Universiteit Utrecht

Energy loss models and jet measurements with ALICE

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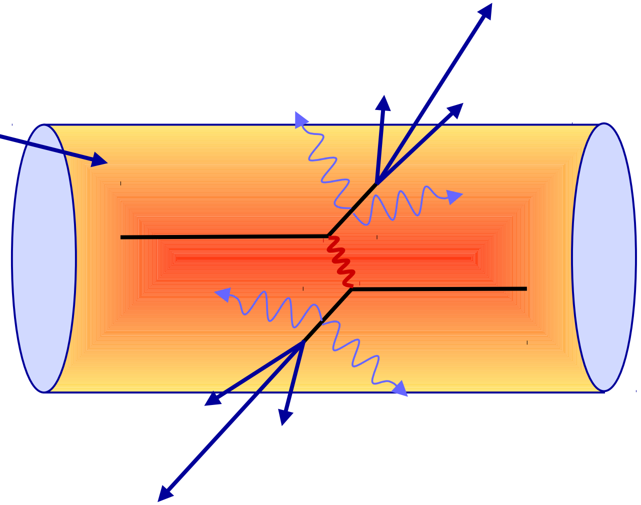
Outline

- In-medium energy loss models
  - Parton energy loss in realistic geometry
  - Systematic comparison of models
- Jets with ALICE in Pb-Pb collisions
  - Jet spectra
  - Jet suppression
  - Jet broadening

Hard Probes in QCD matter

Heavy-ion collisions produce
dense QCD matter

Dominated by soft partons
p ~ T ~ 100-300 MeV



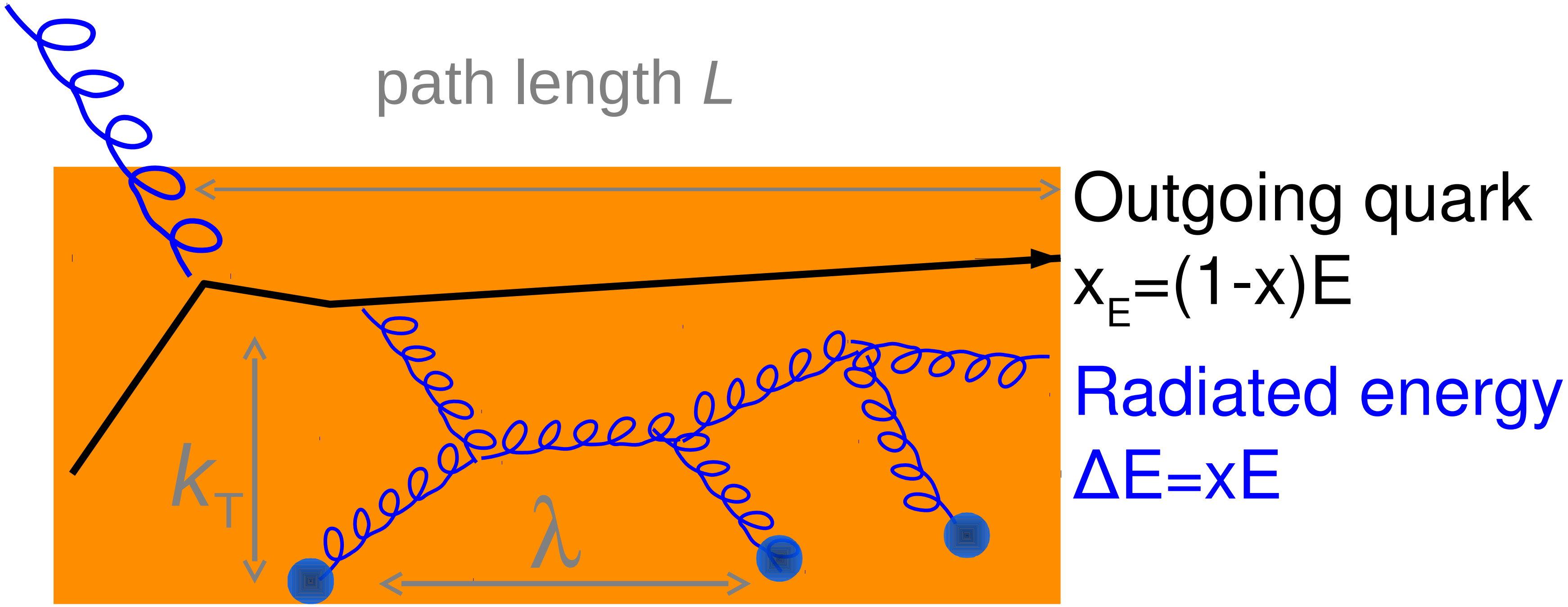
Hard-scatterings produce high energetic partons
⇒ Initial-state production known from pQCD
⇒ Probe medium through energy loss

Use hard partons to explore QCD matter

Sensitive to properties of the medium

Schematic picture of energy loss mechanism

in hot dense matter



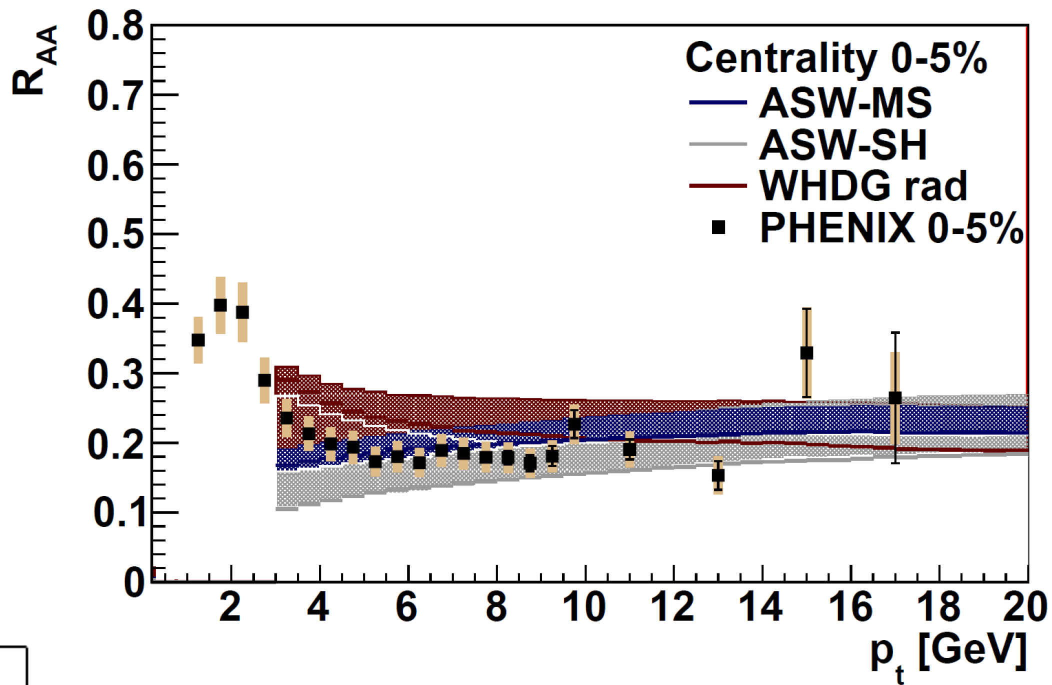
- Energy loss due to gluon bremsstrahlung in a hot dense medium
- What can we learn from Pb-Pb measurements & comparison to models?

Comparison of energy loss models with data

$R_{A\,A}$ at RHIC

$$R_{AA} = \frac{dN/dp_T\big|_{Au+Au}}{N_{coll}\ dN/dp_T\big|_{p+p}}$$

- Common input parameter for all models: medium temperature
- **All models can be fitted to $R_{A\,A}$**



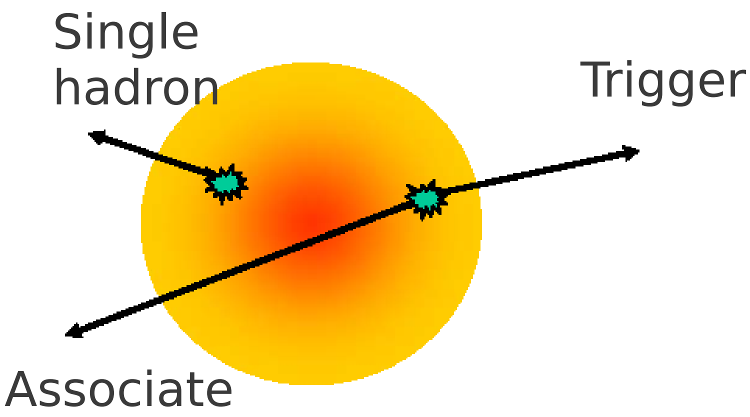
	If $\tau < \tau_0$ $\hat{q} = \hat{q}_0$	
	$\hat{q}_0$ (GeV/fm^2)	T_0 (MeV)
ASW-MS	$20.3^{+0.6}_{-5.1}$	973^{+6}_{-90}
WHDG rad	$5.7^{+0.3}_{-1.9}$	638^{+11}_{-81}
ASW-SH	$3.2^{+0.3}_{-0.3}$	524^{+17}_{-18}

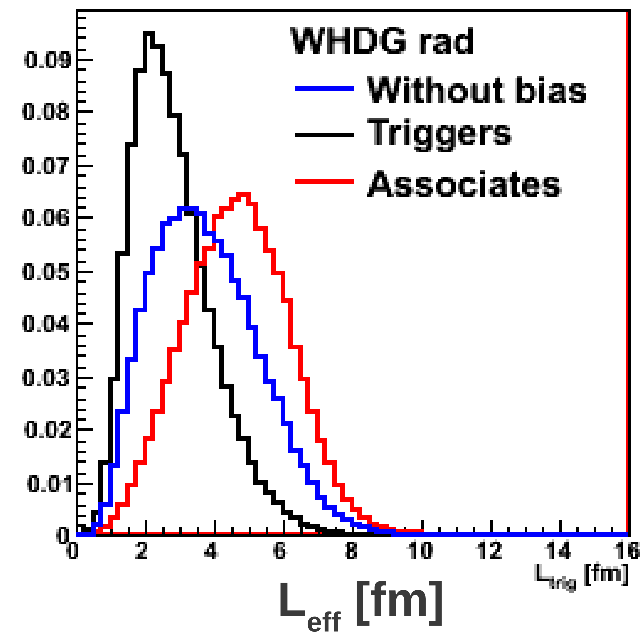
Factor 4-5 difference in estimated medium density between different models

*PHENIX data: Phys. Rev. **C77**, 064907 (2008)*

Path length bias for di-hadrons

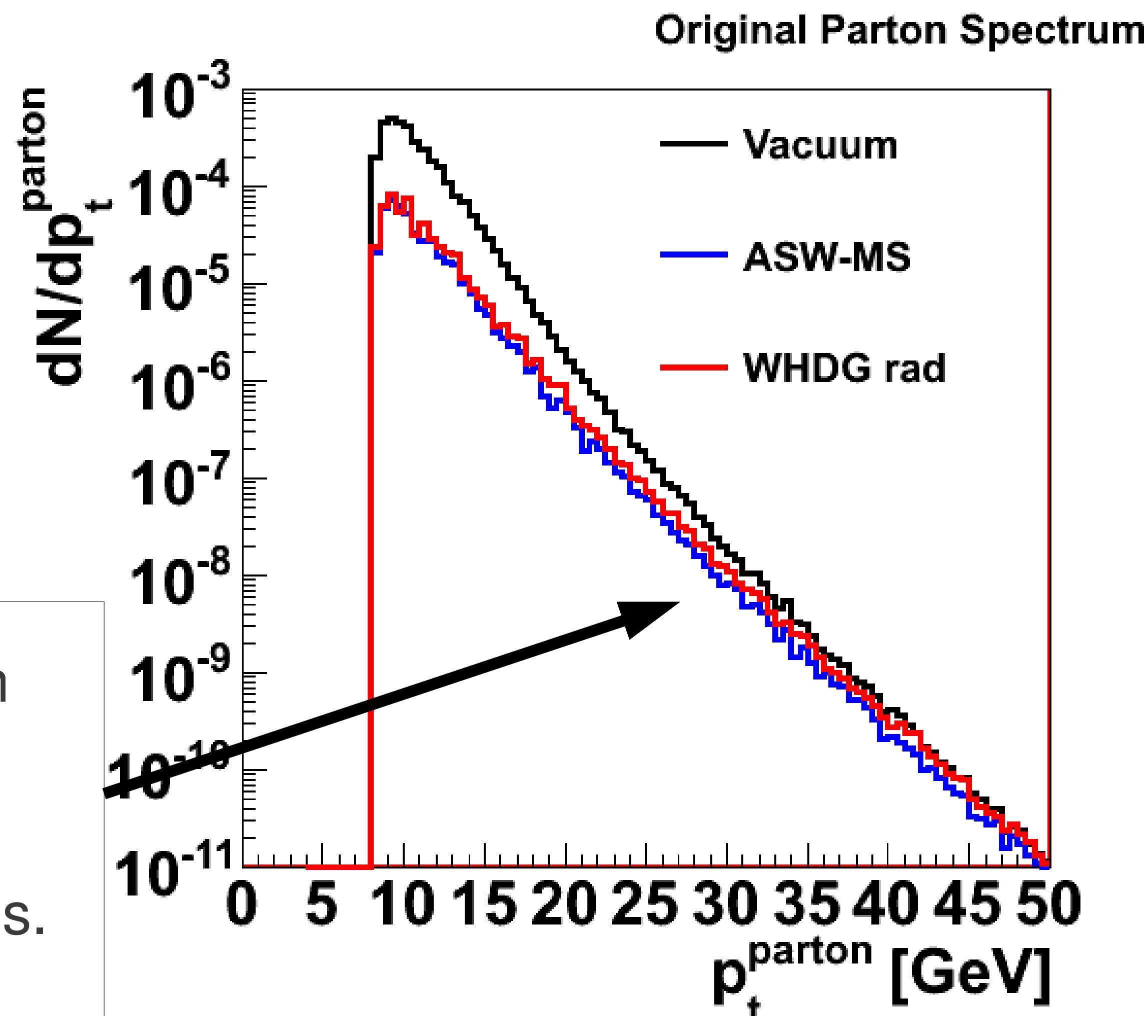
- p_T Trigger > p_T Assoc
- For R_{AA} and I_{AA} different mean path length.
- **Trigger:** bias towards smaller L
- **Associate:** bias towards longer L





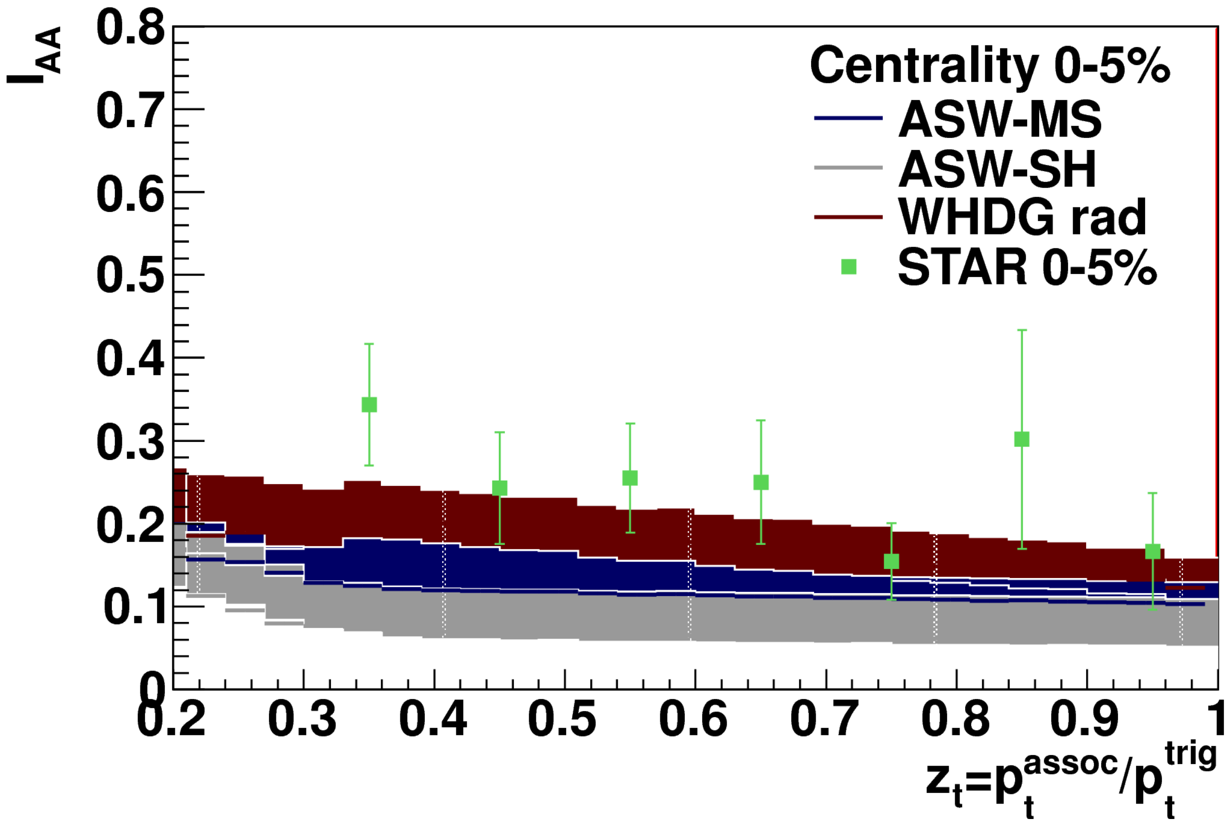
R_{AA} vs I_{AA}

- What is the difference between R_{AA} and I_{AA}?
- Different part of the parton spectrum is probed.

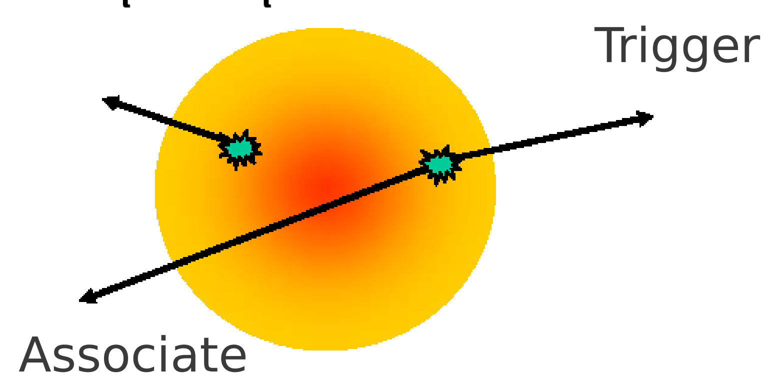


Original parton spectra resulting in hadrons with $8<p_t^{hadron}<15$ GeV for without (vacuum) and with (ASW-MS/WHDG) energy loss.

