8th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions HP2016
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Theory overview

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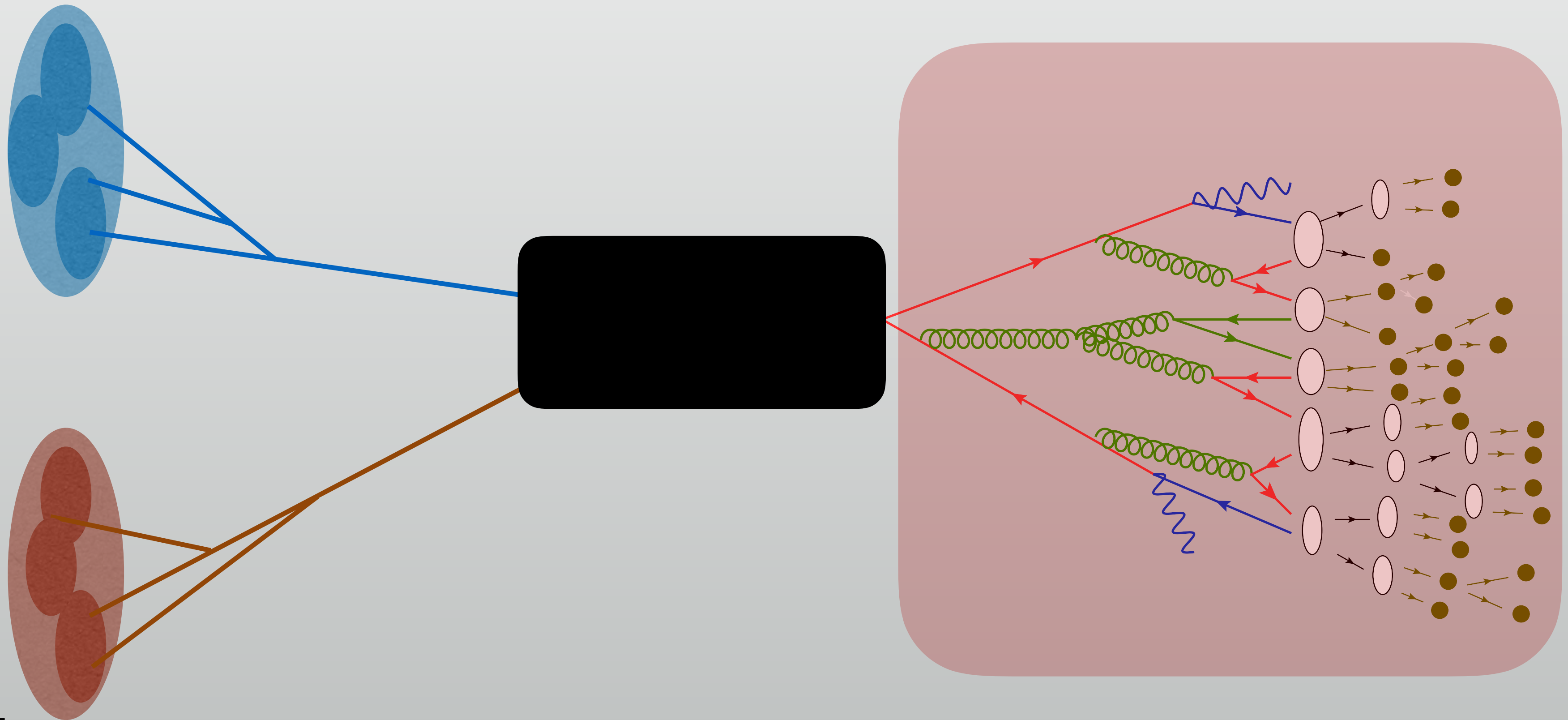
Contents:

1. Initial stage:
   ➜ nPDFs.
   ➜ CGC: evolution equations and particle production.

2. Jet quenching:
   ➜ Single inclusive particle production.
   ➜ Jets.



3. Heavy flavour:
   ➜ Open heavy flavour.
   ➜ Quarkonium.

4. EM probes.

5. Conclusion.

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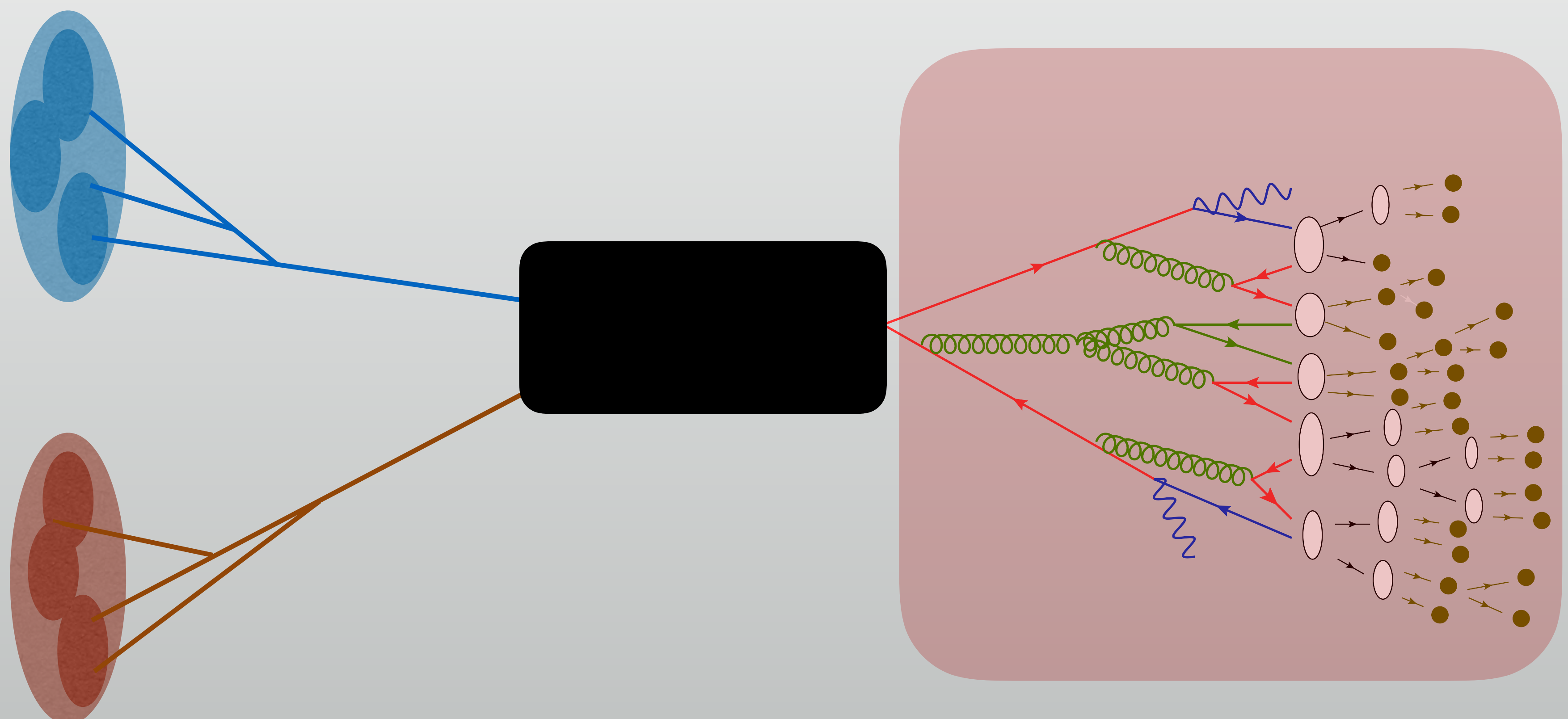

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Disclaimer: biased incomplete overview mainly focused on recent results - my apologies to those whose work is under- or mis-represented.

Factorisation:

$$d\sigma^{AA\to h+\mathrm{rest}}_{(\mathrm{vac})} = \sum_{ijk} f_{i/A}(x_1, Q^2) \otimes f_{j/A}(x_2, Q^2) \otimes \hat{\sigma}_{ij\to f+k} \otimes D^{(\mathrm{vac})}_{f\to h}(z, \mu_F^2) \,.$$

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➜ nPDFs linearly evolved using DGLAP: *dilute system.*
➜ TMDs, GPDs, <W… W†>$_T$ linearly (DGLAP/ BFKL-like) or non-linearly (BK-like) evolved: *dilute-dilute and dilute-dense scattering.*

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- ➜ On-shell matrix elements in the hard regime: collinear factorisation for *dilute systems.*
- ➜ Off-shell matrix elements for k_T-(like)factorisation in the semihard regime: *dilute-dilute and dilute-dense.*

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➜ On-shell matrix elements in the hard regime: collinear factorisation for *dilute systems.*
➜ Off-shell matrix elements for k_T-(like)factorisation in the semihard regime: *dilute-dilute and dilute-dense.*

➜ Medium-modifications of FFs (eloss, hadronisation), jet shapes, screening/dissociation/recombination for quarkonium,…
➜ Initial-final state separation unclear e.g. coherent eloss.

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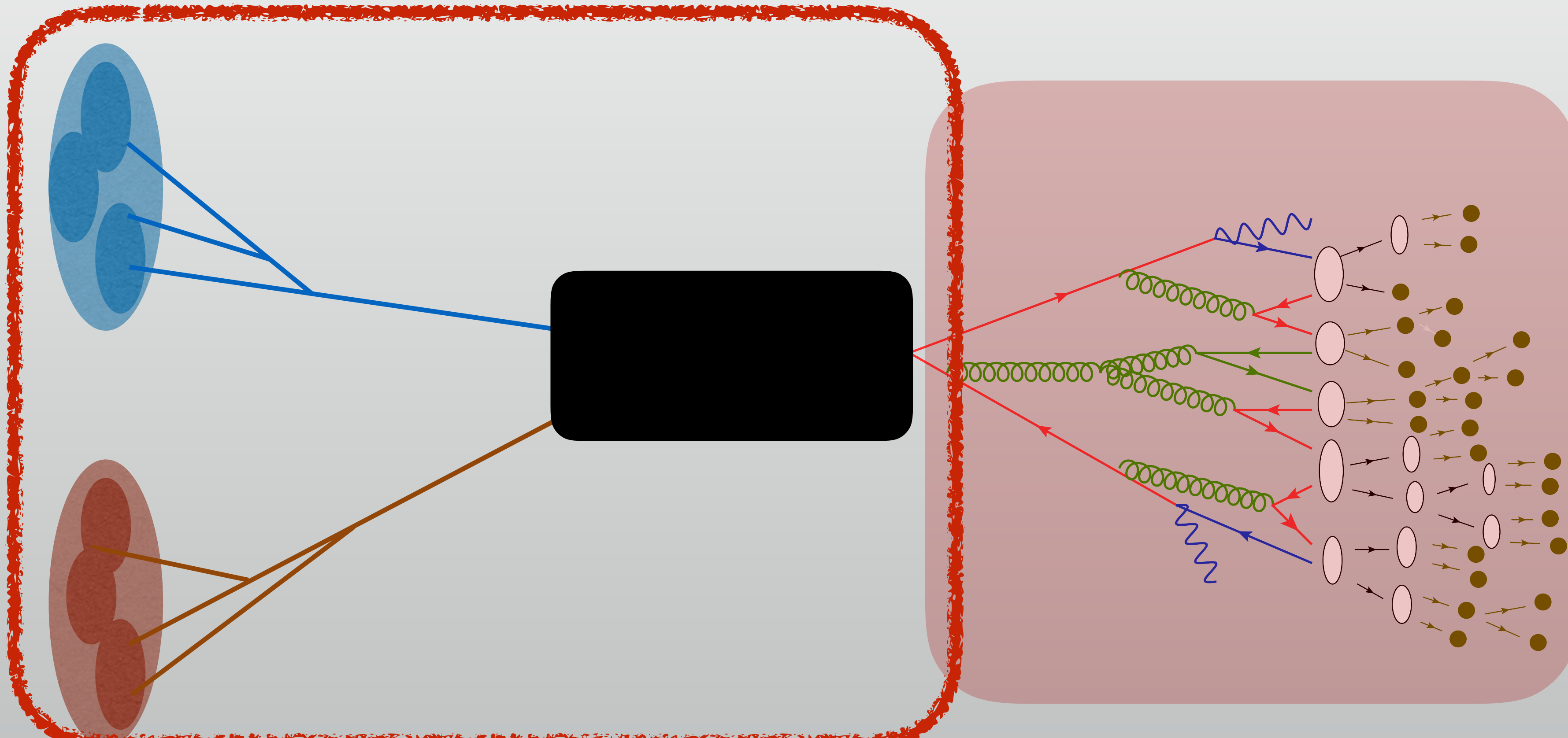
[Plenaries by Arleo, Beuf and Venugopalan]



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data type	e-DIS	✔	✔	✔	✔
	D-Y	✔	✔	✔	✔
	pions	✔	✔	✔	✘
	ν-DIS	✘	✔	✘	✘
# data points		929	1579	740	1479
accuracy		NLO	NLO	NLO	NNLO
proton PDF		CTEQ6.1	MSTW2008	~ CTEQ6.1	JR09
scheme		ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS
comments		huge gluon shadowing/ anti-shadowing found	medium modified FFs	flavour separation considered, not enough sensitivity	deuteron data included

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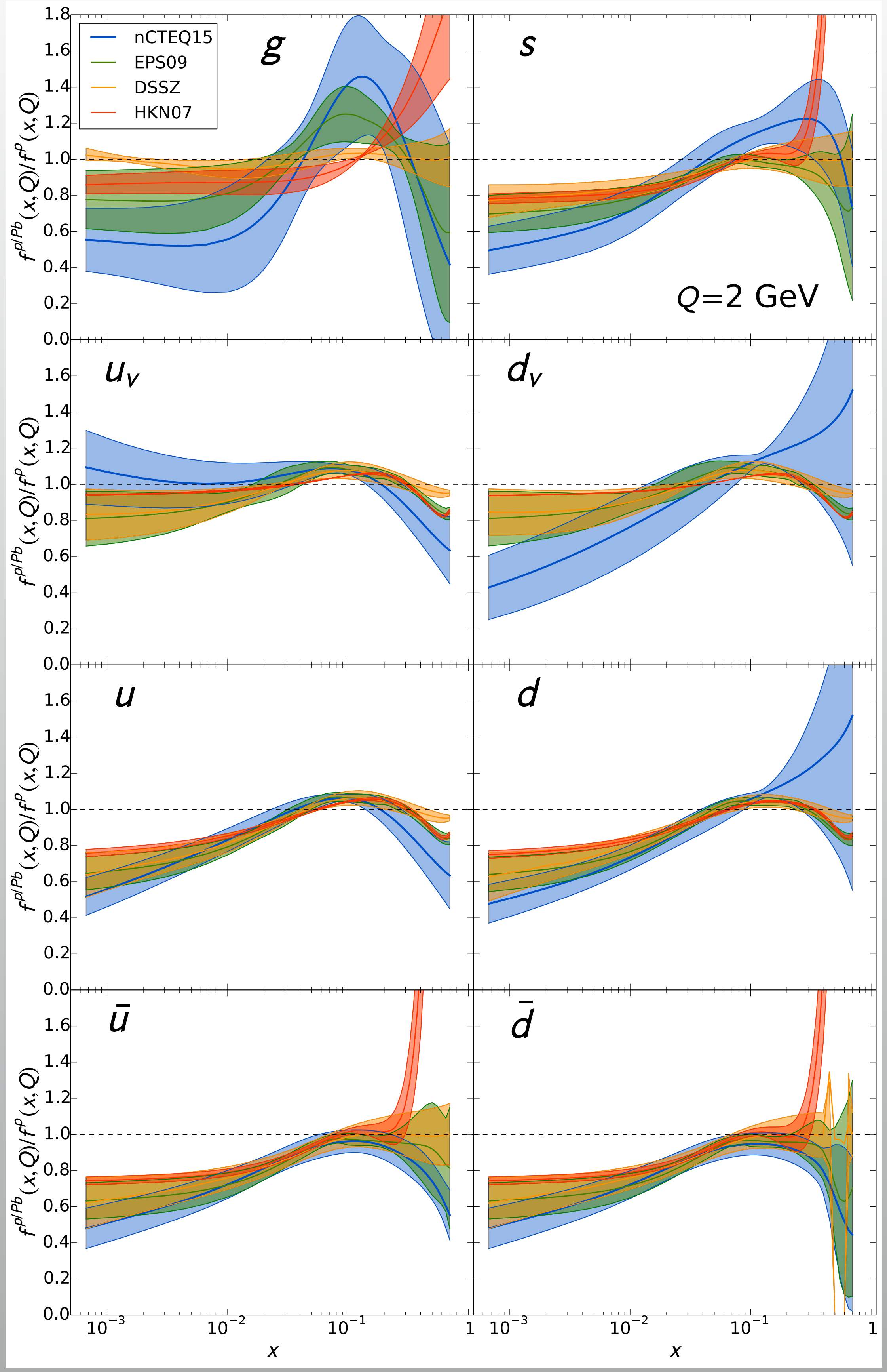

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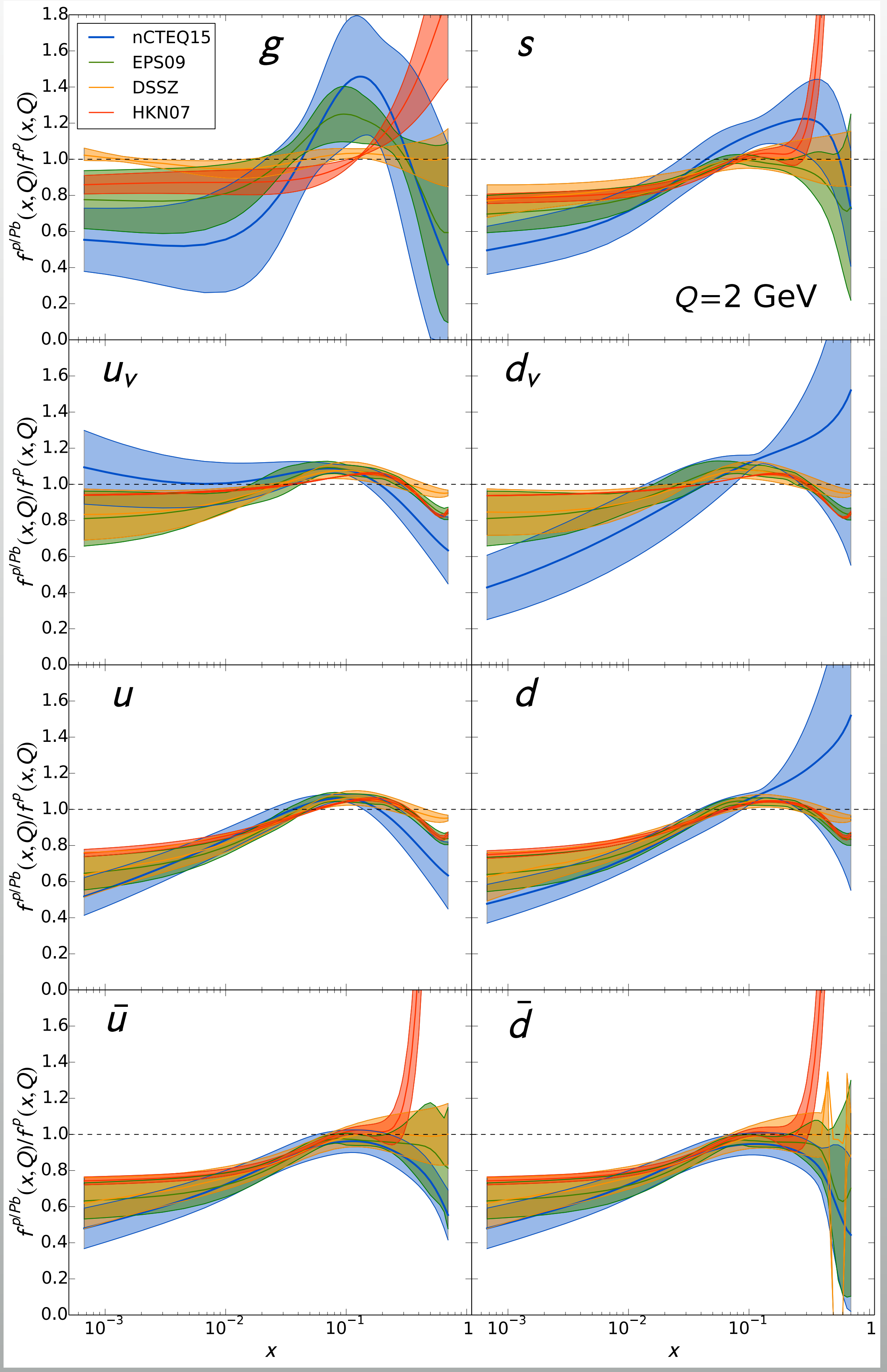


➜ No constrain at high x (g) and low x (g, valence, sea).

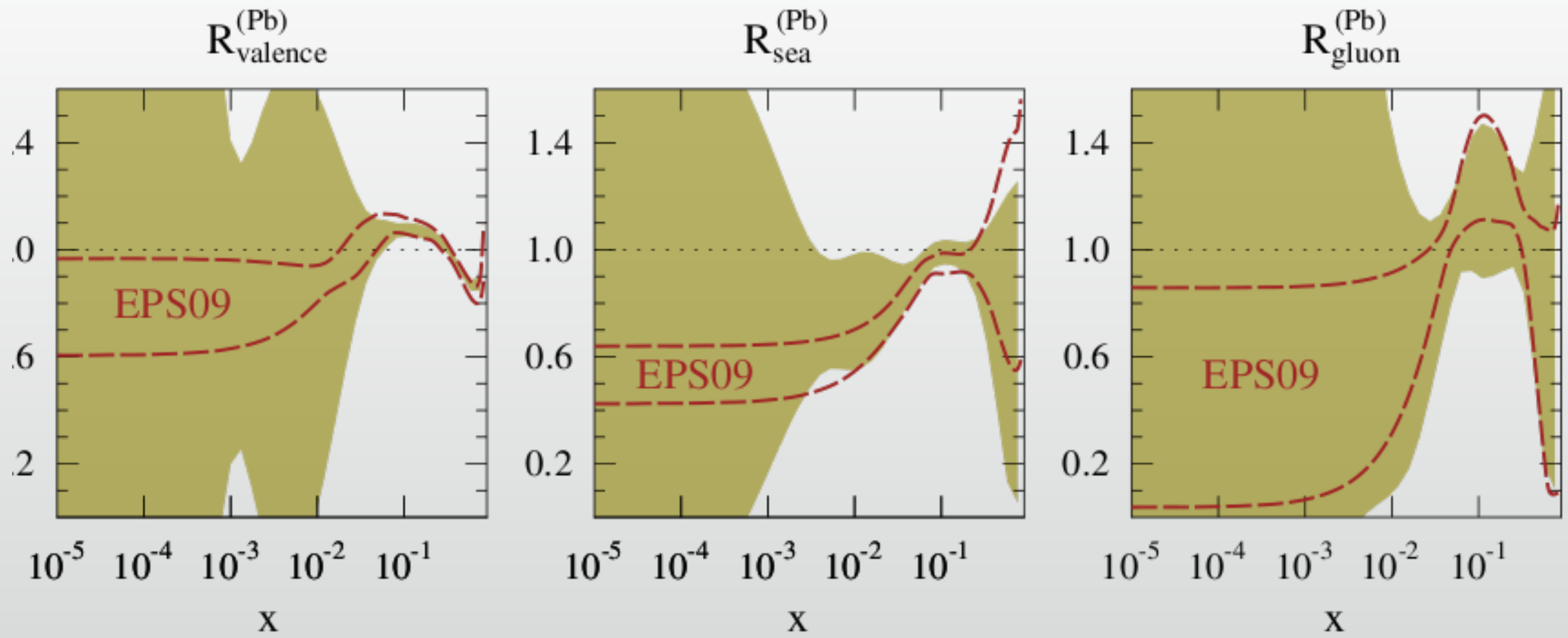
➜ Data do not require flavour separation (R_u=R_d).

➜ Initial condition drives the extrapolations.

➜ LHC data to be introduced: EPS16, AZ,…

nPDFs (II):

➜ More flexible parametrisation reduces the bias at small x. [1606.09003]



nPDFs (II):

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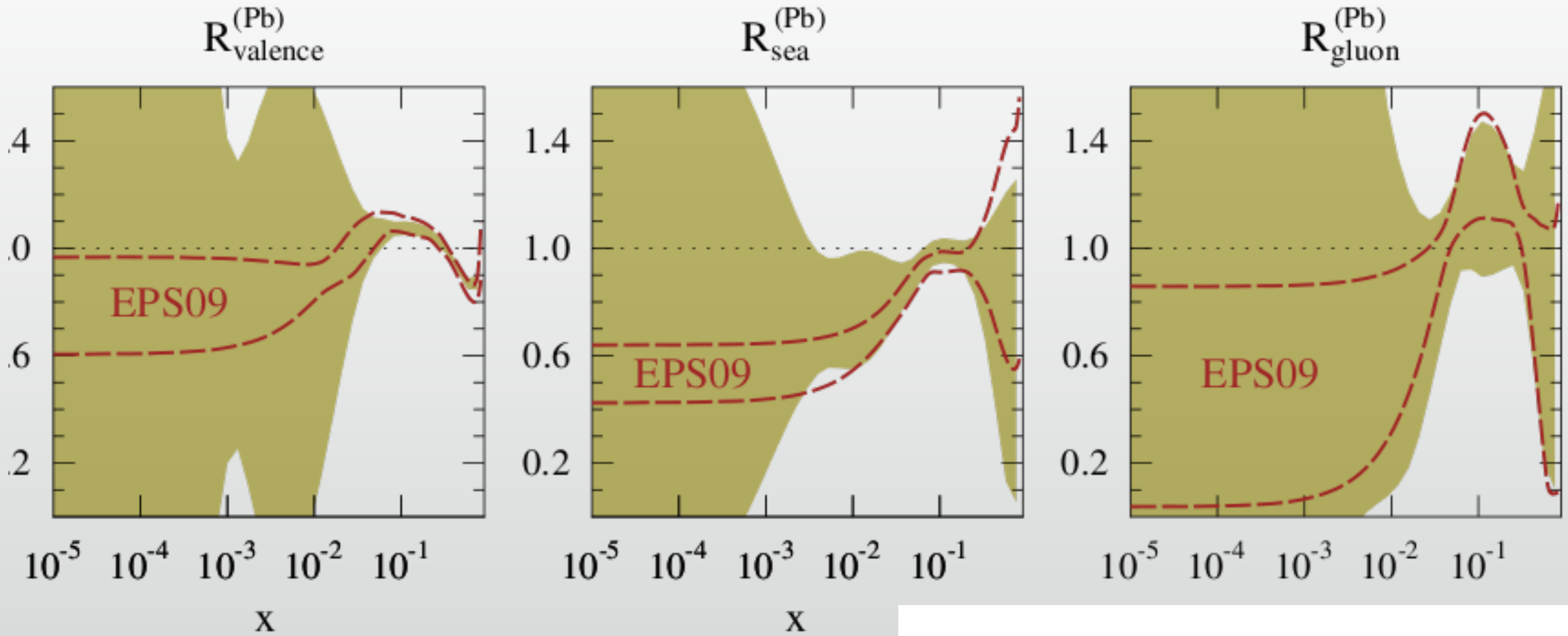
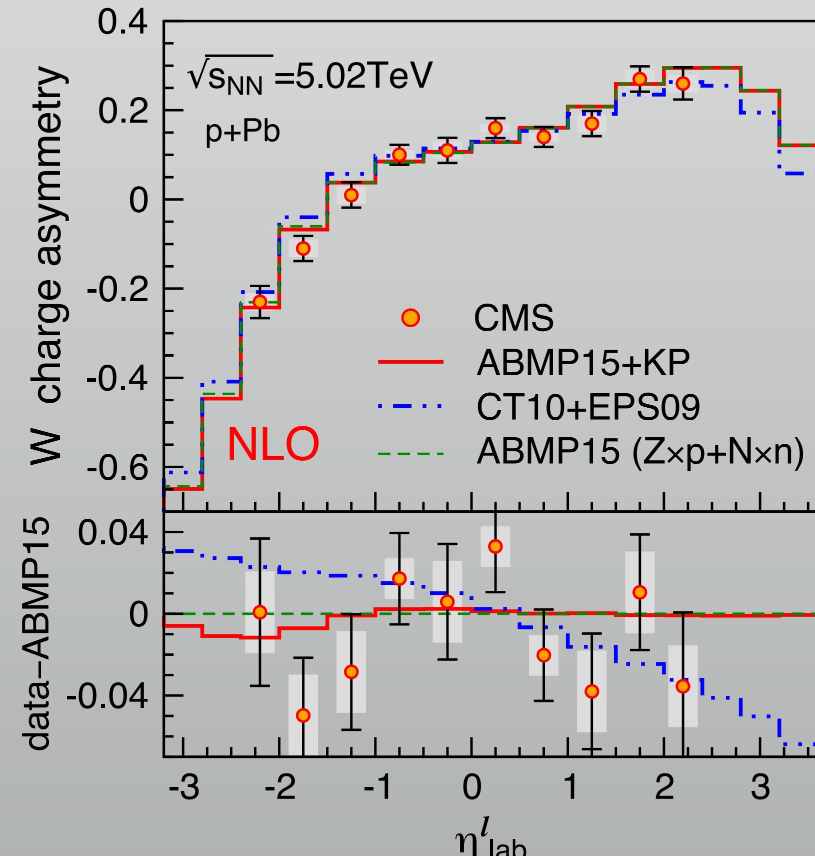
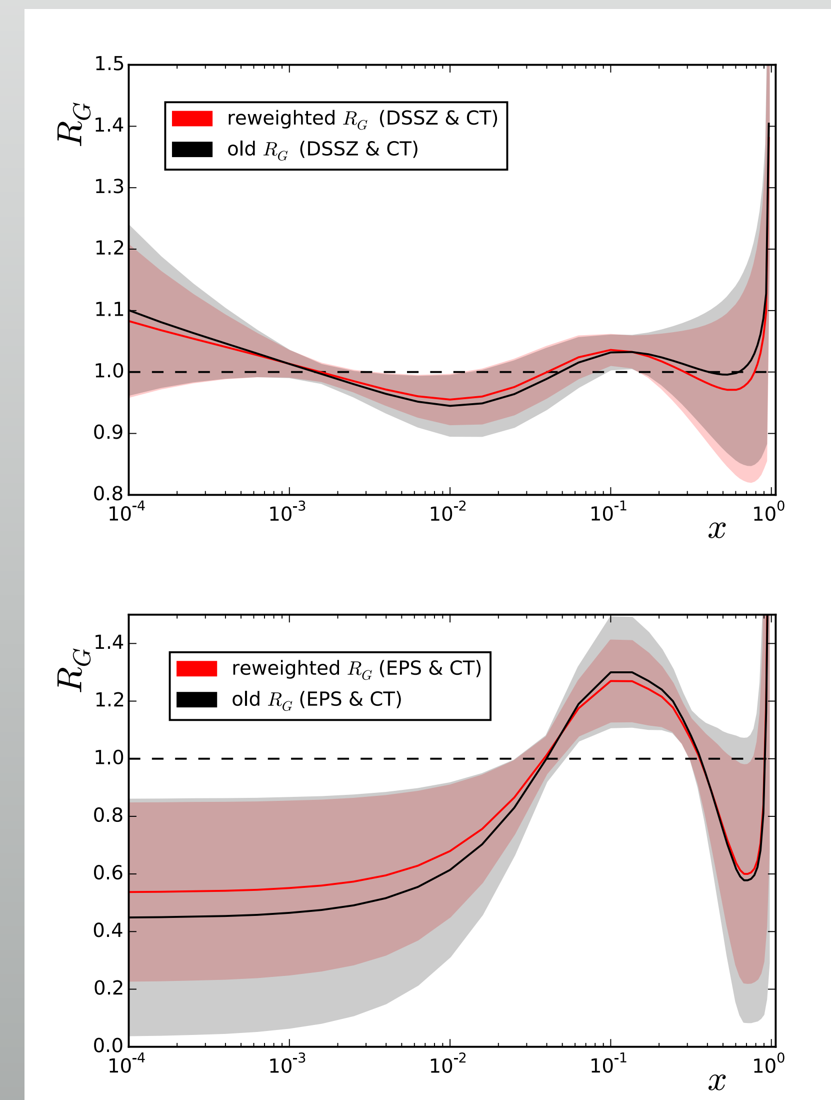
➜ (Present) LHC data have a modest impact on nPDFs [1512.01528]: dijets are the most constraining set, W's show hints of the need of flavour decomposition.

➜ PDFs ⟷ nPDFs.





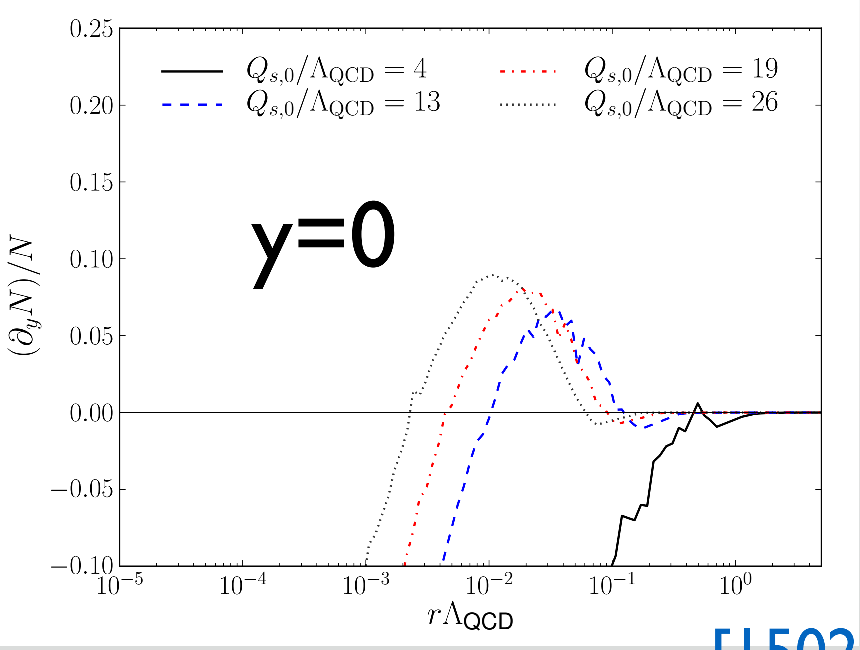
[1608.06835]

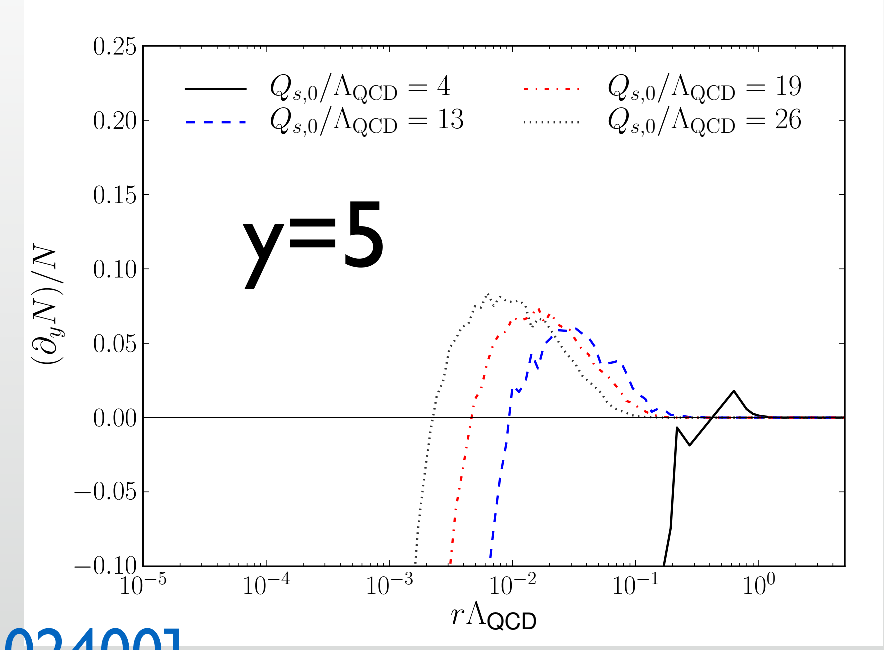


CGC evolution equations:

➜ NLO BK and JIMWLK available. [Balitsky-Chrilli-Grabovsky-Kovner-Lublinsky-Mulian]

➜ Problems of stability due to double and single logs.





