Effective Theory Approach to Jet Propagation in Dense QCD Matter

Grigory Ovanesyan

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Boston Jet Physics Workshop

January 12, 2011

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In collaboration with Ivan Vitev

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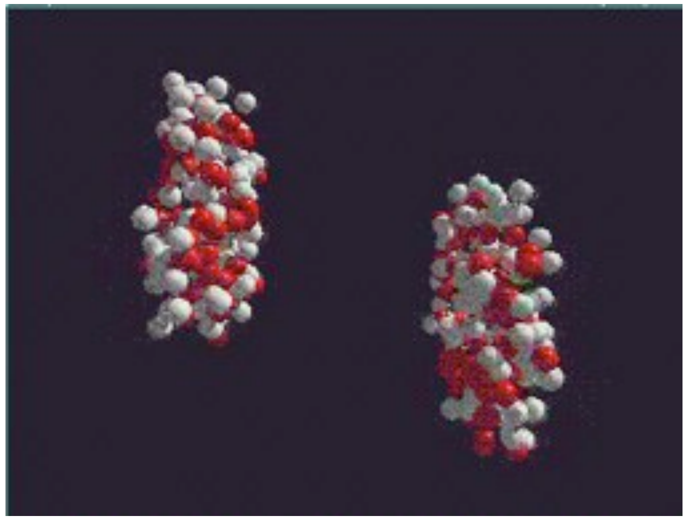
Outline

- Introduction
- Effective theory for jets in the medium
- Results for jet broadening and jet energy loss
- Conclusions

Introduction

Motivation to study heavy-ion collisions



AA at 10GeV

Picture from http://www-subatech.in2p3.fr/~theo/qmd/hic/hic3.html

- Plenty of experimental data available
- To study the properties of Quark Gluon Plasma, predicted by QCD
- Connection to Early Universe (a few microseconds after the Big Bang)

Existing Facilities

Existing Facilities

RHIC

E_{NN}=20-200GeV

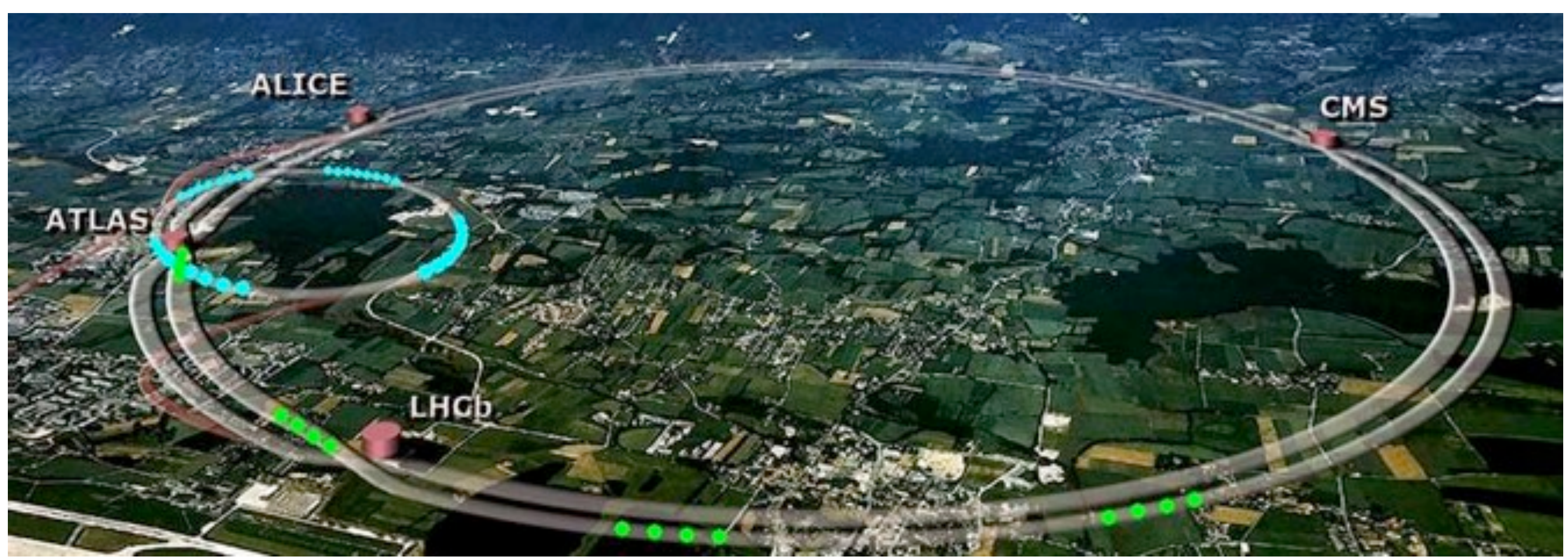
Existing Facilities

E_{NN}=2.76TeV LHC (1 month)

5.5TeV in AA
8.8TeV in pA

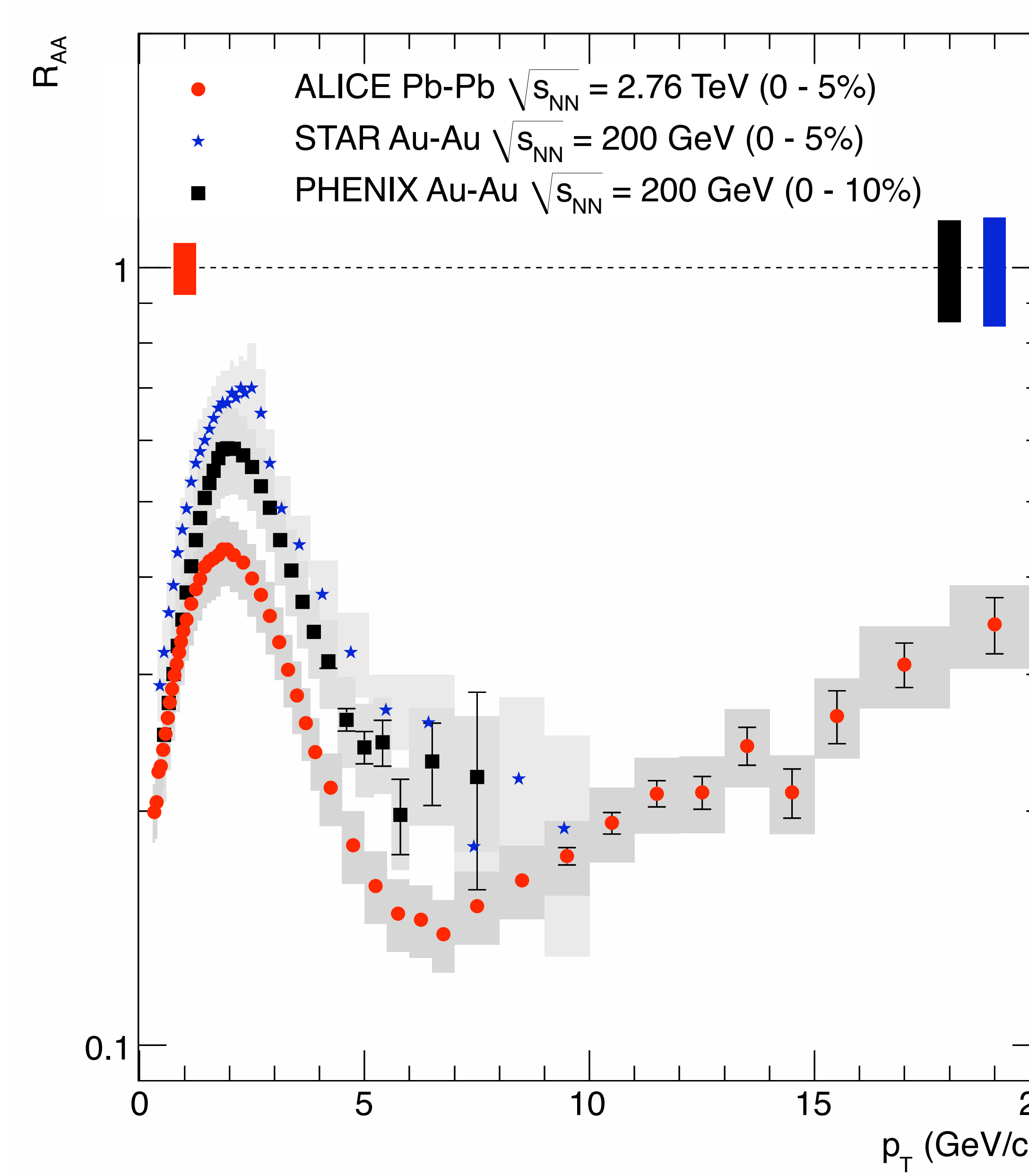
RHIC

E_{NN}=20-200GeV



New LHC heavy ion data!

ALICE collaboration, 11-12/2010



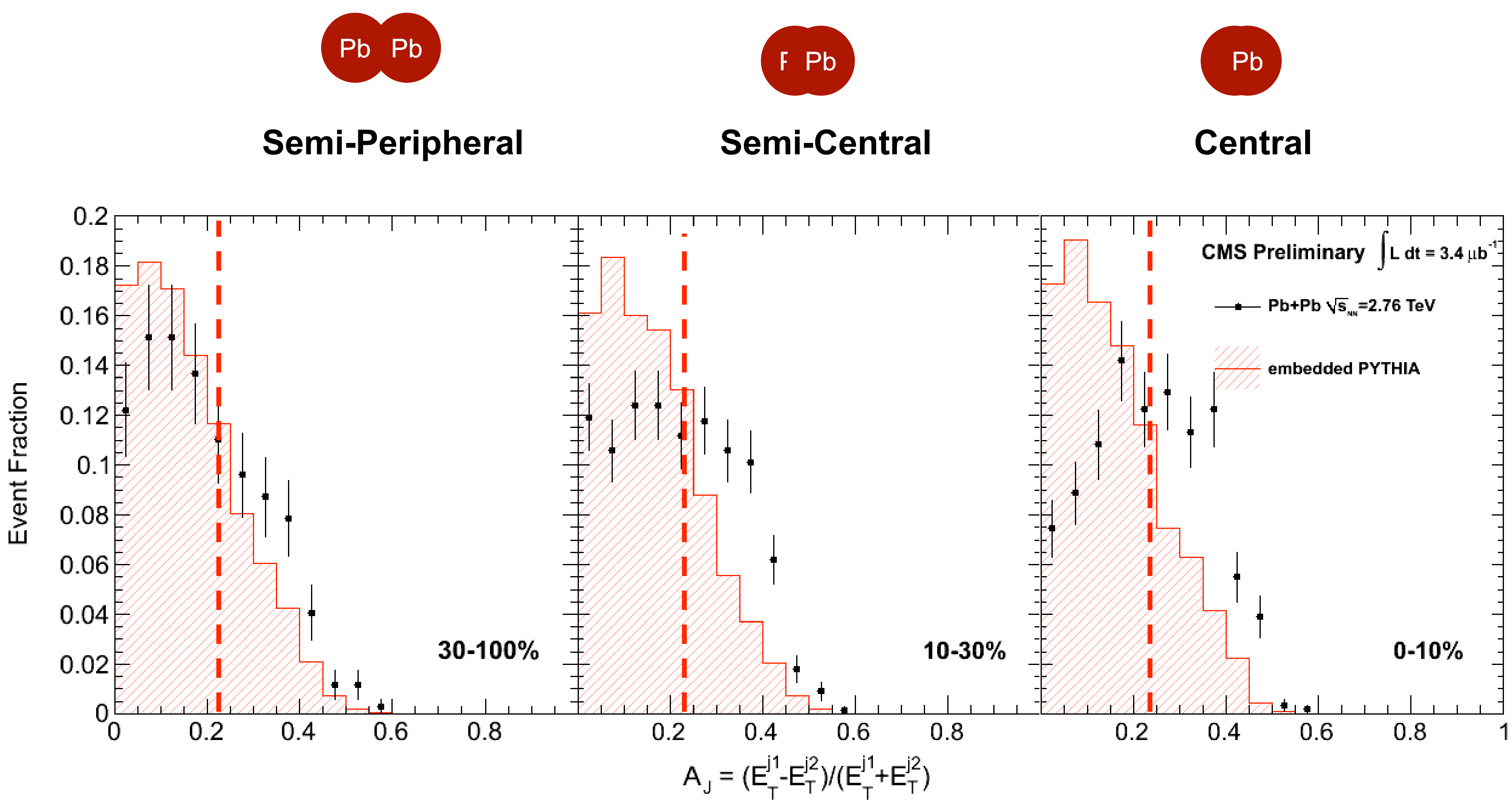
$$R_{AA}(p_T) = \frac{(1/N^{AA}_{evt})\, d^2N^{AA}_{ch}/d\eta\, dp_T}{\langle N_{coll}\rangle\, (1/N^{pp}_{evt})\, d^2N^{pp}_{ch}/d\eta\, dp_T},$$

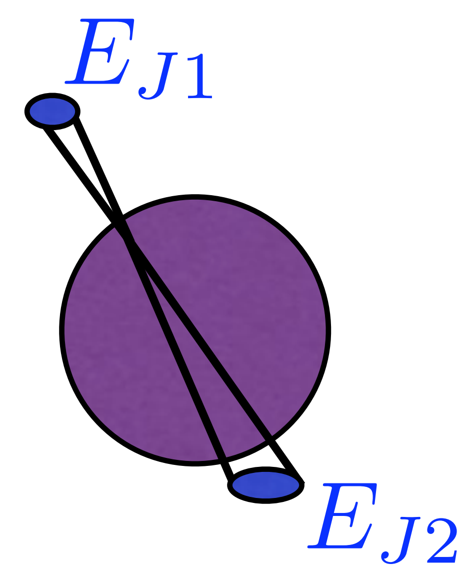
the number of binary nucleon-nucleon collisions

New LHC heavy ion data!

from talk by Bolek Wyslouch

CMS collaboration PRELIMINARY, 2010





$$A_J = \frac{E_{J1} - E_{J2}}{E_{J1} + E_{J2}}$$

A significant dijet imbalance, well beyond that expected from unquenched MC, appears with increasing collision centrality

New LHC heavy ion data!

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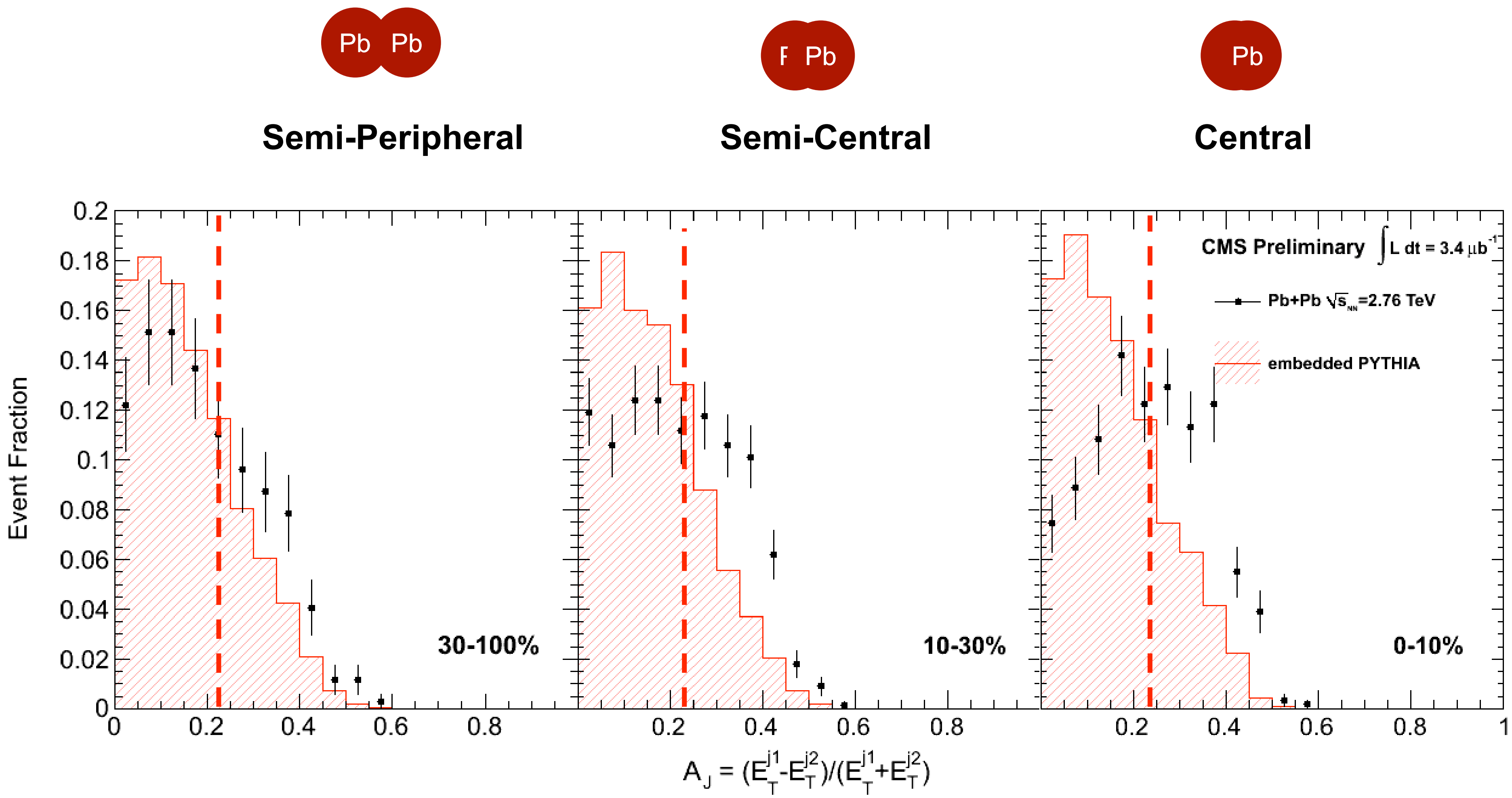