I_{AA} at RHIC



- Calibrate density using R_{AA}
- Most models underestimate I_{AA}



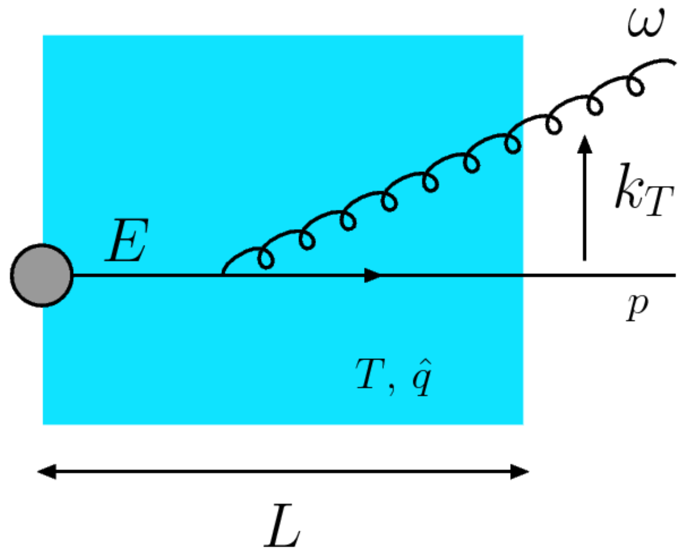
Brick Problem

Goal: understand discrepancy in estimated medium density by models

Brick Problem

TECHQM: Theory-Experiment Collaboration on Hot Quark Matter

arXiv:1106.1106



Compare energy loss models in a well-defined system:

- Fixed medium length *L* and temperature *T* (or *qhat*)
- Parton (quark) propagates through brick, E_{parton} = 10, 20 GeV

Compare outgoing radiated gluon and parton distributions

2 cases: same density, same suppression

Four formalisms

- **Hard Thermal Loops (AMY)**
  - Dynamical (HTL) medium
  - Single gluon spectrum: BDMPS-Z like path integral
  - No vacuum radiation
- **Multiple soft scattering (BDMPS-Z, ASW-MS)**
  - Static scattering centers
  - Gaussian approximation for momentum kicks
  - Full LPM interference and vacuum radiation
- **Opacity expansion ((D)GLV, ASW-SH)**
  - Static scattering centers, Yukawa potential
  - Expansion in opacity L/λ
    (N=1, interference between two centers default)
  - Interference with vacuum radiation
- **Higher Twist (Guo, Wang, Majumder)**
  - Medium characterised by higher twist matrix elements
  - Radiation kernel similar to GLV
  - Vacuum radiation in DGLAP evolution

Multiple gluon emission

Fokker-Planck
rate equations

Poisson ansatz
(independent emission)

DGLAP
evolution

Hard Probes 2010, M. van Leeuwen

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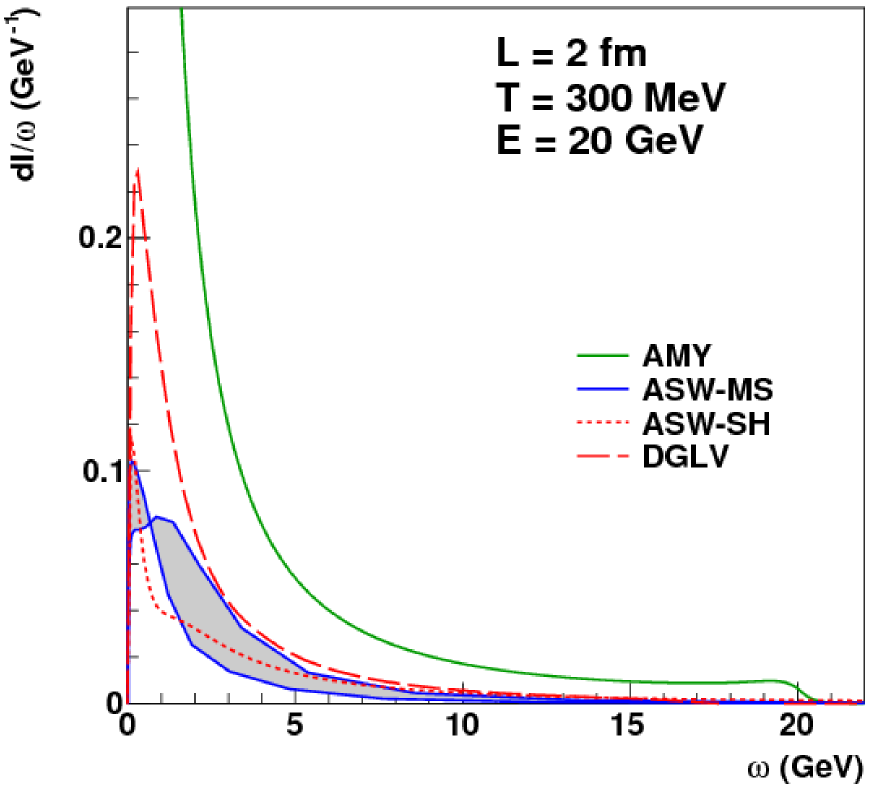
  - Radiation kernel similar to GLV
  - Vacuum radiation in DGLAP evolution

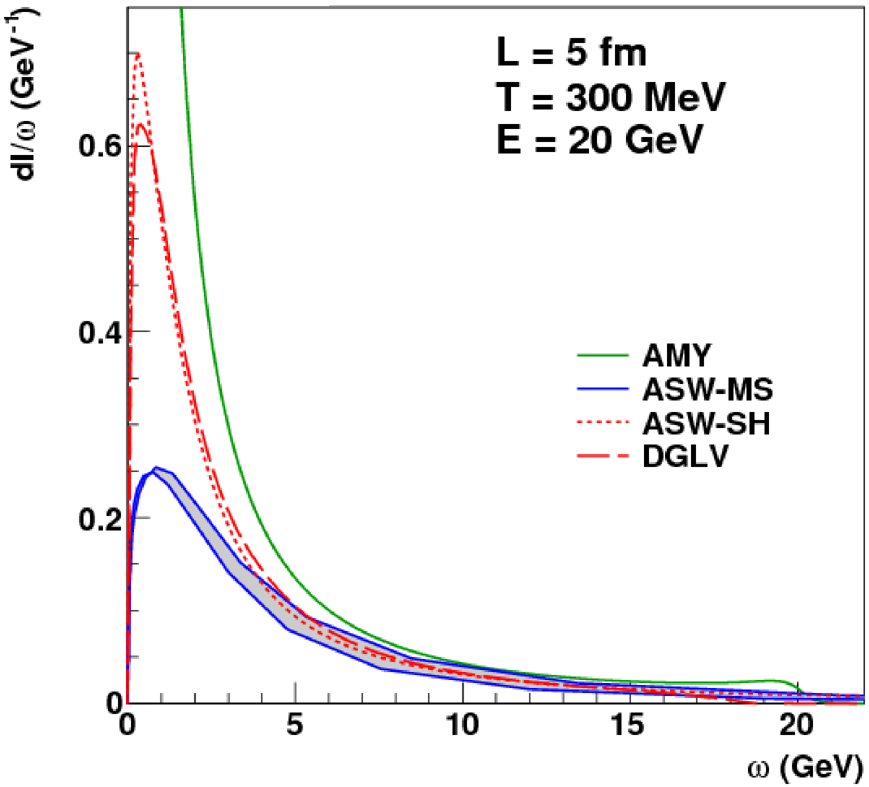
Today focus on these two models

Single gluon spectrum

fixed medium temperature

- Energy spectrum for 1 radiated gluon: for all models this is the starting point
- Clear hierarchy between models. Radiation AMY > GLV > ASW-MS
- Average number of emitted gluons: $\langle N_g \rangle = \int d\omega \frac{dI}{d\omega}.$



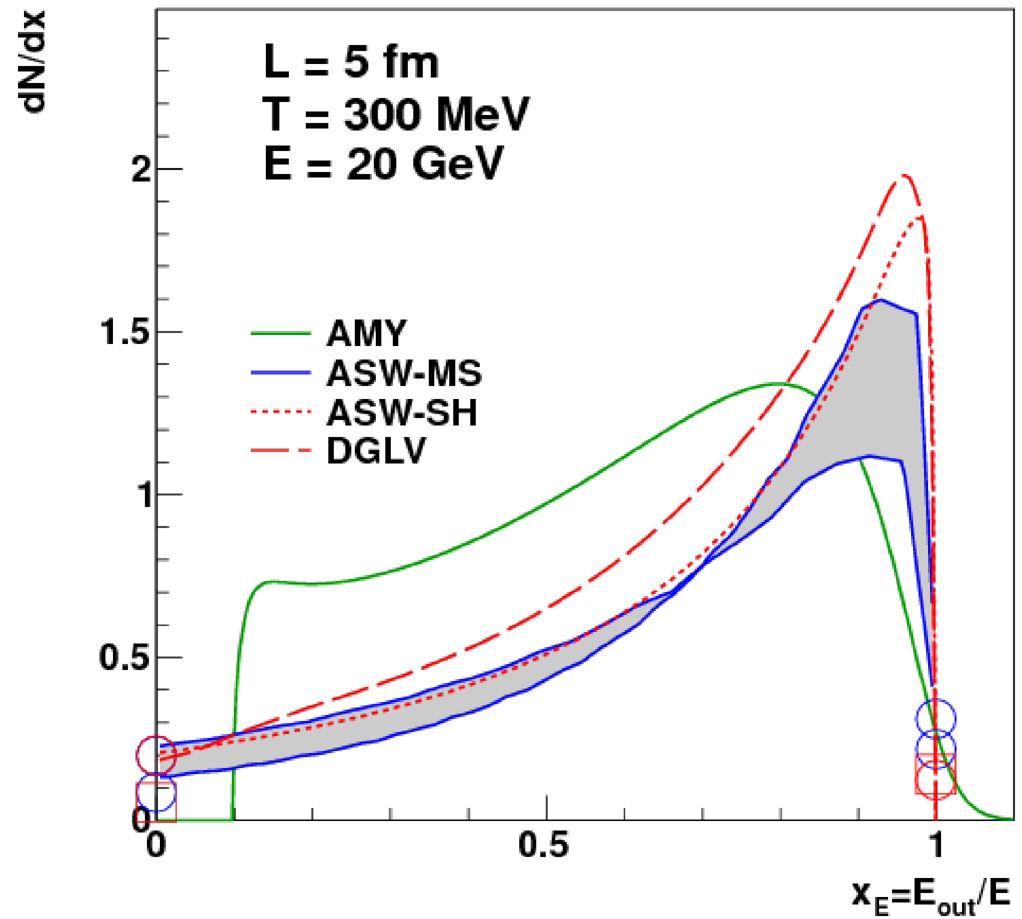


Outgoing quark spectrum

Same temperature

Energy fraction of quark after leaving the medium. Fixed length, fixed temperature for all models

- $x_E = 1 - \Delta E/E$
- $x_E = 0$: Absorbed quarks
- $x_E = 1$: No energy loss



For fixed temperature:

- <Ngluons> larger for opacity expansion than multiple soft scattering approximation
- Suppression: AMY > DGLV > ASW-MS

Suppression in a brick vs qhat

Temperature T is the common variable in all models.

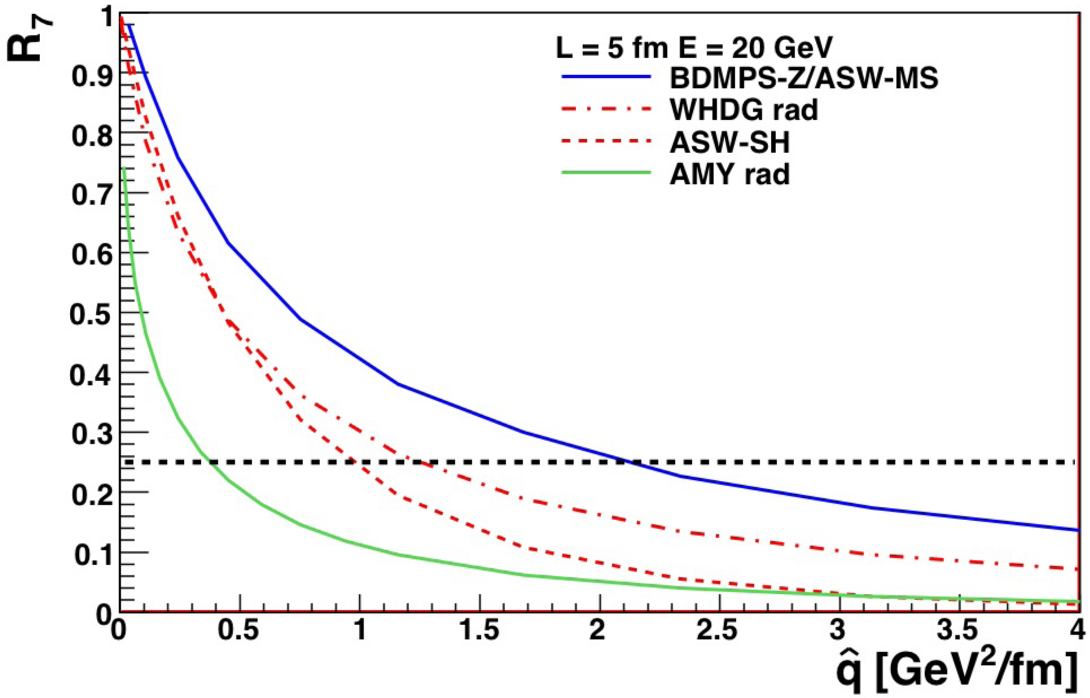
R_7 = approximation for R_{AA}

$$R_n = \int_0^1 d\epsilon (1-\epsilon)^{n-1} P(\epsilon)$$

$$\epsilon = \Delta E / E$$

$R_7 = 0.25$		T (MeV)	$\hat{q}$ (GeV^2/fm)
$L = 2$ fm	ASW–MS	1030	23.2
	WHDG	936	17.8
	ASW–SH	727	8.86
	AMY	480	2.7
$L = 5$ fm	ASW–MS	434	2.11
	WHDG	358	1.23
	ASW–SH	326	0.95
	AMY	235	0.4

Gluon gas $N_f = 0$

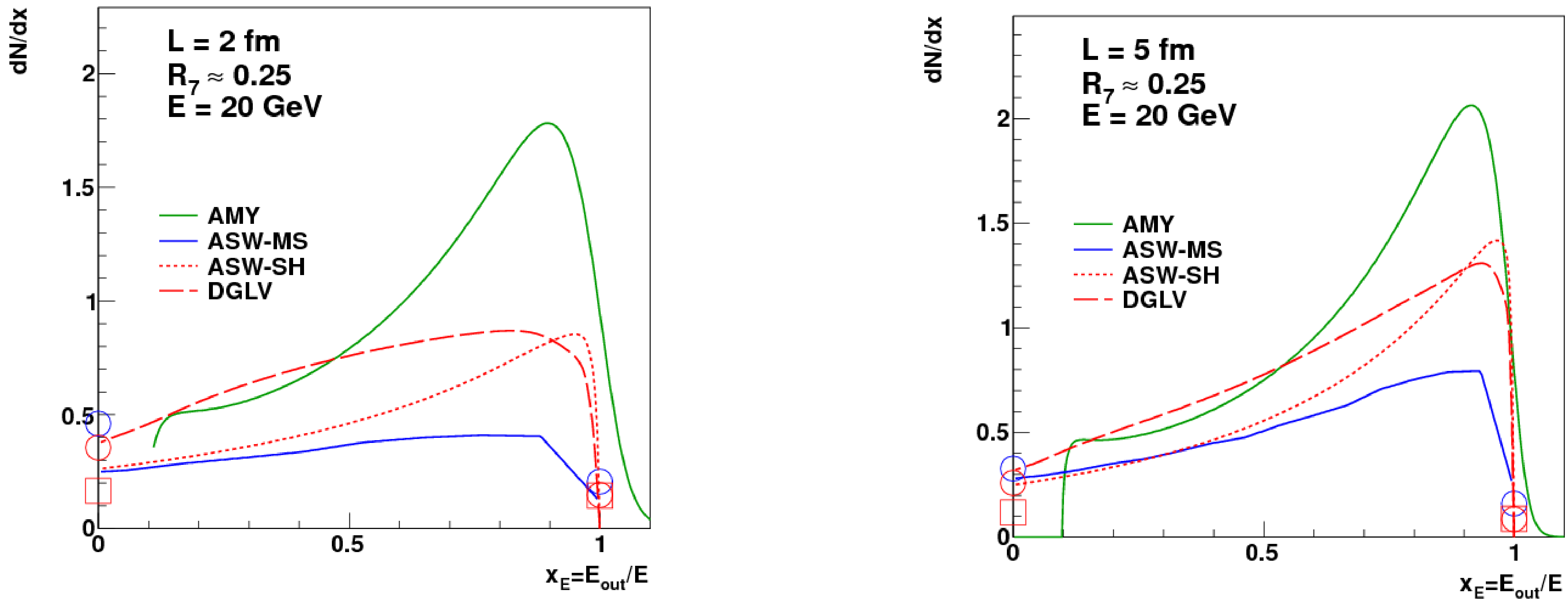


In simple geometry:

Large differences in medium density for R_7 = 0.25

Outgoing quark spectrum

Same suppression

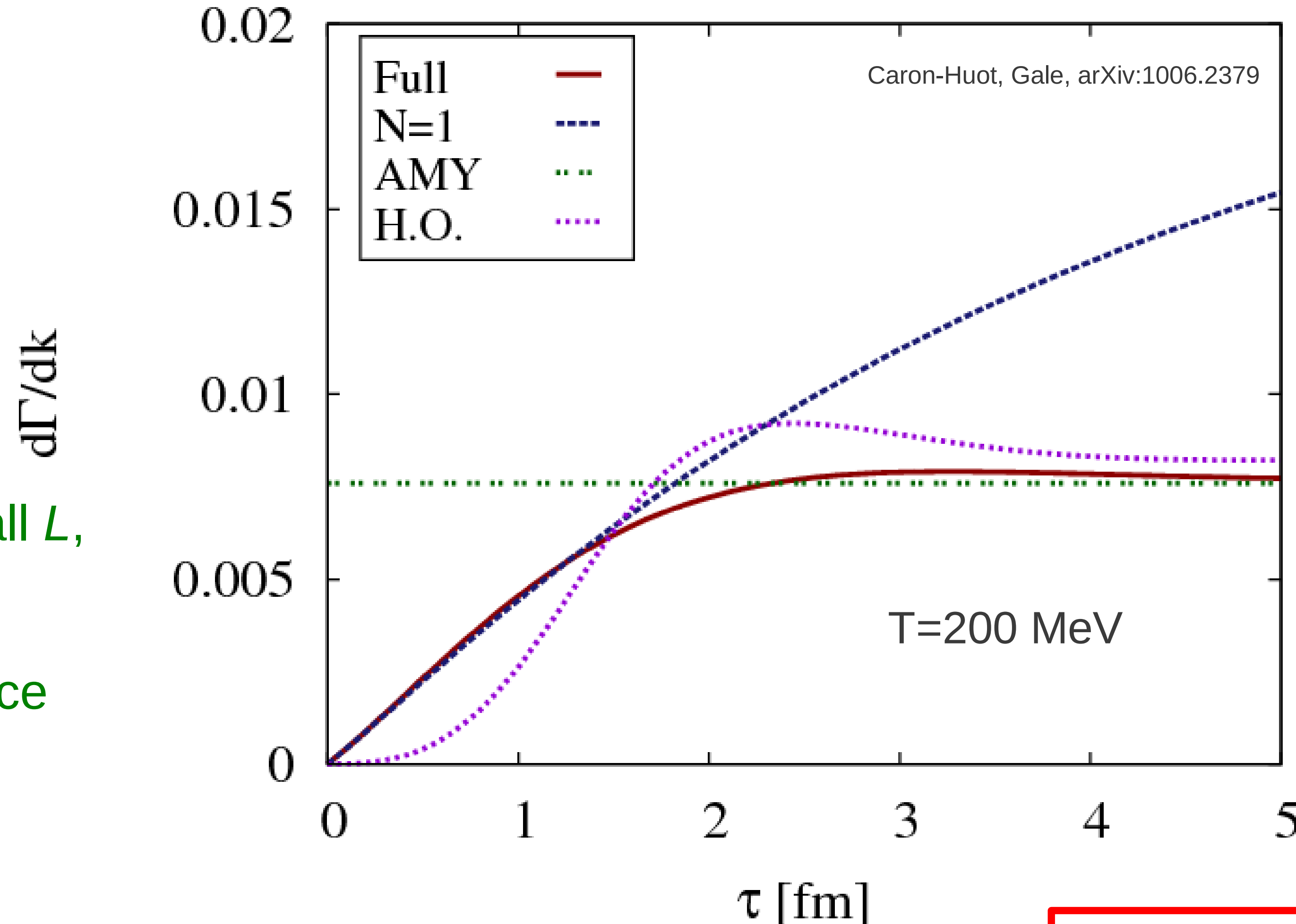


- Fixed suppression: N_{gluons} similar, but different mean energy loss

For detailed discussion, see brick report arXiv:1106.1106

Validity of models

Gluon radiation rate vs τ (=*L*)



