



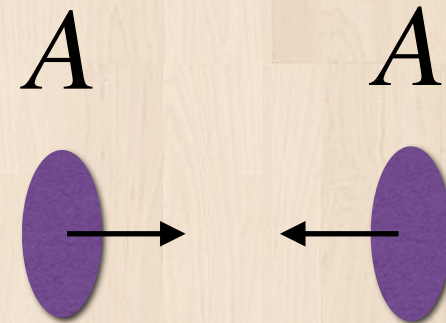
Pinning down the vacuum baseline of jets

Yi (Luna) Chen, Vanderbilt University
Jul 16, 2026. EMMI GSI Workshop

The usual paradigm

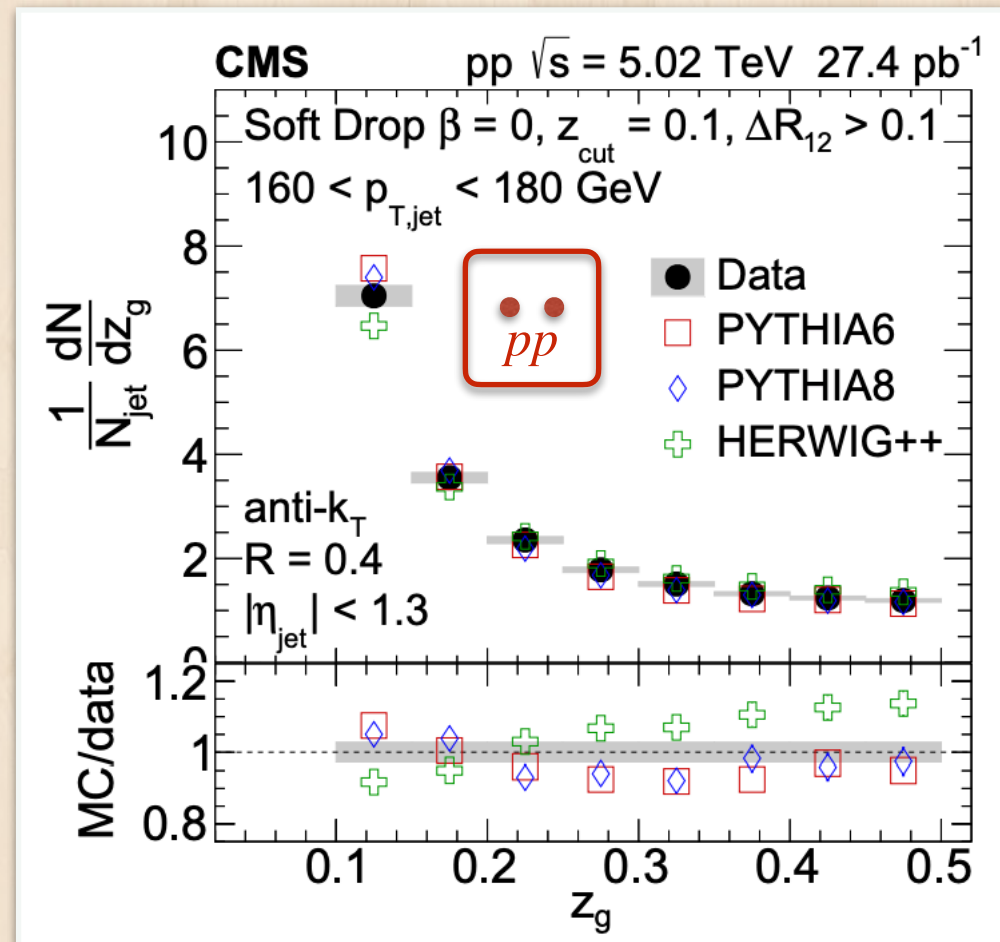


Hadronic initial state
PDF effect
→ variable Q^2
→ no longitudinal control
MPI
Vacuum
Mix of q/g contributions
...



Hadronic initial state
nPDF effect
→ variable Q^2
→ no longitudinal control
MPI
Hot medium effect
Mix of q/g contributions
Geometry
...

How well do we model the baseline?



If we look at jet substructure, typically like 10-20% level from popular generators

Let's go to a simpler system to decouple more effects

The simplest system



Point-like initial state

~~PDF effect~~

→ fixed Q^2

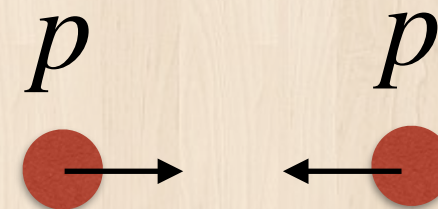
→ full kinematic control

~~MPI~~

Vacuum (very)

Quark-jet dominated

...



Hadronic initial state

PDF effect

→ variable Q^2

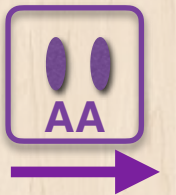
→ no longitudinal control

MPI

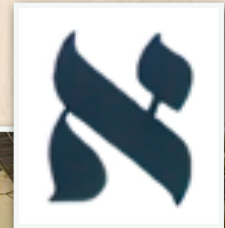
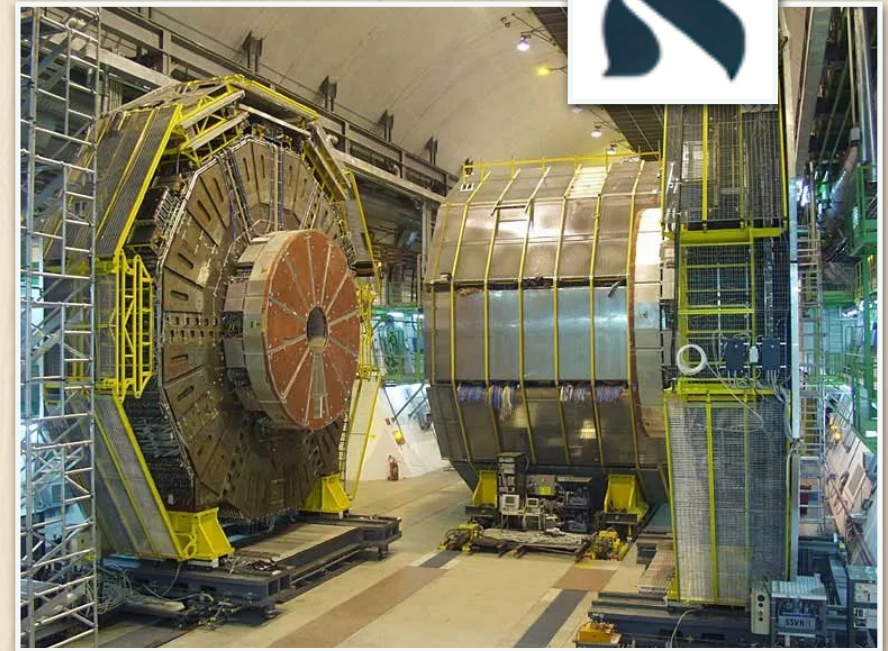
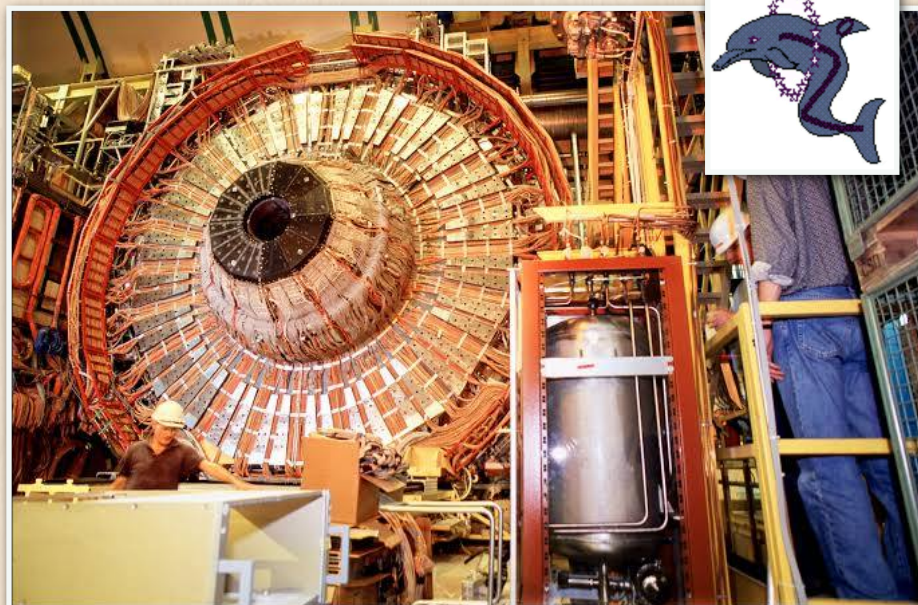
Vacuum

Mix of q/g contributions

...

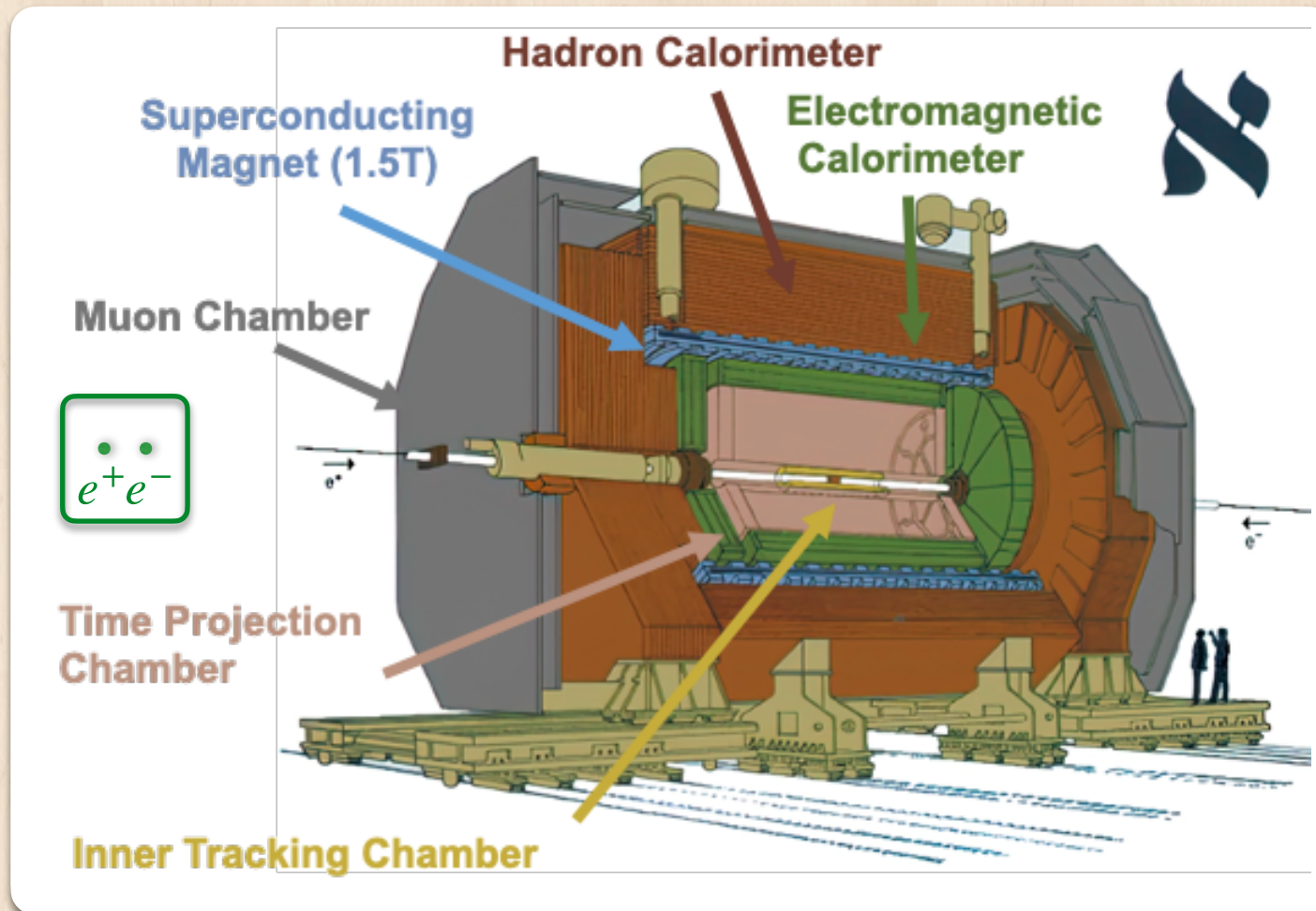


The LEP experiments



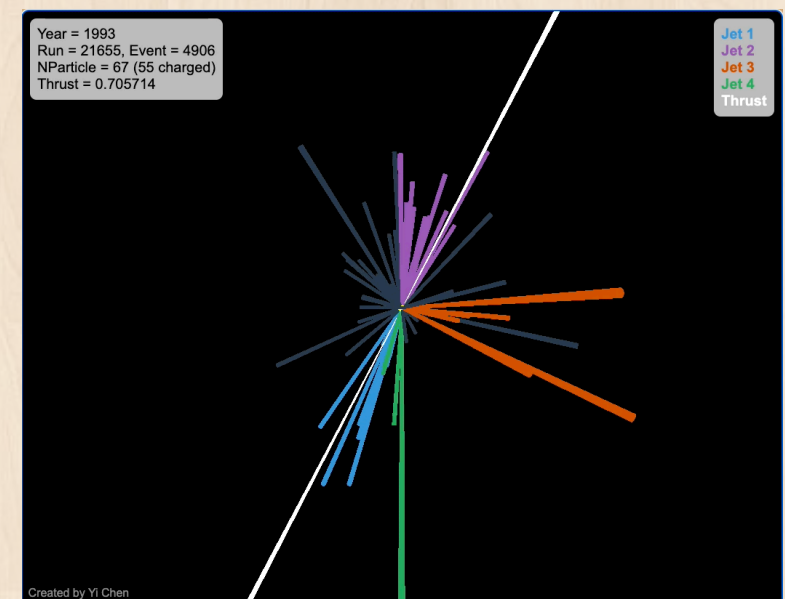
(Not shown: OPAL & L3)

The archived ALEPH data



Available:

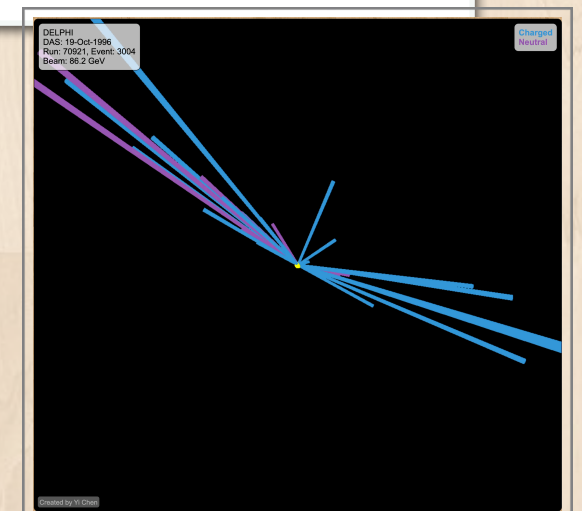
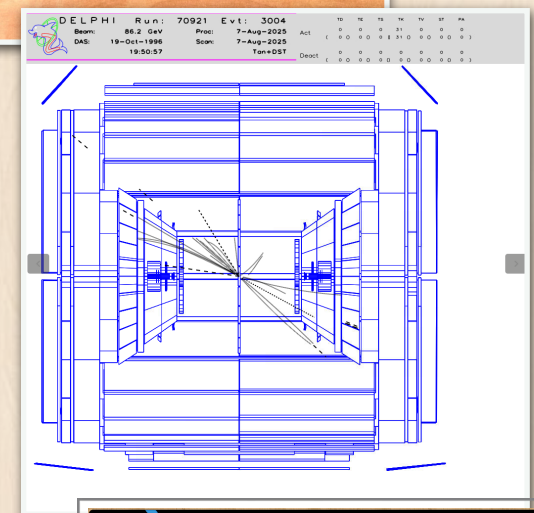
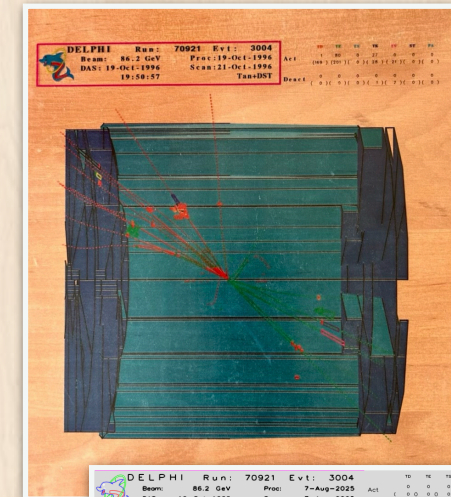
- Archived data
- Archived MC
- PYTHIA6-based



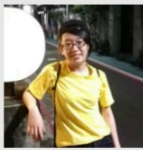
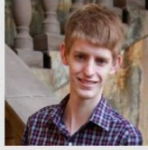
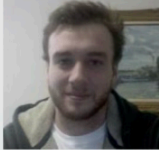
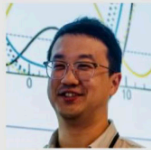
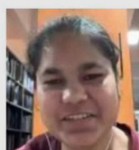
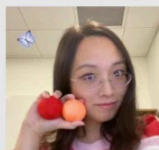
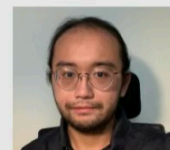
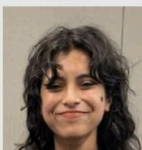
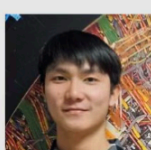
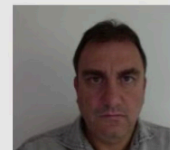
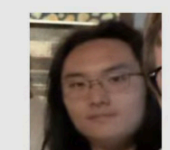
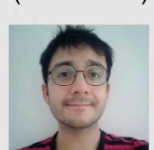
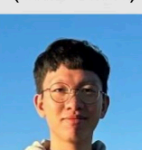
Incredible support from ALEPH members **Marcello Maggi, Roberto Tenchini, Gigi Rolandi, Guenther Dissertori** on the technical aspects and knowledge

The DELPHI open data

- DELPHI Open Data released in 2024
- Full access on data, simulation and simulation software (GEANT3-based)
- We can run modern generator
- Thanks to the DELPHI Collaboration, data preservation team, especially **Dietrich Liko** and **Ulrich Schwickerath** for guidance on how to use the data



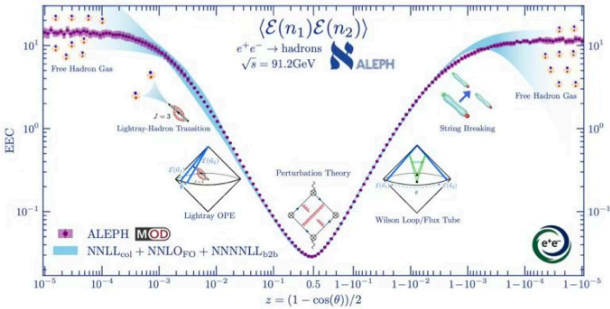
e^+e^- reanalysis effort

 Janice Chen (MIT)	 Austin Baty (UIC)	 Chris McGinn (MIT)	 Michael Peters (MIT)	 Anthony Badea (UChicago)	 Paoti Chang (NTU)	 Cen Mo (SJTU)	 Yulei Zhang U. Washington	 Honey Khindri (IIT Madras)	 Xiaoyuan Zhang (MIT)		
 Tzu-An Sheng (MIT)	 Ben Nachman (Stanford/SLAC)	 Yi Chen (Vanderbilt)	 Jingyu Zhang (Vanderbilt)	 Luke Lu (Vanderbilt)	 MJ Khan (Vanderbilt)	 Chen-Hua Hsu (NTU)					
 Hannah Bossi (MIT)	 Gian Innocenti (MIT)	 Jesse Thaler (MIT)	 Marcello Maggi (INFN Bari)	 Günther Dissertori (ETH Zürich)	 Nishant Gaurav (Vanderbilt)	 David d'Enterria (CERN)					
 Yen-Jie Lee (MIT)	 Jeetendra Gupta (UIC)	 Sascha Diefenbacher (LBNL)	 Bill Zhou (Vanderbilt)	 Cristian Baldenegro (MIT)	 Ting-Hsiang Hsu (NTU)	 Prabhat Pujahari (IIT Madras)					

The Electron-Positron Alliance

About Papers Talks Links

Maximize scientific impact of collected data



Designed and maintained by Yi (Luna) Chen. Last updated Sep 21, 2025.