[1502.02400]

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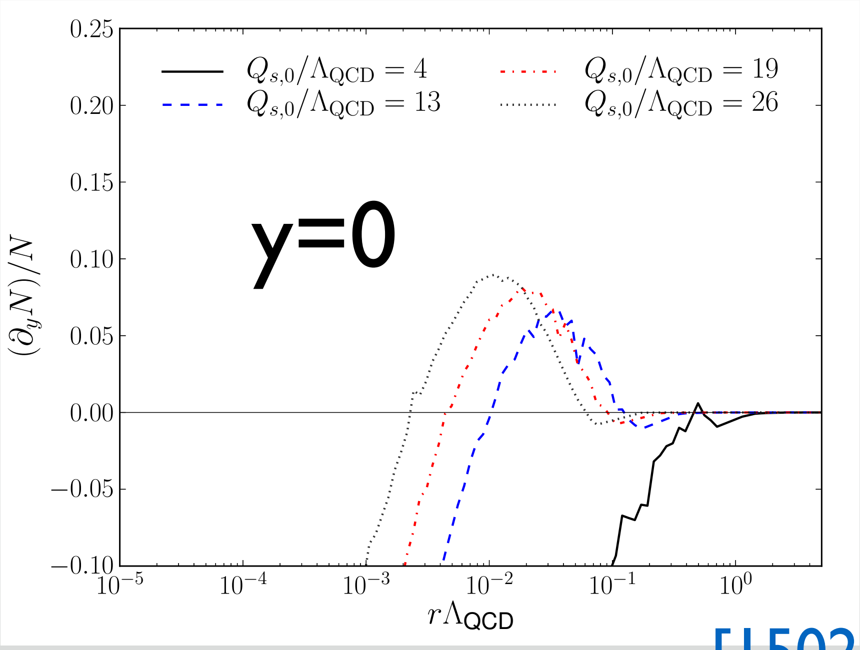
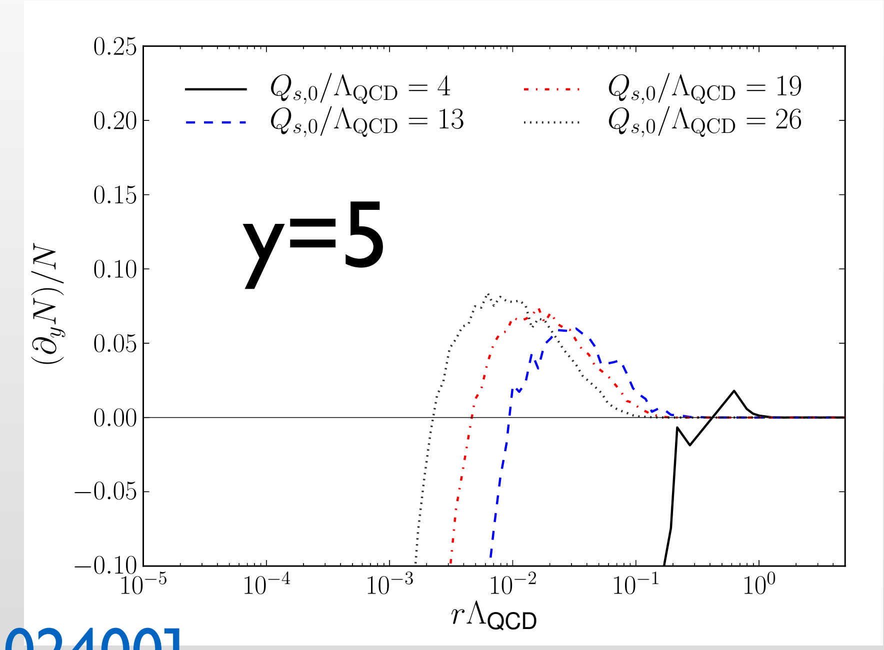
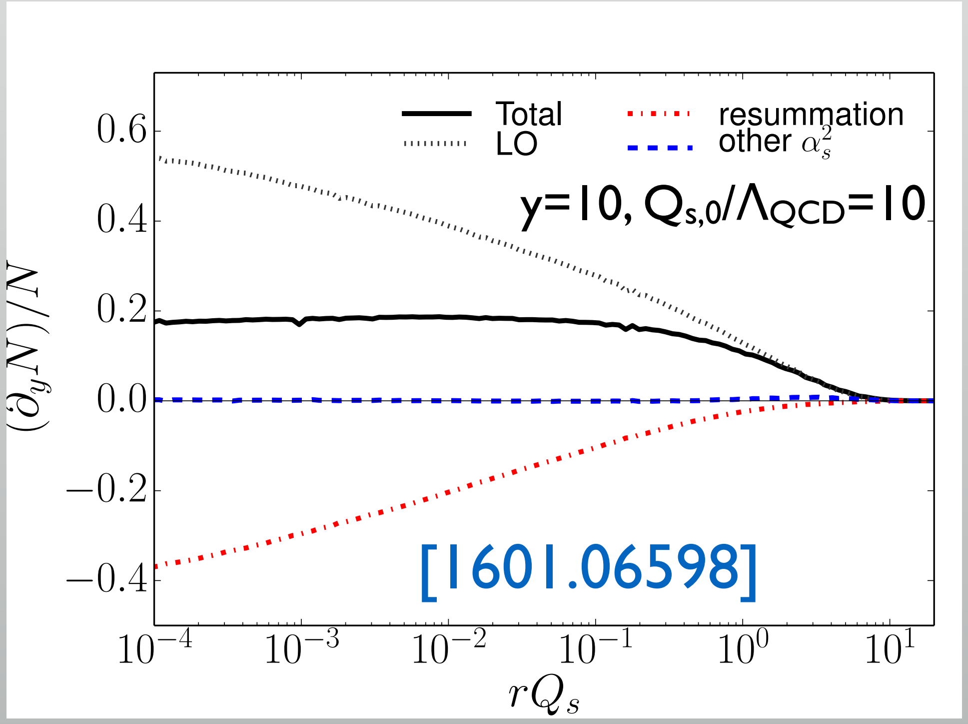




[1502.02400]

➜ Such logs coming from ordering in longitudinal (BFKL-like) and transverse (DGLAP-like) momenta: soft and collinear logs, make NLO huge and must be resummed.
[Iancu-Madrigal-Mueller-Soyez-Triantafyllopoulos]



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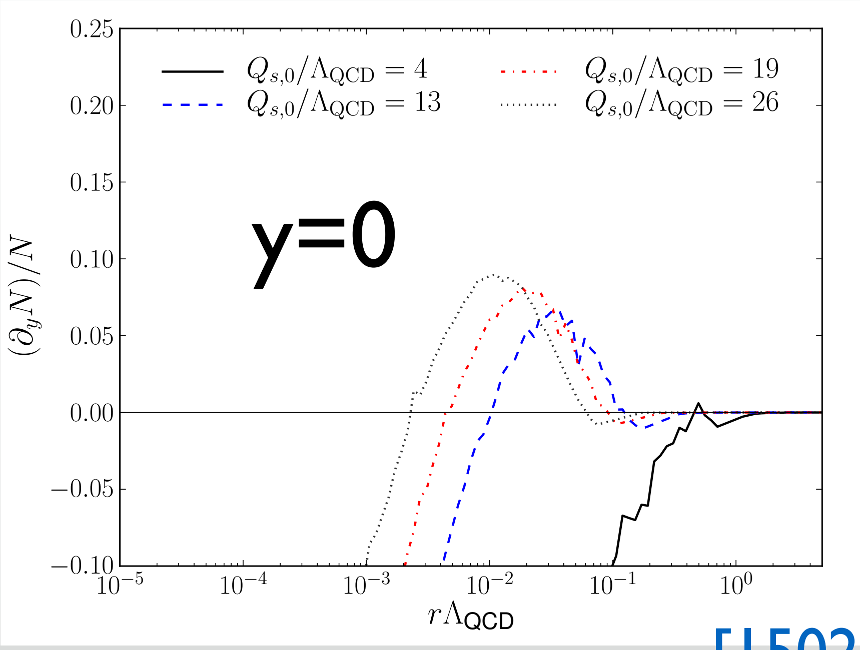

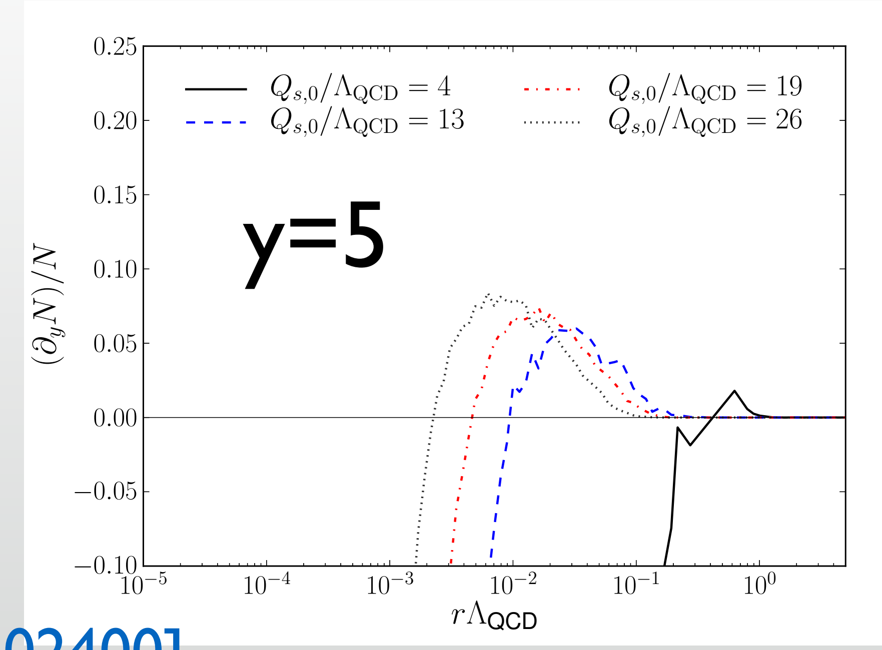

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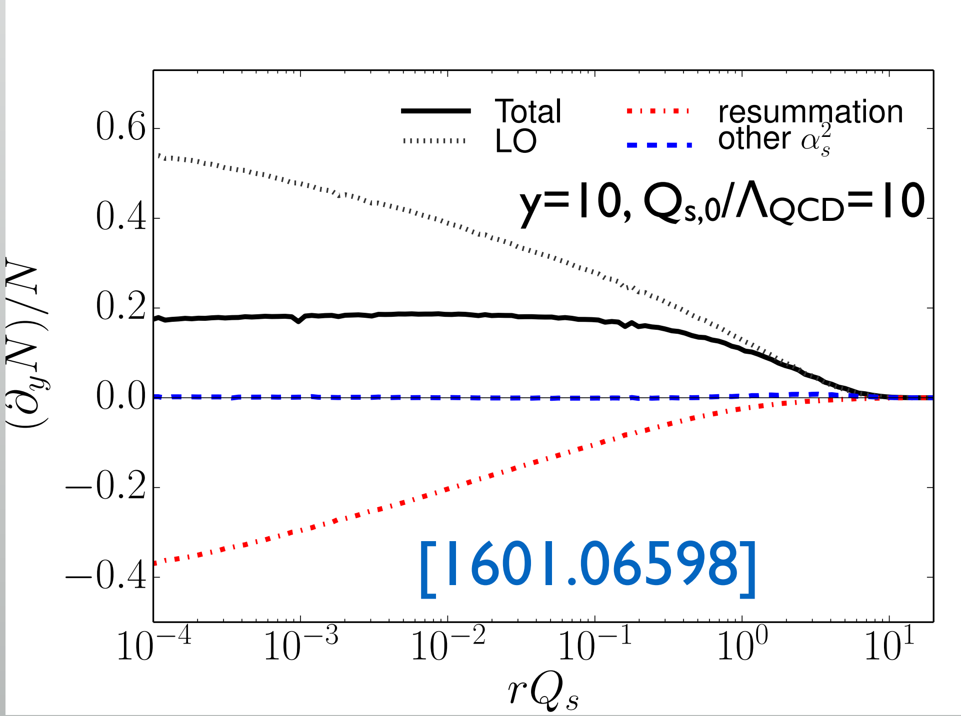
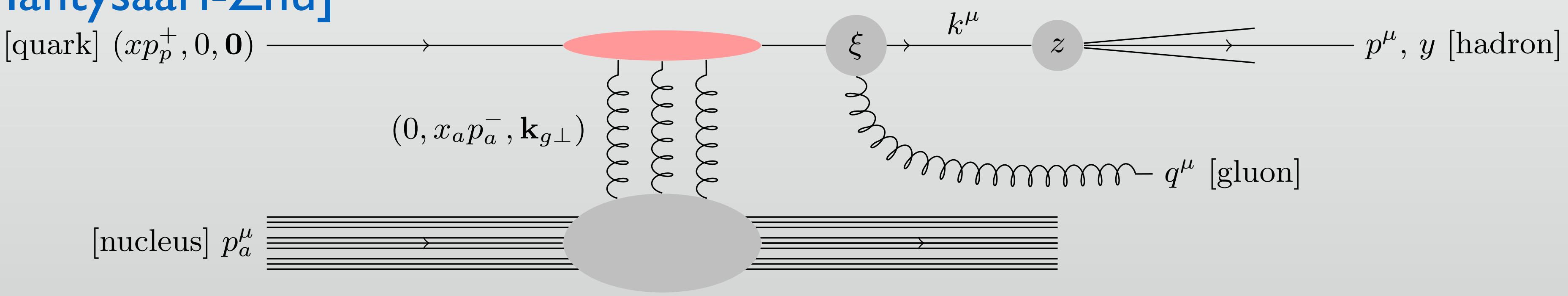


➜ No work employs the NLO impact factor. [Balitsky-Chrilli]

➜ Unclear that resummation improves the results at large Q^2 with respect to rcBK. [1507.07120]

NLO hybrid:

➜ Light and heavy production computed at NLO in the hybrid formalism: collinear parton through a dense target, forward η, yields LO DGLAP PDFs/FFs and LO BK dipoles. [Chirilli-Xiao-Yuan+Stasto-Zaslavsky-Wanatabe, Altinoluk-Kovner+Armesto-Beuf-Lublinsky, Kang-Vitev-Xing, Ducloue-Lappi-Mantysaari-Zhu]



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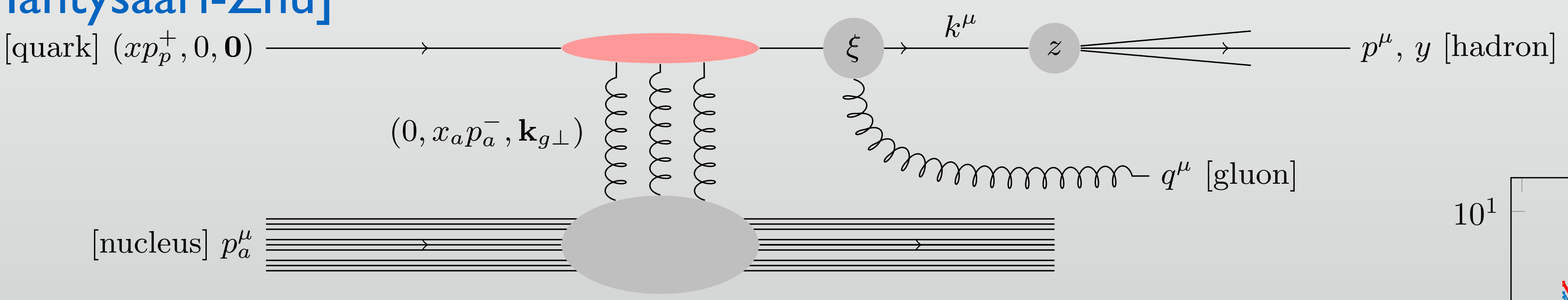
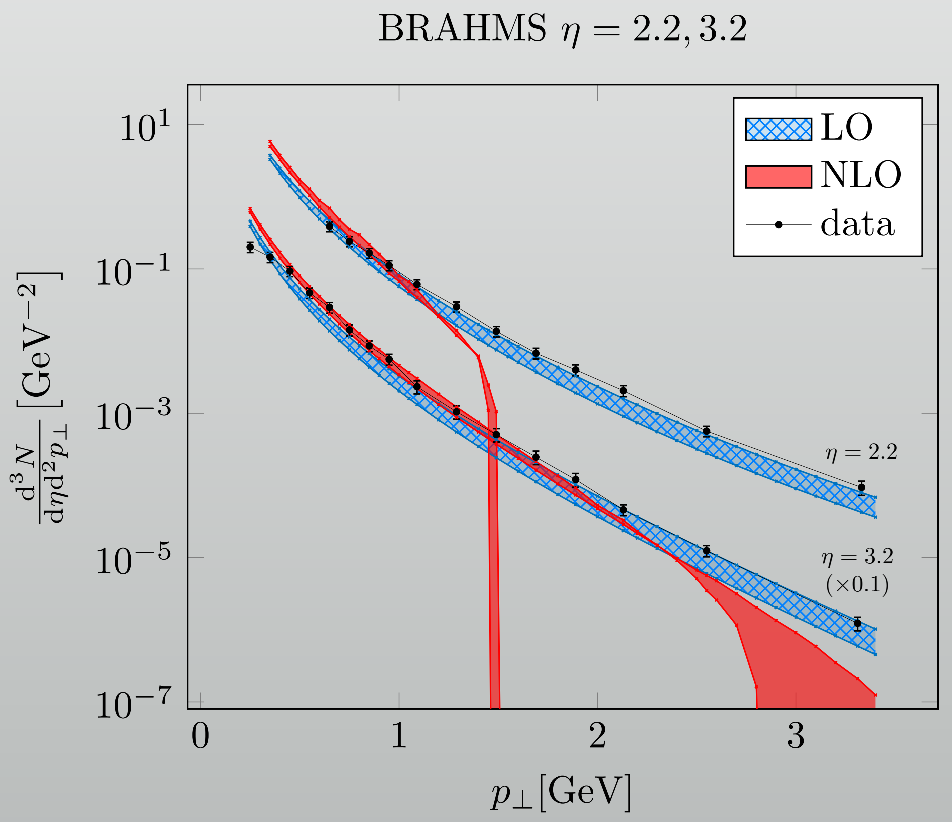


➜ Negative results at large rapidities from the original CXY calculation, with dependence on the choice of dipole.



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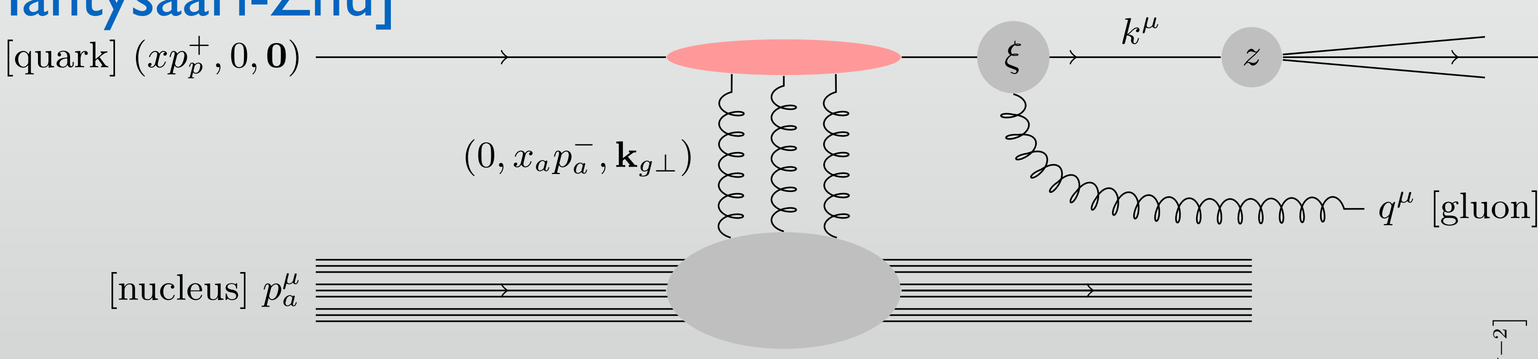

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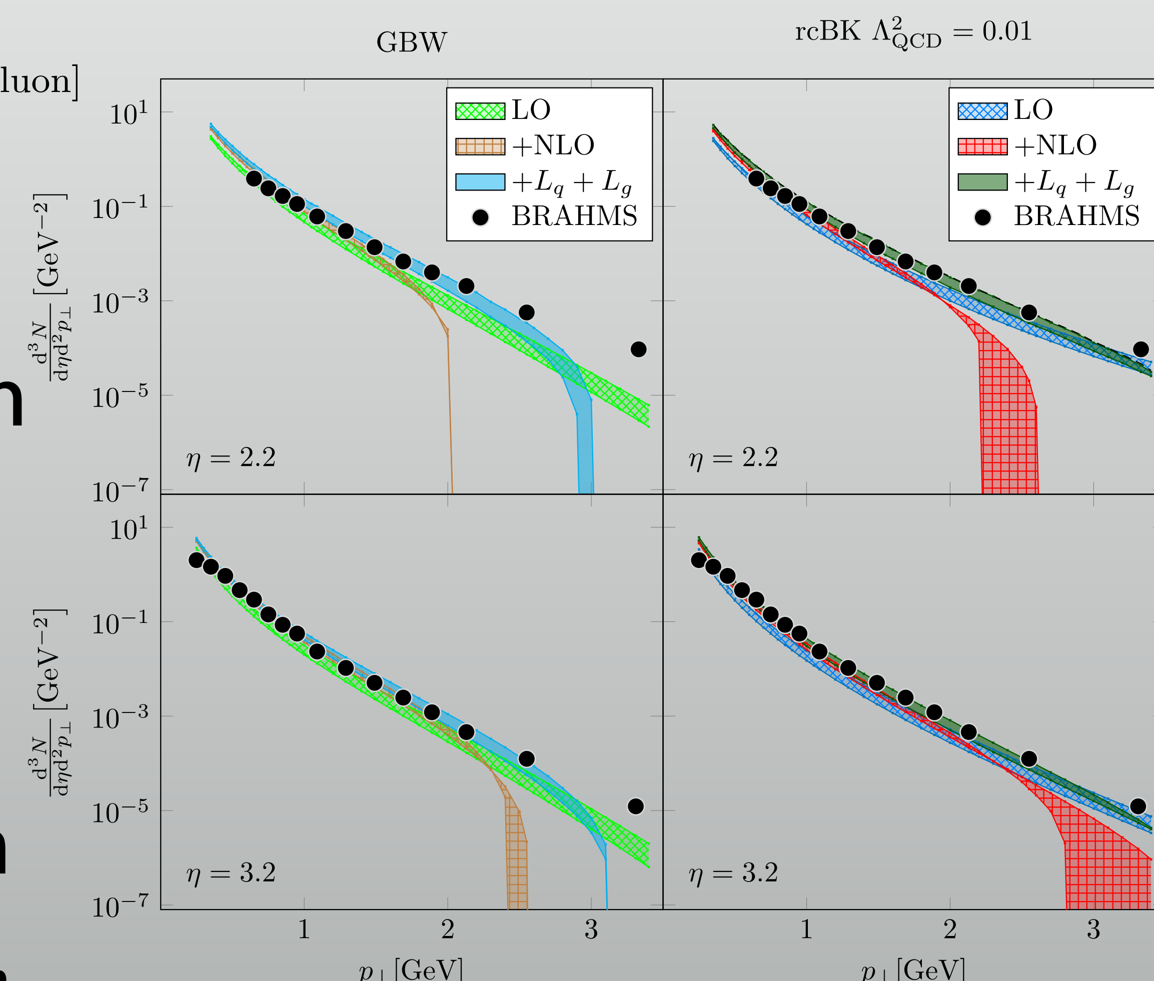

➜ Solutions through matching to collinear factorisation, ordering in minus component of the first emission (Ioffe time) that gives additional terms, setting the scale for rapidity evolution, resummation [1608.05293].

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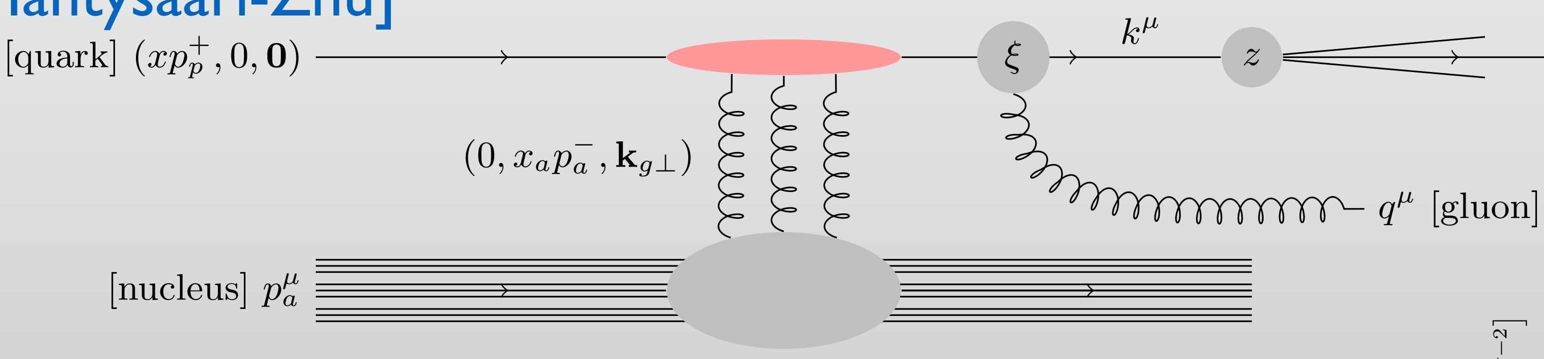

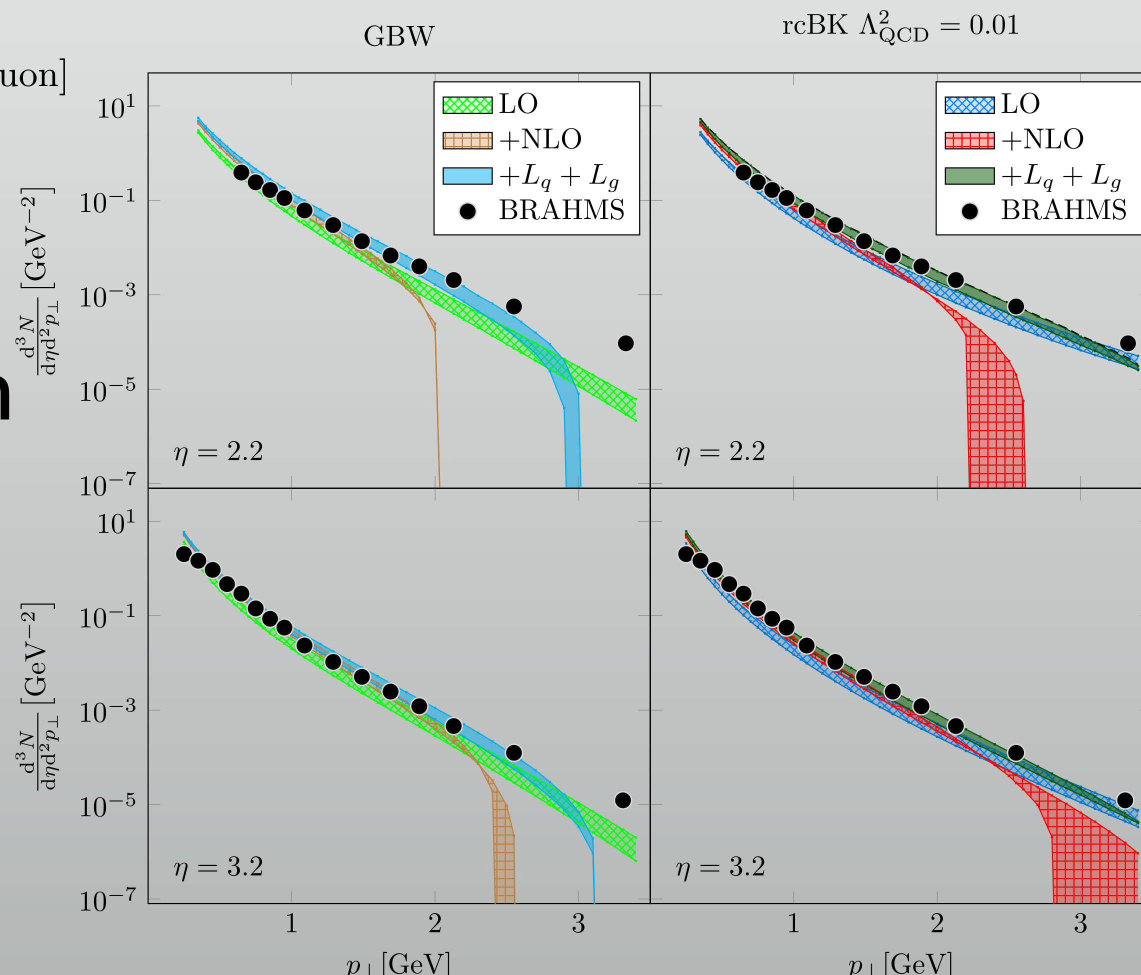

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➜ Note: hybrid valid for $p_T^2/s_0 << 1$.

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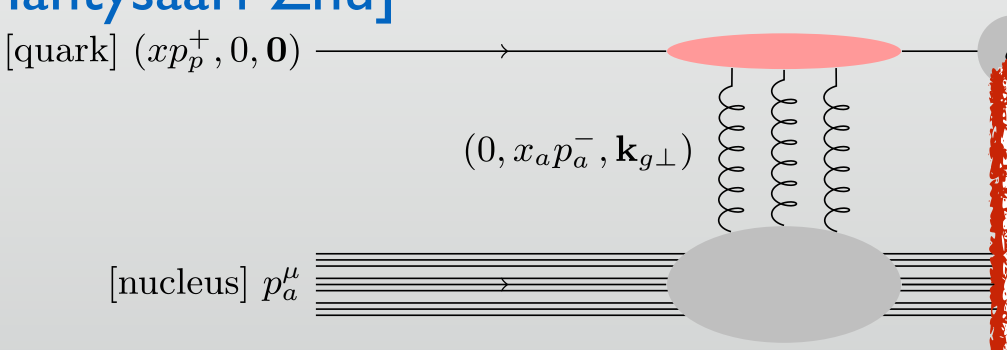

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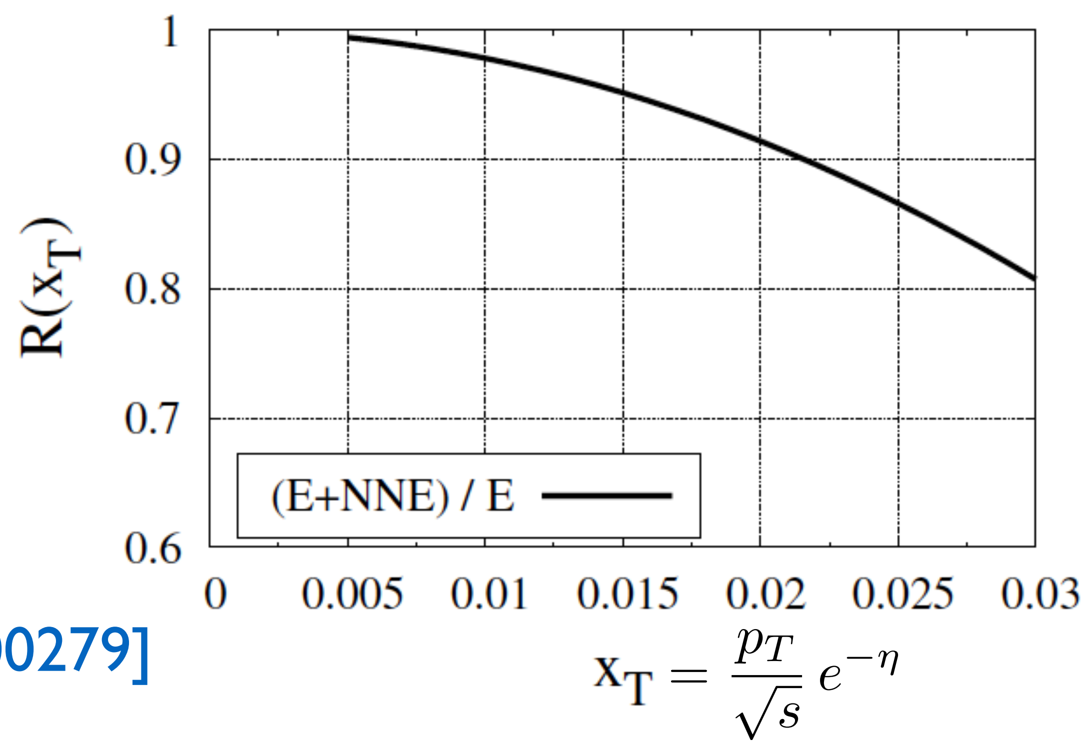
➜ Some non-eikonal corrections examined, they reduce the cross section, may be relevant for RHIC.



[1512.00279]

➜ Note: hybrid
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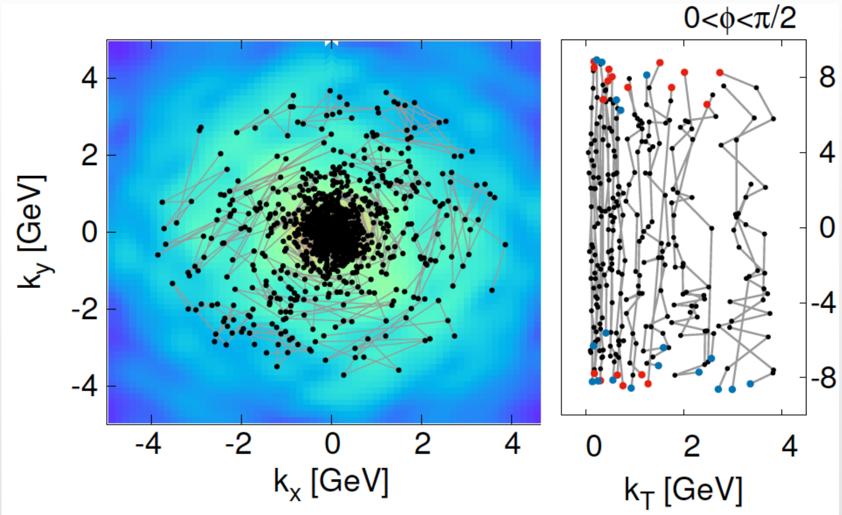
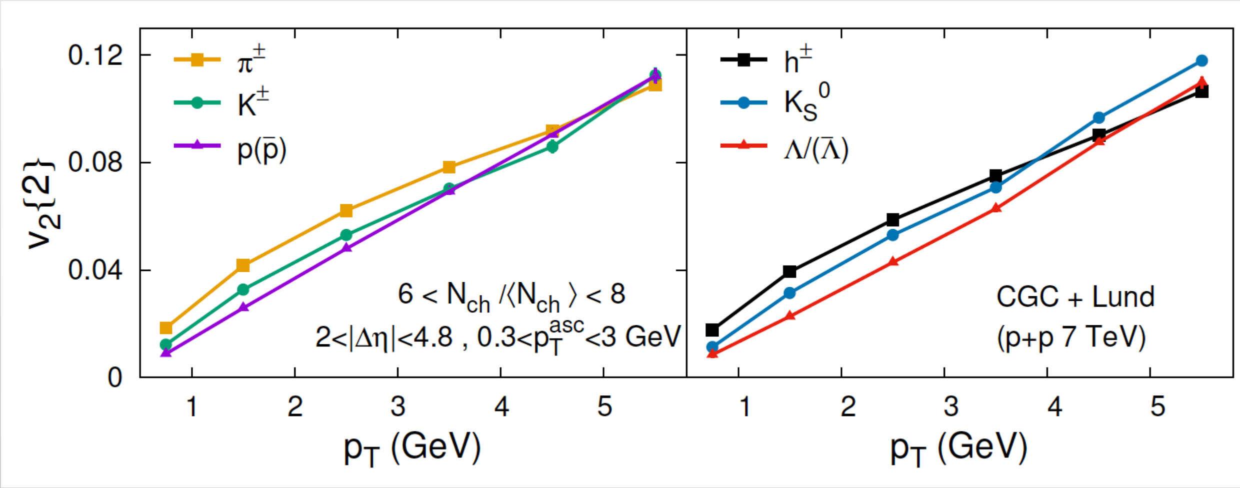
Correlations:

➜ Large activity on azimuthal asymmetries / ridge in pp/pA:

- Compatibility with CGC explanations at different energies. [1509.04410]
- Colour reconnections/fragmentations for mass ordering. [1607.02496]
- Theoretical origin in CGC: Gaussian (glasma graphs vs. nonlinear) or non Gaussian (domain models), longitudinal gluons,… [1508.04438,1509.03499]; quarks?





