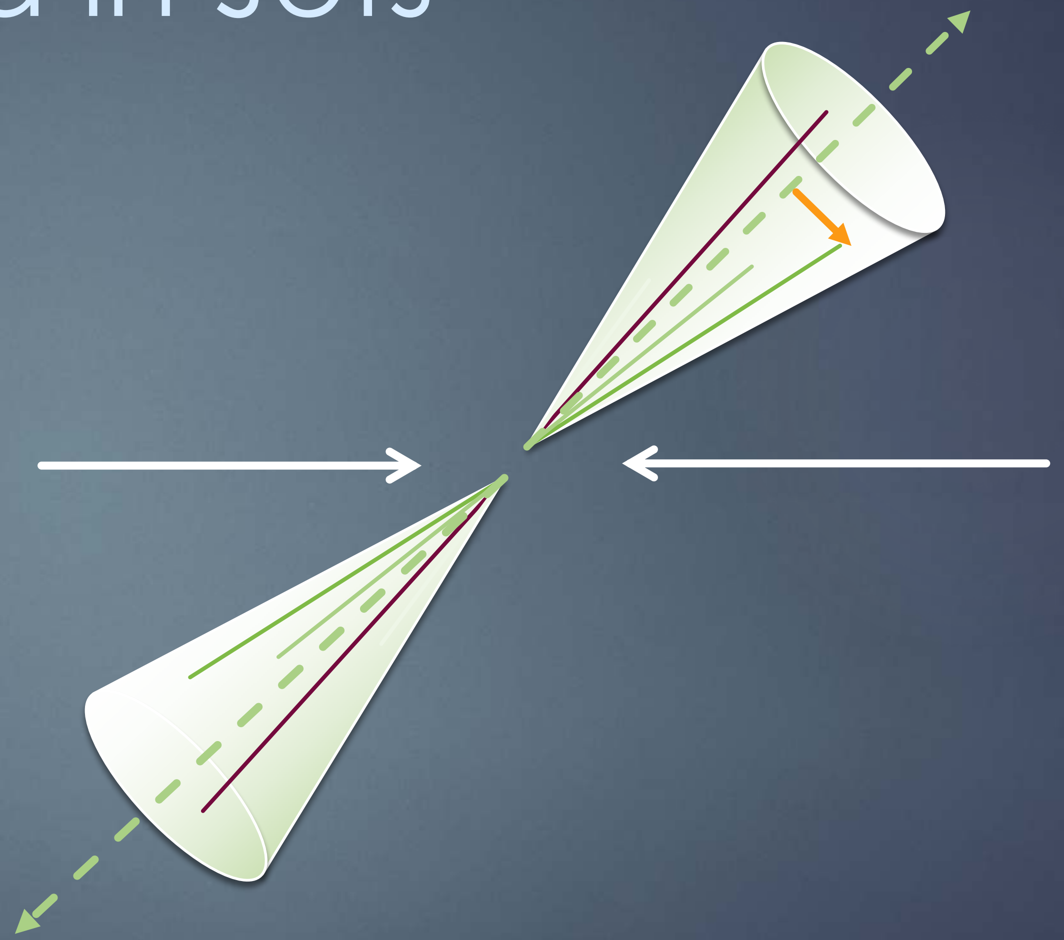
Spin Phenomena in Jets

Renee Fatemi

University of Kentucky



UK

University of Ferrara, September 13th, 2018

SPIN 2018

THE 23RD INTERNATIONAL SPIN SYMPOSIUM

Jets : A Description

What is a jet?

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- Depends on who you ask.

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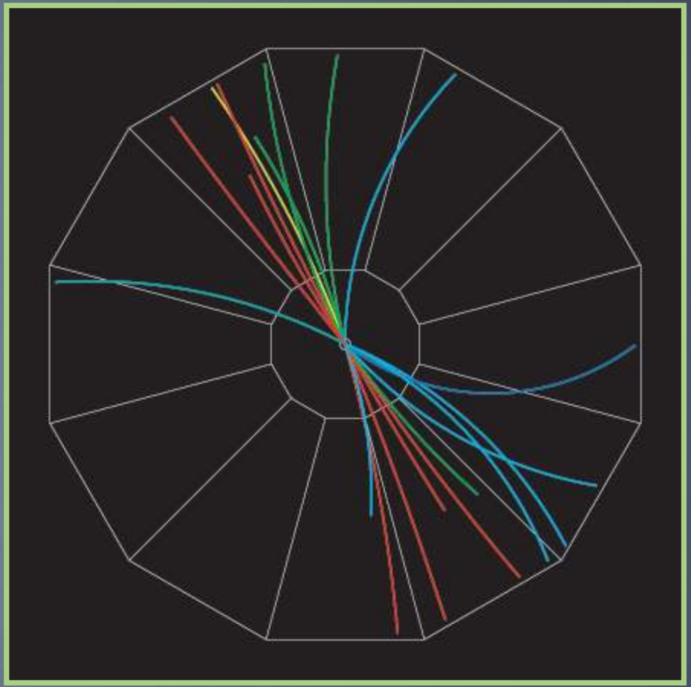
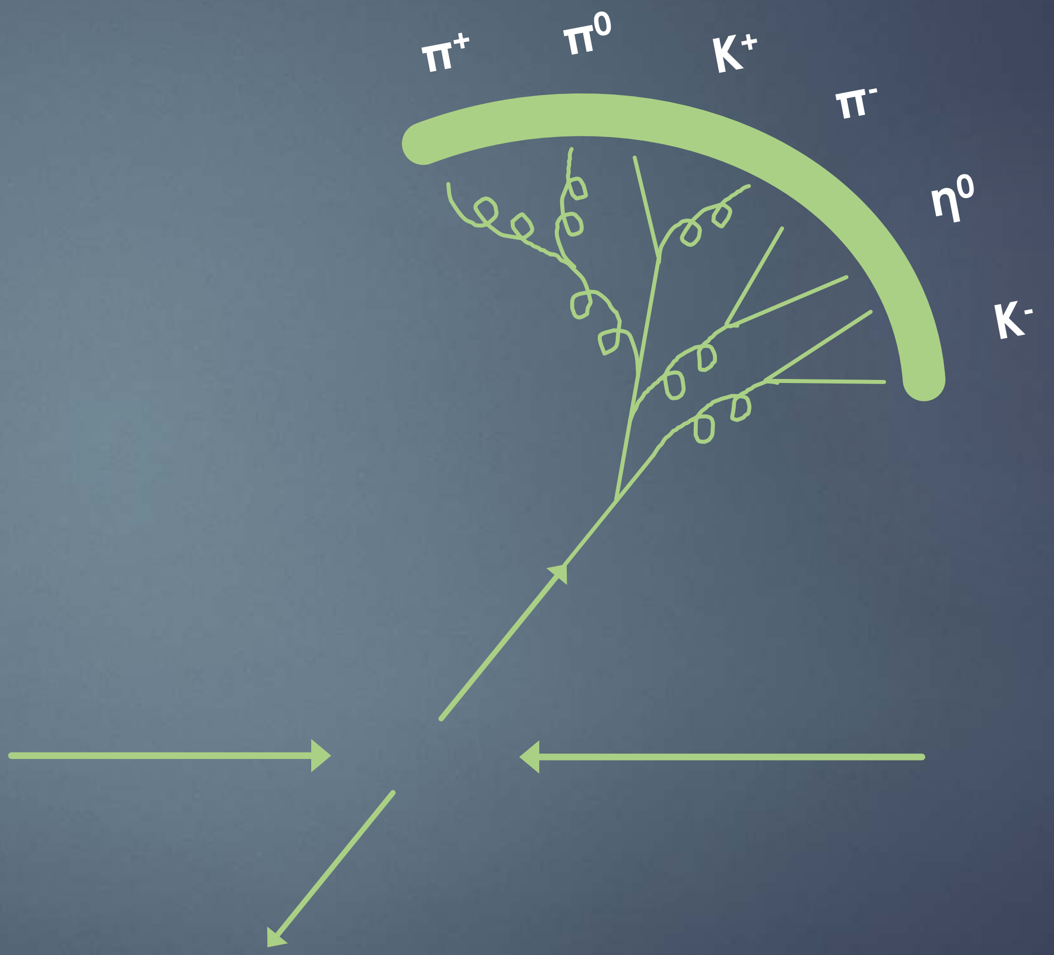
- Depends on who you ask.
- A collimated spray of energy deposited in a detector.



