Jet Production and Fragmentation Functions at Colliders

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Outline (main selected topics):

- Jet Production
- Jet Fragmentation Functions (FF)
- Summary / Outlook

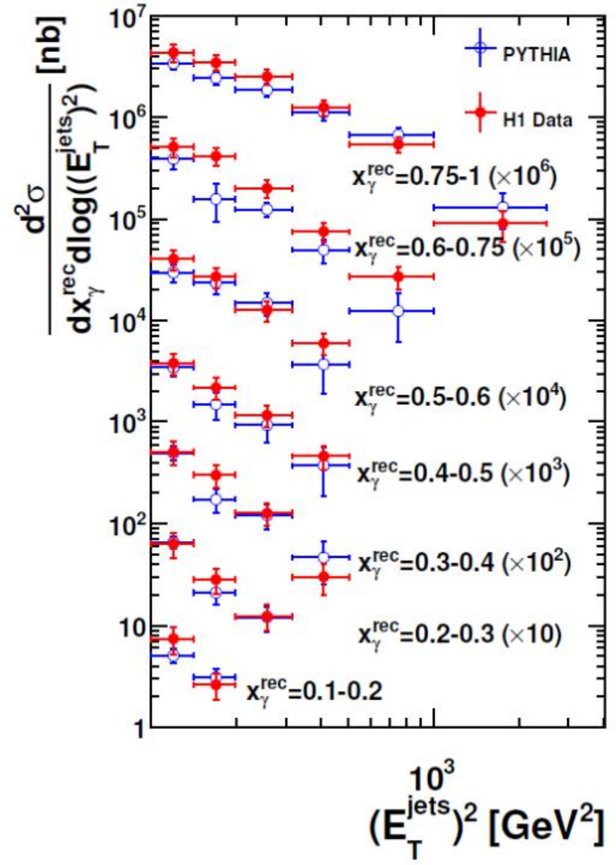
Alexandre SHABETAI

ICHEP2020 - July 2020

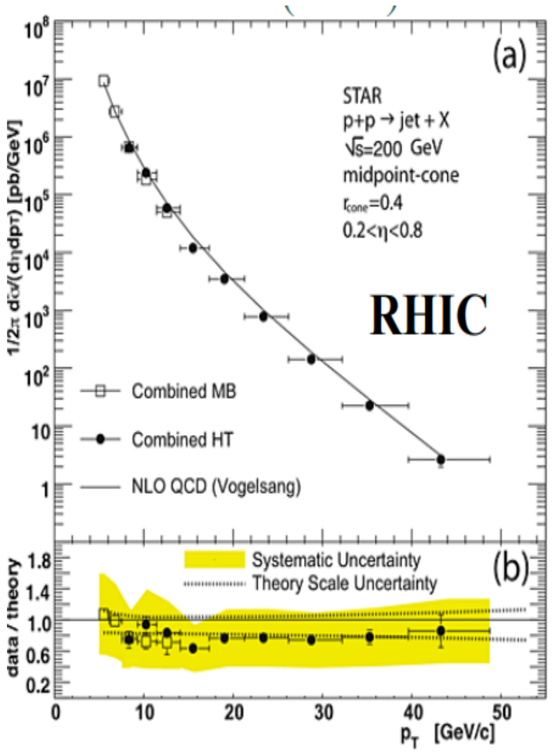
Jet Production

Jet Production: x section

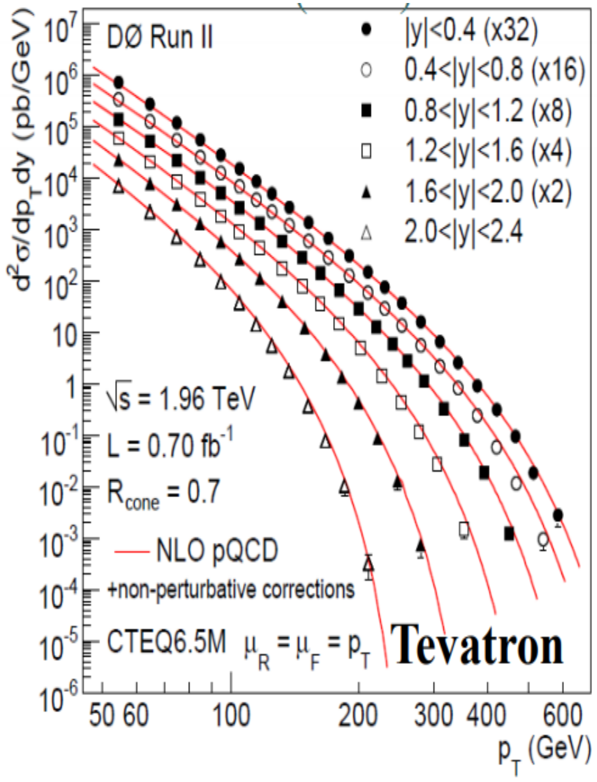
PRD 96 074035 (2017)



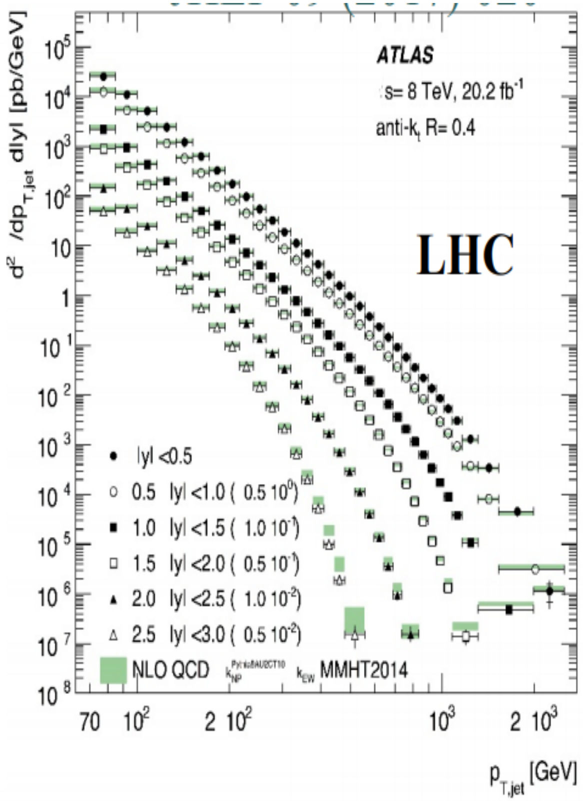
PRL97(2006)252001



PRL101(2008)062001



JHEP09 (2017) 020

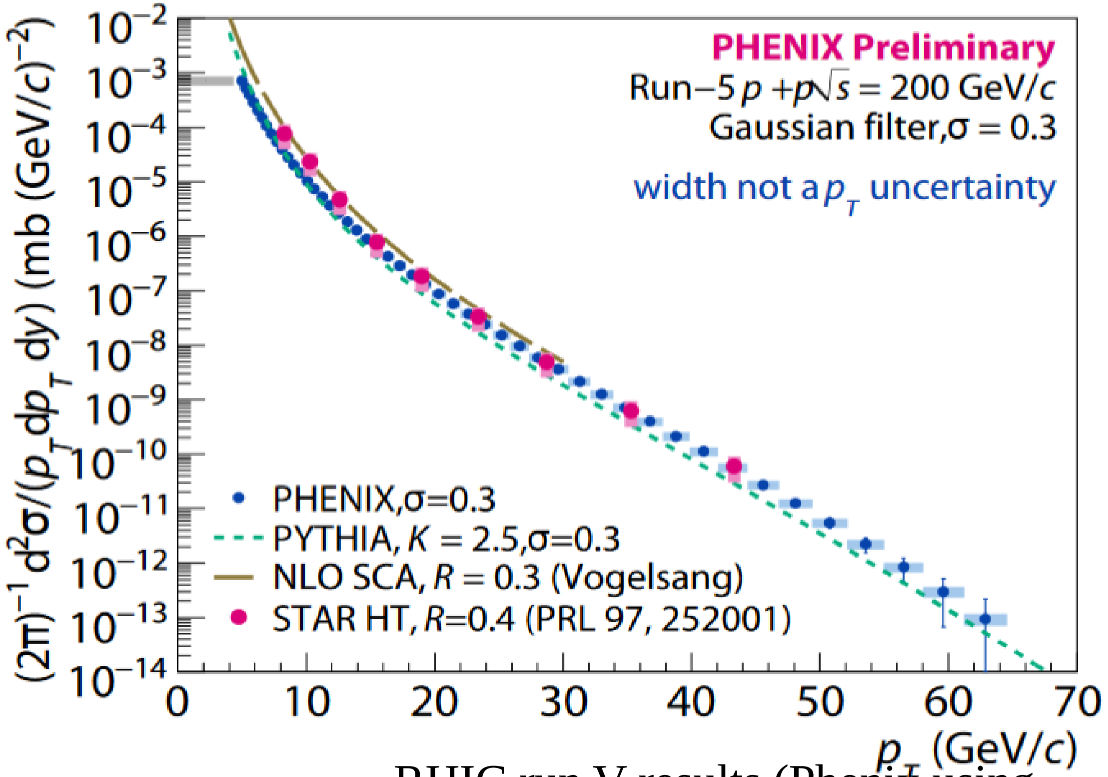


Jet cross section form HERA to RHIC to LHC (note the différence in pT reach)

Steeply falling spectrum over several orders of magnitude (compared to pQCD in e-p and pp data)

RHIC (pp vs CuCu Phenix + Star Jet spetra)

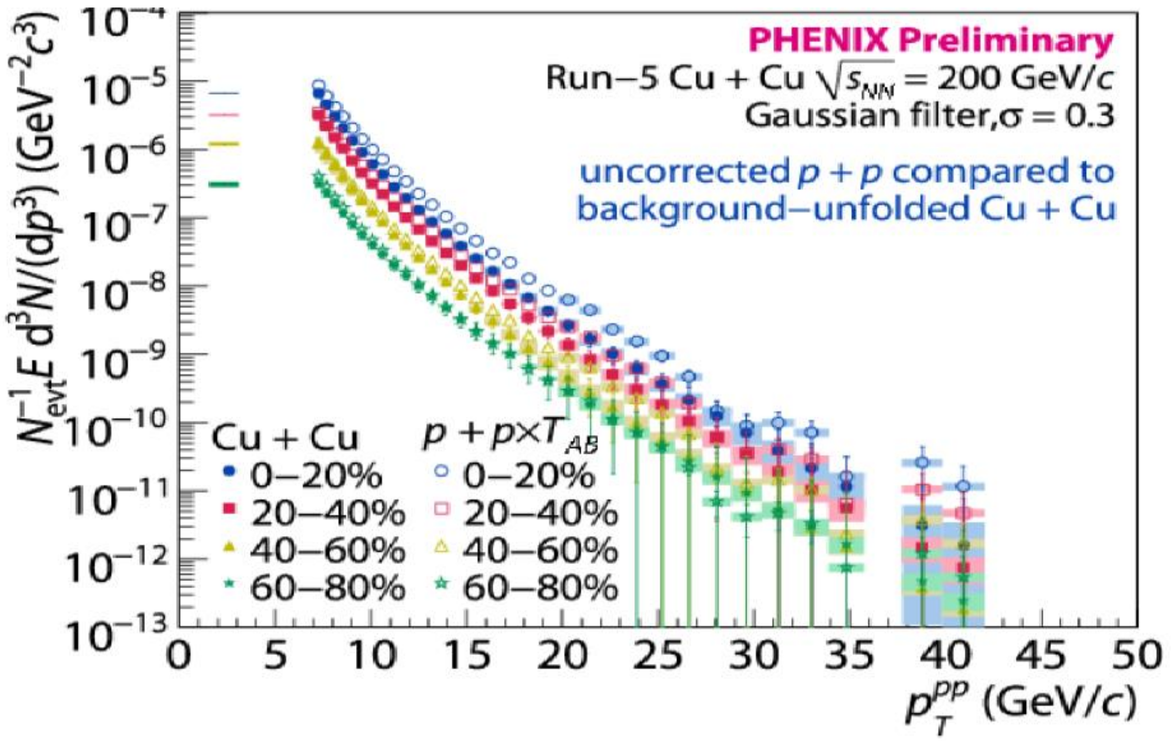
Y.S Lai RHIC AGS User Meeting



RHIC run V results (Phenix using the Gaussian Filter)

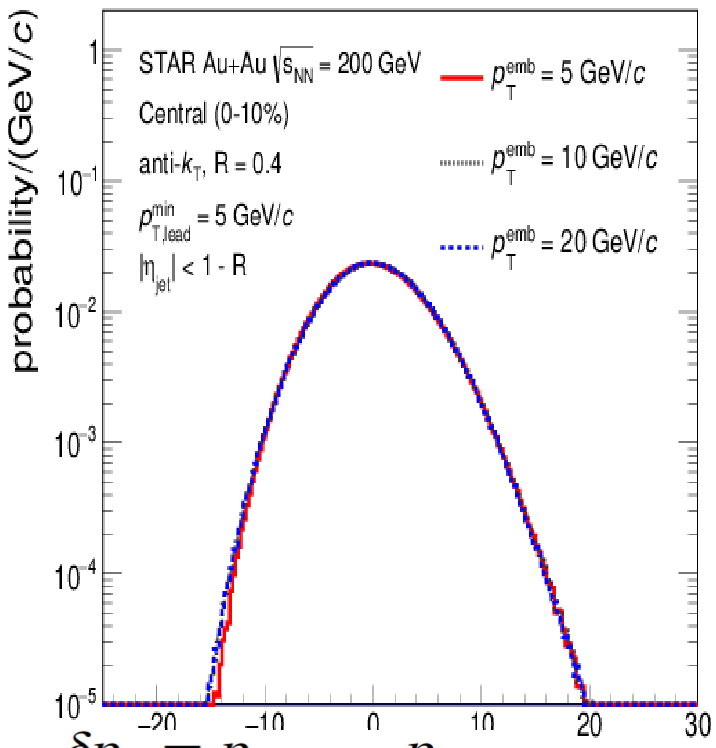
Similar kinematic reach as the one we can expect @ EIC

Cu+Cu data compared to scalled pp



STAR: Au+Au Jet Spectra @ 200 GeV

arXiv:2006.00582

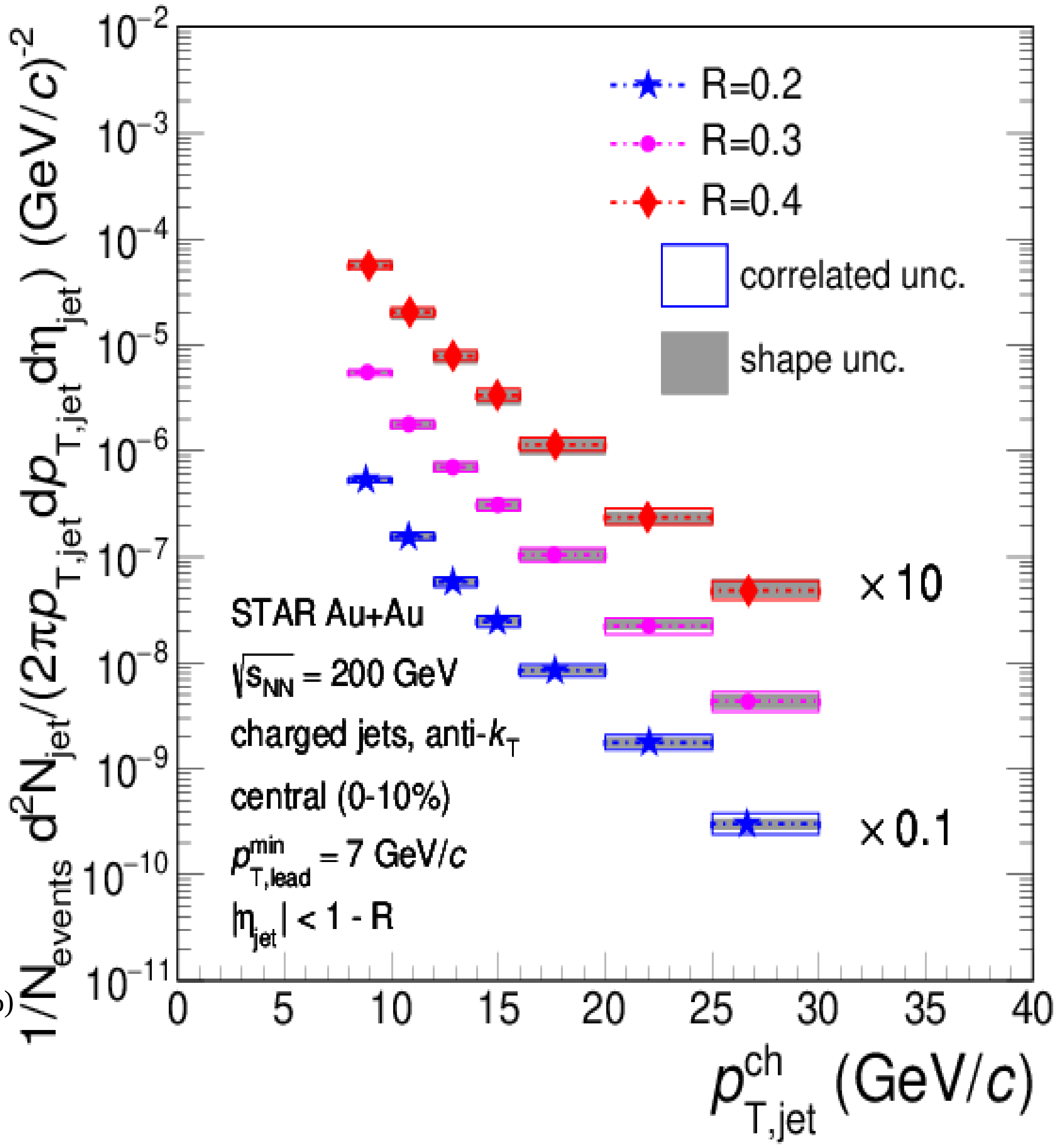


$$\delta p_T = p_{T,rec} - p_{T,true}$$

Background fluctuations and
Fully unfolded jet spetra

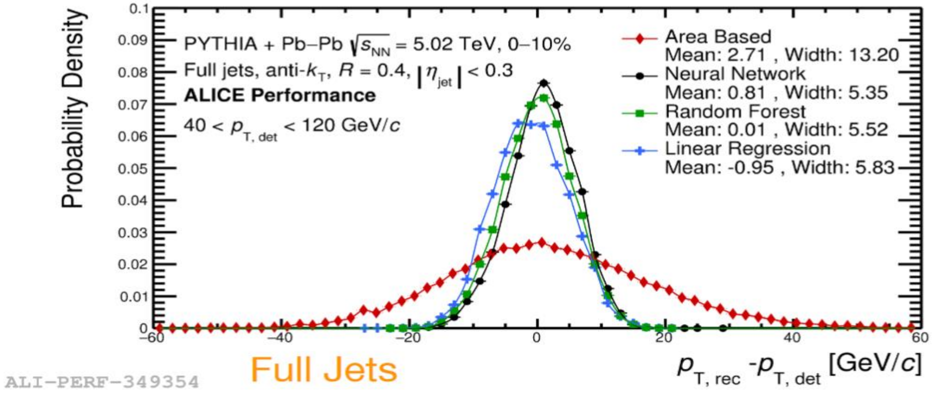
$$p_{T,lead}^{min} = 5\ \mathrm{GeV}/c$$

Bias needed for unfolding (introduces
NP effect and quite small fragmentation bias ~<3%)

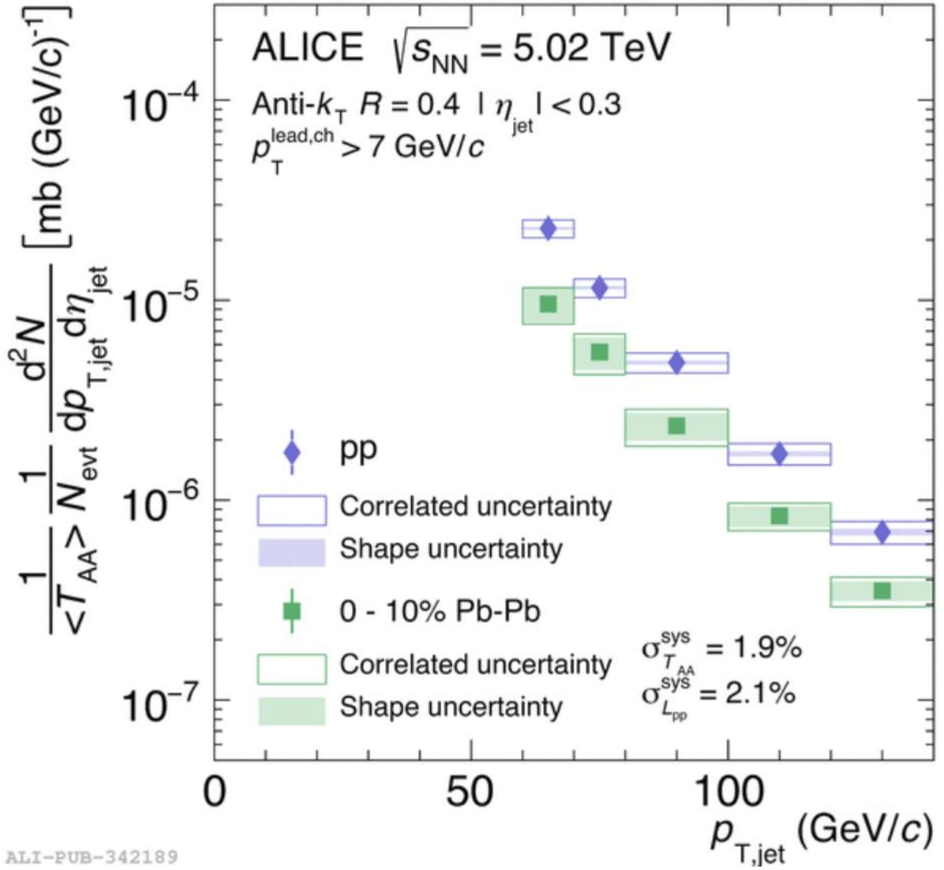


ALICE: Full Jet Spectra @ 5.02 TeV (ML & Std)