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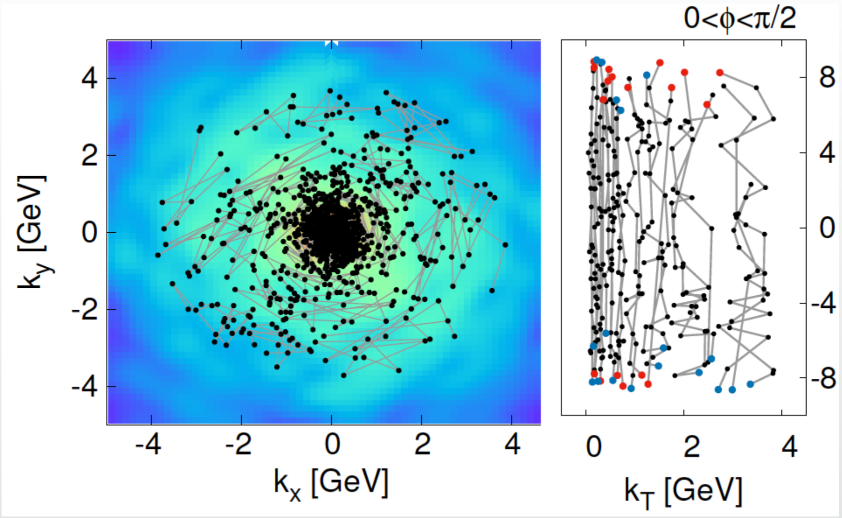
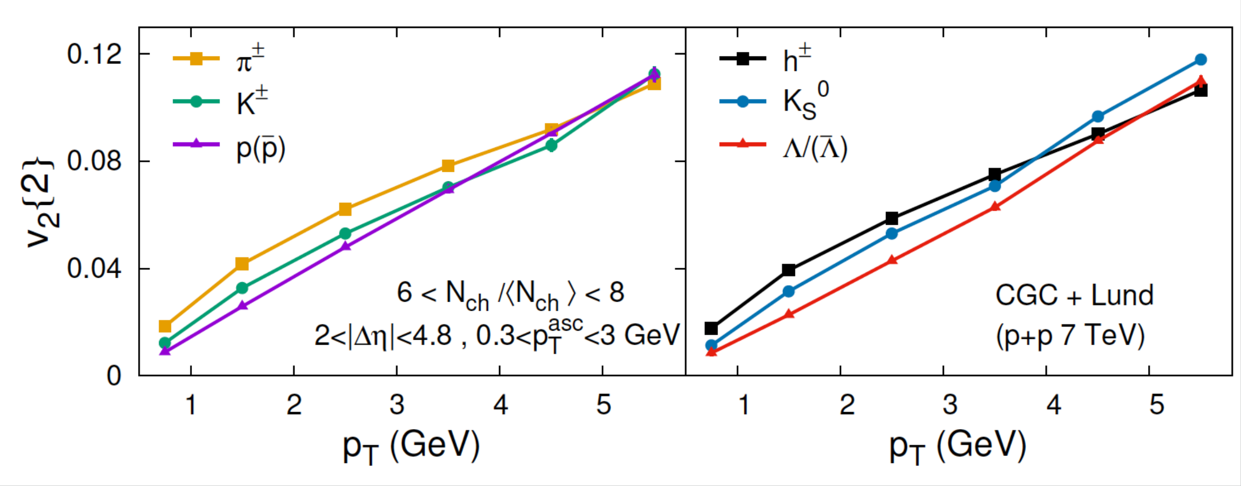
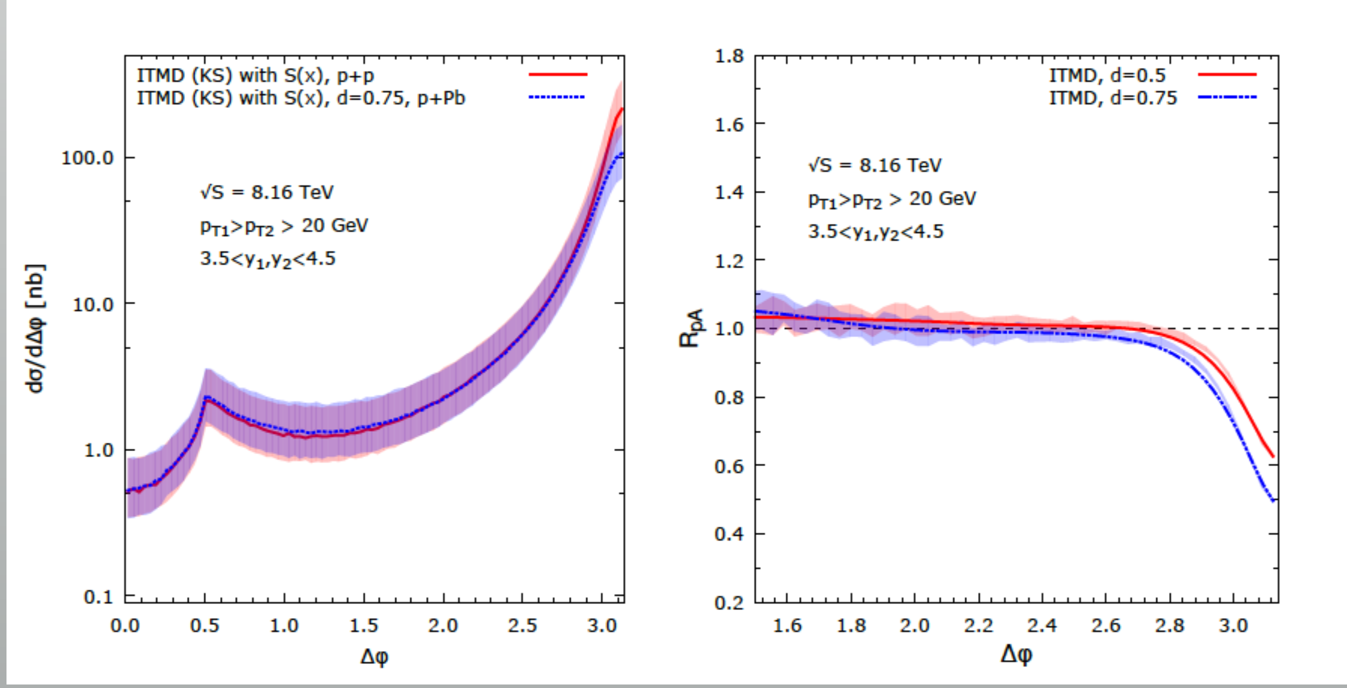




➜ Back-to-back correlations for forward jets may be sensitive to saturation up to large p_T. [1607.03121]



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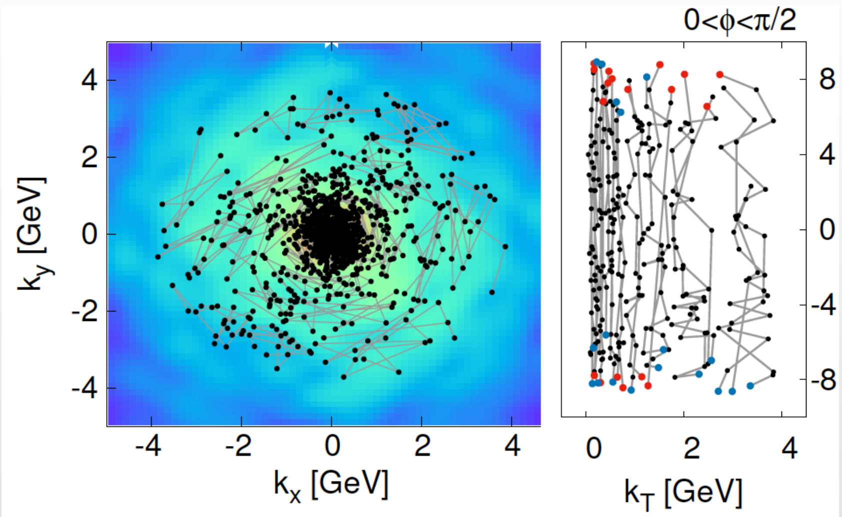

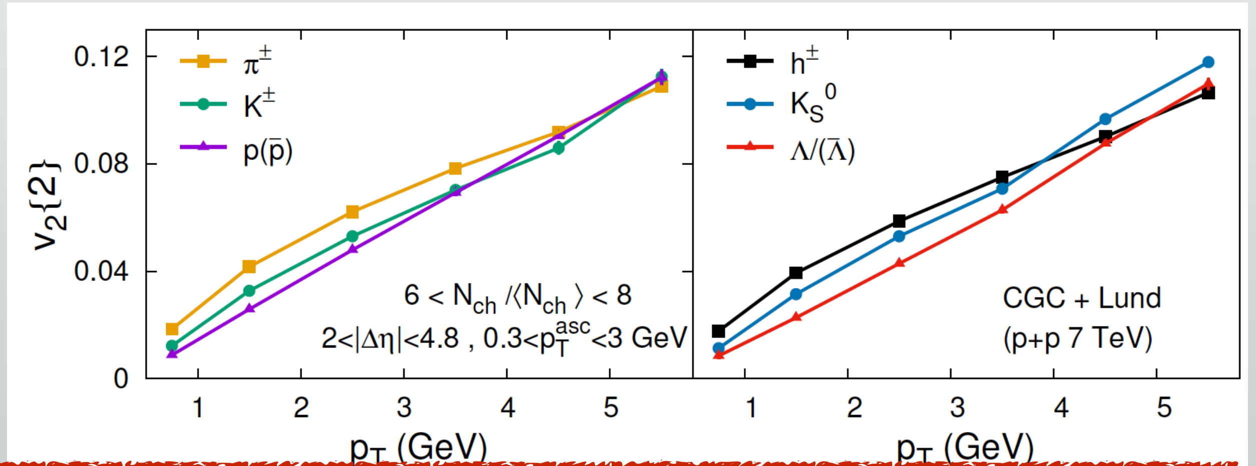

➜ The LHC offers large possibilities to constrain the small x dynamics with forward measurements.

➜ Hydro works for small systems, apparently to almost minimum bias pp. But why? [1609.02820] The statement of hydro as the signal of an equilibrated QGP is moving to the question of what the success of hydro tells about (non-)equilibrium properties of QCD matter.

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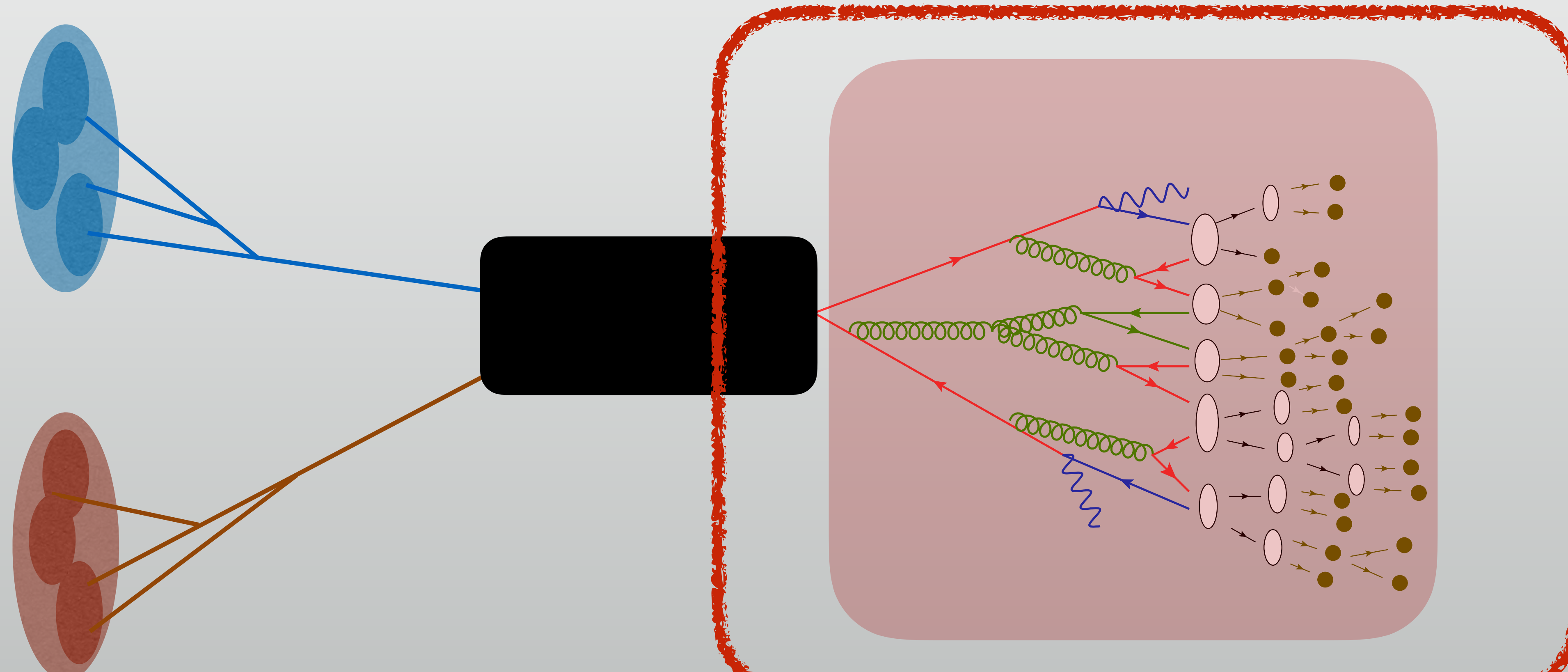
1. Initial stage:
   ➜ nPDFs.
   ➜ CGC: evolution equations and particle production.

2. Jet quenching:
   ➜ Single inclusive particle production.
   ➜ Jets.

[Plenaries by Cacciari, Casalderrey. Noronha-Hostler, Qin, Verweij and Vitev]



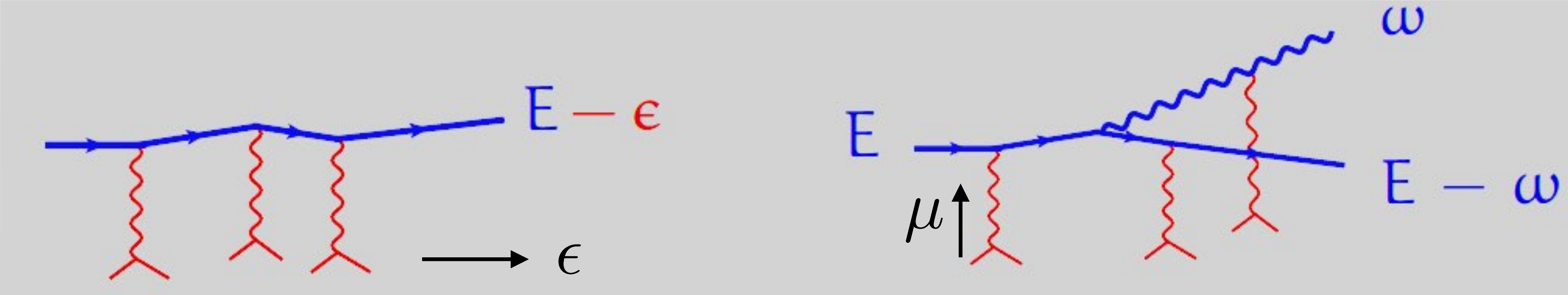
3. Heavy flavour:
   ➜ Open heavy flavour.
   ➜ Quarkonium.

4. EM probes.

5. Conclusion.

The *old* tools:

➜ BDMPS-Z-W, GLV, AMY, GWM (HT) models consider radiation dominant over elastic eloss. They are suitable for dealing with the problem of energy degradation of the leading parton, not with the fate of the lost energy: jet shapes and structures.



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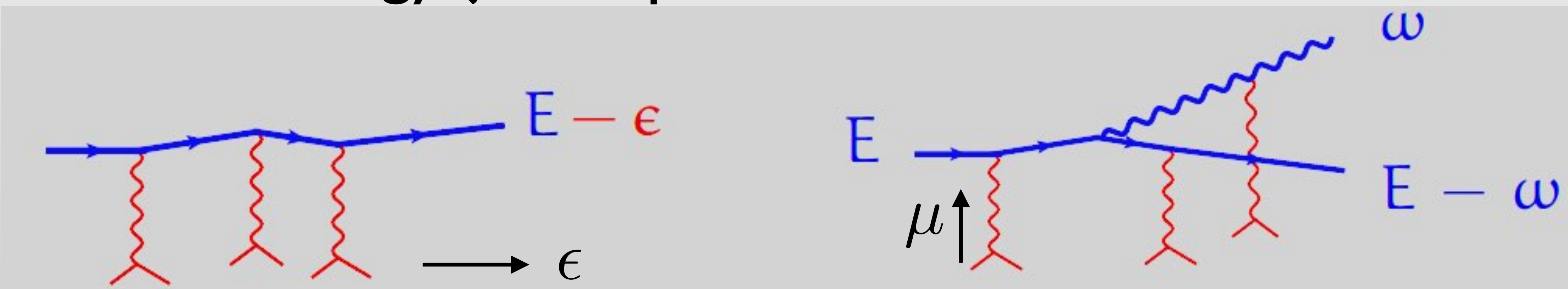

➜ Typical characteristics: soft and collinear safe, large angle semihard radiation.

$$\langle k_T^2\rangle \sim \hat{q} t_{\rm form} \sim \sqrt{\hat{q}\omega}, \quad \theta \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$

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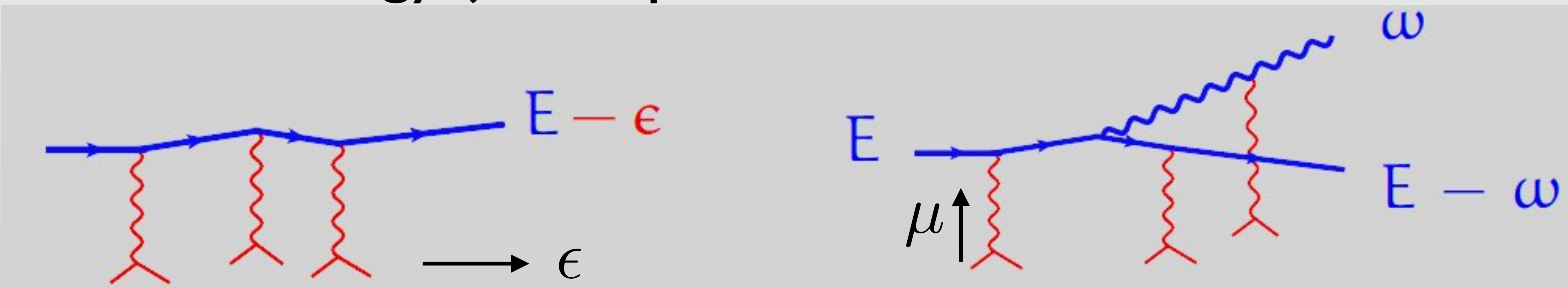

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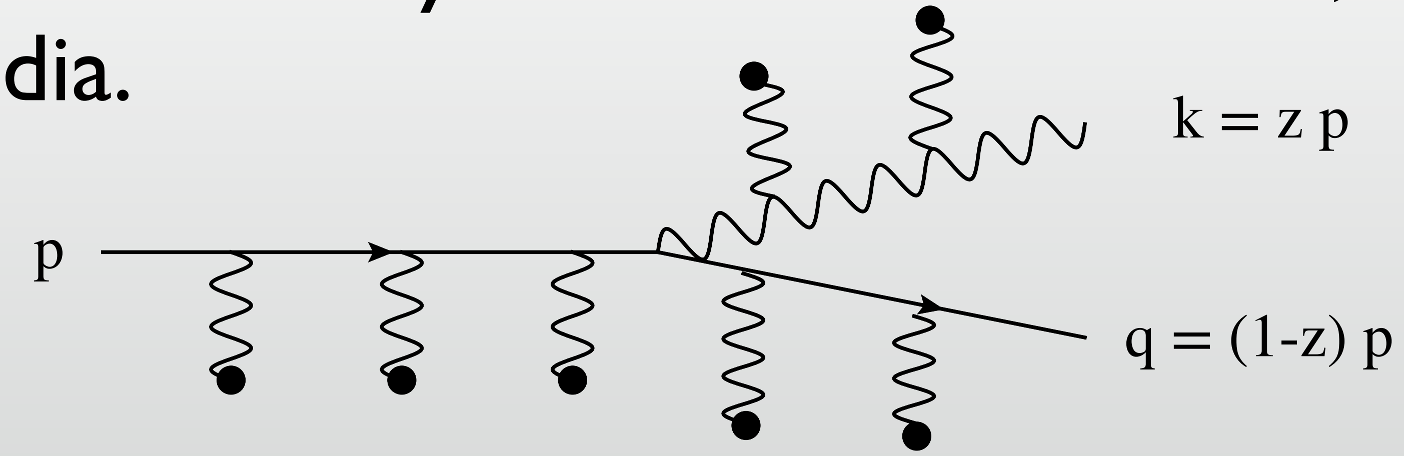
➜ Phenomenology implies assumptions: extension to ω~E, multiple emissions (usually Poissonian independent emissions), relaxation of high-energy approximations, picture of the medium (static/dynamic, weakly/strongly coupled), embedding in the medium,…

➜ Basis for present MCs (PYQUEN, QPYTHIA, JEWEL, YaJEM, MARTINI, CUJET).

The *new* issues:

➜ Path integral approach: include Brownian motion of all particles → more complex colour structures and delayed colour correlations, factorisation for large thick media.

[Apolinario-Armesto-Milhano-Salgado, Blaizot-Dominguez-Iancu-Mehtar-Tani-Fister-Wu]



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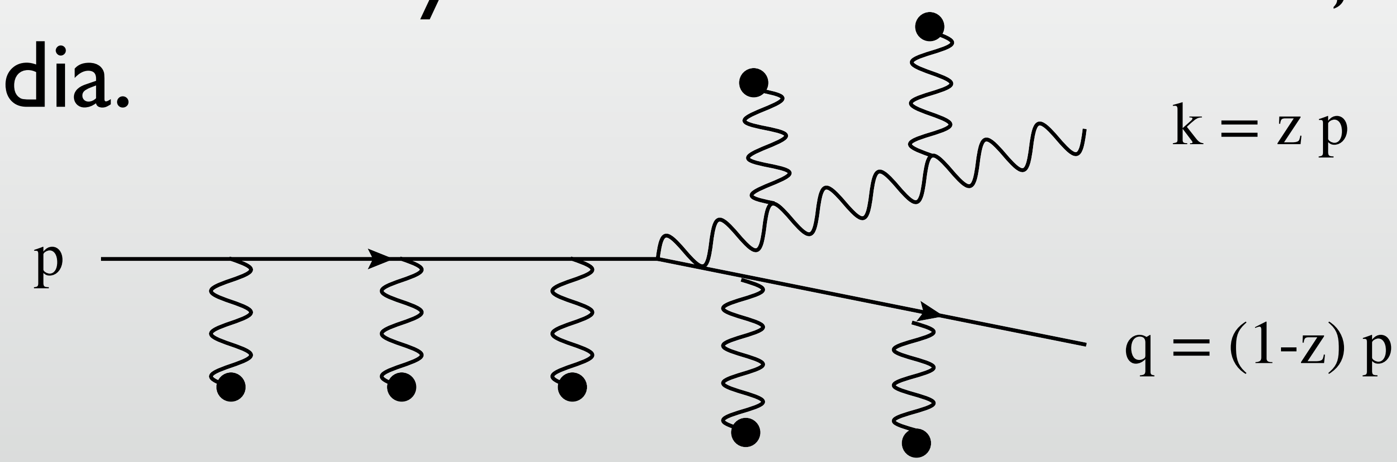

➜ Soft-Collinear Effective Theory: systematic separation of modes, computation of 1→2 and 1→3 splitting functions, jet functions,…

[Ibildi-Majumder, D'Eramo-Liu-Rajagopal, Chien-Emerman-Fickinger-Kang-Ovanesyan-Vitev]

Modes	$(+,-,\perp)$, $\lambda \ll 1$
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soft	$(\lambda^2,\lambda^2,\lambda^2)Q$
Glauber (jet-medium)	$(\lambda^2,\lambda^2,\lambda)Q$

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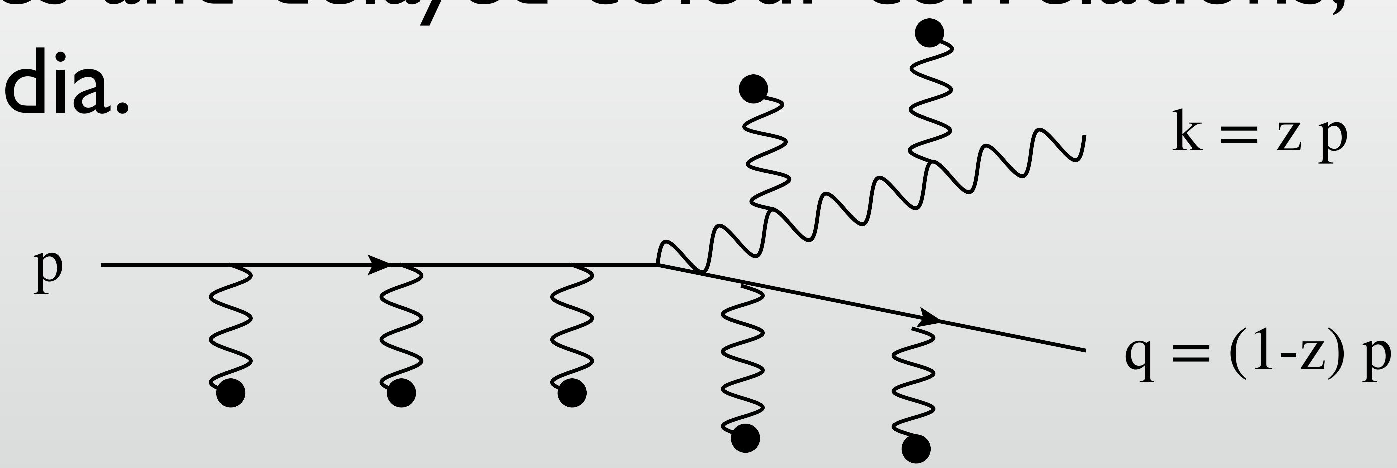

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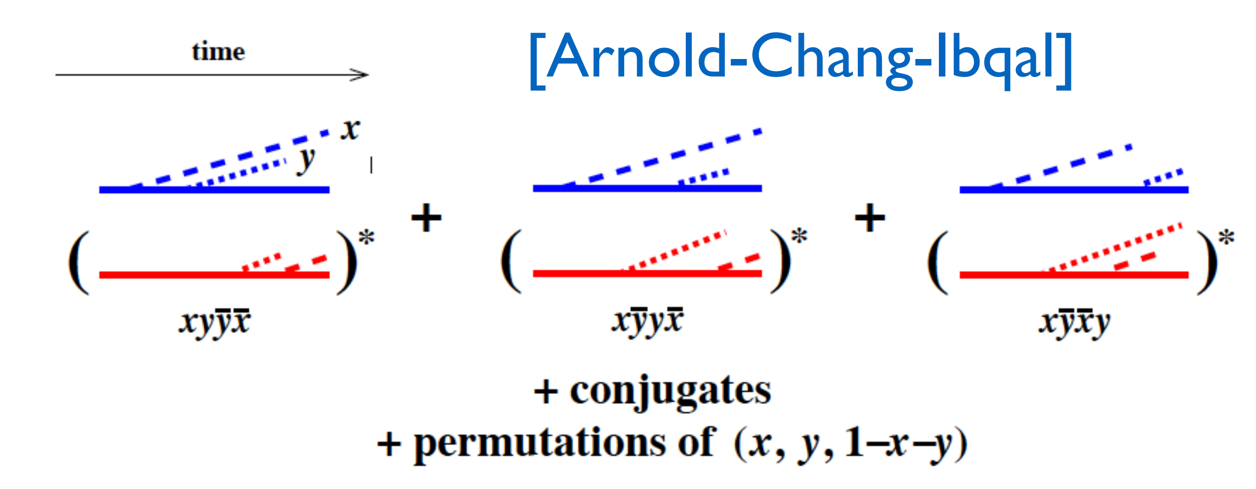

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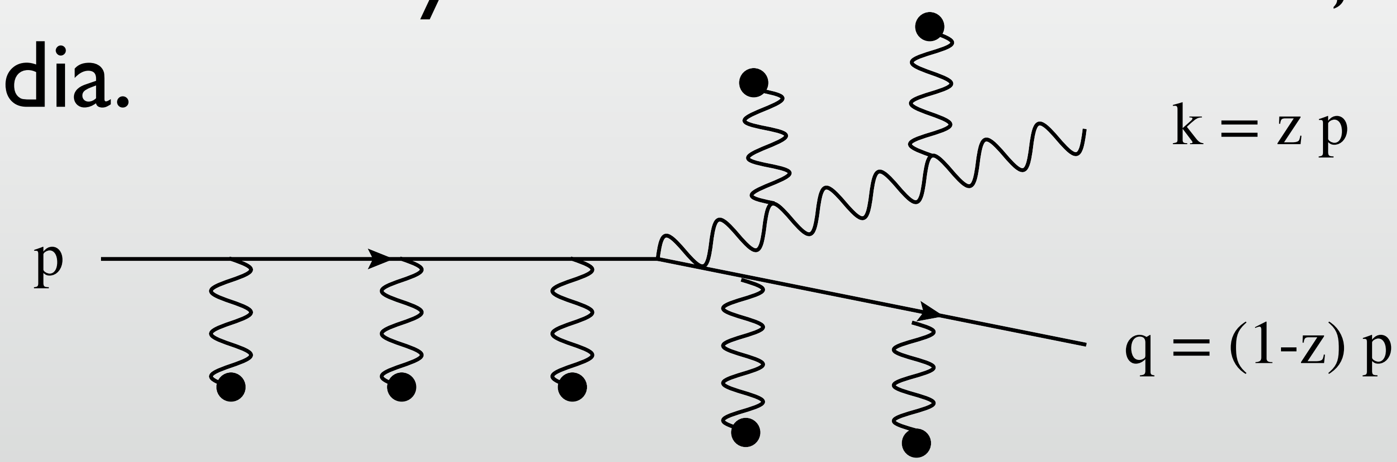

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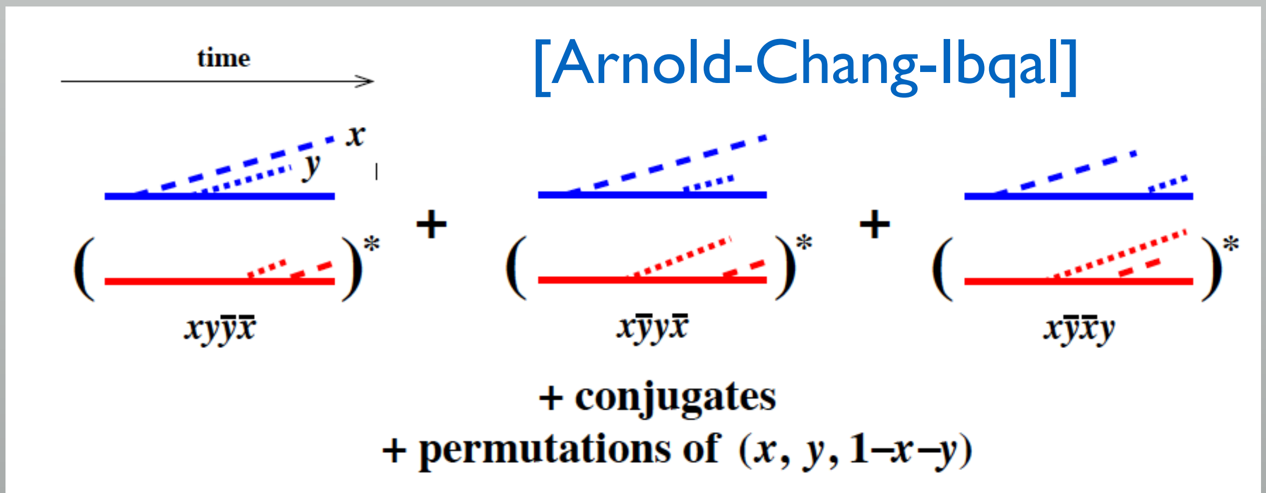

➜ Transverse and longitudinal momentum exchanges. [Majumder-Qin]

The picture:

➜ Interplay between the resolving power of the medium and the jet scale.

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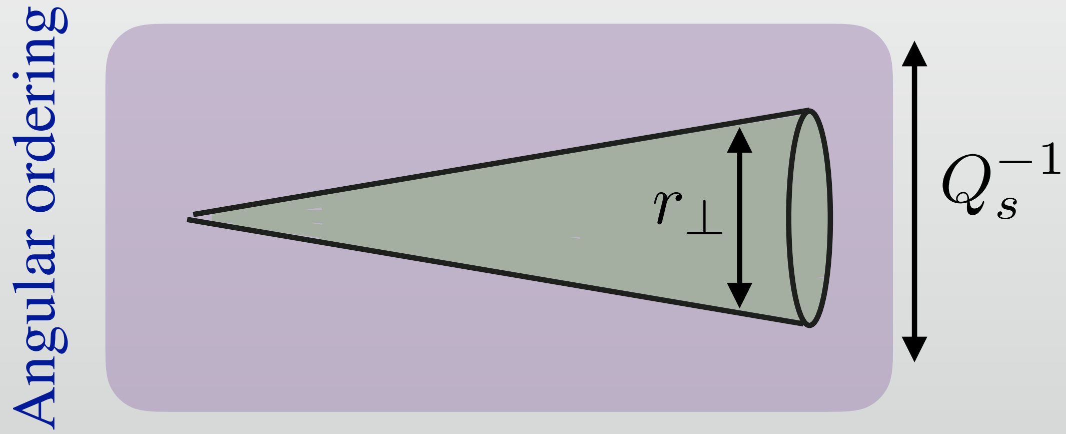

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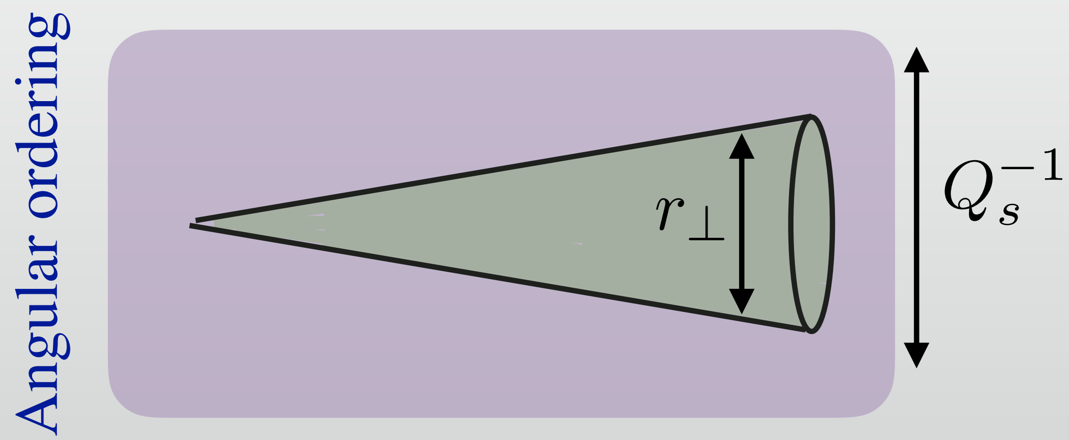

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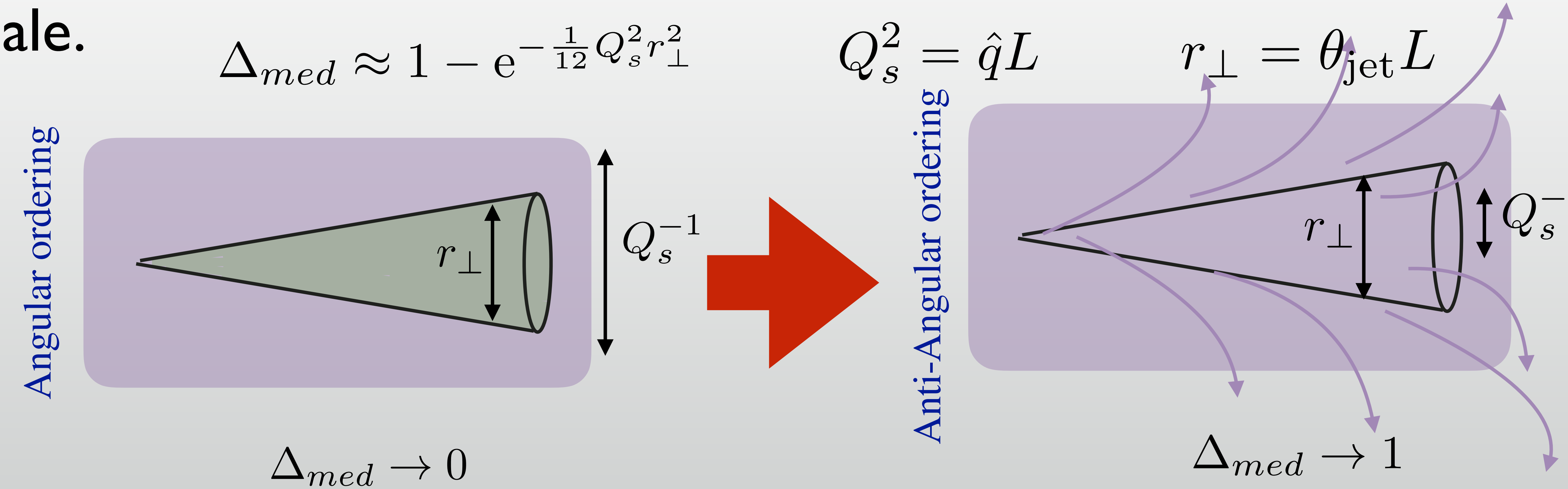

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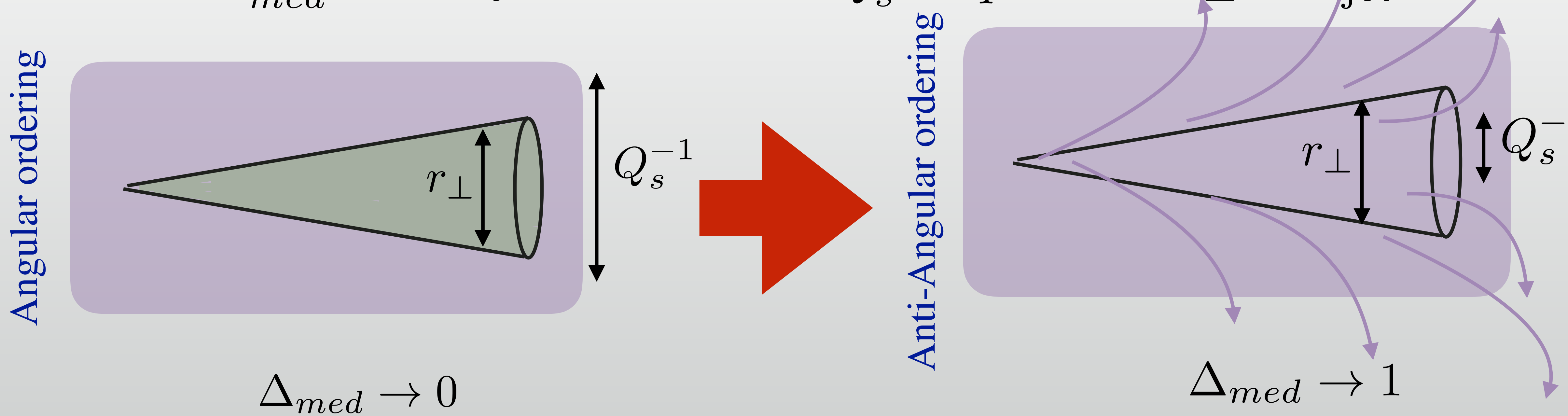

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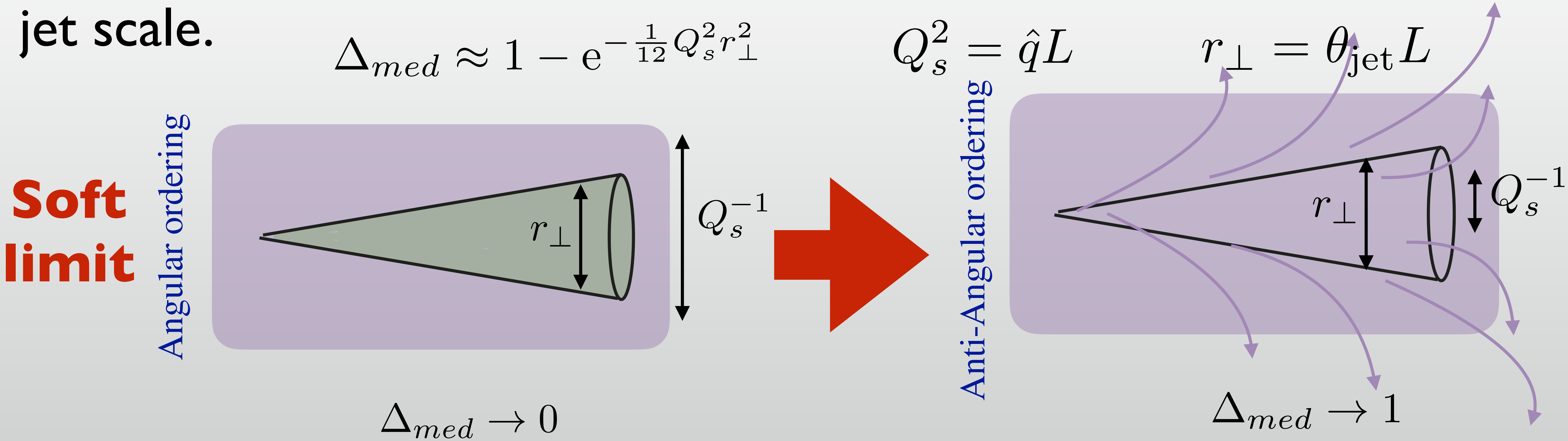

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➜ For the leading parton in a large dense medium: BDMPS/GLV radiation as traditionally implemented (e.g. quenching weights), could be seen as modified DGLAP evolution.