<https://ee-alliance.org>

Main goal: preserve data and knowledge
and reanalyze with new observables



Many ongoing efforts

- Jet studies: jet spectra radius scan, Lund plane & multiplicity, substructure correlation, in-jet asymmetry, HF jet tagging, EIC clustering studies, axis decorrelation, ...
- Event-wide: energy-energy correlator, thrust, Q_1 correlator, ...
- Search for QGP-like effects: 2PC, cumulants, strangeness enhancement, ...
- $Z \rightarrow \tau\tau$ spin measurement, ...
- Methodology: agentic AI, ML, ...

Many ongoing efforts

- Jet studies: **jet spectra radius scan**, Lund plane & multiplicity, substructure correlation, **in-jet asymmetry**, HF jet tagging, EIC clustering studies, axis decorrelation, ...
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- $Z \rightarrow \tau\tau$ spin measurement, ...
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Today: highlight a few recent studies demonstrating what we learn + the capabilities

Jet spectra in e^+e^-

We can measure jets

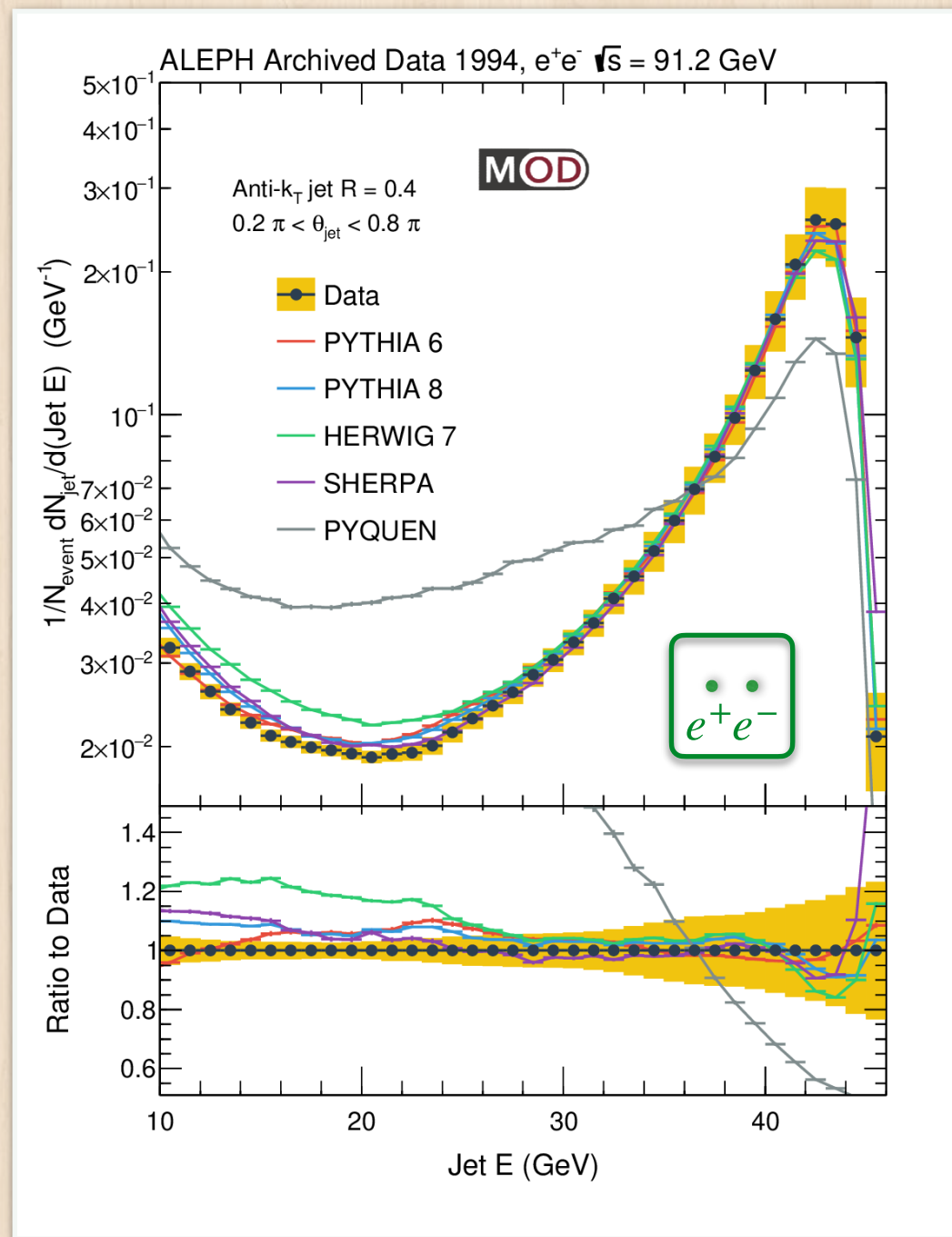
Early jet measurements



Many jet measurements are done with
previous generation of jet algorithms
=> Not ideal for LHC/RHIC/EIC comparisons

Excellent opportunity for re-analysis with new algorithms

Few years back: anti- k_T , $R = 0.4$



Comparison to MC and theory calculations (not shown in this plot)

Most generators can describe the peak region

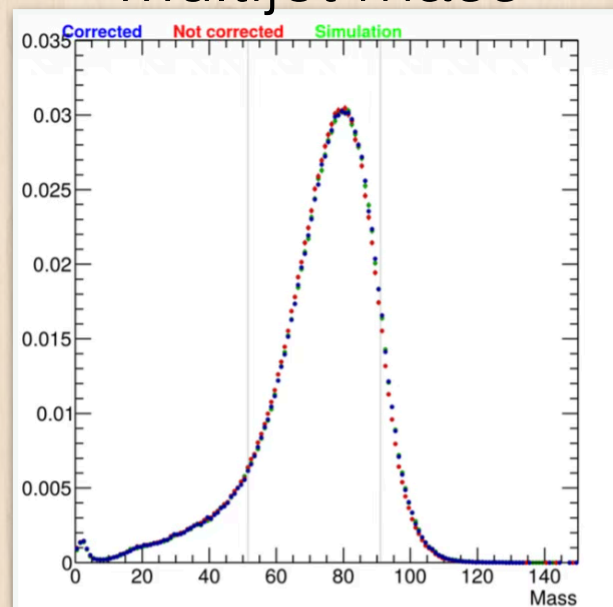
Up to 10-20% disagreement at low E
→ out-of-cone energy, wide angle emission, ...

New: jet radius scan

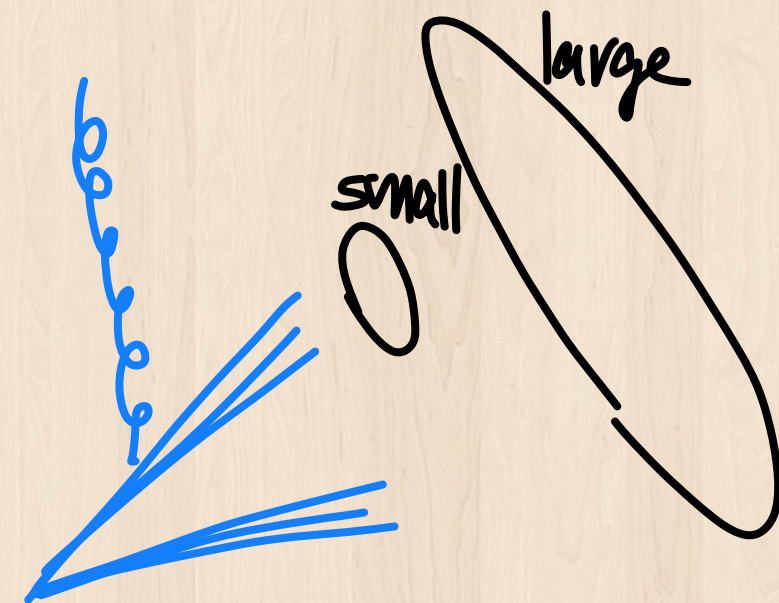
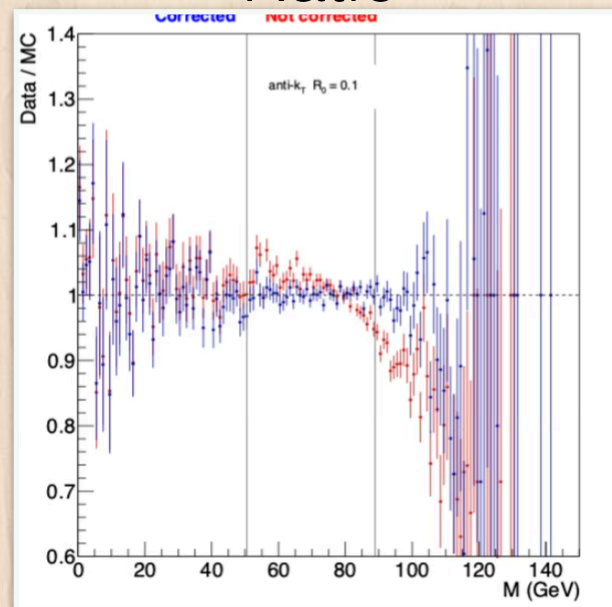
We recalibrated anti- k_T (e^+e^- variant) jets with
 $R = 0.1, 0.2, 0.3, (0.4), 0.5, 0.6, 0.8, 1.0, 1.2$
MC-based + data/MC correction

