Jets in QCD matter: Theory summary

Korinna Zapp

LIP (Lisbon) & CERN

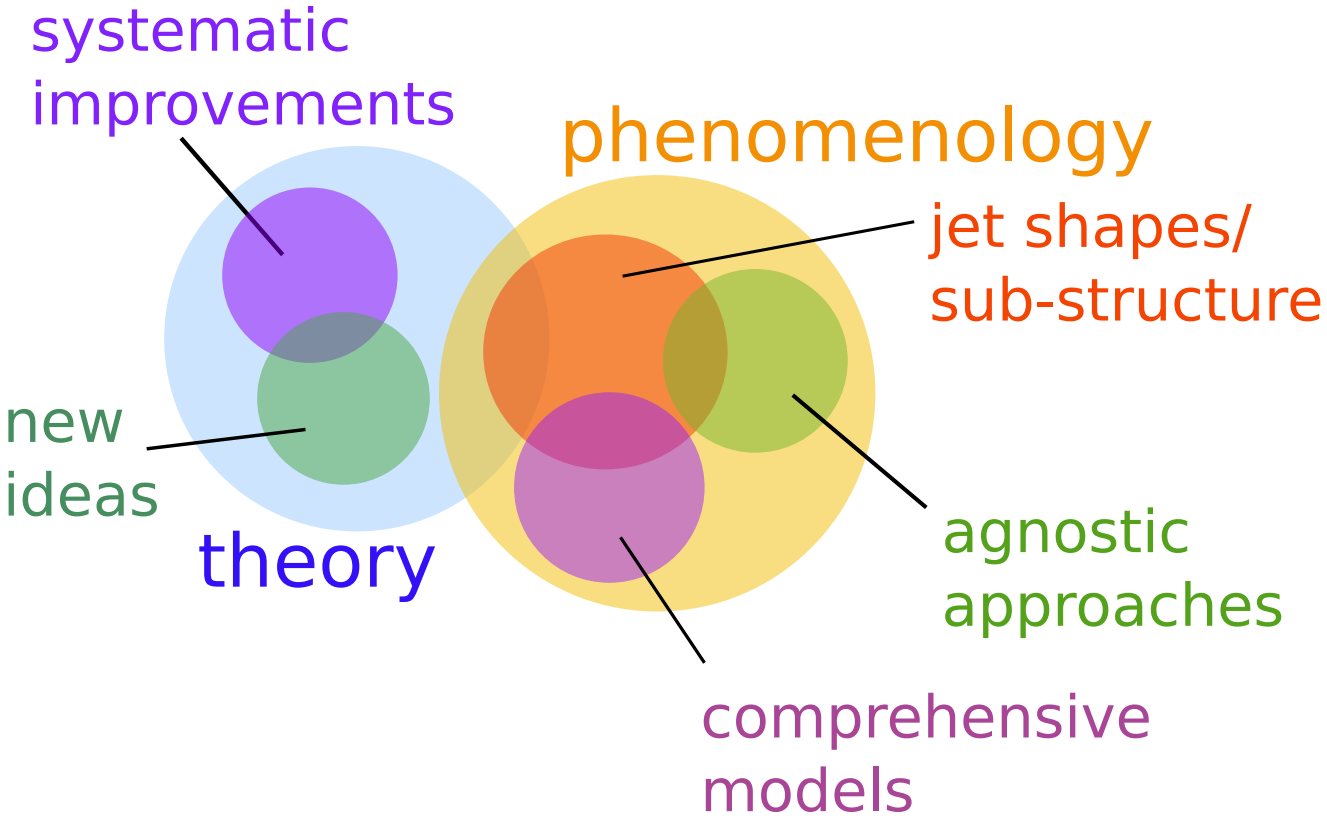
Hard Probes 2018
Aix-les-Bains 1.–5. 10. 2018

Apologies...

- ...to all speakers whose talks I should have attended but didn't, because I was in the other session.

- ...to all speakers whose work I misunderstand or misrepresent.

