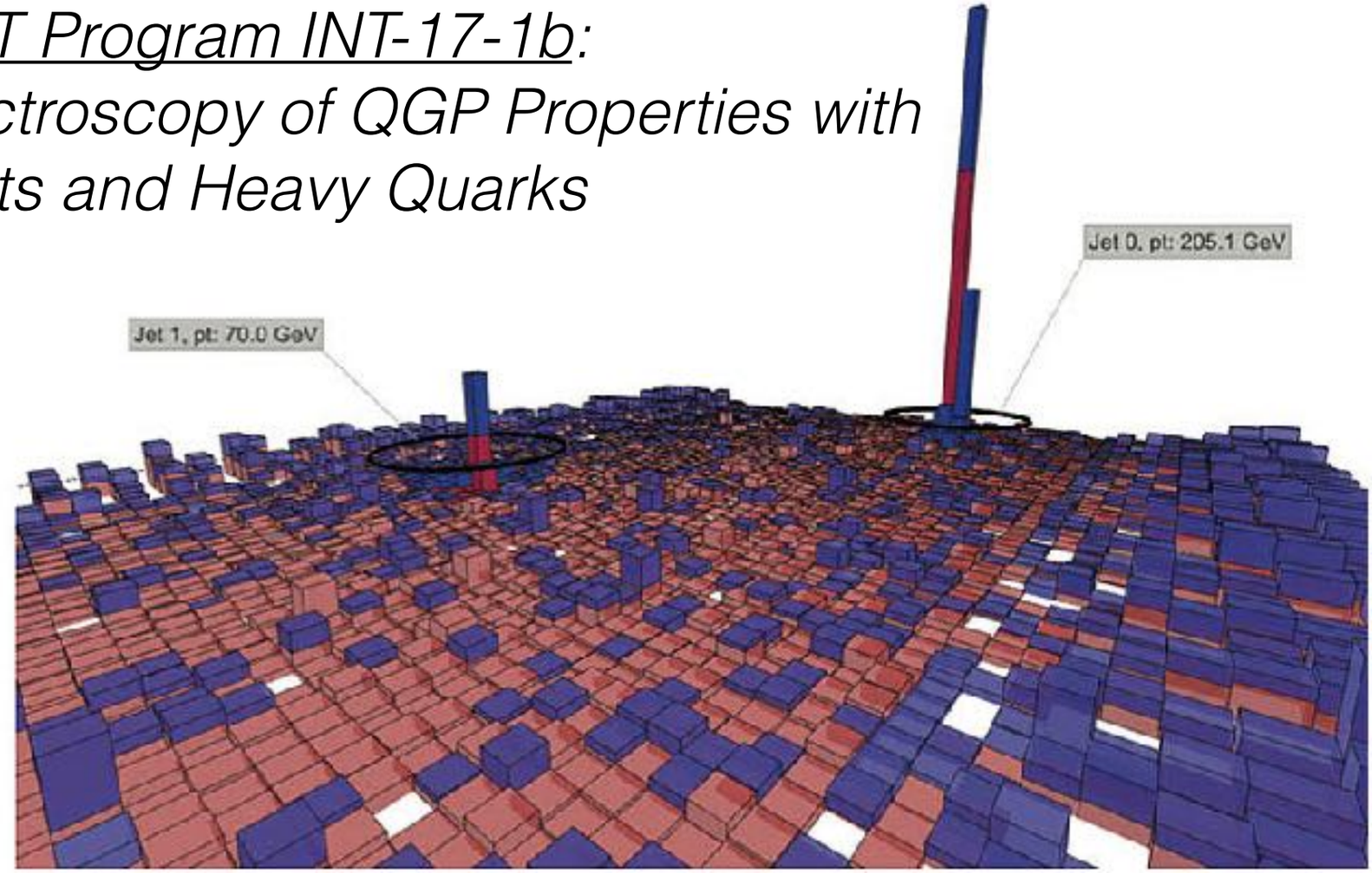
p+A data at the LHC

Dennis V. Perepelitsa
University of Colorado Boulder

11 May 2017

INT Program INT-17-1b:
Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks



INSTITUTE for NUCLEAR THEORY

and A+A & UPC

p+A data at the LHC

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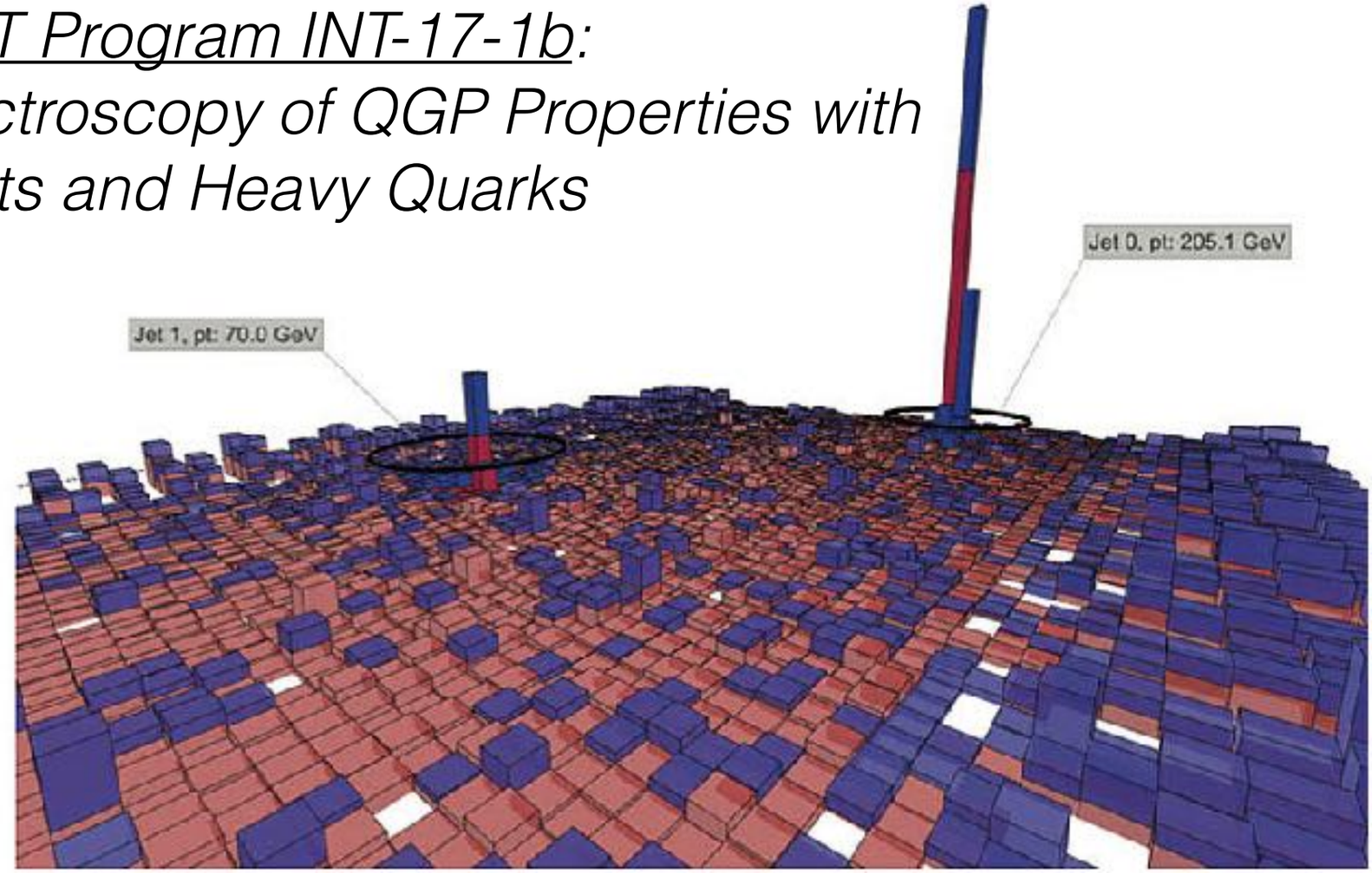
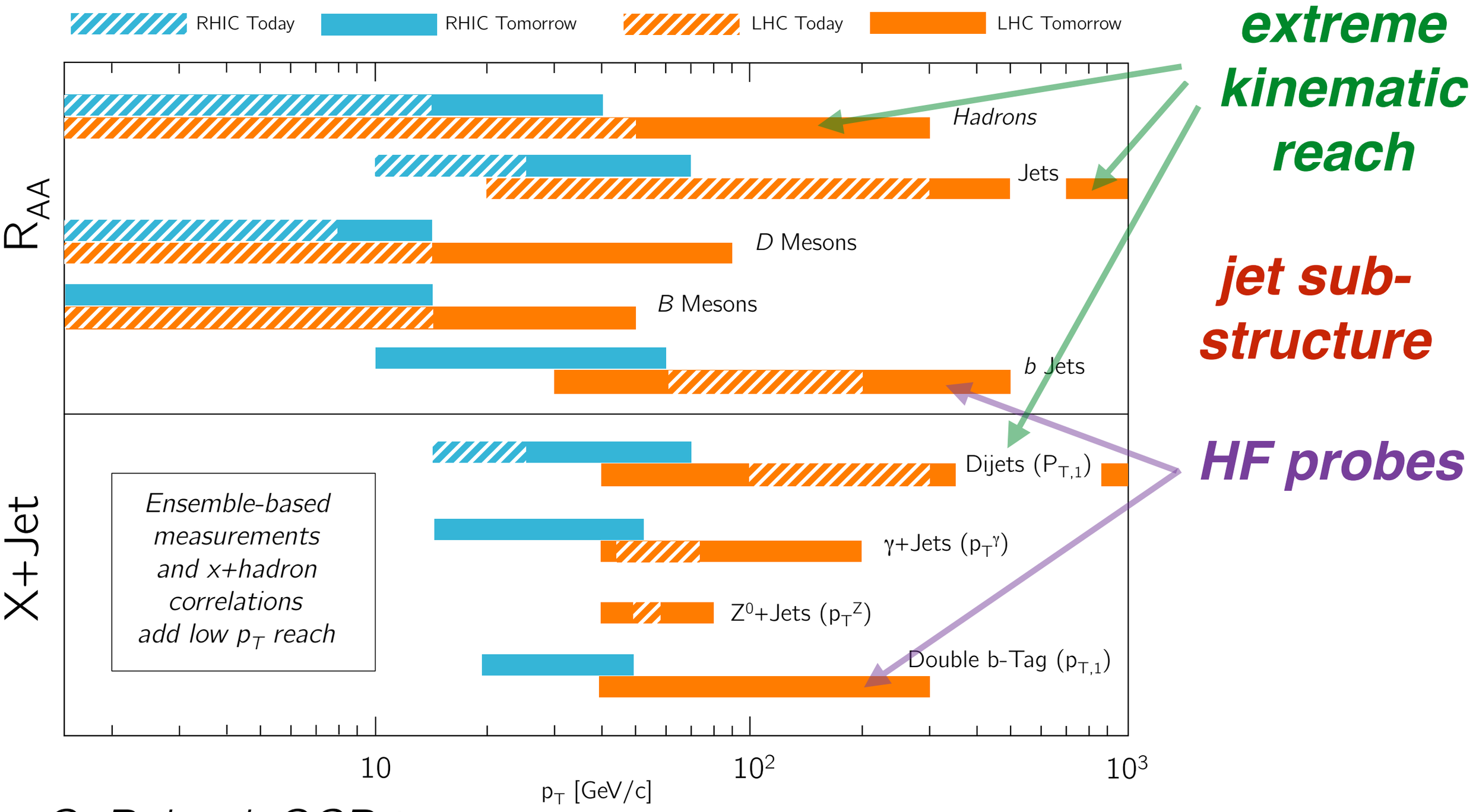
INSTITUTE for NUCLEAR THEORY



A+A

Jet physics during LHC Run 2



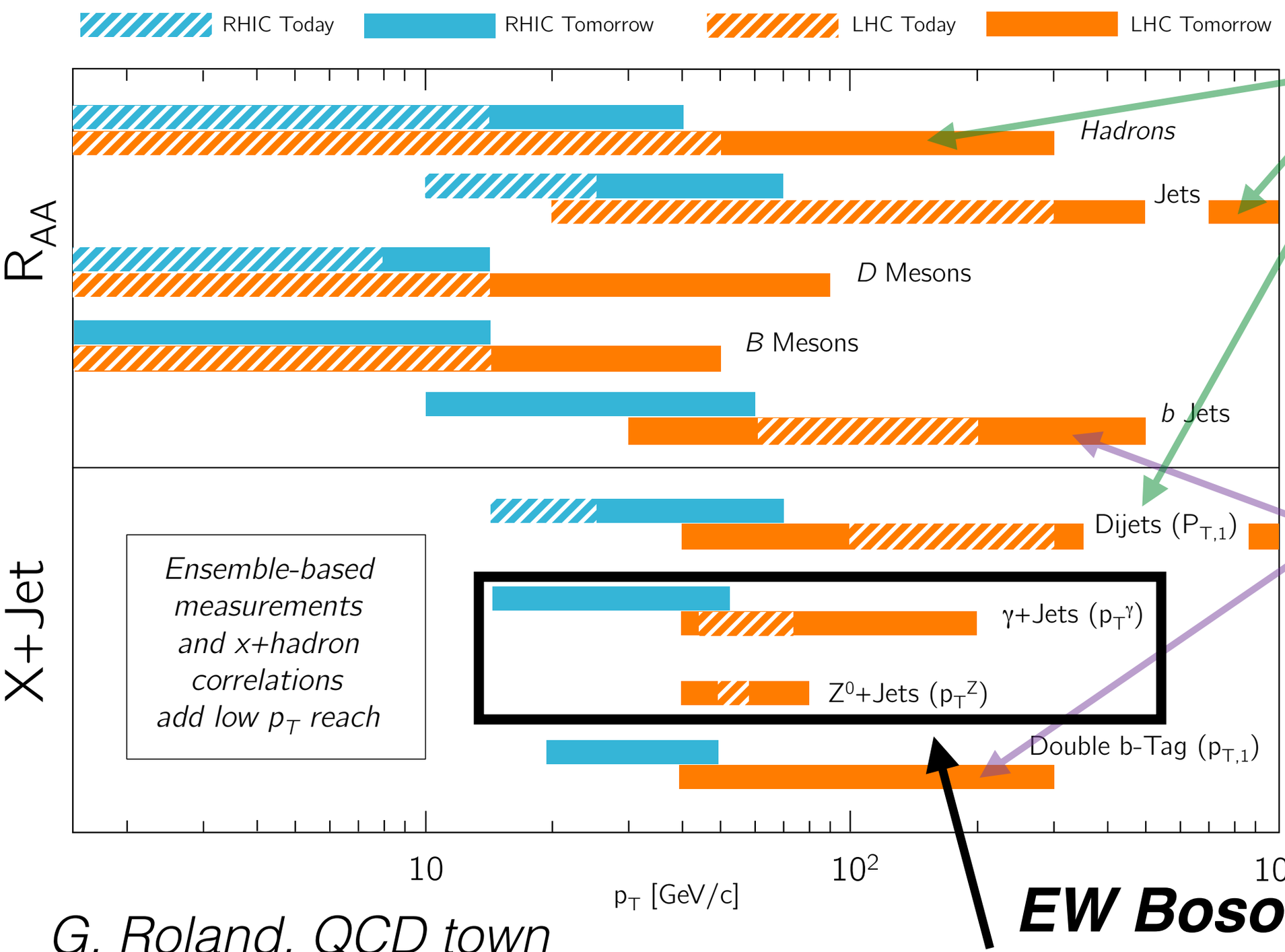
extreme kinematic reach

jet sub-structure

HF probes

G. Roland, QCD town hall meeting at Temple U.

Jet physics during LHC Run 2



extreme kinematic reach

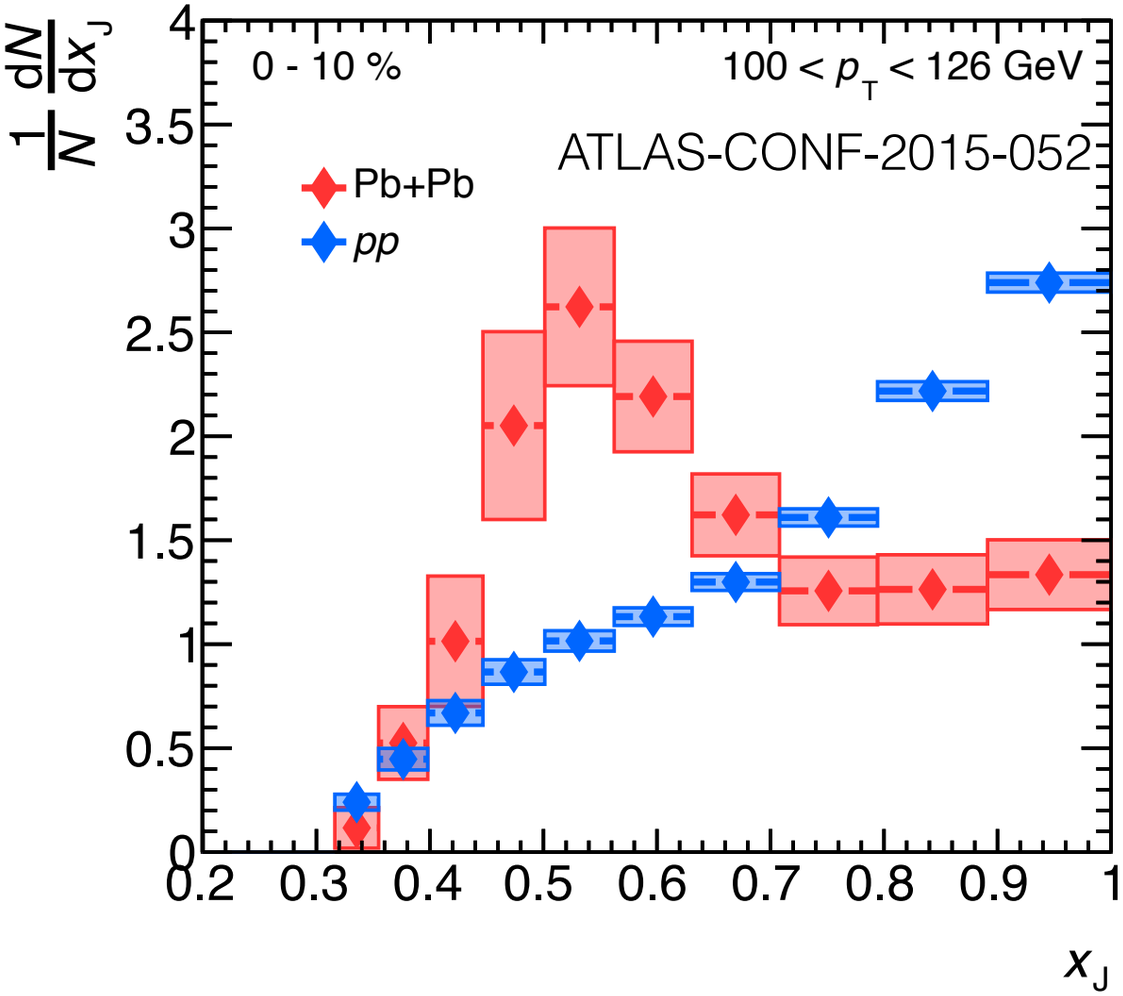
jet sub-structure

HF probes

EW Boson + Jet (my interest)

G. Roland, QCD town hall meeting at Temple U.

dijet p_T correlations



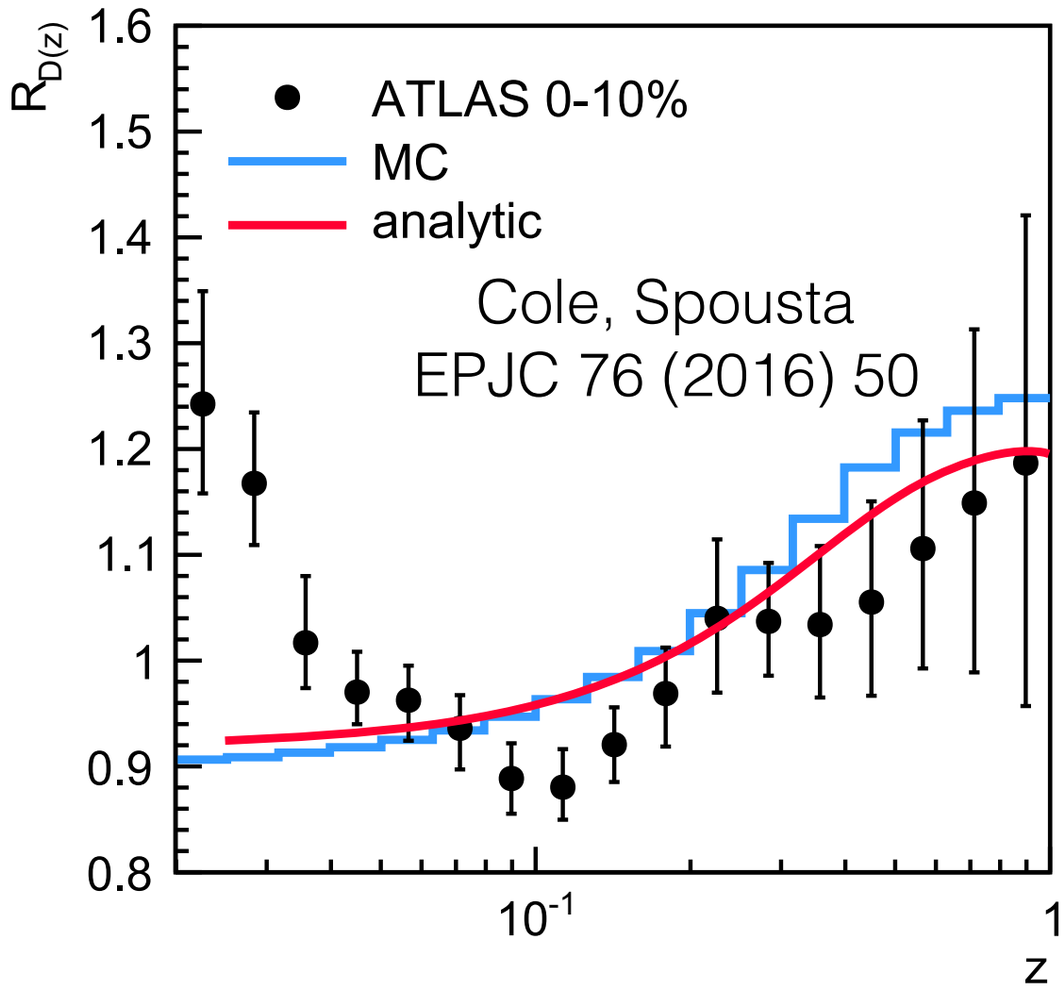
after quenching

$p_{T,2}$ / $p_{T,1}$ in **A+A**

vs.

$p_{T,2}$ / $p_{T,1}$ in ***p+p***

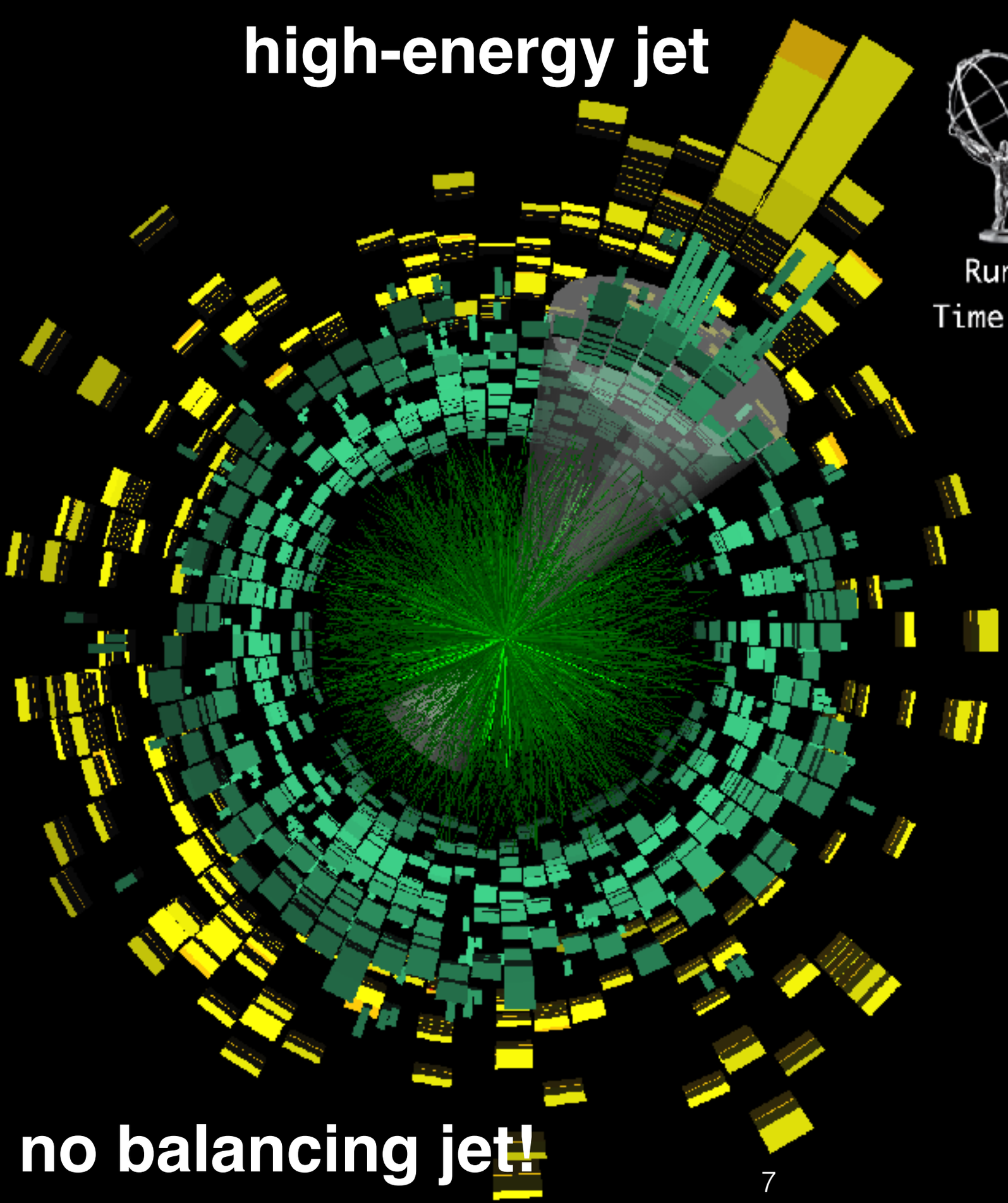
jet structure



after quenching

$$\frac{D(z;\ \mathbf{p_T^{jet}})\ \text{in}\ \mathbf{A+A}}{D(z;\ \mathbf{p_T^{jet}})\ \text{in}\ \mathbf{p+p}}$$

high-energy jet



no balancing jet!

ATLAS EXPERIMENT

Run 168795, Event 7578342

Time 2010-11-09 08:55:48 CET

Pb+Pb 2.76 TeV

LHC Run 1

beams going into/ out of the page

ATLAS EXPERIMENT

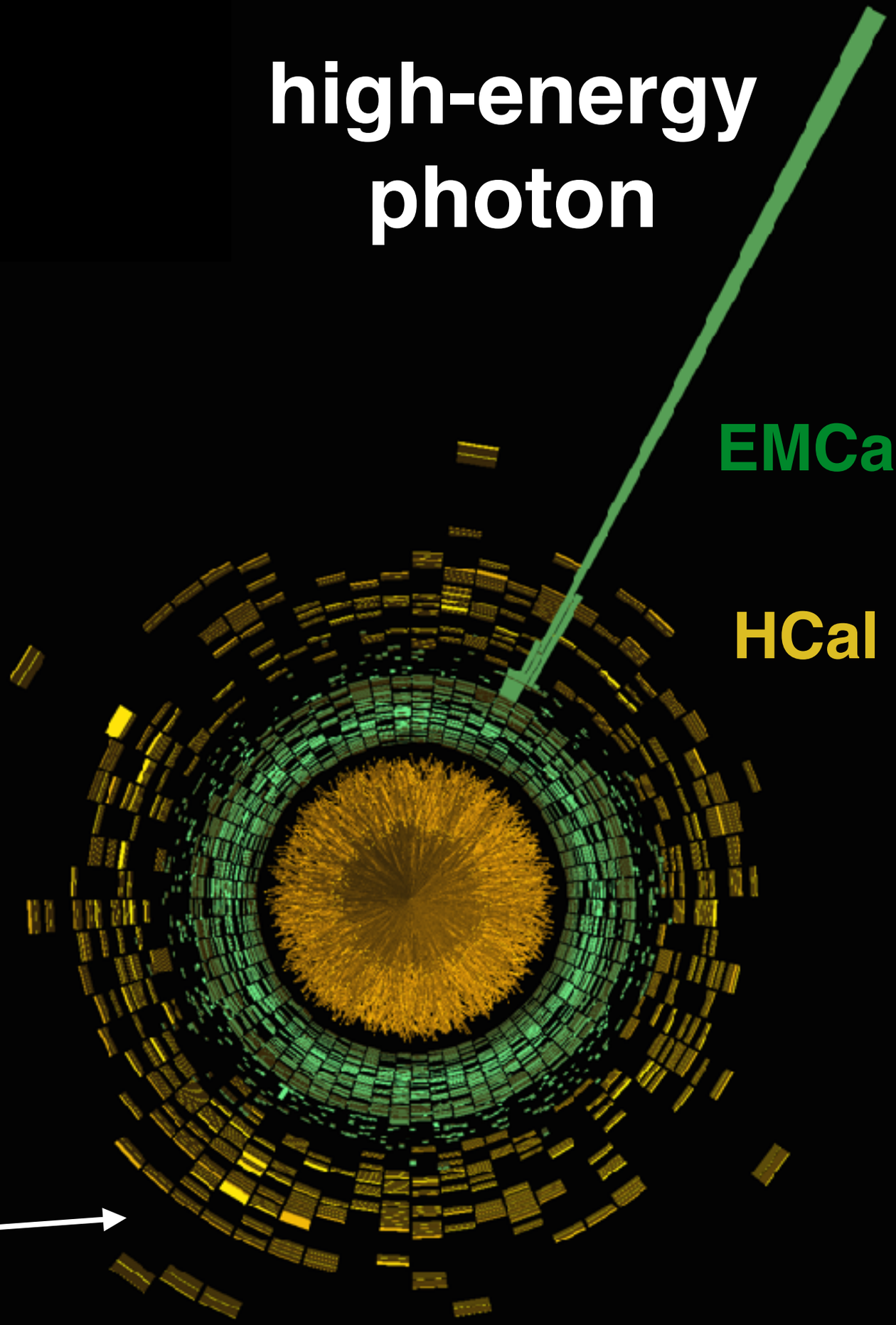
Run: 286834
Event: 124877733
2015-11-28 01:15:42 CEST

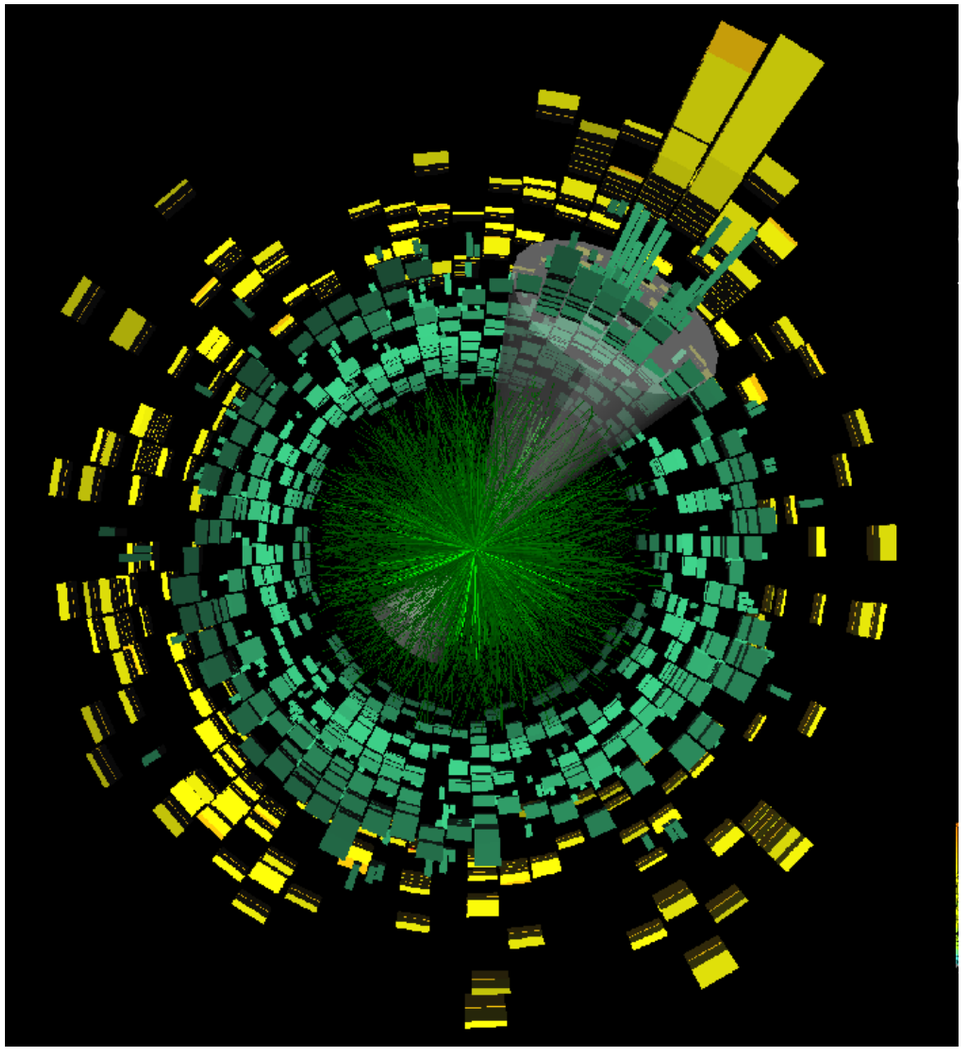
Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV
photon + multijet event
ΣE_T^{FCal} = 4.06 TeV

Pb+Pb 5.02 TeV
LHC Run 2

high-energy photon

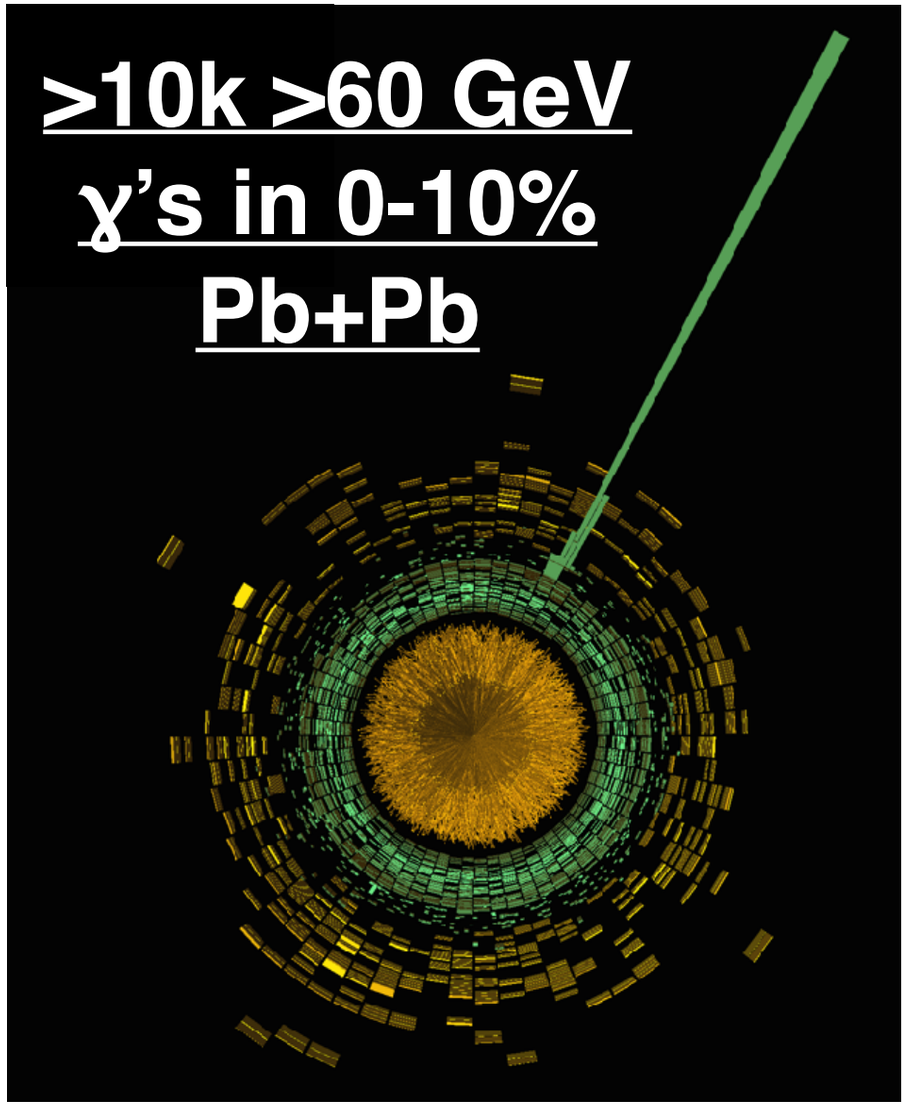
balancing jet?