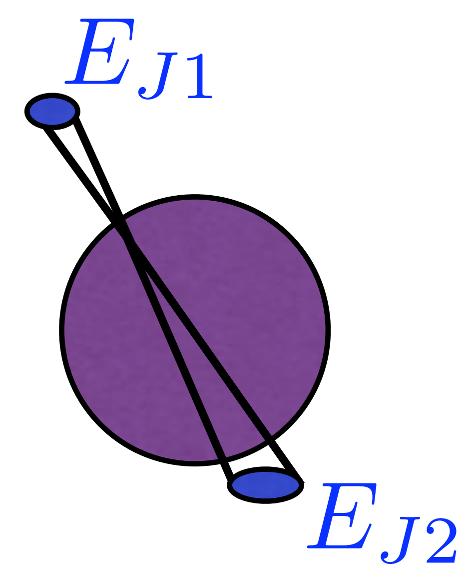

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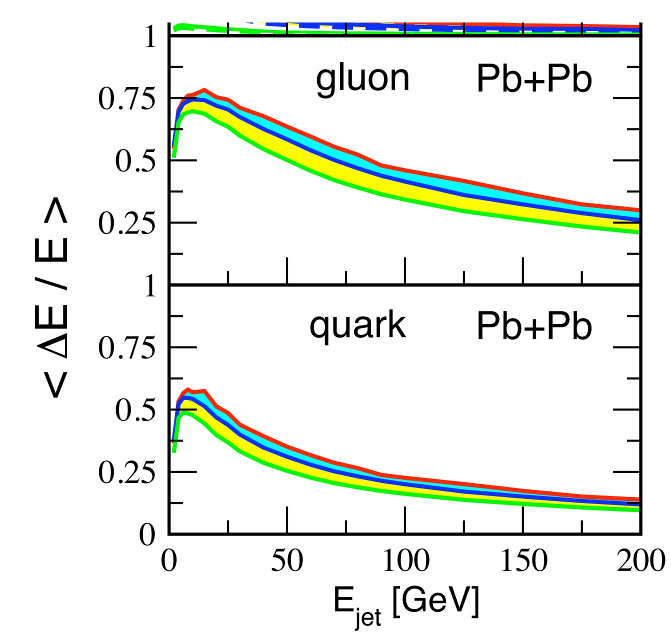
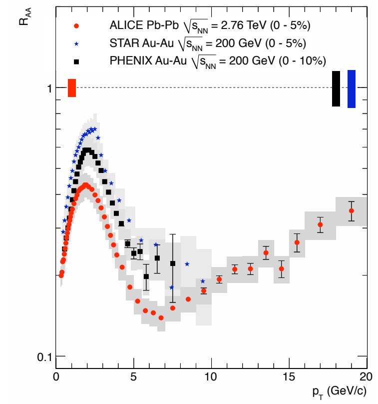


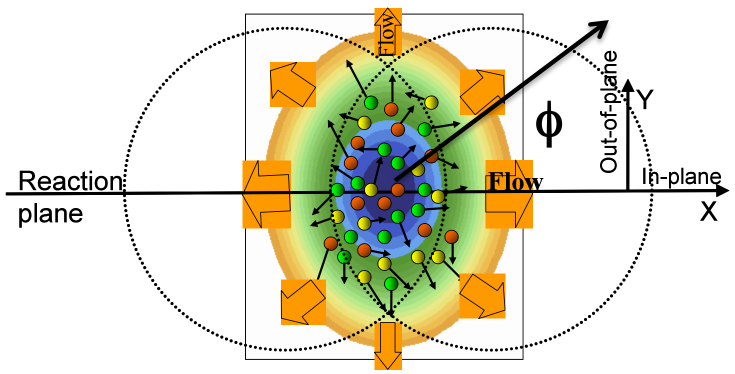
Energy loss ~40% in agreement with prediction in Vitev, 06

Strong indications of QGP production

- R_{AA} suppression (RHIC, LHC)



- Azimuthal angle di-hadron(Jet) correlations I_{AA} (RHIC, LHC)
- Elliptic flow v_2 (RHIC, LHC)

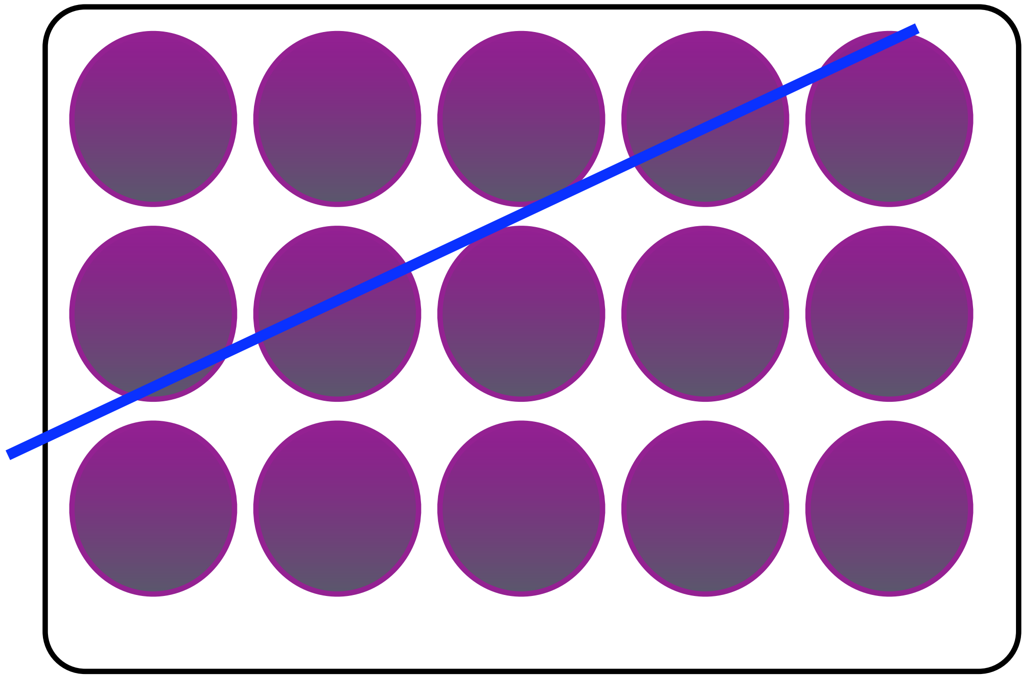


So far R_{AA} and I_{AA} have been analyzed using leading particle approach

Using jets is a new promising direction in heavy ion collisions

Theoretical Approaches

- PQCD
- Thermal Field Theory
- Lattice QCD
- Hydrodynamics
- AdS/CFT symmetry



Gyulassy-Wang model

Gyulassy, Wang, 94

- The medium is modeled with a finite number of scattering centers with static Debye-screened potential

$$H = \sum_{n=1}^{N} H(q; x_n) = 2\pi\delta(q^0)\, v(q) \sum_{n=1}^{N} \mathrm{e}^{iqx_n}\, T^a(R) \otimes T^a(n)$$

$$v(q) = \frac{4\pi\alpha_s}{q_z^2 + \mathbf{q^2} + \mu^2}$$

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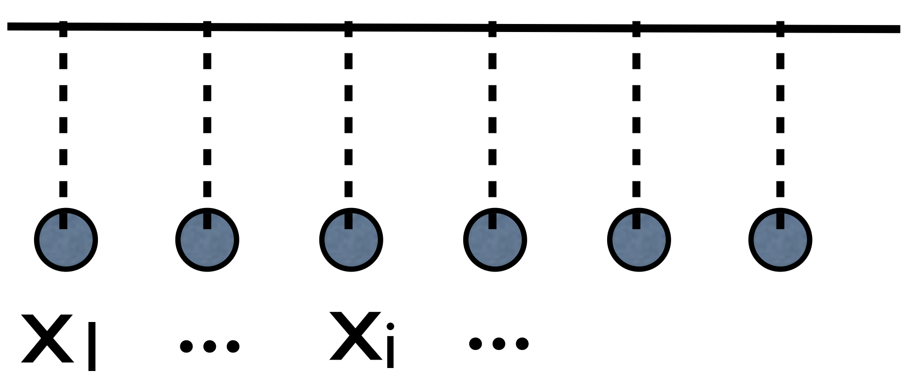

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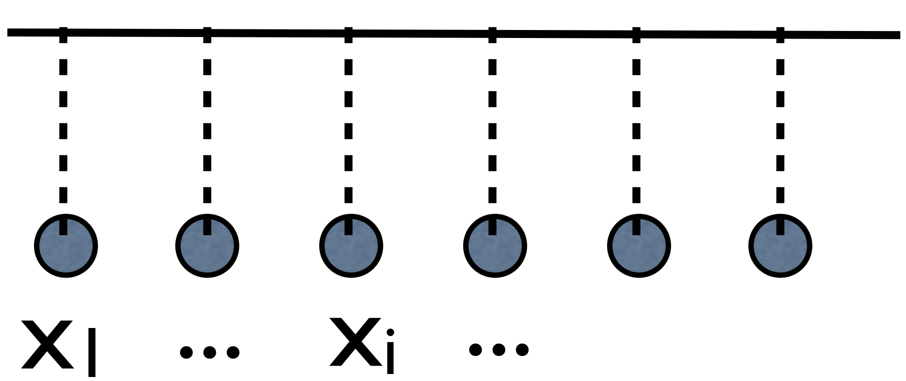


- The momentum scaling of the exchange gluon is that of the Glauber gluon:

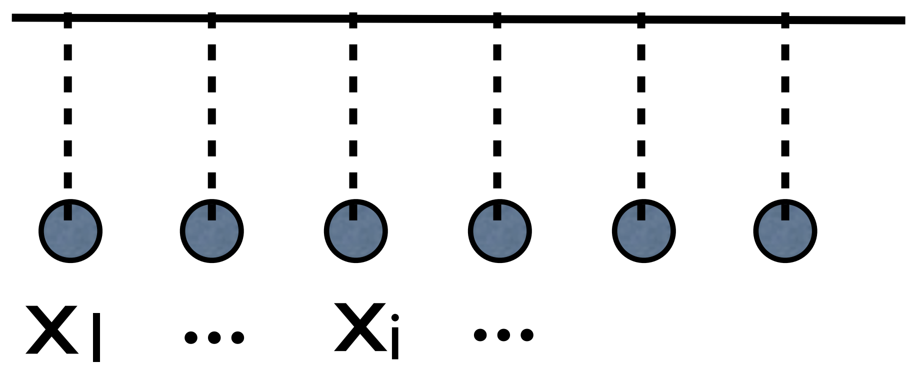
$$q(\lambda^2, \lambda^2, \lambda)$$

Gyulassy-Levai-Vitev reaction operator

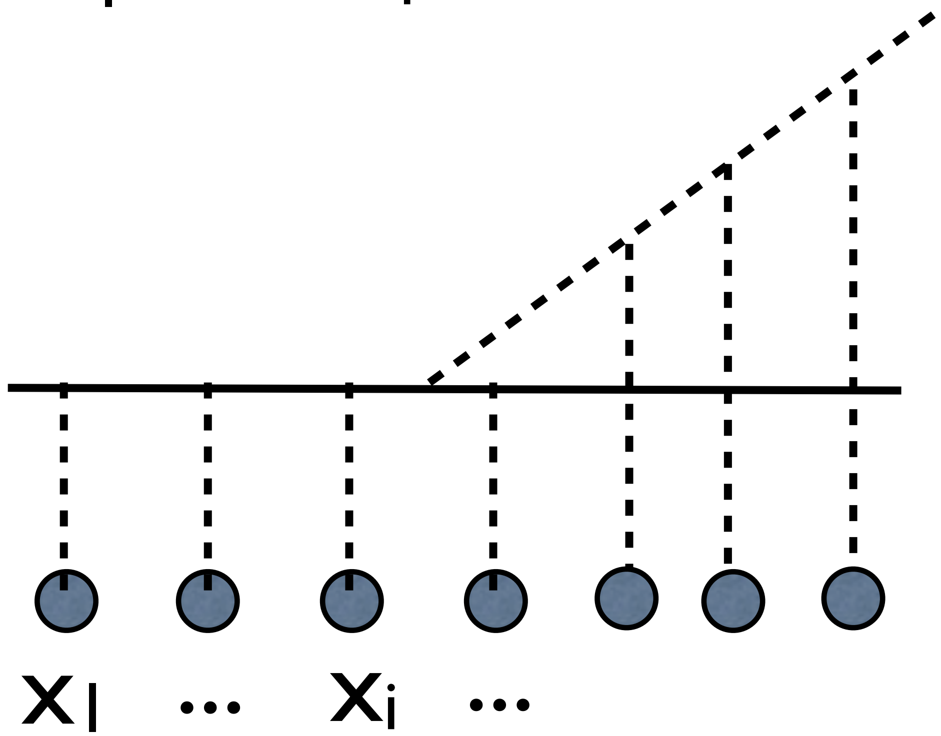
Gyulassy, Levai, Vitev, 00

$$\hat{R}_n = \hat{D}_n^\dagger \hat{D}_n + \hat{V}_n + \hat{V}_n^\dagger$$

Jet broadening



Radiative energy loss



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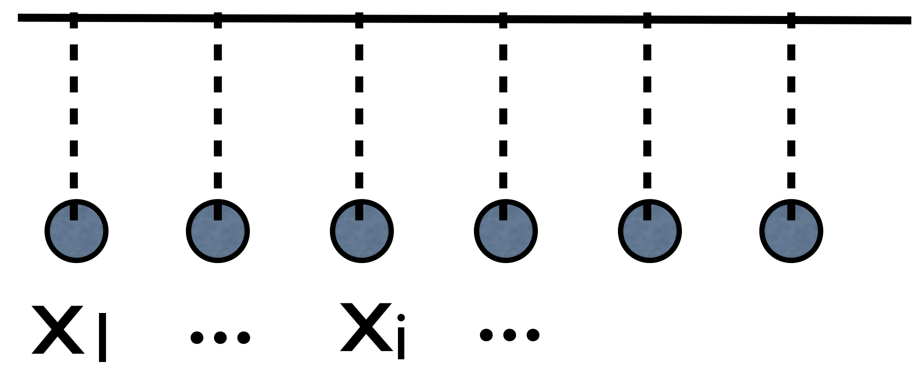

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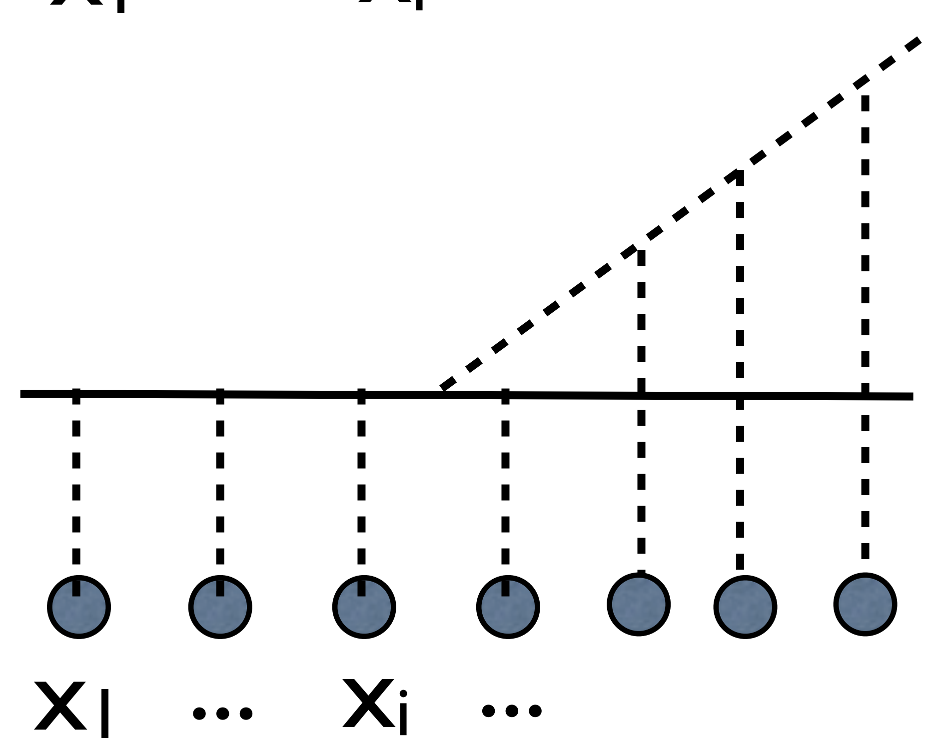

Other applications:
meson dissociation, electromagnetic energy loss

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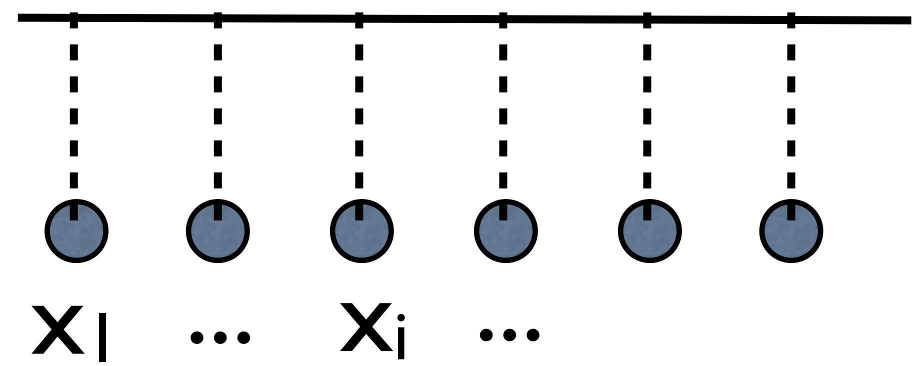

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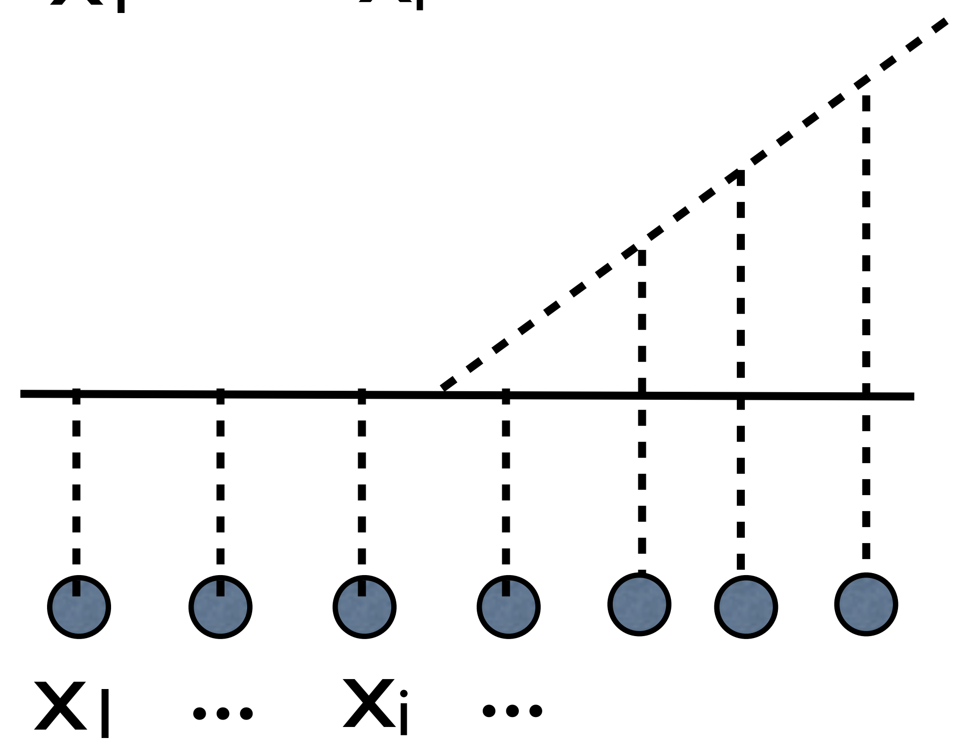

Other applications:
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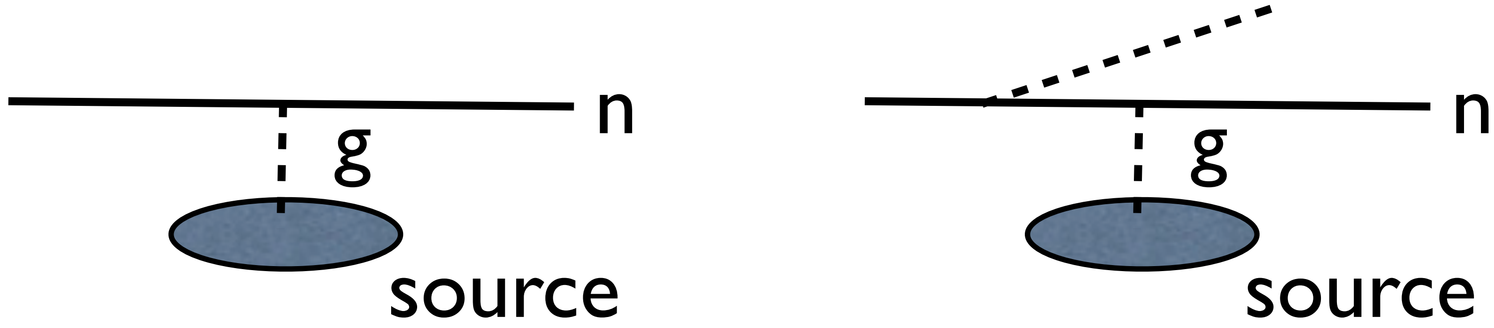
This talk: How to derive Jet broadening and Radiative energy loss using Effective Field Theory?

