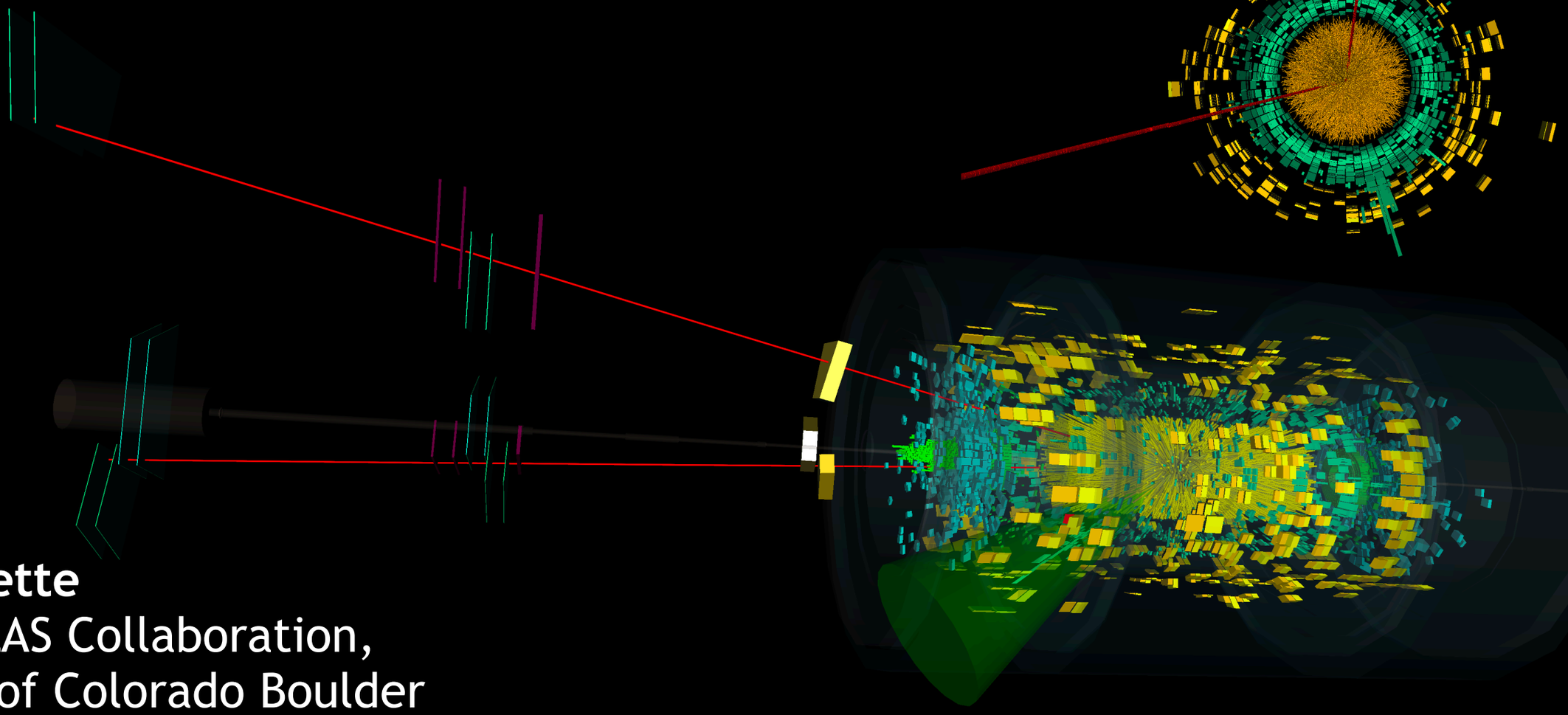
Measurements of photon- and Z-tagged jet quenching by ATLAS



Jeff Ouellette
for the ATLAS Collaboration,
University of Colorado Boulder

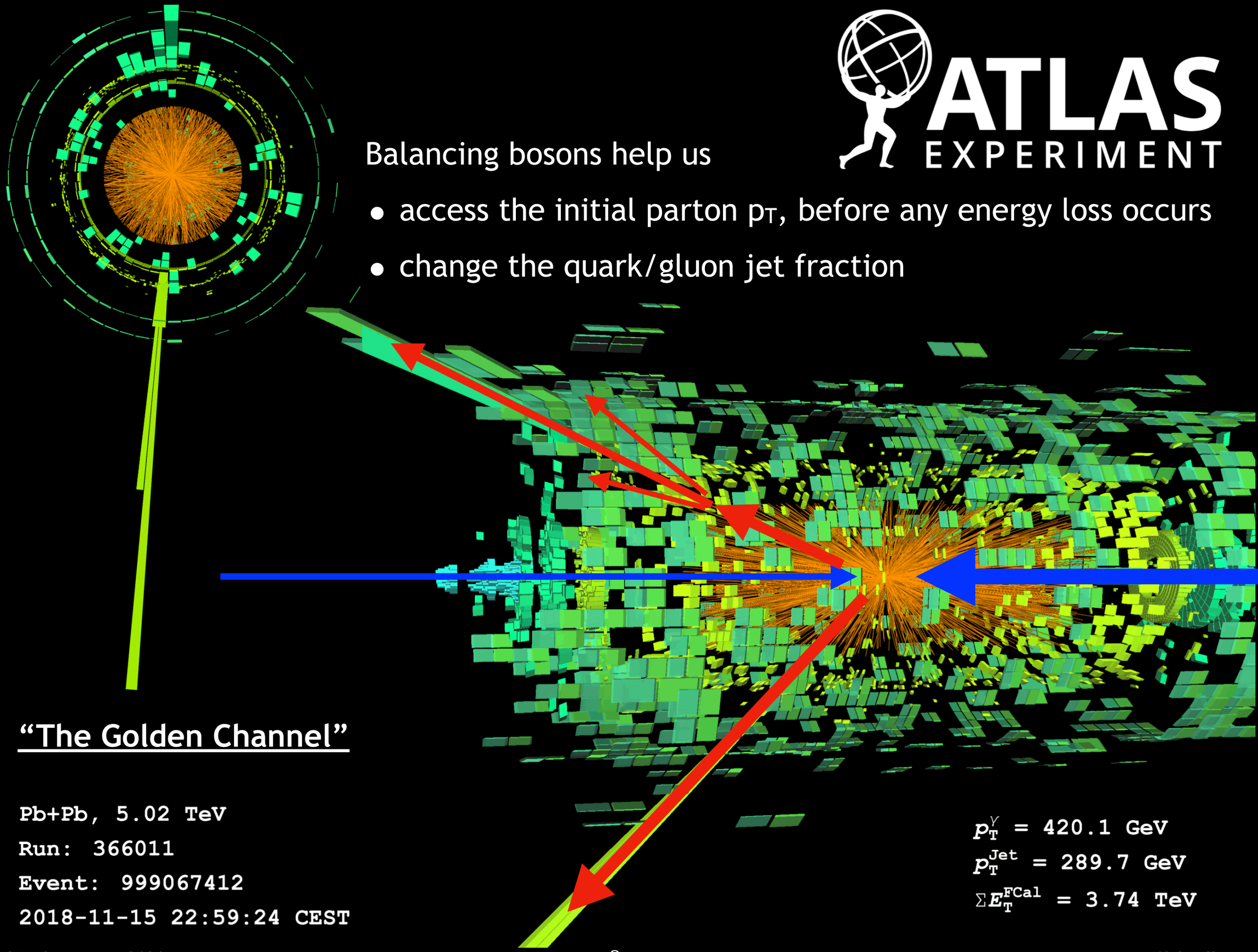
ATLAS EXPERIMENT

June 4th, 2020
10th International Conference on Hard & Electromagnetic Probes of High-Energy Nuclear Collisions

University of Colorado **Boulder**

Balancing bosons help us

- access the initial parton p_T, before any energy loss occurs
- change the quark/gluon jet fraction

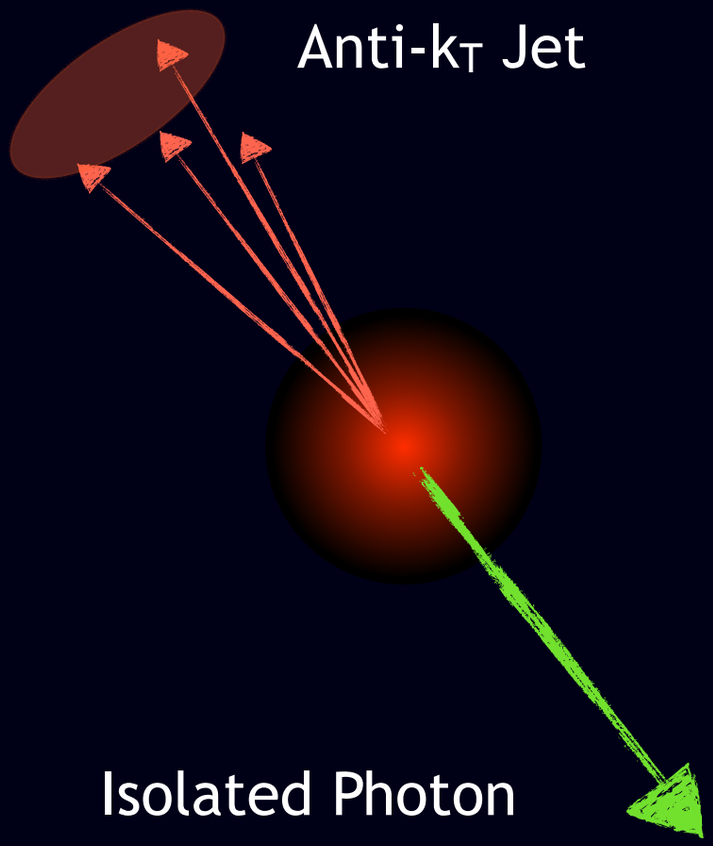


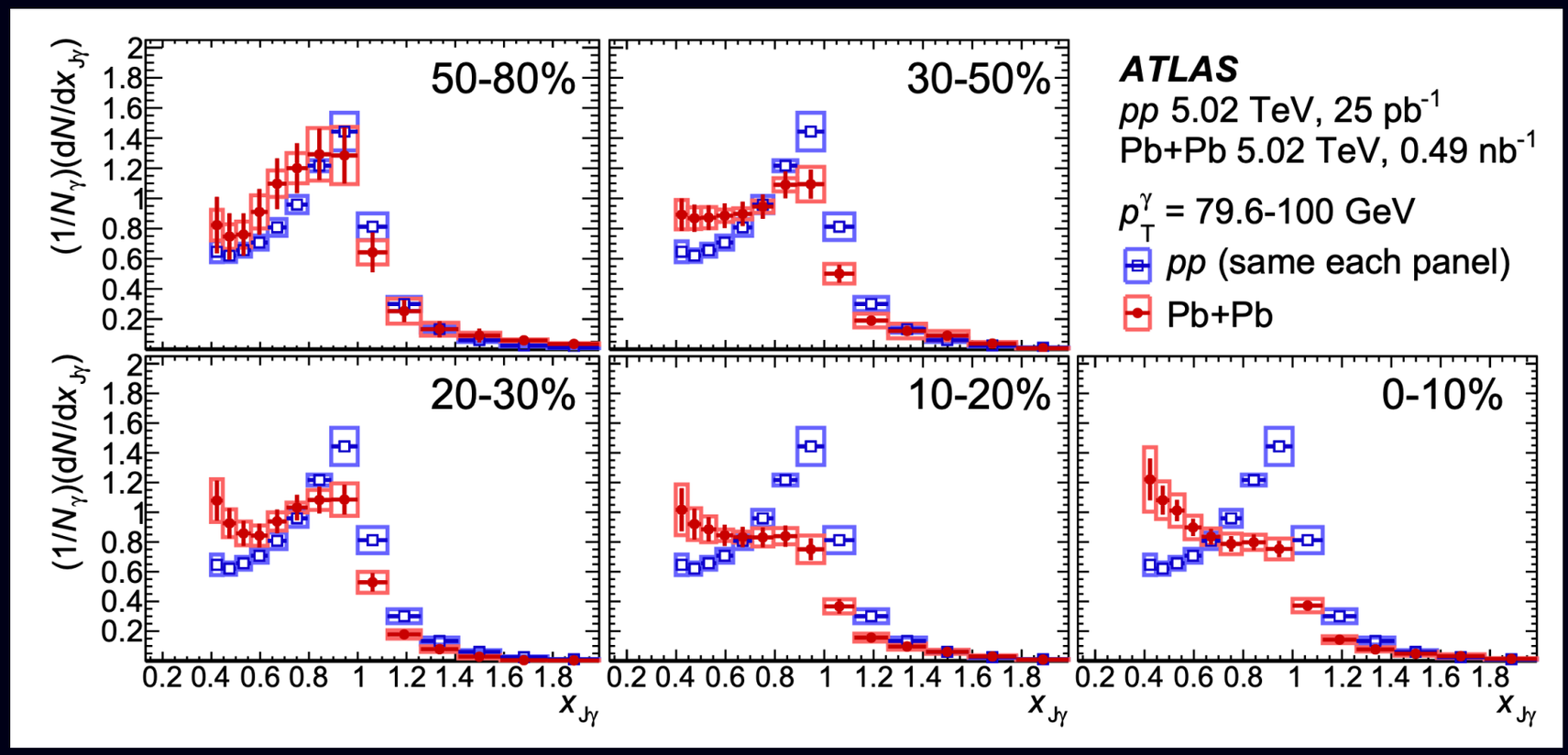
“The Golden Channel”

Pb+Pb, 5.02 TeV
Run: 366011
Event: 999067412
2018-11-15 22:59:24 CEST

p_T^{γ} = 420.1 GeV
p_T^{Jet} = 289.7 GeV
ΣE_T^{FCal} = 3.74 TeV

γ+Jets in Pb+Pb

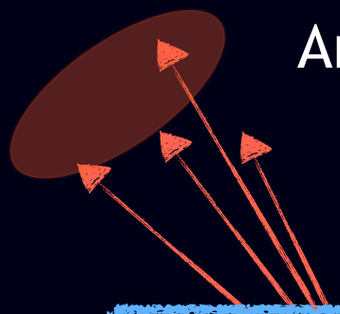




Phys. Lett. B 789 (2019) 167

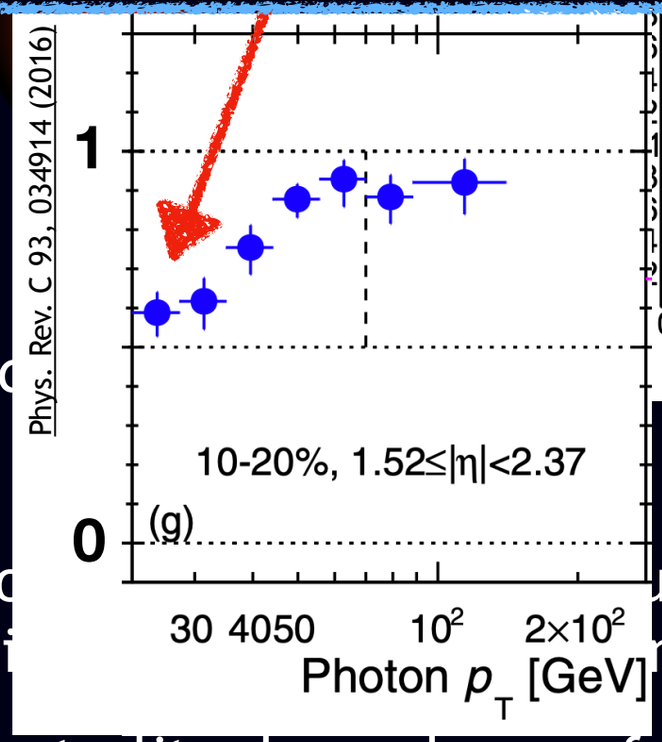
- Momentum balance measurements between γ and anti-k_T (R=0.4) jets exploit initial-and-final momentum information
- Centrality dependence of shape indicates partonic energy loss
- Jet event selection affects results ⇨ hinders study of large E_{loss} events