GLV N=1
Too much radiation at large L (no interference between scattering centers)

Full = numerical solution of Zakharov path integral

AMY, small *L*, no L^2, no vacuum interference

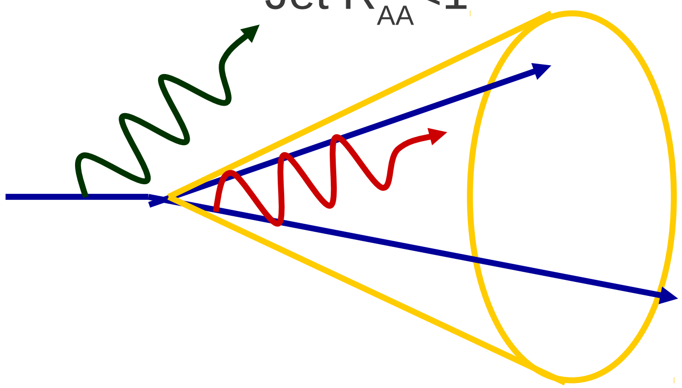
H.O = ASW/BDMPS like (harmonic oscillator)
Too little radiation at small *L*
(ignores 'hard tail' of scatt potential)

Each model is valid for different medium lengths

Jets with ALICE in Pb-Pb collisions

Jets in Heavy Ion Collisions

- Probes to study properties of medium
- Due to interaction of the jet with the medium, the jet is modified:
  Jet Quenching

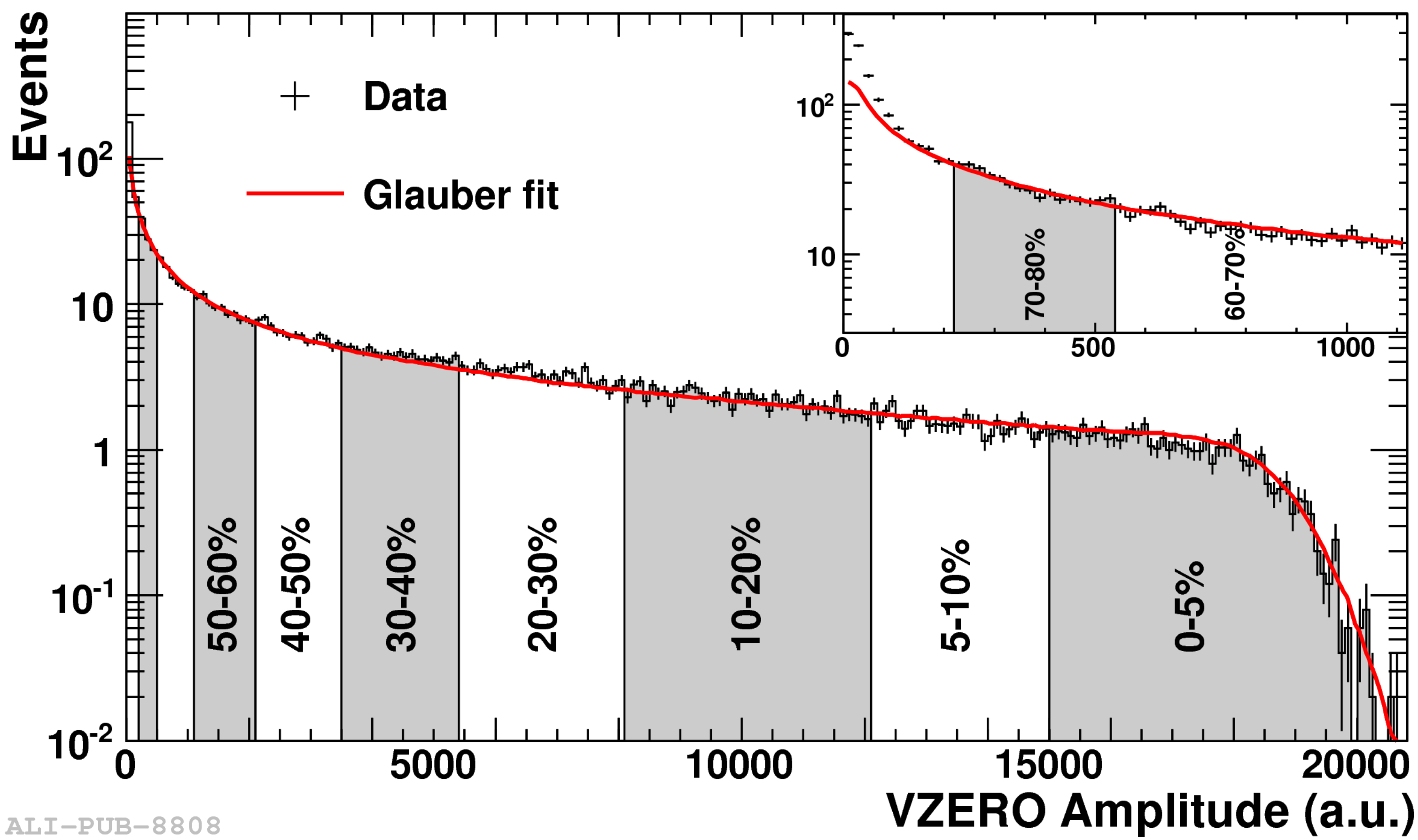


Experimental challenge in HI collisions:
Separate jet signal from large soft background originating from bulk

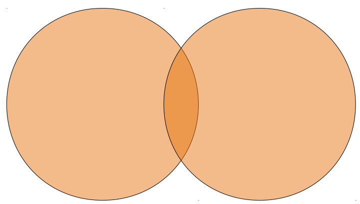
Jet Reconstruction

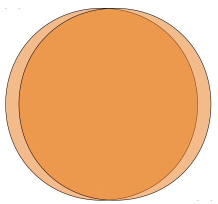
- ALICE uses sequential recombination algorithms from FastJet package [Phys Lett B 641 (2006) 57]:
  - anti-k_T for signal (stable area)
  - k_T to estimate background density
  - Boost invariant p_T recombination scheme
  - Transverse momentum track cut-off $p_T > 0.15$ GeV/c
- Charged jet reconstruction with tracks reconstructed in tracking detectors:
  - High precision on particle level
  - Uniform η-φ acceptance
  - Neutral energy missing, eg. π^0, n, γ

Centrality of HI collisions



Peripheral collisions





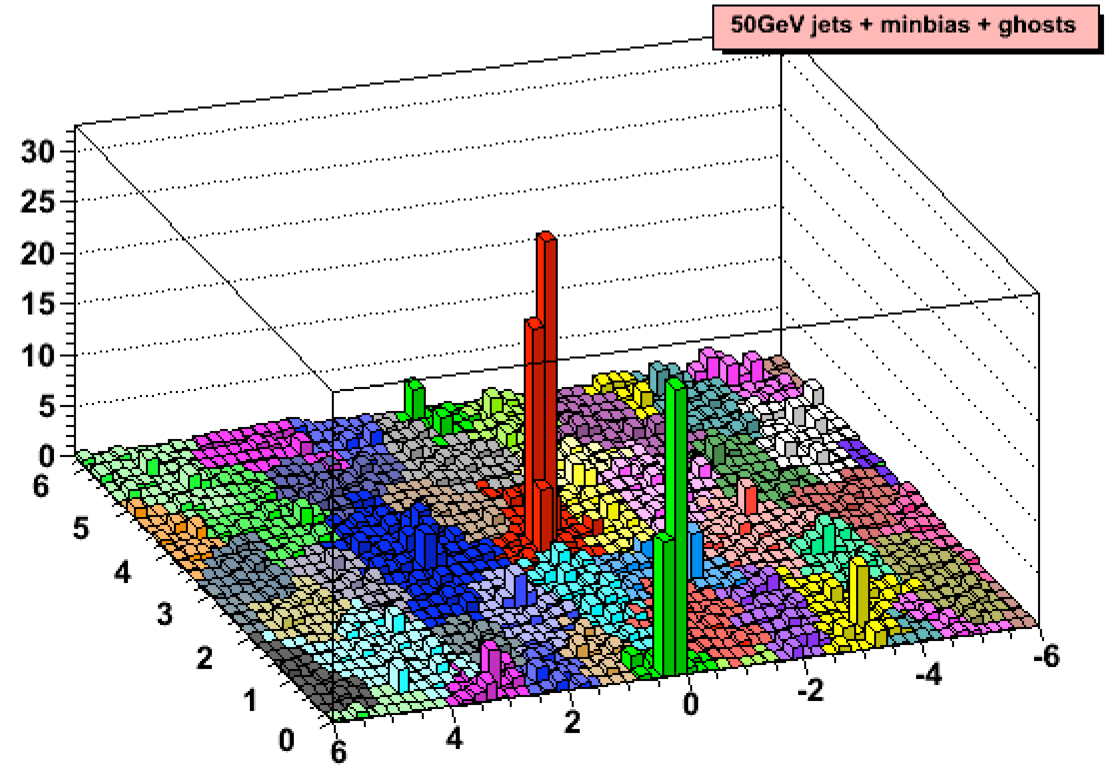
Central collisions

Jets in HI events: background

- Jet sits on top of a soft background
- 2 step procedure to correct for UE contaminating the jet:

1) Background density ρ:
   k_T algorithm excluding the 2 leading clusters.

2) Background fluctuations: inhomogeneous structure of events.
   Quantified by embedding high p_T probes on top of the measured PbPb events.



Jets in HI events: background

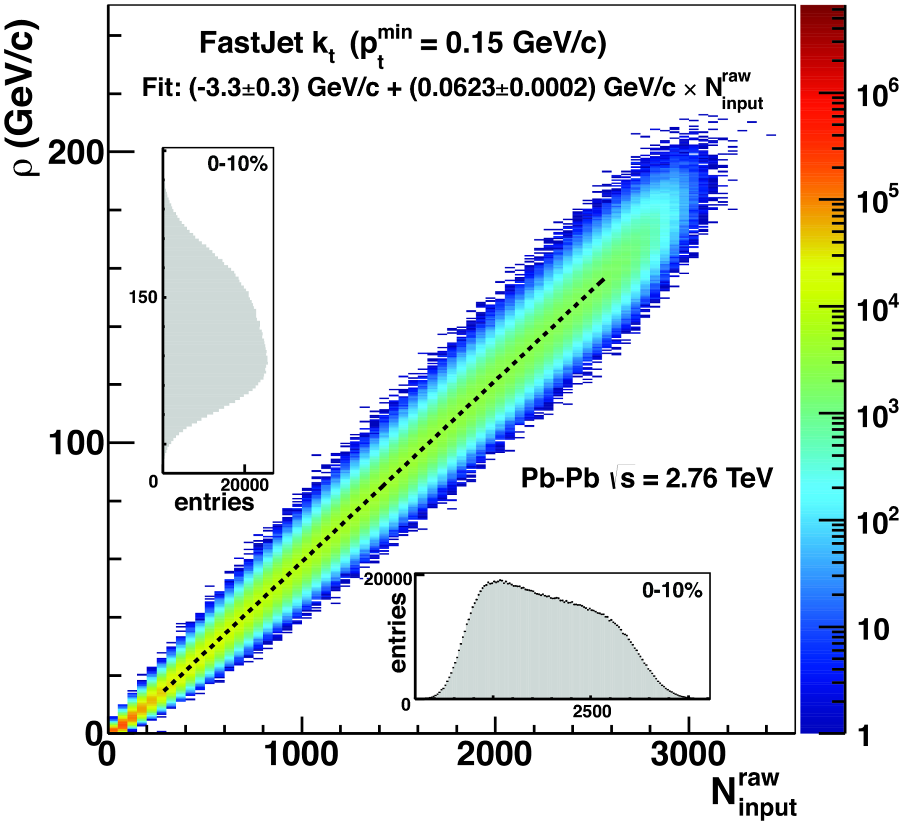
Event-by-event subtraction of average background momentum density ρ.

Background fluctuations quantified by embedding high p_T probes in Pb-Pb events

Width of fluctuations for jets with constituent p_T>150 MeV/c:

$\sigma(\delta p_T, R=0.2)$ = 4.5 GeV

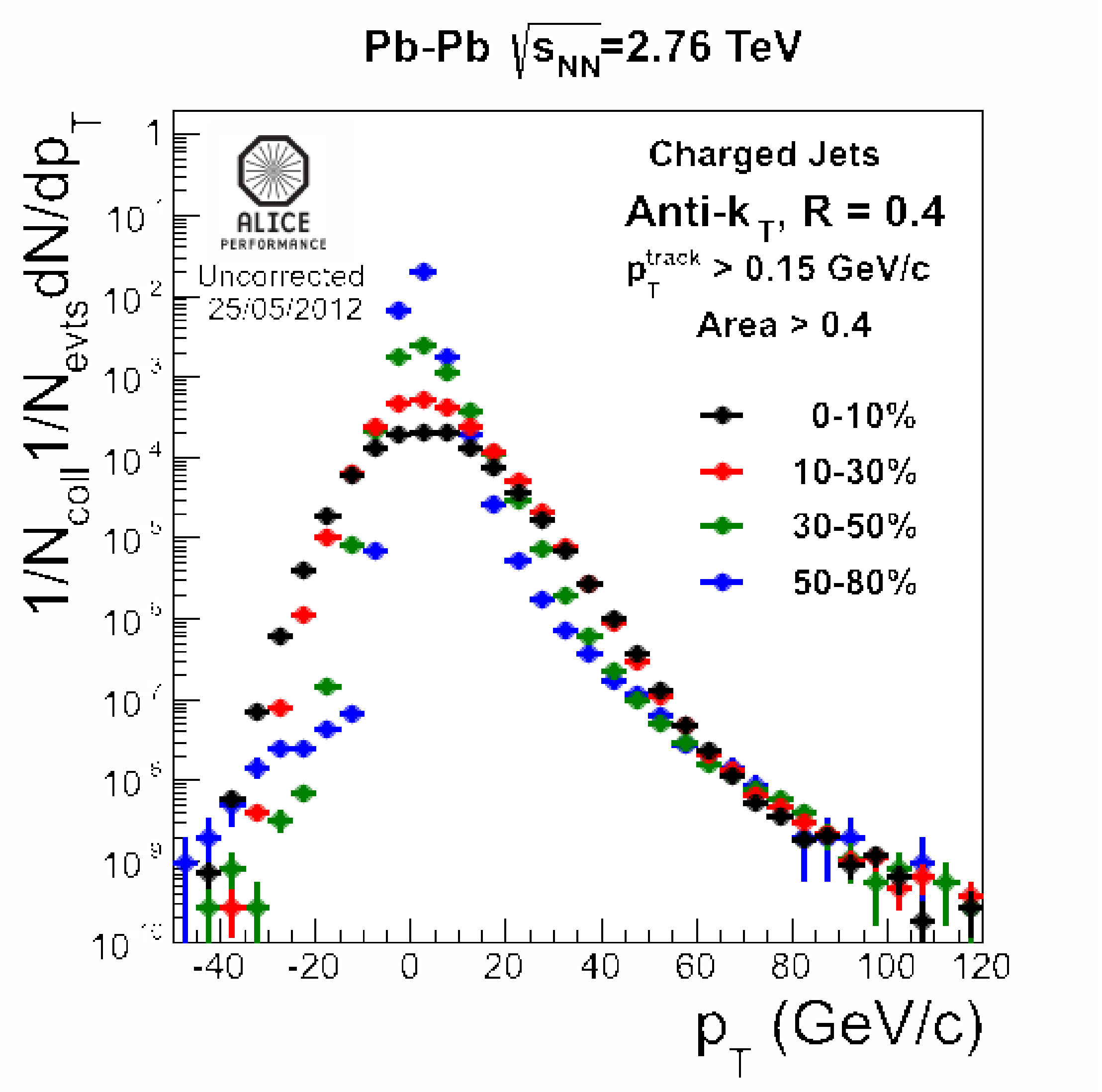
$\sigma(\delta p_T, R=0.3)$ = 7.1 GeV



JHEP, vol 1203, p 053 2012

Uncorrected Jet Spectrum

- Average background subtraction: event-by-event background density for central events ~140 GeV/c/A
- Low p_T jets collect a lot of background energy and appear at very high p_T after clustering

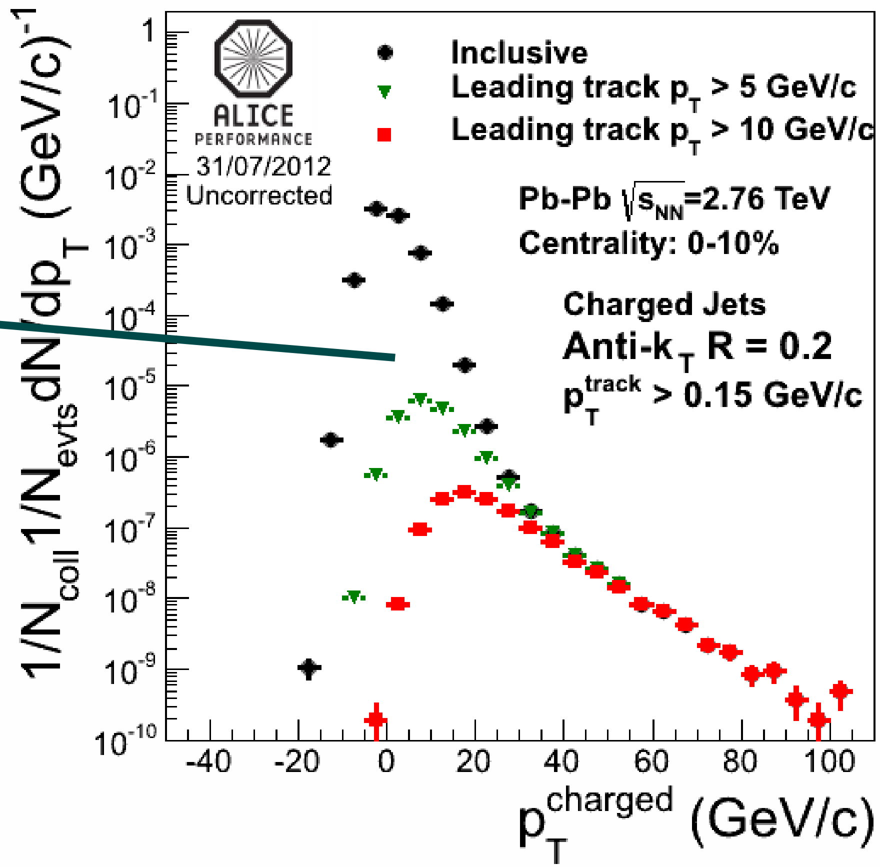


$p_{T,track}$ > 0.15 GeV/c

Jets in HI events: background

Combinatorial jets: clusters which do not originate from a hard process.
Reduced by triggering jets with a leading track of p_T > 5 and 10 GeV/*c*.