Jets : A Description

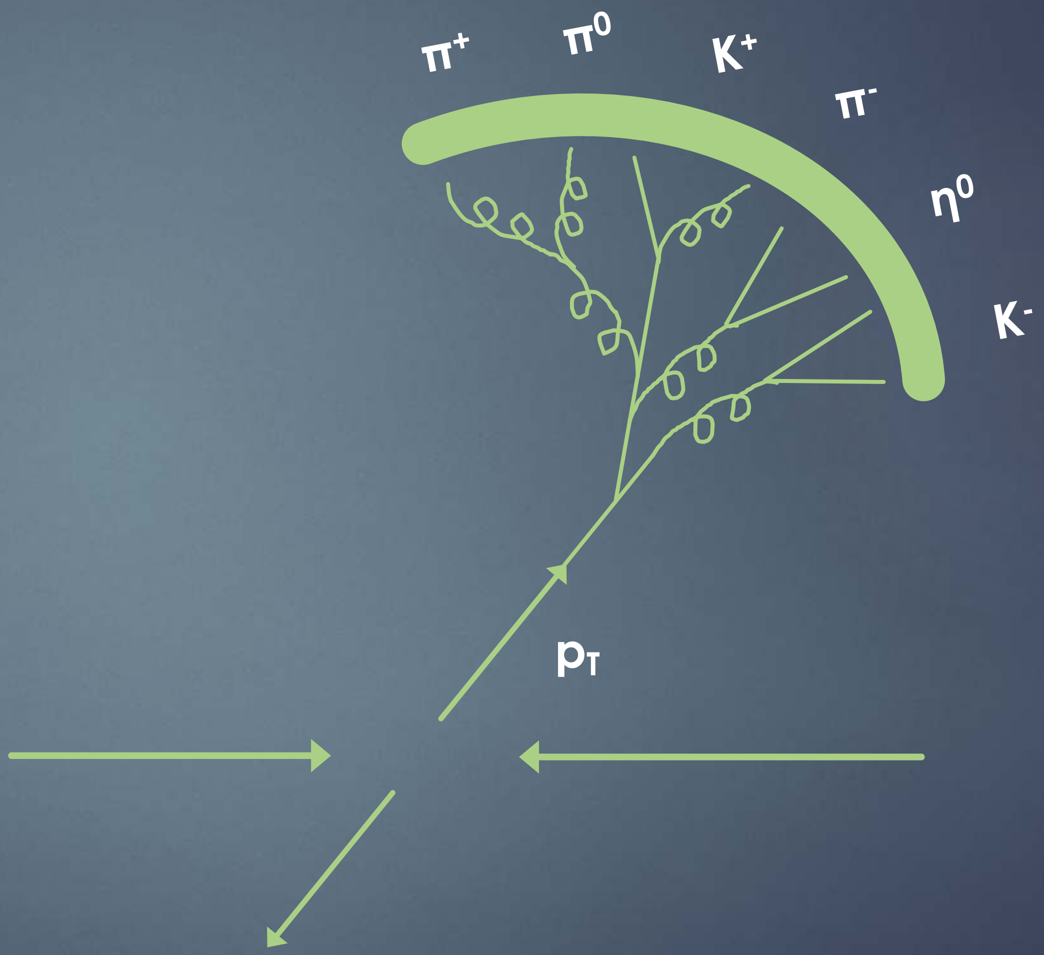
What is a jet?

- Depends on who you ask.
- A collimated spray of energy deposited in a detector.
- The response of a confined parton to a hard interaction.