H. Bossi HP 2020



Phys. Rev. C 101, 034911



Background fluctuations (standard rho based vs ML) and Fully unfolded jet spetra

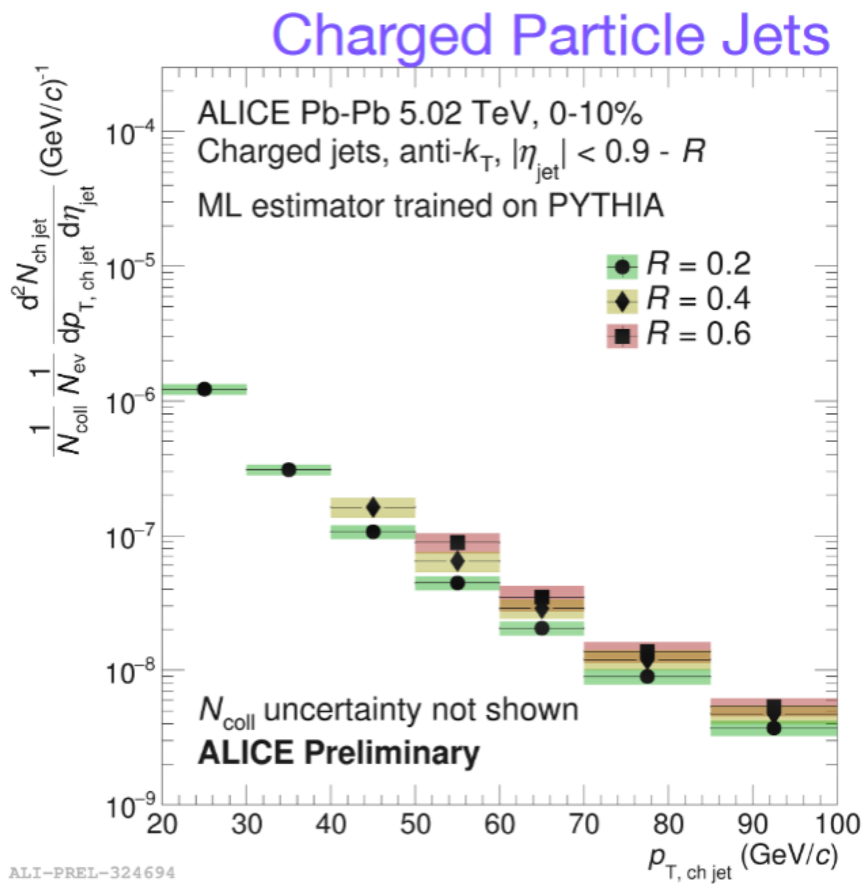
$$p_{\mathrm{T,lead}}^{\mathrm{min}} = 7 \ \mathrm{GeV}/c$$

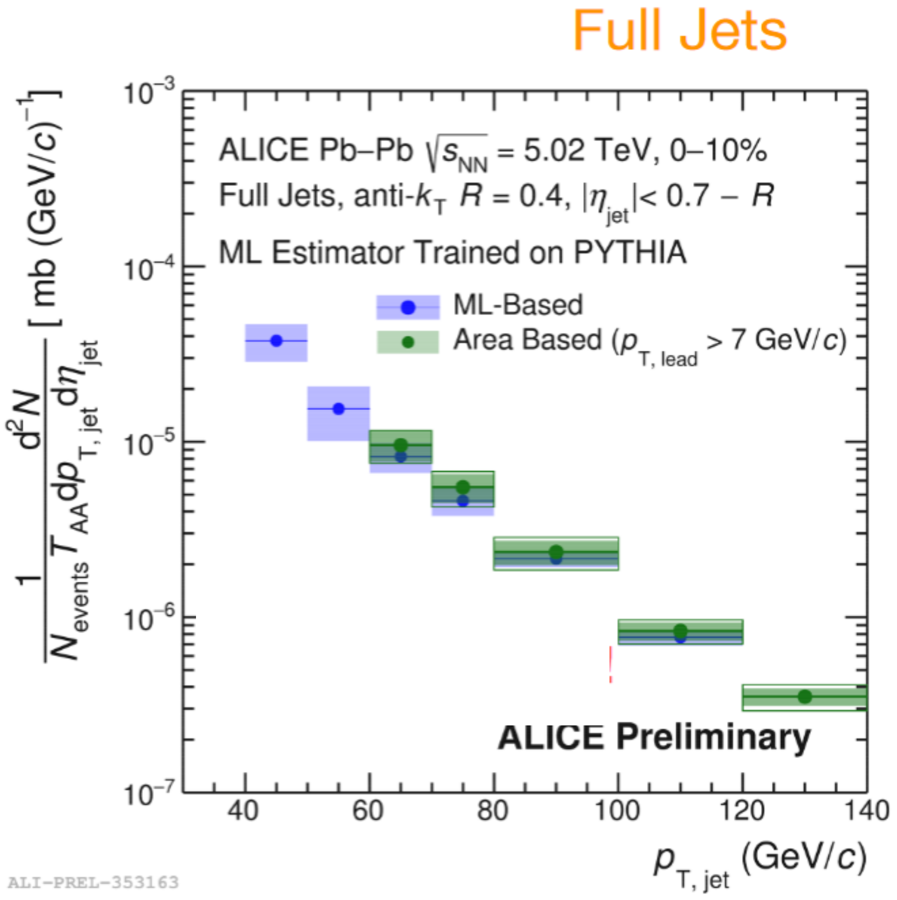
Bias needed for unfolding (introduces NP effect and fragmentation bias larger for the ML method).

In order to deal with bkg fluctuations one cas use FF moments (next slides)

ALICE Pb-Pb Spectra

H.Bossi ALICE Coll. HP2020





Unfolding systematics dominate at lower p_T.

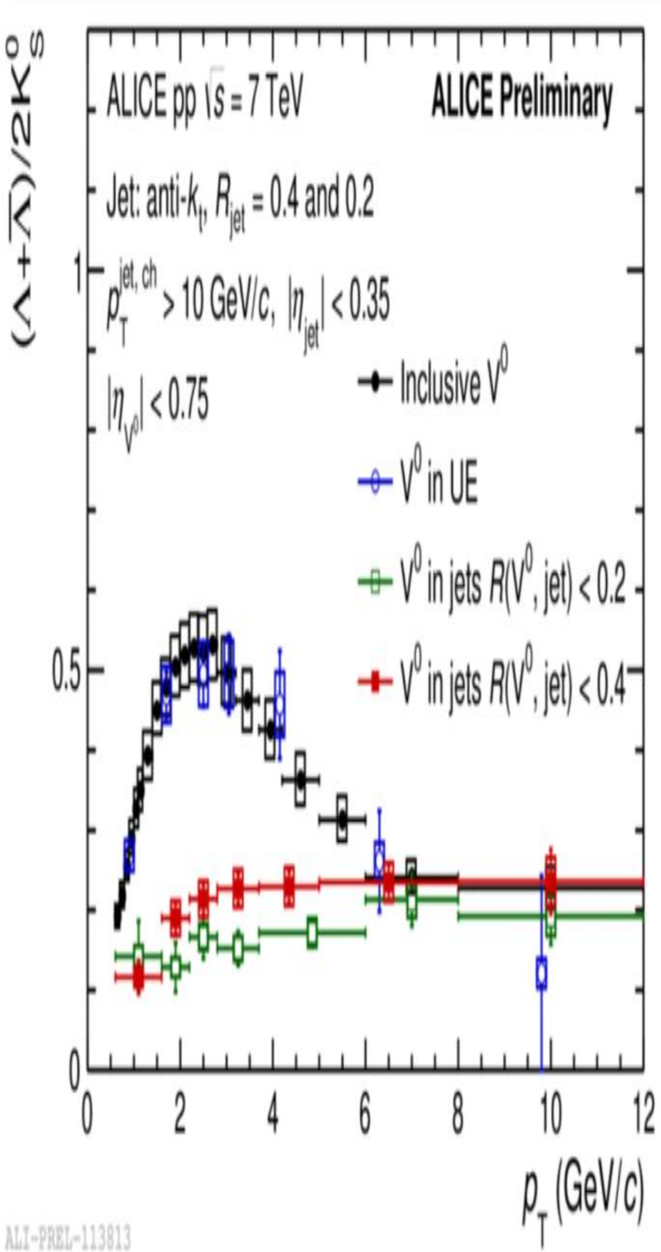
Tracking efficiency systematics dominate at high p_T.

R	Lower p_T Cutoff (GeV/c): Charged Particle Jets	Full Jets
0.2	20	40
0.3	50	60
0.4	40	40
0.6	50	N/A

Able to extend measurements to lower p_T and larger R!

Let’s be strange ….

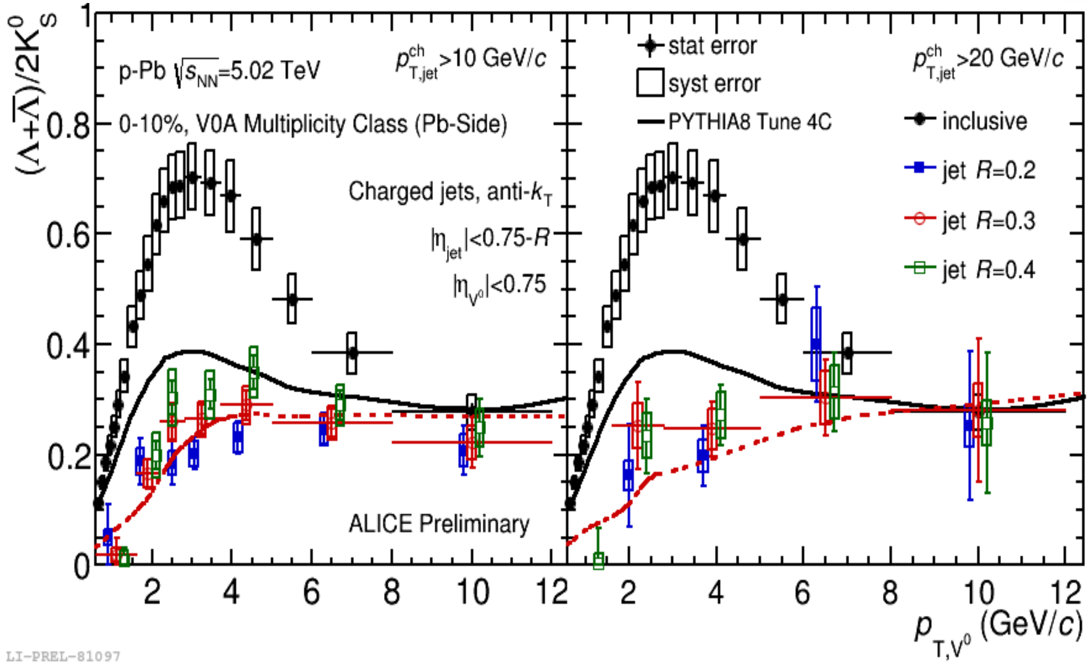
X. Zhang ALICE Coll.



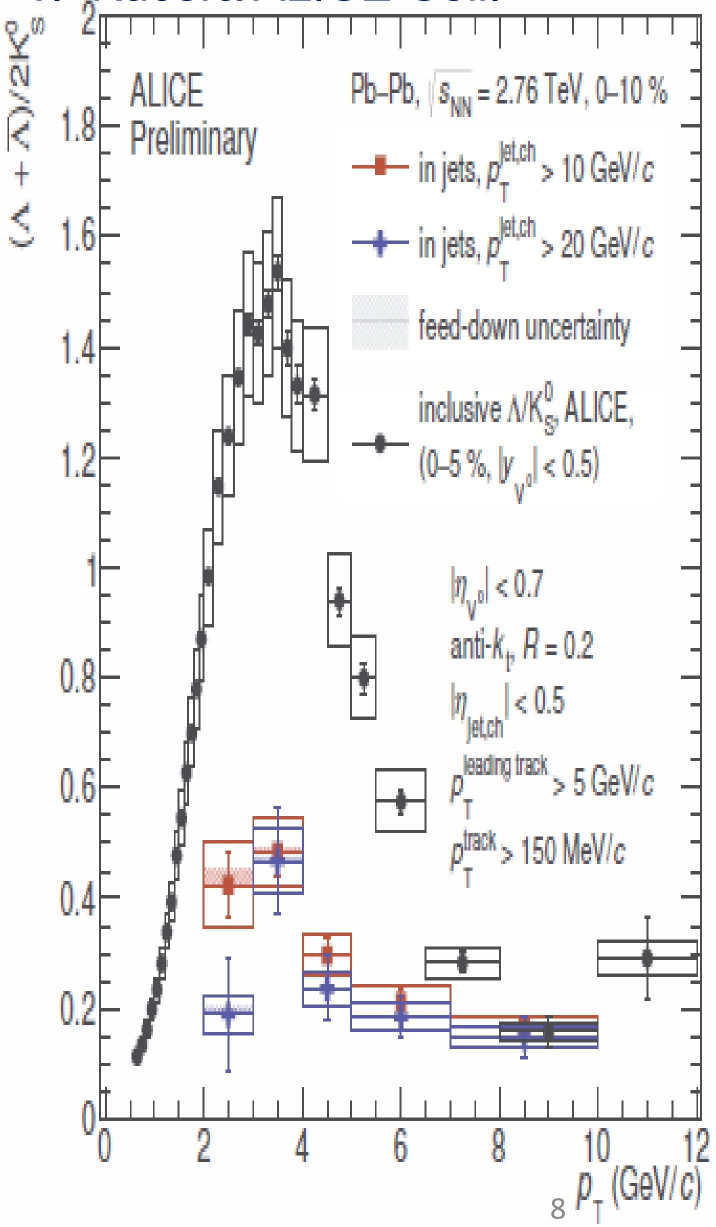
Similal behaviour observed
in pp p-A and Pb-Pb data

Inclusive V0s vs V0 in jets (R=0.2 to R=0.4)
Vs V0 in the UE

Y. Zhang ALICE Coll.

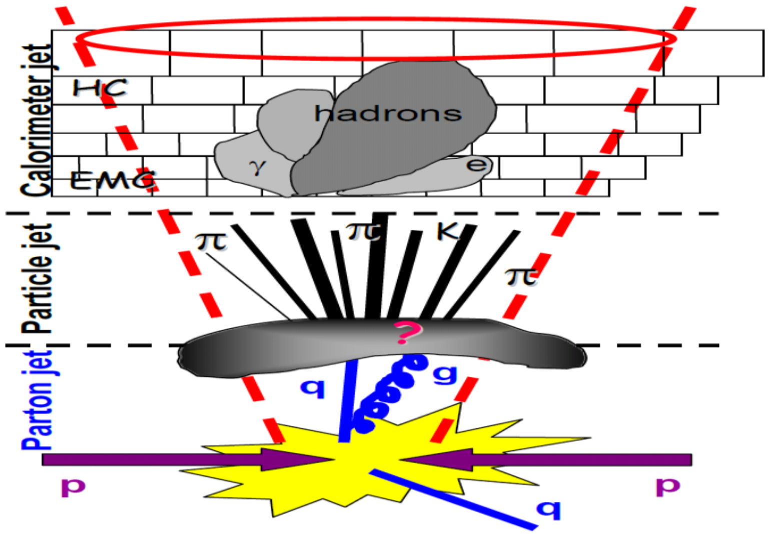


V. Kucera ALICE Coll.



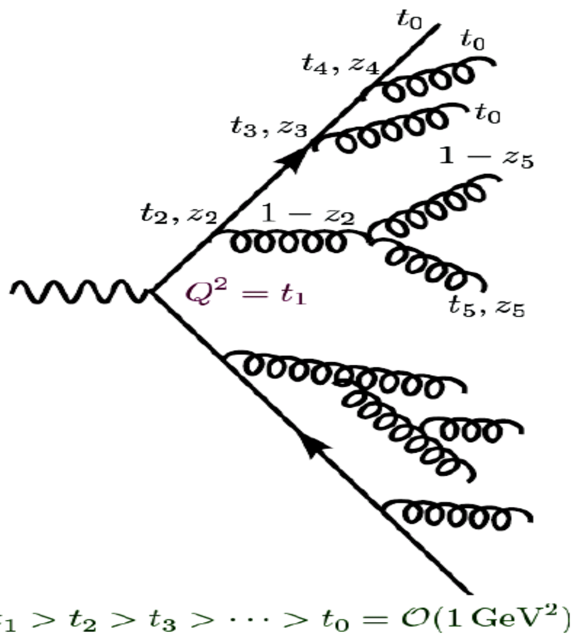
Fragmentation functions (FF)

Jet Fragmentation

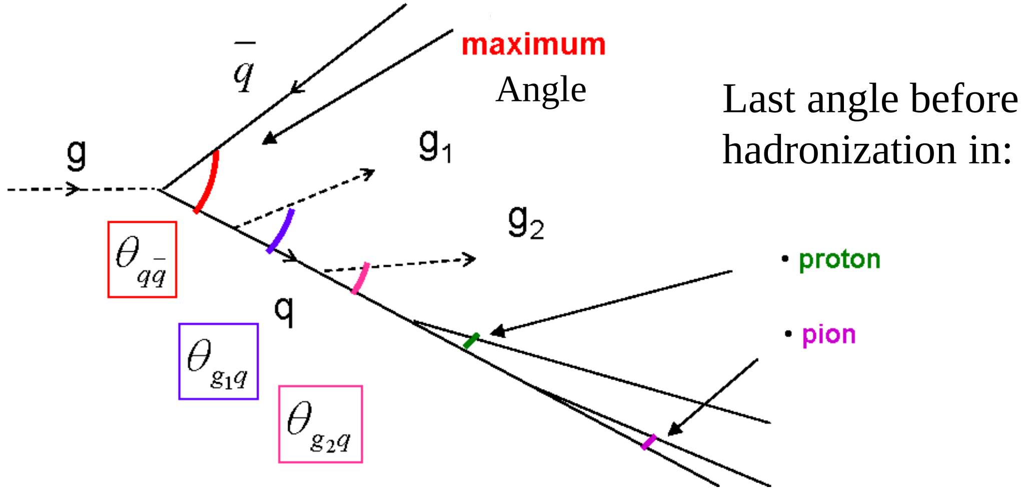


- colored objects ➔ color coherence ➔ angular ordering
- 1/kR < θqg_2 < θqg < θqqbar

1/R ~ hadron mass at the end of the shower



Parton shower evolution:

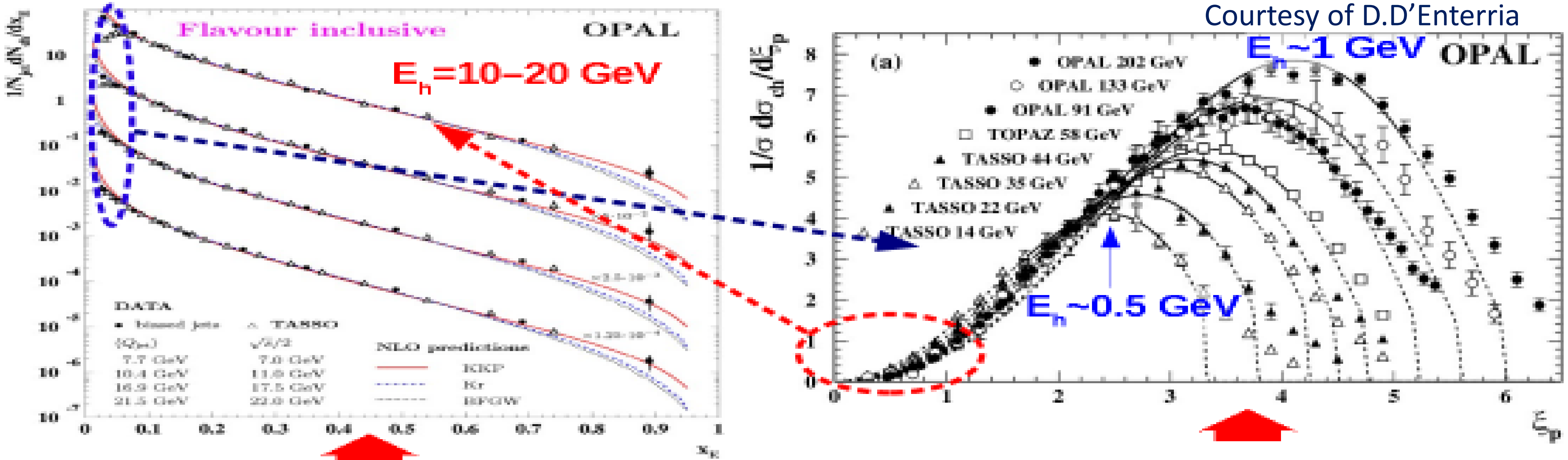


Parton to hadron fragmentation

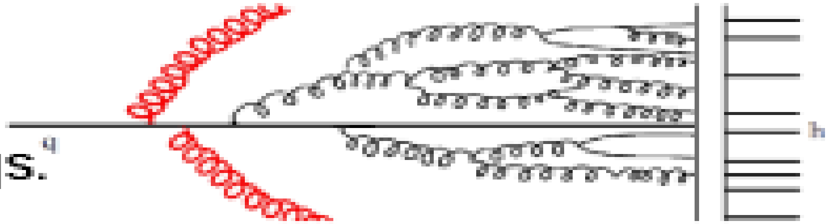
- **Hard** fragmentation function
  $z = p_{had}/p_{jet} > 0.1$
  High-p_T hadrons in jets

- **Soft** fragmentation function
  $\xi = \log(1/z) = \log(p_{jet}/p_{had}) > 1$
  Bulk hadron production in jets

Courtesy of D.D'Enterria



- Hard emission
- Ordered in k_T
- DGLAP evolution eqs.
  $\ln(k_T)$ evolution



- Soft/collinear emission
- Angular ordering
- (N)MLLA evolution eqs.
  $\ln(1/x)$ & $\ln(\theta)$ resummations

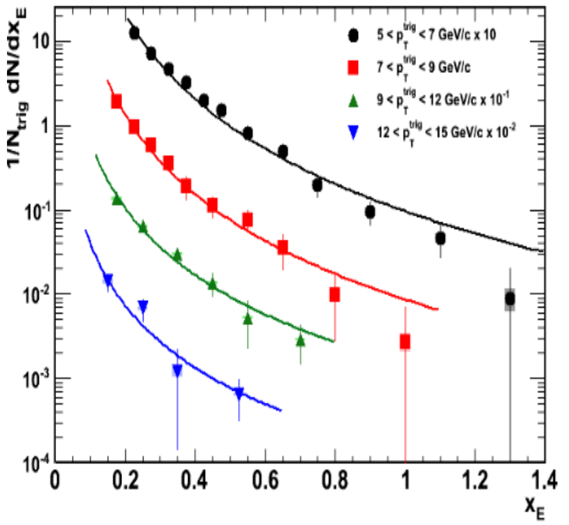
pp: Gamma – h : Z_T

$$z_T = \frac{-\vec{p}_T^{\,parton} \cdot \vec{p}_T^{\,hadron}}{|\vec{p}_T^{\,parton}|^2}$$

(DSS and KKP fragmentation functions are used)

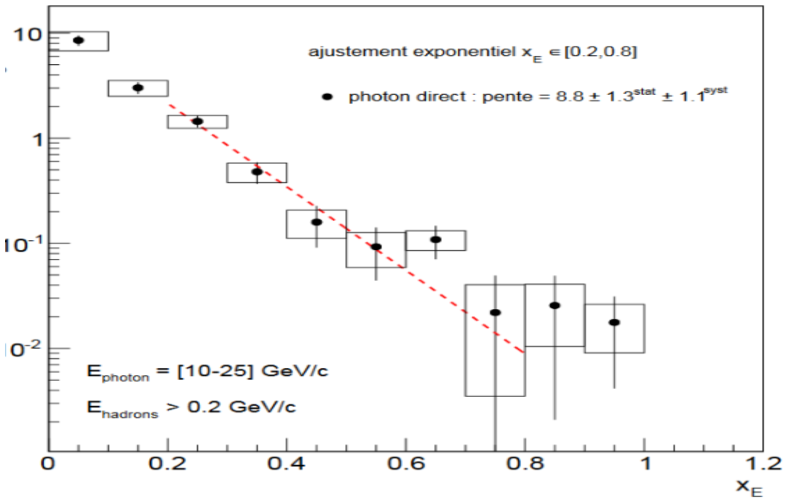
$$x_E = \frac{-\vec{p}_T^{\,\gamma/\pi^0} \cdot \vec{p}_T^{\,hadron}}{|\vec{p}_T^{\,\gamma/\pi^0}|^2} = \frac{p_T^{hadrons}}{p_T^{\gamma/\pi^0}} \cos(\Delta\Phi)$$

PHEINIX



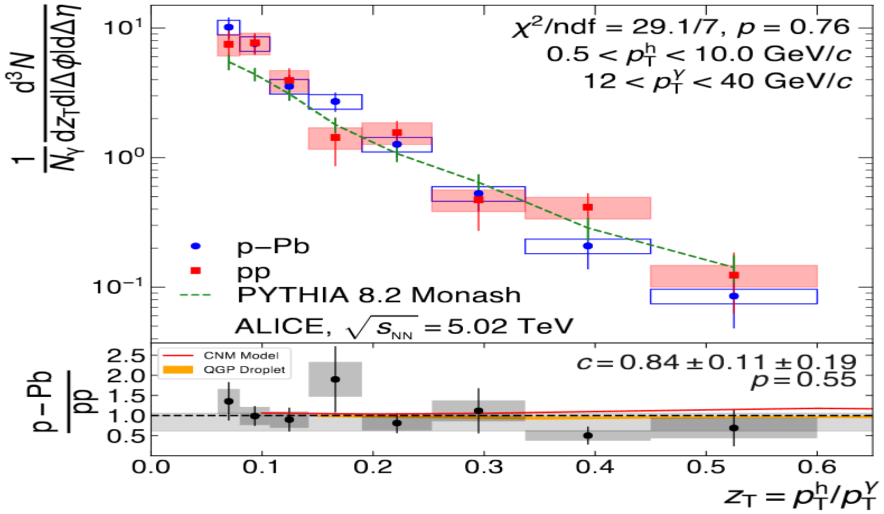
Recoil jet direct photon Xe distribution
As function of pT

ALICE Coll. N. Arbor PhD thesis tel-00944789



In order to test the association criterium the X_E distribution for obtained using isolated photons compared to partonic distributions

ALICE Coll.