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➜ Interplay between the resolving power of the medium and the jet scale.

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➜ Parts of the picture implemented in different available MC: modification of DGLAP (QPYTHIA), preservation of coherence (JEWEL), large angle semihard radiation for dense media (most of them),…

➜ Delicate interplay of vacuum and medium effects. [Milhano-Zapp, Mueller-Wu-Xiao-Yuan]

➜ If the parton-medium interaction is strongly coupled, then model eloss through AdS/CFT ideas. [Casalderrey-Gulhan-Milhano-Pablos-Rajagopal, Renk, Casalderrey-Ficnar]

➜ NLO corrections: renormalisation of qhat. [Mueller-Wu, Blaizot-Mehtar-Tani, Iancu, Kang-Wang-Wang-Xing]

➜ Connections with the CGC formalism. [Altinoluk-Armesto-Beuf-Moscoso-Salgado, 1603.01028]

Some successes:

$$\mathcal{P}_{i\to jl}(x,k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x,k_\perp) + \mathcal{P}^{med}_{i\to jl}(x,k_\perp)$$

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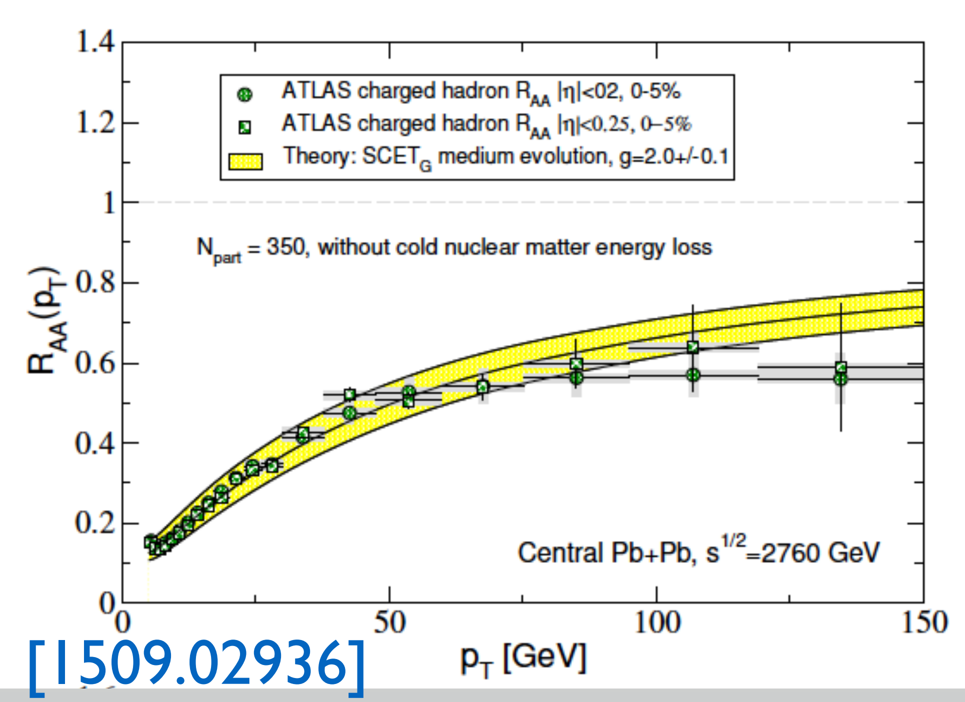
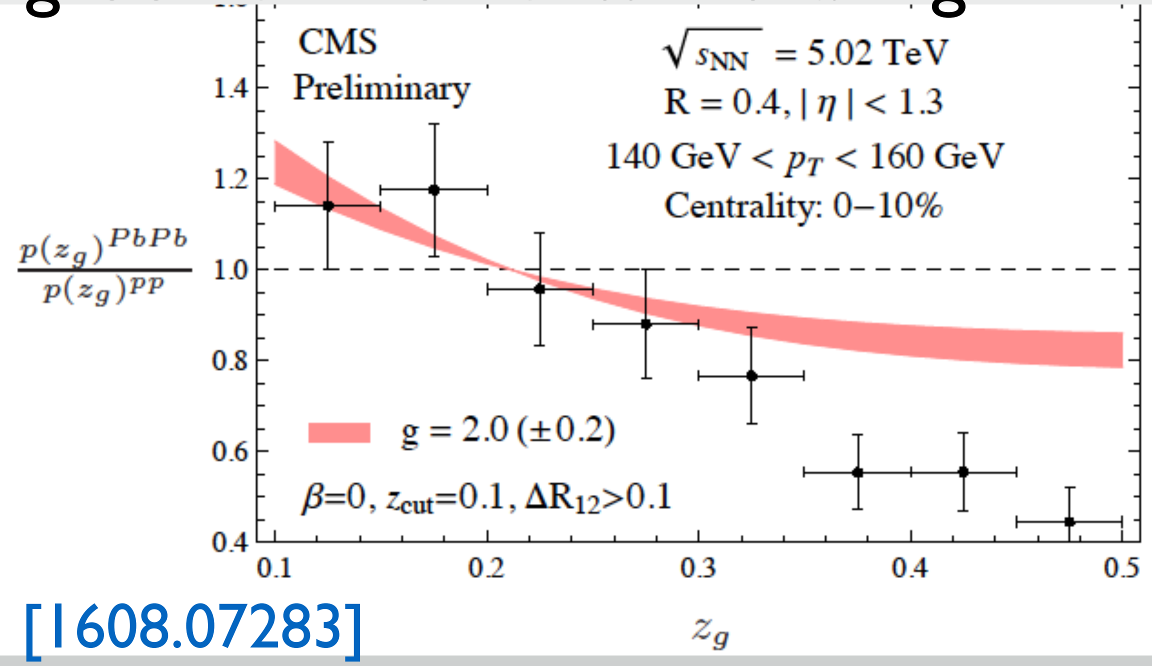
SCET



[1509.02936]

groomed momentum sharing



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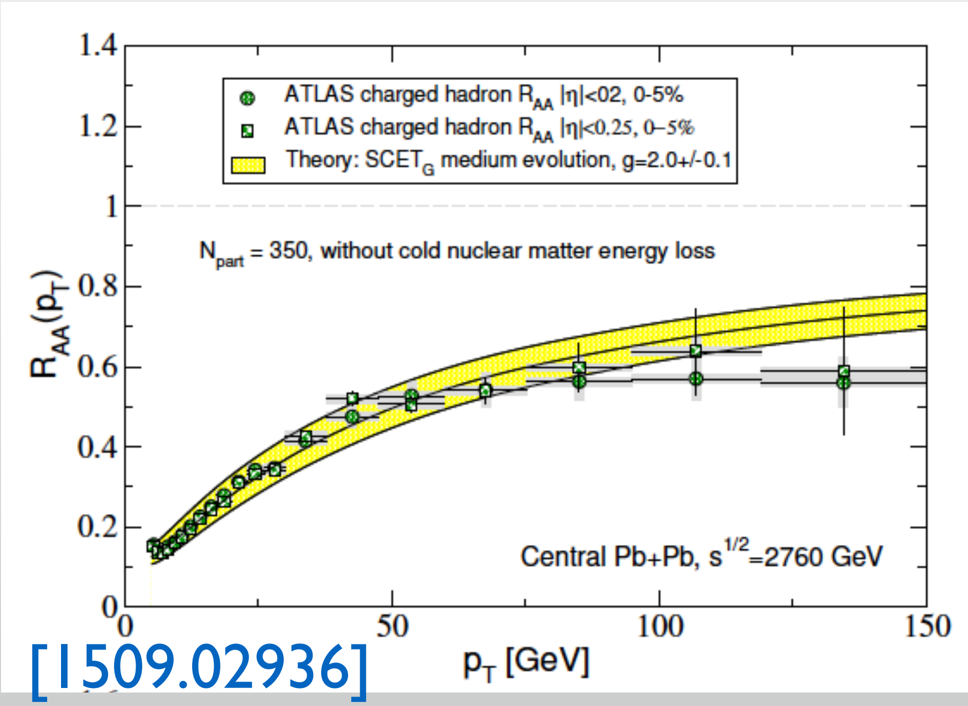

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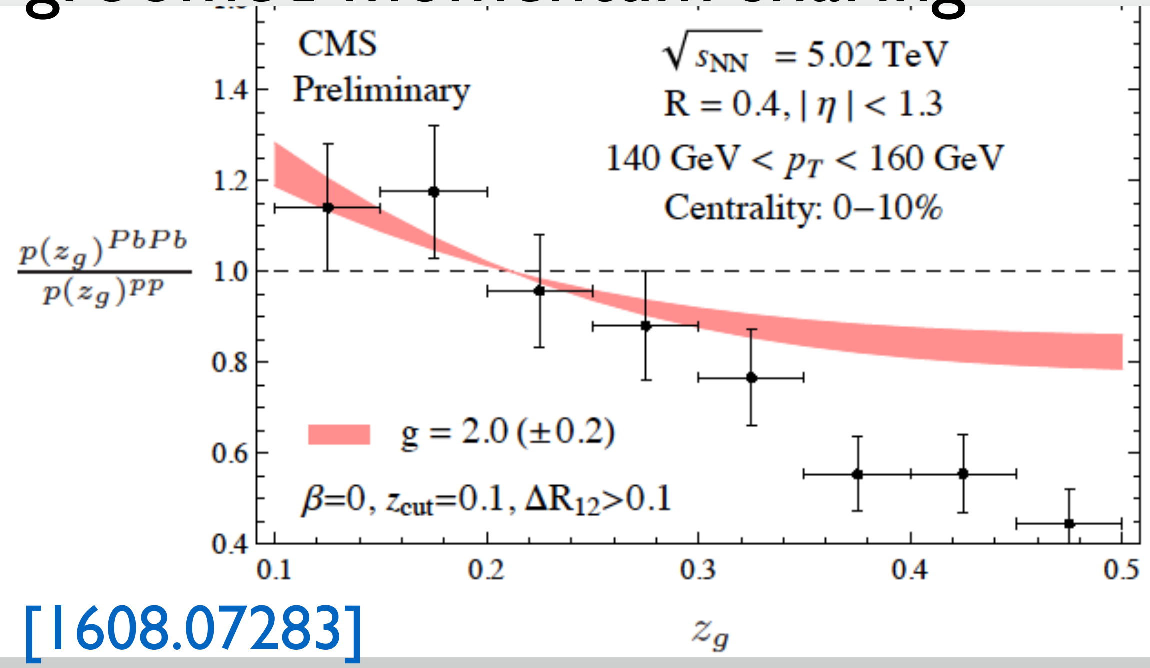


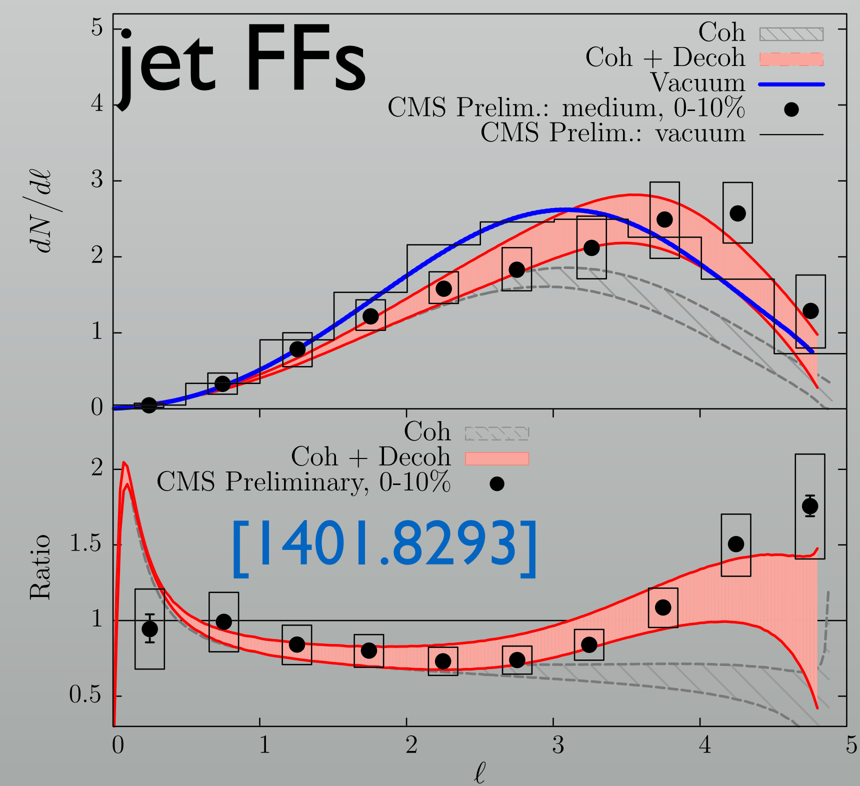
[1608.07283]

Coherence + turbulence:

$$D(z,t) \equiv z\frac{dN}{dz}$$

$$\frac{\partial D(z,t)}{\partial t} = \int dx\,\mathcal{K}(x)\left[\sqrt{\frac{x}{z}}D\left(\frac{z}{x},t\right) - \frac{x}{\sqrt{z}}D(z,t)\right]$$

jet FFs



[1401.8293]

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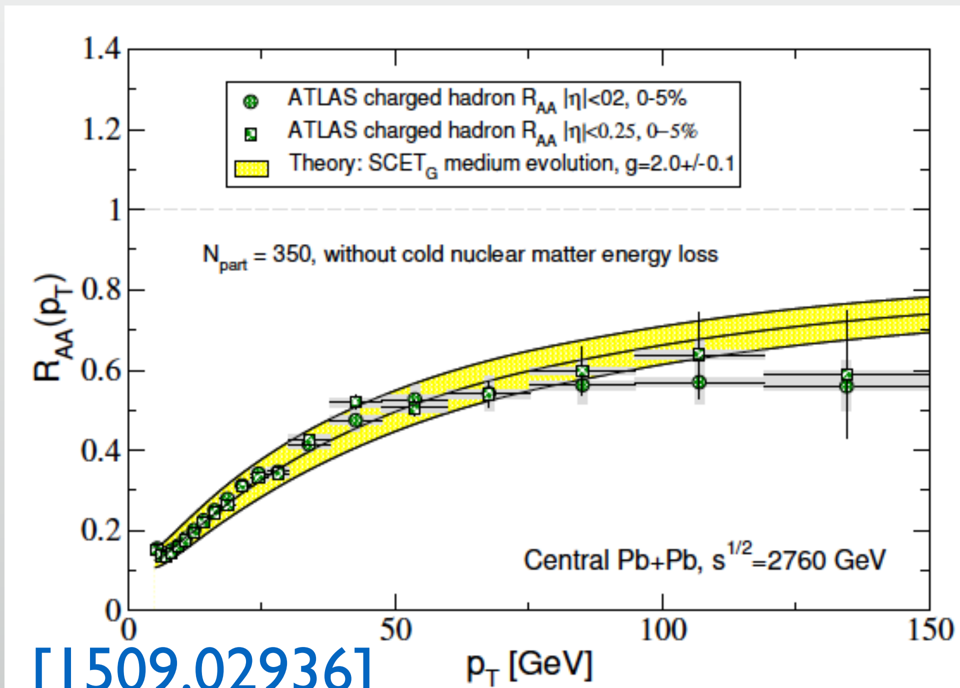

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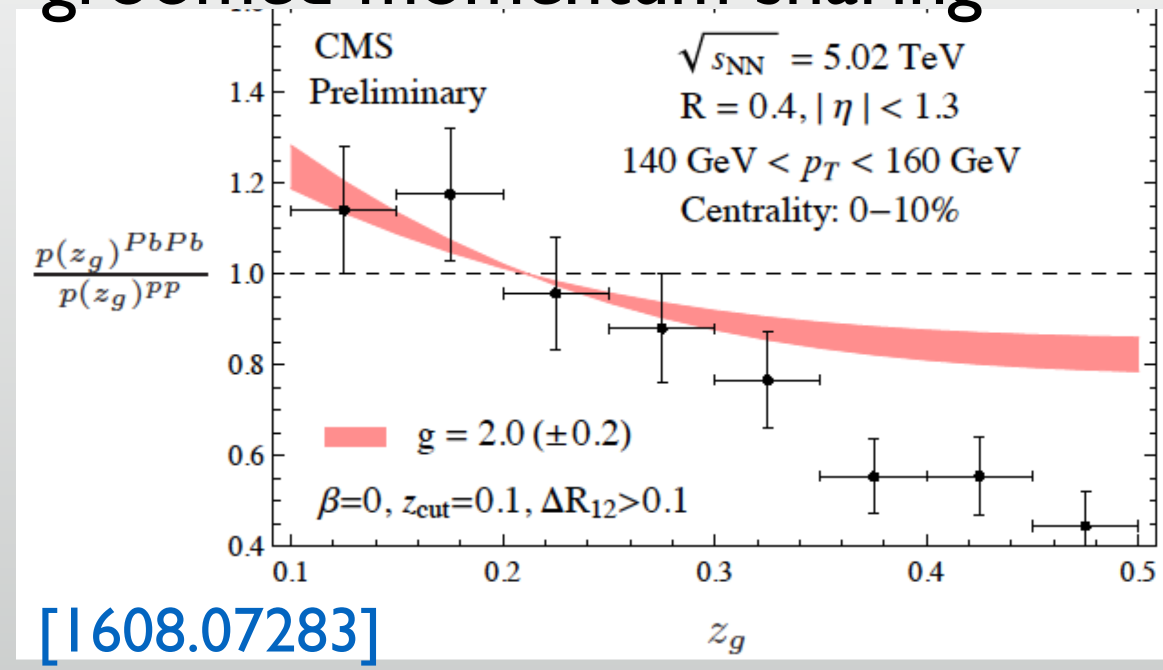
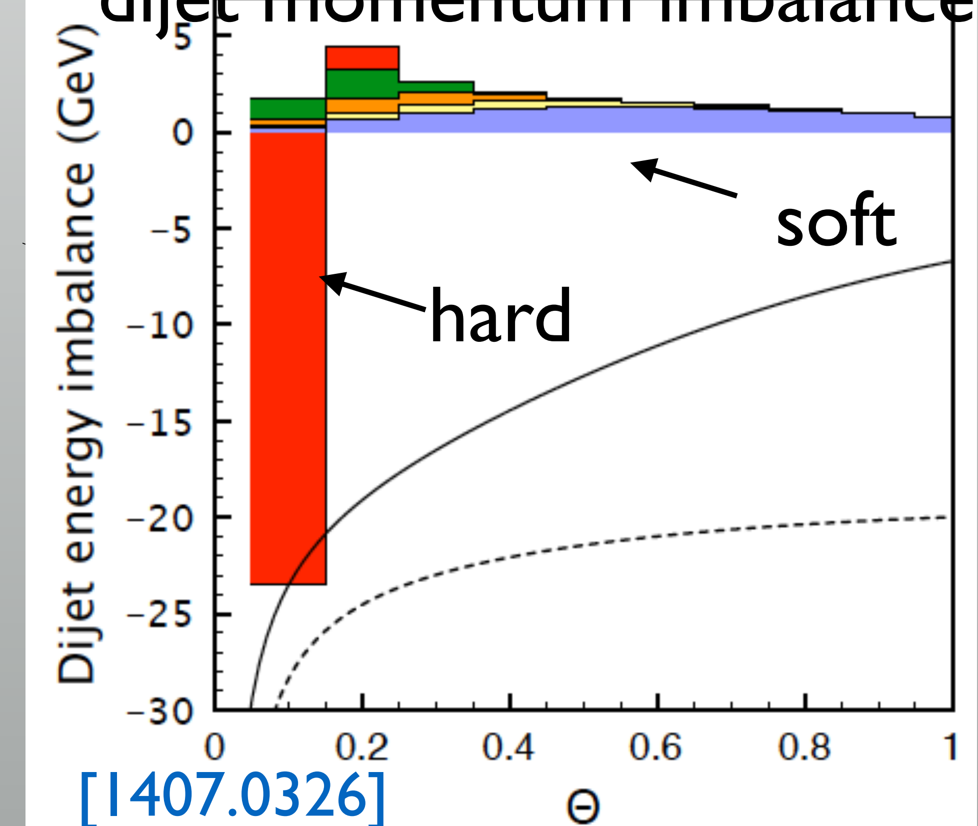


[1608.07283]

dijet momentum imbalance



[1407.0326]

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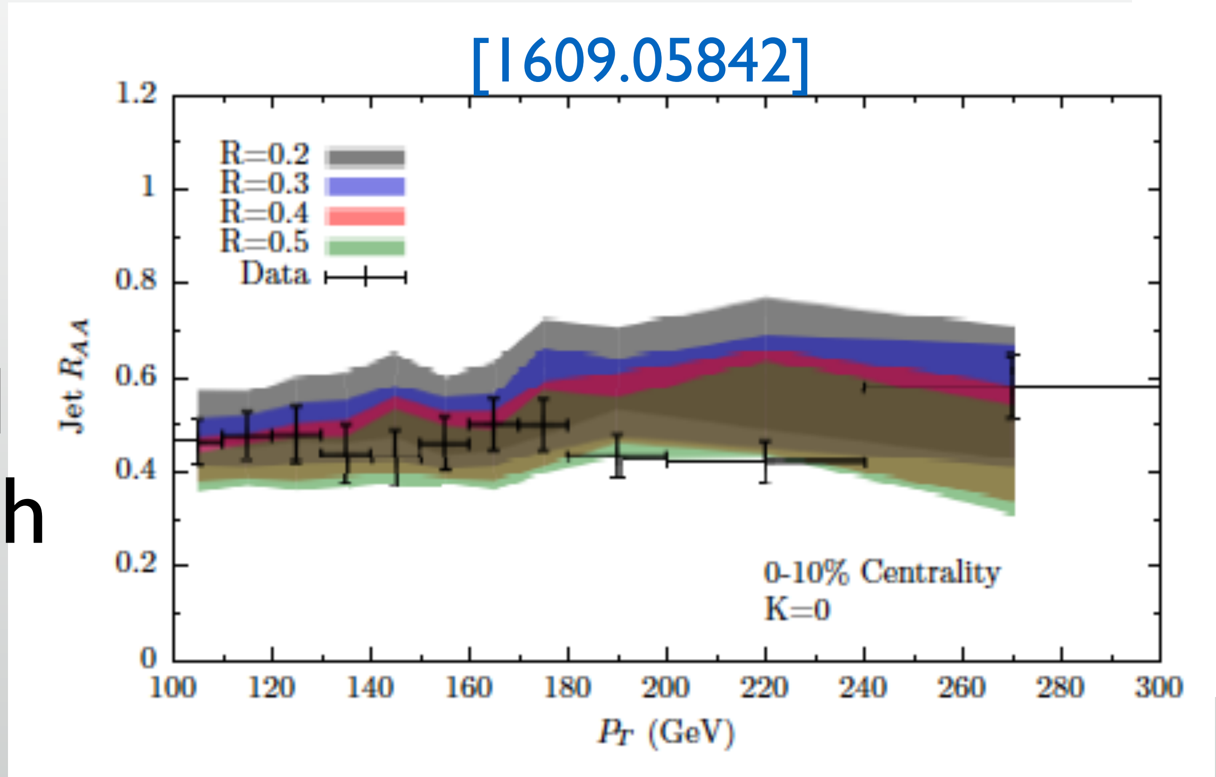

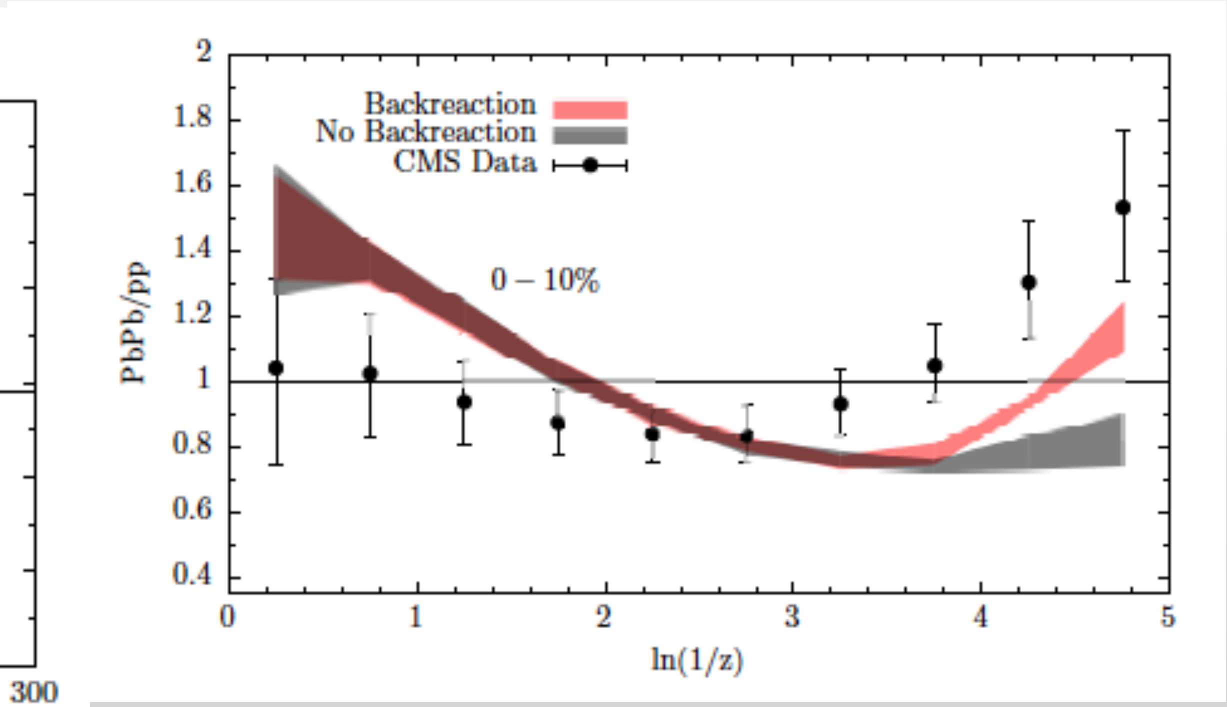

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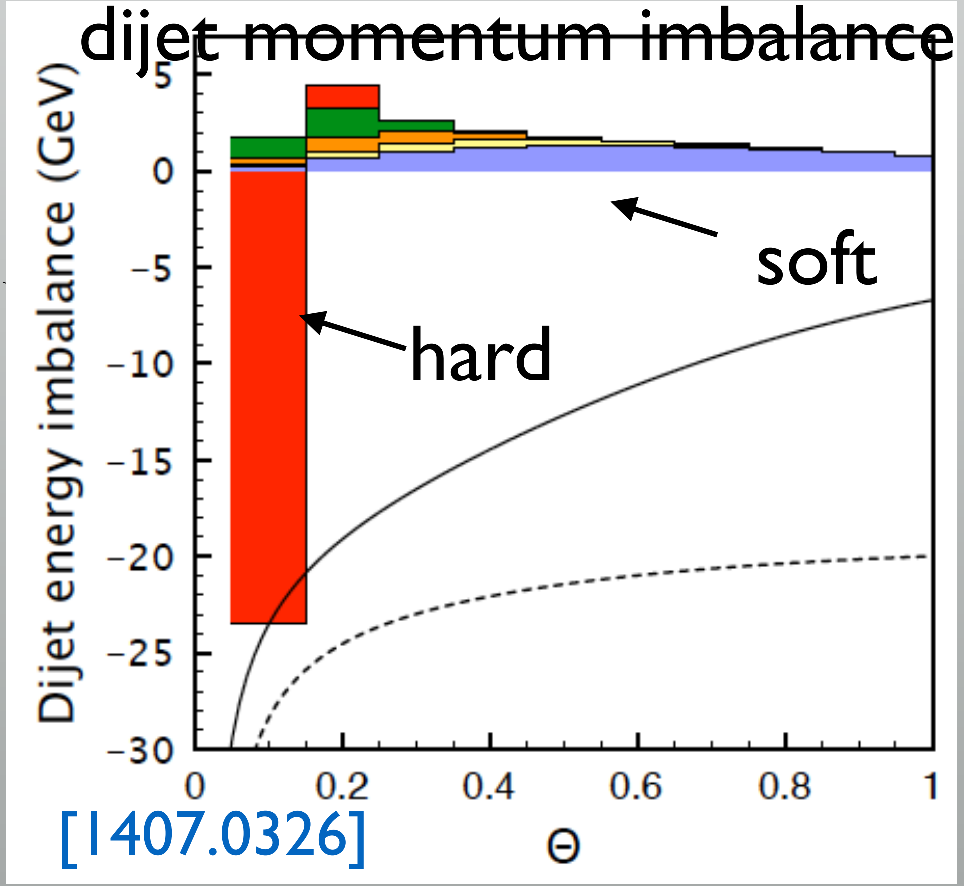

The challenges:

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- General proof of factorisation (calculation of two gluon emission) like in vacuum: importance of overlapping formation times. [Arnold-Chang-Ibqal, 1512.07561]
- Medium response (jet-medium interface): colour rearrangement, recoil (elastic eloss). [Cao-Luo-Qin-Wang, Neufeld-Vitev, Bouras-Betz-Xu-Greiner, Beraudo-Milhano-Wiedemann,Mueller-Qin]

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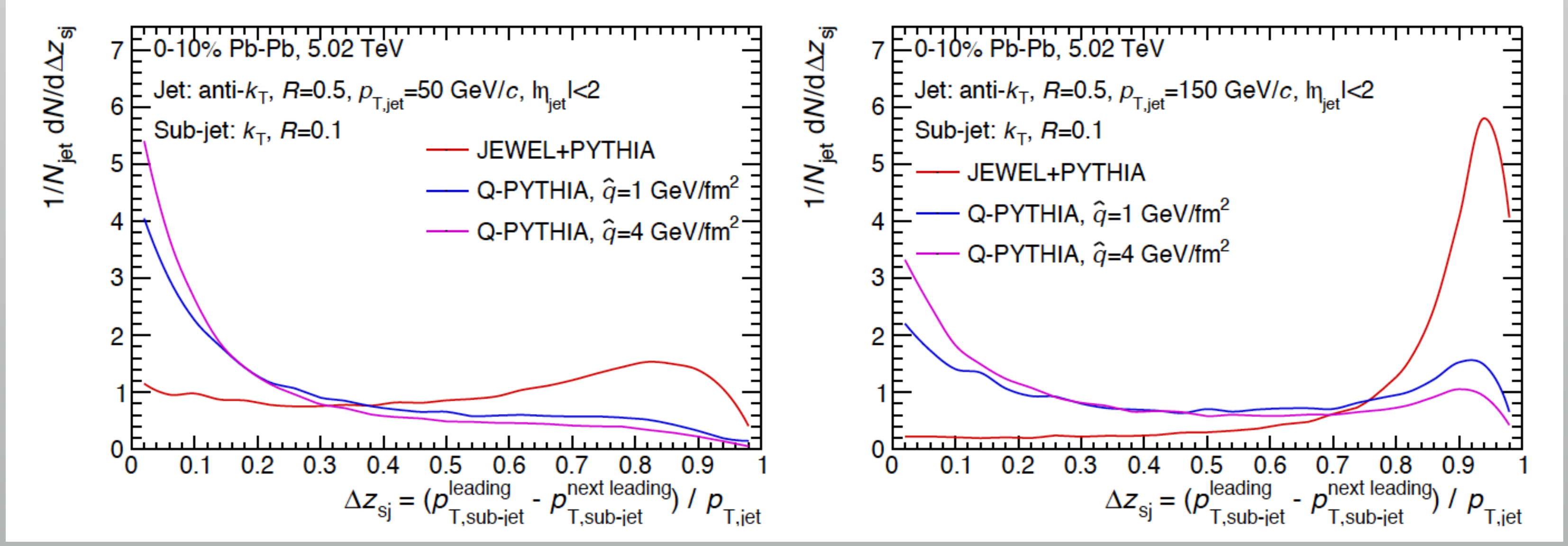

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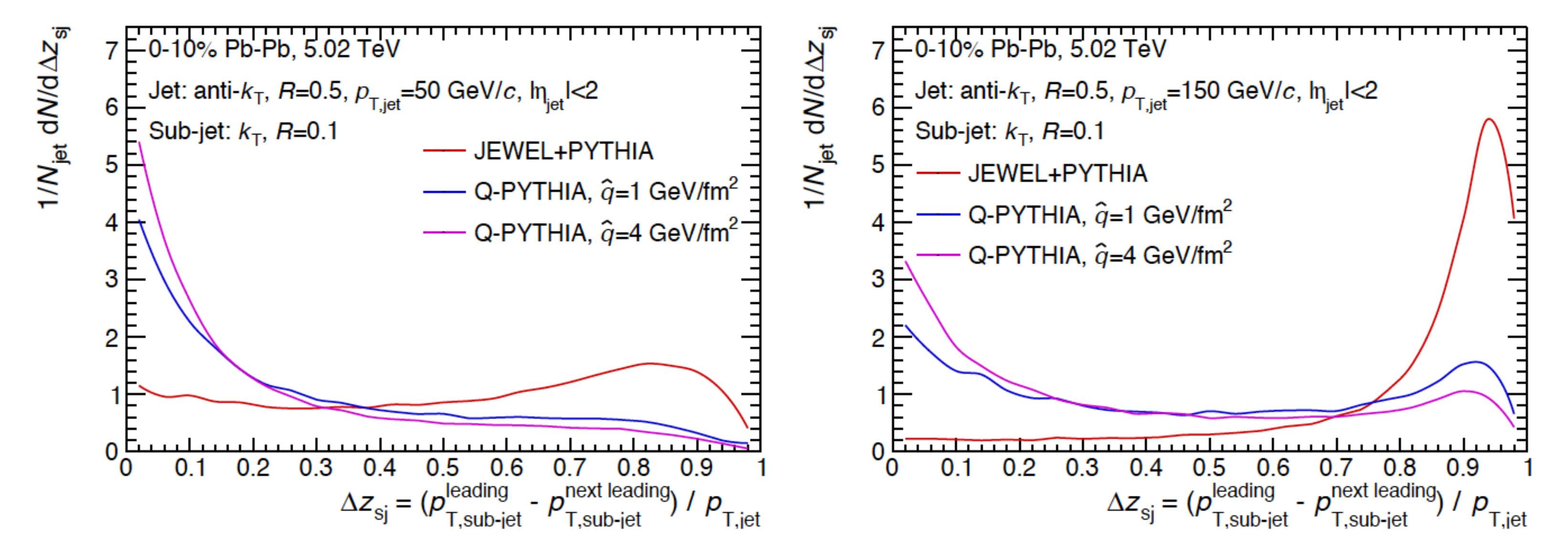
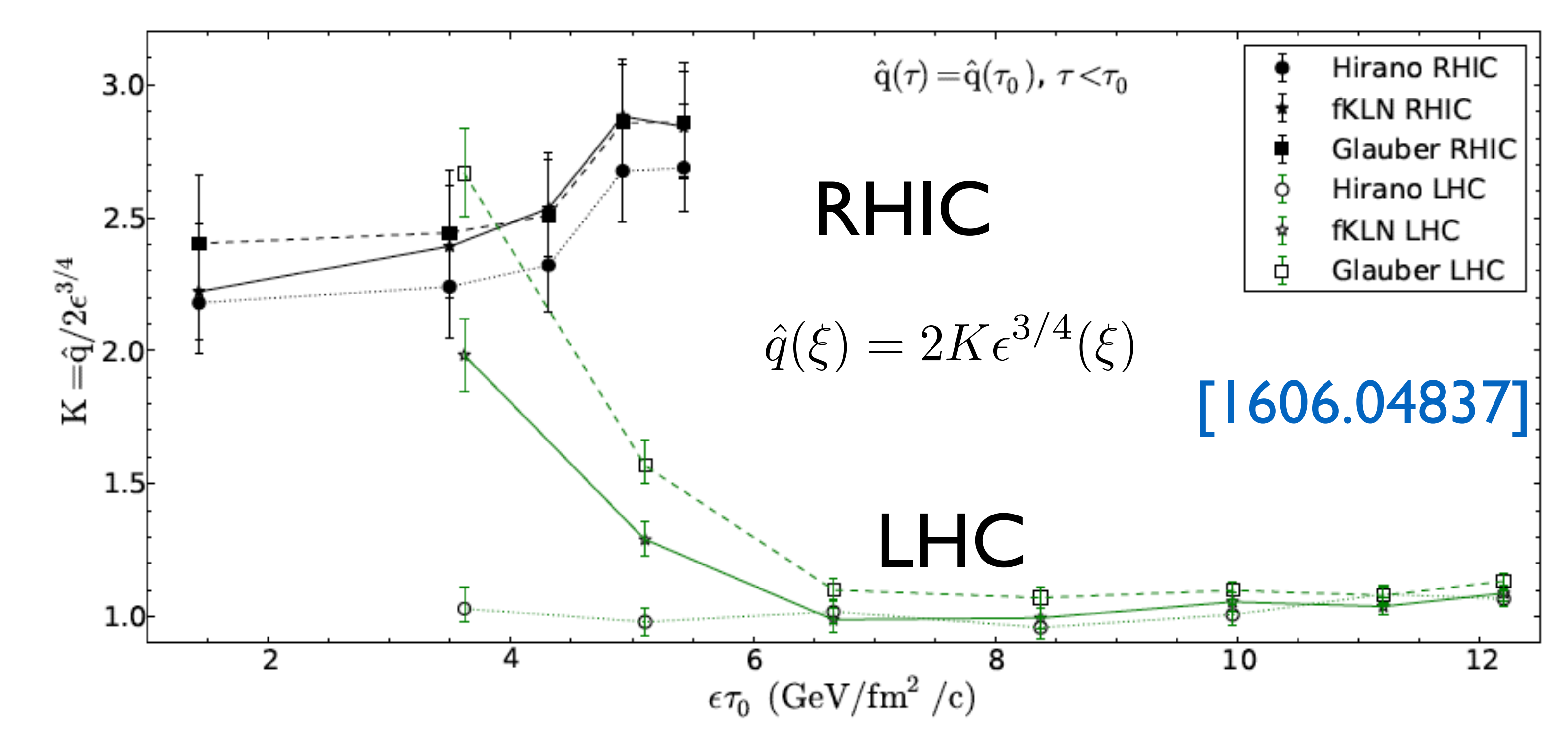


➜ Much can be learned from the pp community, from the treatment of colour reconnections to the design of observables and of validation tools.