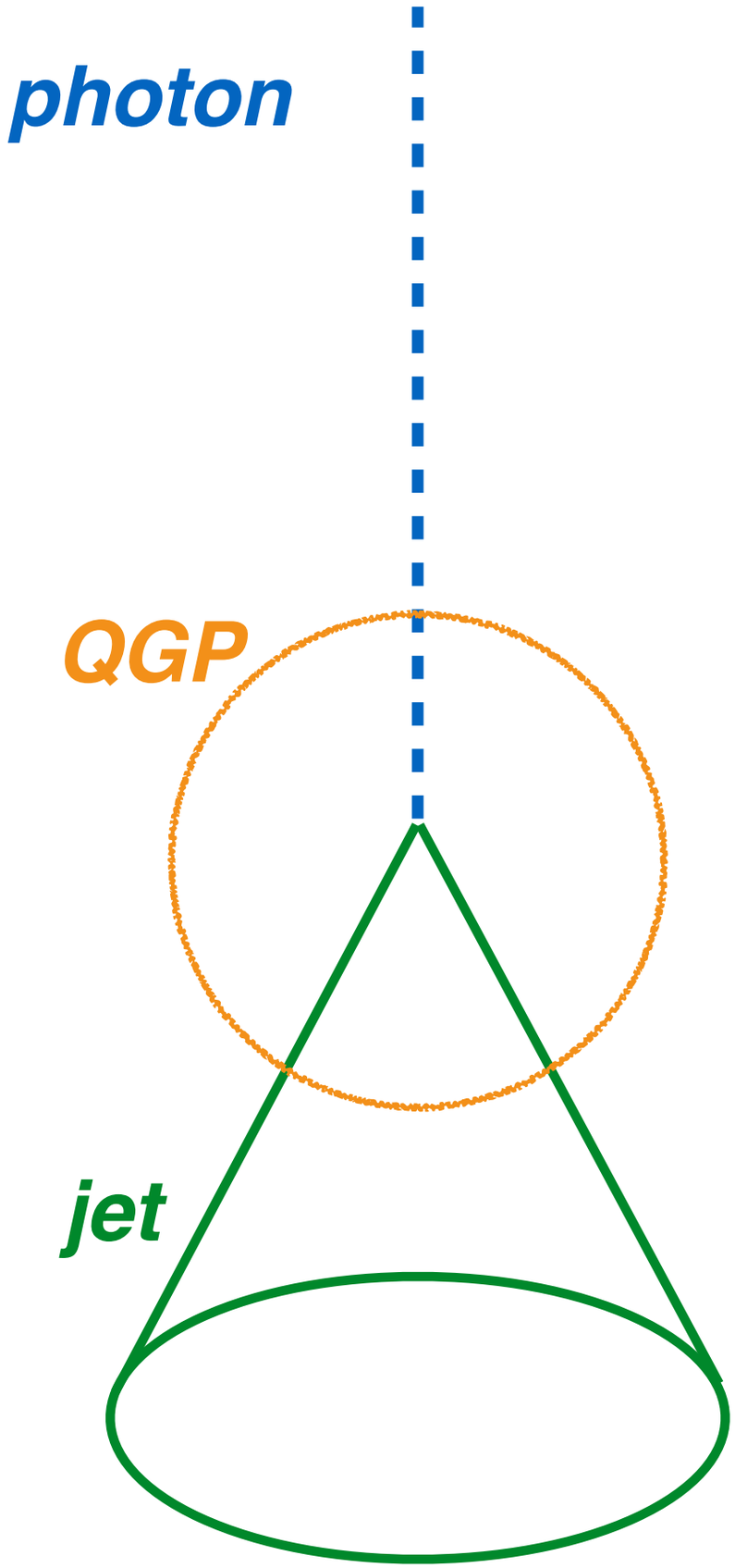
Select jets based on final-state (jet) kinematics:

- ➡ can only explore relative energy balance
- ➡ flavor/topology differences b/w *pp* and Pb+Pb



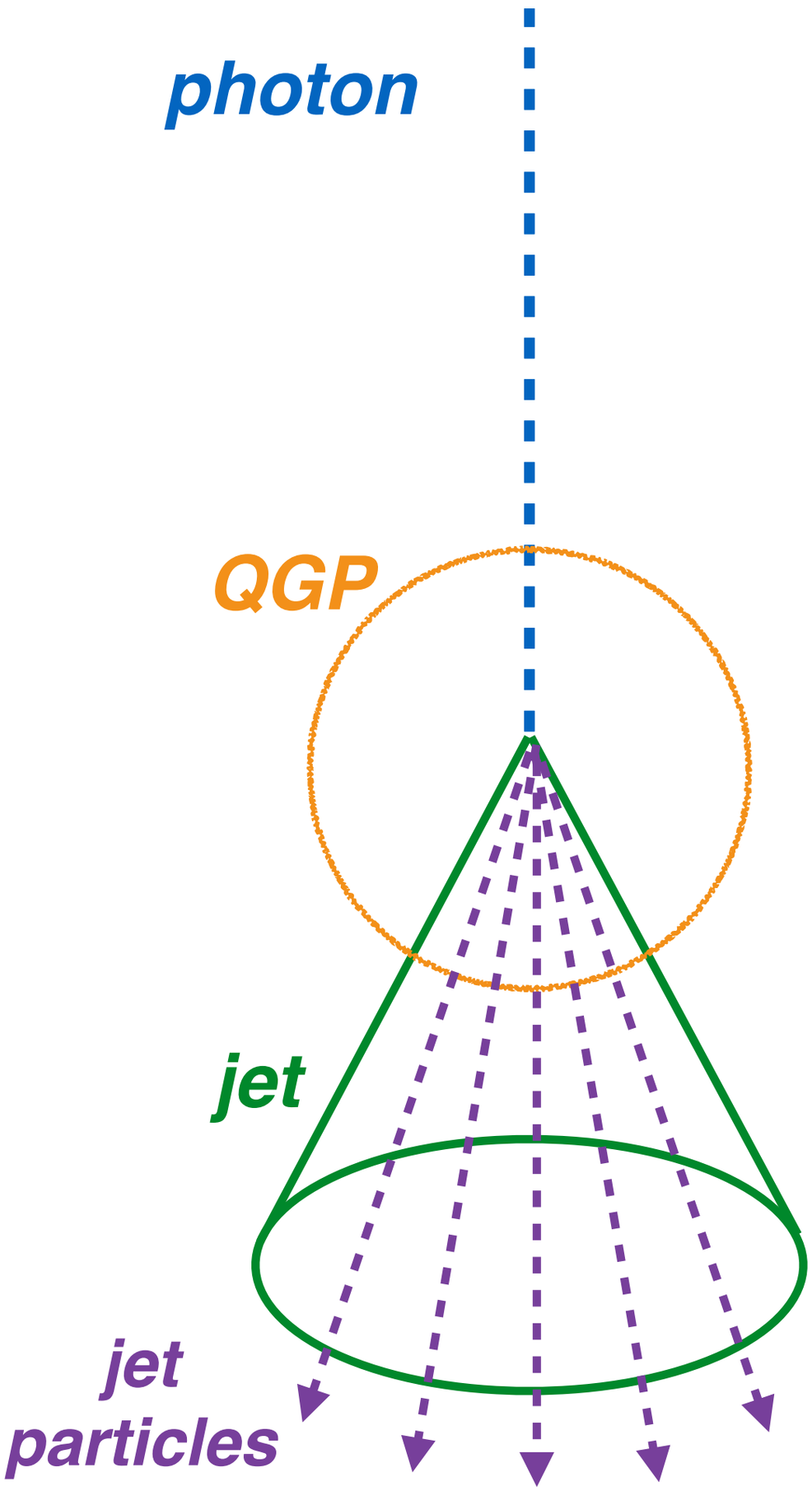
Select jet events based on *boson* kinematic

- ➡ absolute handle on initial *E*, direction, flavor
- ➡ can make consistent selection in *pp* to Pb+Pb
- ➡ no surface bias



1. What is the (absolute) amount of energy lost in cone?

➡ ***photon*+*jet*** *p_T-balance*

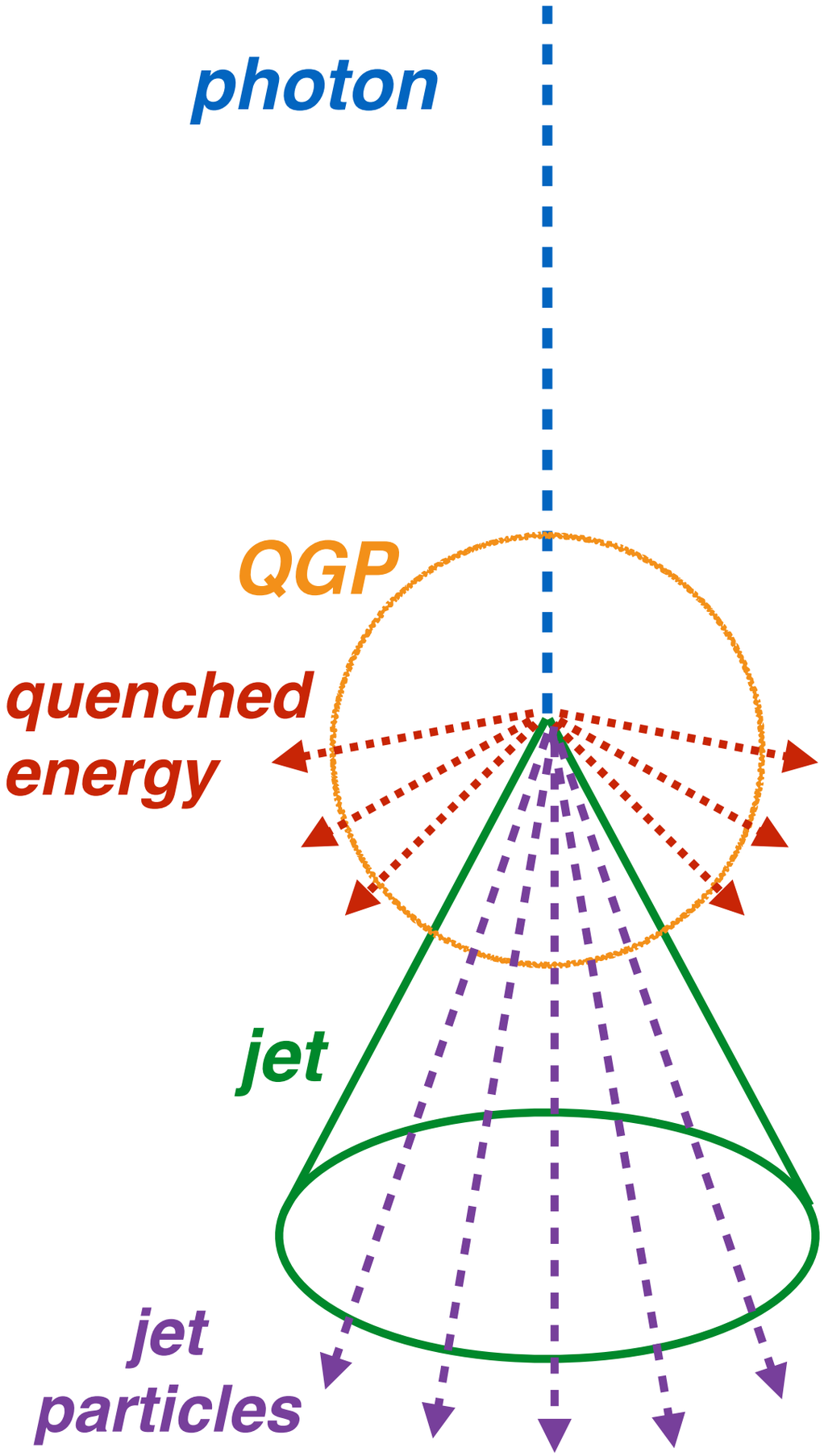


1. What is the (absolute) amount of energy lost in cone?

➡ ***photon*+*jet*** *p_T-balance*

2. How is the parton shower modified by medium?

➡ ***photon***-tagged jet **fragmentation function**



1. What is the (absolute) amount of energy lost in cone?

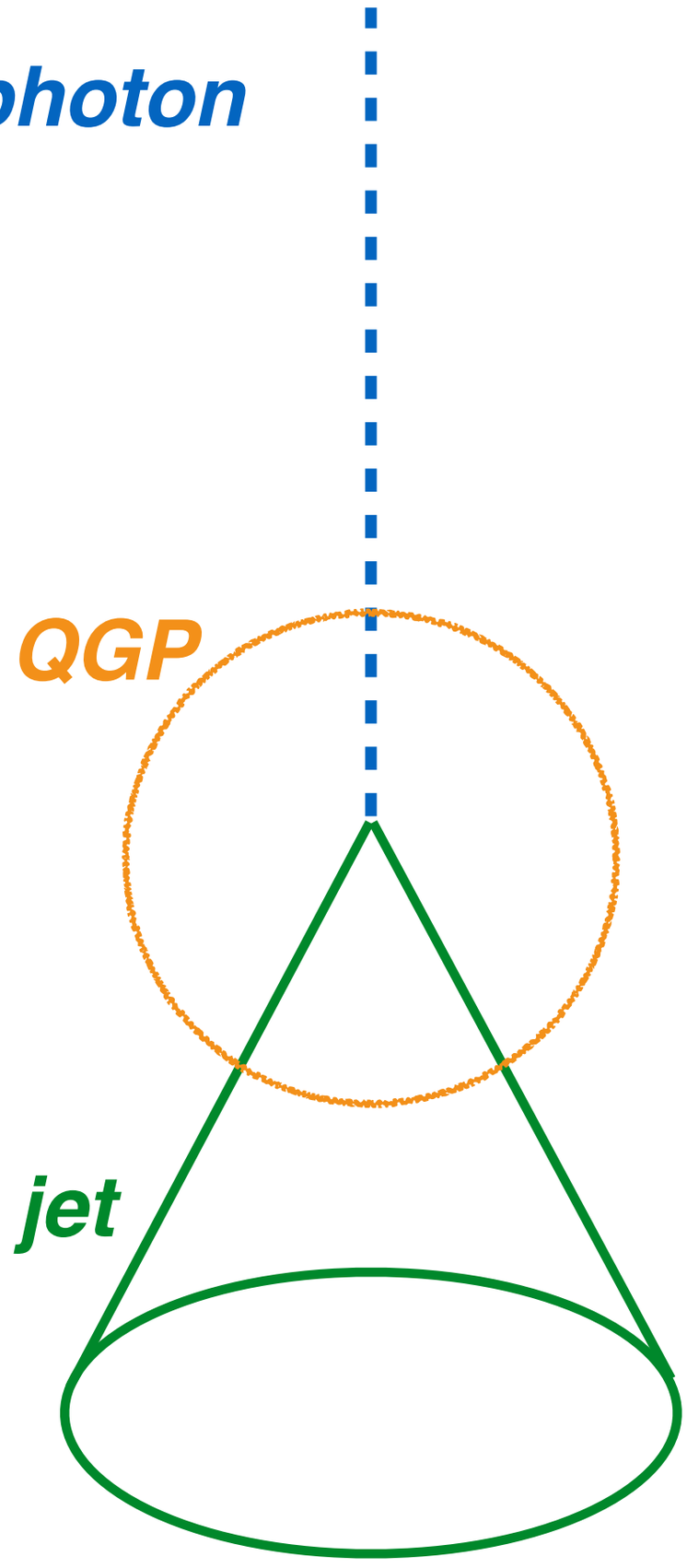
➡ ***photon*+*jet*** p_T*-balance*

2. How is the parton shower modified by medium?

➡ ***photon***-tagged jet **fragmentation function**

3. Where does the lost energy end up?

➡ ***photon*-hadron** correlations



1. What is the (absolute) amount of energy lost in cone?

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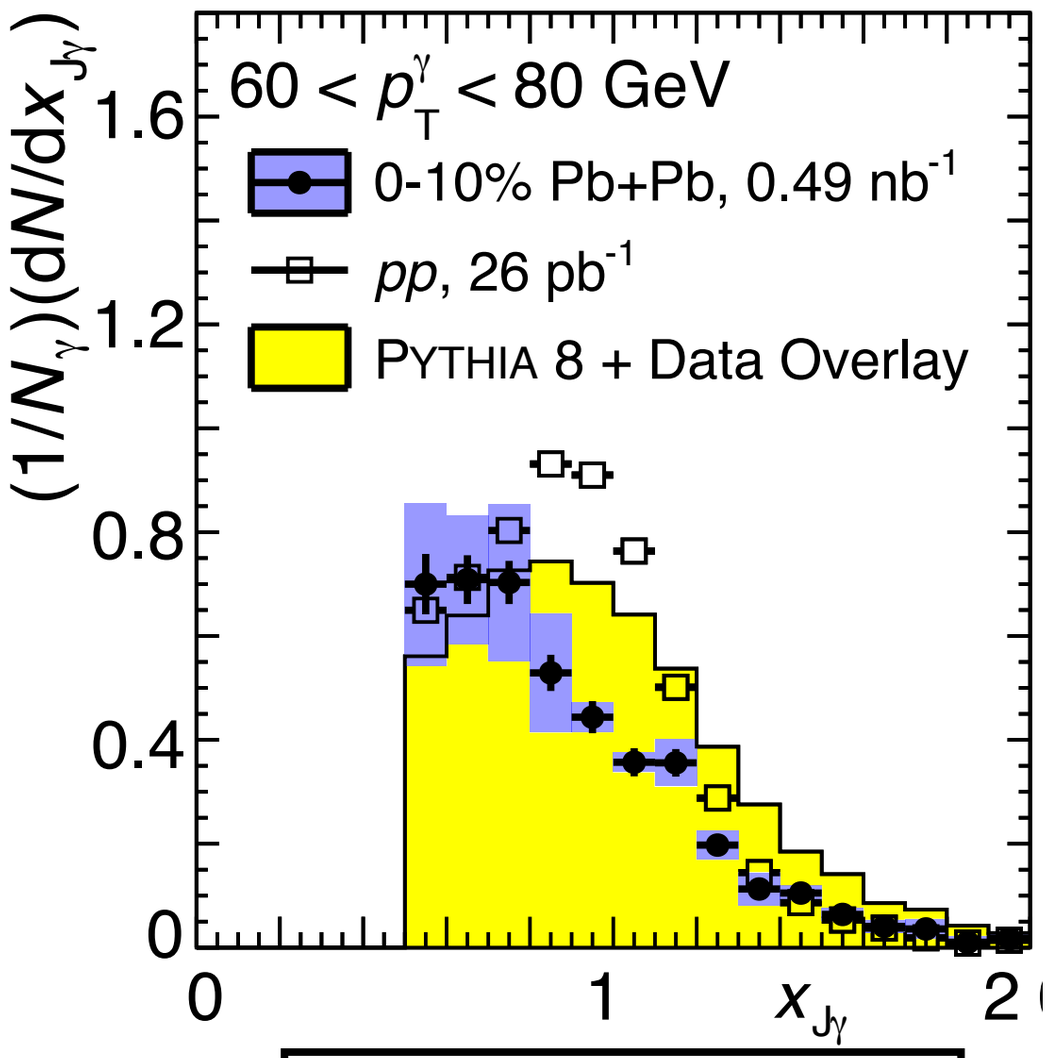


$$x_{J\gamma} = p_T^{jet} / p_{T\gamma}$$

$x_{J\gamma} = p_T^{jet} / p_{T\gamma}$

vary system size

ATLAS-CONF-2016-110

vary initial E before quenching

pp | 50-80% Pb+Pb | 30-50% Pb+Pb | 20-30% Pb+Pb | 10-20% Pb+Pb | 0-10% Pb+Pb

ATLAS Preliminary
5.02 TeV
Pb+Pb, 0.49 nb^{-1}
pp, 26 pb^{-1}
Simulation
Data

$60 < p_T^\gamma < 80$ GeV
$80 < p_T^\gamma < 100$ GeV
$100 < p_T^\gamma < 150$ GeV
$150 < p_T^\gamma < 200$ GeV

$(1/N_{J\gamma})(dN/dx_{J\gamma})$

$x_{J\gamma}$

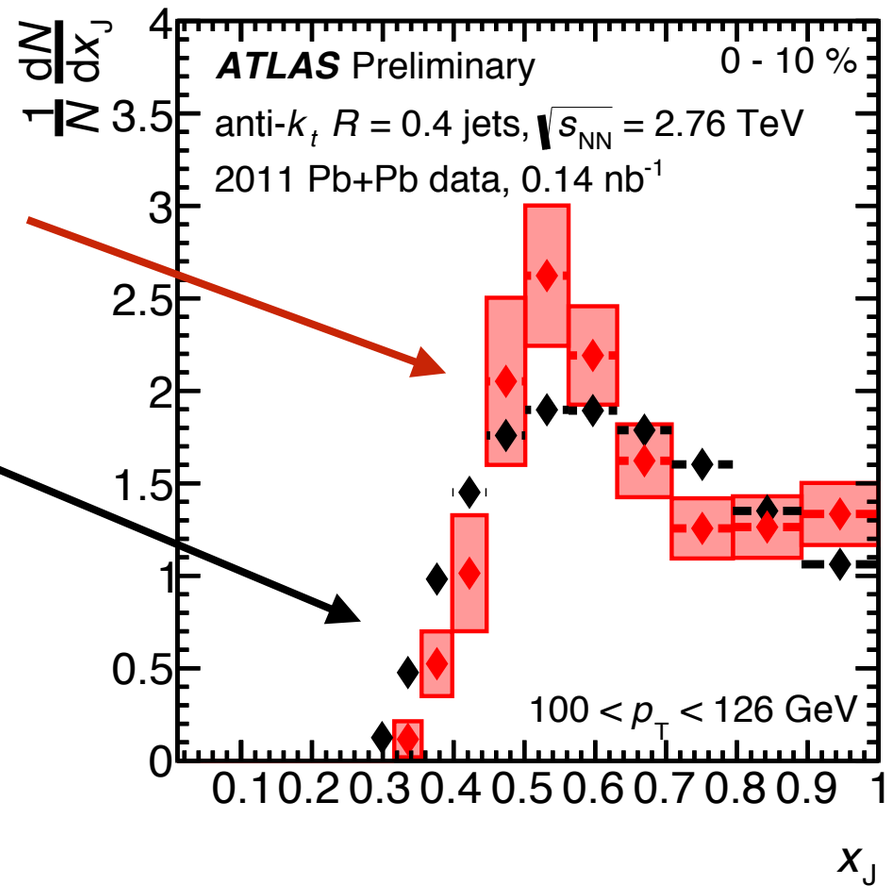
Importance of unfolding…

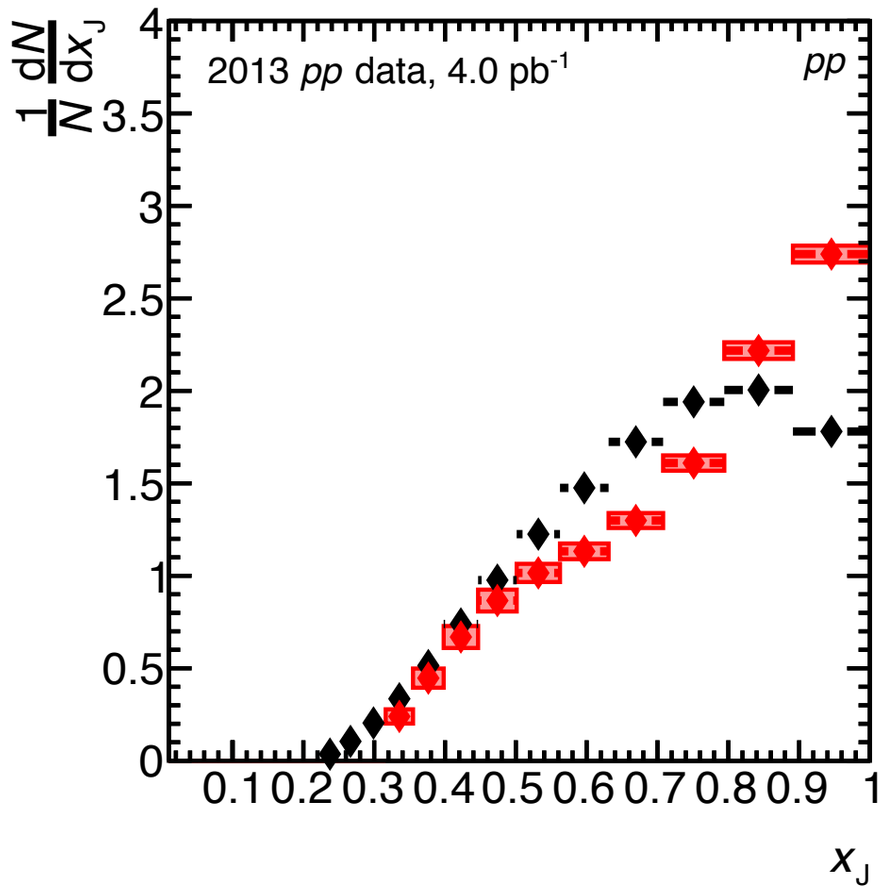
Pb+Pb

pp

detector-free

detector-dependent



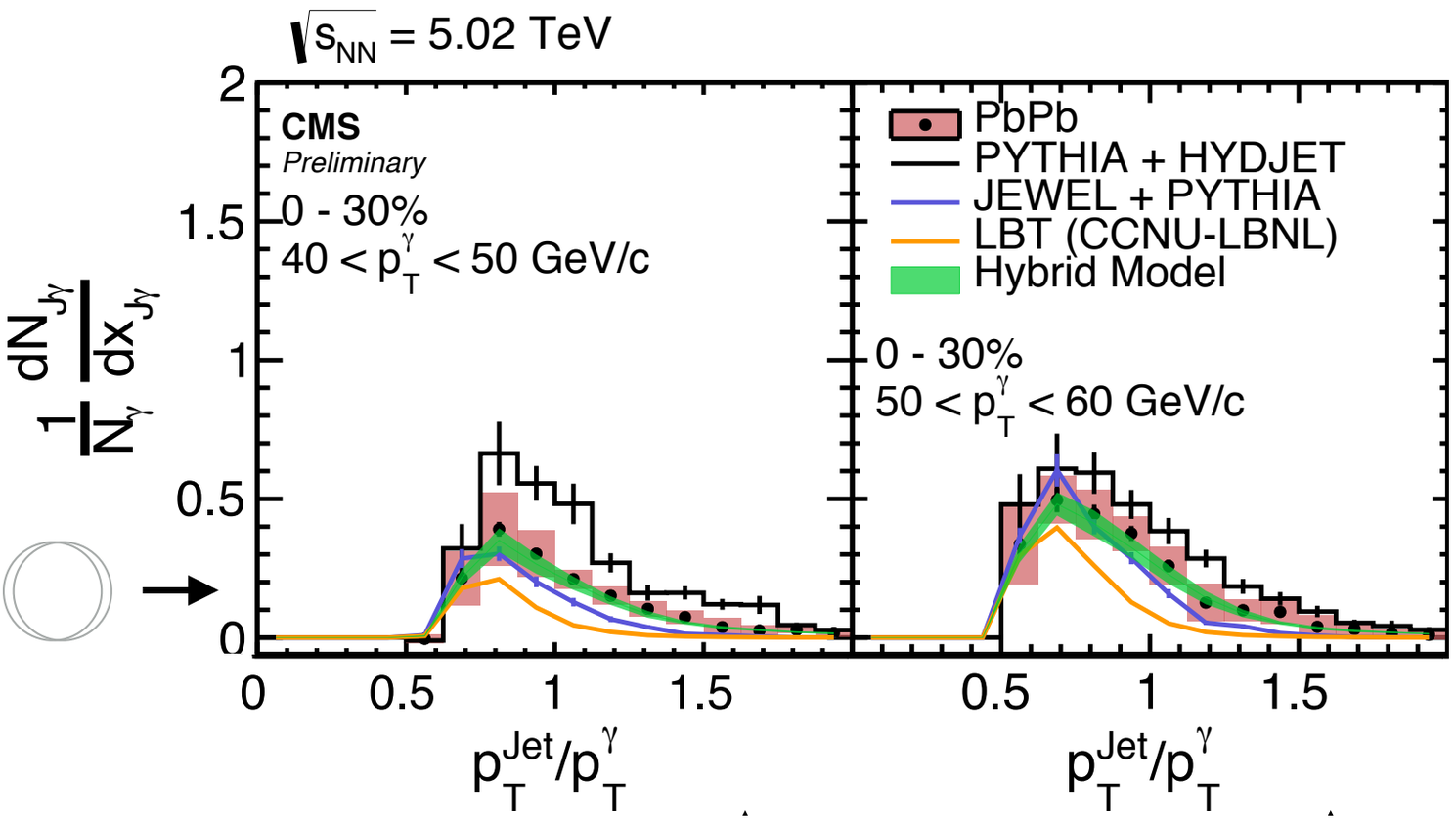


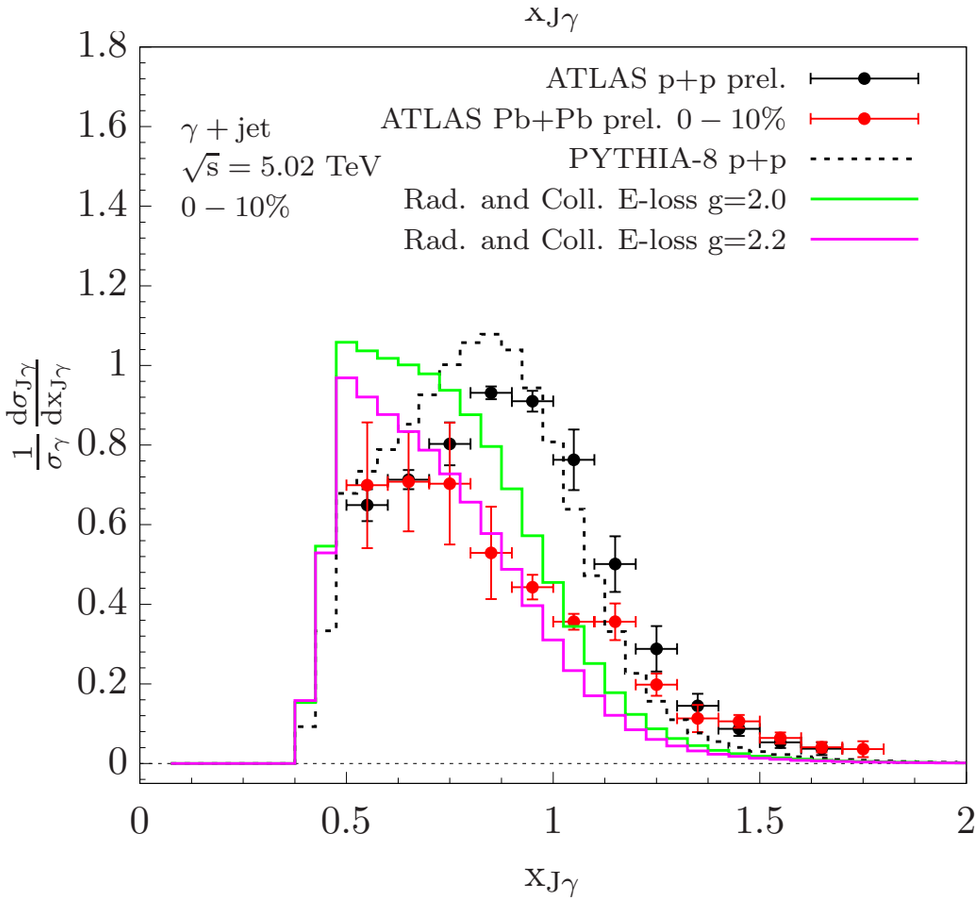
Key final step: unfolding for *all* detector effects

➡ unfolding recovers **non-trivial features** washed away by **resolution**

➡ “2-D” unfolding difficult but ultimately necessary if we want to enter a “precision jet physics” era…

Importance of unfolding…





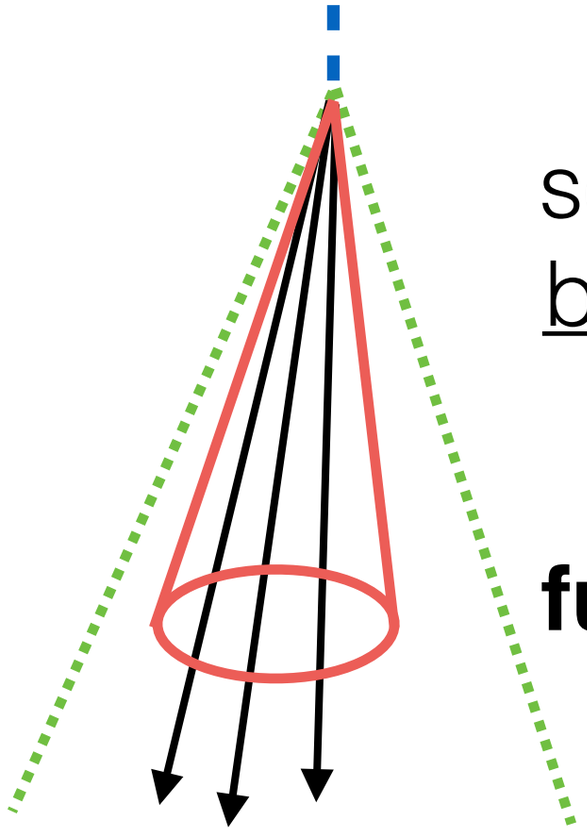
Current γ+jet comparisons are to a "smeared *pp* reference" (data or MC or theory calculations)

➡ major goal from my perspective: producing final, fully unfolded results to allow more than qualitative comparisons

Photon-tagged FF

select *pp* and Pb+Pb events with **photon** in narrow p_T range

pick jets **angularly associated** with photon



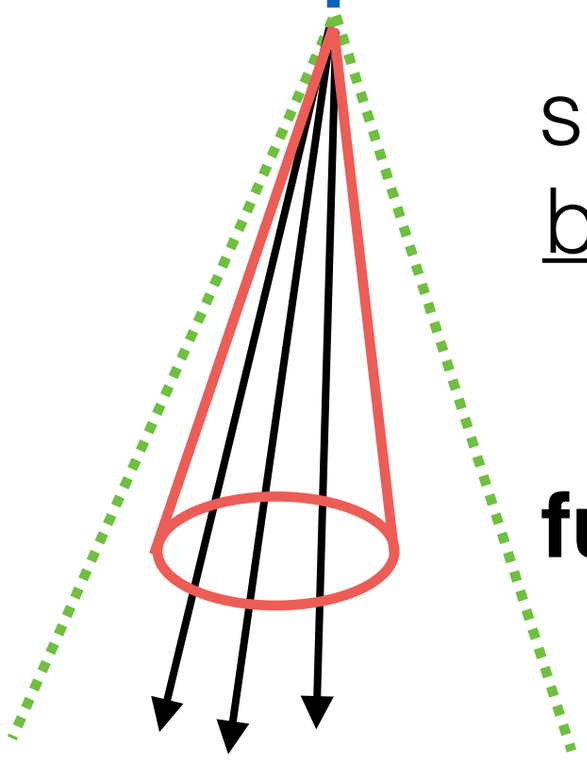
select **jets** over broad p_T range

measure **frag. function** with respect to ***jet*** (not ɣ!)

Photon-tagged FF

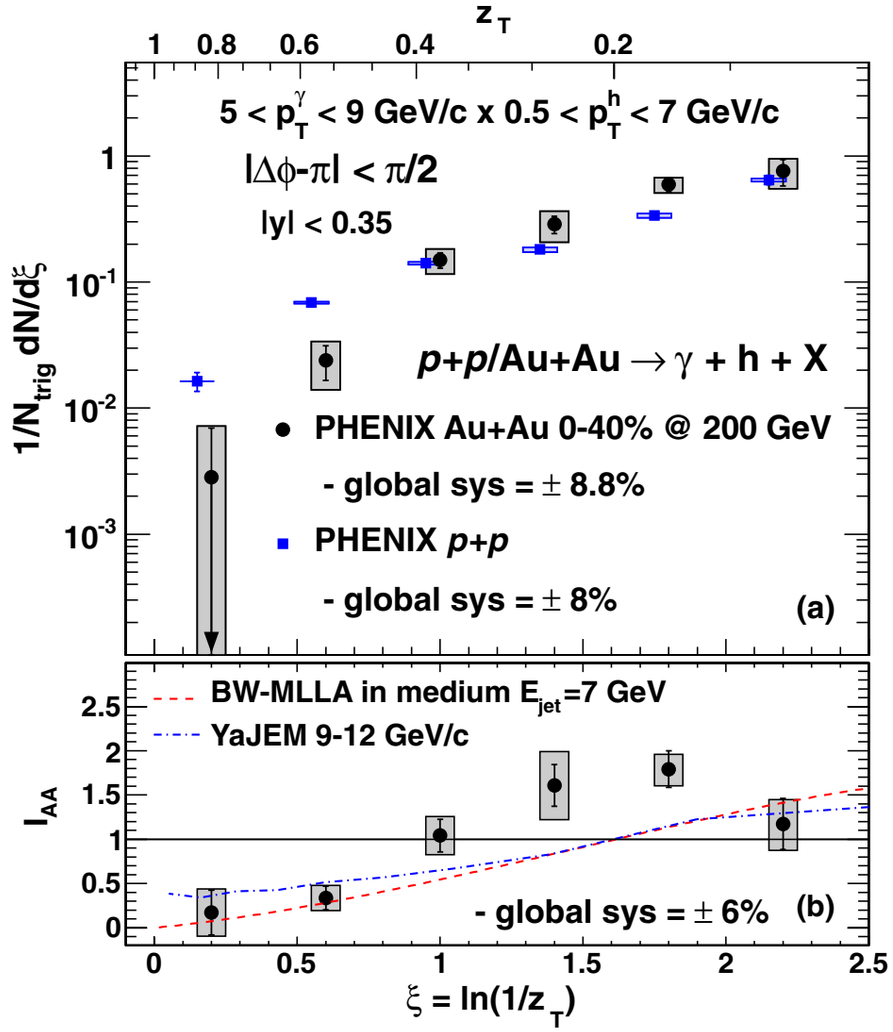
select *pp* and Pb+Pb events with **photon** in <u>narrow</u> p_T range

pick jets **angularly associated** with photon



select **jets** over <u>broad</u> p_T range

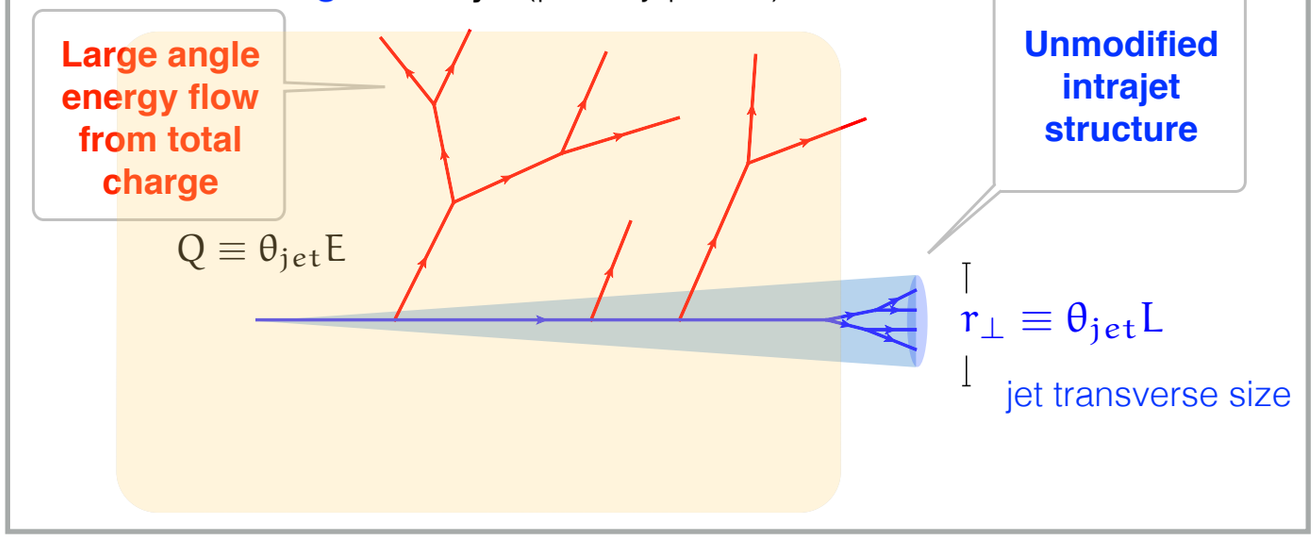
measure **frag. function** with respect to ***jet*** (not ɣ!)



RHIC-style ɣ+h doesn't distinguish E-loss from mod. of fragmentation…

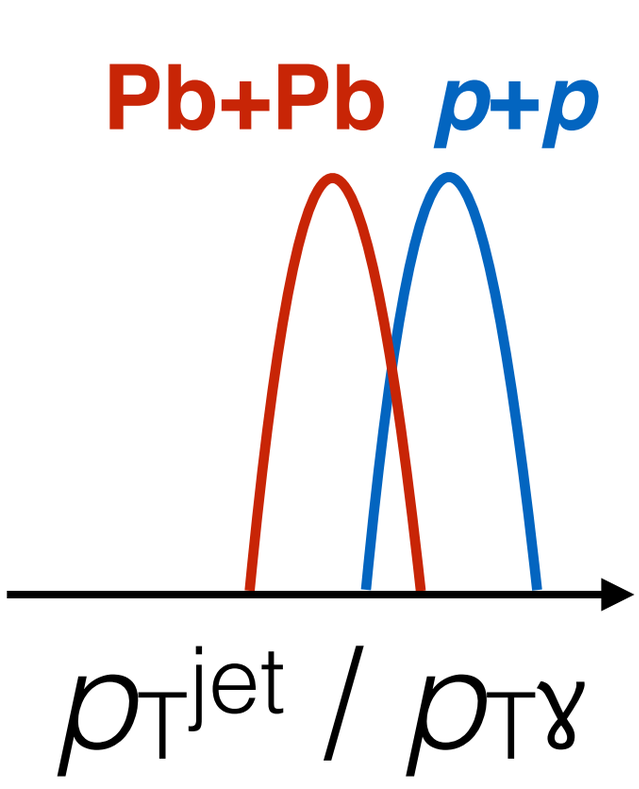
testing color coherence…

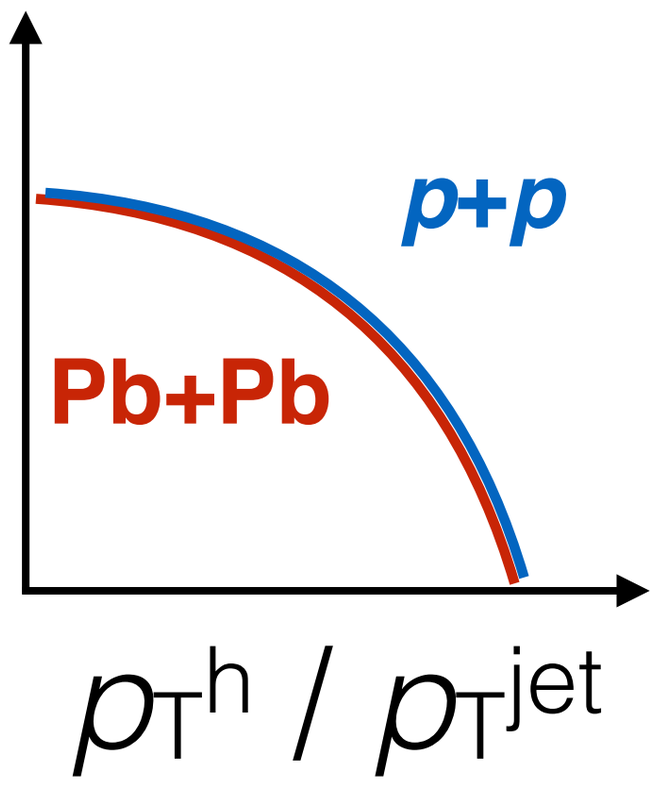
- When the transverse size $r_\perp$ of the jet is smaller than medium resolution scale Q_s^{-1} **the medium interacts "effectively" with the total charge of the jet** (primary parton)

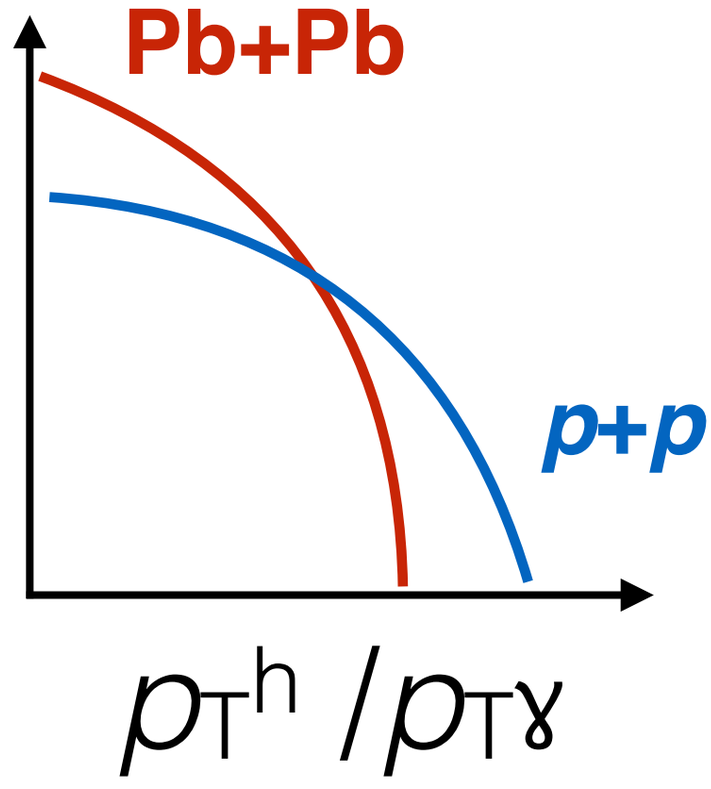


what if <u>entire</u> parton shower loses energy, but relative structure unmodified?

(Y. Mehtar-Tani, QM'15 talk)
PLB 725 (2013) 357







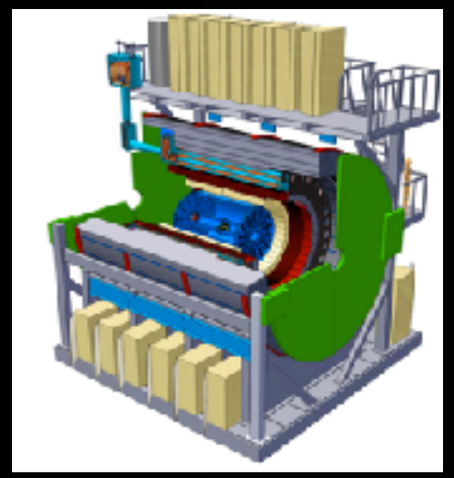
Run 2 γ+jet physics (and Run 3+4 *Z*+jet?)

