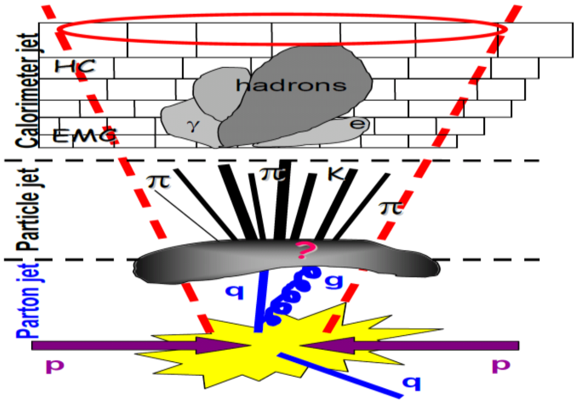
Jet Fragmentation towards an EIC

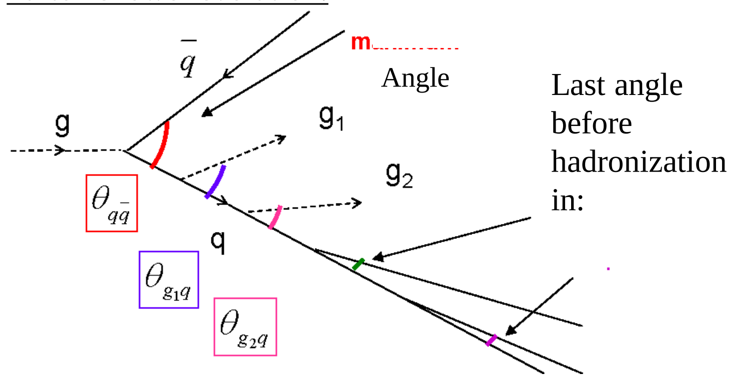
Alexandre SHABETAI
SUBATECH CNRS/IN2P3
Nantes France

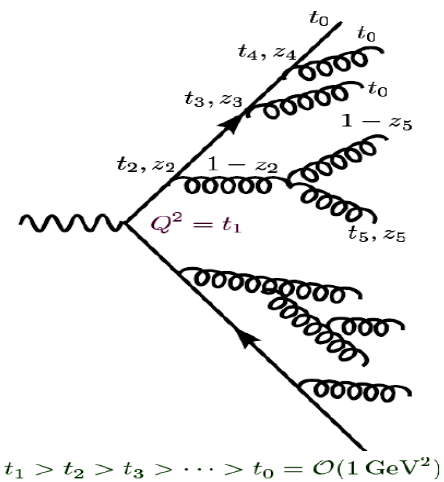
Jet Fragmentation: Motivations



- 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:





$$\frac{d^3\sigma_{p+p\to h+X}}{dy\,d^2p_T} = \int dx_a \int dx_b G_{p\to a}(x_a,\mu_i^2) G_{p\to b}(x_b,\mu_i^2) \times \frac{d\hat{\sigma}_{a+b\to c+X}(Q^2)}{d\hat{t}} \frac{D_{c\to h}(z,\mu_f^2)}{\pi z}.$$

Jet production and Fragmentation @ RHCIC and in ALIC@LHC (selected results)

(used to work in the STAR collab. Now woring on jets in ALICE)

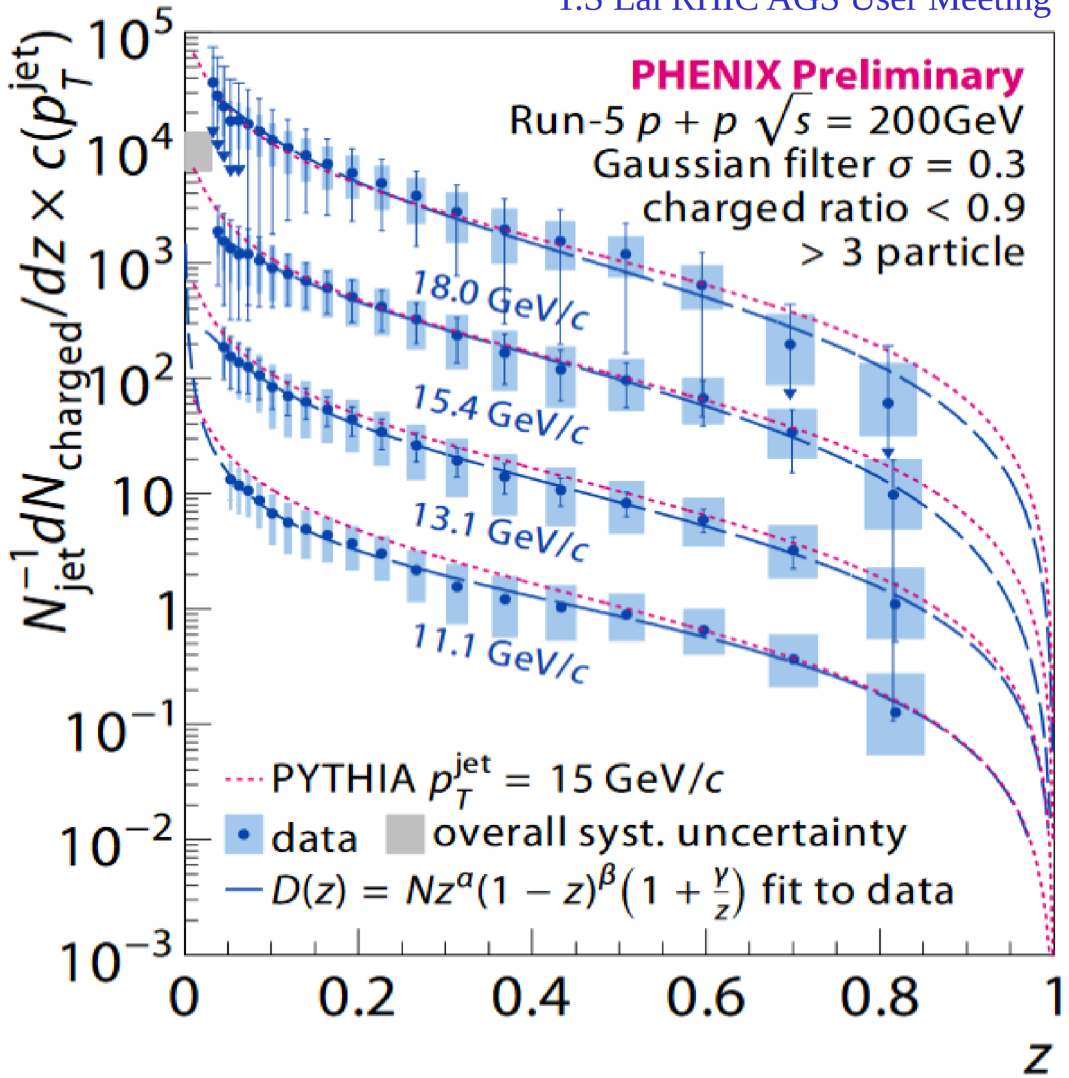
Jet Fragmentation
In pp: baseline (QCD color coherence)
What about Color Reconnections ?
In pA: no modification seen for high pT Jets
In AA modification of jet FF expected (small effect seen)
In the future higher precision measurements w.r.t to **multiplicity**

Phenix: FF

Y.S Lai RHIC AGS User Meeting

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

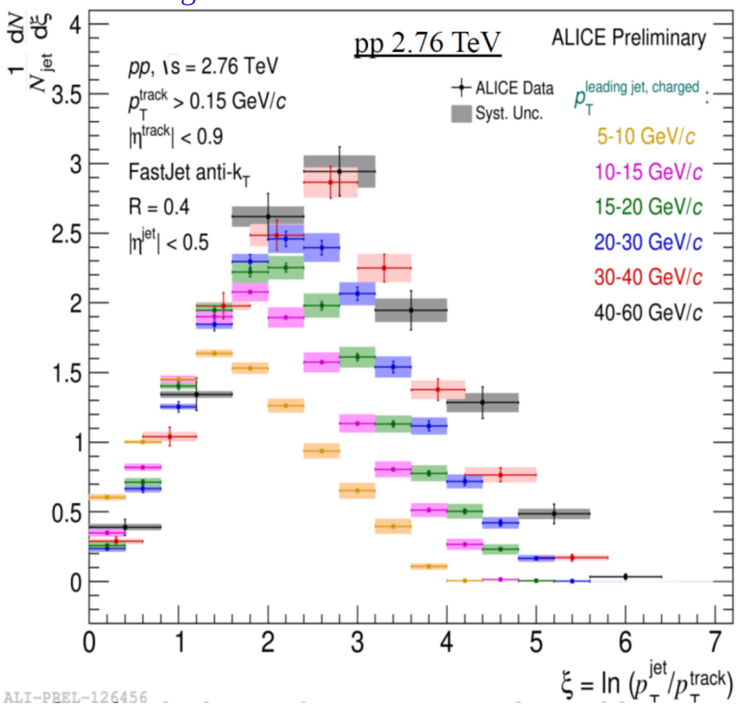
- **Charged particles (with $e^{\pm}$ rejection)**
- $z = p_{\parallel}^{\text{particle}} / p^{\text{jet}}$
- $c(\cdot) = 10^i, i = 0, 1, \ldots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $z_{\max} \approx 0.81$

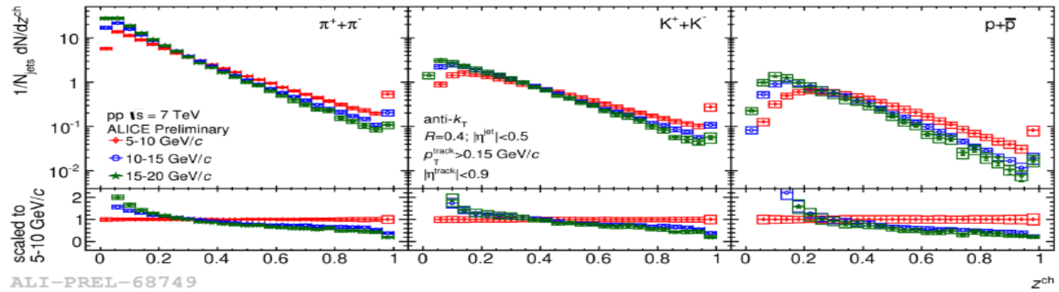


Similar kinematic reach as the one we can expect @ EIC

Inclusive Jet Fragmentation (LHC/HL-LHC) vs Identified Jet FF (ALICE Prelim. Vs HL-LHC)