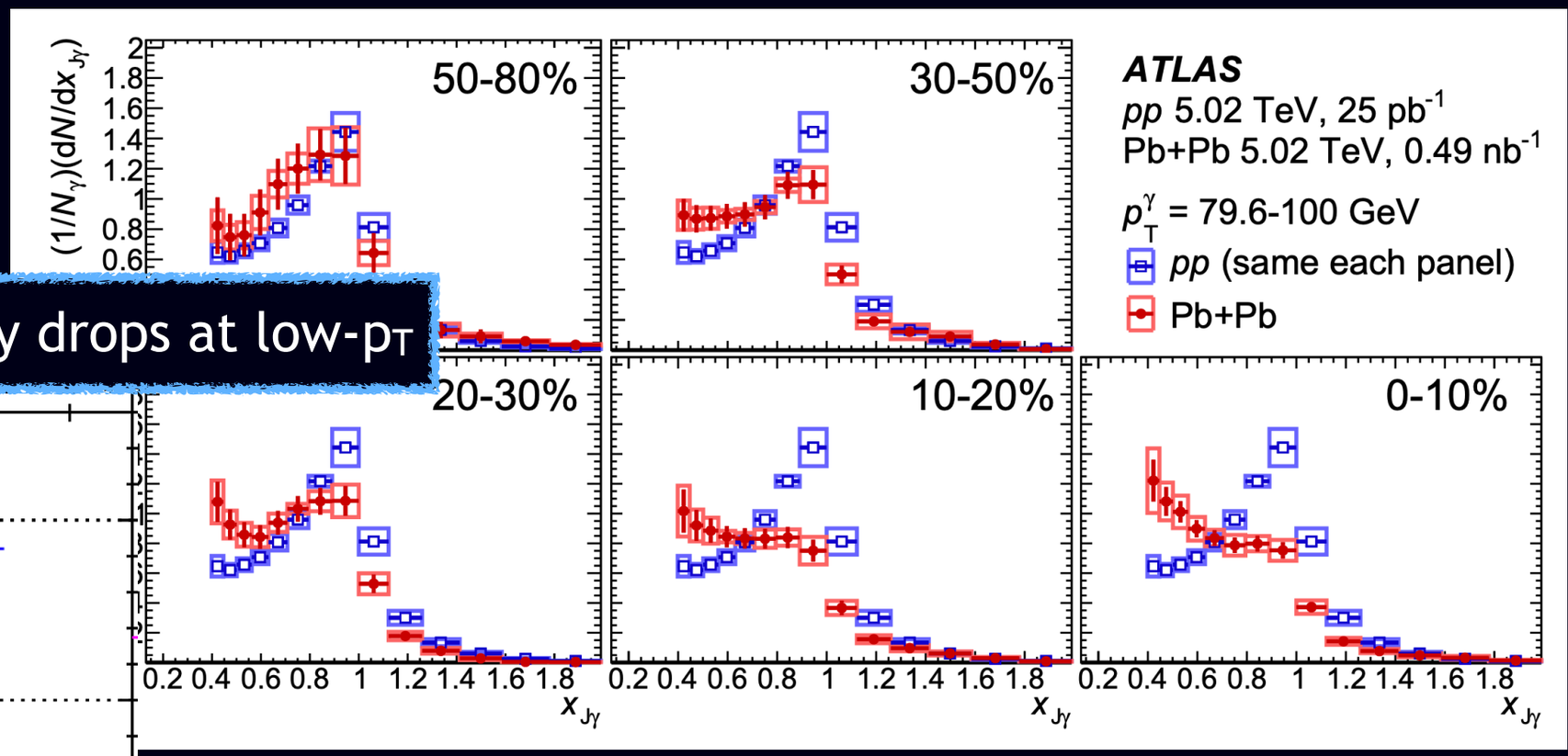
γ+Jets in Pb+Pb



Anti-k_T Jet

Photon purity generically drops at low-p_T



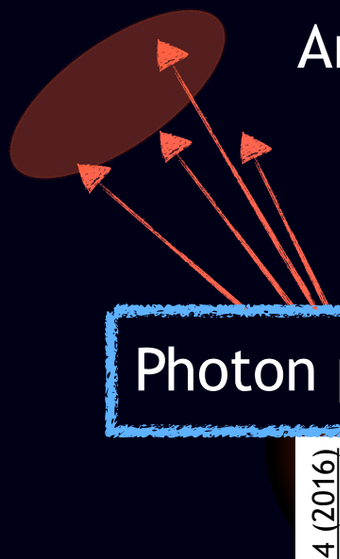


Phys. Lett. B 789 (2019) 167

Isolated

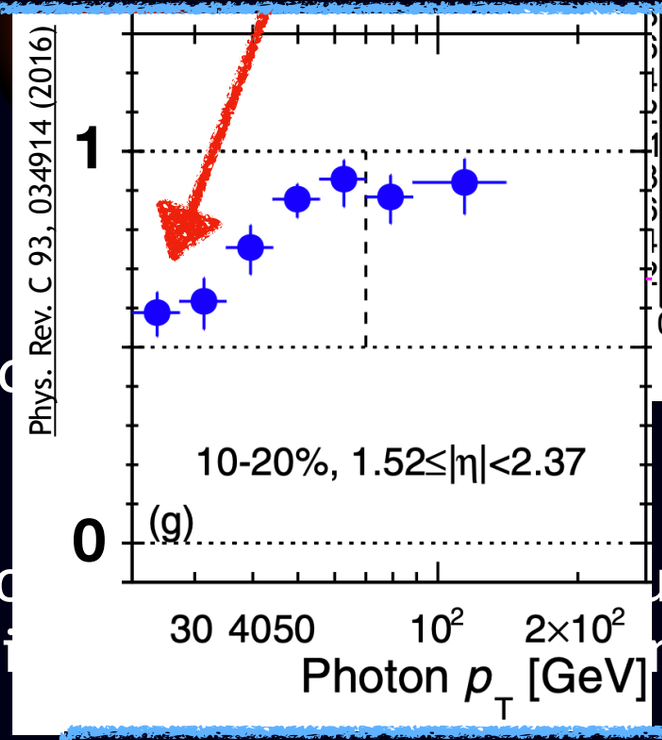
- Mo urements between γ and anti-k_T (R=0.4) jets exploit ini m information
- Centrality dependence of shape indicates partonic energy loss
- Jet event selection affects results ⇨ hinders study of large E_{loss} events

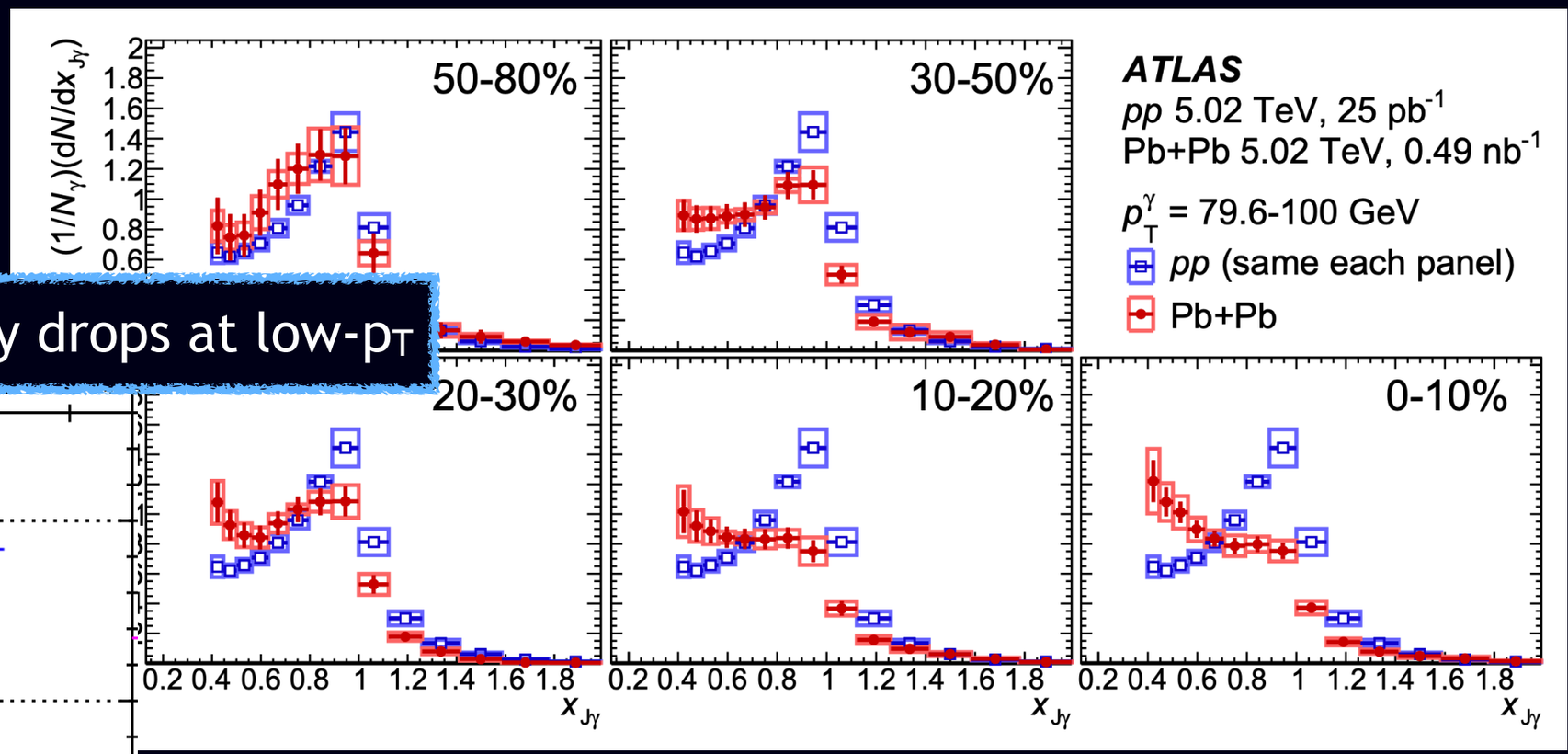
γ+Jets in Pb+Pb



Anti-k_T Jet

Photon purity generically drops at low-p_T





Phys. Lett. B 789 (2019) 167

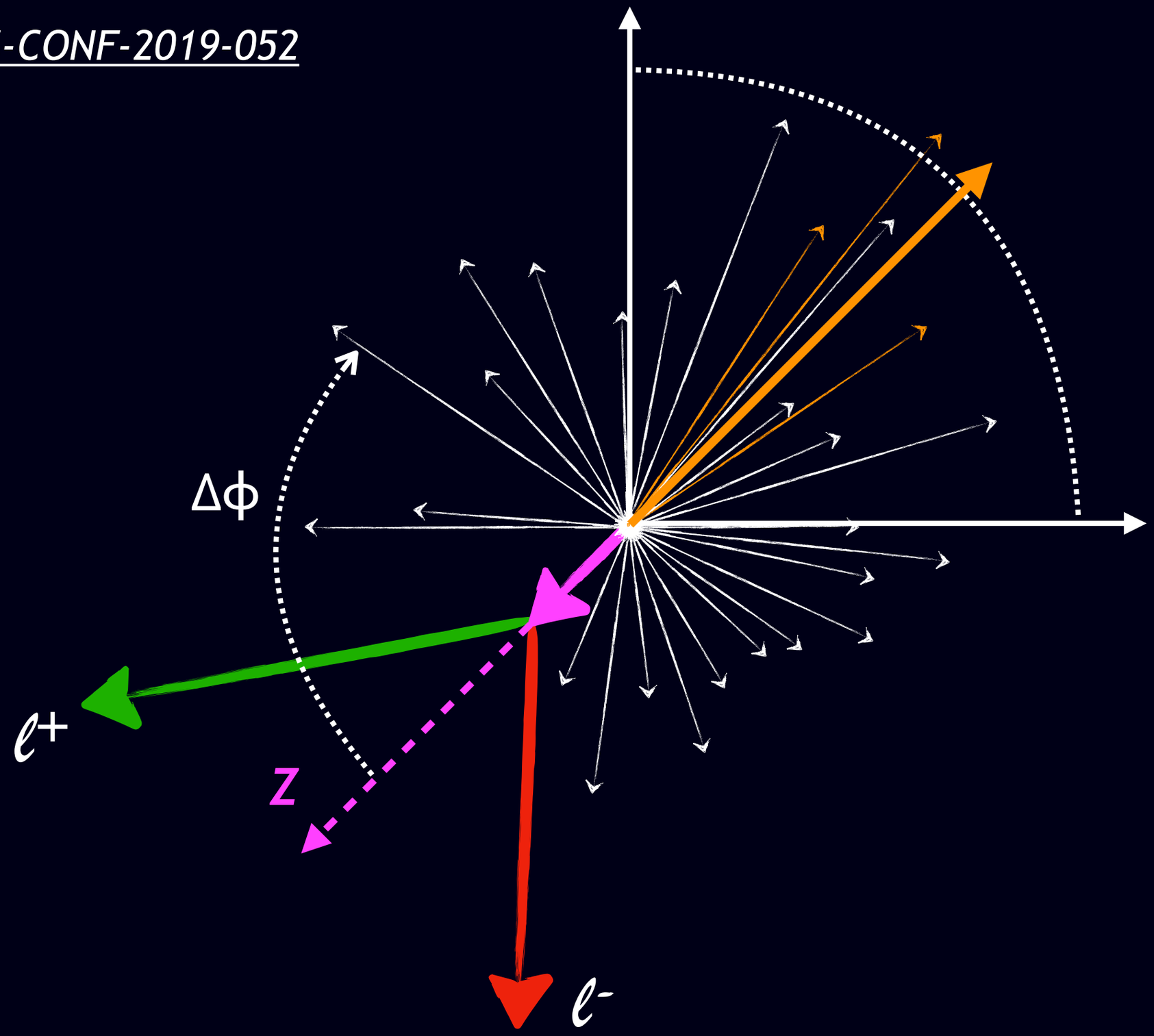
Isolated

- Mo urements between γ and anti-k_T (R=0.4) jets exploit ini m information
- Cen
- Jet

- What is the manifestation of jet quenching at low p_T?
- What effect does selecting on final state jets have on energy loss?

Measuring per-Z charged particle yields

See *ATLAS-CONF-2019-052*

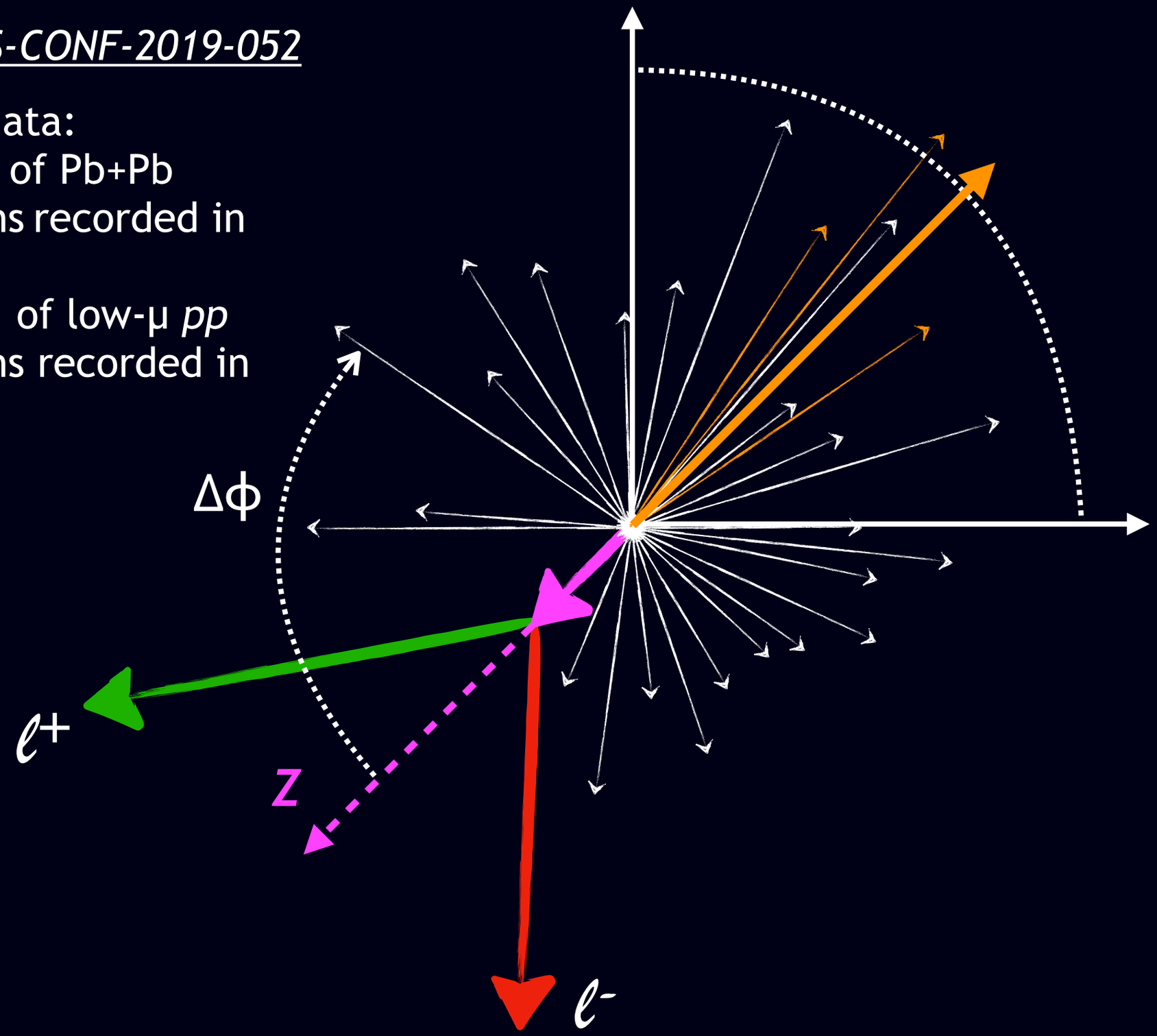


Measuring per-Z charged particle yields

See *ATLAS-CONF-2019-052*

Collision data:

- 1.7 nb^{-1} of Pb+Pb collisions recorded in 2018
- 260 pb^{-1} of low-μ *pp* collisions recorded in 2017