Combinatorial / fake jets



Jets reconstructed from charged particles with p_T>150 MeV/*c*.

Background Fluctuations

- Background fluctuations estimated by studying the response of embedded high p_T probe in heavy ion event.
- Data driven approach to estimate influence of background fluctuations on jet reconstruction.
- We embed different kind of probes:
    - Random cones
    - Single tracks
    - Jets from full detector simulation pp @ 2.76 TeV
- Response is quantified by comparing the reconstructed jet to the embedded probe:

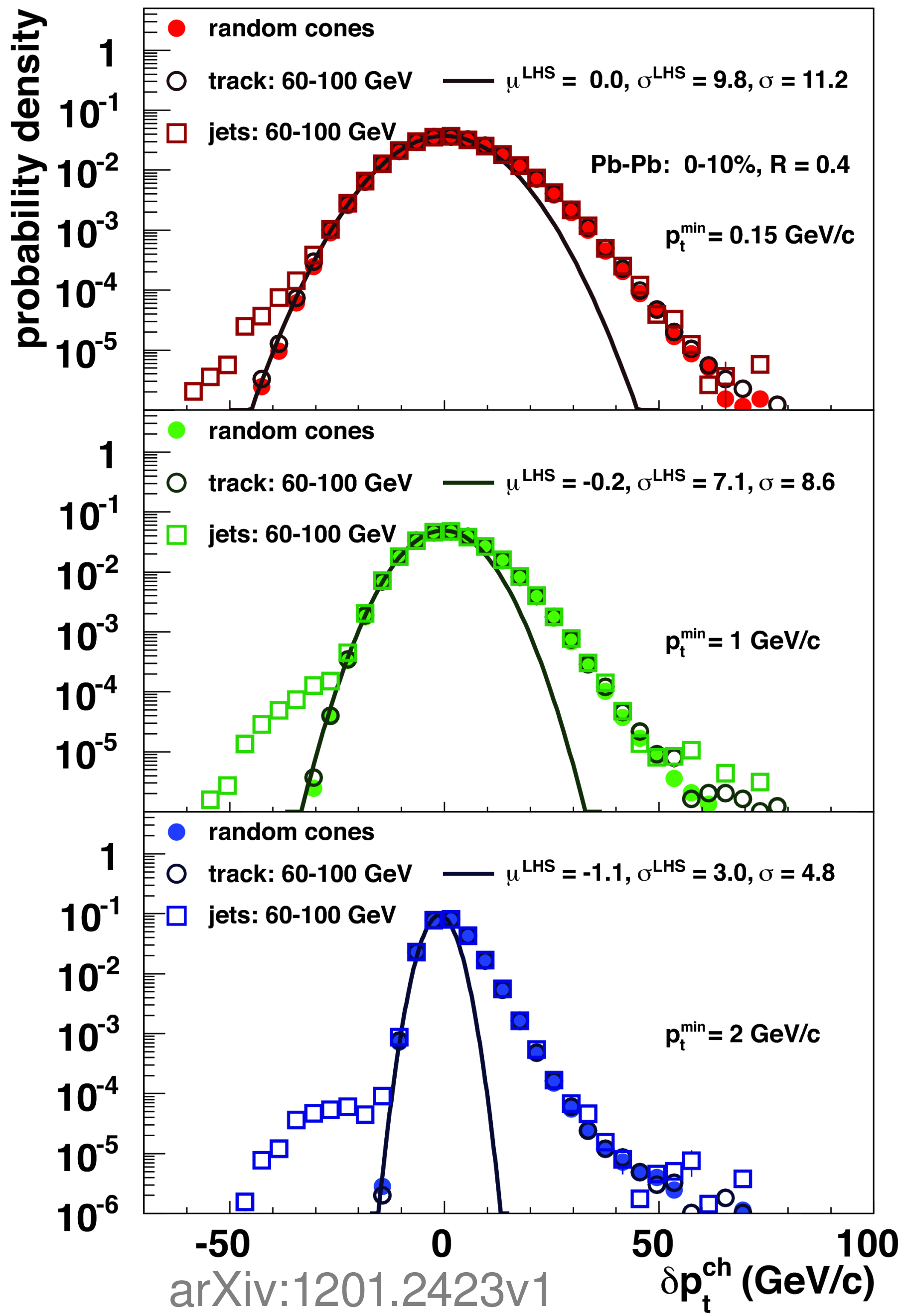
$$\delta_{p_T} = p_{T,jet}^{rec} - \rho A - p_T^{probe}$$

Background Fluctuations

Comparison of Probes

Random Cones
Single Tracks
Pythia jets

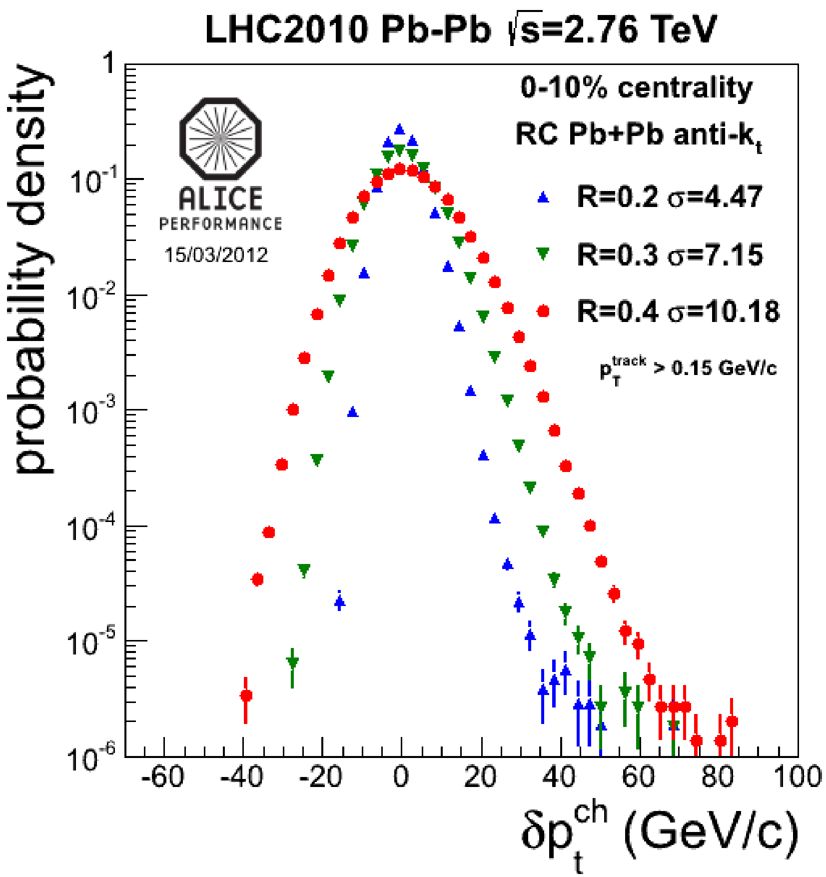
- No dependence on fragmentation pattern observed
  - Small back-reaction effect
- Fluctuations reduced by increasing minimum particle p_T
- High p_T tail same shape as jet spectrum
  - Challenging for unfolding

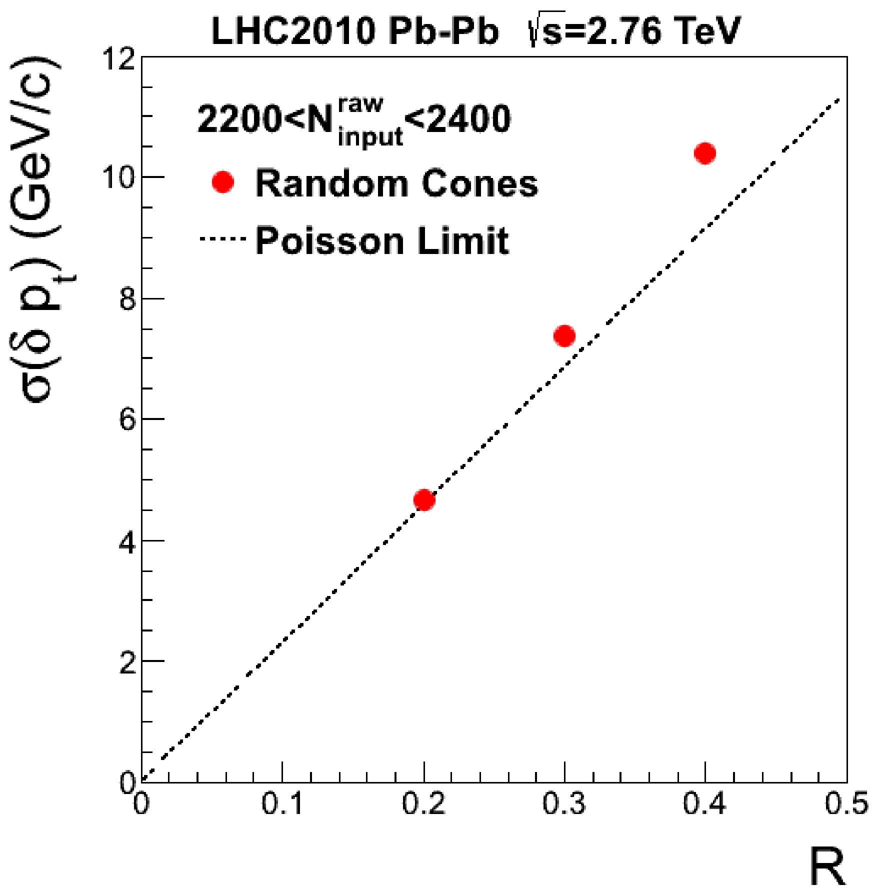


arXiv:1201.2423v1

Background Fluctuations

Comparison of jet radii





Reduced background fluctuation for smaller jet areas

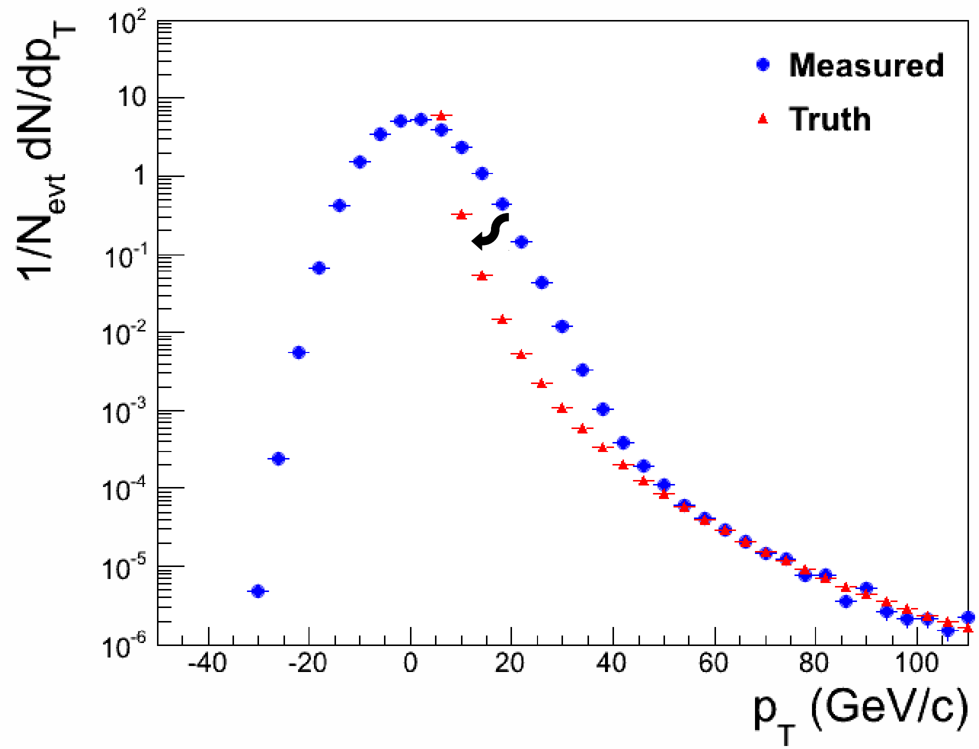
Measured $\sigma(\delta p_T)$ larger than naive expectation from only statistical fluctuations

Unfolding the background

- Need to **unfold** measured jet spectrum to obtain 'real' jet spectrum (Truth)
- Refolded = unfolded jet spectrum smeared with background fluctuations

Assume:

$$\left.\frac{dN}{dp_T}\right|_{meas} = P(\delta p_T) \otimes \left.\frac{dN}{dp_T}\right|_{jet}$$



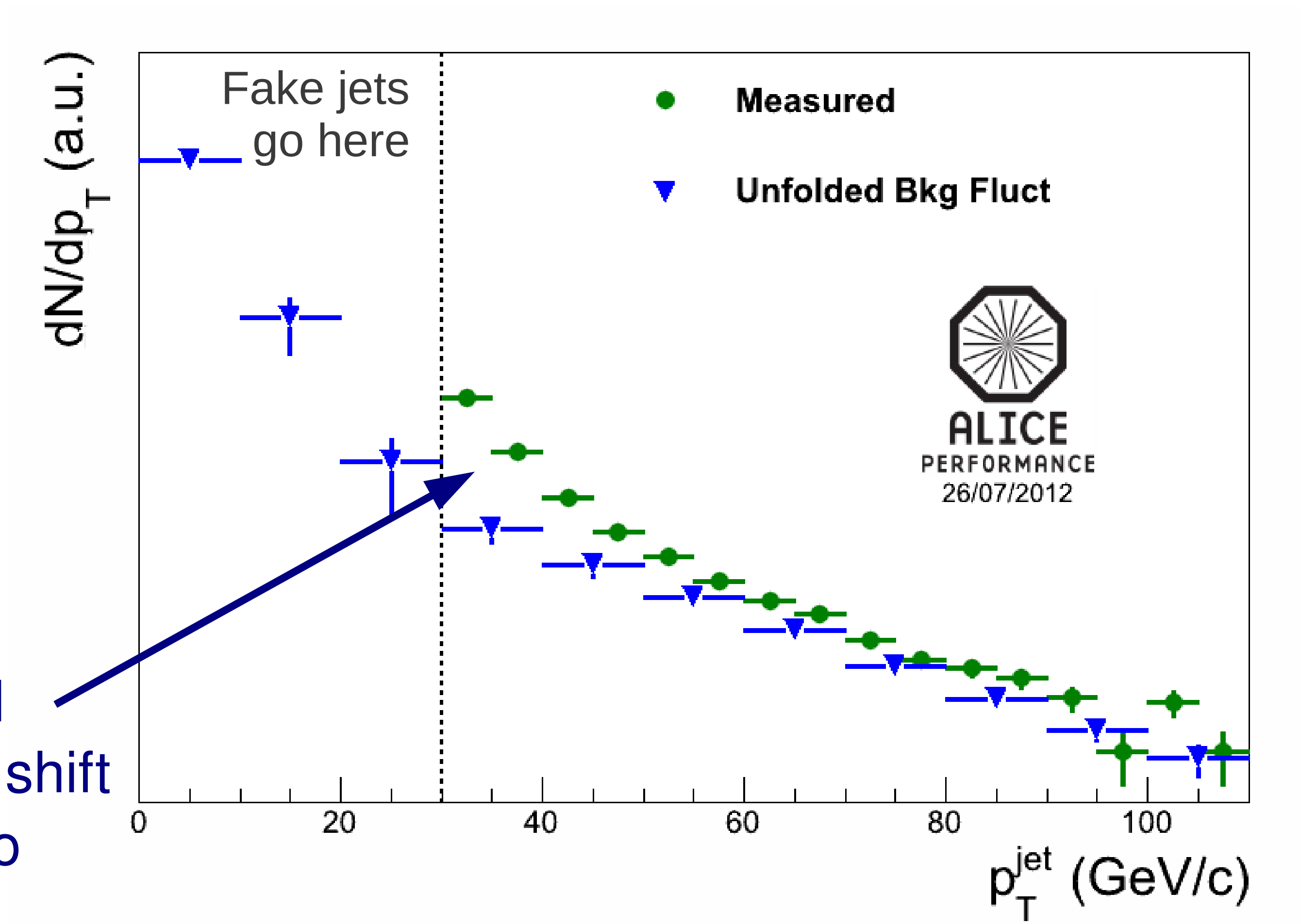
Unfolding done with χ^2 minimization

$$\chi^2 = \sum_{refolded} \left(\frac{y_{refolded} - y_{measured}}{\sigma_{measured}} \right)^2 + \beta \sum_{unfolded} \left(\frac{d^2 \log y_{unfolded}}{d \log p_t^2} \right)^2$$

χ^2-term *Regularization/penalty*

Background and detector corrections

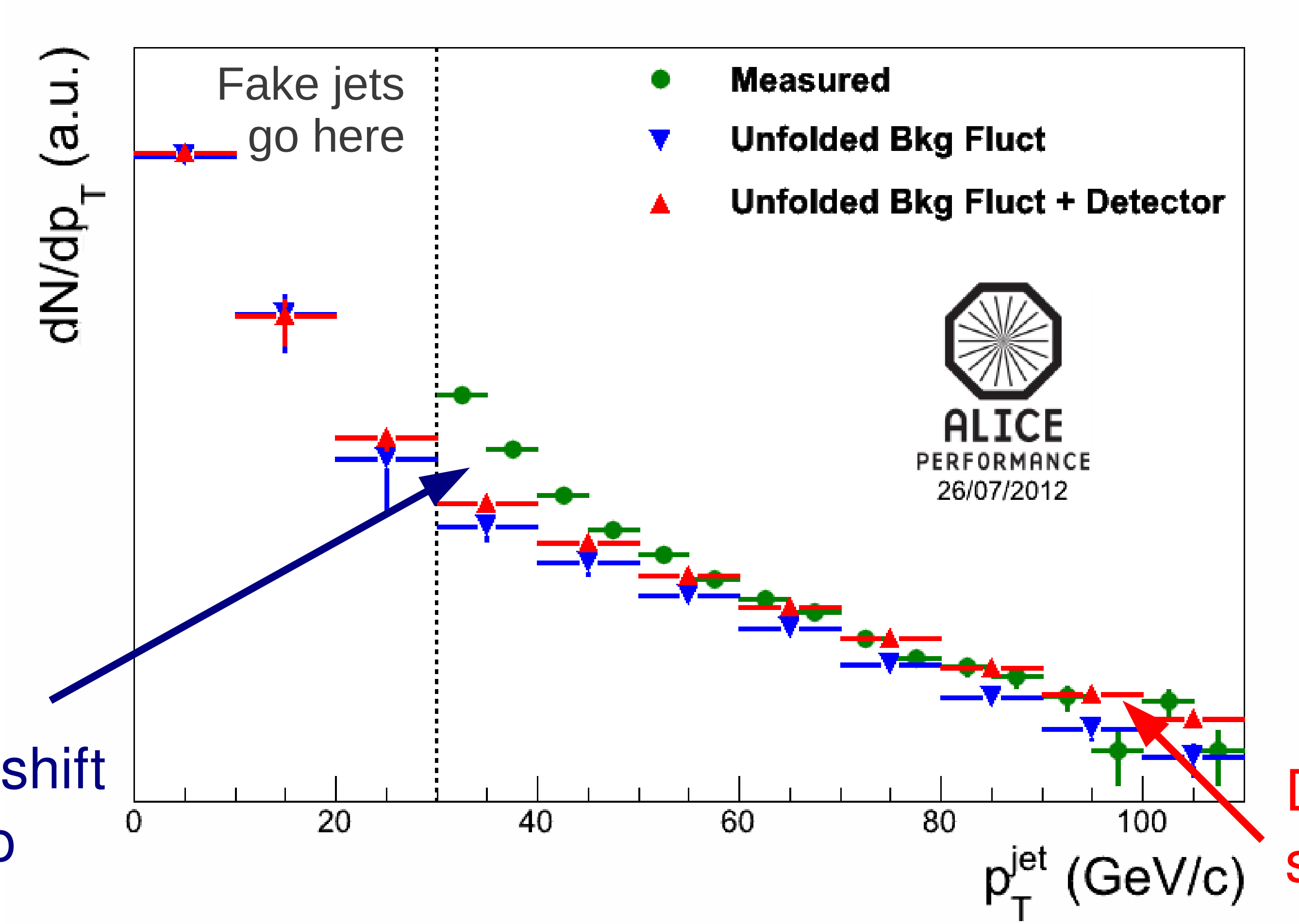
Raw jet spectra need to be corrected for background fluctuations



