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Vector Boson Tagged Jets and Jet Substructure

XLVII International Symposium on Multiparticle Dynamics, September 2017

Tlaxcala, Mexico

Outline

Thanks to the organizers for the opportunity to present this talk

- Vector boson-tagged jets utility and baseline calculations
- Radiative and collisional energy loss effects on V-boson tagged jet asymmetry distributions
- Inclusive and tagged jet substructure - momentum sharing distributions and shapes

γ-tagged & Z°-tagged jets

- Proposed as golden channel to study jet quenching, $p_{T\,jet} = p_{T\,Z}$

T.Awes et al. (2003)

- MCFM (Monte Carlo for Femtobarn Processes)
- JETPHOX

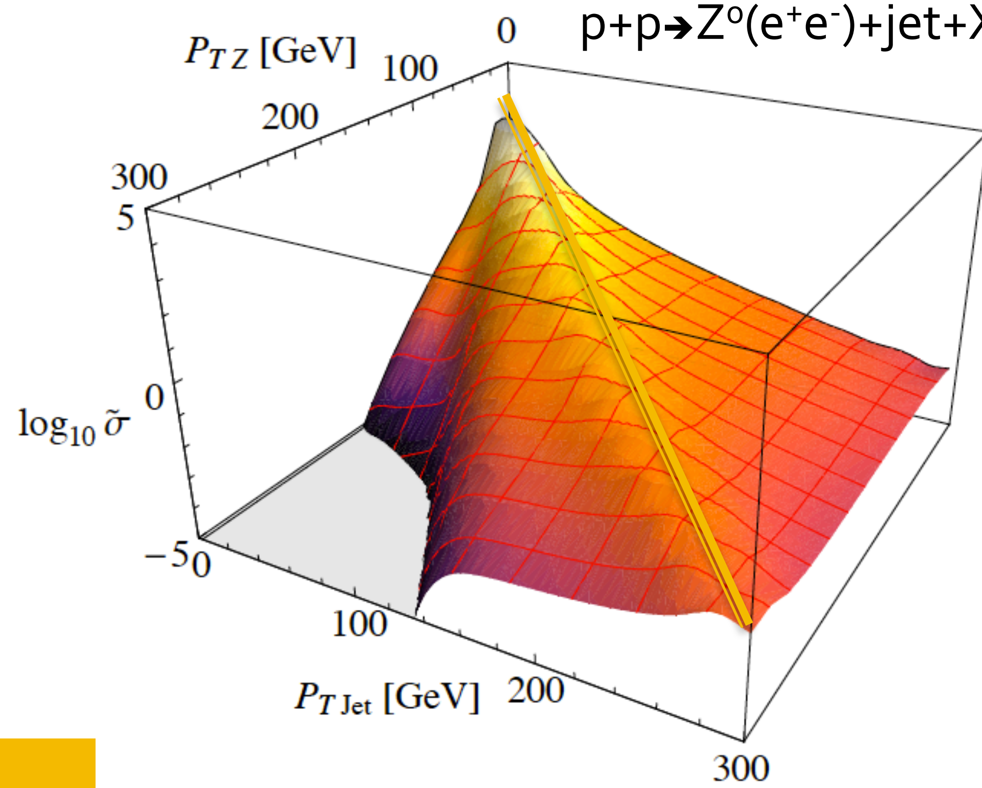
J. Campbell et al (1992, 1996)

S. Catani et al (2002)

- Z° production, integrating over large p_T range – NLO accuracy
- For the double differential cross section - lowest non-trivial order $O(\alpha_s^2 G_F)$, $O(\alpha_s^2 \alpha_{em})$

R.B.Neufeld et al. (2011)

p+p→Z°(e⁺e⁻)+jet+X

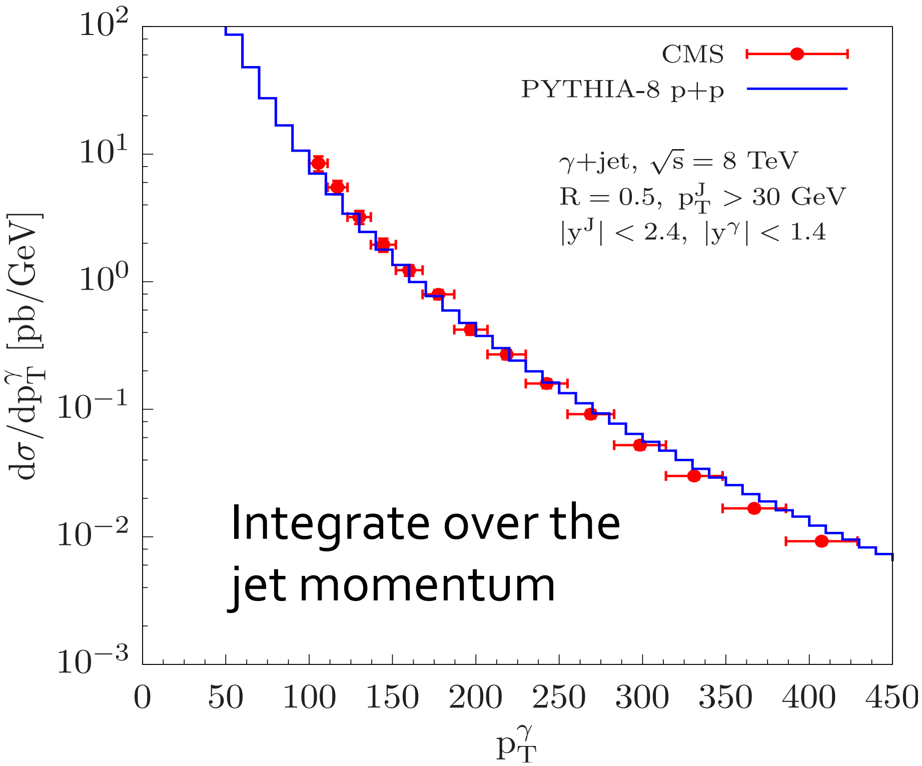


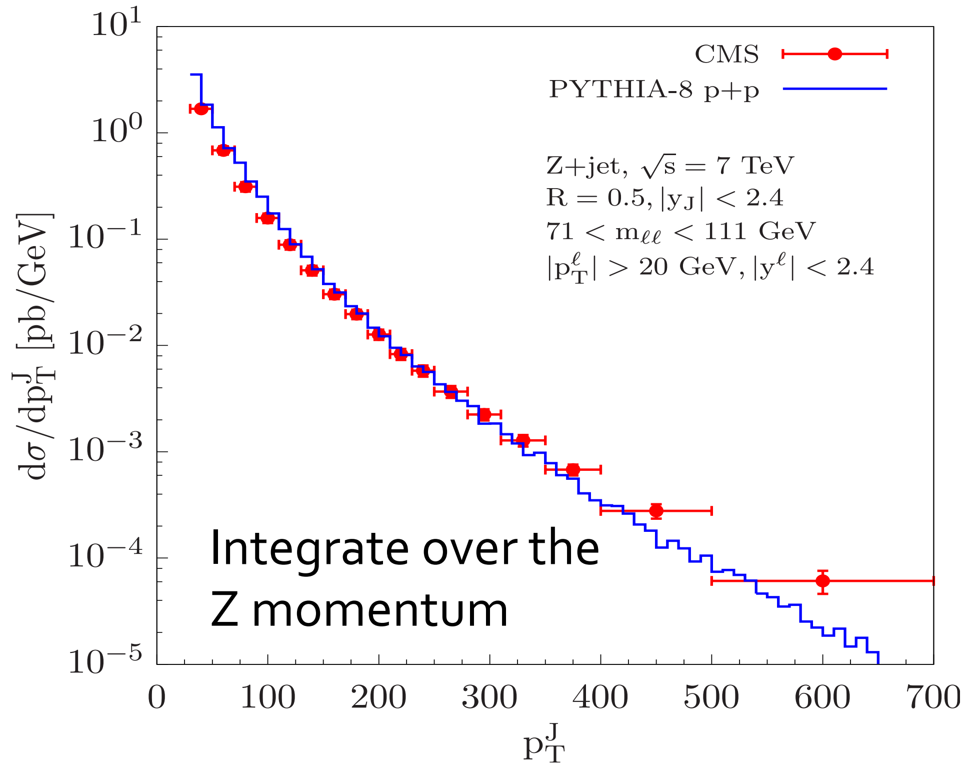
		LO	R = 0.2	R = 0.4
p_T^Z = 7-13 GeV	$\langle p_T^{jet}\rangle$	9.29	8.72	9.38
	$\Delta\langle p_T^{jet}\rangle$	2.18	4.45	4.67
p_T^Z = 92.5-112.5	$\langle p_T^{jet}\rangle$	100.79	93.91	96.63
	$\Delta\langle p_T^{jet}\rangle$	6.95	25.19	24.88