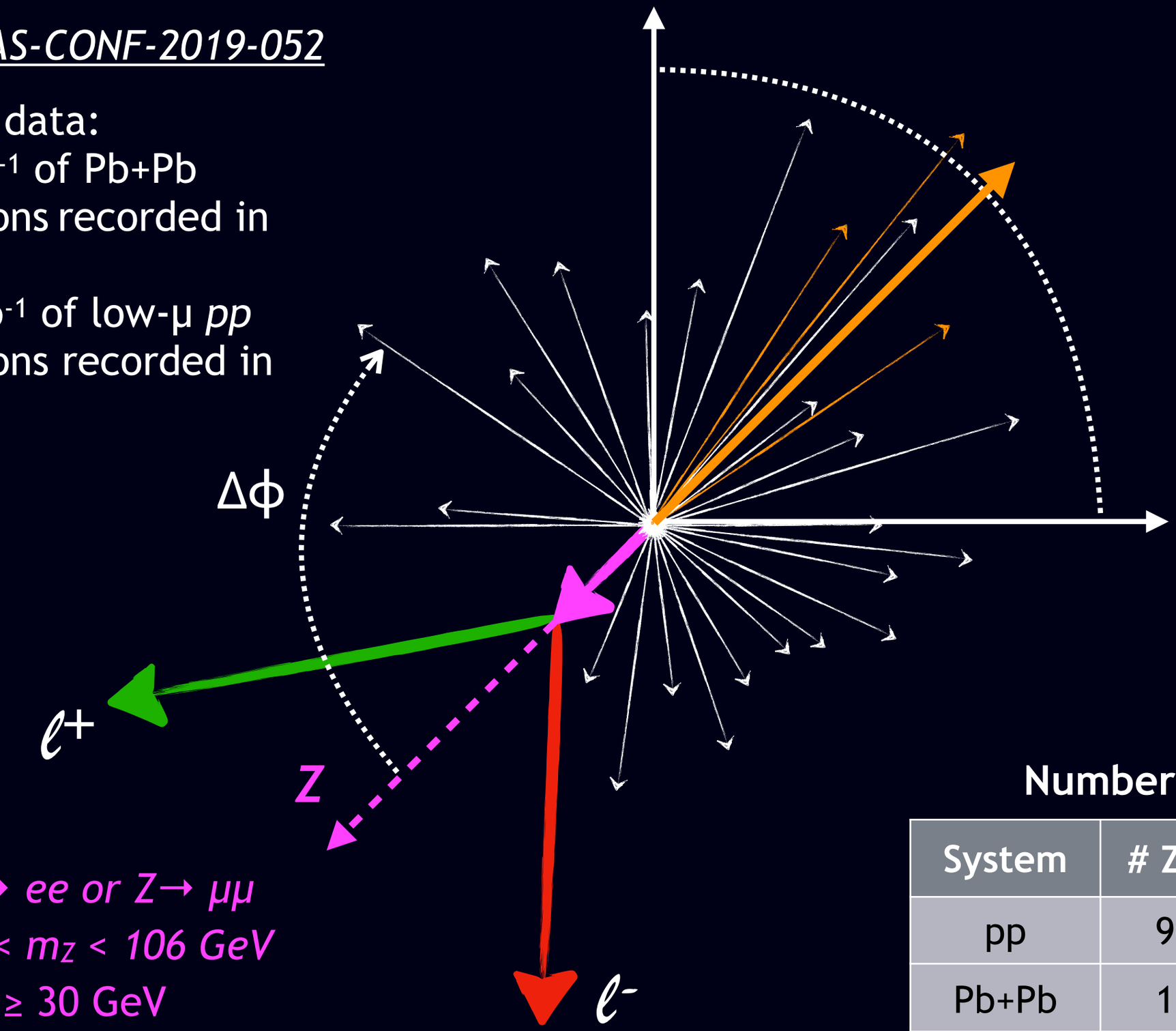


Measuring per-Z charged particle yields

See *ATLAS-CONF-2019-052*

Collision data:

- 1.7 nb^{-1} of Pb+Pb collisions recorded in 2018
- 260 pb^{-1} of low-μ *pp* collisions recorded in 2017



- *Z → ee or Z→ μμ*
- *76 < m_Z < 106 GeV*
- $p_T^Z \geq 30$ GeV

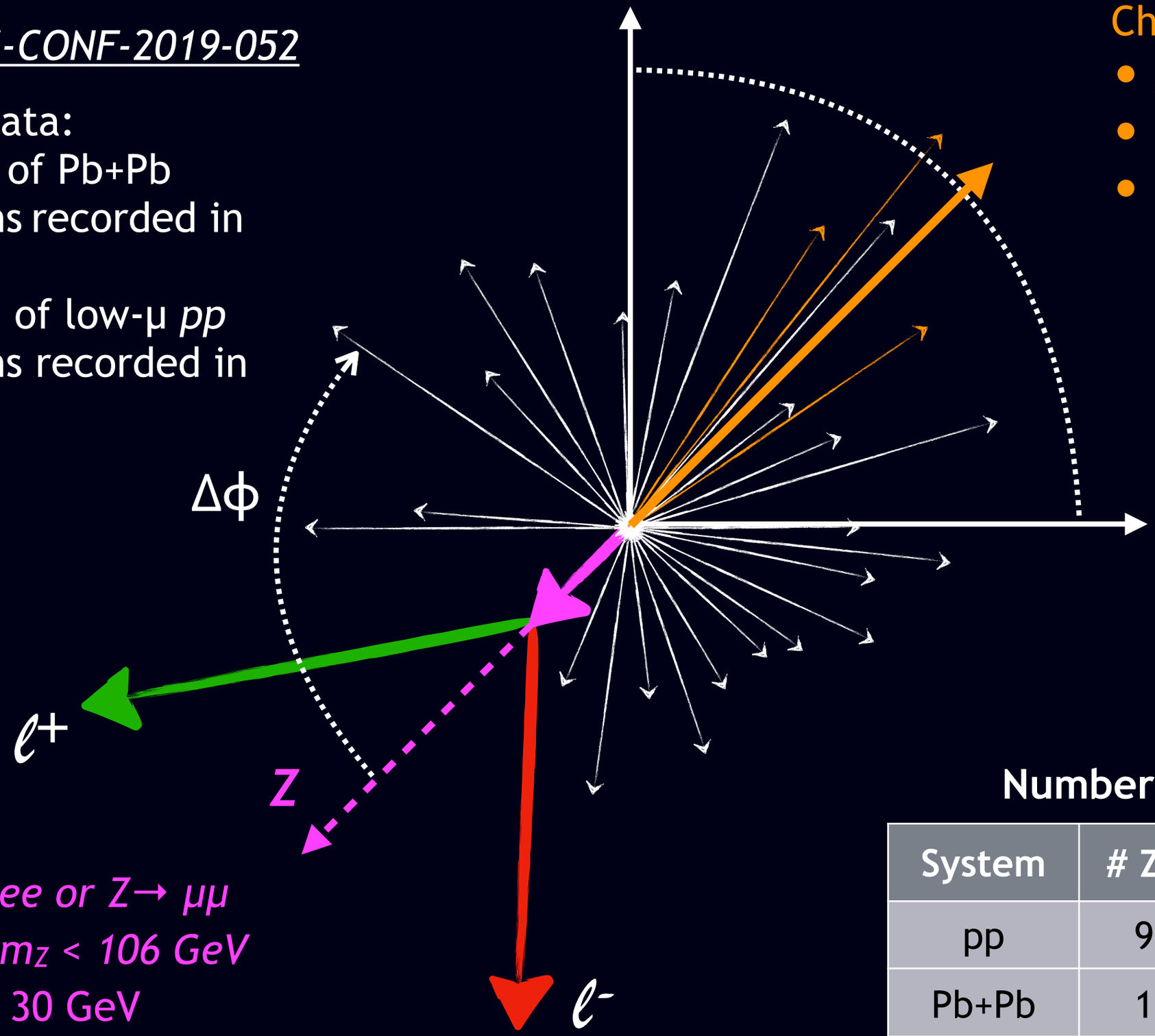
Number of events

System	# Z→ee	# Z→μμ
pp	9000	11000
Pb+Pb	1300	1500

Measuring per-Z charged particle yields

See *ATLAS-CONF-2019-052*

Collision data:
- 1.7 nb^{-1} of Pb+Pb collisions recorded in 2018
- 260 pb^{-1} of low-μ *pp* collisions recorded in 2017



- *Z → ee or Z→ μμ*
- *76 < m_Z < 106 GeV*
- $p_T^Z \geq 30$ GeV

Charged particles
- $p_T^{ch} \geq 1$ GeV
- $|\Delta\phi| > 3\pi/4$
- $|\eta| < 2.5$

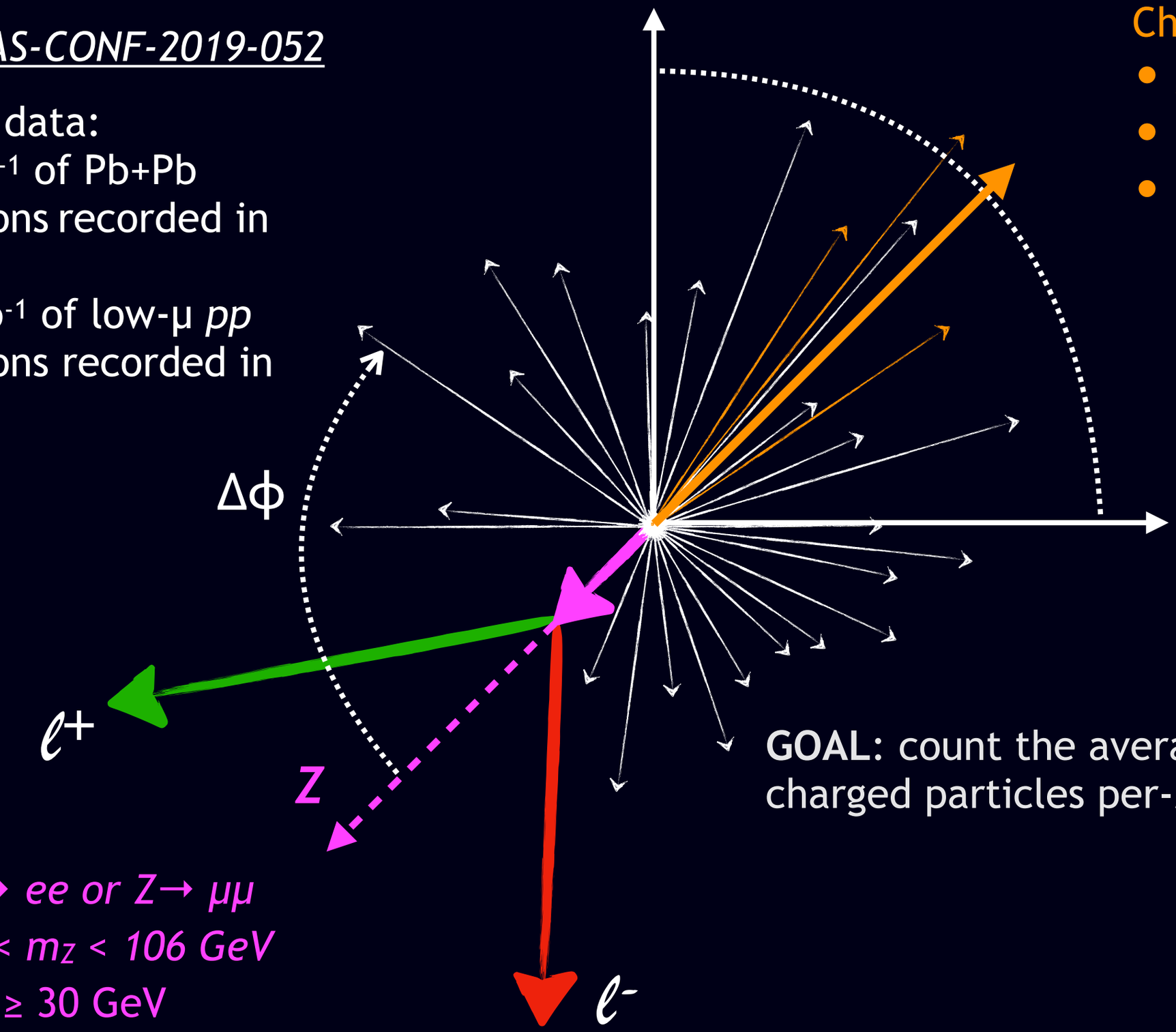
Number of events

System	# Z→ee	# Z→μμ
pp	9000	11000
Pb+Pb	1300	1500

Measuring per-Z charged particle yields

See *ATLAS-CONF-2019-052*

Collision data:
- 1.7 nb^{-1} of Pb+Pb collisions recorded in 2018
- 260 pb^{-1} of low-μ *pp* collisions recorded in 2017



- $Z \rightarrow ee$ *or* $Z \rightarrow \mu\mu$
- $76 < m_Z < 106$ *GeV*
- $p_T^Z \geq 30$ GeV

Charged particles
- $p_T^{ch} \geq 1$ GeV
- $|\Delta\phi| > 3\pi/4$
- $|\eta| < 2.5$

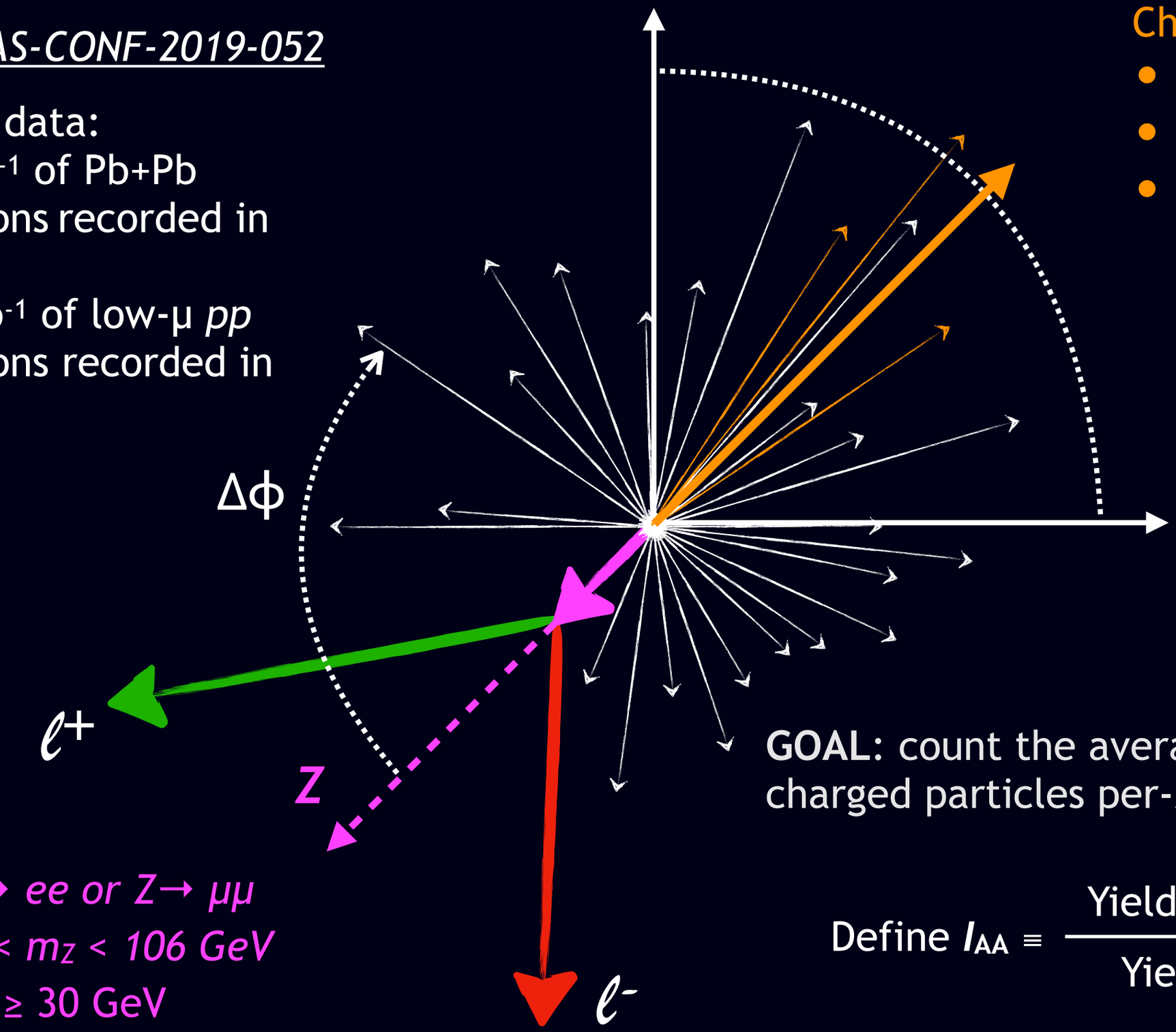
GOAL: count the average number of charged particles per-*Z* in *pp* and Pb+Pb

Measuring per-Z charged particle yields

See *ATLAS-CONF-2019-052*

Collision data:
- 1.7 nb^{-1} of Pb+Pb collisions recorded in 2018
- 260 pb^{-1} of low-μ *pp* collisions recorded in 2017

- $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$
- $76 < m_Z < 106$ GeV
- $p_T^Z \geq 30$ GeV

