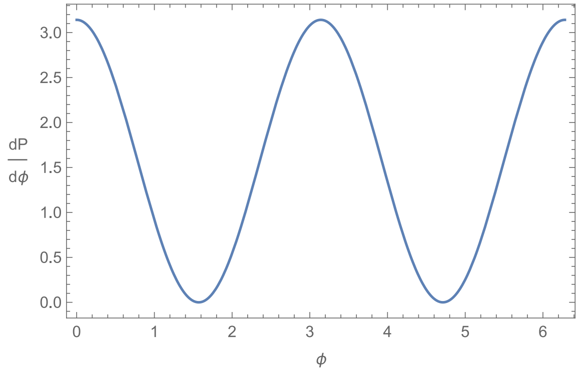
$$W(b) = 2\sigma_x = 2R - b\,,$$

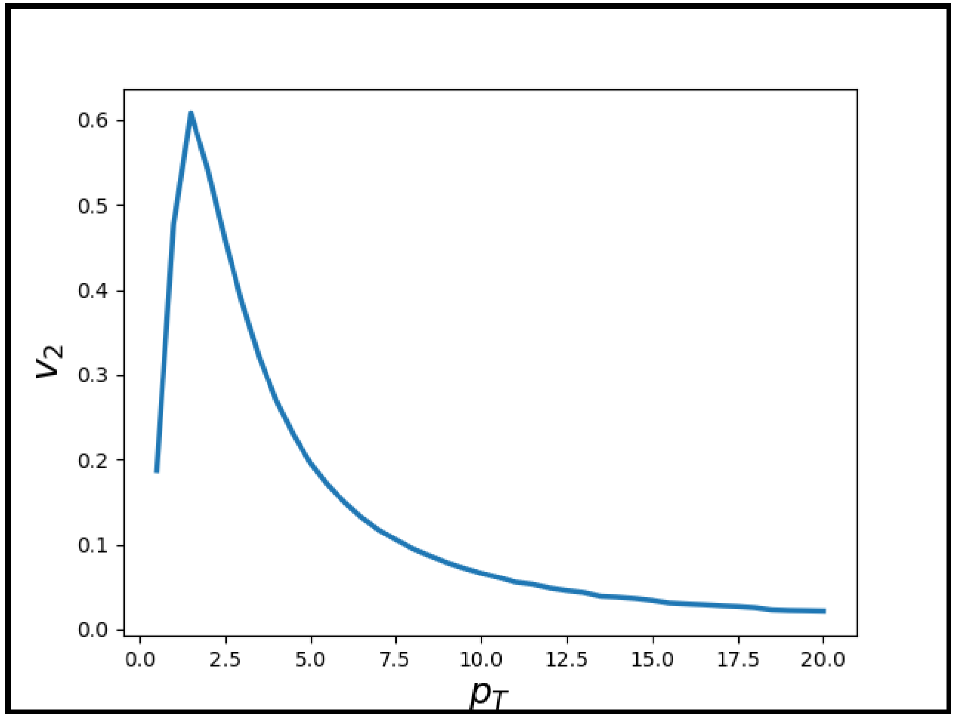
$$H(b) = 2\sigma_y = \sqrt{4R^2 - b^2}$$

- 2D Gaussian Temperature & Flow
- Take an angular sweep of hard partons,
- Compute R_{AA} and v_2 for various p_T
  - Drop all scale factors (no physical scale for medium)

Drift Couples to Event Geometry





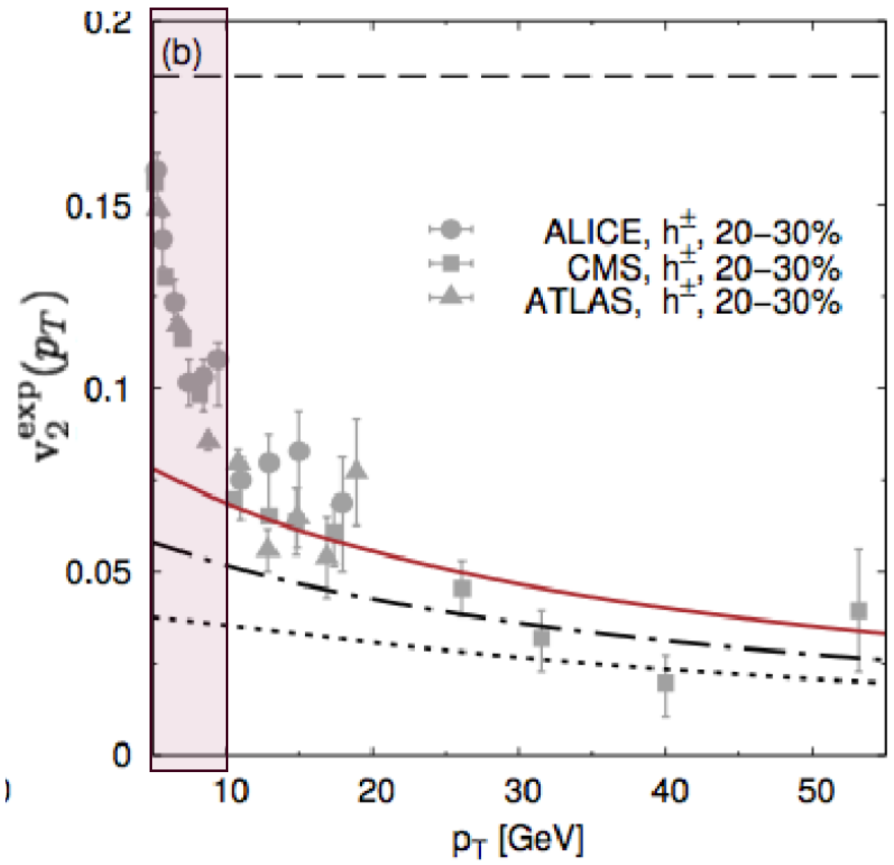


- Drift strength arbitrarily scaled for visual effect
  - Jet p_T dependence accurate
- Elliptic modulation: additional v_2!
  - Drift is strongest at low p_T, matching missing v_2
  - (1/E) log(E) behavior in p_T
- Review:
  - ○ Missing v_2, $p_T < 10$ GeV
  - ○ Jet Drift enhances v_2 , $p_T < 10$ GeV
  - ○ … Suspicious, no?

The Well-Trodden: Elliptic Flow from Energy Loss

Noronha-Hostler et al: (arXiv: 1602.03788)

- Need an energy loss model to address R_{AA} (x) v_2 puzzle
  - Jet quenching responsible for elliptic flow - p_T > 10 GeV
  - Implement analytic approximation to first-order GLV energy loss
- Jet quenching goes roughly quadratically in pathlength
  - Enhances energy suppressed drift at late times
- Largest flow values likely seen by jets at late times near plasma "wavefront"



$$\langle q_{GLV}(\tau)\rangle = -\frac{C_R\alpha_s}{\pi}\int_{\tau_0}^{\infty} d\tau \frac{\mu^2(\tau)}{\lambda(\tau)}(\tau-\tau_0)\ln\left(\frac{E(\tau)}{\mu(\tau)}\right)$$

Vitev: (arXiv:0012092)

Vision to Study Realistic Drift

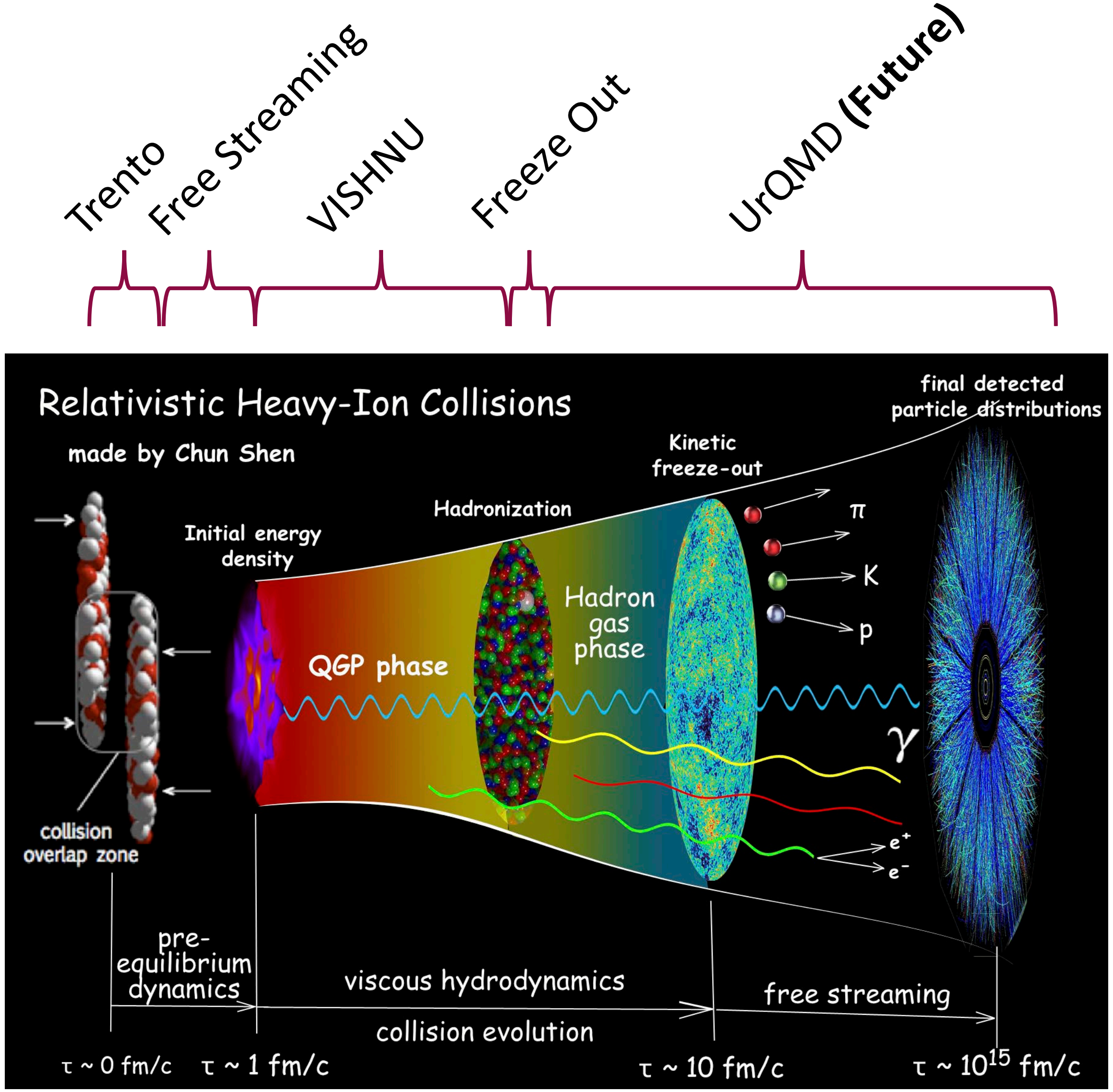
Test effect of addition of jet drift to realistic event-by-event jet-medium simulations on R_{AA} (x) v_2 puzzle

- Realistic 2+1D model of QGP temperature and flow
- Perturbative energy loss model
- Perturbative drift model
- Differential treatment of jet trajectories
- Fragmentation to observable particles
- Experimental-Type R_{AA} and v_2 measurements

Medium Model

Duke QCD – "hic-eventgen"

- Initial HIC Conditions (Trento)
  - Initial energy densities
- Free streaming
  - Generating initial flow in the pre-equilibrium phase from gradients
- Hydrodynamics (VISHNU)
  - Relativistic Fluid Eqs. -> EMT Conservation
- Freezeout
  - Cooper-Frye particlization sampler