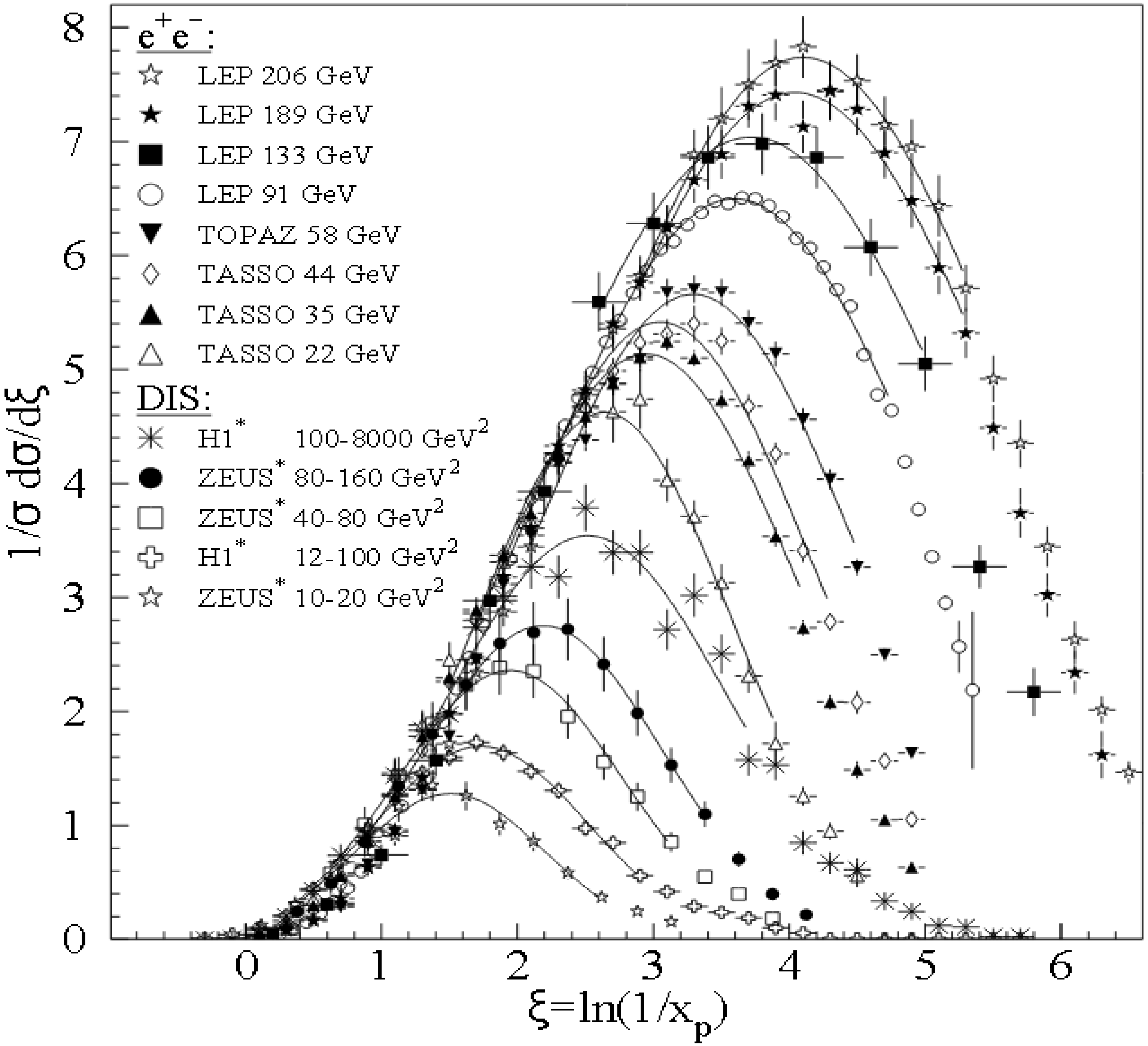


The ratio is compatible to unity withing uncerntenties
& the QGP droplet model is favored

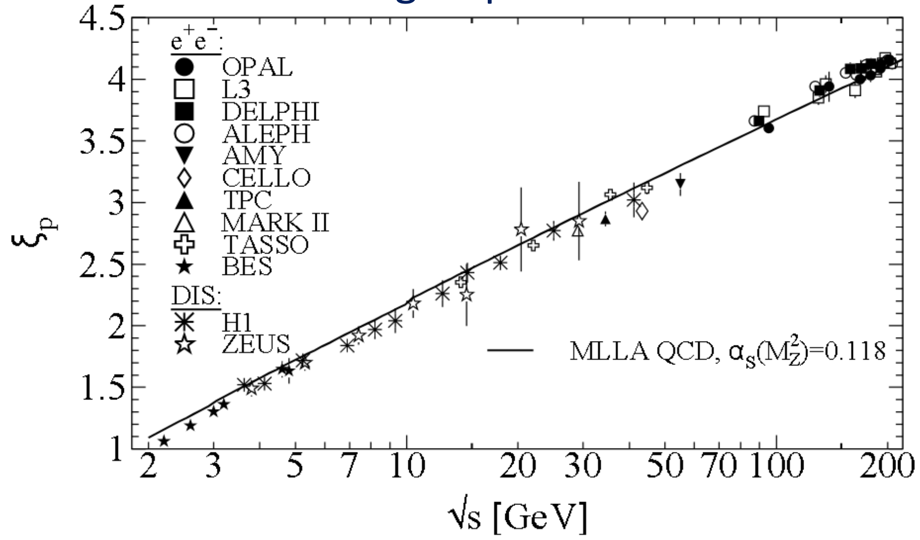
DeltaPhi distrib studied as well

e+e- / DIS

Particle data Group



Particle data group



Evution of the ξ peak position as a function of sqrt(s) as predicted by MMLA (assuming Color Coherence. Data points corresponds to measurments from e+/e- and DIS..

- Expressing the Mellin-transformed hadron distribution in terms of the anomalous dimension: $D \simeq C(\alpha_s(t)) \exp\left[\int^t \gamma(\alpha_s(t'))dt\right]$, $t = \ln Q$ one solves evolution eqs. for an expansion in (half) orders of α_s:

$$\gamma \sim O_{DLA}(\sqrt{\alpha_s}) + O_{MLLA}(\alpha_s) + O_{NMLLA}(\alpha_s^{3/2}) + O(\alpha_s^2) + O(\alpha_s^{5/2}) + \ldots$$

DLA: $\alpha_s \log(1/x) \log \Theta$: resummation of soft and collinear gluons:

- main ingredient to the estimation of inclusive observables in jets,
- neglects the energy balance.

Single Logs (SL): $\alpha_s \log \Theta$:

- collinear splittings (i.e. LLA FFs, PDFs at large $x \sim 1$),
- running of $\alpha_s(k_\perp \to Q_0)$ ($\propto \beta_0$).

MLLA: $\underbrace{\alpha_s \log\log}_{\mathcal{O}(1)} + \underbrace{\alpha_s \log}_{\mathcal{O}(\sqrt{\alpha_s})}$: the SL corrections to DLA:

- "restore" the energy balance,
- take into account the running of $\alpha_s(k_\perp)$.

Next-to-MLLA ("NNLL"): $\underbrace{\alpha_s \log\log}_{\mathcal{O}(1)} + \underbrace{\alpha_s \log}_{\mathcal{O}(\sqrt{\alpha_s})} + \underbrace{\alpha_s \log\log^{-1}}_{\mathcal{O}(\alpha_s)}$:

- improve the restoration of the energy balance,
- NLO running coupling effects ($\propto \beta_1$)

Slide from D.D'Enterria

Hump-backed plateau & MMLA (pp vs Pb-Pb)

$\xi = \log(pTjet / pTpart)$ ➔ zoom low pT

Hump-backed plateau (inclusive spectra of particles in a jet) can be predicted by MLLA

Shape :

- Low pT particles (soft) ➔ emited at large angle wich will become smaller at each parton emissions ➔ high ξ depleted (➔ test color coherence effects)

In heavy ion shape modified ➔ **shift of the peak to high ξ values** (more soft particles)

- **less particles at low ξ** ➔ **energy loss** of high pT particles (hadrons) that are « suppressed »

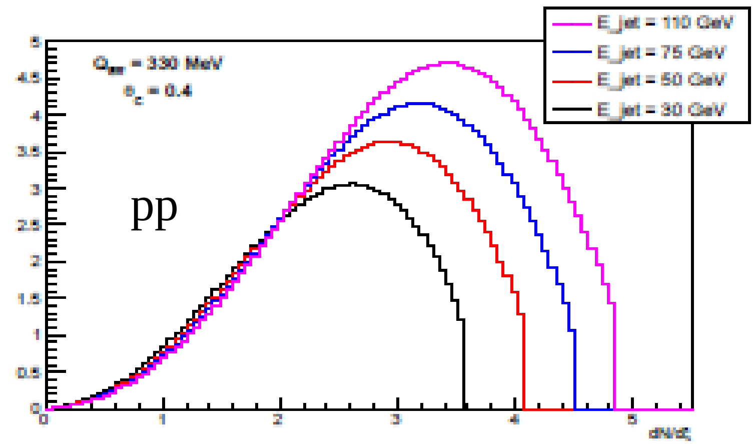
MLLA

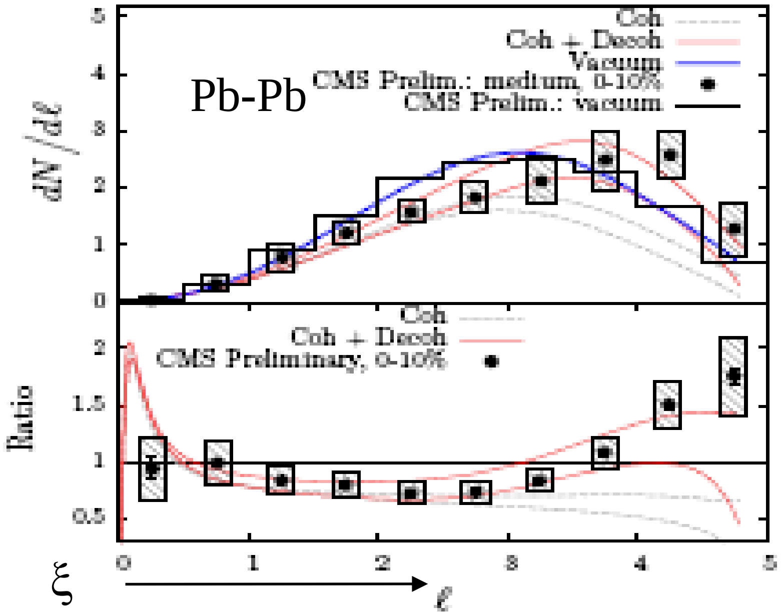
- gluon emmition ➔ colinear and infrared **divergencess** ➔ double log => **resumation** of LO diagrams in all order in α_s

➔ LLA ➔ extended to MLLA next to leading log

➔ **erergy and multiplicity distributions in jets**

- LPHD ➔ **at the end** of parton **shower**, **partion** distrib. are **related to hadron** distributions : $(K_h)\ N_{parton} \sim K_h\ N_{hadron}$



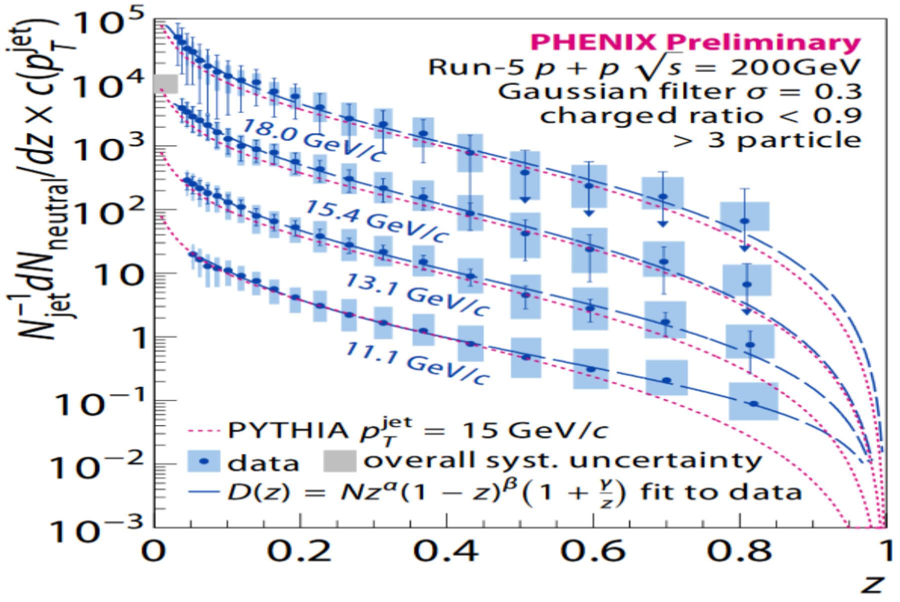


Y. Mehtar-Tani, K. Tywoniuk, hep-ph/1401.8293

Jet FF@RHIC

Phenix: FF

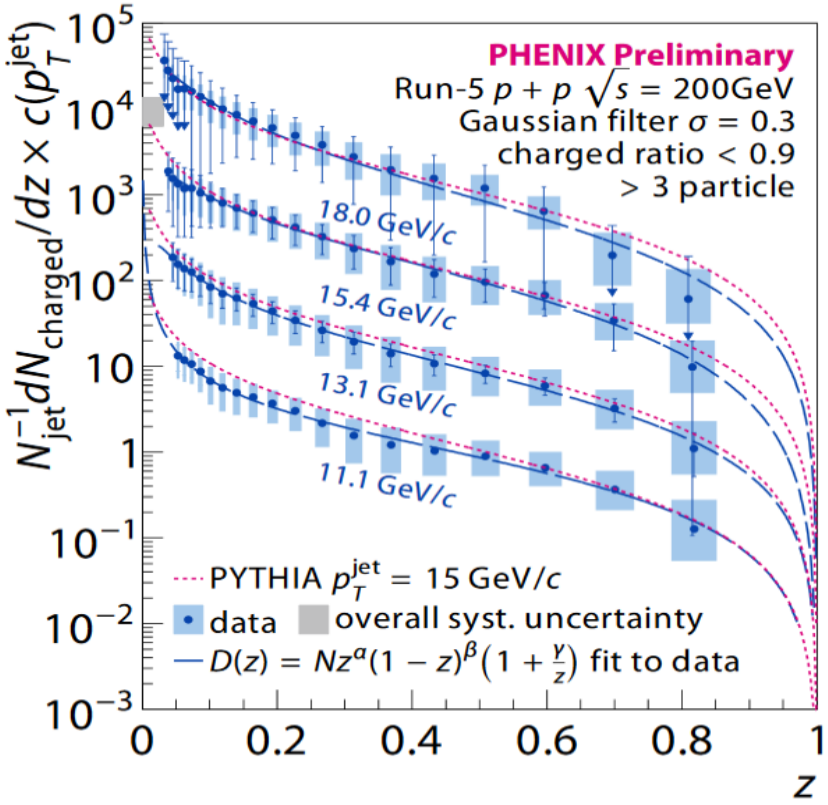
Y.S Lai RHIC AGS User Meeting



$$z = p_{\parallel}^{particle} / p^{jet}$$

- **Neutral particles (electromagnetic)**
- $z = p_{\parallel}^{particle} / p^{jet}$
- $c(\cdot) = 10^i, i = 0, 1, \ldots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $z_{max} \approx 0.81$

Y.S Lai RHIC AGS User Meeting

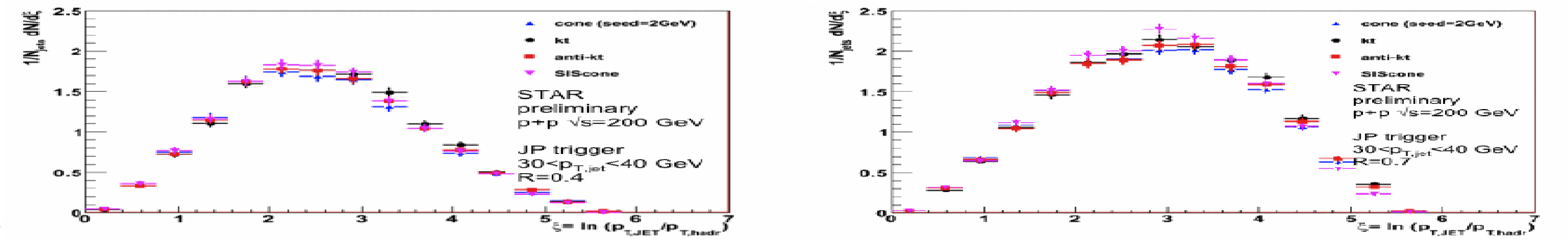


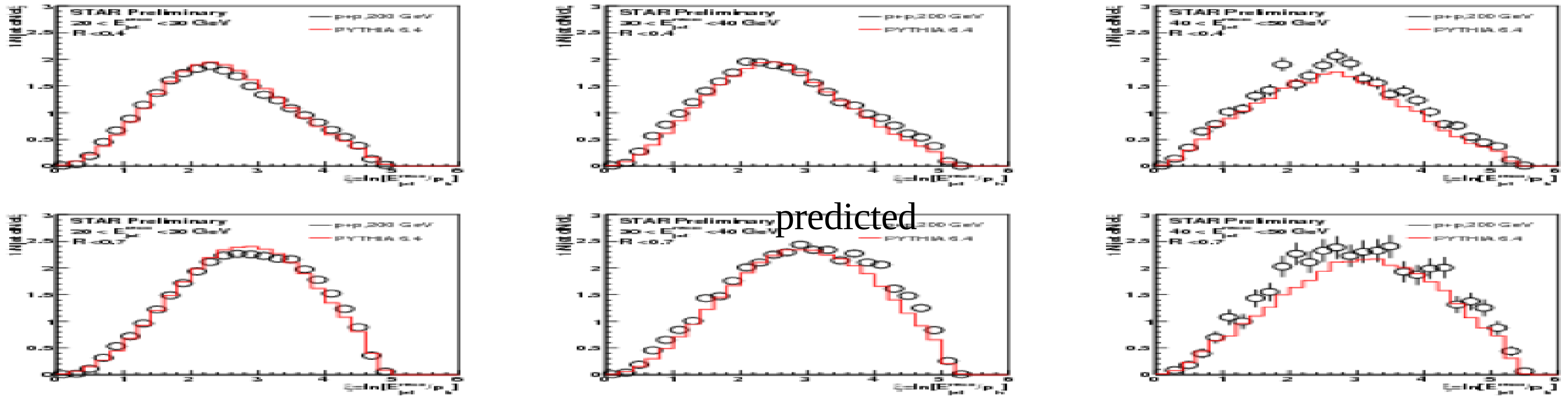
- **Charged particles (with $e^{\pm}$ rejection)**
- $z = p_{\parallel}^{particle} / p^{jet}$
- $c(\cdot) = 10^i, i = 0, 1, \ldots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $z_{max} \approx 0.81$