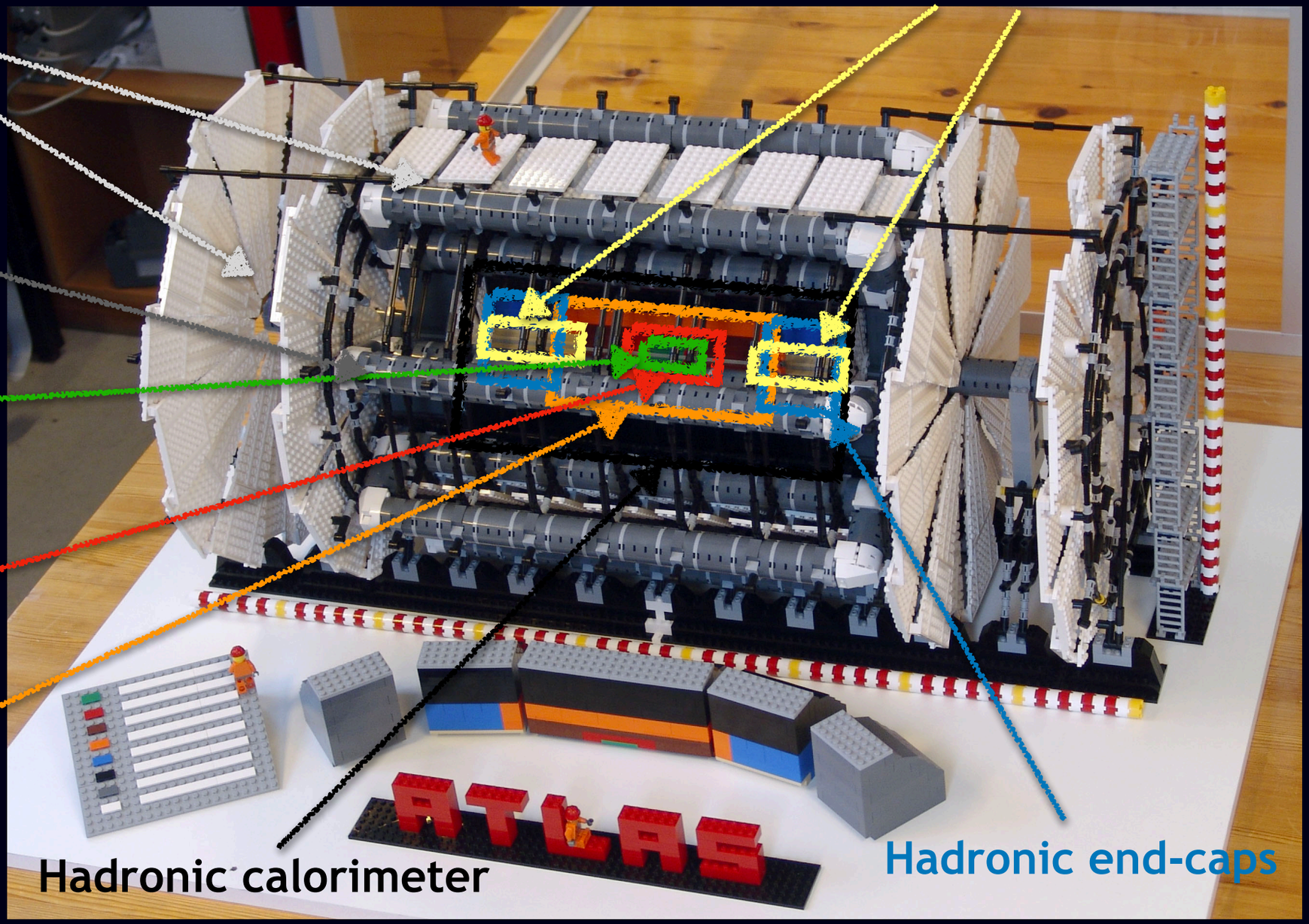


Charged particles
- $p_T^{ch} \geq 1$ GeV
- $|\Delta\phi| > 3\pi/4$
- $|\eta| < 2.5$

GOAL: count the average number of charged particles per-*Z* in *pp* and Pb+Pb

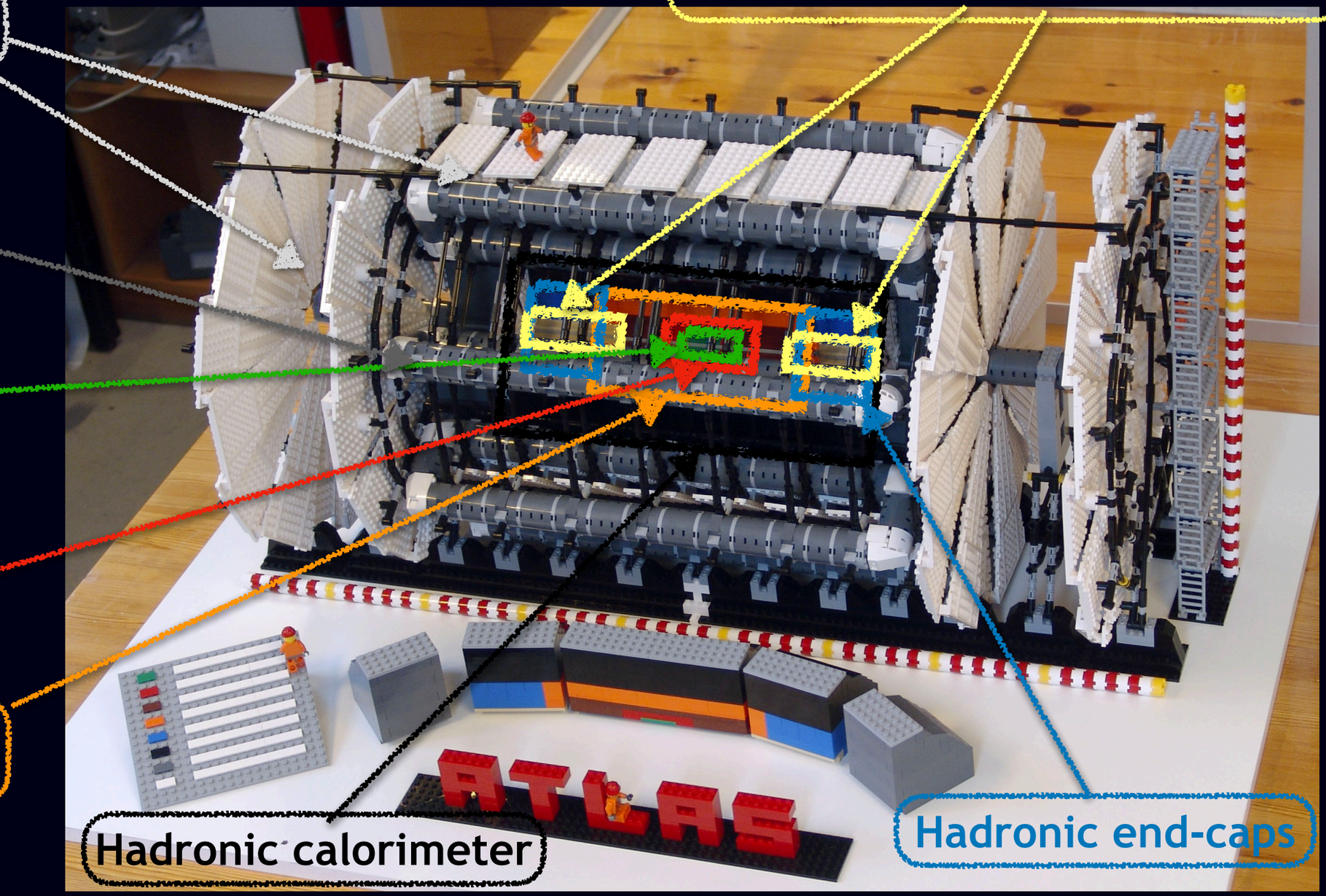
$$\text{Define } I_{AA} \equiv \frac{\text{Yield in Pb+Pb}}{\text{Yield in } pp}$$

Counting Z-tagged hadrons with ATLAS



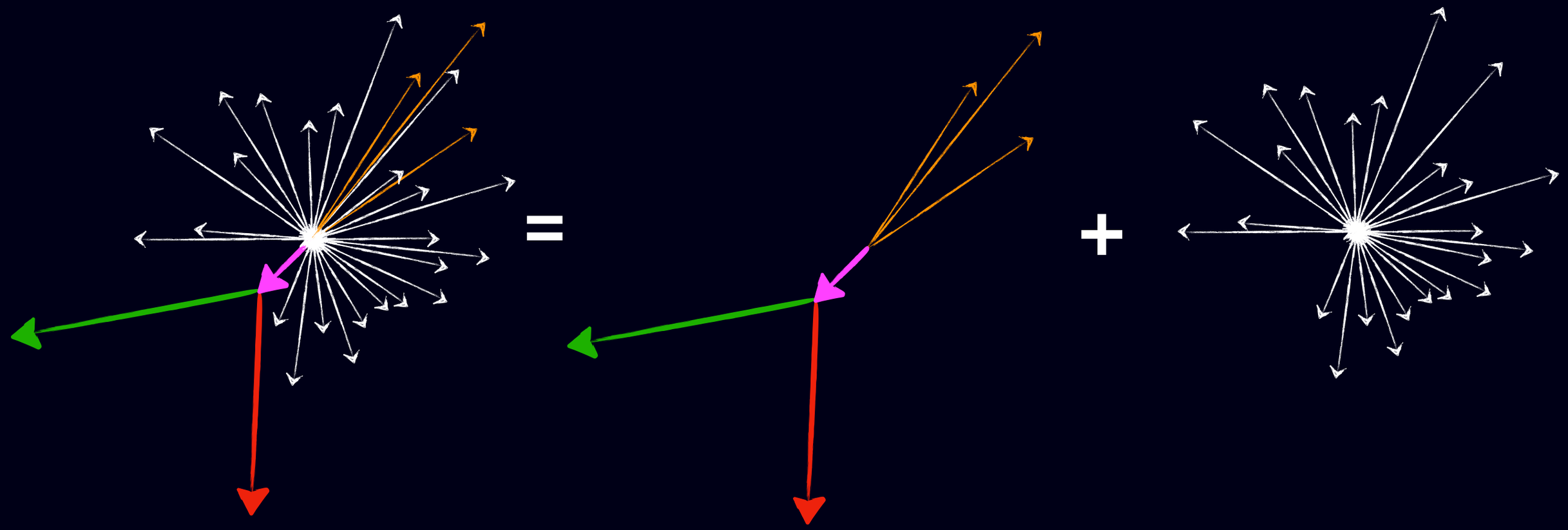
Z boson events are tagged with high-level single electron/muon triggers

Counting Z-tagged hadrons with ATLAS



Z boson events are tagged with high-level single electron/muon triggers

Modeling the underlying event



Observed event = Z+Jet Hard Scattering (Signal) + Underlying event (UE) (Background)

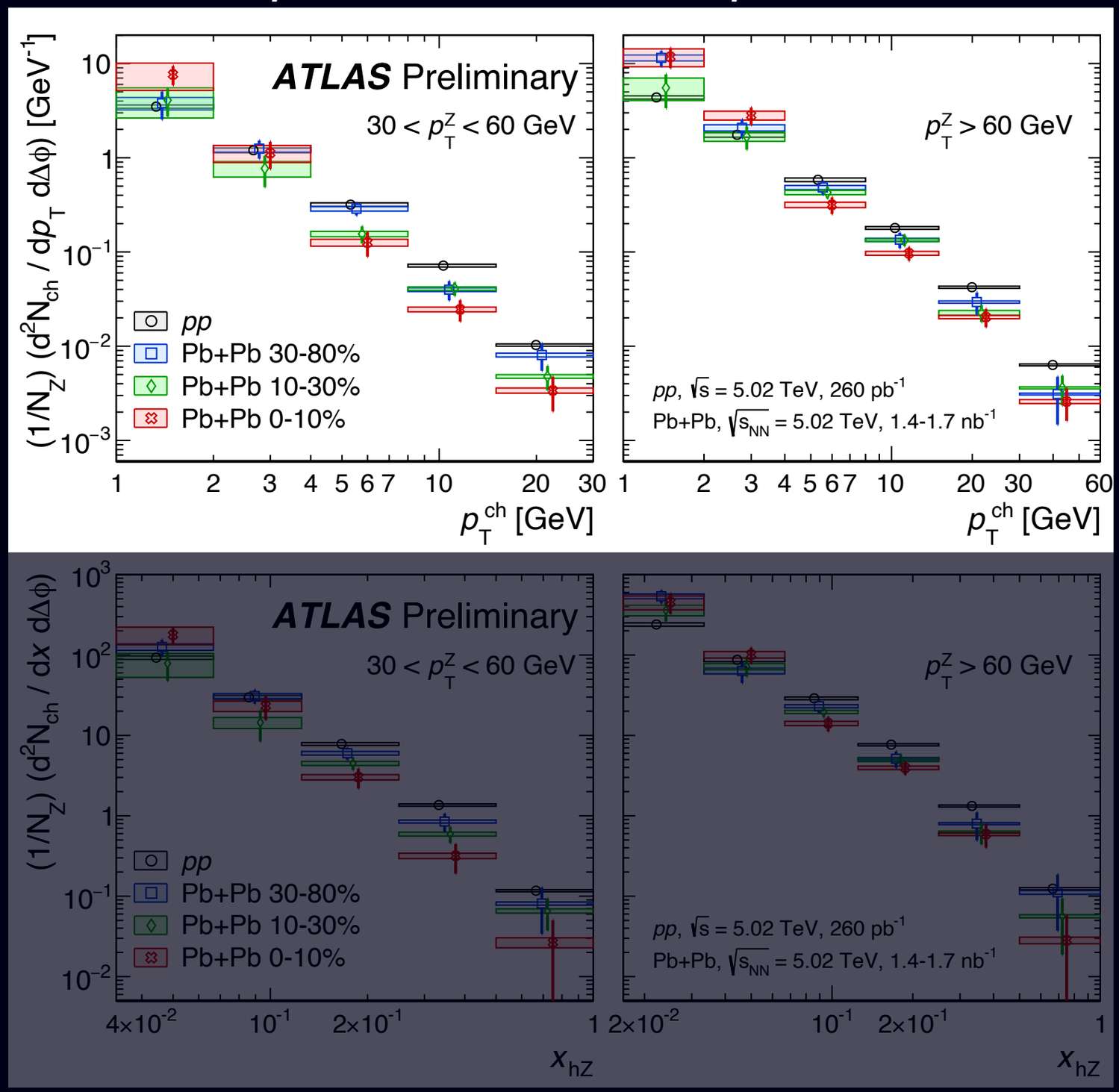
Measure this — Want to obtain this — Model this with *mixed events*

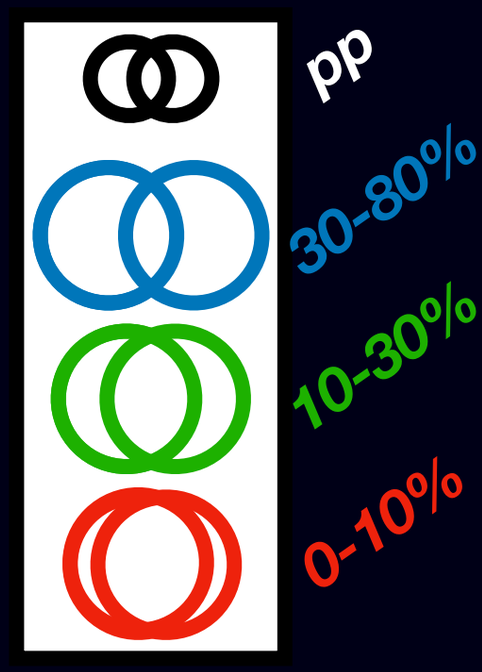
Mixed events have matching centrality & running conditions, but lack a *Z*

UE subtracted yields

$30 < p_T^Z < 60$ GeV $p_T^Z > 60$ GeV

p_T^{ch}





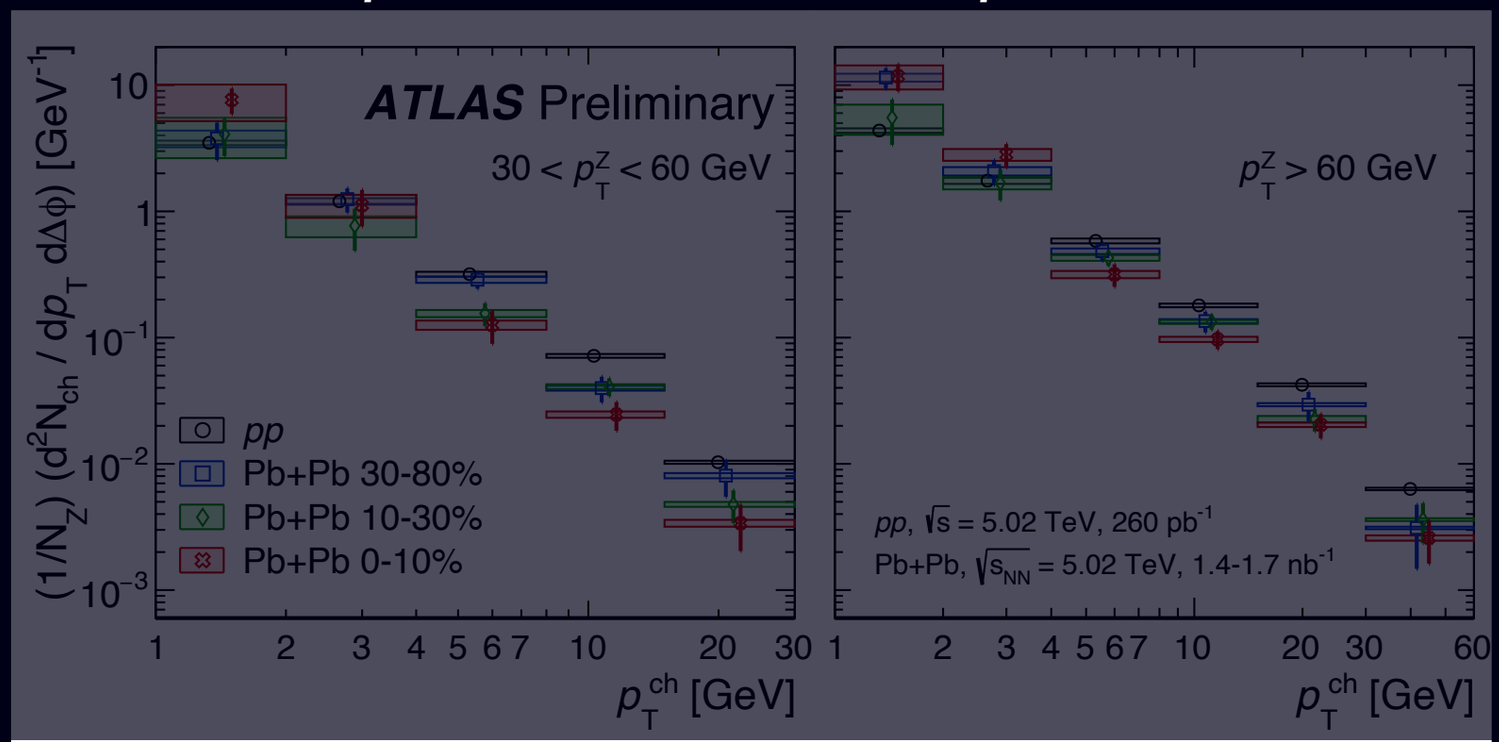
$$x_{hZ} \equiv \frac{p_T^{ch}}{p_T^Z}$$