One example

Multijet mass



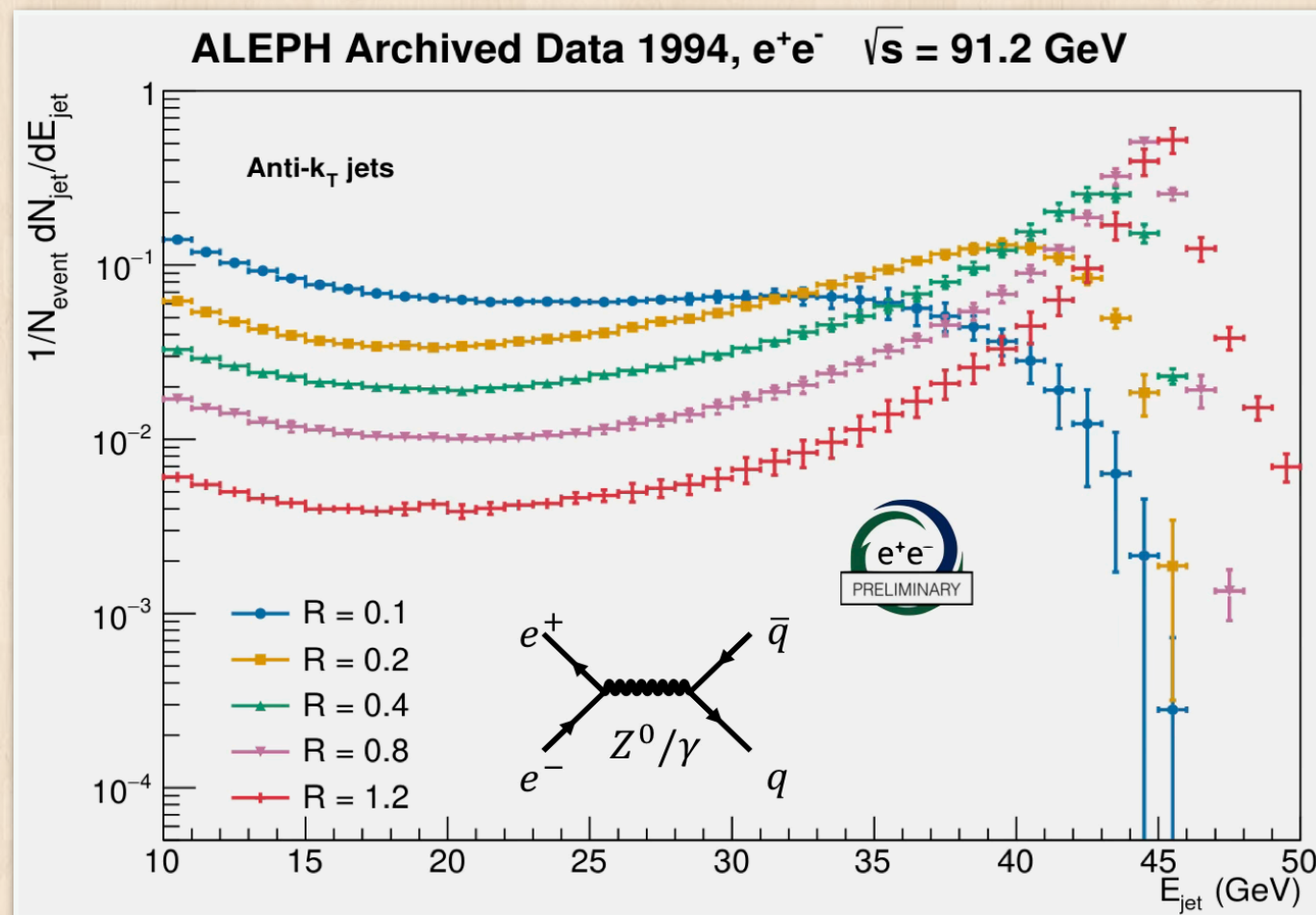
Ratio



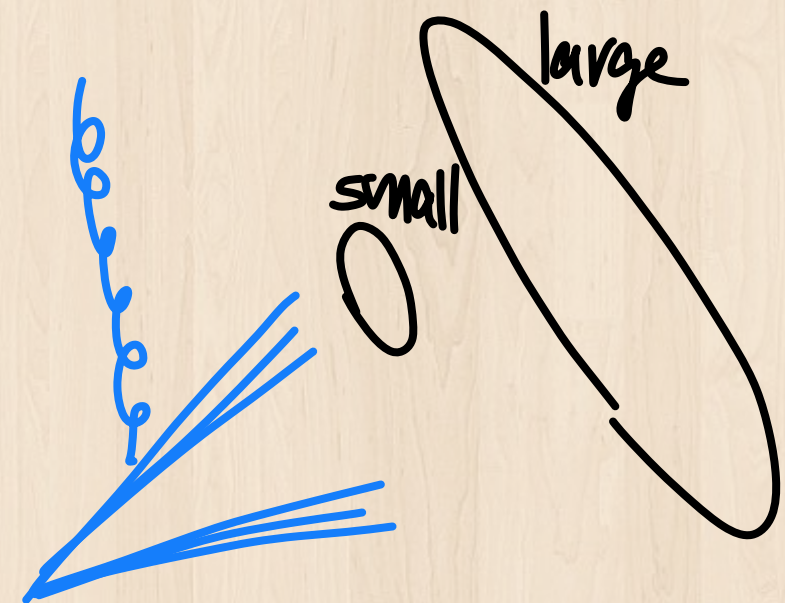
Small R — resolves shower structure

Large R — large angle out-of-cone energy

New: jet radius scan



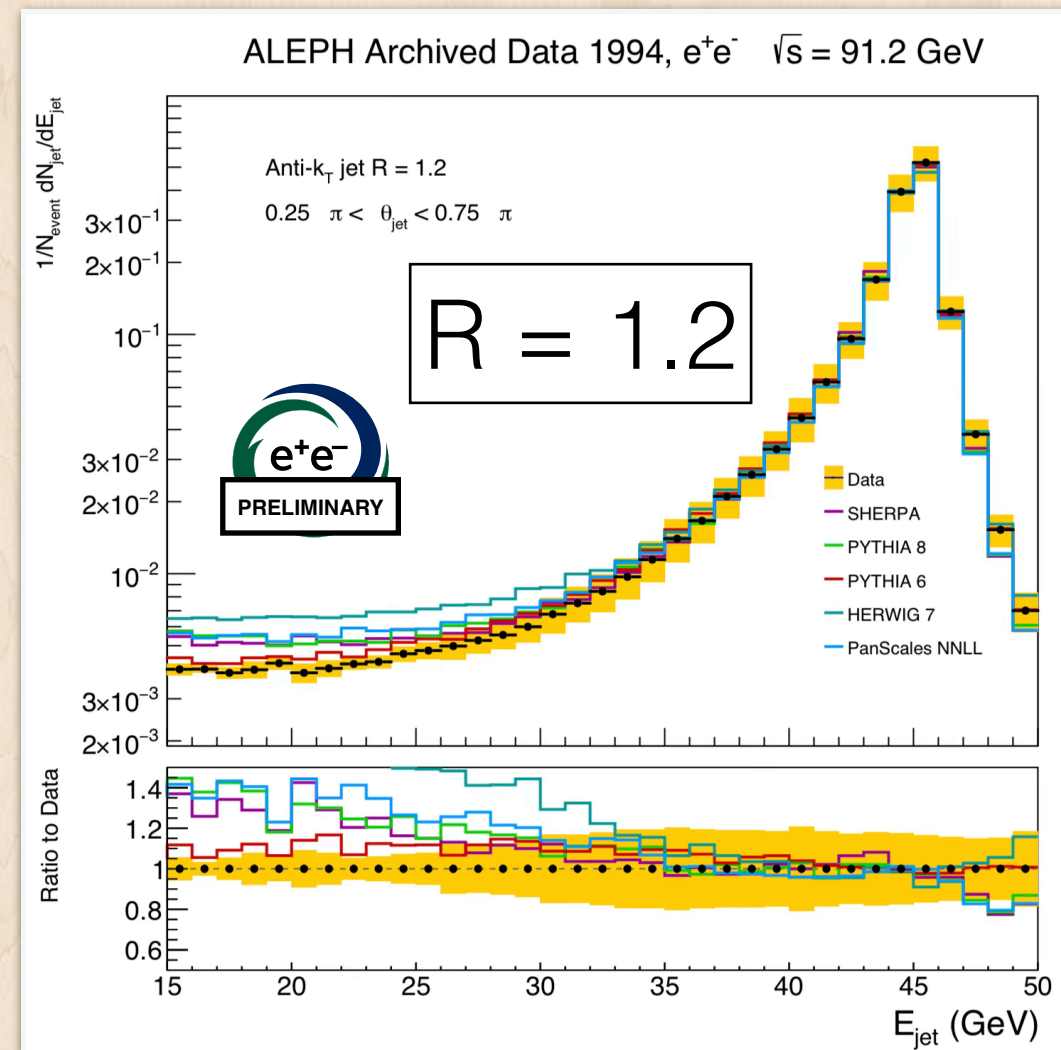
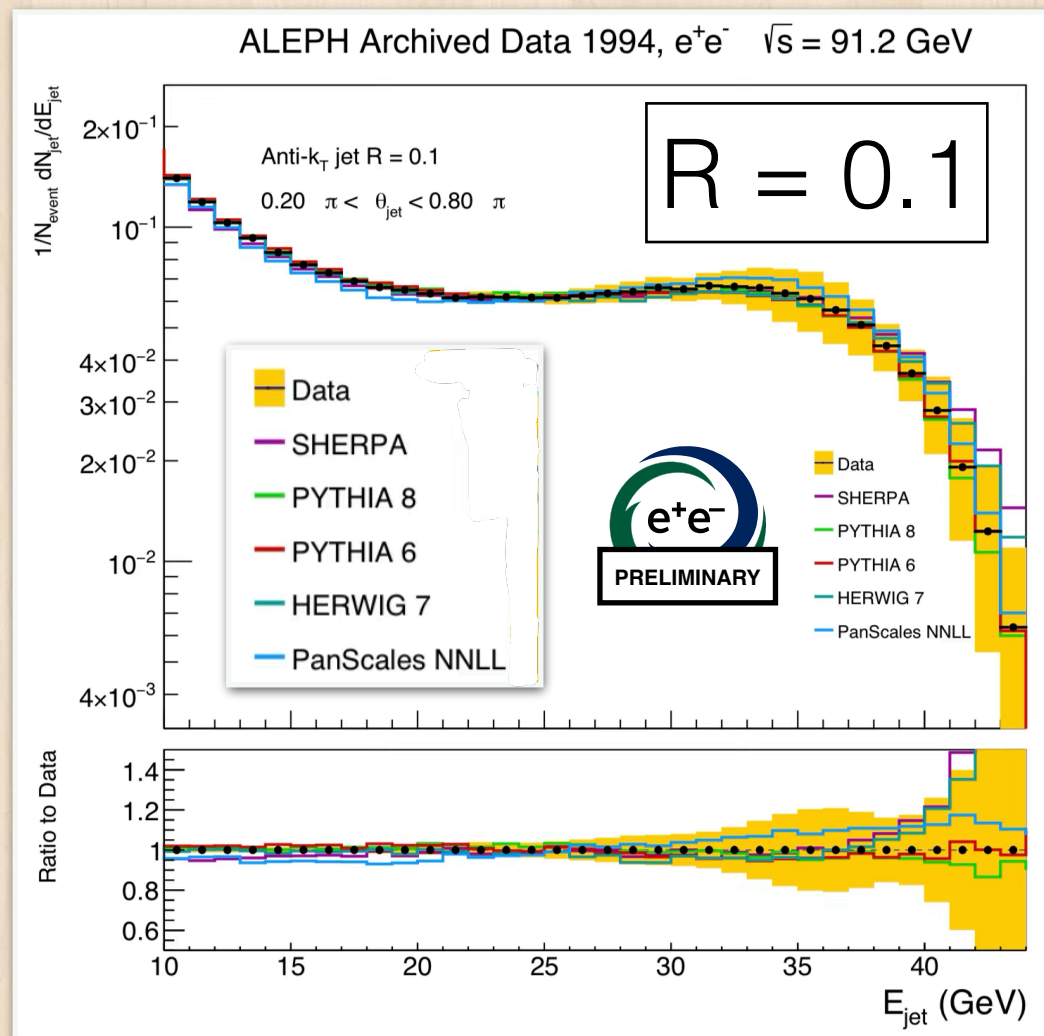
Fully unfolded jet spectra across R 's



Small R — resolves shower structure

Large R — large angle out-of-cone energy

New: jet radius scan



Data compared with modern generators

Most fail to fully describe data — especially low E region

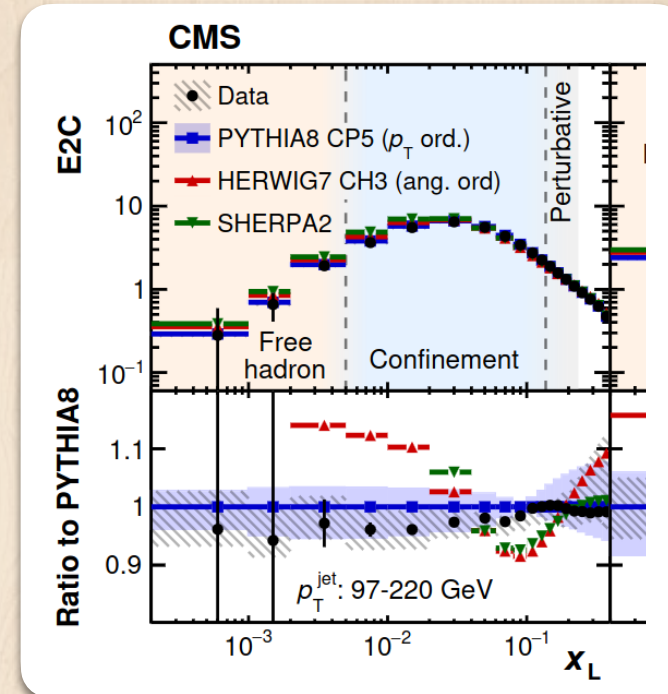
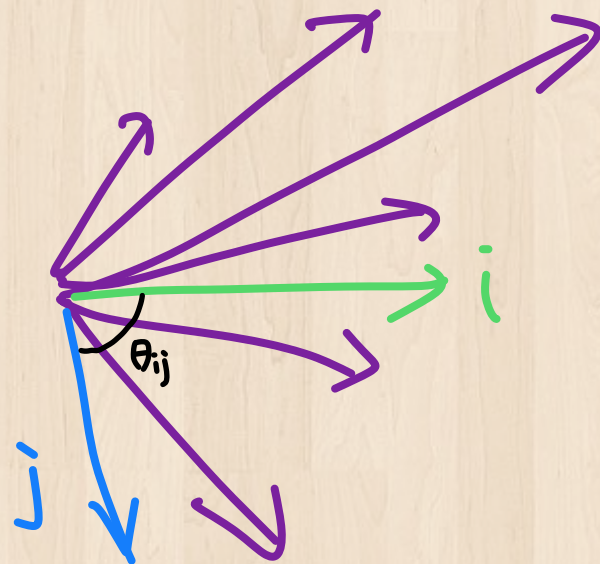
Charged EEC in e^+e^-

High resolution QCD
measurements

Energy-energy correlator

Loop over particle pair, add up energy product as a function of angle

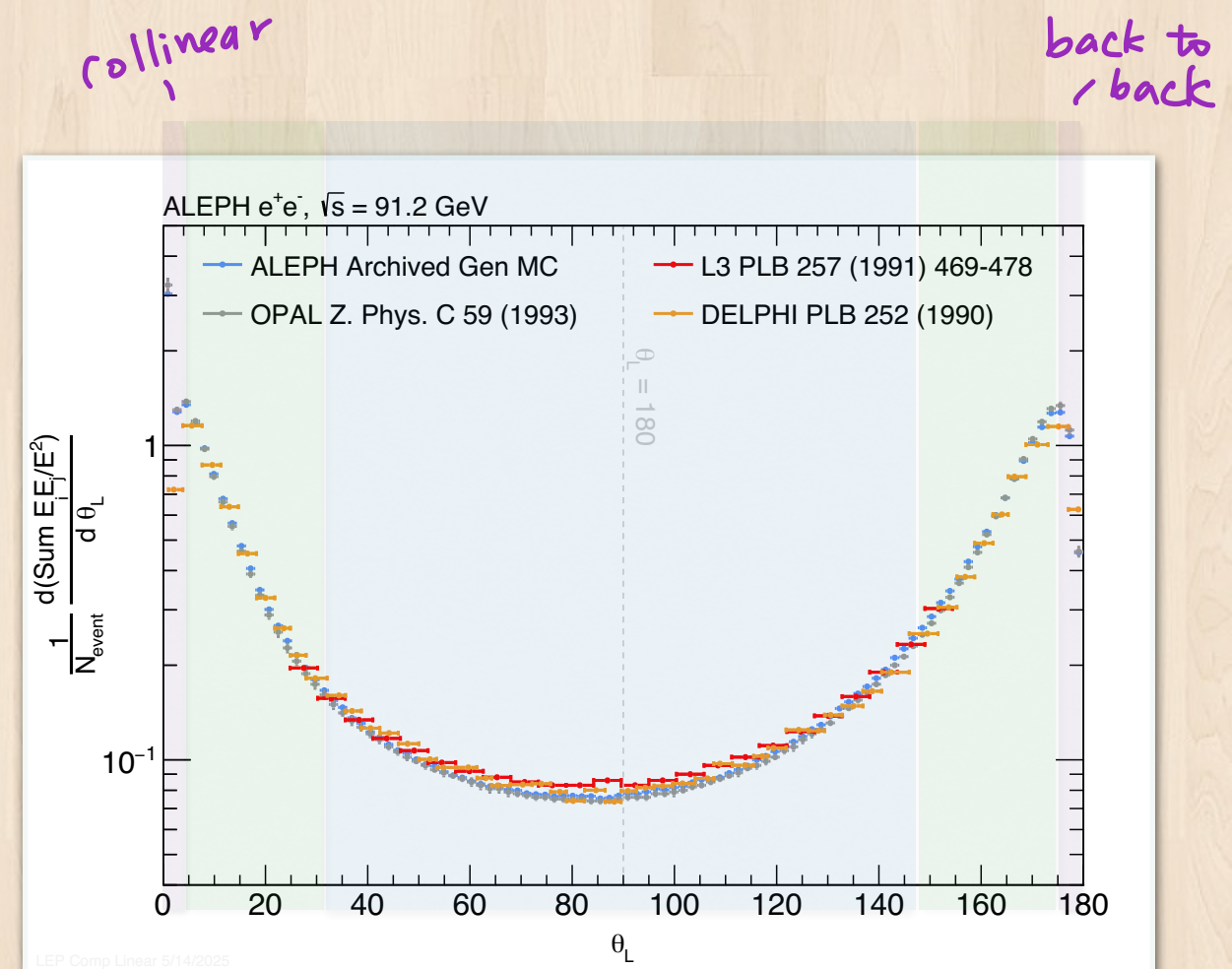
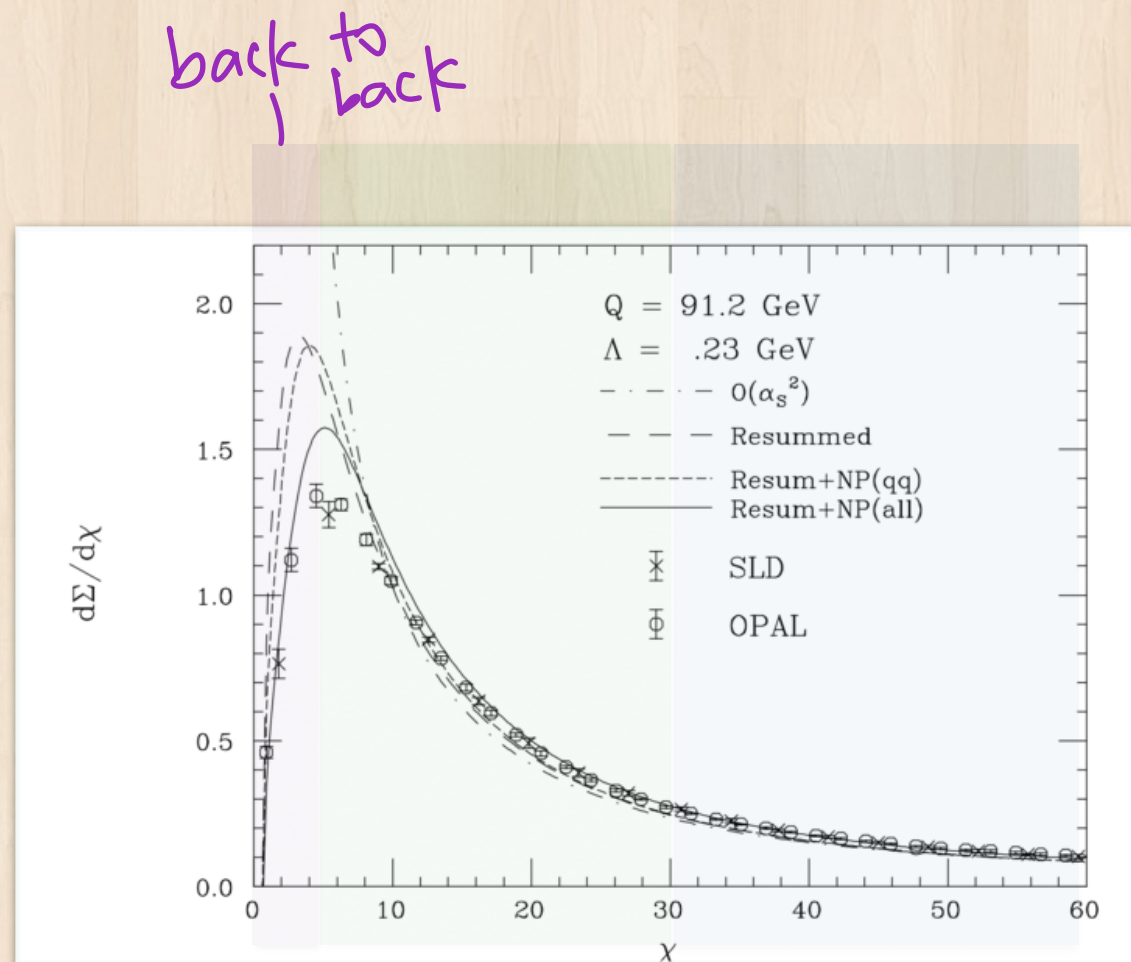
$$\text{EEC}(\theta) \equiv \sum_{i>j} \int d\sigma \frac{E_i E_j}{Q^2} \delta(\theta_L - \theta_{ij})$$



Example
from pp jets

Different angular region = different dominant physics

Previous measurements

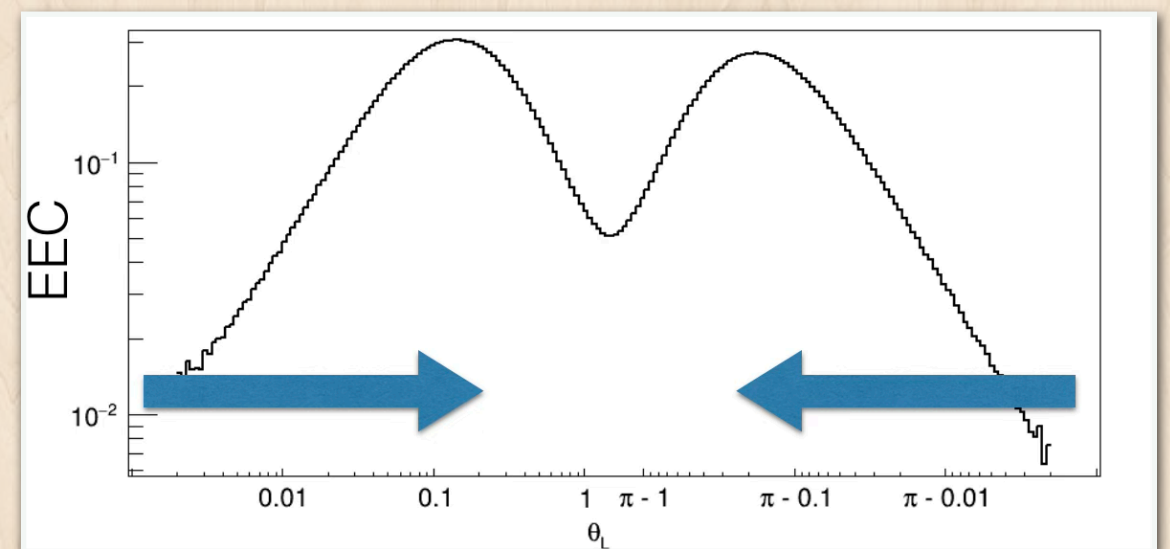
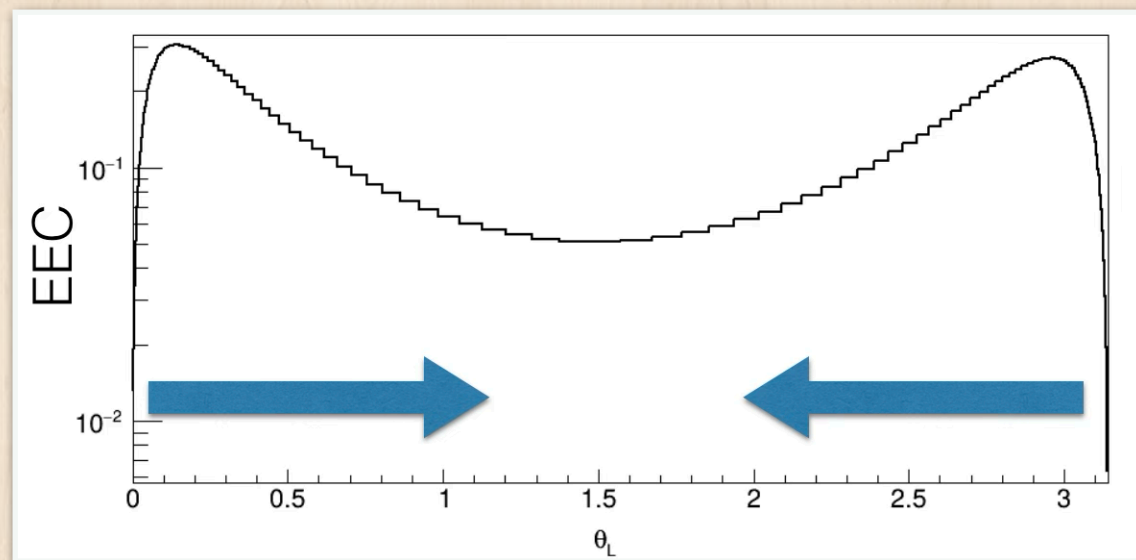