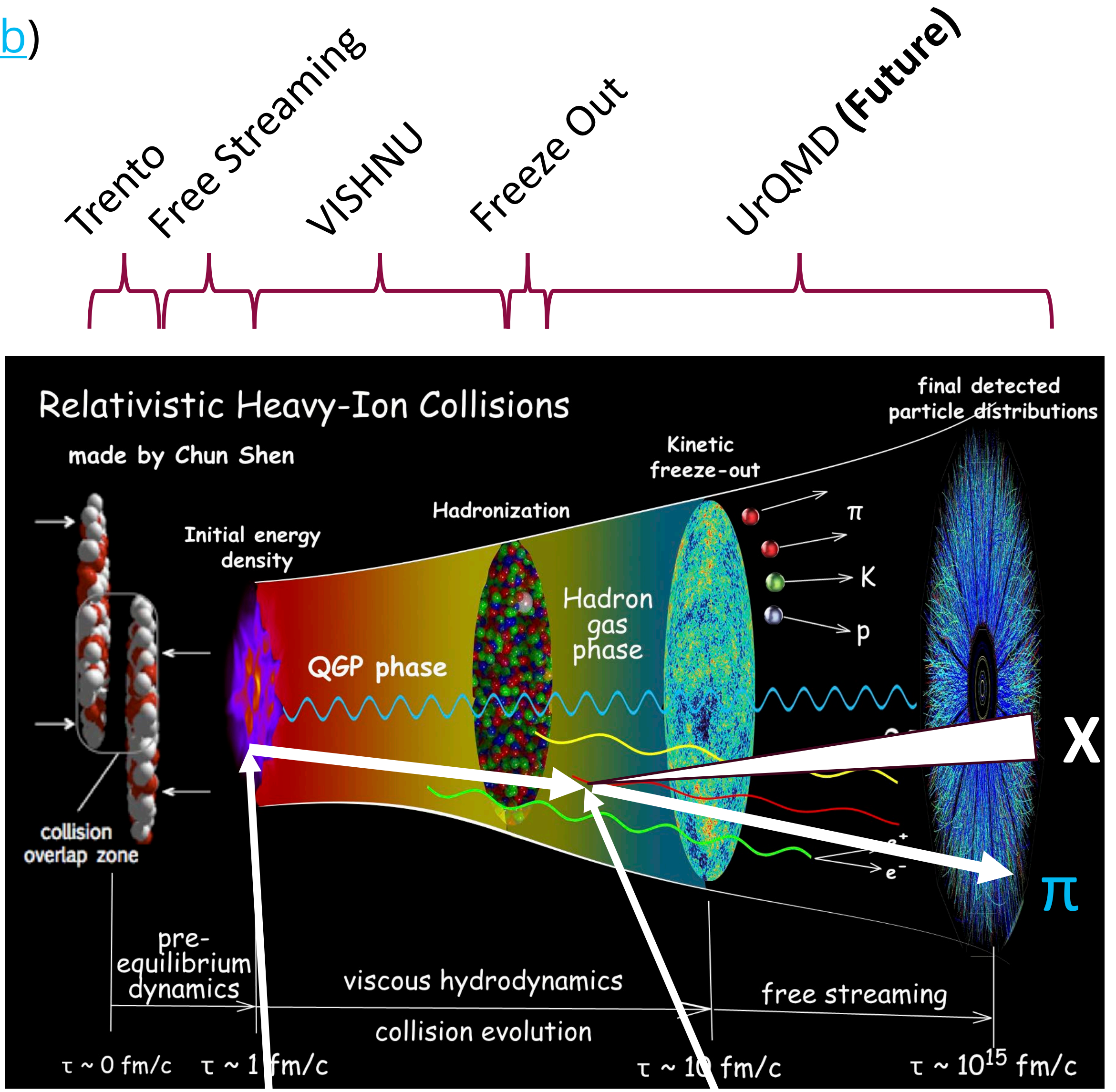
Chun Shen / OSU / VISHNU Collaboration

"hic-eventgen"
(arXiv:1804.06469)
(GitHub)

JMA Jet Model

(GitHub)

- Jet Physics Wrapper overtop "hic-eventgen"
- Partonic Scattering Inputs (Pythia & CNM Theory)
  - Jet production from pp hard partonic scatterings
  - Theoretical cold nuclear matter effects from saturation theory
- Parton Propagation in QGP (EL & Drift Theory)
  - Jet energy loss & drift applied to pA products
- Fragmentation
  - Event-by-event Sampling of Fragmentation Functions for hadron momentum fraction

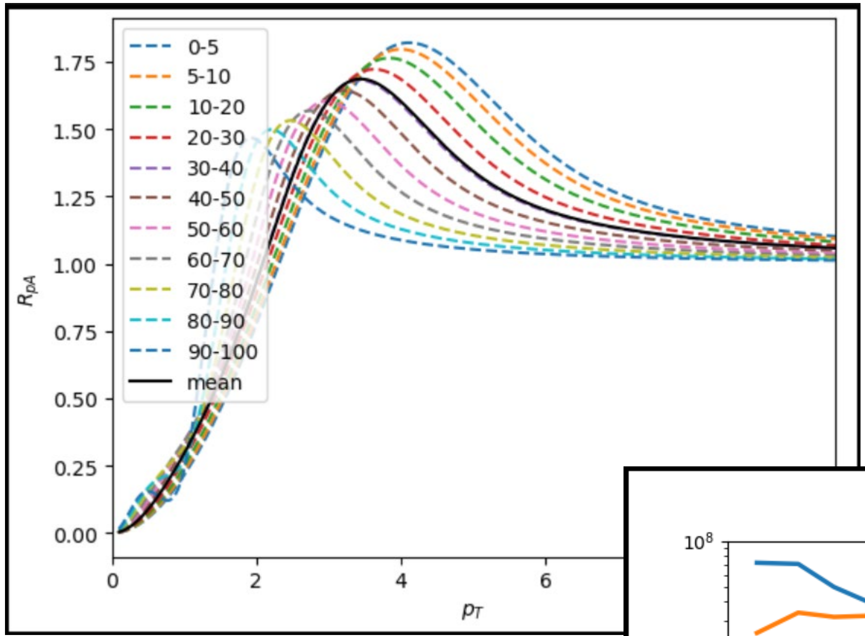


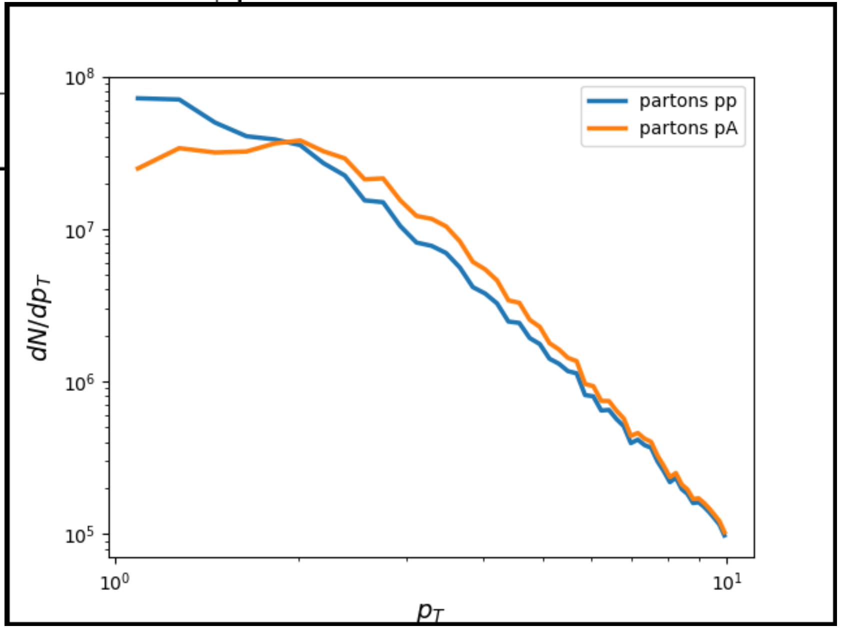
Chun Shen / OSU / VISHNU Collaboration

Pythia Hard Scattering & Theoretical CNM Effects

Fragmentation

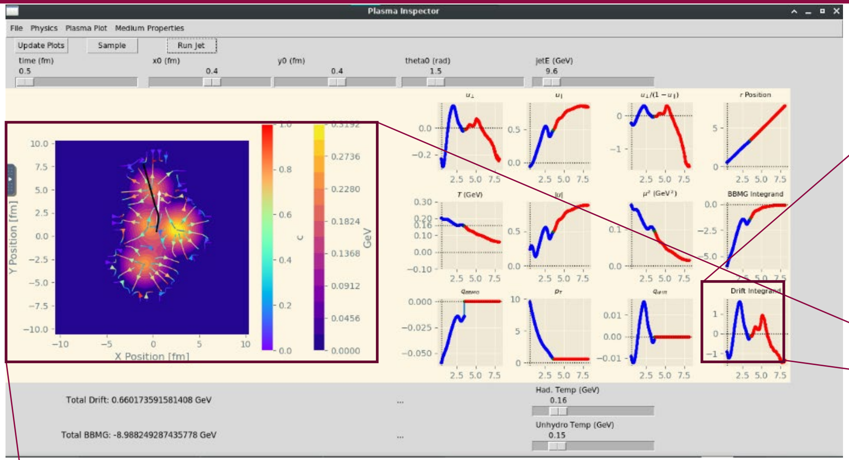
Jet Distribution & Cronin Effect

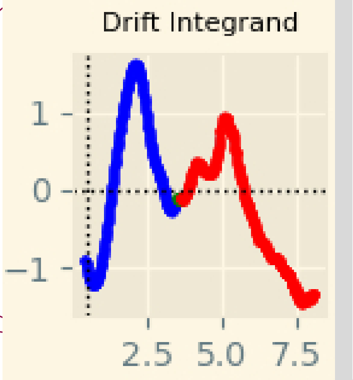




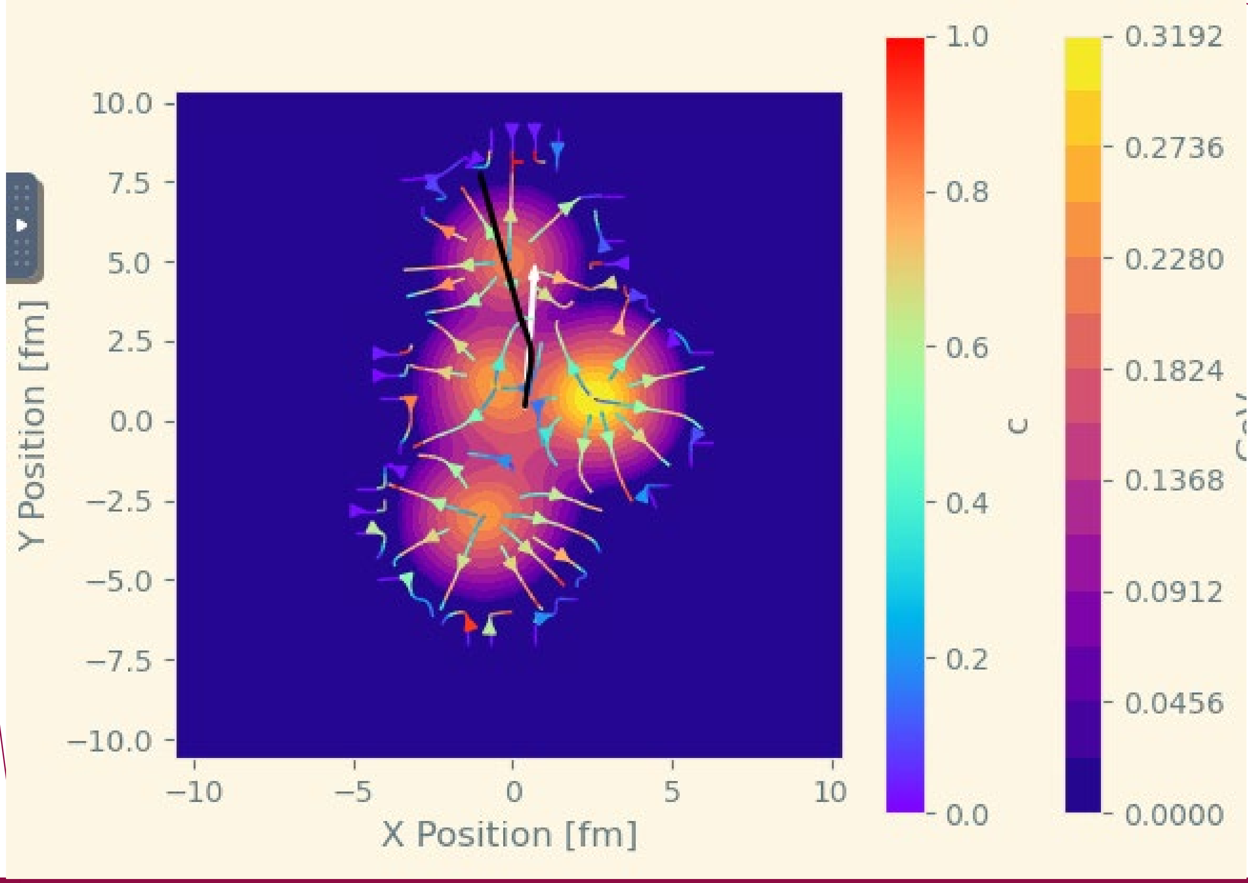
- pp jet distribution from Pythia pp collisions @ 5.02 TeV
- All events 2->2 partonic hard products
  - Dijets (before QGP effects)
  - Light quarks & gluons
  - Access to dijet observables
- RpA computed from saturation theory
  - (arXiv: 0307037)
  - Two parameter, flexible form
  - Needs modification for gluon jets…
  - **Especially important for drift!**