The puzzling old stuff:

➜ Extract qhat embedding an eloss calculation in a hydro model for bulk and fitting R_{AA}^{charged}. Medium more opaque at RHIC than at the LHC [1312.5003, 1506.02854], but centrality???



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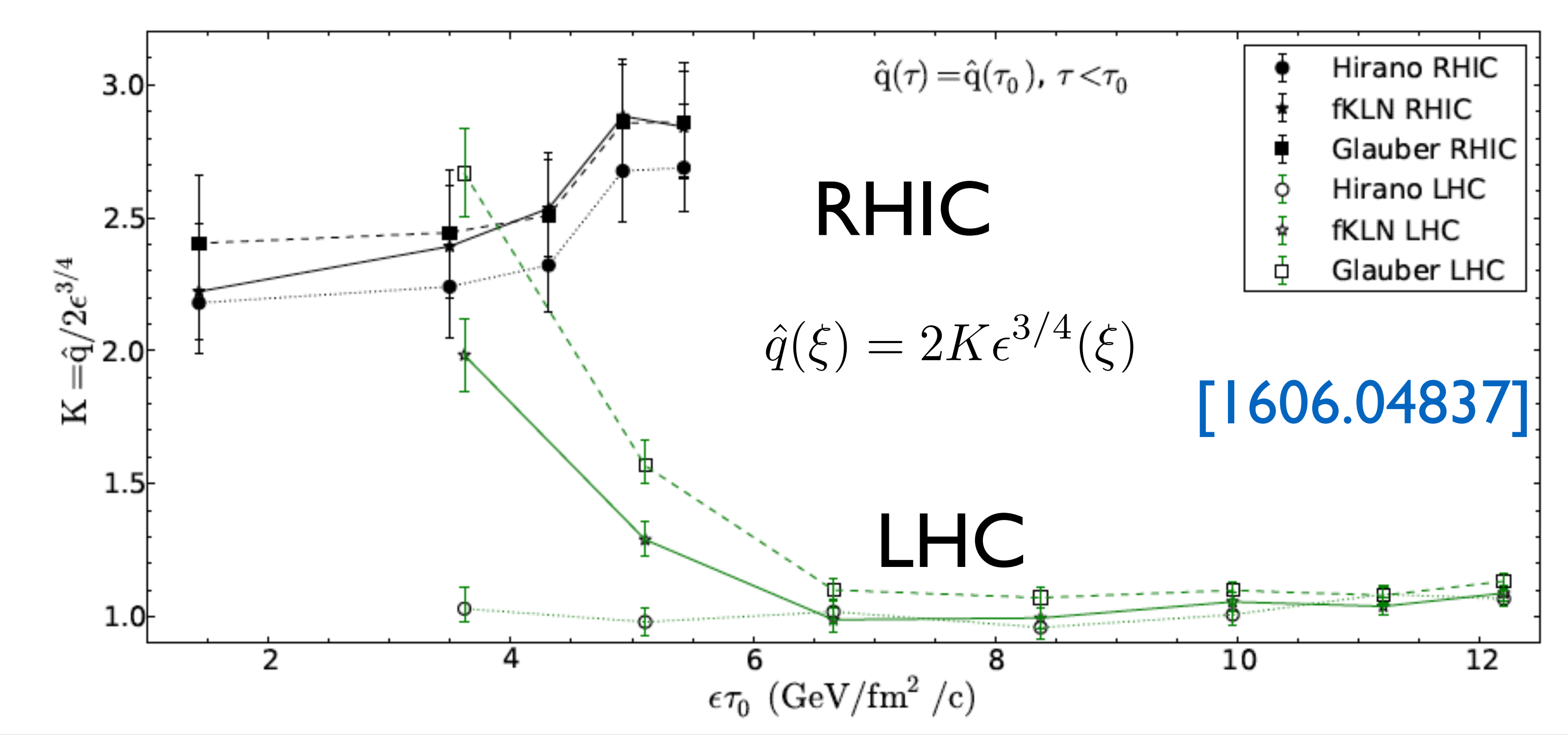

[1606.04837]

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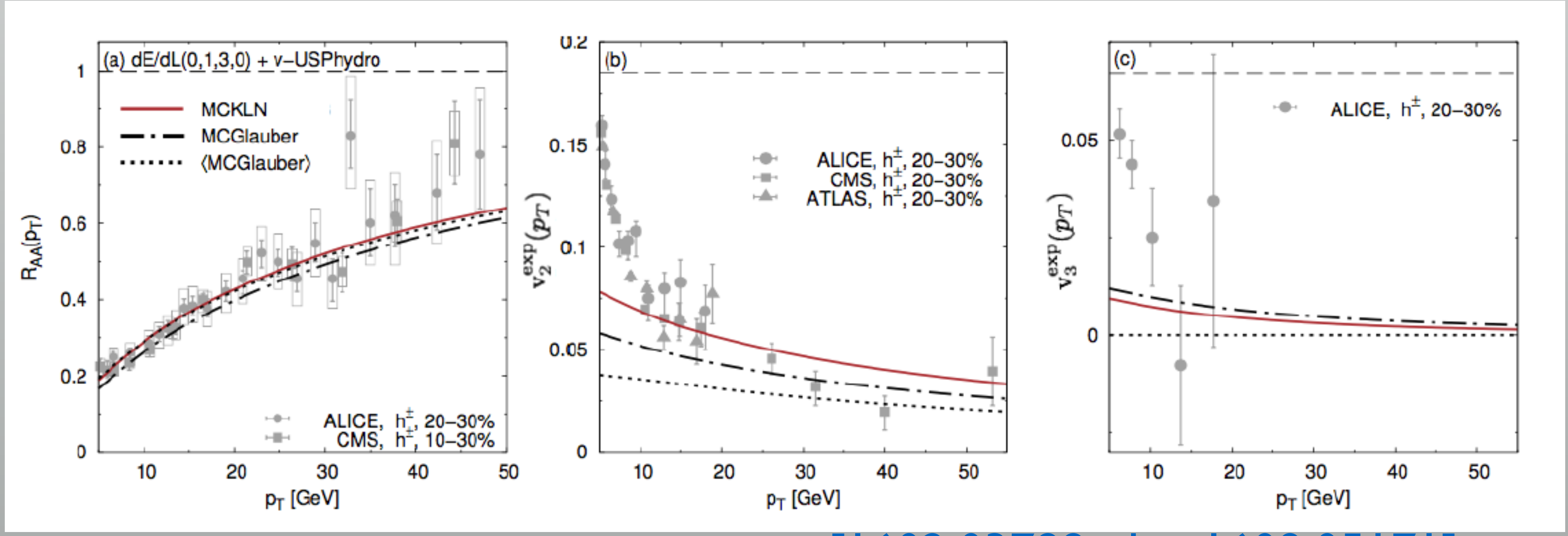

[1602.03788, also 1609.05171]

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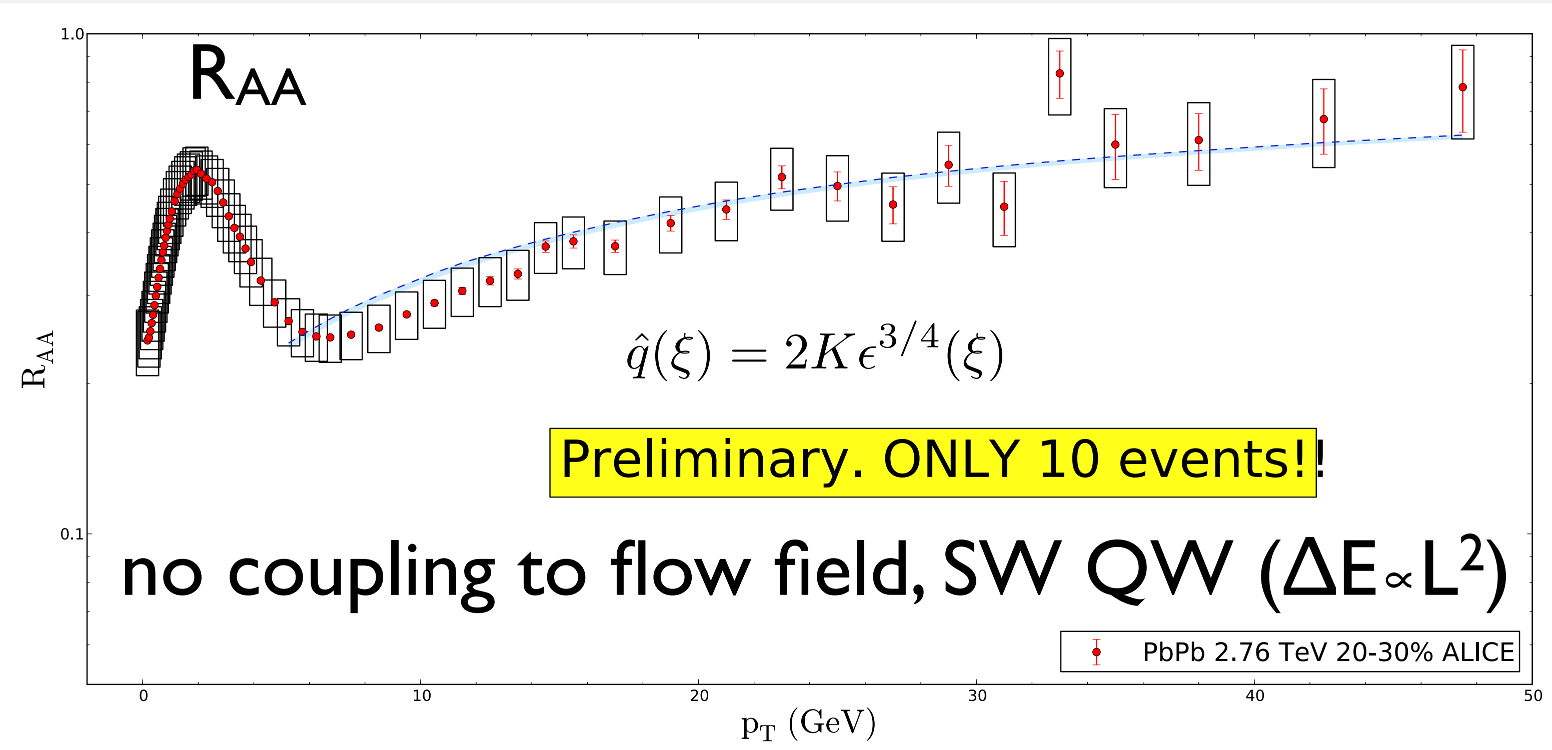
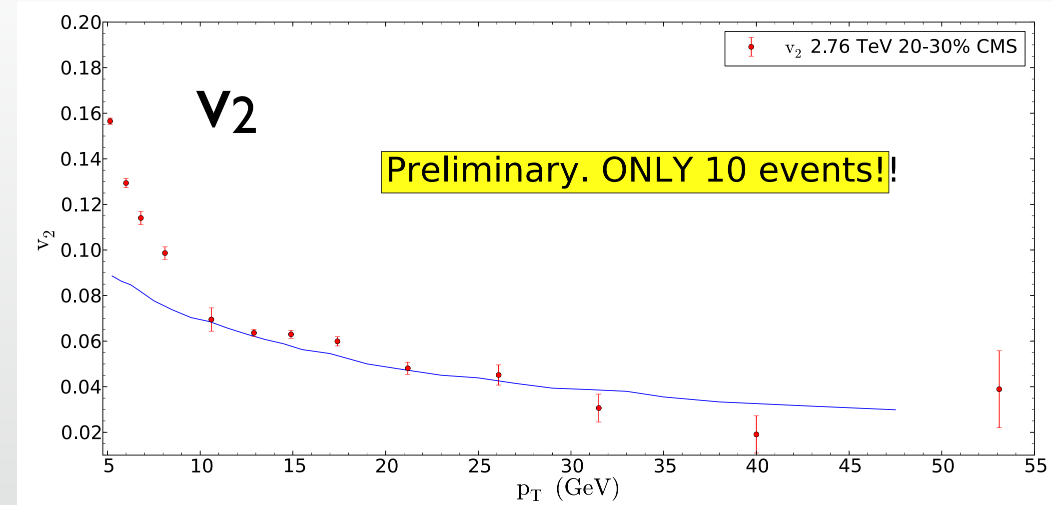
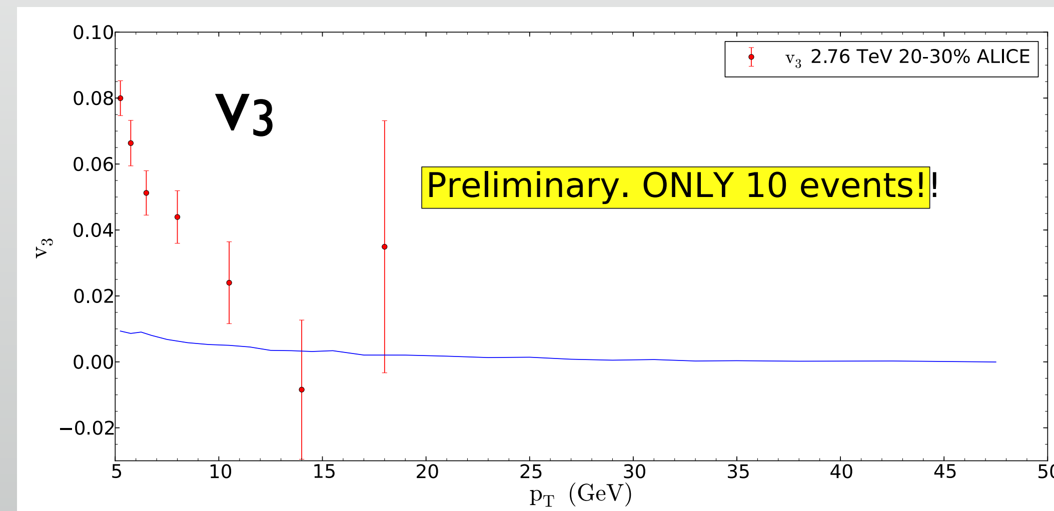
Andres-Armesto-Niemi-Paatelainen-Salgado-Zurita, in progress, see parallel







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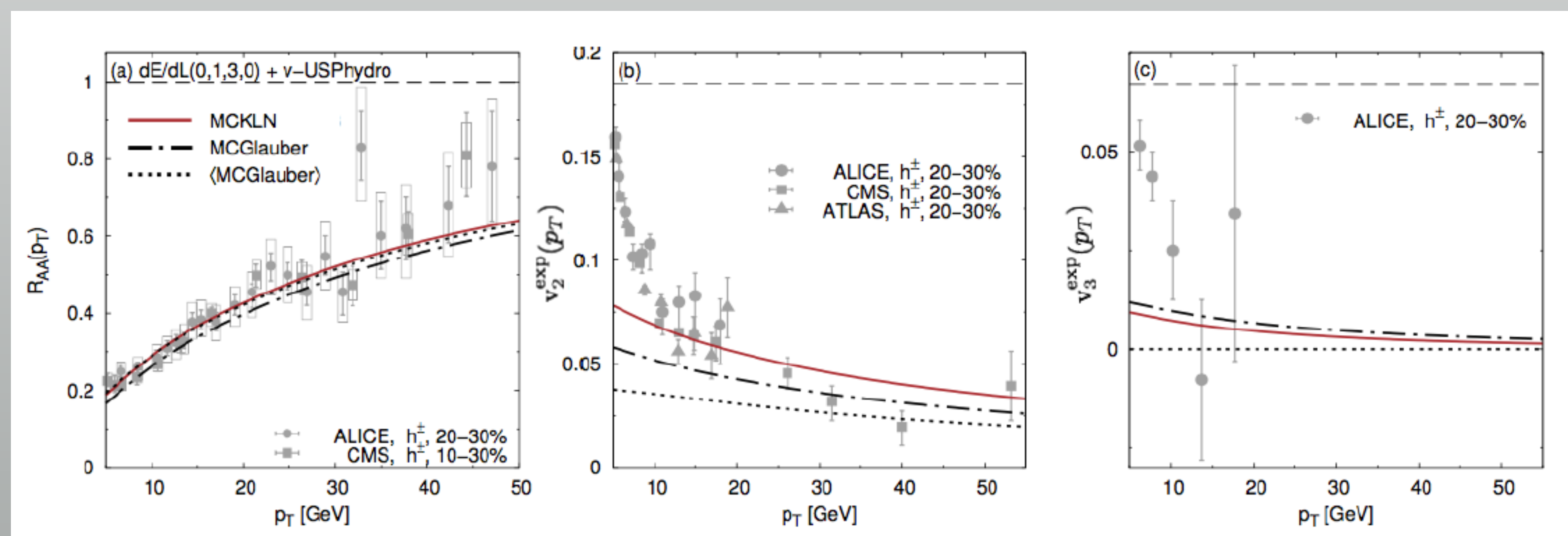

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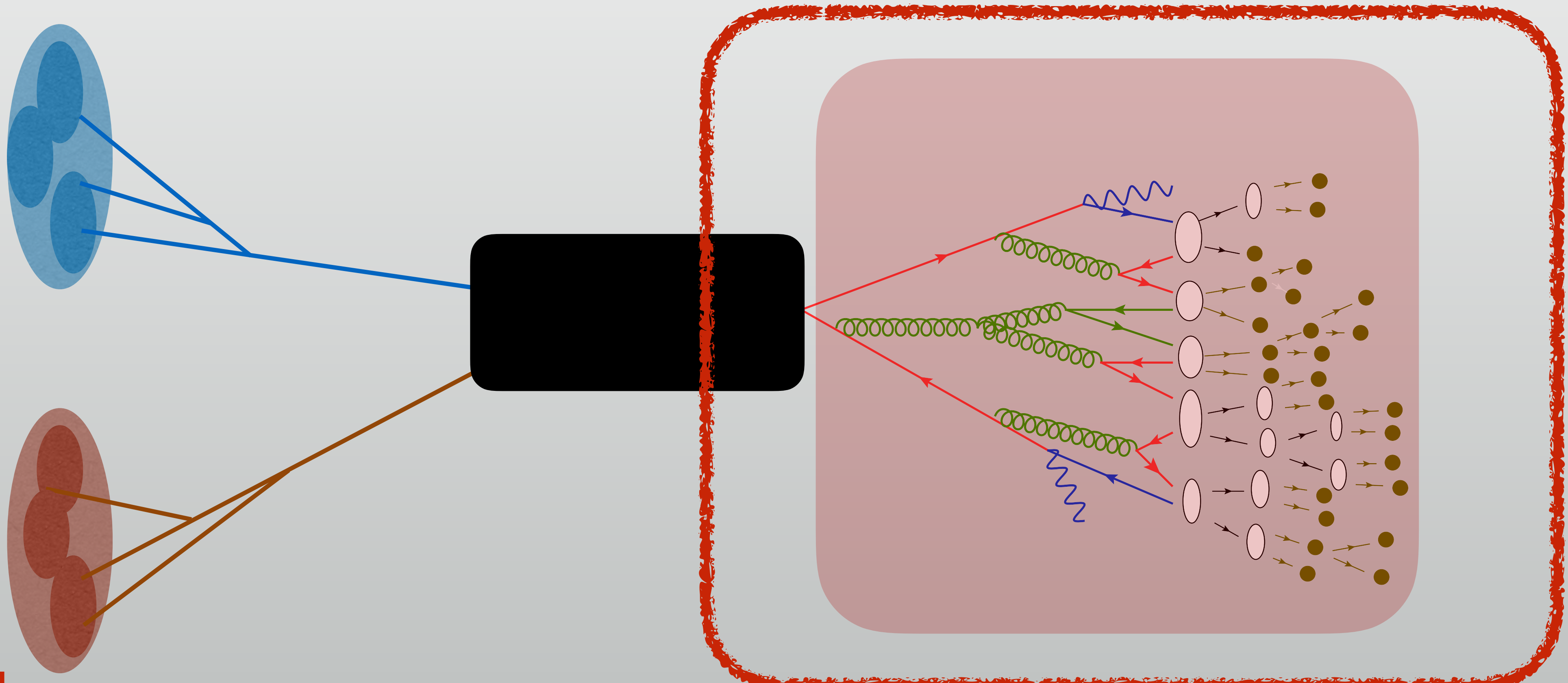
[Plenaries by Ferreiro, Nahrgang and Strickland]



3. Heavy flavour:
    ➜ Open heavy flavour.
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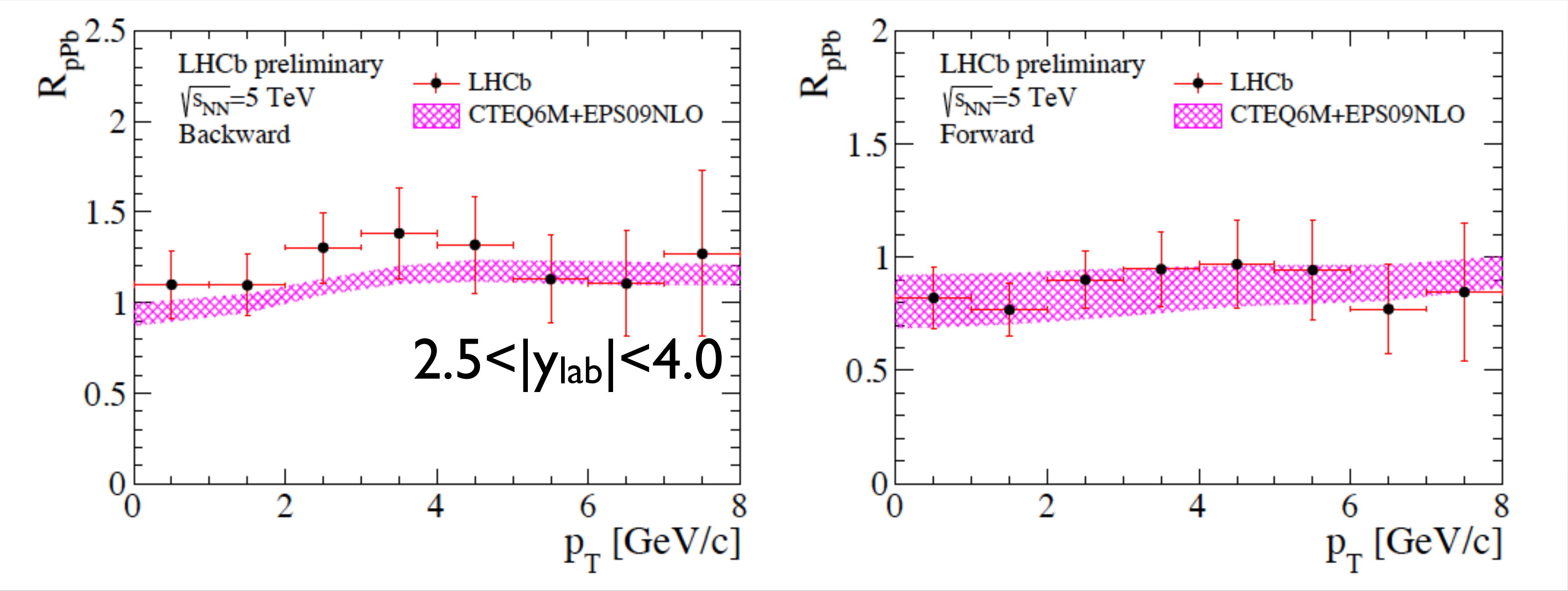
Open HF in pA:

➜ NLO pQCD with nPDFs seems to work in pPb, even at forward and backward rapidities, to be compared with other approaches.



[LHCb-CONF-2016-003]

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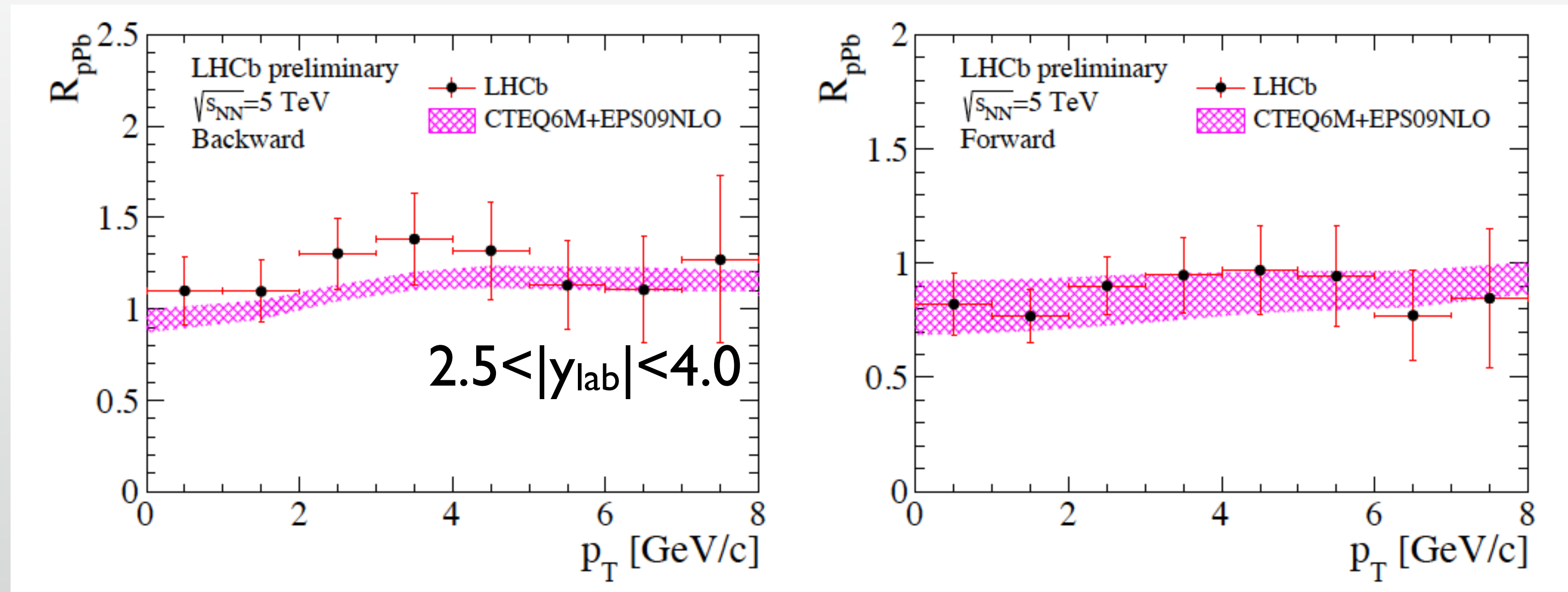
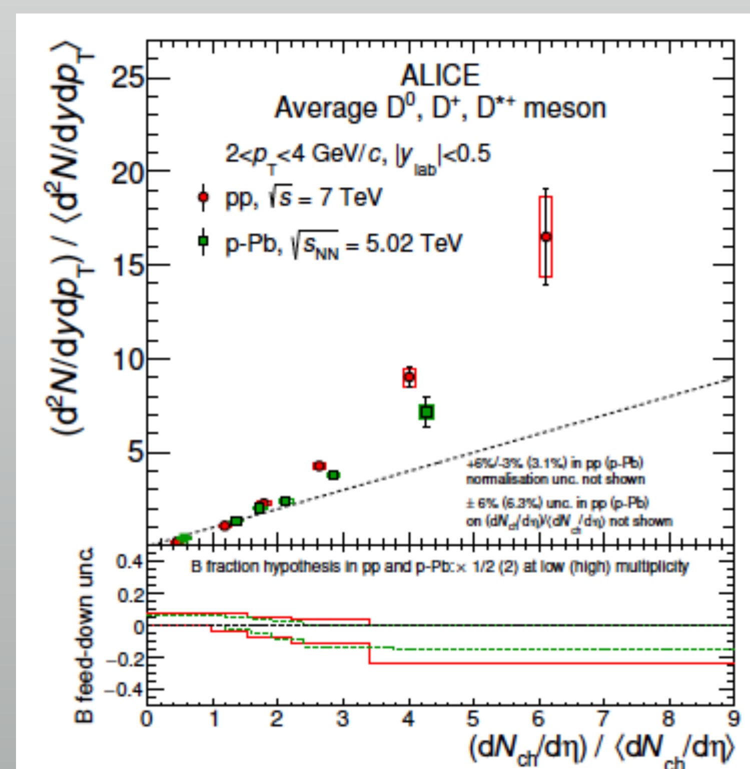
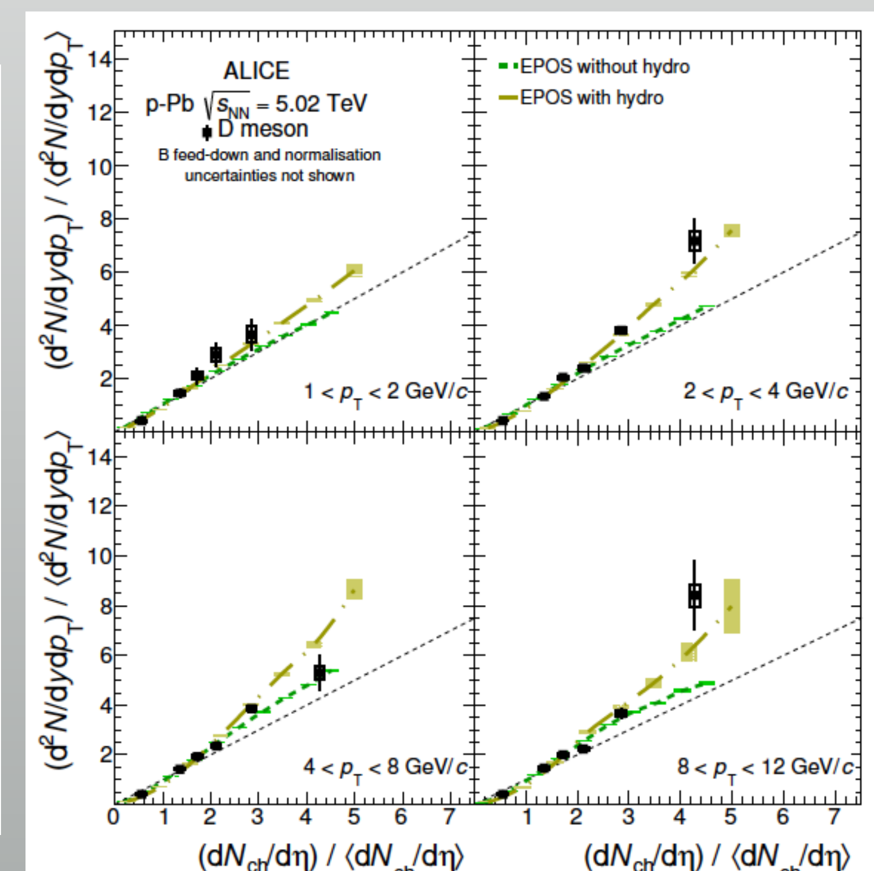


[LHCb-CONF-2016-003]

➜ Multiplicity dependence difficult to describe: non-trivial interplay between soft and hard production (as jets). MPIs, final state interactions leading to hydro?



[1602.07240]



Open HF in AA (I):

Table 11: Comparative overview of the models for heavy-quark energy loss or transport in the medium described in the previous sections.

Model	*Heavy-quark production*	*Medium modelling*	*Quark–medium interactions*	*Heavy-quark hadronisation*	*Tuning of medium-coupling (or density) parameter(s)*
Djordjevic *et al.* [511–515]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss finite magnetic mass	fragmentation	Medium temperature fixed separately at RHIC and LHC
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[1506.03981]

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[587, 628]	EPS09 (LO) PDF shadowing	viscous fl. dyn.	rad. + coll. energy loss	recombination	fixed at RHIC and LHC (same value)

➜ pQCD based, simultaneous description of charged and charm and beauty.

➜ Suitable for relatively large p_T, vacuum fragmentation, tend to fail for v_2 at low pt.

➜ The hierarchy of radiative energy loss $\Delta E_Q < \Delta E_q$ is only seen for b: interplay of collisional and radiative eloss, fragmentation, different partonic slopes.

[1506.03981]

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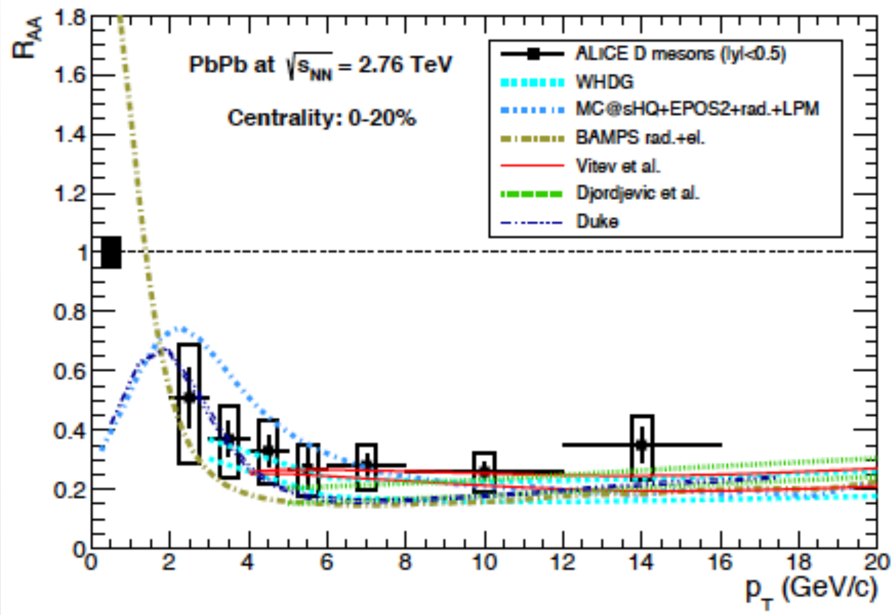

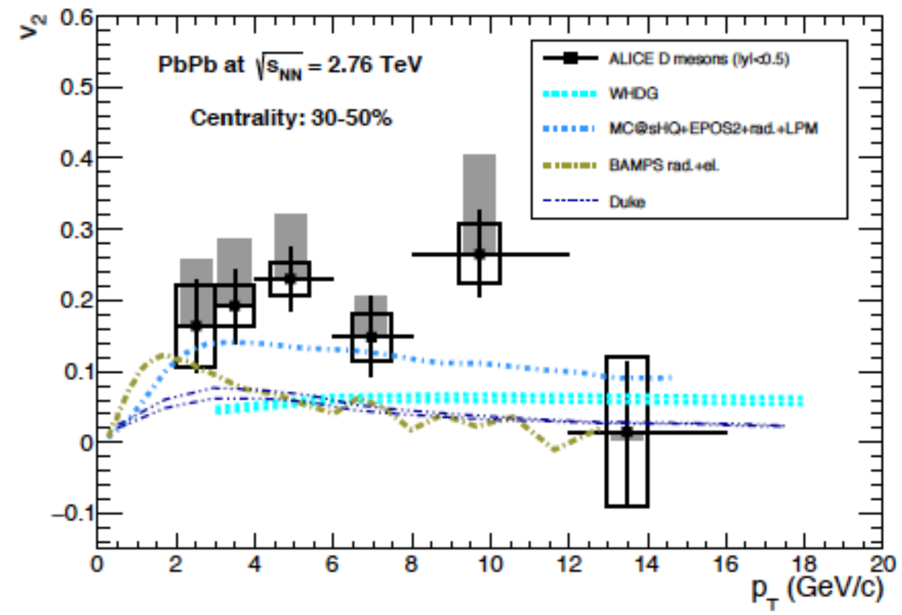

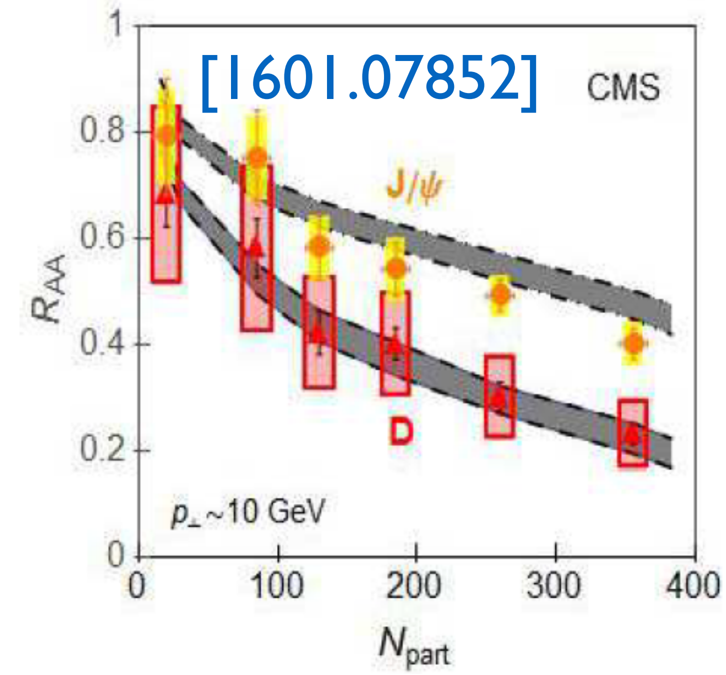

Bjorken expansion

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[587, 628]	EPS09 (LO) PDF shadowing	viscous fl. dyn.	rad. + coll. energy loss	recombination	fixed at RHIC and LHC (same value)

[1506.03981]