Baseline calculations and validation for the LHC

- We use PYTHIA for the baseline jet

T. Sjostrand et al (2008)



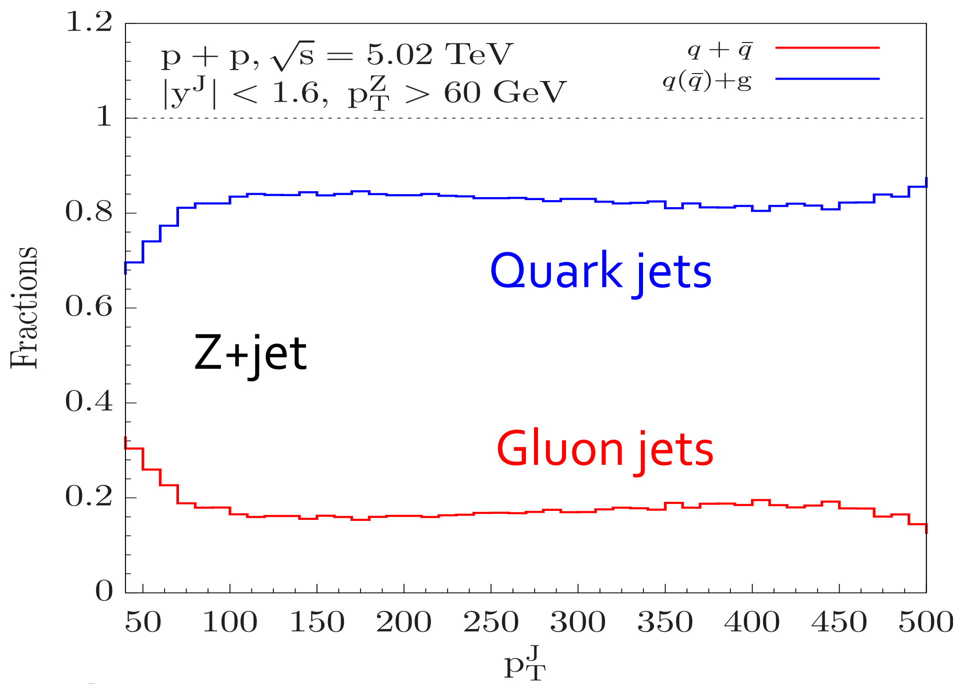


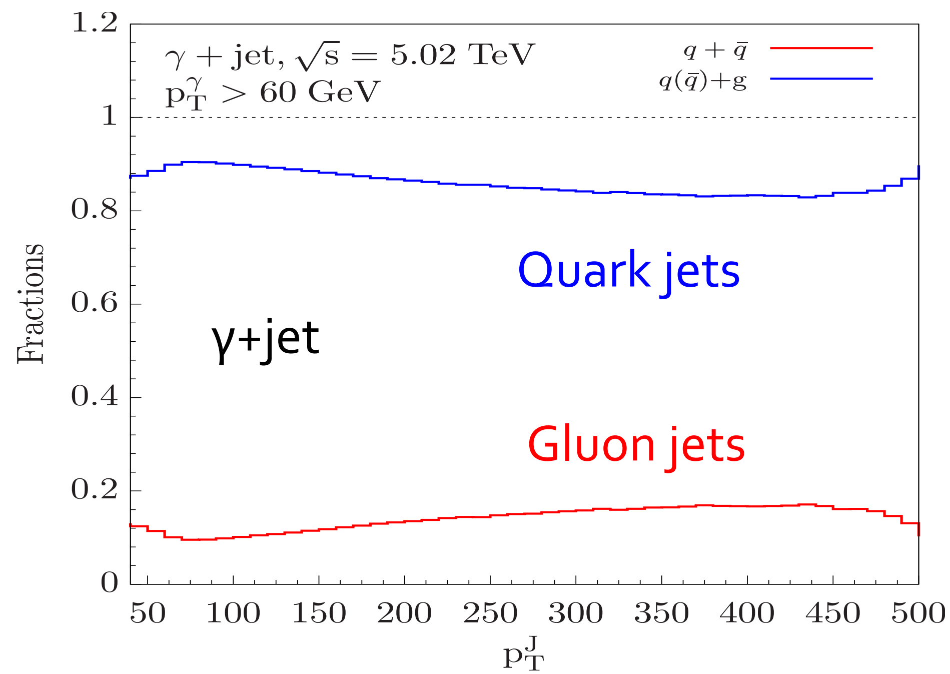
- Fixed order calculations exhibit soft divergence around $p_{T\,jet} = p_{T\,Z}$. Must integrate over a wide bin to ensure R+V cancelation. In this region need improved treatment
- PYTHIA parton shower, soft gluon resummation at LL or better accuracy. Gives good (for LO+PS) description of γ-tagged & Z^o-tagged jets at the LHC

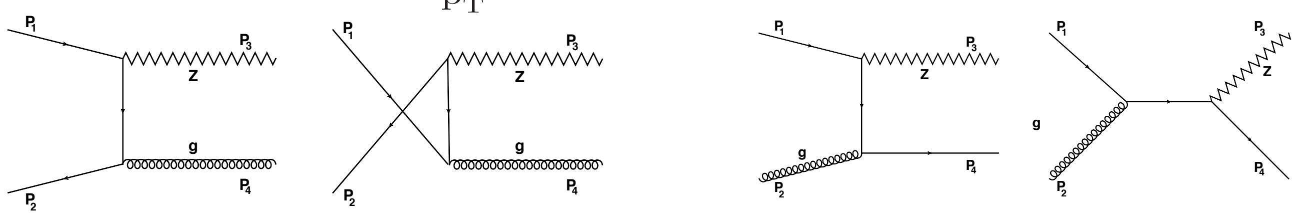
Flavor tagging of jets

- Growing interest in flavor separation for jets. Within SCET various techniques have been proposed

A. Larkoski et al (2014)





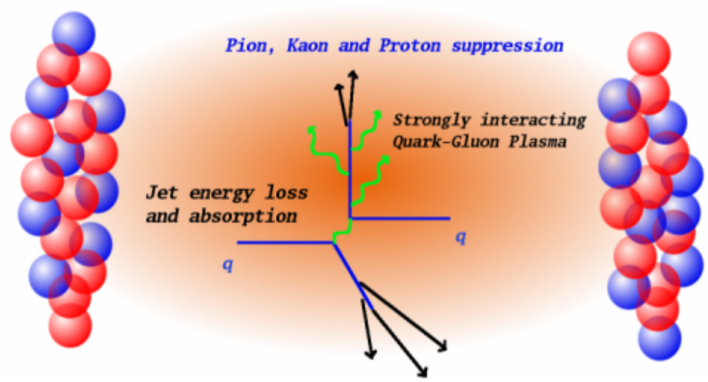


Dominate due to gluonic initial state

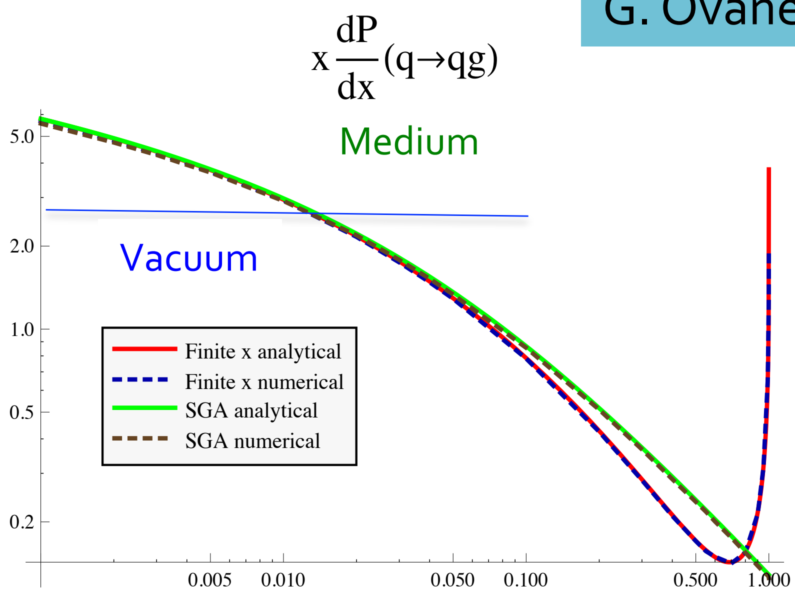
- Vector boson tagging – simplest way to achieve ~80% quark jet purity

Theoretical foundations

- The origin of all jet quenching phenomena is a medium-modified parton shower



G. Ovanesyan et al. (2011)



- Evaluated the medium induced splitting kernels beyond the soft gluon approximation
- Demonstrated the factorization of the final-state radiative corrections form the hard scattering

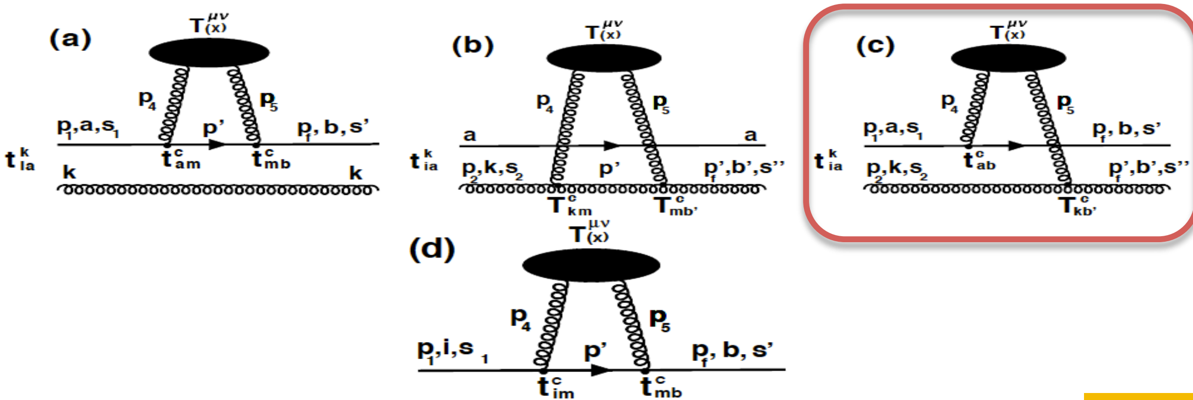
Different angular (broader) and momentum fraction x (softer) distributions