Similar kinematic reach as the one we can expect @ EIC

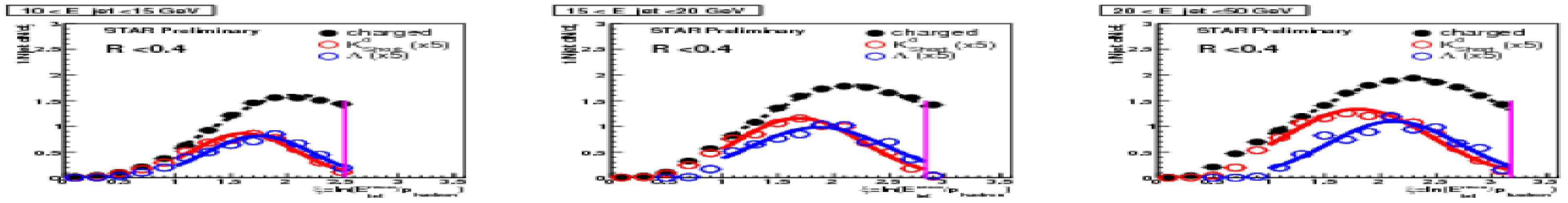
STAR : FF pp 200 GeV

STAR Coll



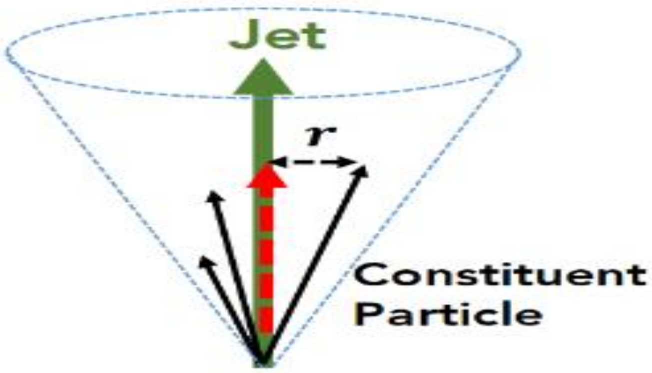


STAR Inclusive and identified Xi distribution in pp collisions @ 200 GeV compared to PYTHIA

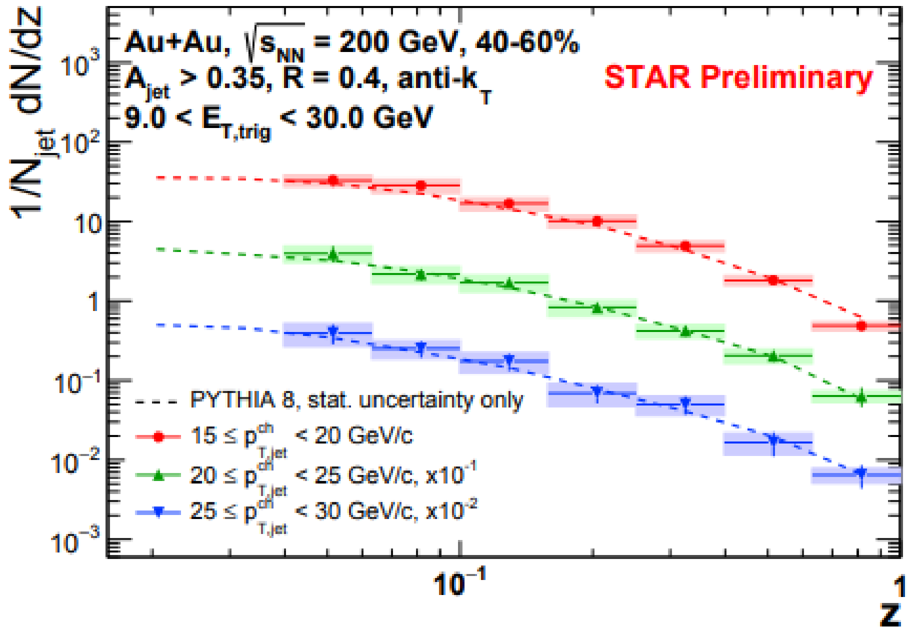


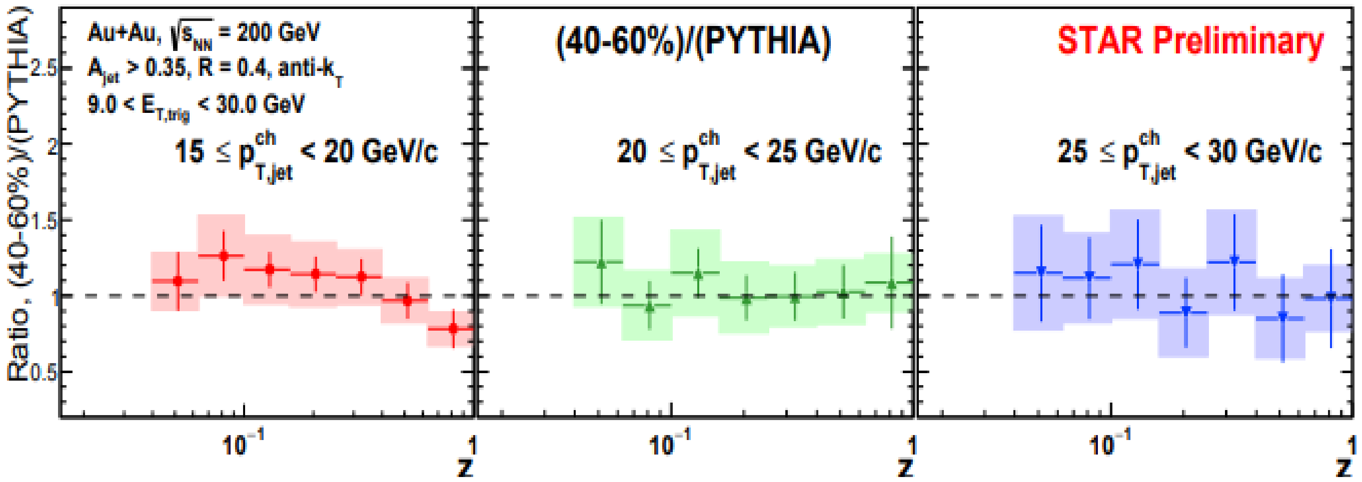
Star z Au-AU

STAR Coll HP2020
Fully corrected jet FF at RHIC



$$z = \frac{p_{T,track}\cos(r)}{p_{T,jet}}$$





Possible bias on jet selection by requiring high pt trigger

Good agreement with PYTHIA8.

Analysis in pp and central AuAU ongoing

Towards an EIC

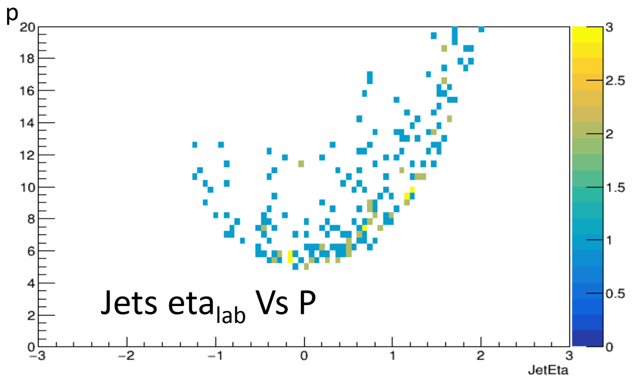
A.S BRBC EIC
Jet workshop
2020

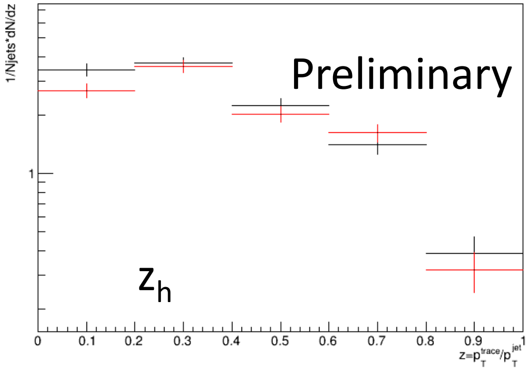
FF simulation in e+p (for the EIC) : a first look

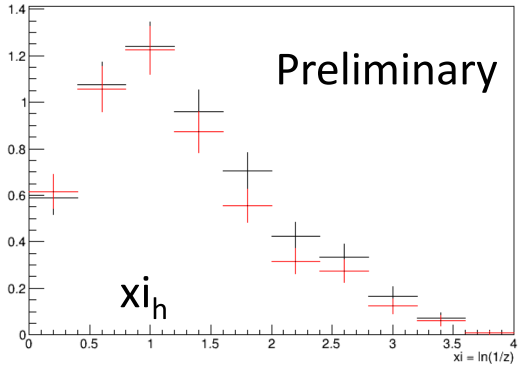
Electron –Proton events generated at √s = 141 GeV using PYTHIA (Full energy eRHIC design 20x250 GeV electron x proton)

- Cut on inelasticity: 0.01<y<0.95
- Jet Algorithm: Anti_kT
- Jets found in Lab frame
- Particles used in jet finding:
- Stable
- p≥ 200 MeV
- η≤ 3.0
- Parent cannot originate from scattered electron

PythiaeRHIC $10<Q^2<1000$ GeV^2 10 000 Evts . Lab Frame



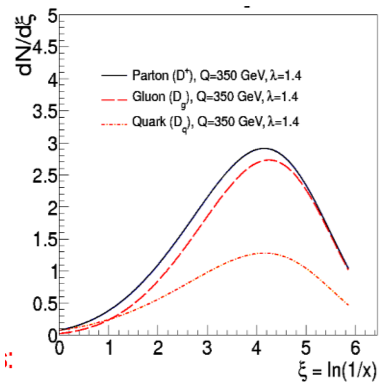




Next: to be optimized and studied as function of sqrt(s), jet resolution parameter R, possibly Q2
Add stat. (see next slide).

ep 20x250 GeV √s=141 GeV Uncorrected Charged jets Antik$_T$ R=0.3 |eta$_{jets}$| < 3 - R p_{Tjet} > 5 GeV/c no e-/e+/gamma (black: particle level, red: smeared using Matrix_0.1

Next: Switch to full simulation (several framework exists ATM tracking is implemented).
Mass and flavor dependence of (identified) jet Fragmentation functions
q/g separation
Easy access to the gluon sector at the EIC



JetScape for EIC : Status

JETSCAPE is an ideal, complementary, candidate to double the current number of e+A GPMCs

Goals:

- e+P baseline Done
- Further improvements out of scope (but possible in collaboration)
- e+A: Reference quenching tuned to HERMES is nearing completion

Next:

Provide medium template (boosted Brick/Glauber Ball)

In progress

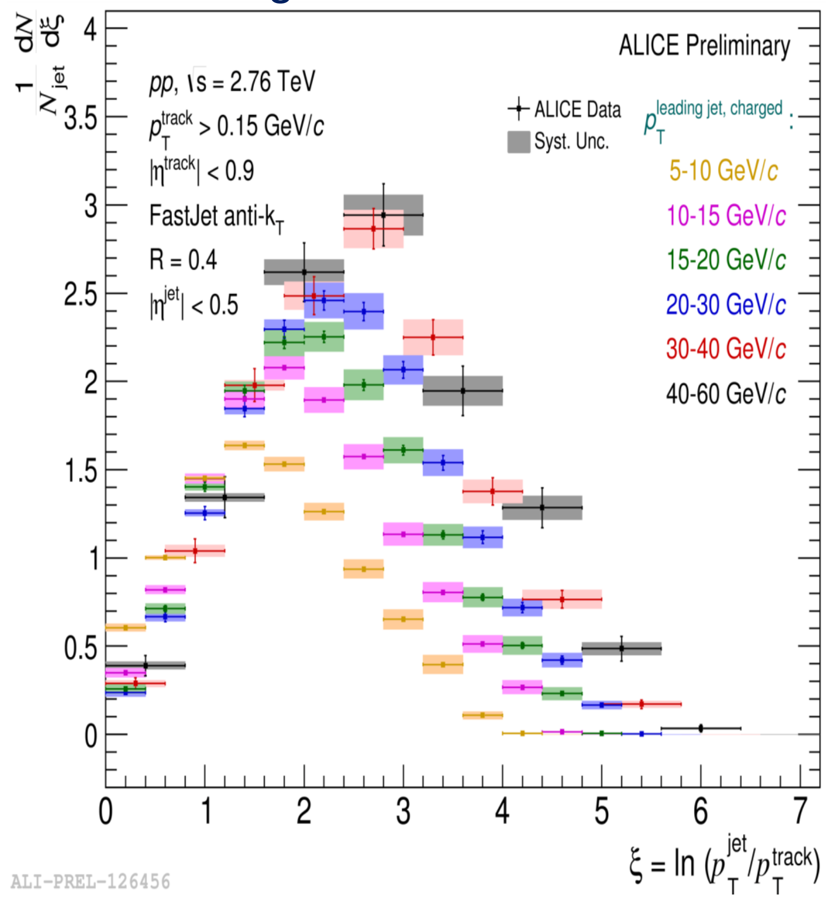
- Include into official distribution
- Leverage collaboration
- Use to explore quenching @ EIC!

Kolja Kauder – JetScape Coll. EIC@JETSCAPE Status
MCEGs for future ep and eA facilities (Nov 2019)

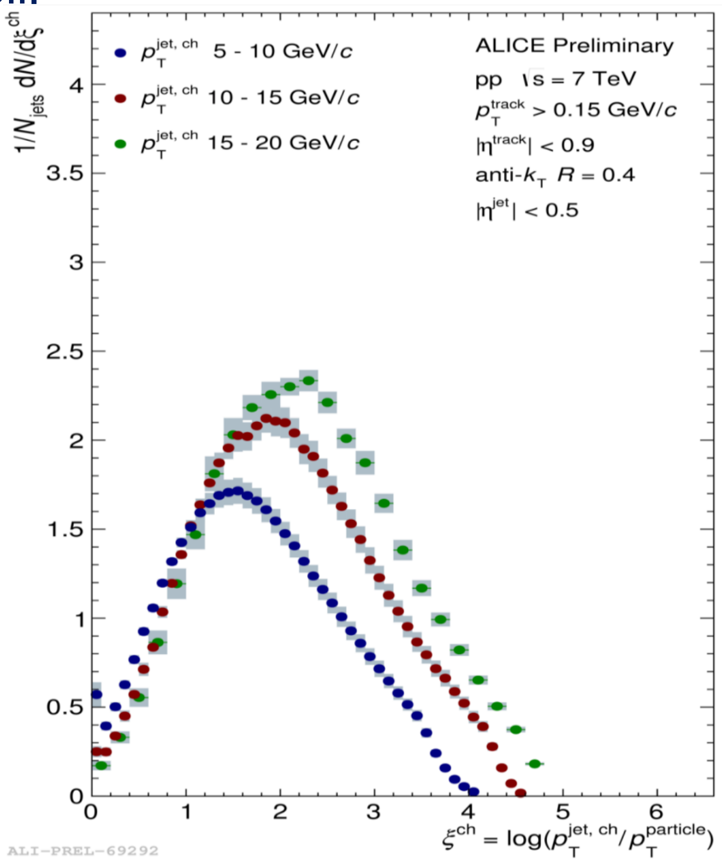
Jet FF at the LHC

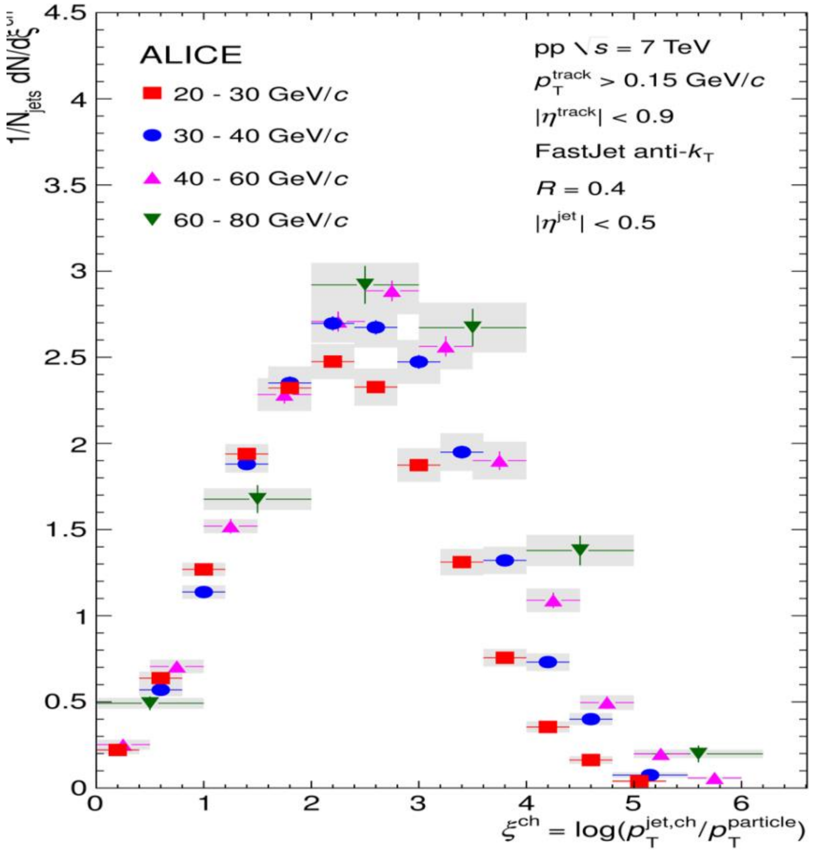
ξ (2.76 / 7 TeV)

M.Wang M.Estienne A.S ALICE Coll.



O. Bush ALICE Coll

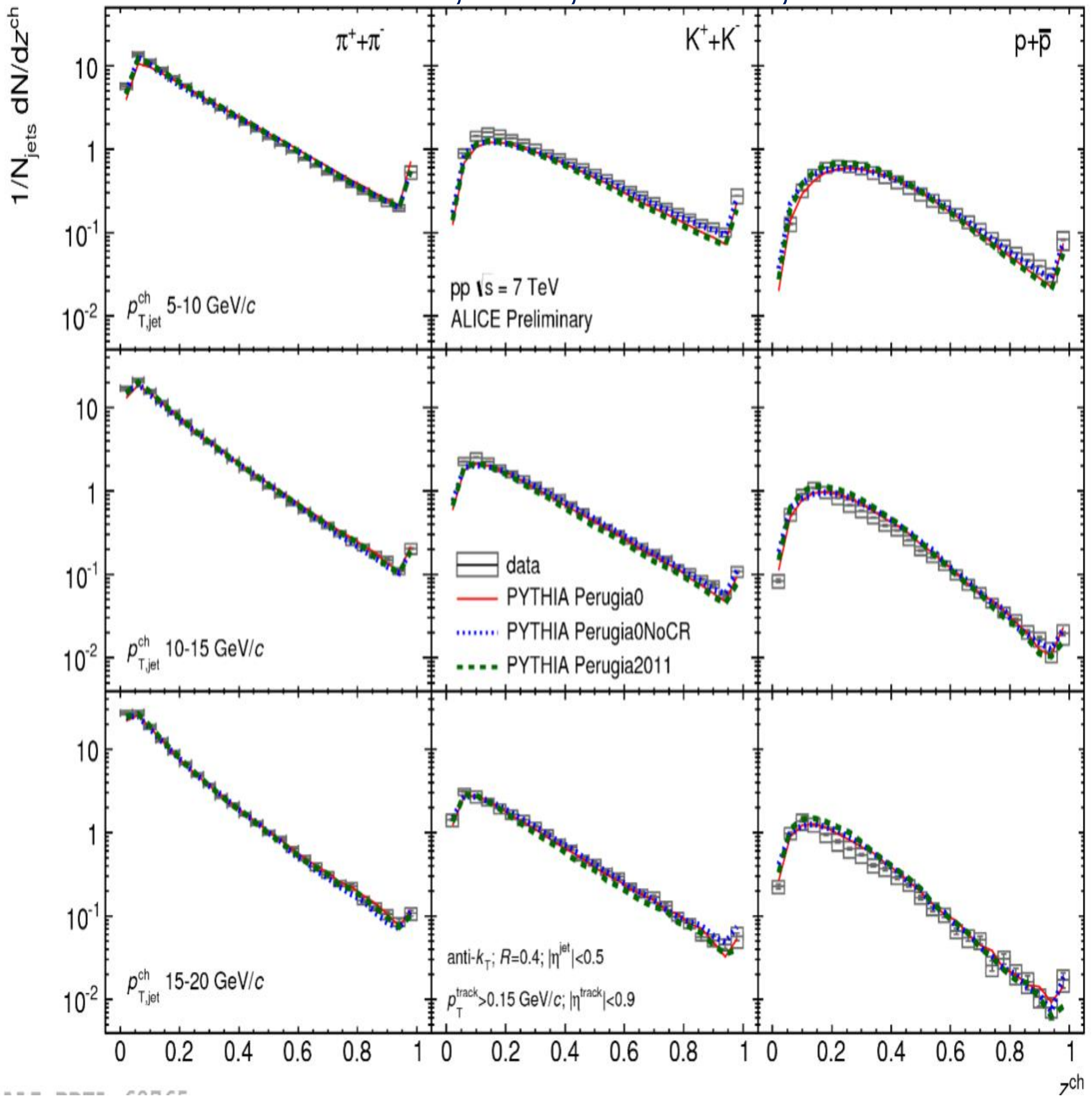


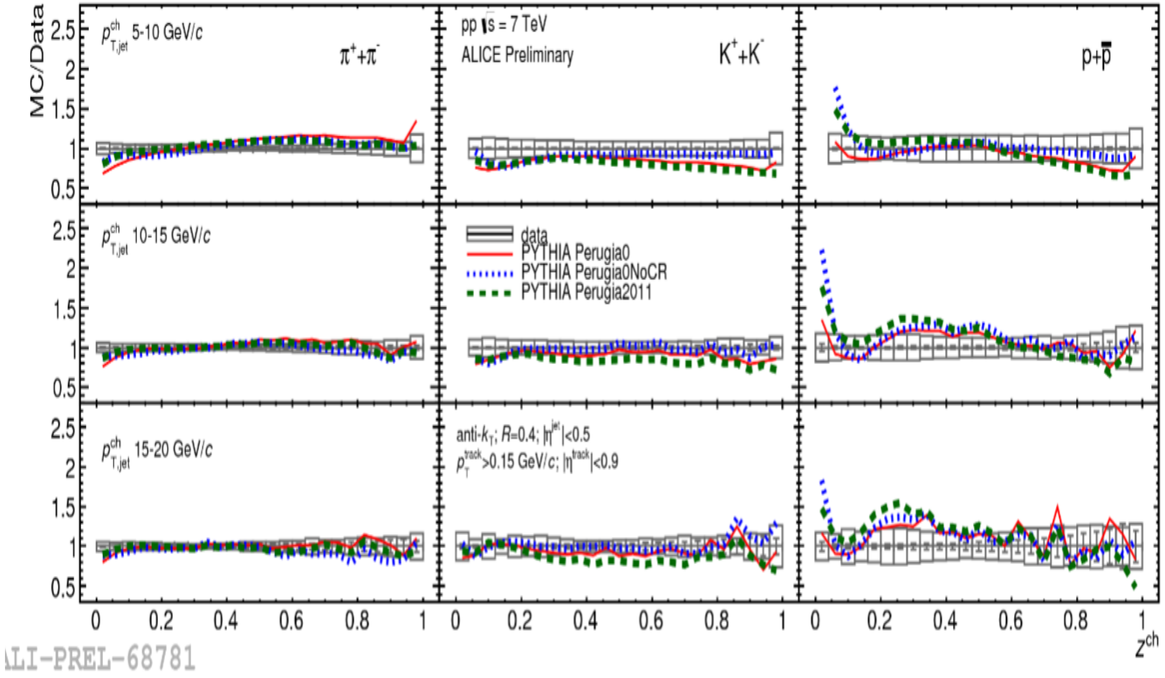


For ξ **< 2 same scalling** as for z.
At higher ξ (small z), maximum :**'hump-backed plateau**' ➔ **suppression of low momentum particle** production by QCD coherence
With **increasing jet pT,** the **area** of the distributions **increases** (**higher** particle **multiplicity** in jets), maximum shifts to higher values of ξ
This observation is in qualitative agreement with **MLLA**

identified z distrbutions

O. Bush O. Busch, BAH, M. Ivanov, X. Lu ALICE Coll





Largest deviation at 5-10 GeV/c jet low *z*
Better agreement at high jet p_T and *z*