Background fluctuations shift low p_T jets to high p_T

Background and detector corrections

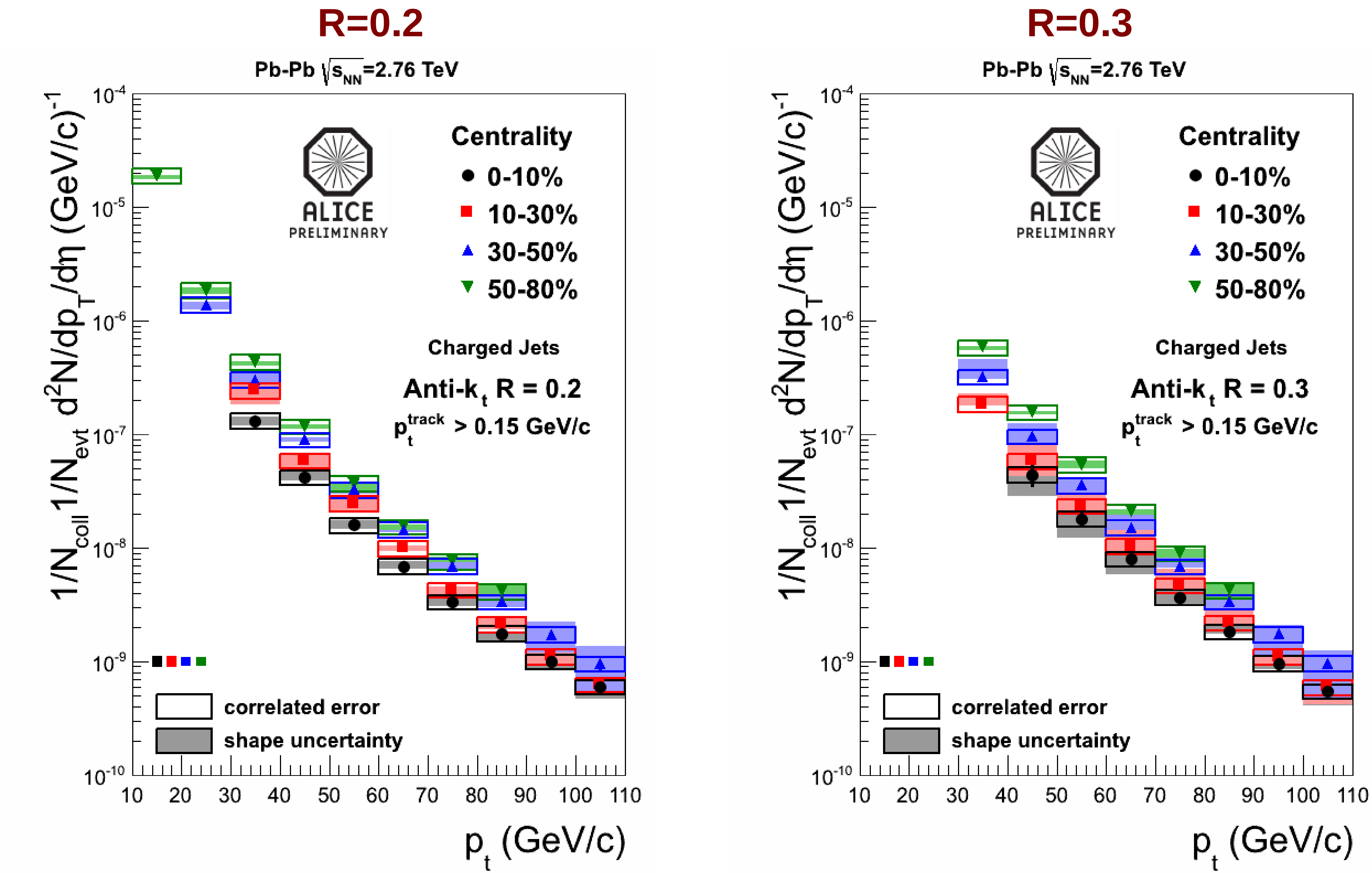
Raw jet spectra need to be corrected for background fluctuations and detector effects.



Background fluctuations shift low p_T jets to high p_T

Detector effects shift jets to lower p_T

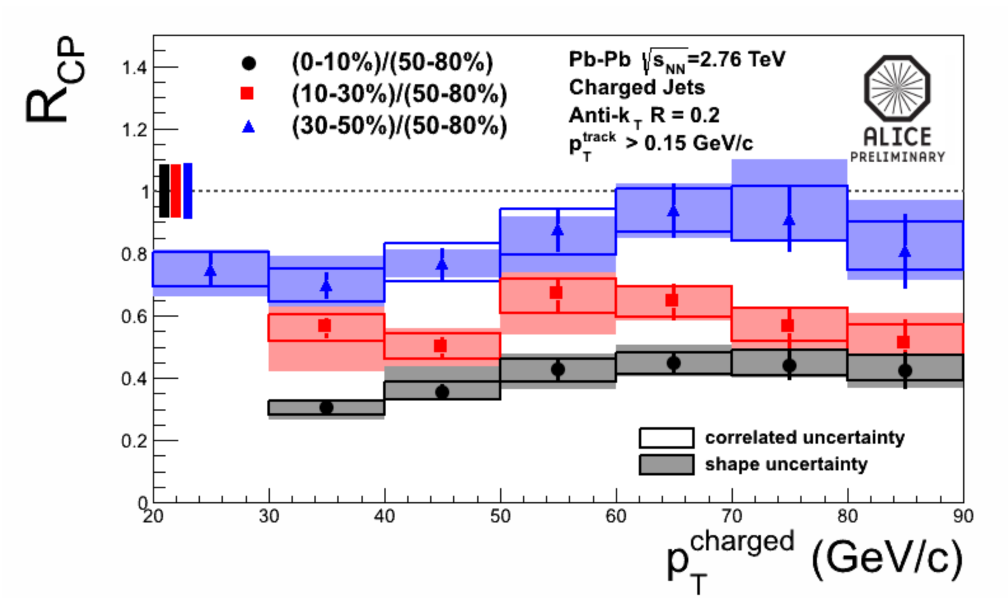
Pb-Pb Jet Spectrum



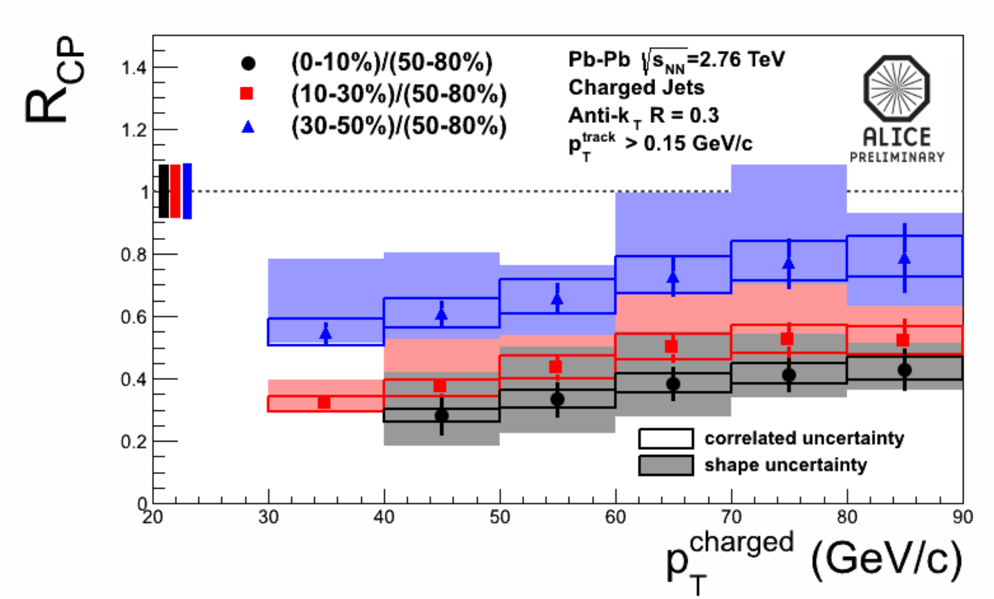
Jet spectra have been measured for 2 cone radii and 4 centrality bins

Jet R_{CP}

R=0.2



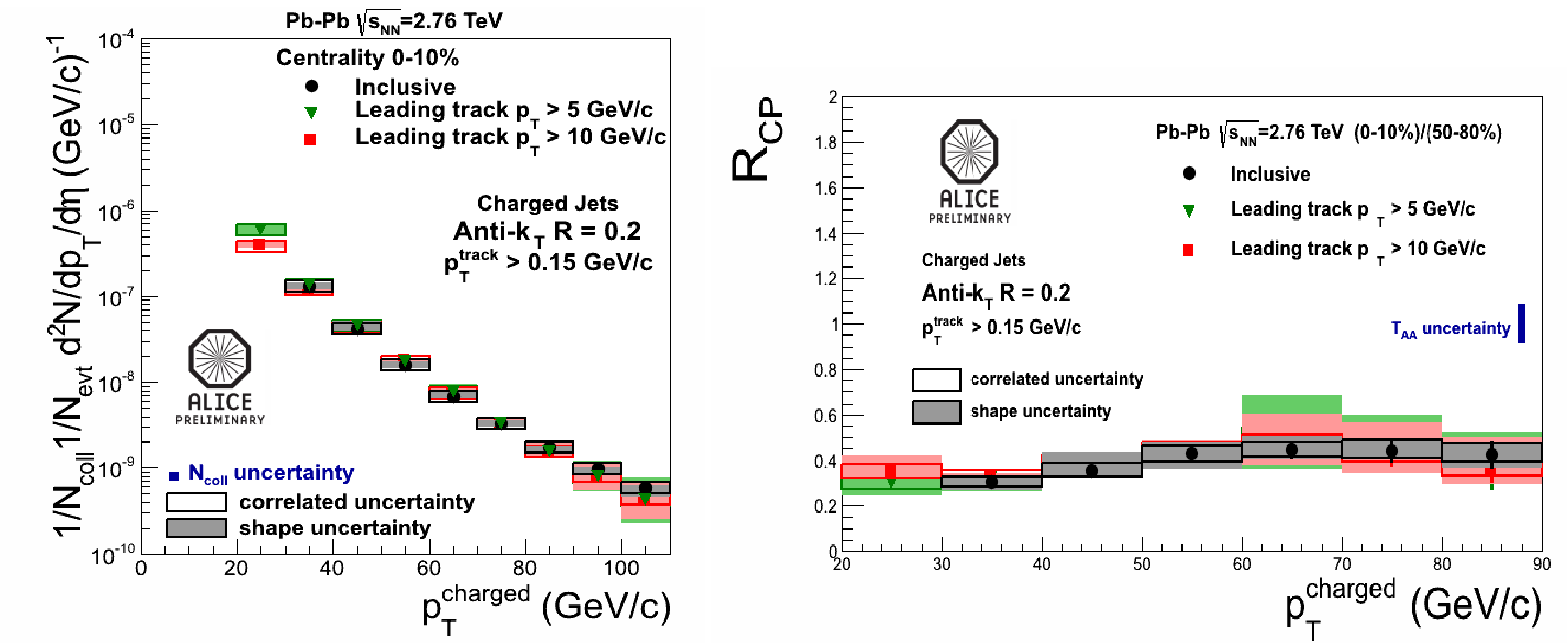
R=0.3



Strong suppression for jets
No strong p_T dependence
Similar suppression for jet radii R=0.2 and R=0.3

Central events jet R_{CP} ~ 0.5
Peripheral closer to 1

Jet Suppression

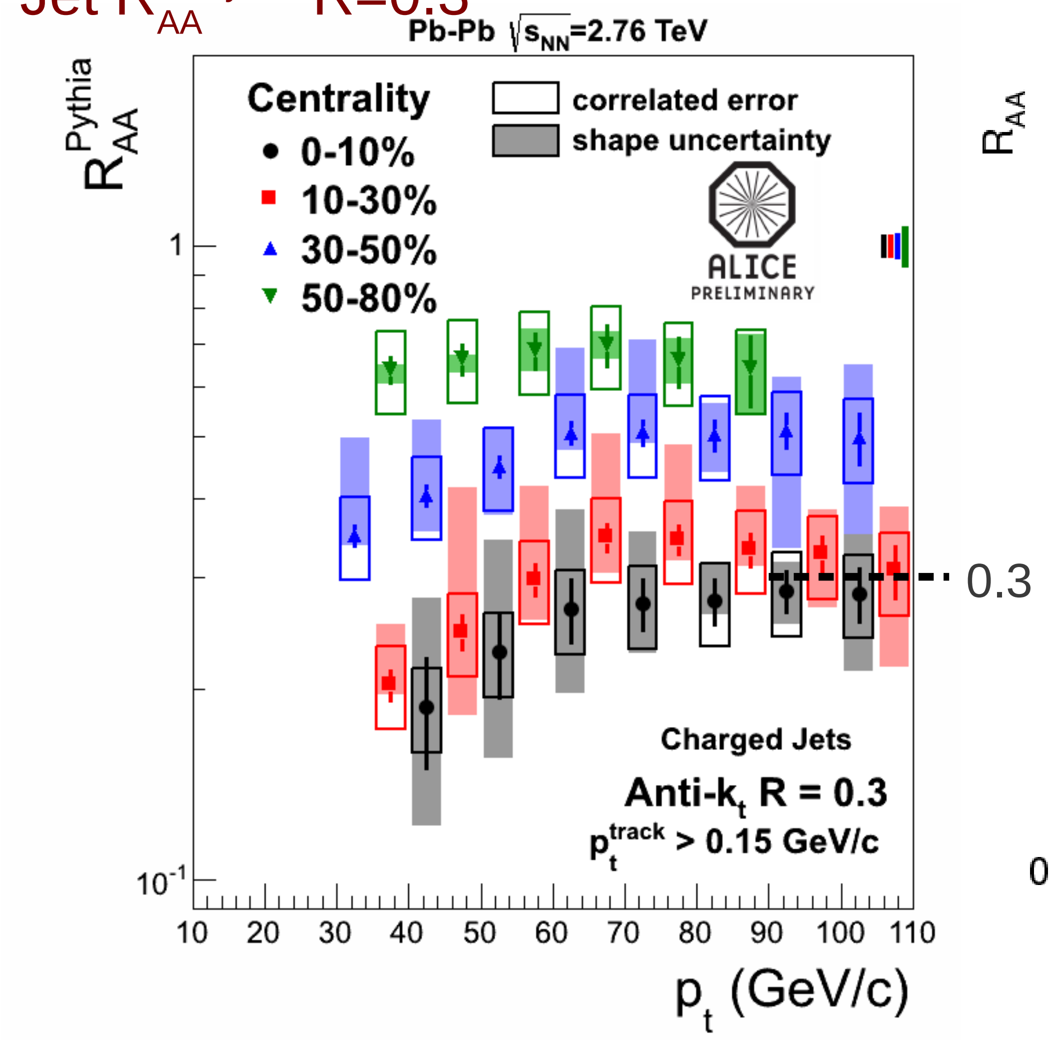


- Leading track requirement → fragmentation bias at low p_T → potentially modified by jet quenching

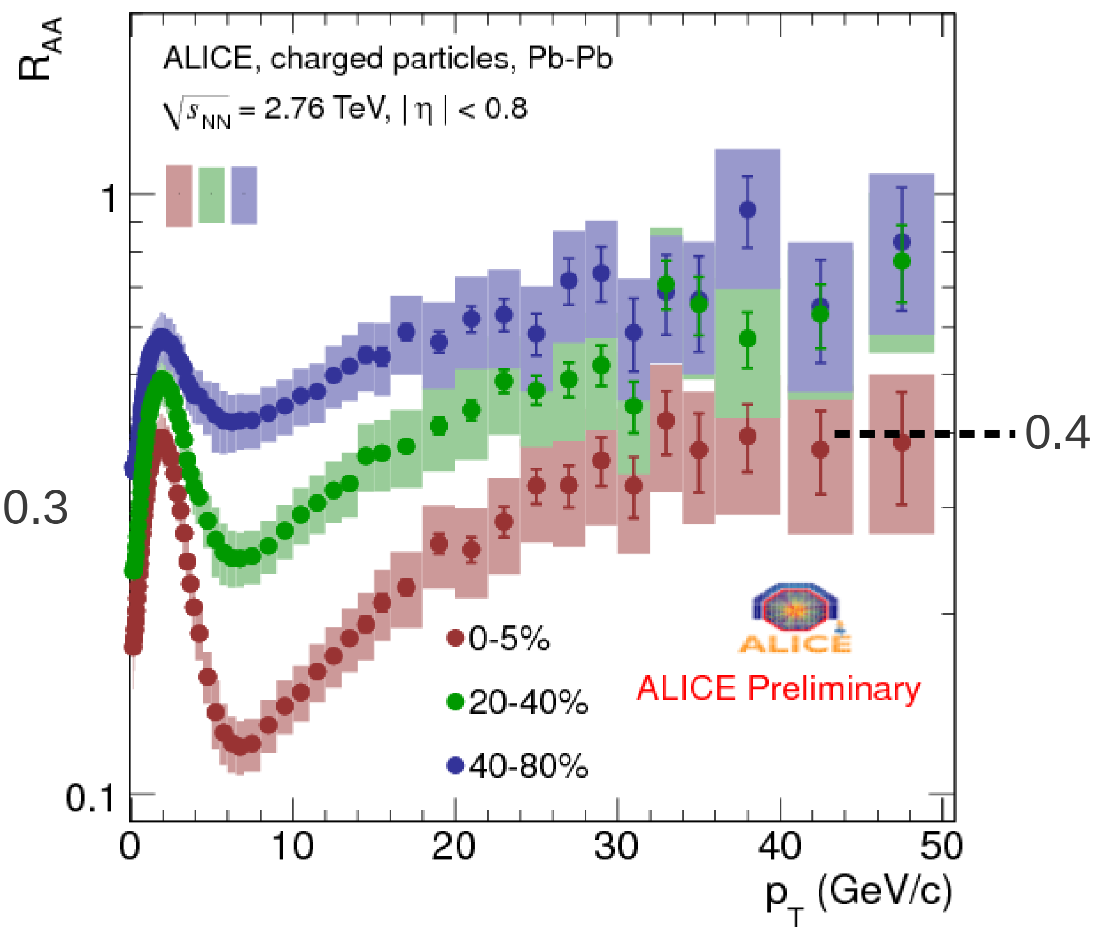
Fragmentation bias the same for central and peripheral events.