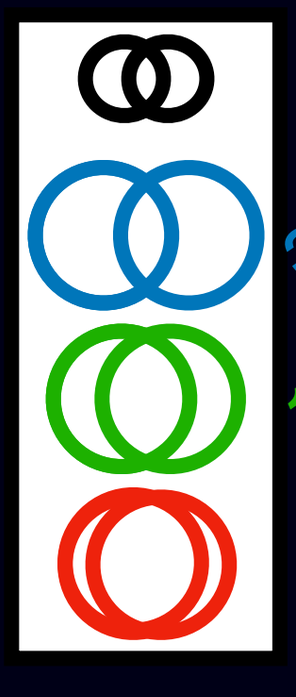
ATLAS-CONF-2019-052

UE subtracted yields

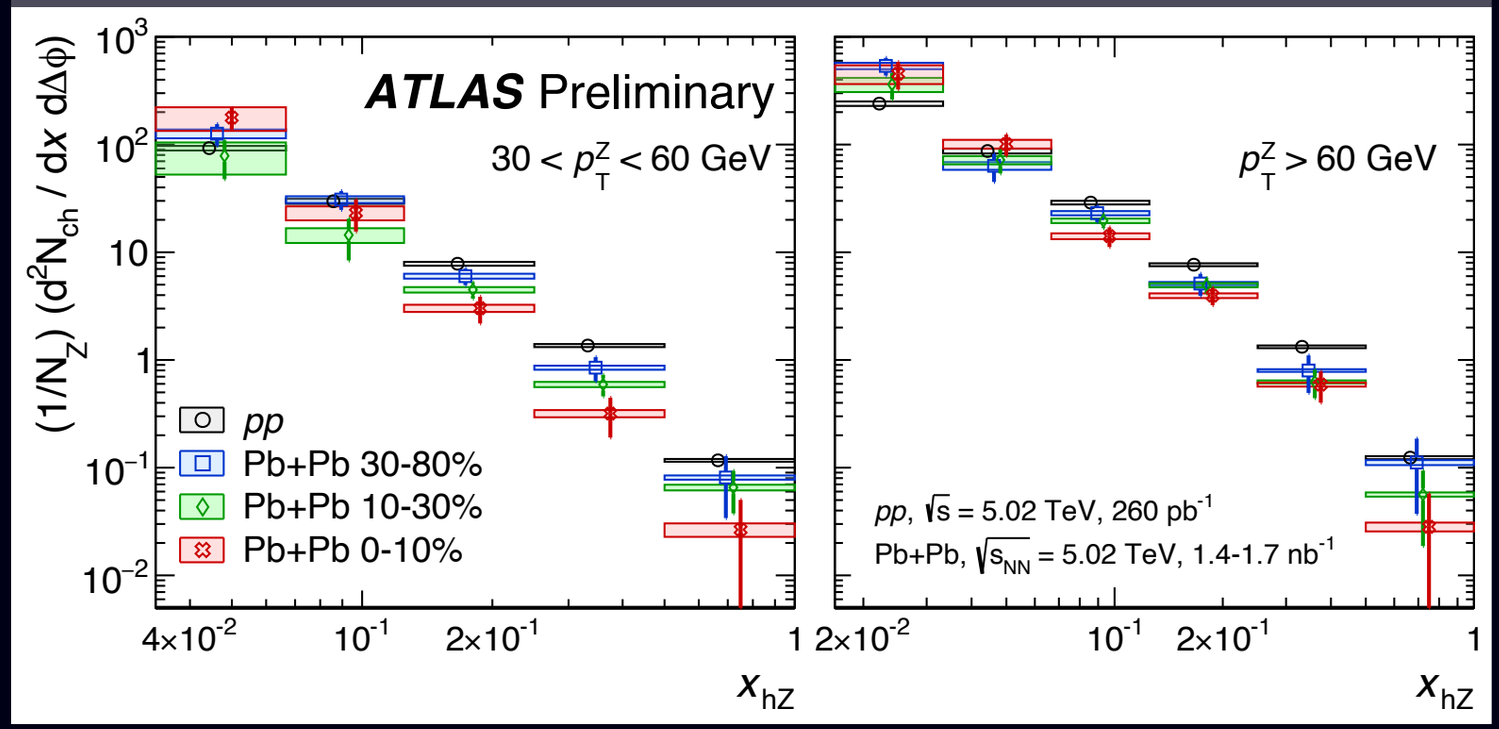
$30 < p_T^Z < 60$ GeV $p_T^Z > 60$ GeV

p_T^{ch}





$$x_{hZ} \equiv \frac{p_T^{ch}}{p_T^Z}$$

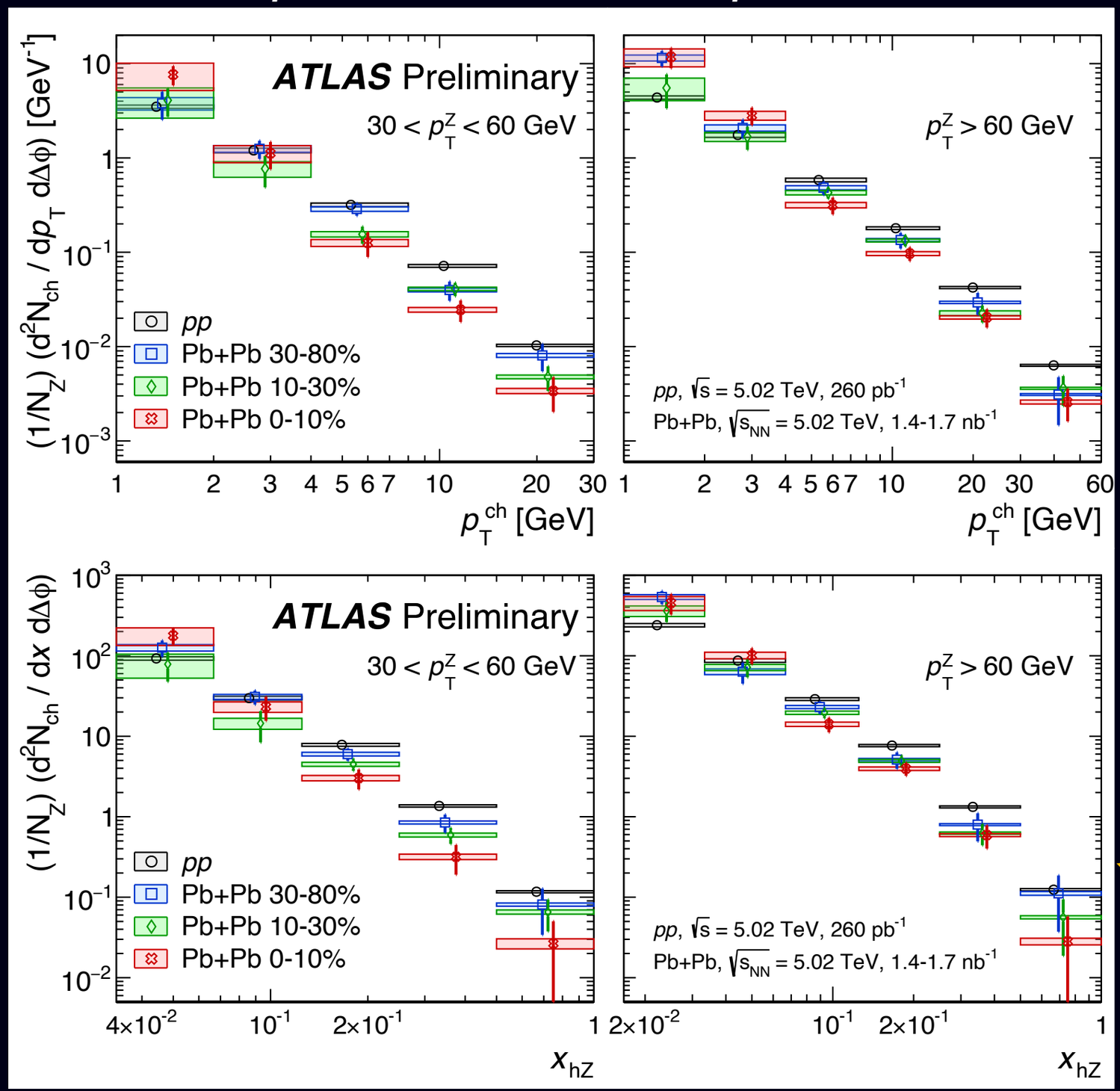


ATLAS-CONF-2019-052

UE subtracted yields

$30 < p_T^Z < 60$ GeV $p_T^Z > 60$ GeV

p_T^{ch}



pp
30-80%
10-30%
0-10%

$$x_{hZ} \equiv \frac{p_T^{ch}}{p_T^Z}$$

★ **Striking visual differences between *pp* & Pb+Pb**

ATLAS-CONF-2019-052

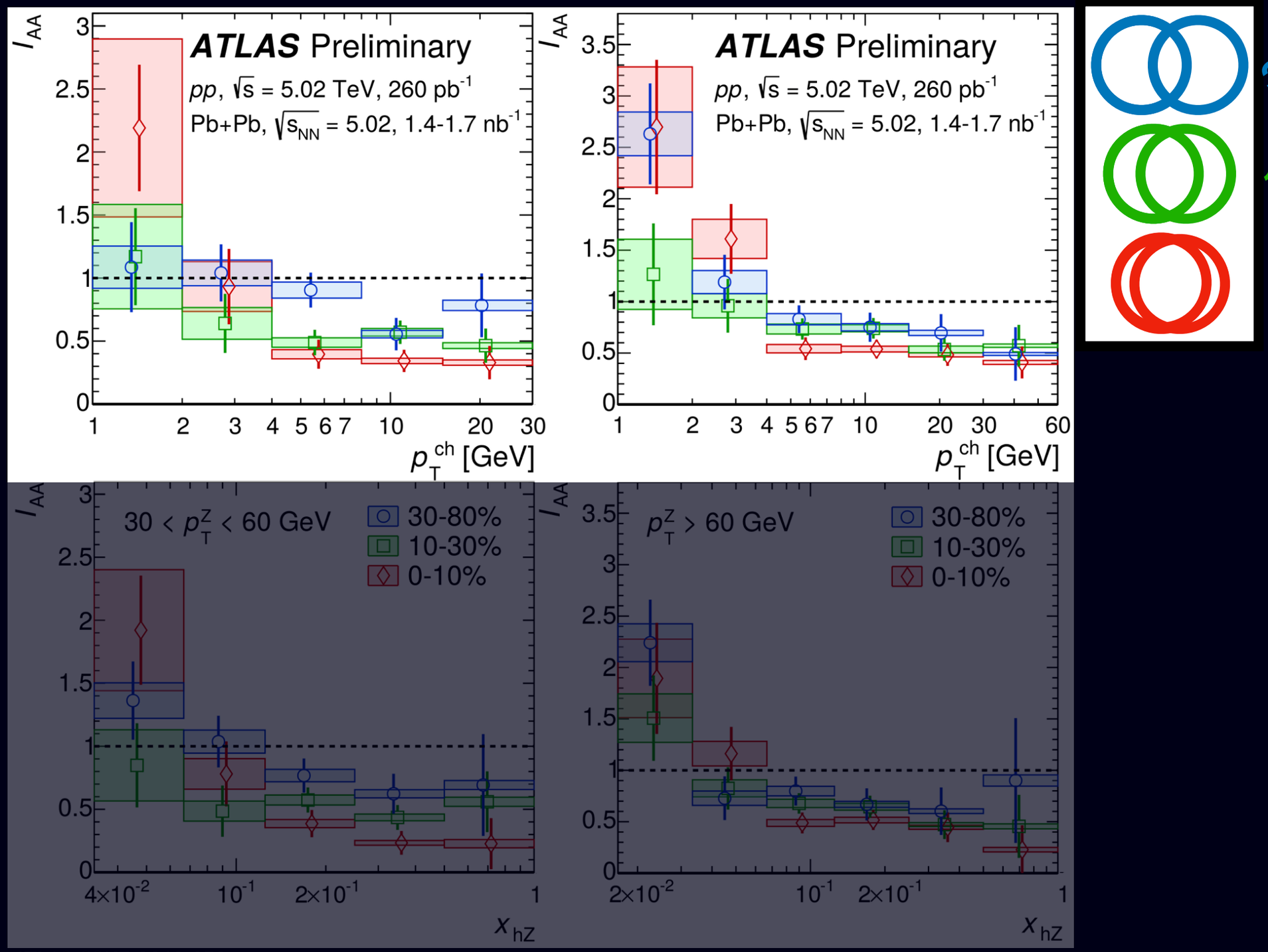
$I_{AA} \equiv \dfrac{\text{Yield in Pb+Pb}}{\text{Yield in } pp}$

Pb+Pb modification

$30 < p_T^Z < 60$ GeV

$p_T^Z > 60$ GeV

p_T^{ch}



$x_{hZ} \equiv \dfrac{p_T^{ch}}{p_T^Z}$

ATLAS-CONF-2019-052

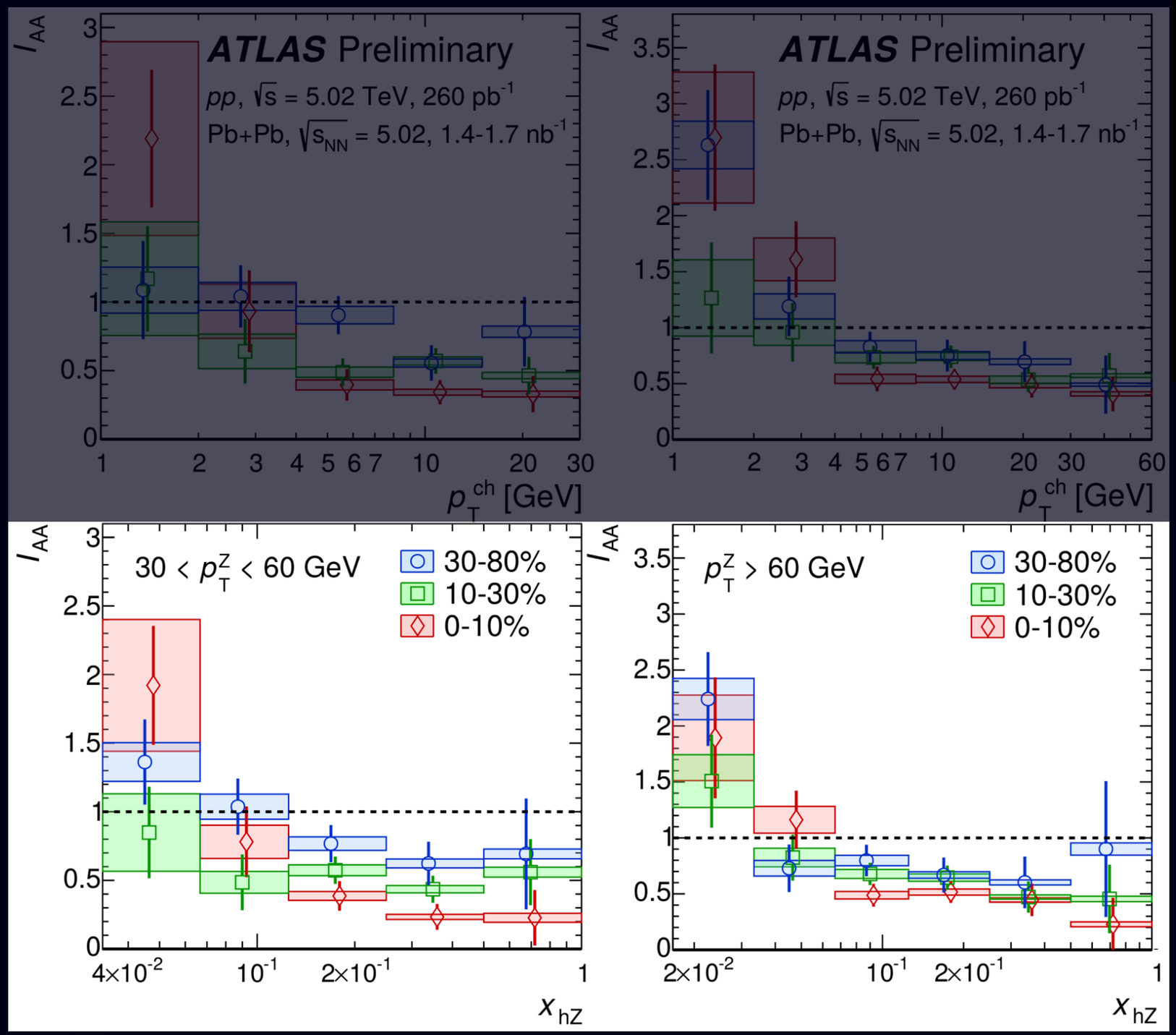
$$I_{AA} \equiv \frac{\text{Yield in Pb+Pb}}{\text{Yield in } pp}$$