Kaons favour *PerugiaNoCR* (pre LHC tune, no color reconnection)

Models *reproduce the proton maximum and its position*,
but *fail to describe the width and high z slope*

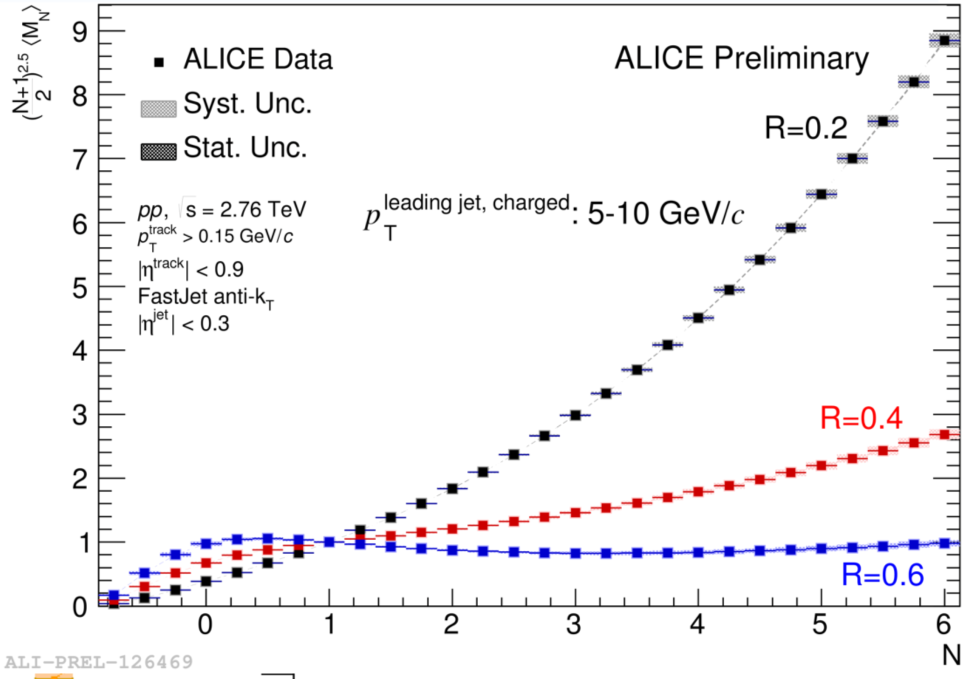
First measurement: Jet fragmentation moments in pp collisions @ 2.76 TeV

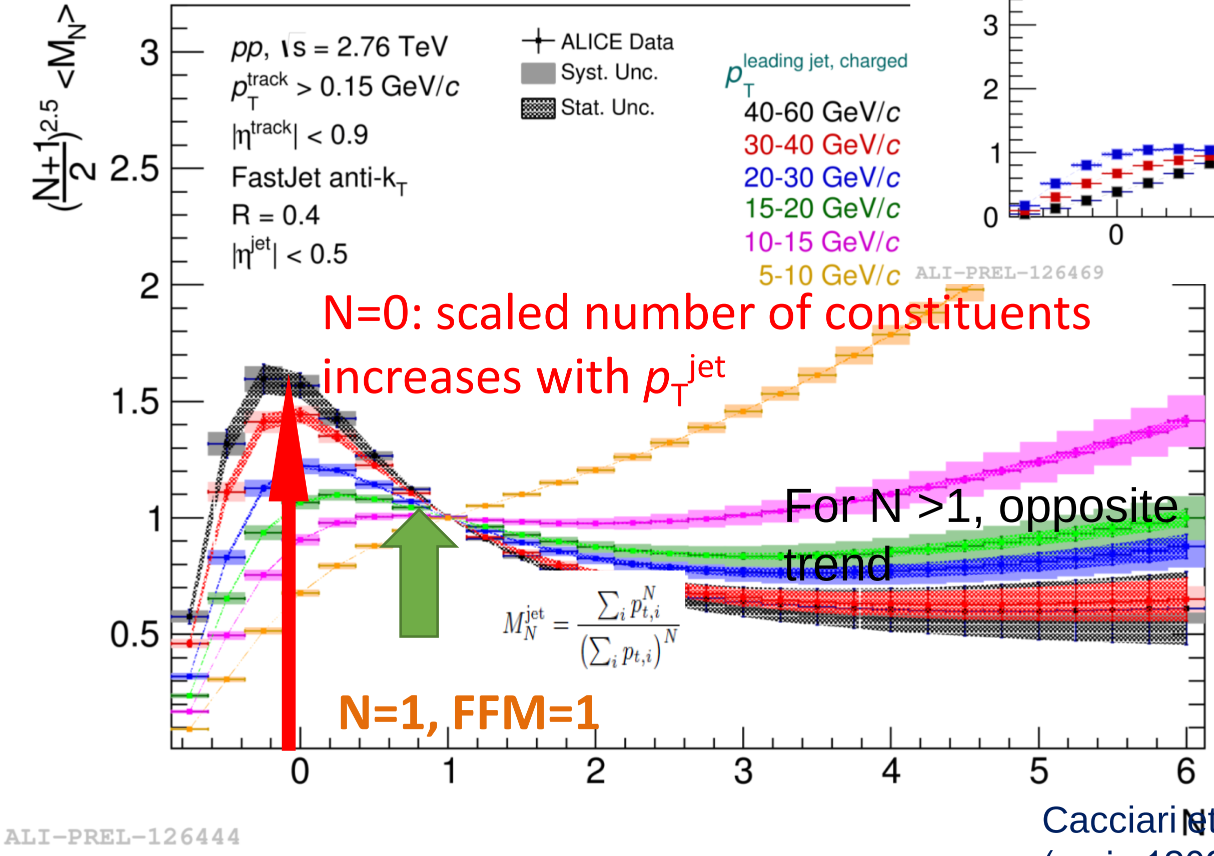
M.Wang M.Estienne A.S ALICE Coll

First measurement of the jet fragmentation moments

$\sqrt{s}$ = 2.76 TeV. Charged jets, 5 < pT < 60 GeV/c R=

$$M_N = \frac{1}{N_{\rm jet}} \int_0^1 z^N \frac{dN_{\rm hadron}}{dz}\, dz\,,$$





N=0: scaled number of constituents increases with $p_T^{\rm jet}$

For N >1, opposite trend

N=1, FFM=1

Good agreement between data and PYTHIA Perugia 11

Strong dependence of the FFM distribution vs R

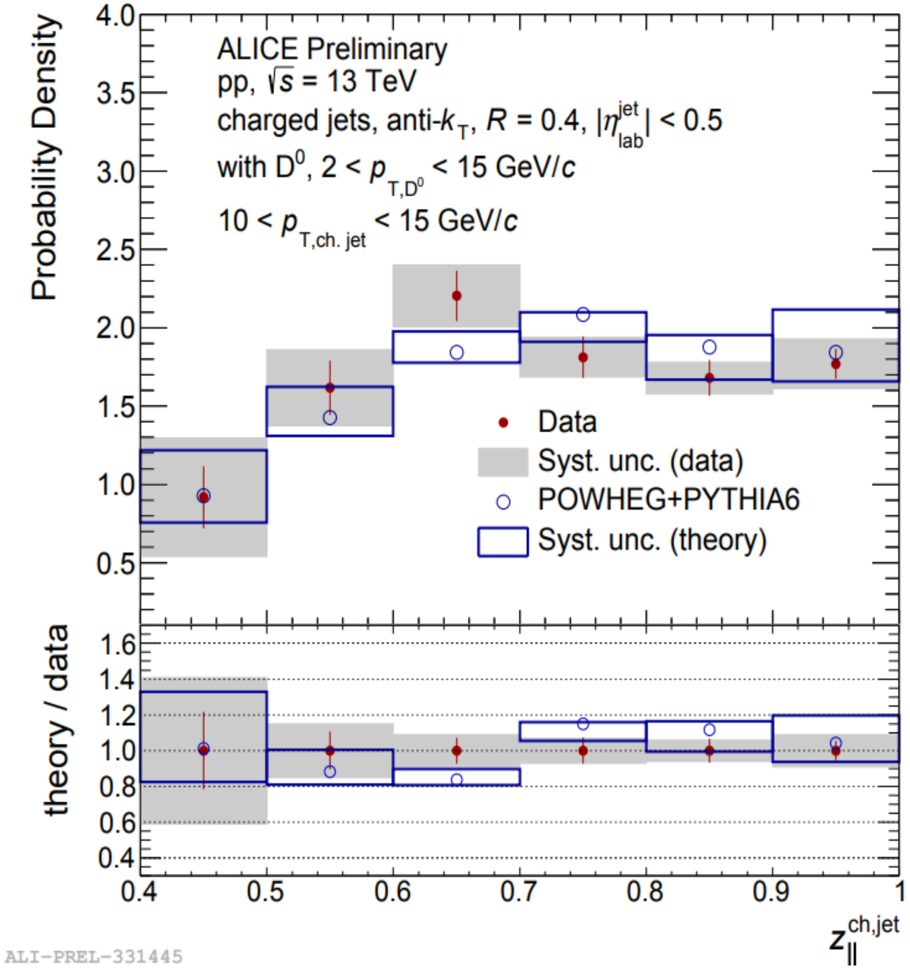
Cacciari et al Eur.Phys.J. C73 (2013) 2319 (arxiv:1209.6086), “Jet fragmentation function moments in heavy ion collisions

Reference for future Pb-Pb measurements

ALICE HF FF : D0 &Λc

ALICE Coll

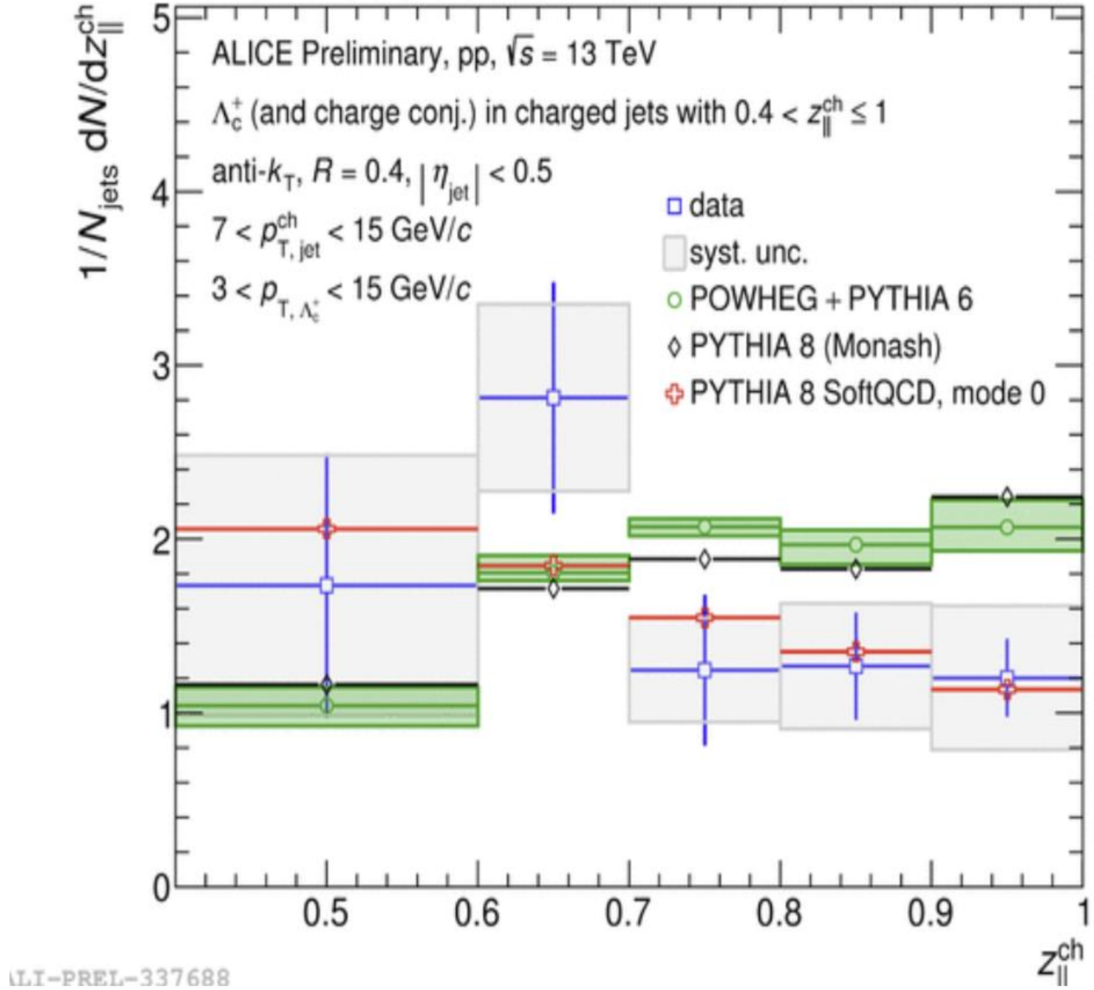
$$z_{||}^{ch} = \frac{\vec{p}_{jet}^{\,ch} \cdot \vec{p}_{HF}}{\vec{p}_{jet}^{\,ch} \cdot \vec{p}_{jet}^{\,ch}}$$



Fair agreement with PYTHIA8 (soft QCD)
are far from POWEG+PYTHA6 for high z values

ALICE Coll

Nima Zardoshti (CERN), Vit Kučera (Inha/CERN), G.M.Innocenti (CERN)

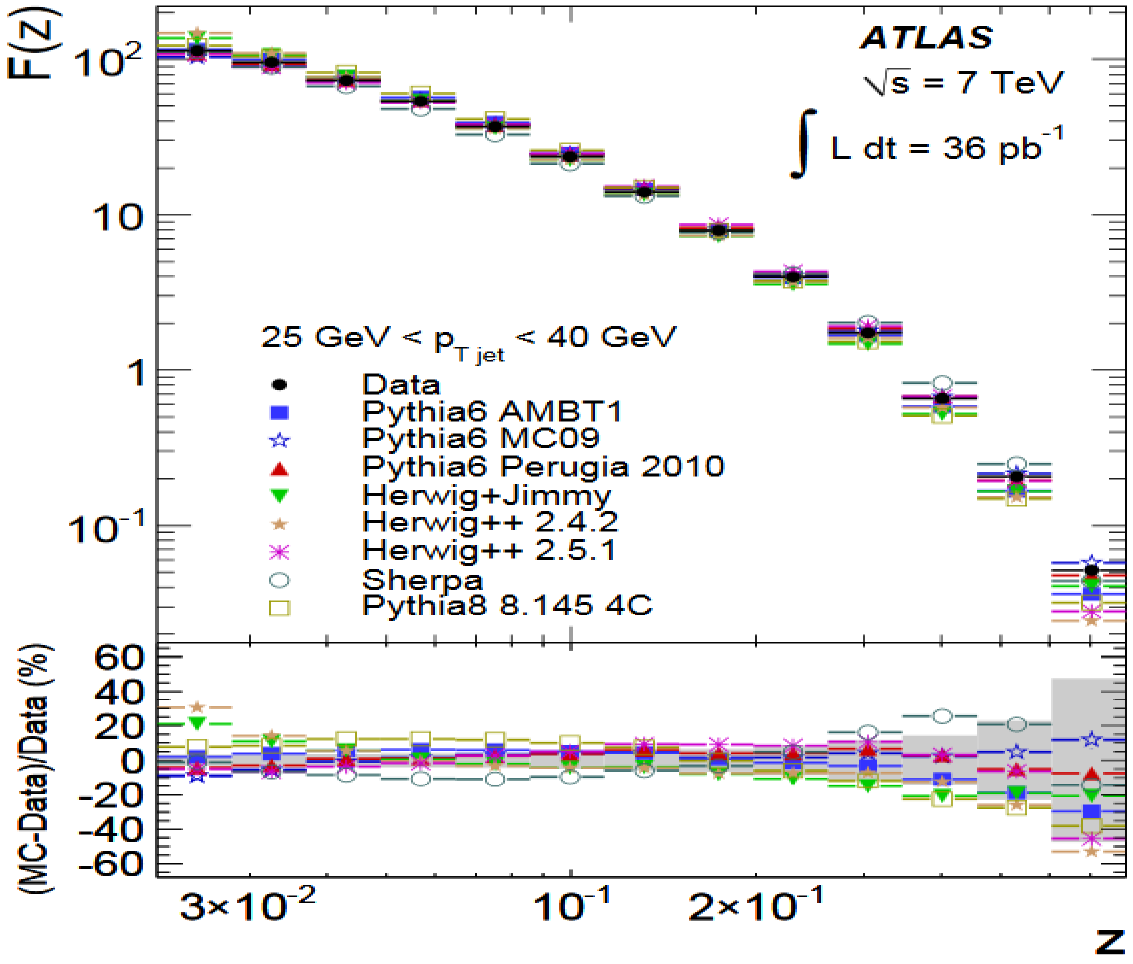


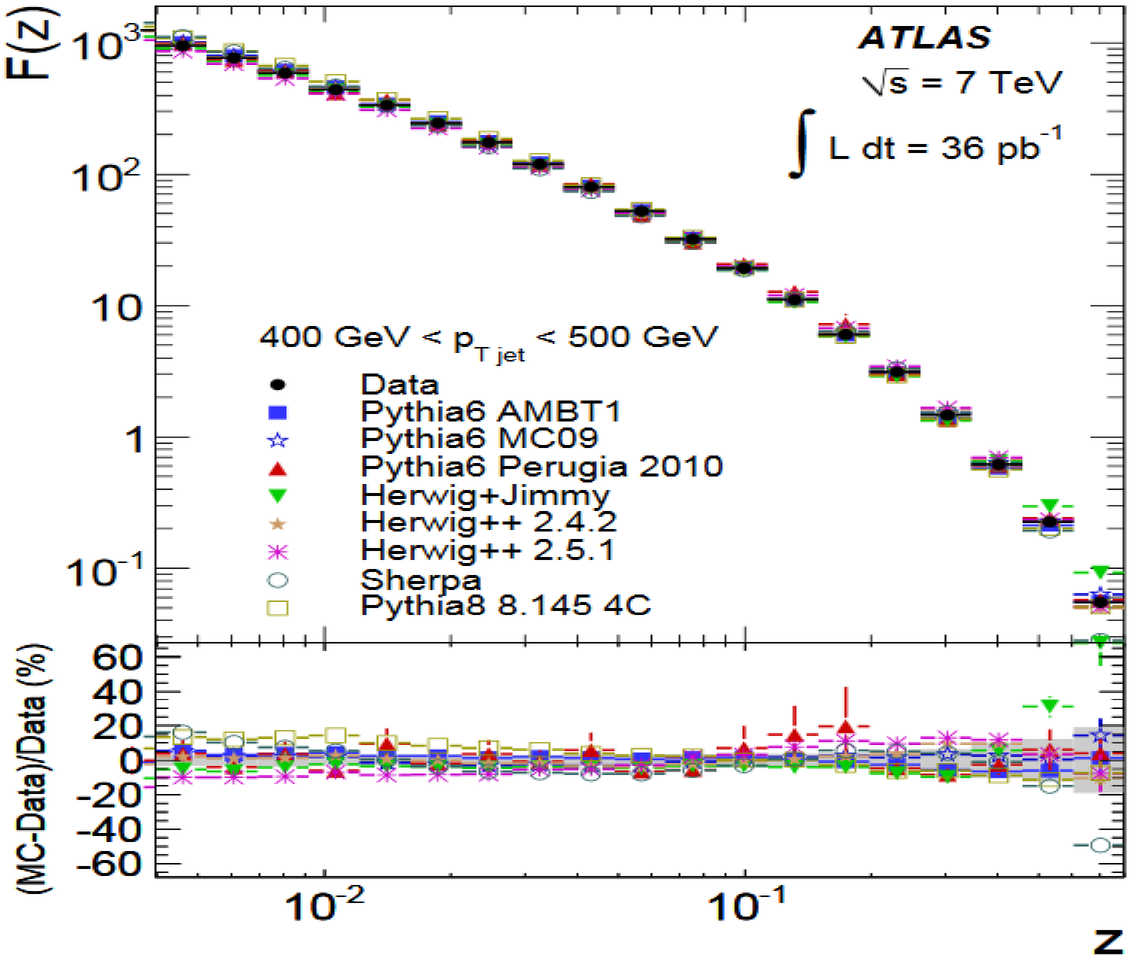
Good agreement with POWEG+PYTHIA6 for 15<p_T<50 GeV/c

ATLAS 7 TeV

ATLAS Coll arXiv:1805.05424

ATLAS Coll



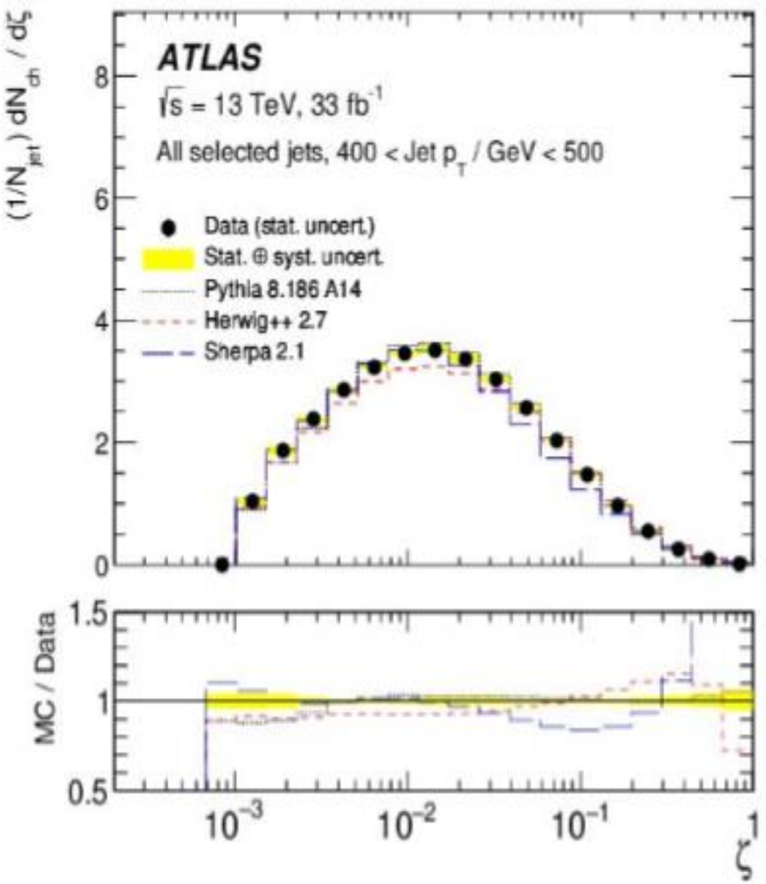


pp Data compared to a few models

arXiv:1906.09254v2

ATLAS 13 TeV: FF Quarks vs Gluons

ATLAS Coll



q/g extraction by use of MC flavour fractions *f*, nominally from Pythia:

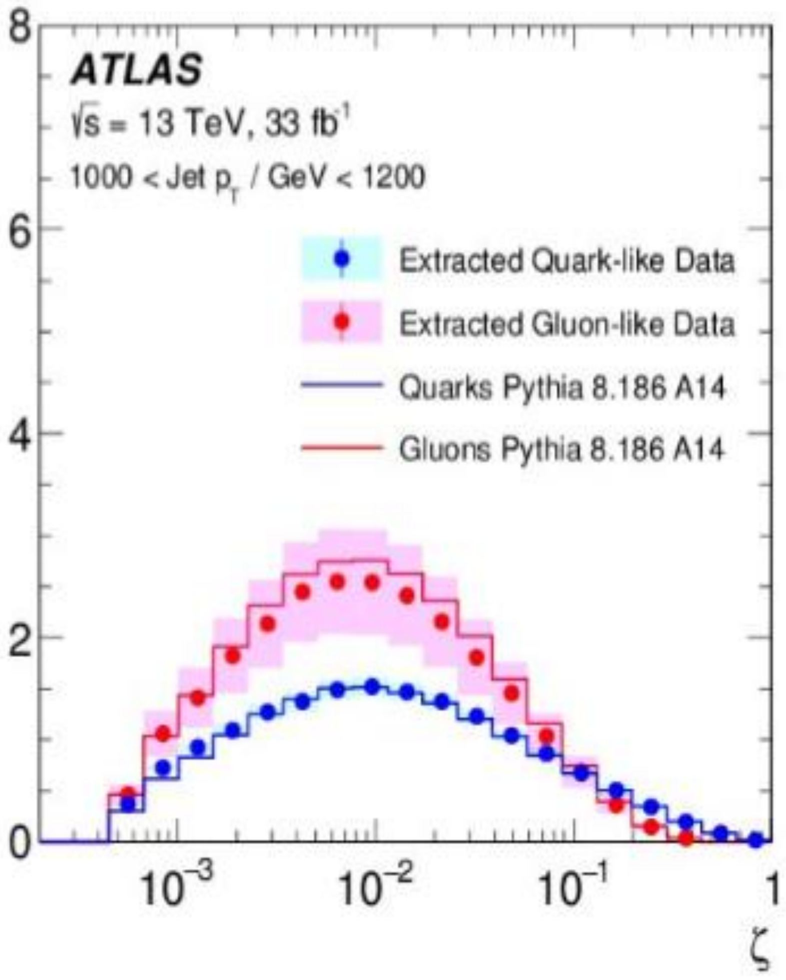
$$h_i^f = f_q^f h_i^q + (1 - f_q^f) h_i^g$$
$$h_i^c = f_q^c h_i^q + (1 - f_q^c) h_i^g$$

pp Data compared to PQCD (Pythia8, Herwig, sherpa)

Jet flavor defined by hardest parton associated to the jet (theoretical issues leading to uncertenties)

Extracted q/g-like fragmentation observables fit expectations:

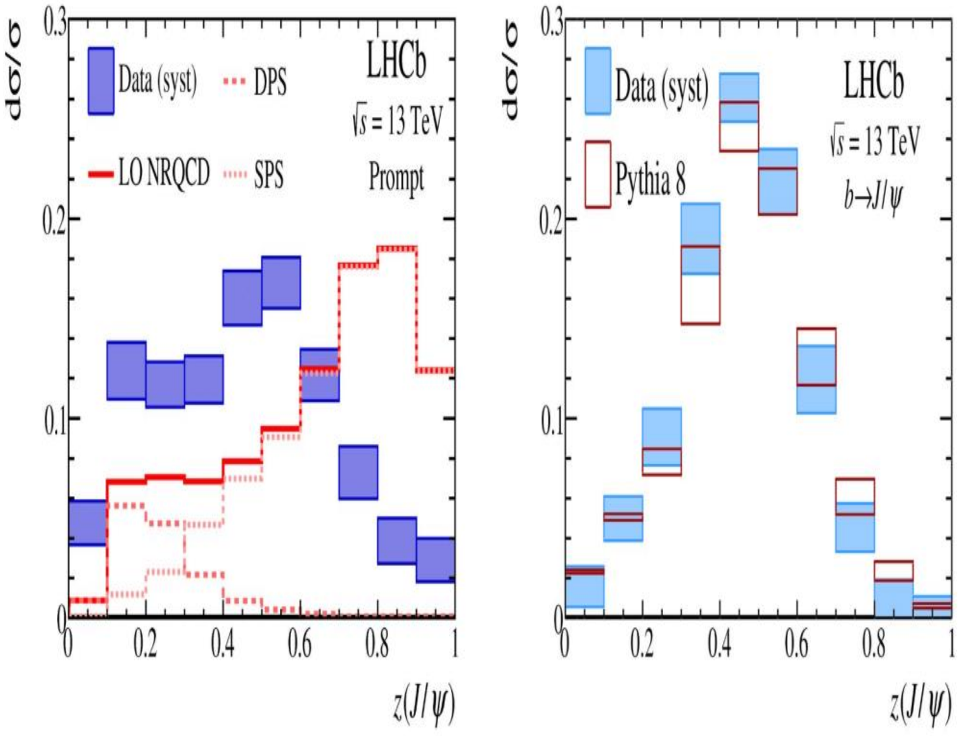
ATLAS Coll



Phys Rev. Lett 118 19
Axiv::1904.08878

LHCB z & J/psy in jets

LHCB Coll

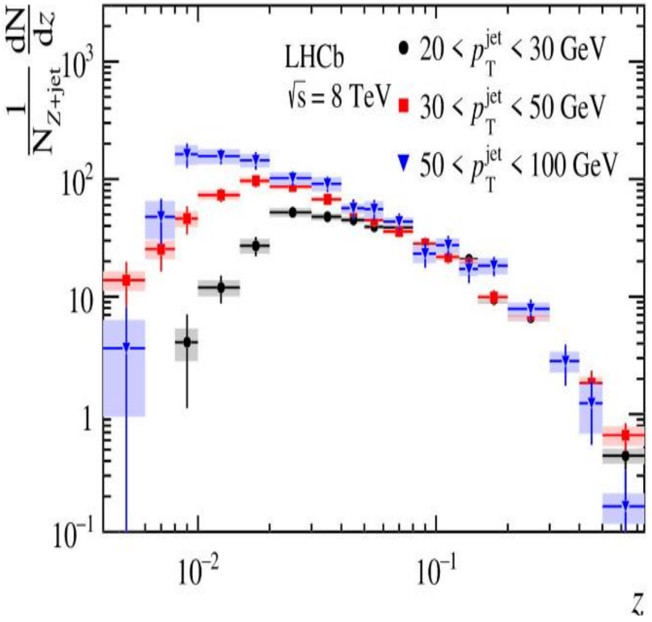


Prompt result do not agree with LO-NRQCD (Pythia8)
B-hadrons fragmentation is consistant with Pythia 8 Predictions

3 jet pt bins
Independent of jet p_T (scalling) at high z
Divergence at low z (kinematic / phase space)

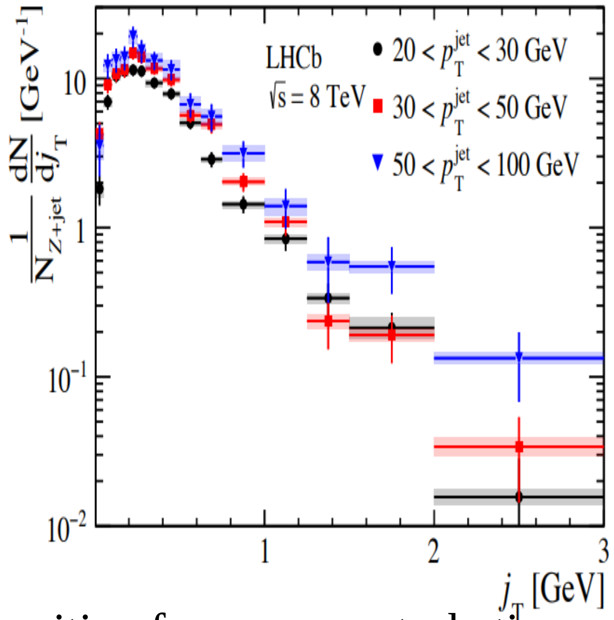
$$j_T \equiv \frac{|\mathbf{p}_{jet} \times \mathbf{p}_{hadron}|}{|\mathbf{p}_{jet}|}$$

$$z \equiv \frac{\mathbf{p}_{jet} \cdot \mathbf{p}_{hadron}}{|\mathbf{p}_{jet}|^2}$$



Sensitive mainly to light quark fragmentation

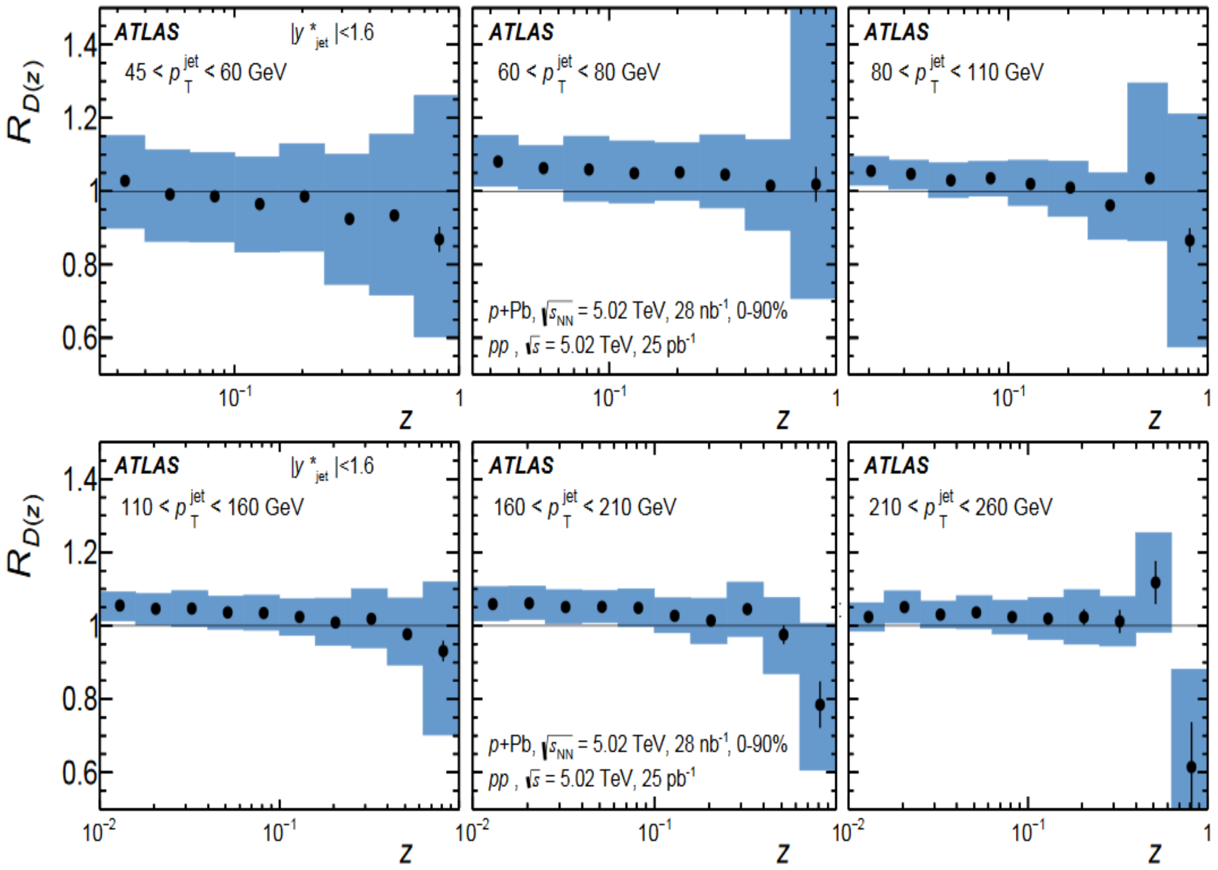
LHCB Coll



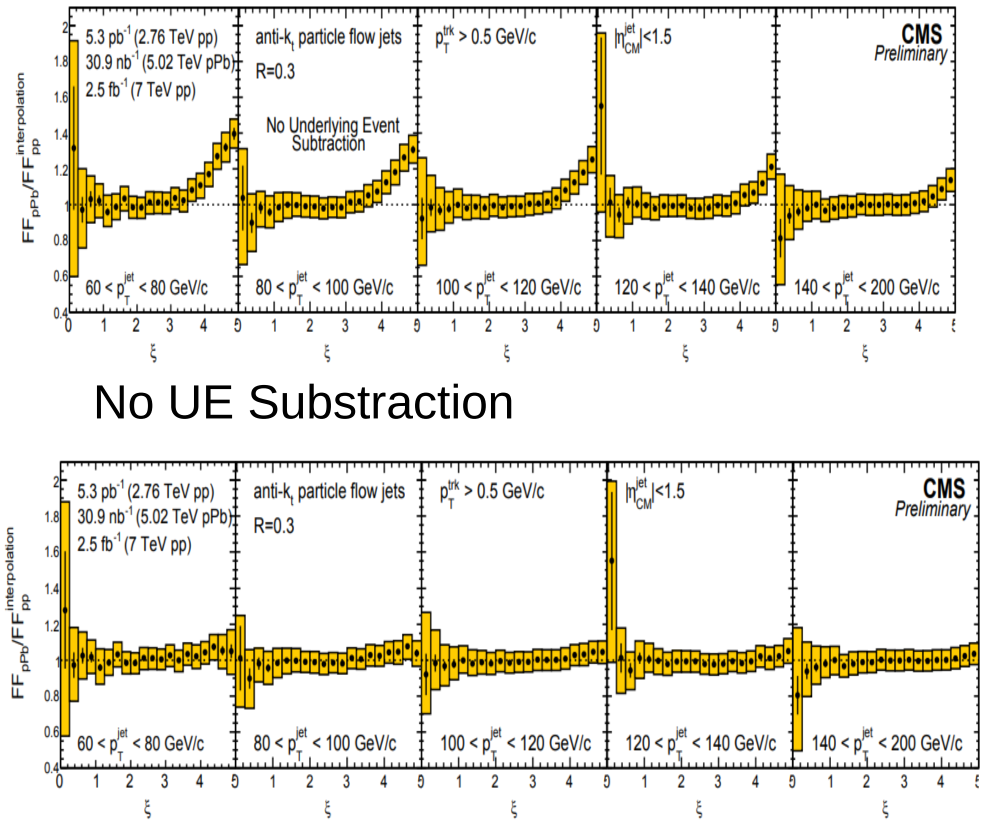
Transition from non perturbative (low jt) to perturbative tail (hight jt) is visible Similar for all jet pt bins

ATLAS: jet FF in pA : no mod?

ATLAS Coll. (2018)



CMS PAS HIN-15-004



No UE Substraction

UE Substracted

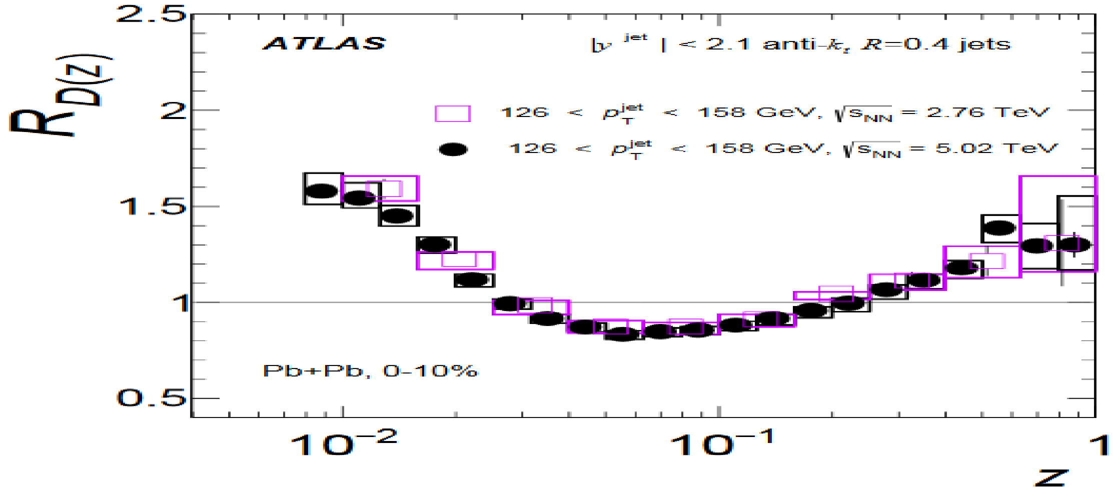
No FF modification observed in pA collisions

ATLAS arXiv:1805.05424

Phys. Rev. C 98, 024908 (2018)

ALTAS: jet FF in PbPb @ 5.02 TeV

ATLAS Coll



At 2.76 TeV: ATLAS Enhancement at large z not seen by CMS (see backup slide)

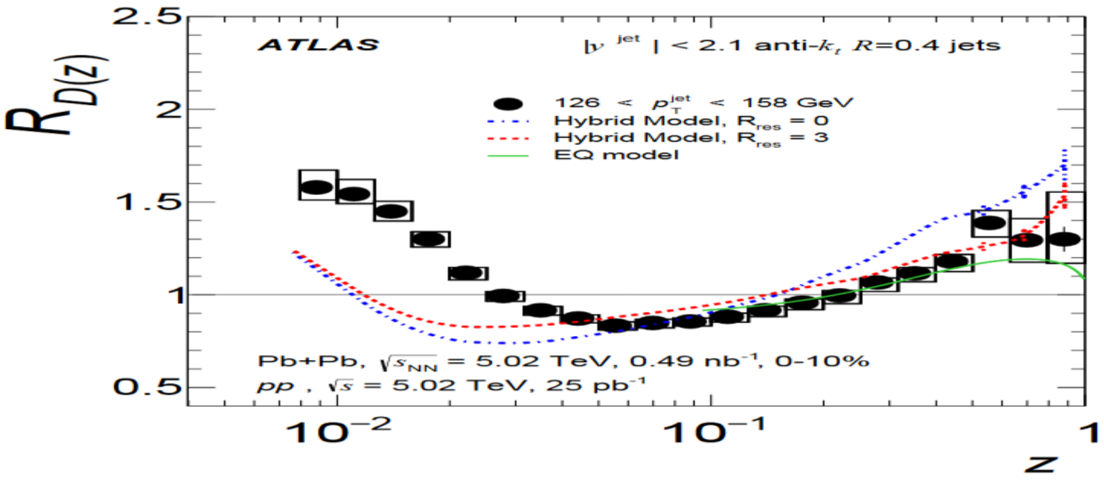
At 5.02 TeV: In central collisions (0-10%): enhancement at low pT, suppression at intermediate pT, enhancement at high pT in all jet pT bins

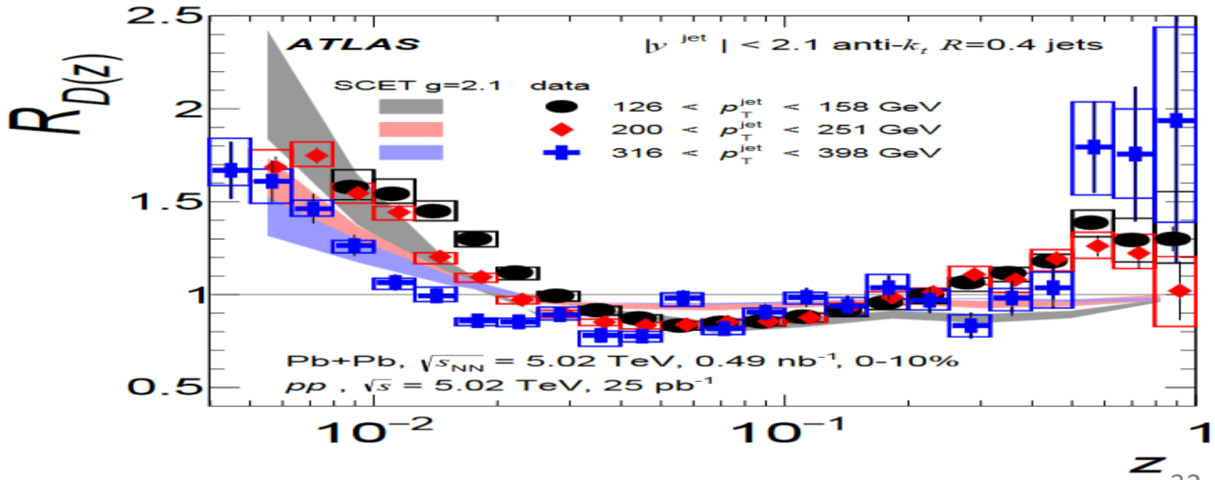
In peripheral collisions (60-80%): the magnitude of these modifications decreases

No jet pT dependence

No CM energy dependence: jet FF comparable between 2.76 and 5.02 TeV

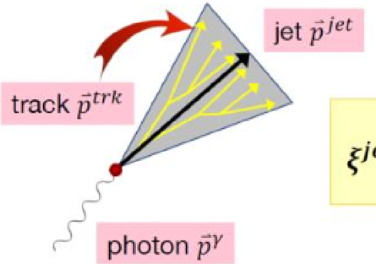
A small dependence with rapidity observed