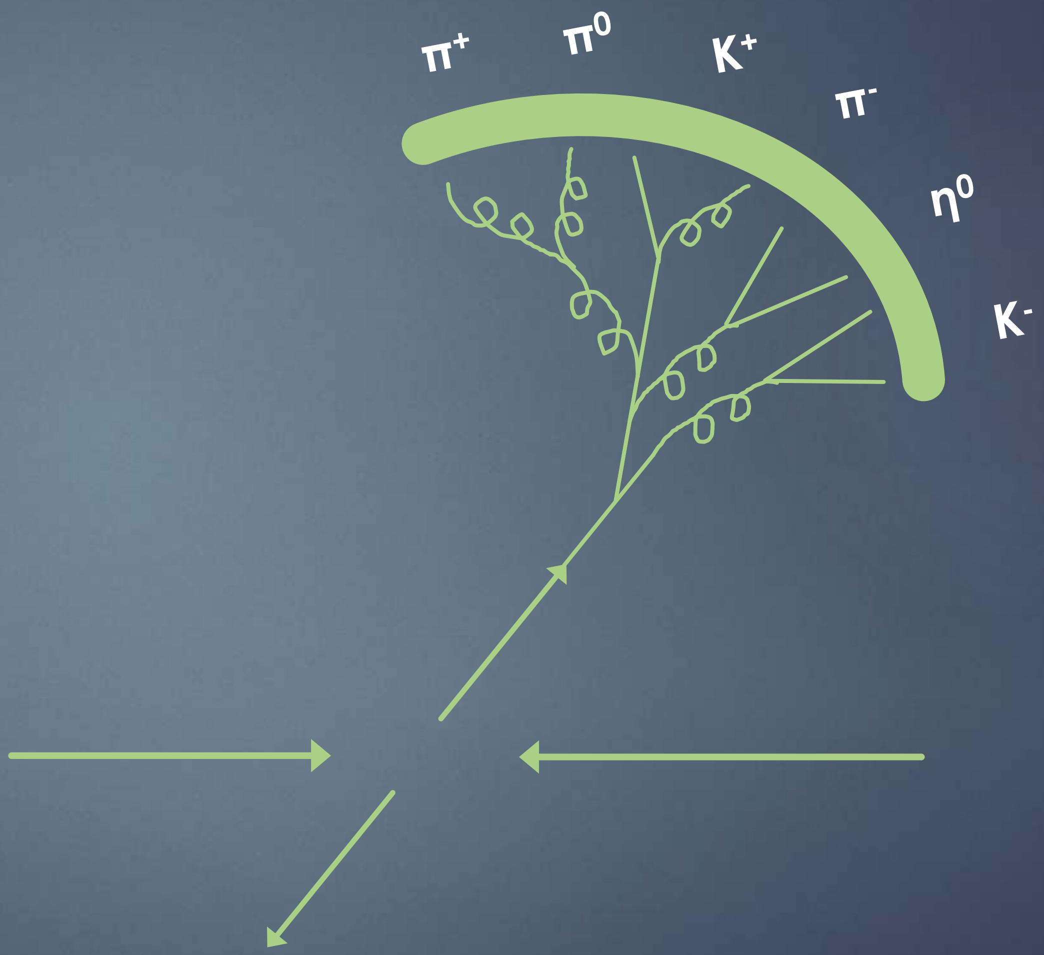
Jets : Microcosm of QCD

- Hard Scattering



Jets : Microcosm of QCD

- Hard Scattering
- Fragmentation and Hadronization



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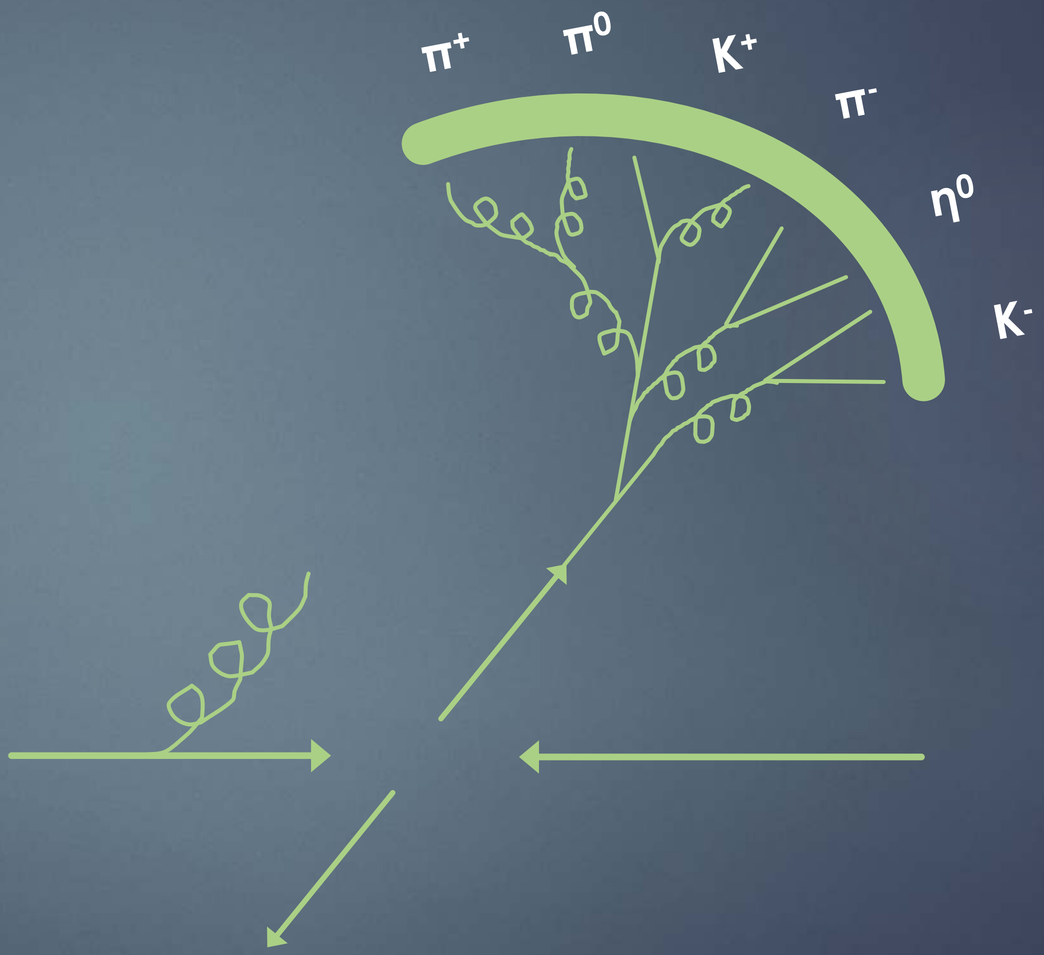
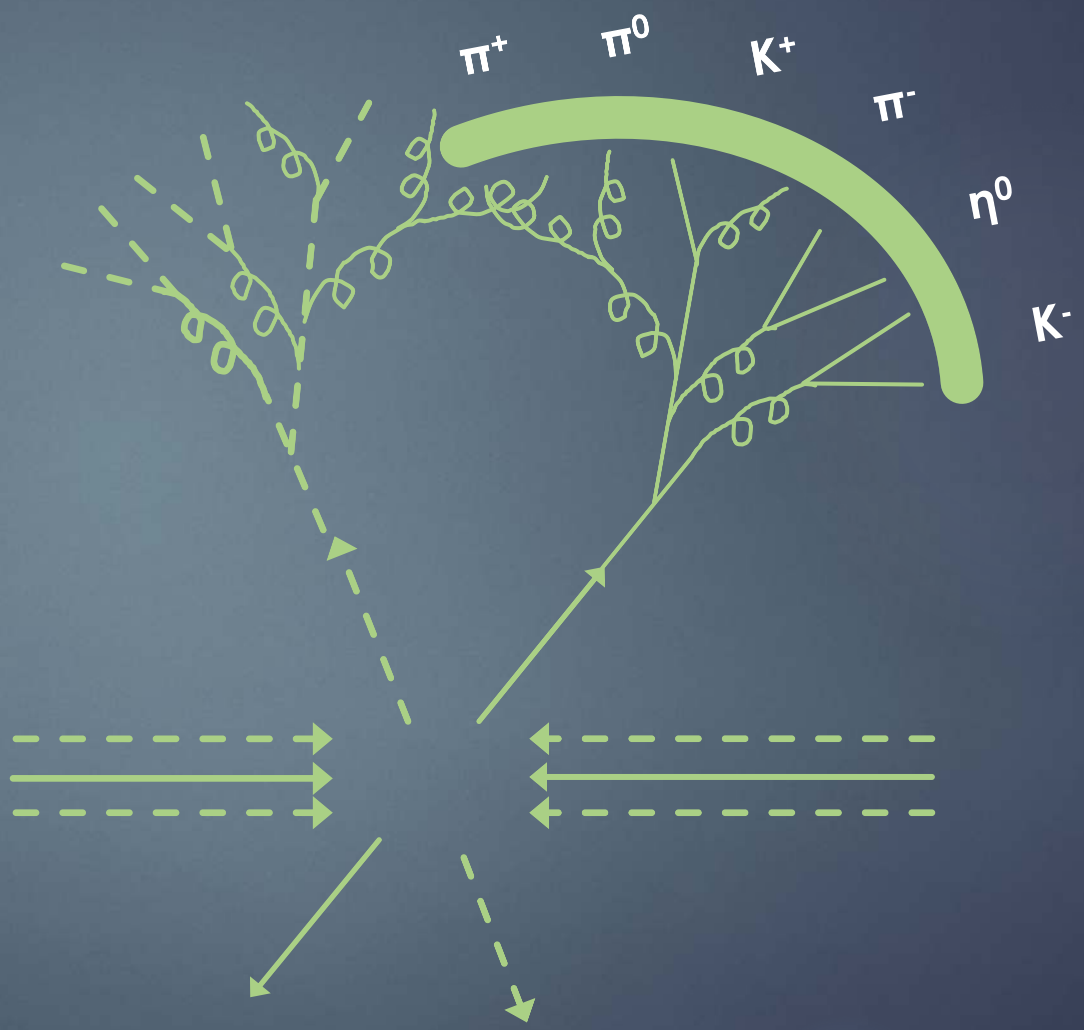