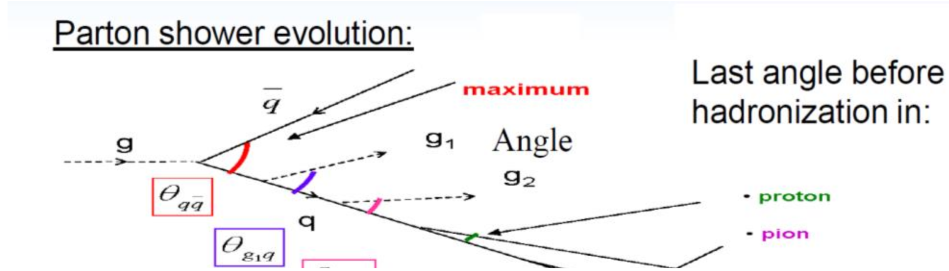
M.Wang PhD Thesis





Good PID also expectred for EIC

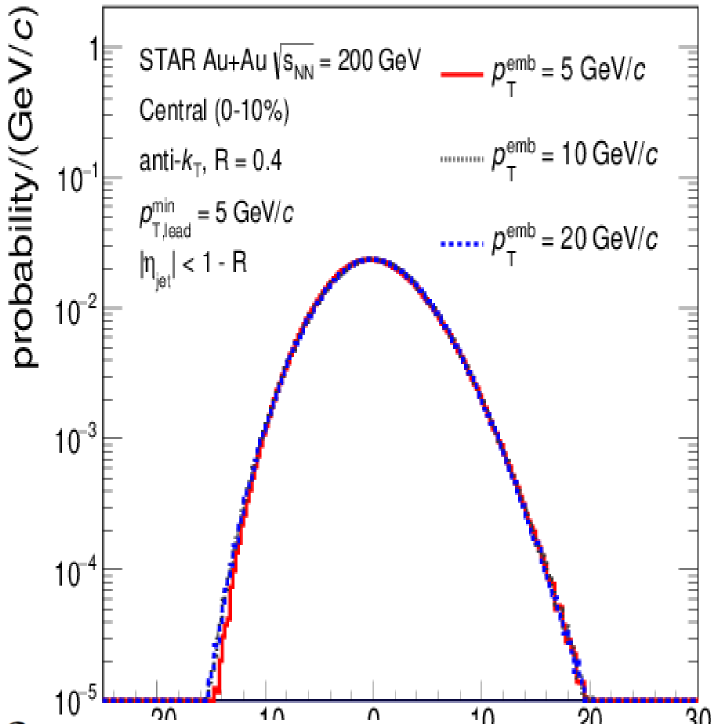
$z^{ch} = p_T^{particle}/p_T^{jet,\ ch}$



QCD color coherence

STAR: Au+Au Jet Spectra @ 200 GeV

arXiv:2006.00582

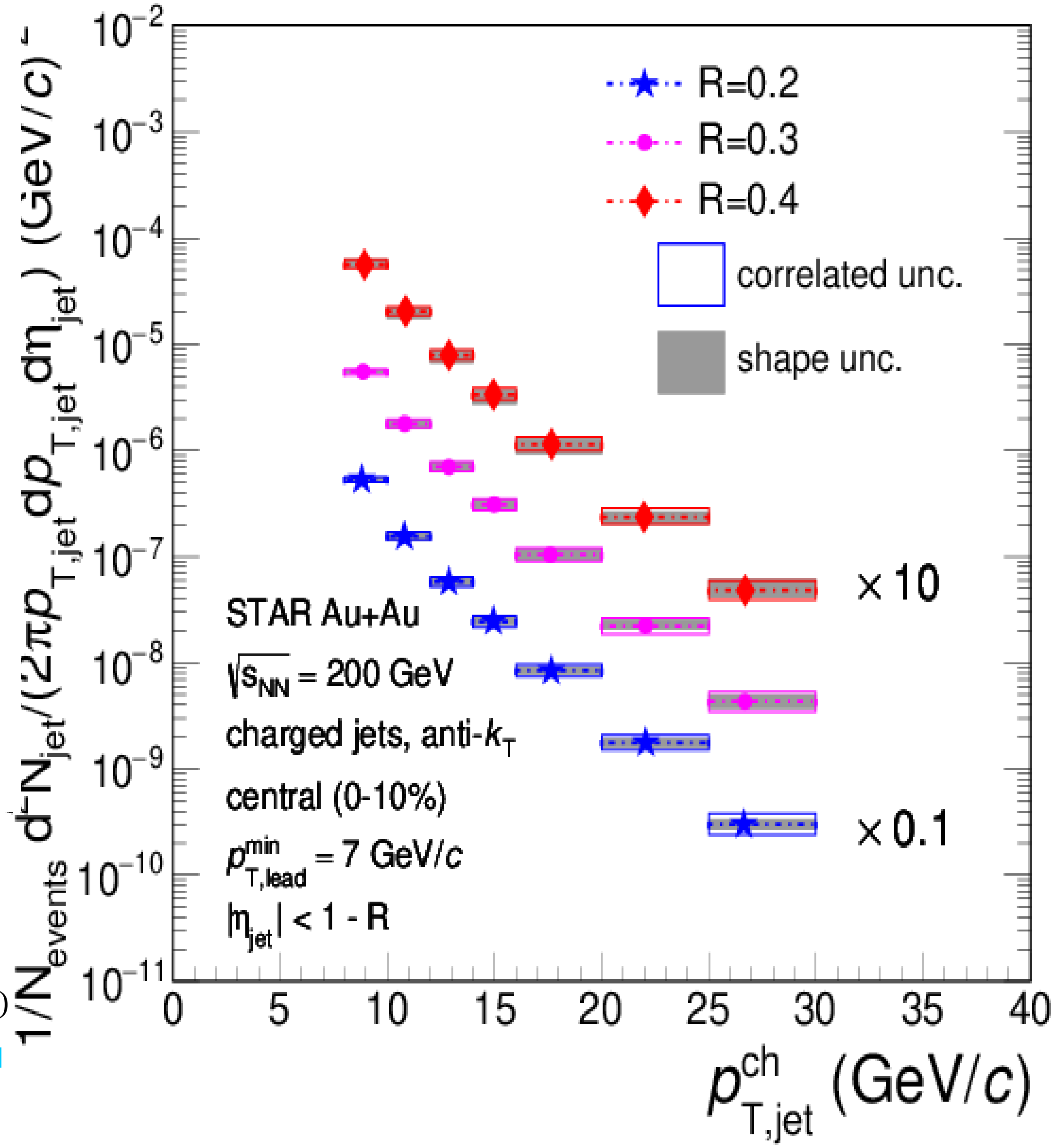


$$\delta p_T = p_{T,rec} - p_{T,true}$$

Background fluctuations and
Fully unfolded jet spetra

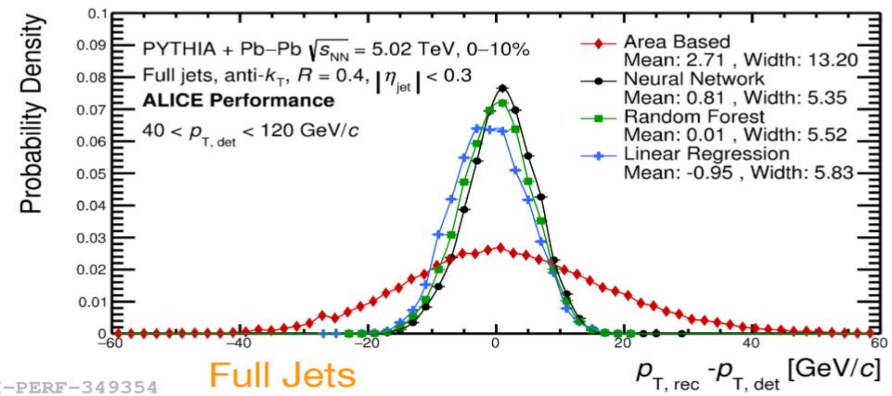
$$p^{min}_{T,lead} = 5 \text{ GeV}/c$$

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

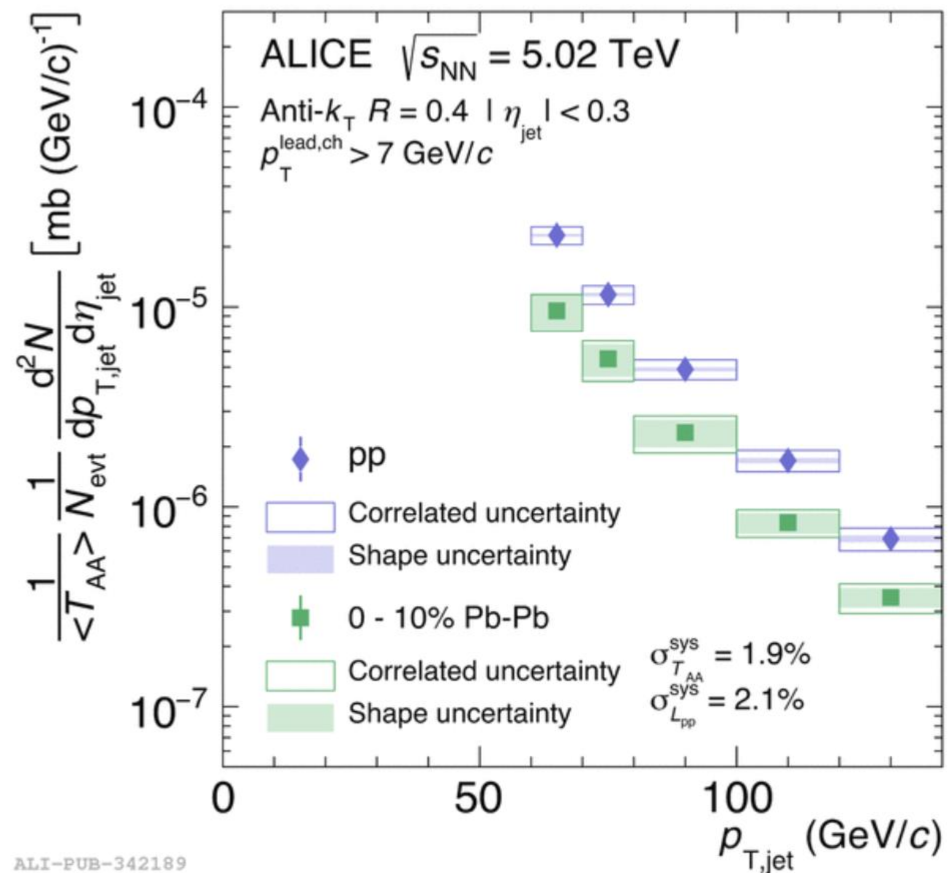


ALICE: Full Jet Sptra @ 5.02 TeV (ML & Std)

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)

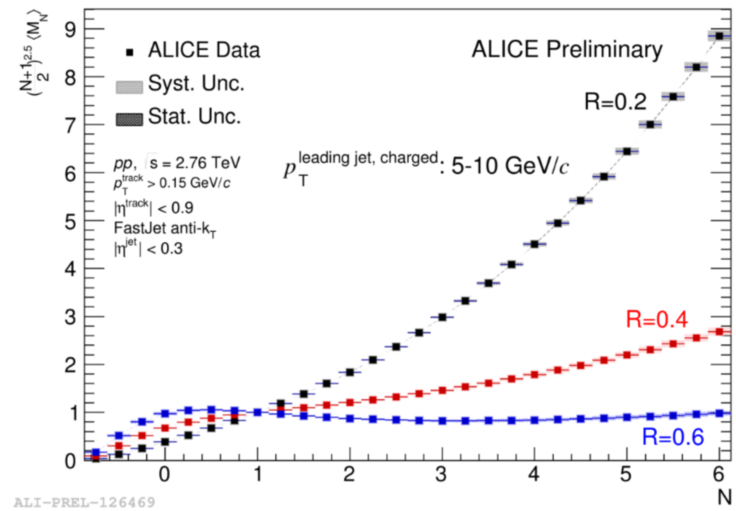
ALICE: Jet fragmentation moments in pp collisions

M.Wang PhD. M.Estienne A.S

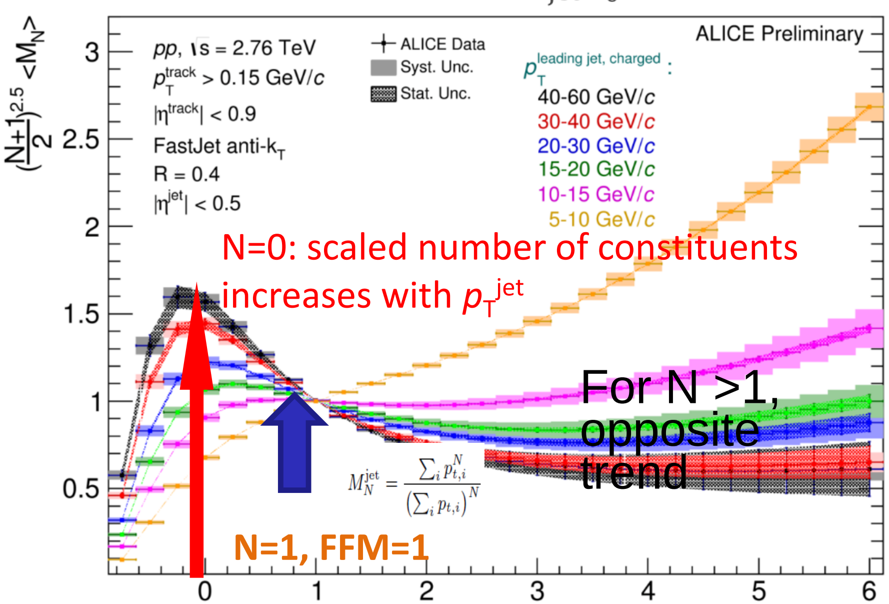
First measurement of the jet fragmentation function moments

$\sqrt{s}$ = 2.76 TeV. Charged jets, 5 < pT < 60 GeV/c R=0.2.R=0.4, R=0.6

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



Strong dependence of the FFM distribution vs R



ALI-PREL-126444

Good agreement between data and PYTHIA Perugia 11

Reference for future Pb-Pb measurements

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

What about EIC from the Jet (framentation) point of view ?