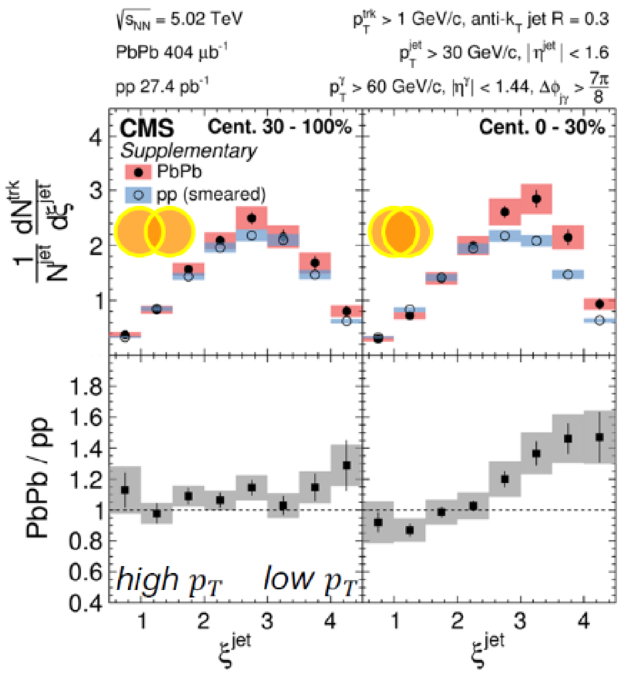


See talk by J. Belichikova HP2020

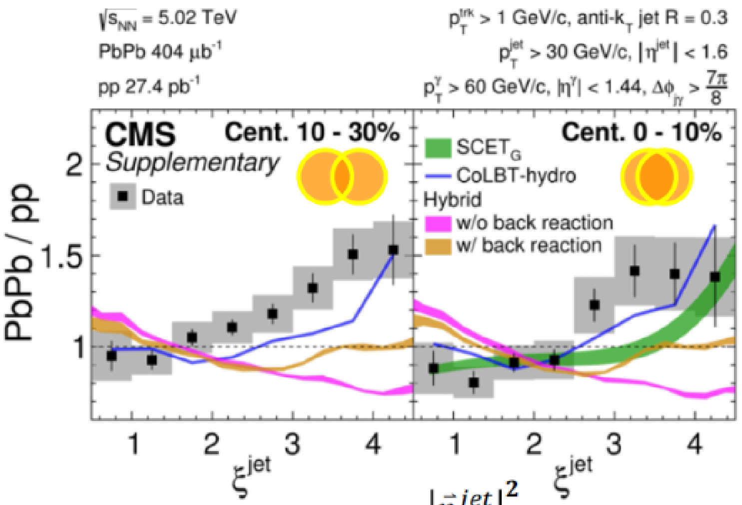
Gamma taged jet FF



$$\xi^{jet} = \ln \frac{|\vec{p}^{jet}|^2}{\vec{p}^{trk} \cdot \vec{p}^{jet}}$$



PRL 121 (2018) 242301



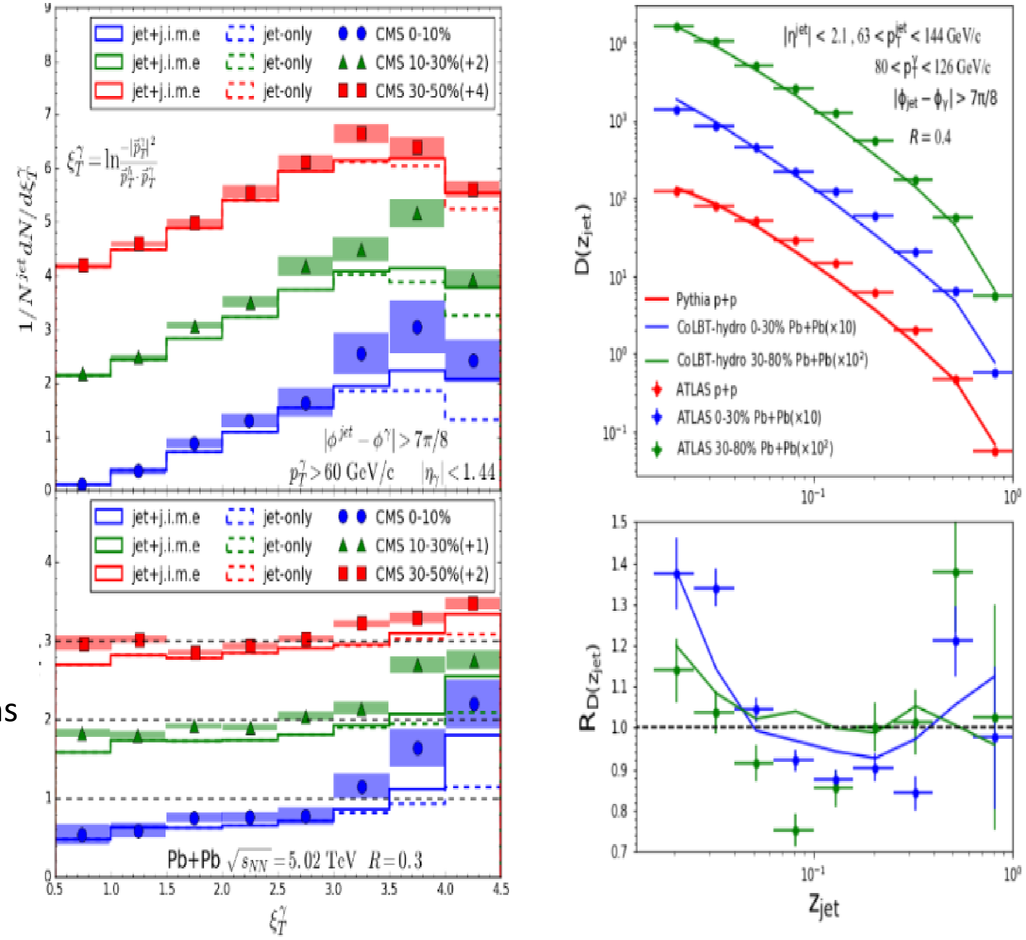
$$\xi^{jet} = \ln \frac{|\vec{p}^{jet}|^2}{\vec{p}^{trk} \cdot \vec{p}^{jet}}$$

Energy redistribution into soft particles (multiple scattrting, gluon radiation and medium excitation)

Excess of lox pt particles (many due to medium response) and depletion at high pt in central collisions (similar behaviour at RHIC for γ-h correlations)

Hybrid model: back reaction needed, but not sufficient

SCET$_G$ and CoLBT-hydro qualitatively describe the trend

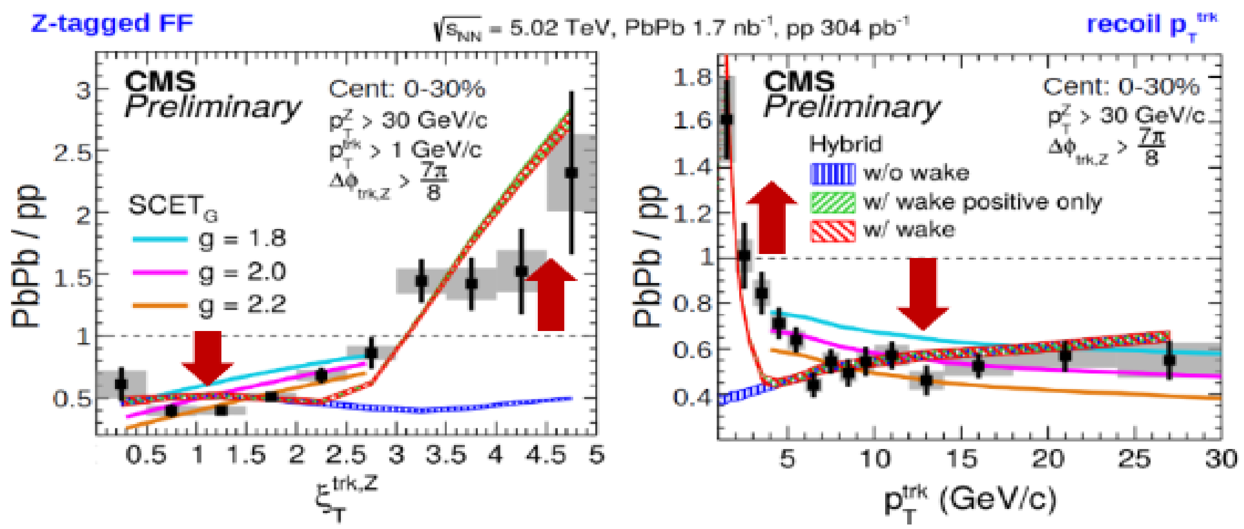


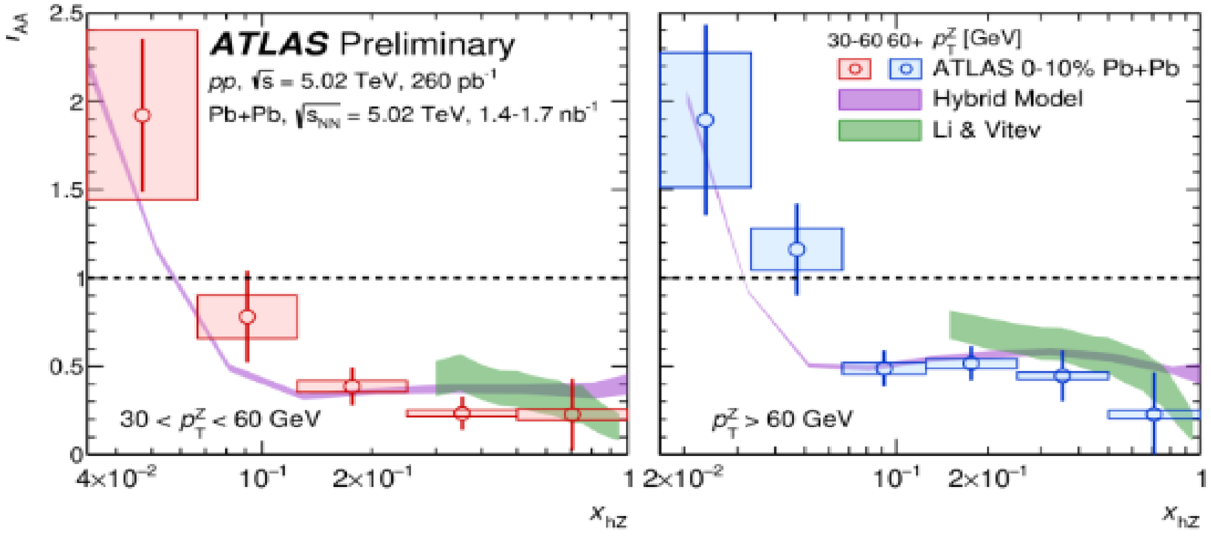
W. Chen, S. Cao, T. Luo, L.-G. Pang, X.-N. Wang, 2005.09678

ALTAS: z taged jet FF

CMS PAS HIN 19 006 & arXiv:1902.10007

SCET$_G$ PRD 93 (2016) 07403(
PRD 101 (2020) 07602
Hybrid JHEP 1410 (2014) 019

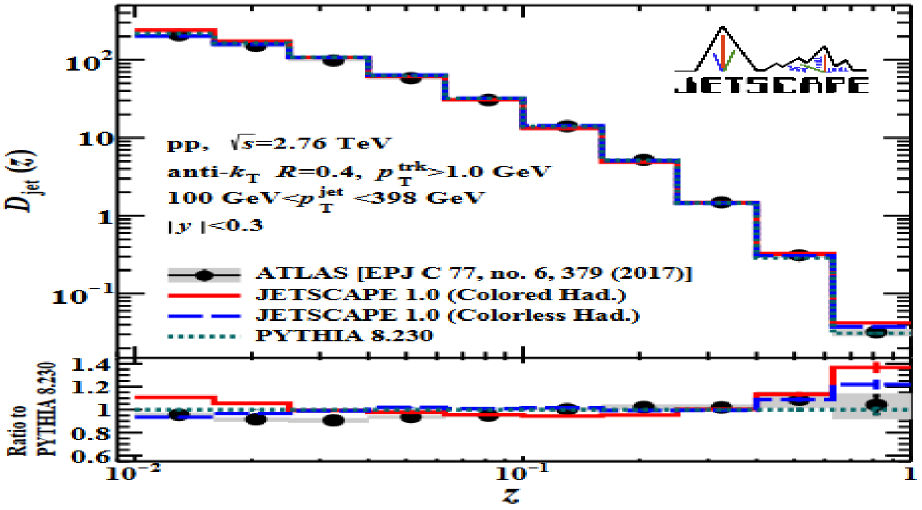


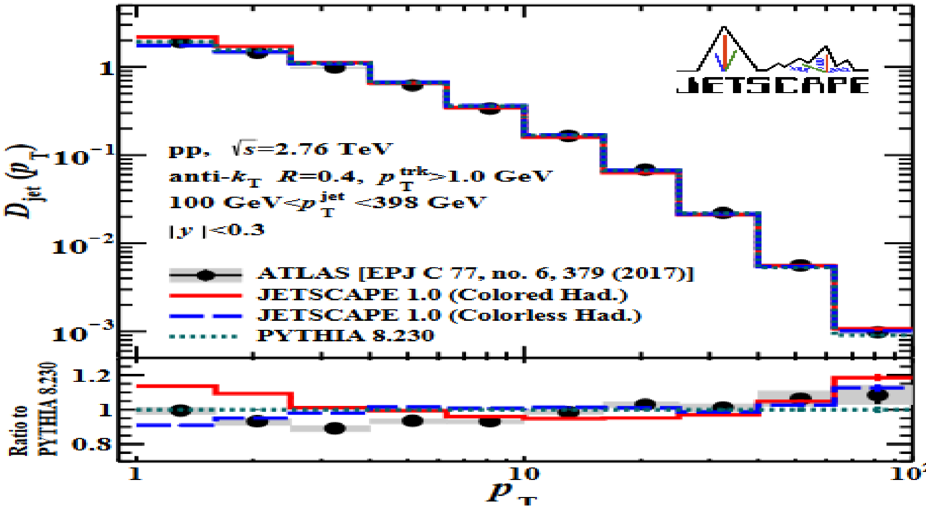


Excess of low momentum particles and depletion of high pt particles
Similar to gamma-tagged correlations

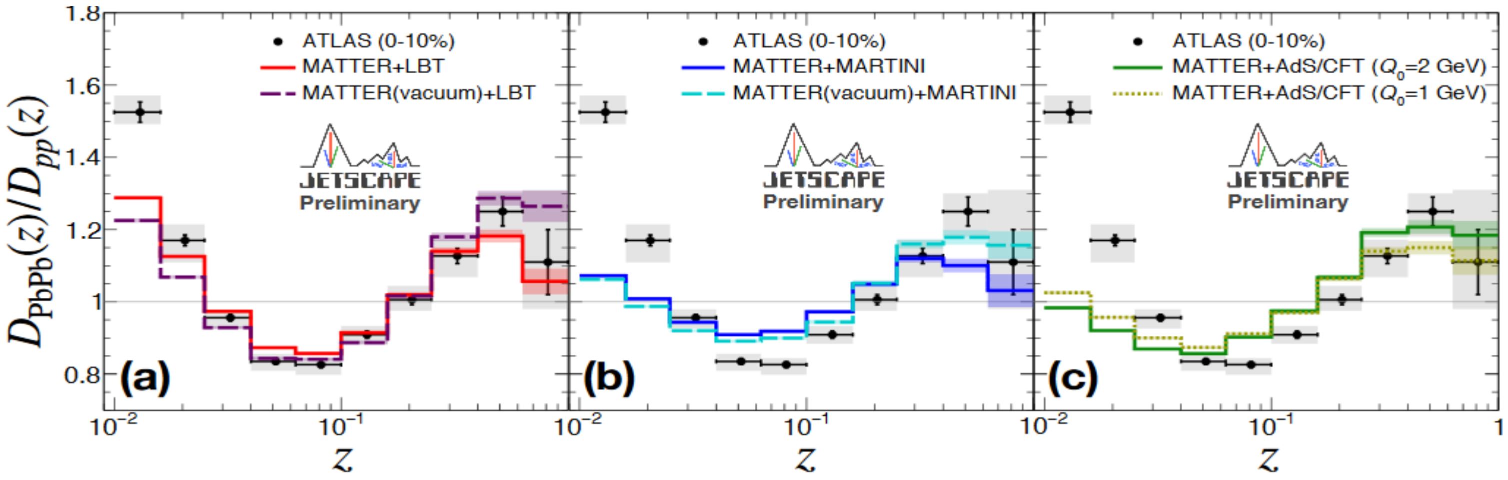
Need to improve jet medium response to jets
SCETg describes the data
The hybrid model with medium wake under estimate the data at intermediate pT

ALTAS: jet FF vs JetScape



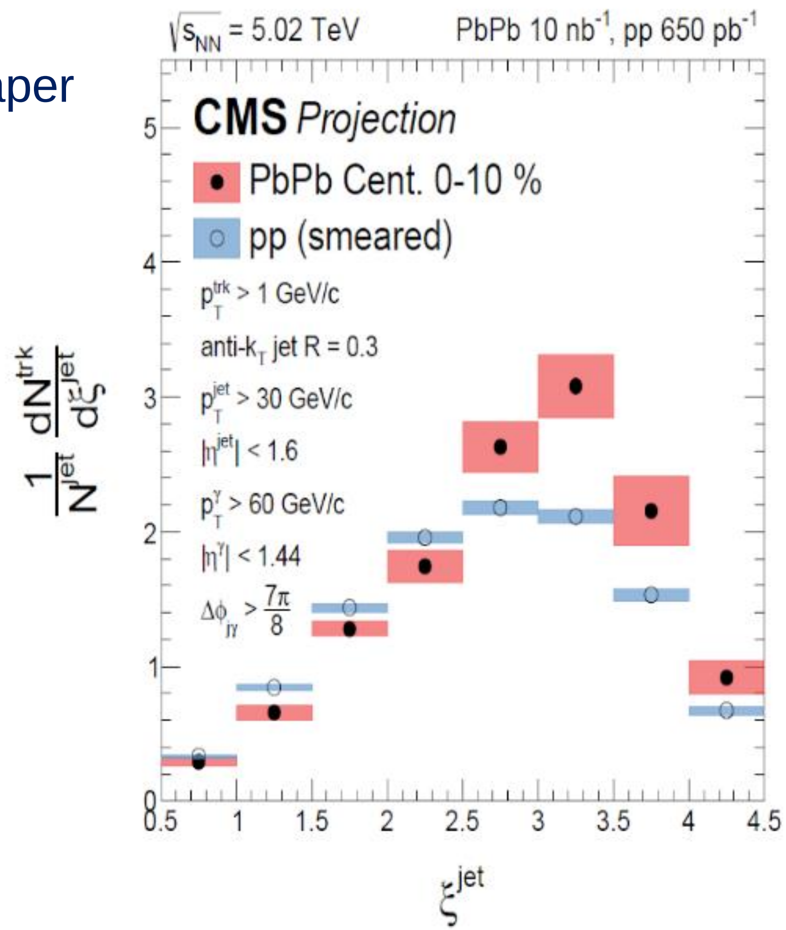


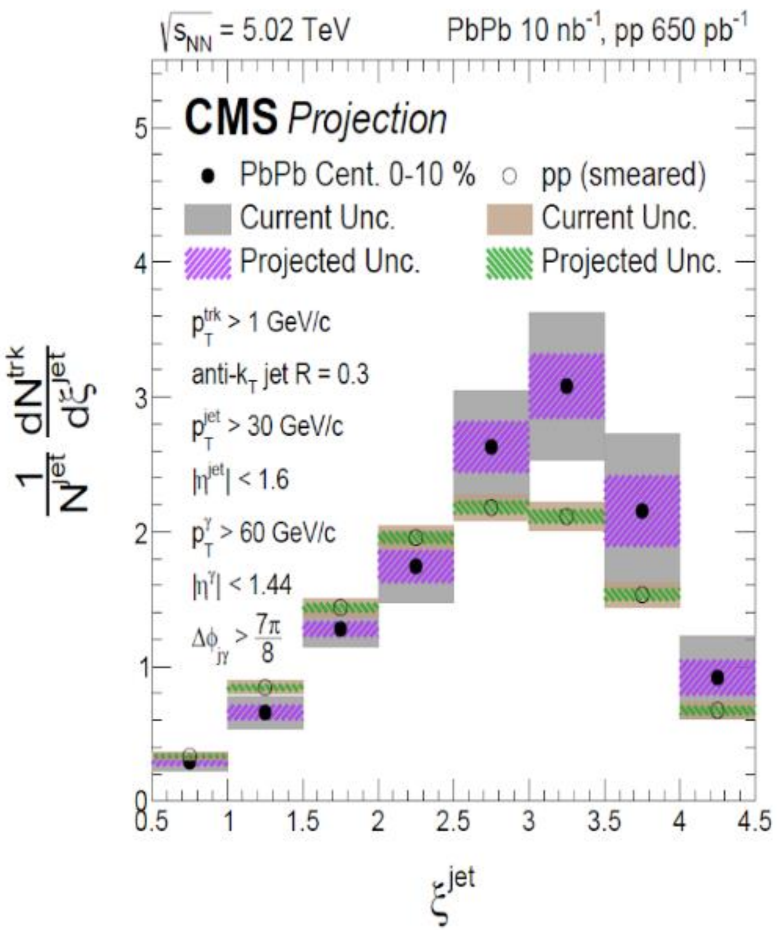
good agreement between ATLAS data and JETScape predictions (pp & PbPb – Matter + LBT except at very low z)



FF@HL-LHC

HL-LHC
White paper





HL-LHC: L~10^34 $cm^{-2}s^{-1}$
Same order of magnitude expected for the EIC
Current unc. Compared to projected onces

Summary / outlook

A lot of existing results were discussed from a very wide range of energies and several colliders.