Both the small angle region and the back-to-back region compressed into 1-2 bins

We can achieve finer resolution with track-based EEC

Change of axis scale

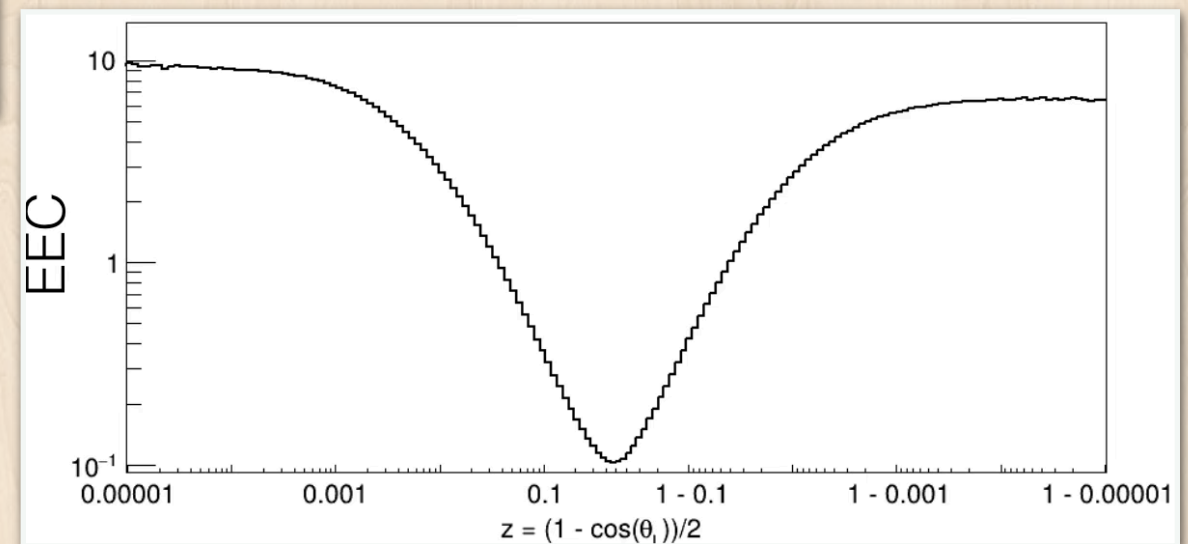
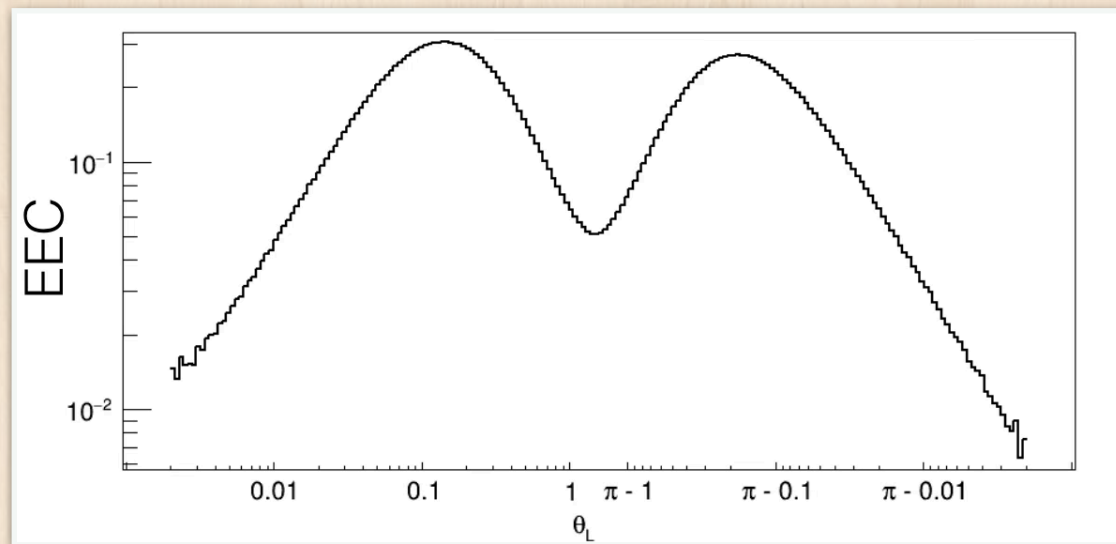
Change to **double-log** style to focus on the ends



The small angle region should scale like θ_L^2
 Let's change variable to make this self-evident

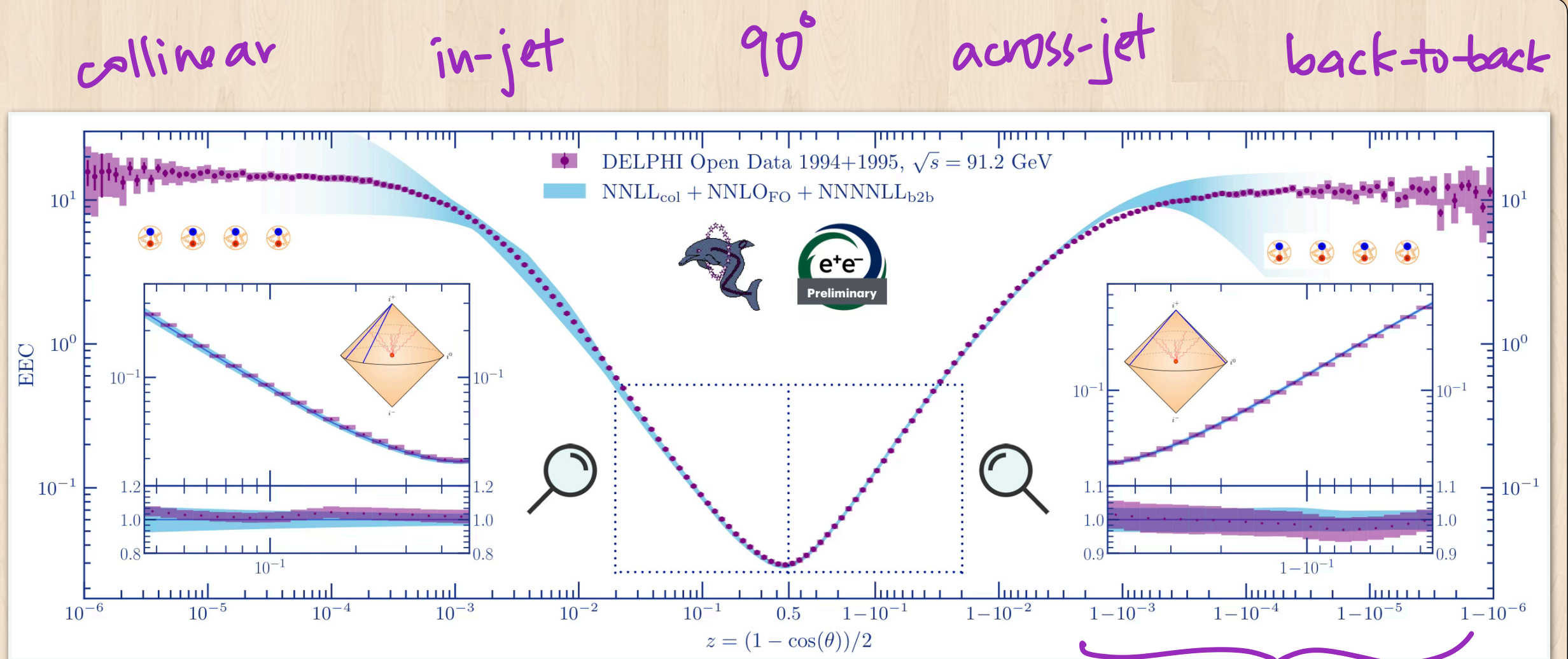
Change of variable

Change variable to $z \equiv (1 - \cos \theta)/2$

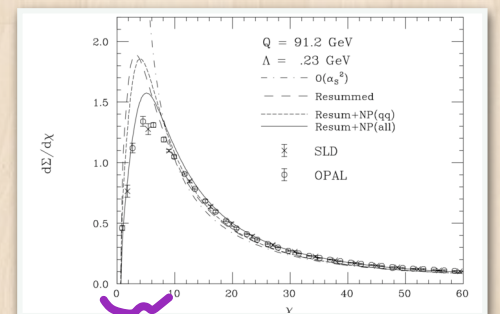


The small angle region is now $\sim$ flat
Measure charged particle EEC in this round

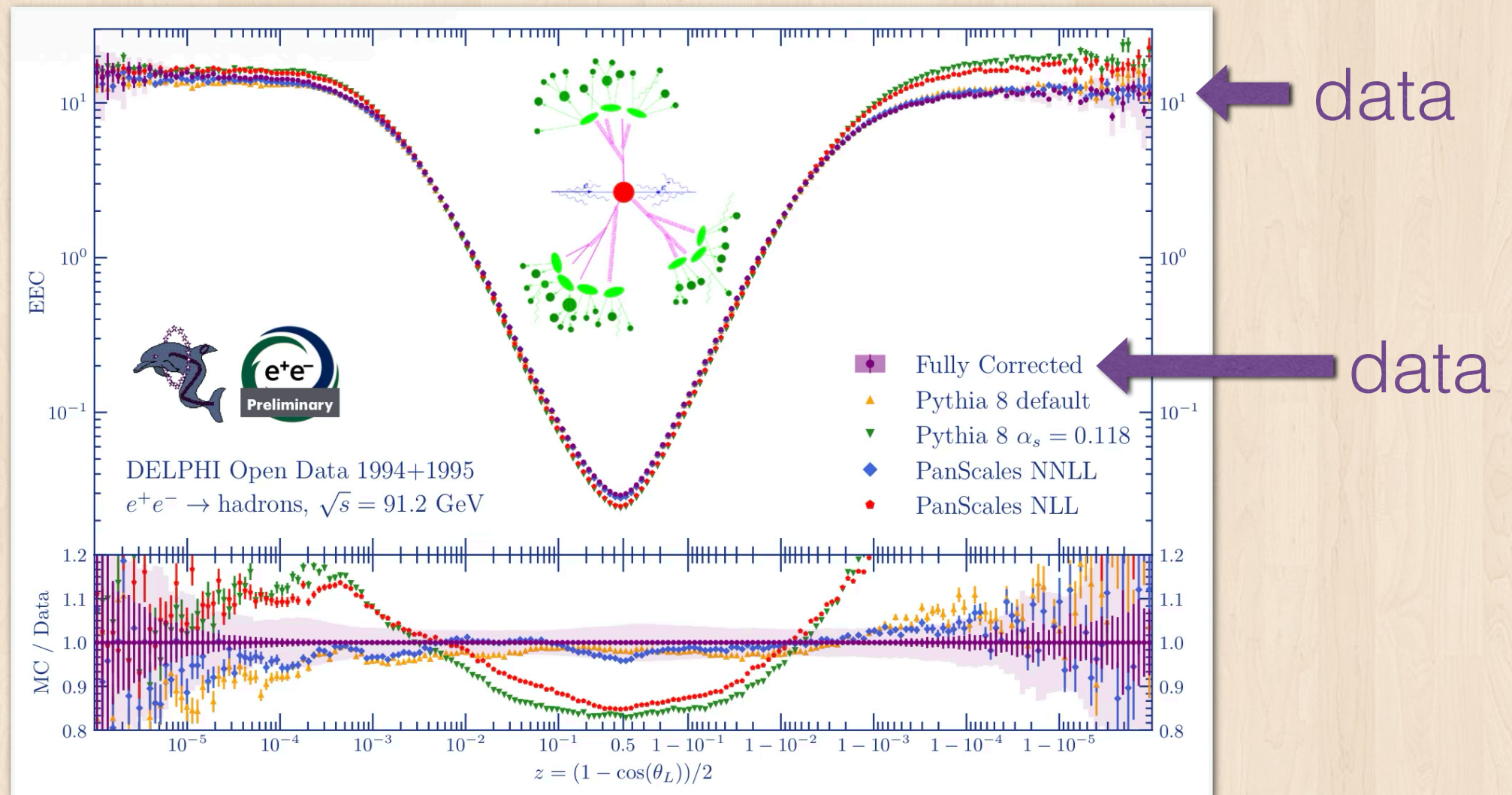
Unfolded results



Compared with state of the art theory calculation
 npQCD-heavy region less well controlled
 Finer resolution in the npQCD-heavy regions



Comparison to simulation



Pythia8 + fixing α_s to world average = 20+% off

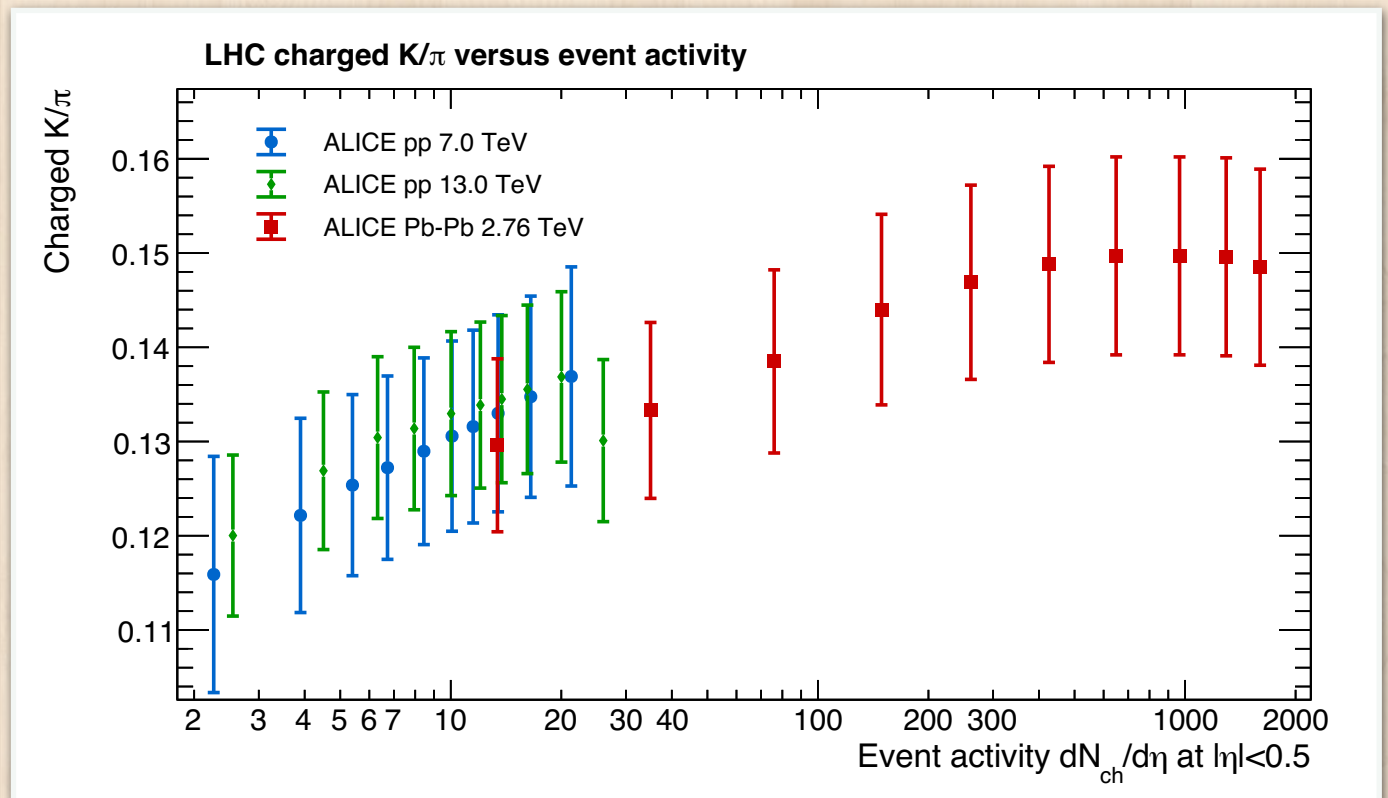
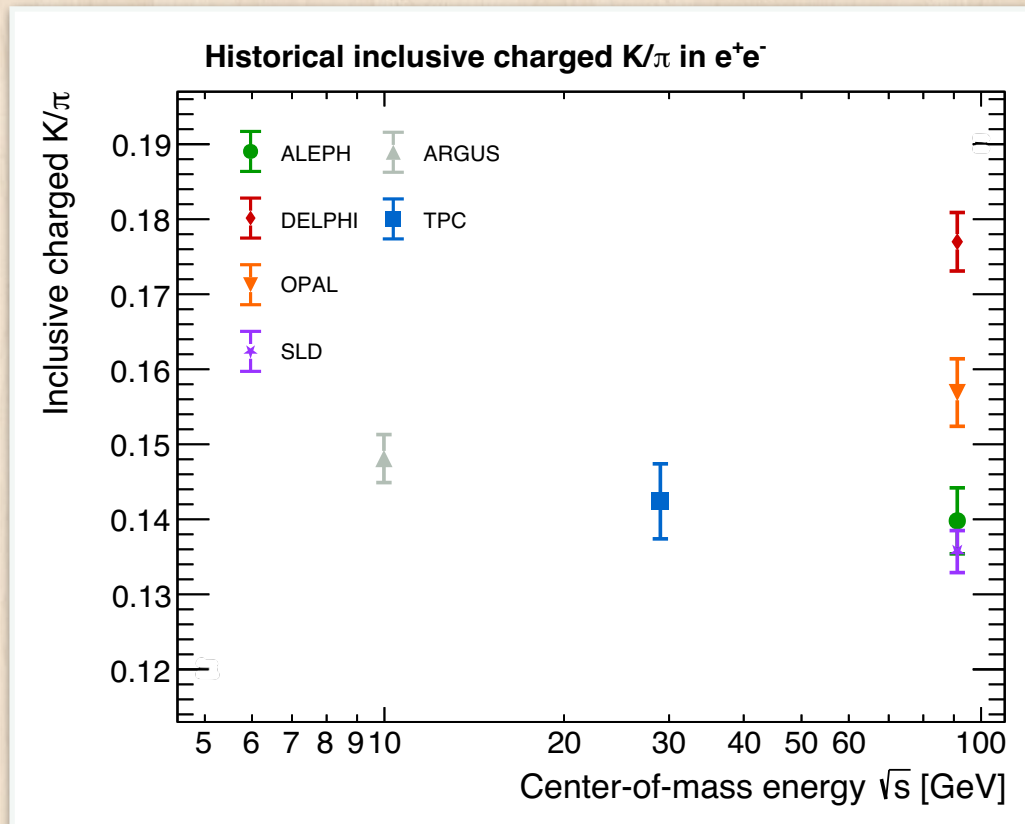
PanScales: **NLL** not sufficient, **NNLL** performs better