JMA Jet Trajectories



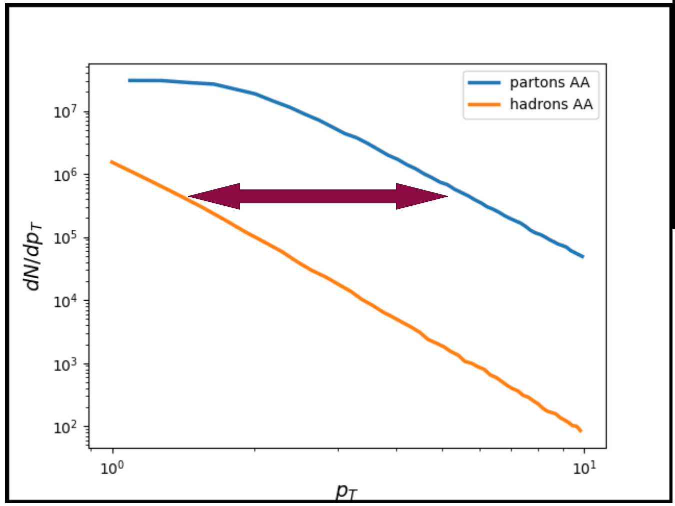


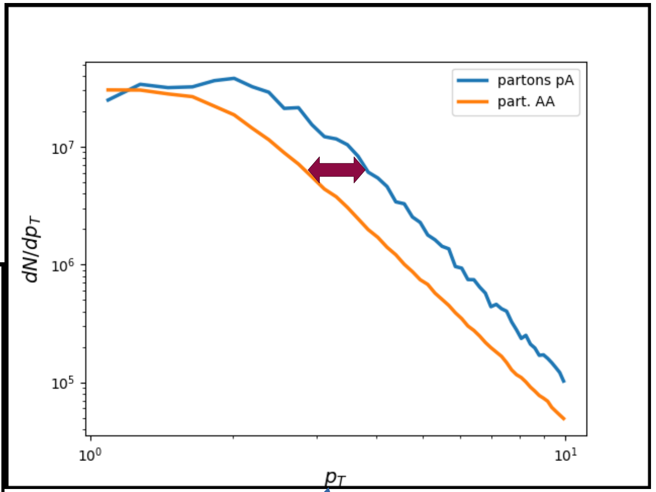
- Hard partons - not “jets”
  - Uncontrolled factorization of hadronization from jet-medium int.
- Jet trajectories
  - Binary collision density weighting of production points
  - Computed within QGP phase of hydro backgrounds
    - EL & Drift cut off at T < 155 MeV

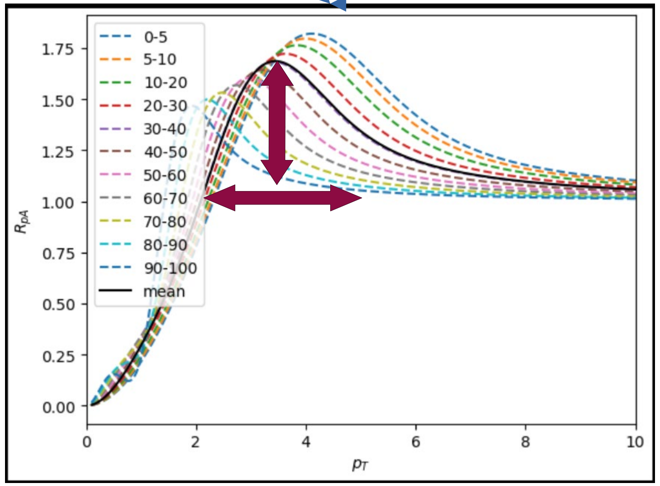


On Free Parameters

- DukeQCD “hic-eventgen” medium model parameters set by Bayesian parameter estimation
  - ([arXiv:1804.06469](https://arxiv.org/abs/1804.06469))
- Jet spectra set by choice of scattering & CNM theory
  - Pythia tuned to pp data
  - 2 parameter CNM analytic model
- Jet-medium interaction theory fully defined by coupling
- Fragmentation
  - Choice of fragmentation functions
  - Very non-trivial

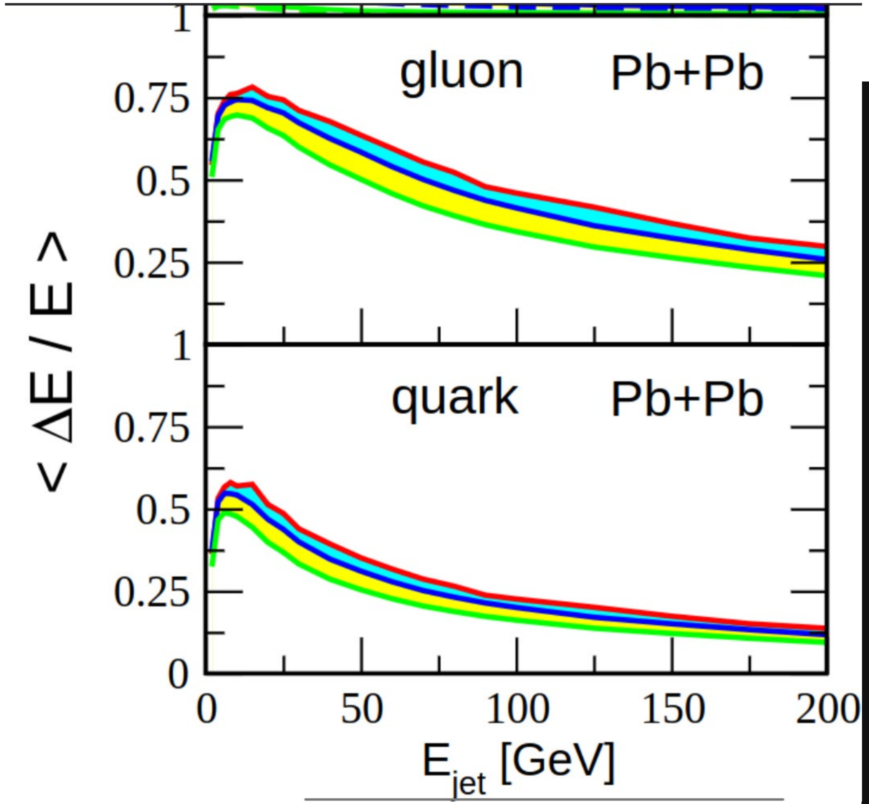




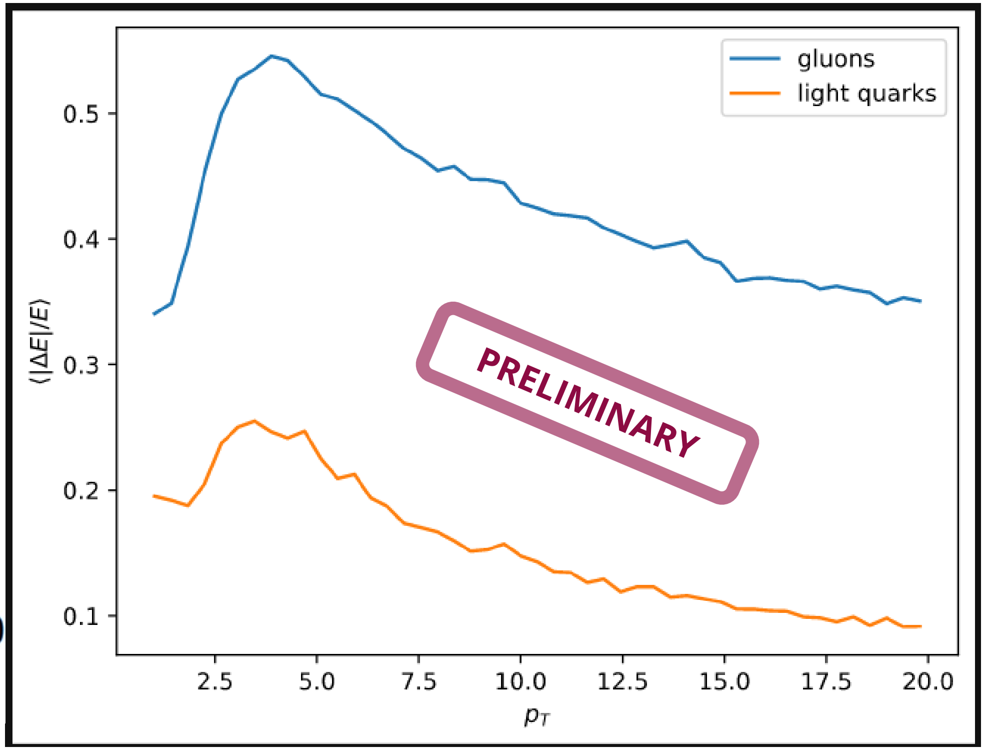


Effect Strengths - EL

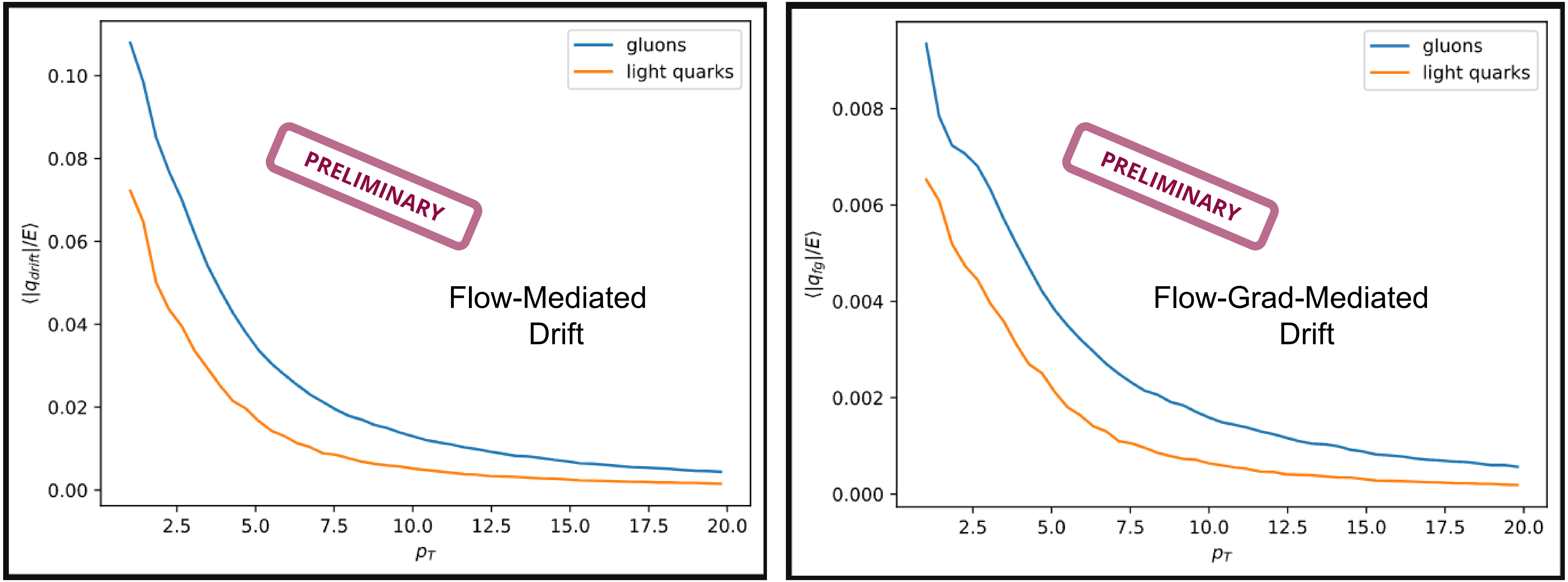
- Compare JMA (right) to perturbative simulation results in Woods-Saxon Glauber models (left)
  - Mismatch to simple analyses
    - Red Flag!
  - Wait to see R_{AA}
  - More details shortly



arXiv:0603010



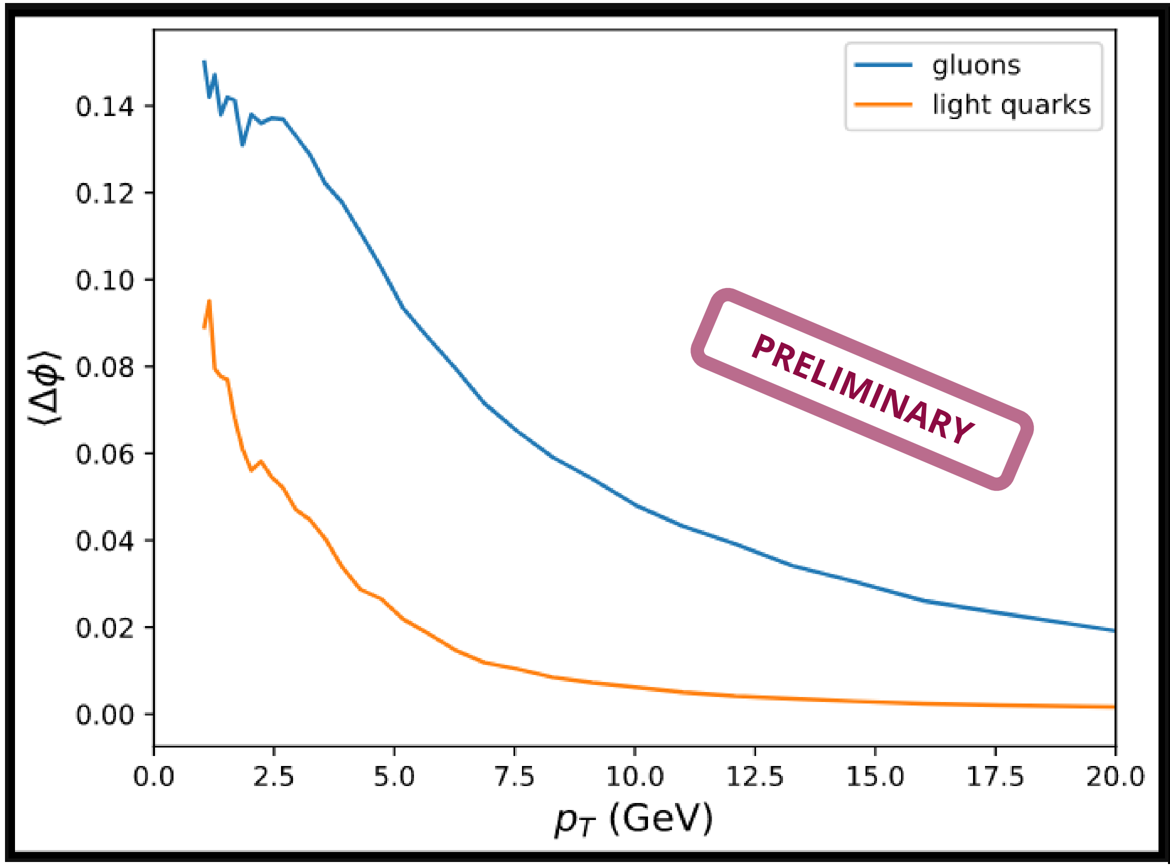
Effect Strengths – Flow & Flow-Grad Drift