EIC / Jets

- Jets will be studied in all systems (e + e, e + p, p + p, hadron + hadron and nucleus + nucleus)
- Precision probe for studying the partonic structure of matter.
  Study of jets properties which form outside and inside the nuclear medium, in e + A collisions compared to e + p collisions,
- Information on the propagation of partons through nuclear matter and the dynamics associated with the emergence of hadrons from colored partons.
- The evolution of partons in a color field
- Transport coefficients in cold nuclear mater.
- Production of diffractive dijets
- Direct access to Wigner functions
- Access via jets to measurement to the gluon helicity distribution inside the proton and its evolution via the photon-gluon fusion process.

Jet fragmentation functions will be discussed today

EIC Detector Concepts: BNL

BeAST (Brookehaven eA Solenoidal Tracker)

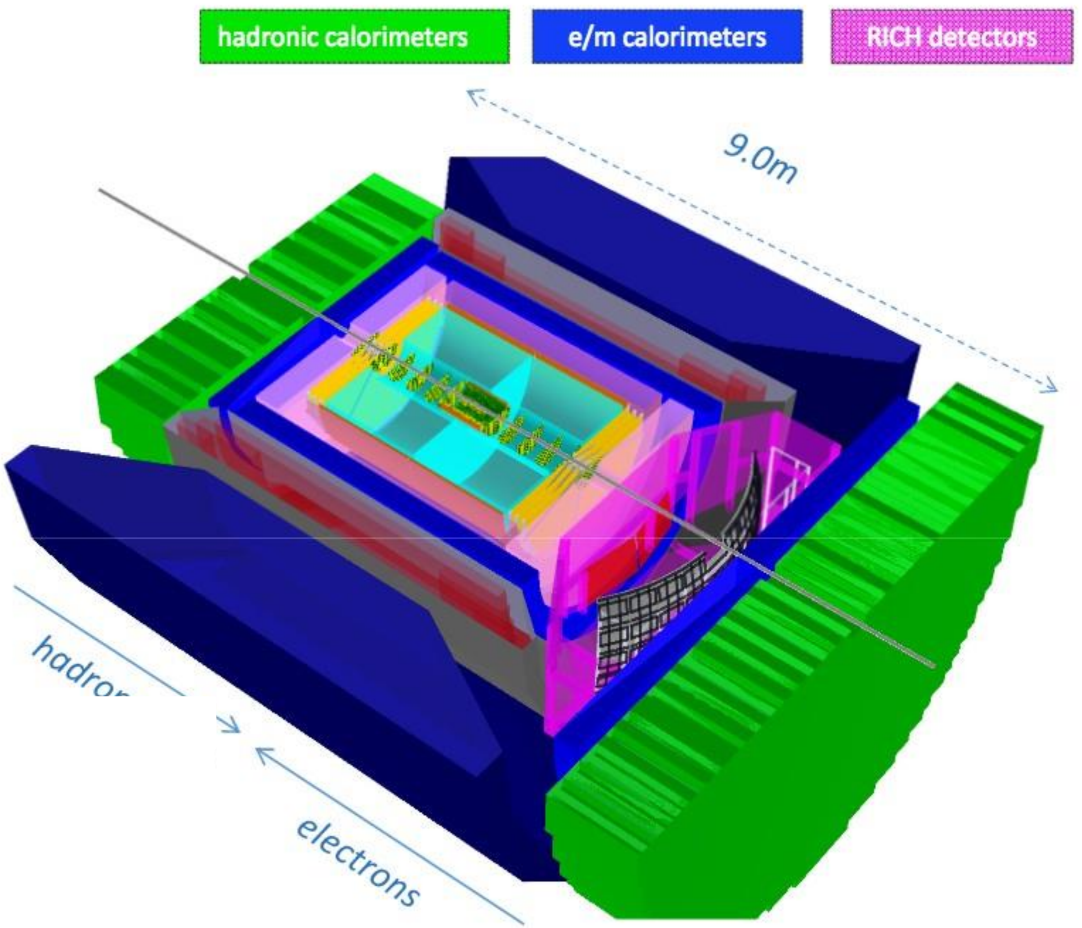
- **From the center outwards:**

✓ Silicon vertex in the center
✓ Trackers
✓ Cerenkov detectors
✓ EM and hadronic calorimeters
✓ Solenoid

- **Detectors are standard collider designs, using latest technologies**

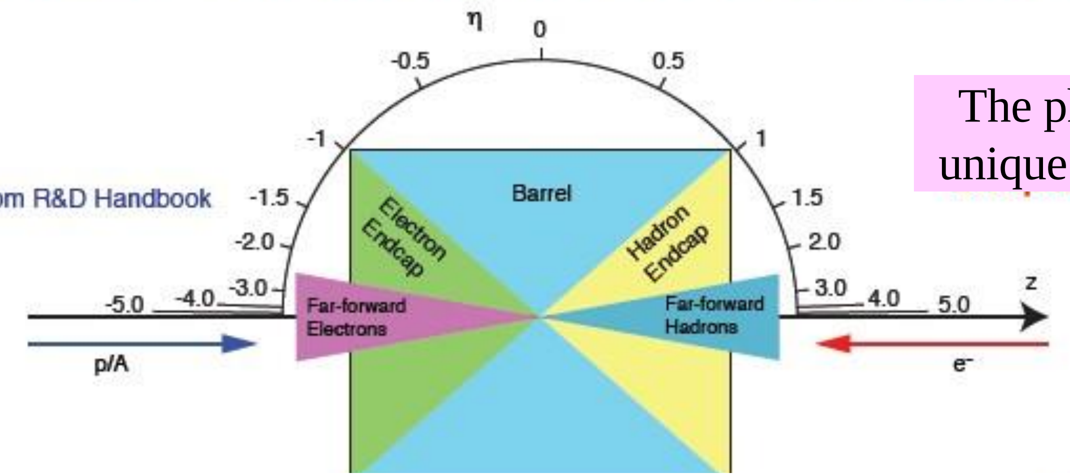
✓ Very similar to RHIC or LHC detectors, with emphasis on PID capabilities
✓ Asymmetry between the hadron and electron sides, with different PID requirements

Superseded by the detector Handbook http://www.eicug.org/web/sites/default/files/EIC_HANDBOOK_v1.2.pdf
and the the Matrix (JLab) https://physdiv.jlab.org/DetectorMatrix/



EIC detector requirements

Detector requirements are mostly **site-independent**, with some slight differences in the forward region (IR integration)



From R&D Handbook

The physics characteristics bring unique challenges to EIC detectors

General requirements:
- Hermetic detector
- Low mass inner tracking, good PID (e/K/p) at wide angle, calorimetry, forward and backwards tracking
- Moderate radiation hardness requirements, low pile-up, low multiplicity

Detector Req.

View Matrix View Model View Help Login to Edit

η	Nomenclature			Tracking			Electrons		π/K/p		HCAL	Muons
				Resolution	Allowed X/X_0	Si-Vertex	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Resolution σ_E/E	
-6.9 to -5.8			low-Q2 tagger	$\sigma\theta/\theta$ < 1.5%; 10-6 < Q2 < 10-2 GeV2								
...												
-4.5 to -4.0	↓ p/A	Auxiliary Detectors	Instrumentation to separate charged particles from photons									
-4.0 to -3.5							2%/√E					
-3.5 to -3.0				σ_p/p ~ 0.1%⊕0.5%								
-3.0 to -2.5												
-2.5 to -2.0			Backward Detector	σ_p/p 0.1%⊕0.5%		TBD	2%/√E		≤ 7 GeV/c		~50%/√E	
-2.0 to -1.5				σ_p/p 0.05%⊕0.5%			7%/√E					
-1.5 to -1.0							7%/√E	π suppression up to 1:10^4				
-1.0 to -0.5												
-0.5 to 0.0				σ_p/p ~0.05%×p+0.5%		σ_{xyz} ~ 20 μm, $d_0(z)$ ~$d_0(r\Phi)$ ~ 20/p_TGeV μm + 5 μm						
0.0 to 0.5		Central Detector	Barrel		~5% or less X				≤ 5 GeV/c	≥ 3 σ		TBD
0.5 to 1.0												
1.0 to 1.5				σ_p/p ~0.05%×p+1.0%								
1.5 to 2.0							(10-12)%/√E		≤ 8 GeV/c			
2.0 to 2.5			Forward Detectors			TBD					~50%/√E	
2.5 to 3.0									≤ 20 GeV/c			
3.0 to 3.5				σ_p/p ~ 0.1%×p+2.0%					≤ 45 GeV/c			
3.5 to 4.0			Instrumentation to separate charged particles from photons									
4.0 to 4.5												
...	↑ e	Auxiliary Detectors	Neutron Detection									
> 6.2			Proton Spectrometer	$\sigma_{intrinsic}(\|t\|)/\|t\|$ < 1%; Acceptance: 0.2 < p_T < 1.2 GeV/c								

For measuring Jets: precise tracking (MAPS) + ECal + HCal are key. Good PID will help

EIC-Smear

- **eic-smear is fast, light-weight, extensible, well-written**

- First stage unifies a host of EIC-relevant MC output

- Cannot replace a full simulation
  – but gives a good estimate of detector effects on observables in <10% of the time it takes to generate PYTHIA6.