This is without parton shower tuning (ME 3 jets)

K/π in e^+e^-

We have particle ID

K/π ratio measurement



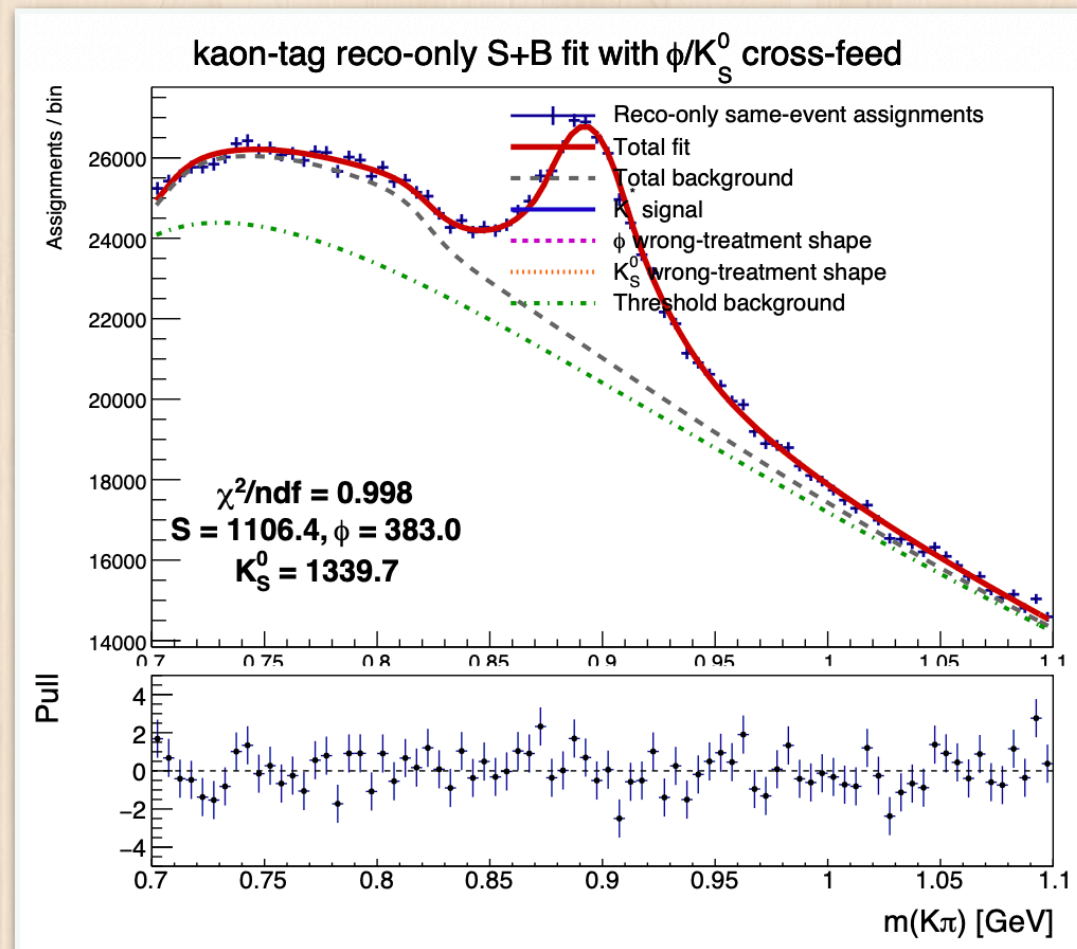
K/π ratio in the same ballpark as pp

However no directly analogous results from e^+e^-

Perform measurement with DELPHI Open Data
PID available + rederive data/MC efficiency scale factor

Particle ID capability

$p/K/\pi$ particle ID available in DELPHI open data
(People are also studying **HF jet tagging**)

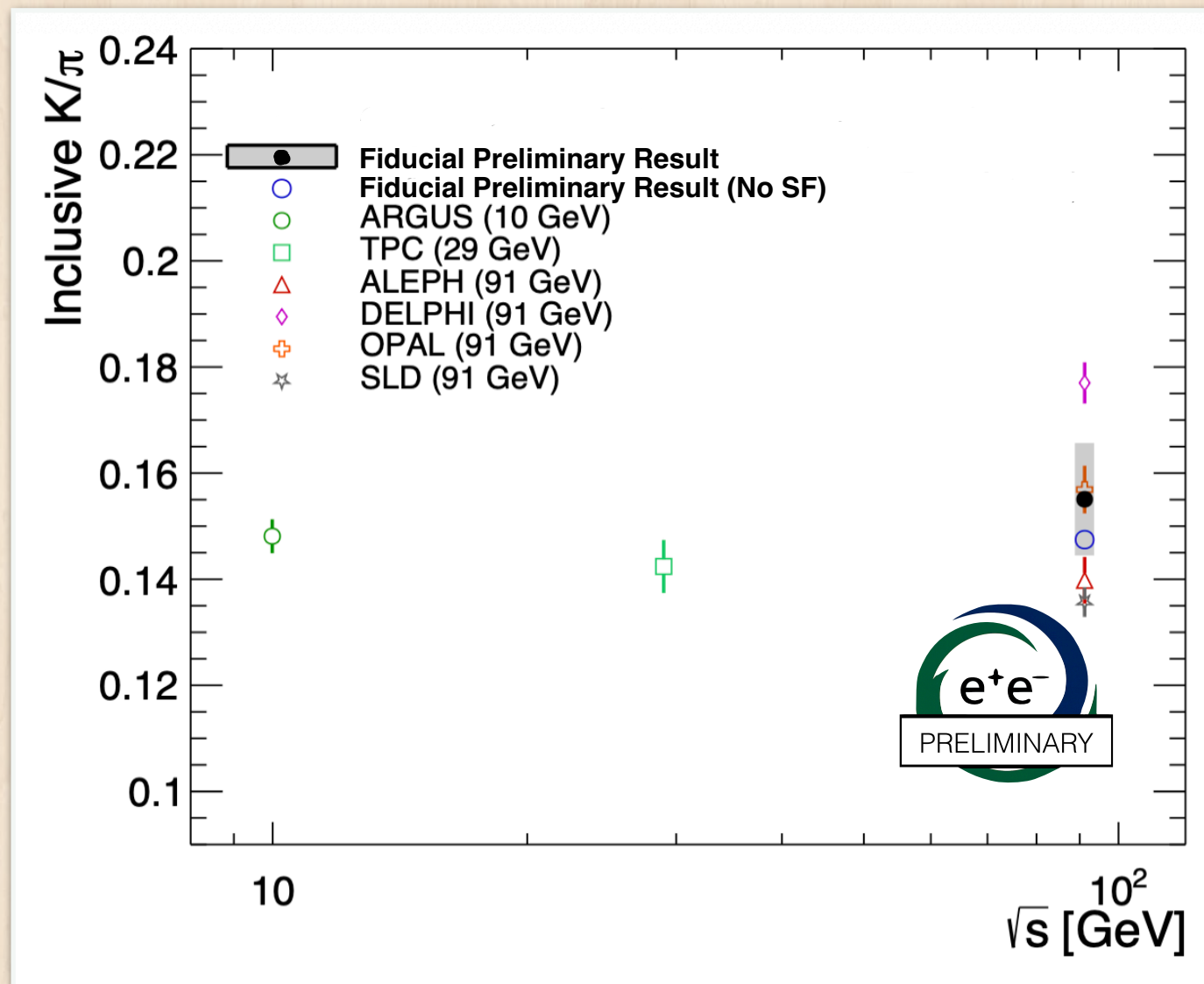


Example fit: K^*

In order to control tagging efficiency, we study the resonances

Efficiency of data & MC under good control

Integrated result



Broadly compatible
with other 91 GeV
results

Caveat: current result
is fiducial region

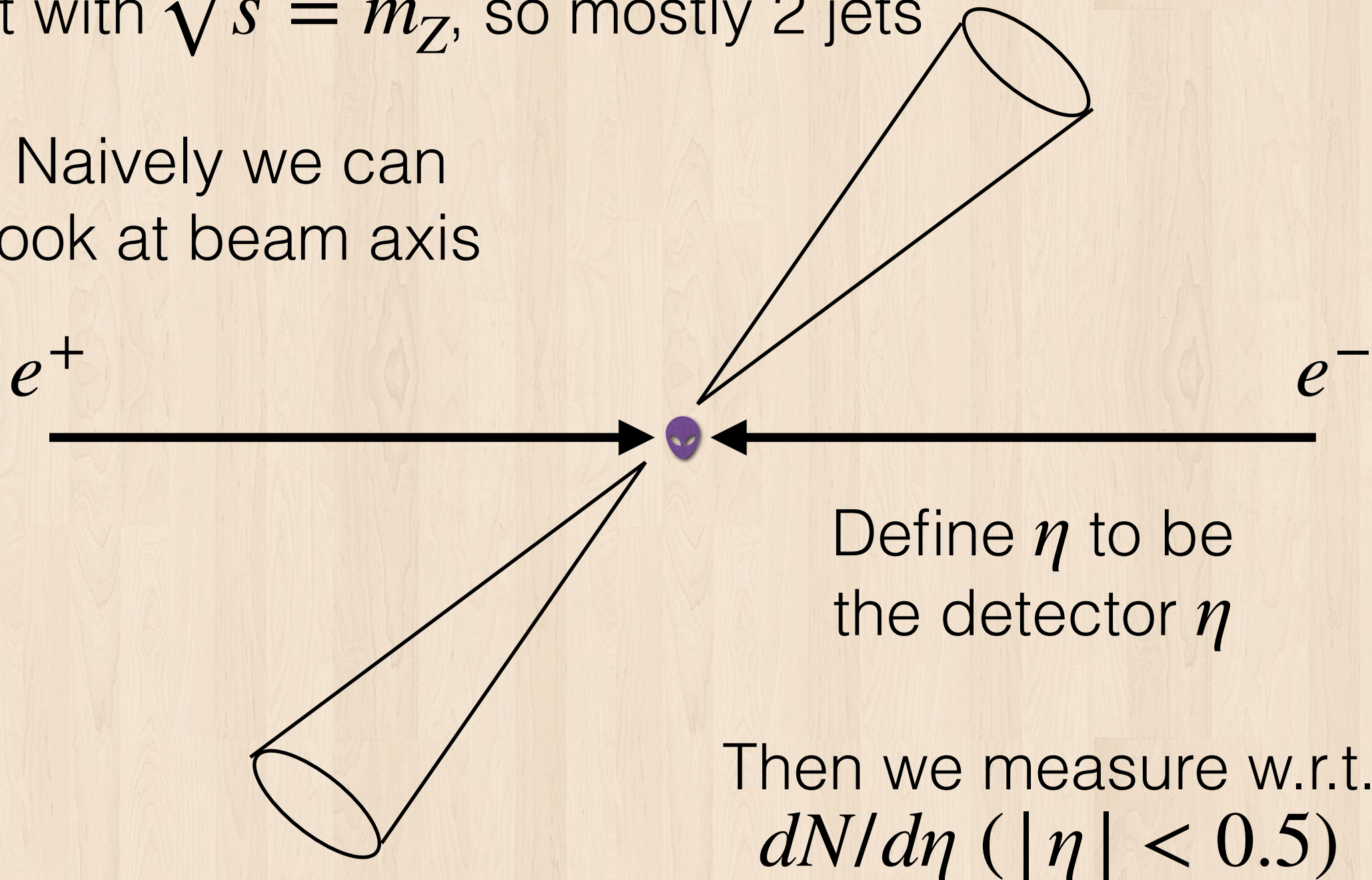
$$|\cos \theta| \in 0.15 - 0.675,$$
$$p_T \in 0.4 - 5.0$$

Beware of the fiducial cuts

How to measure event activity?

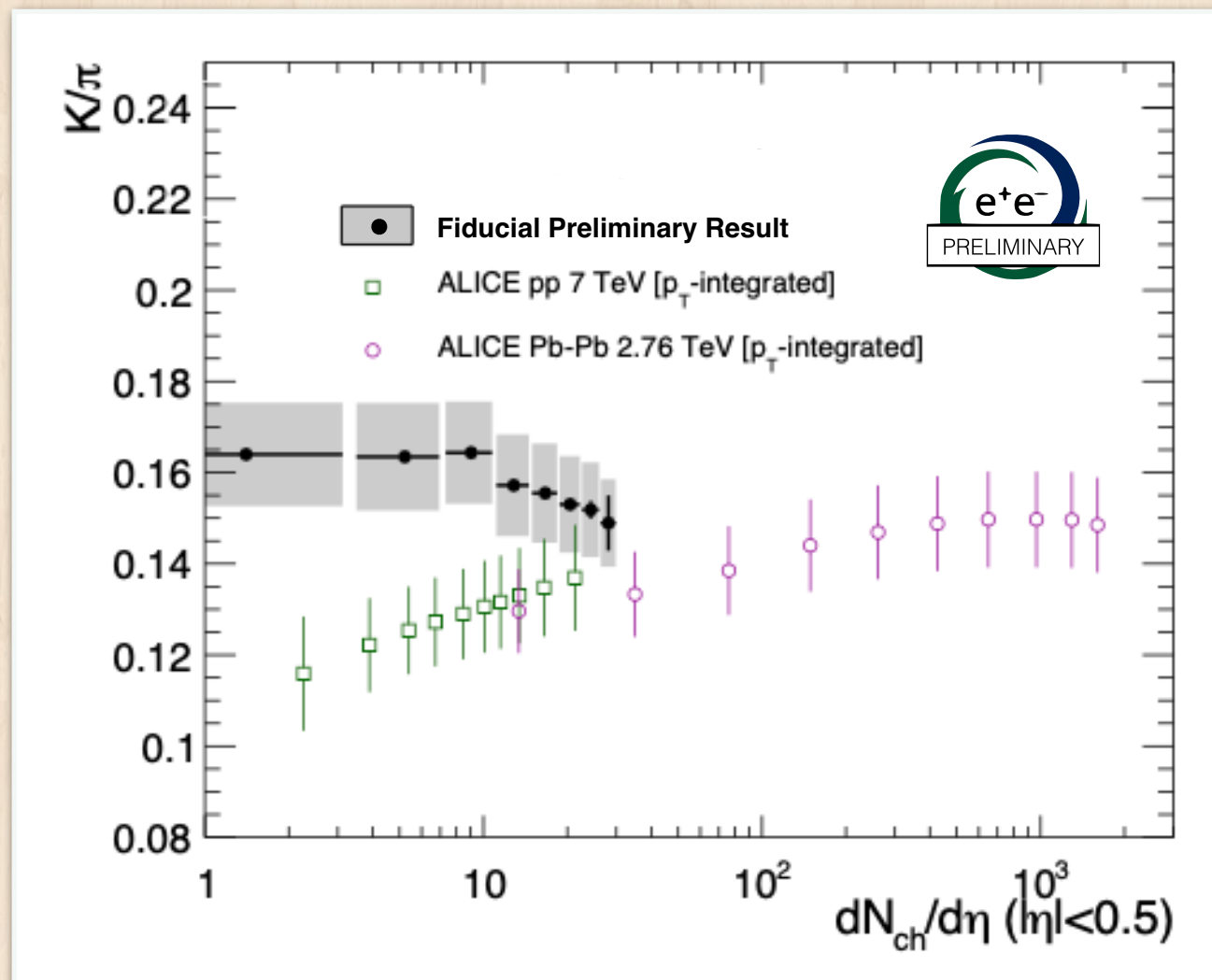
Start with $\sqrt{s} = m_Z$, so mostly 2 jets

Naively we can
look at beam axis



Beam $dN/d\eta$

Beware of the fiducial cuts



Dijet direction is random $\rightarrow dN/d\eta$ captures part of dijet

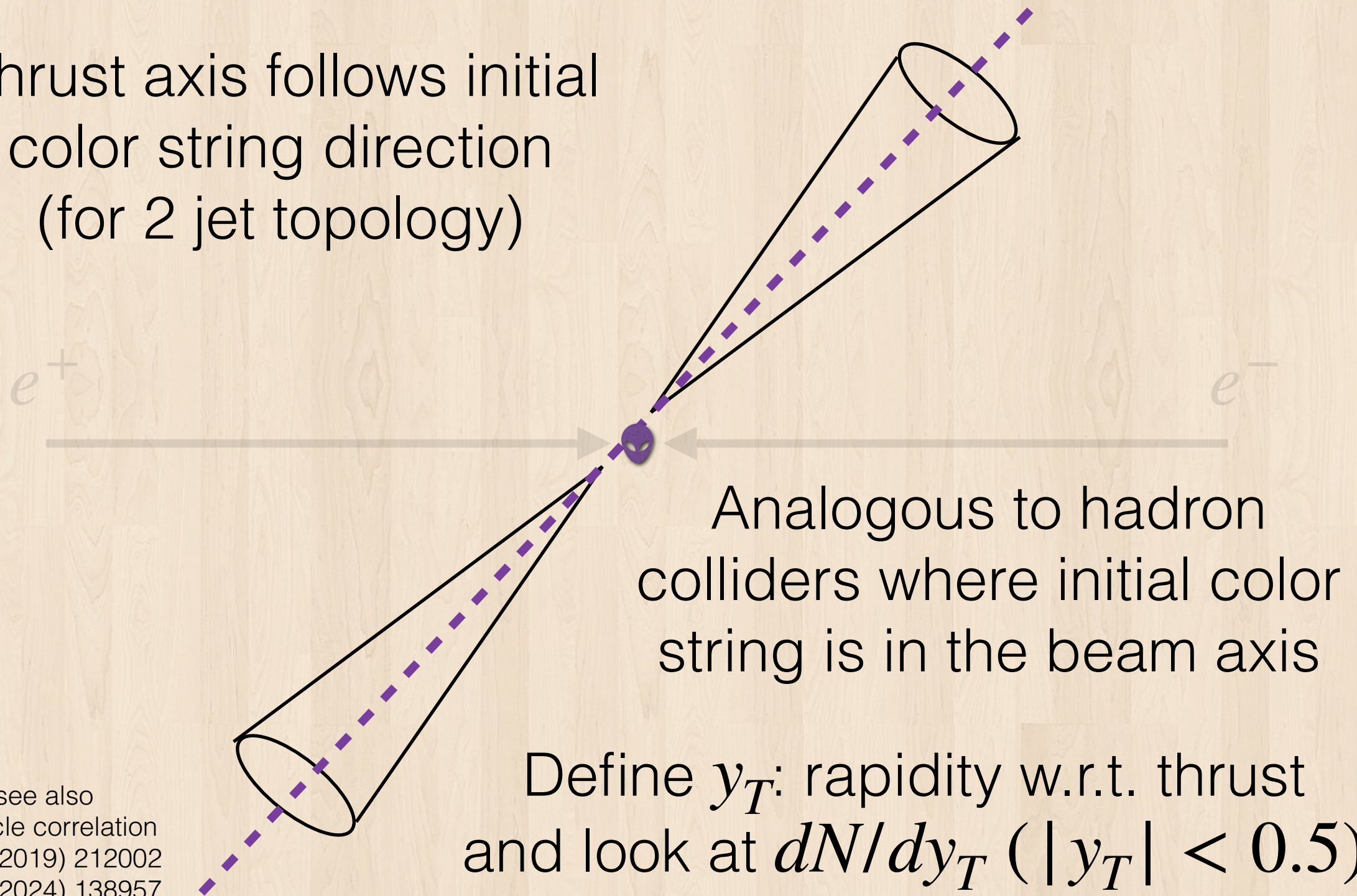
Doesn't seem to follow same trend as hadron colliders

Higher $dN/d\eta \rightarrow$ more shorter strings $\rightarrow$ harder to make $s/\bar{s}$?