HP18 jet talk topology



- theory: understanding specific aspects
- phenomenology: modeling of all relevant aspects

allows for comparison to experimental data

What is needed to model jet shapes/sub-structure

- vacuum baseline: jet production + evolution
  - extra emissions give rise to jet sub-structure

\+ radiative energy loss
  - out-of-cone: jet energy loss
  - in-cone: redistribution of energy inside jet
    $\rightarrow$ modification of sub-structure

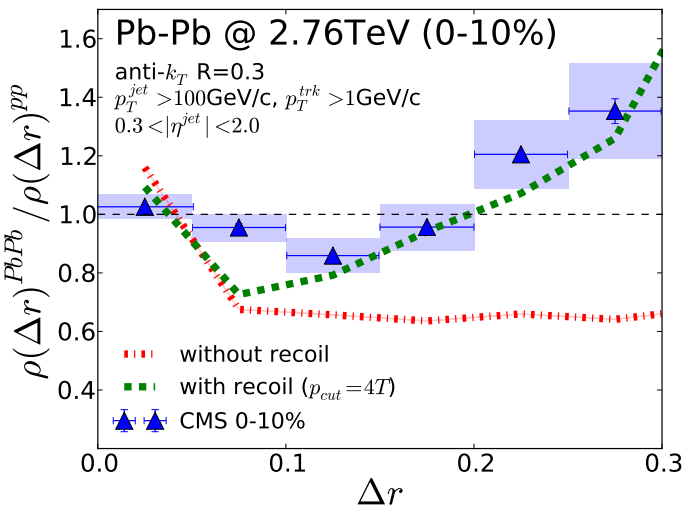
\+ collisional energy loss + medium response
  - partial recovery of lost energy
  - medium response distribution wider
    $\rightarrow$ modification of jet sub-structure

important mostly at large r

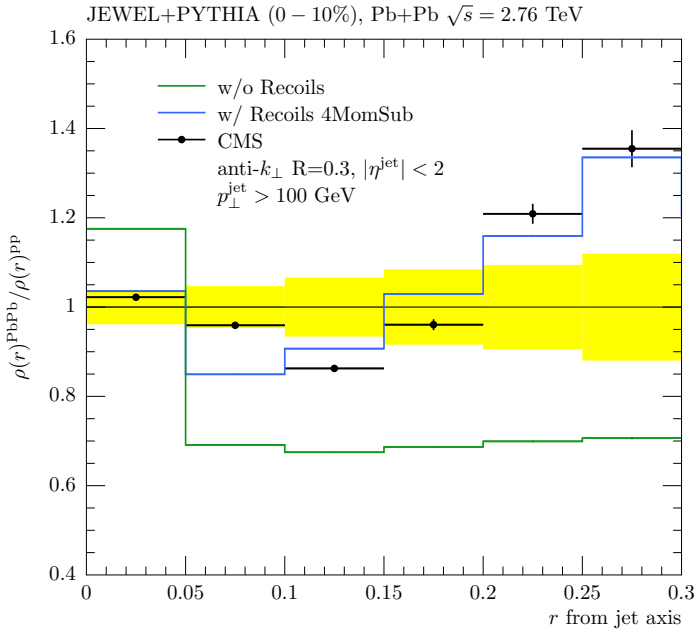
Approaches presented at Hard Probes 2018

- LBT/coLBT — Wei Chen (Tue), Xin-Nian Wang (Wed)
- $SCET_G$ — Hai Tao Li (Tue), Yang-Ting Chien (Wed)
- AdS/CFT — Wilke van der Schee (Tue)
- hybrid model — Daniel Pablos (Thu)
- JETSCAPE — Yasuki Tachibana (Wed)
- Pythia + Boltzmann + higher twist + hydro — Ning-Bo Chang (Tue)
- vacuum + higher twist + LBT + hydro — Guang-You Qin (Wed)