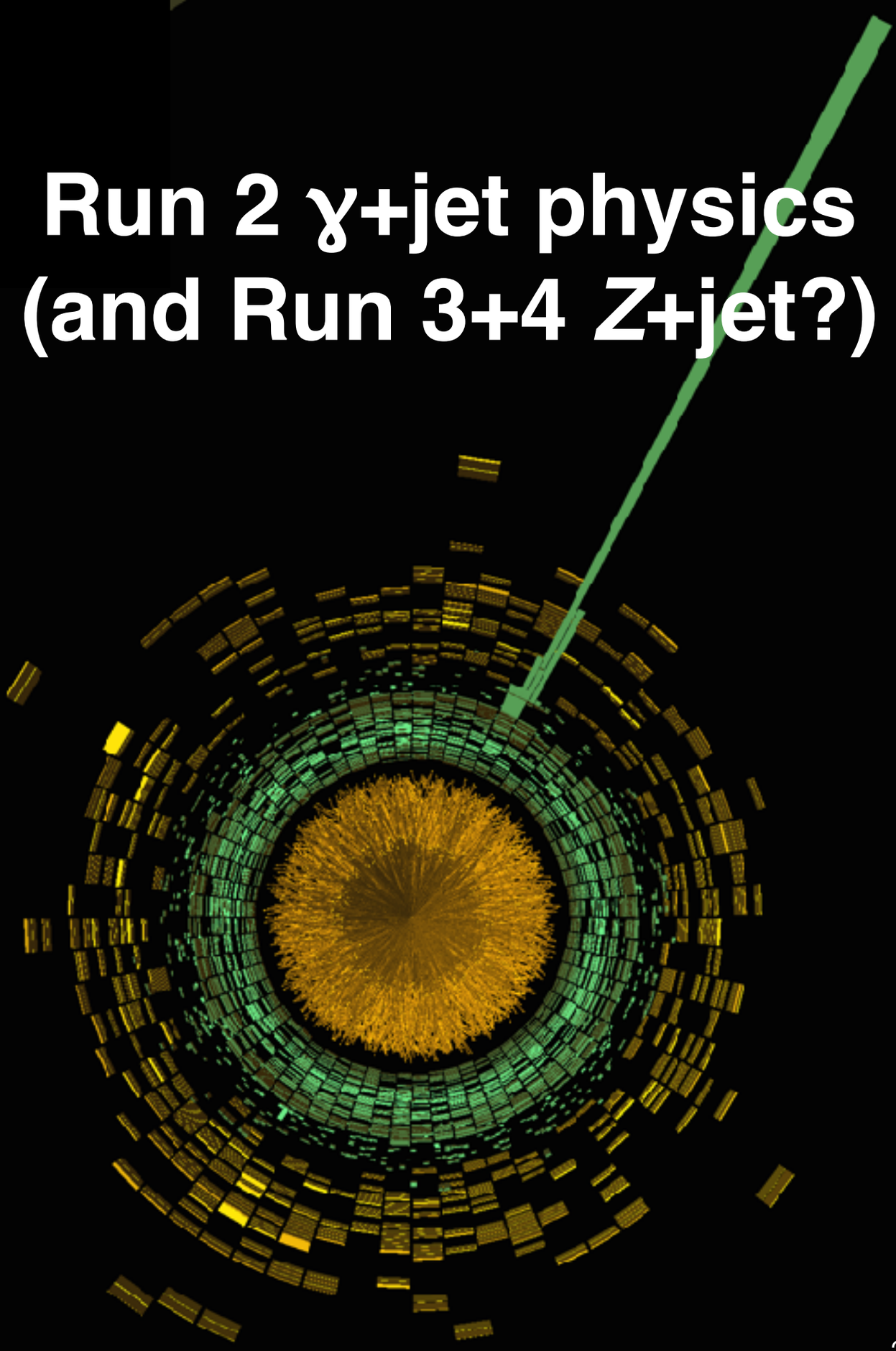
1. γ+jet: absolute E-loss
2. γ+jet vs. reaction plane
3. γ-tagged R_{AA}
4. missing-p_T flow w/ external scale
5. D(*z*) for γ-tagged jets in Pb+Pb & *p*+*p*

➡ very nice talks on these Wed. afternoon

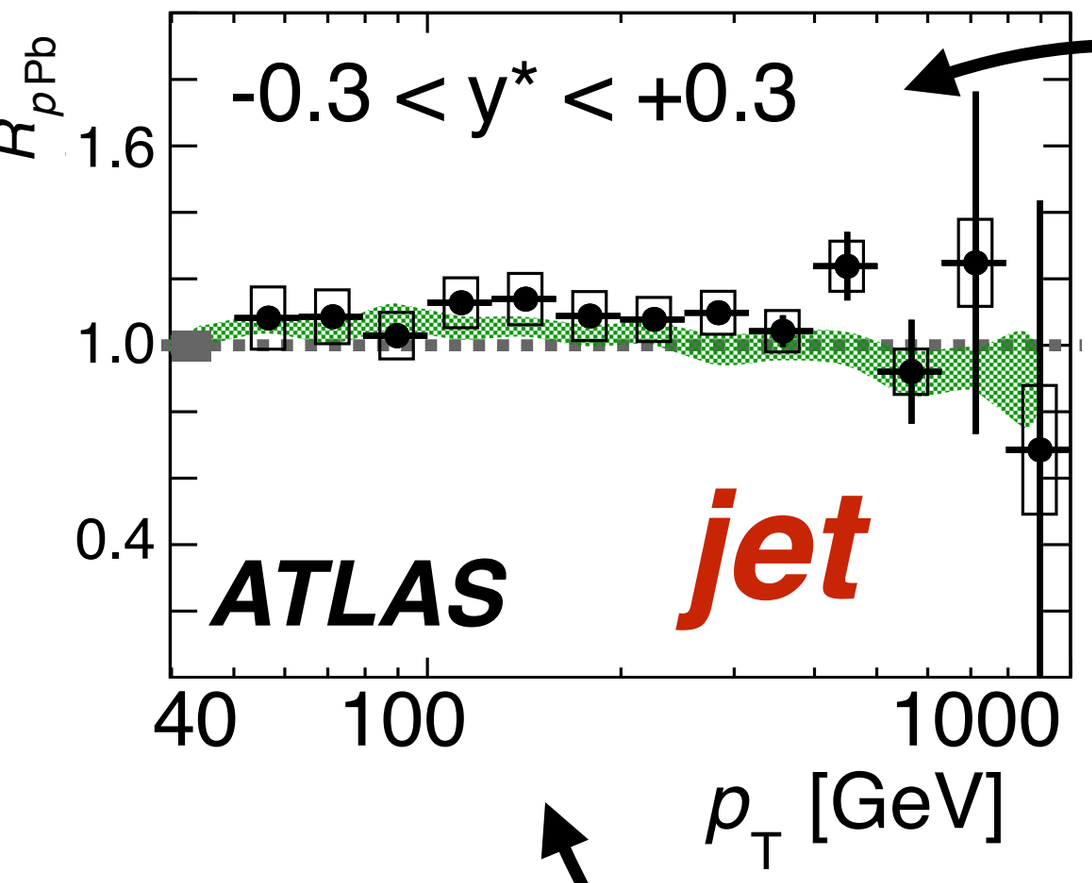
6. low-p_T quark jets, compare to RHIC

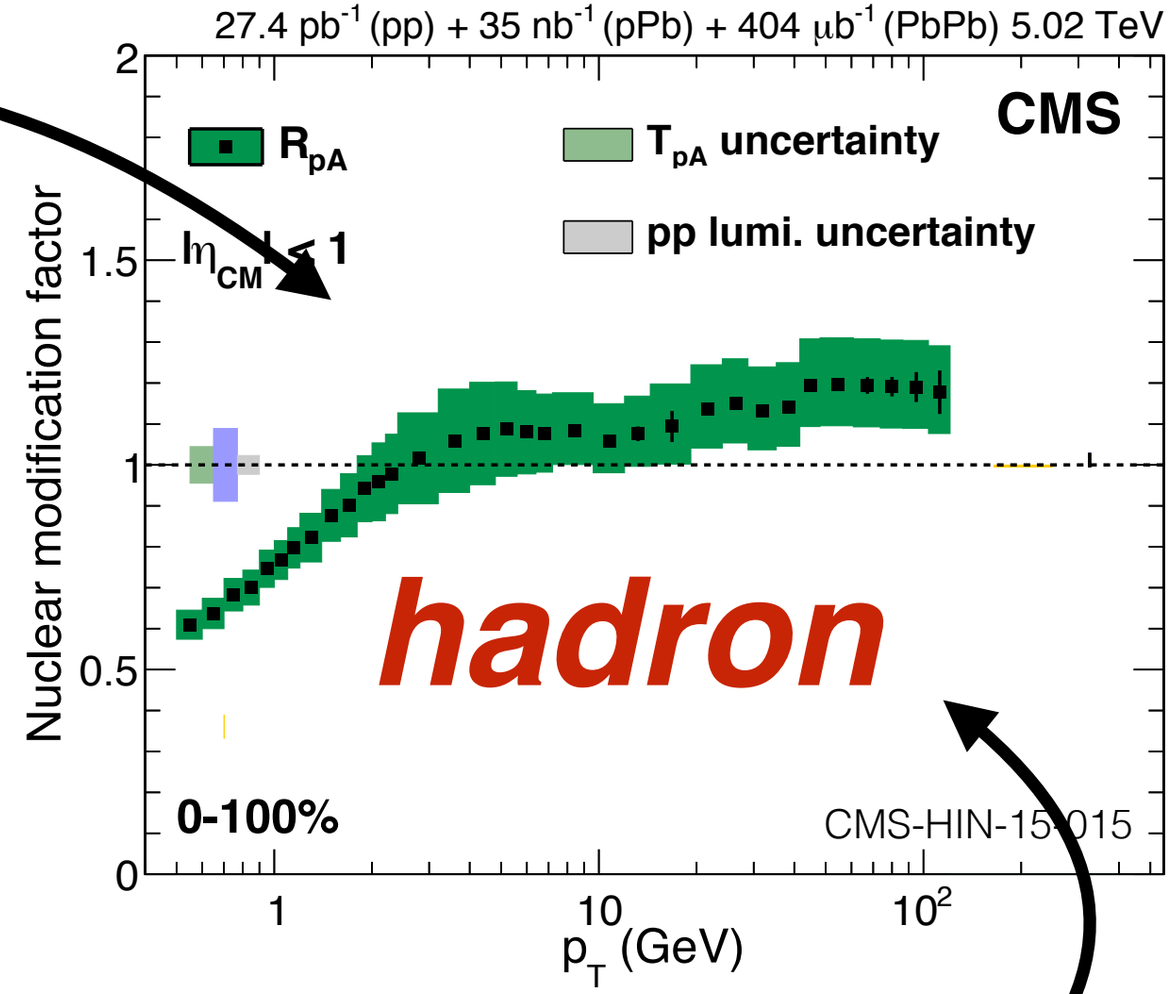
… etc.

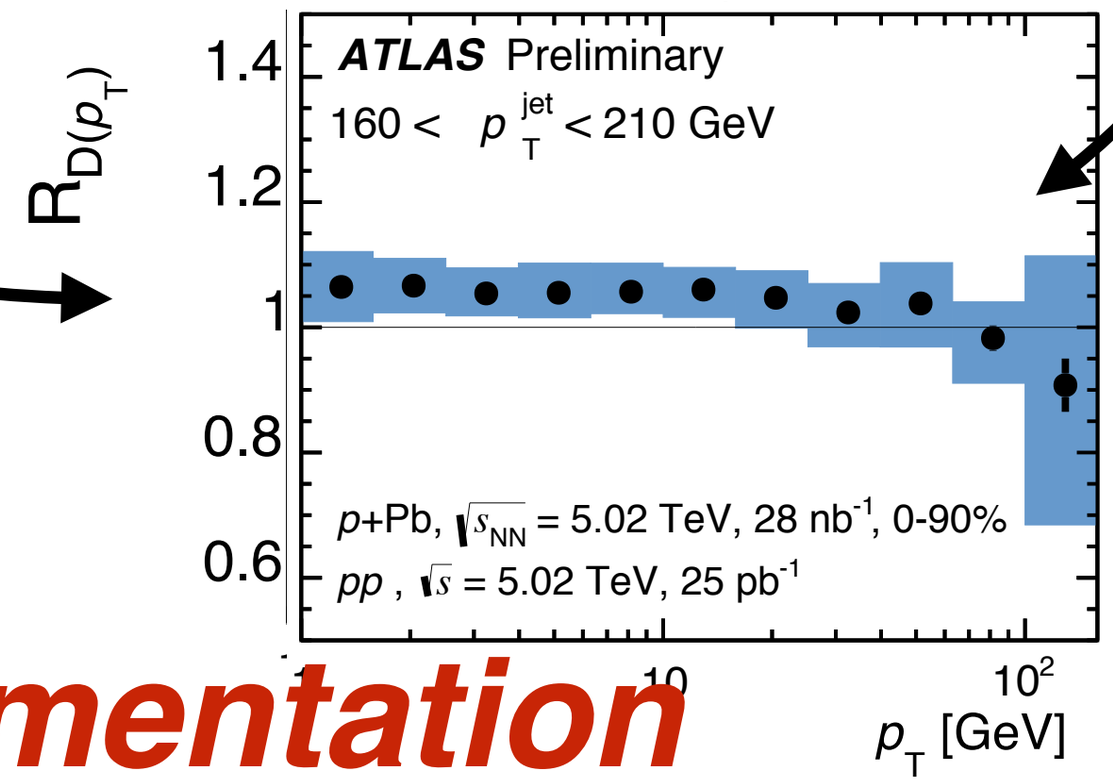




p+A: initial state effects



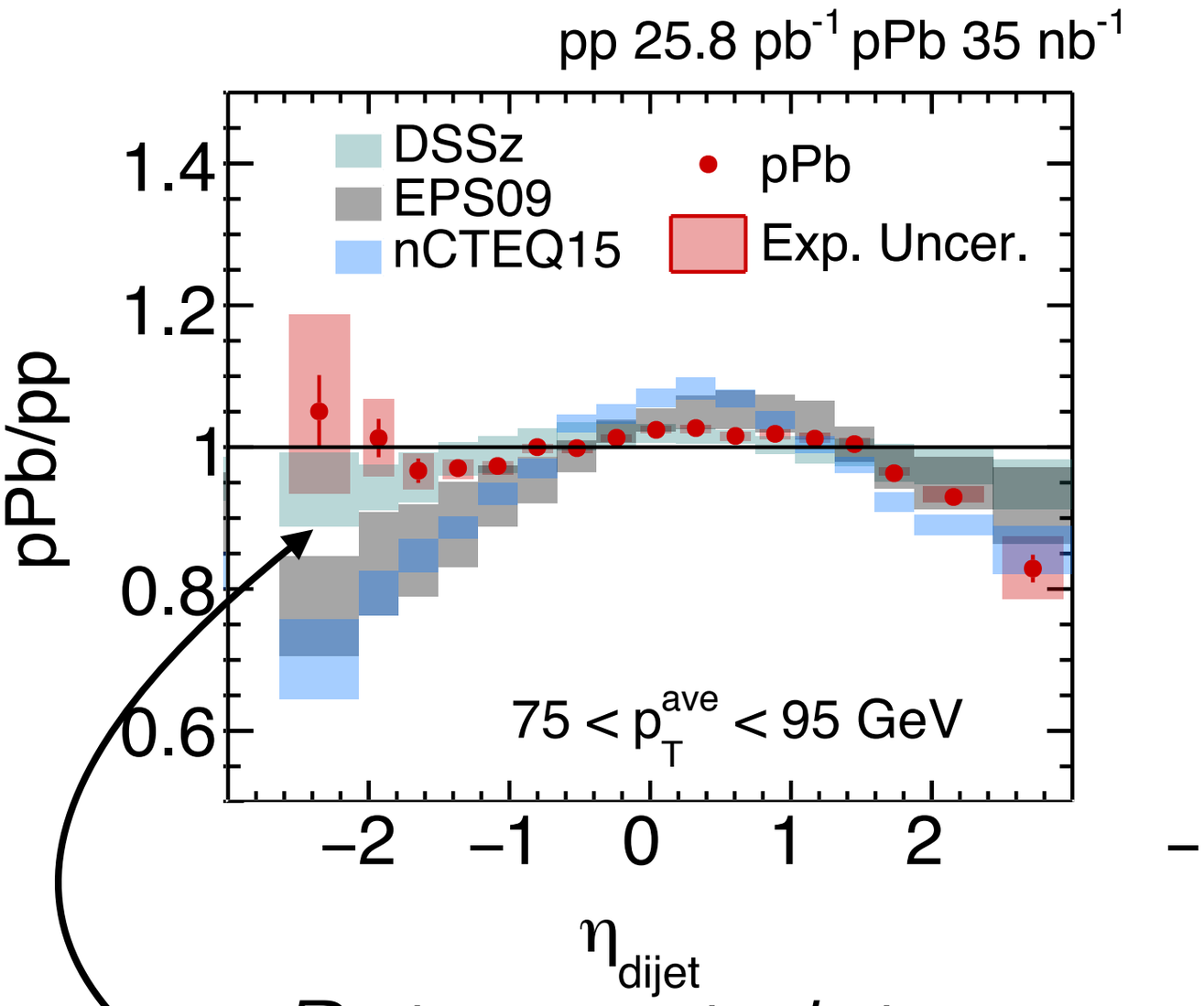




internal self-consistency

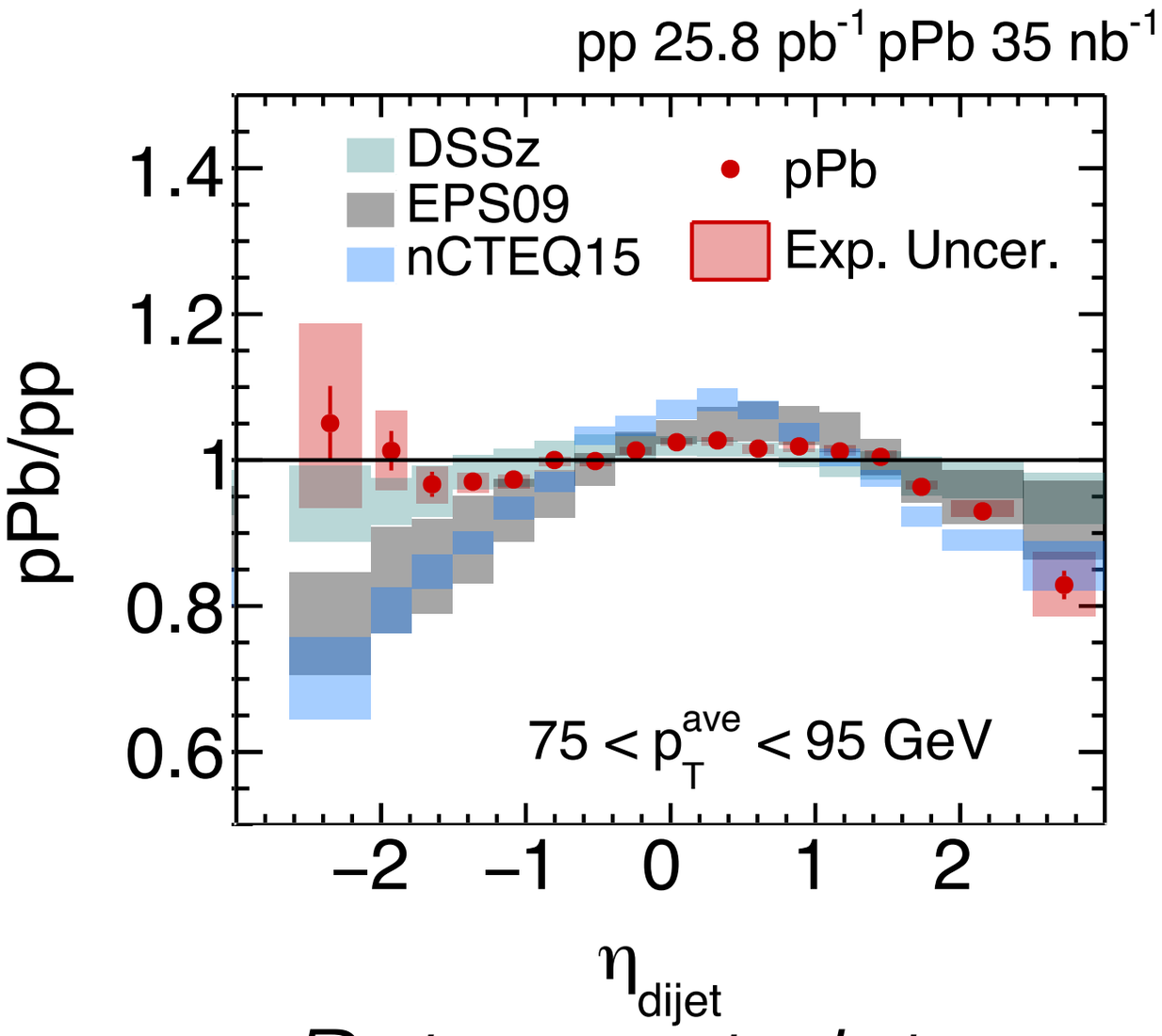
fragmentation

initial state effects



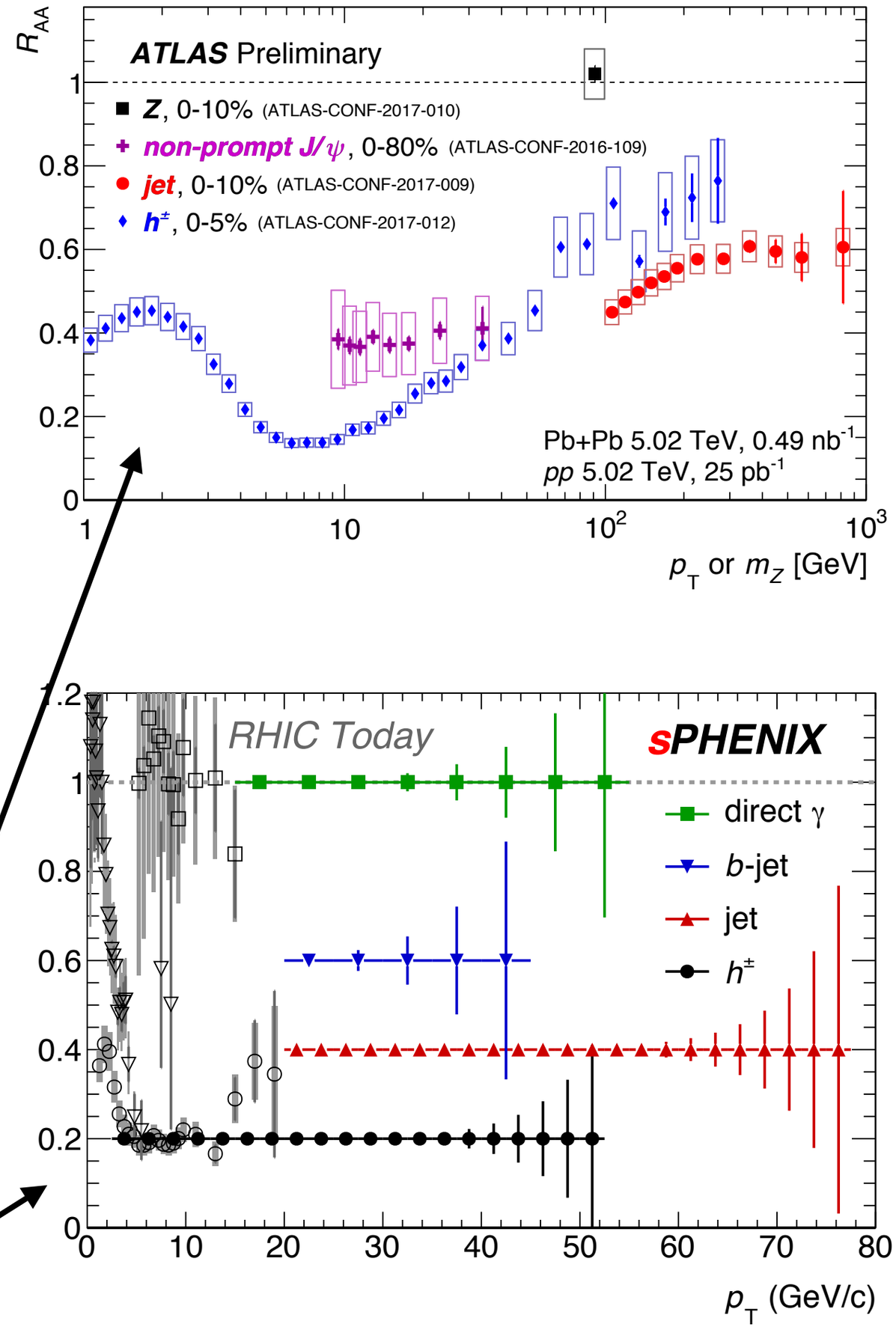
Data constraints on EMC region

initial state effects



Data constraints on EMC region

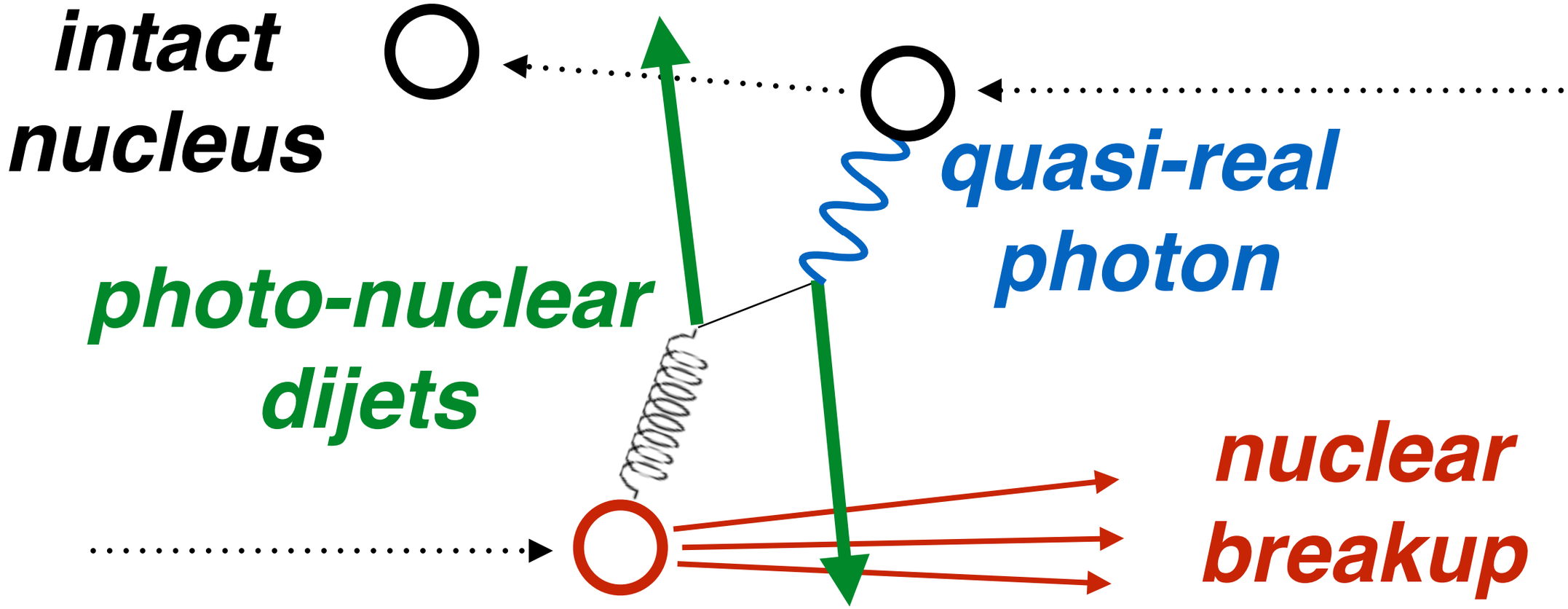
large-x (> 0.4) jets at ***LHC*** *and (future)* ***RHIC***

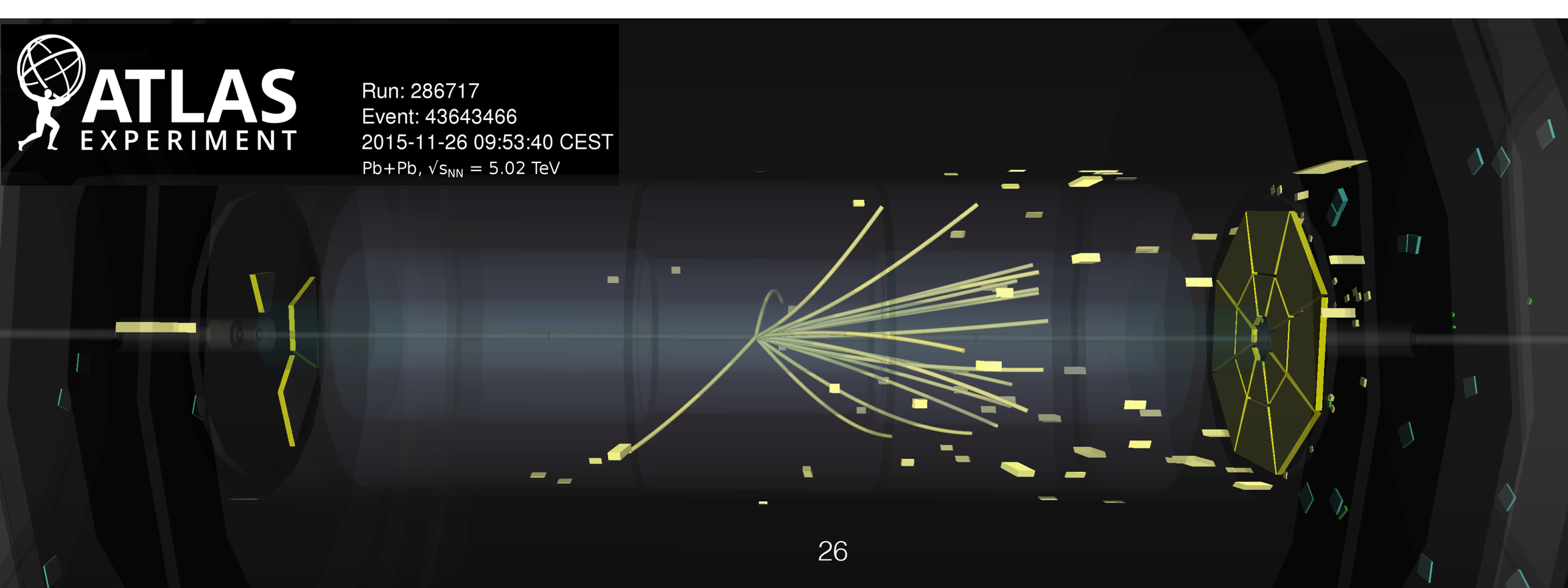


how to access other (x_A, Q^2) regions?

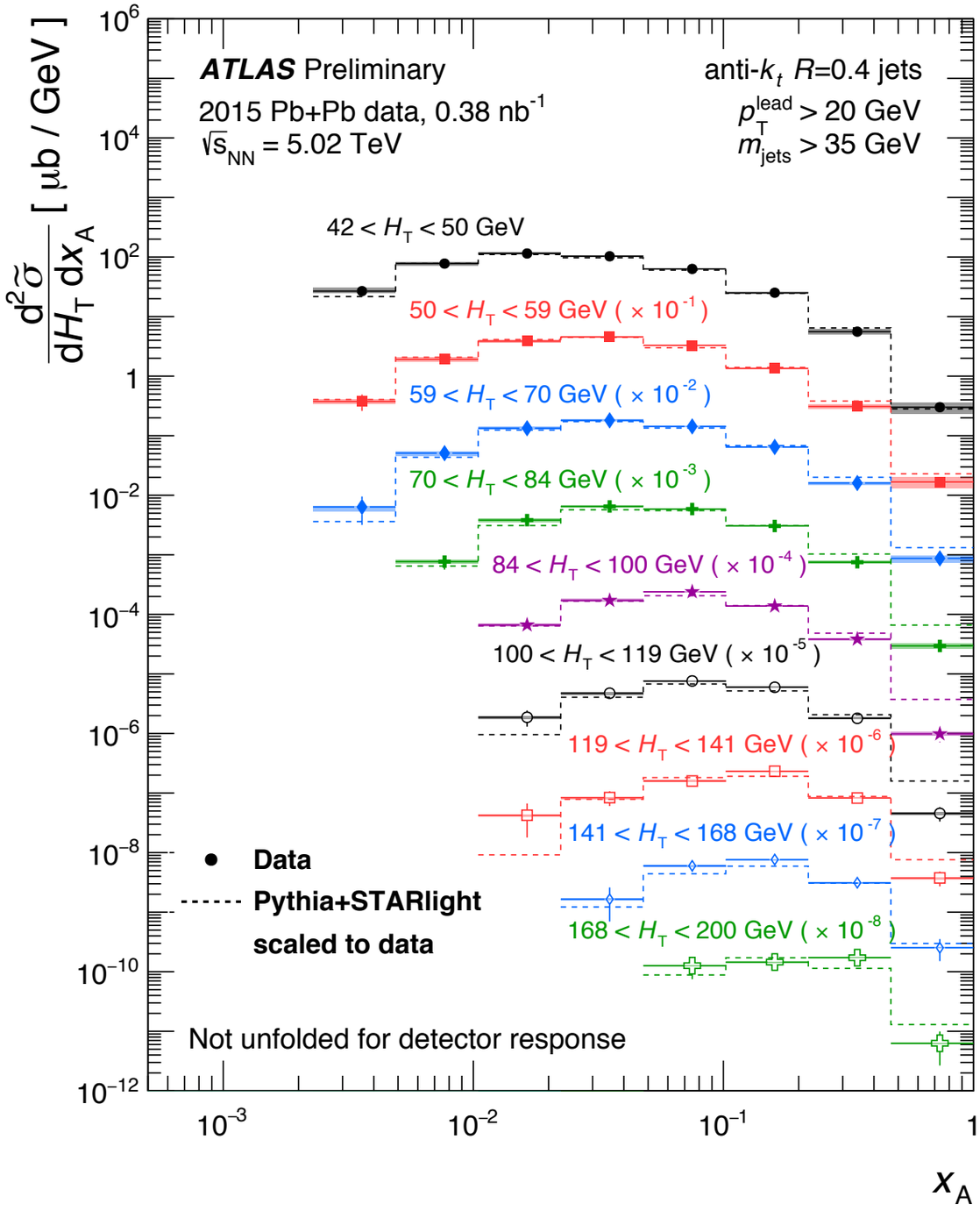
➡ *cleaner environments (UPC)*

➡ *cleaner probes (EW in 8.16 TeV p+Pb)*


intact
nucleus
quasi-real
photon
photo-nuclear
dijets
nuclear
breakup

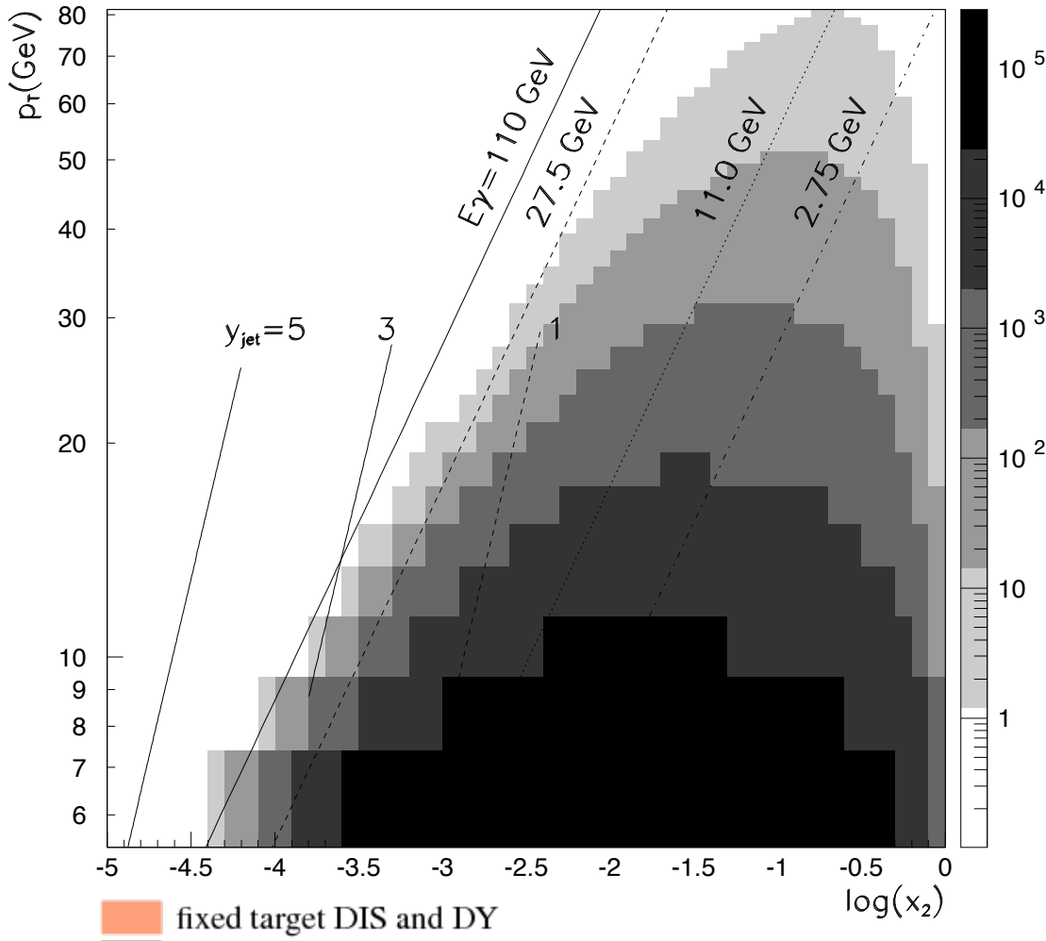

ATLAS
EXPERIMENT
Run: 286717
Event: 43643466
2015-11-26 09:53:40 CEST
Pb+Pb, √sNN = 5.02 TeV

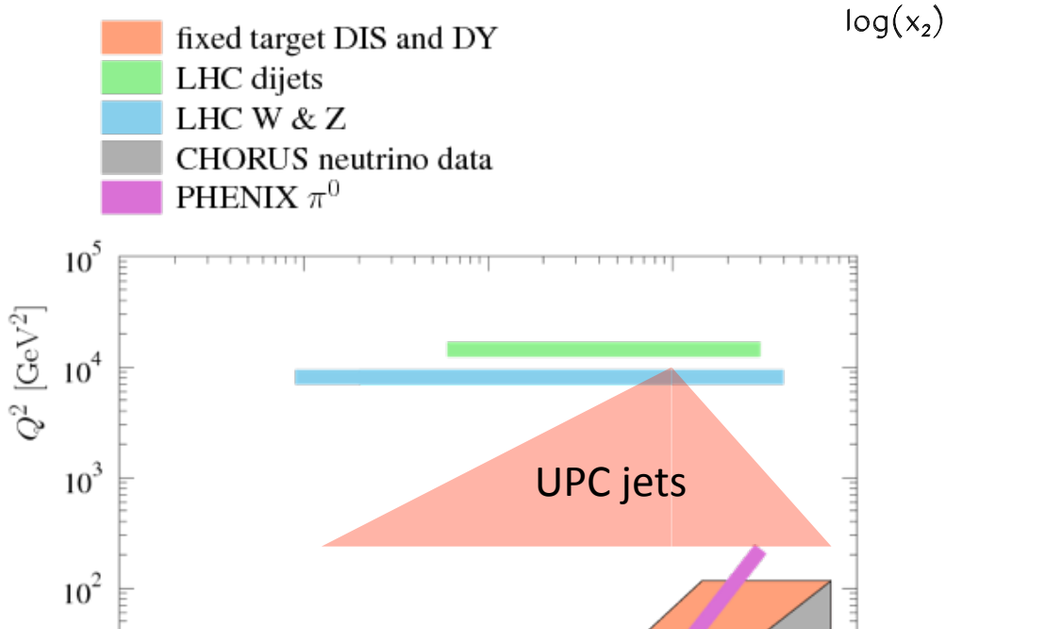
dijets in γ+Pb



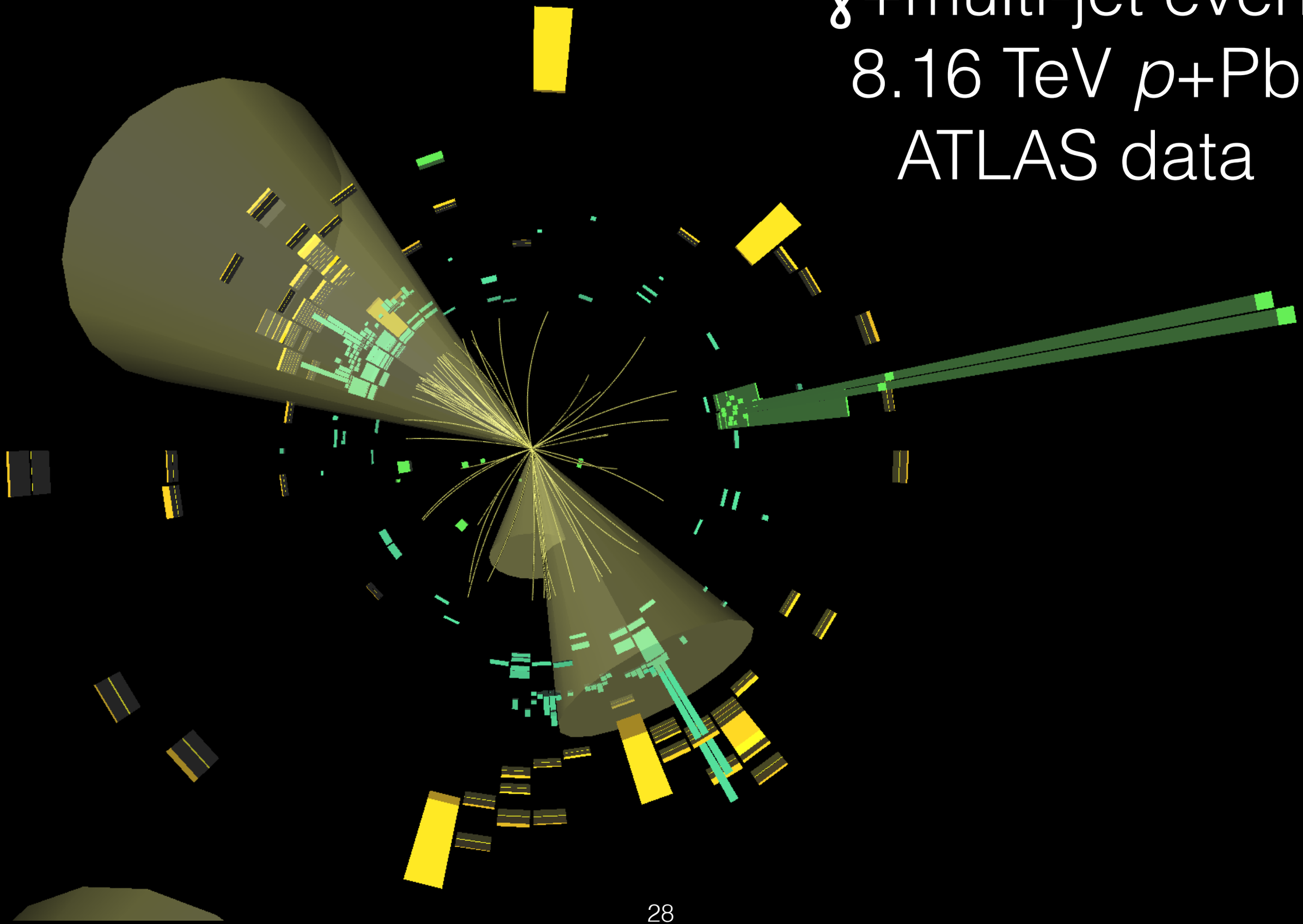
cleanly access nPDF effects in entirely new (x_A, Q^2) range