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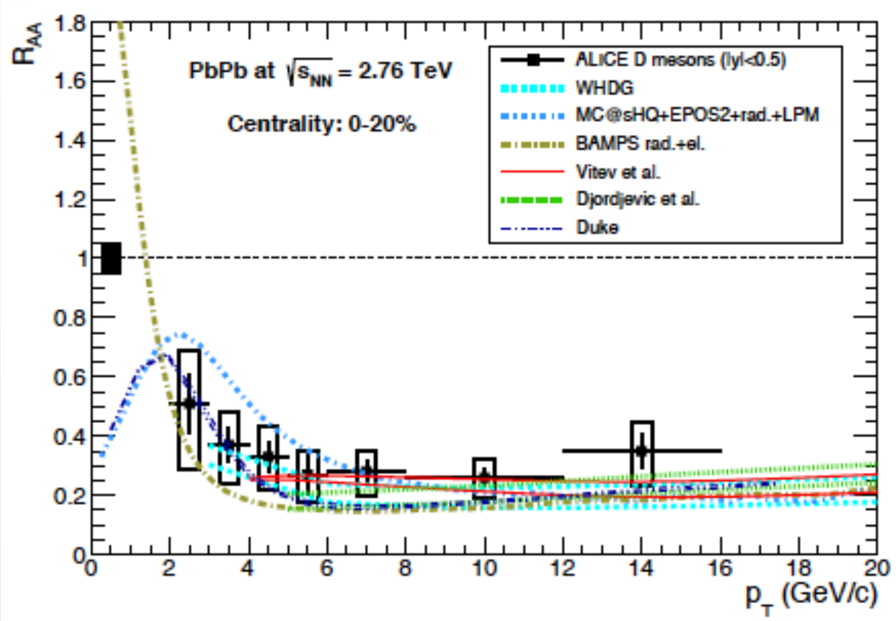

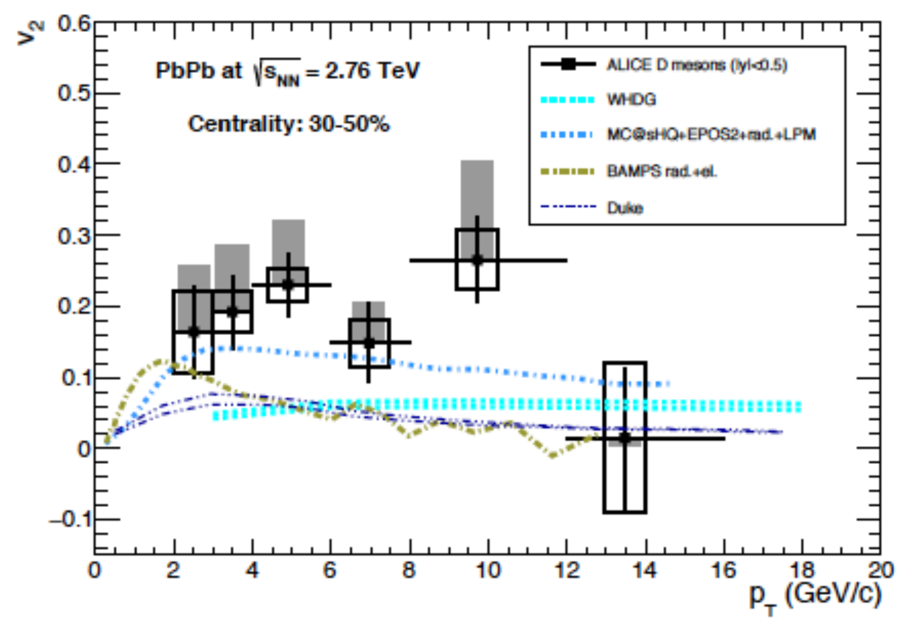

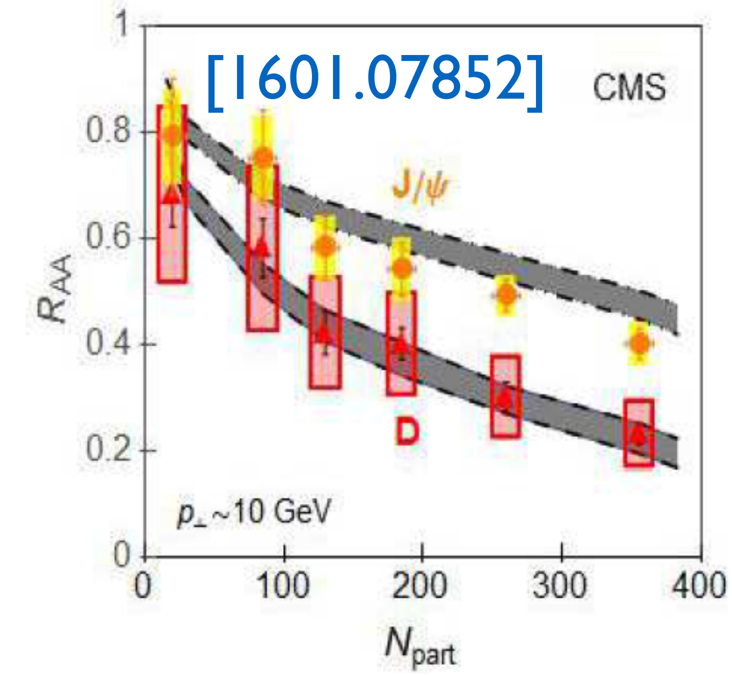

Bjorken expansion

AdS/CFT (HG) FONLL Glauber model AdS/CFT drag fragmentation RHIC

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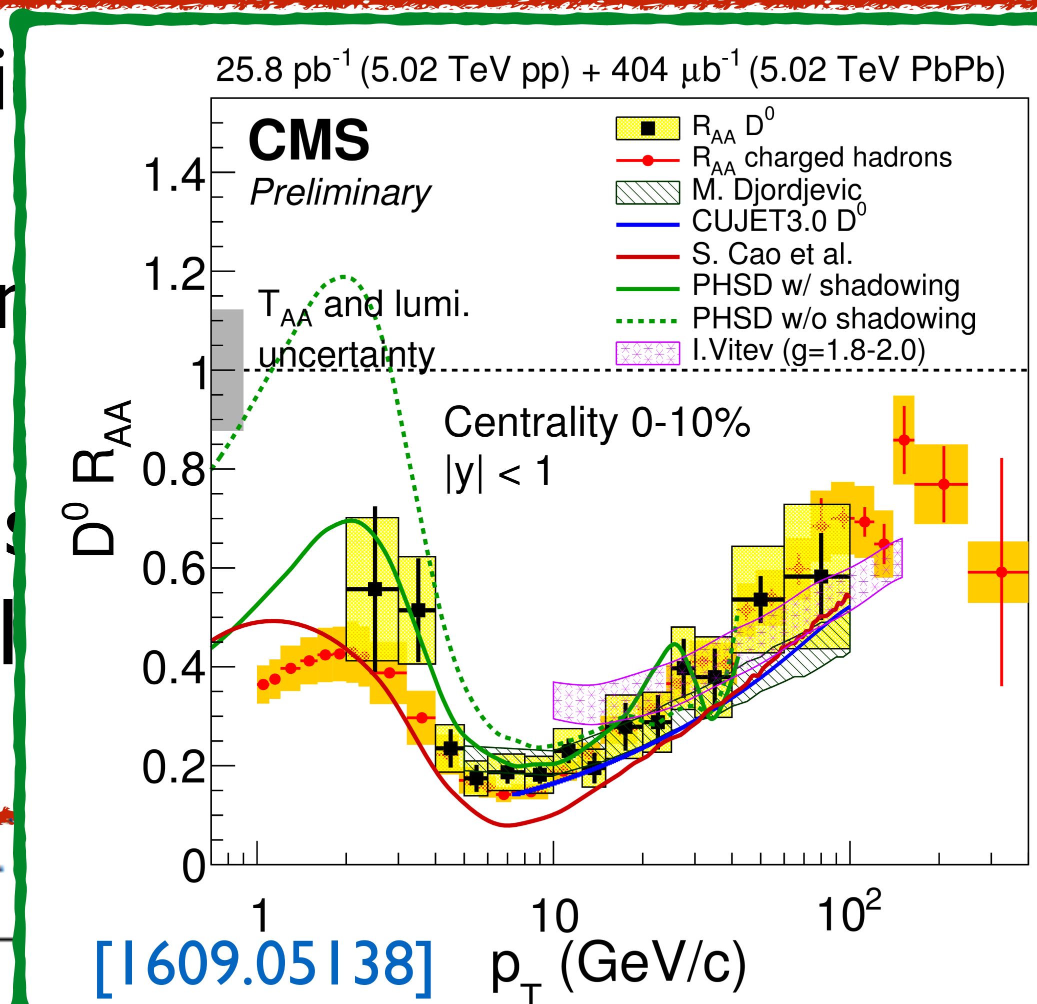
[587, 628] EPS09 (LO) PDF shadowing viscous fl. dyn. rad. + coll.

[1506.03981]



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[1506.03981]

Open HF in AA (II):

➜ Transport equations, in principle more suitable for small p_T, usually describe v_2.

➜ Differences:

- Initialisation.
- Medium interactions: partons, quasi particles, treatment of transport coefficients, elastic versus inelastic,…
- Medium description.
- Hadronisation: fragmentation, coalescence.

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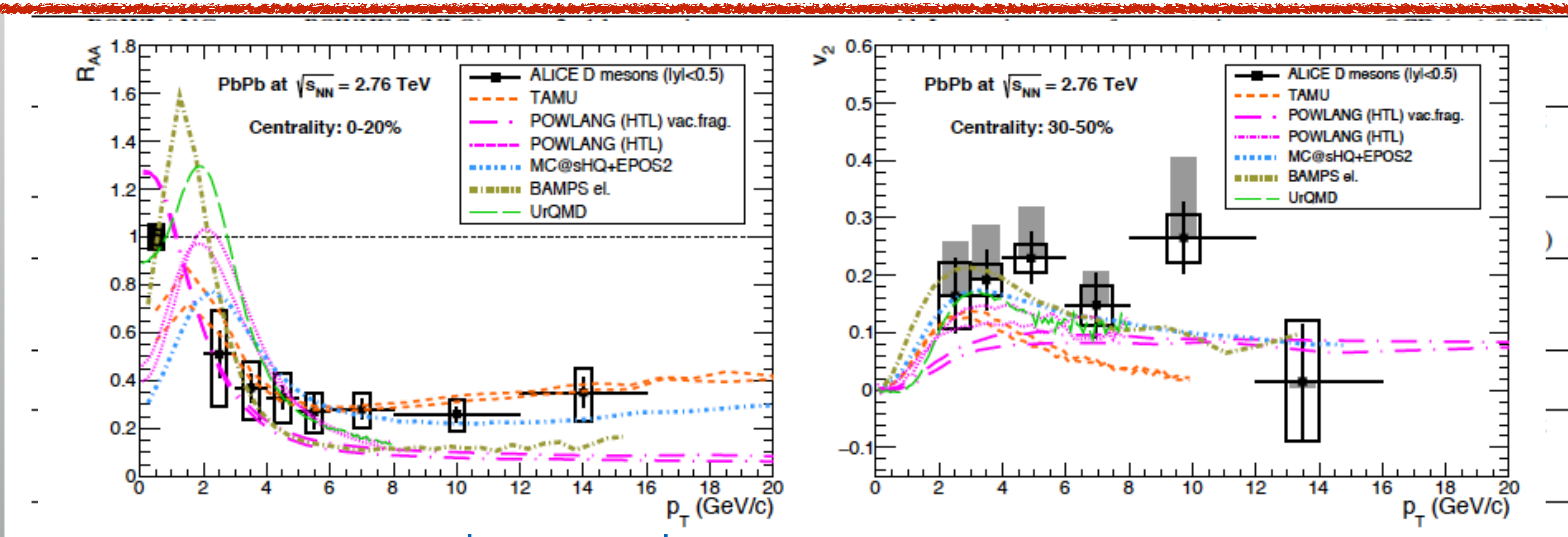

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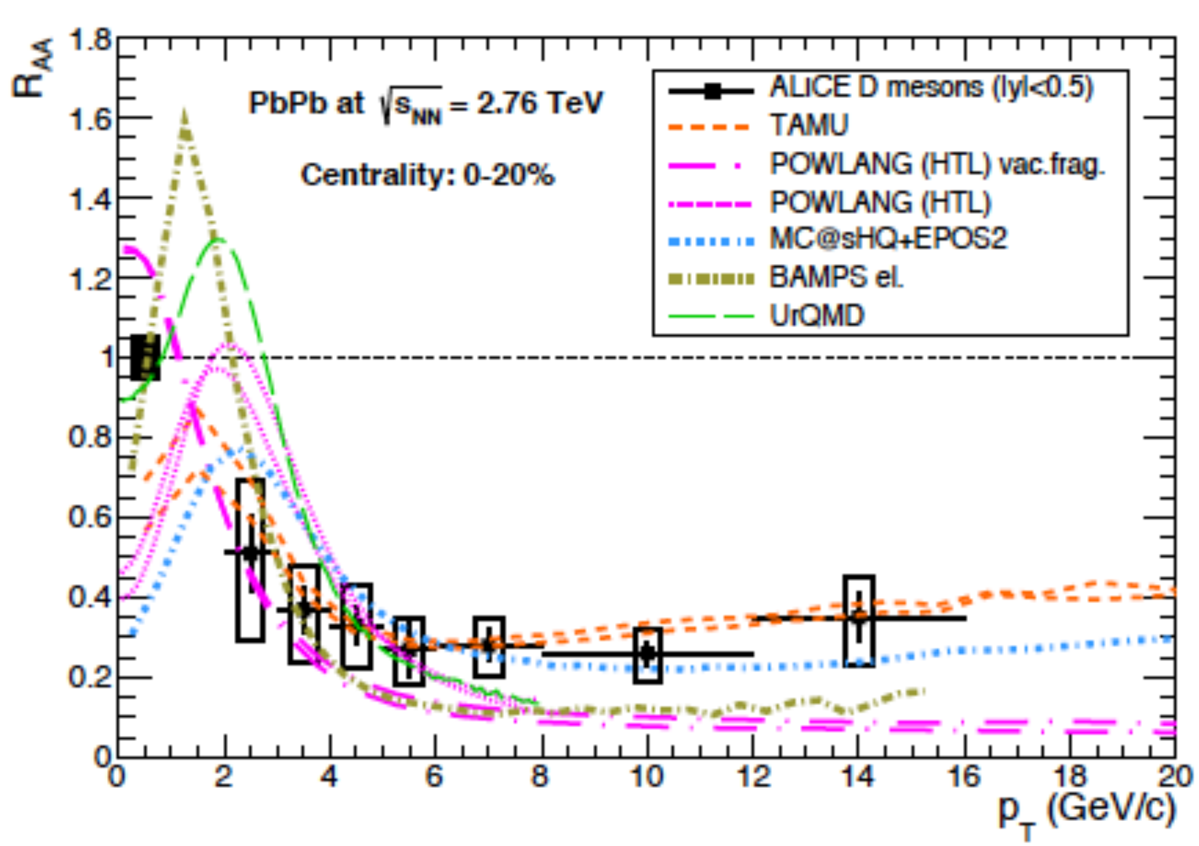
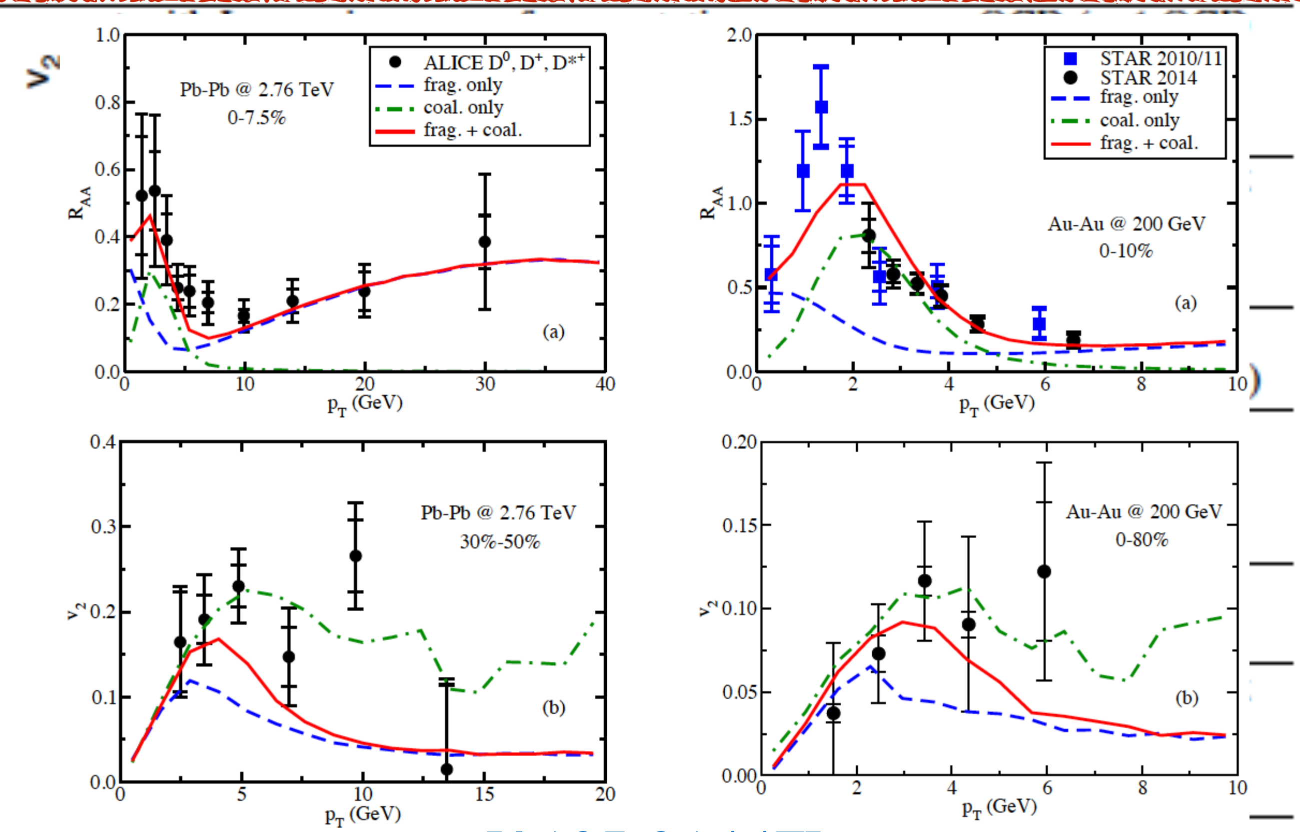




[1605.06447]

Quarkonium:

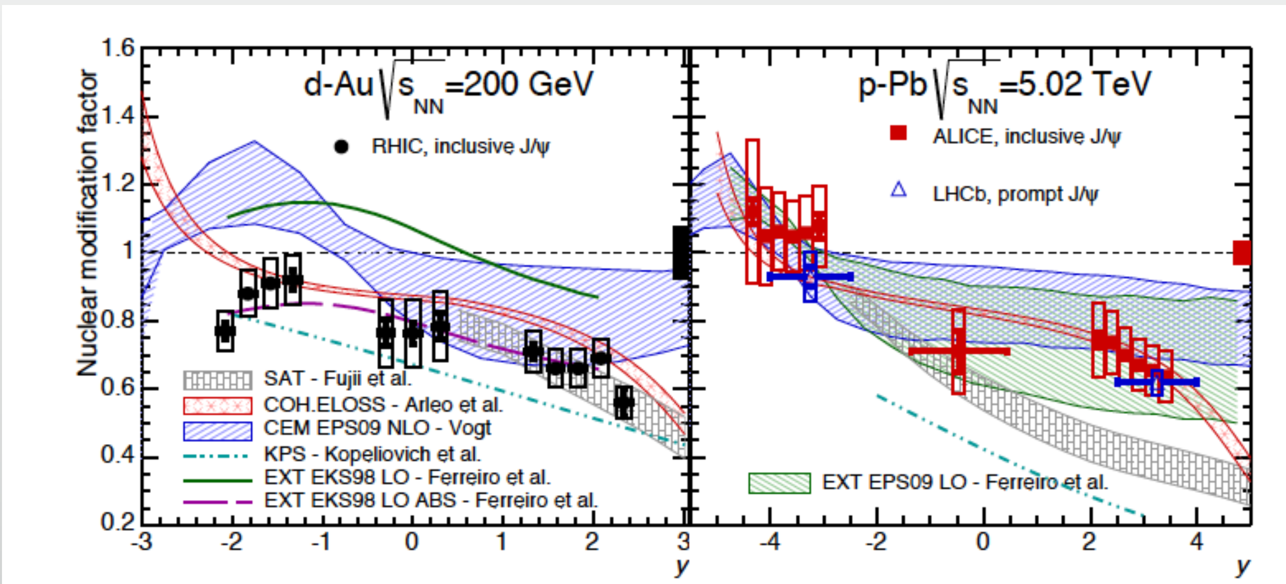
➜ The description within pQCD of quarkonium production in pp is not fully clarified: CEM, NRQCD, CSM,…

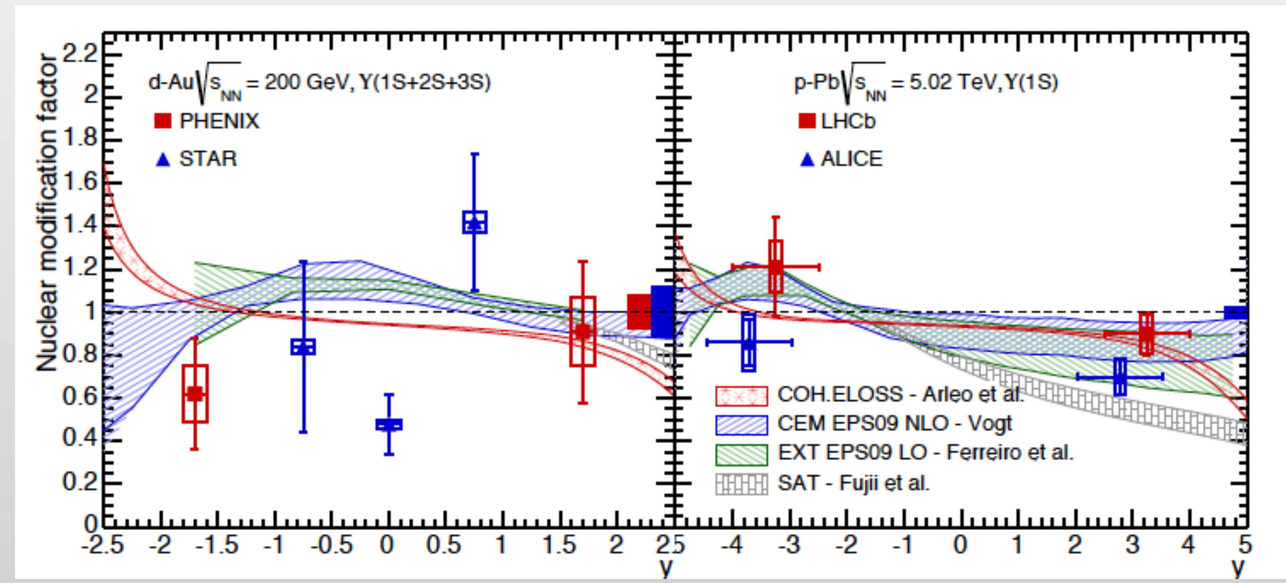
➜ In nuclear collisions, several effects may modify the yield with respect to the expectation from a superposition of nucleon-nucleon collisions:

	Effect	Comment
CNM: pA and AA	nPDFs/CGC	Common with open HF, blind to the state, initial effect
	Absorption	Important at low energies and in the backward region, probably irrelevant for the LHC, blind to the state?
	Energy loss	Connection with jet quenching, blind to the state
Hot effects	Debye screening	Equilibrated system, thermometer
	Dissociation	Different implementations: partonic or hadronic transport/ comovers, potential models; different pictures of the medium, equilibrated or not
	Regeneration	Dynamical or statistical (at freeze-out)

From pA to AA:

➜ Description based on pQCD + nPDFs + absorption + Eloss is quite successful in pA for J/ψ and the ϒ family. [1506.03981]





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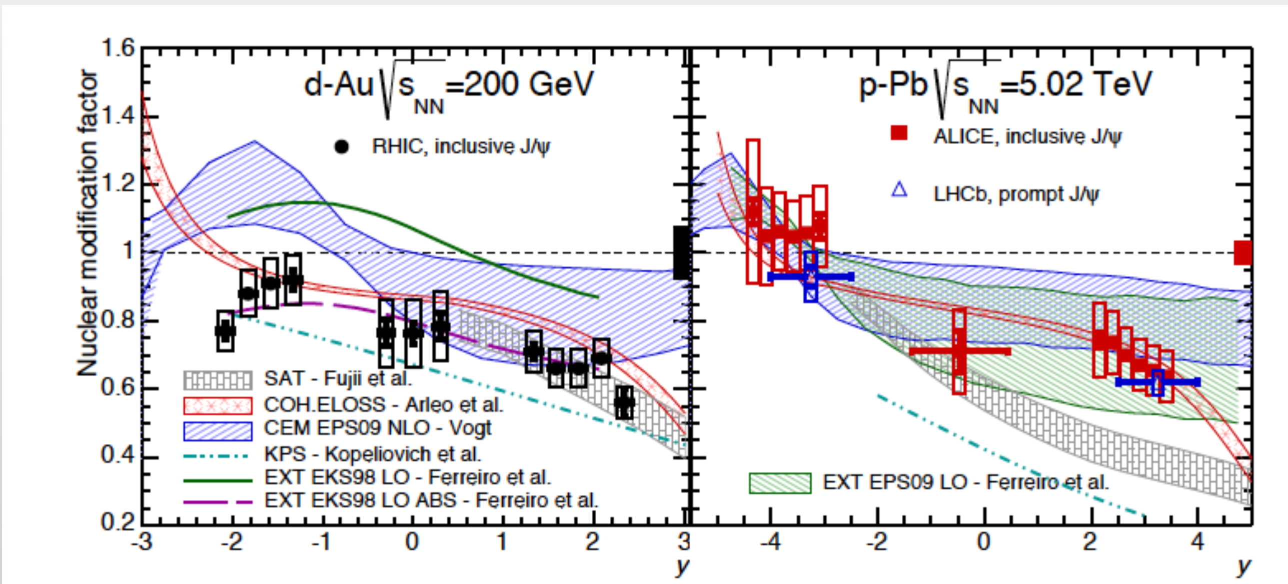
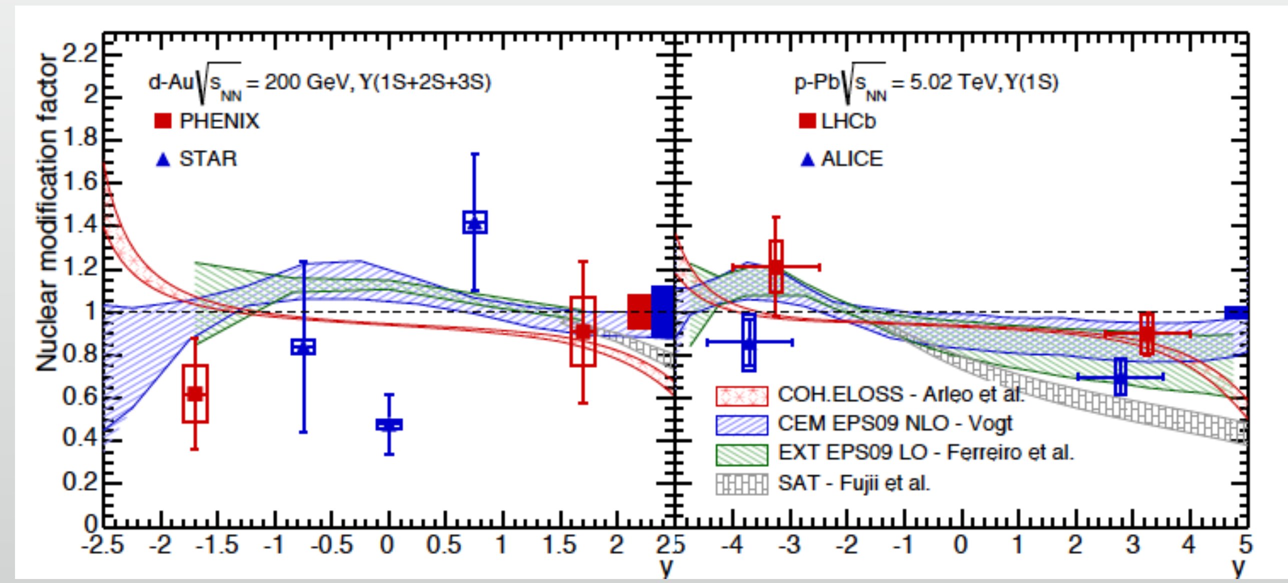
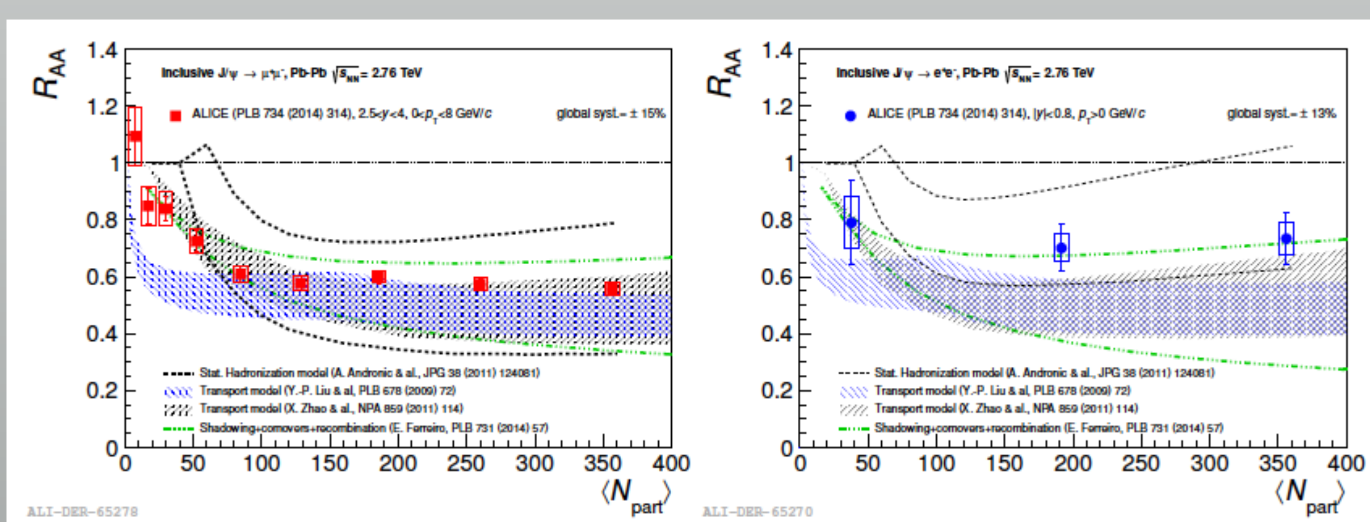
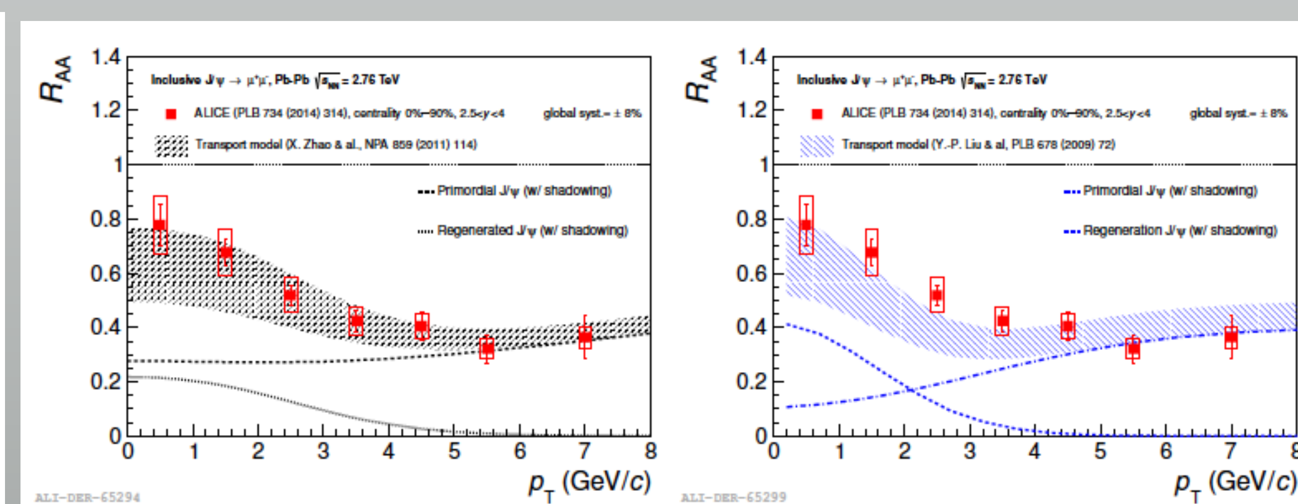




➜ CNM effects plus Debye screening or dissociation work well for AuAu/PbPb if regeneration is allowed: relative rate depends on the details of the model.