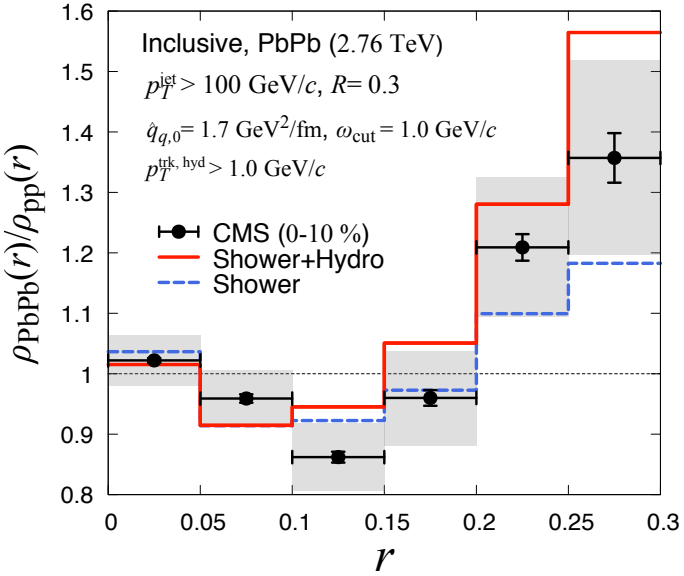
Jet profile



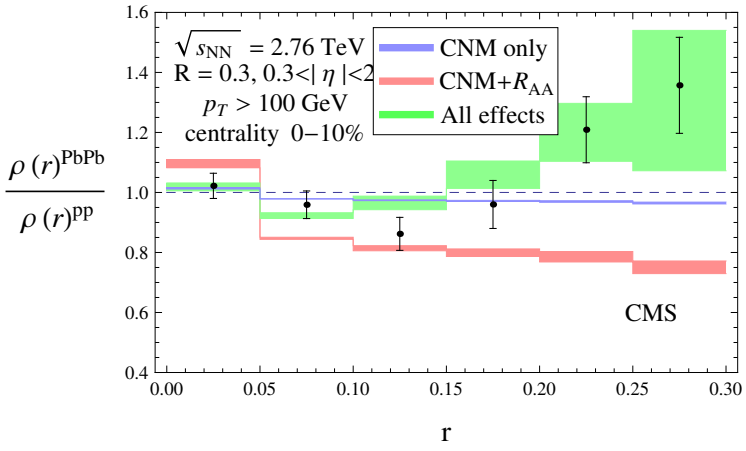
Park, Jeon, Gale, arXiv:1807.06550



Kunnawalkam Elayavalli, Zapp, JHEP 1707 (2017) 141

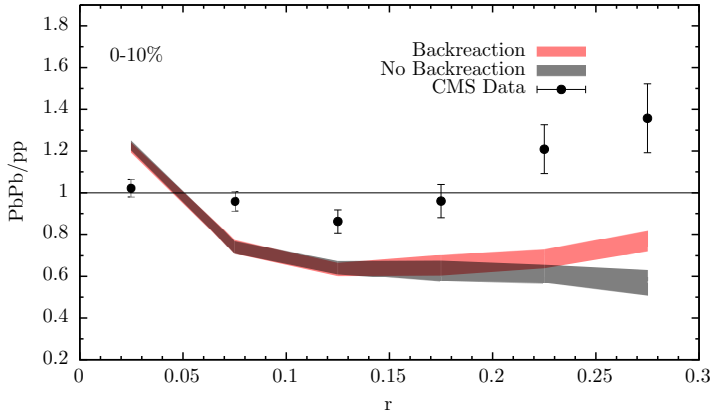


Tachibana, Chang, Qin, Phys. Rev. C 95 (2017) no.4, 044909

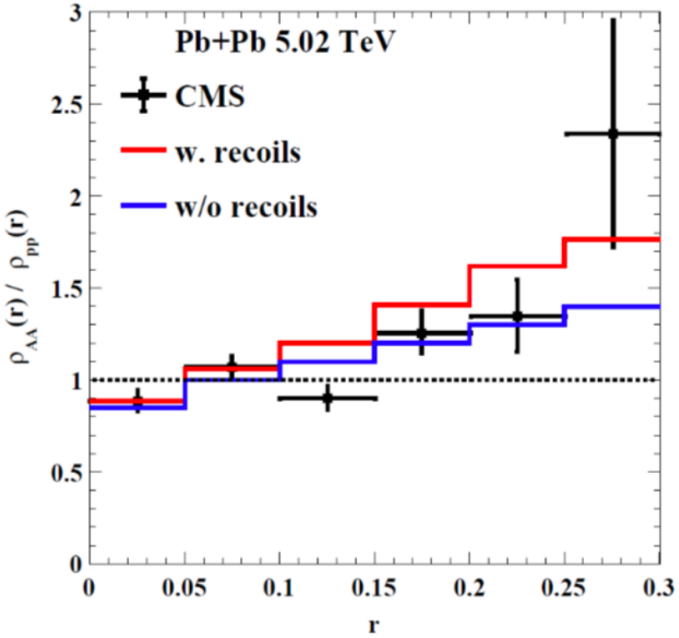


Chien, Vitev, JHEP 1605 (2016) 023

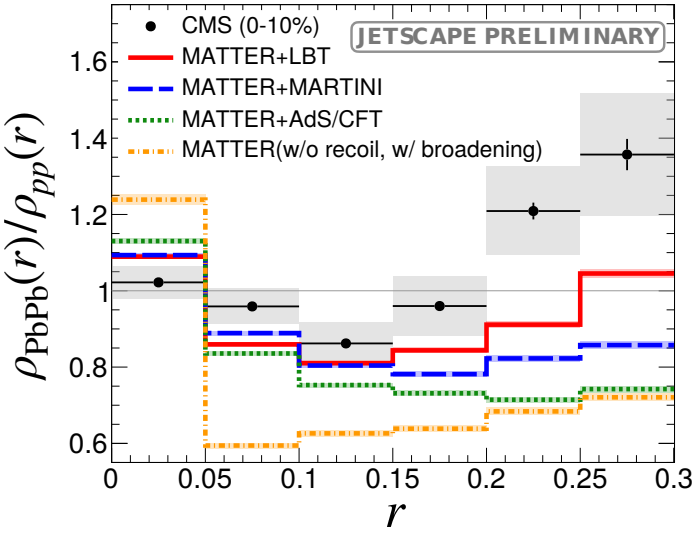
Jet profile continued



Casalderrey-Solana *et al*, JHEP 1703 (2017) 135



talk by Xin-Nian Wang (Wed)



talk by Yasuki Tachibana (Wed)

- unclear, whether increase due to medium response or induced radiation

Agnostic approaches

Goal

extract energy loss characteristics or medium properties from data as model independently as possible

Talks at Hard Probes 2018

- systematically scan radiation phase space (Lund diagram) $\leftrightarrow$ jet sub-structure — Marta Verwej (Wed), Yi Chen (Wed)
- machine learning — Yue Shi Lai (Tue), Yang-Ting Chien (Wed)
- generic models — François Arleo (Tue), Martin Rohrmoser (Tue), Xin-Nian Wang (Wed)
- quantile matching — Jasmine Brewer (Tue)

Scanning the Lund diagram (slide from Marta Verwej)