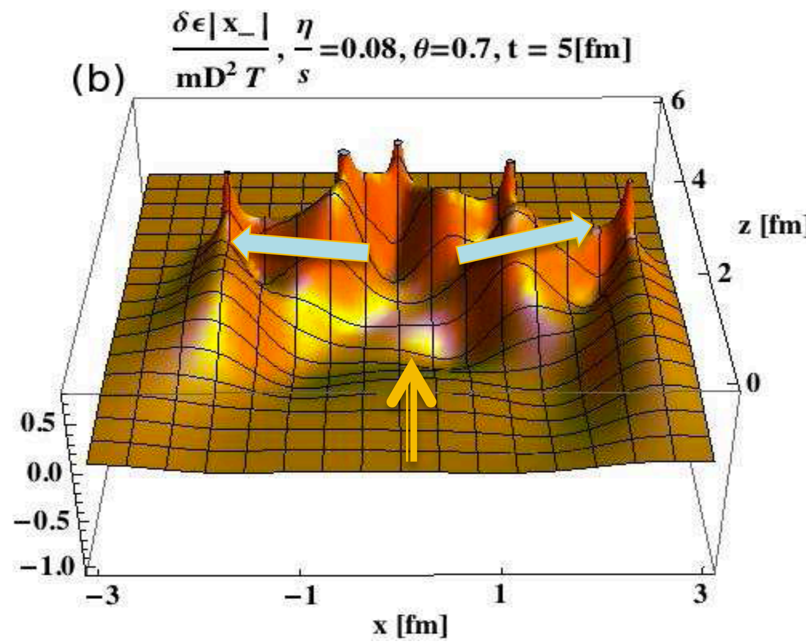
$$k^+\frac{dN^g_{q,g}(k^+,\mathbf{k})}{dk^+d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\int_0^\infty d\Delta z\,\frac{1}{\lambda_g(\Delta z)}\left[\int d^2\mathbf{q}\left(\frac{1}{\sigma_{el}(\Delta z)}\frac{d\sigma_{el}(\Delta z)}{d^2\mathbf{q}}-\delta^2(\mathbf{q})\right)\right] \times\frac{2\mathbf{k}\cdot\mathbf{q}}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}\left\{1-\cos\left[\frac{(\mathbf{k}-\mathbf{q})^2}{k^+}\Delta z\right]\right\}$$

M.Gyulassy, P.Levai, I.V. (2000)

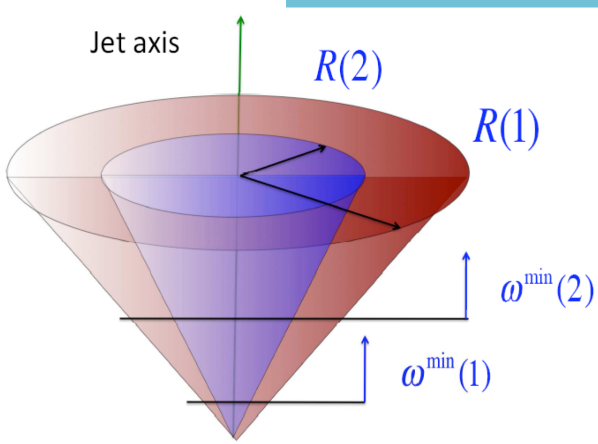
Theoretical foundations

- Collisional energy loss evaluated from the response of the medium to the external color currents of the shower





B. Neufeld et al.. (2011)



Parton shower energy dissipation in the QGP. Approximation that the soft modes are thermalized

$$\Delta E^{\rm coll}_{q,g}({\rm tot.}) = \sum^{N^{\rm tot.\ partons}_{q,g}} \int^{\infty} \frac{d\Delta E^{\rm coll}_i}{d\Delta z} d\Delta z \, ,$$

$$\Delta E^{\rm coll}_{q,g}({\rm tot.}) = \int_0^{\omega_{\rm min}} d\omega \int_0^{R_{\rm max}} dr \, \omega \frac{dN^g_{q,g}(\omega, r)}{d\omega dr} .$$

Application to phenomenology

- Cross section evaluation, contains full 2D information about the quenching of vector boson-tagged jets

$$\frac{d\sigma^{AA}(|\mathbf{b}_\perp|)}{dp_T^V dp_T^J} = \int d^2\mathbf{s}_\perp T_A\left(\mathbf{s}_\perp - \frac{\mathbf{b}_\perp}{2}\right) T_A\left(\mathbf{s}_\perp + \frac{\mathbf{b}_\perp}{2}\right) \sum_{q,g} \int_0^1 d\epsilon \frac{P_{q,g}(\epsilon; \mathbf{s}_\perp, |\mathbf{b}_\perp|)}{1 - f_{q,g}^{\rm loss}(R; \mathbf{s}_\perp, |\mathbf{b}_\perp|)\,\epsilon}$$
$$\times \frac{d\sigma_{q,g}^{NN}\left(p_T^V, p_T^J/\{1 - f_{q,g}^{\rm loss}(R; \mathbf{s}_\perp, |\mathbf{b}_\perp|)\,\epsilon\}\right)}{dp_T^J dp_T^V}.$$

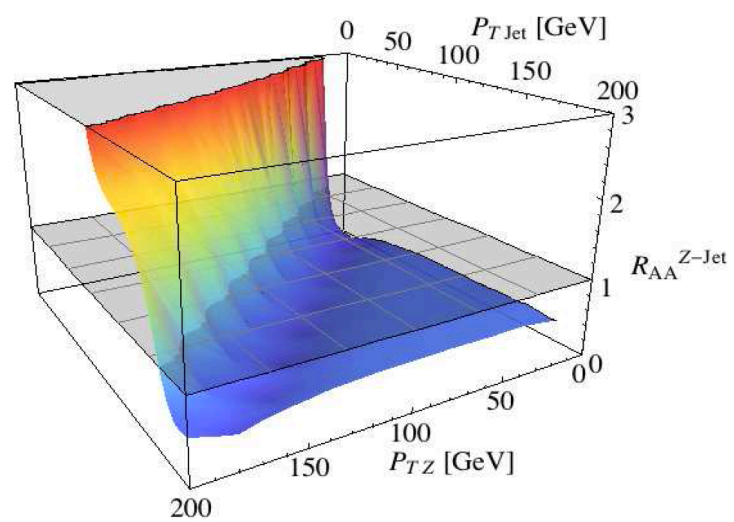
Energy fraction ε redistributed to in-medium shower

$$f_{q,g}^{\rm loss}(R; {\rm rad + coll}) = 1 - \left(\int_0^R dr \int_{\omega_{\rm min}}^E d\omega \frac{dN_{q,g}^g(\omega, r)}{d\omega dr}\right) \Big/ \left(\int_0^{R_{\rm max}} dr \int_0^E d\omega \frac{dN_{q,g}^g(\omega, r)}{d\omega dr}\right)$$

Energy loss fraction (both radiative and collisional) from the point of view of the jet

- Example of Z⁰+jet quenching

$$R_{AA}^{\rm Z-jet}(p_{T\,Z}, p_{T\,\rm Jet}; R, \omega_{\rm min}) = \frac{\frac{d\sigma_{AA}}{dp_{T\,Z}\,dp_{T\,\rm Jet}}}{\langle N_{\rm bin}\rangle \frac{d\sigma_{pp}}{dp_{T\,Z}\,dp_{T\,\rm Jet}}}$$



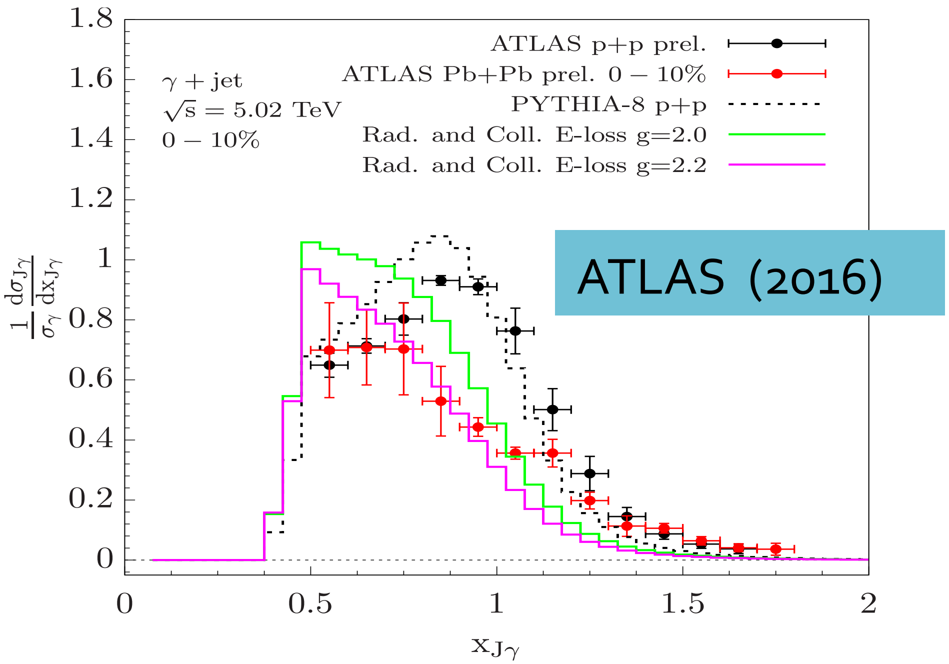
Evaluating momentum imbalance distributions