PRL 96 (2006) 082001

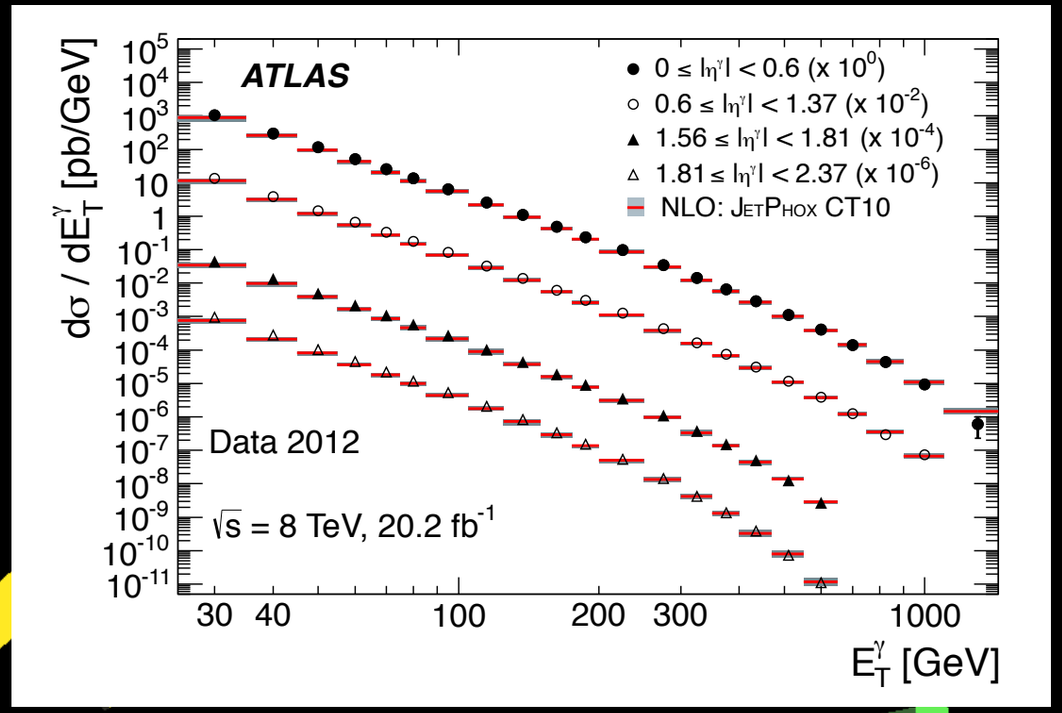




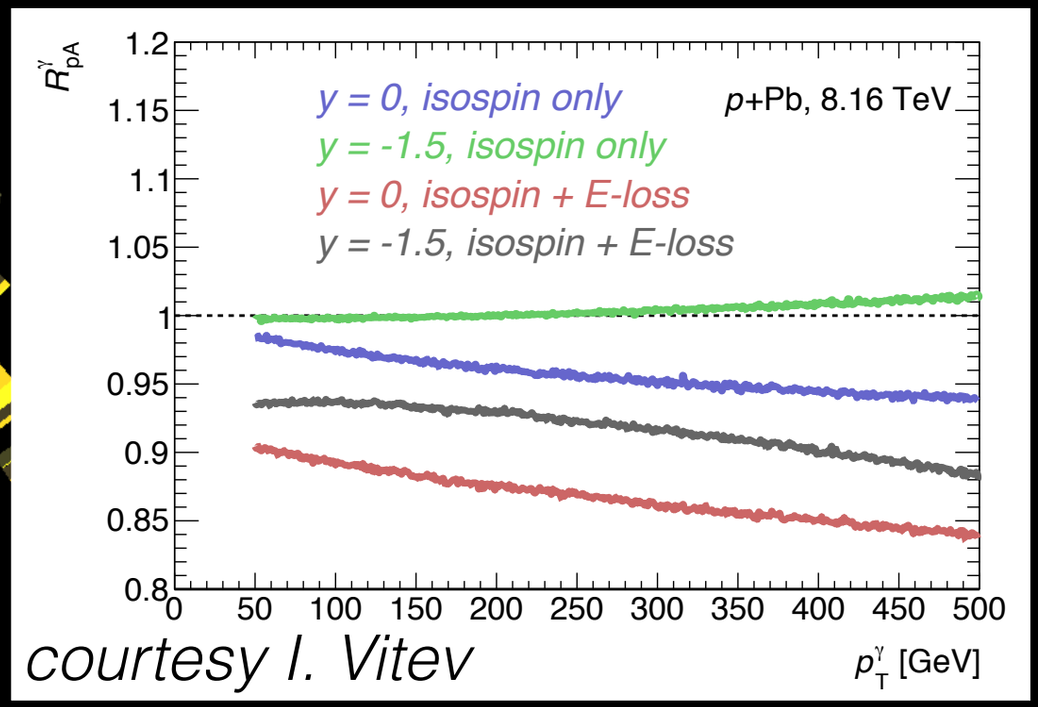
γ+multi-jet event
8.16 TeV *p*+Pb
ATLAS data



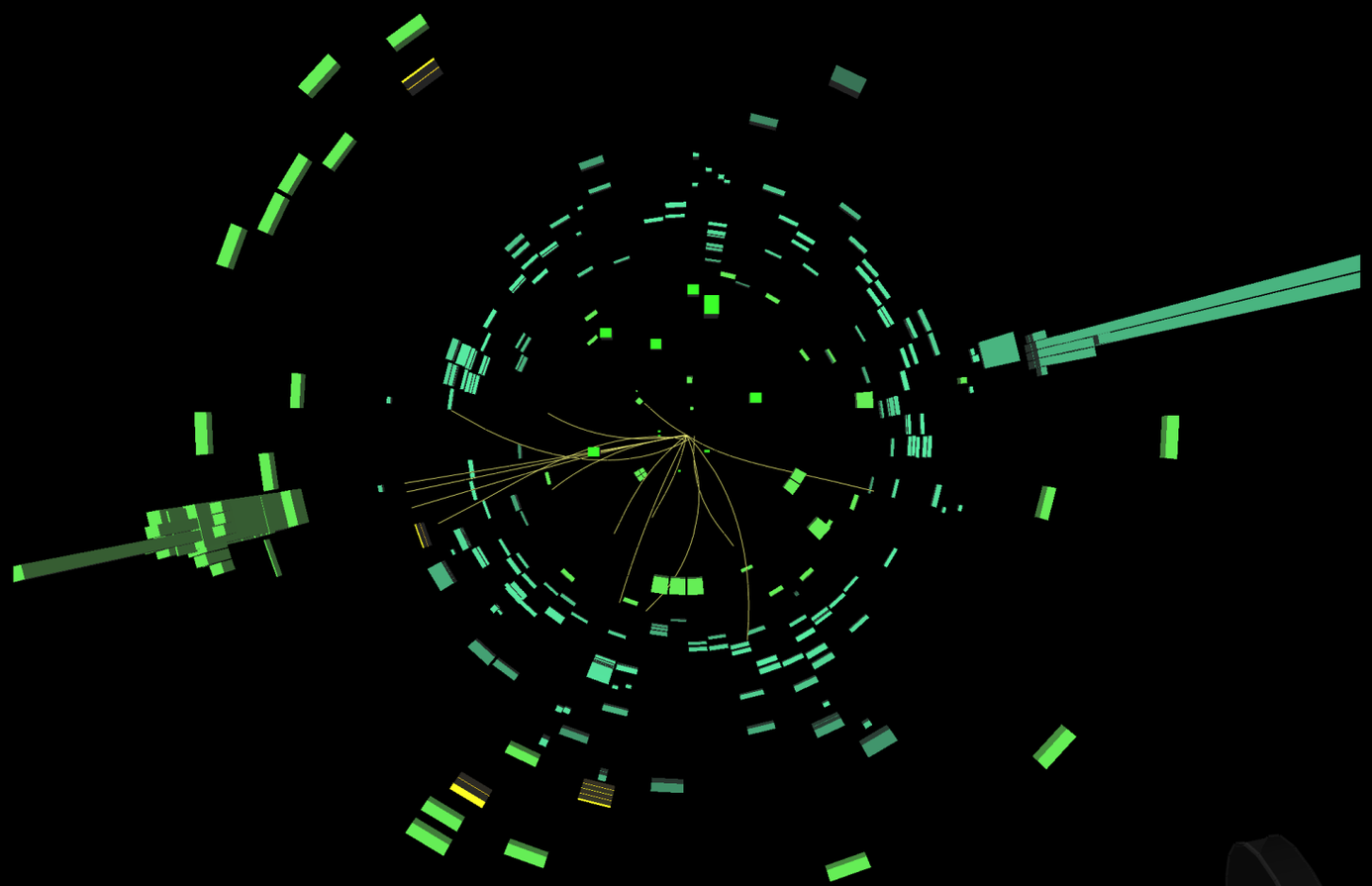
Precise, large-statistics pp reference data at √s=8 TeV



Appreciable initial state E-loss effects for several-hundred GeV photons…



courtesy I. Vitev



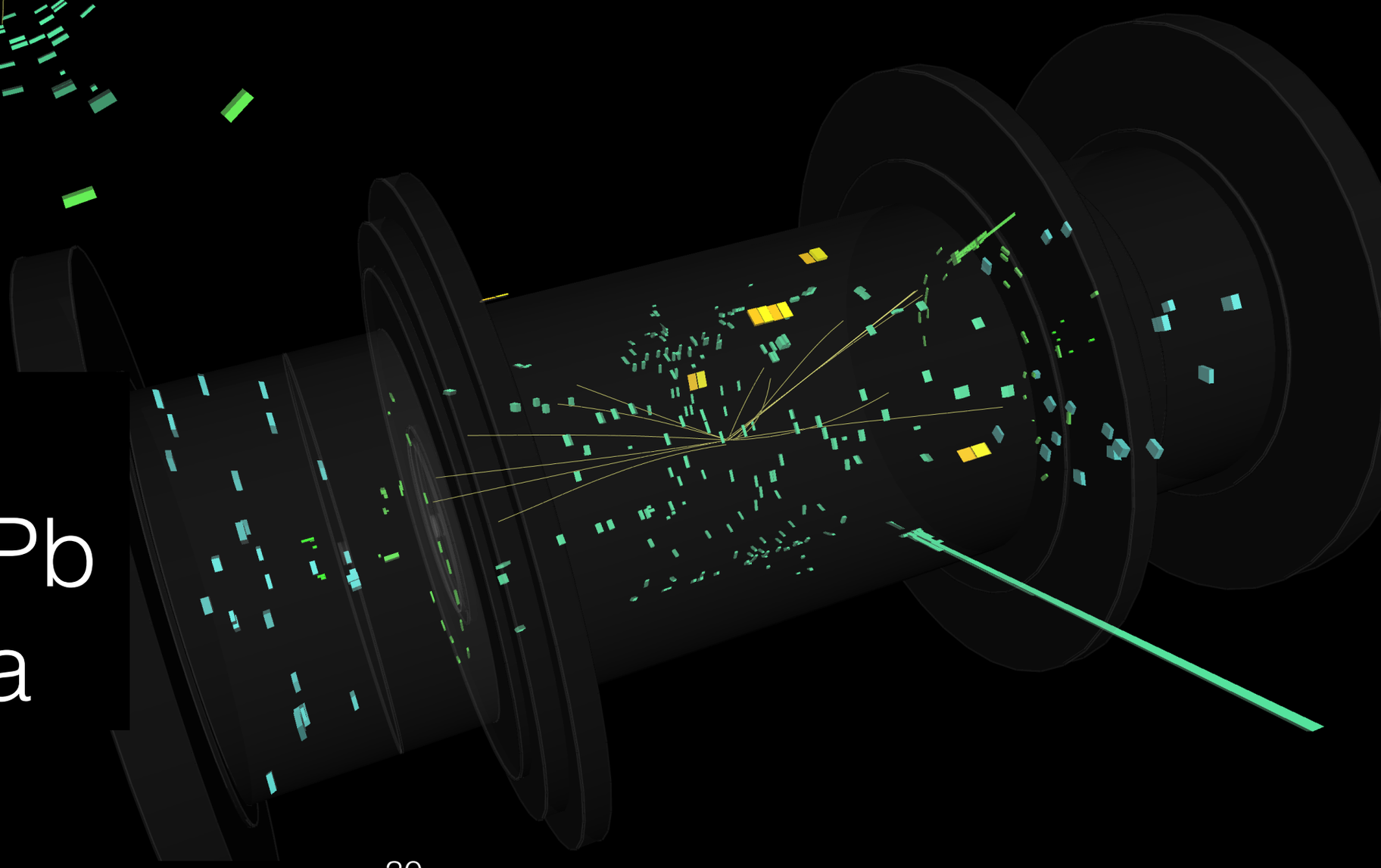
Di-photon event

p+Pb $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV

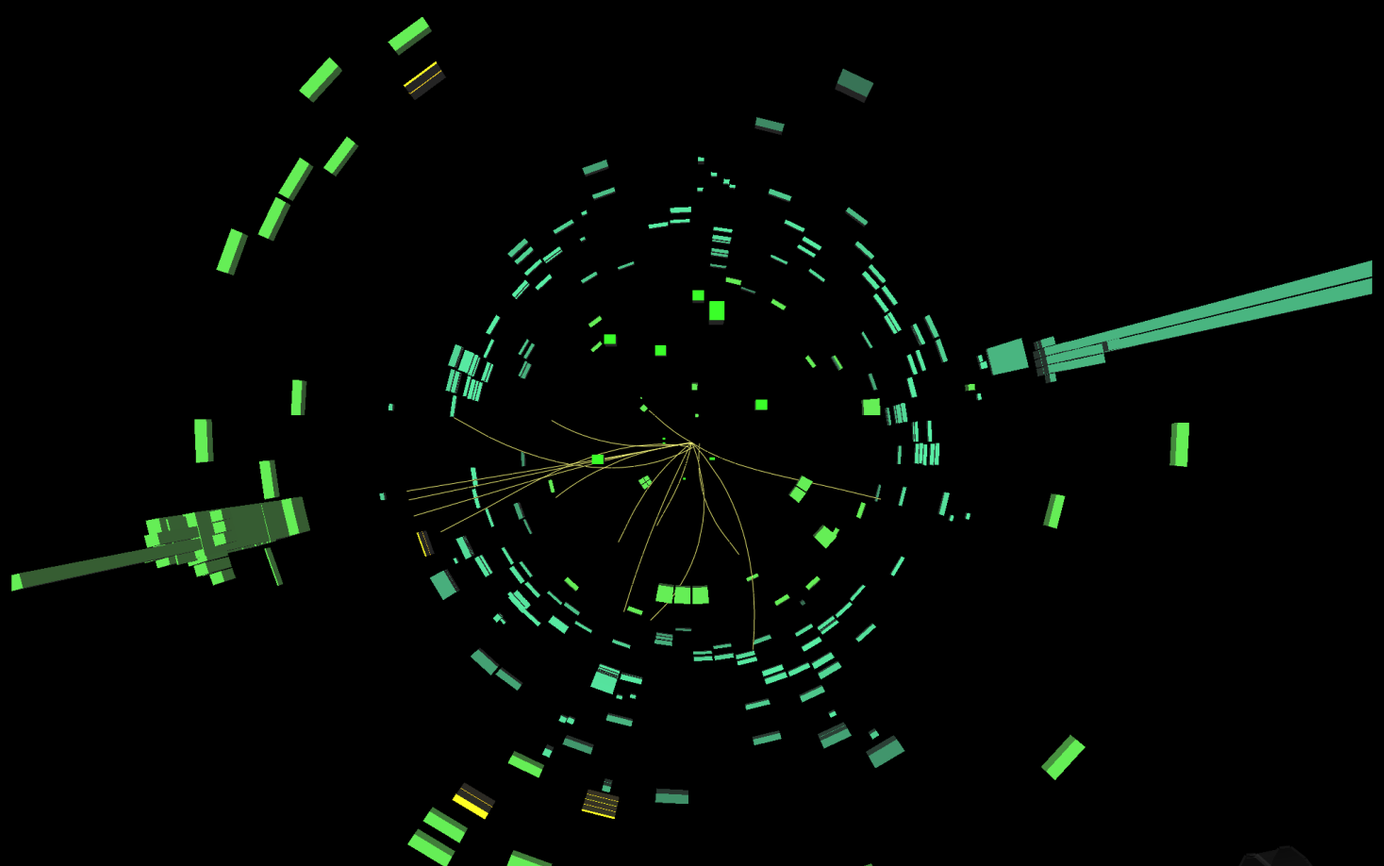
$p_{\mathrm{T},1}^{\gamma}$ = 36.7 GeV, η_1 = 0.96, ϕ_1 = 0.21

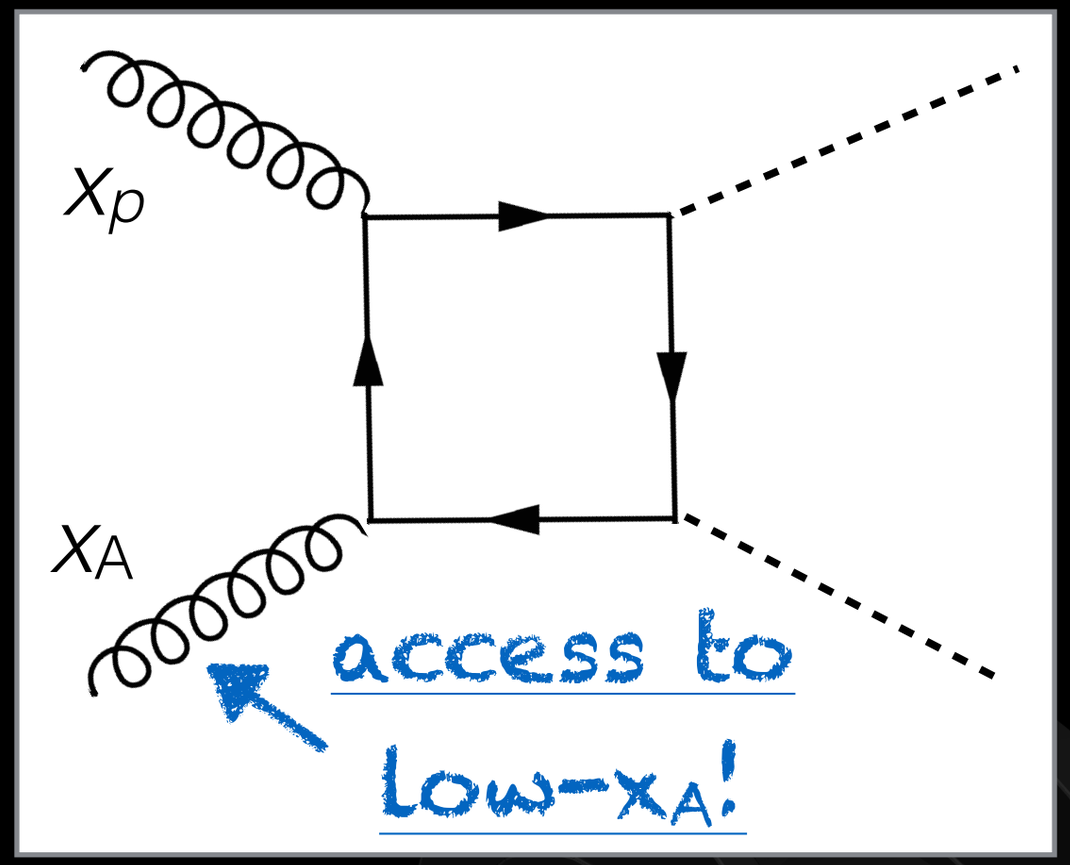
$p_{\mathrm{T},2}^{\gamma}$ = 34.2 GeV, η_2 = 1.68, ϕ_2 = -2.91

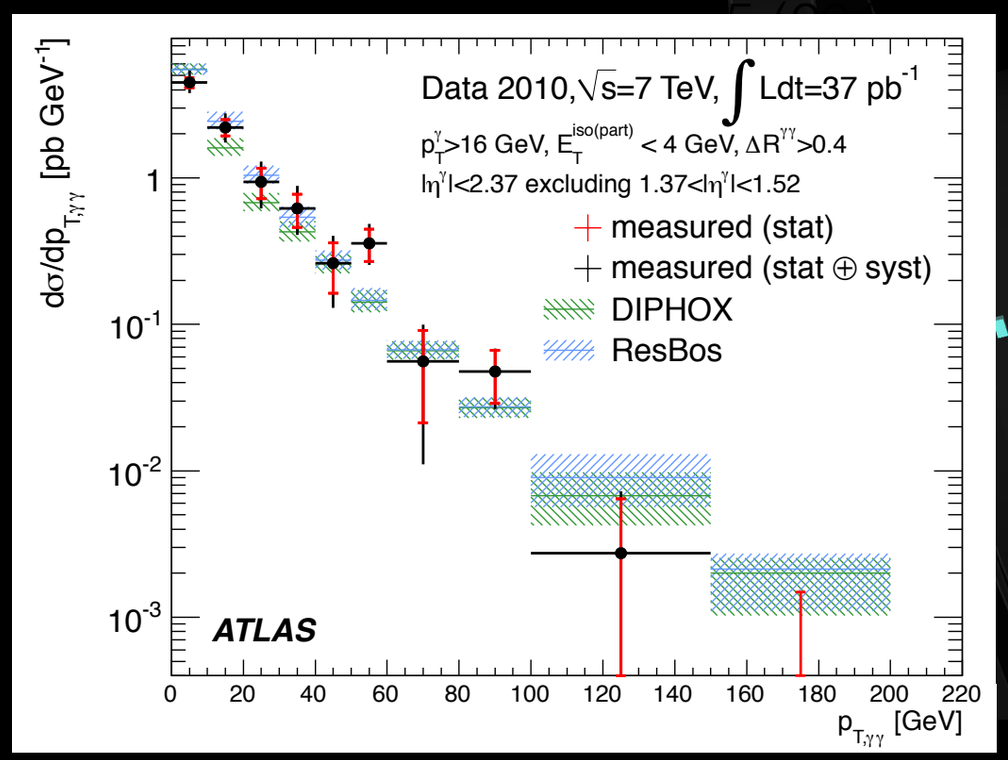
$\sum E_{\mathrm{T}}^{\mathrm{Pb}}$ = 19.9 GeV

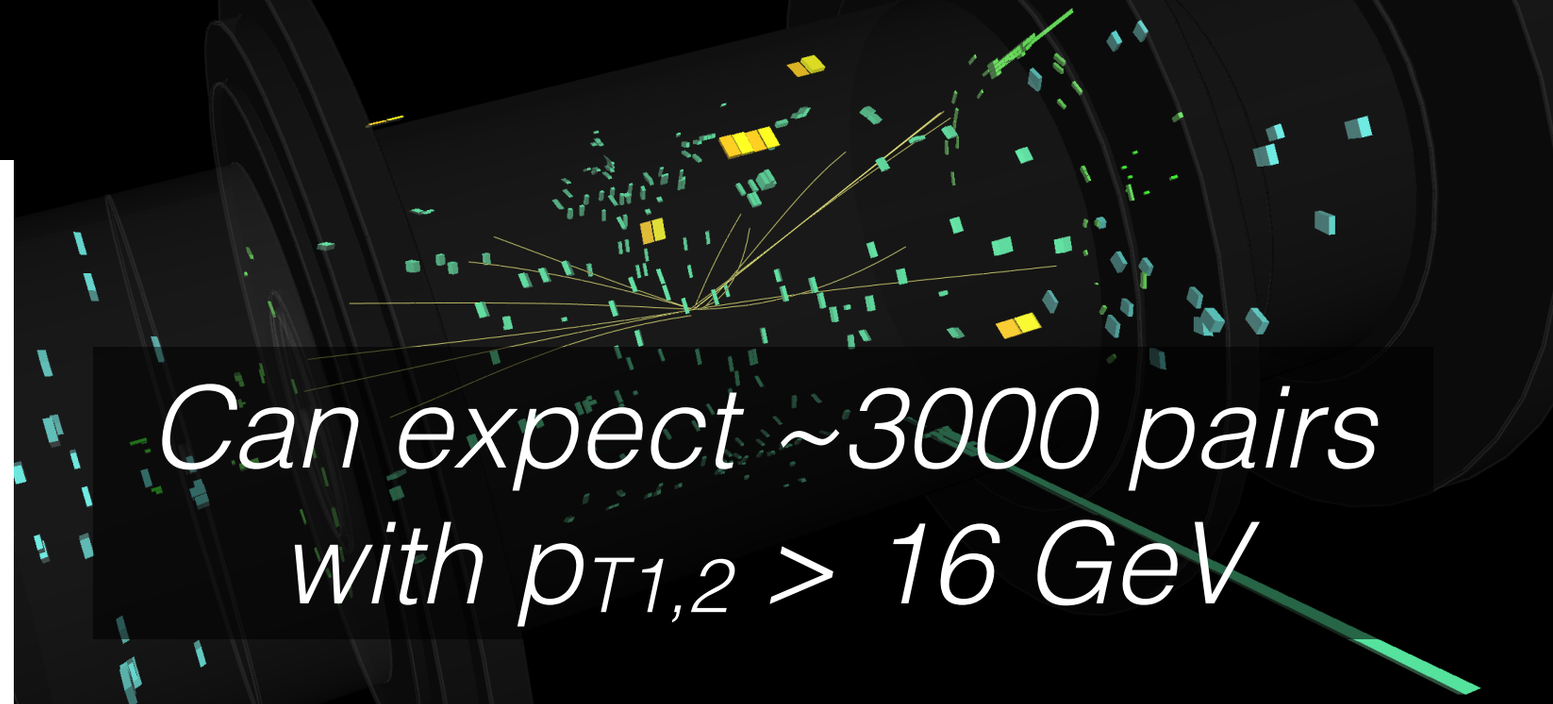


γ+γ event
8.16 TeV *p*+Pb
ATLAS data



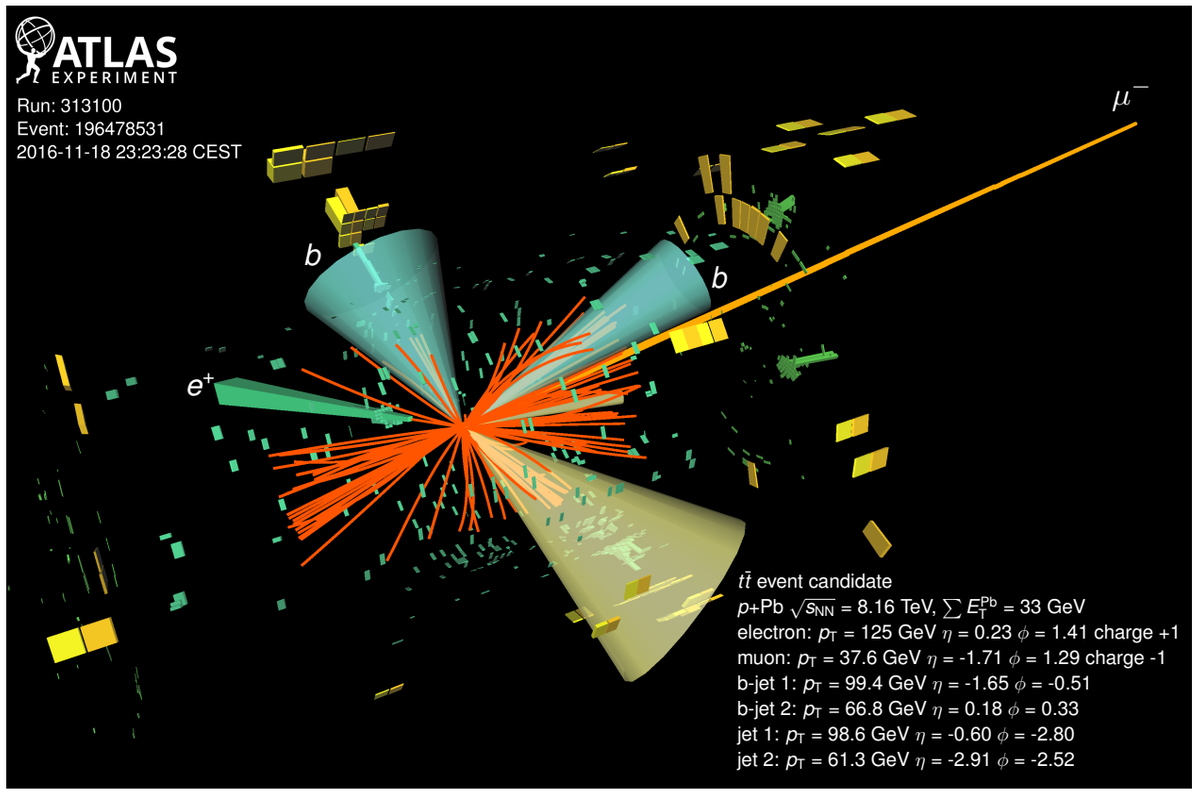


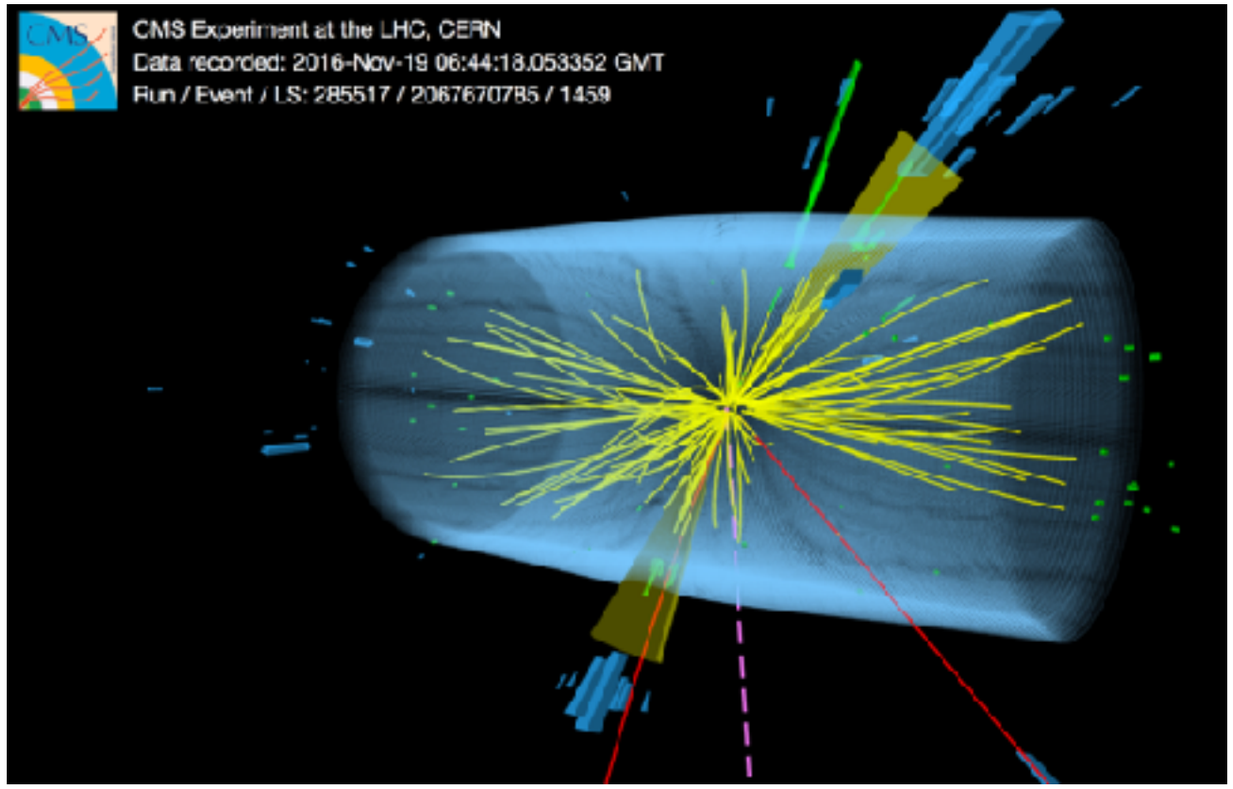




Can expect ~3000 pairs with $p_{T1,2}$ > 16 GeV

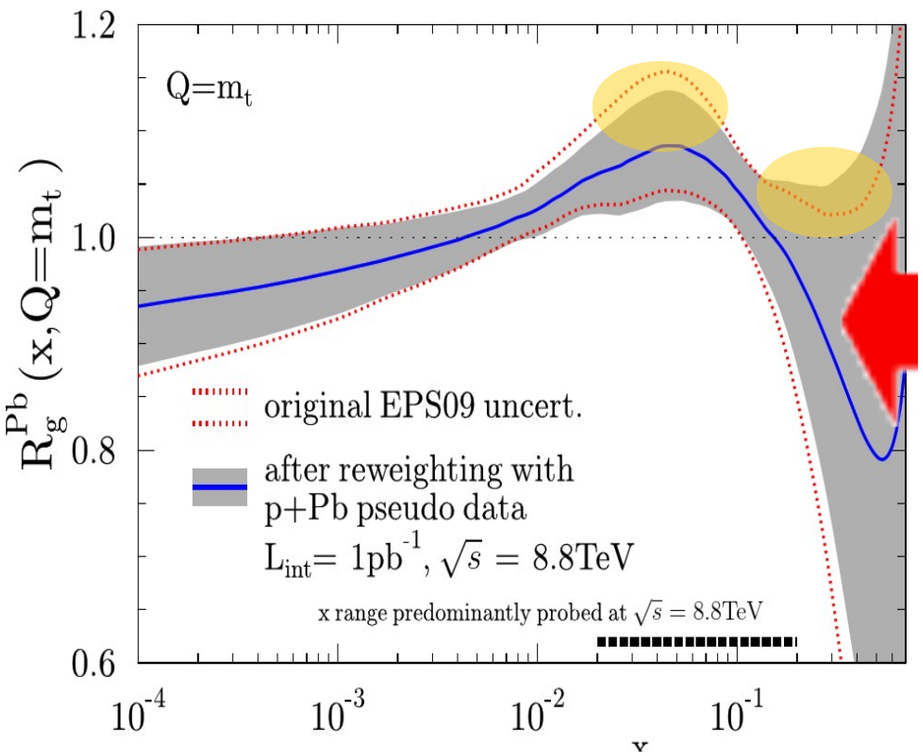
top quarks in *p*+A





Fundamental particle, previously unobserved in HI collisions

➡ *some impact for nPDFs*

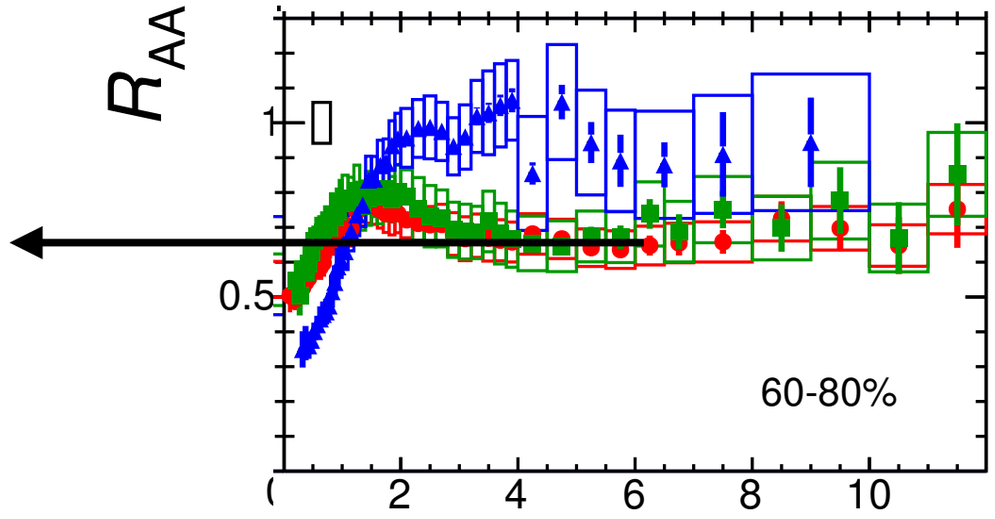


p+A: final state effects(?)