Jet R_{AA} vs Hadron R_{AA}

Jet R_{AA}^{Pythia} R=0.3



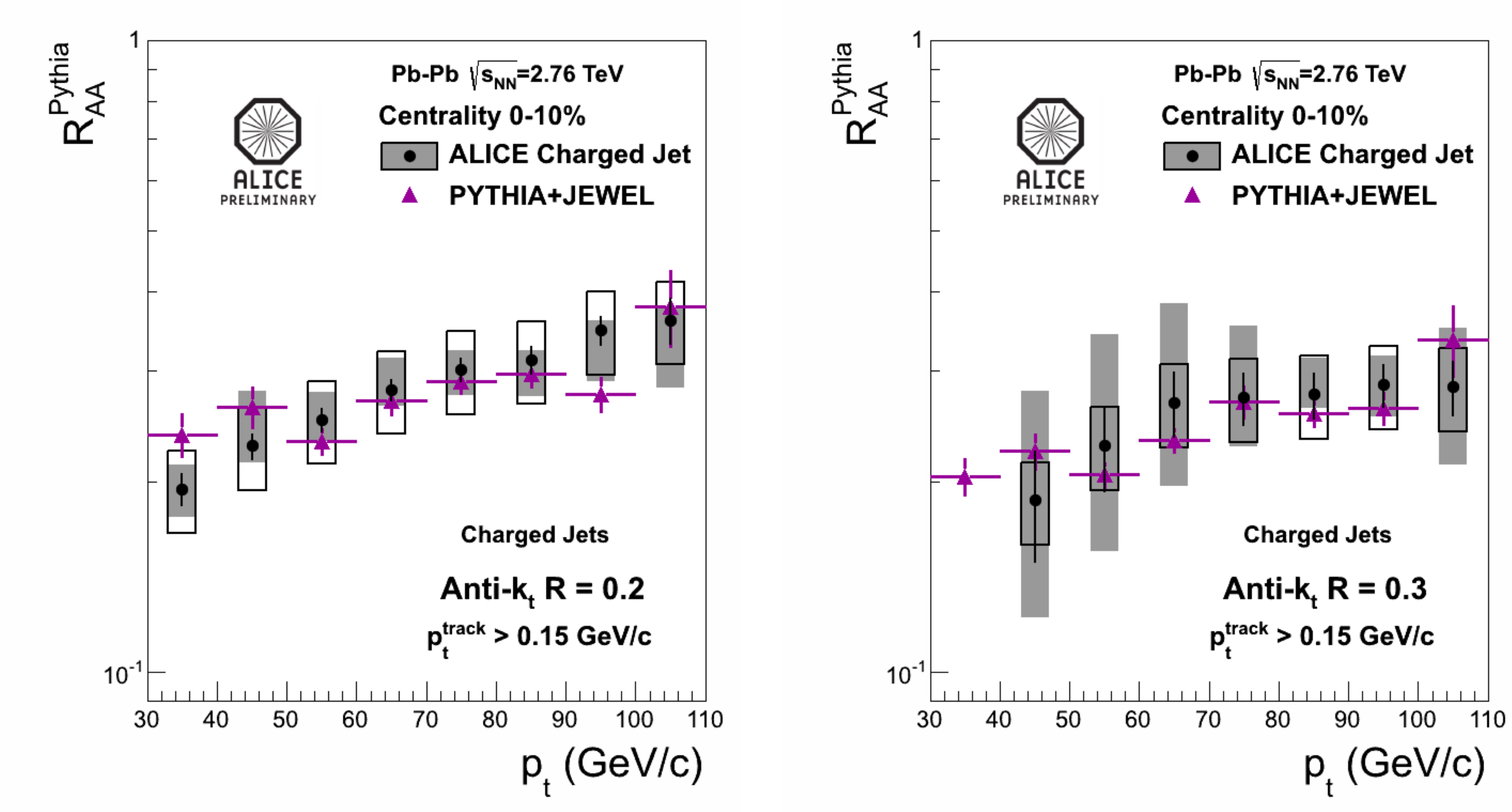
Charged Particle R_{AA}



Jet $R_{AA}^{Pythia} \leq$ Hadron R_{AA}

Model Comparison

Jet R_{AA}: ALICE vs JEWEL



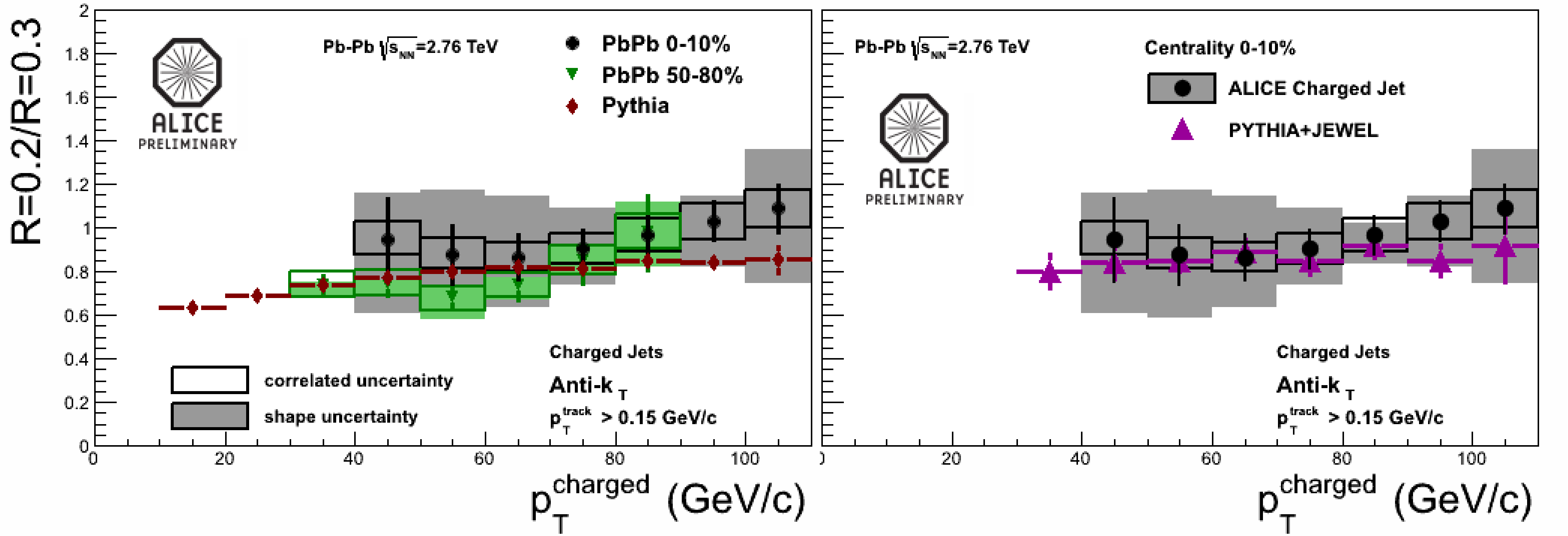
JEWEL (radiative + elastic energy loss MC) reproduces

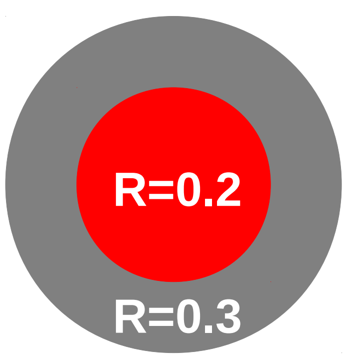
→ Hadron R_{AA} (*Zapp, Krauss, Wiedemann arXiv:1111.6838*)

→ Charged jet R_{AA} for R=0.2 and R=0.3 *JEWEL jet results: private communication*

Ratio of jet cross sections

R=0.2/R=0.3





σ(R=0.2)/**σ(**R=0.3) consistent with vacuum jets for peripheral and central collisions
→ no sign of jet broadening

Good agreement with energy loss MC JEWEL.

JEWEL: Zapp, Krauss, Wiedemann arXiv:1111.6838

Summary

- TECHQM Brick: differences between formalisms identified. Not physics but approximations

- Jets with ALICE
  - Strong jet suppression in central events
  - No signs of modified jet structure observed in ratio of jet cross section R=0.2/R=0.3
  - Jet $R_{AA} \leq$ Hadron R_{AA}

backup

Track Selection

Requirements for jet analysis

- Uniform acceptance in eta and phi
- Avoid outliers (tracks with low p_T generated which are reconstructed at very high p_T)

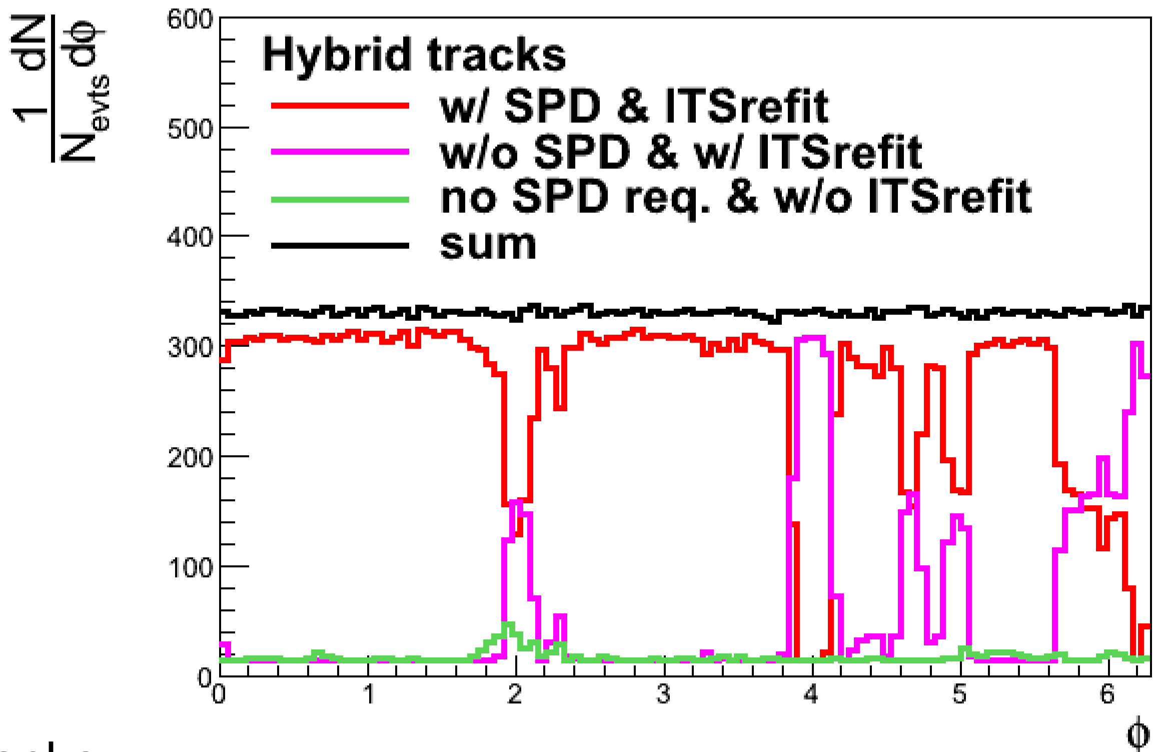
Jet clustering

- Track momentum resolution
- High tracking efficiency

Jet energy resolution

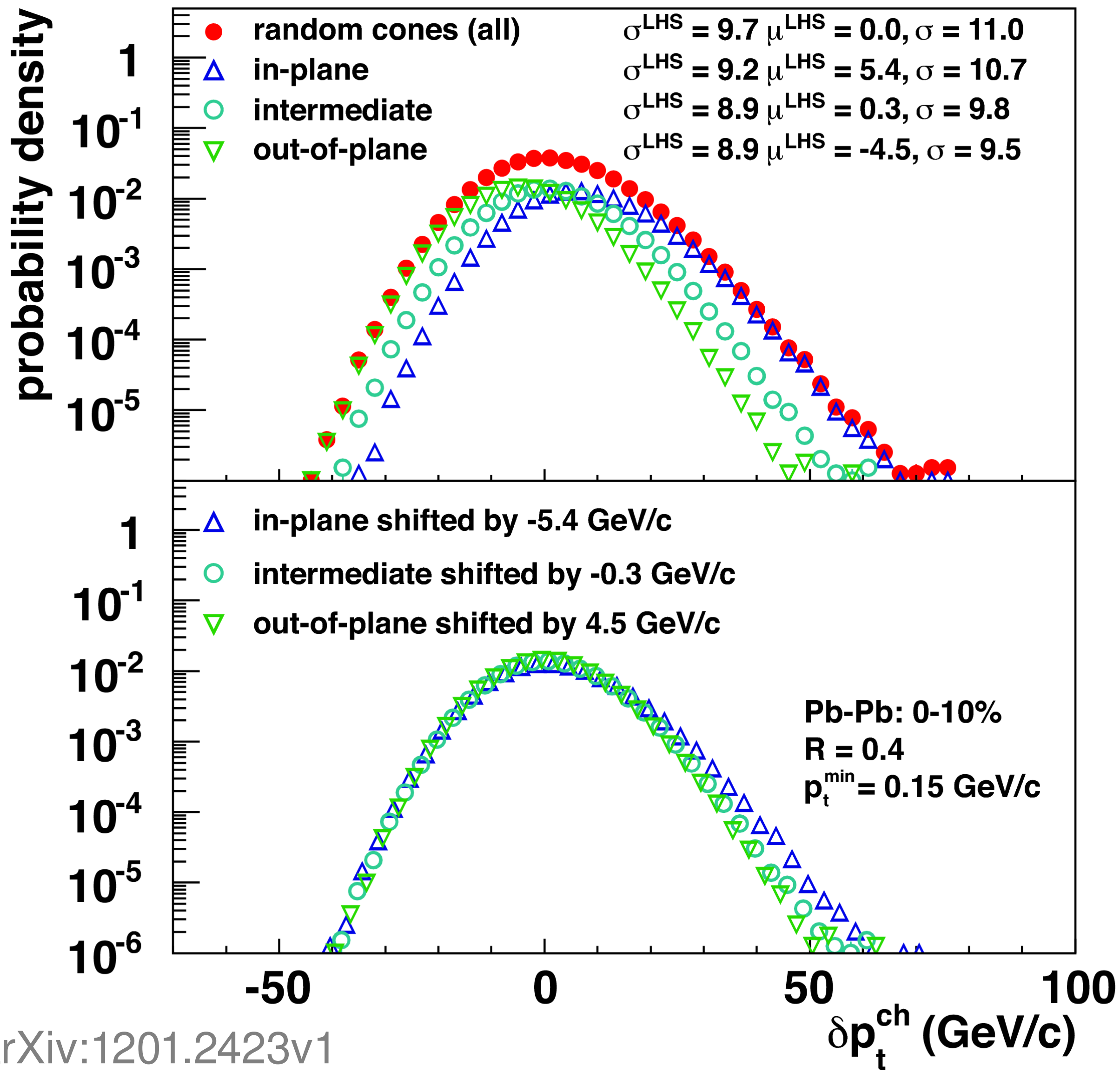
Strategy for track selection:
Use the best available → hybrid tracks

Hybrid Tracks



- Hybrid tracks
  - Standard global tracks: w/SPD && ITSrefit (82%)
  - Constrained global tracks: w/o SPD || w/o ITSrefit (12 + 6%)
- Constrained tracks fill the gaps in phi caused by missing SPD layers. Constrained to primary vertex to improve momentum resolution
- Tracking efficiency: 80-85% at high p_T. (~70% for global standard tracks)

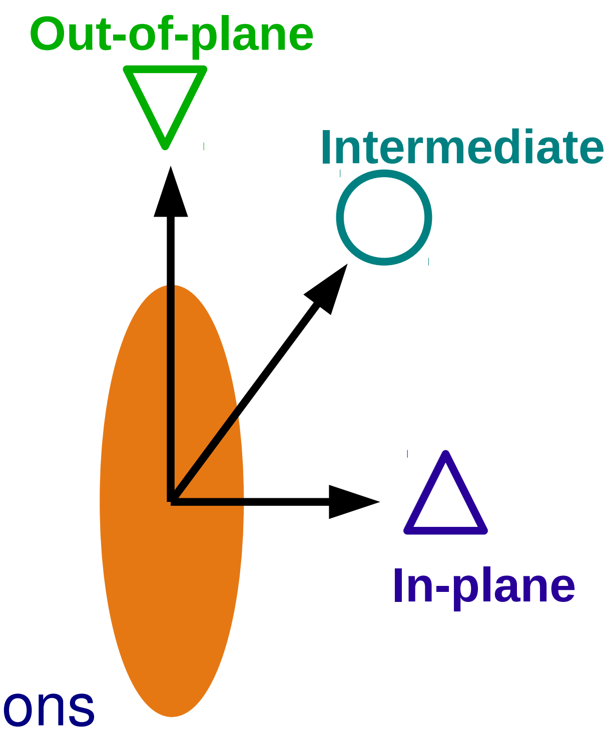
Fluctuations vs reaction plane



arXiv:1201.2423v1

Goal: estimate influence of region-to-region fluctuations of correlated background.