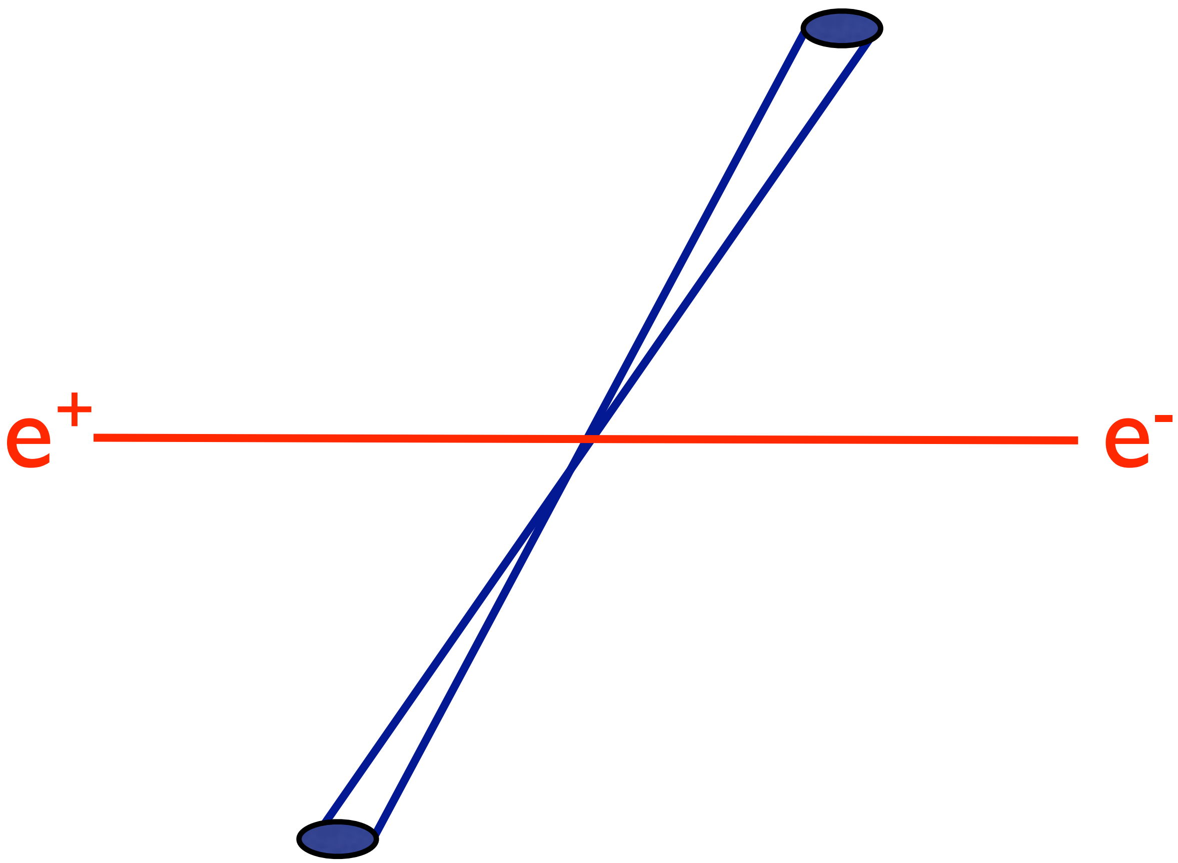
Effective Theory for Jets in the medium

Expectations from the effective theory



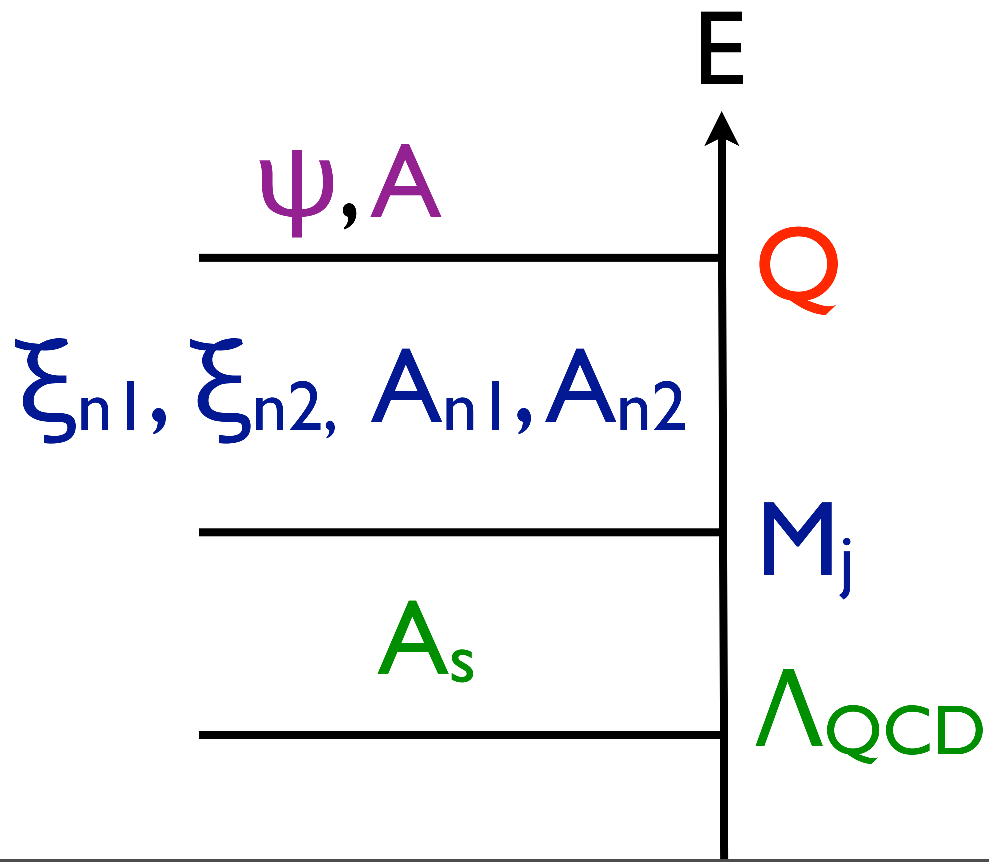
- Our goal is to construct an effective theory for highly energetic quarks and gluons in the medium
- Soft Collinear Effective Theory(SCET) is a good start
- Need to add the transverse(Glauber) gluons to the SCET lagrangian: $SCET_G$
- We want to go beyond the static source approximation
- Check gauge invariance of the broadening and bremsstrahlung

Soft Collinear Effective Theory



Bauer, Fleming, Luke, Pirjol, Stewart, (00-01)

- Clear separation of scales between hard emission, collinear splittings and soft radiation
- In SCET the small parameter λ describes how close to the jet axis the collinear emissions occur
- Power counting of SCET requires couplings between collinear quarks, gluons, and soft gluons



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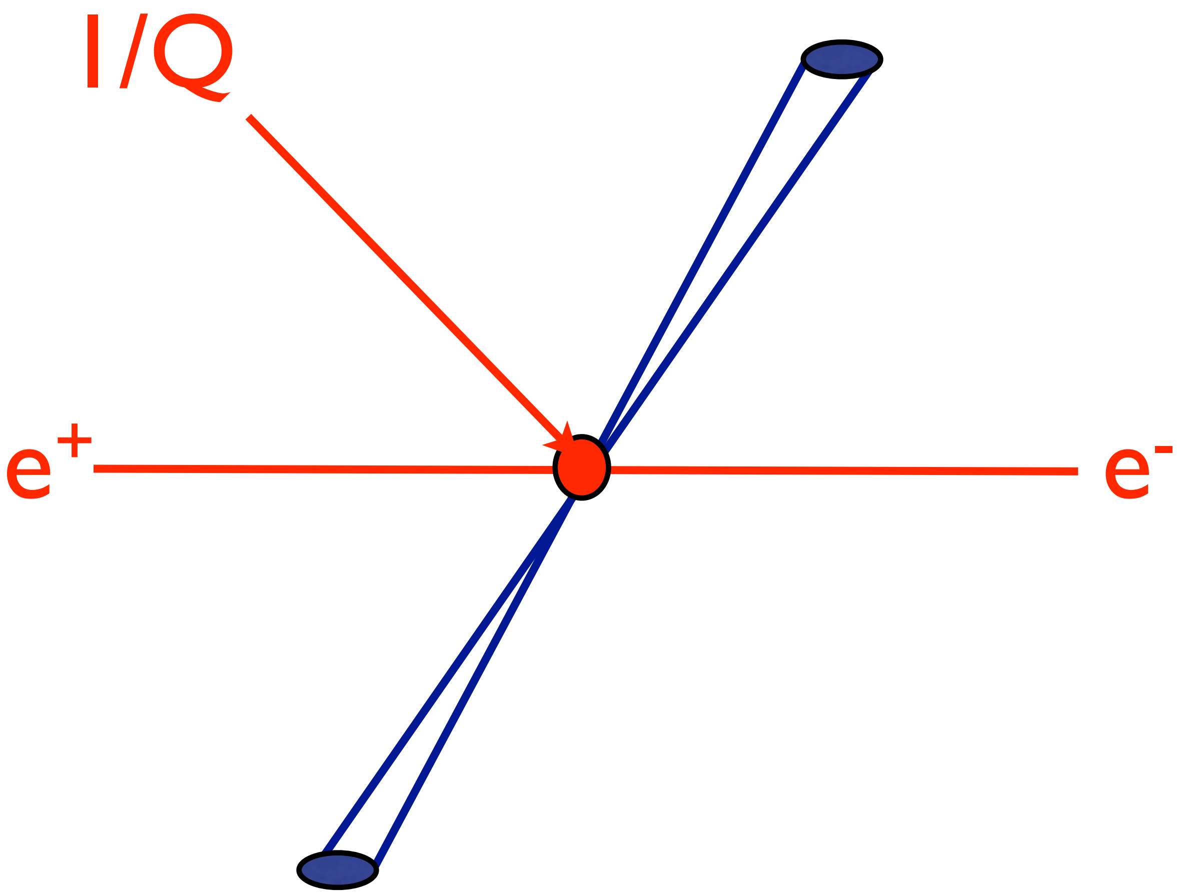

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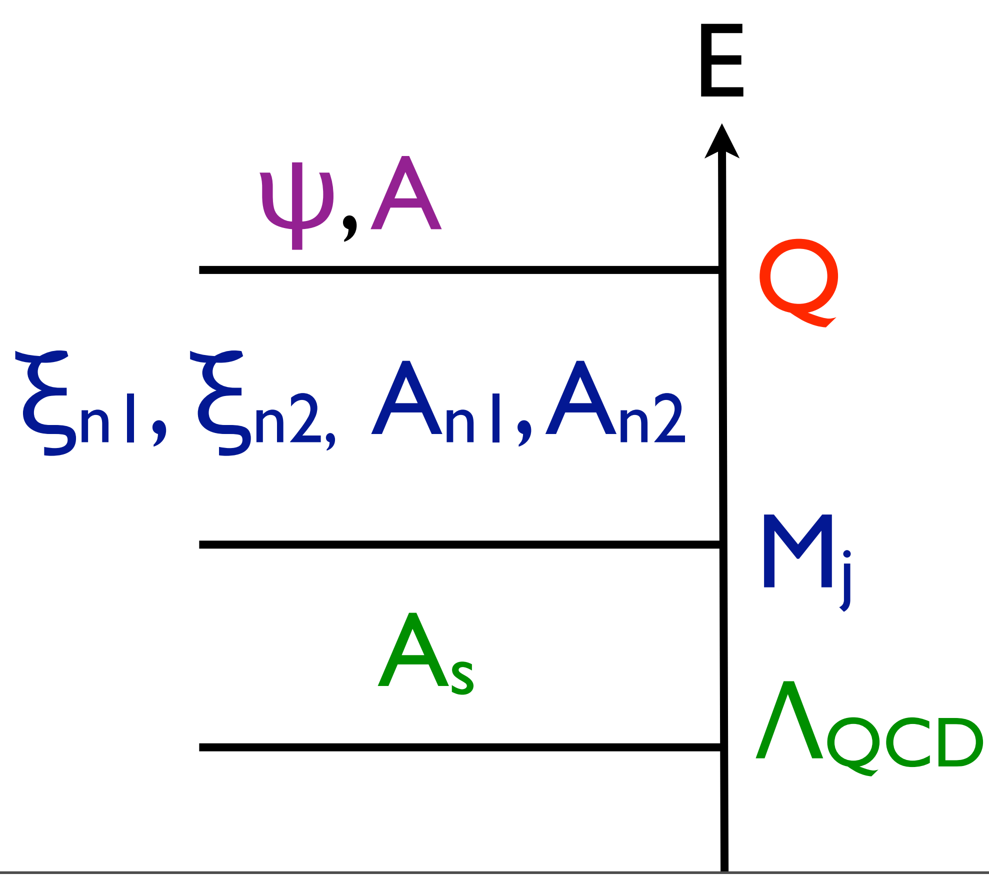

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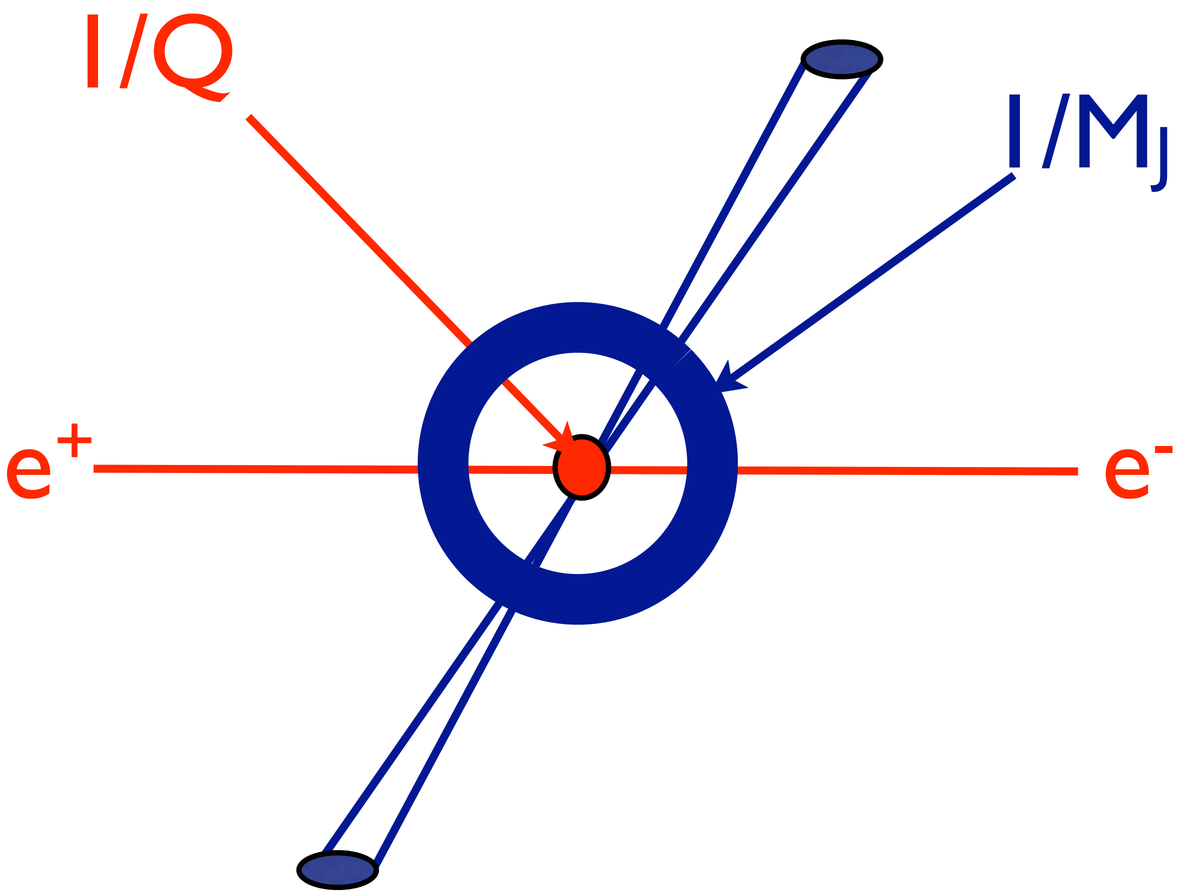