Kolja Kauder EIC UG meeting 2019

Detector Matrix used for our FF study
(and EIC-Smear v 1.04-fix1 (EIC sw. release PRO 2020a)

EIC Simulation: jet FF cuts used e+p

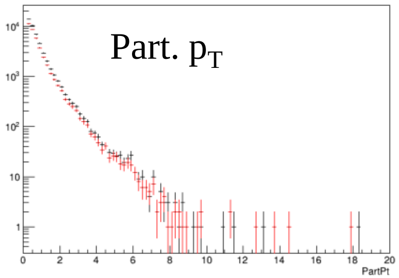
Electron –Proton events generated at $\sqrt{s}$ = 141 GeV using PYTHIA
(Full energy eRHIC design 20x250 GeV electron x proton)

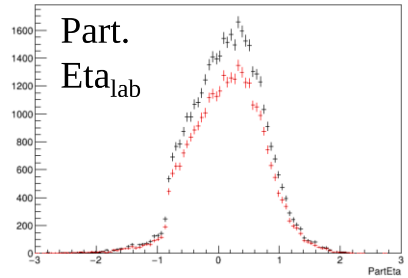
- Cut on inelasticity: $0.01<y<0.95$ 0.
- Jet Algorithm: Anti_kT
- Jets found in Lab frame
- Particles used in jet finding:
- Stable
- $p_T \geq$ 200 MeV
- $\eta \leq 3.0$
- Parent cannot originate from scattered electron

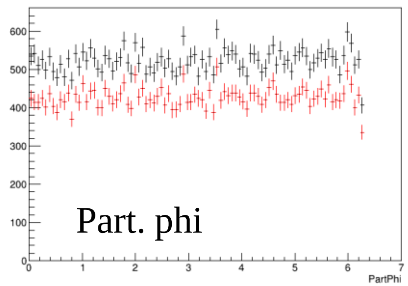
Based on B.. Page's talk (DIS2019)

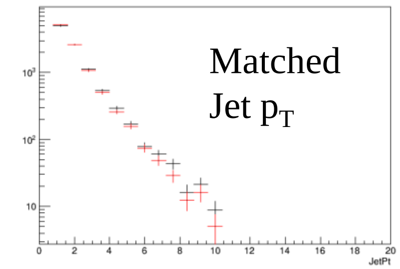
FF simulation in e+p (for EIC) : first look

ep 20x250 GeV √s=141 GeV Uncorrected p_{Tjet} > 5 GeV/c
Charged jets Antik_T R=0.3 $|eta_{jets}|$ < 3 – R; UE not subtracted
no e-/e+/gamma (black: particle level, red: smeared using Matrix_0.1

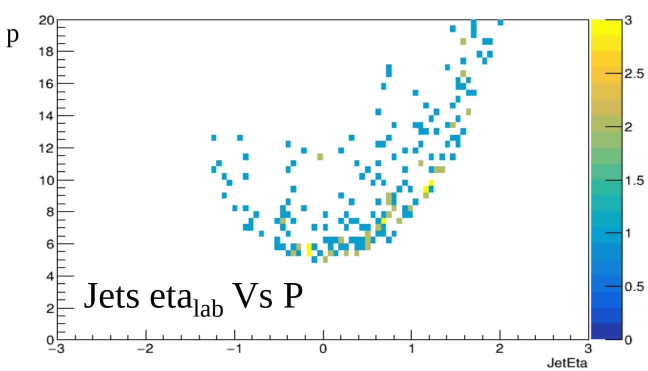


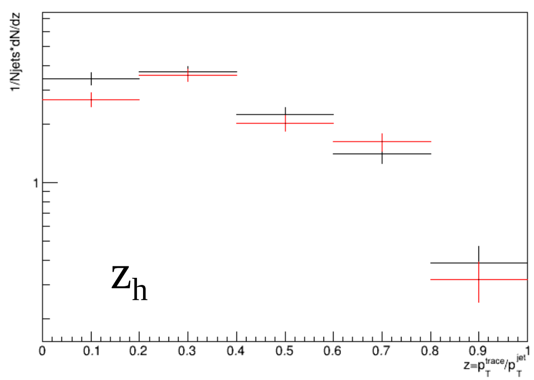


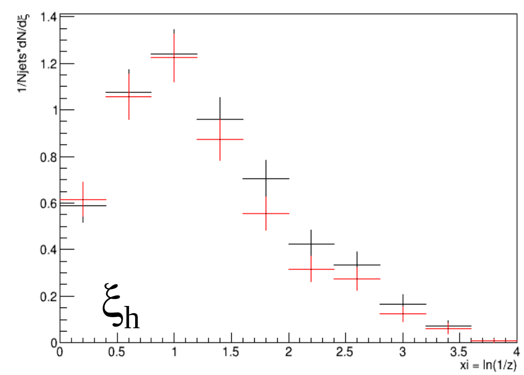




PythiaeRHIC 10<Q^2<1000 GeV^2 10 000 Evts . Lab Frame







Next: to be optimized (p_T jet min, use larger R ref.) and studied as function of sqrt(s), jet resolution parameter R, possibly Q2
Add stat. (see next slide). More statistics will be used soon (Yello Report Events - Thanks Brian)

Fragmentation functions @ EIC next steps

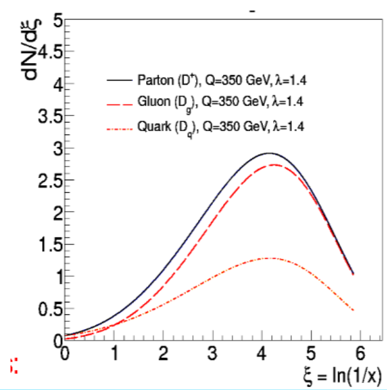
- Started looking at z and JES/JER in e-p using PHYTHIAerhic hiQ2 events (stat limited) smeared using EIC-Smear (see backup slide)

⇒ In order to add statistics could use AGILe (https://agile.hepforge.org) to get HepMC output from the fortran driver.

⇒ That will allow to run it on the fly and on the grid

- 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: candidate for general e+A MC with unique strengths
* e+P baseline:
-Hard process generation done
-Hadronization done à further improvements out of scope
-Infrastructure mostly done à Streamline DIS observable output
-Next: Include into official distribution, fine-tune & validate
* e+A
-Switch to E-loss modules in principle trivial, works
-Next: tuning (e.g., HERMES) and attract users!

Kolja Kauder – BRBC EIC virtual Workshop on jet Observable

Outlook Jets & Prospects (french Community)

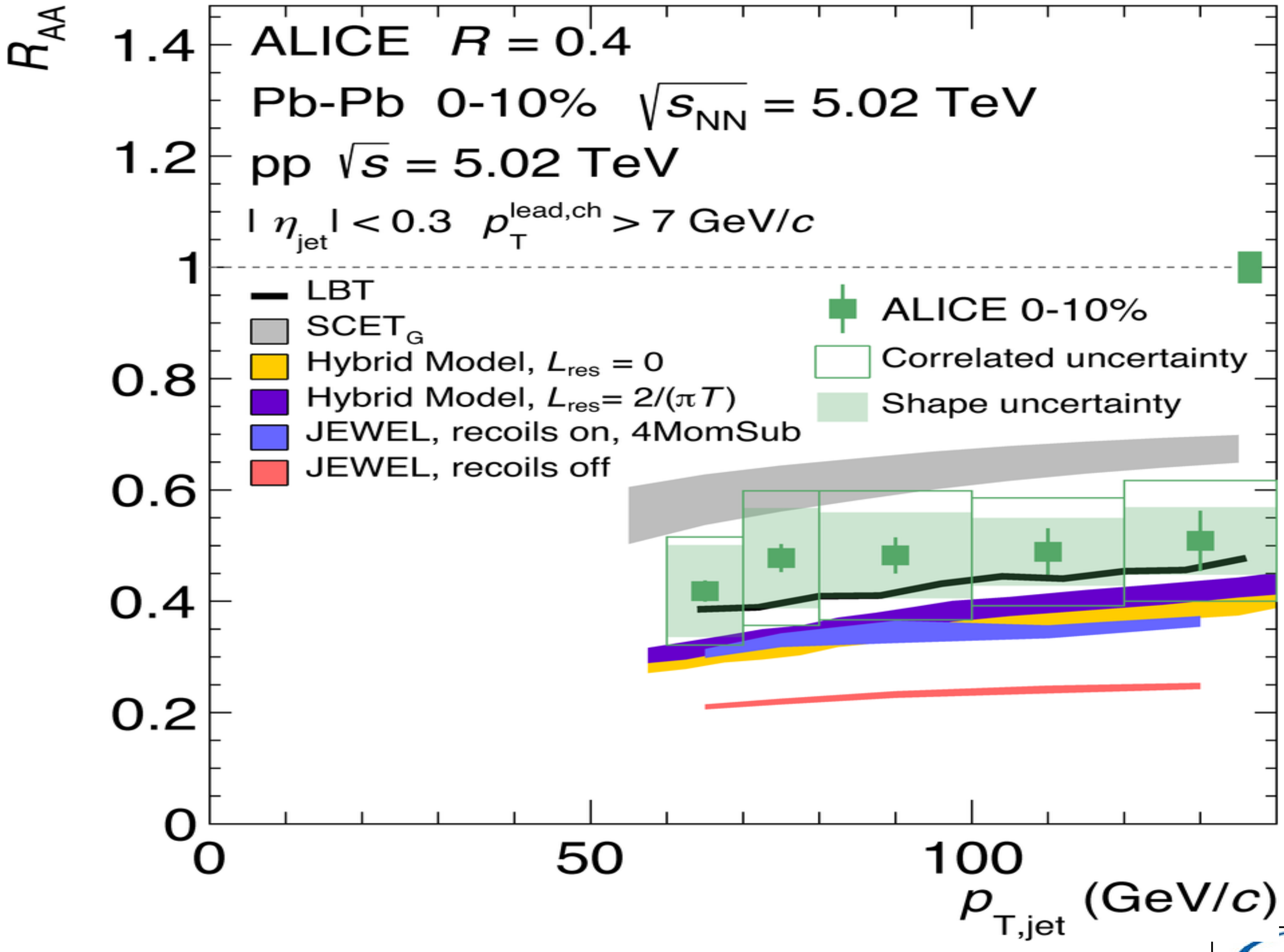
- Jets and their (identified) fragmentation functions will be studied @ the EIC (already ongoing).
- The EIC should provide good PID and a unique setup allowing to produce e-A collisions for the first time
- Jets allow to test QCD as well as to probe cold nuclear effects that can be used as a baseline for QGP studies.
- QCD physics is also a useful baseline heavy ion / QGP studies
- Part of the French community is thinking about contributing / joining the EIC collaboration. Possible physics contributions could include : Hadronic physics (in particular DVCS studies), initial state, saturation effects at small x focusing on the gluonic sector as well as some QGP related physic for which quarkonia could be used and of course jet physics. On the hardware side contributions could focus on calorimetry or tracking detectors/subsystems not forgetting the potential muon detector. For more, have a look at:

https://indico.in2p3.fr/event/20116/contributions/77909/attachments/57789/77267/Prospectives-v3.pdf

https://indico.cern.ch/event/862727/contributions/3671079/attachments/1962086/3261428/EIC_shabetai.pdf

Backup

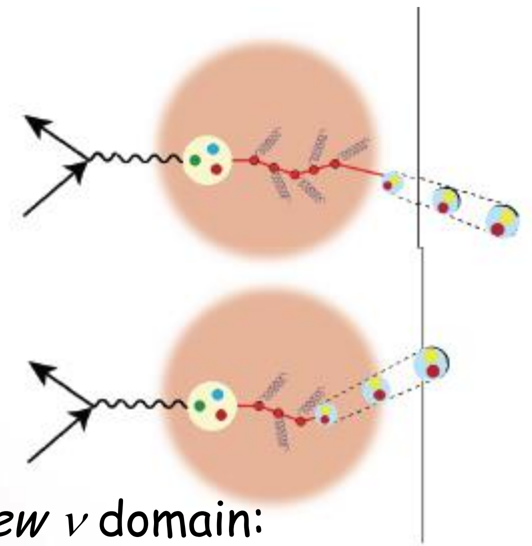
ALICE Pb-Pb Full Jets Raa vs Models



Emergence of hadrons from partons

Hadronisation inside a nucleus provides information about the dynmaics

$$\nu = \frac{Q^2}{2mx}$$



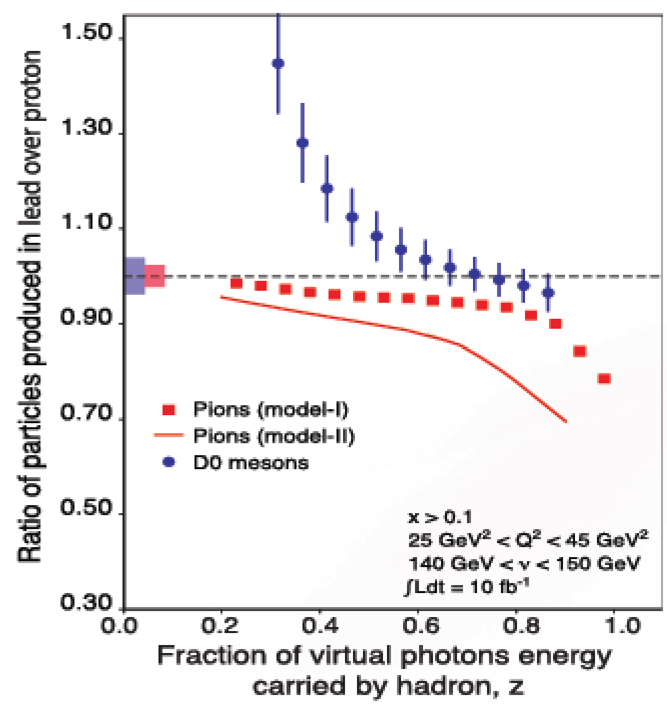
New ν domain:

- Isolate preturbative effects
- Control the pactonic cinematic using perturbative effects

High Luminosity:

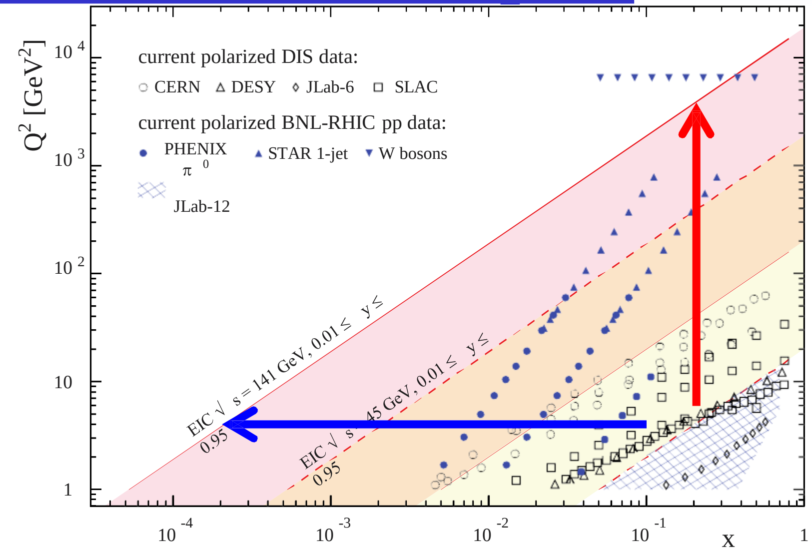
- Phénomènes rares probse, like quarkonia, open heavy flavor of jets

- Propagation of partons inside cold nuclear matter
- Benchmark for hot nuclear matter (QGP)



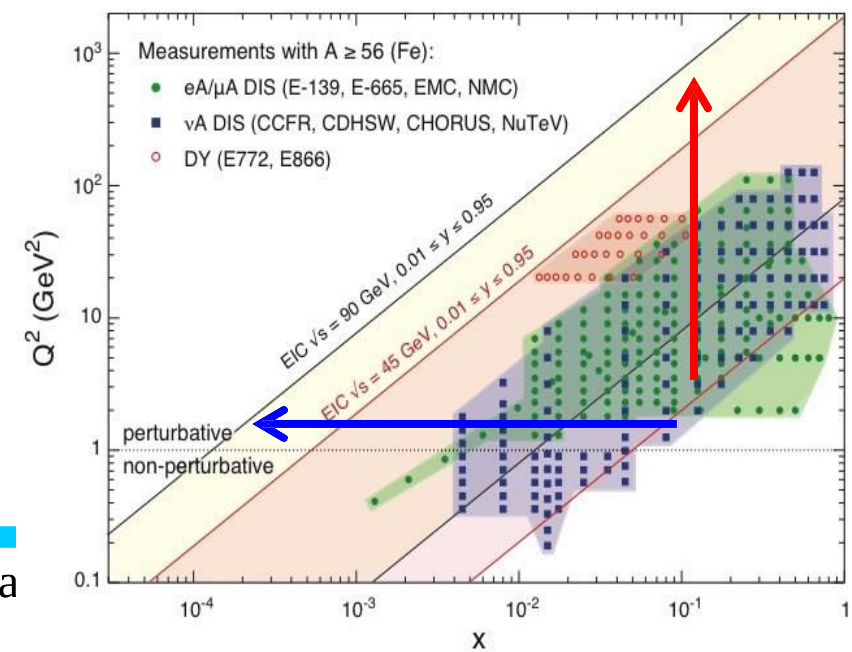
Electron-Ion Collider: specs

First collider in the world in $\vec{e}$-$\vec{p}$/$\overrightarrow{light\ nuclei}$ mode
+ electron-nuclei mode



For e-p/n collisions:
- Polarized e, p, deuteron or ^{3}He beams
- Electron beam energy ~ 5-20 GeV
- Proton beam energy up to ~50 - 250 GeV
- Luminosity L_{ep} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
- Center of mass energy s ~ sqrt($4E_pE_e$) ~ 30 – 140 GeV

For e-A collisions (use the same collider ring…):
- Wide range in nuclei (proton-to-uranium)
- Luminosity per nucleon (scaled) by the one for e-p
- Variable CM energy (scaled by A)

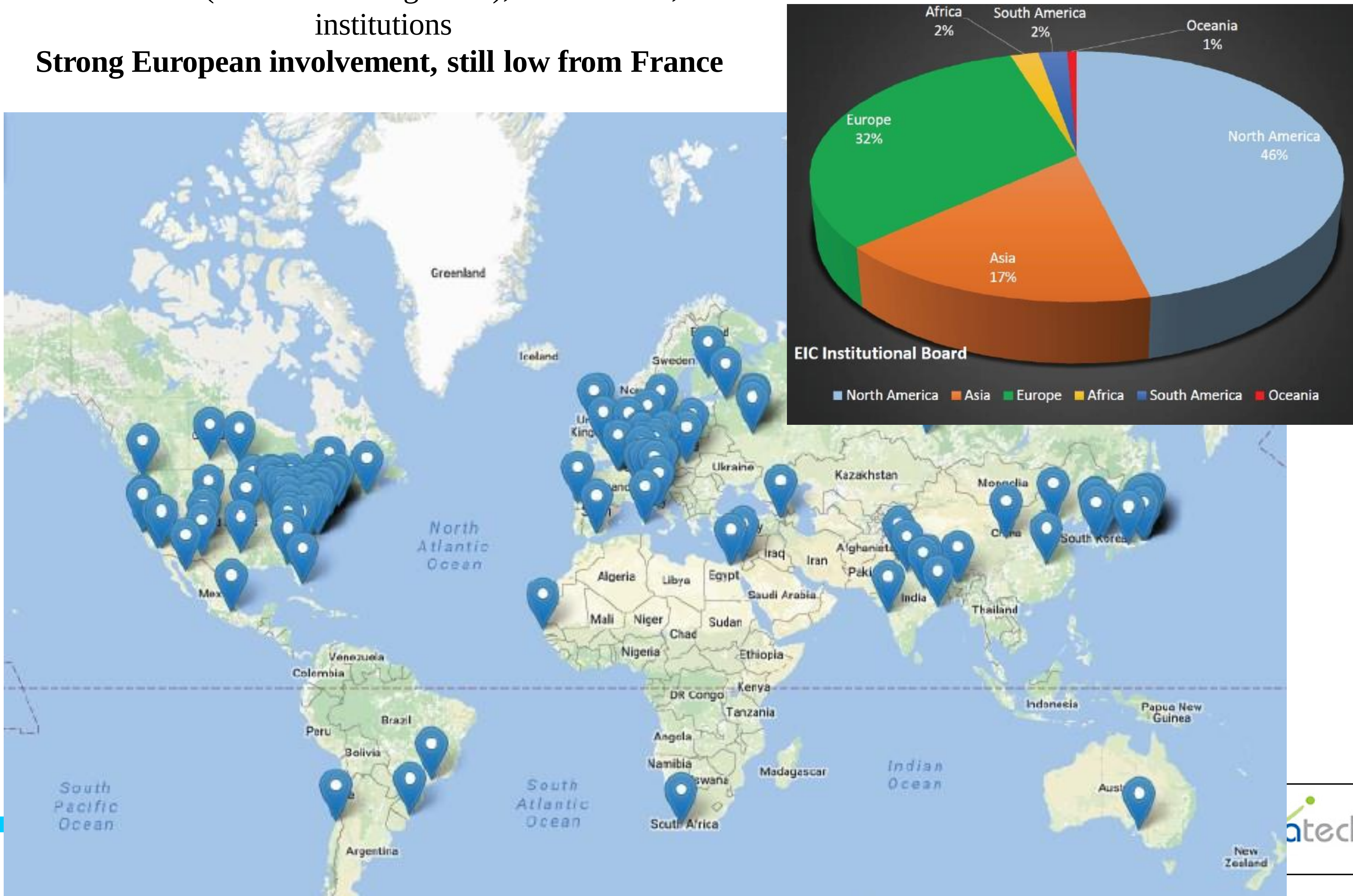


As it was recently annonced by DOE, the EIC will be hosted by BNL (under Jlab supervision)

EIC Users Group

697 scientists (+students & engineers), 29 countries, 160 institutions

Strong European involvement, still low from France



Event gen in DIS

Hard scattering

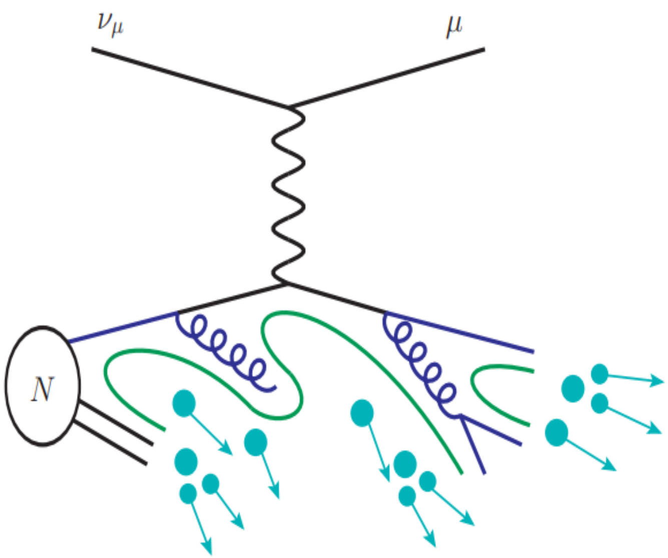
- Convolution between PDFs and matrix element (ME) for partonic scattering

Parton shower

- Final state radiation (FSR)
- Initial state radiation (ISR) for hadron
- QED emissions from leptons
- ME corrections for the hardest splitting
- Matching of high-multiplicity MEs and PS