~5 GeV shift for in- and out-of-plane: $\propto v_2 \rho$



Collective effects (v_n) broaden background fluctuations

Suppression Factor

in a brick

- Hadron spectrum if each parton loses ϵ energy:

$$\frac{dN}{dp_t} = \frac{1}{[(1-\epsilon)p_t]^n}\frac{dp_t}{dp_t'} = \frac{1}{(1-\epsilon)^{n-1}p_t^n}$$

$p_t' = (1-\epsilon)\, p_t$

$\epsilon = \Delta E/E$

Weighted average energy loss:

$$R_n = \int_0^1 d\epsilon (1-\epsilon)^{n-1} P(\epsilon)$$

For RHIC: n=7

- R_7 approximation for R_{AA}

Model input parameters

- Multiple soft scattering approximation (ASW-MS):

$$N_{gluon} = \int d\omega \frac{dI}{d\omega}(\omega_c, R) = \int d\omega \frac{dI}{d\omega}(\hat{q}, L)$$

"Medium density"

- Opacity expansion (GLV, etc.):

$$N_{gluon} = \frac{L}{\lambda} \int d\omega \frac{dI}{d\omega}(\mu, L)$$

#scattering centers   Debye screening mass

- No qhat for opacity expansions. $\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda} \sim \frac{\mu^2}{\lambda}$

- **In evolving medium: effective path averaged input parameters. Common variable between models: medium temperature**

Energy loss models in realistic geometry

Scattering rate in (D)GLV

$$x\frac{dN_g}{dx} = \frac{C_R C_g g^2}{2\pi^3}\int \frac{d^2\mathbf{q}}{(2\pi)^2} d^2\mathbf{k}\, dz\, C(\mathbf{q}, z) \times \mathcal{K}(\mathbf{k}, \mathbf{q}, z)$$

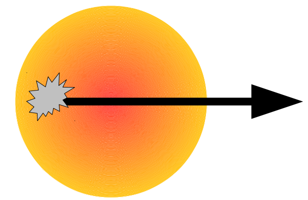
$$C(\mathbf{q}, z)^{GLV} = \frac{(2\pi)^2}{\lambda C_R} \boxed{\frac{1}{\pi}\frac{\mu^2}{(q^2+\mu^2)^2}} \boxed{\rho(z)} \longrightarrow$$

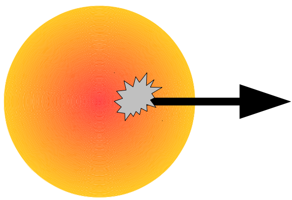
Depends on medium properties

Reference: S. Caron-Huot & C. Gale, arXiv:1006.2379

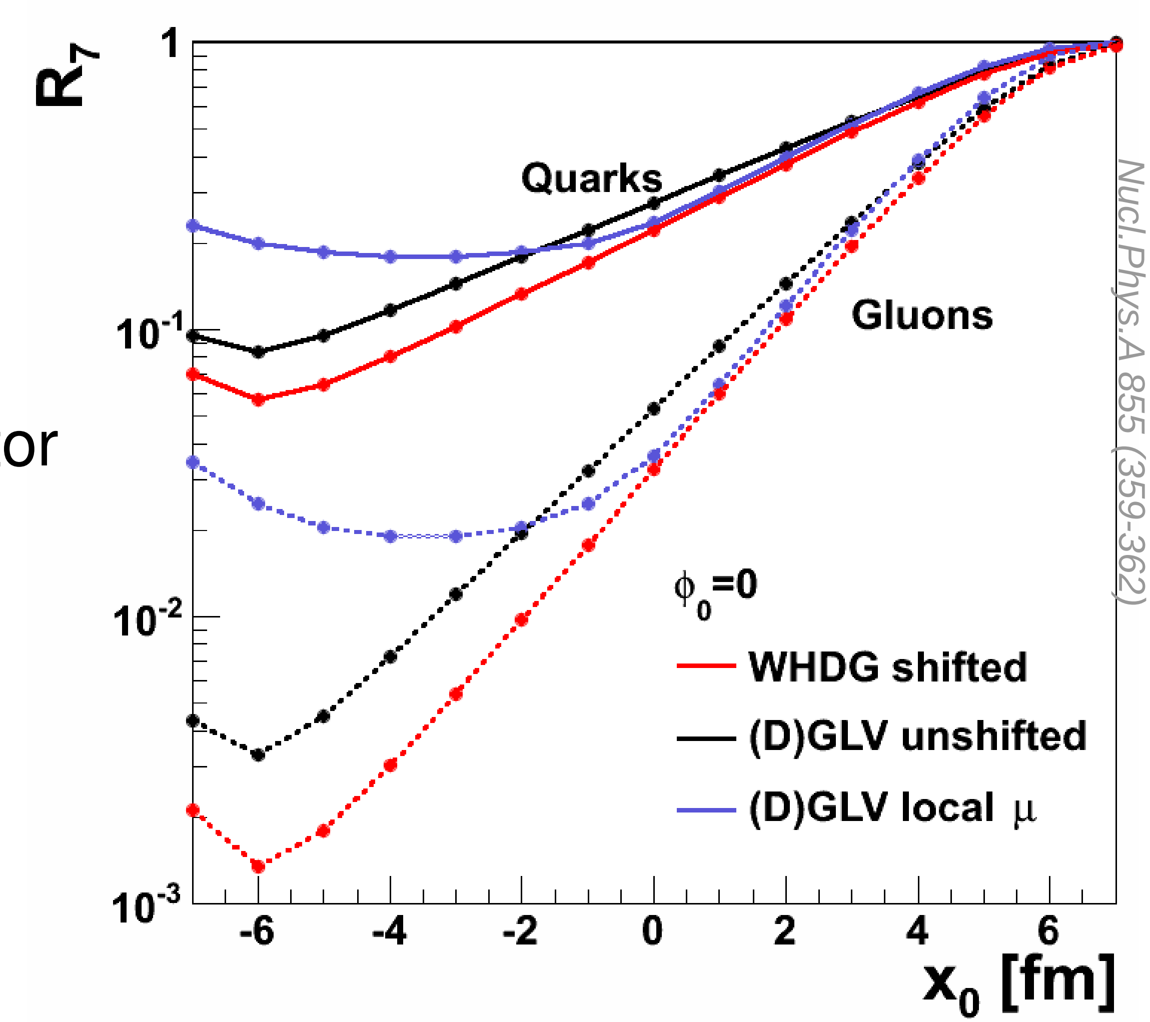
- Normalized Yukawa potential and ρ(z)
- ρ(z) is the probability to have a scattering at position z
  → ρ/λ = scattering rate per unit length
- Explore effect of constant C(**q**) (uniform medium, GLV default) vs position-dependent C(**q**) (non-uniform medium)

Medium as seen by parton



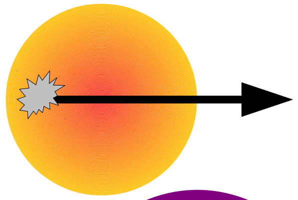


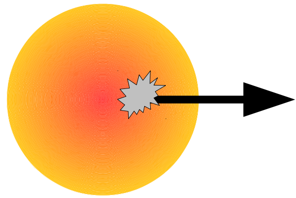
- Exercise:
  - Parton is created at x_0 and travels radially through the center of the medium until it leaves the medium or freeze-out has taken place.
- Characterize energy loss of parton with suppression factor R_7
- More soft gluon radiation in case of inhomogeneous distribution of scattering centers

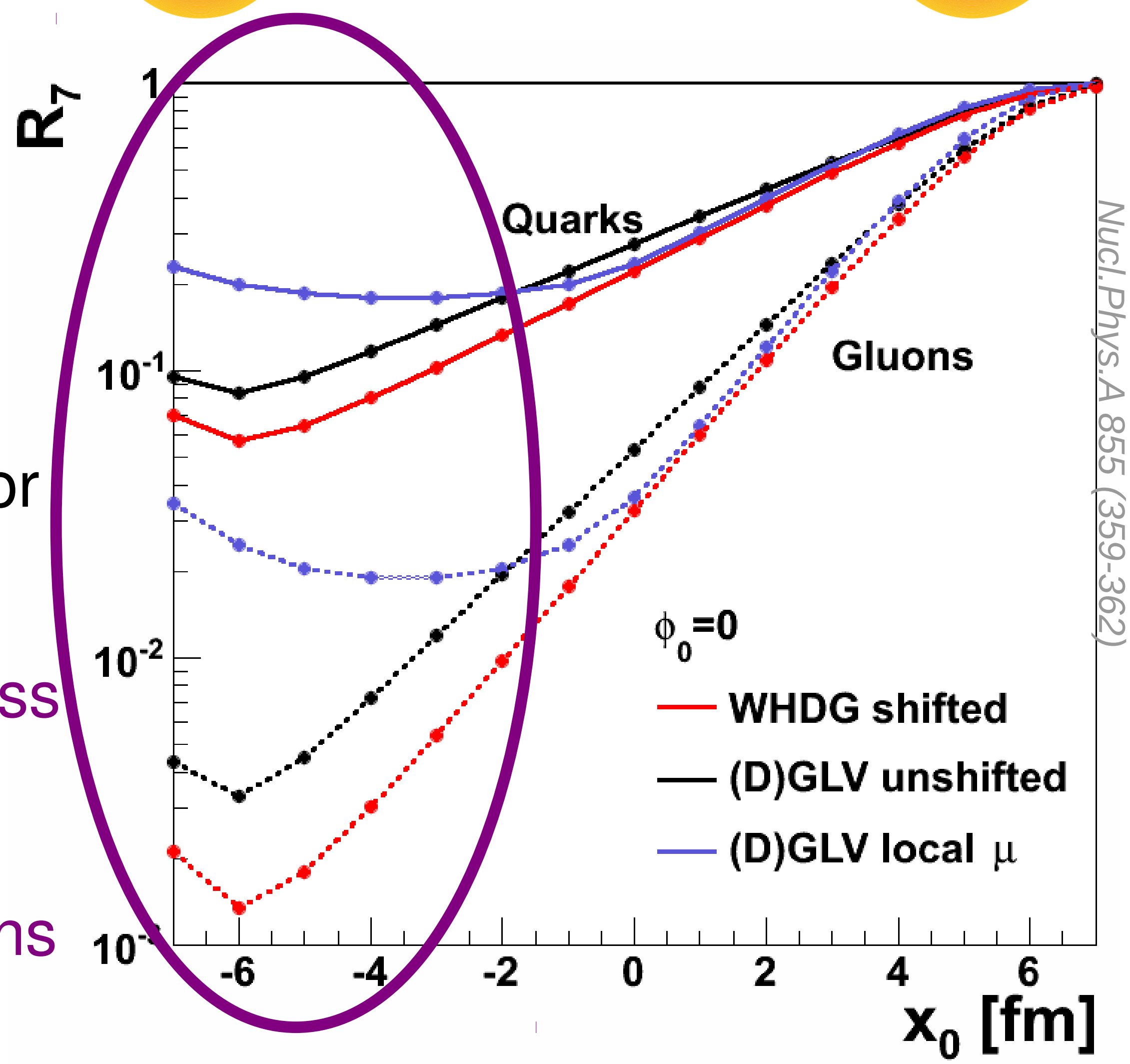


Medium as seen by parton

- Exercise:
  - Parton is created at x_0 and travels radially through the center of the medium until it leaves the medium or freeze-out has taken place.
- Characterize energy loss of parton with suppression factor R_7
- Large difference in energy loss for partons with long path lengths
  → important for I_{AA} calculations



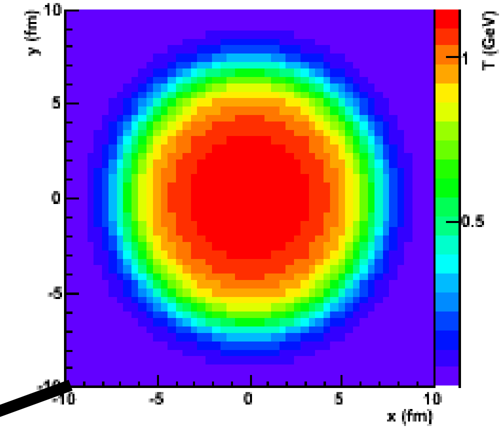




Geometry of HI collision

- Woods-Saxon profile
- Wounded Nucleon Scaling with optical Glauber
- Medium formation time: $\tau_0 = 0.6$ fm
- Longitudinal Bjorken Expansion $1/\tau$
- Freeze out temperature: 150 MeV

Temperature profile of central collision



$$\frac{dN}{dp_{t,hadr}} = \frac{dN}{dp_{t,parton}} \circ P(\Delta E) \circ D(p_{t,hadr}/p_{t,parton})$$

Measurement

Input parton spectrum Known LO pQCD

Energy loss

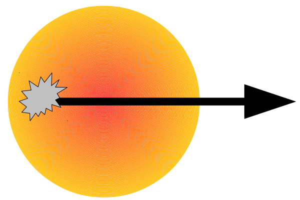
geometry

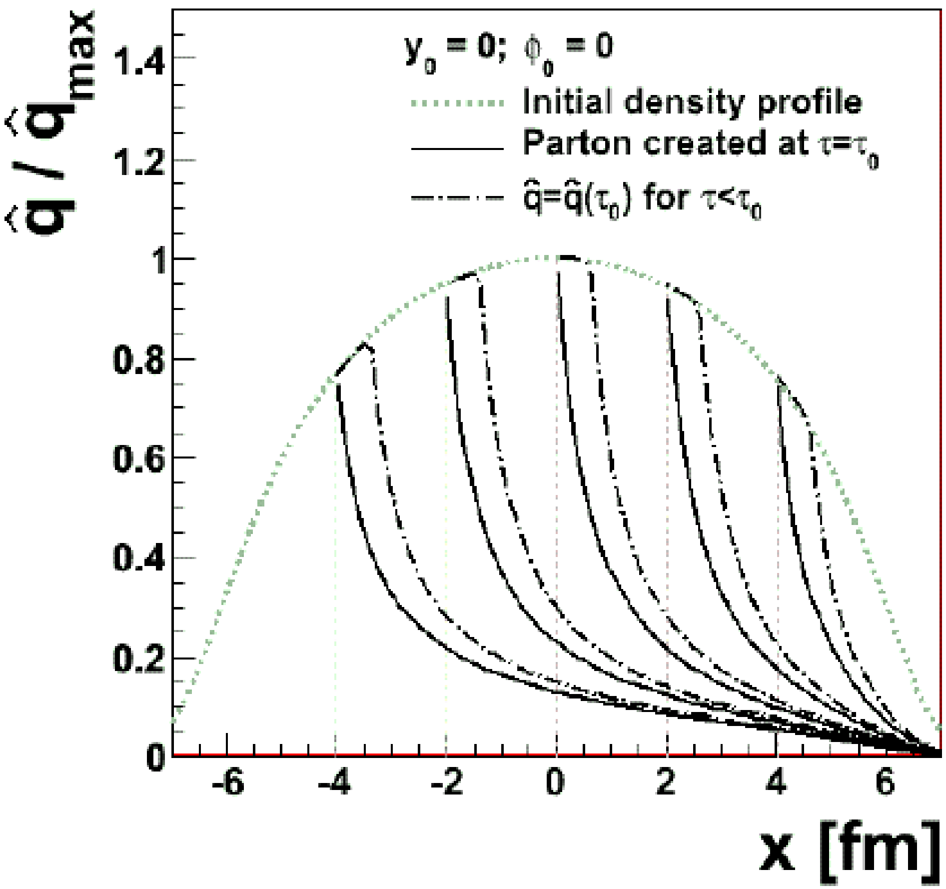
medium

Fragmentation Function Known from e+e-

Medium density profile

- Parton travels through evolving medium
- Parton *sees* different medium at each step in space and time
- Density of medium decreases as function of space and time
- In evolving medium: effective path averaged parameters which depend on T^n
  → same treatment of geometry for different models (ASW-MS and GLV)

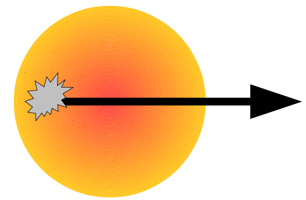




Local qhat as function of space-time coordinate x for different starting points

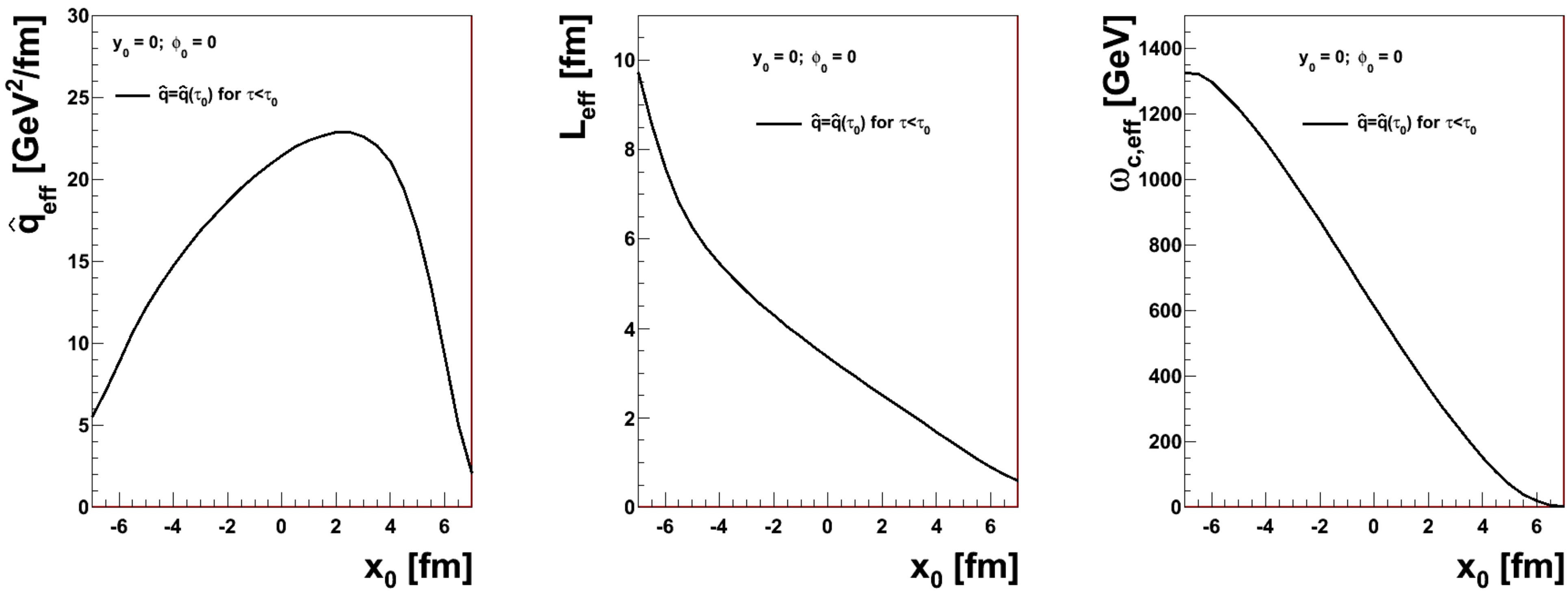
Medium as seen by parton

- Path average variables which characterize the energy loss.