Jets : Microcosm of QCD

- Hard Scattering
- Fragmentation and Hadronization
- Radiation
- Underlying event
  - Multiple parton interactions



Jets : Microcosm of QCD

- Hard Scattering
- Fragmentation and Hadronization
- Radiation
- Underlying event
  - Multiple parton Interactions
  - Interactions with beam remnants

Jets : Microcosm of QCD

Jets have played an integral role in the construction and testing of QCD

- Discovery of the gluon
- The strong coupling constant
- Discovery of the top quark
- Parton Distribution Functions

Ellis, Gaillard and Ross, Nucl. Phys. **B111** (1976) 253
MARK-J Collaboration, Phys. Rev. Lett. **43**, (1979) 830
TASSO Collaboration, Phys. Lett. **86B** (1979) 243
PLUTO Collaboration, Phys. Lett. **86B** (1979) 418

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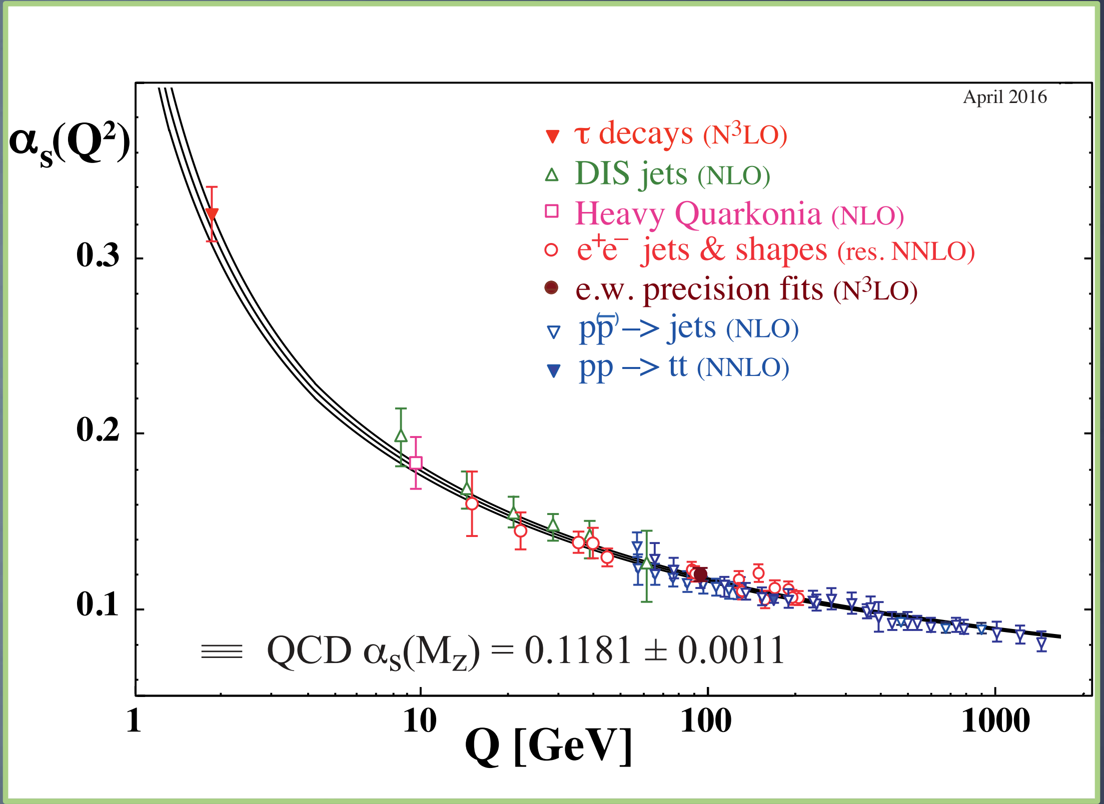