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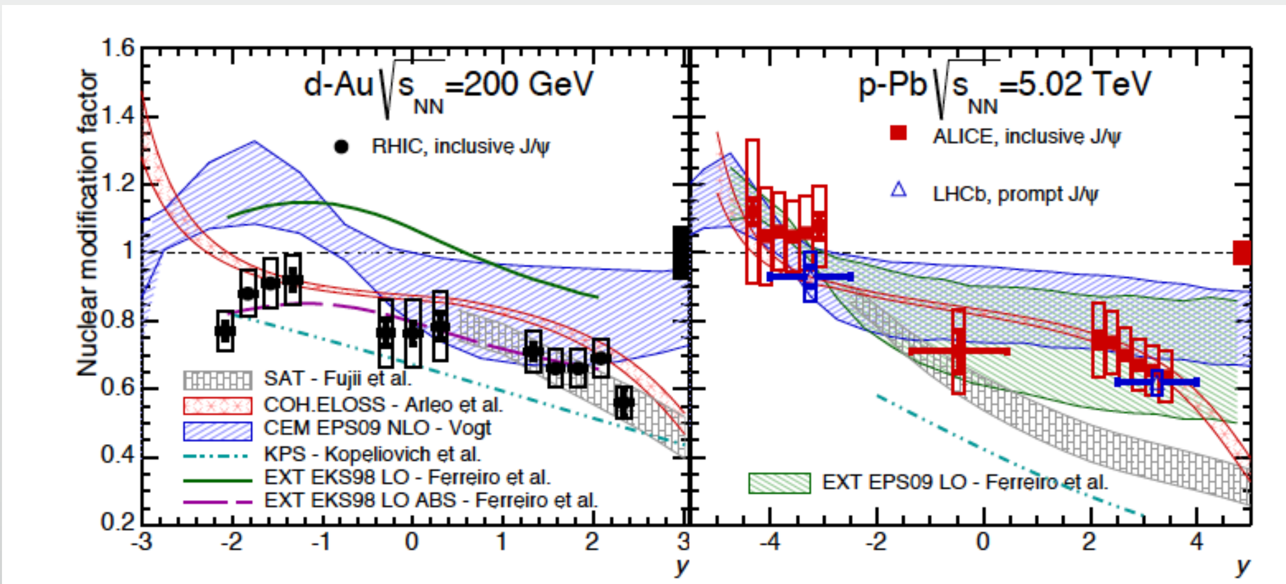

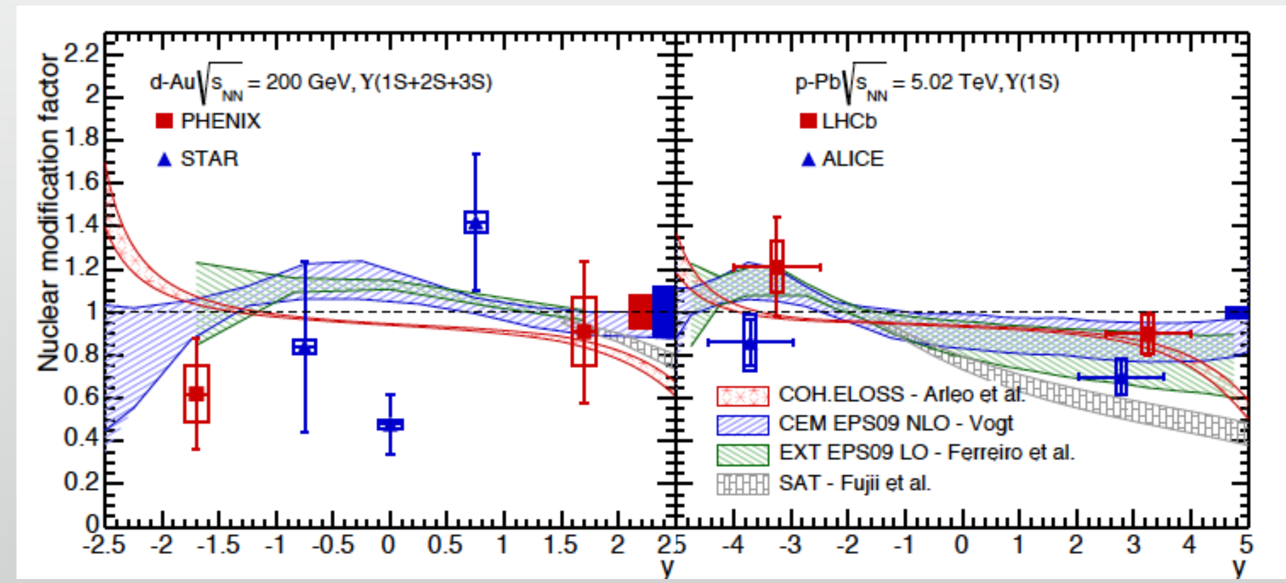

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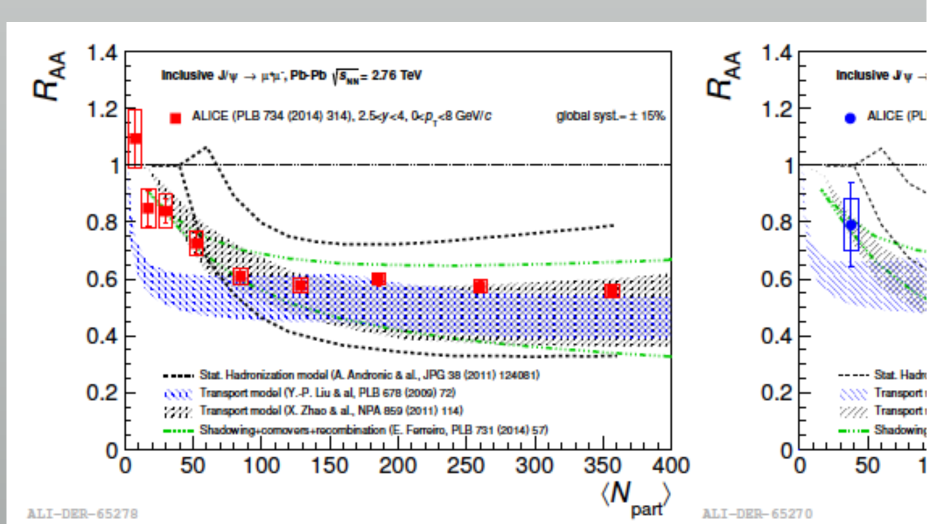
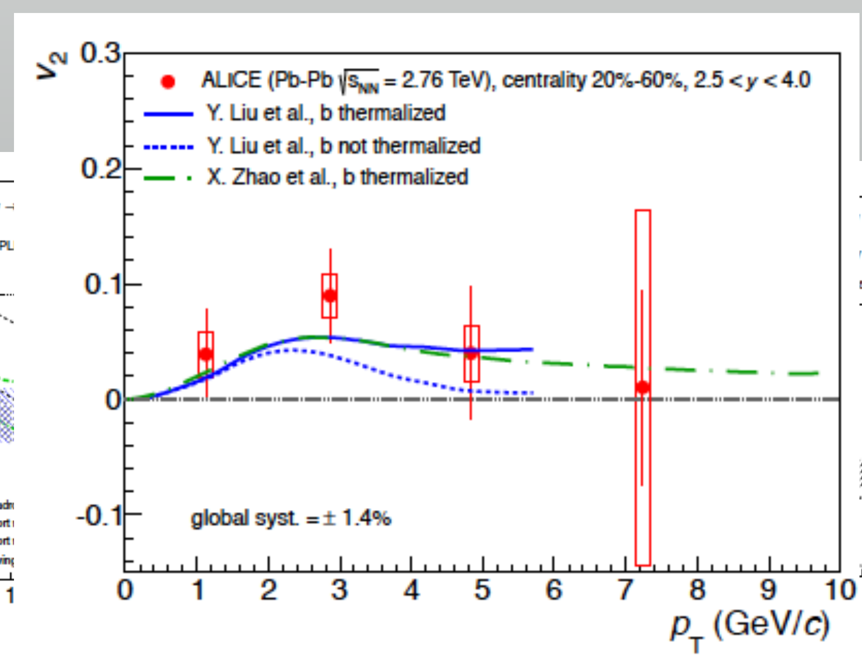
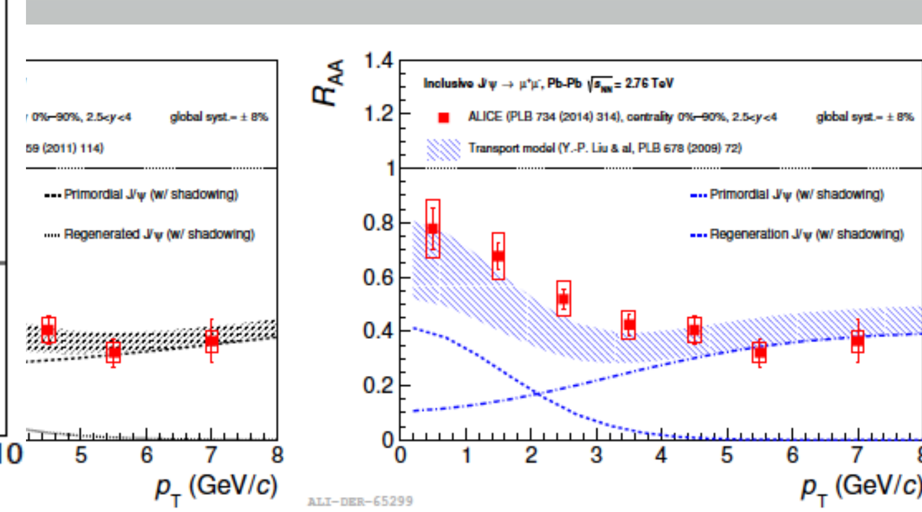
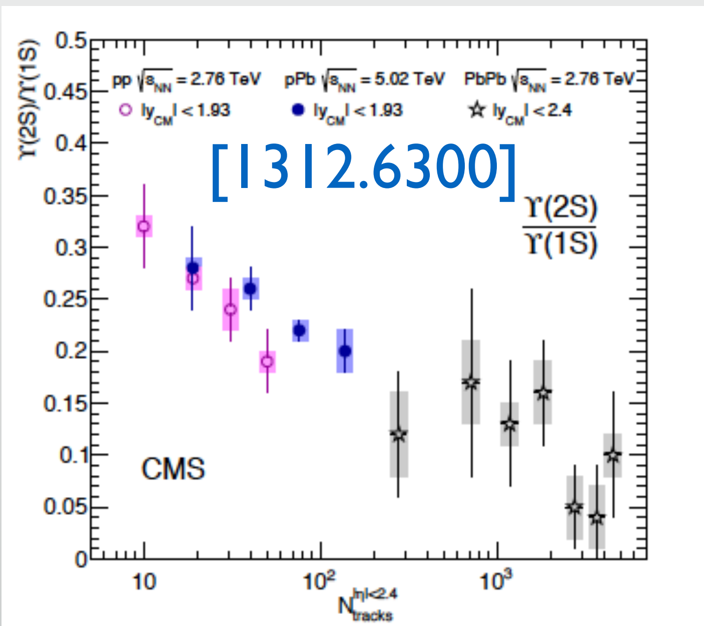




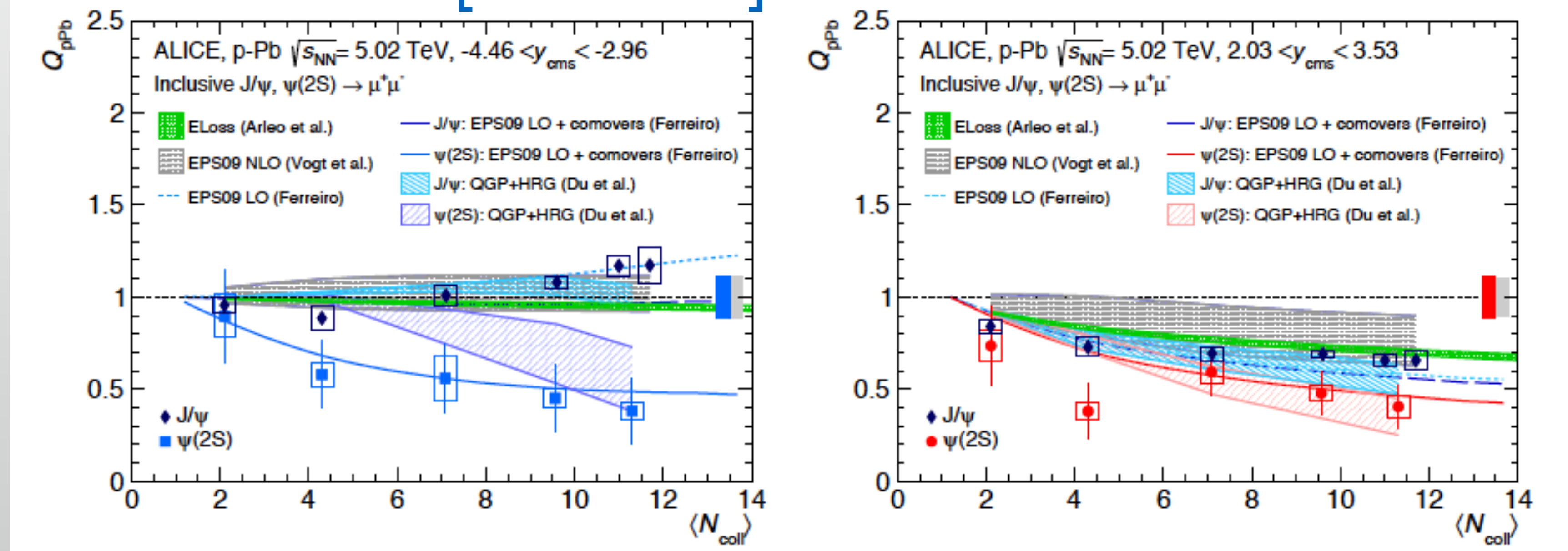


The ψ(2S) puzzle:

➜ ψ(2S) (and ϒ(2S), ϒ(3S)) more suppressed than J/ψ and ϒ(1S) in pA: challenge? for CNM in pA. Final state effects in pPb?



[1603.02816]



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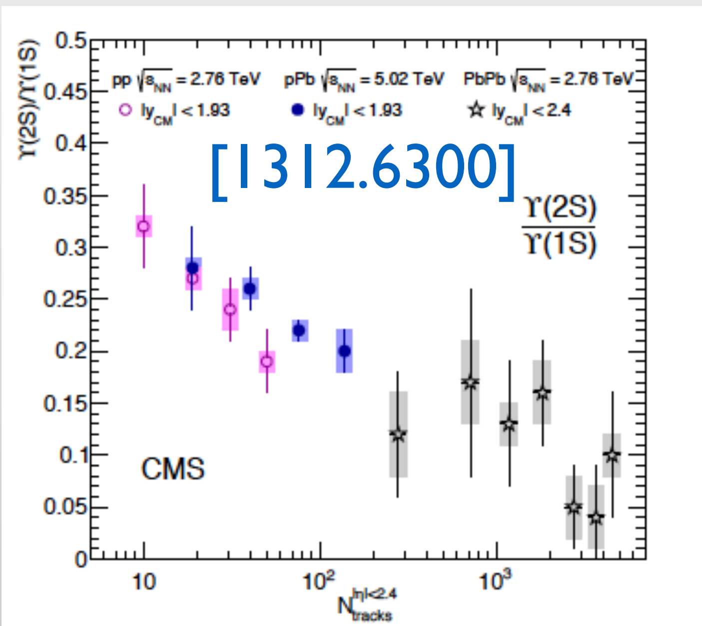
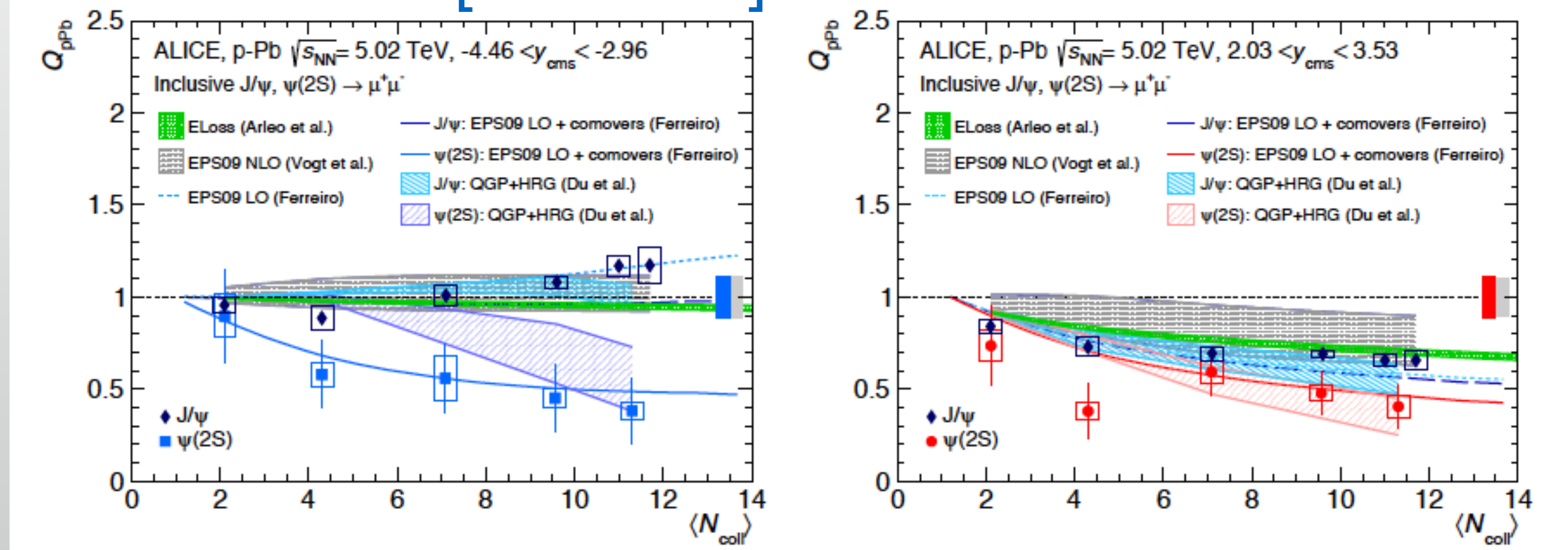
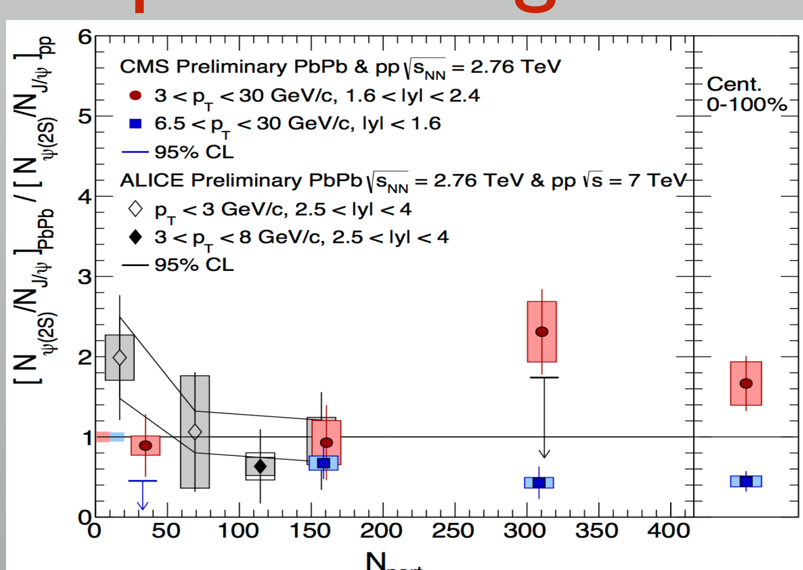
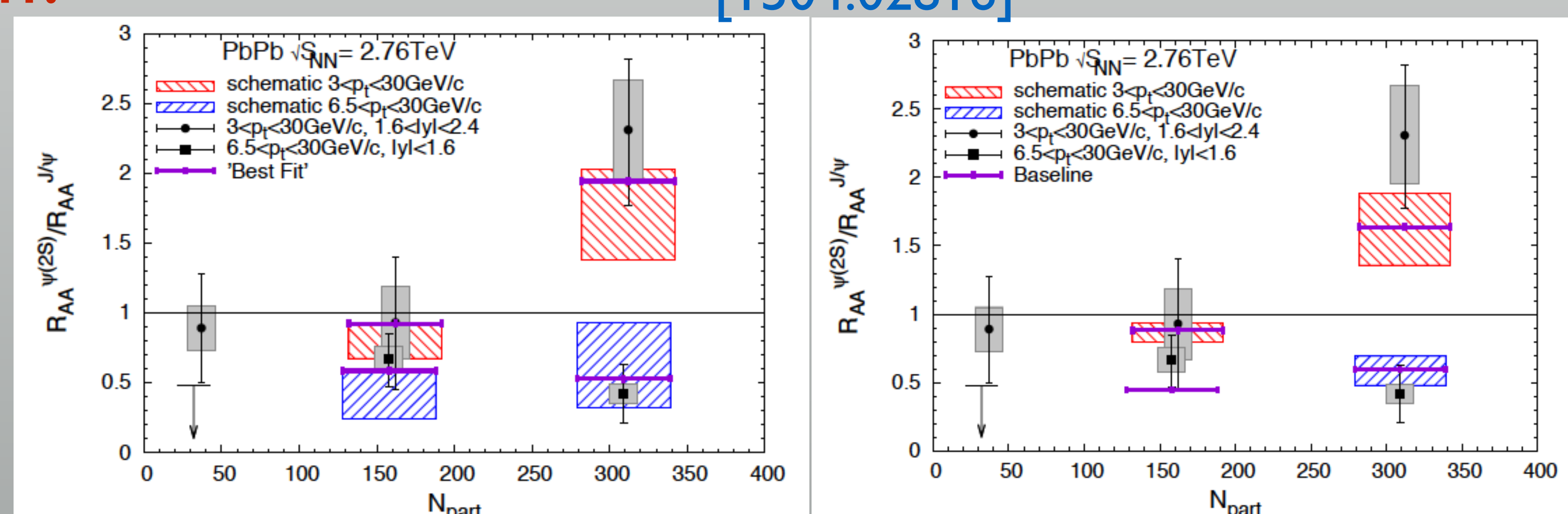




➜ ψ(2S) less relatively suppressed in PbPb: suppression + sequential regeneration?

[1504.02816]



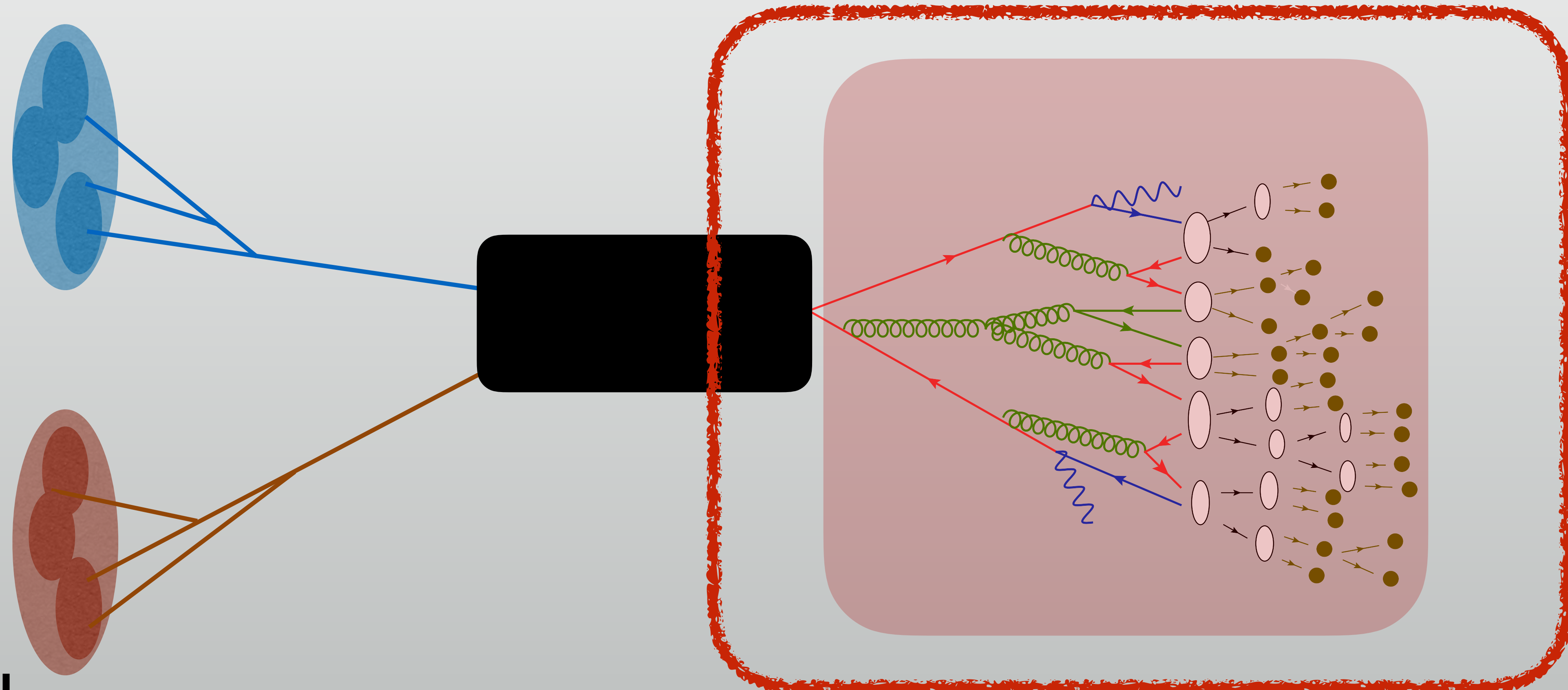


Contents:

1. Initial stage:
   ➜ nPDFs.
   ➜ CGC: evolution equations and particle production.

2. Jet quenching:
   ➜ Single inclusive particle production.
   ➜ Jets.

[Plenary by Paquet]



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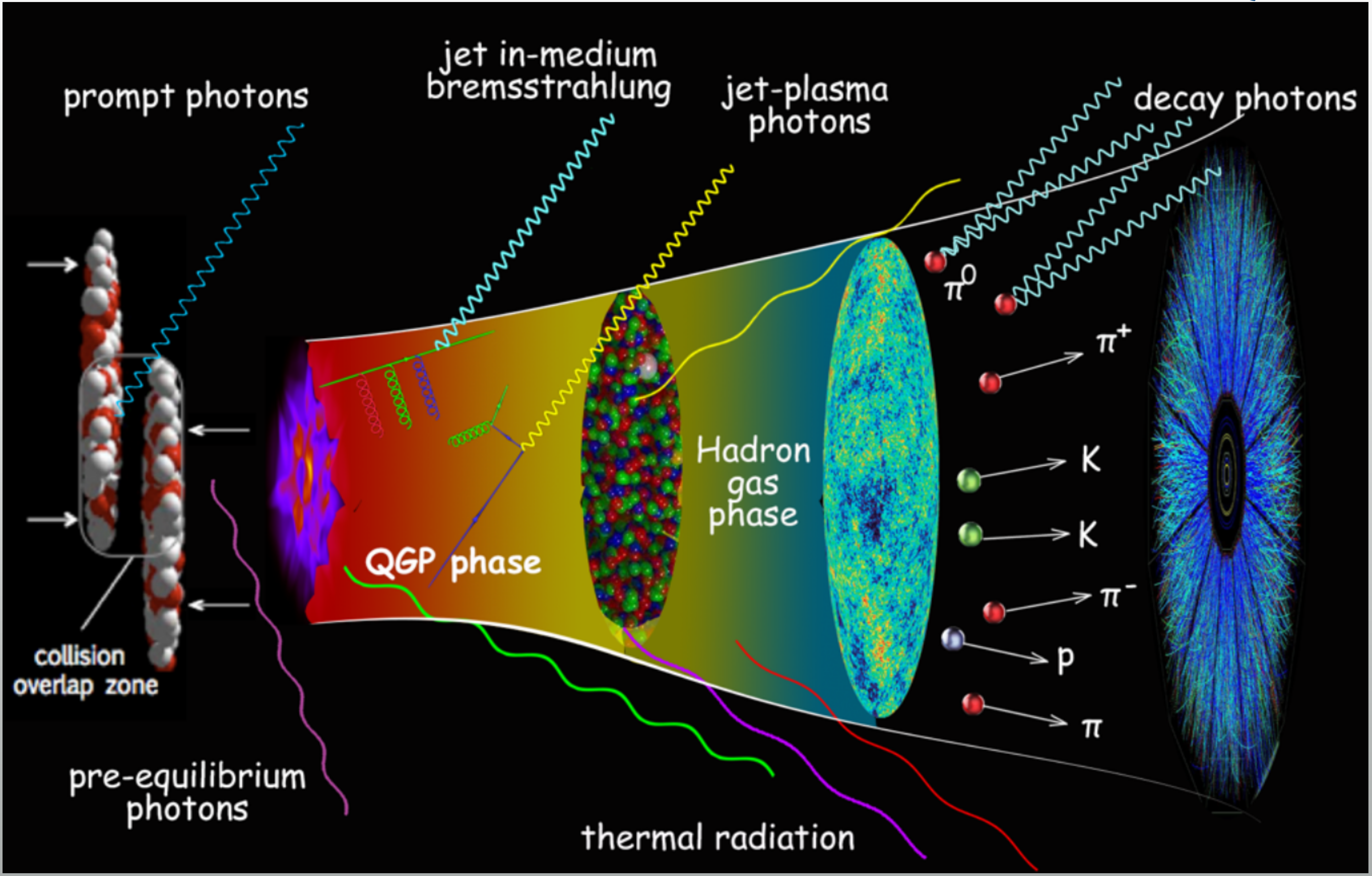
The frame:

Picture from Shen at QM2015



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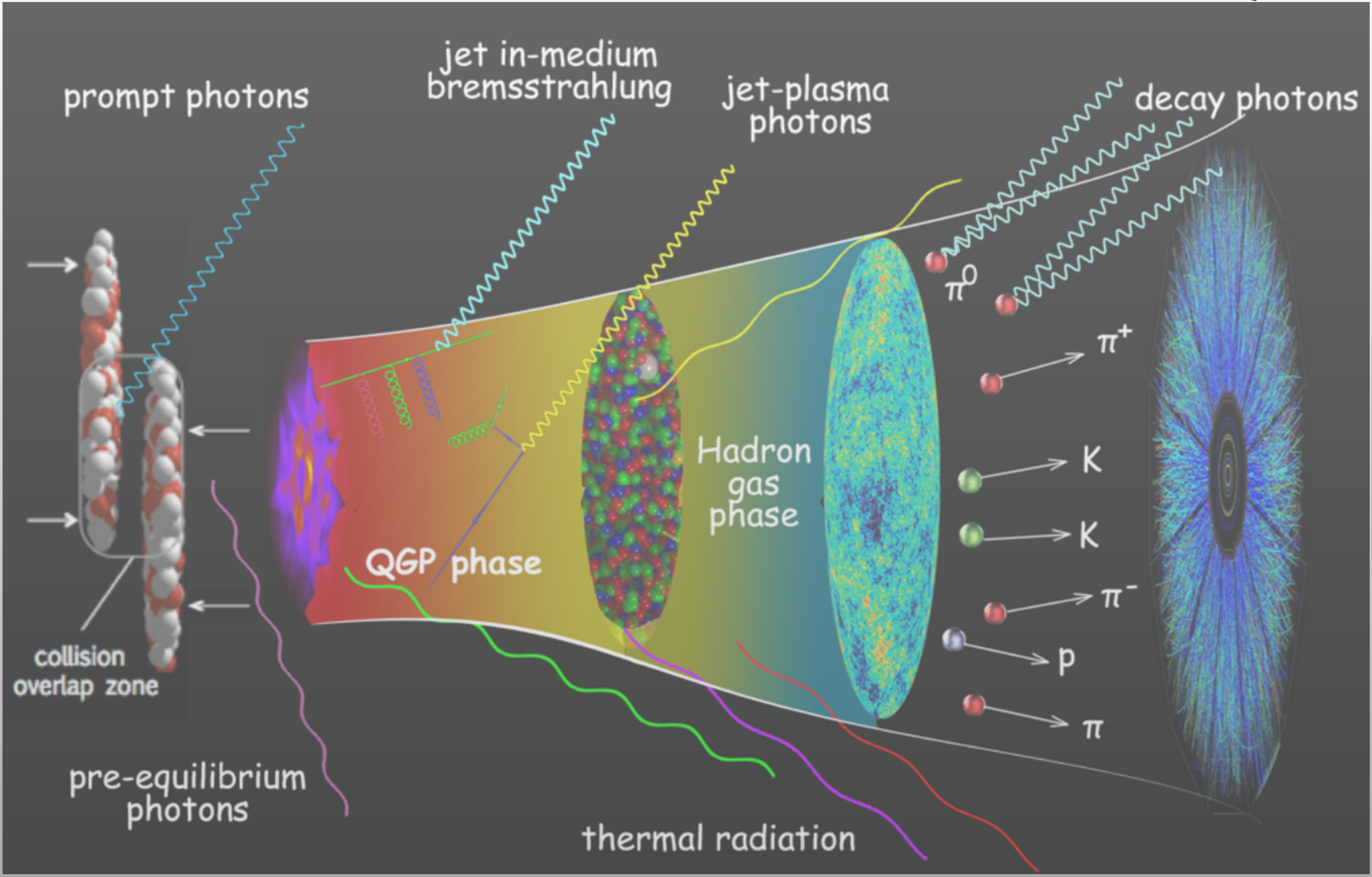

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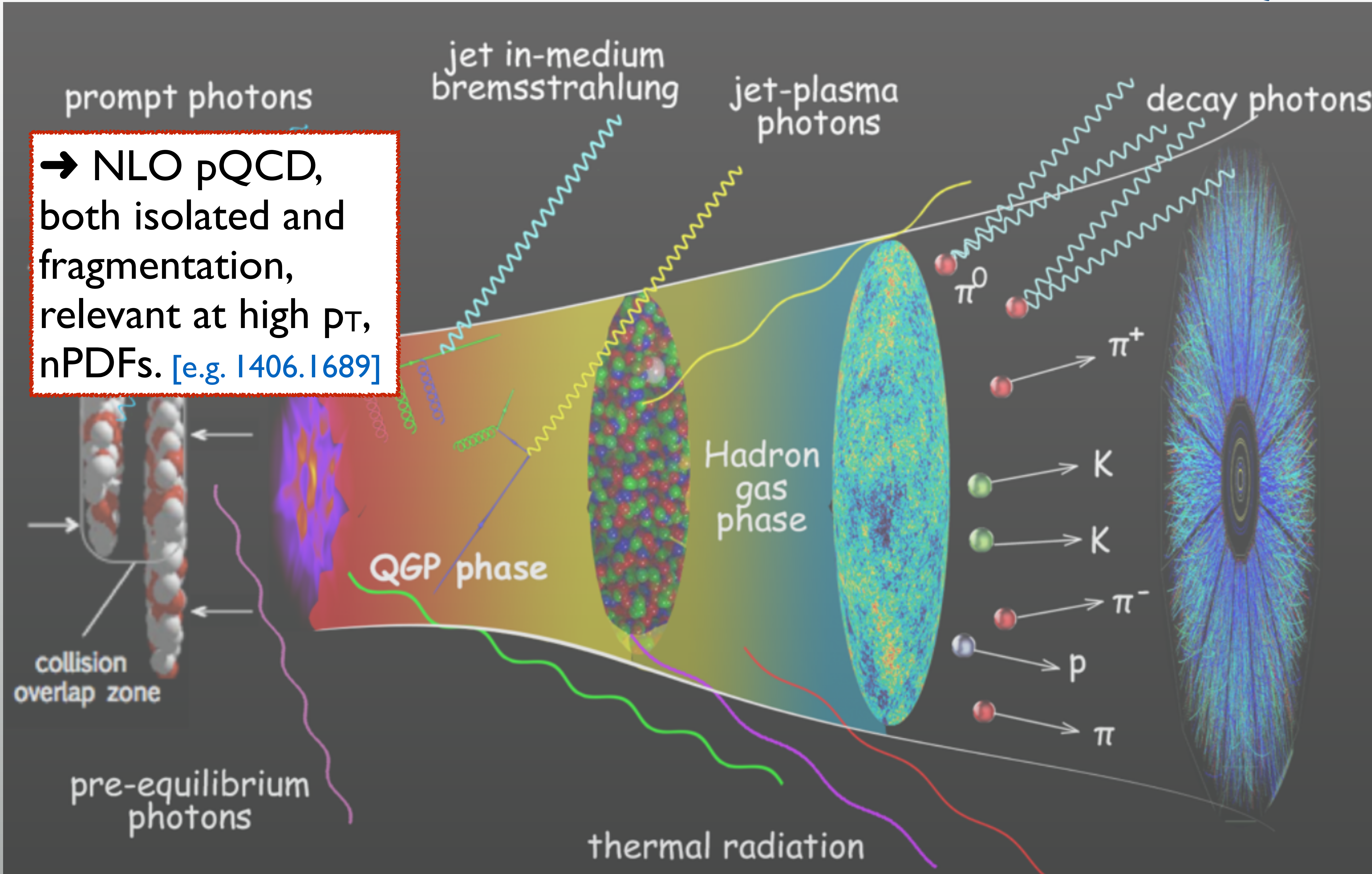

→ NLO pQCD, both isolated and fragmentation, relevant at high p_T, nPDFs. [e.g. 1406.1689]

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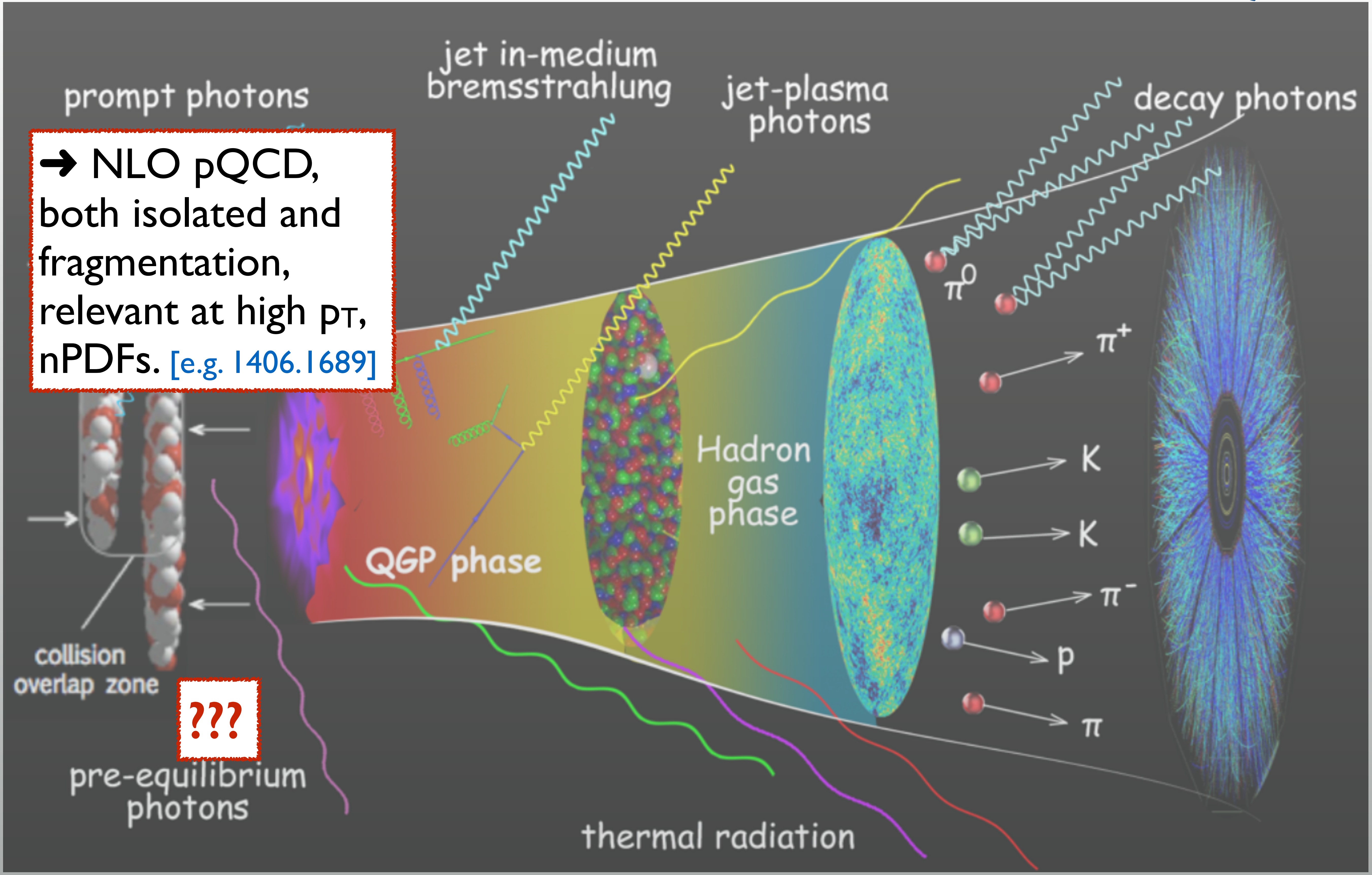

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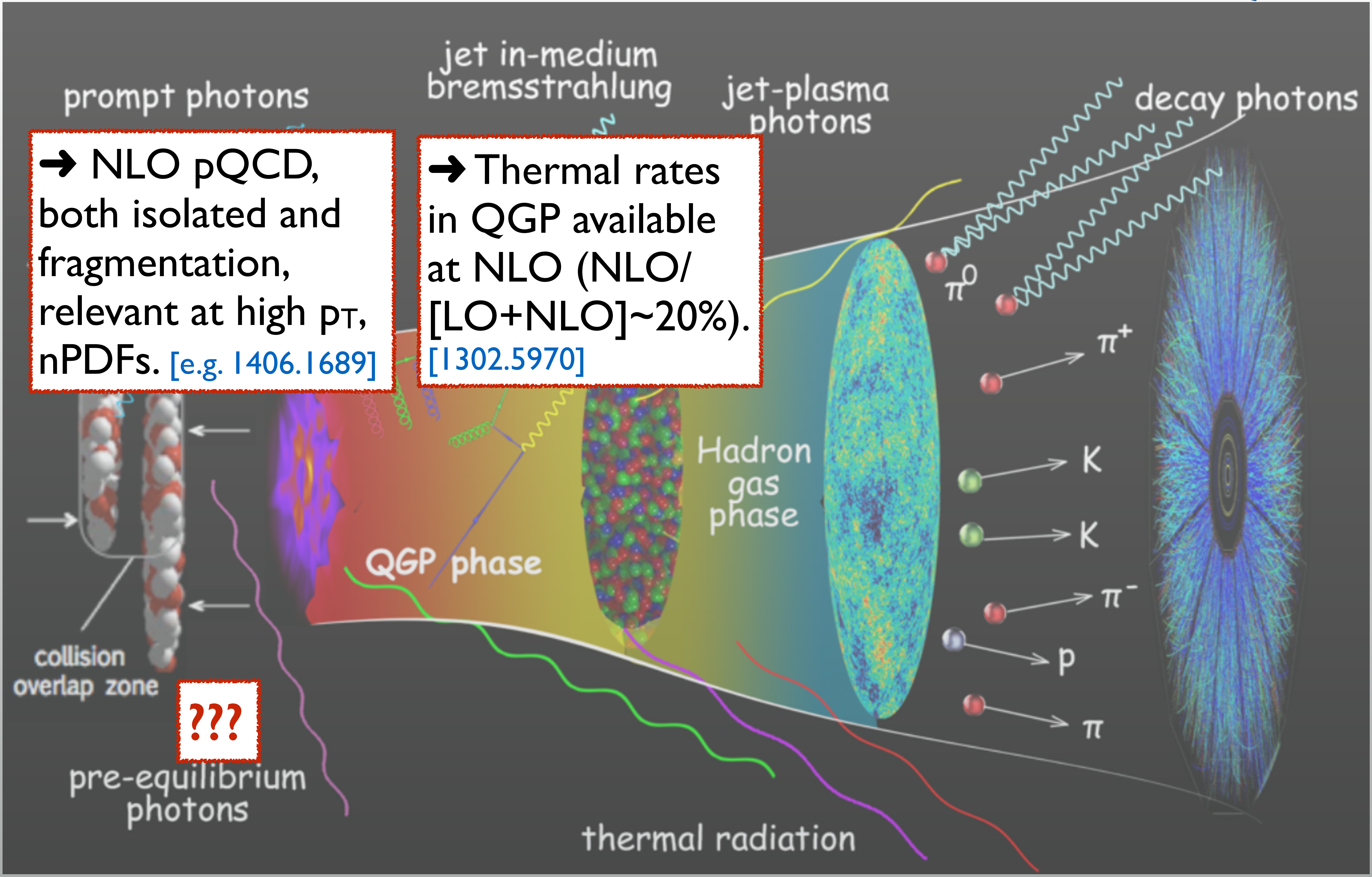

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???