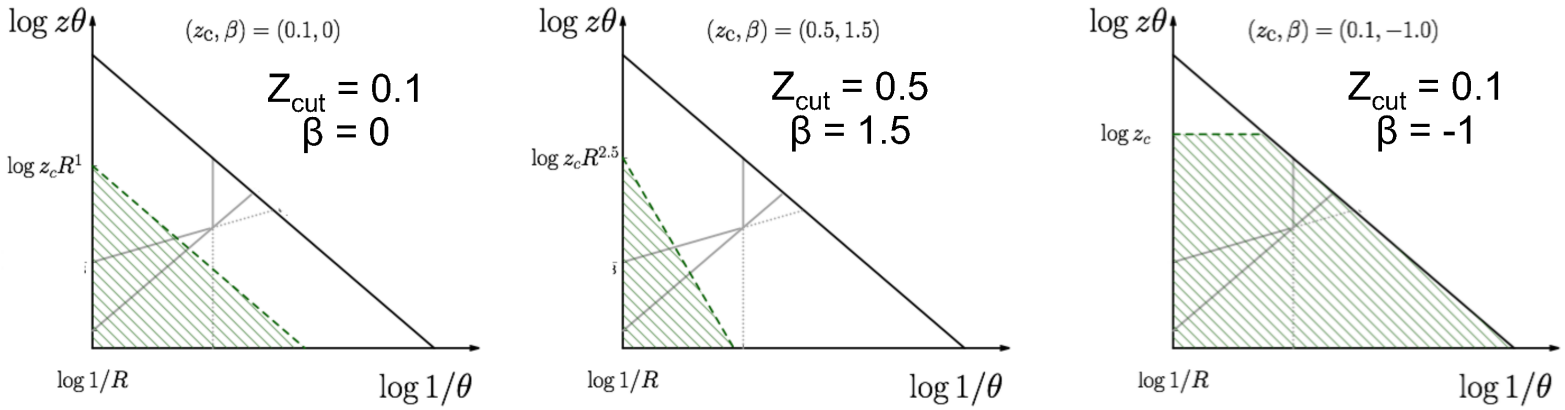
Lund and grooming

Grooming selects on momentum fraction and angle of branches in angular ordered tree

$$z > z_{\rm cut}\,\theta^{\beta}$$

energy threshold — angular exponent

[Shaded region is excluded.]



cuts only on the energy sharing fraction

stronger grooming at large angle

only hard radiation remains

Varying the grooming condition allows to select different regions of radiation phase space

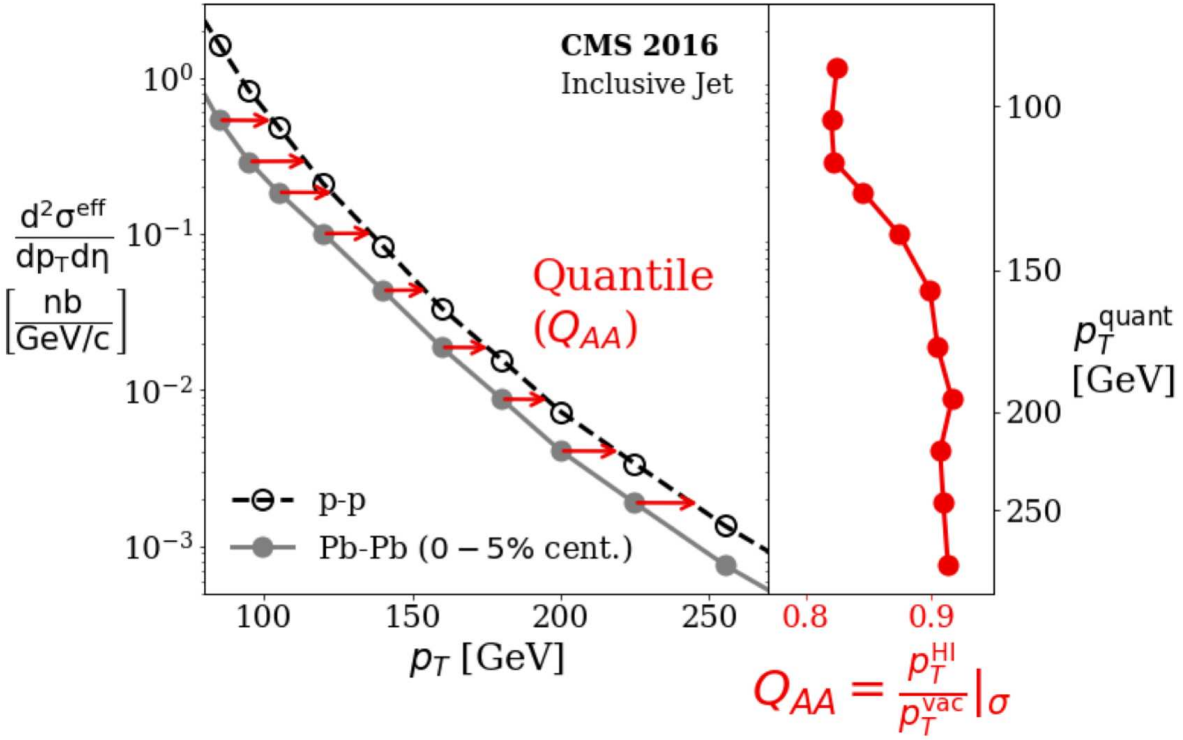
Quantile matching (slide from Jasmine Brewer)