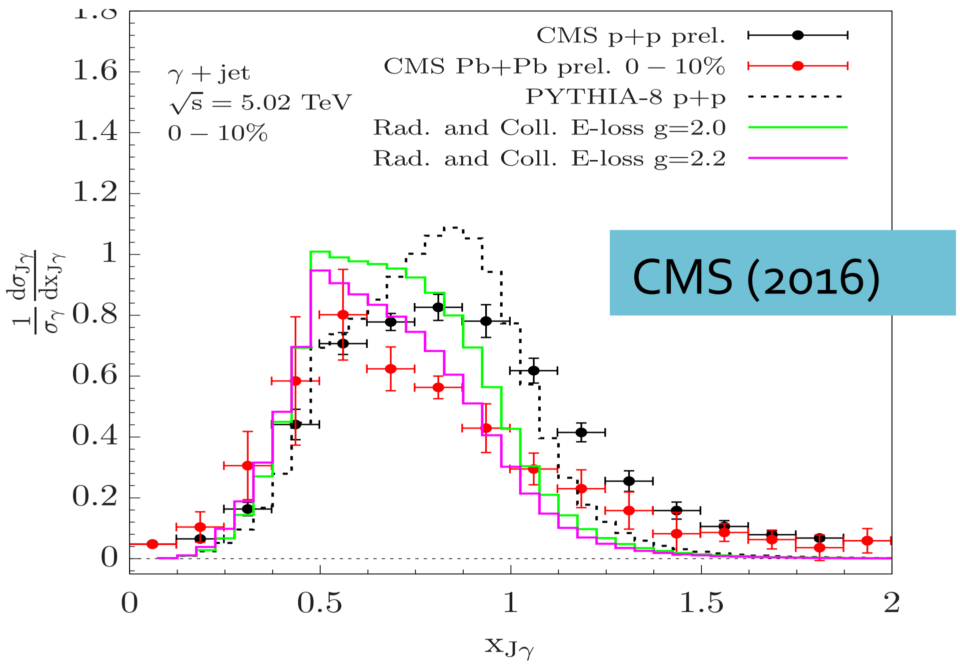
- Momentum imbalance. Jacobian transformation

Z. Kang et al (2017)

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

$$\frac{d\sigma}{dx_{JV}} = \int_{p_T^{J,\min}}^{p_T^{J,\max}} dp_T^J \frac{p_T^J}{x_{JV}^2} \frac{d\sigma(p_T^V = p_T^J / x_{JV}, p_T^J)}{dp_T^V dp_T^J}$$





- Downshift in the momentum imbalance distributions comparable to what is see in the experiment. Sensitivity of the coupling of the jet to the medium
- Theory distributions are slightly narrower and sharper but don't include resolution efects

Quantifying the momentum imbalance shift

- Evaluate the mean and shift of the distributions

Z. Kang et al (2017)

$$\langle x_{JV} \rangle = \left(\int dx_{JV} x_{JV} \frac{d\sigma}{dx_{JV}} \right) \Big/ \left(\int dx_{JV} \frac{d\sigma}{dx_{JV}} \right)$$

$$\Delta \langle x_{JV} \rangle = \langle x_{JV} \rangle_{pp} - \langle x_{JV} \rangle_{PbPb}$$

- Photon-jets

	$\Delta\langle x_{J\gamma}\rangle$				
p_T^γ (GeV)	$40-50$	$50-60$	$60-80$	$80-100$	$100-120$
CMS prel. [25]	0.008±0.074	0.043±0.069	0.081±0.059	0.054±0.044	0.115±0.047
Rad. + Coll. $g=2.0$	0.021	0.044	0.065	0.075	0.065
Rad. + Coll. $g=2.2$	0.025	0.055	0.085	0.103	0.115

typo

This is the place to look in the imbalance shift to look at energy loss

- Compare theory input to theory output Ejet = 100 GeV, R=0.3

	$\langle \Delta E^{out}_{q,g} \rangle = E^{jet}_{q,g} \langle \epsilon \rangle f^{loss}_{q,g}(R)$			
Type of E-loss	Rad. g=2.0	Rad.+Col. g=2.0	Rad. g=2.2	Rad.+Col. g=2.2
Prompt quark-initiated jet	7 GeV	8 GeV	10 GeV	14 GeV
Prompt gluon-initiated jet	15 GeV	18 GeV	21 GeV	29 GeV

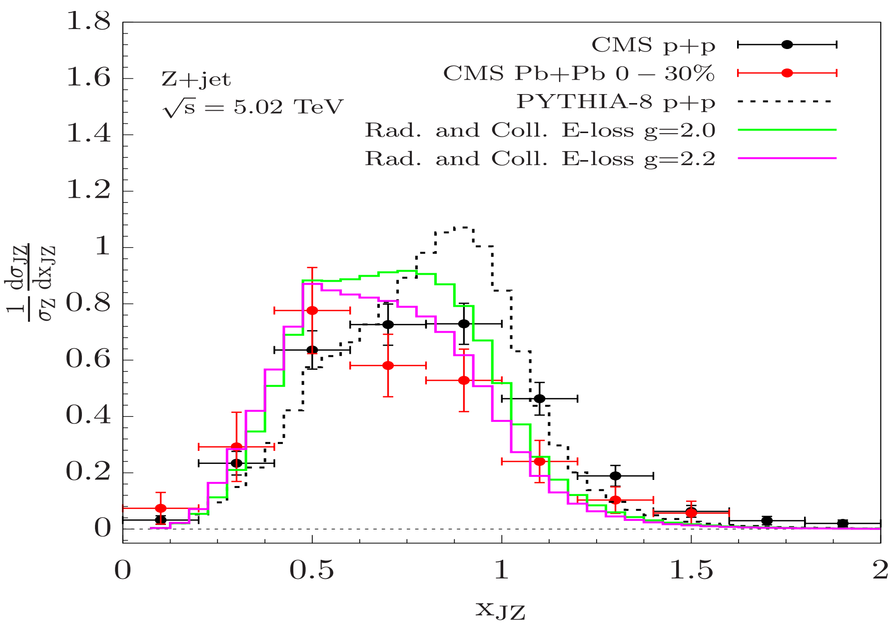
Zº-tagged jets

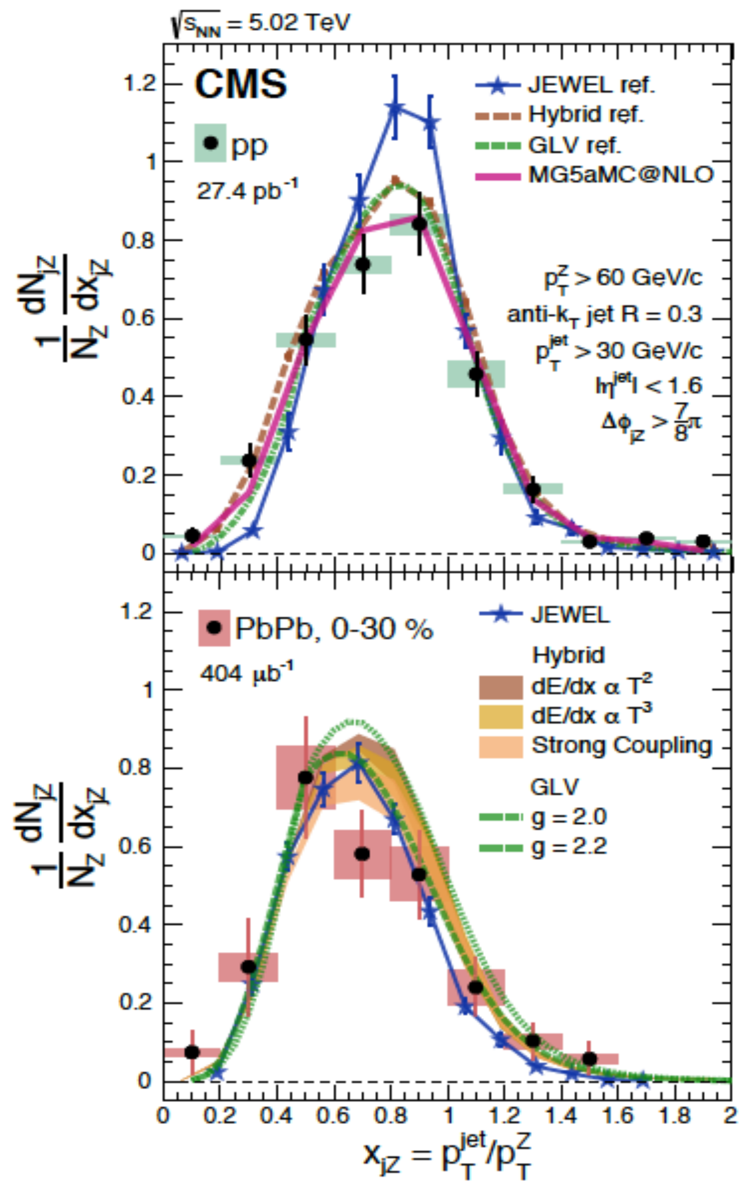
- ATLAS had the first preliminary data back at 2011. CMS now

ATLAS (2011)

CMS (2011)

- Different experiments use different strategies. ATLAS hold on for unfolding. Of detector resolution. CMS provides smearing function