Pb+Pb modification

$30 < p_T^Z < 60$ GeV

$p_T^Z > 60$ GeV

p_T^{ch}



$$x_{hZ} \equiv \frac{p_T^{ch}}{p_T^Z}$$

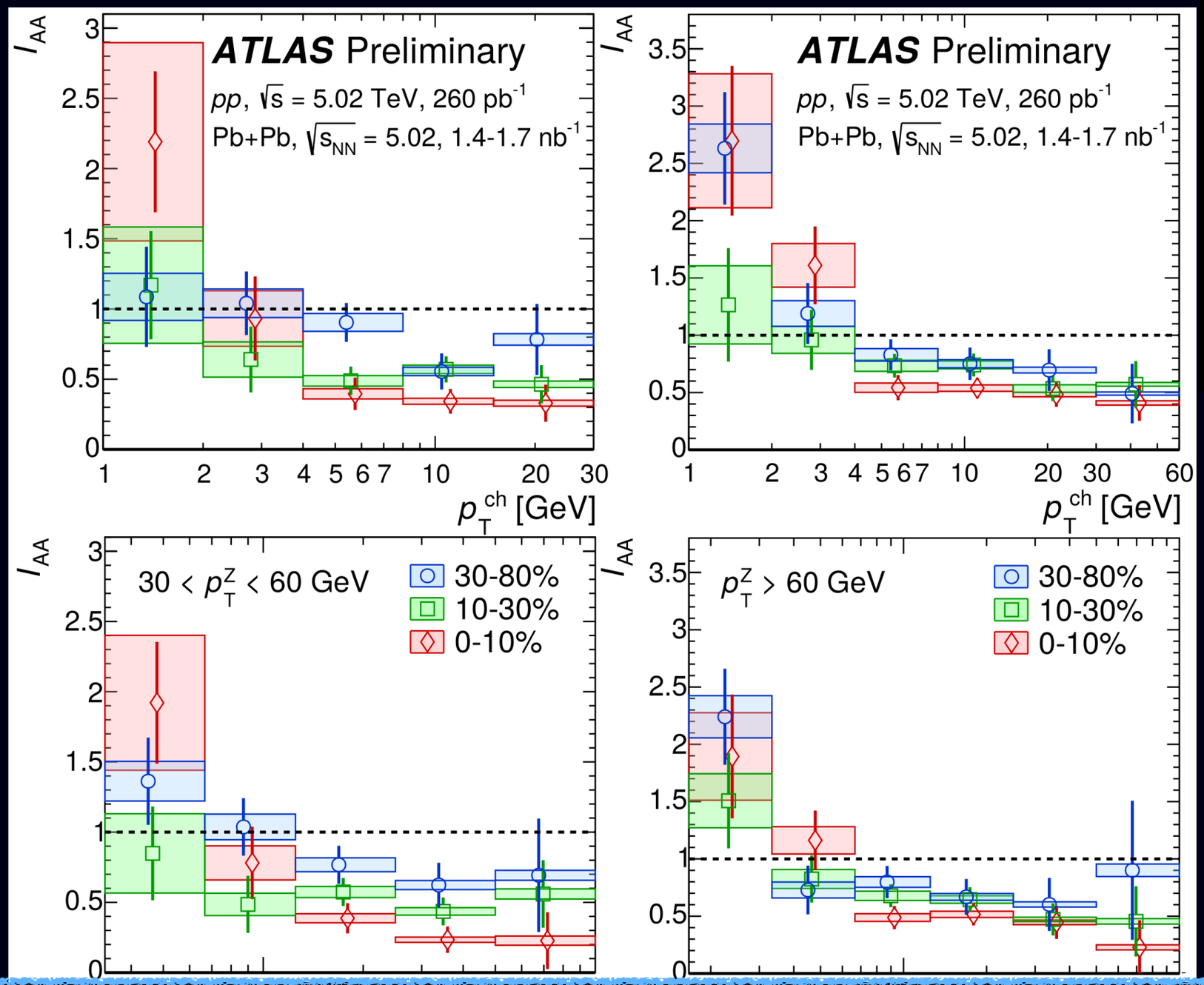
ATLAS-CONF-2019-052

$I_{AA} \equiv \dfrac{\text{Yield in Pb+Pb}}{\text{Yield in } pp}$

Pb+Pb modification

$30 < p_T^Z < 60$ GeV

$p_T^Z > 60$ GeV



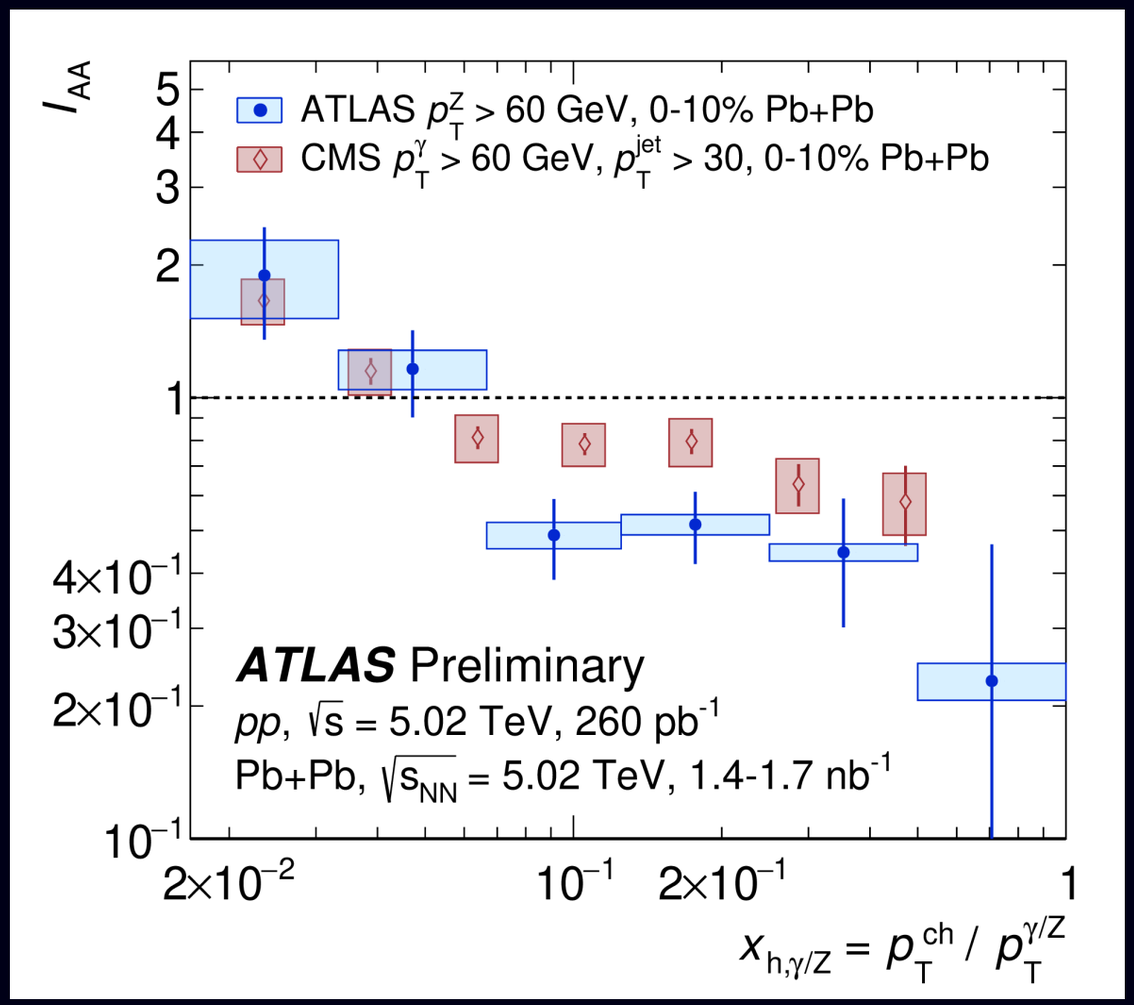
p_T^{ch}

$x_{hZ} \equiv \dfrac{p_T^{ch}}{p_T^Z}$

p_T^{ch}-dependent suppression/enhancement pattern of charged hadrons observed by ATLAS

ATLAS-CONF-2019-052

Comparison to γ-tagged jet FF

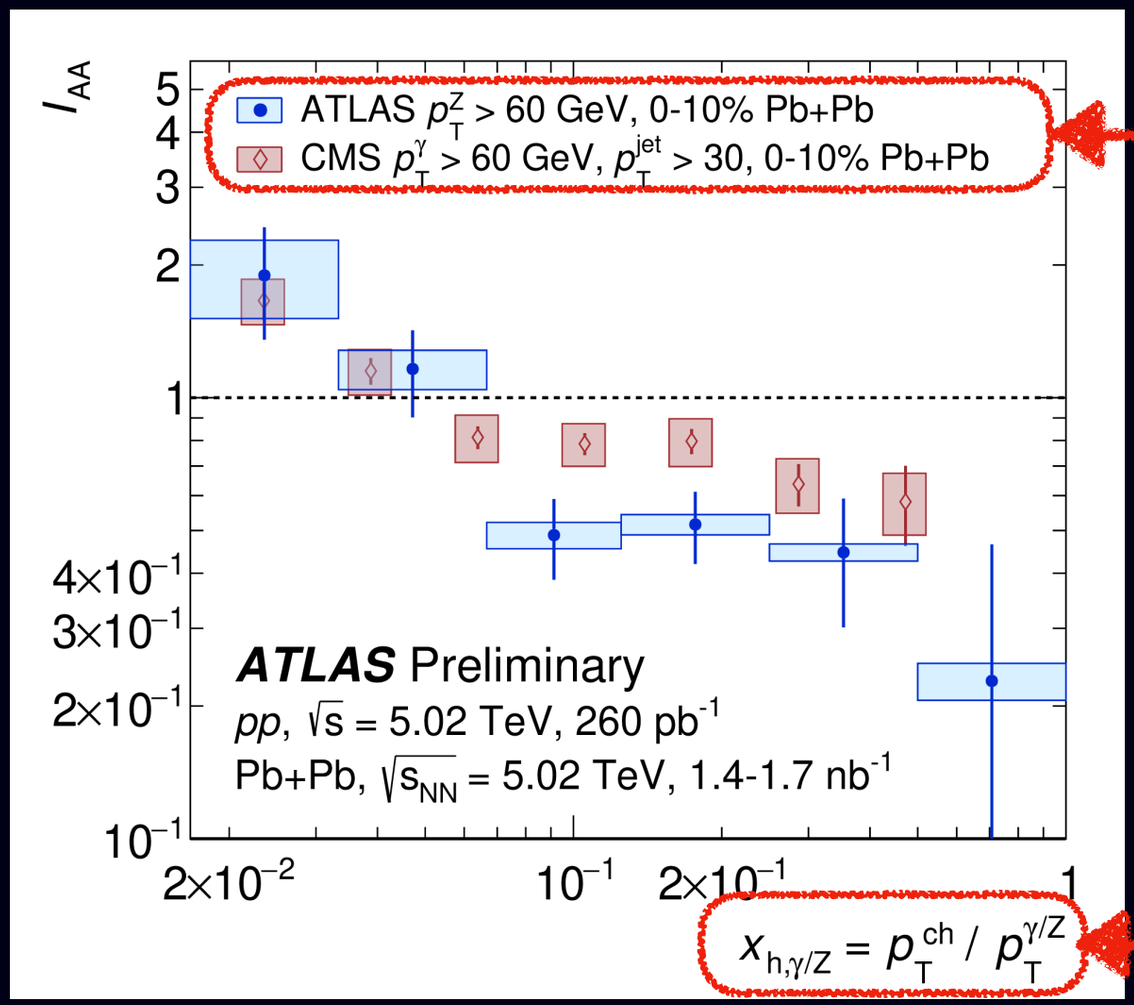


ATLAS-CONF-2019-052 CMS: Phys. Rev. Lett. 121, 242301 (2018)

ATLAS Z-tagged hadrons
CMS γ-tagged hadrons (in jets)

- *More* suppression without jet requirement ⇨ likely a result from minimum p_T requirement on jets

Comparison to γ-tagged jet FF



Similar event selection

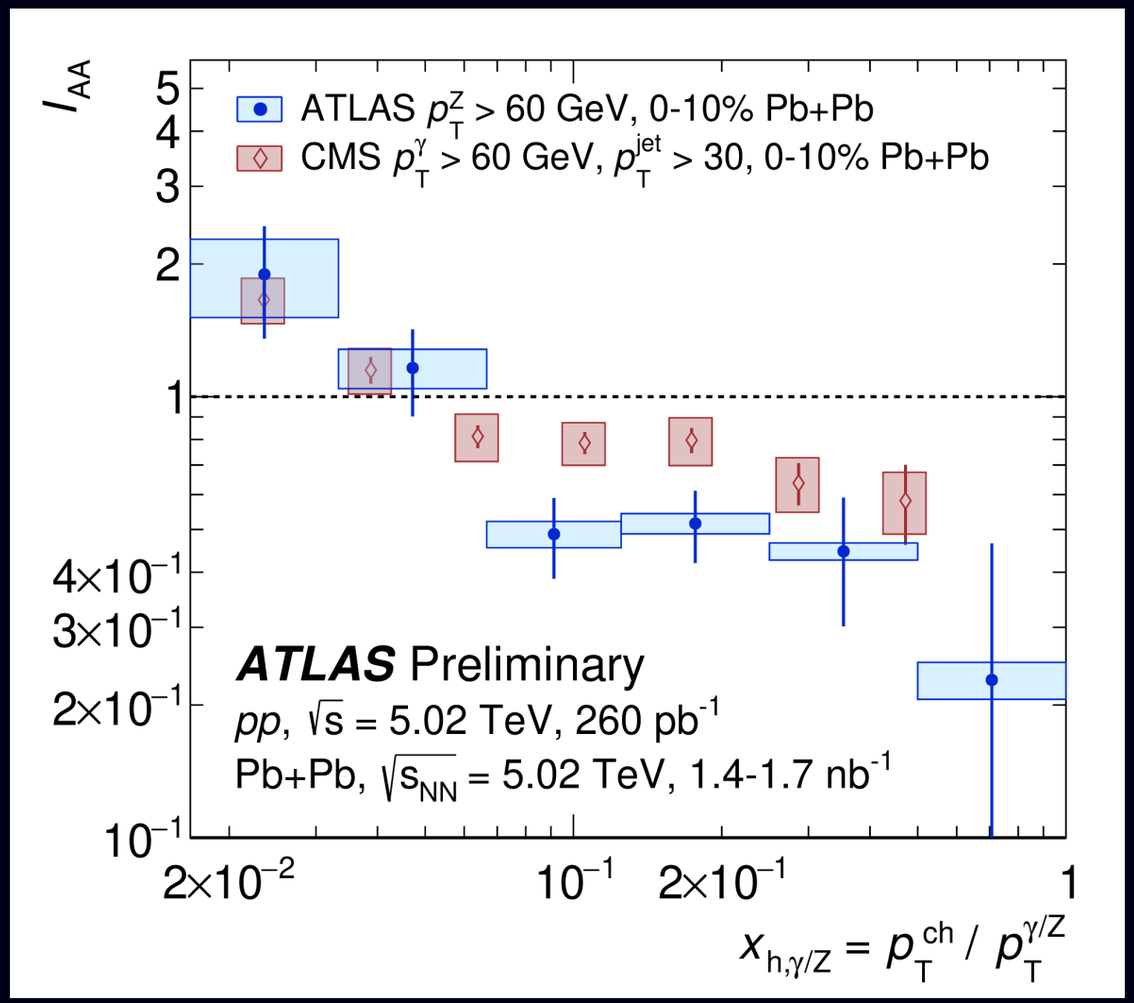
Similar measure

ATLAS-CONF-2019-052 CMS: Phys. Rev. Lett. 121, 242301 (2018)

ATLAS Z-tagged hadrons
CMS γ-tagged hadrons (in jets)