Larger Q^2 might also lead to larger K/π

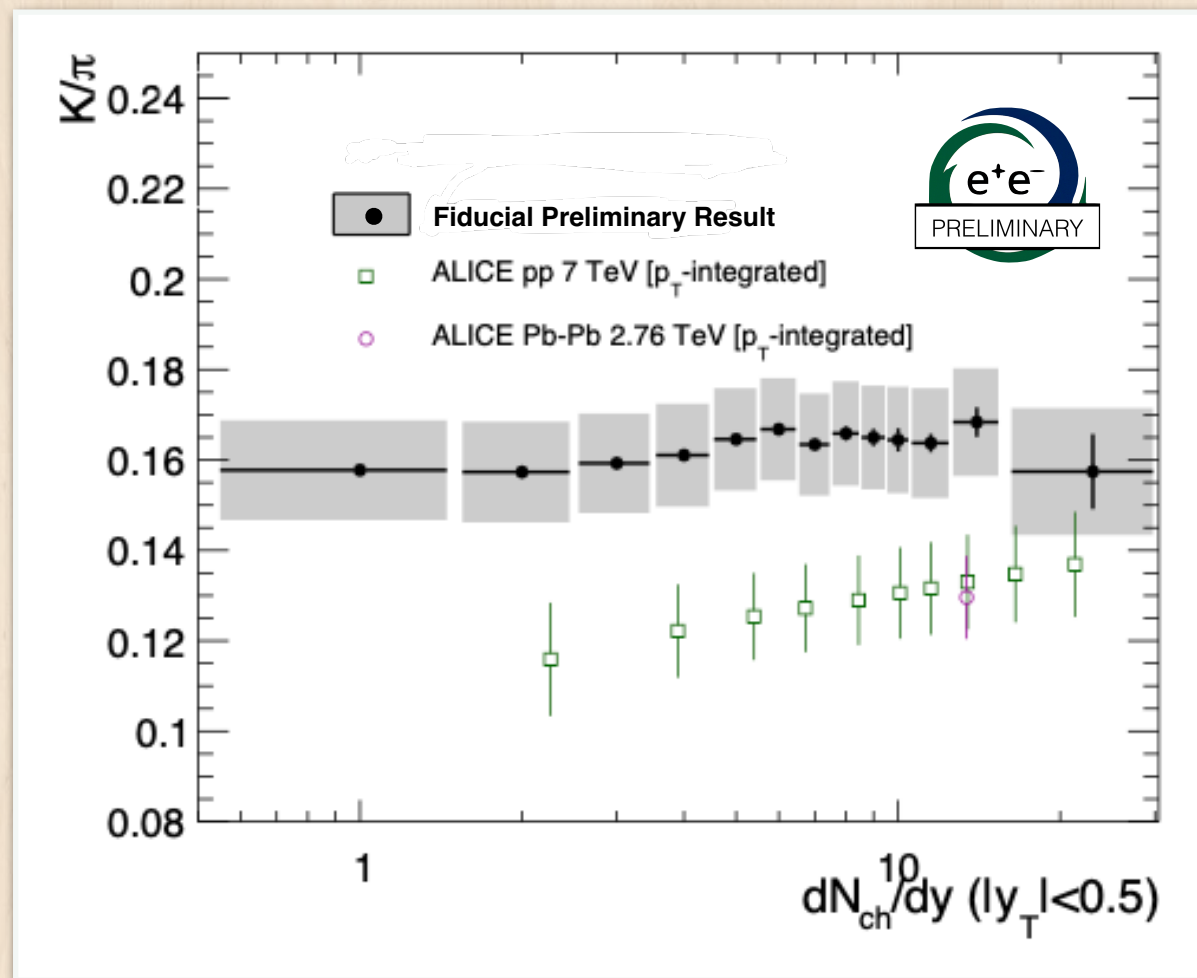
How to measure event activity?

Thrust axis follows initial
color string direction
(for 2 jet topology)



c.f. see also
two-particle correlation
PRL 123 (2019) 212002
PLB 856 (2024) 138957

Thrust dN/dy



Beware of the fiducial cuts

Thrust lines up with dijet

dN/dy largely
devoid of jet particles
if it's 2-jet topology

Multijet = higher dN/dy

No clear rising/
dropping trend

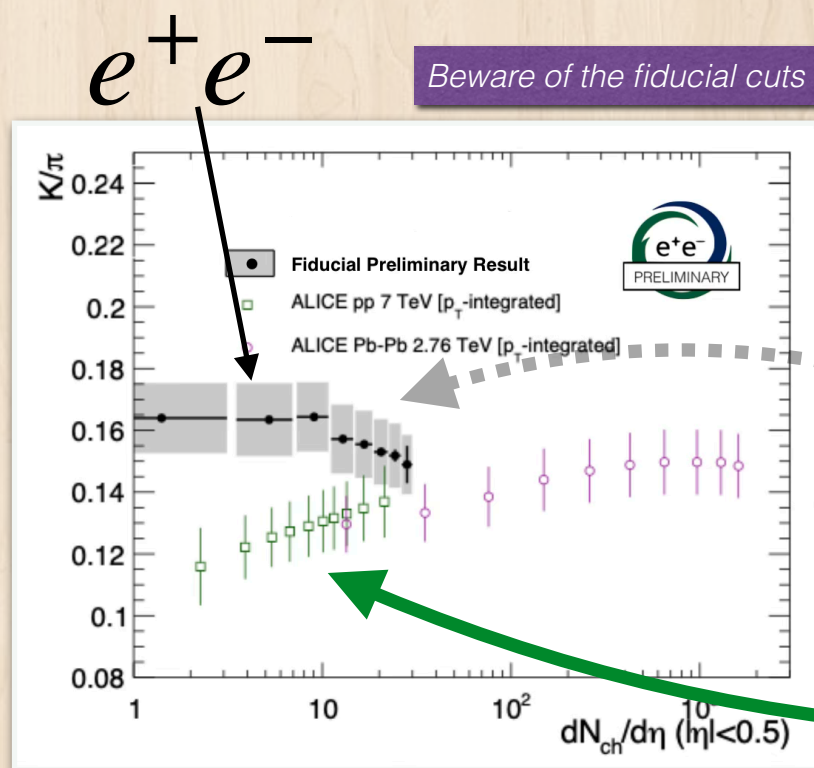
Caution: not apple-to-apple — “multiplicity” not the same

Compare to identified 2PC

e^+e^- : Z pole = mostly 2 jet, $dN/d\eta \rightarrow$ jet fragmentation

pp : $dN/d\eta \rightarrow$ MPI amount

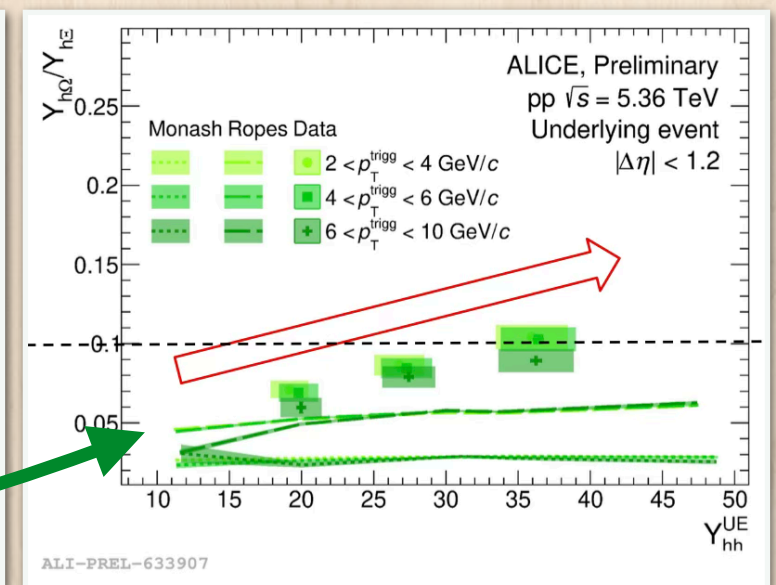
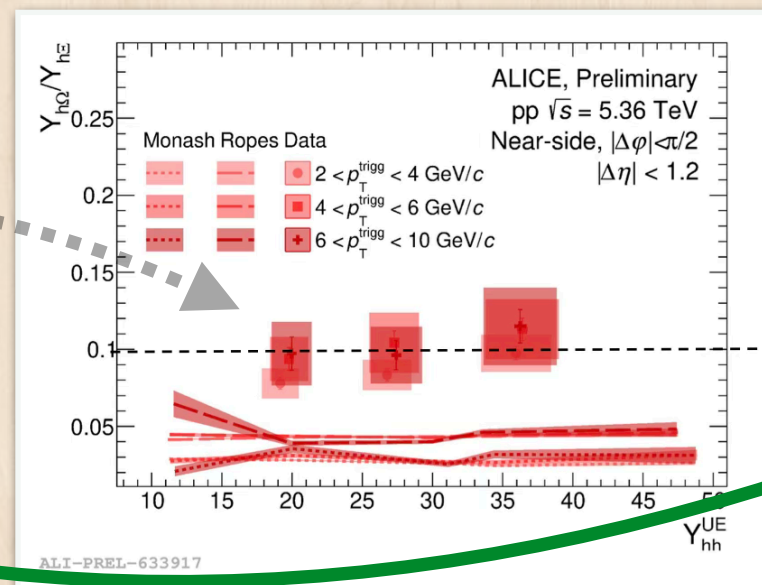
e^+e^- conceptually more comparable with in-jet result



K/π ratio

Near-side (jetty)

UE

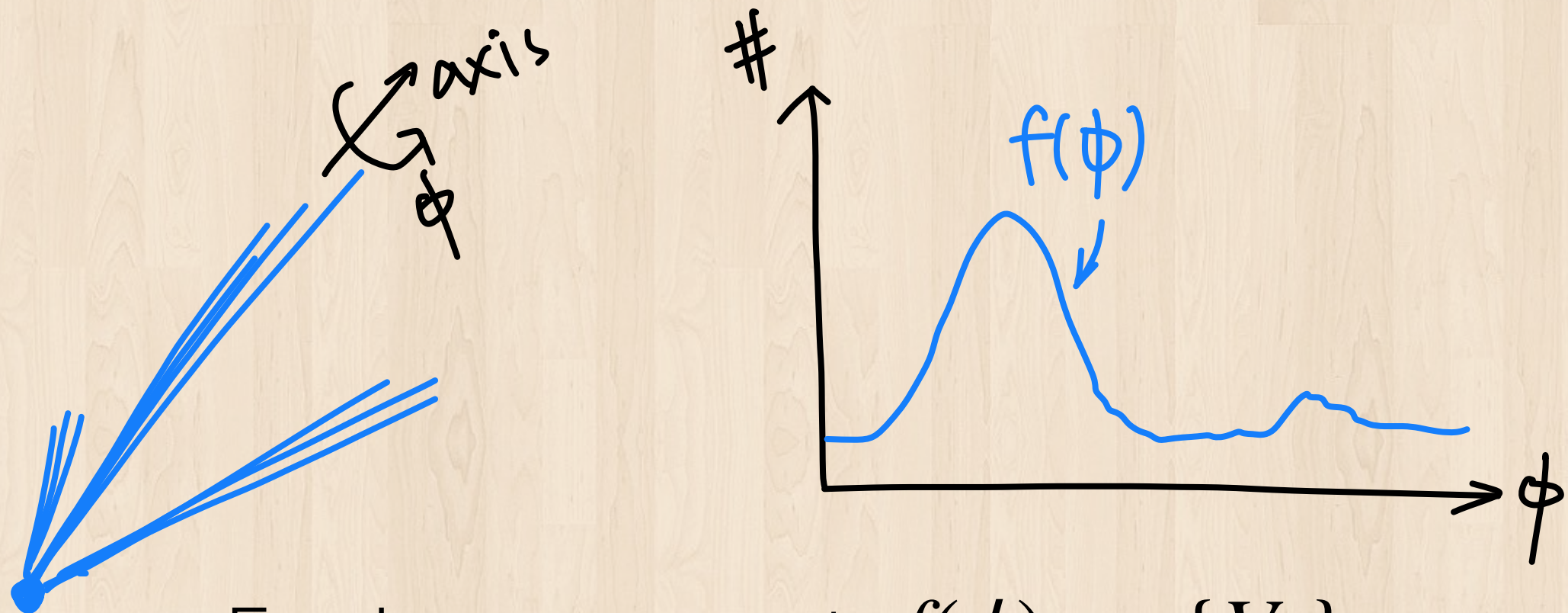


Associated yield ratio: $h\Omega/hE$

In-jet azimuthal asymmetry

We can measure
novel observables

In-jet azimuthal asymmetry



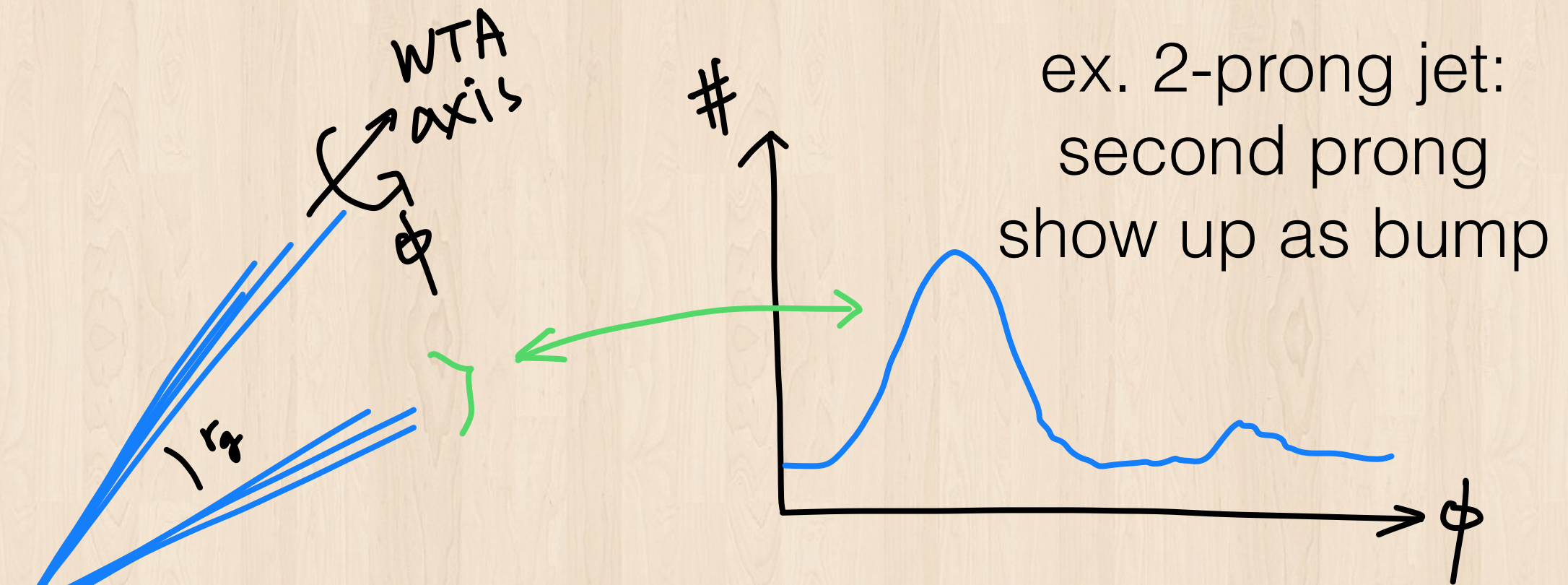
Fourier components $f(\phi) \rightarrow \{V_n\}$
Encodes jet substructure information