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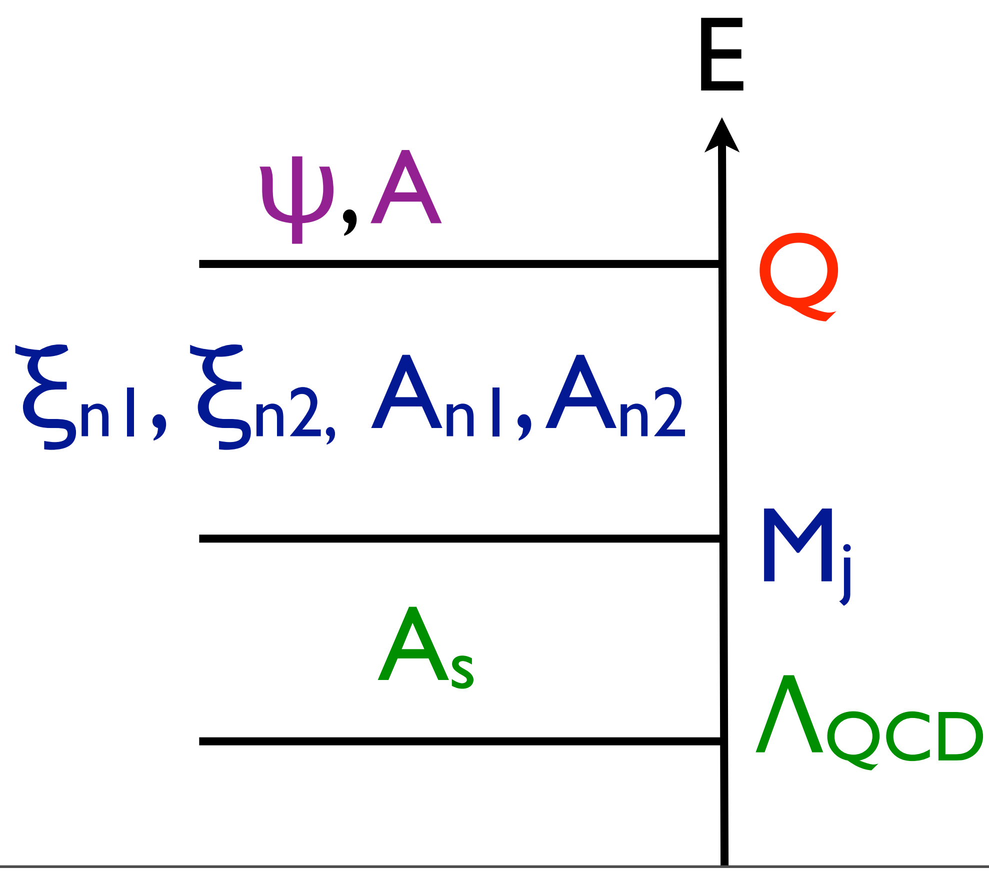

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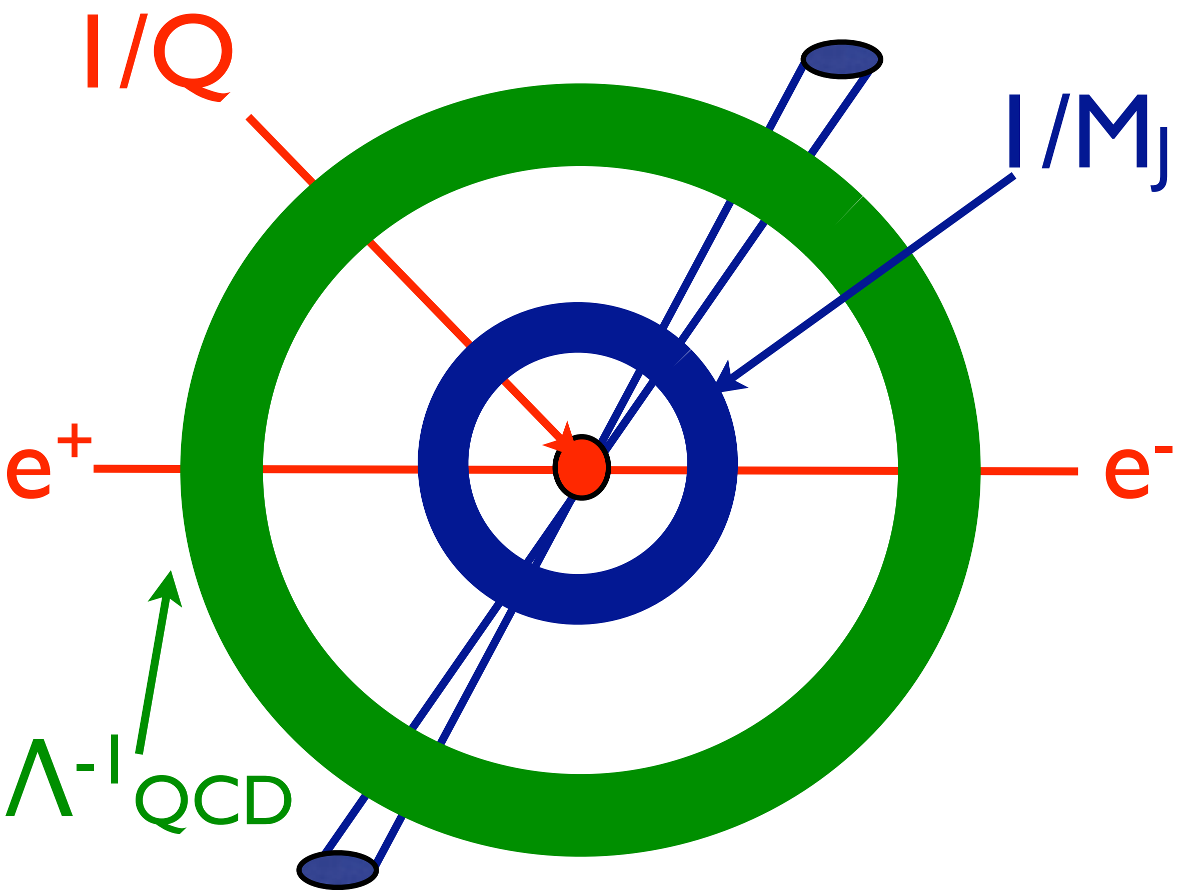

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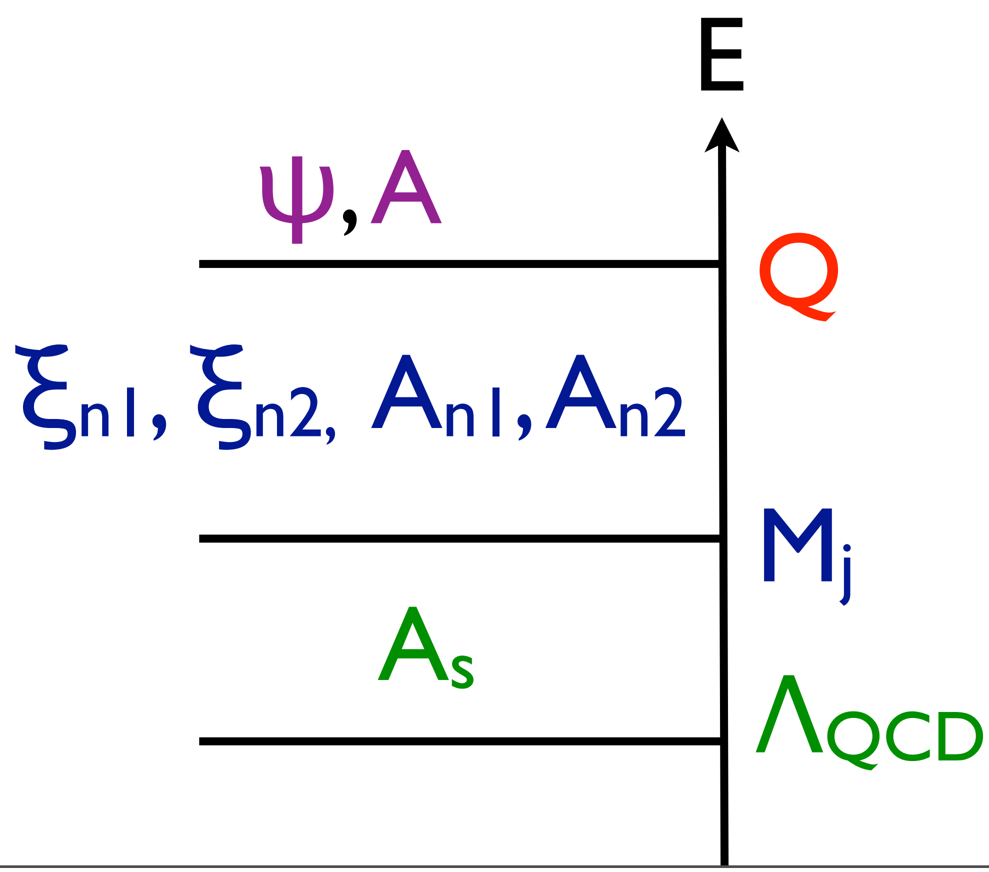

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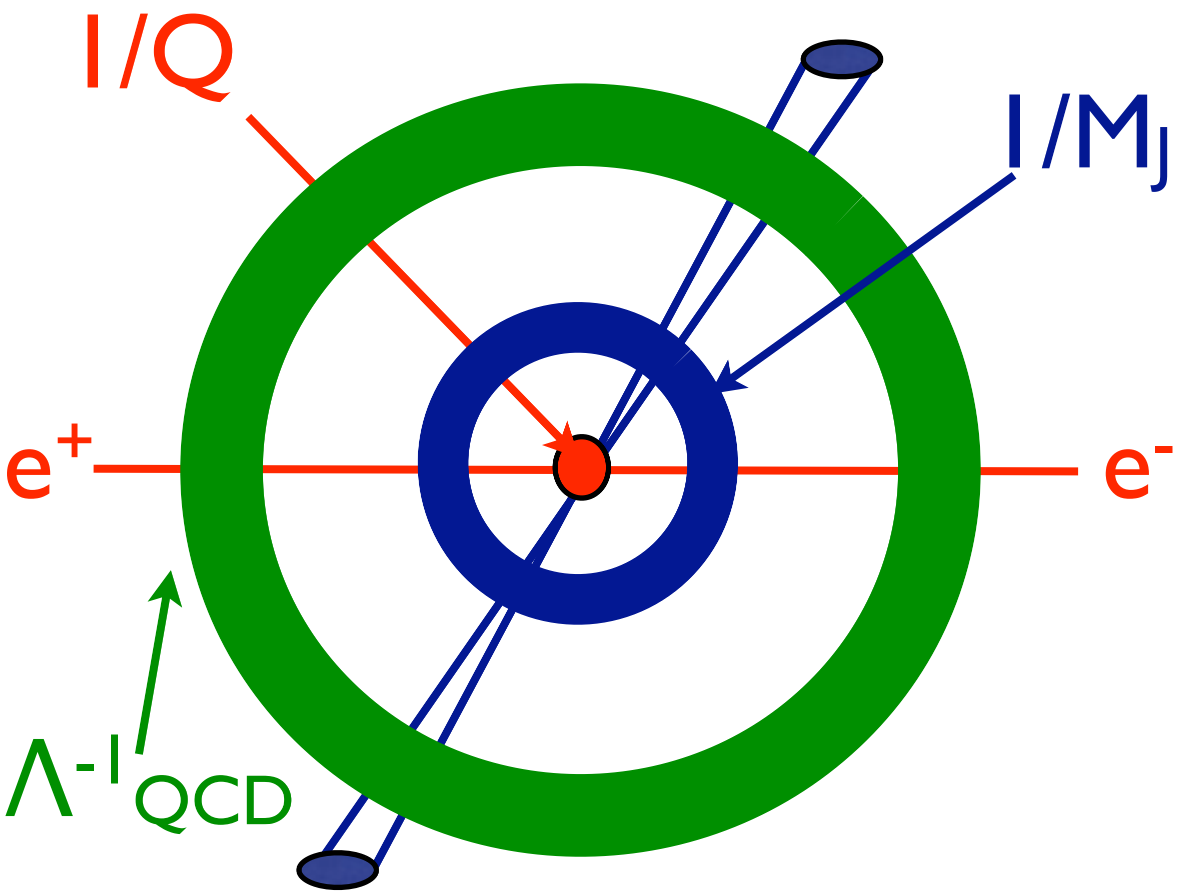

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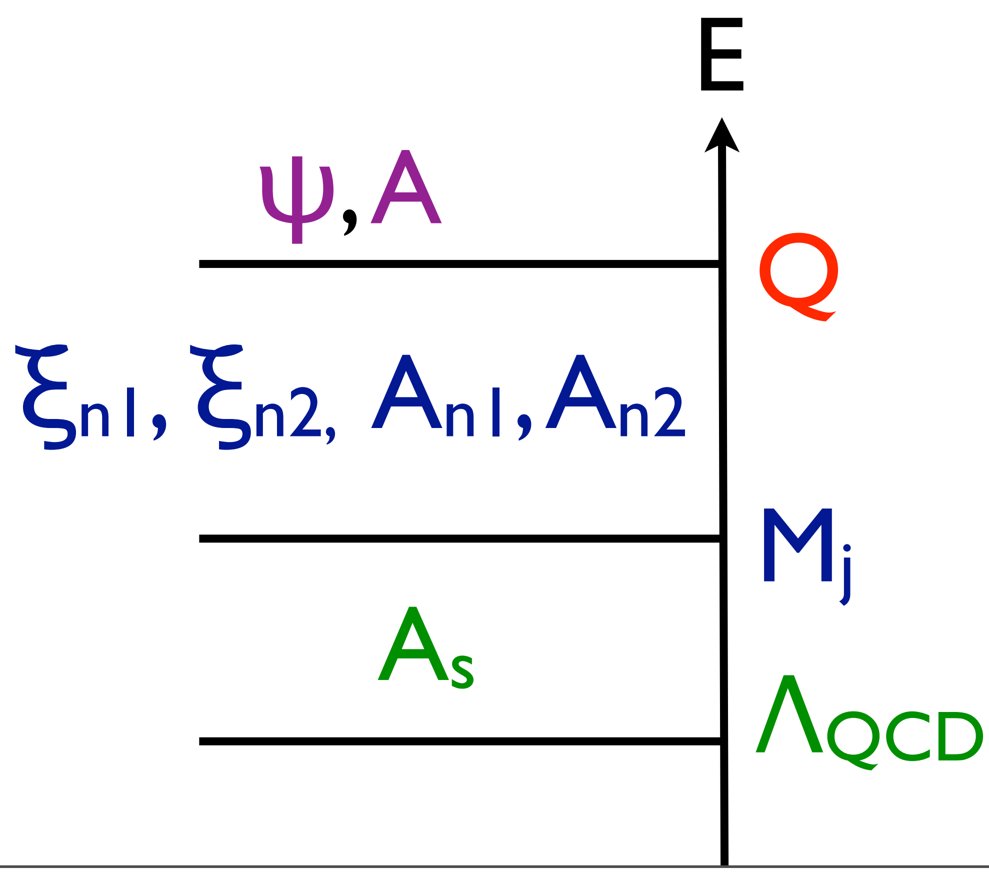
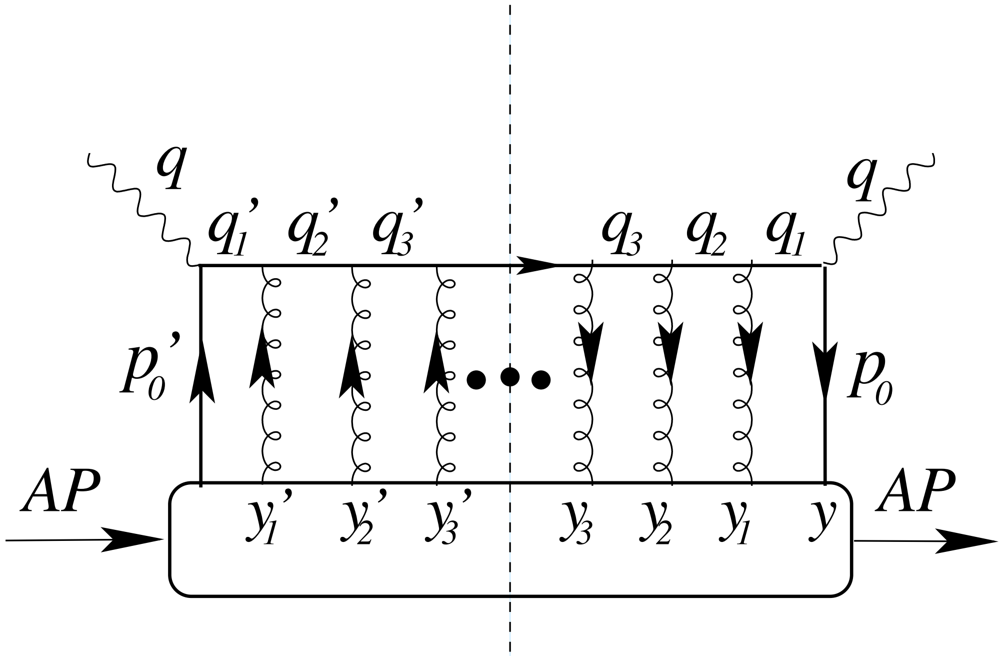


Need to include Glauber gluons to SCET

SCET$_G$=SCET+Glauber gluons

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

Idilbi, Majumder(08)



L$_G$($\xi_{\bar{n}}$, A$_G$)

SIDIS

- n-collinear source
- covariant, light-cone gauge

D'Eramo, Liu, Rajagopal(10)

$$P(k_\perp) = \int d^2x_\perp \, e^{-ik_\perp \cdot x_\perp} \, \mathcal{W}_{\mathcal{R}}(x_\perp)$$

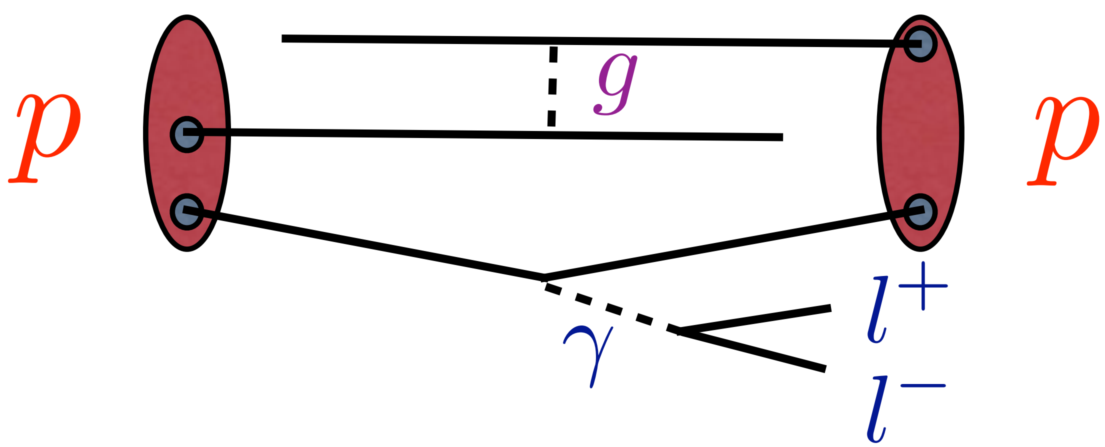
$$\mathcal{W}_{\mathcal{R}}(x_\perp) = \frac{1}{d\,(\mathcal{R})} \left\langle \mathrm{Tr} \left[W_{\mathcal{R}}^\dagger[0, x_\perp] \, W_{\mathcal{R}}[0,0] \right] \right\rangle$$

$$W_F\left[y^+, y_\perp\right] \equiv P \left\{ \exp\left[ig \int_0^{L^-} dy^- \, A^+(y^+, y^-, y_\perp) \right] \right\}$$