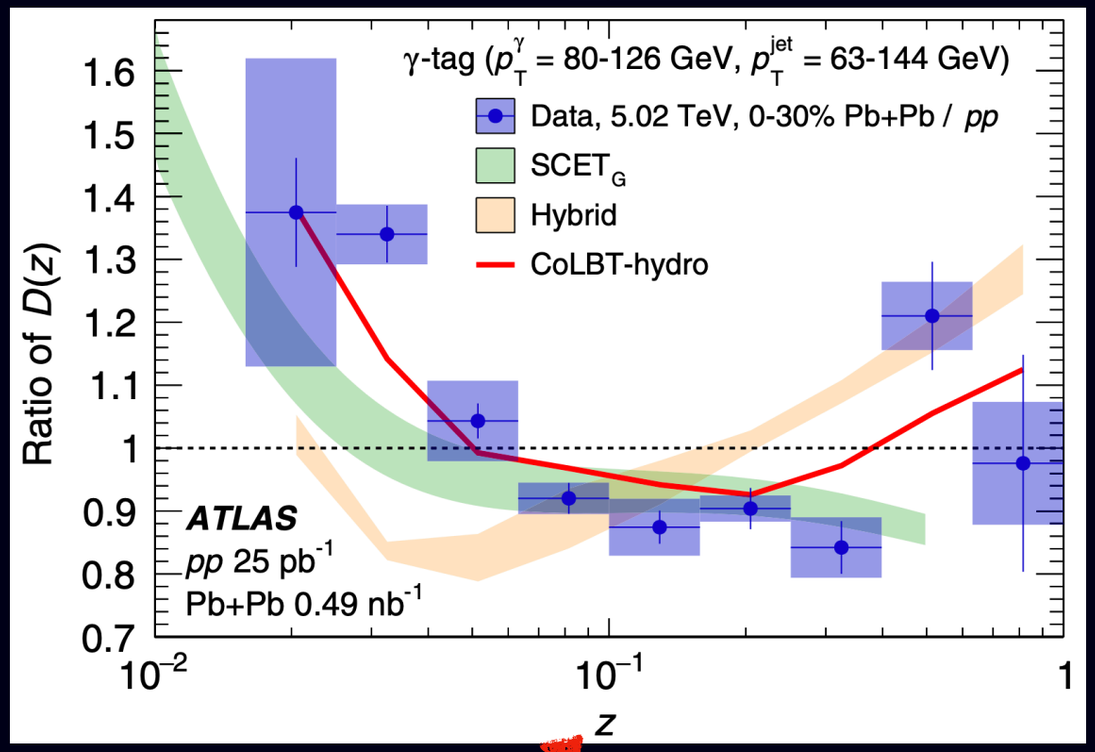
- *More* suppression without jet requirement ⇨ likely a result from minimum p_T requirement on jets

Comparison to γ-tagged jet FF



ATLAS-CONF-2019-052 CMS: Phys. Rev. Lett. 121, 242301 (2018)

Phys. Rev. Lett. 123, 042001 (2019)



$z \equiv p_T^{ch}/p_T^{jet}$

ATLAS Z-tagged hadrons
CMS γ-tagged hadrons (in jets)

- *More* suppression without jet requirement ⇨ likely a result from minimum p_T requirement on jets

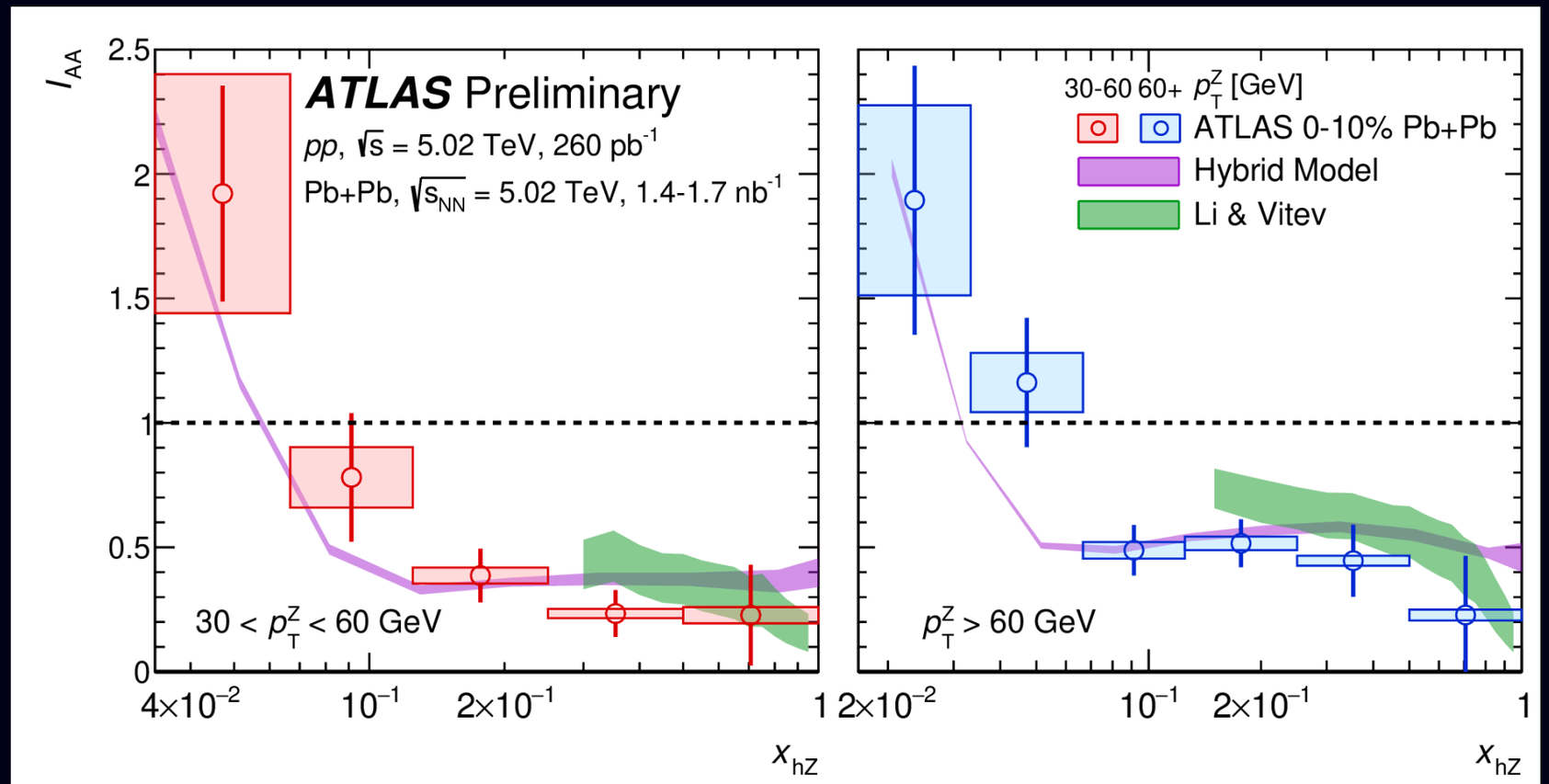
In γ-tagged jet fragmentation functions,

- SCET$_G$ & CoLBT-hydro competitive at low-z
- Hybrid strong/weak coupling provides qualitatively correct behavior

Theoretical predictions

We are thankful to the theorists who provided us with predictions:

- Hybrid strong/weak coupling (JHEP 03 (2016) 053)
  - Includes back-reaction (⇨ leads to low-x_{hZ} enhancement)
- SCET$_G$ (arXiv:1908.06979; PRD 93 (2016) 074030)
  - Bands represent variations on g from 1.8-2.2

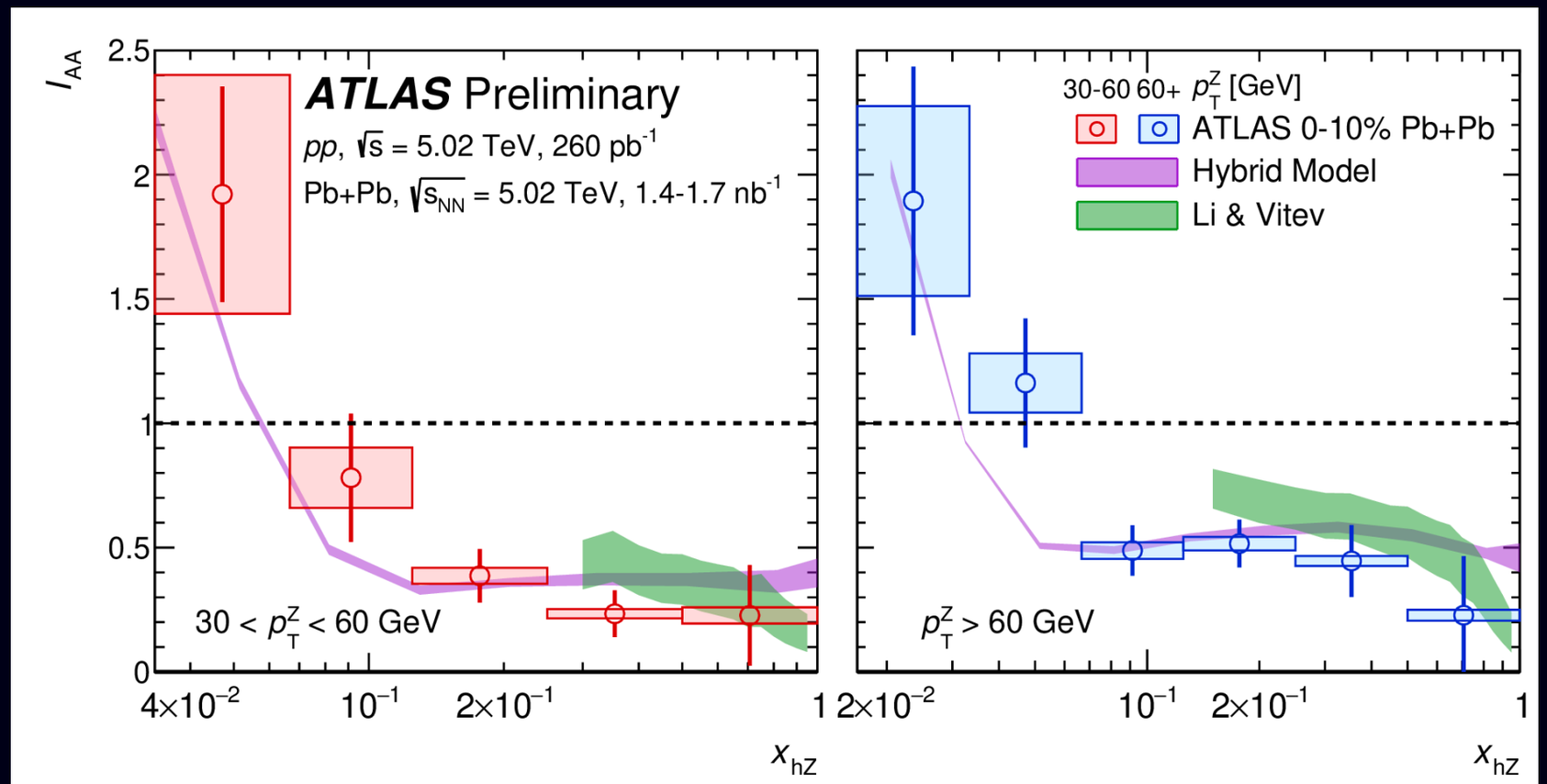


ATLAS-CONF-2019-052

Theoretical predictions

We are thankful to the theorists who provided us with predictions:

- Hybrid strong/weak coupling (JHEP 03 (2016) 053)
  - Includes back-reaction (⇨ leads to low-x_{hZ} enhancement)
- $SCET_G$ (arXiv:1908.06979; PRD 93 (2016) 074030)
  - Bands represent variations on g from 1.8-2.2

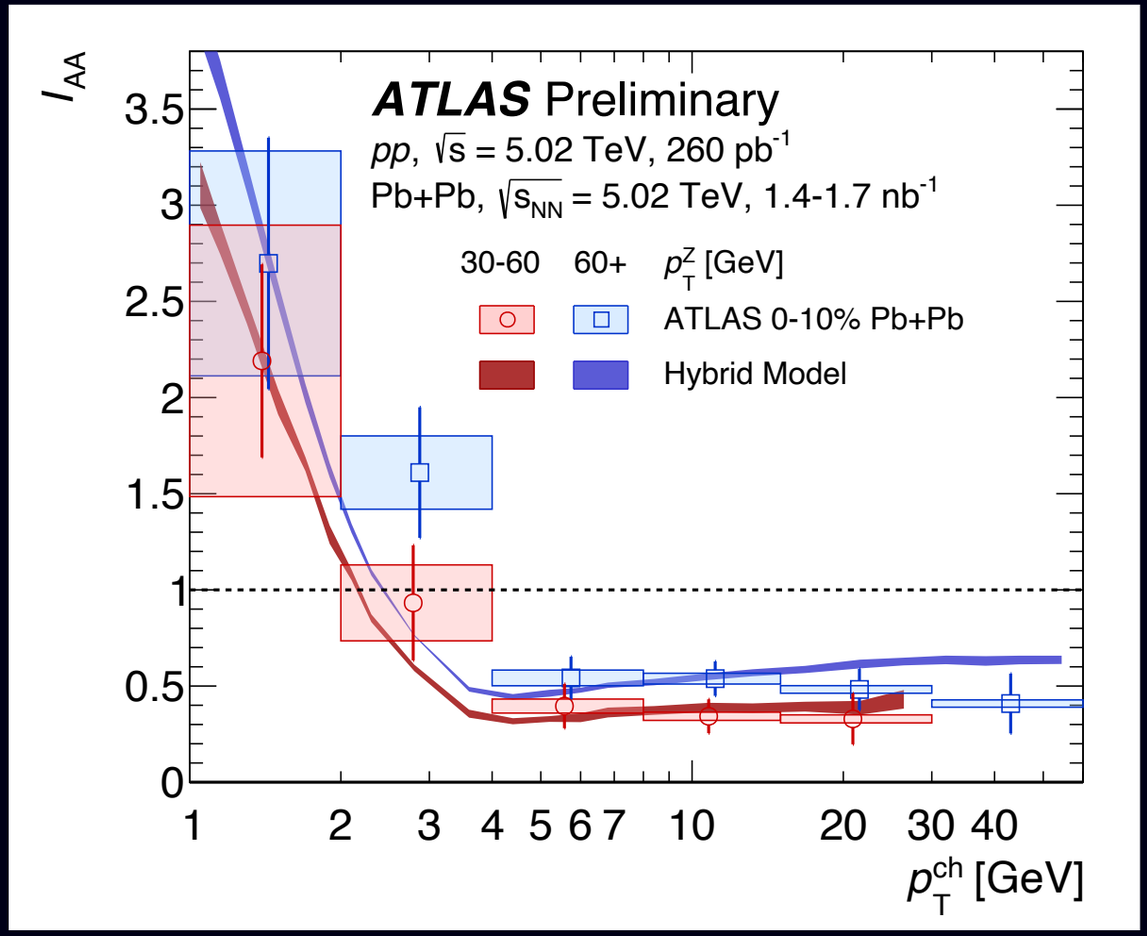


ATLAS-CONF-2019-052

- Hybrid model predicts the data quite well
  - … maybe disagrees around x_{hZ}~0.05-0.1? ⇨ Experimental uncertainties need work.
- $SCET_G$ captures x_{hZ} dependence of suppression, but not quite enough

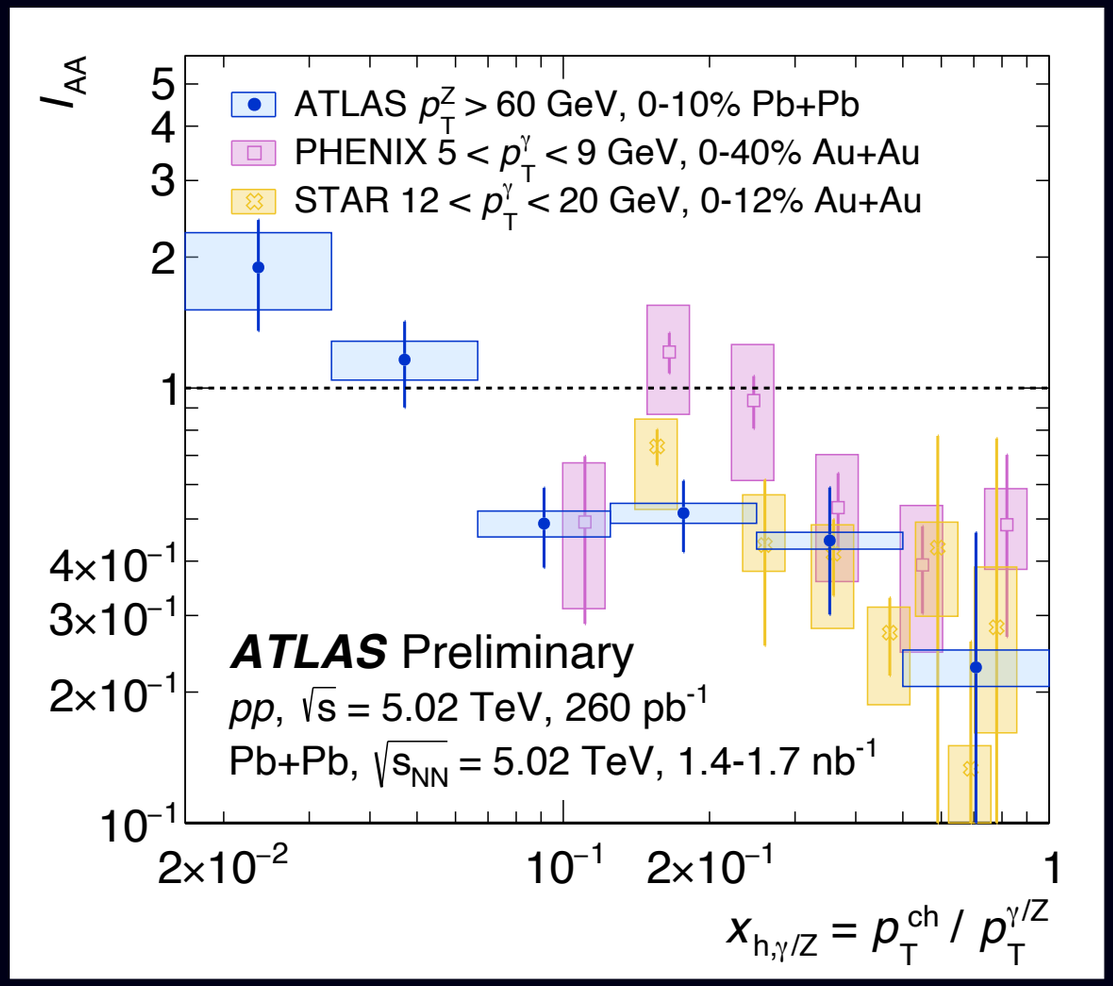
Theoretical predictions

- How do models predict behavior as a function of hadron p_T?
- Enhancement and suppression amplitudes very well-predicted
- *Similar to results from ϒ-tagged FF*
- Need smaller uncertainties to be more definitive about p_T^{ch} ~ 3 GeV behavior