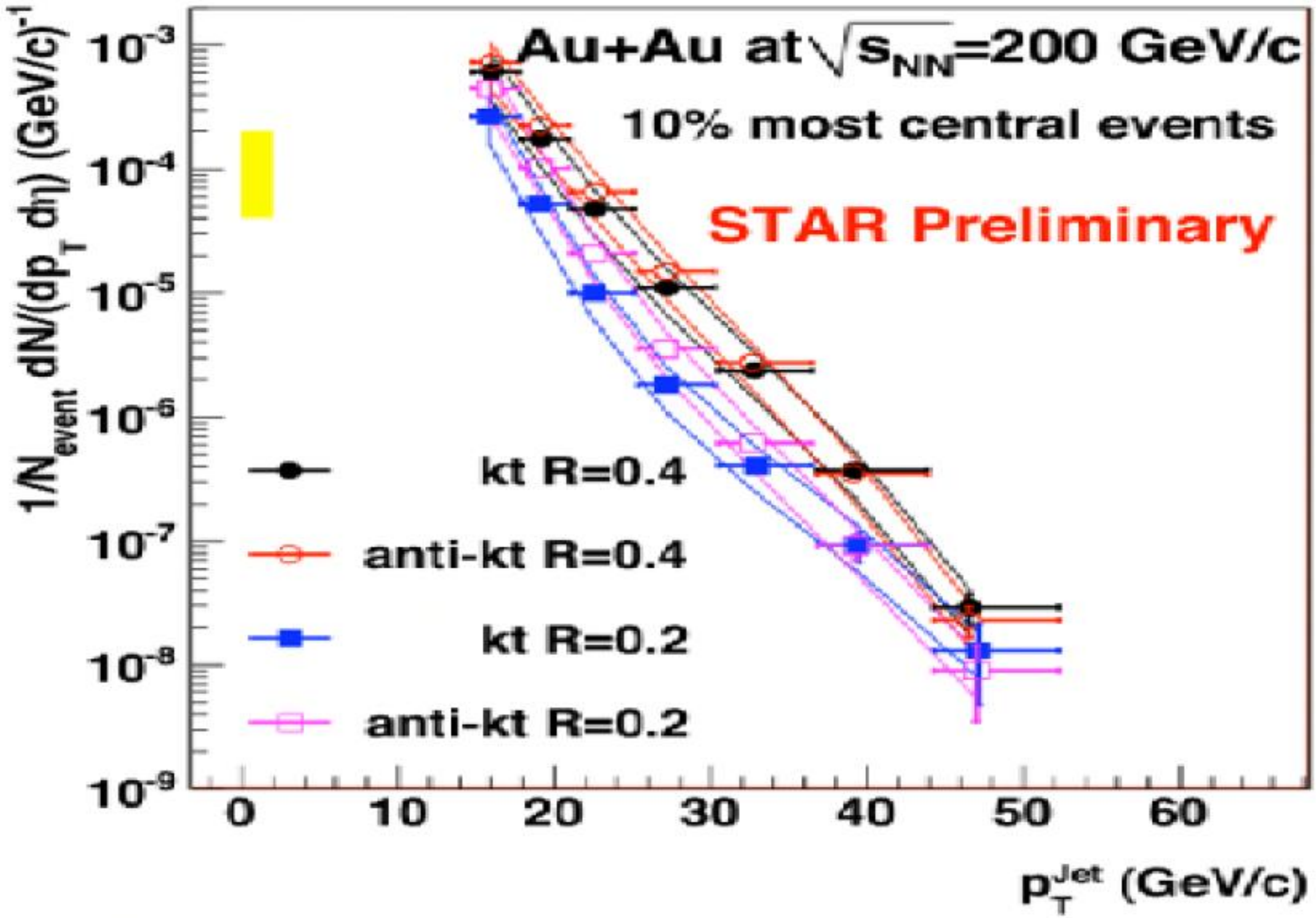
Hadronization

- Colour reconnection
- Decays to stable hadrons

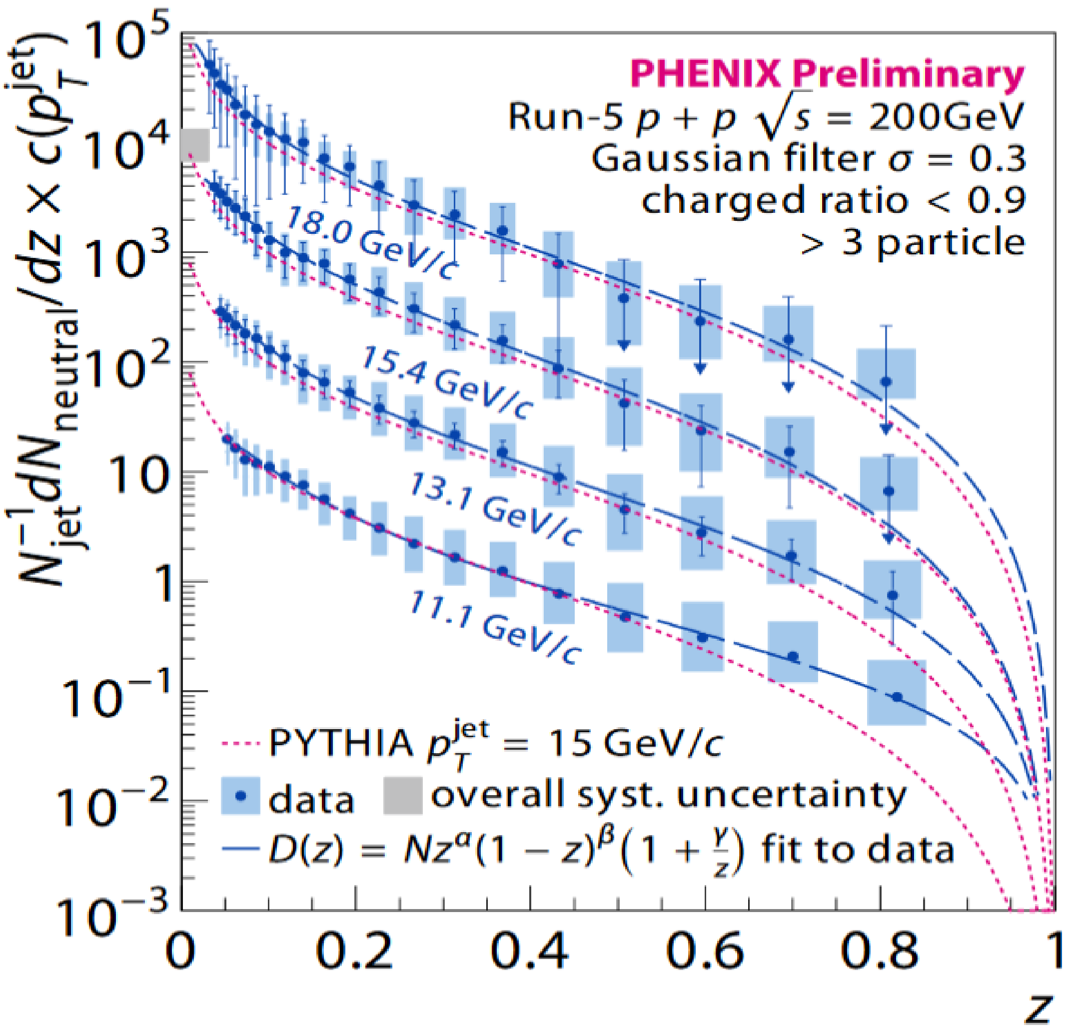


[Figure: S. Prestel]

STAR Au+Au Spetra (previous result)



Phenix FF (neutral)

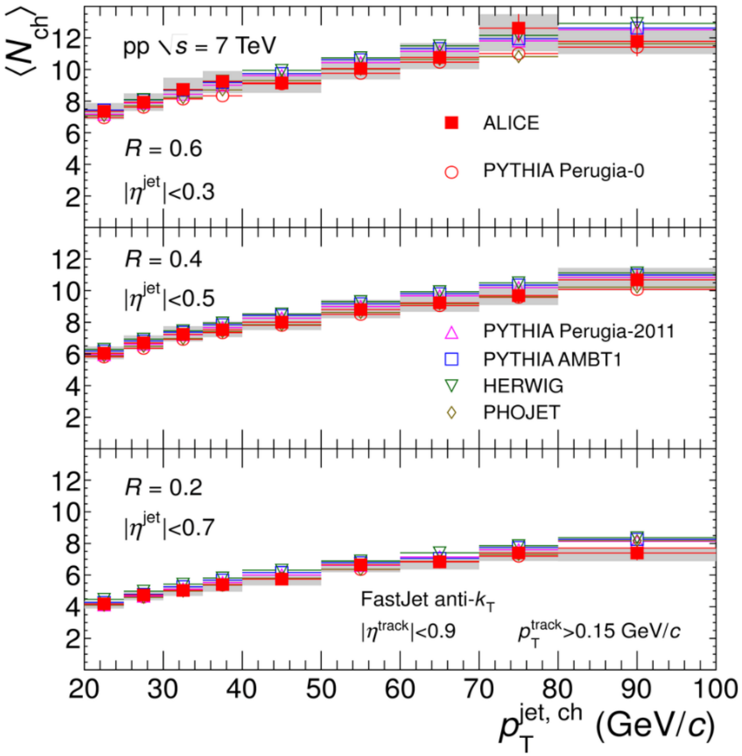


$$z = p_{\parallel}^{particle} / p^{jet}$$

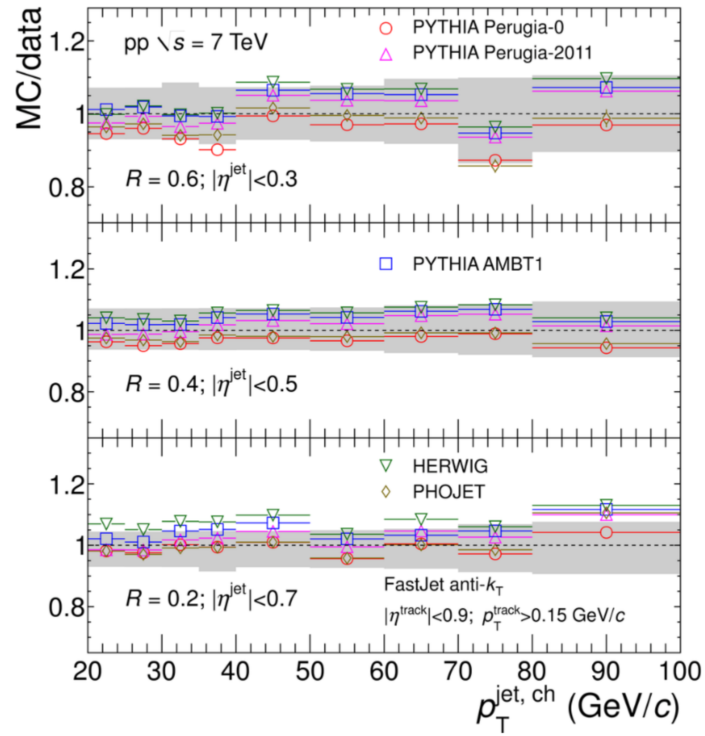
- **Neutral particles (electromagnetic)**
- $z = p_{\parallel}^{particle} / p^{jet}$
- $c(\cdot) = 10^i, i = 0, 1, \ldots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $z_{max} \approx 0.81$

Jet: ALICE: charged track multiplicity

arXiv:1411.4969v1



<Nch> **rises** monotonically with **increasing jet pT** as well as with increasing **R** (0.2,0.4,0.6)

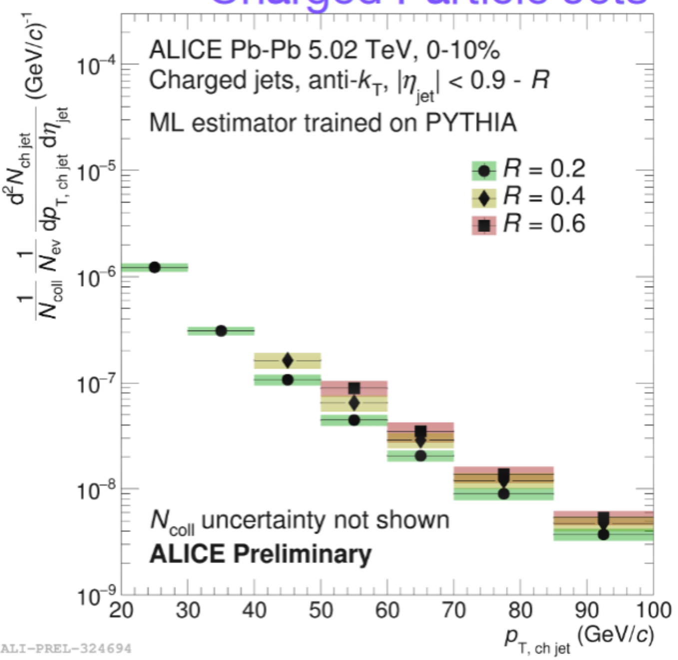


overall **agreement between data and MC** best with **PYTHIA Perugia-2011 and PHOJET.**