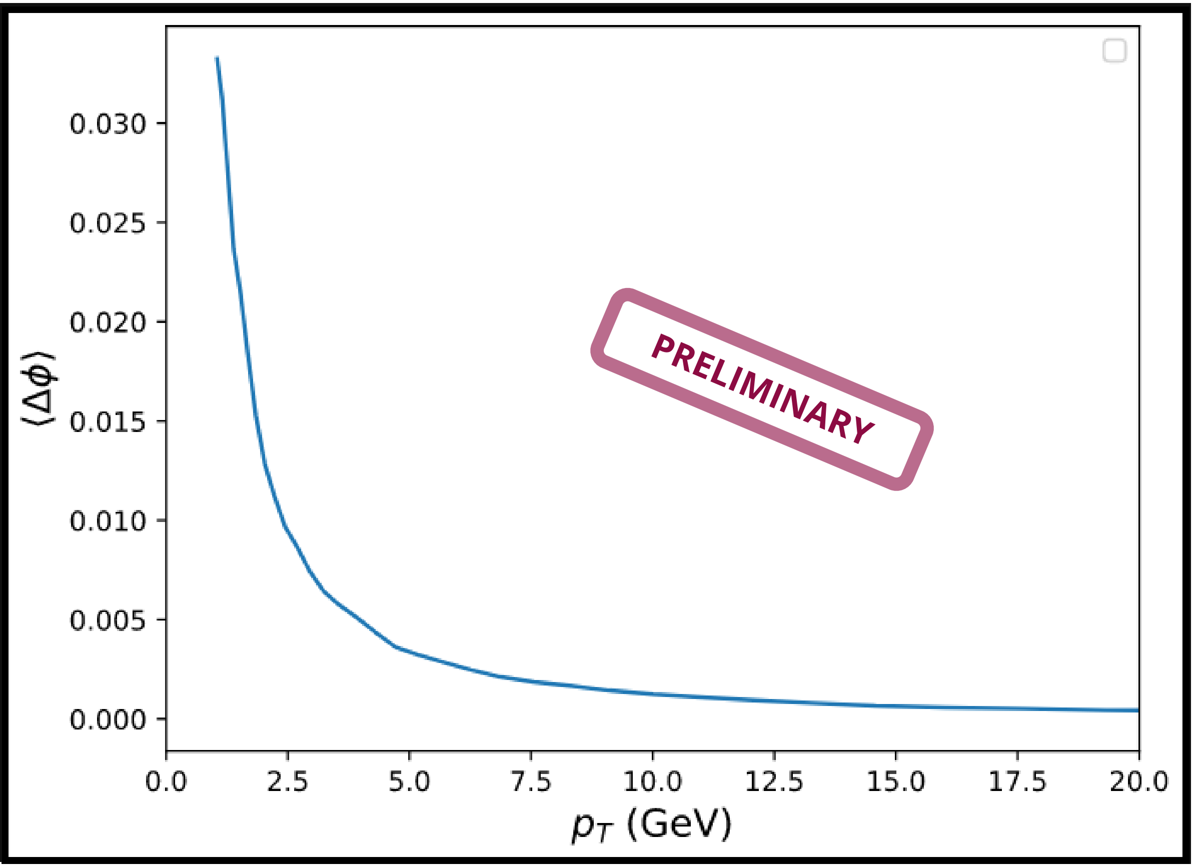


- No other perturbative simulation for comparison
- We will evaluate when we talk v_2 !

Note y-axes scale difference left to right panel

Typical Deflections

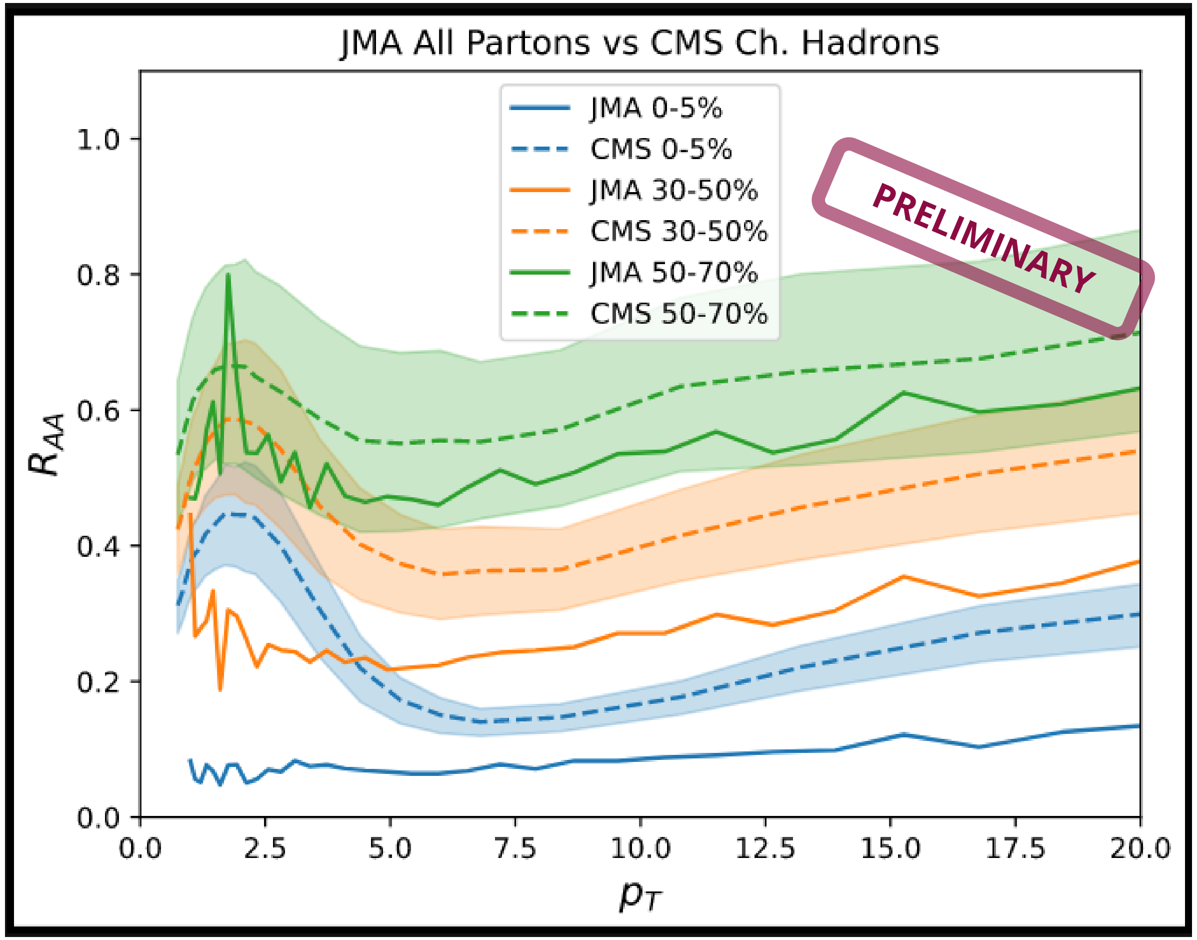




- Some deflections are experimentally measurable! (0.1 rad ~= 5.7 deg)
  - Anecdotally: experimentalists have said 5 deg is measureable
  - Note: Deflections binned in *partonic* pT
- **Large numbers of hard partons experience measurable drift deflection!**
- Fragmentation seems to wash out much of the effect

R_{AA} Insights - Partonic

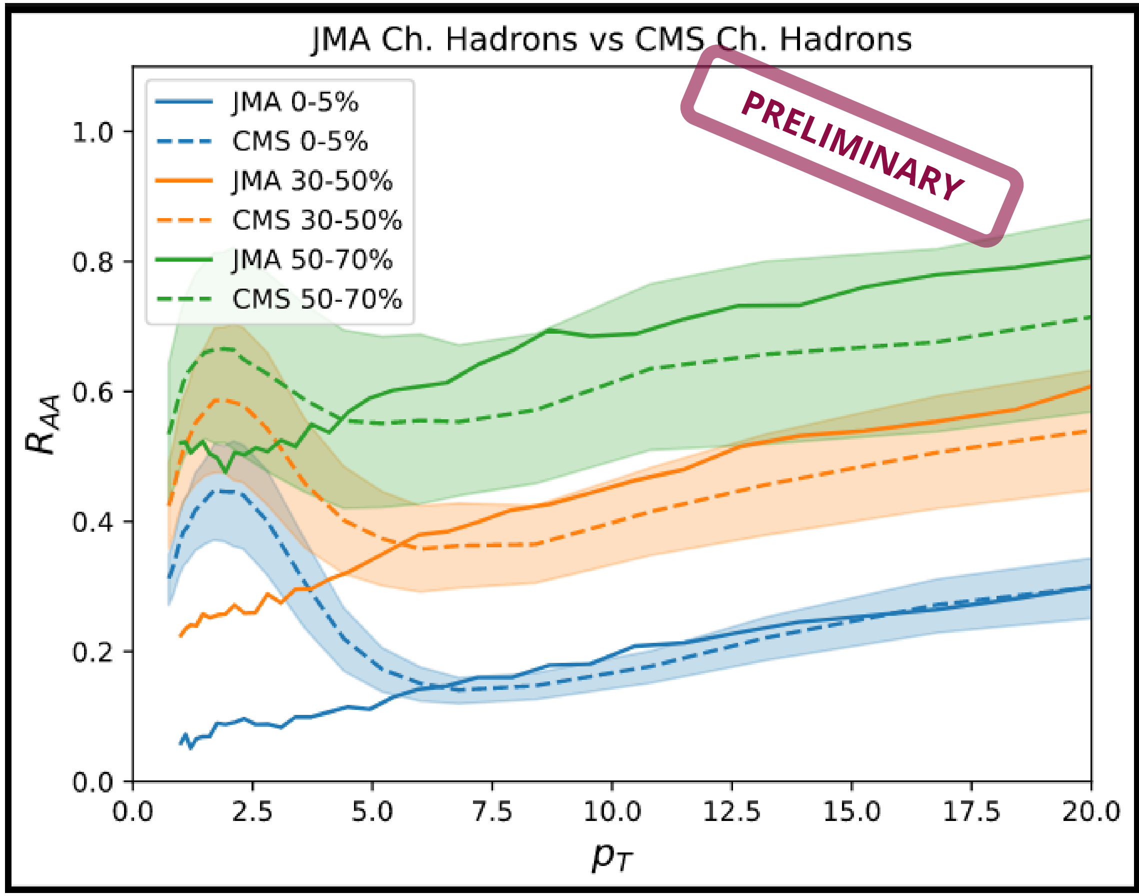
- General behavior in the right ballpark
  - Scale of suppression reduced after fragmentation
- “Low end” of hard pT R_AA structure
  - Probably some sort of nonperturbative / other physics driving R_AA
  - Small upturn due to CNM effects