60-80% Pb+Pb, R_{AA} = 0.65

$\langle N_{part} \rangle$ = 23

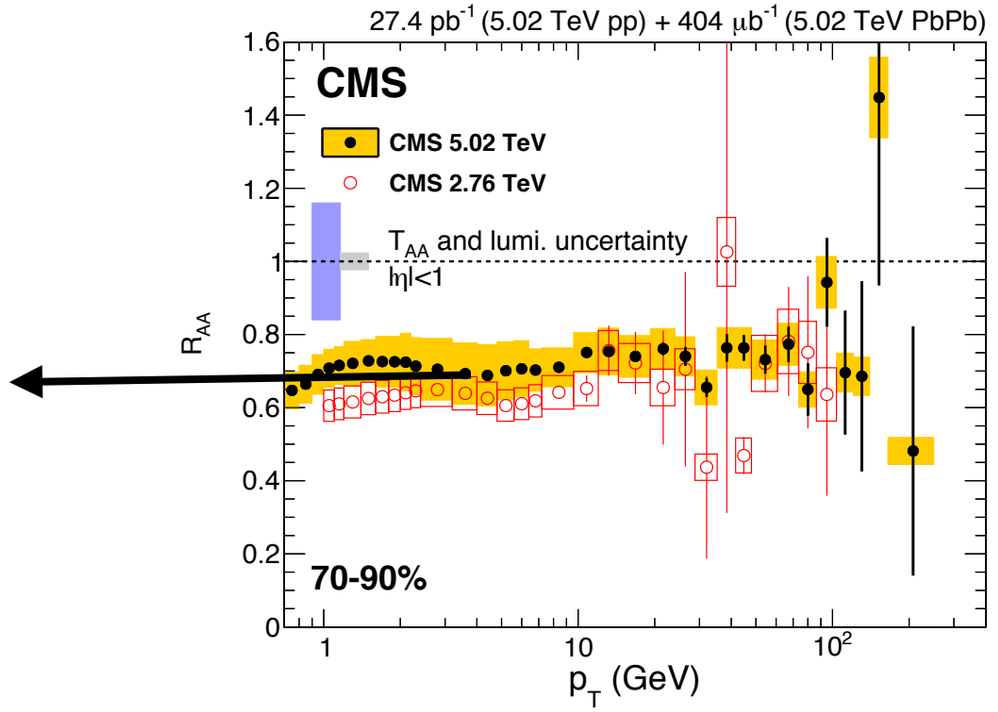
<1% *p*+Pb



70-90% Pb+Pb, R_{AA} = 0.7

$\langle N_{part} \rangle$ = 11

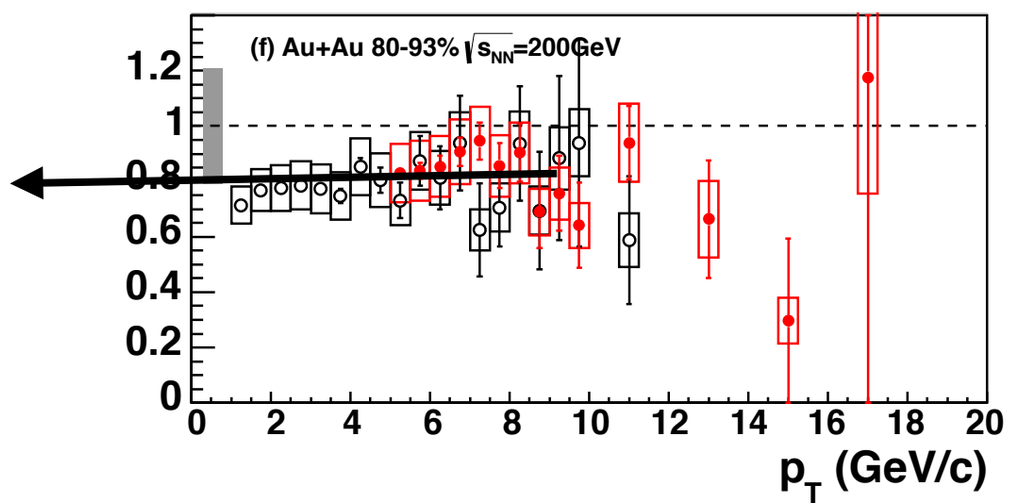
~20-30% *p*+Pb



80-93% Au+Au, R_{AA} = 0.8

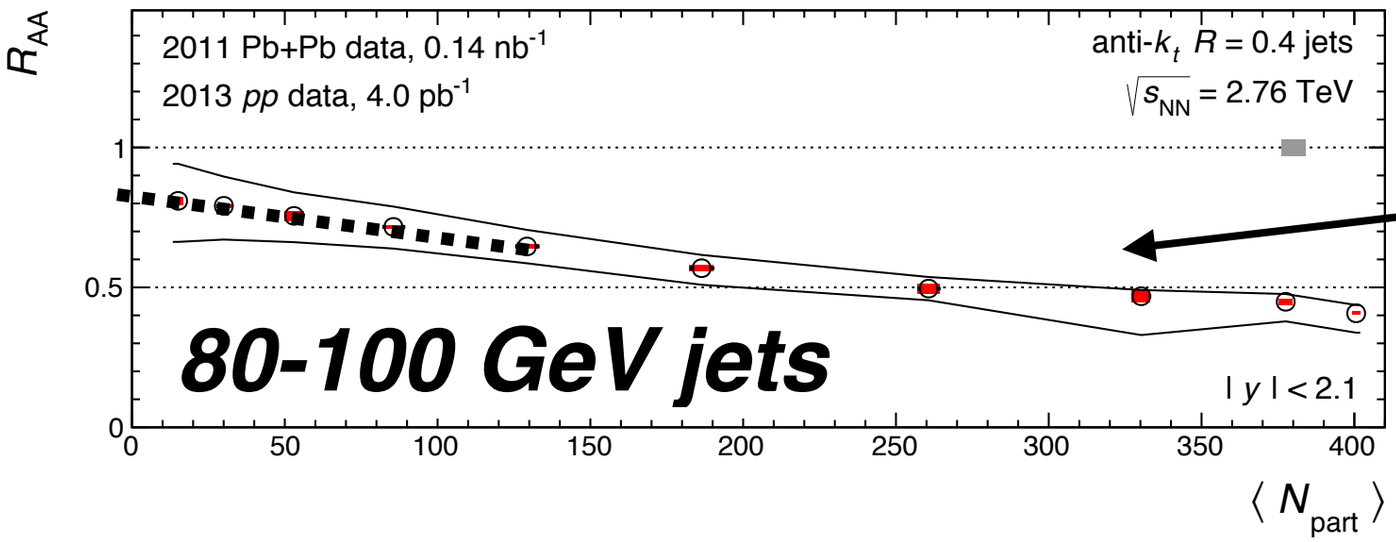
$\langle N_{part} \rangle$ = 5

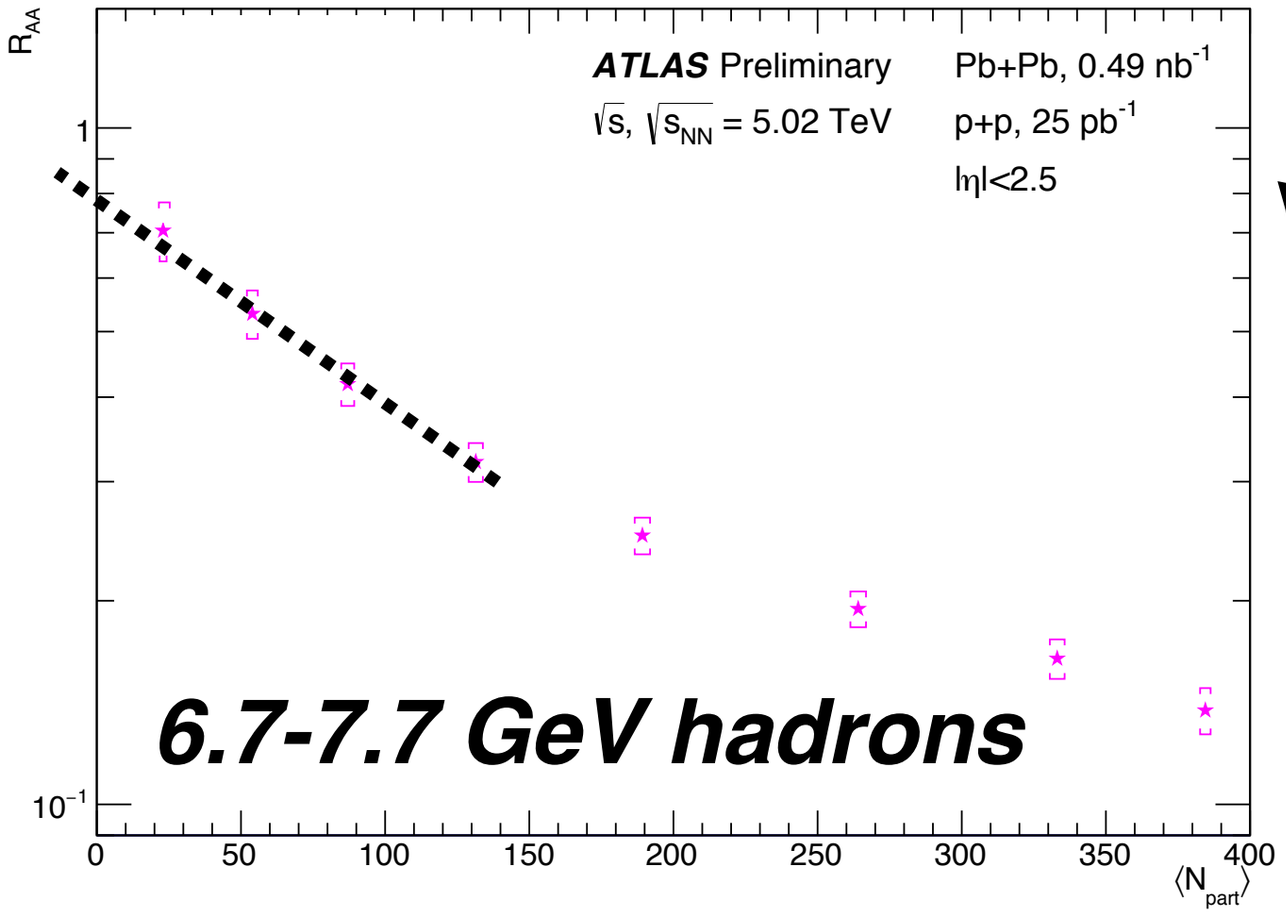
~50-70% *p*+Pb



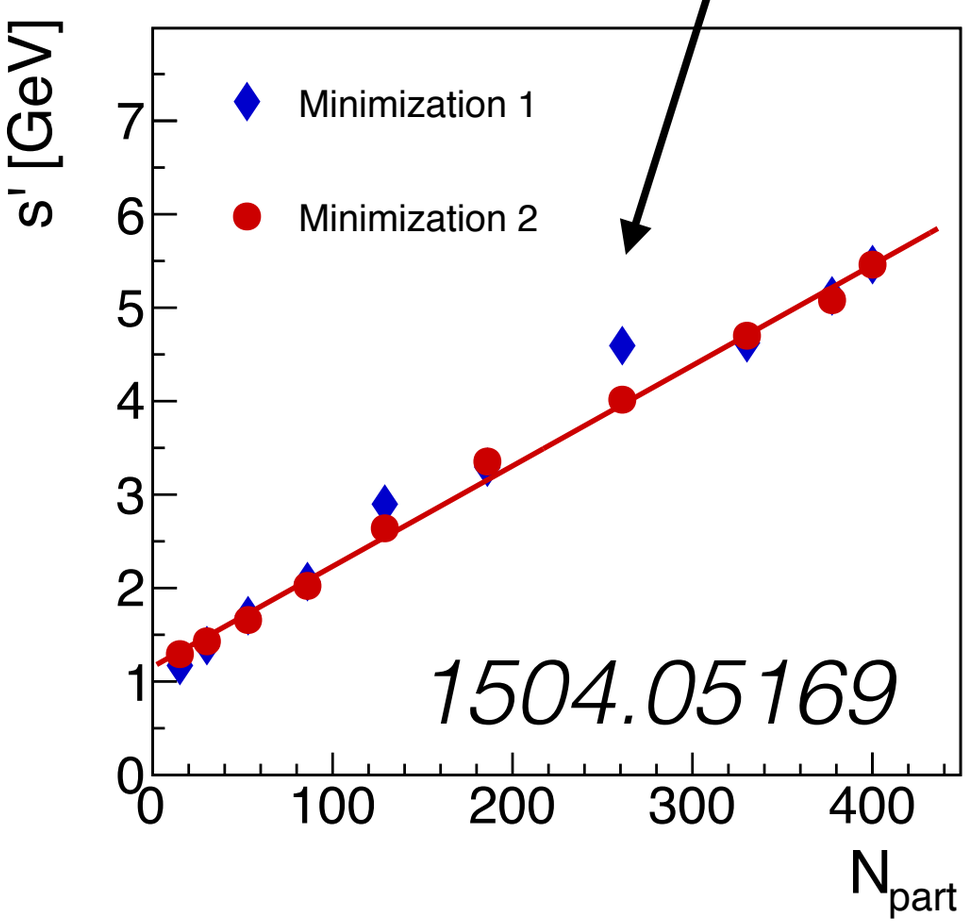
decreasing N_{part}

extrapolate N_{part} dependence of jet and hadron R_{AA}...

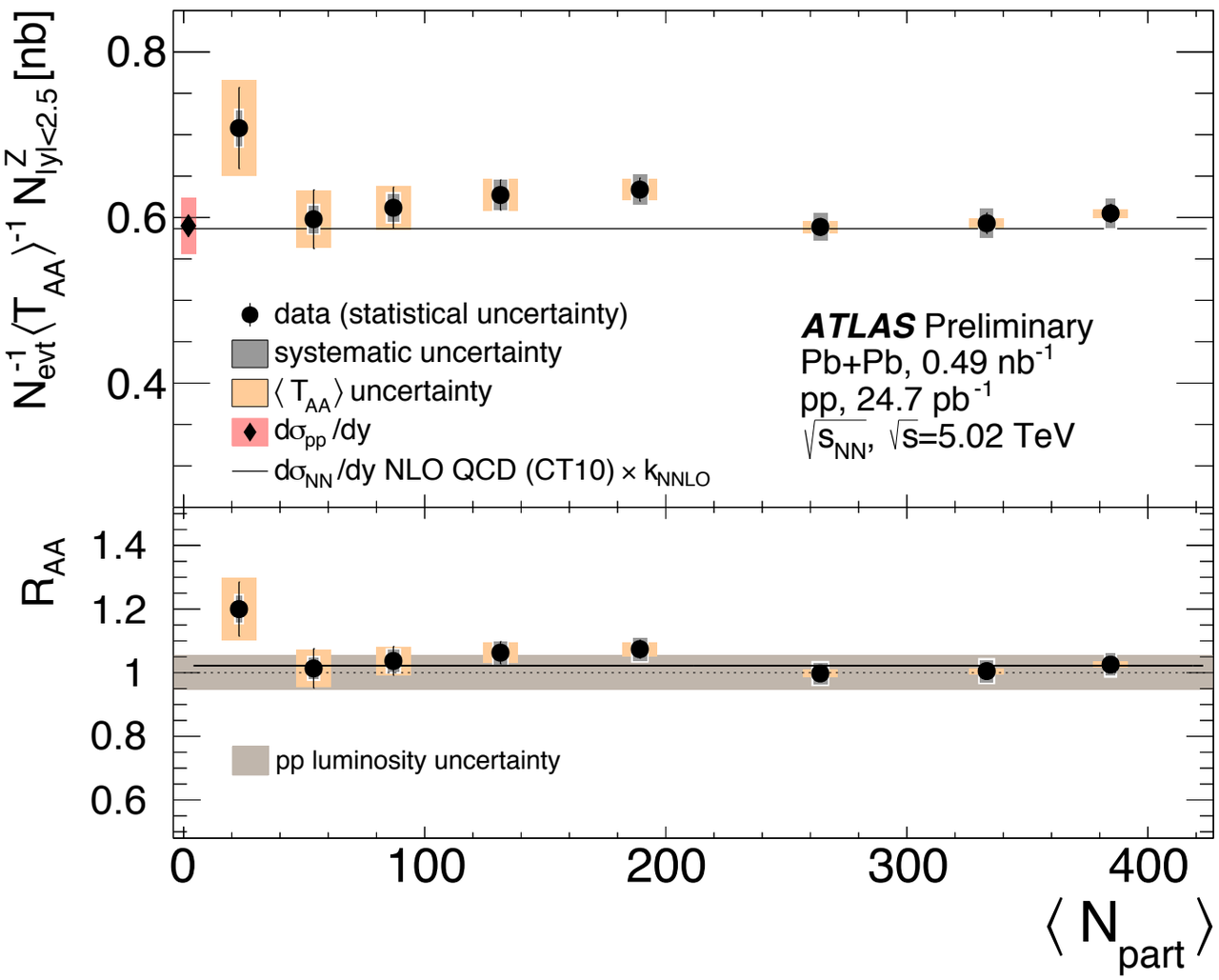


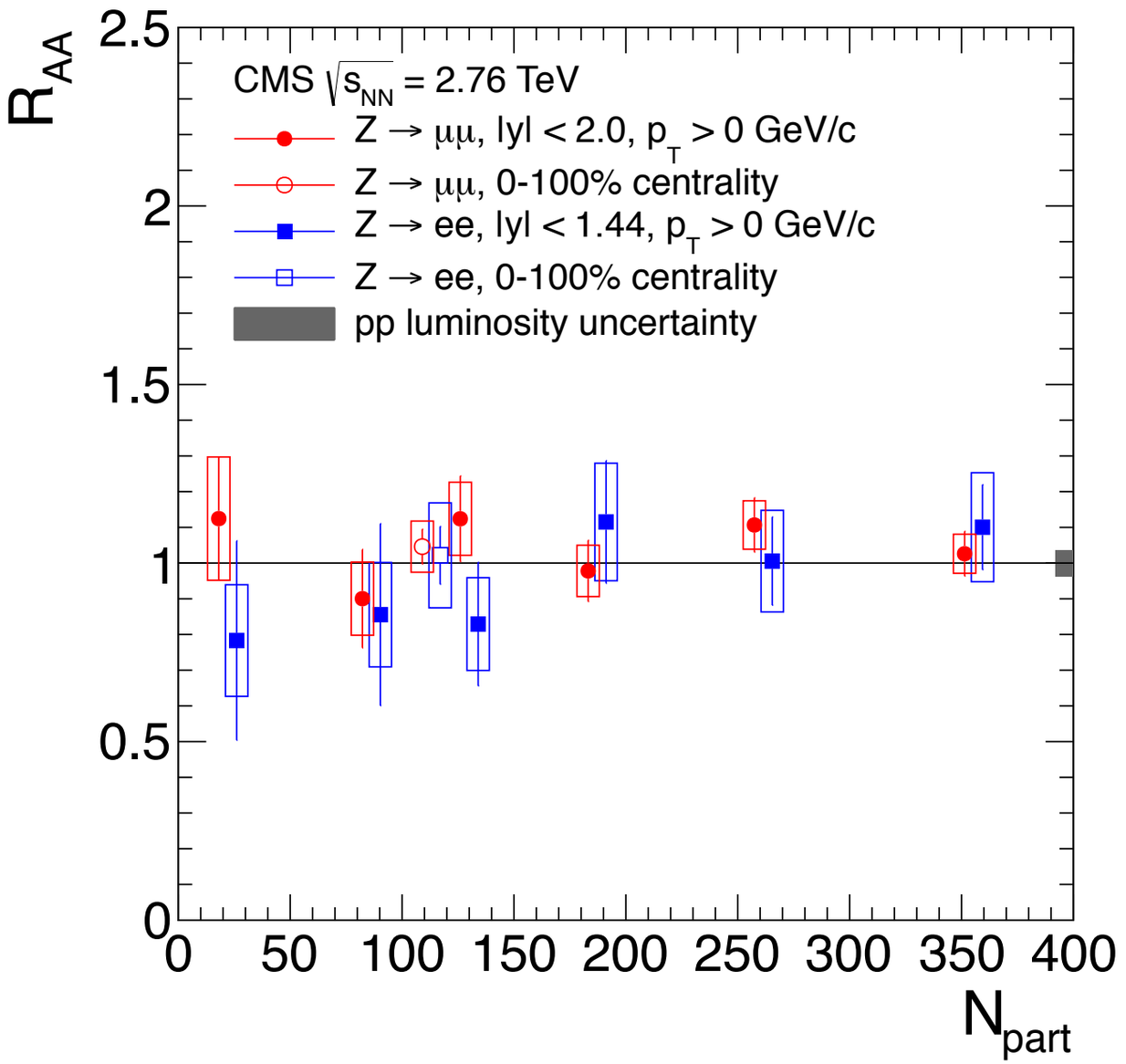


… or of the extracted $\langle E_{loss} \rangle$



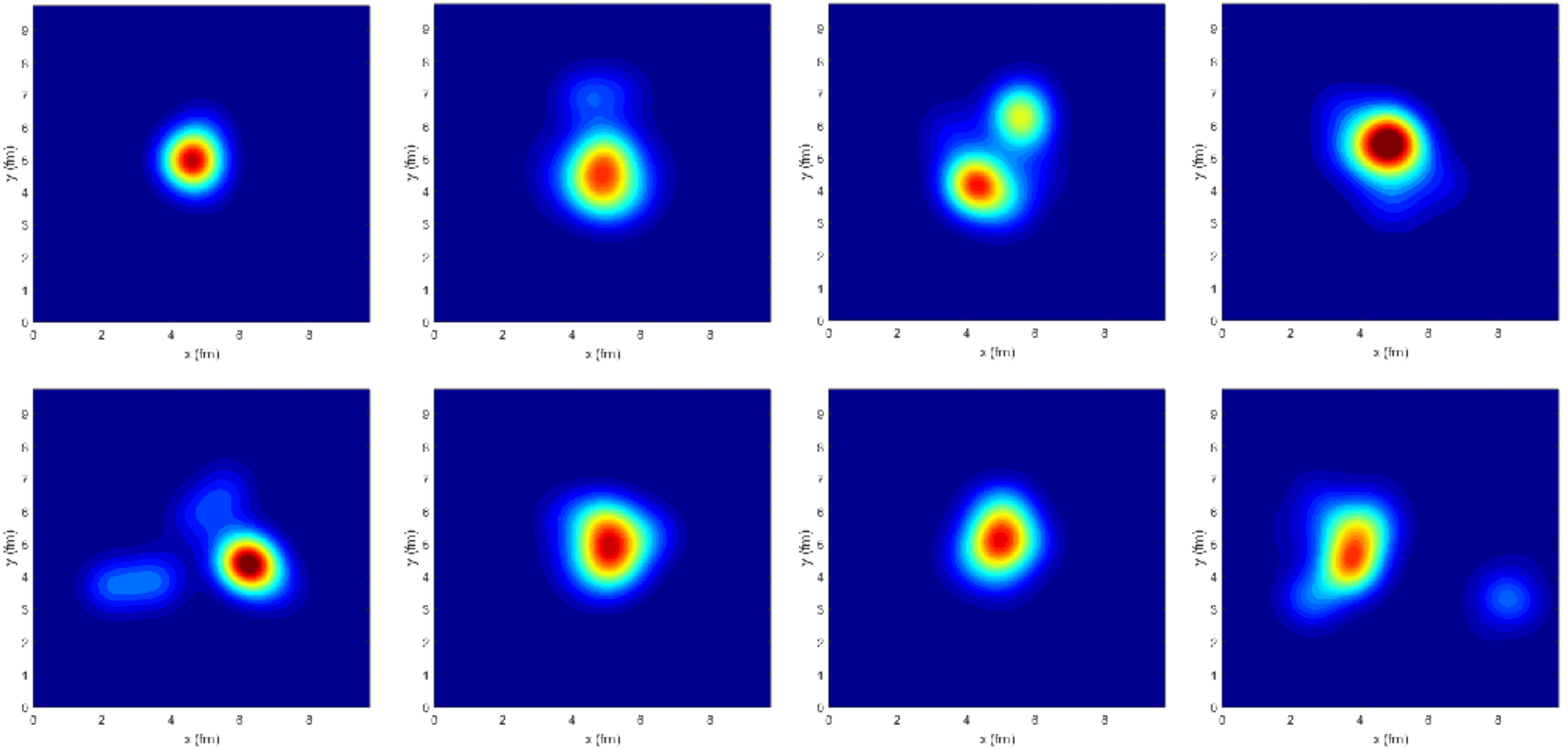
Checking N_{coll} calibration with EW bosons…





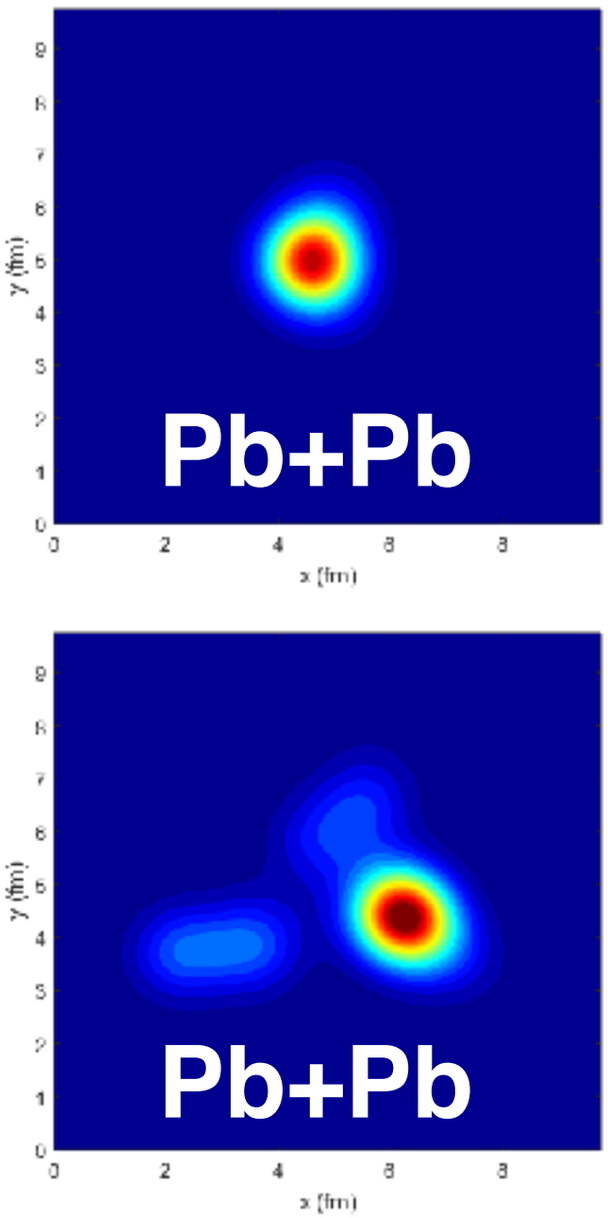
… higher statistics W measurements in Run 2 data soon available

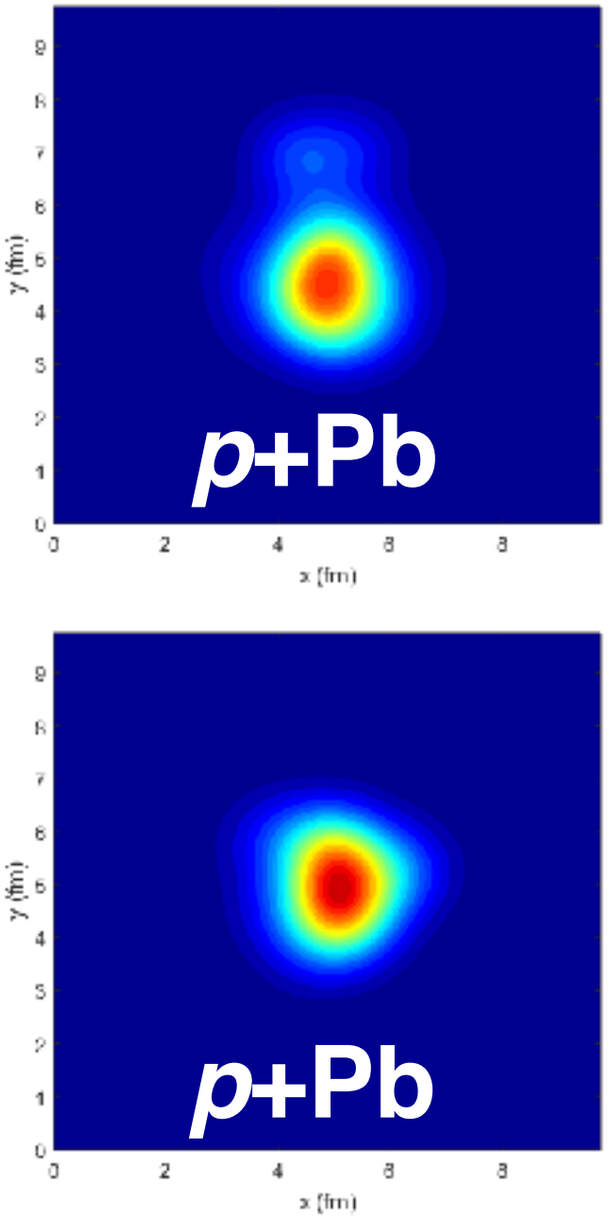
0-10% *p*+A or 70-90% A+A?

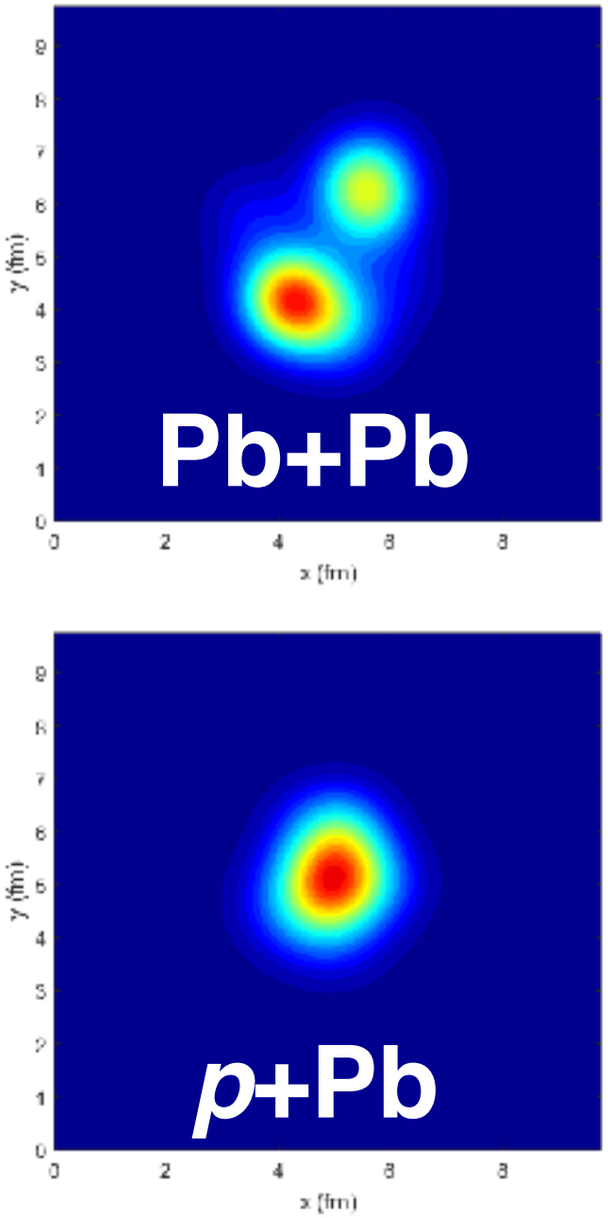


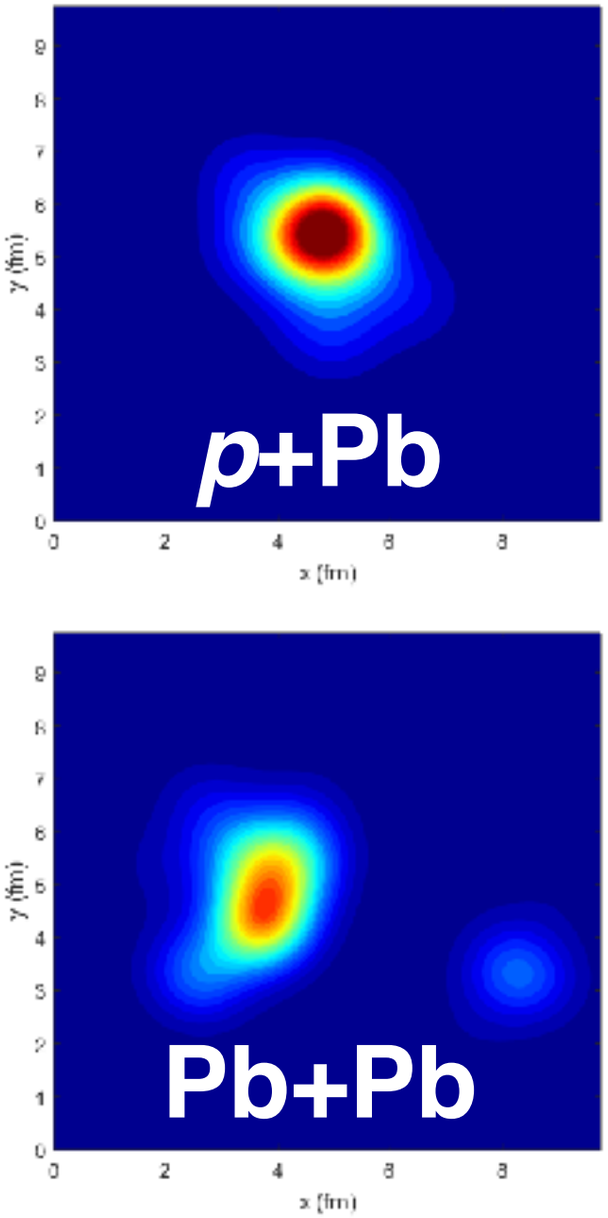
credit to R. Weller and P. Romatschke

0-10% *p*+A or 70-90% A+A?



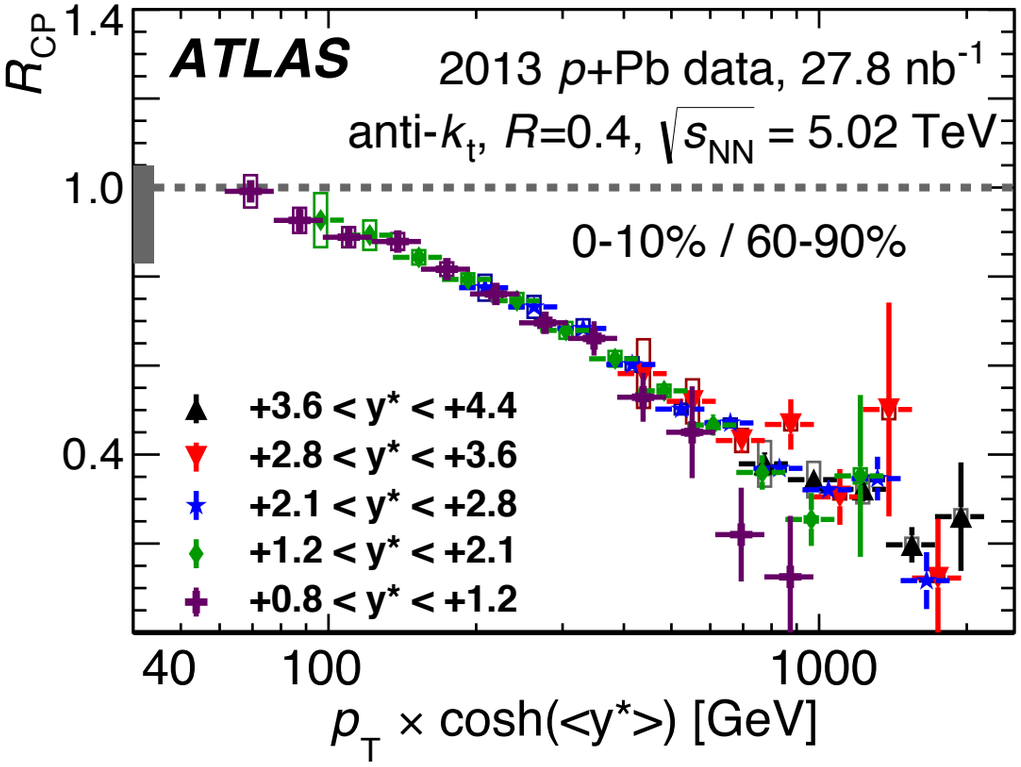




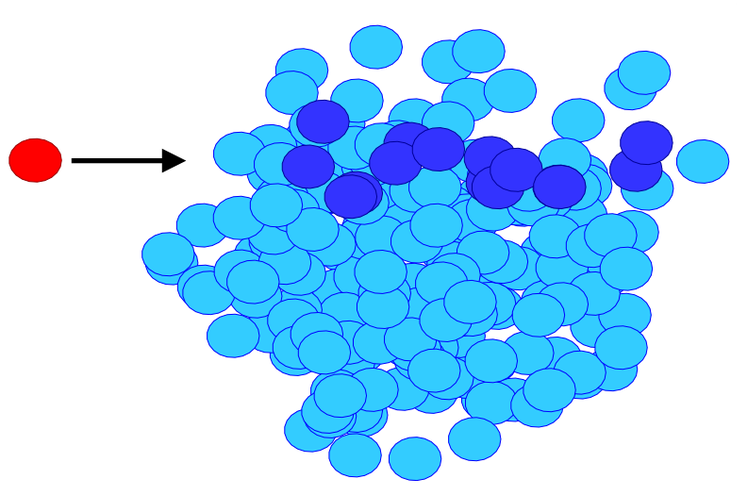


credit to R. Weller and P. Romatschke

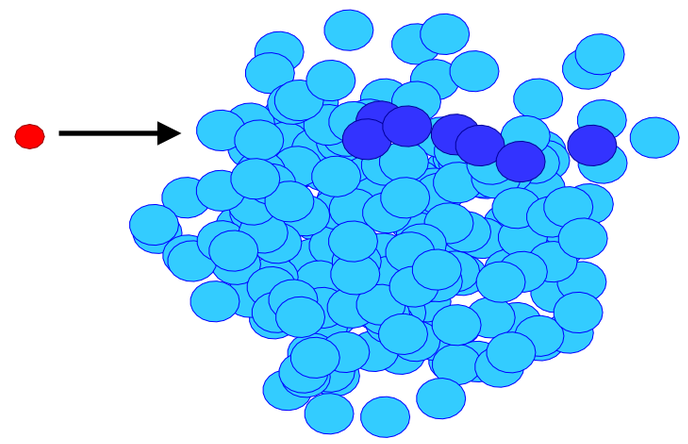
Would like to use N_{coll}-scaled hard process rates (R_{pA})…



scaling in E_{jet}



typical proton

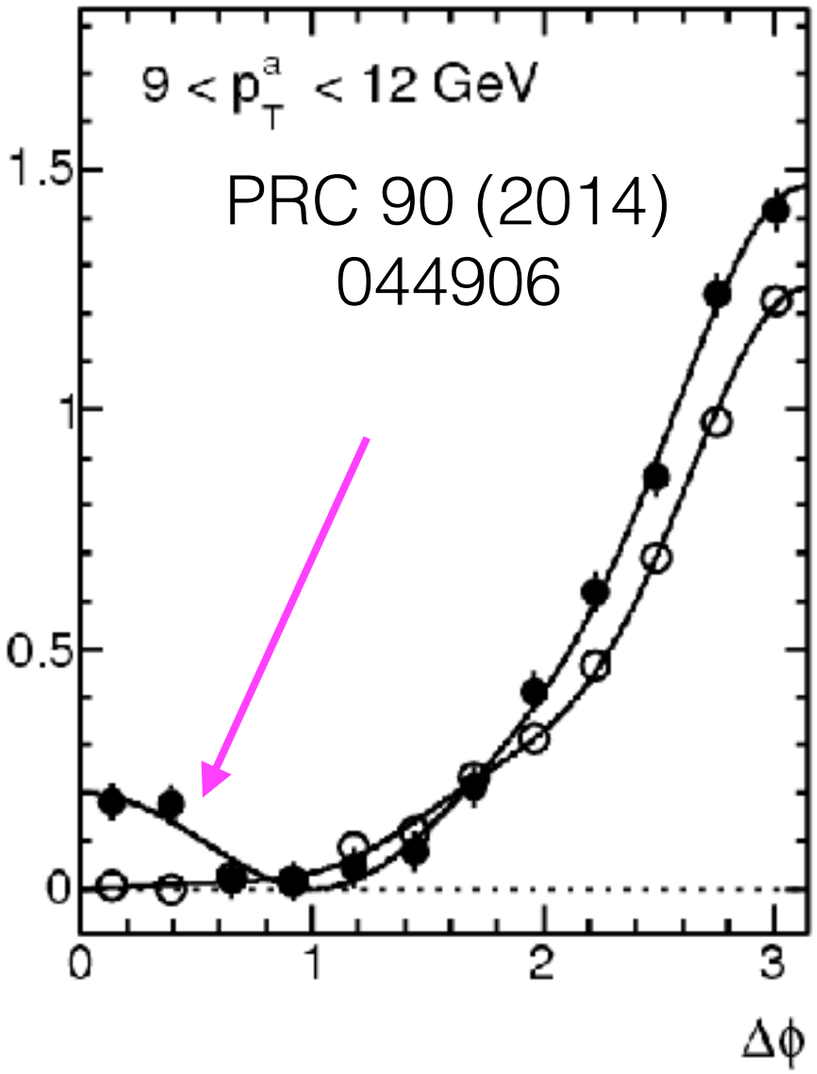


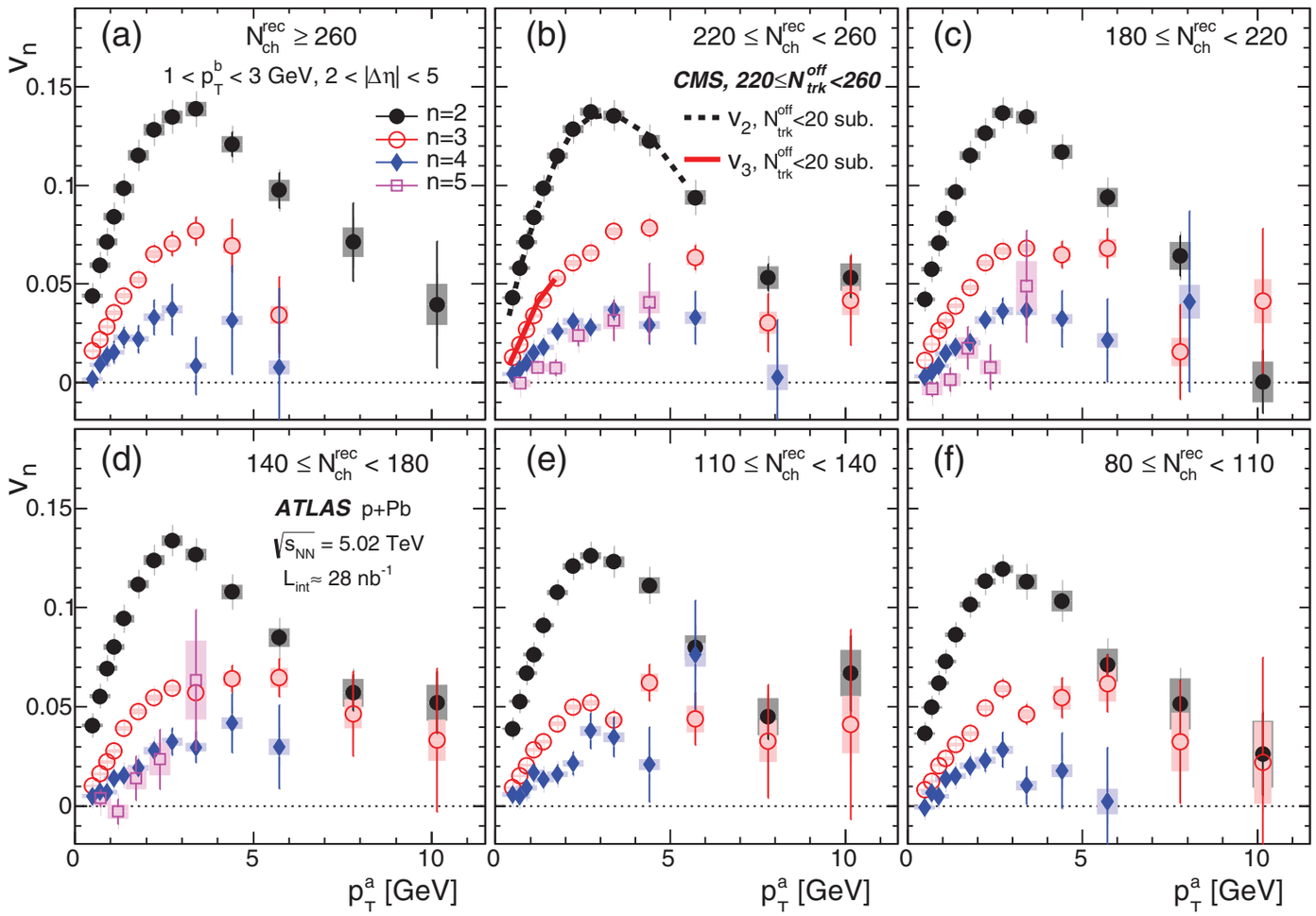
shrinking proton

… unfortunately, contributions from interesting (but likely not jet quenching) physics…

… so use intra-event momentum correlations

jet quenching in ultra-central p+A?