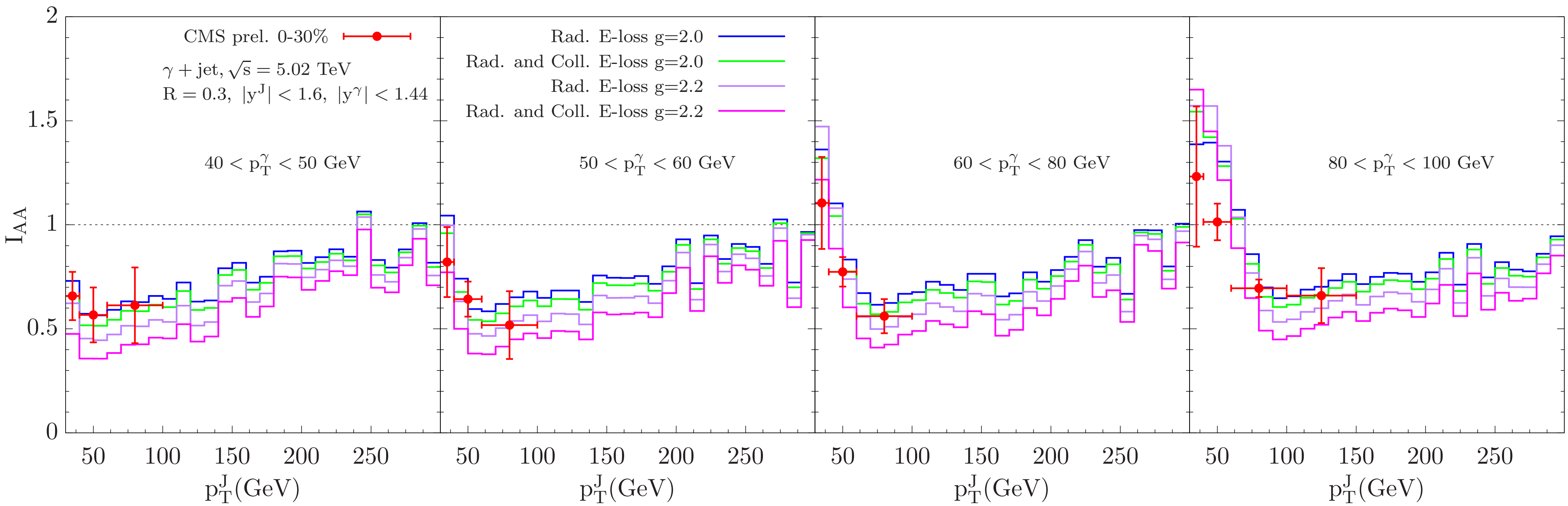




The nuclear modification of tagged jets

- The non-monotonic R_{AA}, I_{AA} for jets discovered at LHC

$$I_{AA} = \frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^{AA}}{[p_T^V] dp_T^J} \Big/ \frac{d\sigma^{pp}}{[p_T^V] dp_T^J} \qquad \frac{d\sigma}{[p_T^V] dp_T^J} \equiv \int_{p_T^{V,min}}^{p_T^{V,max}} \frac{d\sigma}{dp_T^V dp_T^J}$$



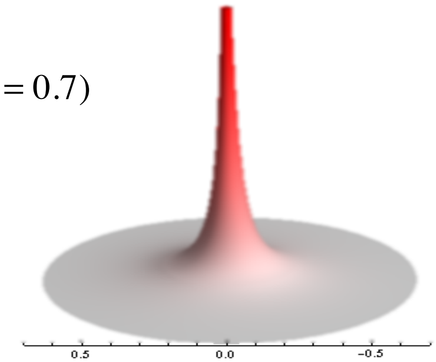
- For Z^o + jet production, predictions are available. Measurements likely limited by statistics. Qualitatively the same behavior

Z. Kang et al (2017)

What is jet substructure?

Reconstruct the jet and then look inside

$r \subset (0, R = 0.7)$



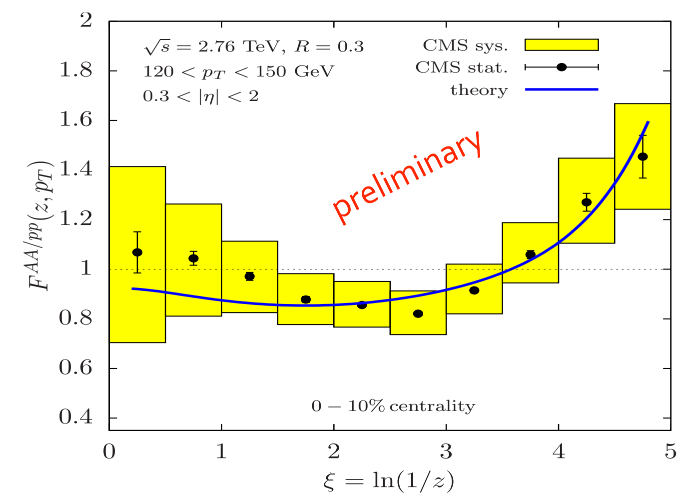
Jet shapes

$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r - (R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R - (R_{\rm jet})_i)} ,$$

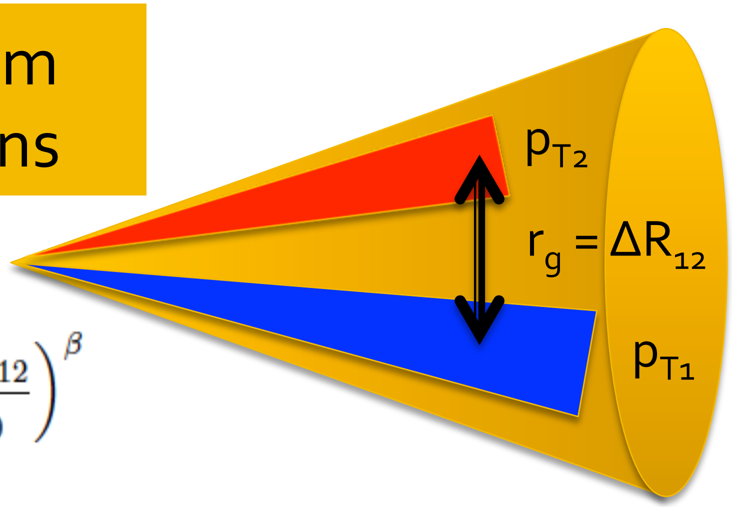
$$\psi(r;R) = \frac{d\Psi_{\rm int}(r;R)}{dr} .$$

Jet fragmentation functions

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



Subject momentum sharing distributions

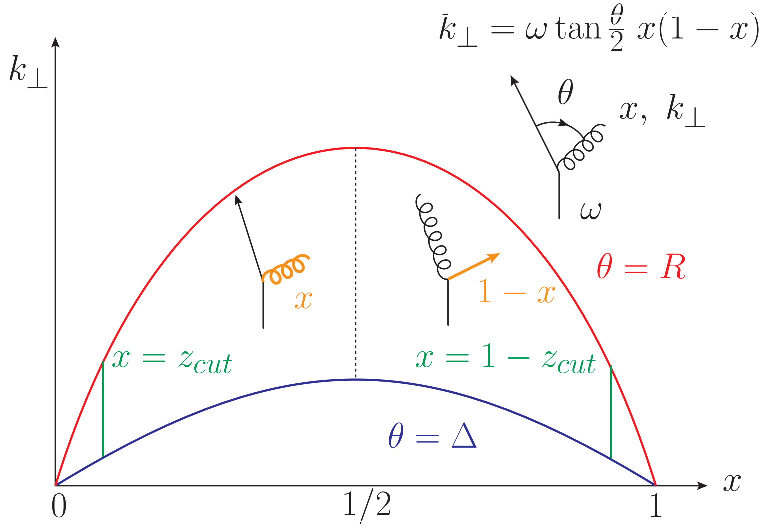


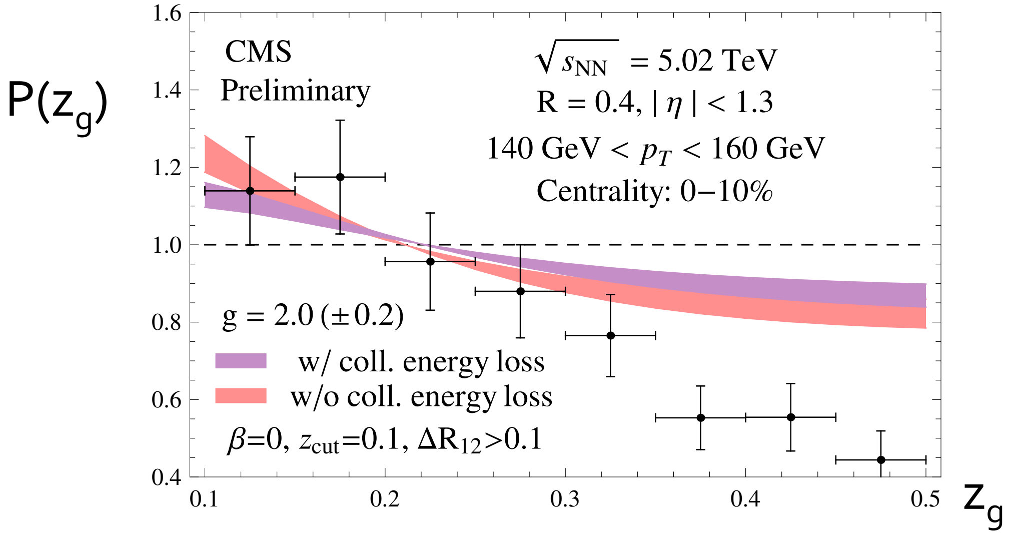
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

A. Larkoski et al . (2014)

Accessing the hardest branching in HIC – longitudinal modification

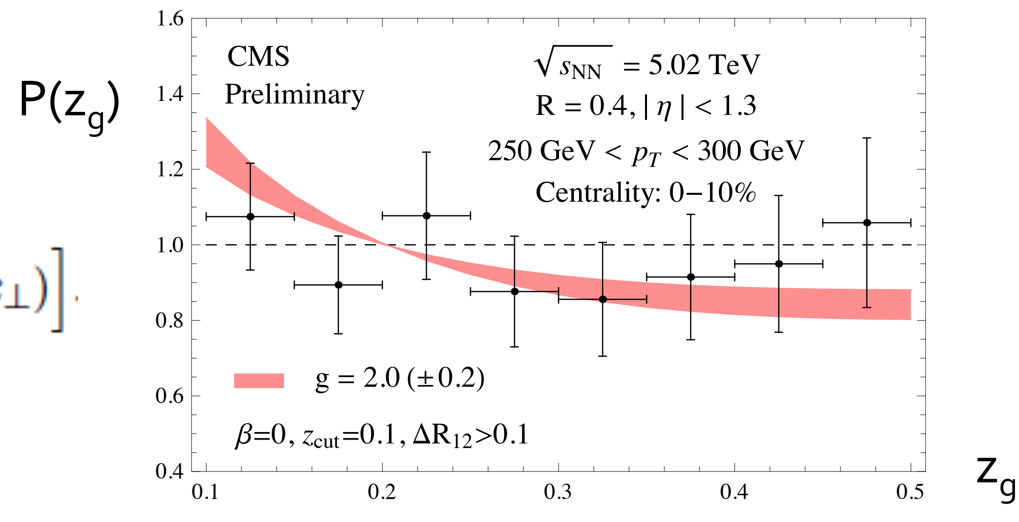
Calculating the soft dropped distribution with β=o