- Probability density of the scattered jet is equal to exp.value of two Wilson Lines
- Derived in the covariant gauge

SCET$_G$: effective theory for Drell-Yan

Bowdin, Brodsky, Lepage, (81)
Collins, Soper, Sterman, (82)
Bauer, Lange, GO(10)



- An explicit calculation shows that for consistency of effective theory SCET should be expanded with Glauber modes to describe Drell-Yan process
- Factorization of Drell-Yan should be reconsidered using SCET$_G$

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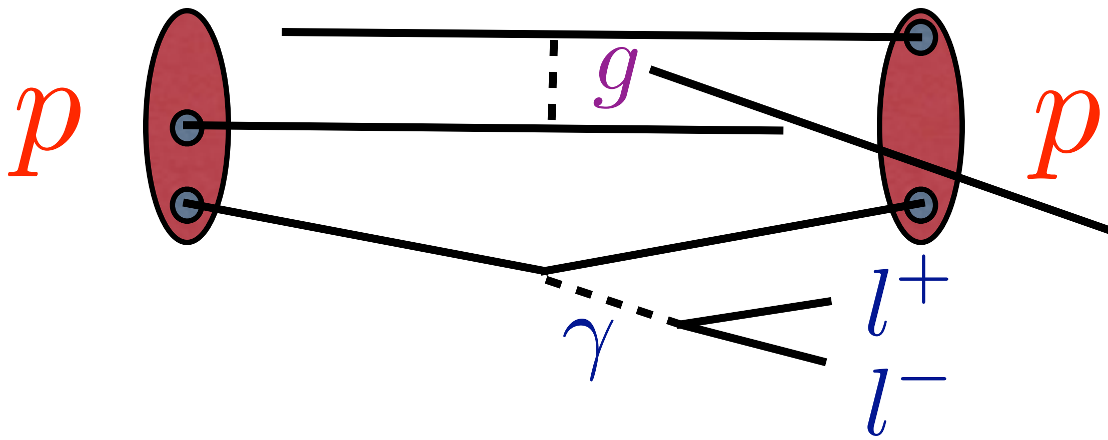

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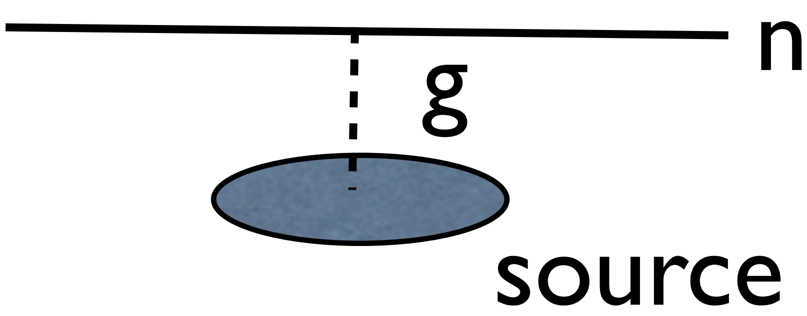
Glauber(Coulomb) gluon, transverse to the beam axis: $q(\lambda^2, \lambda^2, \lambda)$

- An explicit calculation shows that for consistency of effective theory SCET should be expanded with Glauber modes to describe Drell-Yan process
- Factorization of Drell-Yan should be reconsidered using SCET$_G$

SCET$_G$ Lagrangian



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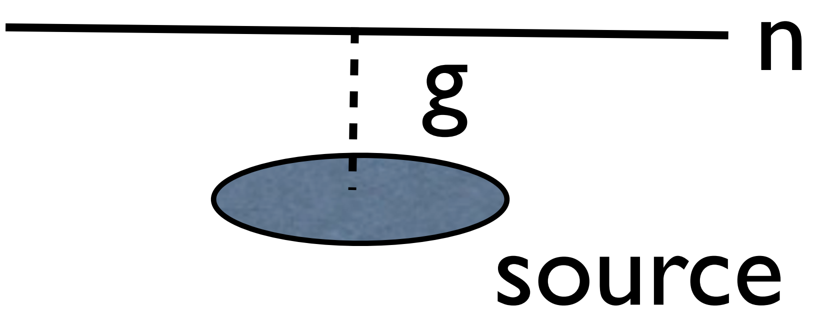
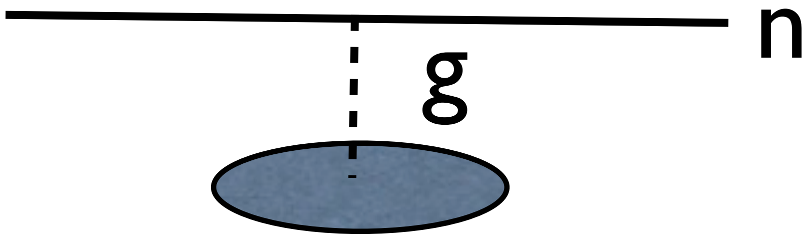


- Use full QCD fields to derive the scaling of the vector potential created by the source of the Glauber gluons
- Consider collinear, static and soft quark sources
- Use background field method to deduce the Feynman rules of interaction of the target jet with the Glauber vector potential

SCET$_G$ Lagrangian



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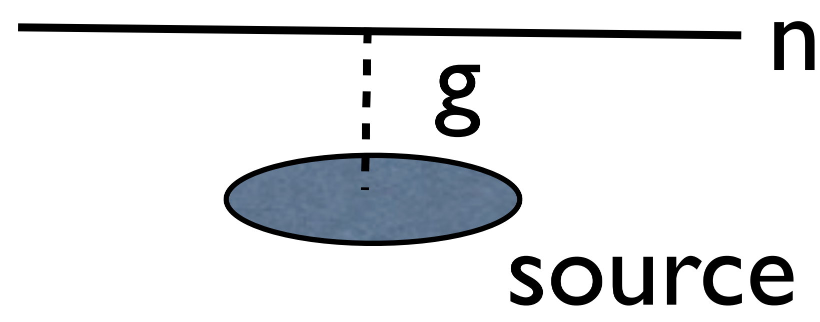
$$\mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, \eta\right) = \sum_{p,p',q} \mathrm{e}^{-i(p-p'+q)x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\mathrm{qqA_G}} \frac{\bar{\not{n}}}{2} \xi_{n,p} - i \Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}} \left(A^b_{n,p'}\right)_\nu \left(A^c_{n,p}\right)_\lambda \right) \bar{\eta}\, \Gamma^{\nu,a}_{\mathrm{s}}\, \eta\, \Delta_{\mu\nu}(q)$$

SCET$_G$ Lagrangian



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Gauge	Object	Collinear source	Static source	Soft source
	p	$[\lambda^2, 1, \boldsymbol{\lambda}]$	$[1, 1, \boldsymbol{\lambda}]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
	$a_{\boldsymbol{p}}, a_{\boldsymbol{p}}^\dagger$	λ^{-1}	$\lambda^{-3/2}$	$\lambda^{-3/2}$
	$u(p)$	1	1	$\lambda^{1/2}$
	$\bar{u}(p_2)\gamma_\nu u(p_1)$	$[\lambda^2, 1, \boldsymbol{\lambda}]$	$[1, 1, \boldsymbol{\lambda}]$	$[\lambda, \lambda, \boldsymbol{\lambda}]$
R_ξ	$A^\mu(x)$	$[\lambda^4, \lambda^2, \boldsymbol{\lambda}^3]$	$[\lambda^2, \lambda^2, \boldsymbol{\lambda}^3]$	$[\lambda^2, \lambda^2, \boldsymbol{\lambda}^2]$
	$\Gamma_{\mathrm{qqA_G}}$	Γ_1^μ	Γ_1^μ	Γ_1^μ
	$\Gamma_{\mathrm{ggA_G}}$	$\Sigma_1^{\mu\nu\lambda}$	$\Sigma_1^{\mu\nu\lambda}$	$\Sigma_1^{\mu\nu\lambda}$
	Γ_{s}	$\Gamma_1^\mu \ (n \leftrightarrow \bar{n})$	Γ_3^μ	Γ_4^μ
$A^+ = 0$	$A^\mu(x)$	$[0, \lambda^2, \boldsymbol{\lambda}^3]$	$[0, \lambda^2, \boldsymbol{\lambda}]$	$[0, \lambda^2, \boldsymbol{\lambda}]$
	$\Gamma_{\mathrm{qqA_G}}$	Γ_1^μ	$\Gamma_1^\mu + \Gamma_2^\mu$	$\Gamma_1^\mu + \Gamma_2^\mu$
	$\Gamma_{\mathrm{ggA_G}}$	$\Sigma_2^{\mu\nu\lambda}$	$\Sigma_2^{\mu\nu\lambda}$	$\Sigma_2^{\mu\nu\lambda}$
	Γ_{s}	$\Gamma_2^\mu \ (n \leftrightarrow \bar{n})$	Γ_3^μ	Γ_4^μ
$A^- = 0$	$A^\mu(x)$	$[\lambda^2, 0, \boldsymbol{\lambda}]$	$[\lambda^2, 0, \boldsymbol{\lambda}]$	$[\lambda^2, 0, \boldsymbol{\lambda}]$
	$\Gamma_{\mathrm{qqA_G}}$	Γ_2^μ	Γ_2^μ	Γ_2^μ
	$\Gamma_{\mathrm{ggA_G}}$	$\Sigma_3^{\mu\nu\lambda}$	$\Sigma_3^{\mu\nu\lambda}$	$\Sigma_3^{\mu\nu\lambda}$
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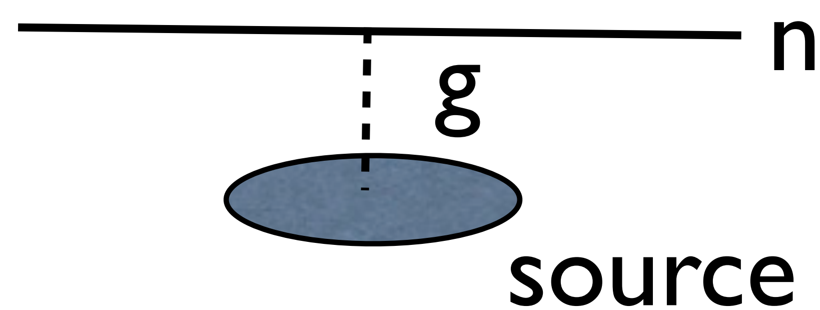
$$\mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, \eta\right) = \sum_{p,p',q} \mathrm{e}^{-i(p-p'+q)x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\mathrm{qqA_G}} \frac{\bar{\not{n}}}{2} \xi_{n,p} - i \Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}} \left(A^b_{n,p'}\right)_\nu \left(A^c_{n,p}\right)_\lambda \right) \bar{\eta}\, \Gamma_{\mathrm{s}}^{\nu,a}\, \eta\, \Delta_{\mu\nu}(q)$$

SCET$_{\text{G}}$ Lagrangian



Elements in the table:

$$\Gamma_1^\mu = igT^a\, n^\mu \frac{\bar{\not{n}}}{2}, \qquad \Sigma_1^{\mu,\nu,\lambda} = gf^{abc}\, n^\mu \left[g^{\nu\lambda}\, \bar{n}\cdot q_1 + \bar{n}^\nu \left(q_{2\perp}^\lambda - q_{1\perp}^\lambda \right) - \bar{n}^\lambda \left(q_{2\perp}^\nu - q_{1\perp}^\nu \right) - \frac{1-\frac{1}{\xi}}{2} \left(\bar{n}^\lambda q_1^\nu + \bar{n}^\nu q_2^\lambda \right) \right],$$

$$\Gamma_2^\mu = igT^a \frac{\gamma_\perp^\mu \not{p}_\perp + \not{p}'_\perp \gamma_\perp^\mu}{\bar{n}\cdot p} \frac{\bar{\not{n}}}{2}, \qquad \Sigma_2^{\mu,\nu,\lambda} = gf^{abc} \left[g_\perp^{\mu\lambda} \left(-\frac{n^\nu}{2} q_1^+ + q_{1\perp}^\nu - 2q_{2\perp}^\nu \right) + g_\perp^{\mu\nu} \left(-\frac{n^\lambda}{2} q_1^+ + q_{2\perp}^\lambda - 2q_{1\perp}^\lambda \right) + g_\perp^{\nu\lambda} \left(n^\mu\, \bar{n}\cdot q_1 + q_{1\perp}^\mu + q_{2\perp}^\mu \right) \right]$$

$$\Gamma_3^\mu = igT^a\, v^\mu,$$

$$\Gamma_4^\mu = igT^a\, \gamma^\mu, \qquad \Sigma_3^{\mu,\nu,\lambda} = gf^{abc} \left[g_\perp^{\mu\lambda} \left(\frac{\bar{n}^\nu}{2} (q_1^- - 2q_2^-) + q_{1\perp}^\nu - 2q_{2\perp}^\nu \right) + g_\perp^{\mu\nu} \left(\frac{\bar{n}^\lambda}{2} (q_2^- - 2q_1^-) + q_{2\perp}^\lambda - 2q_{1\perp}^\lambda \right) + g_\perp^{\nu\lambda} \left(q_{1\perp}^\mu + q_{2\perp}^\mu \right) \right]$$

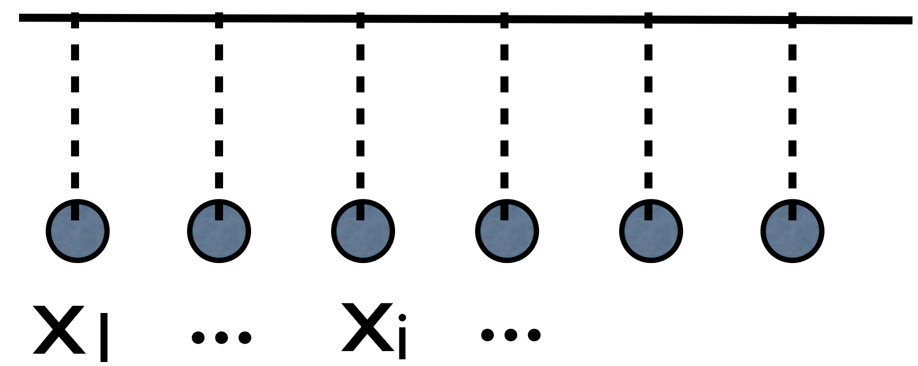
- Our Glauber Lagrangian is invariant under the gauge symmetries of SCET $\mathcal{L}_{\text{G}}\left(\xi_n, A_n, \eta\right) \to \mathcal{L}_{\text{G}}\left(W_n^\dagger \xi_n, \mathcal{B}_n(A_n), \eta\right) \equiv \mathcal{L}_{\text{G}}\left(\chi_n, \mathcal{B}_n, \eta\right)$
- We derived the Feynman rules for three types of sources: collinear, static, and soft quarks and three gauges: covariant, $A^+=0$ and $A^-=0$ gauges.