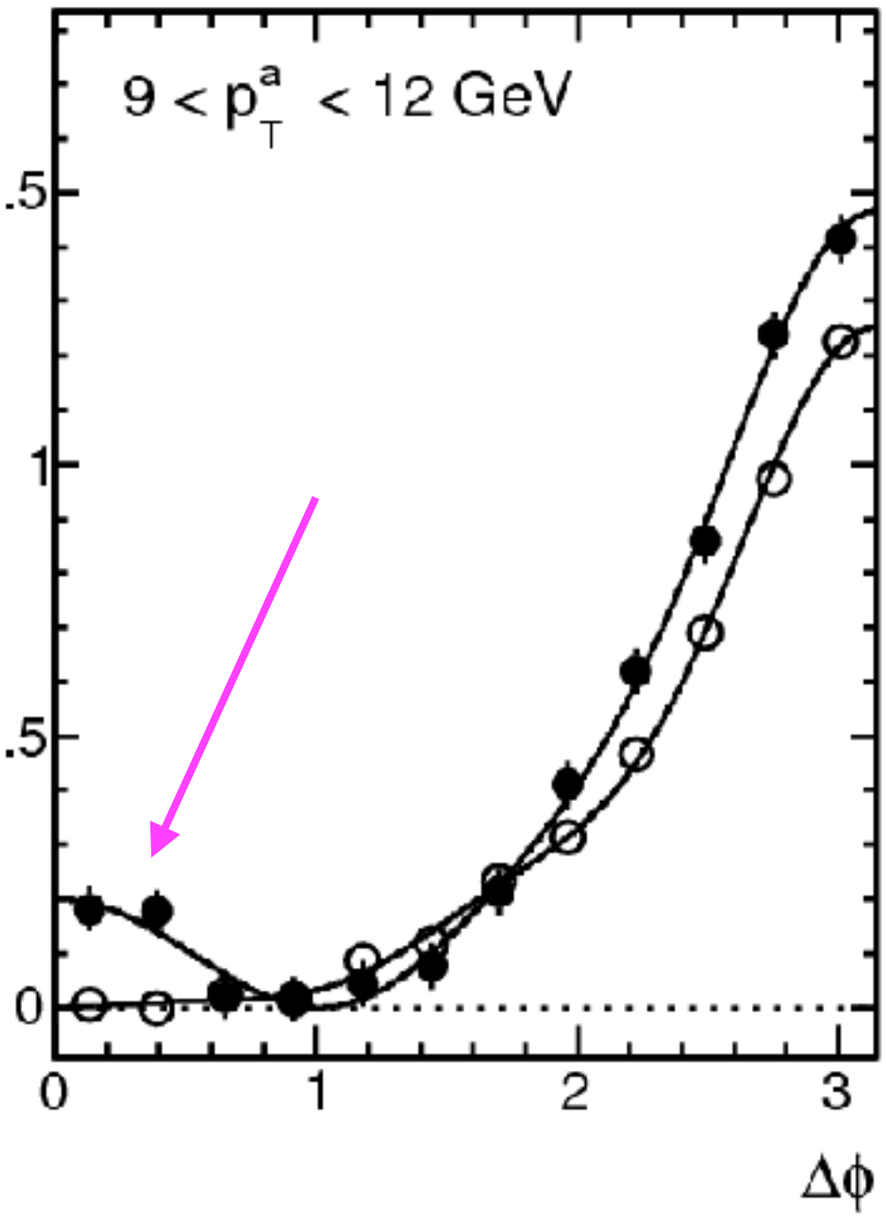


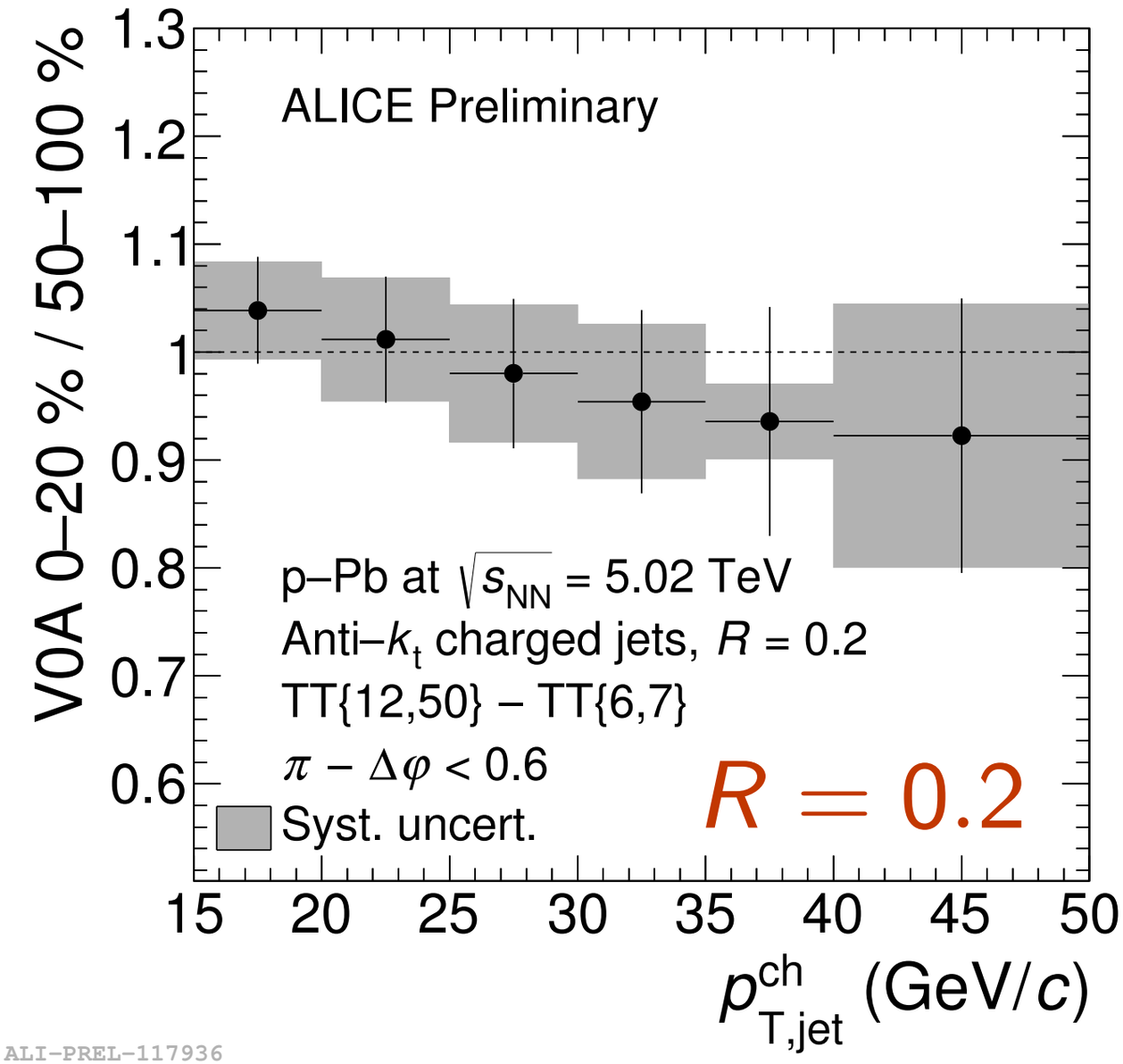


near-side ridge persists to 9-12 GeV in p+A (0-0.003% events)

finite-v_2 out to 10 GeV (0-1% events)

➡ *<u>repeat in 8.16 TeV!</u>*



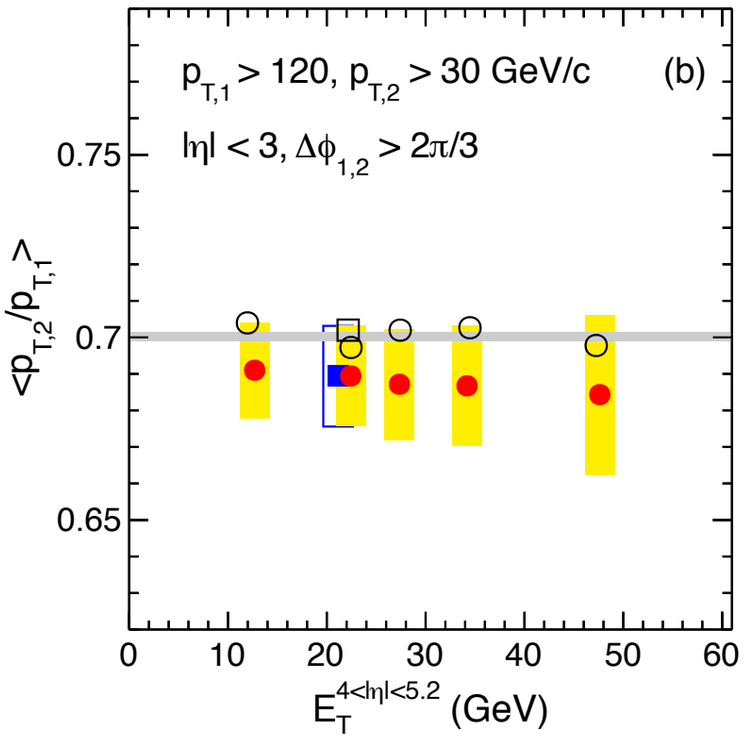


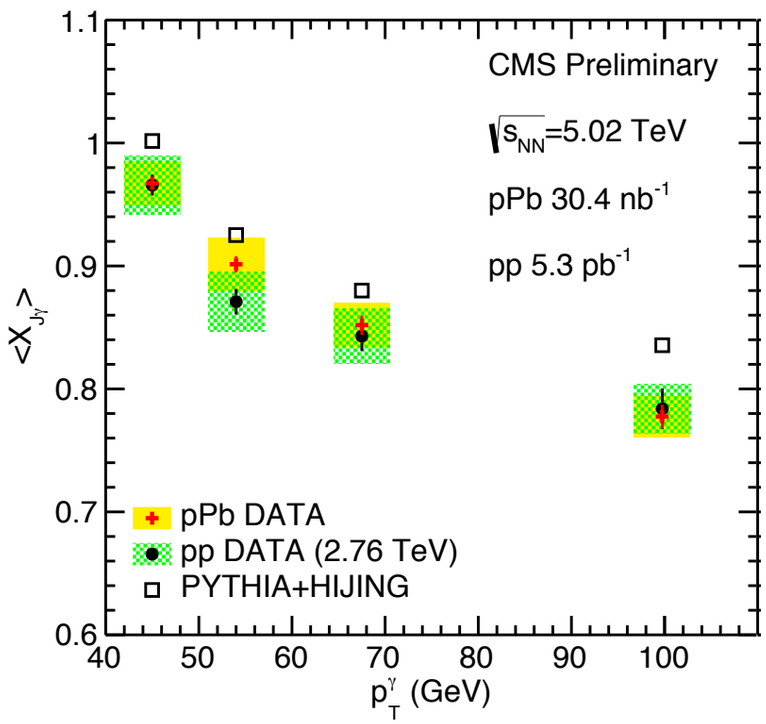
high-p_T near-side ridge in <1%

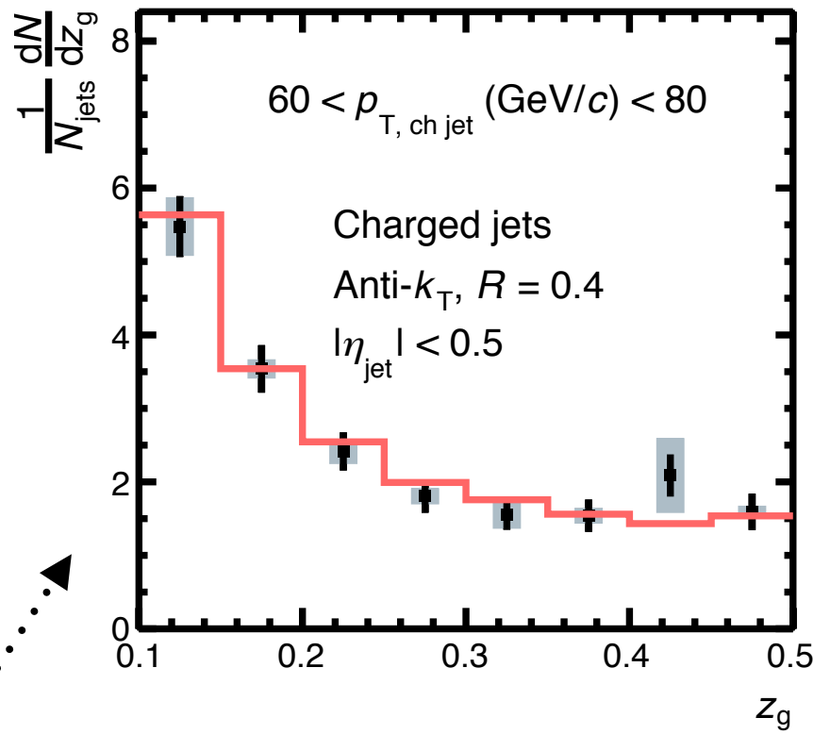
unmodified recoil jet distributions in 0-20% events

… search for onset of jet quenching?

E-by-*E* energy loss



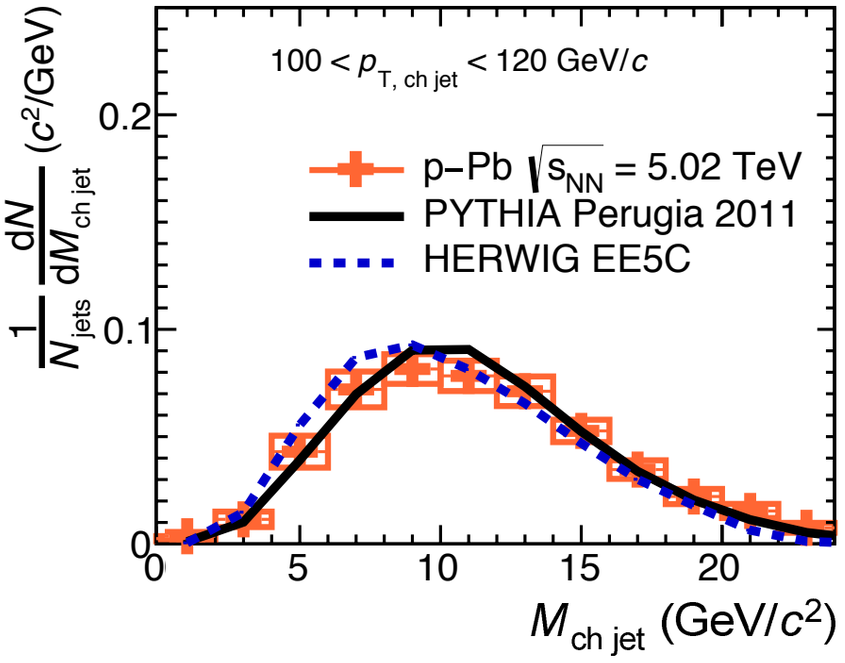


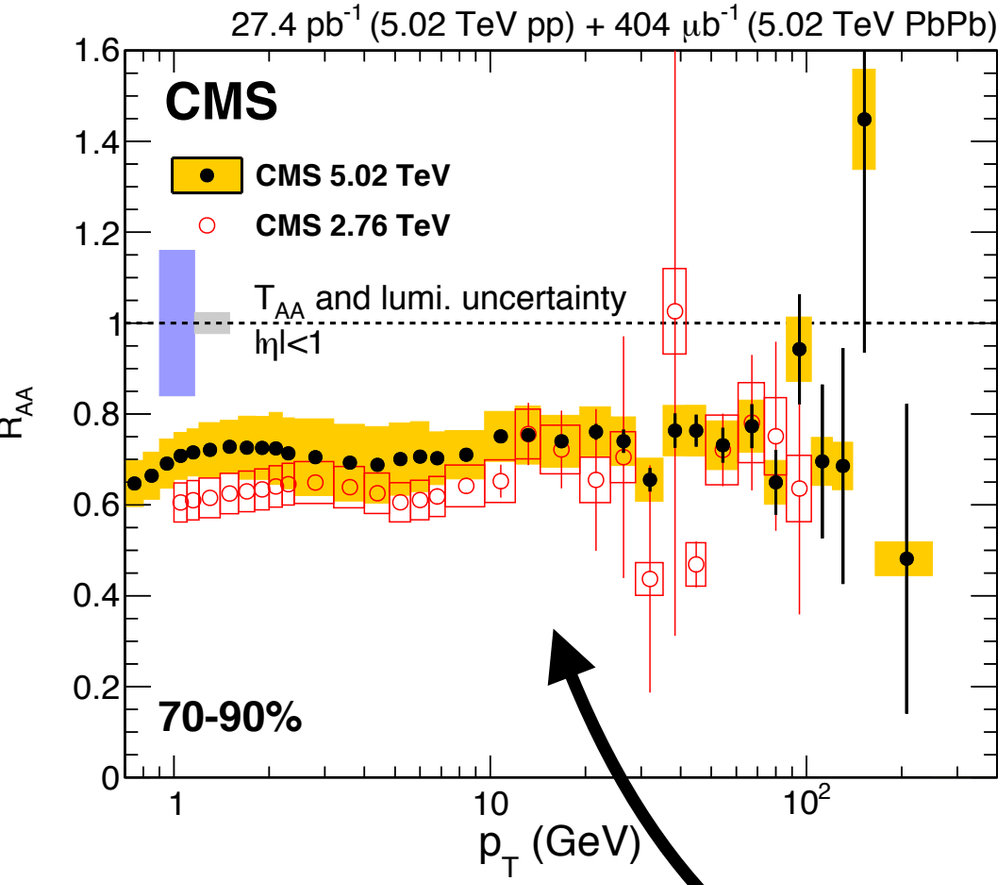


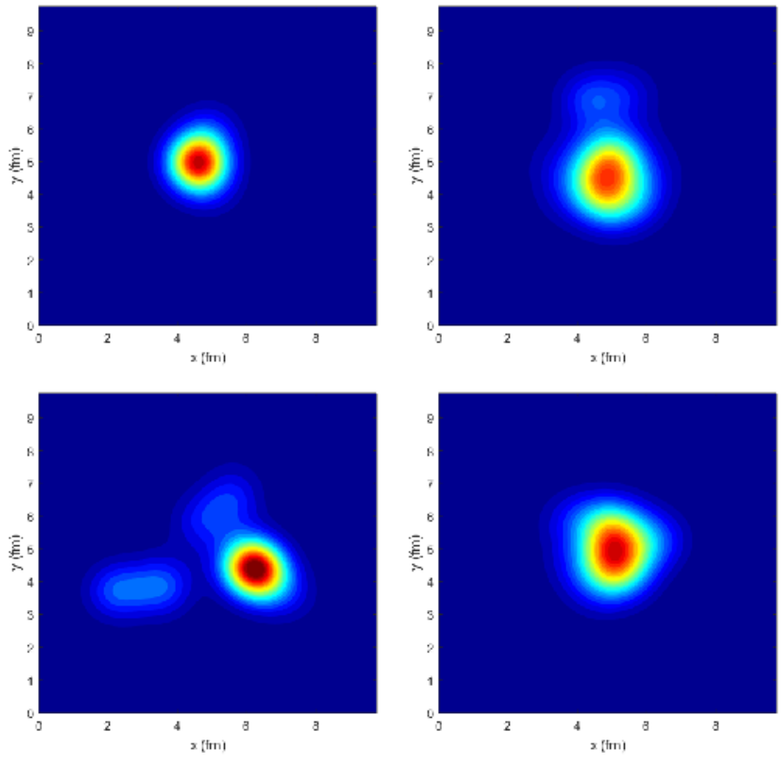
dijet and γ+jet p_T balance (older)

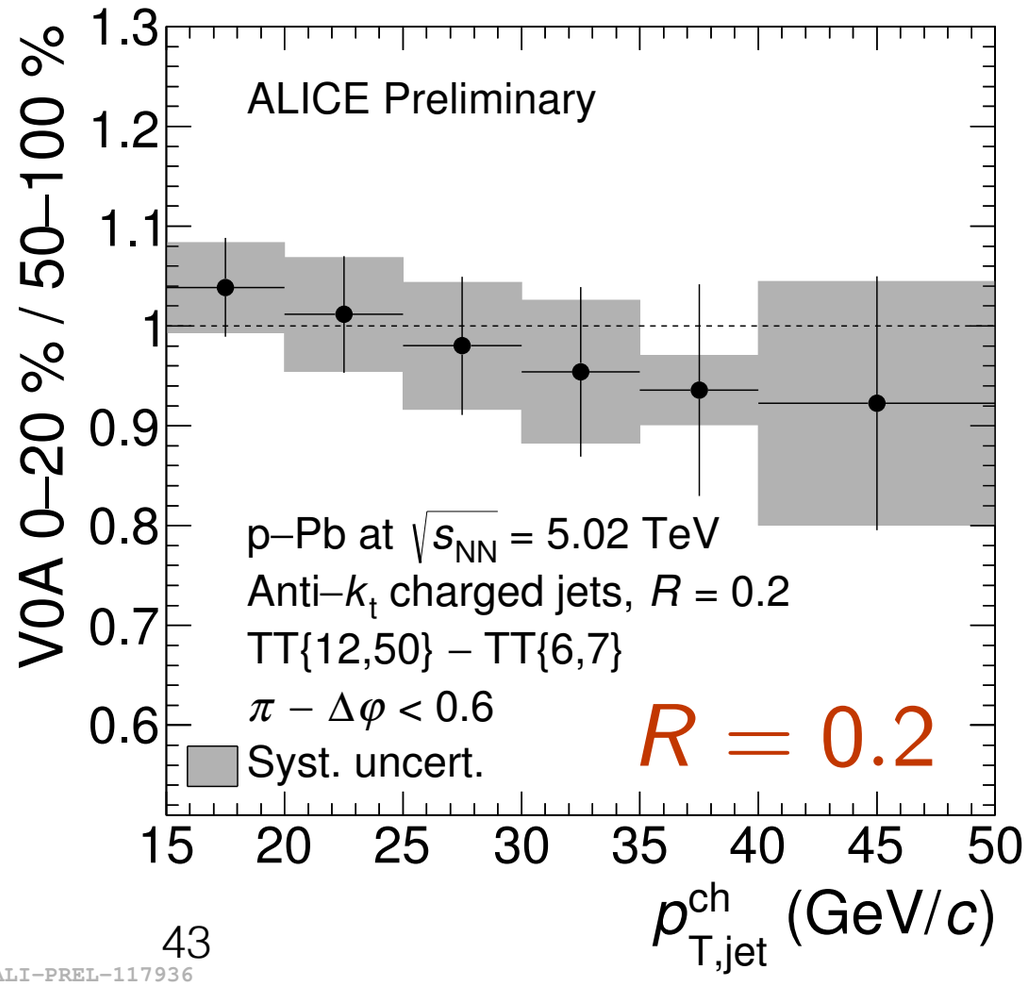
quenching-sensitive jet shapes in p+Pb (newer)

ALI-PREL-120123



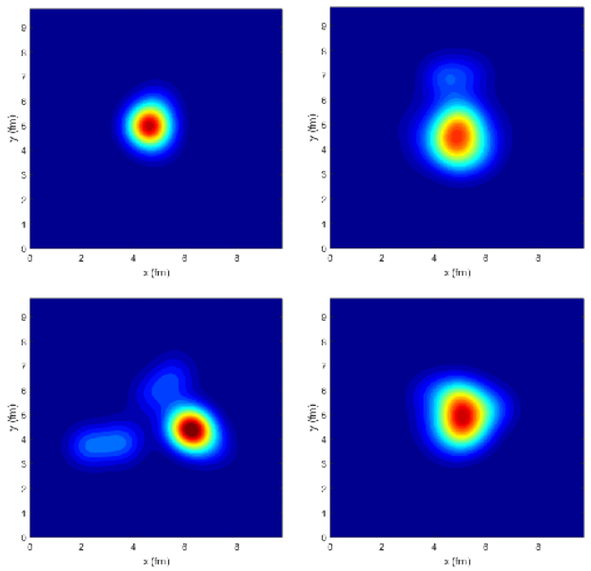




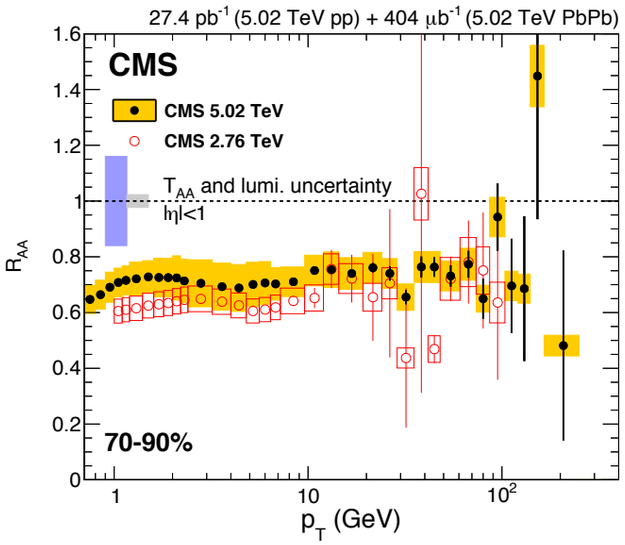


internally self-consistent?

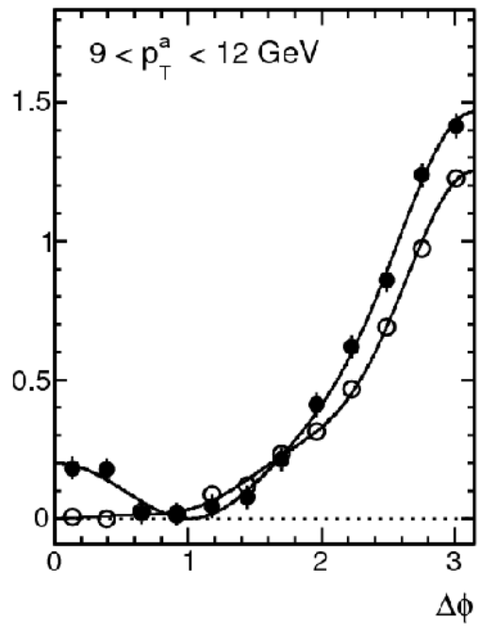
1. do we understand small-N_{part} collision geometries?



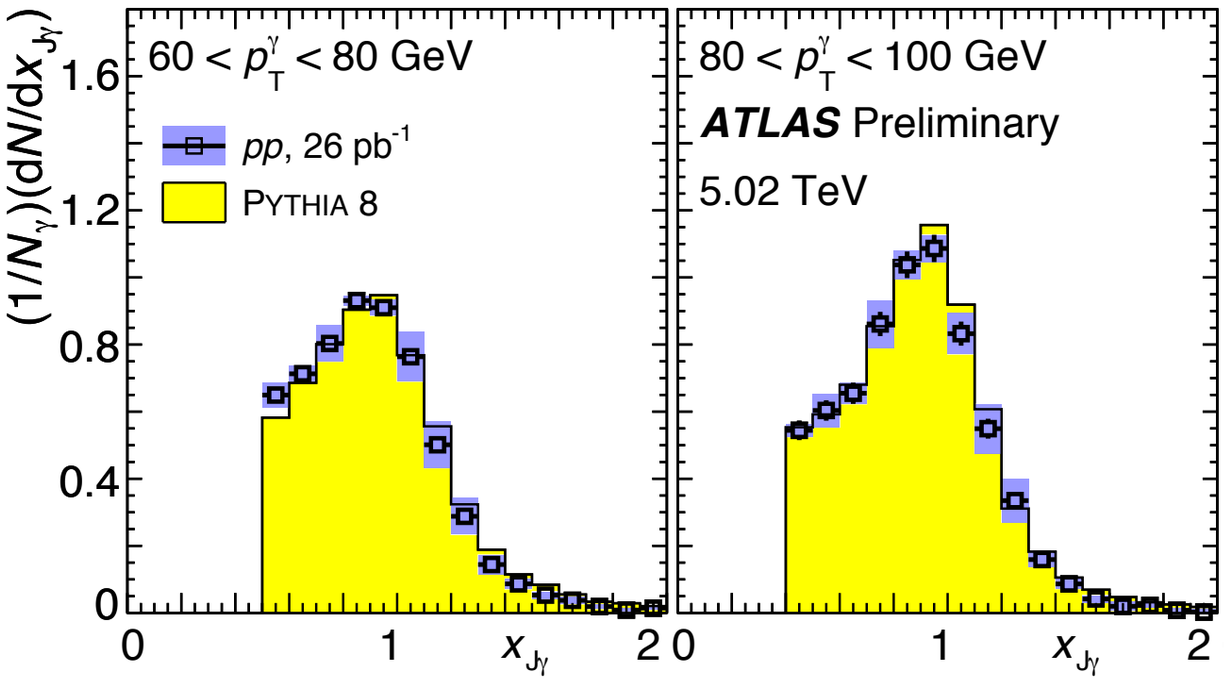
2. models that successfully describe periph. R_{AA} data — what do they predict for p+A E-loss?

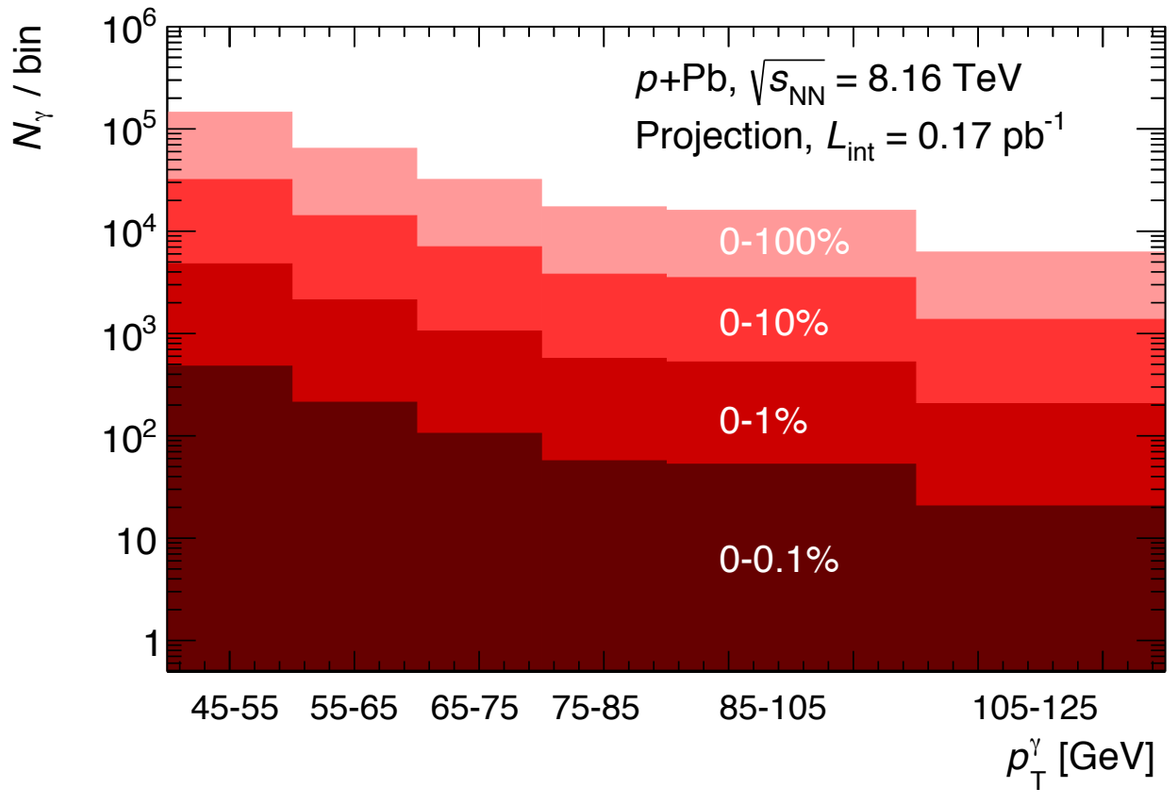


3. can we place a limit (or observe?) energy loss in small systems?



γ+jet in 8.16 TeV *p*+A data



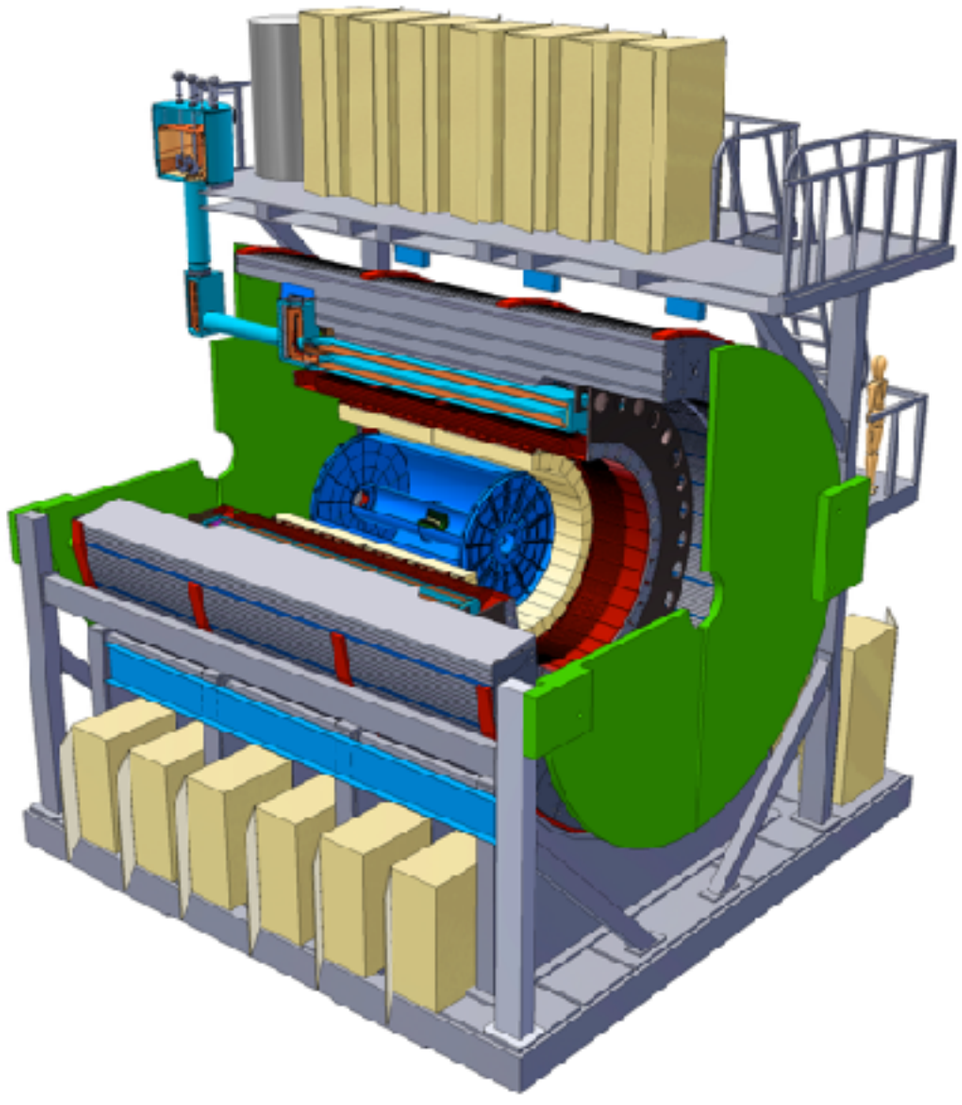


high degree of experimental control in pp

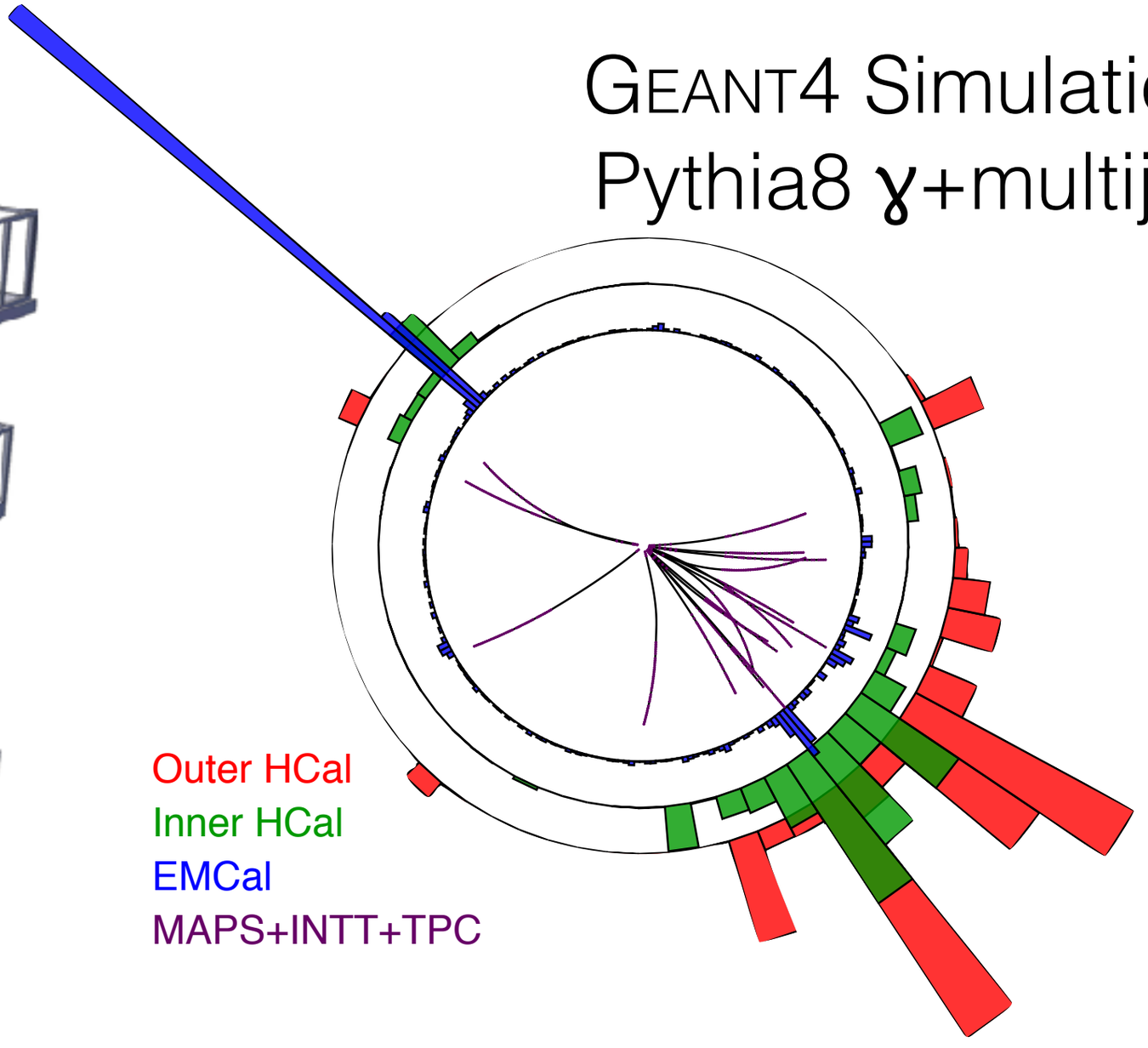
>10k $p_{T\gamma}$ > 40 GeV in 0-1% events

(based on measured 8 TeV pp x-section)

small systems at sPHENIX

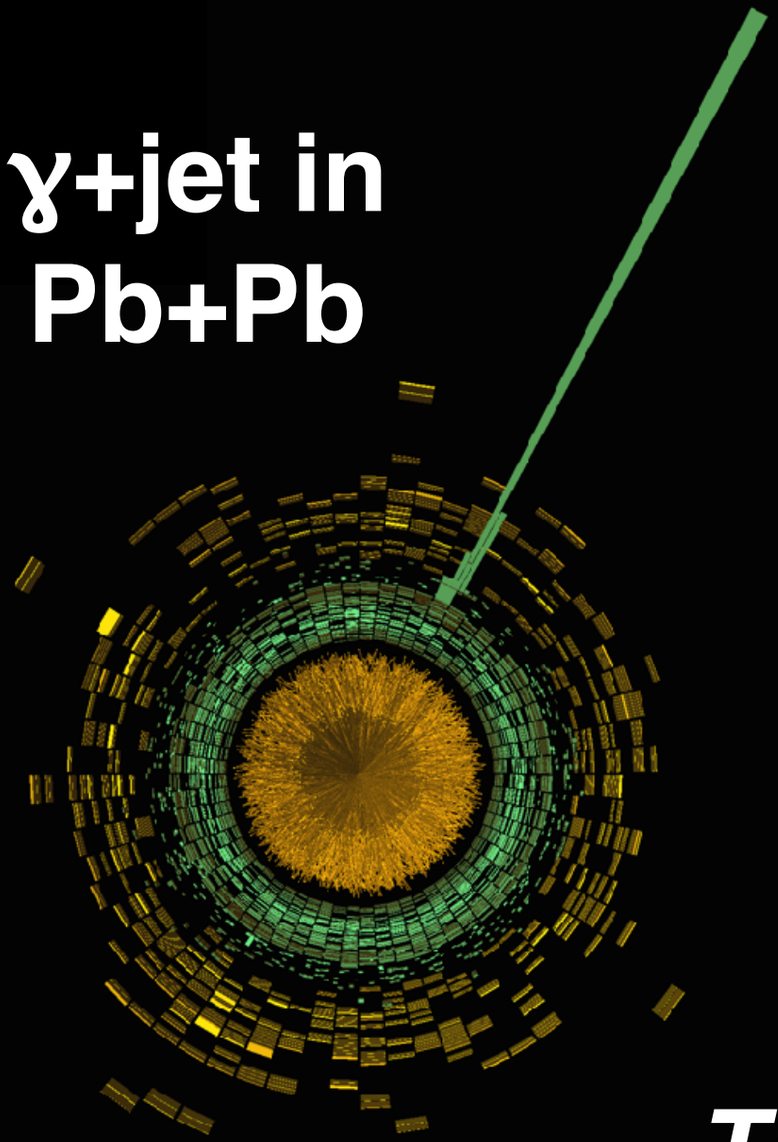


GEANT4 Simulation
Pythia8 γ+multijet

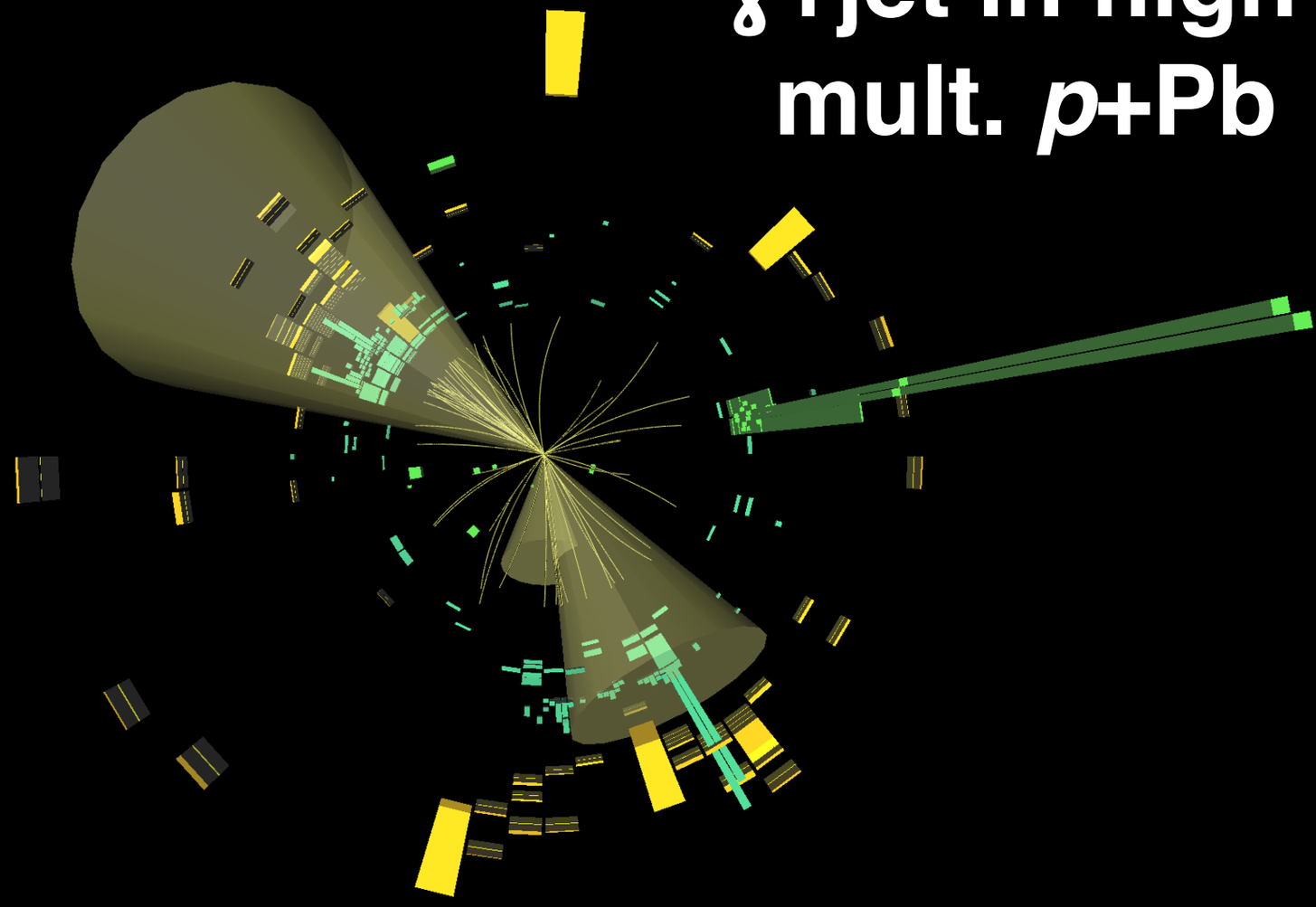


200 GeV p+Au @ L_{int} = 400 nb^{-1} / week × 10 weeks:
precise, high-statistics program to probe small systems

γ+jet in Pb+Pb

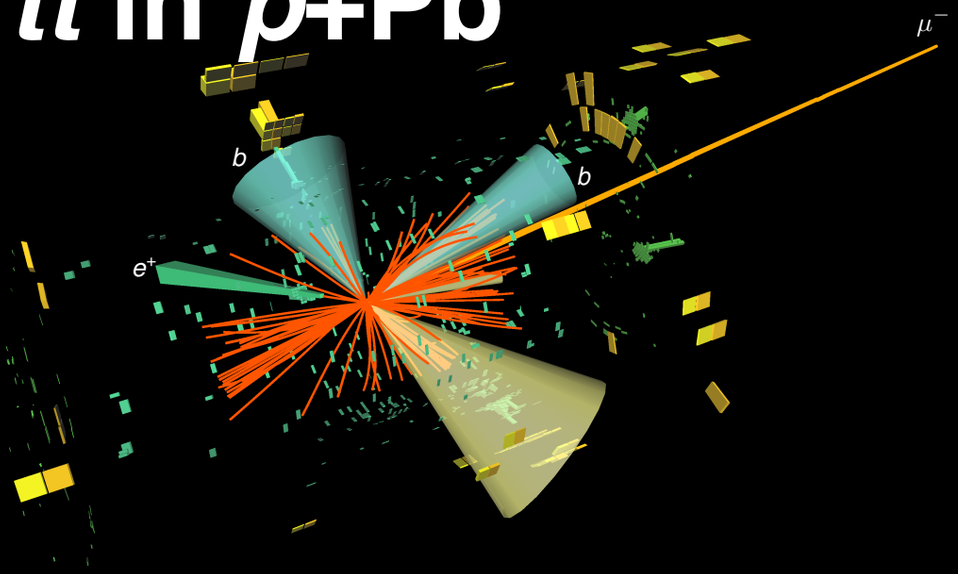


γ+jet in high-mult. *p*+Pb

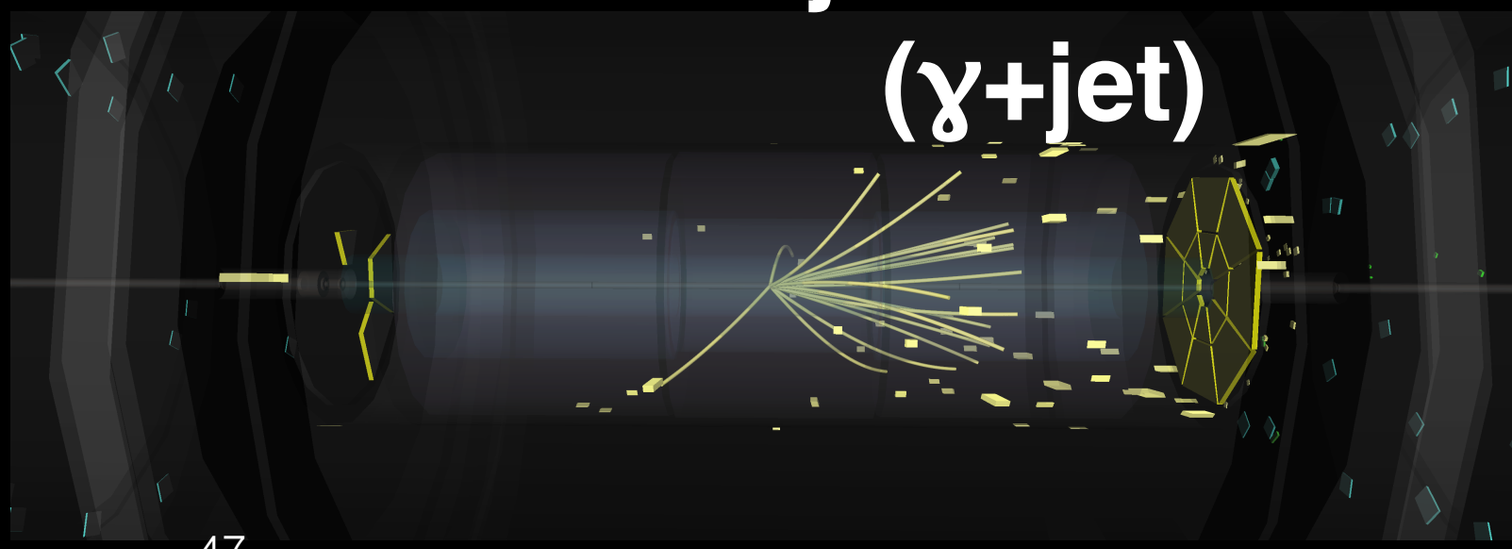


Thank you!