ATLAS-CONF-2019-052

Comparison to γ-tagged hadrons @ RHIC



ATLAS-CONF-2019-052

PHENIX: Phys. Rev. Lett. 111 (2013) 032301
STAR: Phys. Lett. B 760 (2016) 689

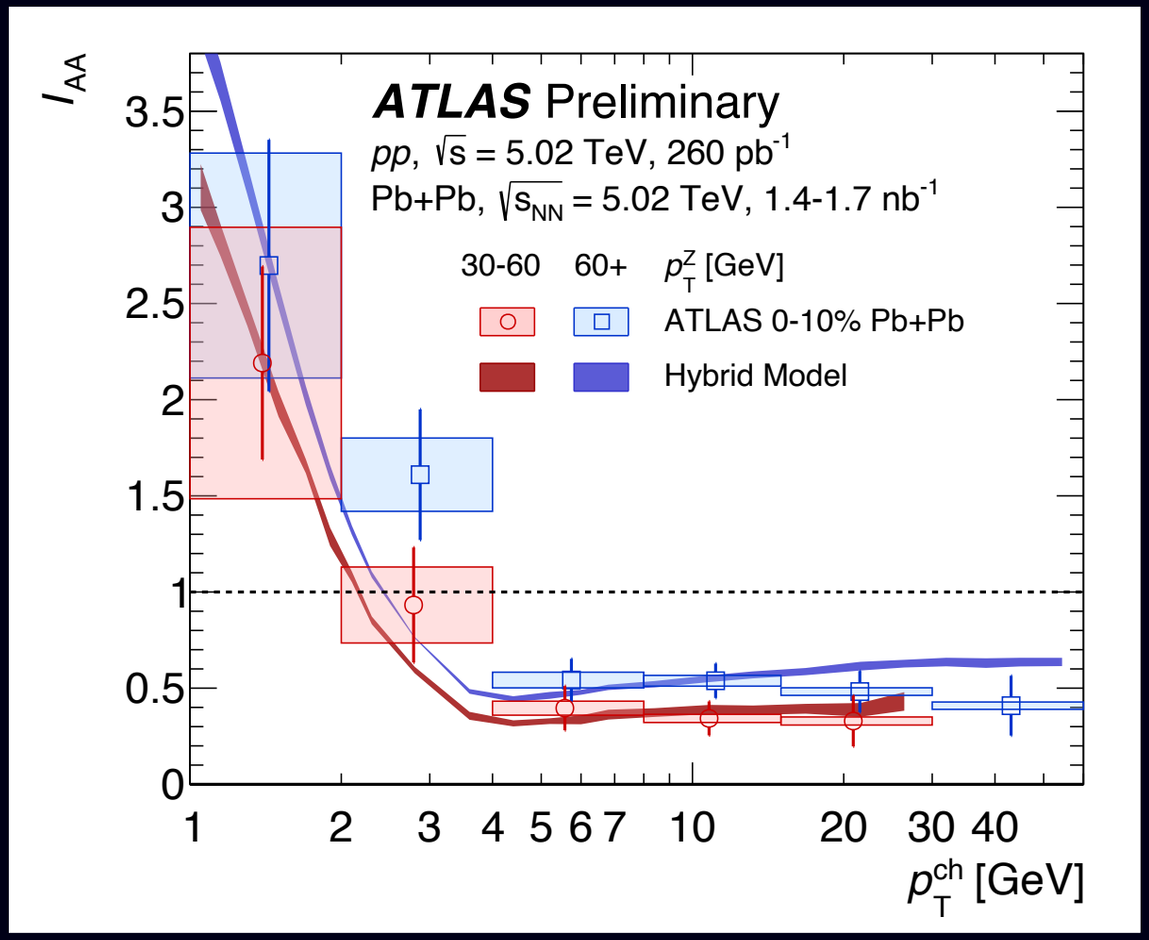
- Z-tagged and γ-tagged measurements directly comparable
- Despite different √s, nuclei, boson p_T… suppression remains comparable in magnitude between LHC & RHIC experiments
- But… LHC sees extra hadrons at lowest x_{hZ} values (larger phase space to probe)
- ***Look forward to γ+jet physics at sPHENIX!***

PHENIX γ-tagged hadrons
STAR γ-tagged hadrons
ATLAS Z-tagged hadrons

Au+Au @ 200 GeV
Pb+Pb @ 5.02 TeV

Summary

- Modification to Z-tagged hadron yields measured for the first time by ATLAS
- *Complements* measurements of jet quenching by LHC experiments
- Indications of suppression of high-p_T hadrons, enhancement at low-p_T (new kinematic region)
- *Final paper to be released soon!*
- All ATLAS HI public results available here



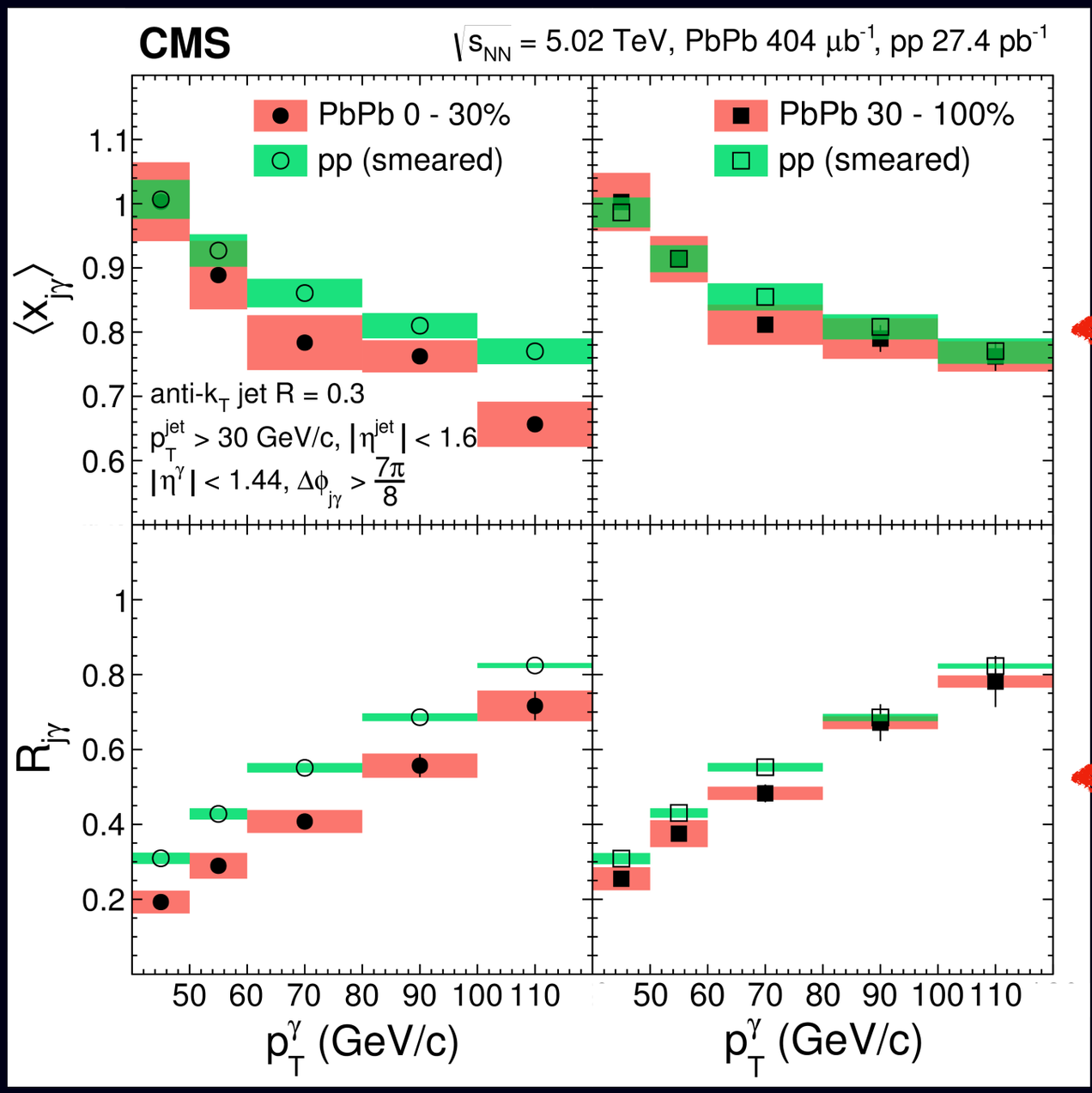
ATLAS-CONF-2019-052

Continually increasing sensitivity in experiment ⇨ new kinematic reaches are accessible to test our models of jet quenching

Thanks for your attention!

Backup

γ+jet balance & $R_{j\gamma}$



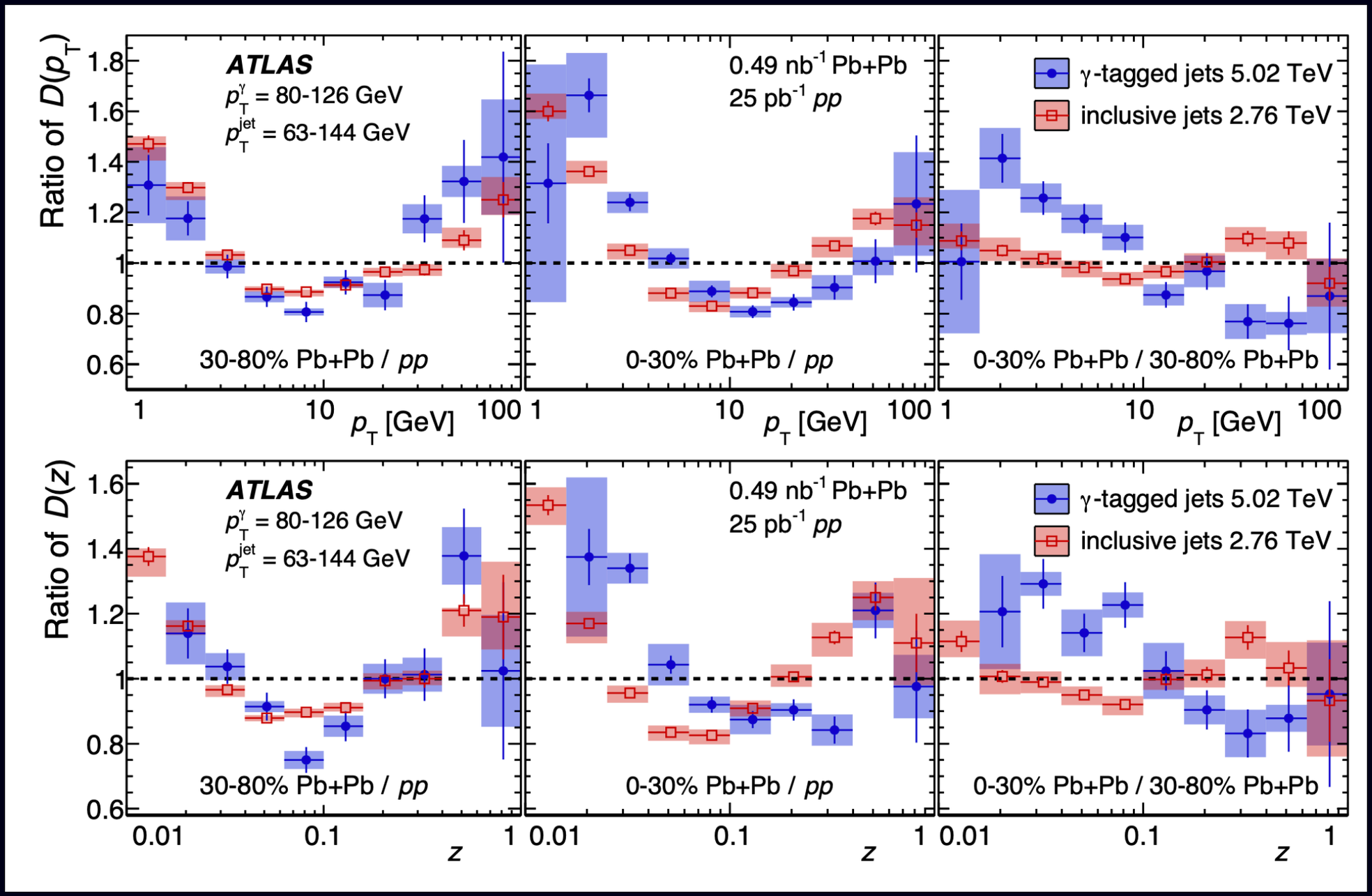
γ-jet momentum balance

# of jets per photon

Phys. Lett. B 785 (2018) 14

⇨ fewer jets observed for low-p_T photons

γ-tagged jet frag. function

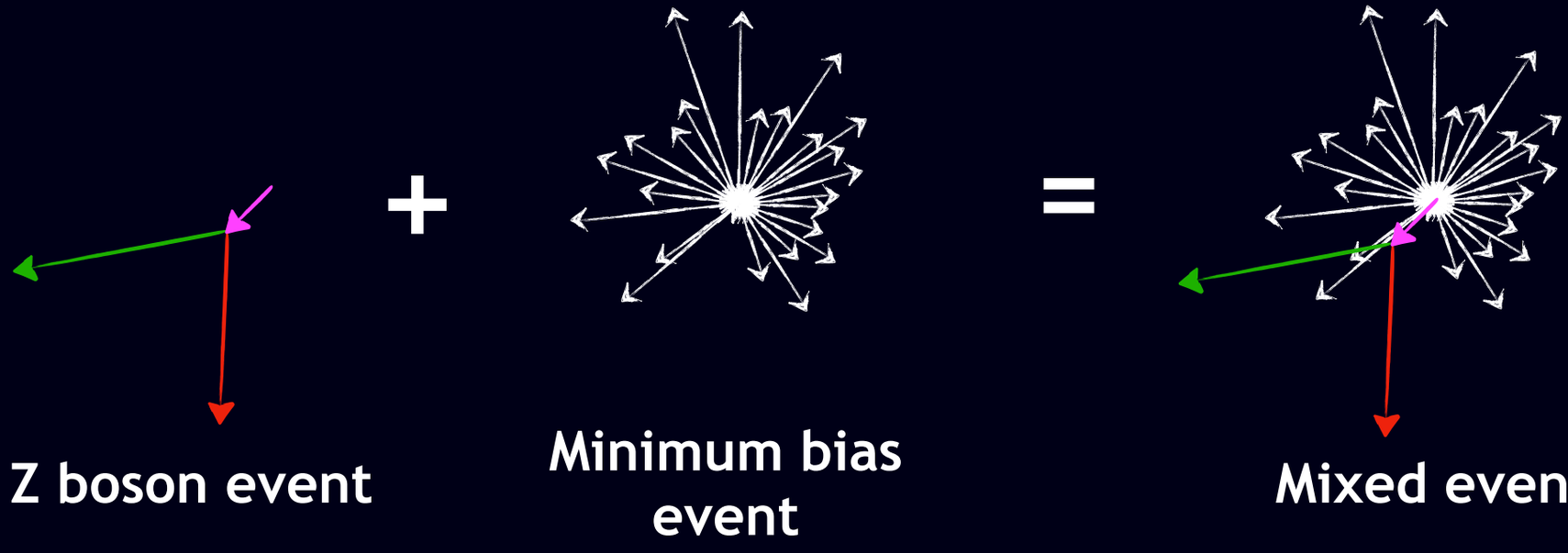


Phys. Rev. Lett. 123, 042001 (2019)

Modeling the underlying event

How do we mix events?

1. Reconstruct Z bosons in Pb+Pb data, measuring the total per-Z hadron yield
2. Randomly select a Z event and a minimum bias (MB) event with similar $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ and running conditions
3. Extract UE yield by correlating the Z with hadrons in the MB event
4. Repeat until each Z boson has been mixed exactly 40 times



Mixing procedure is validated by MC closure test in which I_{AA} is calculated within ~few % of unity