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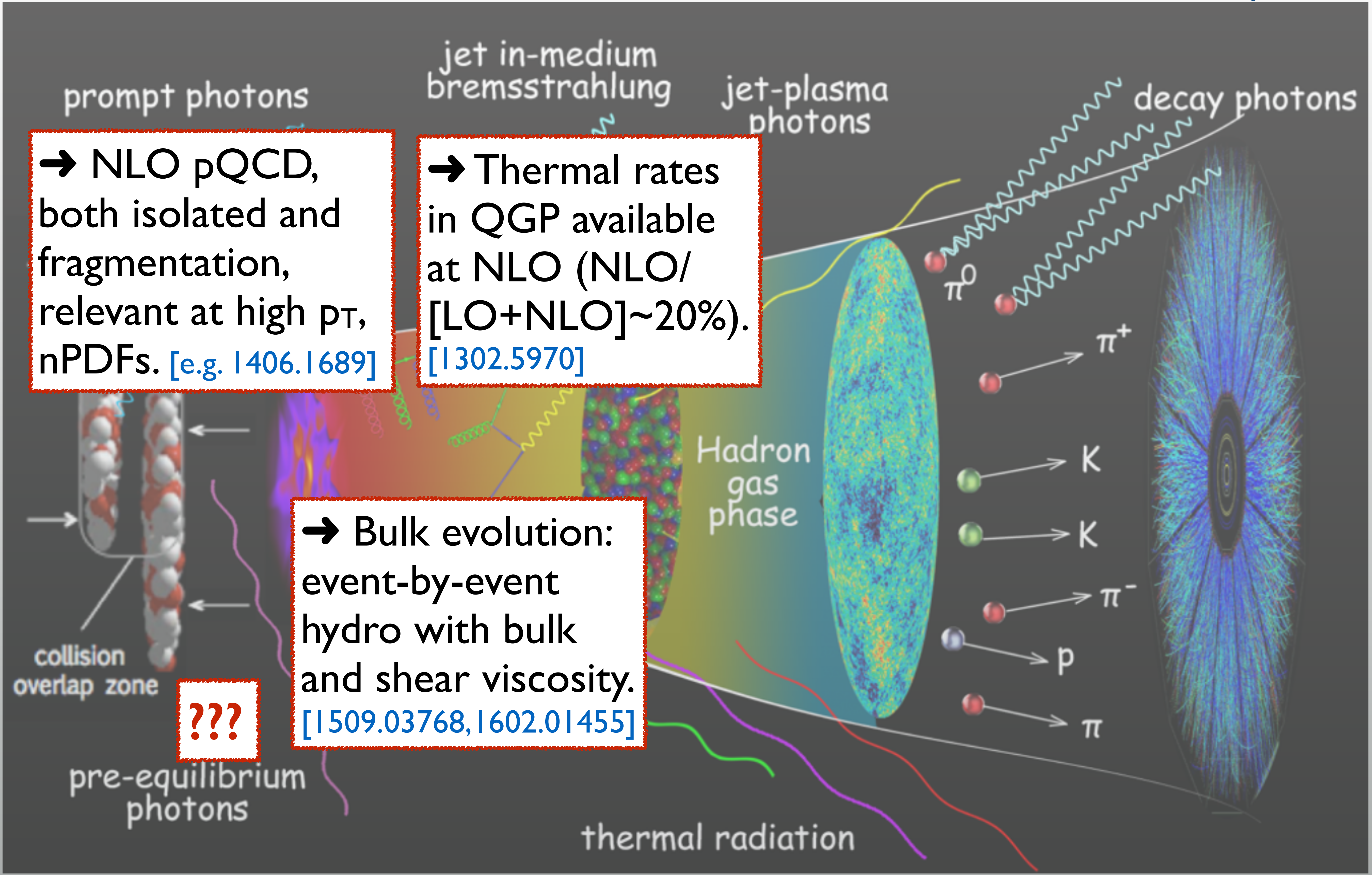

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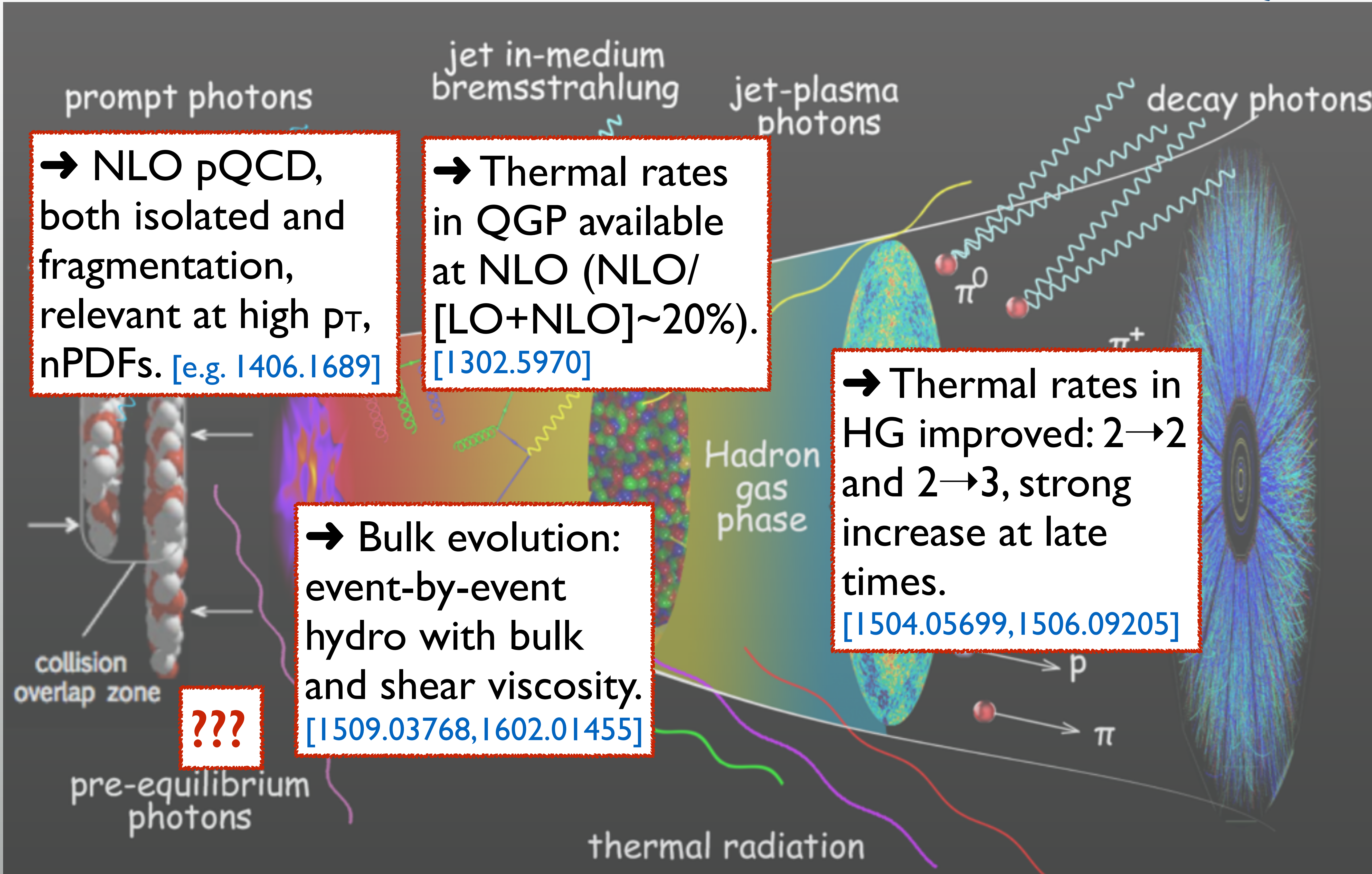

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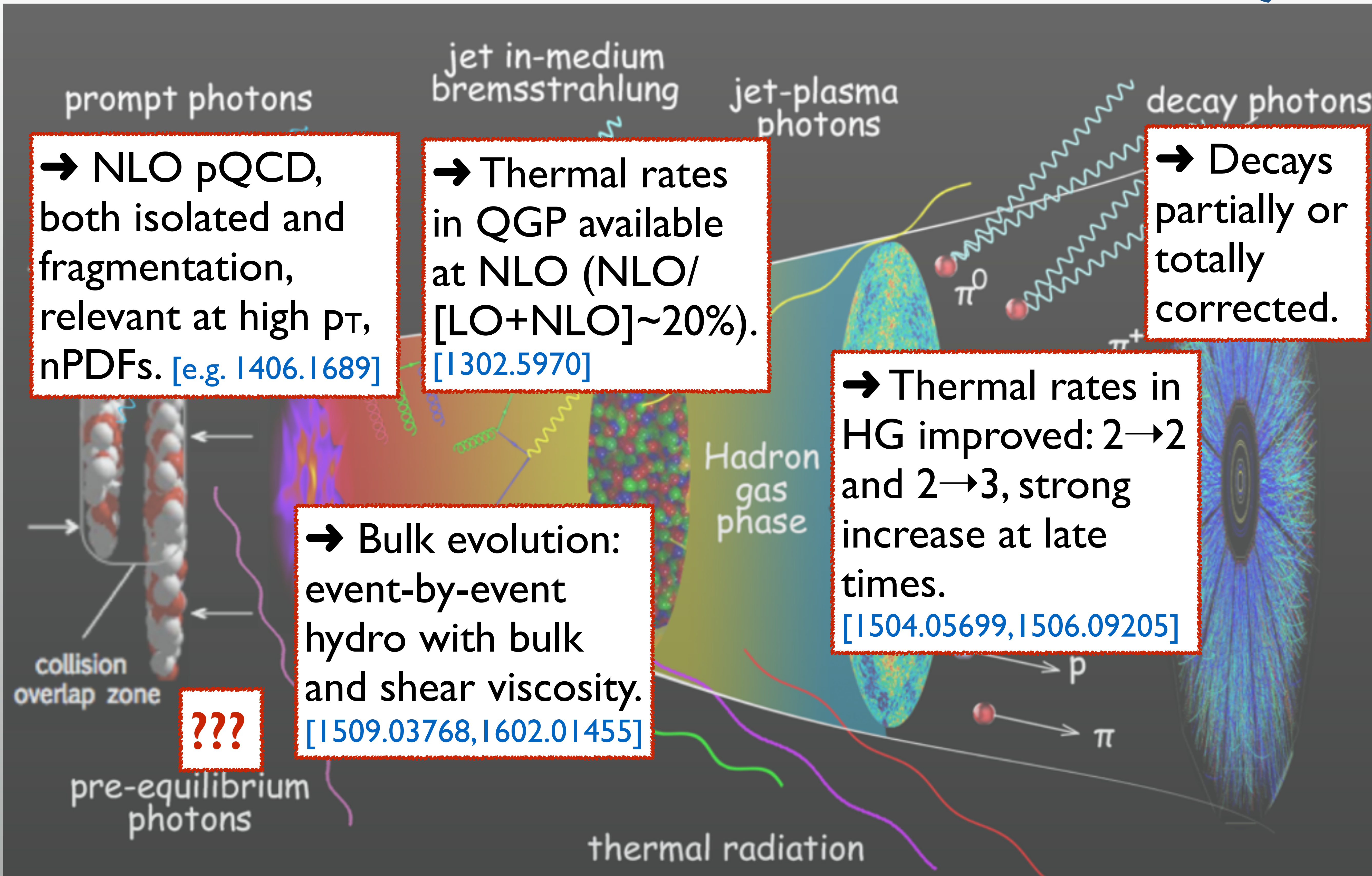

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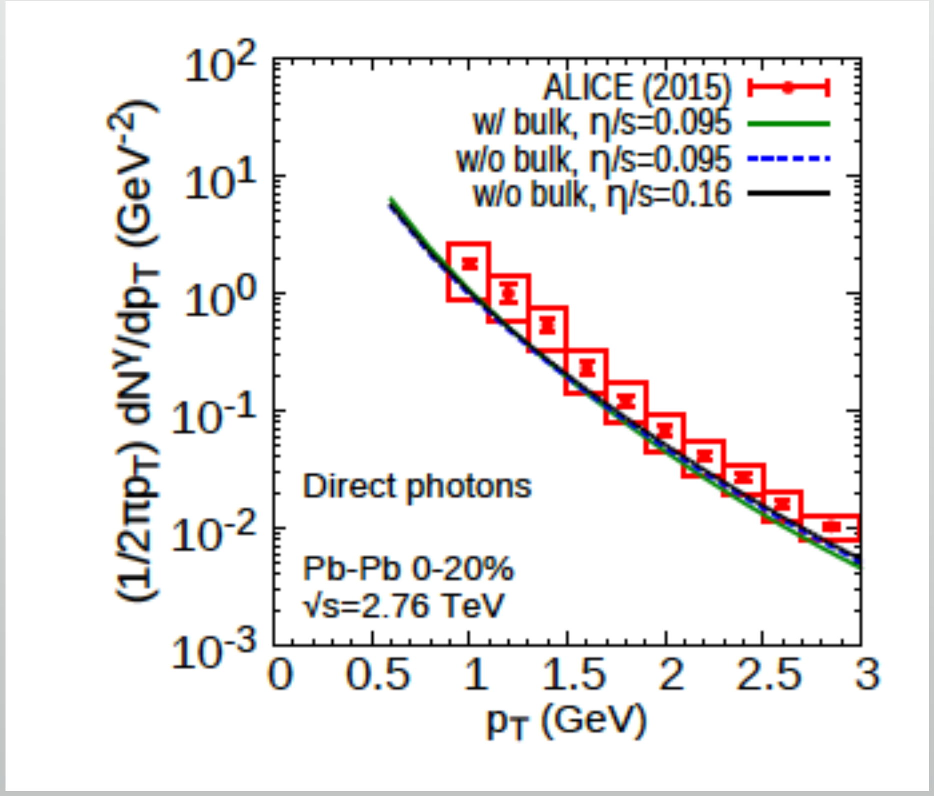

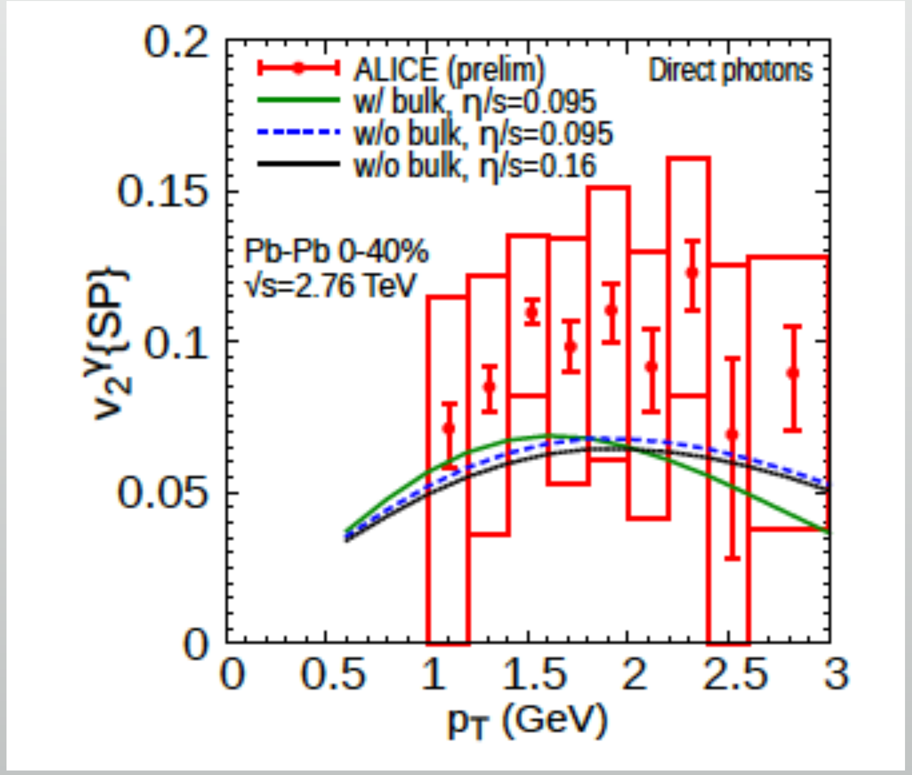

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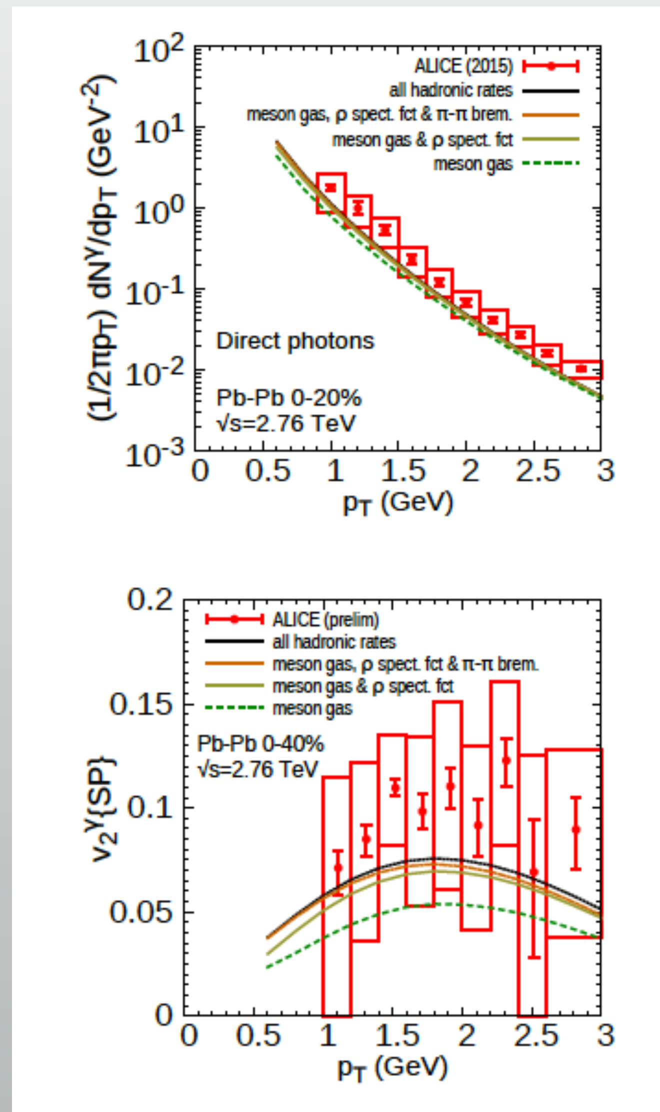

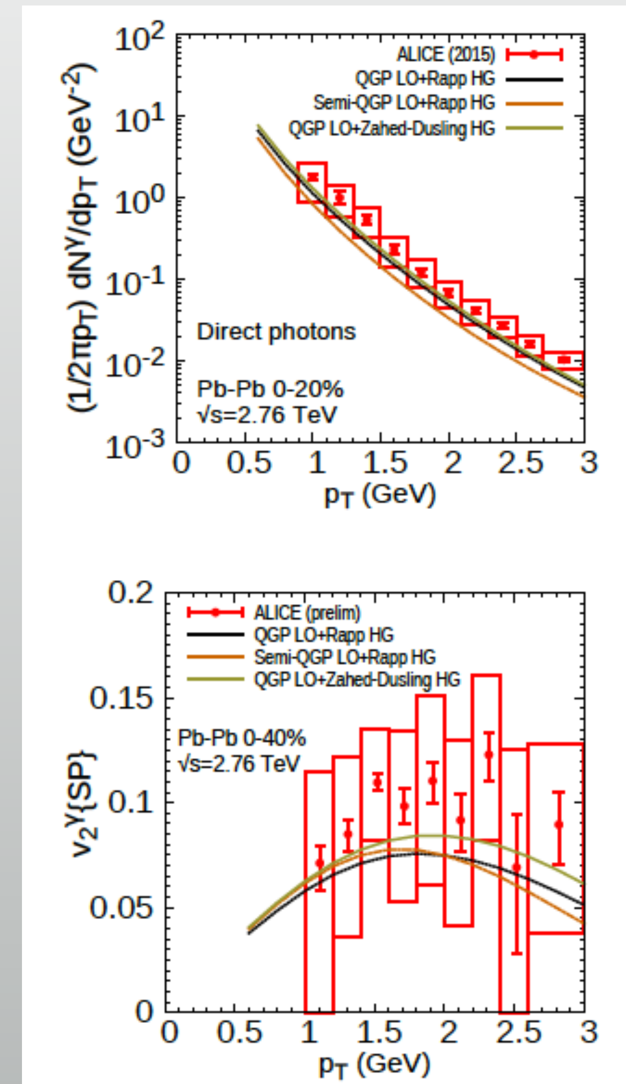

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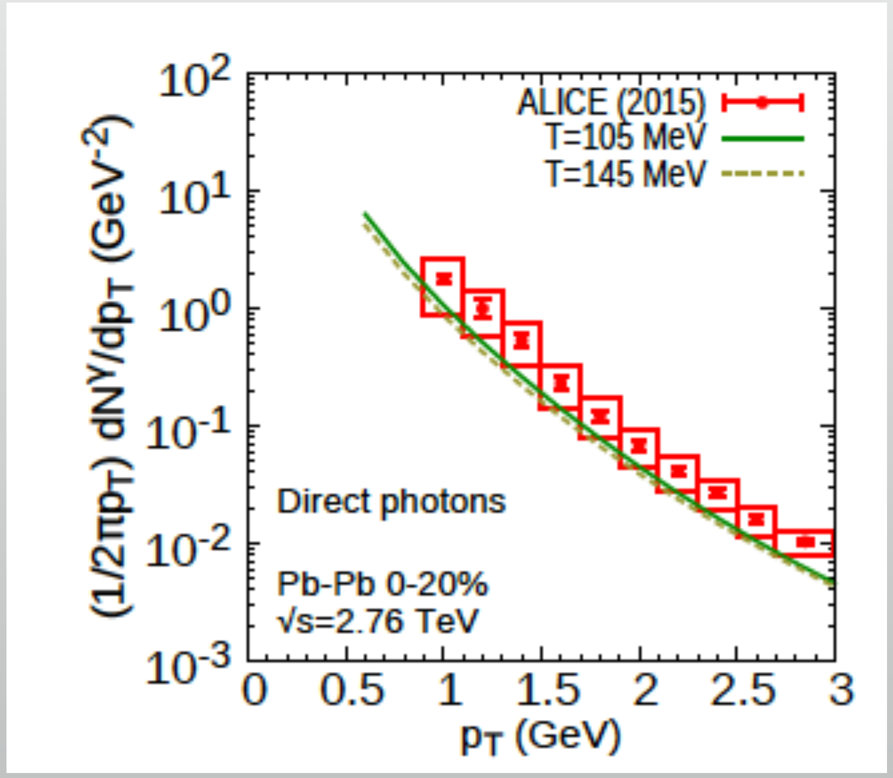

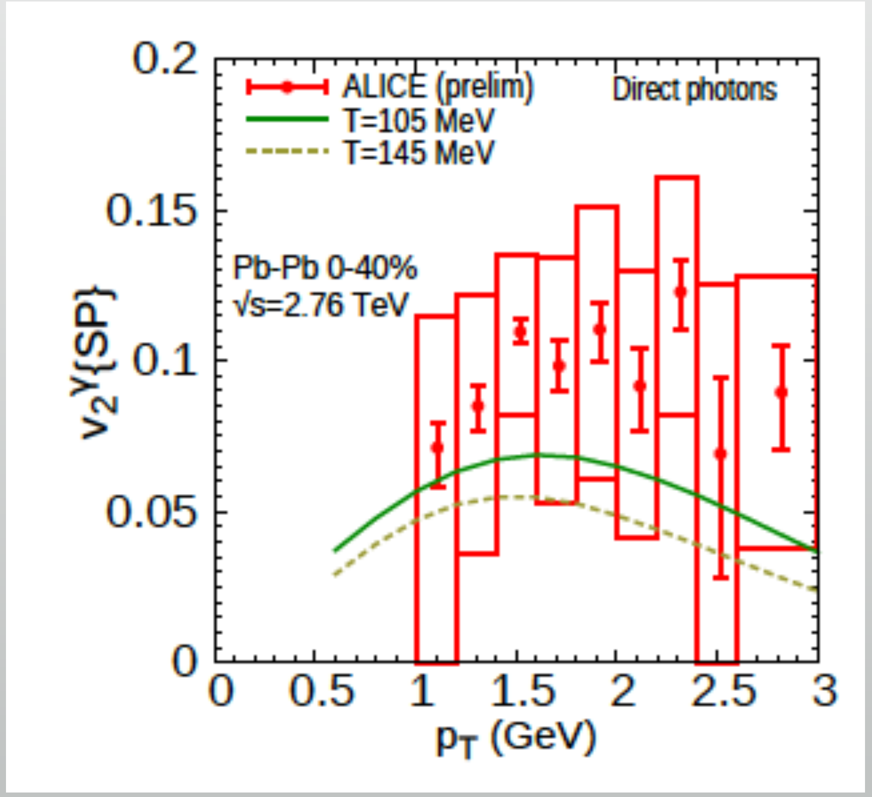

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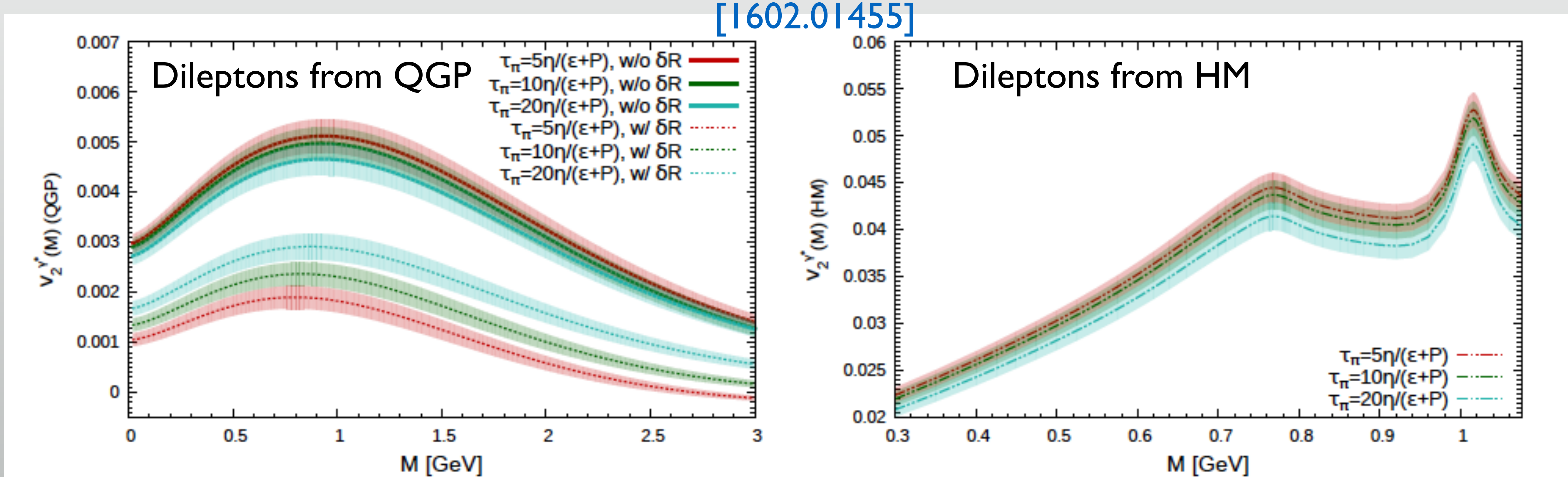

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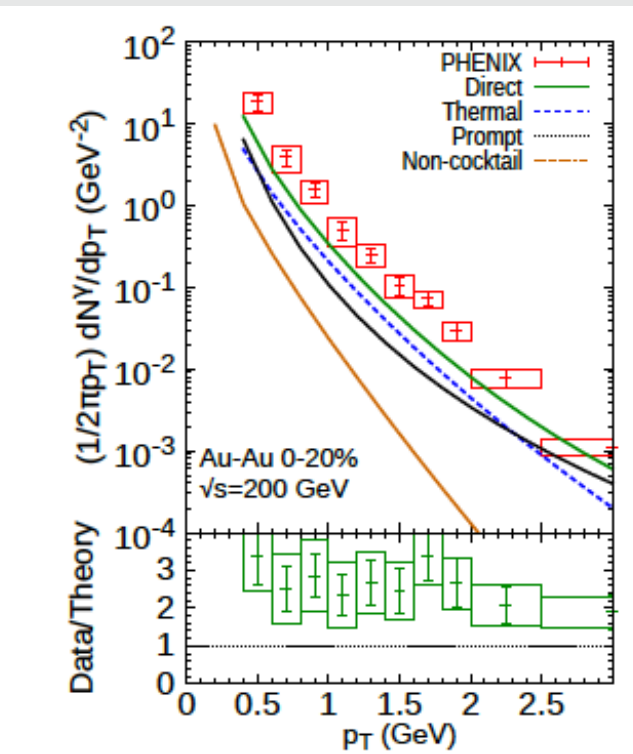

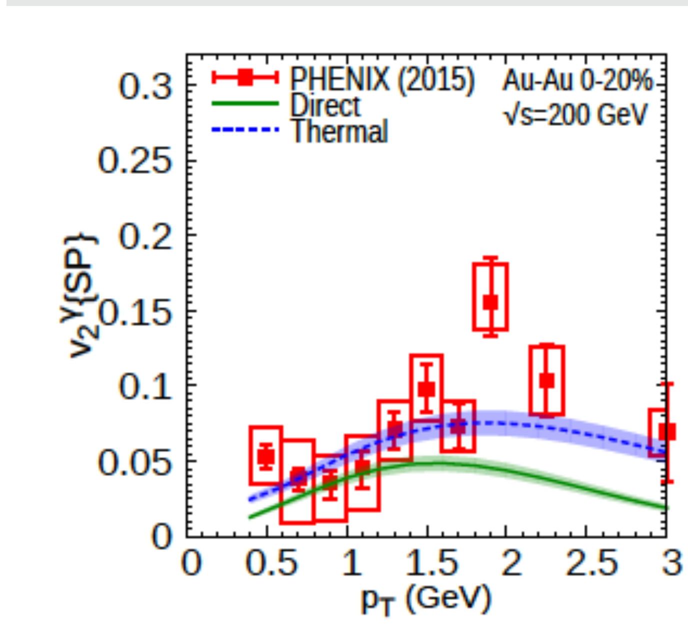

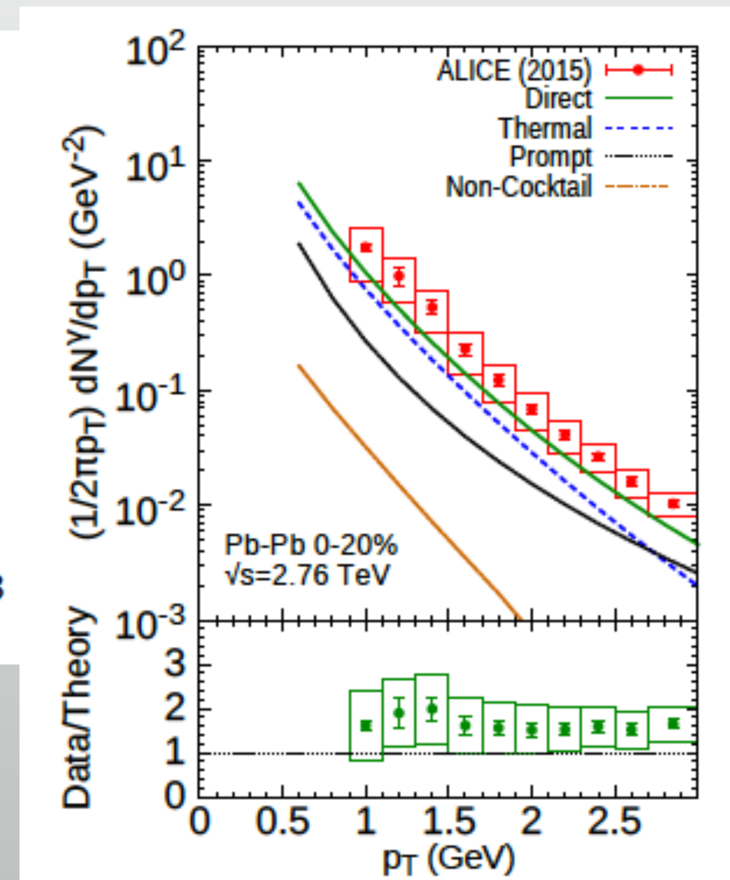

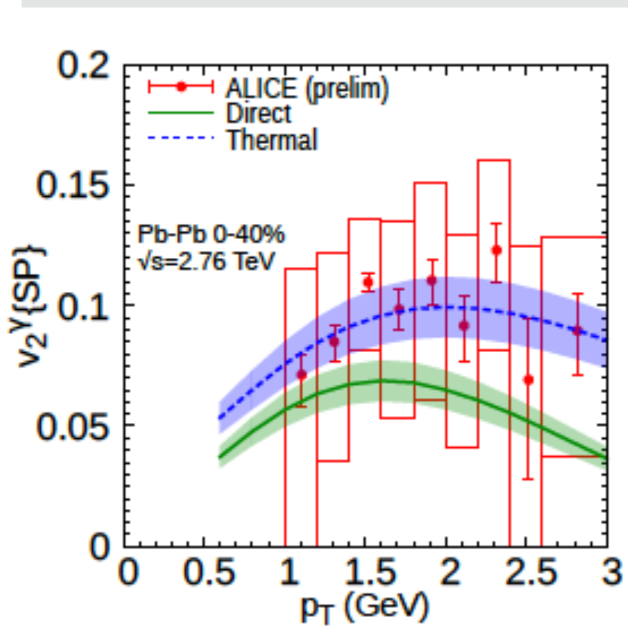

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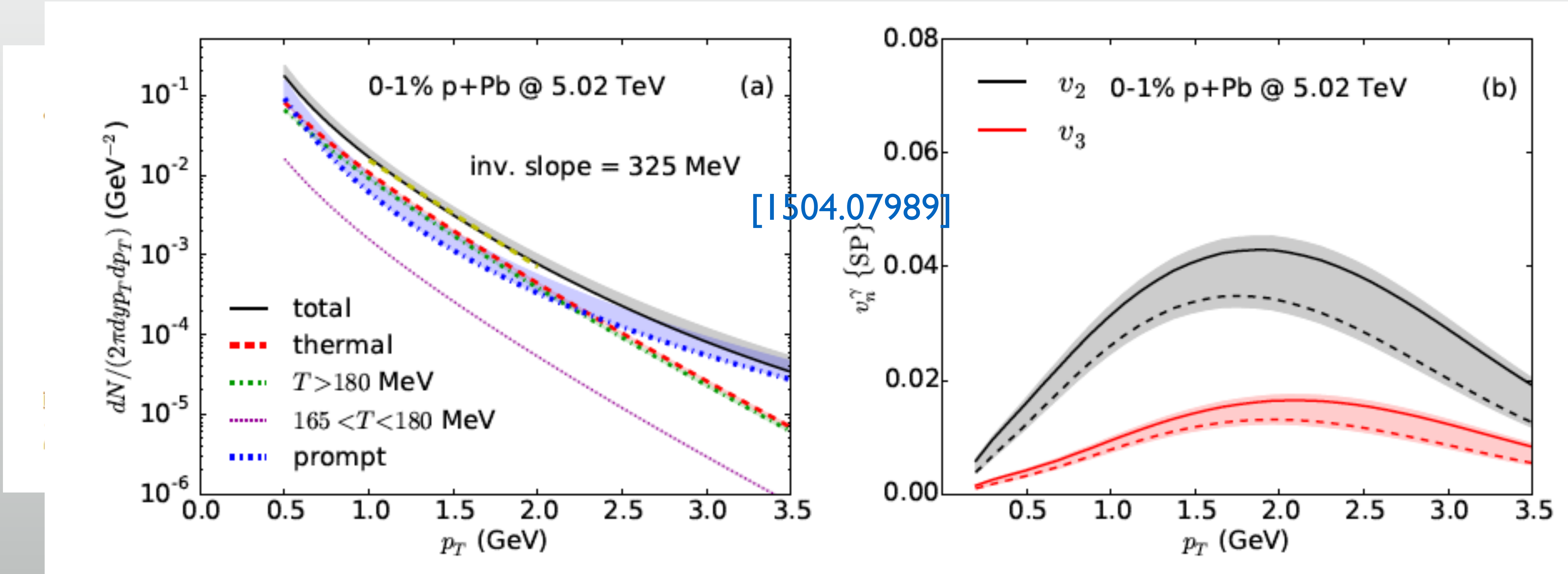

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Many thanks to:

➜ *Jorge Casalderrey, Elena Ferreiro, Guilherme Milhano and Carlos Salgado for having a look to this.*

➜ *The **organisers** for their invitation to provide this talk.*

➜ *You all for your attention.*

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