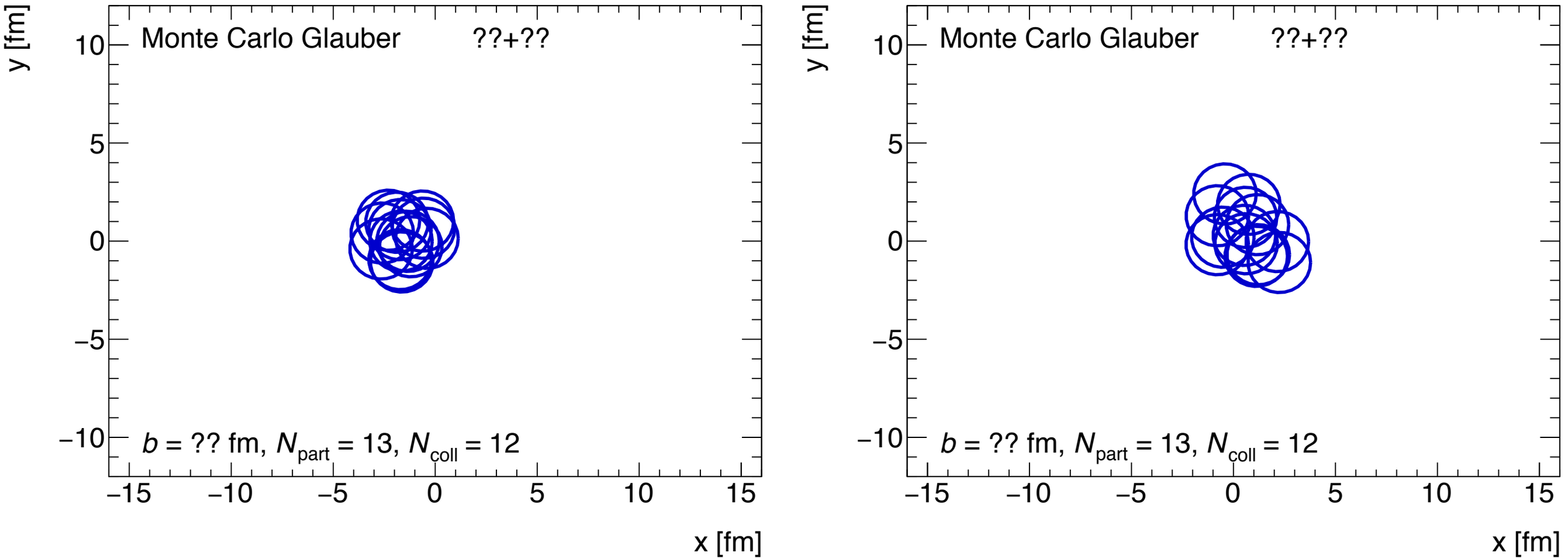
$t\bar{t}$ in *p*+Pb



dijets in UPC (γ+jet)



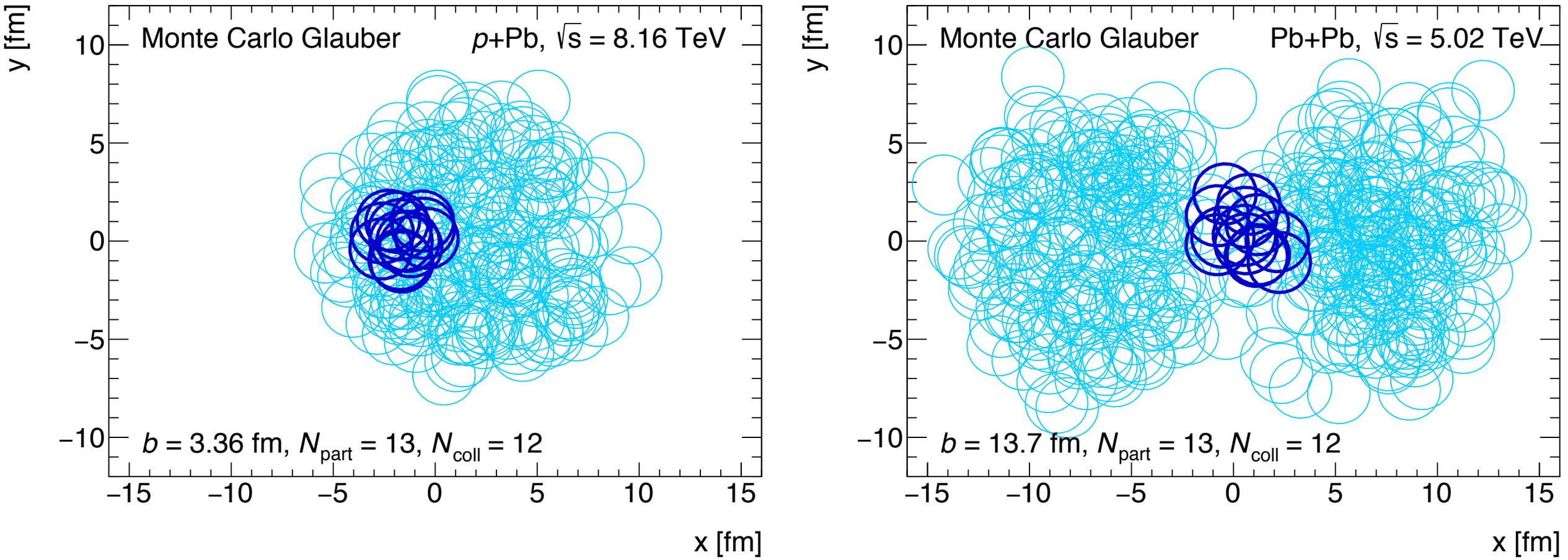
backup



two MC Glauber events showing only the **participating** nucleons in the transverse plane

same $N_{\text{part}}/N_{\text{coll}}$ value

one is *p*+A, one is A+A…

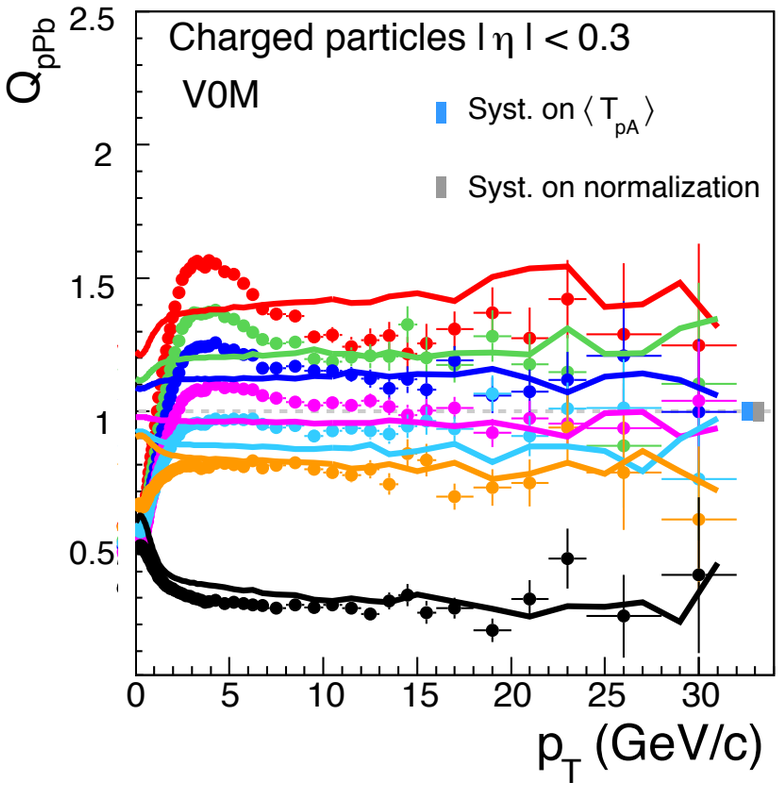


two MC Glauber events showing only the **participating** nucleons in the transverse plane

same N_{part}/N_{coll} value

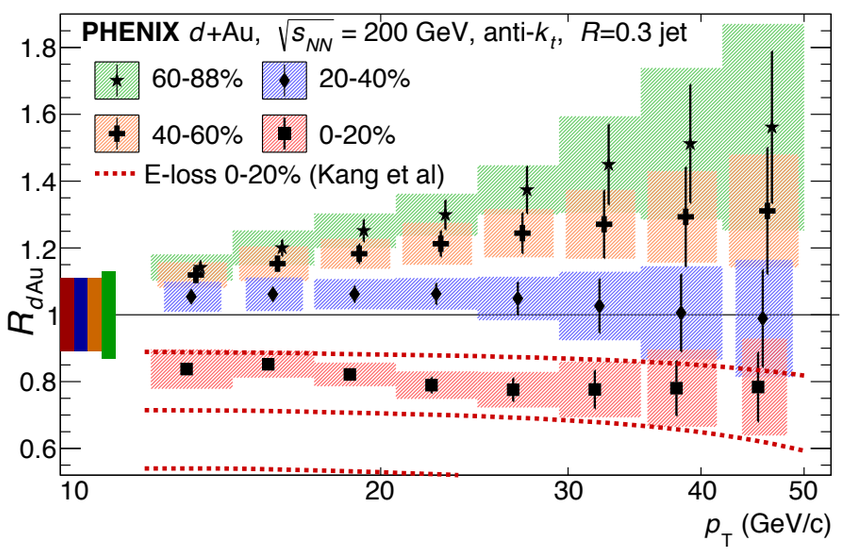
one is *p*+A, one is A+A…

Centrality “biases”



cent.

peri.



peri.

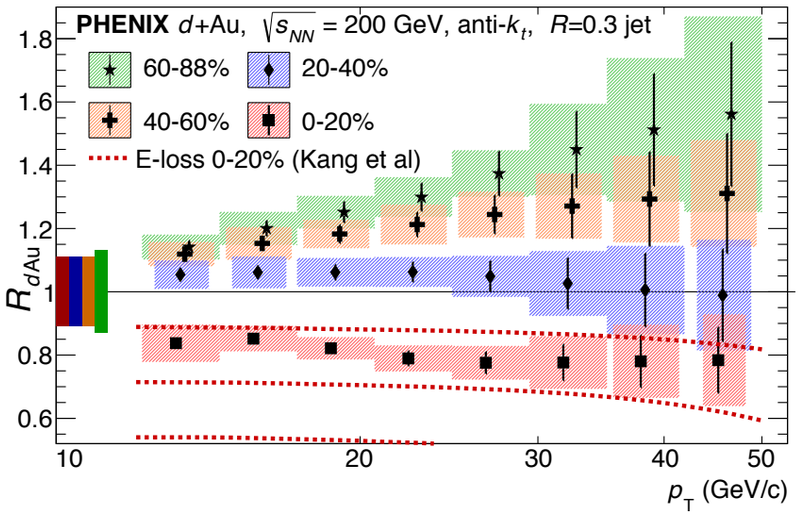
cent.

multiplicity bias in hard-scattering events

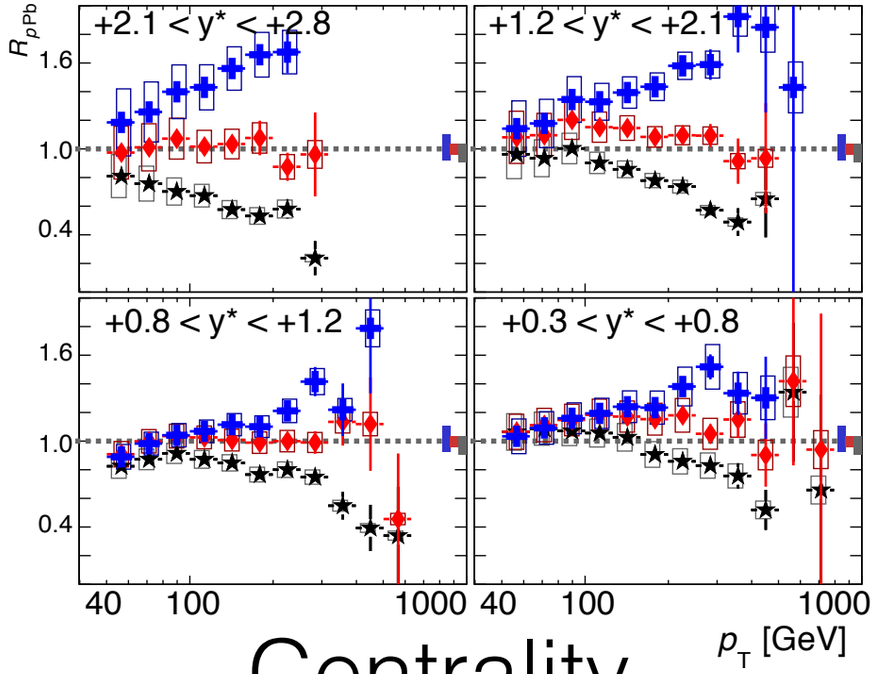
physics effect manifesting as “bias” in some observables (such as R_{pA})

x < 0.1

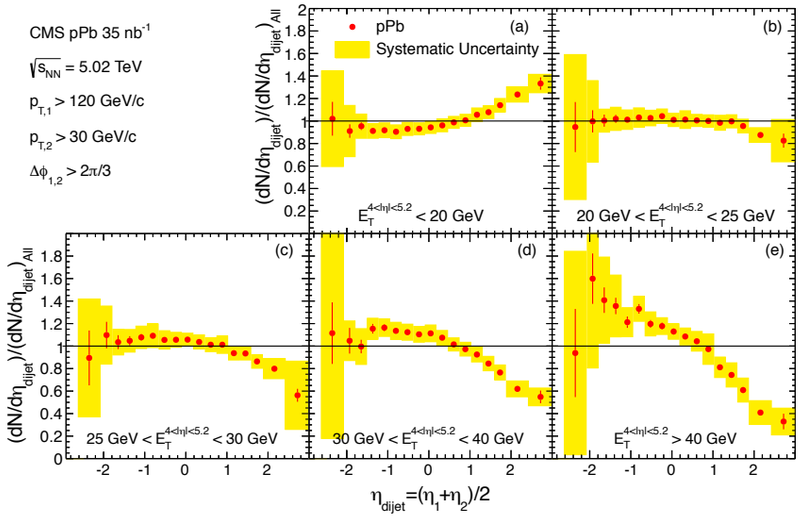
x > 0.1



Centrality "splitting" for jets at RHIC

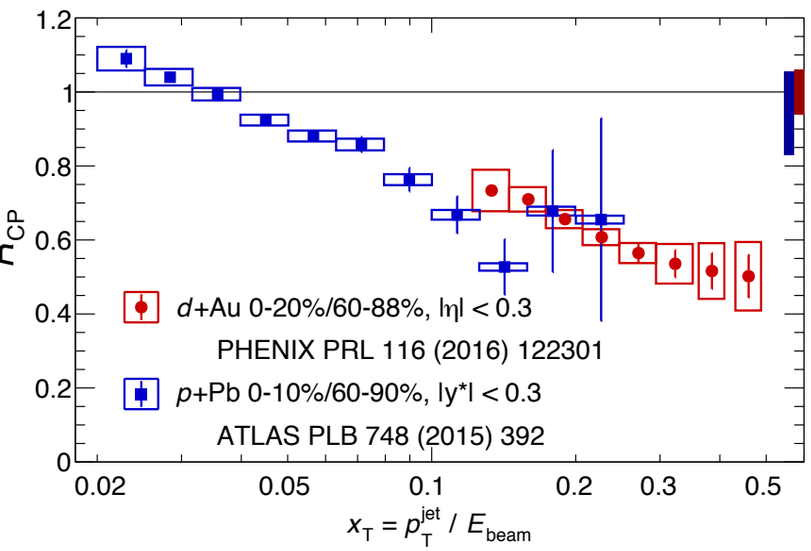


Centrality "splitting" for single jets at LHC

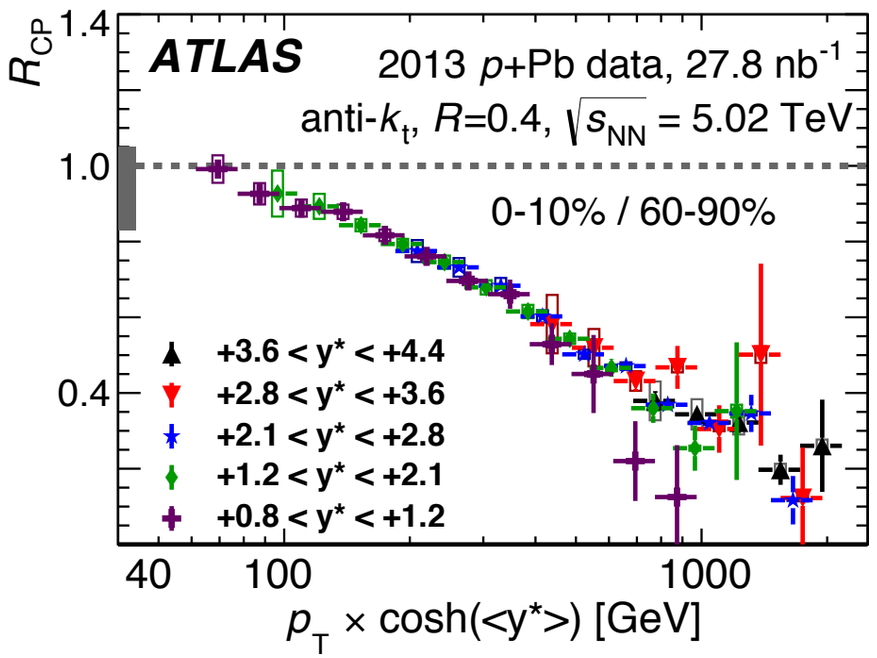


"Splitting" for dijets at large η

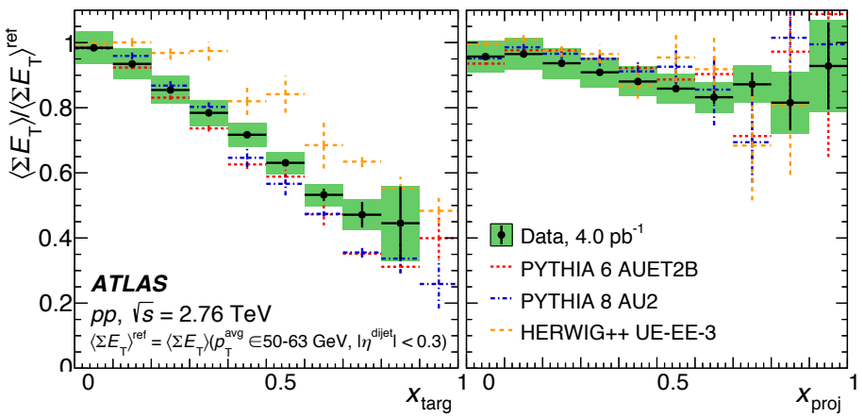
scales with x_T b/w RHIC & LHC



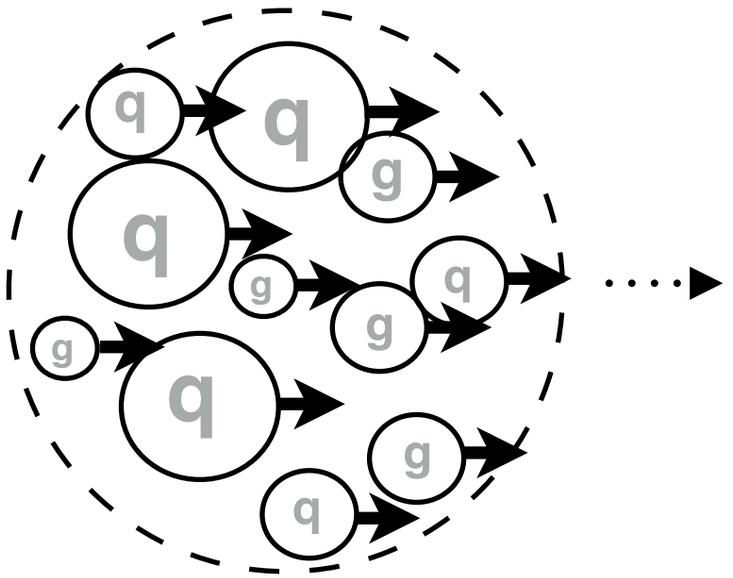
scales with x_p (or x_F) b/w rapidities at LHC



not trivial energy conservation



“shrinking proton” picture



typical proton

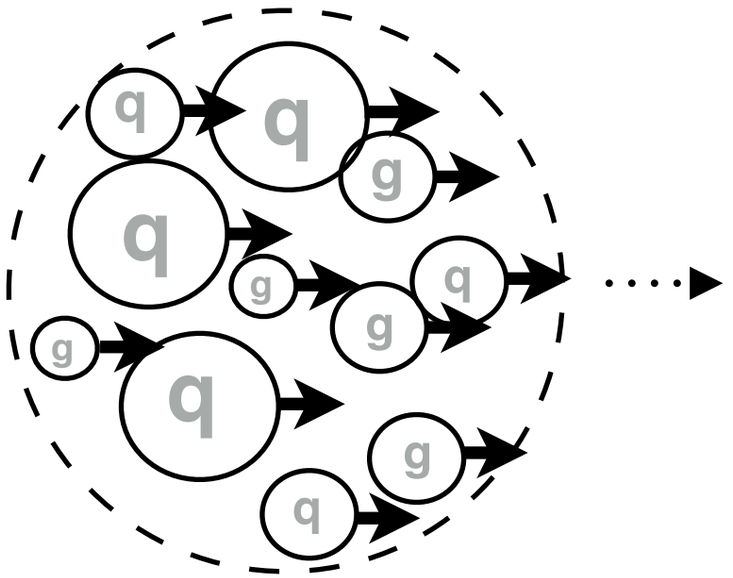
“small” proton with ***large-x parton***

anti-correlation between longitudinal momentum structure and transverse spatial structure

DVP, Cole, Strikman, PRC 93 (2016) 011902
Bzdak et al. PRC 93 (2016) 044901

Armesto et al. PLB 747 (2015) 441
Kordell, Majumder hep-ph/1601.02595

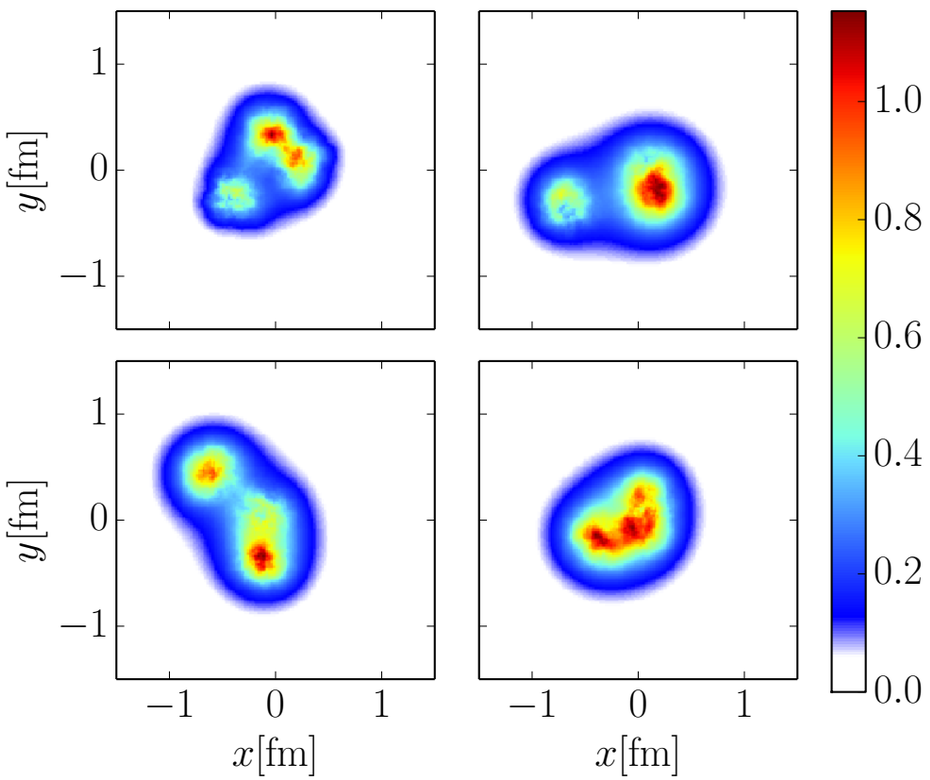
“shrinking proton” picture



typical proton

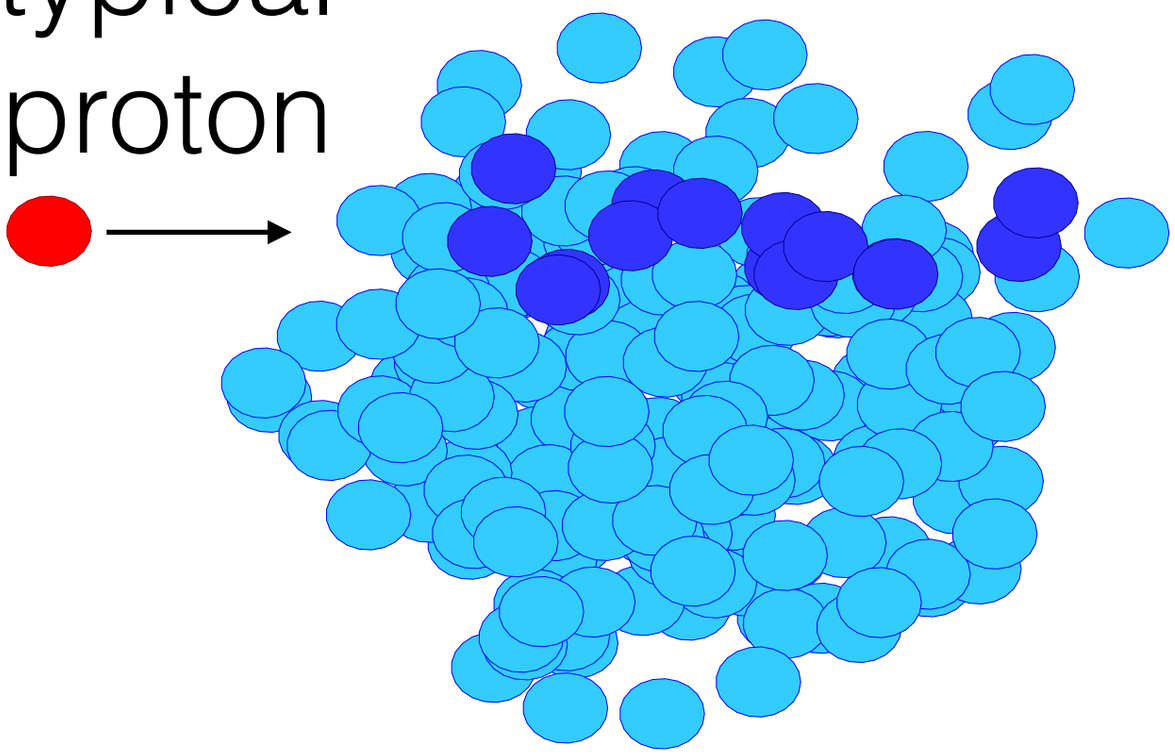
“small” proton with ***large-x parton***

we know the proton fluctuates event by event…

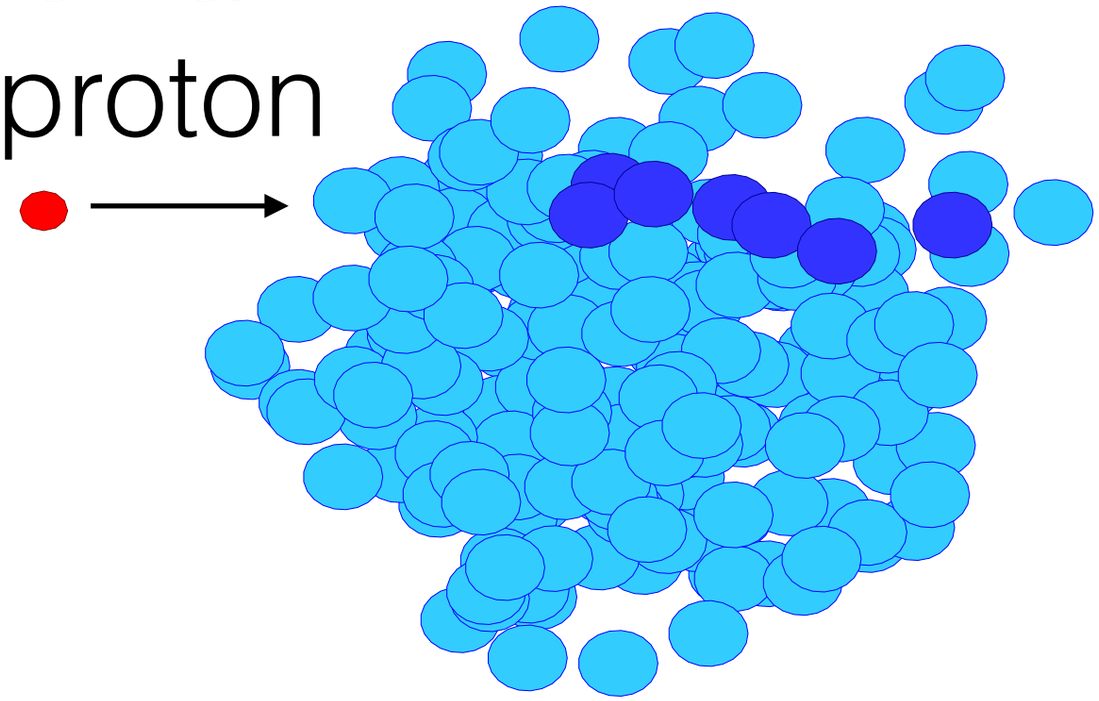


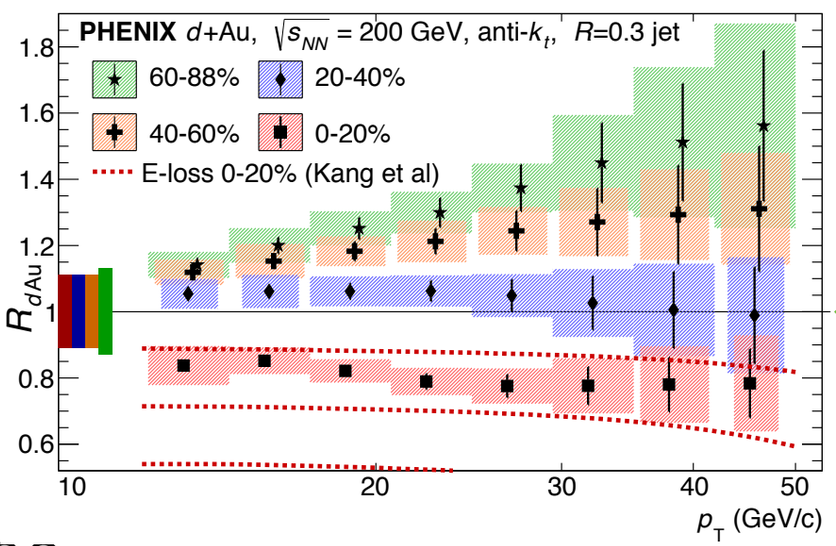
nucleus acts as an "analyzer" sensitive to the proton's transverse size

typical
proton



small
proton





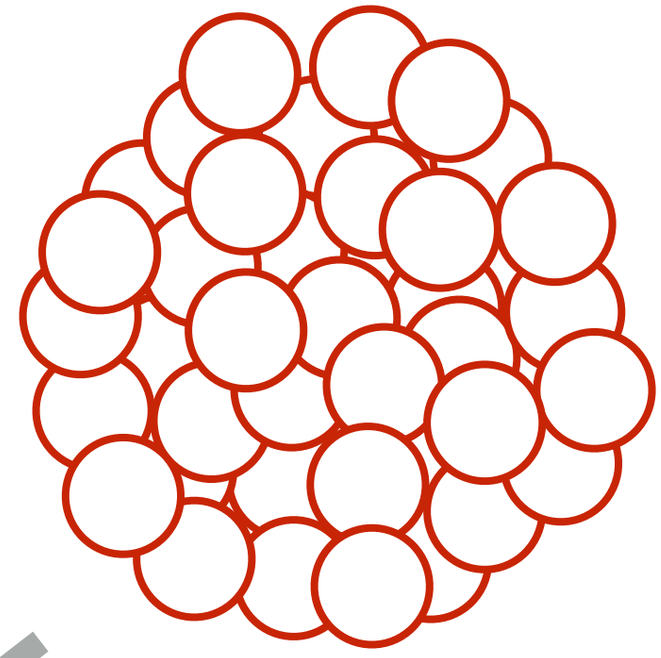
peri.

cent.