Results for jet broadening and jet energy loss

Diagrams to be evaluated

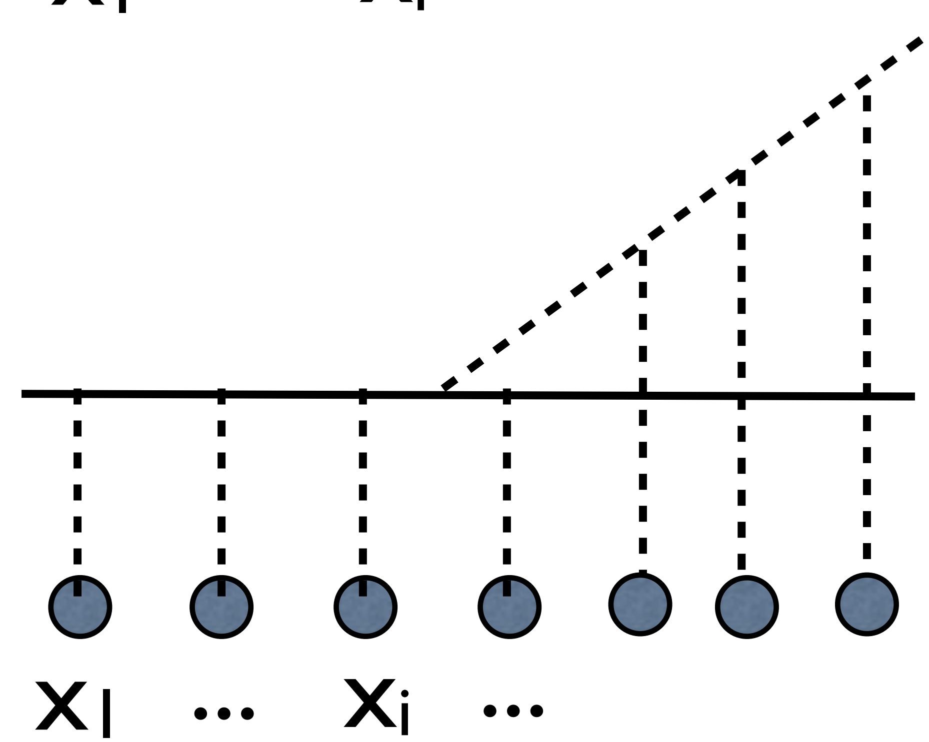
Jet broadening

$$B(x_i)^{(n)} =$$



Radiative energy loss

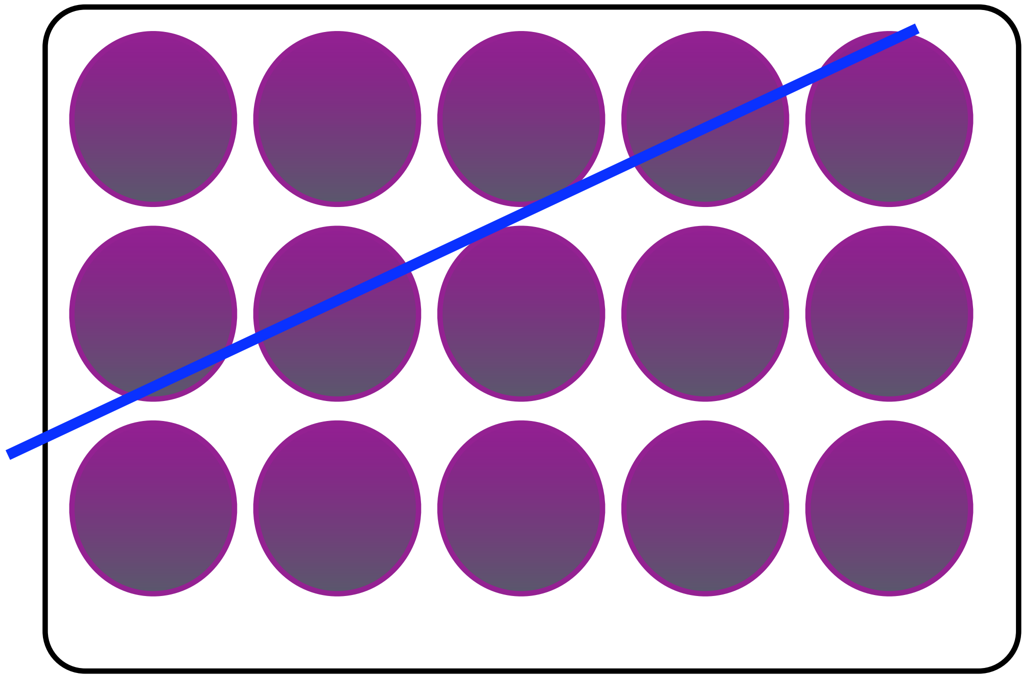
$$R(x_i)^{(n)} =$$

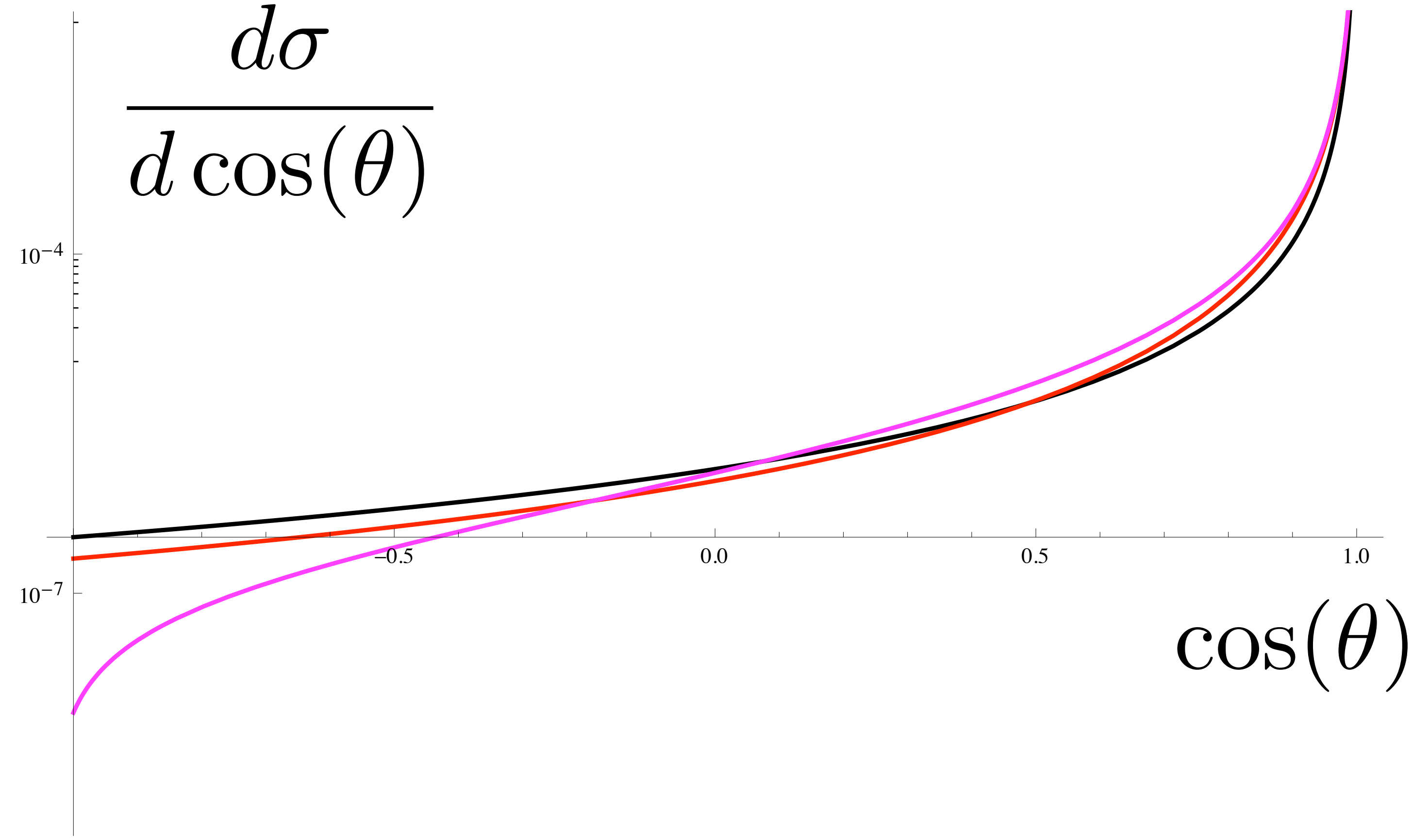


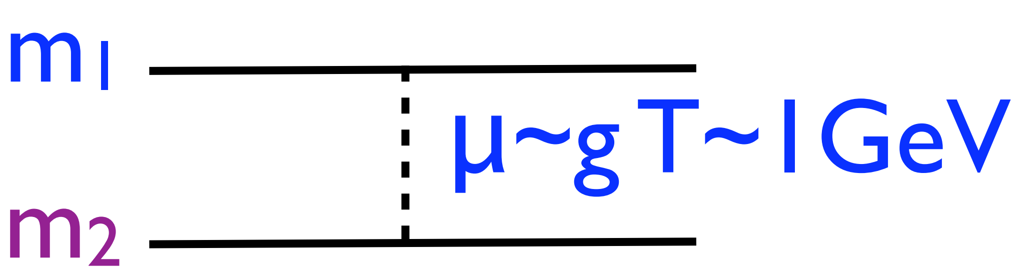
$n-$opacity

What kinematics should we assume for the source term?

Kinematics of the source



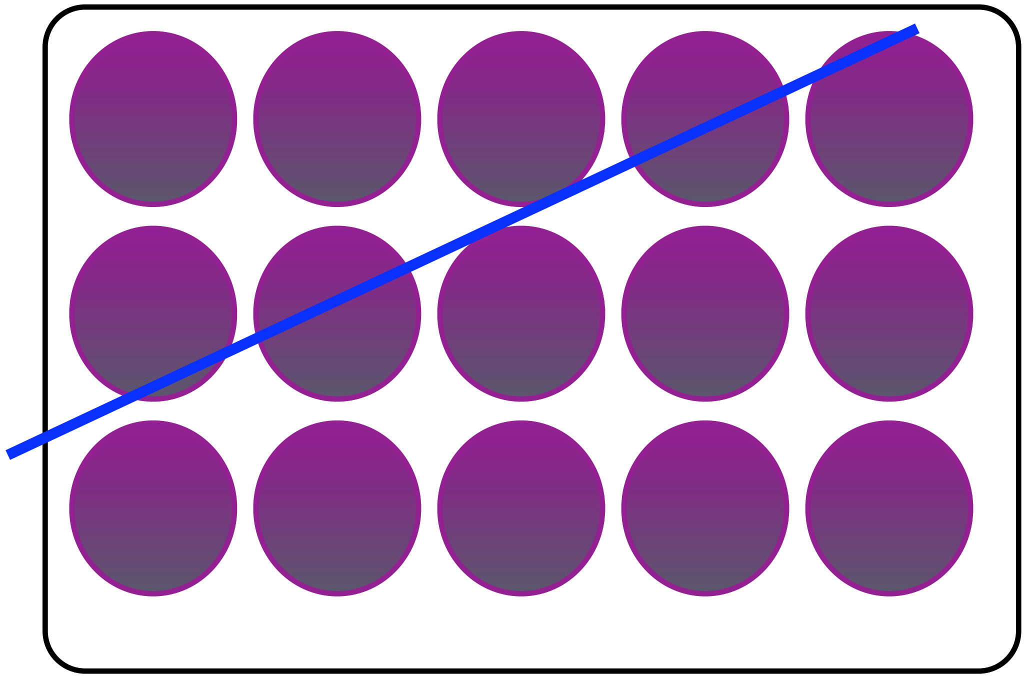


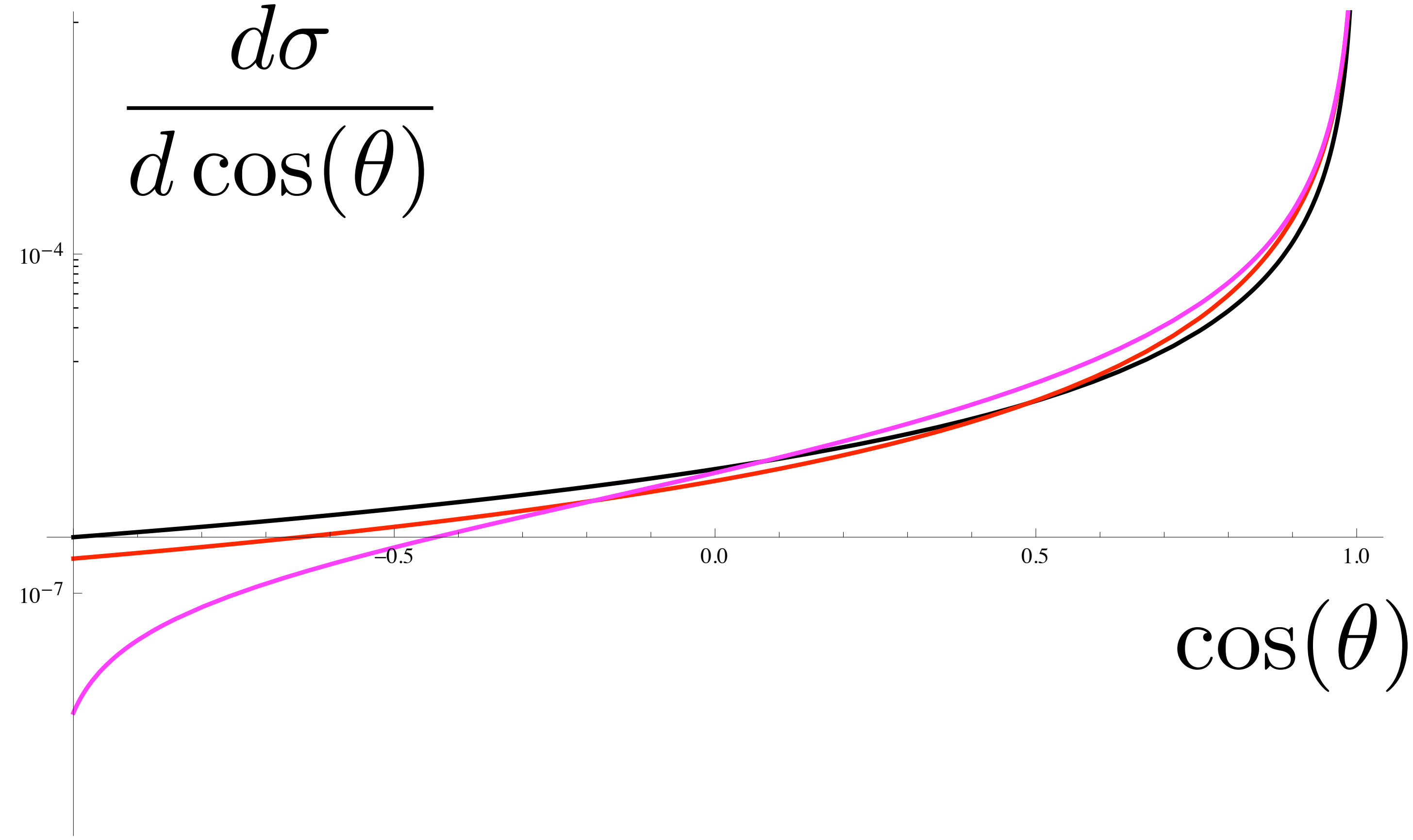


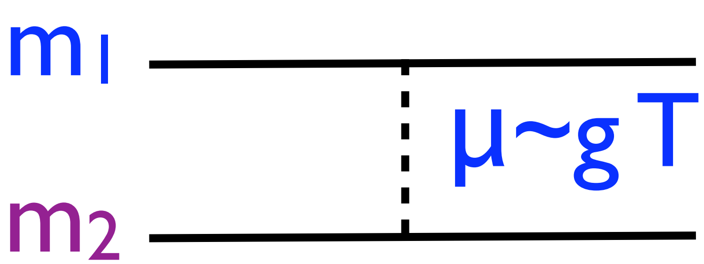
RHIC, E=10GeV: $\frac{\sigma(m_2 = 1000\text{GeV}) - \sigma(m_2 = 1\text{GeV})}{\sigma(m_2 = 1000\text{GeV})} \approx 13\%$

LHC, E=100GeV: $\frac{\sigma(m_2 = 1000\text{GeV}) - \sigma(m_2 = 1\text{GeV})}{\sigma(m_2 = 1000\text{GeV})} \approx 2\%$

Kinematics of the source







μ~g T~1GeV

RHIC, E=10GeV: $\frac{\sigma(m_2 = 1000\text{GeV}) - \sigma(m_2 = 1\text{GeV})}{\sigma(m_2 = 1000\text{GeV})} \approx 13\%$

LHC, E=100GeV: $\frac{\sigma(m_2 = 1000\text{GeV}) - \sigma(m_2 = 1\text{GeV})}{\sigma(m_2 = 1000\text{GeV})} \approx 2\%$

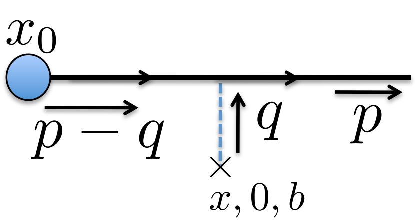
Static source is a realistic assumption

Gauge invariance

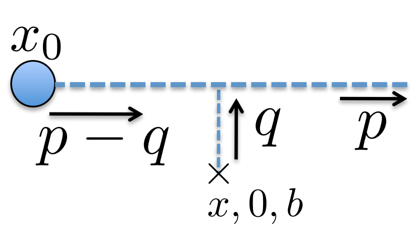
Broadening

$$\mathcal{L}_{\rm G}\left(\xi_n, A_n, \eta\right) = \sum_{p,p',q} {\rm e}^{-i(p-p'+q)x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\rm qqA_G} \frac{\bar{n\!\!\!/}}{2} \xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{\rm ggA_G} \left(A^b_{n,p'}\right)_\nu \left(A^c_{n,p}\right)_\lambda\right) \bar{\eta}\,\Gamma^{\nu,a}_{\rm s}\,\eta\,\Delta_{\mu\nu}(q)$$

$$\Delta_{\mu\nu}(q) = \frac{(-d_{\mu\nu})}{q^2-\mu^2}$$

$M_1^{(q)} =$ 

$$\left(M_1^{(q)}\right)_{(A^+,A^-)} = -{\rm e}^{ipx_0}\, T^a_r T^a_{r'}\, J(p) \int \frac{d^2\boldsymbol{q}_\perp}{(2\pi)^2}\, \tilde{v}(\boldsymbol{q}_\perp)\, {\rm e}^{-i\boldsymbol{q}_\perp(\boldsymbol{x}-\boldsymbol{x}_0)_\perp} \left[{\rm e}^{i\omega(z-z_0)} + \Delta_{(A^+,A^-)}\right]$$

$M_1^{(g)} =$ 

$$\left(M_1^{(g)}\right)_{(R_\xi,A^+,A^-)} = -i\,{\rm e}^{ipx_0}\, f^{abc} T^b_{r'}\, J(p)_{\nu_1} \int \frac{d^2\boldsymbol{q}_\perp}{(2\pi)^2}\, \tilde{v}(\boldsymbol{q}_\perp)\, \varepsilon_\lambda(q_2) \left(g_\perp^{\nu_1\lambda}\right) {\rm e}^{-i\boldsymbol{q}_\perp(\boldsymbol{x}-\boldsymbol{x}_0)_\perp} \left[{\rm e}^{i\omega(z-z_0)} + \Delta_{(R_\xi,A^+,A^-)}\right]$$

Prescription	$\frac{1}{[k^+]}$	Δ_{A^+}	Δ_{A^-}
+i0	$\frac{1}{k^++i0}$	1	0
-i0	$\frac{1}{k^+-i0}$	0	-1
PV	$\frac{1}{2}\left(\frac{1}{k^++i0}+\frac{1}{k^+-i0}\right)$	$\frac{1}{2}$	$-\frac{1}{2}$
ML	$\frac{1}{k^++i0\,{\rm sign}(k^-)}$	$\frac{1}{2}$	$-\frac{1}{2}$

The light-cone prescription dependence suggest that a new Wilson line be introduced