CMS: https://doi.org/10.17182/hepdata.77101.v2

R_{AA} Insights - Hadronic

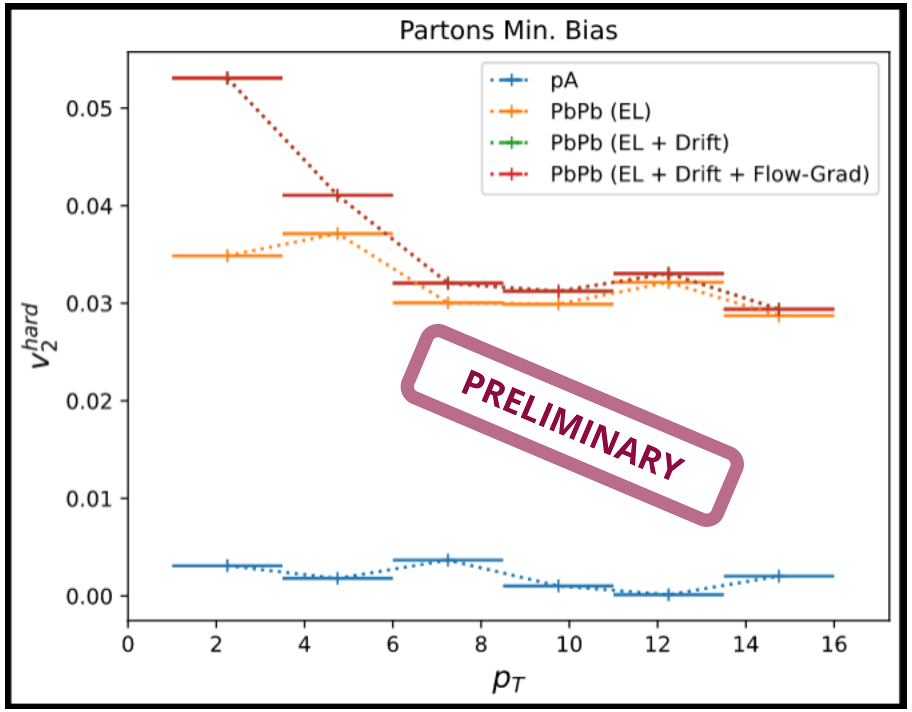
- Coupling g=2 under-predicts suppression
  - Coupling scans in progress, g=2.2 eyeballed
- Centrality scaling accurate-ish, but seems to get worse in peripheral bins

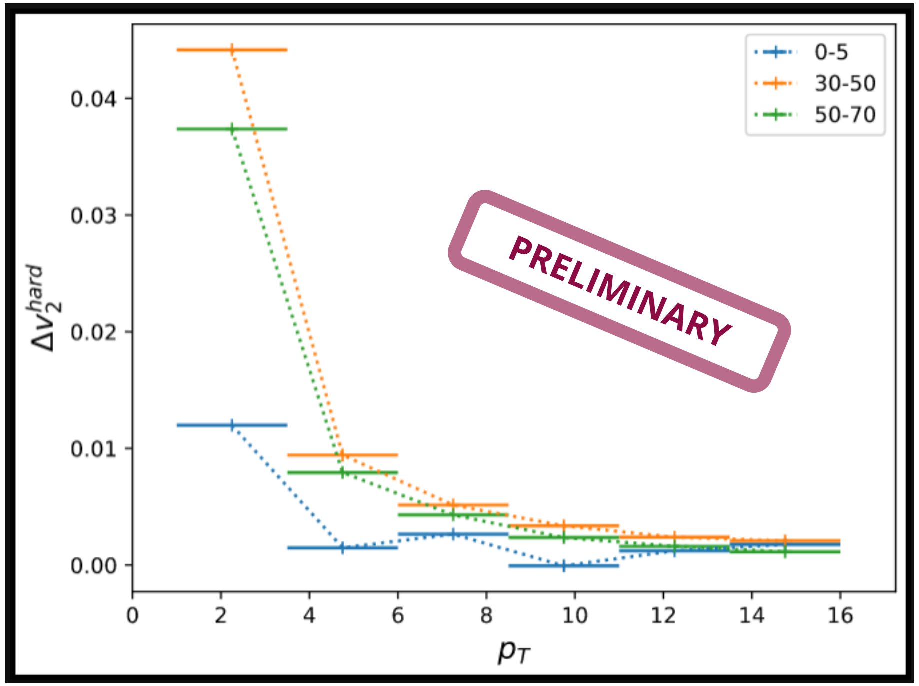


CMS: https://doi.org/10.17182/hepdata.77101.v2

v_2 Insights - Partonic

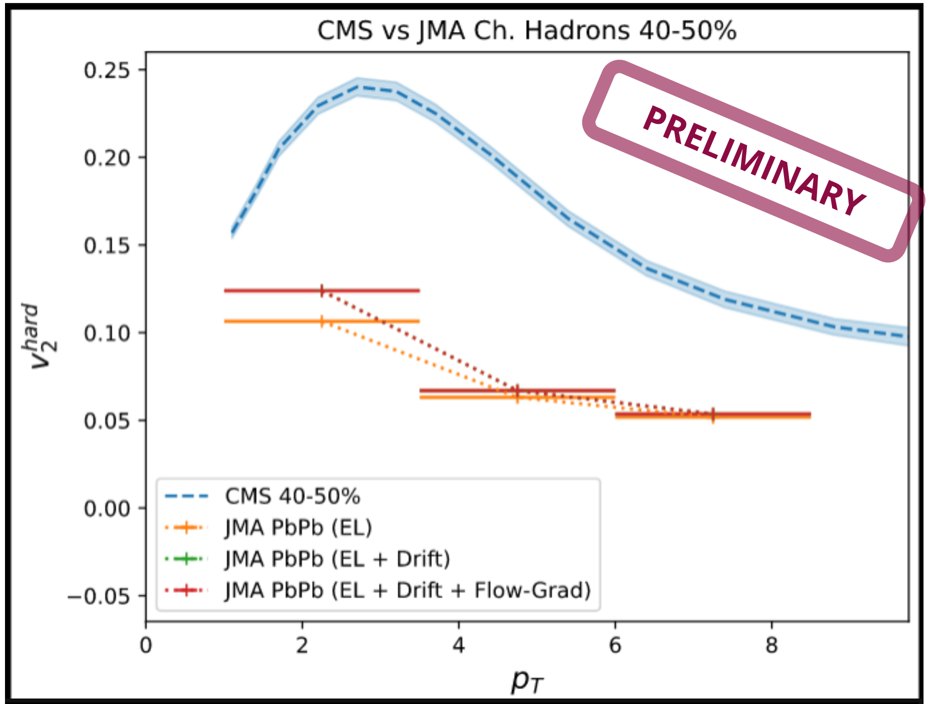
- Elliptic modulation of hard partons is clear and systematic at low pT
- Drift effects show nontrivial enhancement over energy loss alone in partonic distribution
- Absolute scale uncertain…
  - Needs convergence testing
  - Affected by fragmentation, CNM, etc.

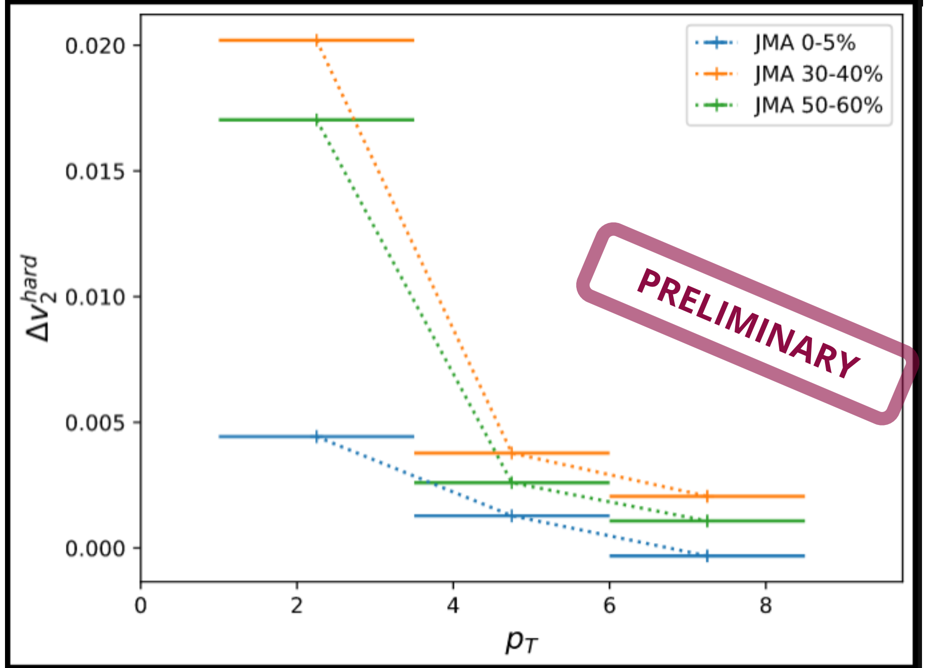




v_2 Insights - Hadronic

- Drift enhancement of elliptic flow of charged hadrons is still clear and systematic at low pT
  - Scale dependent on FF choice, coupling, & sensitive to variation with MC sampling changes
  - Systematics robust & similar to expected effects
- Secretly, this is not the correct quantity to compare to data...