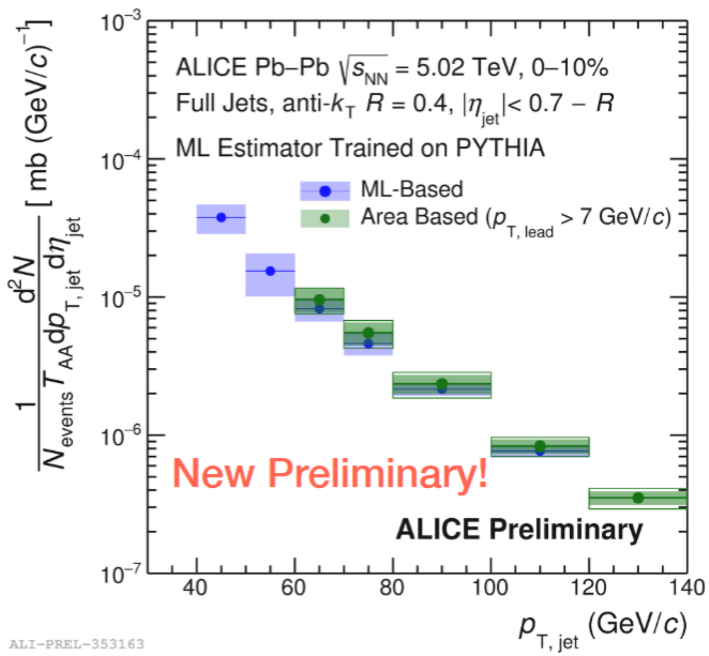
ALICE Pb-Pb Spectra

H.Bossi HP2020

Charged Particle Jets



Full Jets



Unfolding systematics dominate at lower p_T.

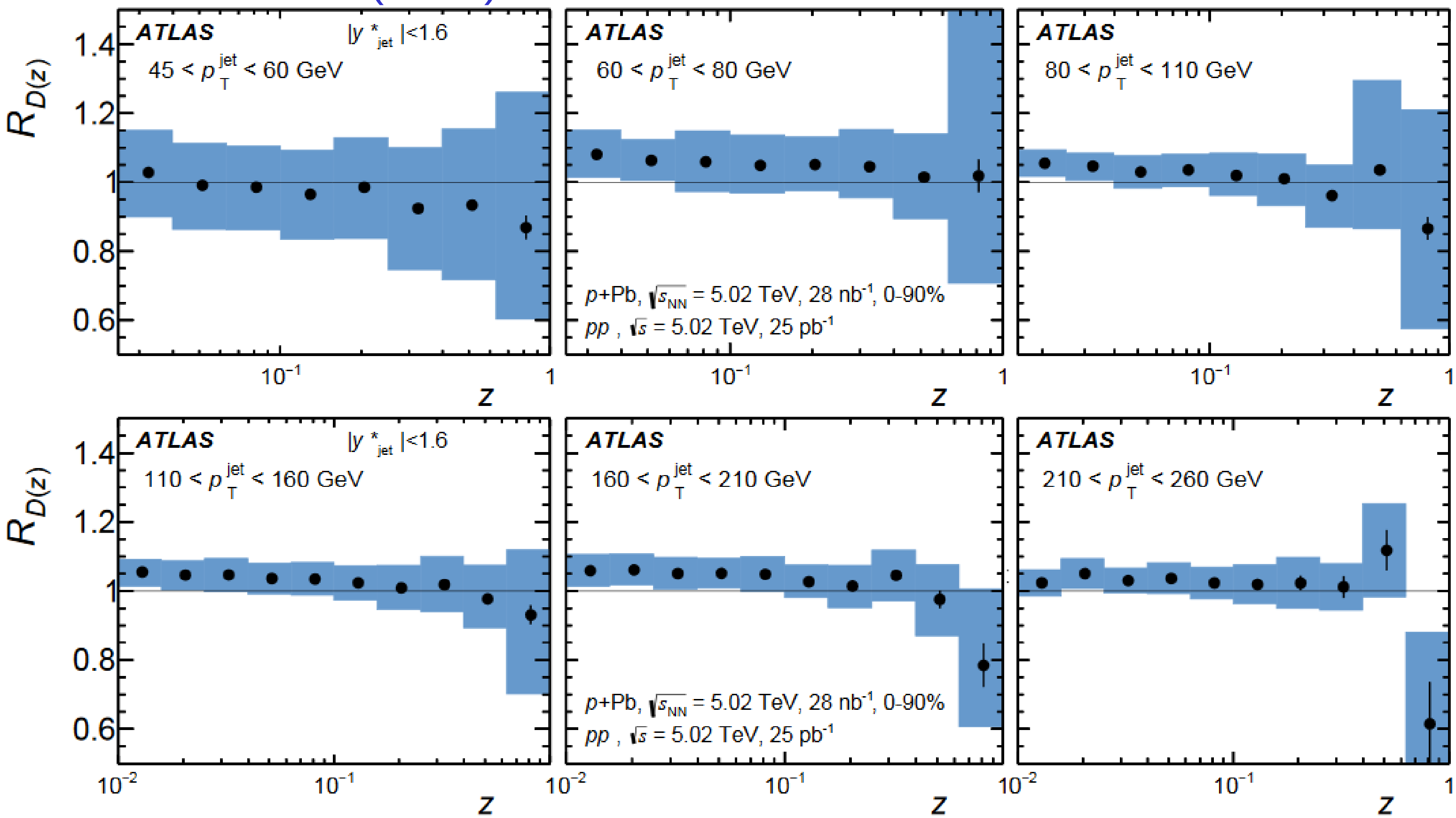
Tracking efficiency systematics dominate at high p_T.

	Lower p_T Cutoff (GeV/c)	
R	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!

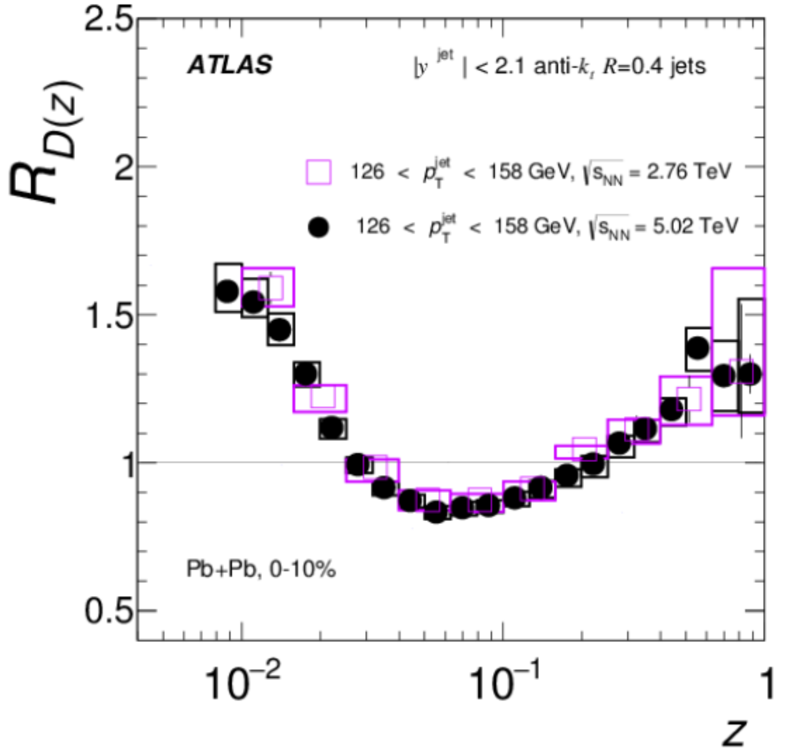
ATLAS: jet FF in pA : no mod.

ATLAS Coll. (2018)



ATLAS : jet FF in PbPb

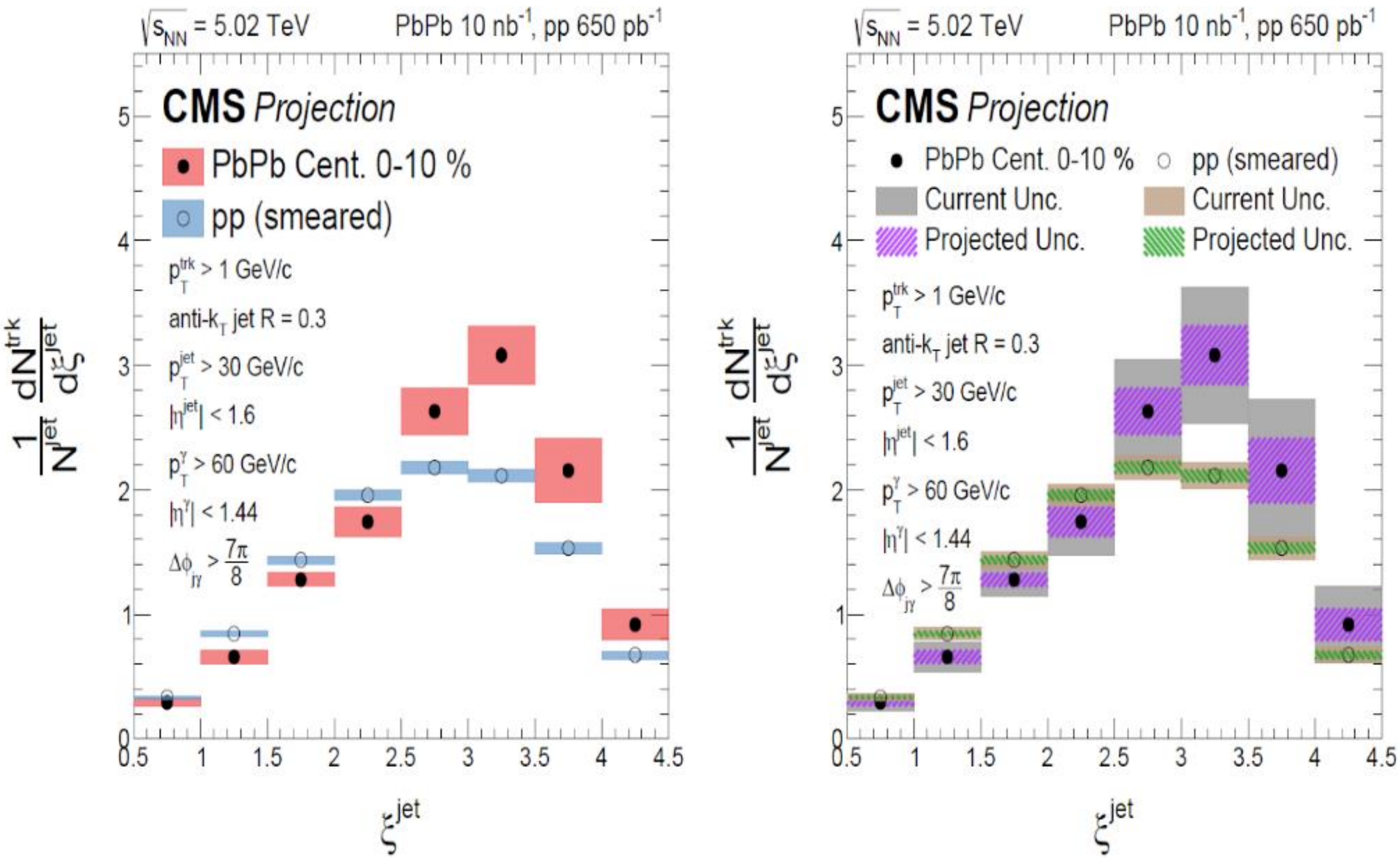
ATLAS Coll.