DVP, Cole, Strikman, PRC 93 (2016) 011902

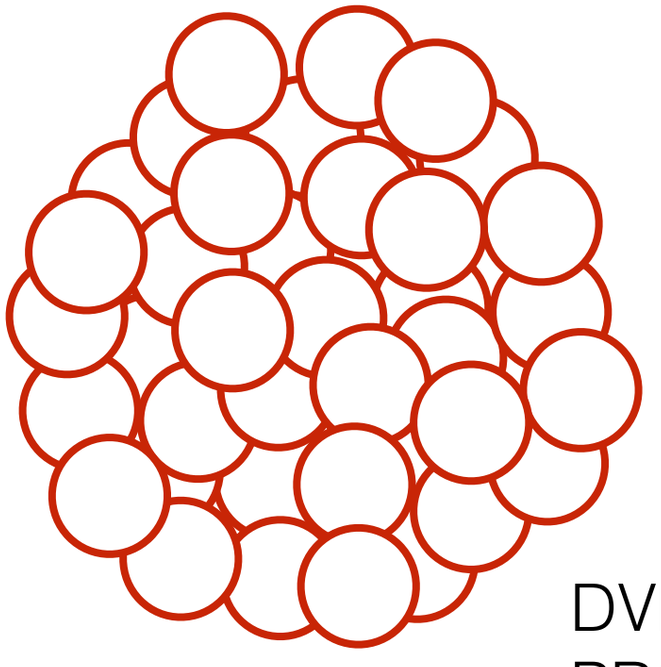
p/d/h+A scan at RHIC

shrinking high-x proton in d+Au



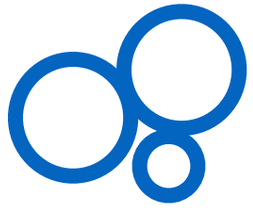
stronger effect

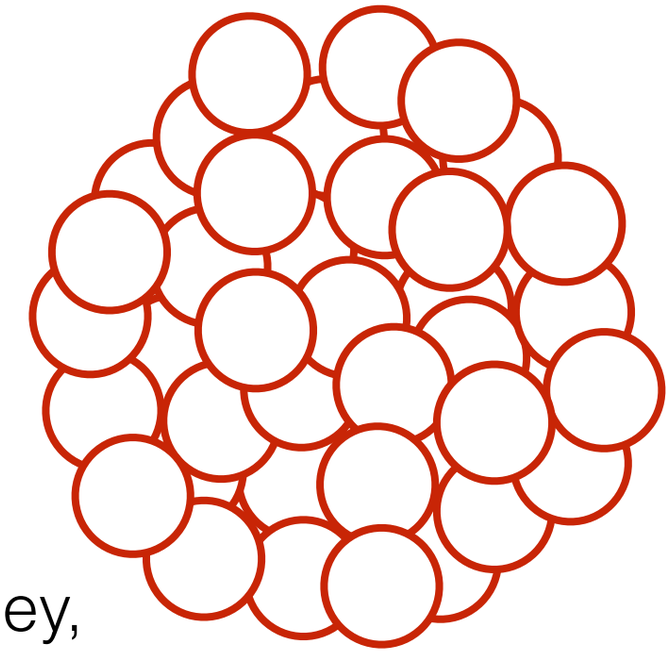
in p+Au



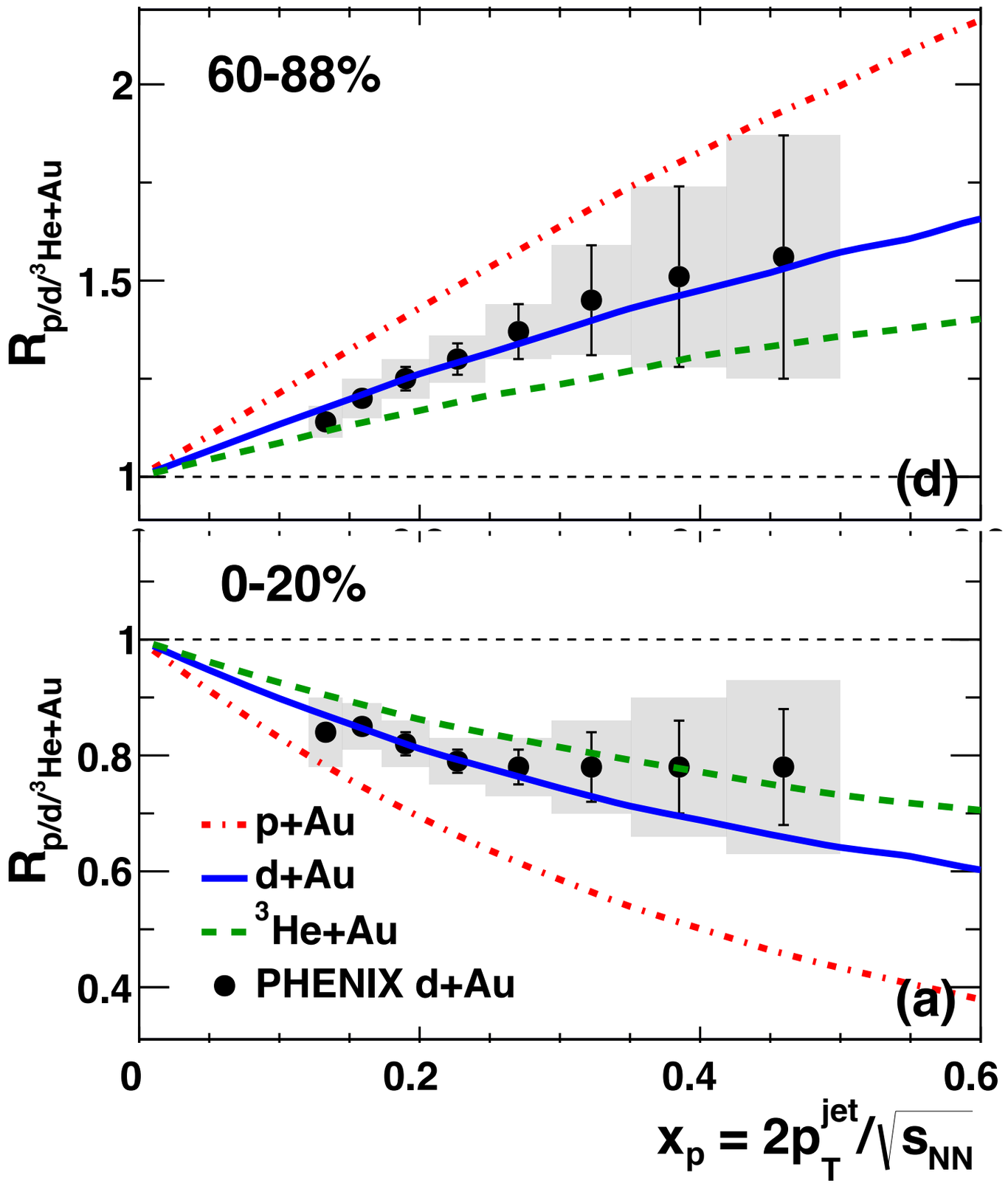
weaker effect

in ^{3}He+Au





DVP, J. Nagle, D. McGlinchey,
PRC 94 (2016) 024915



Tune a model to ***d+Au****, predict* ***p+Au*** *and* ***^{3}He+Au***

DVP, J. Nagle, D. McGlinchey,
PRC 94 (2016) 024915

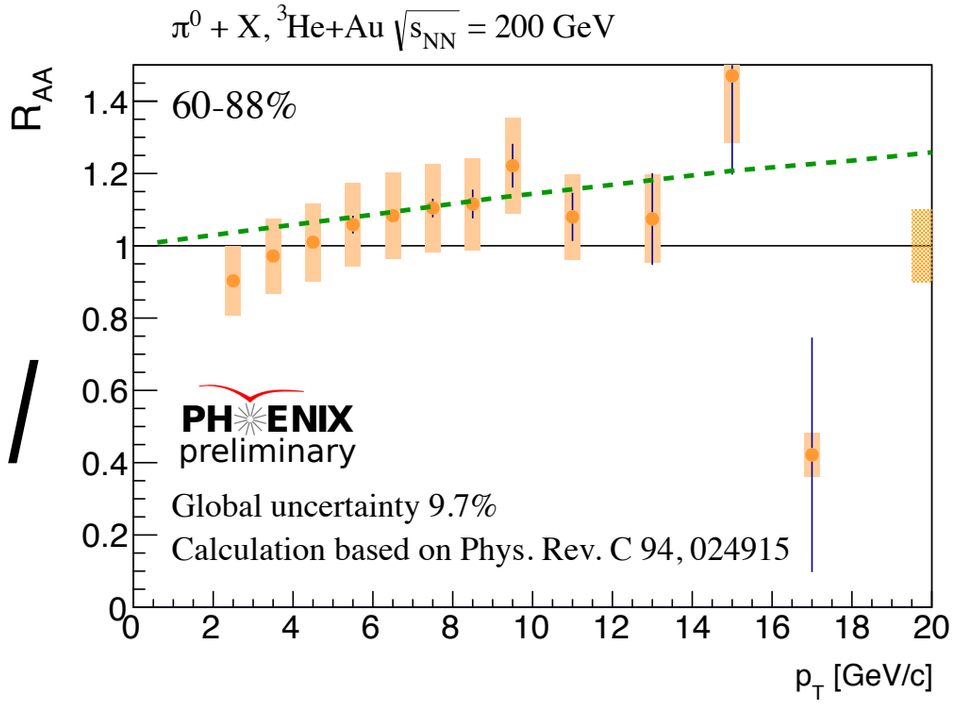
tension here

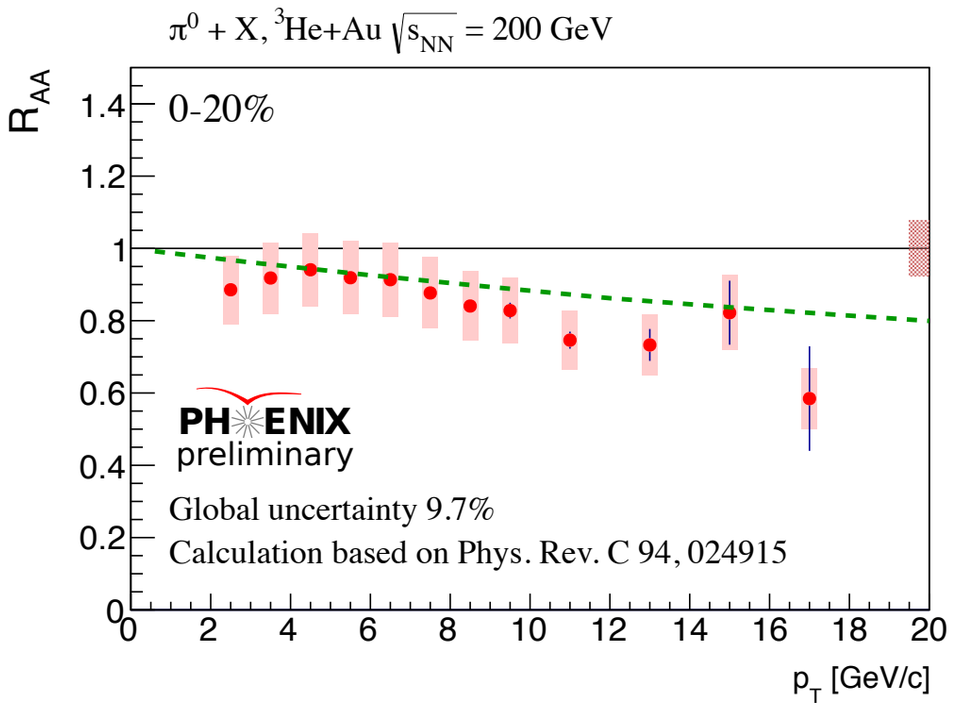
^{3}He+Au

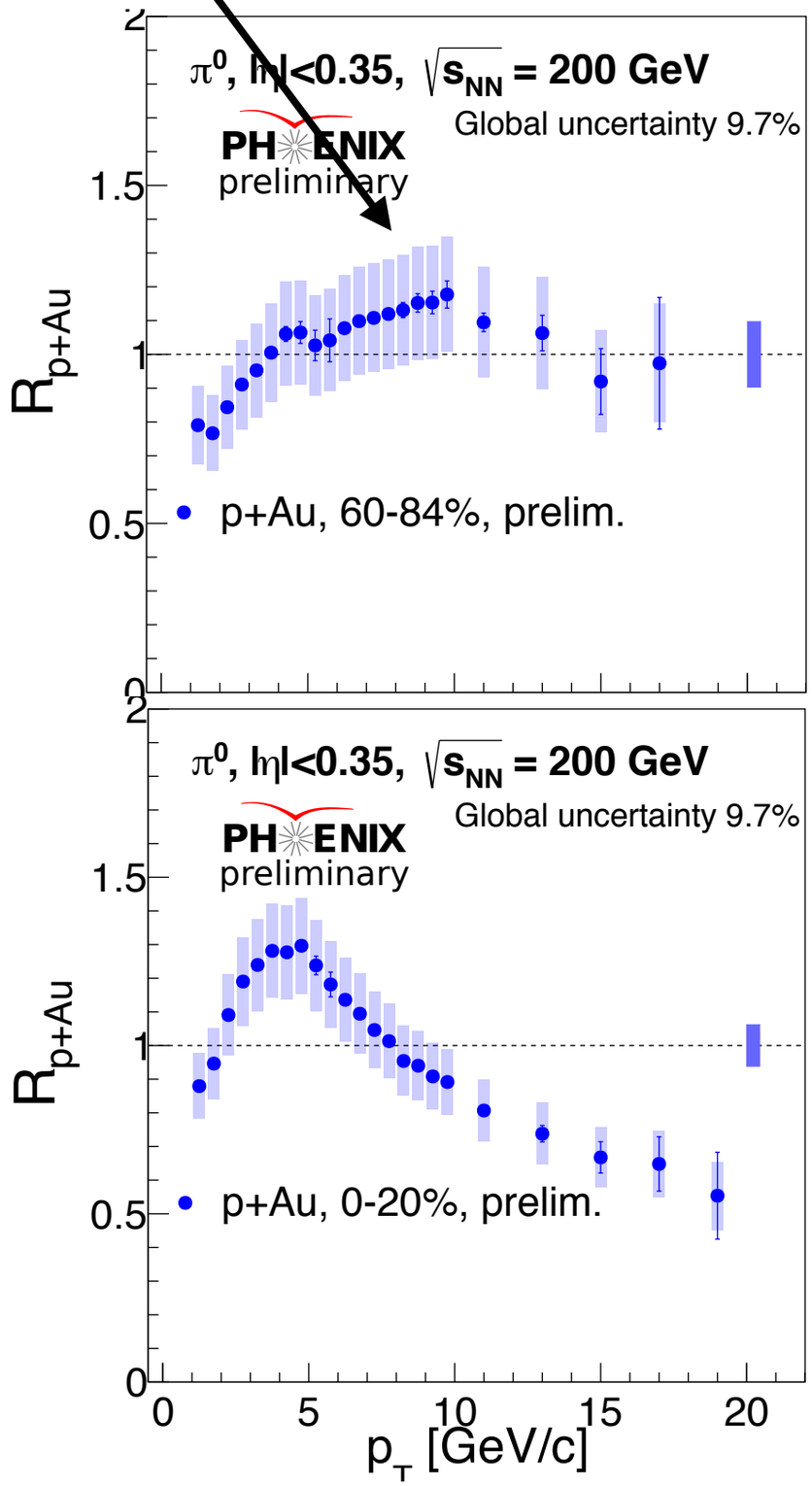
p+Au

peripheral

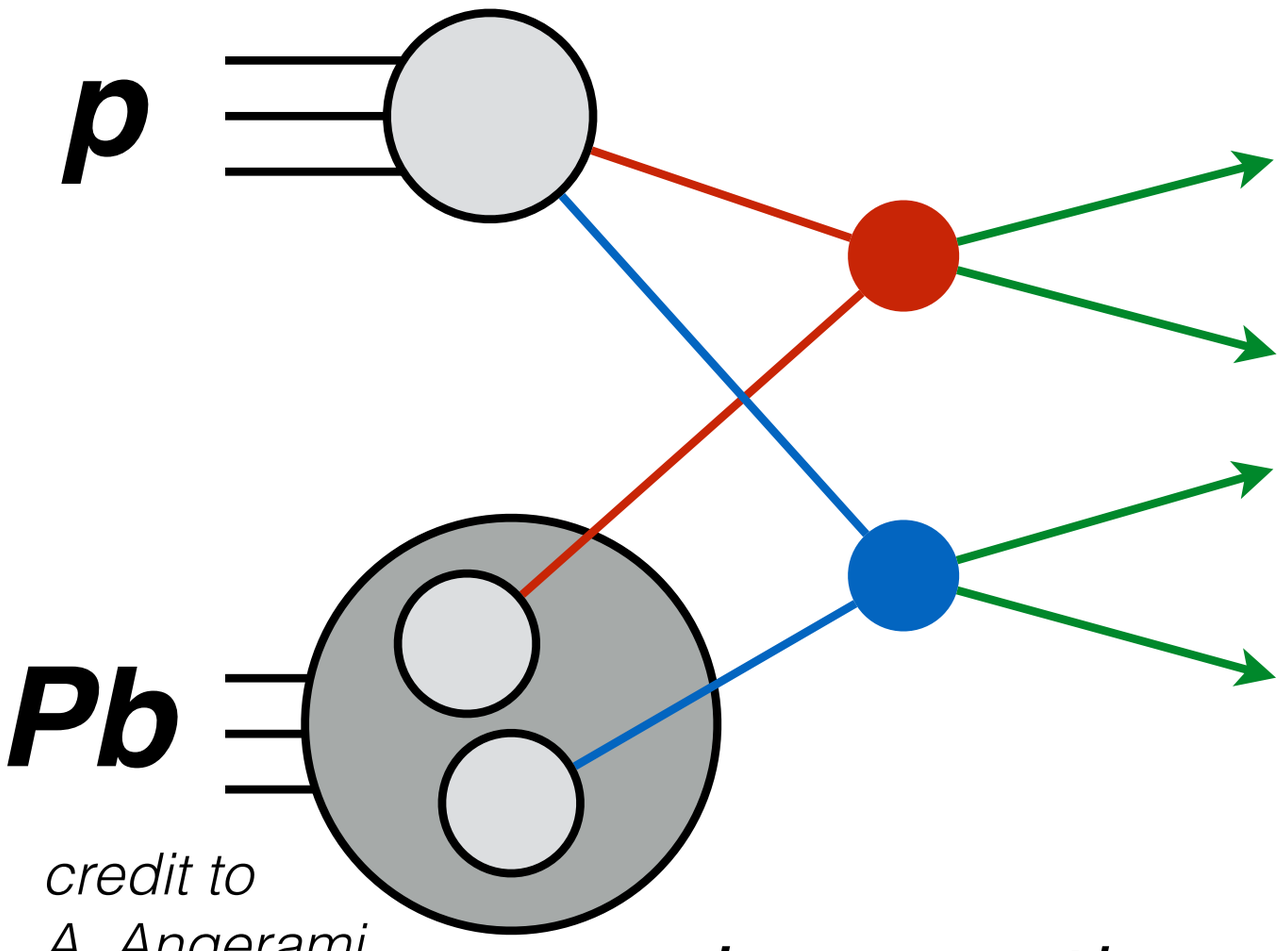
central







double parton scattering in *p*+A



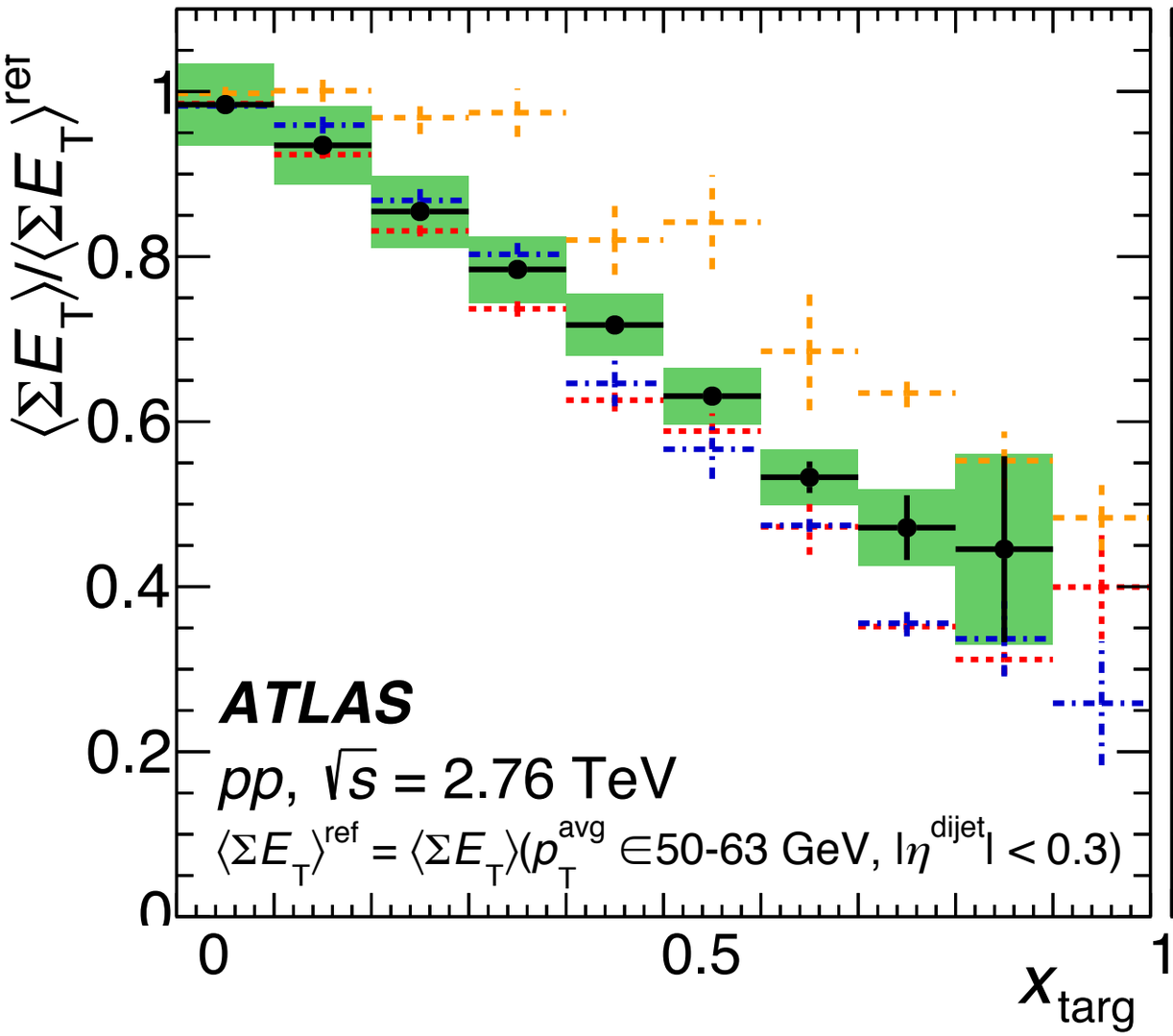
credit to A. Angerami

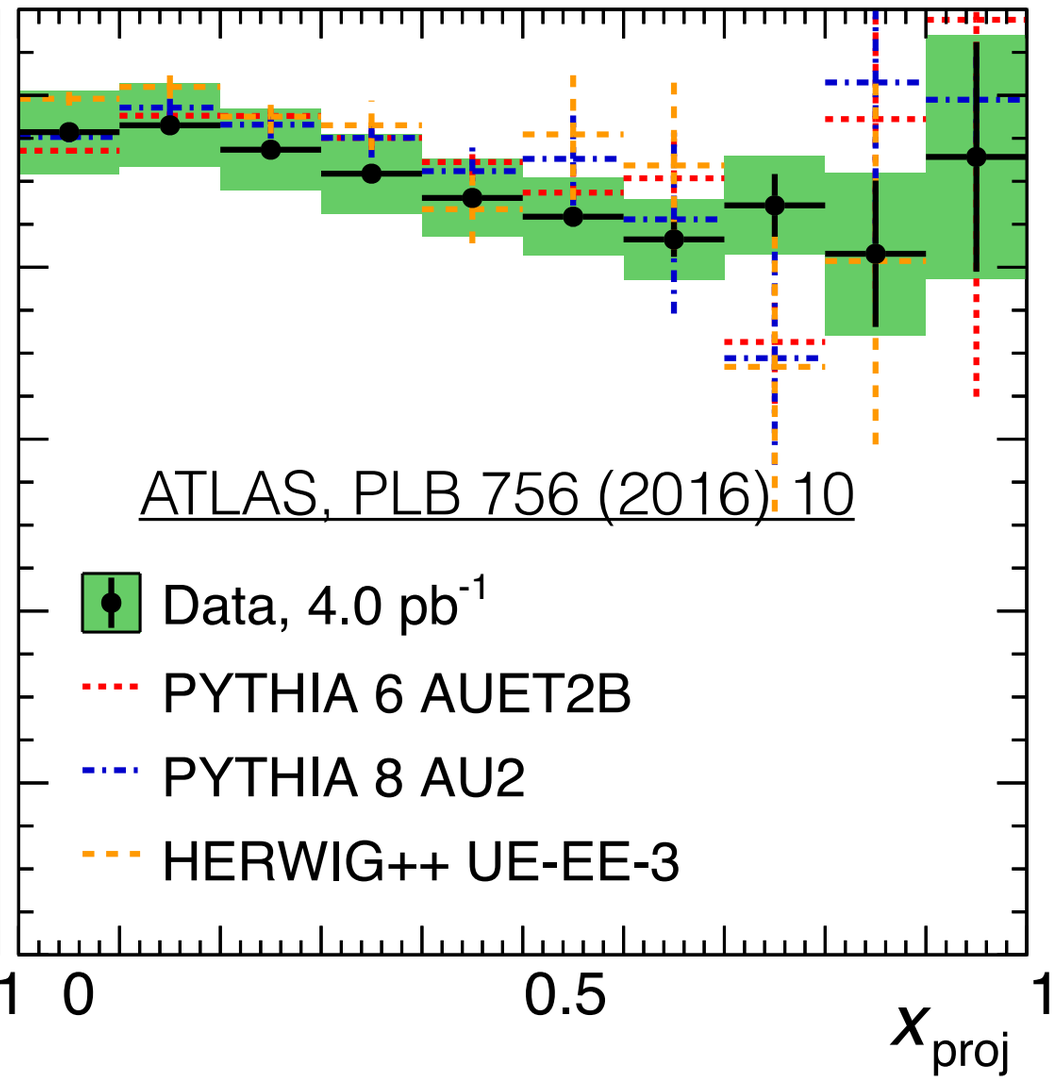
Select ***large-x_p*** *configuration*

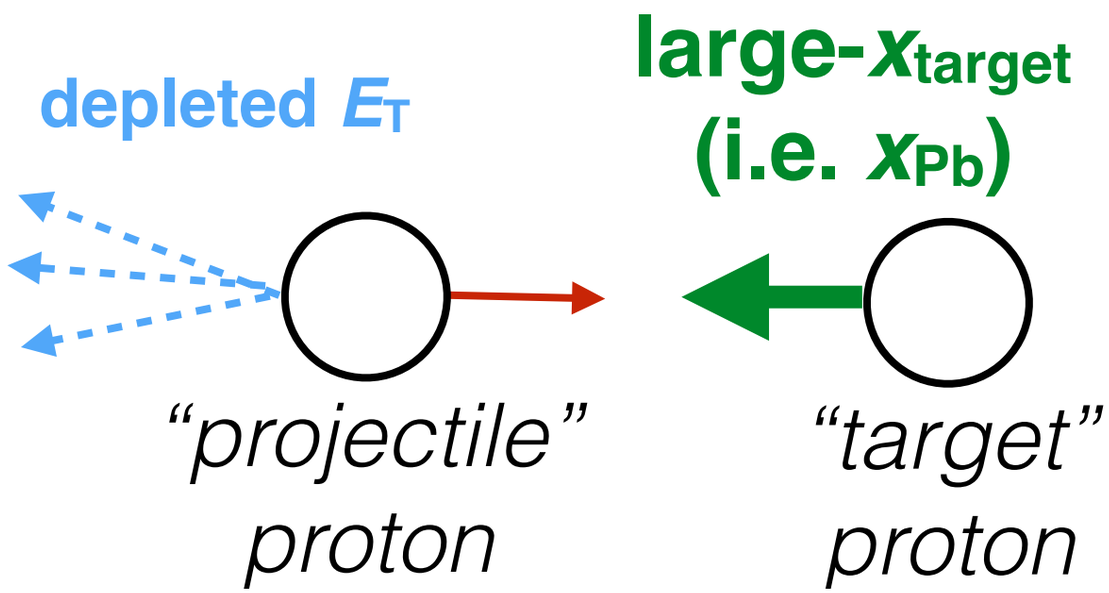
Look for ***independent parton scattering***

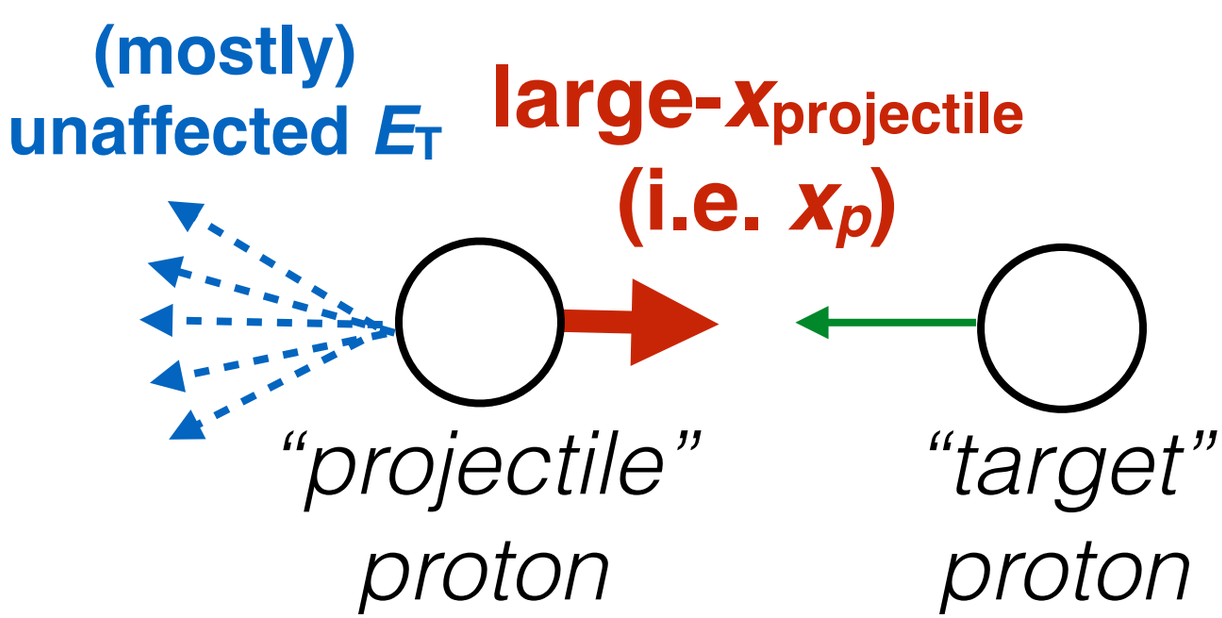
Image the structure of the beam remnant (${}_2$GPD's)

4-jet production:
Blok, Strikman, Wiedemann EPJC 73 (2013) 2433

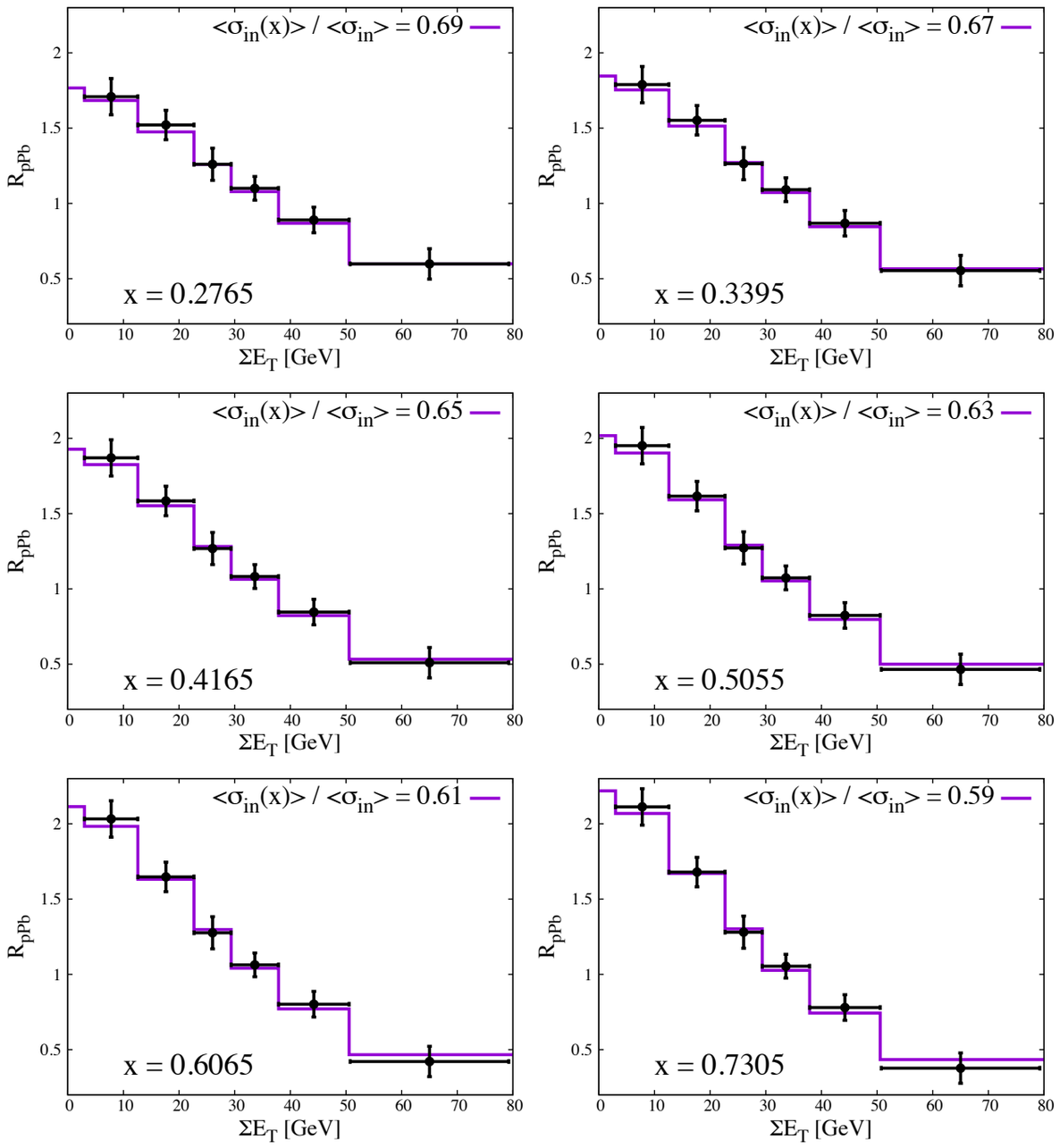

$\langle \Sigma E_T \rangle / \langle \Sigma E_T \rangle^{ref}$
1
0.8
0.6
0.4
0.2
0
0.5
1
x_{targ}
ATLAS
pp, $\sqrt{s}$ = 2.76 TeV
$\langle \Sigma E_T \rangle^{ref} = \langle \Sigma E_T \rangle (p_T^{avg} \in$50-63 GeV, $|\eta^{dijet}| < 0.3)$


ATLAS, PLB 756 (2016) 10
Data, 4.0 pb^{-1}
PYTHIA 6 AUET2B
PYTHIA 8 AU2
HERWIG++ UE-EE-3
0
0.5
1
x_{proj}


depleted E_T
large-x_{target}
(i.e. x_{Pb})
"projectile"
proton
"target"
proton

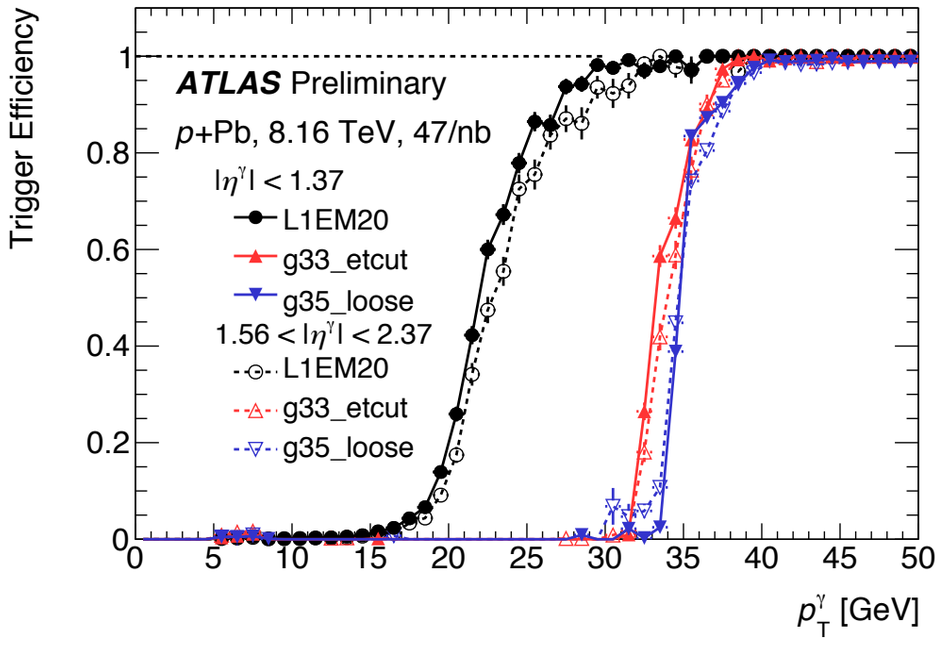

(mostly)
unaffected E_T
large-$x_{projectile}$
(i.e. x_p)
"projectile"
proton
"target"
proton

Systematic extraction of $\langle\sigma_{NN}(x_p)\rangle / \langle\sigma_{NN}\rangle$

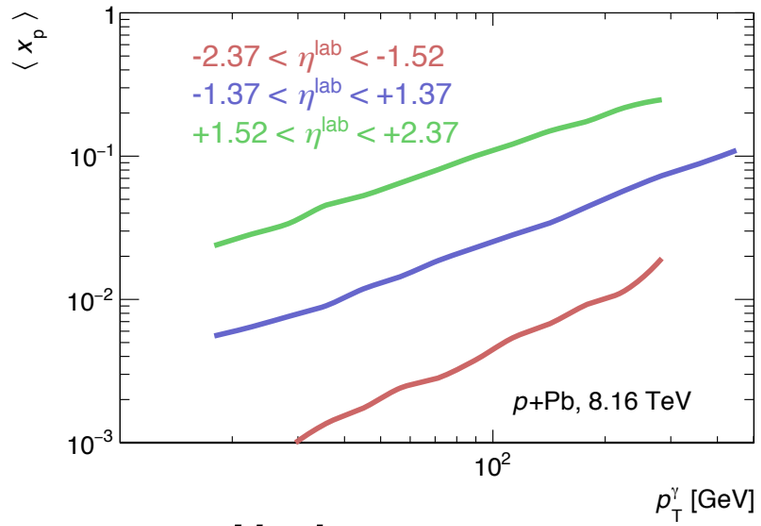


DVP, Strikman, Alvioli, in progress, p/γ+A workshop @ CERN

Useful cross-check with photon spectra in p+A



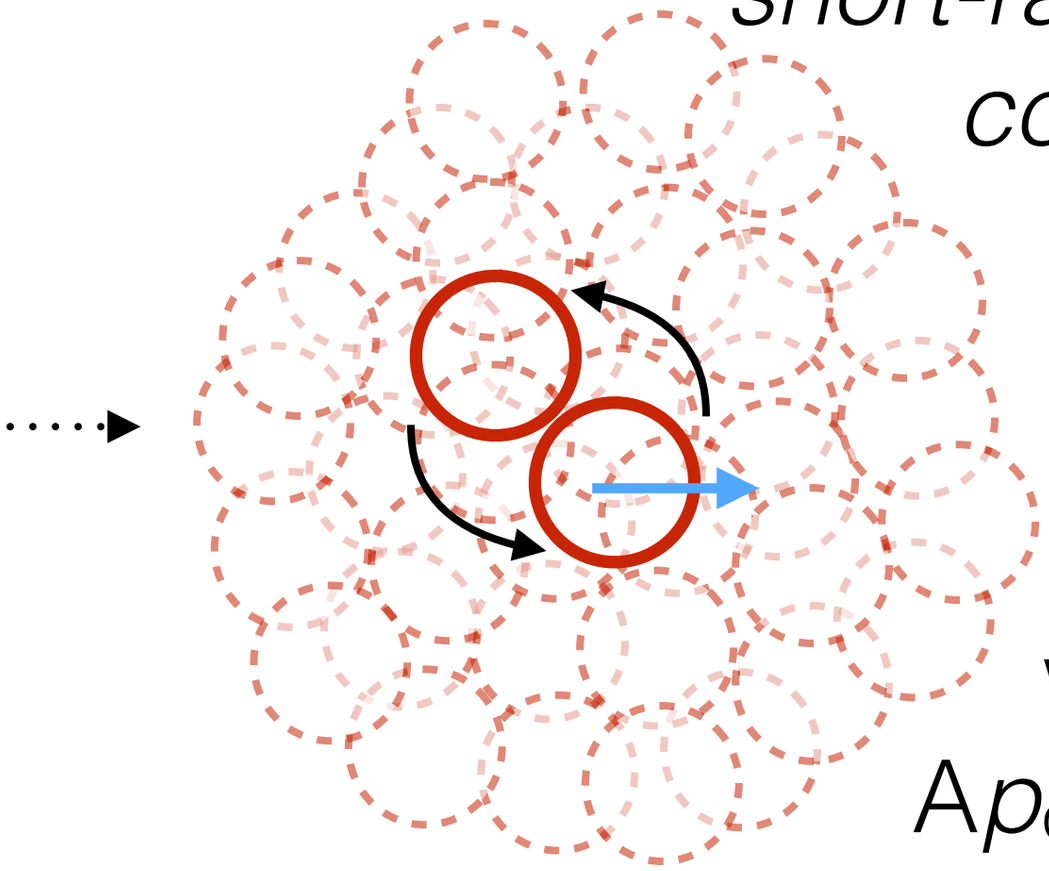
ATLAS forward photon trigger



accessible $\langle x_p \rangle$ values

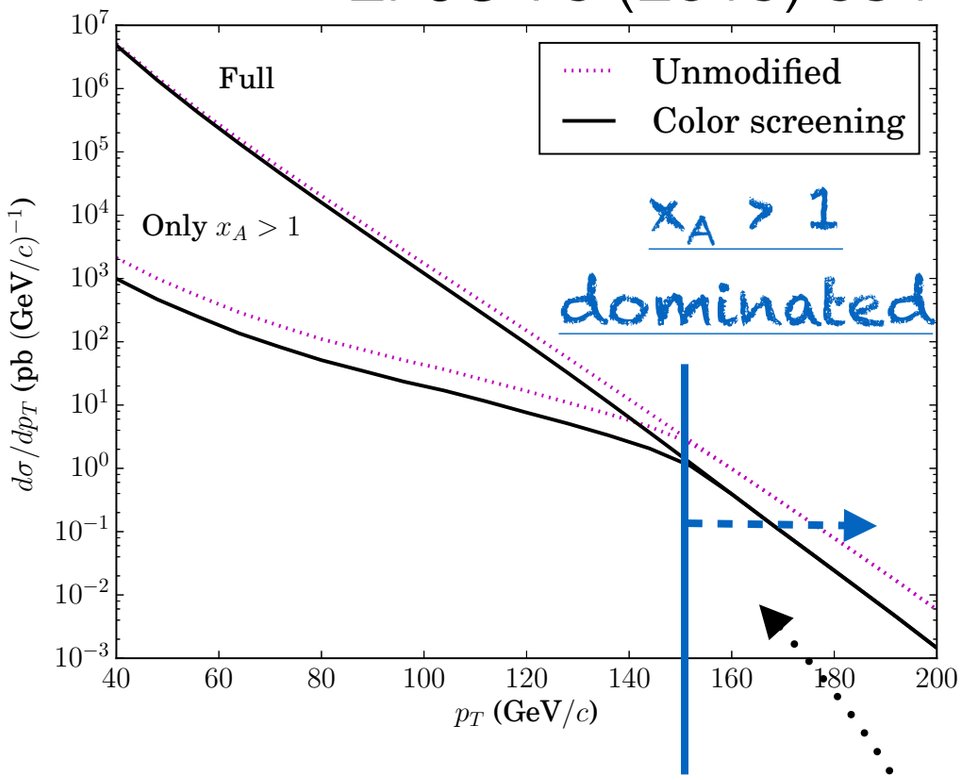
superfast quarks

*short-range **p-n** correlation*

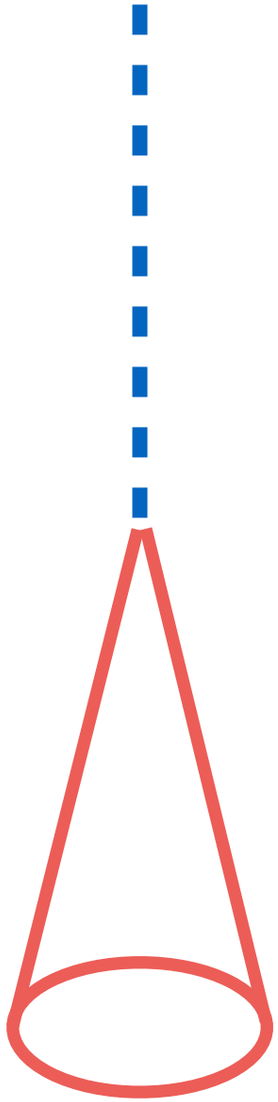


quark with $x_A = Ap_q^-/p_A^- > 1$

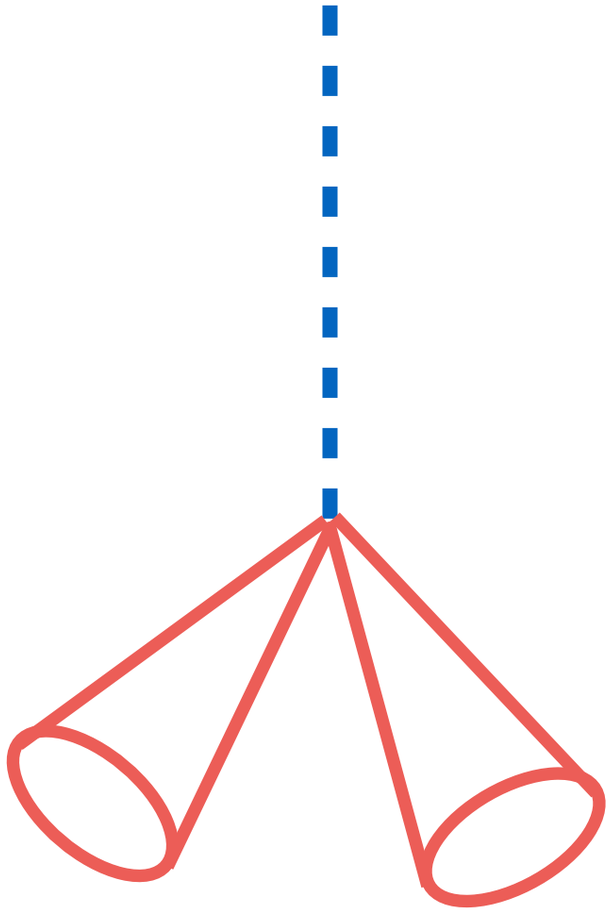
EPJC 75 (2015) 534



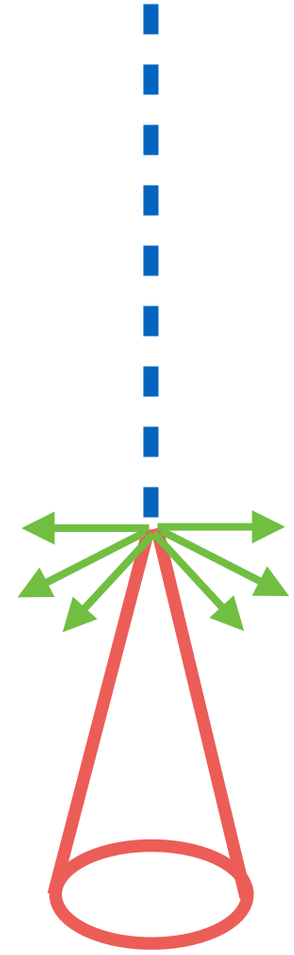
- Select final-state dijet events where $x_A > 1$ configurations dominate
  - ➡ e.g. $-5 < \eta_1 < -3$, $|\eta_2| < 2.5$, $p_T^{\text{dijet}} > 150$ GeV
- Rate sensitive to the nucleon interactions at very short distance scales
  - ➡ for 70/nb of 8 TeV p+Pb data, 200-1200 events depending on SRC model



baseline



bias towards multi-jet final states



E-loss