Particle Data Group, Phys. Rev. **D98** (2018) 030001

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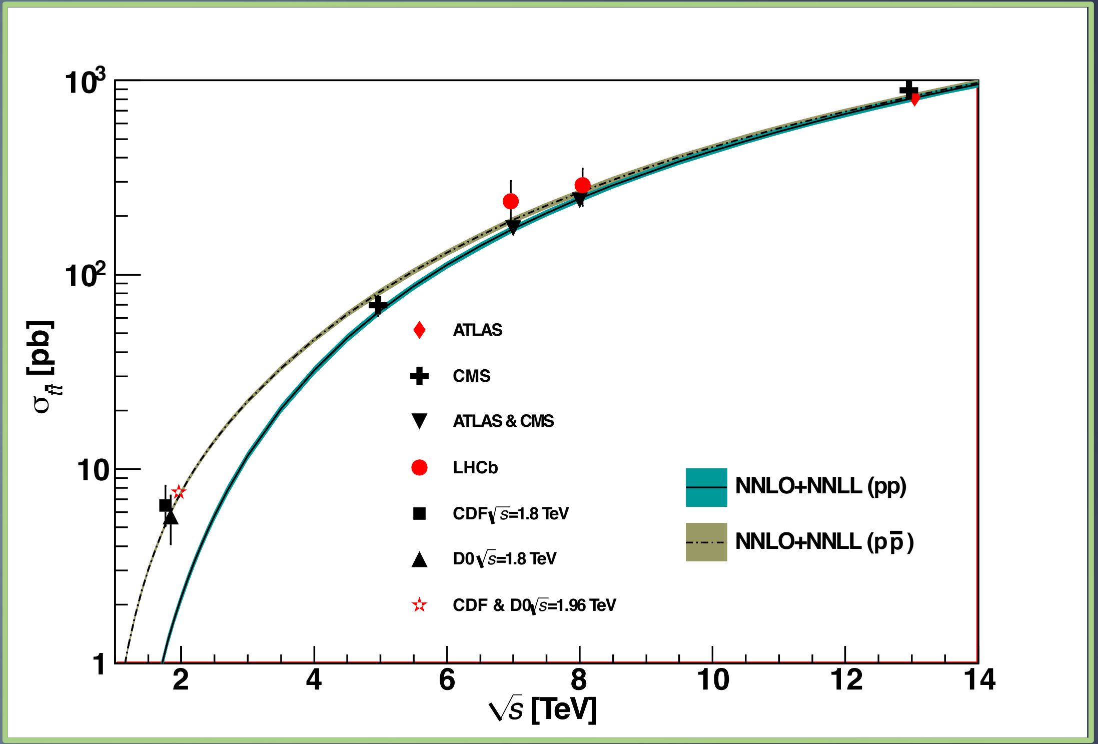

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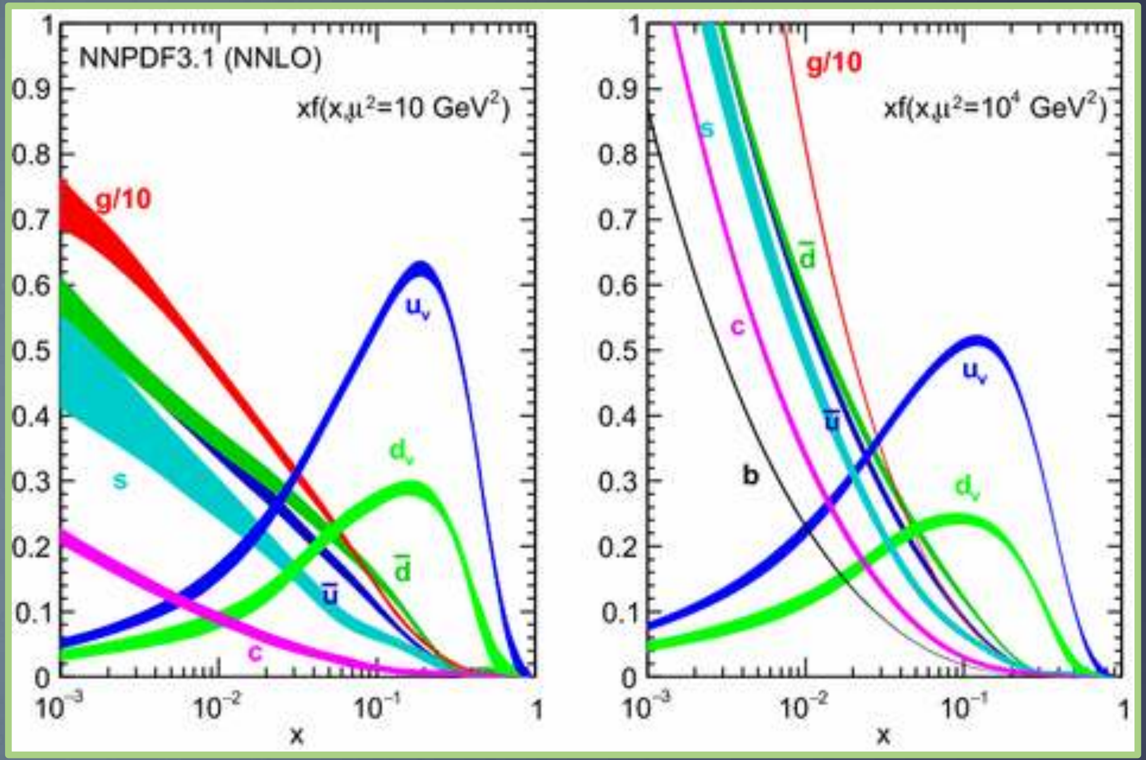
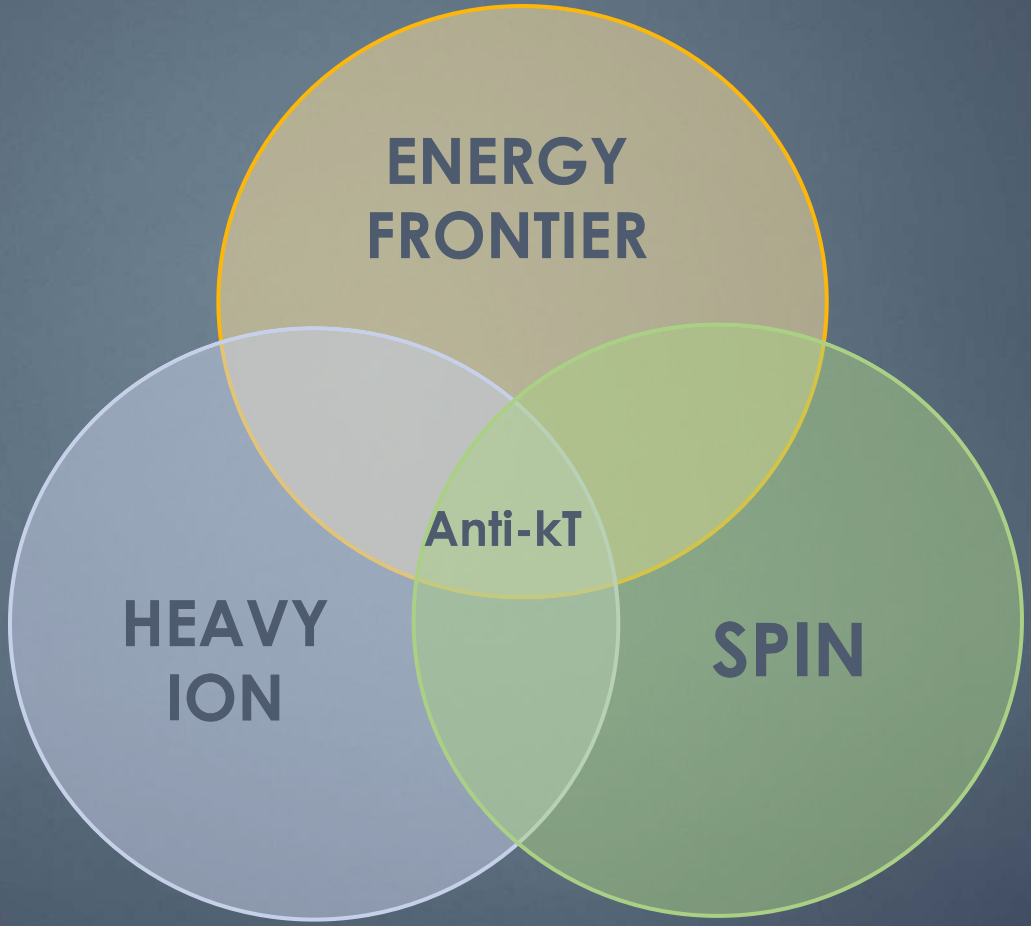