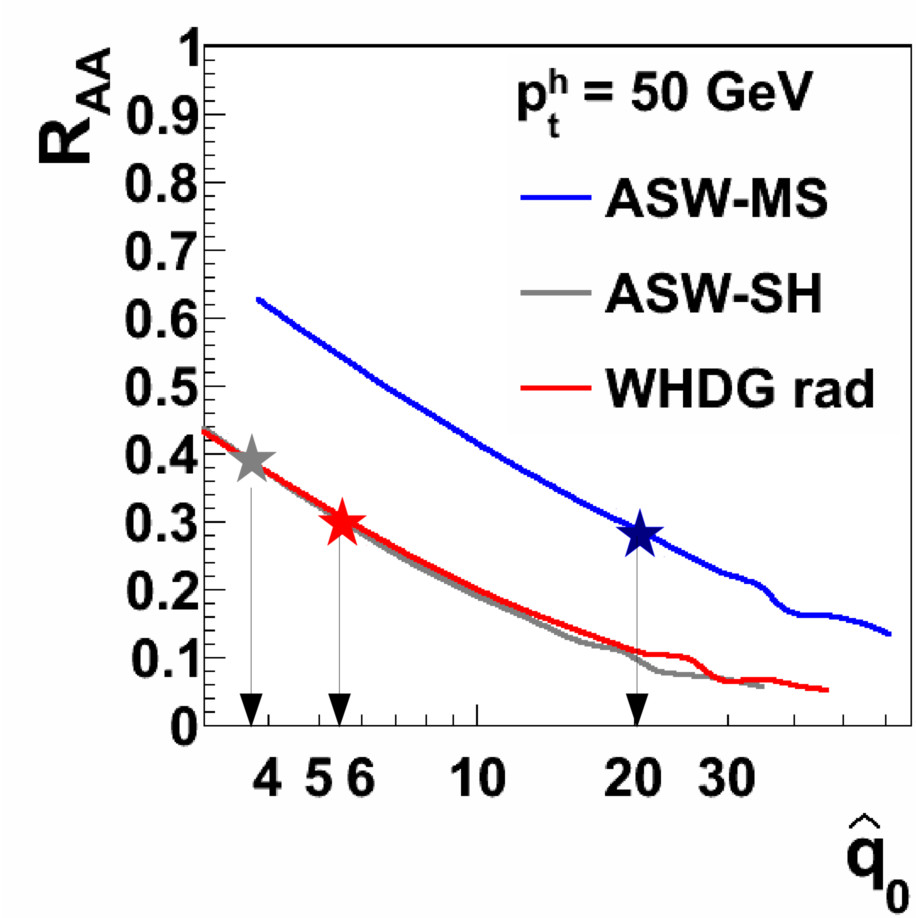


$$\langle \Delta E \rangle \propto \hat{q} L^2 \propto \omega_c$$

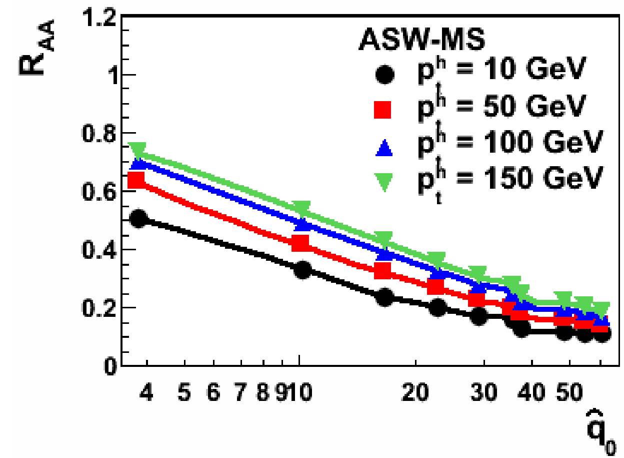
- Exercise:
  - Parton is created at x_0 and travels radially through the center of the medium until it leaves the medium or freeze out has taken place.

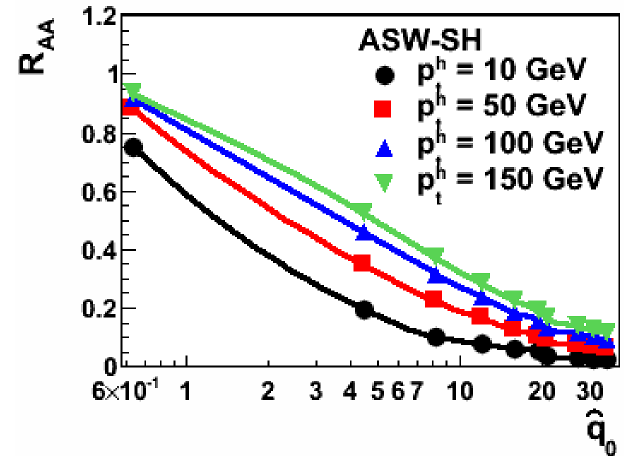


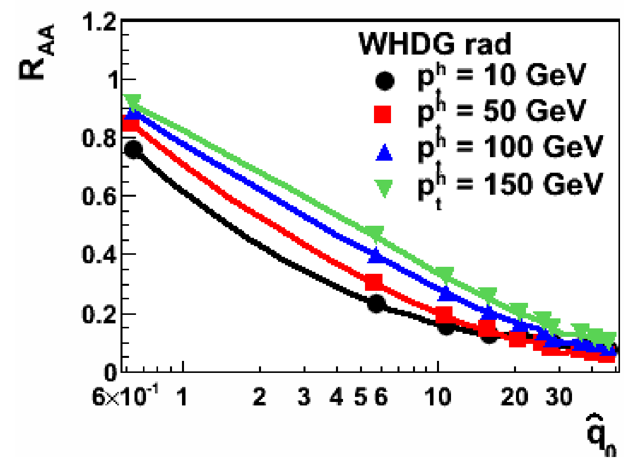
LHC estimates



RHIC best fits	If $\tau < \tau_0$ $\hat{q} = \hat{q}_0$ $\hat{q}_0$ (GeV/fm^2)	T_0 (MeV)
ASW-MS	$20.3^{+0.6}_{-5.1}$	973^{+6}_{-90}
WHDG rad	$5.7^{+0.3}_{-1.9}$	638^{+11}_{-81}
ASW-SH	$3.2^{+0.3}_{-0.3}$	524^{+17}_{-18}







Opacity Expansion Single Gluon Spectrum

- General formula:

$$x\frac{dN_g}{dx} = \frac{C_R C_g g^2}{2\pi^3}\int \frac{d^2\mathbf{q}}{(2\pi)^2} d^2\mathbf{k}\, dz\, C(\mathbf{q},z) \times \mathcal{K}(\mathbf{k},\mathbf{q},z)$$

in which:

$$\mathcal{K}(\mathbf{k},\mathbf{q},z) = \frac{\mathbf{k}\cdot\mathbf{q}(\mathbf{k}-\mathbf{q})^2 - \beta^2\mathbf{q}\cdot(\mathbf{k}-\mathbf{q})}{[(\mathbf{k}-\mathbf{q})^2+\beta^2]^2(\mathbf{k}^2+\beta^2)} \times \left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\beta^2}{2Ex}z\right)\right]$$

$$C(\mathbf{q}) = \frac{1}{C_s}(2\pi)^2\frac{d^2\Gamma_{\mathrm{el}}(\mathbf{q})}{d^2\mathbf{q}}$$

Reference: S. Caron-Huot & C. Gale, arXiv:1006.2379

- C(**q**) depends on medium properties.
- Explore effect of constant C(**q**) (uniform medium) vs position-dependent C(**q**) (non-uniform medium).

Local ρ and μ

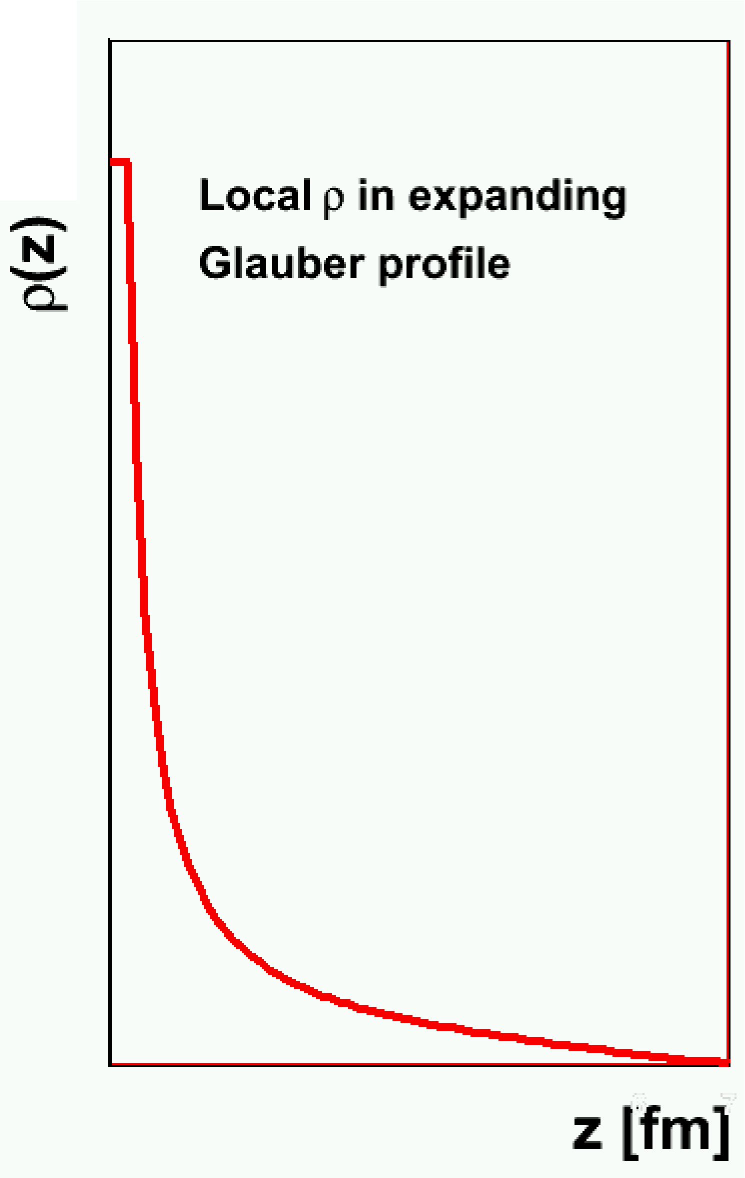
- $\rho(z)$ = medium density = $\mathcal{N}(z) \sim T^3$
- Differential cross-section temperature dependent while the parton propagates through the medium.

$$C(\mathbf{q},\mathbf{z}) = \frac{g^4 \mathcal{N}(\mathbf{z})}{(\mathbf{q}^2 + \mu(\mathbf{z})^2)^2}$$

$$\mathcal{N}(\mathbf{z}) = \frac{\zeta(3)}{\zeta(2)}(1 + \frac{1}{4}N_f)\mathbf{T}(\mathbf{z})^3$$

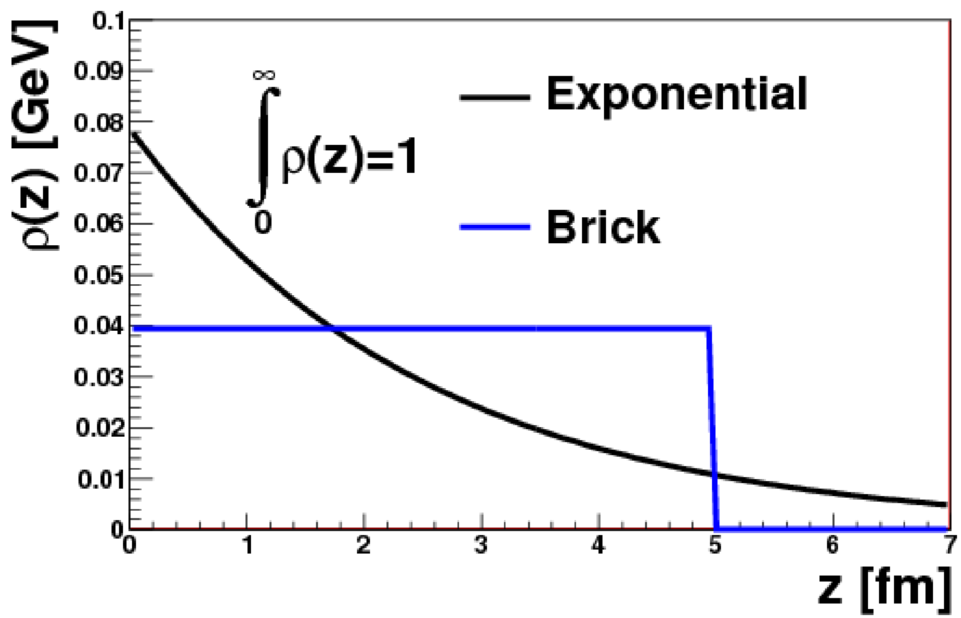
$$\mu(\mathbf{z})^2 = (1 + \frac{1}{6}N_f)g^2\mathbf{T}(\mathbf{z})^2$$

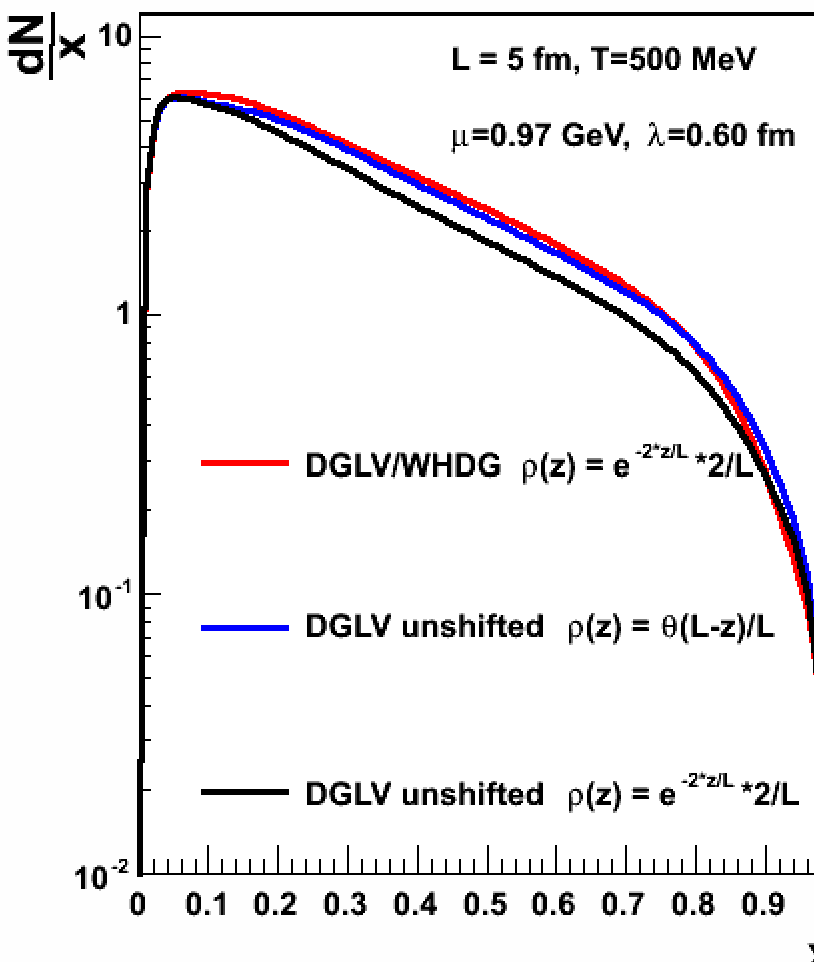
- Medium: participant scaling + Bjorken expansion + constant medium density prior to formation time



Single gluon spectrum (D)GLV

- Normalized $\rho(z)$ is varied and compared to the WHDG result
- In WHDG radiative change of variables $\mathbf{q} \rightarrow \mathbf{q+k}$ is applied
- **Similar spectrum in case of exponentially decaying and uniform (brick) distribution of scattering centers.**





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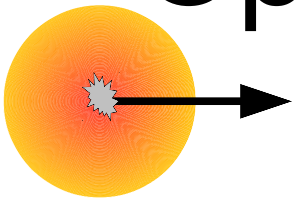
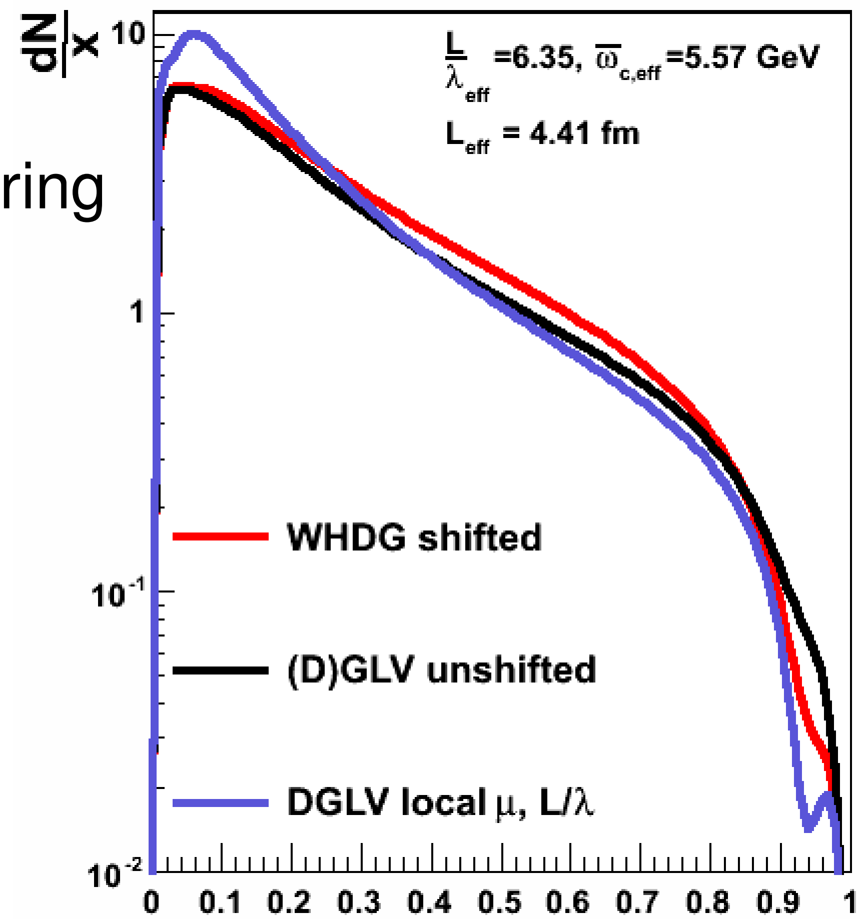
Opacity expansion + evolving participant scaling



- Parton starts at center of medium and moves radially outwards.
- More soft gluon radiation in case of inhomogeneous distribution of scattering centers

Single gluon spectrum



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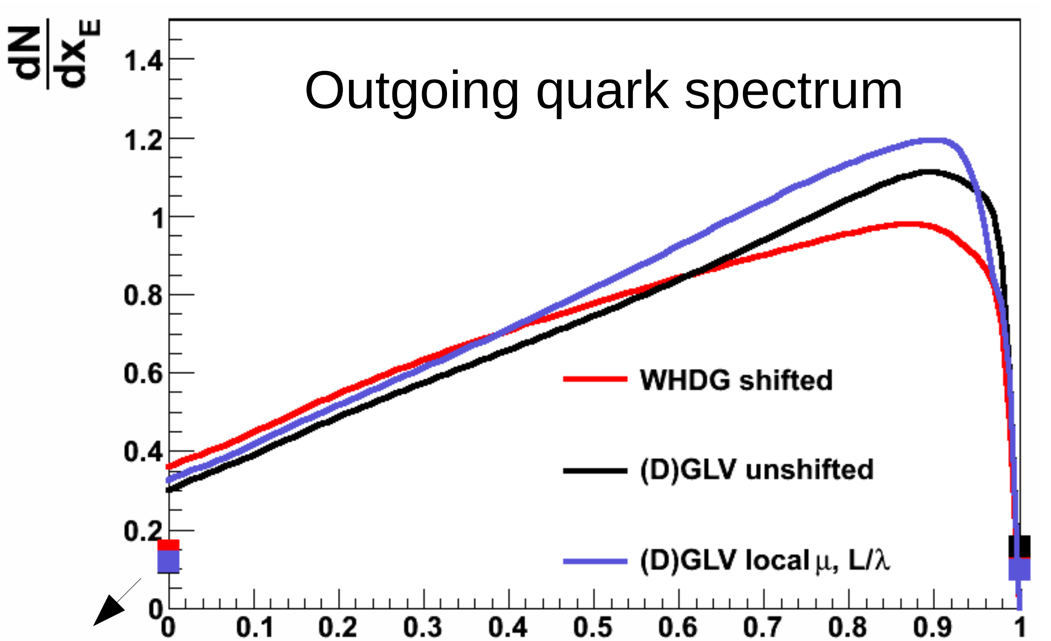

Parton is absorbed by the medium

No energy loss