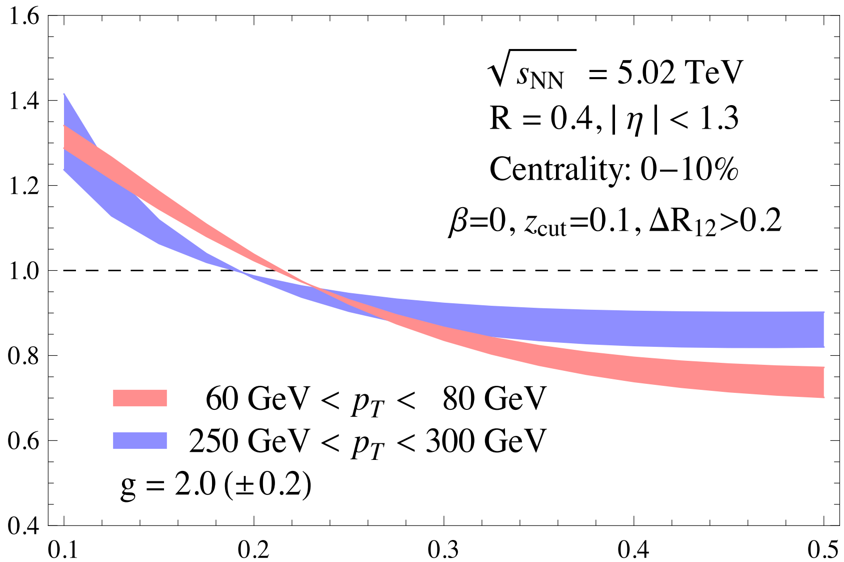
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}$$

$$\overline{\mathcal{P}}_i(x, k_\perp) = \sum_{j,l} \left[\mathcal{P}_{i\to j,l}(x, k_\perp) + \mathcal{P}_{i\to j,l}(1-x, k_\perp)\right].$$



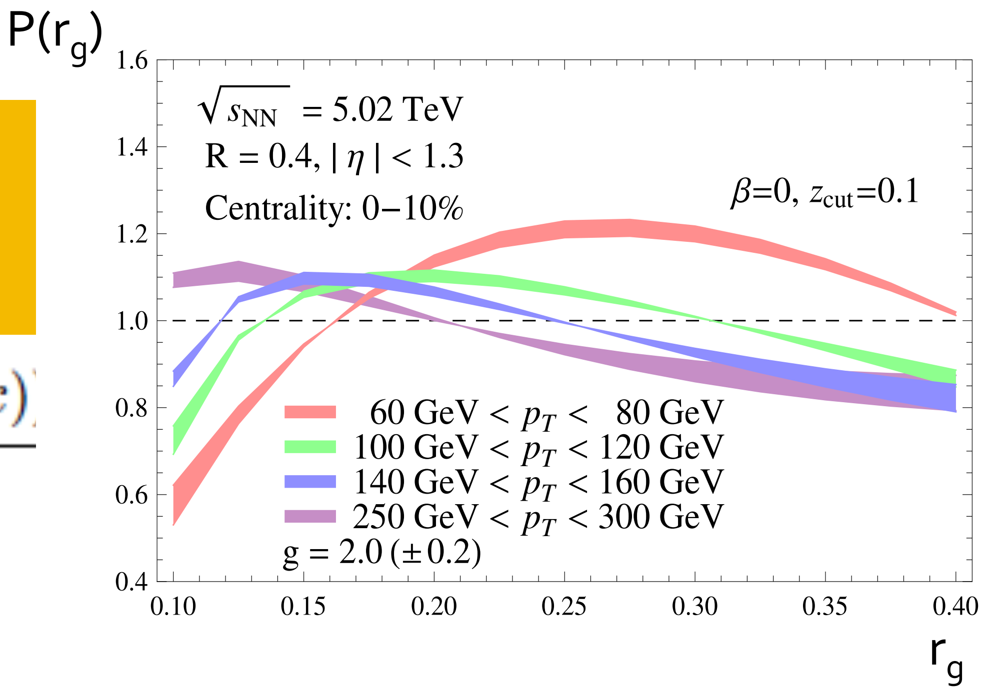
Y.T Chien et al . (2016)

Modification of the angular distribution of hardest branchings



Flexibility in selecting angular separation r_g

Found that inermediate values r_g = 0.2 give the strongest p_T dependence. Though not nearly as strong as preliminary data



New observable proposed – measures the typical splitting angle modification in HIC

$$p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x)\overline{\mathcal{P}}_i(x, k_\perp(r_g, x))}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}$$

Y.-T. Chien et al . (2016)

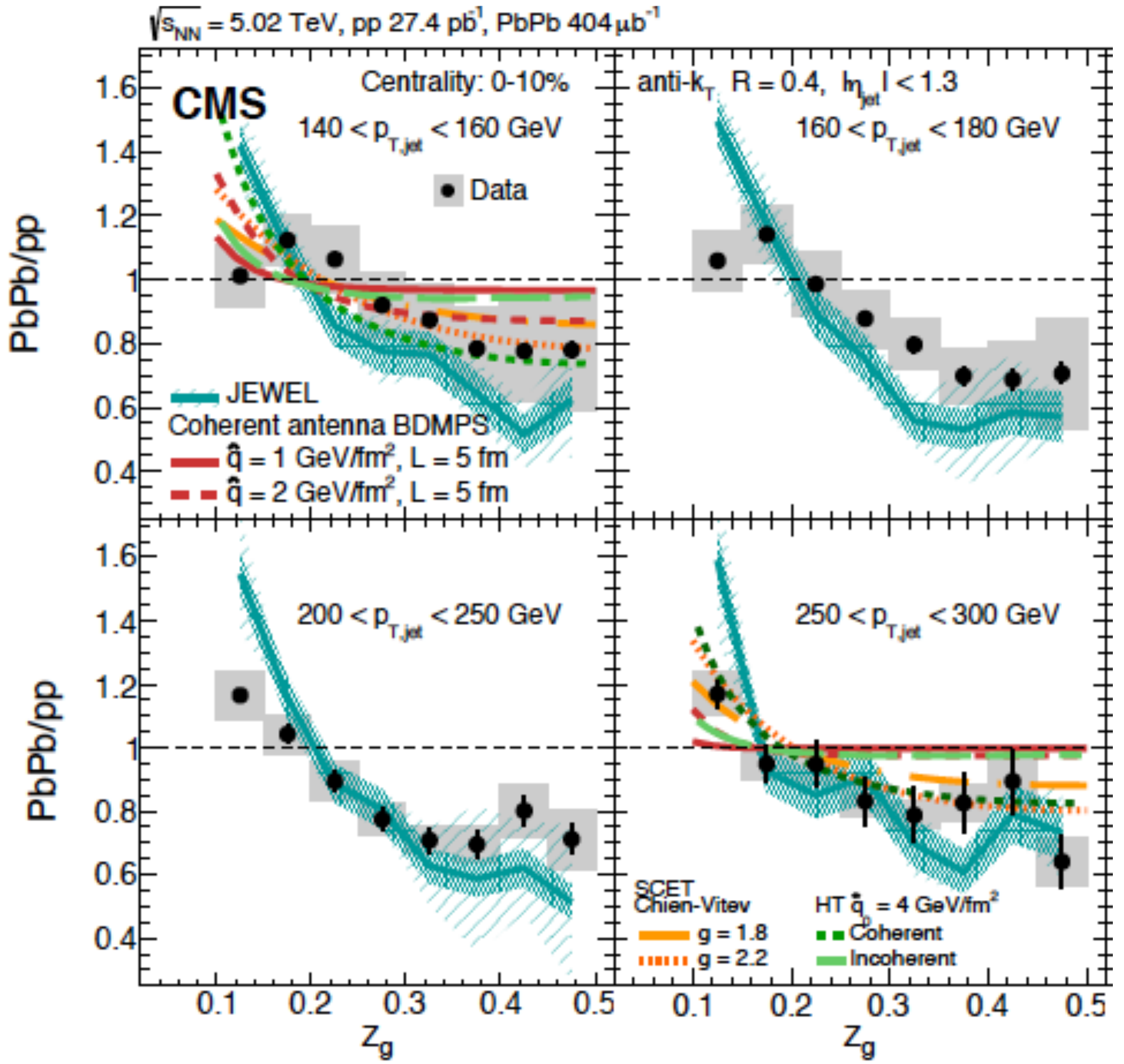
Update on the CMS data

Lowest p_T bin data moved up quite significantly. Systematic error bars large (but perfect agreement with predictions)

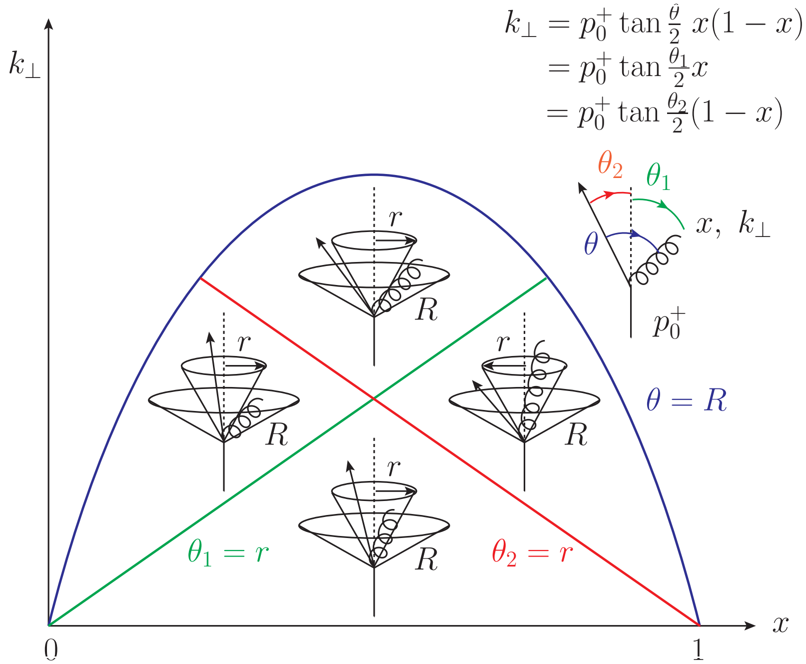
Comments on the earlier figure "~ The strong p_T dependence dependence is a salient feature of the data. The letter should be rejected"

There is a lesson to be learned (at least for the young participants)

And a concern: is there any understanding left in the field what theory (and science in general) is all about?