Idilbi, Scimemi, 10

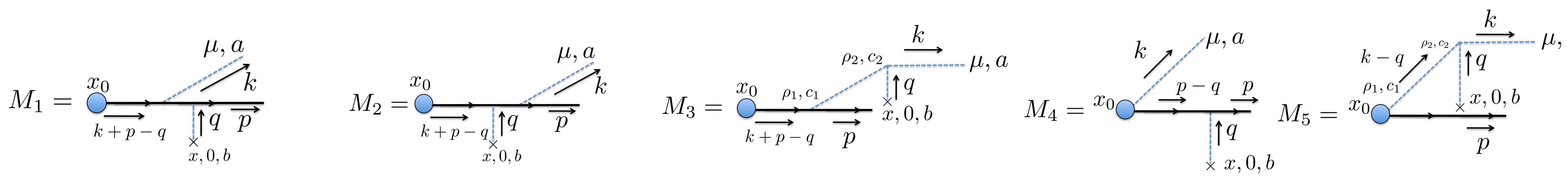
Gauge invariance

Radiative Energy Loss

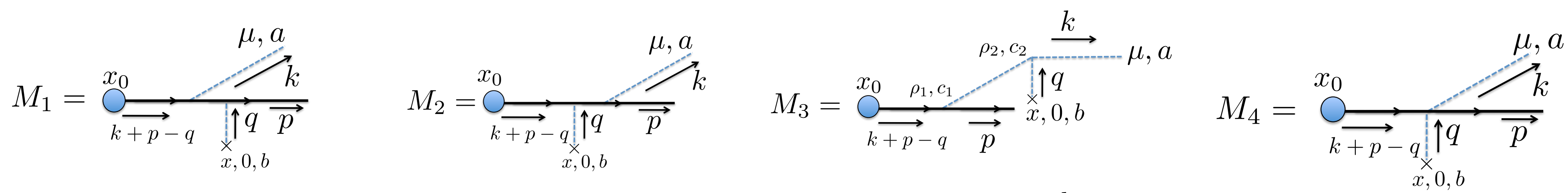
$$\mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, \eta\right) = \sum_{p,p',q} \mathrm{e}^{-i(p-p'+q)x}\left(\bar{\xi}_{n,p'}\Gamma^{\mu,a}_{\mathrm{qqA_G}}\frac{\bar{\not{n}}}{2}\xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}}\left(A^b_{n,p'}\right)_\nu\left(A^c_{n,p}\right)_\lambda\right)\bar{\eta}\,\Gamma^{\nu,a}_{\mathrm{s}}\,\eta\,\Delta_{\mu\nu}(q)$$

$$\Delta_{\mu\nu}(q) = \frac{(-d_{\mu\nu})}{q^2-\mu^2}$$

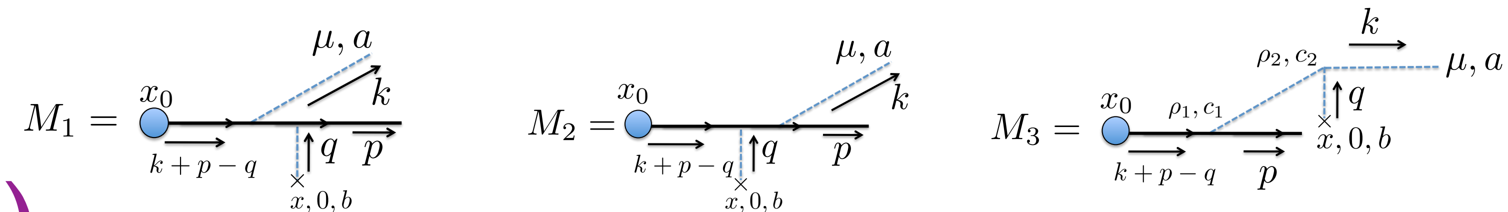
Rξ



A+=0



Hybrid Rξ(glauber), A+(collinear)



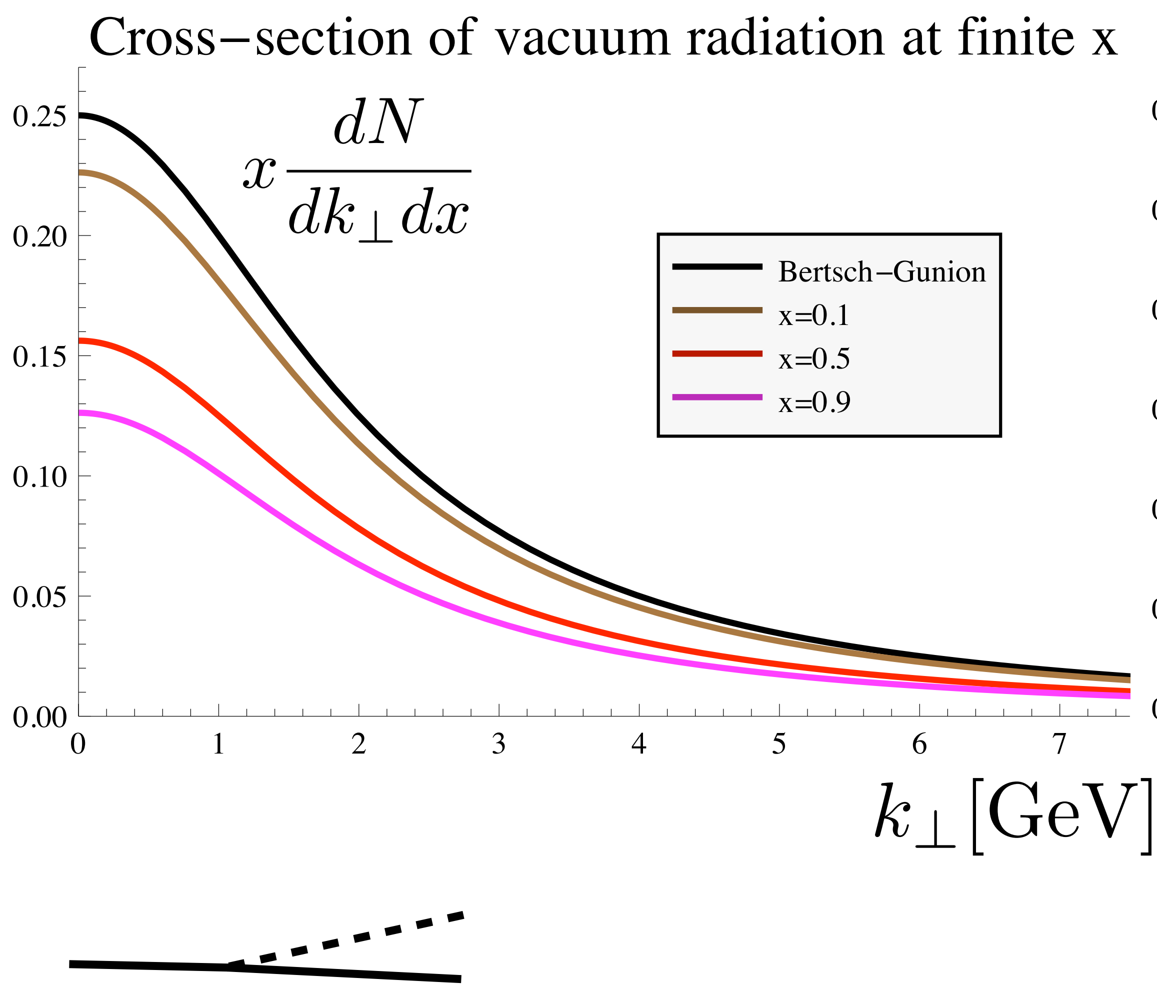
Again gauge invariance works non-trivially in all cases, up to T-Wilson line necessity in A+=0 gauge

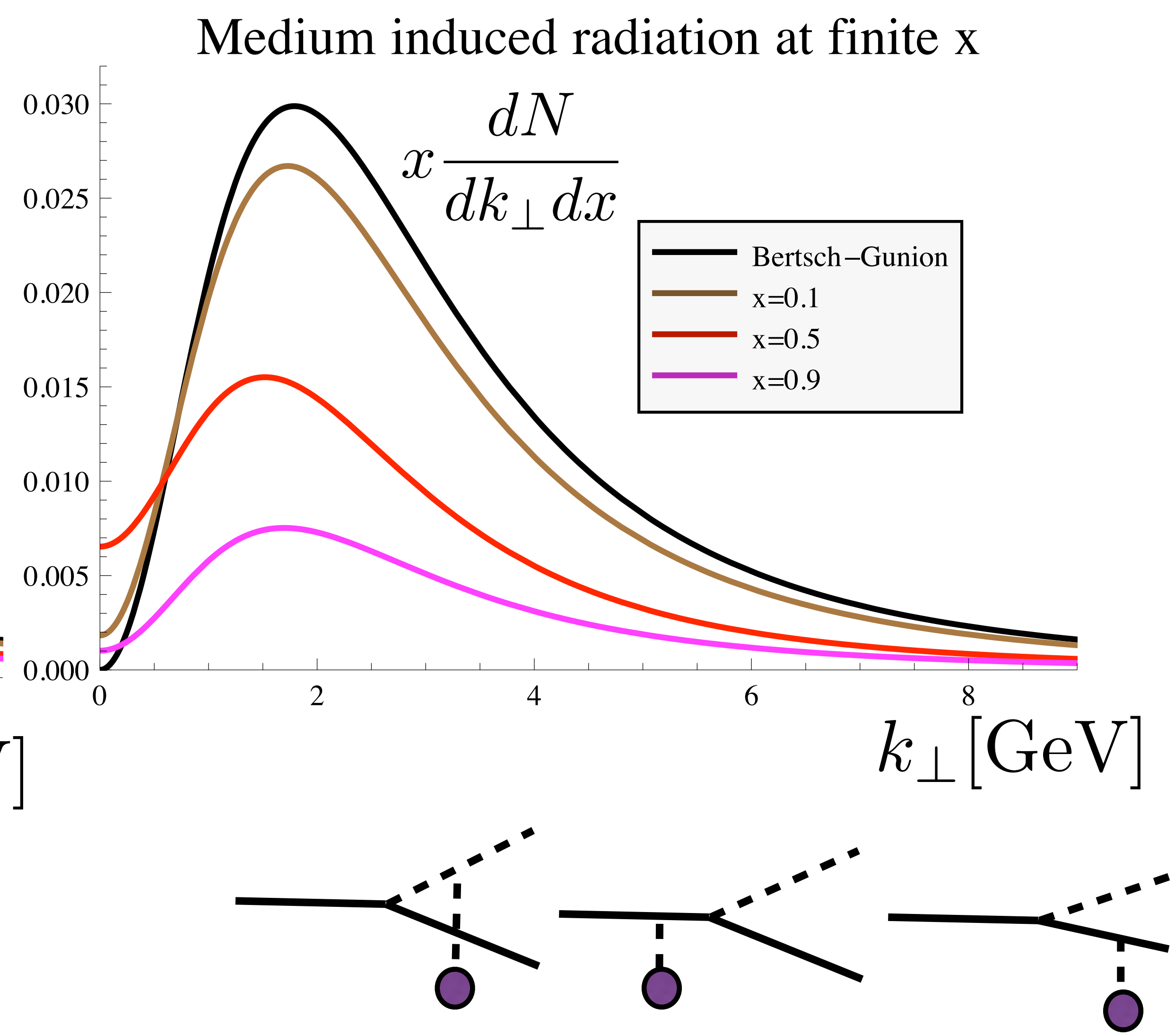
Comparison with previous results

Gyulassy, Levai, Vitev, 00

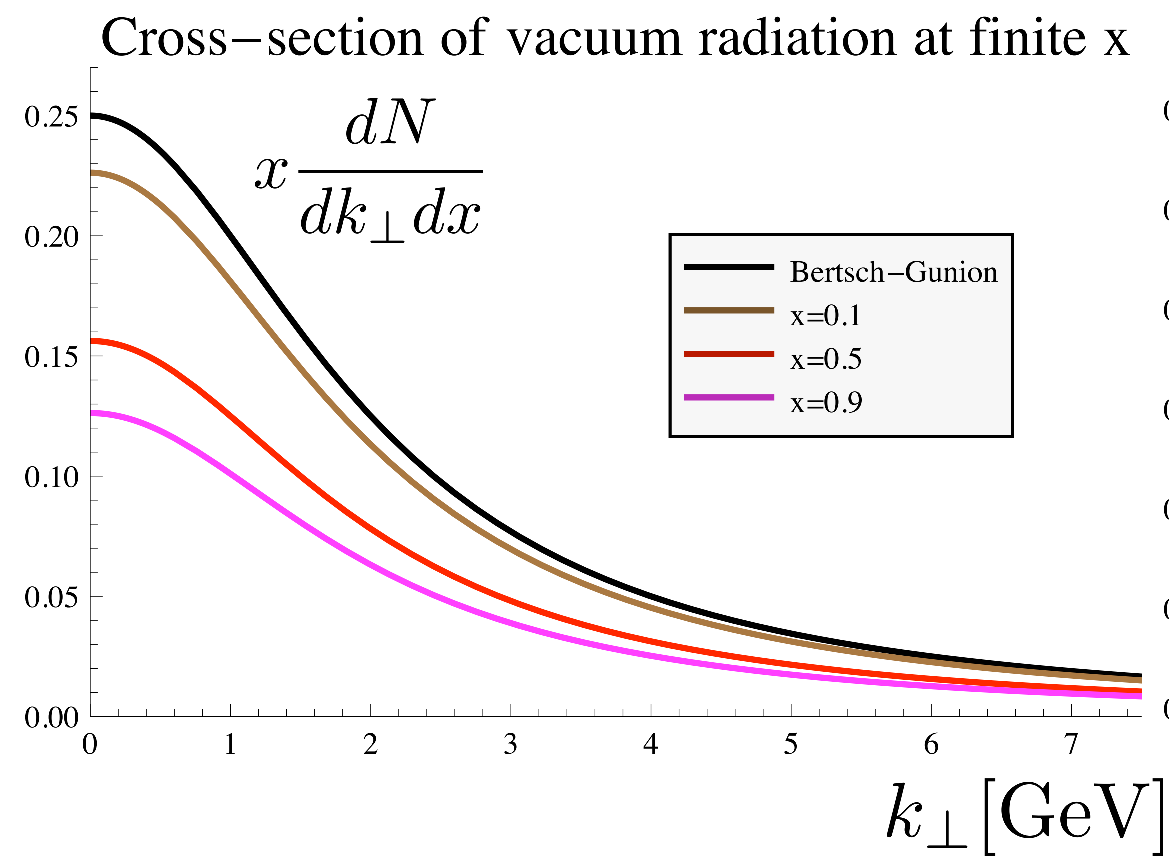
- For Jet broadening and Radiative energy loss we have verified that the scattering kernels are gauge invariant
- For the Jet broadening our results agree with previously derived results in GLV approach
- For the Radiative energy loss our results agree with GLV approach in the soft gluon approximation