NNPDF Collaboration, Eur. Phys. J. **C77**, no 10, (2017) 663

Last Decade → Explosion of Jetfinding Techniques

$\sqrt{s}$ = 7-13 TeV pp

$\sqrt{s}$ = 0.2-13 TeV
pp, pA, AA



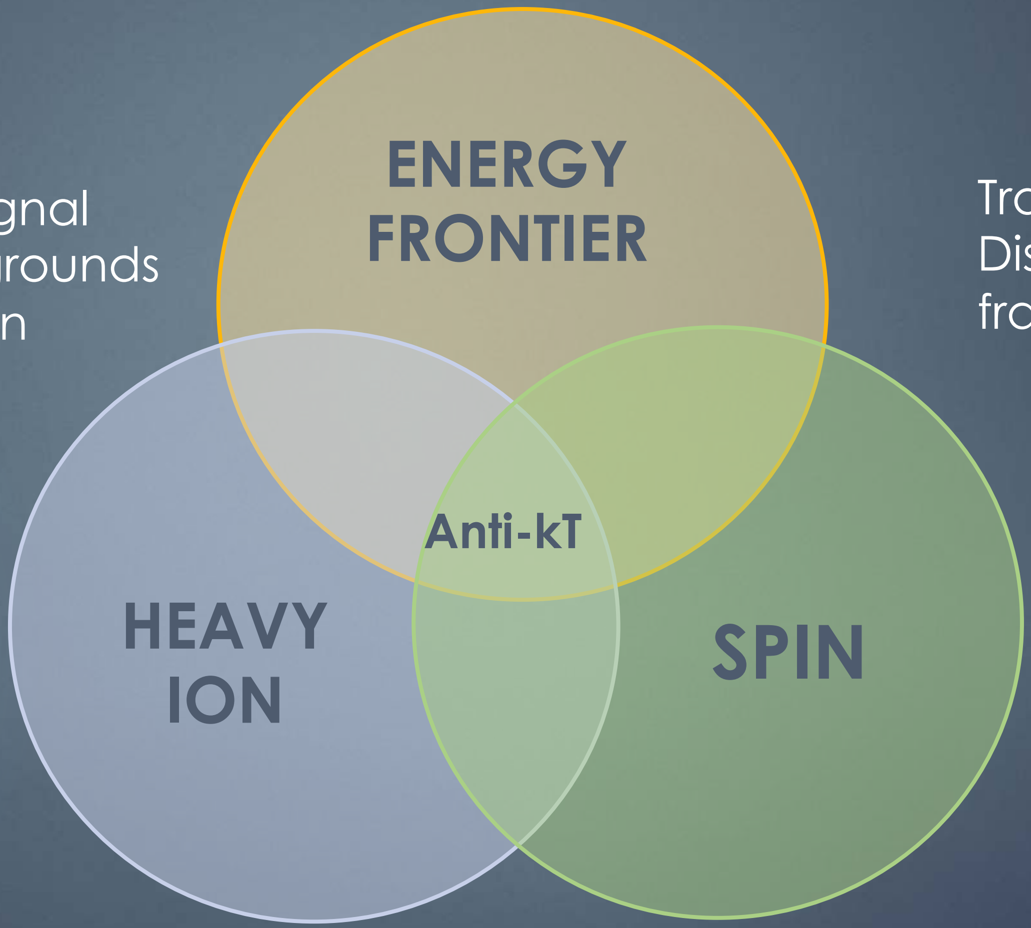
$\sqrt{s}$ = 0.2-0.5 TeV
polarized pp, pA

Last Decade → Explosion of Jetfinding Techniques

$\sqrt{s}$ = 7-13 TeV pp

Extraction of jet signal amid large backgrounds and fragmentation functions.