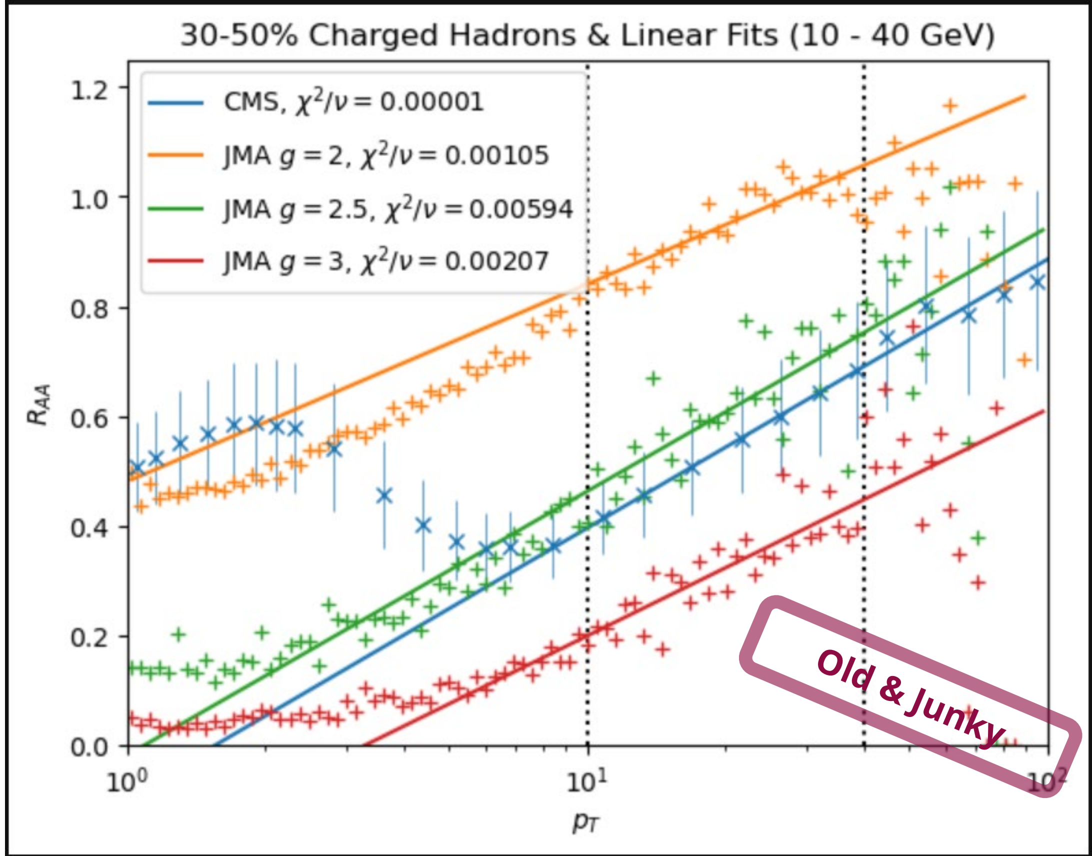


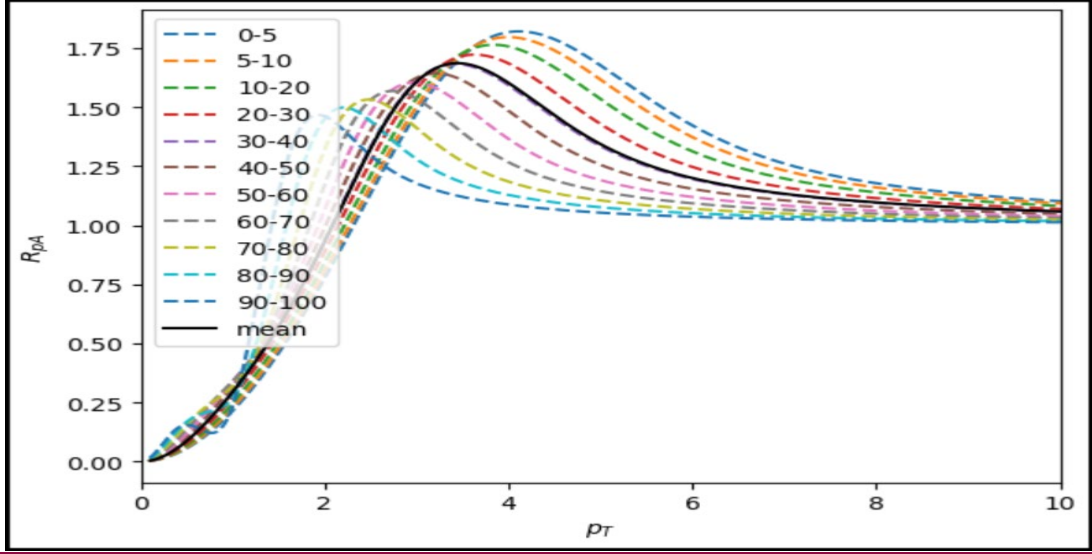


CMS: https://doi.org/10.17182/hepdata.77603

Future: Parameter Fits

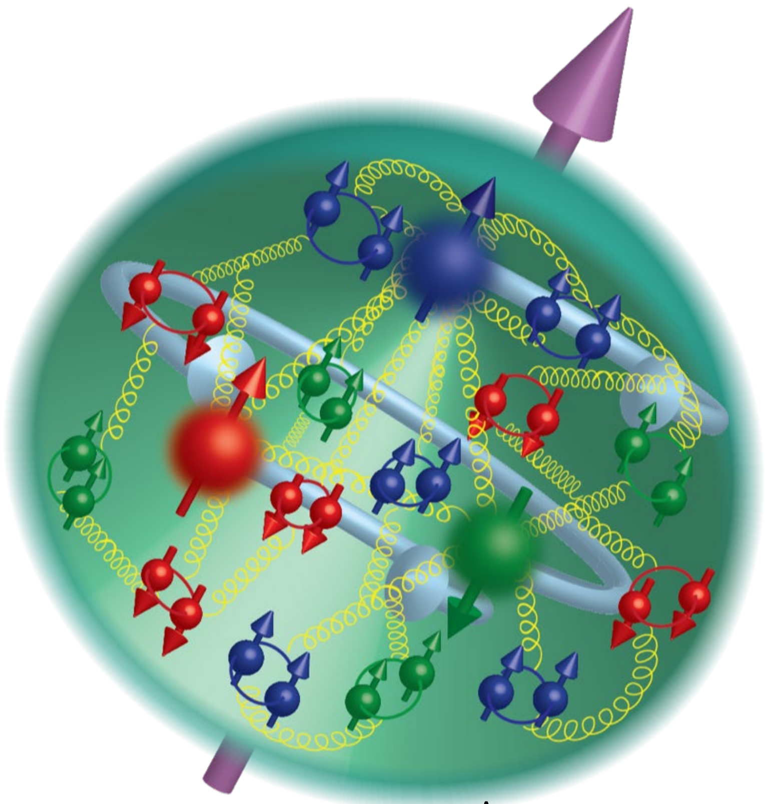
- g from high pt
  - Min-bias & max-drift centralities
  - log fit of high pt region
- CNM params from low pt
  - Fixed coupling…
  - Bayesian inference against R_{AA} and v_2 data





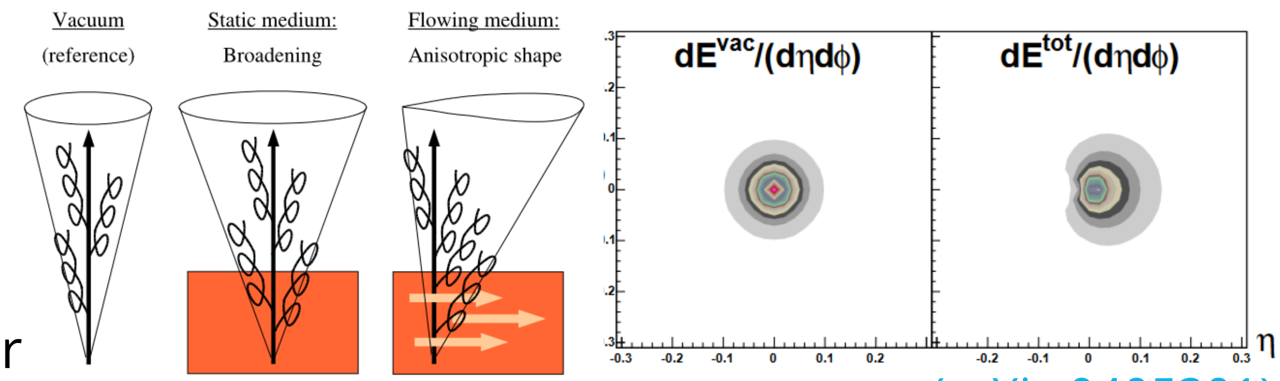
Future: Competing Timescales & Hadron Gas

- Jets see substantial pathlengths in hadron gas phase
- Plan to form theory of parton-hadron interaction via Parton Distribution Functions (PDFs) for hadrons
  - Potential parton-hadron drift-like interactions
- Possible to have post-fragmentation deflection
  - Potential hadron-hadron drift-like interactions



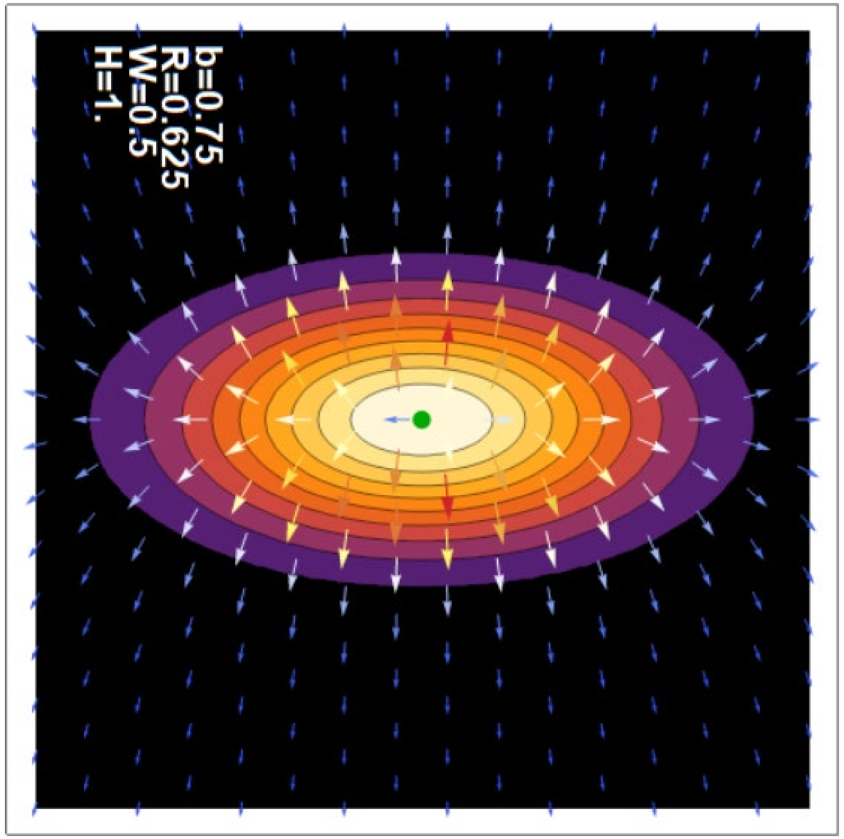
Argonne National Lab

Future:
New Observables



(arXiv:0405301)

- "JMA" machinery is robust
- Drift likely has implications for many other observables
  - Jet shapes
    - See "Jet Drift-Like" effect from Lorentz Boost with medium (arXiv:0405301)
  - **Jet wake asymmetries!**
    - E3C wake imaging could see asymmetric wake!
    - Wake may couple to parton level – larger drift
  - **Elliptic modulation correlators?**



Other ideas?

The Bottom Line:

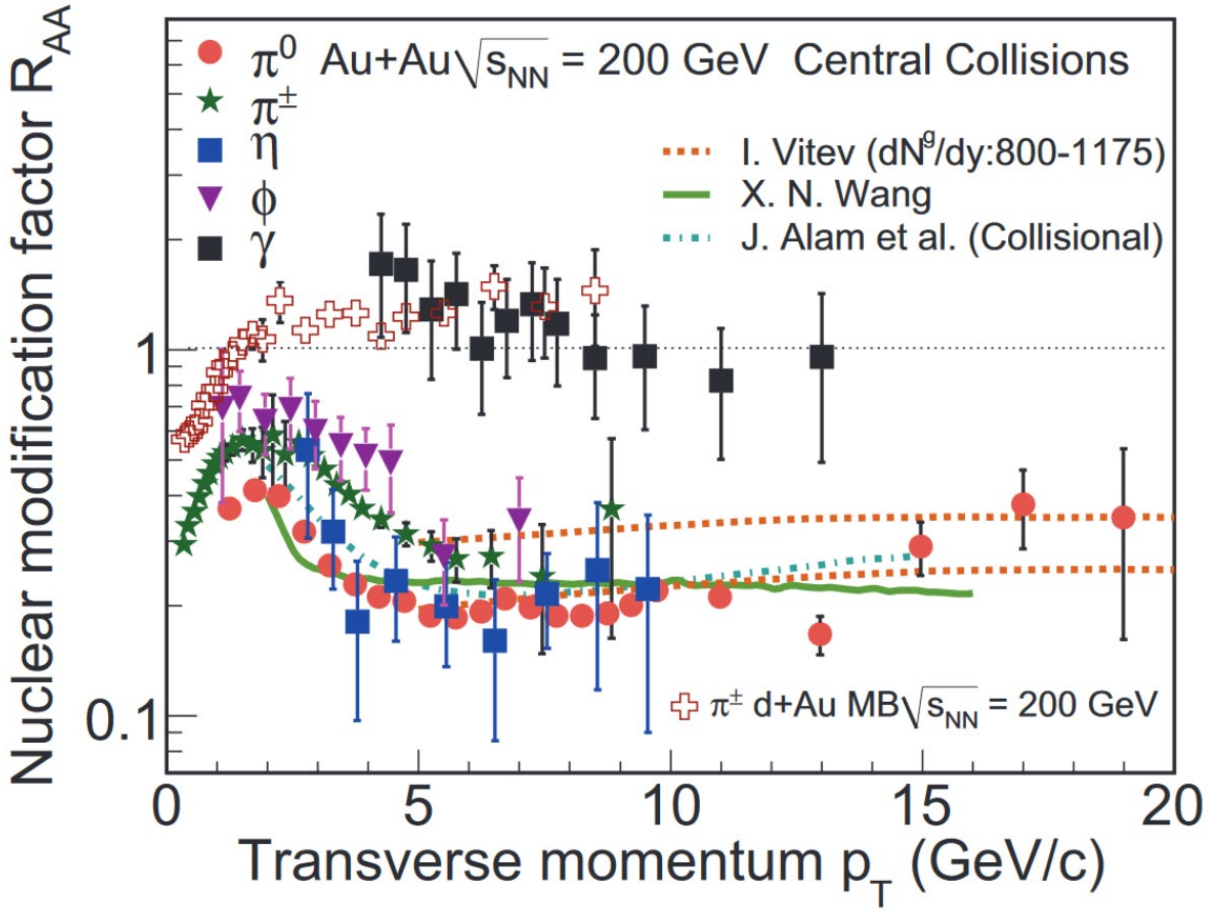
"Jet Drift" (Asymmetric Broadening) enhances hard particle v_2 for $p_T < 10$ GeV!

Hot Takes!

Questions!

Ideas!

Discriminating Power is Very Limited



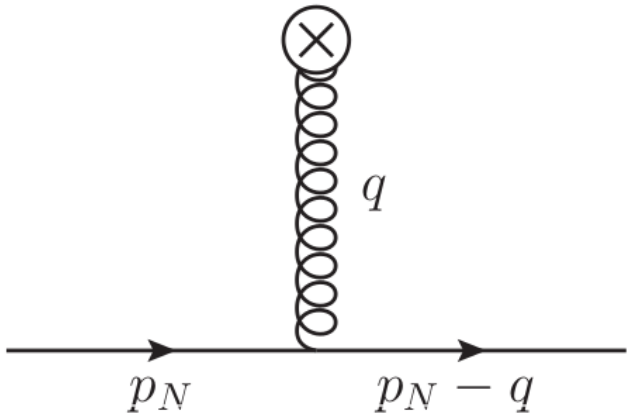
arXiv:1207.7028

What's wrong?

Observables are essentially model agnostic!

- R_{AA} – Nuclear modification factor
  - Can be fit with many competing models
- v_n^{hard} – Flow harmonics
  - Easy to fudge by scaling quenching
- Acoplanarities
  - Excessive background noise
  - Often impossible to even distinguish broadening from narrowing!