Axis choice: regular total momentum vs. WTA axis

Note: NOT the same as the CMS v_2 -in-jet measurement

In-jet azimuthal asymmetry

In the absence of QGP, we are measuring substructure

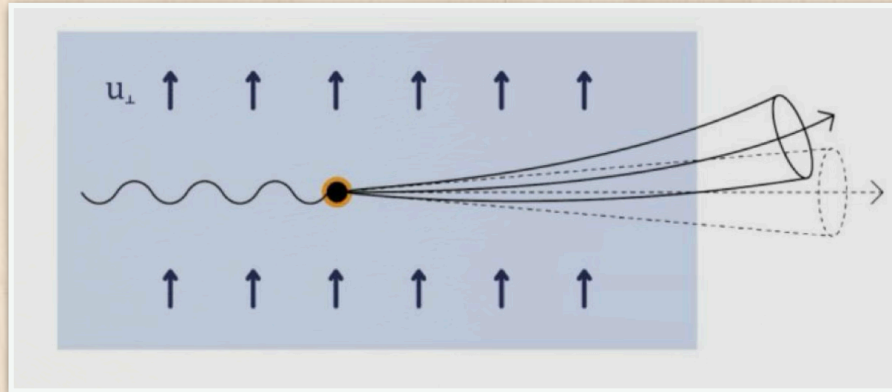


Small $r_g \rightarrow$ bump appear wider in $\phi \rightarrow$ lower V_n

Wider second prong $\rightarrow$ bump wider in $\phi \rightarrow$ lower V_n

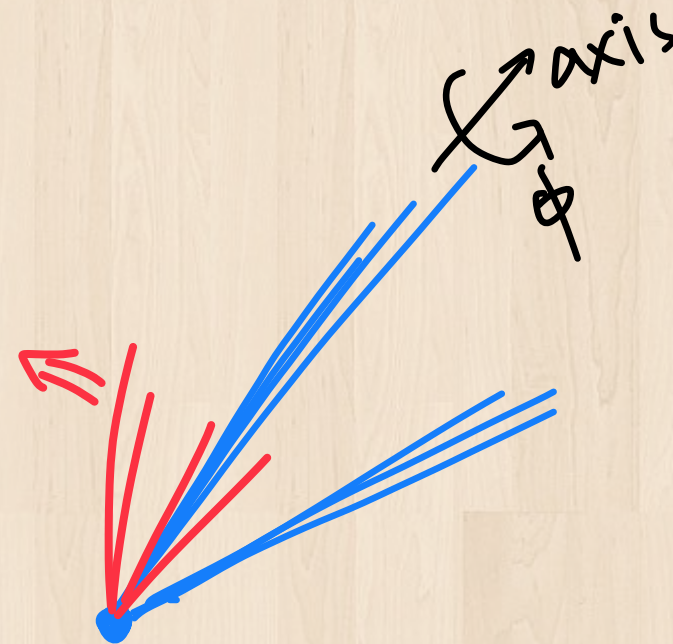
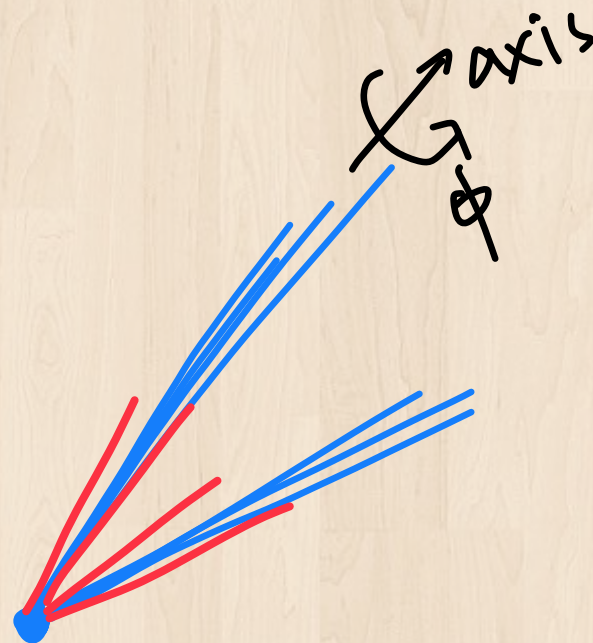
...etc

In-jet azimuthal asymmetry



If there is local flow

Different particles can deflect by different (angular) amount in addition to quenching



→ flow effects could show up as changes to V_n

c.f. Jo Bahder's talk Monday

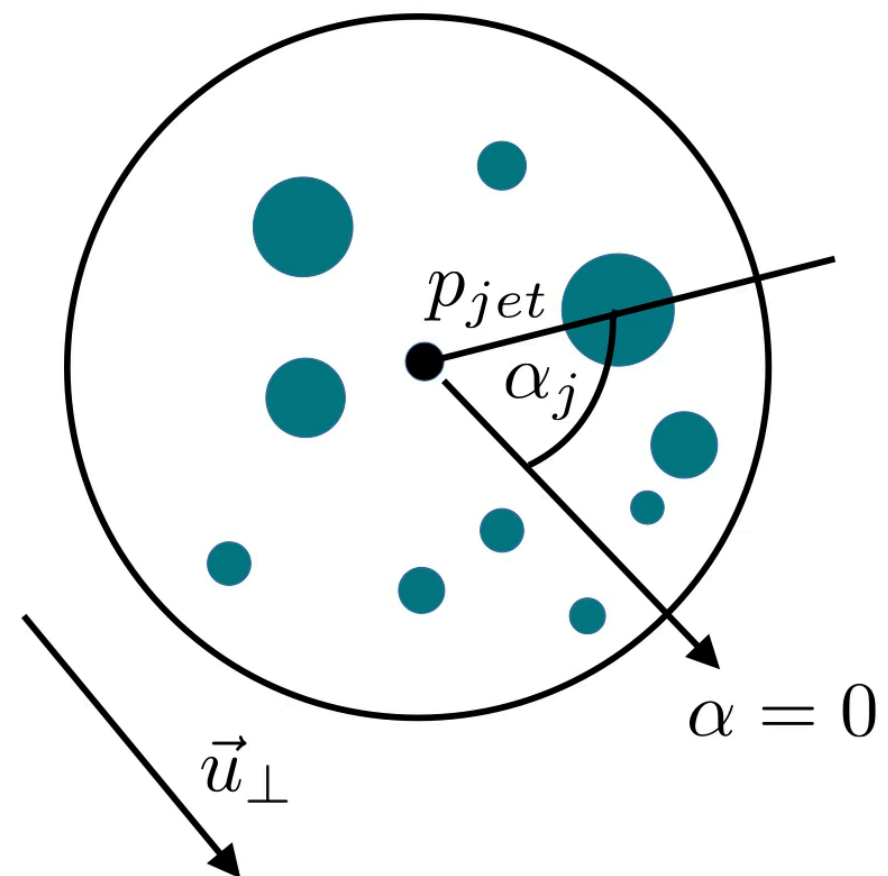
Jet Substructure Harmonics

- Phase alignment with flow coupling direction
- Measures azimuthal distortion towards flow
- Highly dependent on your jet algorithm
 - E.g. anti-kT, enforces a circular jet on $y\phi$ cylinder
- We'll focus on this one for the moment...

$$v_n(E) = \left\langle \frac{\sum_j \cos(n\alpha_j)}{\sum_j} \right\rangle_{events}$$

To eliminate contribution from
pp dist. in small sample:

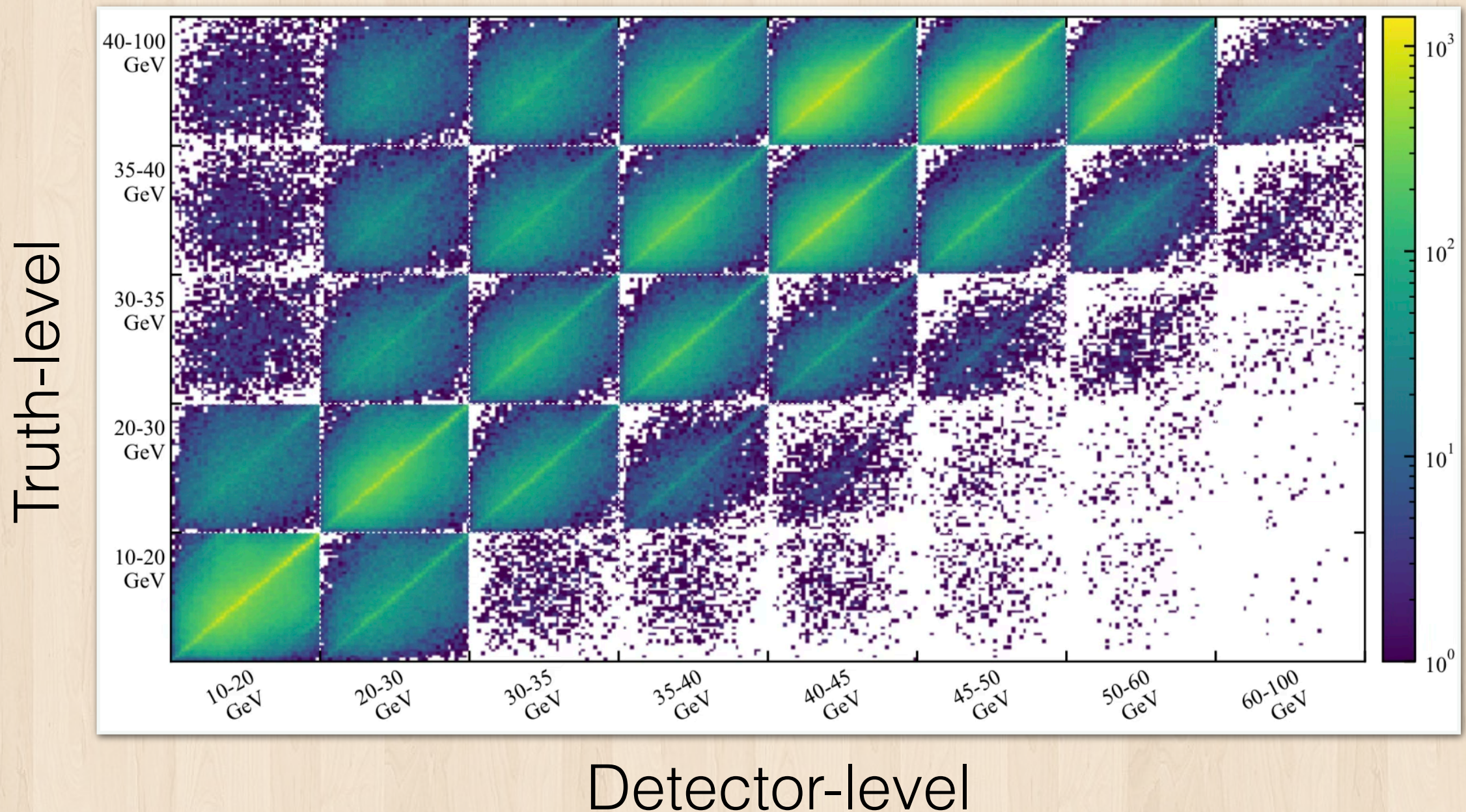
$$\Delta v_n(E) = v_n^{AA}(E) - v_n^{pp}(E)$$



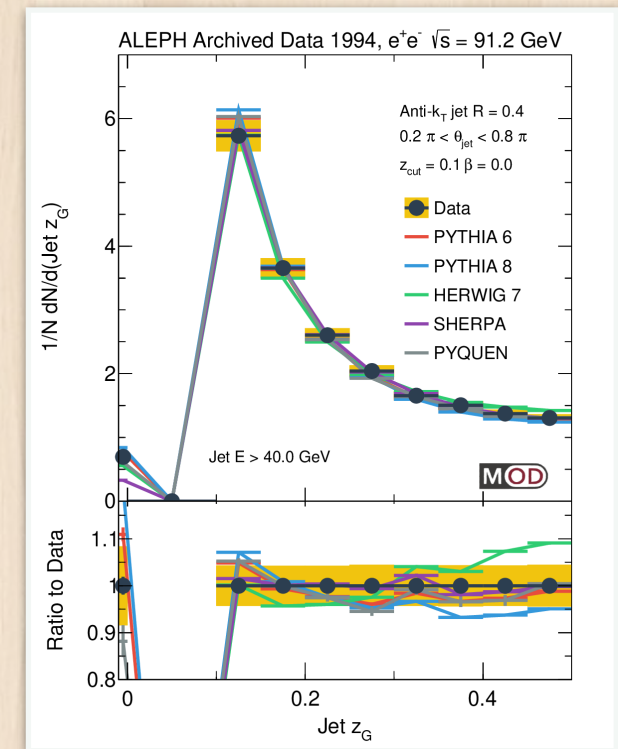
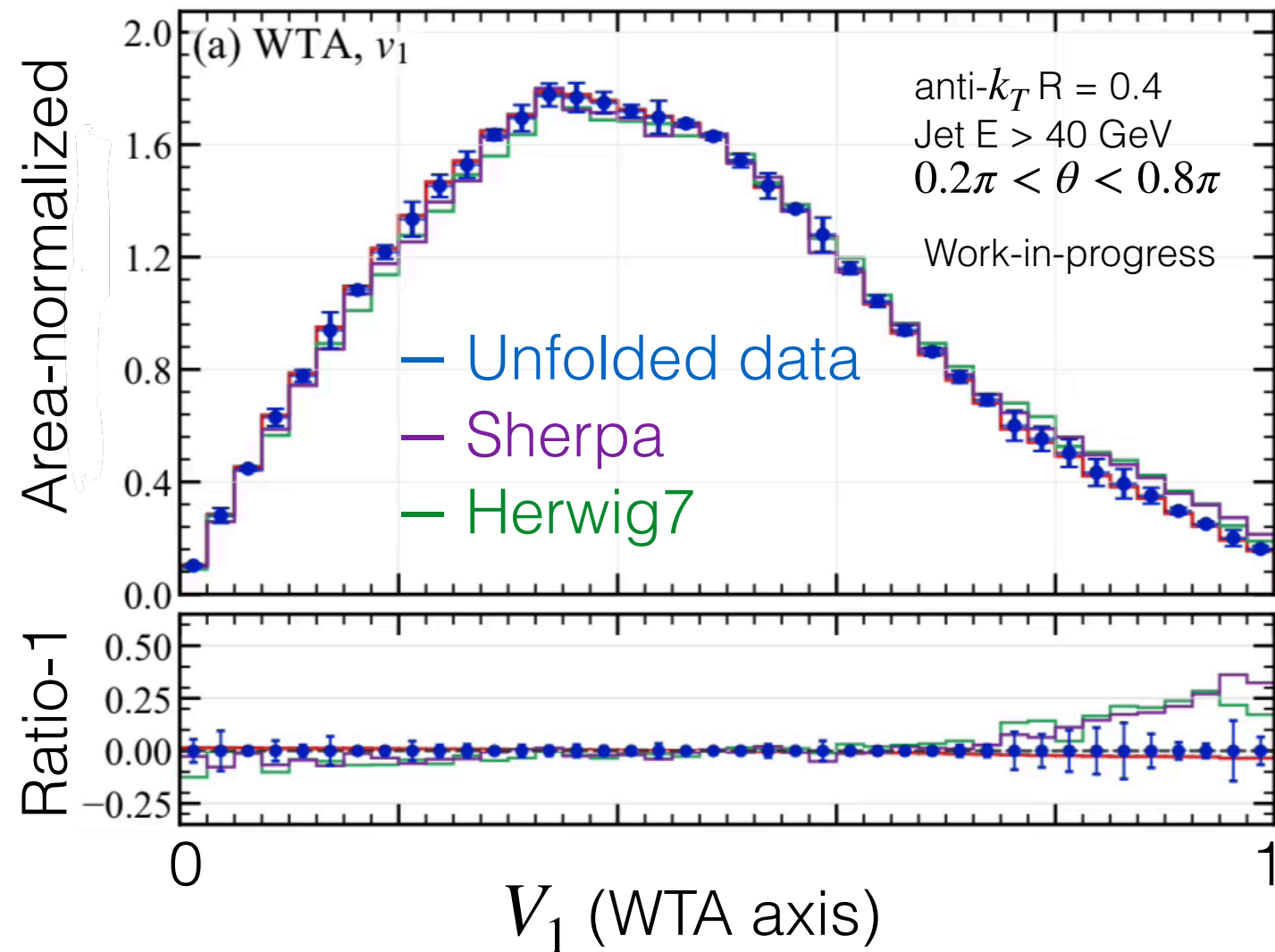
We're doing the no-reference version here

Unfolding for detector effect

Perform 2D unfolding in jet energy and V_n



Very preliminary results



Small trend in V_n

e.g. more balanced prongs $\rightarrow$ busier second subjet $\rightarrow$ slightly larger V_n

We are finalizing the results, arXiv coming soon

Concluding Remarks

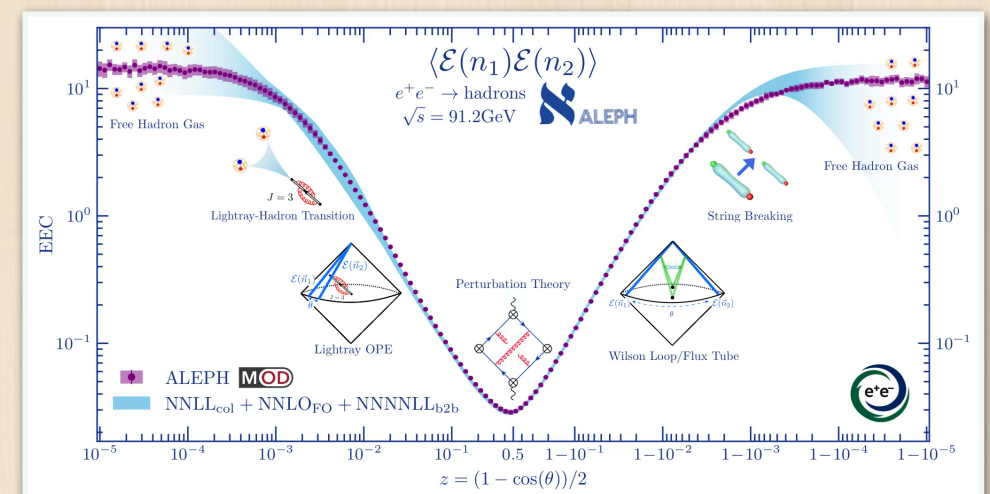
Many ongoing efforts

- Jet studies: **jet spectra radius scan**, Lund plane & multiplicity, substructure correlation, **in-jet asymmetry**, HF jet tagging, EIC clustering studies, axis decorrelation, ...
- Event-wide: **energy-energy correlator**, thrust, Q1 correlator, ...
- Search for QGP-like effects: 2PC, cumulants, **strangeness enhancement**, ...
- $Z \rightarrow \tau\tau$ spin measurement, ...
- Methodology: agentic AI, ML, ...