Key question: compare A-A jets to which p-p jets?

- Another answer: match in (effective) cumulative jet cross-section

$$\sigma^{\rm eff} = \sigma^{\rm pp}, \frac{\sigma^{\rm HI}}{\langle T_{AA}\rangle}$$

- "Quantile" matching



(see backup for technicalities)

Jasmine Brewer (MIT)

14

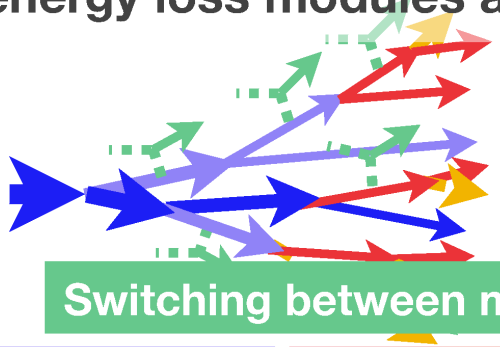
Constructing comprehensive models

- consistency of single-inclusive hadron observables — Carlota Andrés (Tue)
- AMY kinetic energy loss in JETSCAPE — Tianyu Dai (Tue)
- modeling of b-jets — Sa Wang (Tue)
- LPM effect in BAMPS — Florian Senzel (Tue)
- jet R_{AA} and v_2 in LBT — Yayun He (Thu)
- integrate jets in EPOS-HQ — Iurii Karpenko (Thu)
- hadron & jet suppression and v_2 in JETSCAPE — Chanwook Park (Thu)

The JETSCAPE philosophy (slide from Yasuki Tachibana)

Multi-stage jet evolution in JETSCAPE

- **Jet energy loss modules and their transition in JETSCAPE**



Virtuality separation scale: Q_0

Switching between modules for parton by parton

Large-Q ($> Q_0$)	Small-Q ($< Q_0$)		
	Large-E		Small-E
MATTER	**LBT**	**MARTINI**	**AdS/CFT**
Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)	Wang, Zhu(13), Luo, et al.(15,18) Cao, et al.(16,17), He, et al.(18)	Schenke, Gale, Jeon(09), Park, Jeon, Gale(17, 18)	Chesler, Rajagopal(14, 15) Pablos, et al.(15, 16, 17)
Radiation dominated Virtuality ordered splitting	Scattering dominated On-shell parton transport		Diffusion into medium
Higher Twist Formalism	Higher Twist Formalism	AMY Formalism	$\mathcal{N}$ = 4 super Yang-Mills

4

Systematic improvements of existing approaches

Moving to higher precision

- cancellation of IR singularities in medium — Yacine Mehtar-Tani (Tue)
- definition of $\hat{q}$ — Bin Wu (Tue)
- baseline for $p_\perp$ imbalances: pQCD expansion + resummation — Shu-yi Wei (Tue)