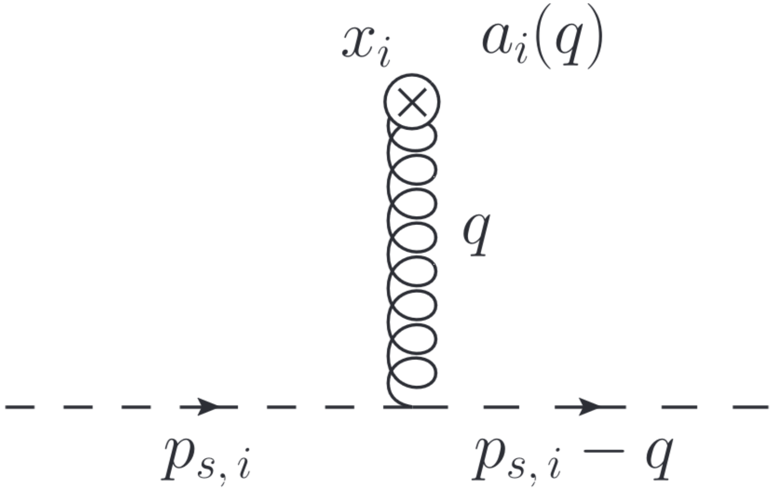
Medium Gluon Field Potentials



$$a_i^{\mu\, a}(q) = g^{\mu +}(t^a)_i \; [2\pi\delta(q^+)] \; \left[\frac{-g_{eff}}{q_T^2}\right]$$

Eikonal delta function (antiparallel)

v(q) Static scattering centers



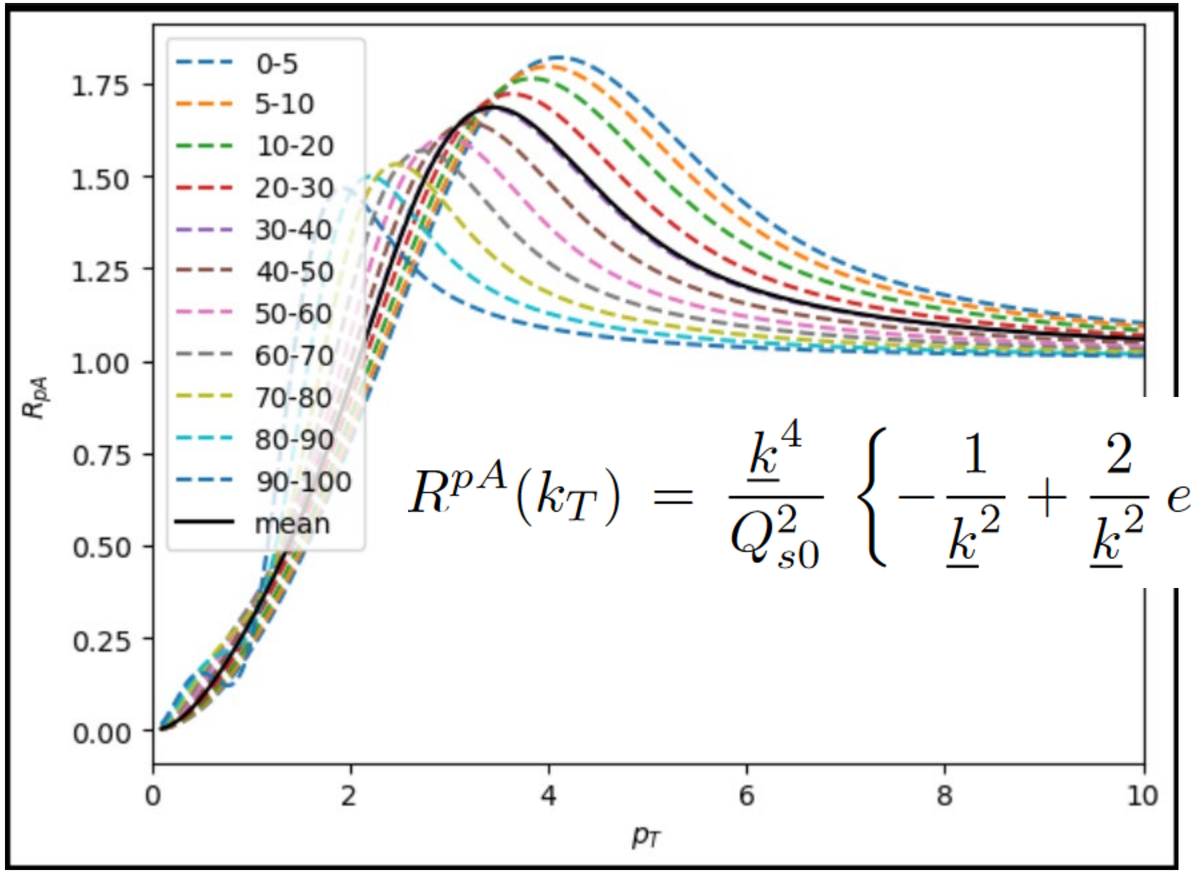
$$g\, a_i^{\mu a}(q) = t_i^a\, u_i^\mu\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \boldsymbol{u}_i \cdot \boldsymbol{q}\right)$$

Quark moves with medium

$$v_i(q) \equiv v_i\left(\boldsymbol{q}^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2\right) \equiv \frac{-g^2}{\boldsymbol{q}^2 + \mu_i^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2 - i\epsilon}$$

v(q) Dynamic directional scattering centers

Jet Spectrum & Cronin Effect

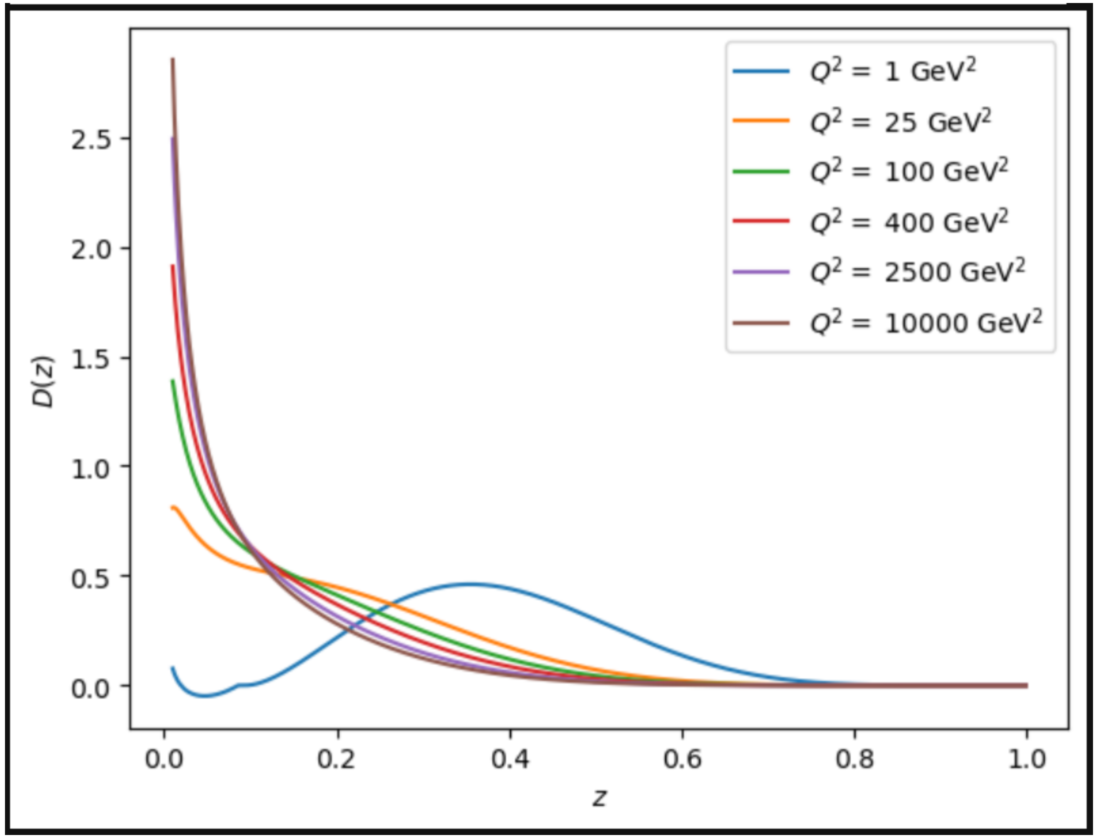


- RpA computed from saturation theory
  - [(arXiv: 0307037)]
  - Two parameter, flexible form

$$R^{pA}(k_T) = \frac{\underline{k}^4}{Q_{s0}^2}\left\{-\frac{1}{\underline{k}^2} + \frac{2}{\underline{k}^2}\, e^{-\underline{k}^2/Q_{s0}^2} + \frac{1}{Q_{s0}^2}\, e^{-\underline{k}^2/Q_{s0}^2}\left[\ln \frac{Q_{s0}^4}{4\,\Lambda^2 \underline{k}^2} + \mathrm{Ei}\left(\frac{\underline{k}^2}{Q_{s0}^2}\right)\right]\right\}$$

- Qs0 saturation scale
- Lambda – infrared cutoff

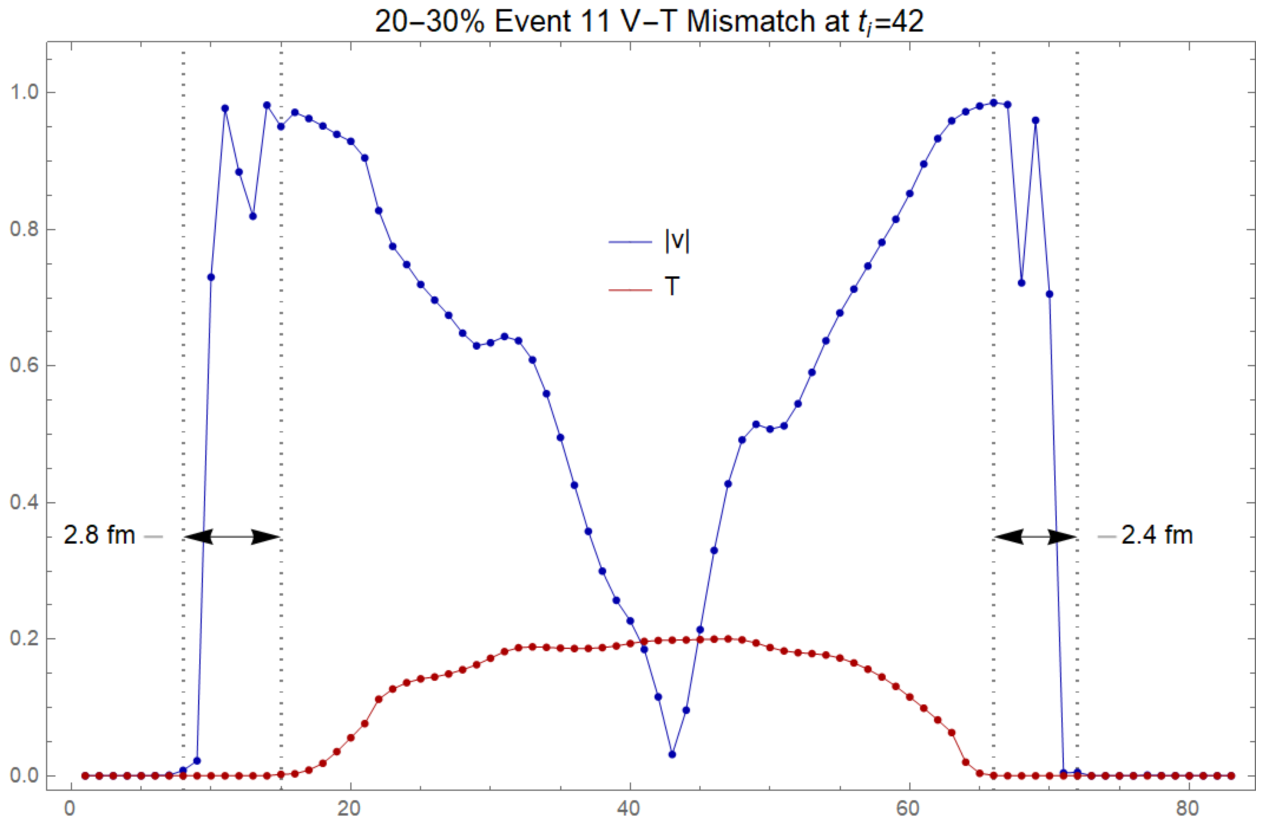
Fragmentation



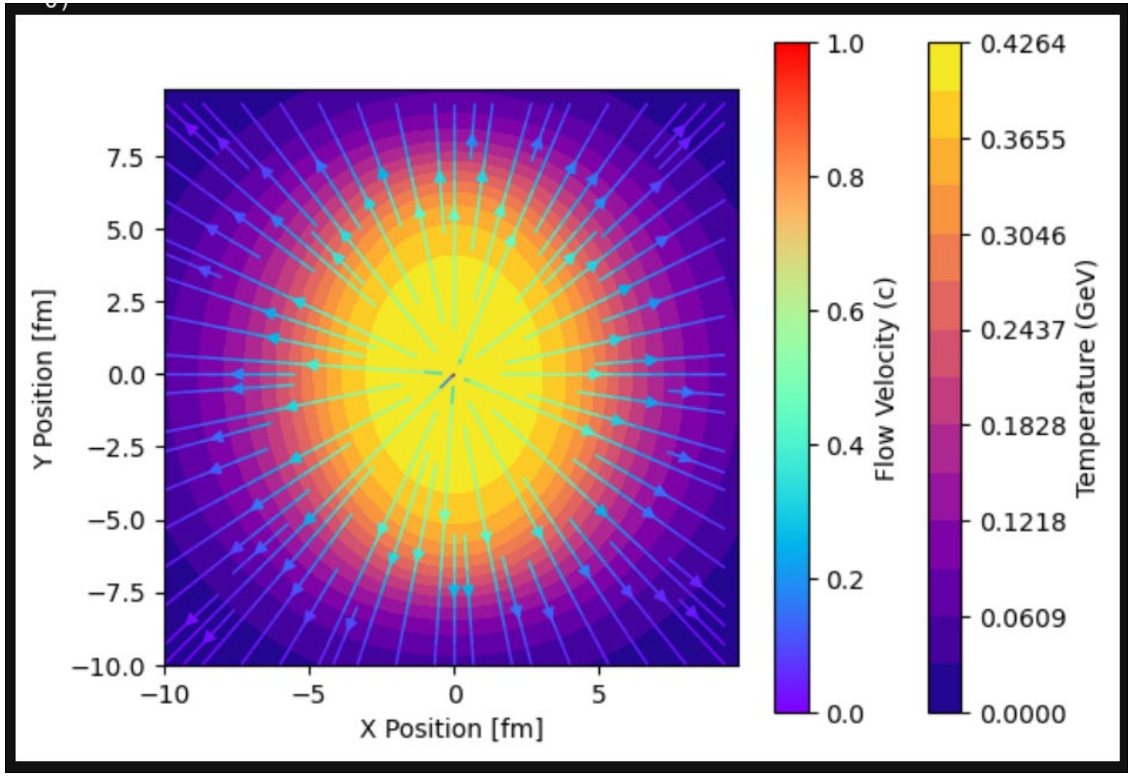
- Fragmentation functions describe probability distribution for hadron momentum, given parton momentum
- "JAM20-SIDIS_FF_pion_nlo"
  - (arXiv: 2101.04664)
- Simple sampling… Complicated implications for Drift
  - Fragmentation downshifts p_T of hard particles
  - Shifts domain of strong drift even farther down

Questions Raised by Hyro

- "Velocity spill" may be reflective of problems with event-edge velocity accuracy
  - Most important region for drift!