Transverse Momentum Distributions and gluon fragmentation functions



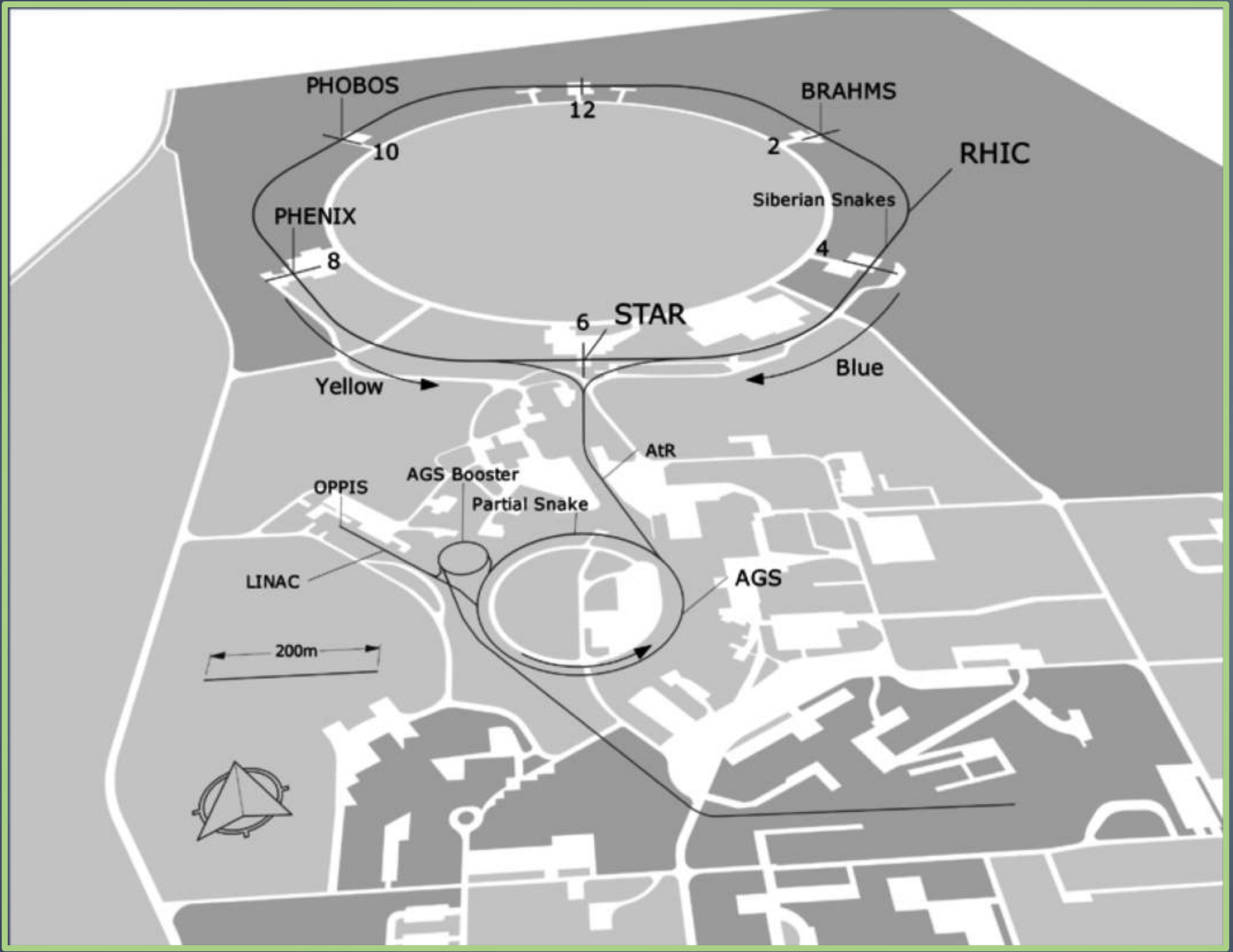
$\sqrt{s}$ = 0.2-13 TeV
pp, pA, AA

$\sqrt{s}$ = 0.2-0.5 TeV
polarized pp, pA

Jet cross-sections and fragmentation functions

Relativistic Heavy Ion Collider

the world's first and only polarized proton collider…



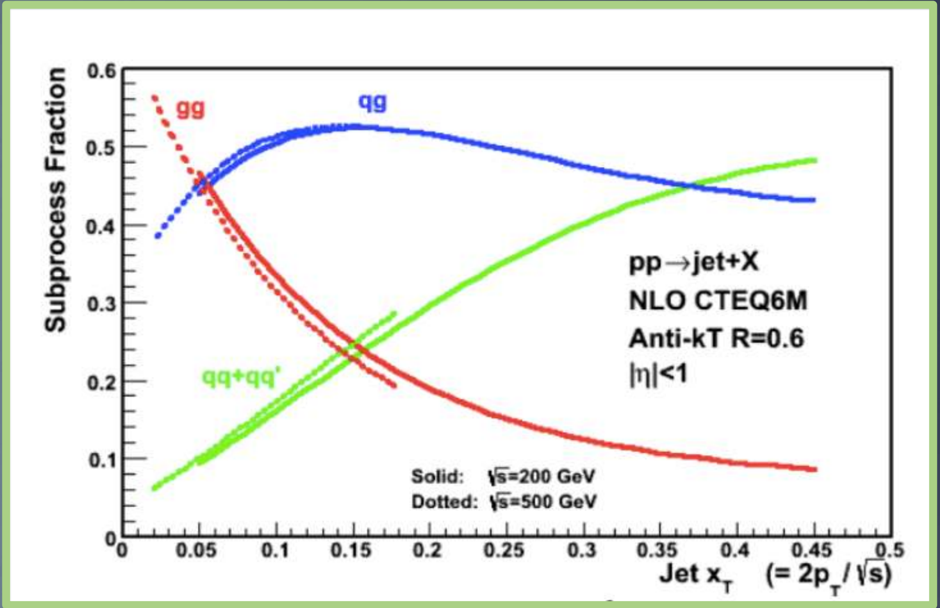
This talk will discuss results from the following runs:

YEAR	√s GeV	∫ℒ* pb^{-1}	Spin	Pol%
2009	200	114	L	56
2011	500	166	T	48
2012	200	74	T	59
2012	510	283	L	52
2013	510	1040	L	52

Jet physics at a $\vec{p}\vec{p}$ collider

Gluons!

- Leading order sensitivity to $\Delta g(x, Q^2)$
- Lower jet $p_T \rightarrow$ more gluons
- Inclusive jets give highest statistical power, while dijets permit reconstruction of x_1 & x_2 at leading order
- Use double spin asymmetries A_{LL} in longitudinally polarized collisions to gain sensitivity to the gluon helicity.