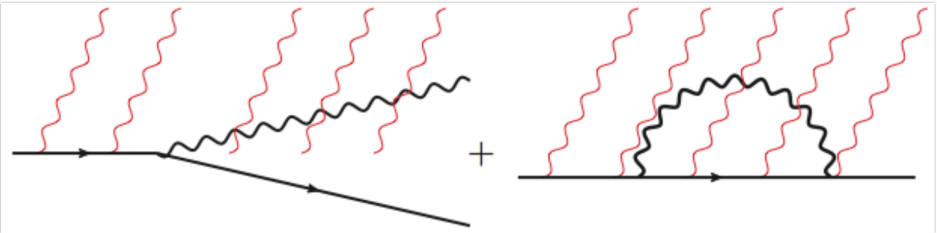
Others

- in-medium antenna with finite formation time — Víctor Vila (Tue)
- BDMPS quenching weights in expanding medium — Souvik Priyam Adhya (Tue)
- DGLV beyond soft gluon approximation — Bojana Balgojevic (Tue)
- generalised higher twist approach — Yuang-Yuang Zhang (Thu)
- distribution of partons scattering off pointlike objects — Yi Yin (Thu)
- $\hat{q}$ from lattice simulations — Amit Kumar (Thu)

Modified cancellation of IR divergences (slide from Yacine Mehtar-Tani)

NLO correction to the jet spectrum

Mismatch between real and virtual



gluon + quark energy loss $\gg$ quark energy loss

$$Q^{(1)}(p_T) = \bar{\alpha} \int_{\theta_c}^{R} \frac{\mathrm{d}\theta}{\theta} \int_{(\hat{q}/\theta^4)^{1/3}}^{p_T} \frac{\mathrm{d}\omega}{\omega} \left[Q_q^2(p_T) - 1\right] Q_{\mathrm{tot}}(p_T)$$

Generalised Higher Twist (slide from Yuang-Yuang Zhang)

Radiative energy loss:assumptions

Approaches to radiative energy loss : BDMPS-Z, GLV, AMY, SCET, High Twist

- Scattering Center : Static or Dynamic?

  Static: no energy transfer (BDMPS-Z, GLV)

  Extension of GLV to dynamic S.C. Djordjevic,Heinz PRL 101,022302

  Dynamic: both momentum and energy transfer ✓

- Radiated Gluon : Soft or hard ?

  z → 0 (BDMPS-Z, GLV, SCET)

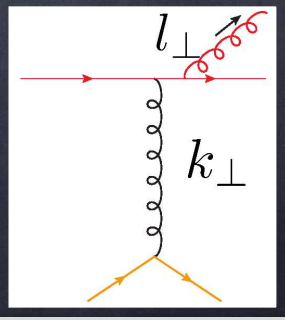
  Discussion on soft appr. of GLV Blagojevic *et al*. arXiv:1804.07593

  z finite ✓

- Transverse momentum transfer : smaller or same order $l_\perp$?

  $k_\perp \ll l_\perp$ (High Twist)

  $k_\perp \sim l_\perp$ ✓



(Mostly) new ideas & approaches

- parton energy loss in unstable plasma — Sigtryggur Hauksson (Tue)
- vacuum like emissions in medium — Paul Caucal (Thu)
- calculate spectral function on lattice — Kirill Boguslavski (Thu)
- new jet function for small R jets — Chathuranga Sirimanna (Thu)

Quark vs. gluon jet energy loss

Jet evolution (vacuum & medium)

João Barata (Thu)

- parton energy loss:
  - QCD: $\frac{\Delta E^{(q)}}{\Delta E^{(g)}} = \frac{C_F}{C_A} = \frac{4}{9}$
  - AdS/CFT: $\frac{\Delta E^{(q)}}{\Delta E^{(g)}} = \left(\frac{C_F}{C_A}\right)^{1/3}$
- jet energy loss: only out-of-cone radiation contributes
- MC study: energy loss ratio much closer to 1

Turbulent in-medium cascade

Sören Schlichting (Thu)

- chemistry of in-medium cascade
- at large x and strong quenching: most energy carried by quarks

Some personal thoughts

- jet quenching many-faceted and interesting
- but do we learn anything about the medium?
- something that can only be learned from jets:

At which scale are quasi-particles resolved?

- scattering off quasi-particles: power-law tail to large angles
- is this observable?
- in jets/leading partons: difficult due to large fluctuations in vacuum part of fragmentation pattern
- medium response: additional source of fluctuations

Conclusions

Conclusions

See you at Hard Probes 2020!