Today: highlight a few recent studies

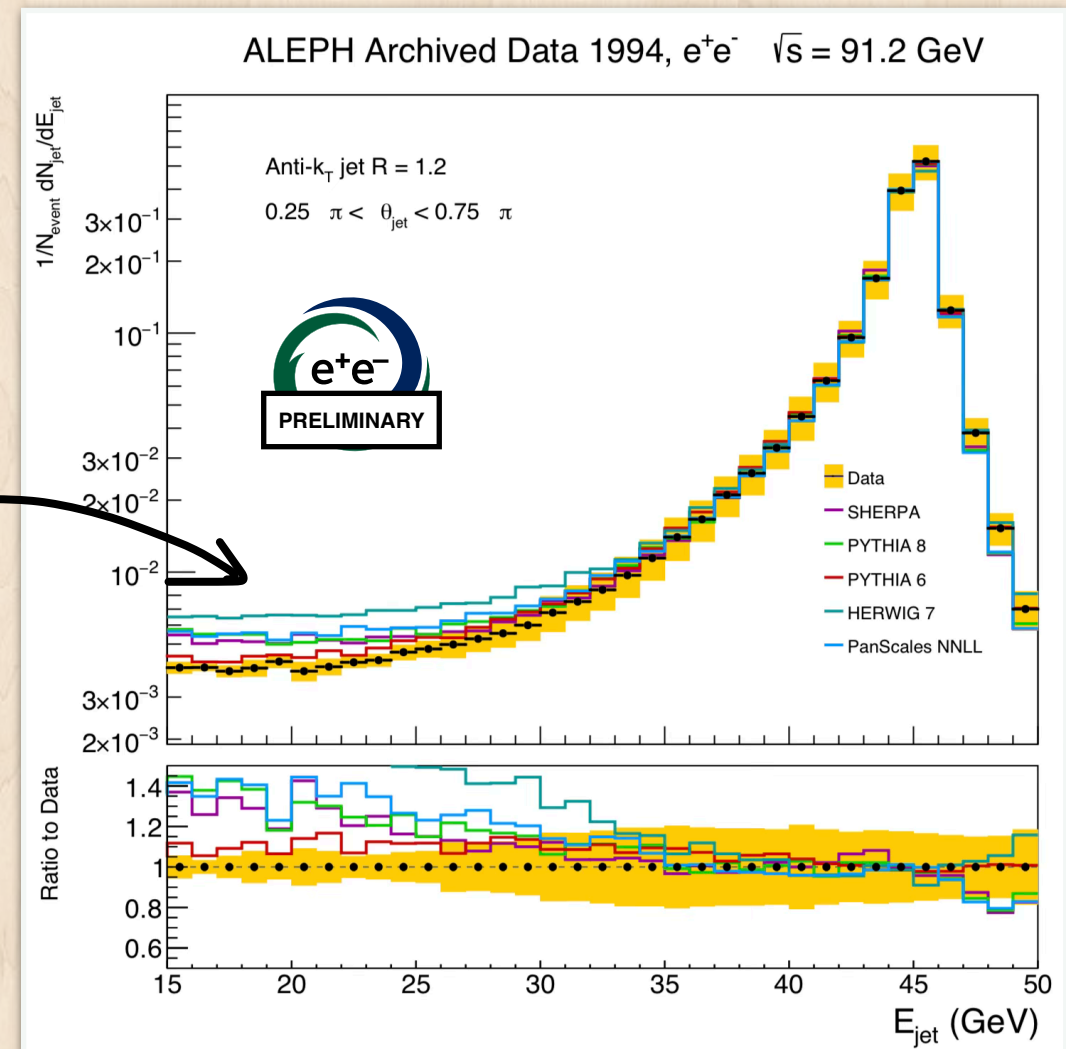
Summary

- e^+e^- provides a **unique dataset to study QCD** without the complication that comes with pp
- Good place to understand baseline for **quark jets**
- **Additional information** can be gained from LEP data
- Capabilities on **jets, correlators, identified particle and novel observables**
- Good place to look for **signatures** attributed to the **QGP** (and glasma)

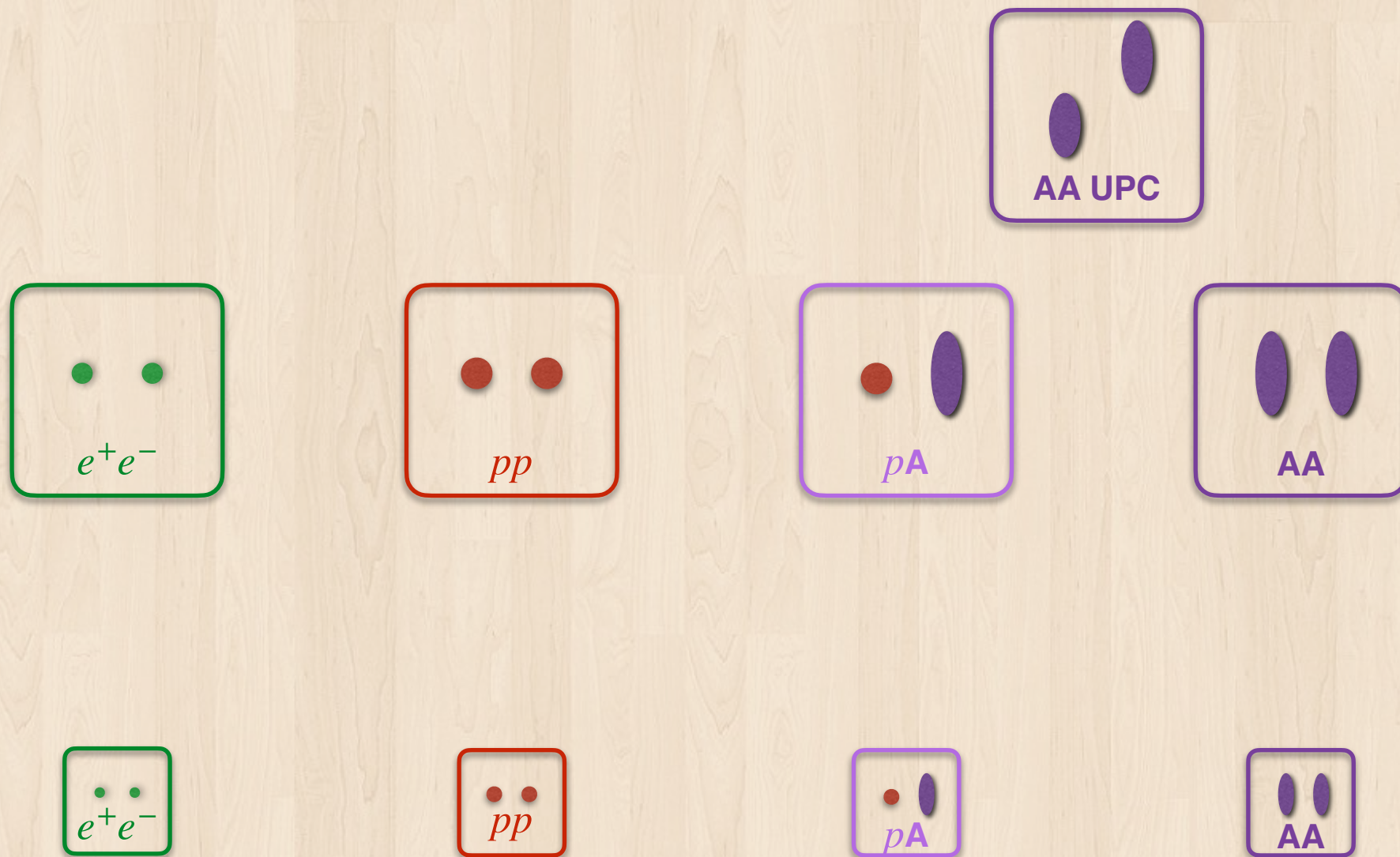


Backup Slides Ahead

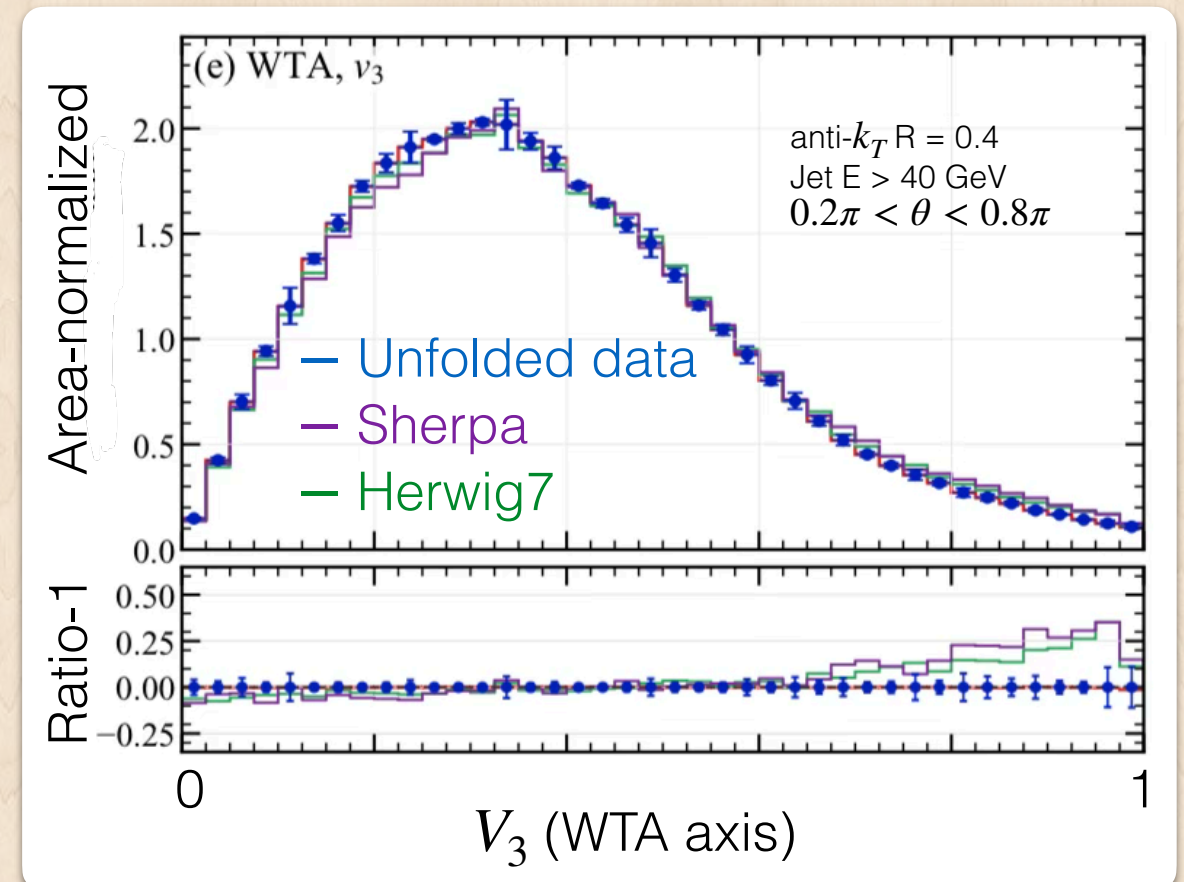
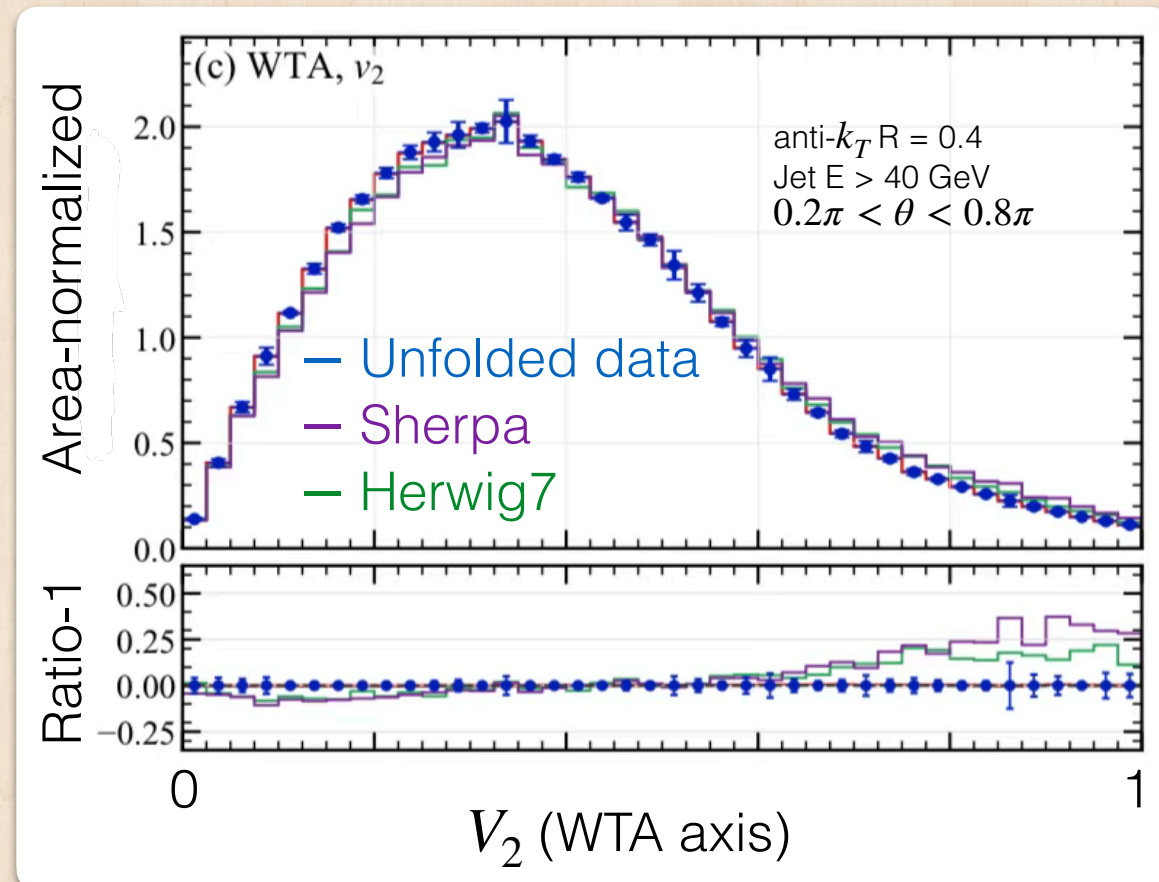
Low E in large R jets



Icons

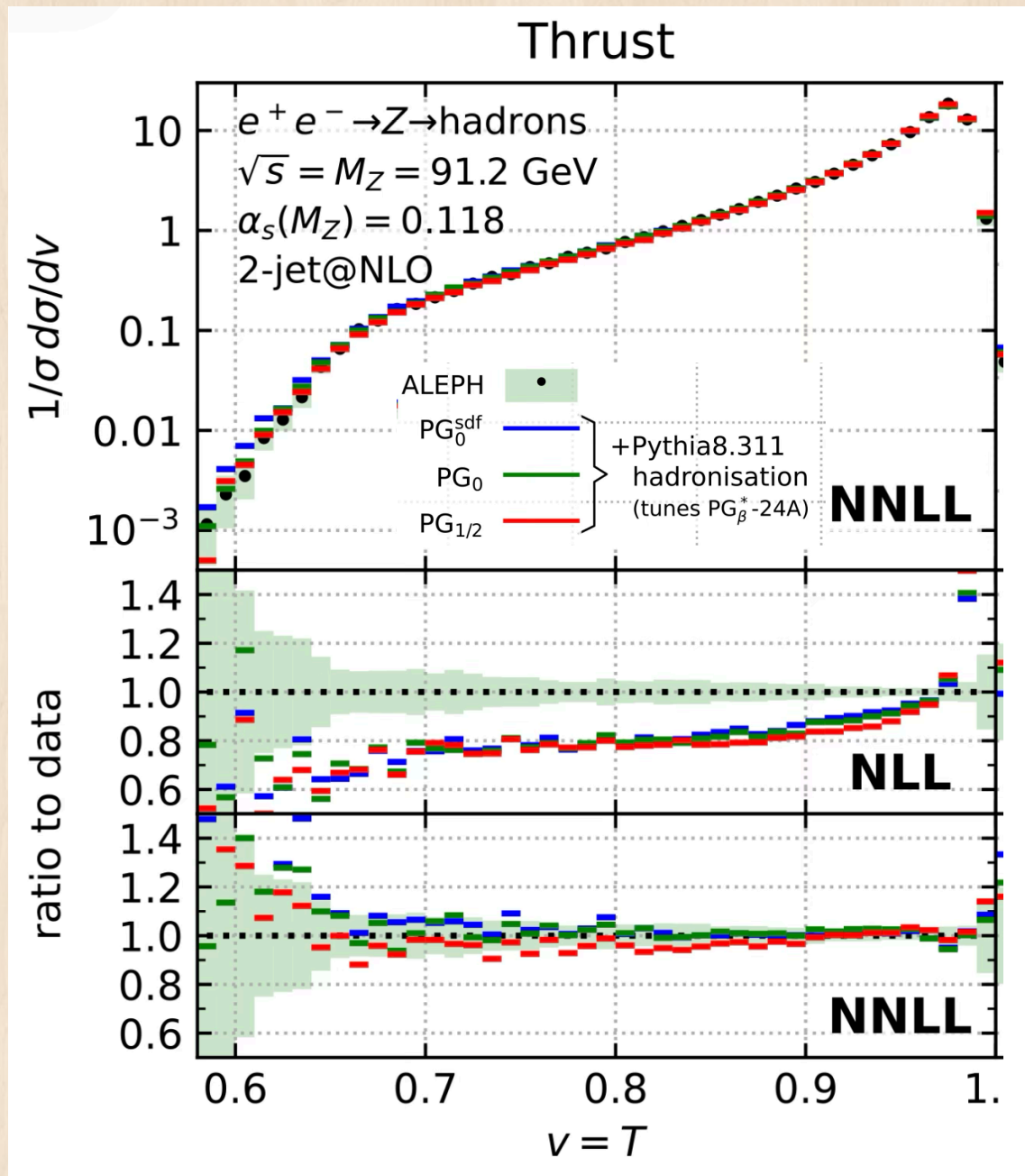


Very preliminary results



We are finalizing the results, arXiv coming soon

c.f. thrust from Panscales



Long-standing issue;
using lower-accuracy
shower one need to
“tune” α_s to describe data

α_s fixed to world average
+ NNLL shower can
potentially resolve this