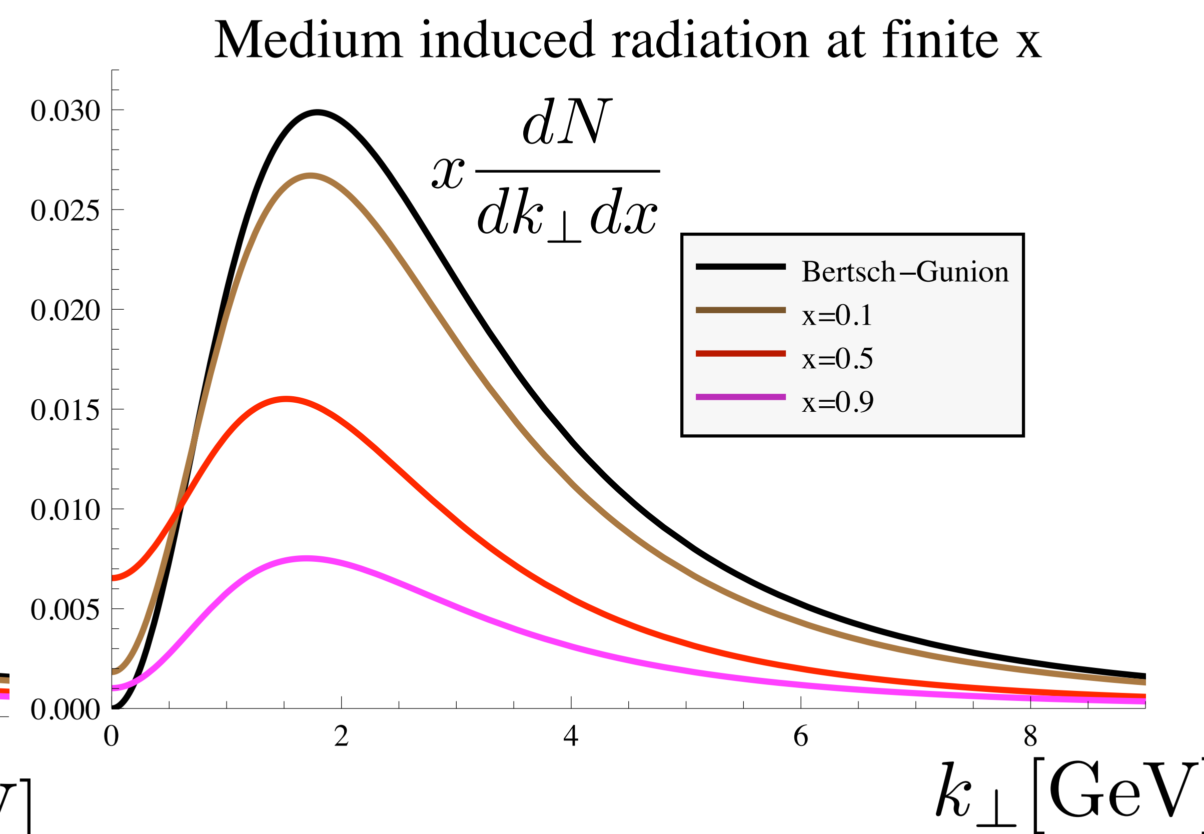
Energy loss at finite x, using $SCET_G$

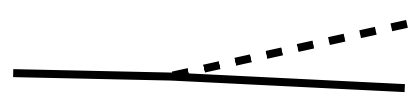


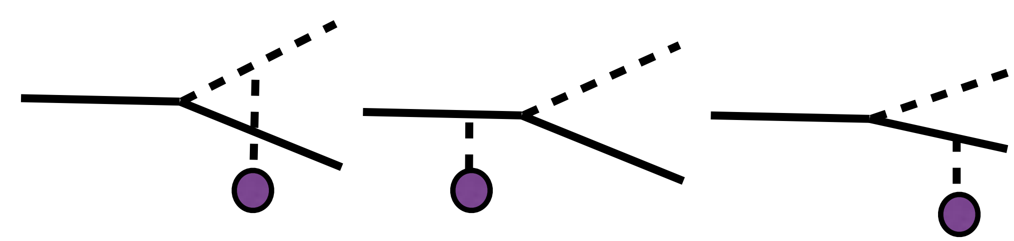


Energy loss at finite x, using $SCET_G$





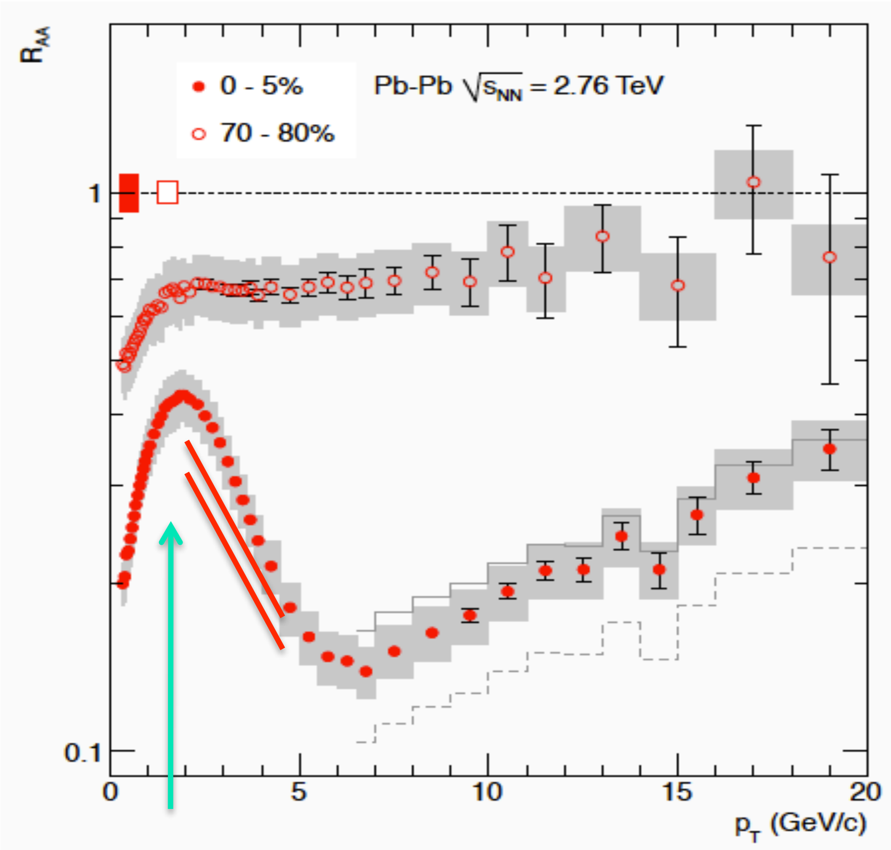


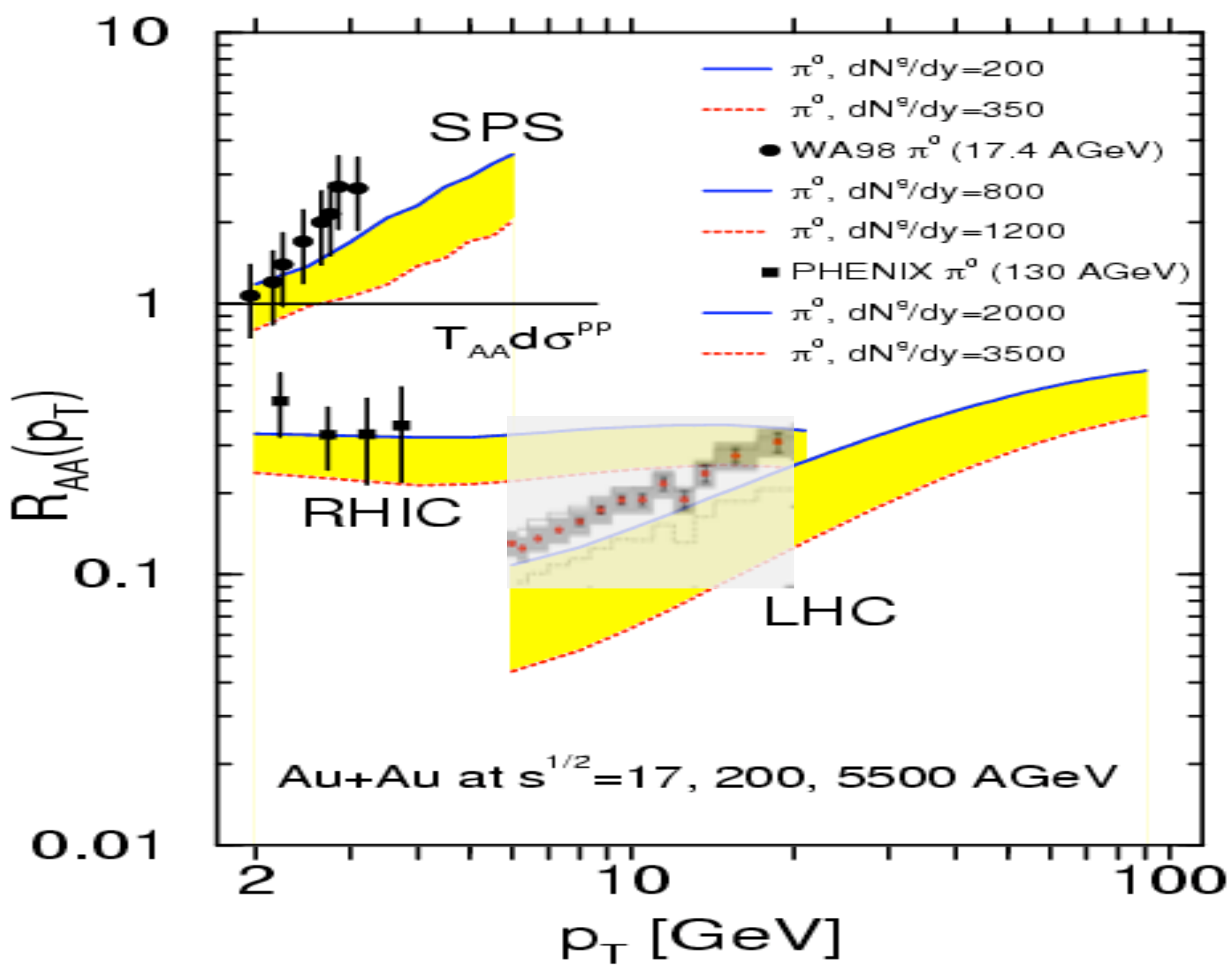


- Typical treatment of energy loss uses soft gluon approximation x<<1
- Our results show that the finite x effects push towards the smaller energy loss

First heavy ion data from LHC well explained by GLV 2002 prediction!

K. Amadot et al, (2011)





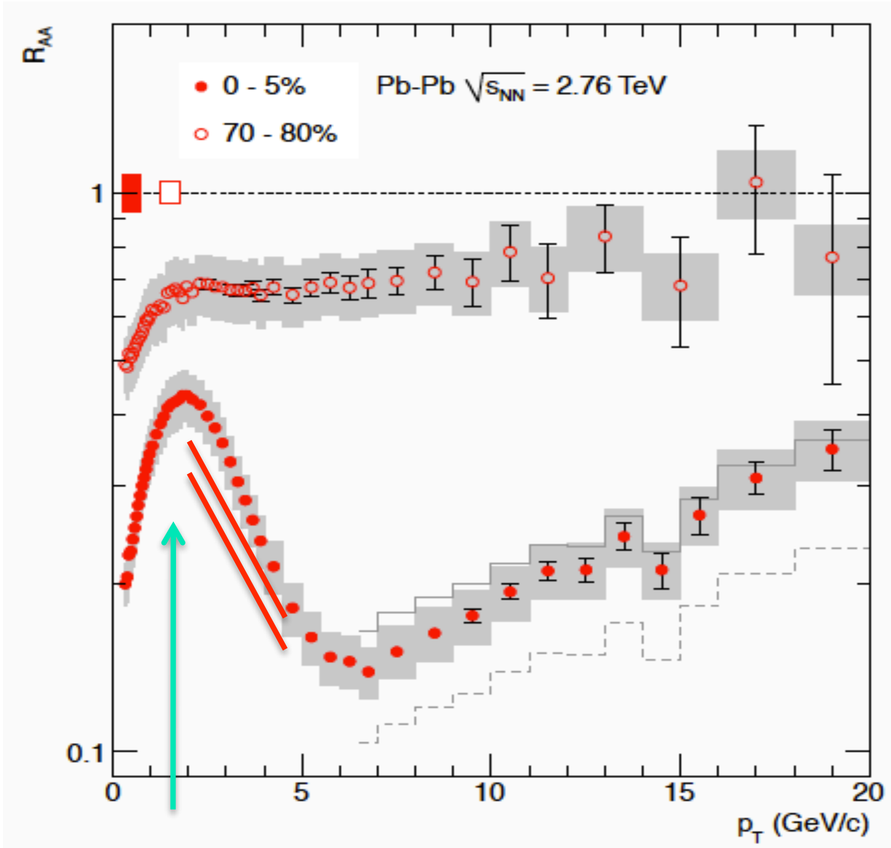
Vitev, (2005)

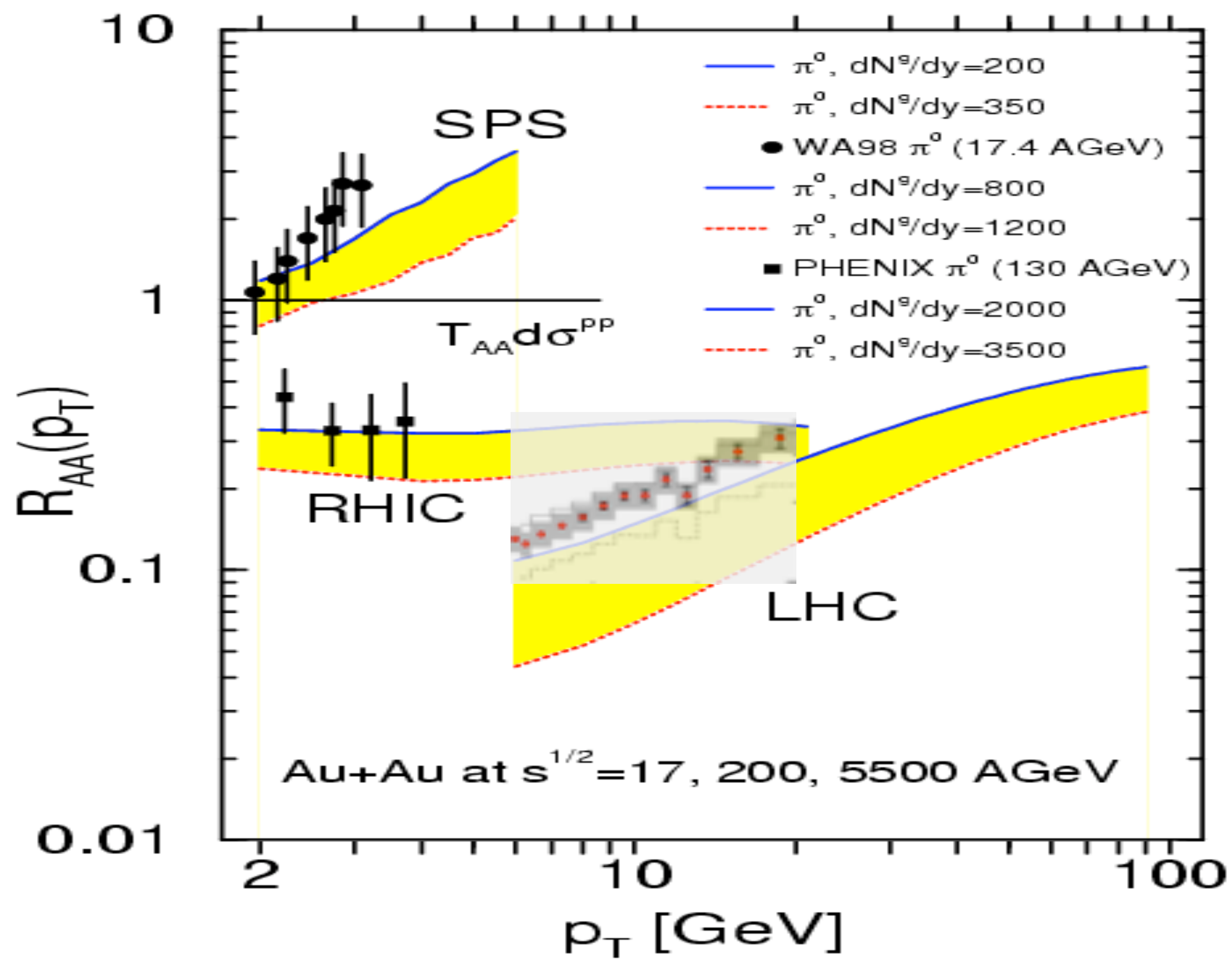
Vitev, Gyulassy (2002)

Larger R_{AA} can be explained by:

First heavy ion data from LHC well explained by GLV 2002 prediction!

K. Amadot et al, (2011)





Vitev, (2005)

Vitev, Gyulassy (2002)

Larger R_{AA} can be explained by:

- Smaller coupling to medium at higher energies
- Smaller energy loss

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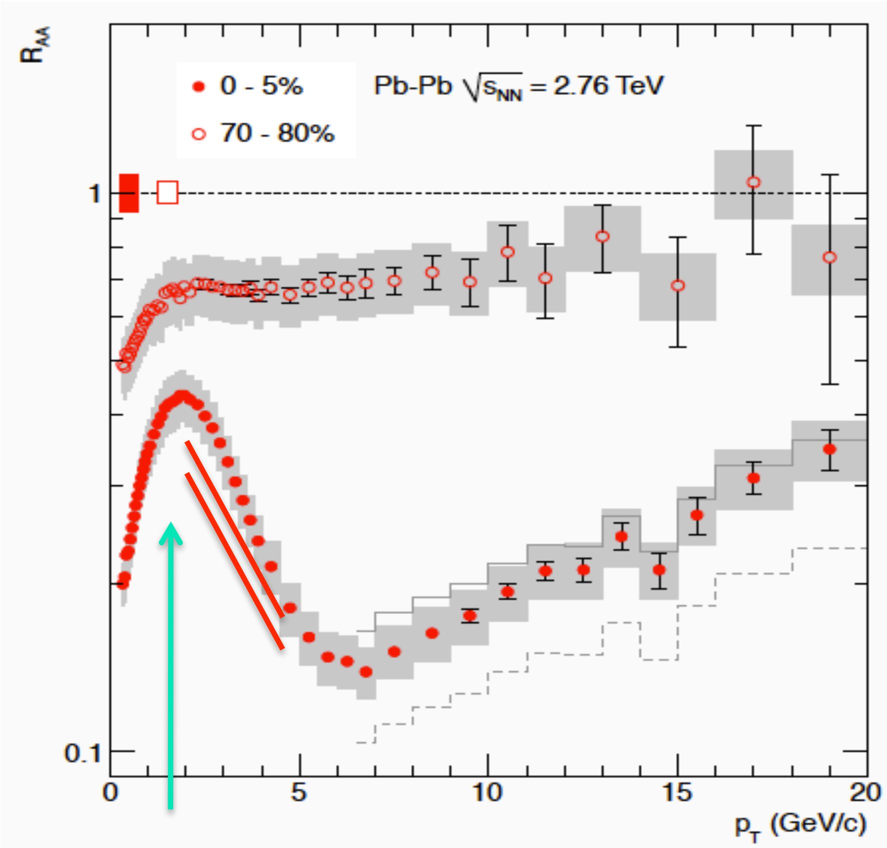

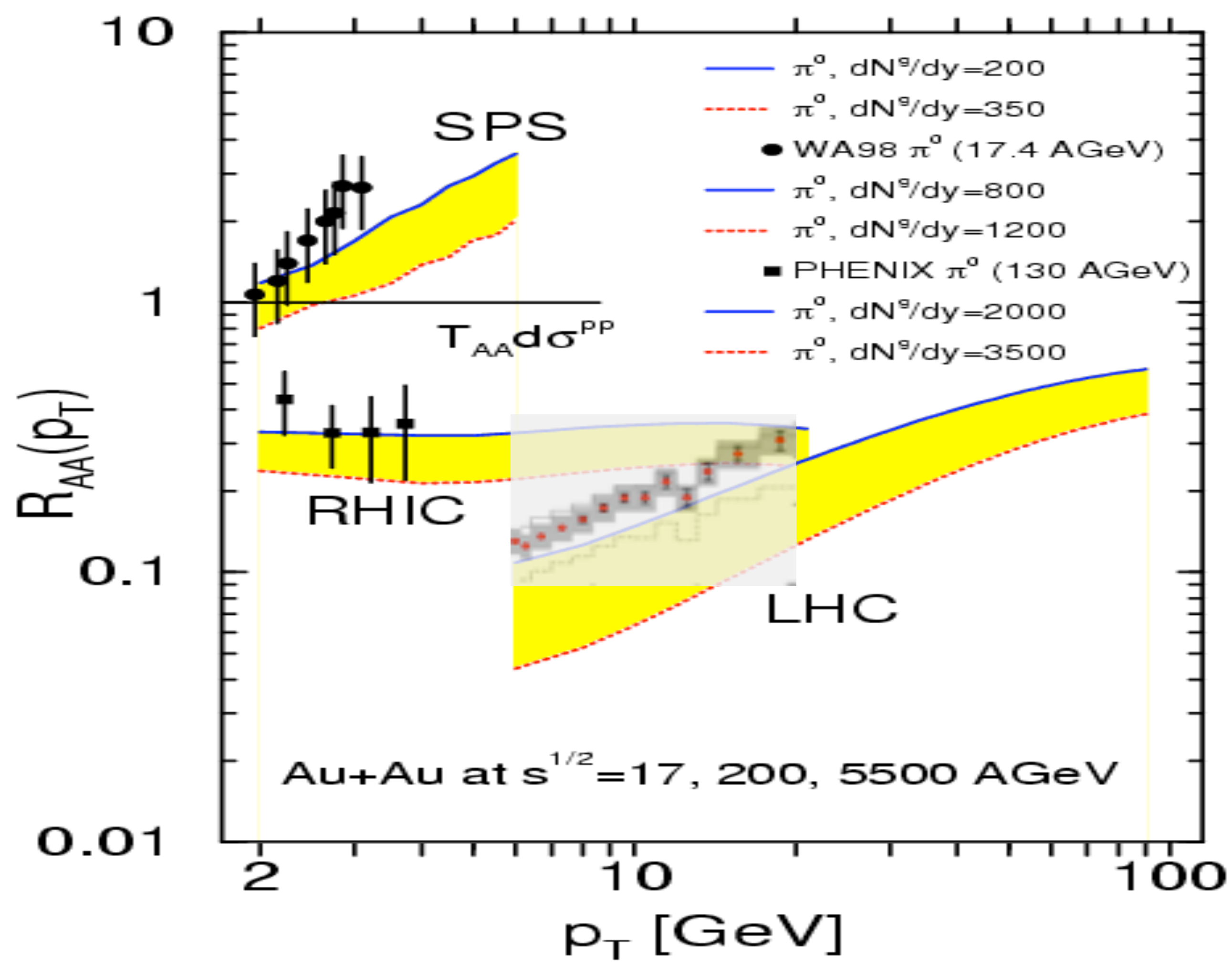

Vitev, (2005)

Vitev, Gyulassy (2002)

Larger R_{AA} can be explained by:

- Smaller coupling to medium at higher energies
- Smaller energy loss (finite x corrections?)

Conclusions

- We constructed effective theory for jet propagation in medium, including collinear quarks and gluons
- We formulated the effective theory in three different gauges and demonstrated the gauge invariance of the scattering kernels, derived previously in PQCD in soft gluon approximation
- Effective theory Feynman rules allowed us to go beyond the soft gluon approximation
- Constructed Lagrangian of $SCET_G$ needs to be completed with soft gluons
- Such effective theory should be applied to factorization of the Drell-Yan process