Future: Simple Models



E.G. Woods-Saxon Density
Glauber model

$$T_A(\vec{x}_\perp) = \int dz \rho(\vec{r}) = \int dz \frac{\rho_0}{1 + \exp\left(\frac{\vec{r}-R}{a}\right)}$$

$$n_{bc}(\vec{x}_\perp) \propto T_A(\vec{x}_\perp) T_A(\vec{x}_\perp) \propto [S(\vec{x}_\perp)]^2 \propto [T(\vec{x}_\perp)]^6$$

$$T(\vec{x}_\perp) \propto \left(\int dz \rho(\vec{r} + \vec{b}/2) \int dz \rho(\vec{r} - \vec{b}/2) \right)^{1/6}$$

- Step-wise build-up of realistic optical Glauber models
- Gives insights into parts of medium model that affect drift & EL
- Time consuming…

NM STATE

Bread & Butter Jet Observables in QGP

- R_{AA} – Nuclear modification factor
  - Measurement of jet energy loss (quenching)

Ratio of yield in AA collisions to scaled yield of pp collisions:
"Jet Suppression via QGP Effects"

$$R_{AA} = \frac{\frac{d\sigma^{AA}}{dp_T}}{\left(\frac{d\sigma^{pp}}{dp_T}\right) N_{coll}}$$

- v_n^{hard} – Flow harmonics
  - Measurement of event geometry coupling

$$v_n e^{in\Psi_n}(p_T, \eta) \equiv \frac{\int_0^{2\pi} d\phi \frac{dN}{d\phi dp_T d\eta} e^{in\phi}}{\int_0^{2\pi} d\phi \frac{dN}{d\phi dp_T d\eta}}$$

Essentially just Fourier harmonics of the azimuthal distribution of jets:
"Shape of jet azimuthal distribution"

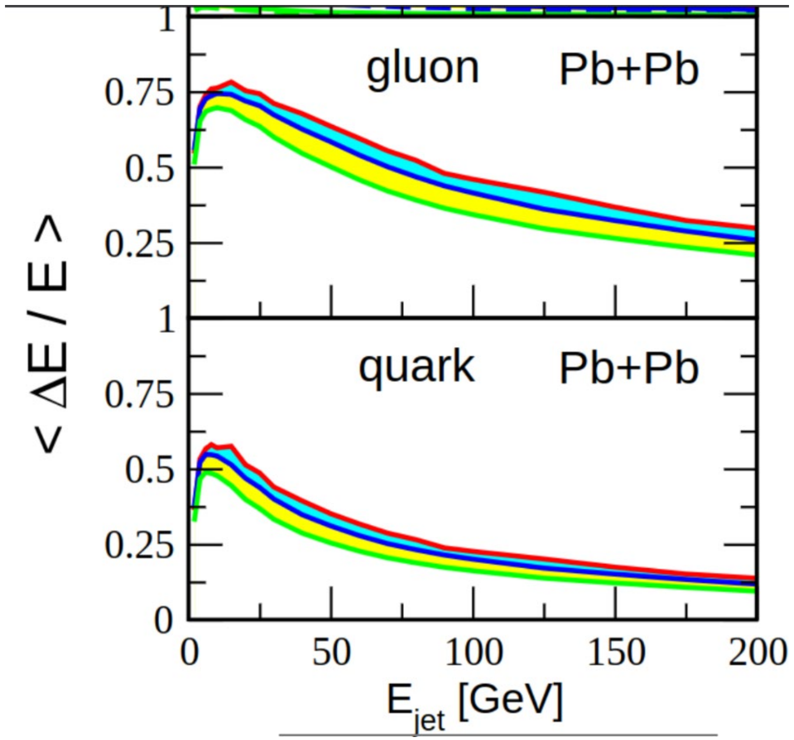
- Acoplanarities
  - Measurement of broadening effects

"Relative jet cone broadening measures"

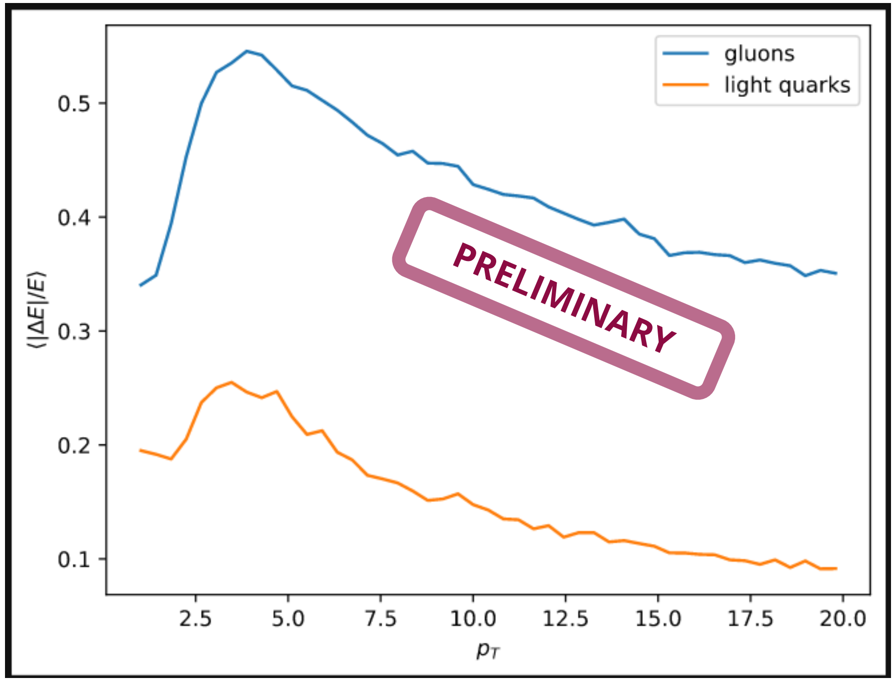
Not relevant here...

Future: Numerical Energy Loss & Drift

- Currently using analytic approximations for average
- Numerical calculations may change the proportionality of drift to EL strength
  - Distinct from coupling shift
- Analytic approximations do not predict identical mean strength of EL



arXiv:0603010



Elliptic modulation vs v_2

- Particles are correlated
  - Dijet events
- Nontrivial modification to v_2 as measured in experiment
- Mixing of hard and soft v_2
- Possible enhancement to v_2

$$v_n e^{in\Psi_n}(p_T,\eta) \equiv \frac{\int_0^{2\pi} d\phi \frac{dN}{d\phi dp_T d\eta} e^{in\phi}}{\int_0^{2\pi} d\phi \frac{dN}{d\phi dp_T d\eta}}$$

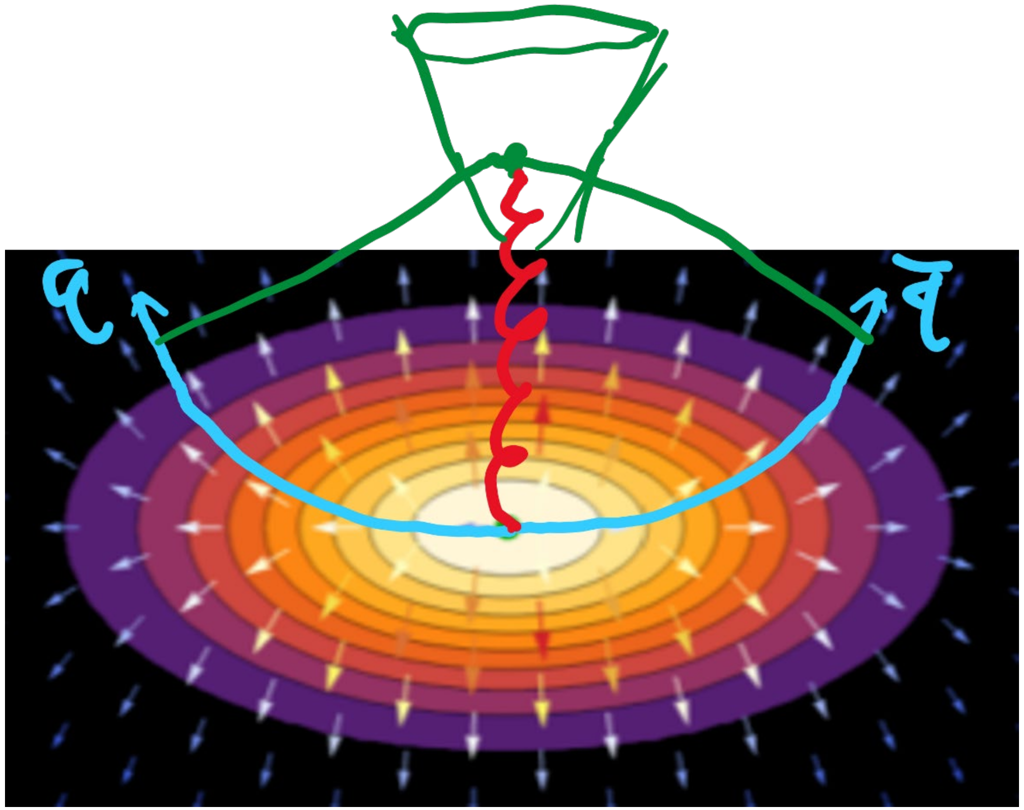
$$\frac{dN_{\text{pairs}}}{d^3p^a d^3p^b} = \frac{dN}{d^3p^a}\frac{dN}{d^3p^b} + \delta_2(p^a,p^b)$$

$$\begin{aligned} v_n\{2\}(p_T,\eta) &\equiv \frac{\langle V_{n\Delta}(p_T,\eta,p_T^b,\eta^b)\rangle_{p_T^b,\eta^b}}{\sqrt{\langle V_{n\Delta}(p_T^a,\eta^a,p_T^b,\eta^b)\rangle_{p_T^a,\eta^a,p_T^b,\eta^b}}} \\ &= \frac{\langle v_n(p_T,\eta)\bar{v}_n \cos n(\Psi_n(p_T,\eta)-\bar{\Psi}_n)\rangle}{\sqrt{\langle \bar{v}_n^2\rangle}} + \langle \delta_{2,n}\rangle \\ &\simeq \sqrt{\langle v_n(p_T,\eta)^2\rangle}. \end{aligned}$$

ArXiv:1312.5503

Note on "Coalescence" in Fragmentation

- Many in the field believe quark "coalescence" is a source of enhanced v_2 of hard particles
- If coalescence is a significant effect, jet drift may enhance it
- No perturbative QCD model for fragmentation involving coalescence
  - Hard to treat on the same footing as our other jet effects



- Market model is "Lund String" fragmentation
- Curiosity-level tests with Pythia Lund-String fragmentation give evidence of coalescence
  - Enhanced high "z" hadrons with drift
- Plans in the works to do measurements of coalescence significance as function of $\Delta\phi_{jets}$, still not understood

Dataset Info

Quick Note on Error Assessment

- g=2.2: ~13k Events
- Event geometries oversampled by 100x hard processes
- 11 uniformly sampled angles per production point
- ~= 16M parton trajectories / case

- Error estimates have been done with jack-knife resampling
- Time consuming to compute, but shown to correlate with number of trajectories.
- Suspect with this dataset we have precision on v2 measurements of +/- < 0.25%, as compared to similarly sized result sets