Medium-modified jet shapes at NLL



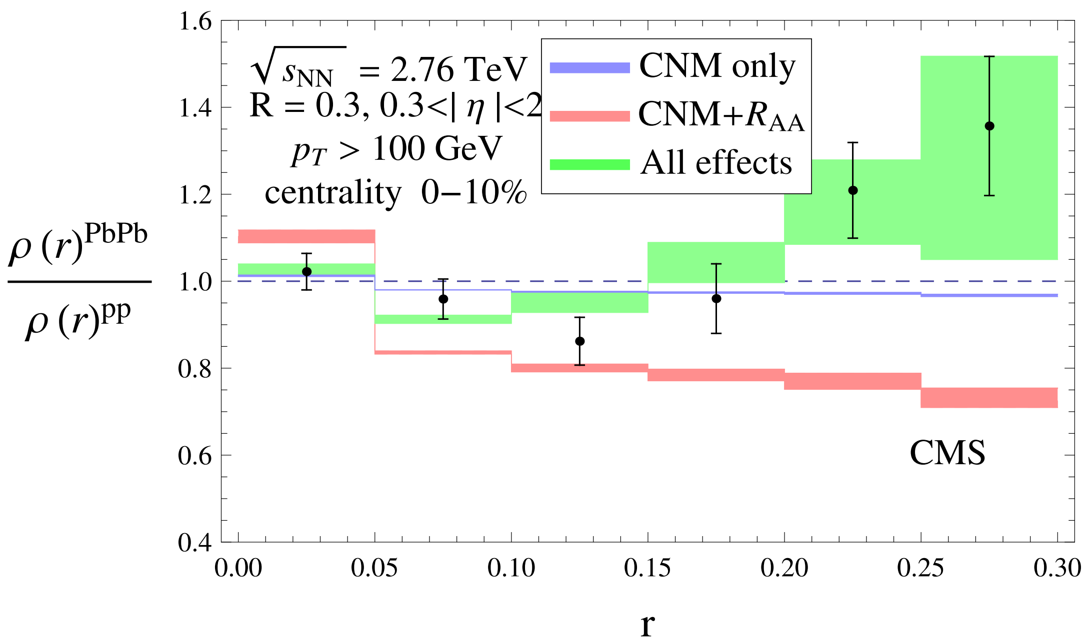
$$E_r(x, k_\perp) = \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3 + \mathcal{M}_4$$

Measurement operator – tells us how the above configurations contribute energy to J (jet function)

- One can evaluate the jet energy functions from the splitting functions

$$J^i_{\omega,E_r}(\mu) = \sum_{j,k} \int_{PS} dx dk_\perp \mathcal{P}_{i\to jk}(x, k_\perp) E_r(x, k_\perp)$$

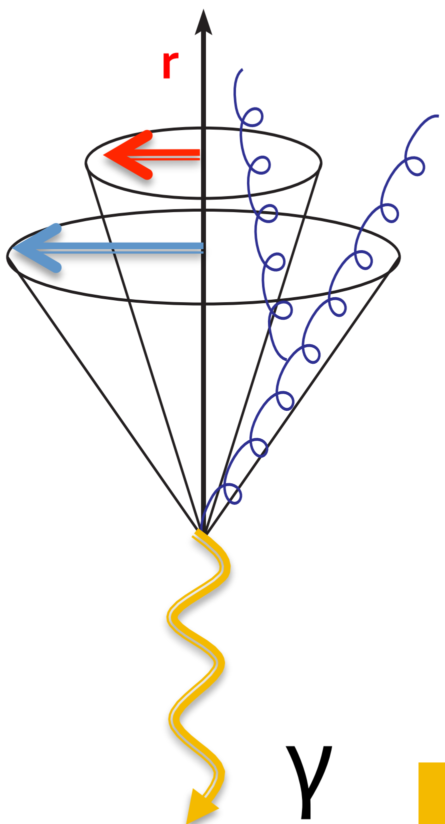
$$J_{\omega,E_r}(\mu) = J^{vac}_{\omega,E_r}(\mu) + J^{med}_{\omega,E_r}(\mu).$$



- First quantitative pQCD/SCET description of jet shapes in HI

Predictions for the 5.1 TeV Pb+Pb run at the LHC

- We extend predictions for other observables – photon tagged jets and photon tagged jet shapes

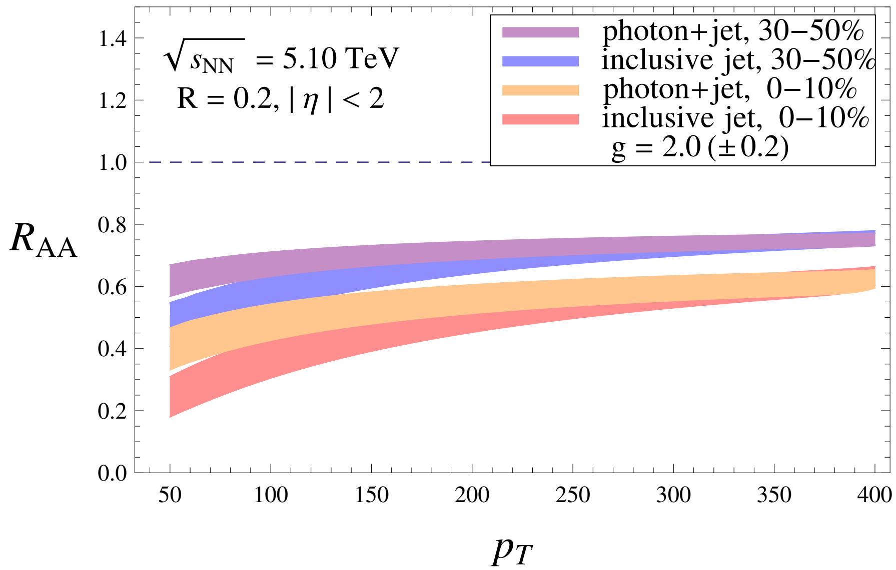


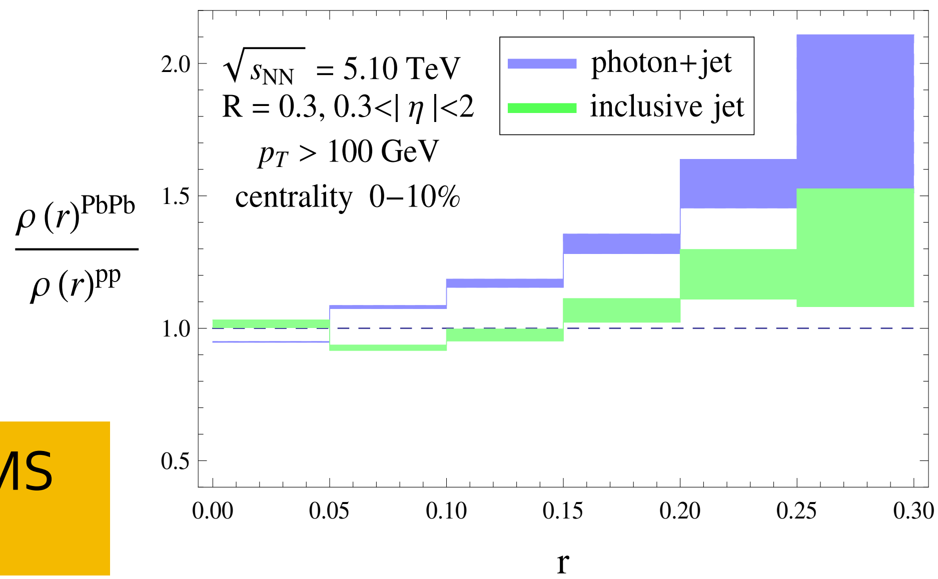
Y.-T. Chien et al. (2015)

Photon tagging allows to alter/control the recoil jet composition

Measurable differences are predicted in the jet suppression at low p_T

Significant differences are expected in the jet shapes





- Being measured by CMS
- FFs by ATLAS

2018 Jets and heavy flavor workshop

- The in a series of workshops to bring the NP and HEP communities working on jets and heavy flavor, with emphasis on QCD and SCET. And the underlying medium dynamics

Conclusions

- Vector boson-tagged jet measurements are a very important part of the toolkit of jet quenching observables. They provide a way to assess in an almost model independent way the energy loss of reconstructed jets. They also give us access to quark jet samples of good purity (80%)
- An effective theory for jet propagation in matter $SCET_G$ was constructed (collinear and Glauber sectors). Derived all medium-induced parton splittings, proved factorization and gauge invariance for the medium-induced parton splittings. There is also well established soft gluon emission parton energy loss limit. Collisional energy loss of the parton shower also evaluated
- Presented constrained theoretical predictions for the γ-jet and Z^0-jet momentum imbalance distributions and shifts. (We find good agreement with preliminary or published data with g= 2 - 2.2). More importantly we verified that the momentum imbalance shift indeed corresponds to with 10-20% accuracy to the energy loss of reconstructed jets. More detailed studies vs p_T are moving toward a more detailed 2D jet quenching tomography
- Jet substructure observables are difficult to measure but progress is being made. The momentum sharing distributions directly probe the in-medium splitting. At the LHC energies this modification is directly observed and described by a clean theoretical calculation. Important verification of the theory
- Traditional jet substructure observables are also measured (jet shapes and fragmentation functions). Photon tagged jet shape modification predictions are available and we will compare in the future to LHC measurement to pin down the parton flavor dependence of jet quenching phenomena