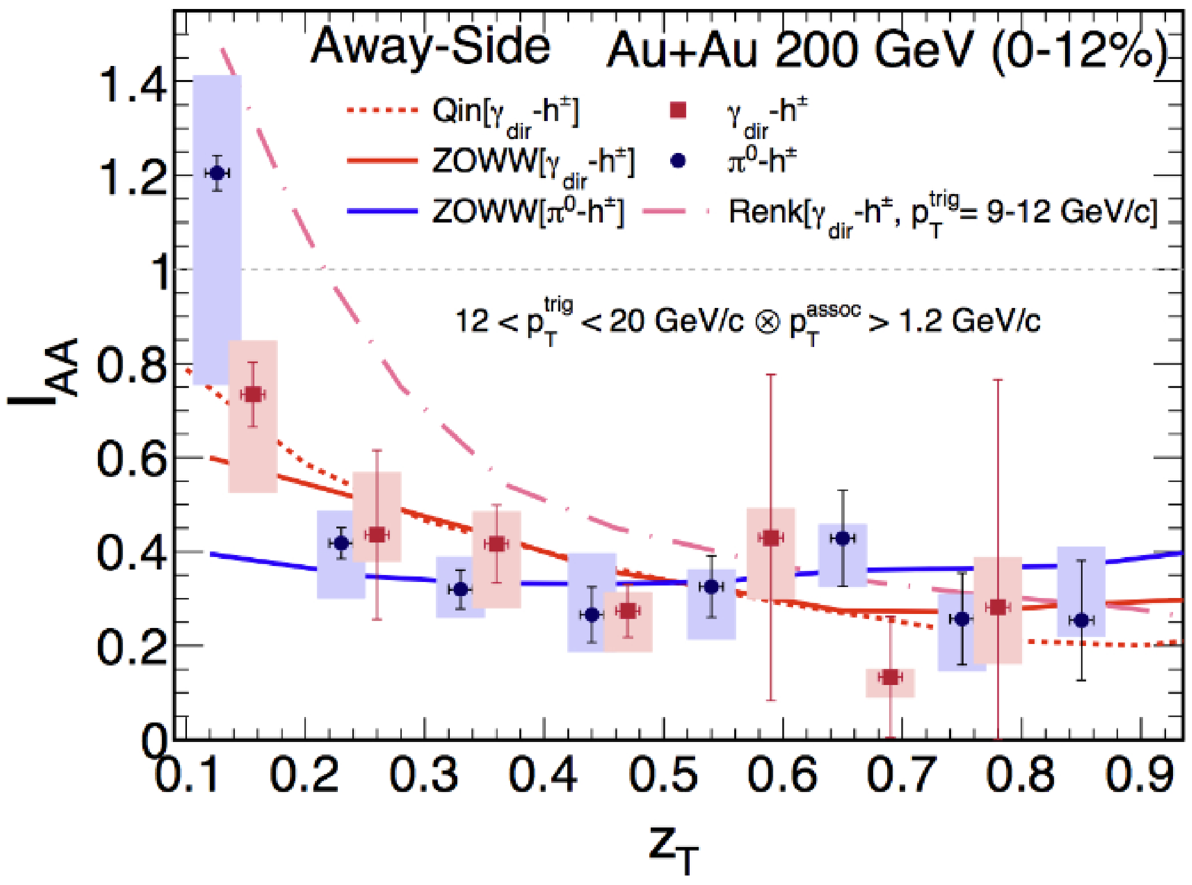
The jet cross-section is well described by pQCD over several orders of magnitude
Jet spectra and the nuclear modification factor Raa is affected by a large background fluctuating event by event
New technics (e,g, ML) are used to extend the measurements to larger jet resolution parameters

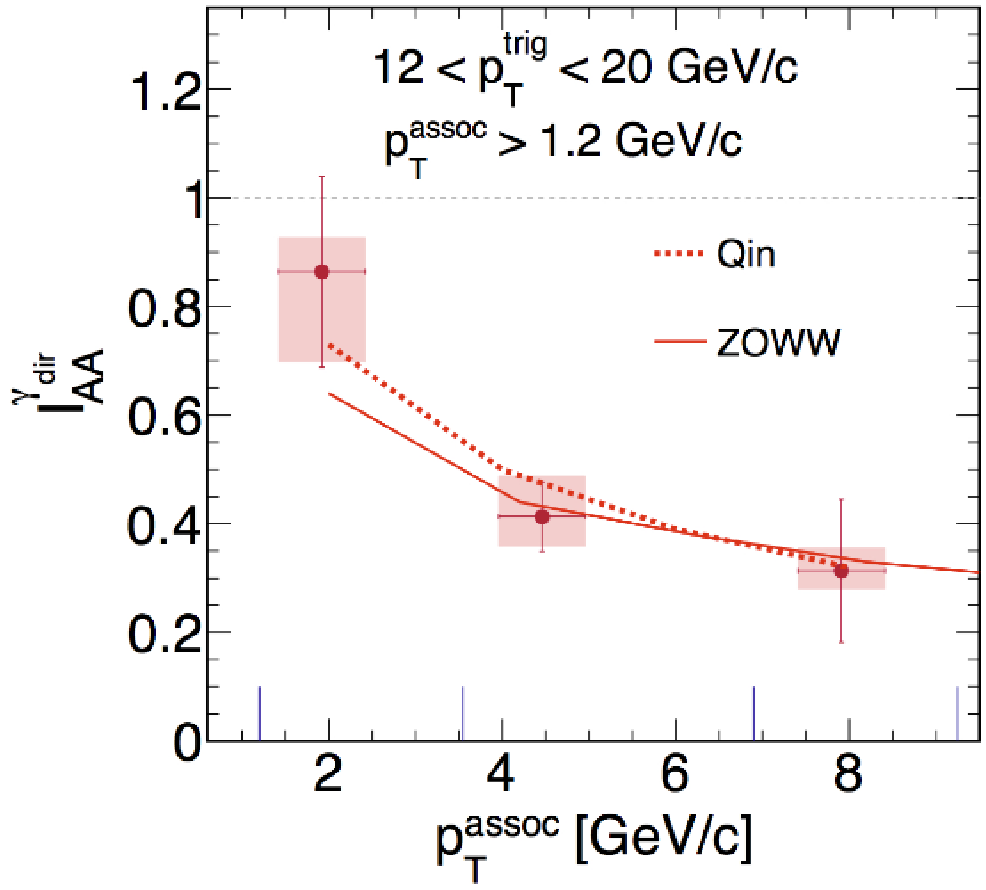
Jet Fragmentation functions:
- e+-e-, DIS and In pp results can be compared to pQCD calculations (eg MLLA)
  The large fluctuating background (and its response to jets) plays a big role for measuring jet FF and needs to be treated with care and improved theoretical treatment.
  In p-A no medium modifications are seen
  In heavy ions, jet FF are seen to be modified (reflecting the redistribution of jet energy in the medium).

- Resent results were discussed e,g heavy quarks as well as gamma-and z-tagged FF
Those will become easier with increasing luminosity (HL-LHC and EIC)
In the future **flavor dependent identified fragmentation** should be studied.
q/g separation is becoming possible as well
The new EIC project hosted by BNL should help accessing the gluon sector as well as to study Mass and flavor dependence of (identified) jet Fragmentation functions (simulations have started).

Backup

Star pi0-h gamma-h Iaa

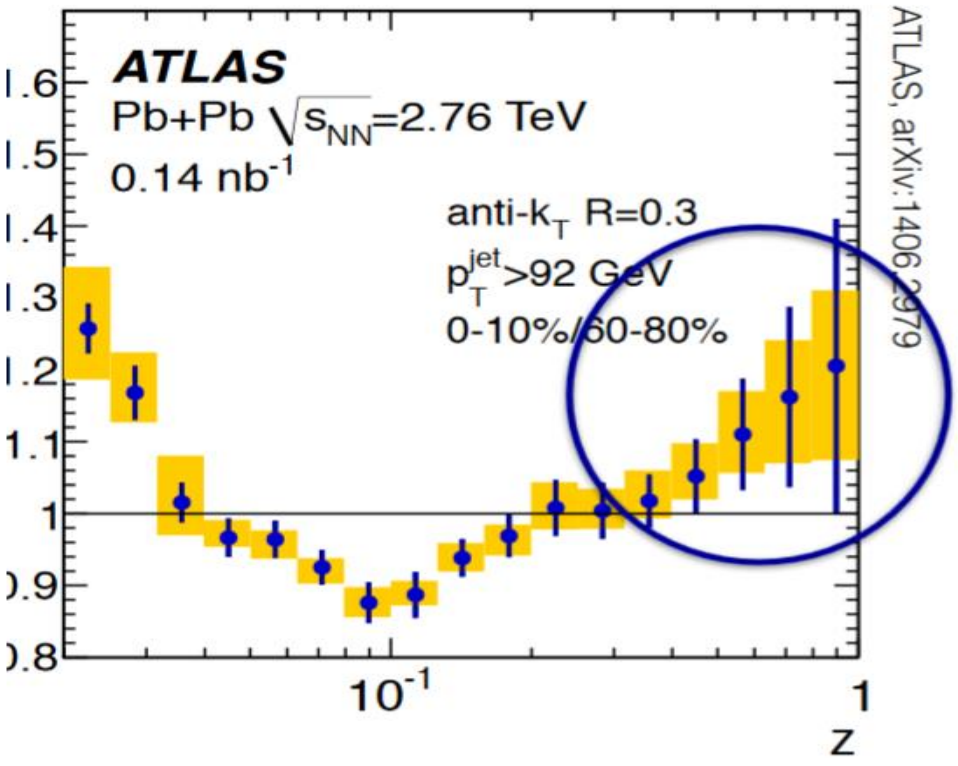


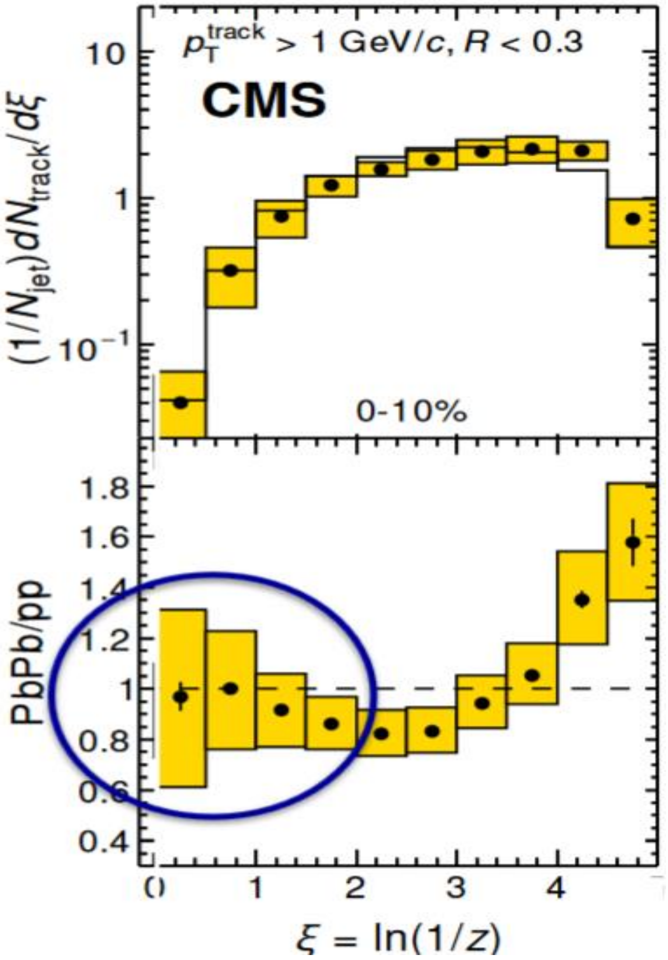


ATLAS vs CMS FF@2.76 TeV

CMS Coll arxiv:1406.0932

ATLAS Coll.

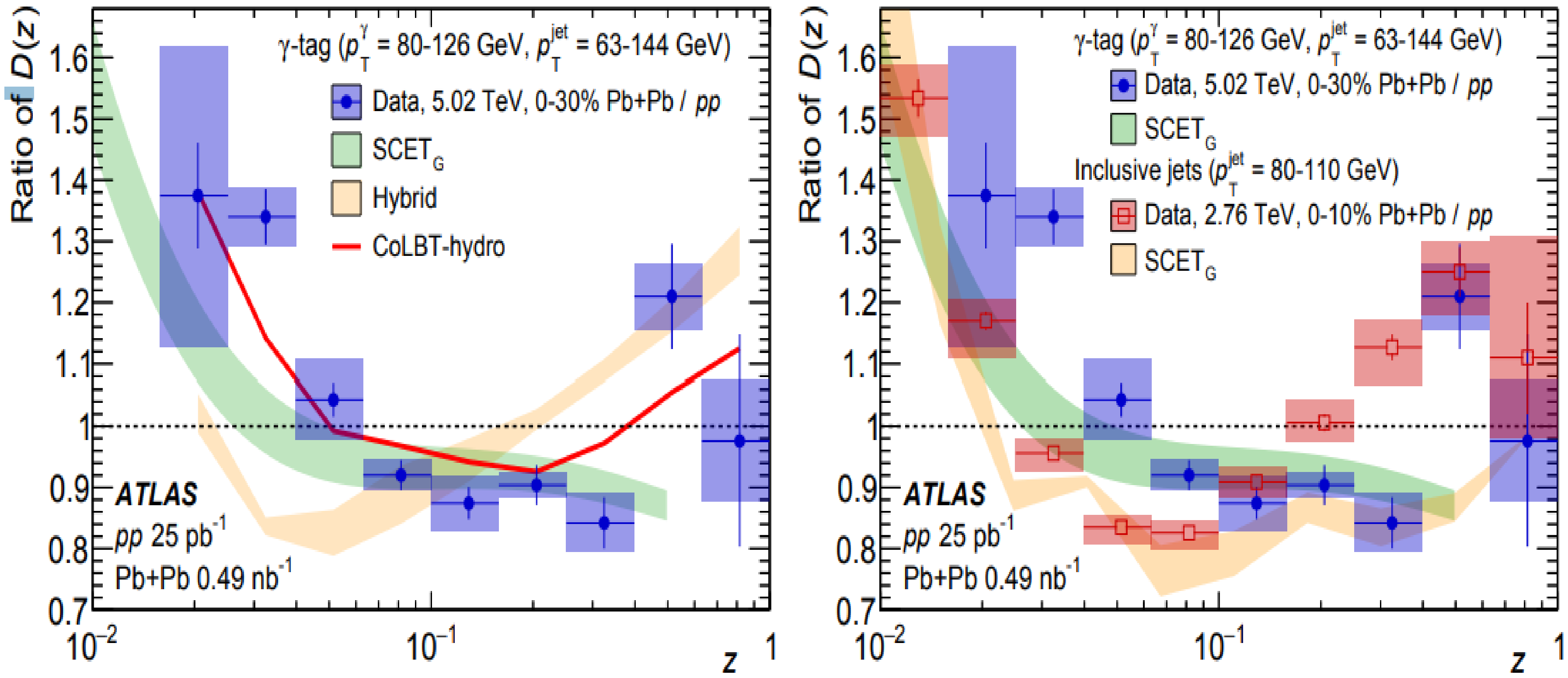




ATLAS Enhancment at large z not seen by CMS

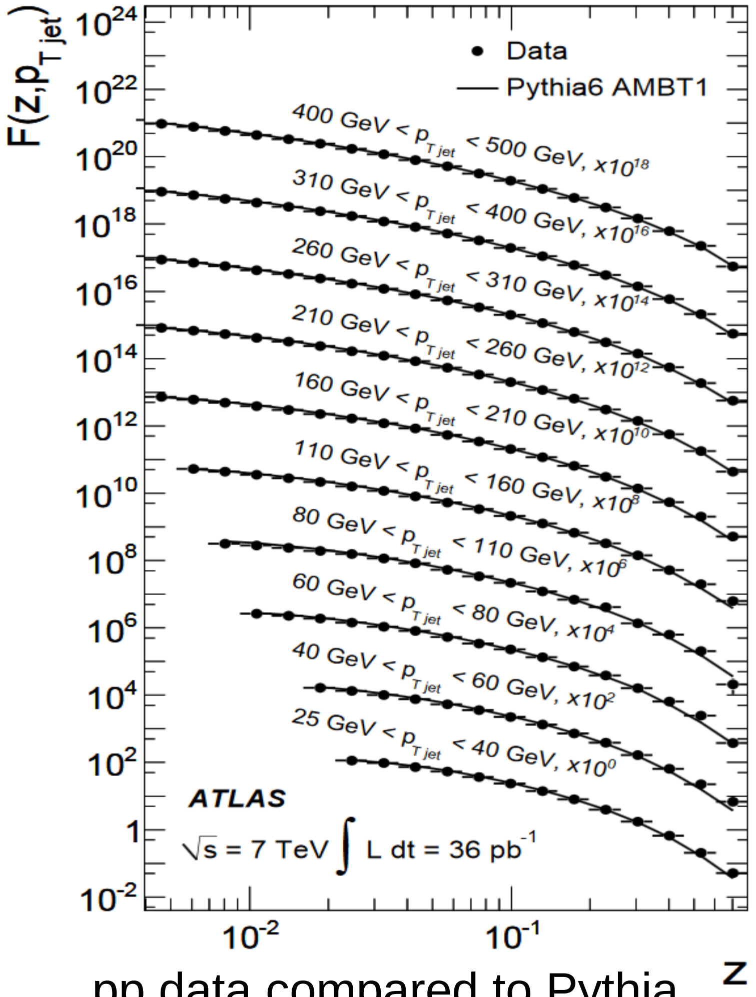
gamma taged jet FF ATLAS

ATLAS coll. PRL 123, 042001 (2019) arxiv::1902.10007



FF ATLAS 5 & 7 TeV

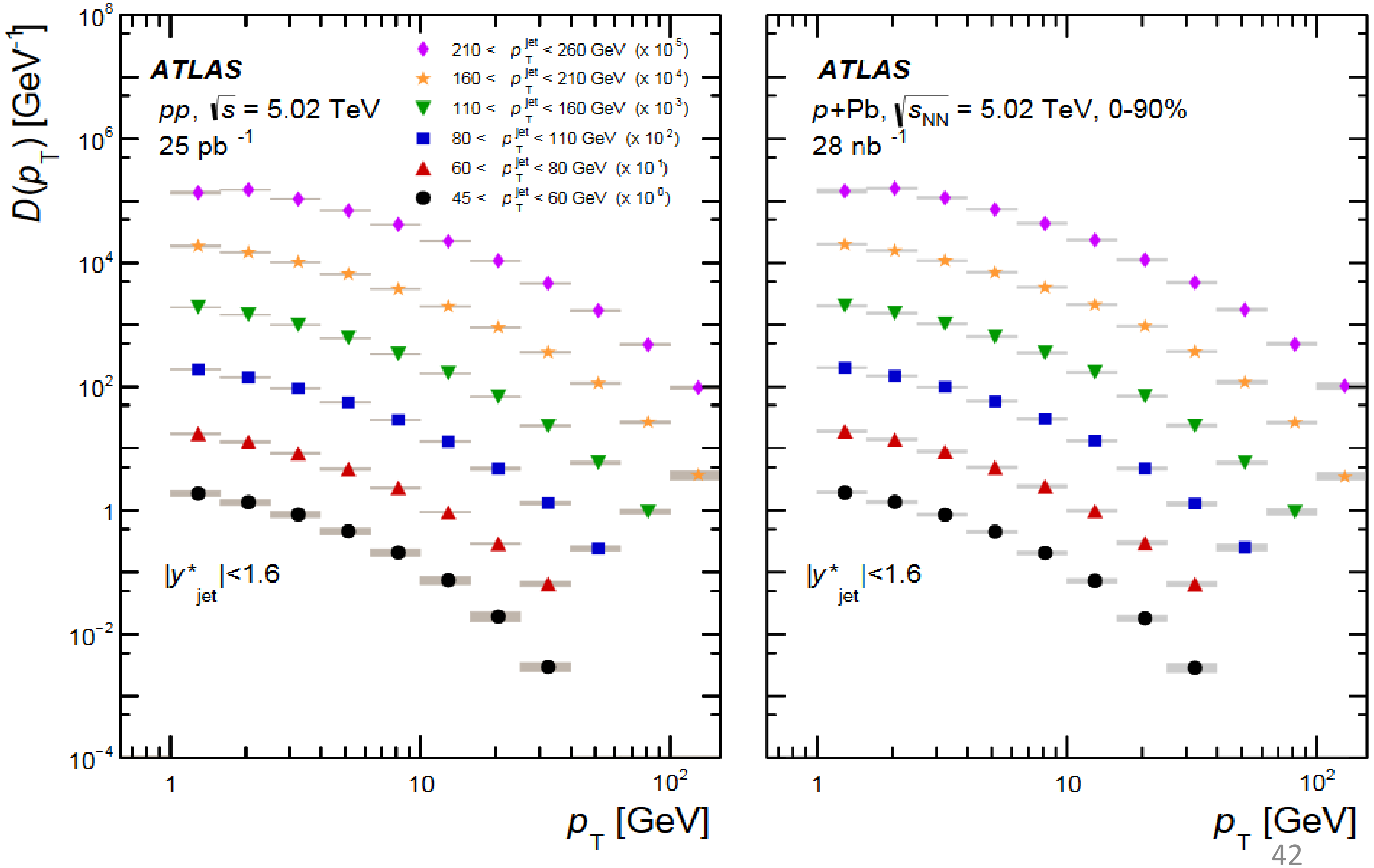
ATLAS Coll. arxiv::1109.5816



pp data compared to Pythia

$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{dN_{\rm ch}}{dz},$$

arxiv.org::1706.02859



SCET & SCET$_G$

Slide from I. Vitev

- Jet physics presents a multiscale problem, EFT treatment

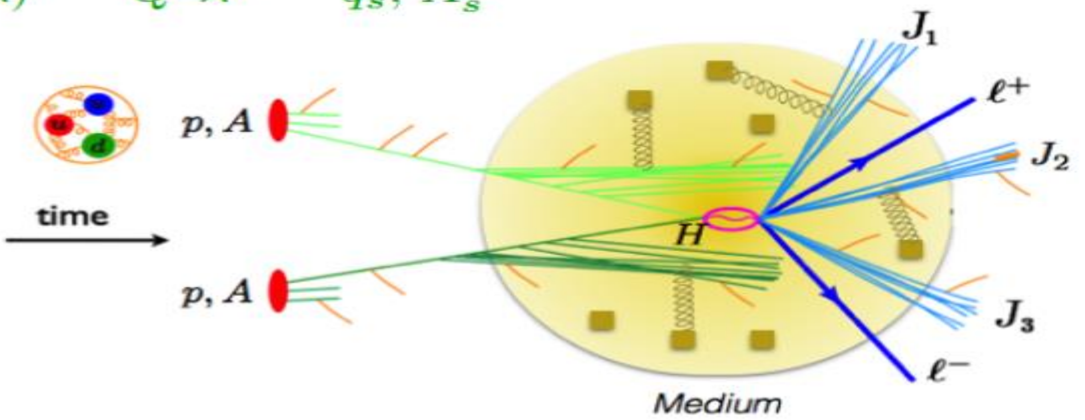
D. Pirol et al. (2004)

C. Bauer et al. (2001)

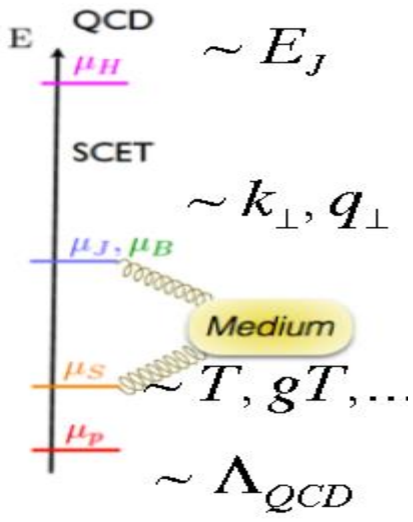
SCET (Soft Collinear Effective Theory)

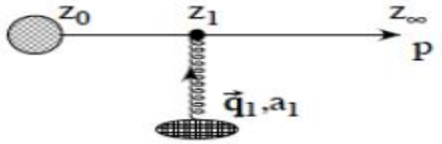
modes	$p^\mu = (+, -, \perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$

$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j \cdot$$



- Factorization, with modified J, B, S





Glauber gluons to mediate physical interactions with the QCD medium

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

A. Idilbi et al. (2008)

Ovanesyan et al. (2011)