Phys. Rev. C 98, 024908 (2018)

FF@HL-LHC

HL-LHC
White paper



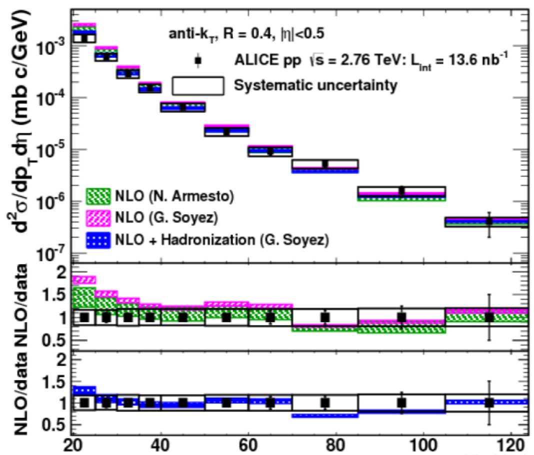
HL-LHC: L~10^34 cm^{-2}s^{-1}
Same order of magnitude expected for the EIC

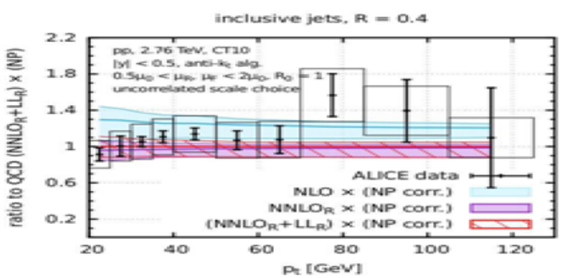
QCD: jet production in pp (ALICE)

Full jets, $\sqrt{s}$ = 2.76 TeV

Phys. Lett. B 722 (2013) 262

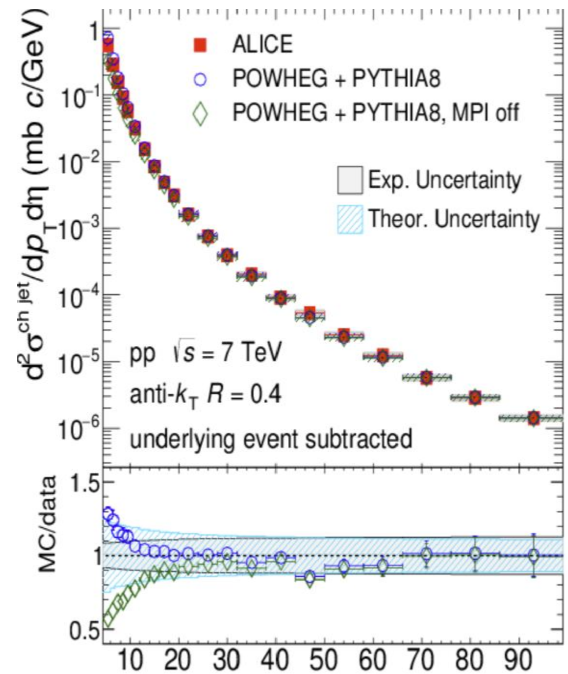
R=0.4
EMCAL L0





M. Dasgupta et a
JHEP 1606 (201
057

R=0.4
Min

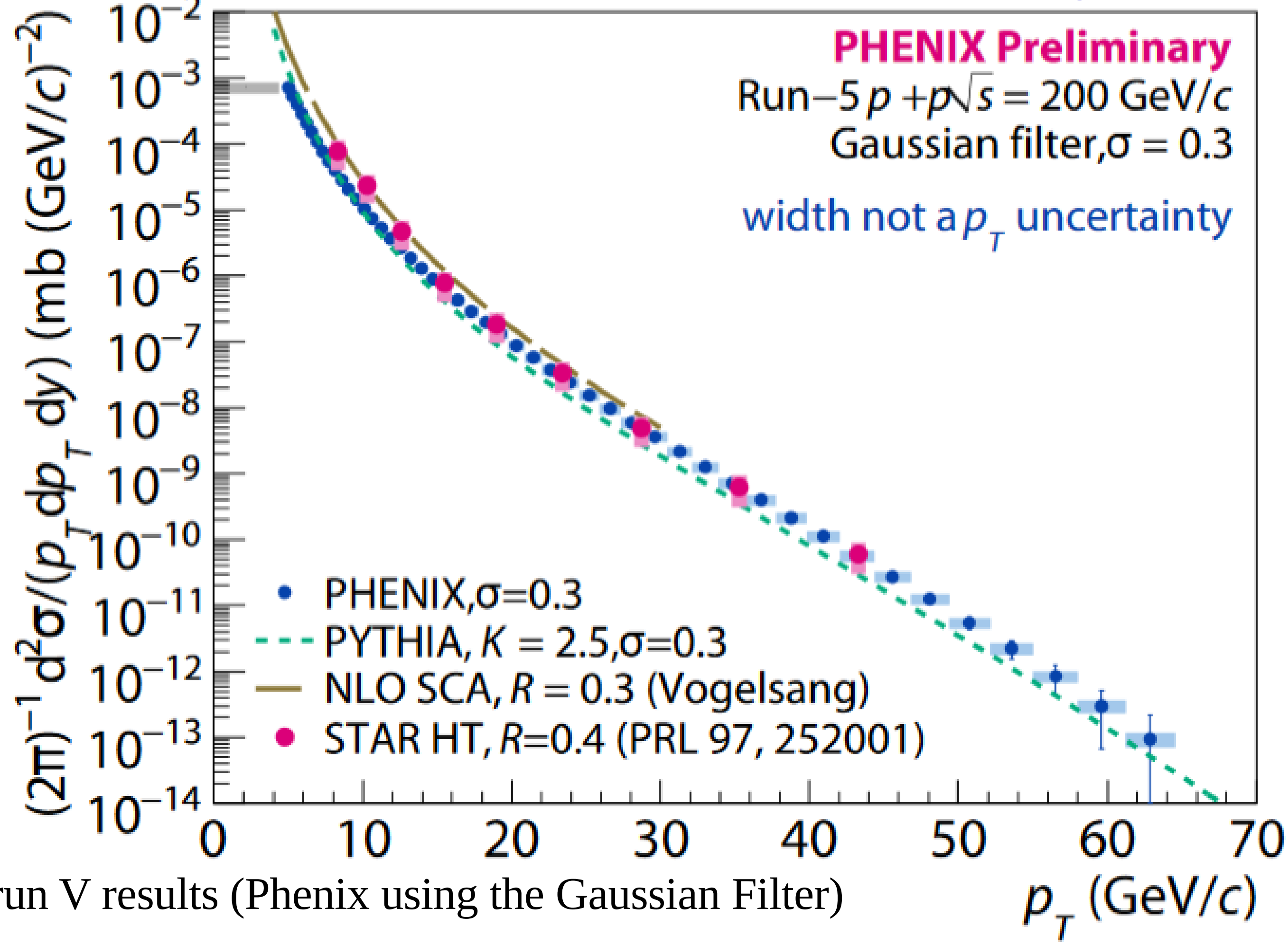


Good agreement between data and NLO calculations (+hadronization). Recent calculations based on $NNLO+LL_R$ including UE and hadronization effects are in even better agreement than just NNLO calculations.

<u>Jet cross-section</u>:
Measurement down to very low pT : for pT > 5 GeV/c jets are still originating from 2->2 hard processes (as opposed to soft hadrons being clustered by the clustering algorithm).
Quantification of **MPI** effects

RHIC (Phenix + Star Jet spetra)

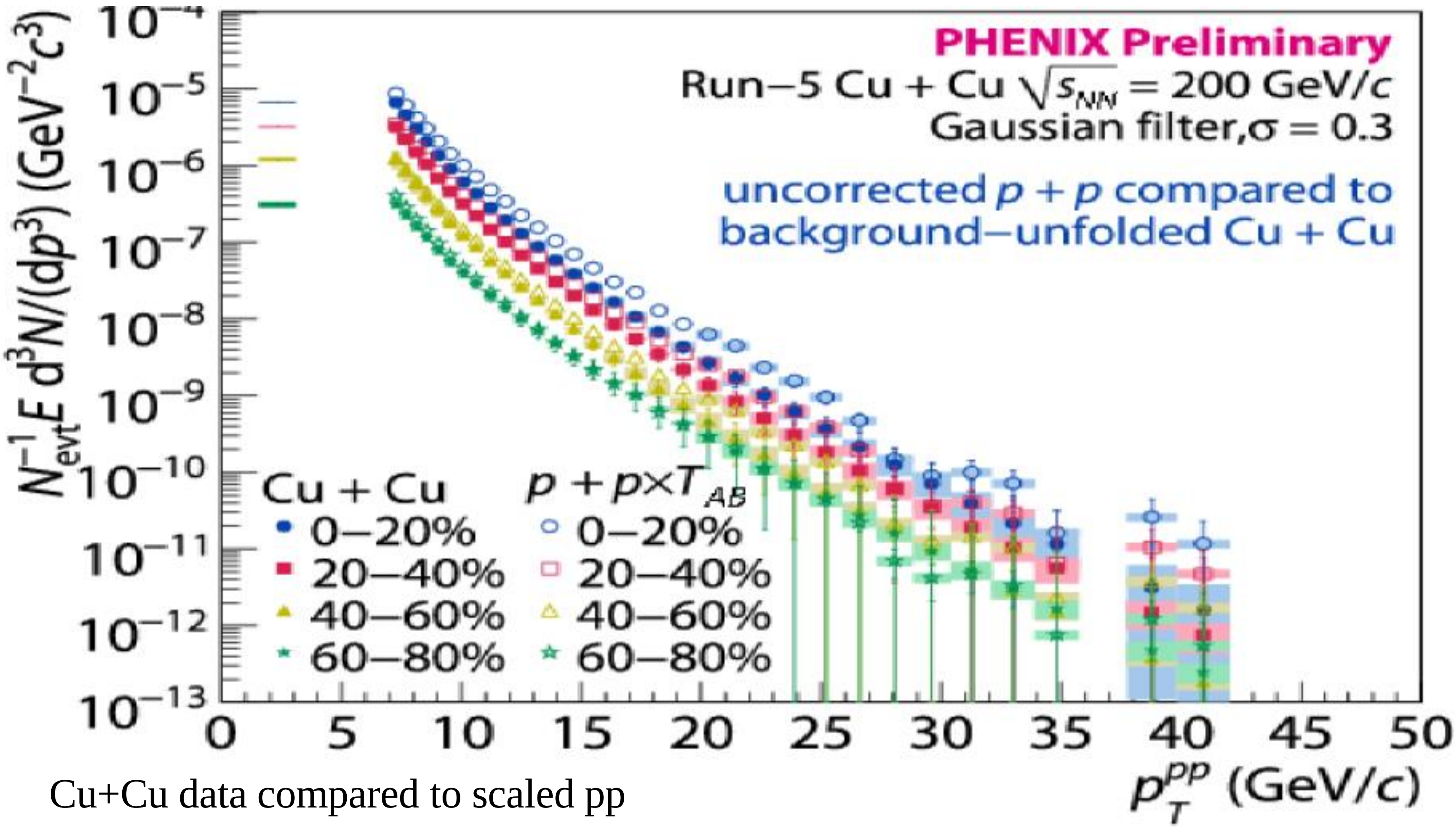
Y.S Lai RHIC AGS User Meeting



RHIC run V results (Phenix using the Gaussian Filter)

Similar kinematic reach as the one we can expect @ EIC

Phenix: pp vs Cu+CU



Cu+Cu data compared to scaled pp