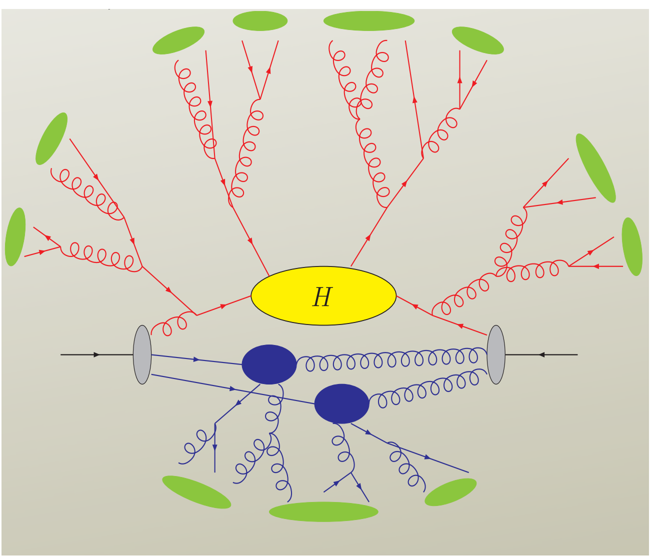
The splitting kernels

- What is missing in the SCET Lagrangian is the interaction between the jet and the medium
- Background field approach

A. Idilbi et al. (2008)

G. Ovanesyan et al. (2011)

$$\mathcal{L}_{\mathrm{G}}(\xi_n, A_n, A_{\mathrm{G}}) = g \sum_{\tilde{p},\tilde{p}'} e^{-i(\tilde{p}-\tilde{p}')\cdot x} \left(\bar{\xi}_{n,p'} T^a \frac{\bar{\not{n}}}{2} \xi_{n,p} - i f^{abc} A^{\lambda c}_{n,p'} A^{\nu,b}_{n,p} g^{\perp}_{\nu\lambda} \bar{n} \cdot p \right) n \cdot A^a_{\mathrm{G}}$$



- Operator formulation for forward scattering / BFKL physics

I. Rothstein et al. (2016)

- Splitting functions are related to beam (B) and jet (J) functions in SCET

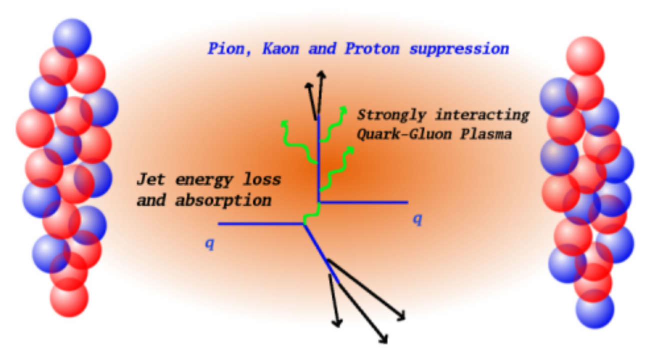
W. Waalewjin. (2014)

Gribov et al. (1972)

G. Altarelli et al. (1977)

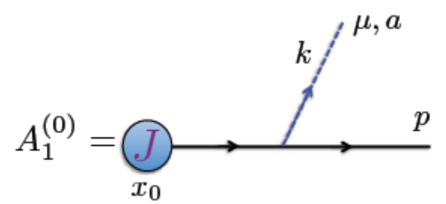
Y. Dokshitzer (1977)

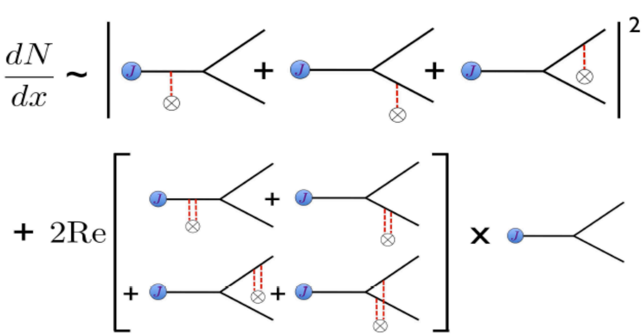
Main results: in-medium splitting / parton energy loss



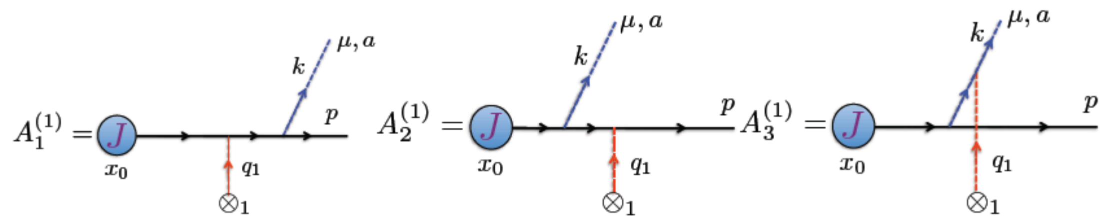
- Organizing principle – build powers of the scattering cross section in the medium

"Vacuum" diagrams

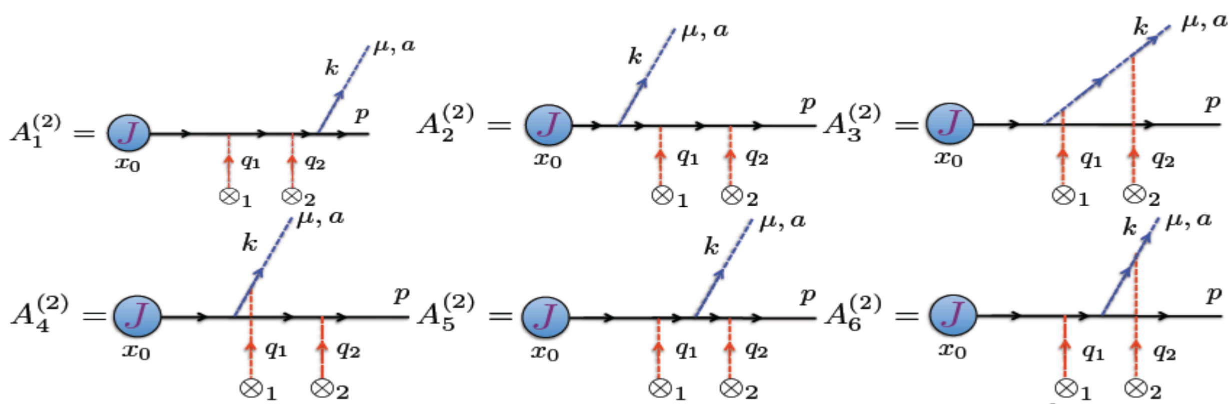




Single Born diagrams



Double Born diagrams



In-medium parton splittings and medium properties

- Direct sum

$$\frac{dN(tot.)}{dxd^2k_\perp} = \frac{dN(vac.)}{dxd^2k_\perp} + \frac{dN(med.)}{dxd^2k_\perp}$$

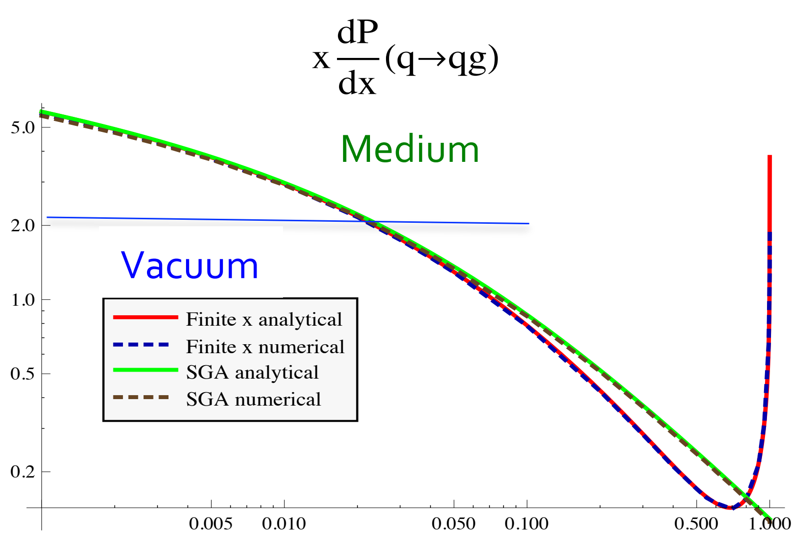
- Derived using SCET_G
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium

G. Ovanesyan et al. (2012)

$$\left(\frac{dN}{dxd^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\mathrm{medium}}}{d^2\mathbf{q}_\perp}\left[-\left(\frac{A_\perp}{A_\perp^2}\right)^2+\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{B_\perp}{B_\perp^2}-\frac{C_\perp}{C_\perp^2}\right)\right.$$
$$\times\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)+\frac{C_\perp}{C_\perp^2}\cdot\left(2\frac{C_\perp}{C_\perp^2}-\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)$$
$$+\frac{B_\perp}{B_\perp^2}\cdot\frac{C_\perp}{C_\perp^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right)+\frac{A_\perp}{A_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{D_\perp}{D_\perp^2}\right)\cos[\Omega_4\Delta z]$$
$$\left.+\frac{A_\perp}{A_\perp^2}\cdot\frac{D_\perp}{D_\perp^2}\cos[\Omega_5\Delta z]+\frac{1}{N_c^2}\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\right].$$

$$N.B.\;\; x\to 1-x \qquad A,\ldots D,\Omega_1\ldots\Omega_5 - functions(x,k_\perp,q_\perp)$$

New physics – many-body quantum coherence effects



- Can be evaluated numerically
- Ready for implementa-tion