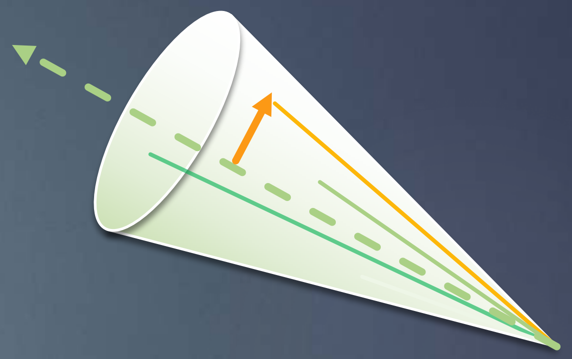


$x \sim x_T e^{\pm\eta} = \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$

$$A_{LL} \propto \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{AB} \Delta f_A \Delta f_B \times \Delta\sigma_{AB\rightarrow jet+X}}{\sum_{AB} f_A f_B \times \sigma_{AB\rightarrow jet+X}}$$

Jet physics at a $\vec{p}\vec{p}$ collider

Transverse Momentum Distributions



- Reconstruction of hadrons inside a jet gives access to momentum *along* (z) and *transverse* (j_T) to the jet axis. Note J_T is similar to SIDIS hadron p_T but it is relative to the jet axis .
- Access to both **quark and gluon TMDS** via modulations of the transverse single spin asymmetry.

$$A_{UT}^{\sin\phi}\sin(\phi)=\frac{\sigma^{\uparrow}(\phi)-\sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi)+\sigma^{\downarrow}(\phi)}$$

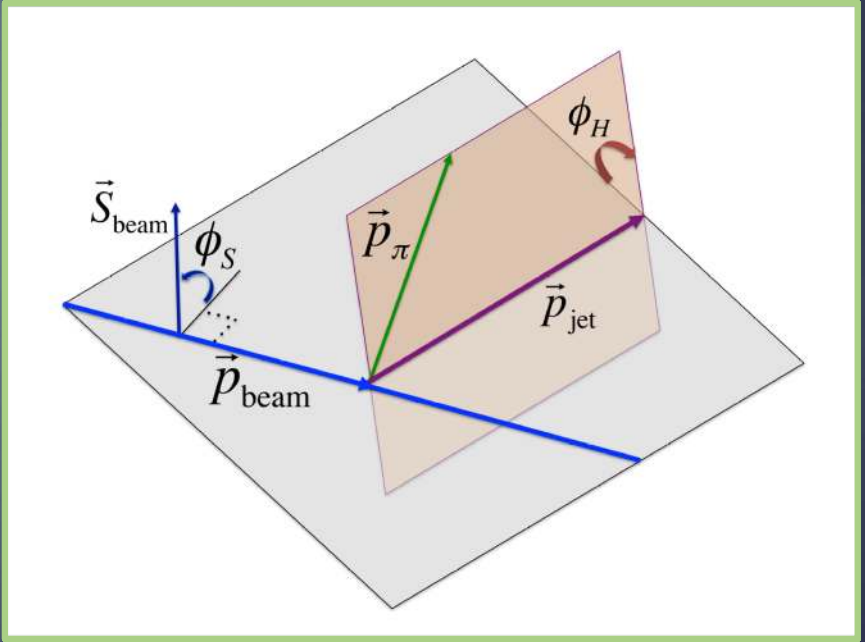
- **$\sin(\phi_s-\phi_H)$**

  Transversity $\otimes$ Collins FF

  Recent work by Kang, Liu, Ringer and Xing JHEP 1711 (2017) 068 indicate universality holds in pp collisions!

- **$\sin(\phi_s-2\phi_H)$**

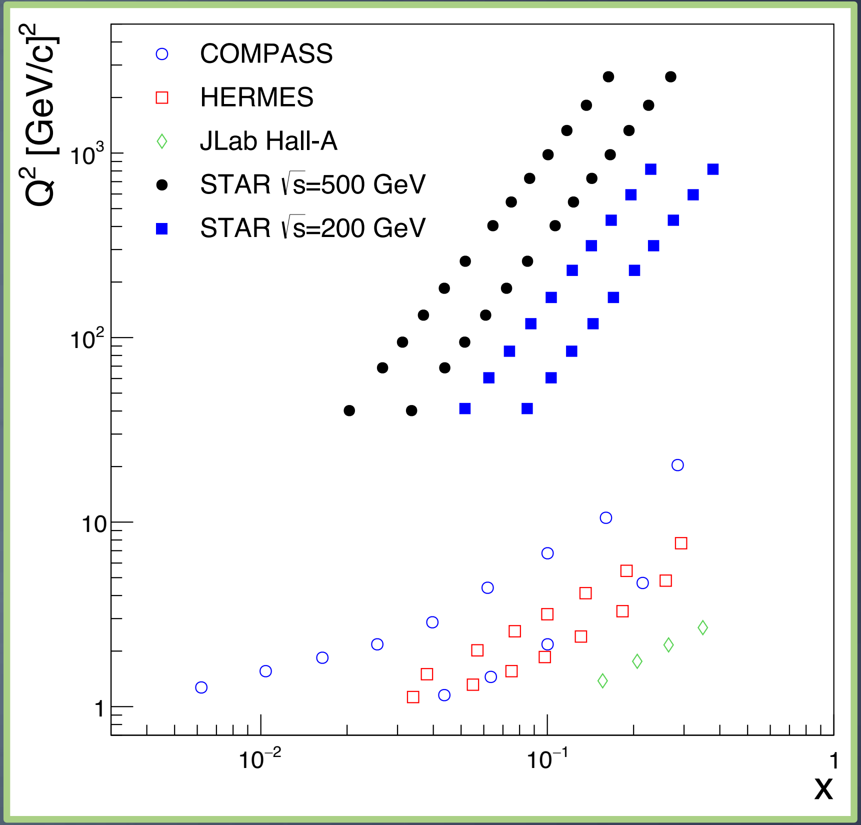
  Gluon Linear Polarization $\otimes$ Collins-Like FF



Jet physics at a $\vec{p}\vec{p}$ collider

Transverse Momentum Distributions

- Reconstruction of hadrons inside of jet gives access to hadron transverse momentum j_T and **z**
- Access to both **quark and gluon TMDS** via modulations of the transverse single spin asymmetry.
- **Evolution**
  - non-perturbative factors that must be measured
  - pp colliders access higher Q^2 than fixed target experiments
  - Provides insights into the size of observables we want to measure at an EIC.
- **Universality**
  - Comparisons to SIDIS allow separation of intrinsic properties of hadrons from interaction dependent dynamics



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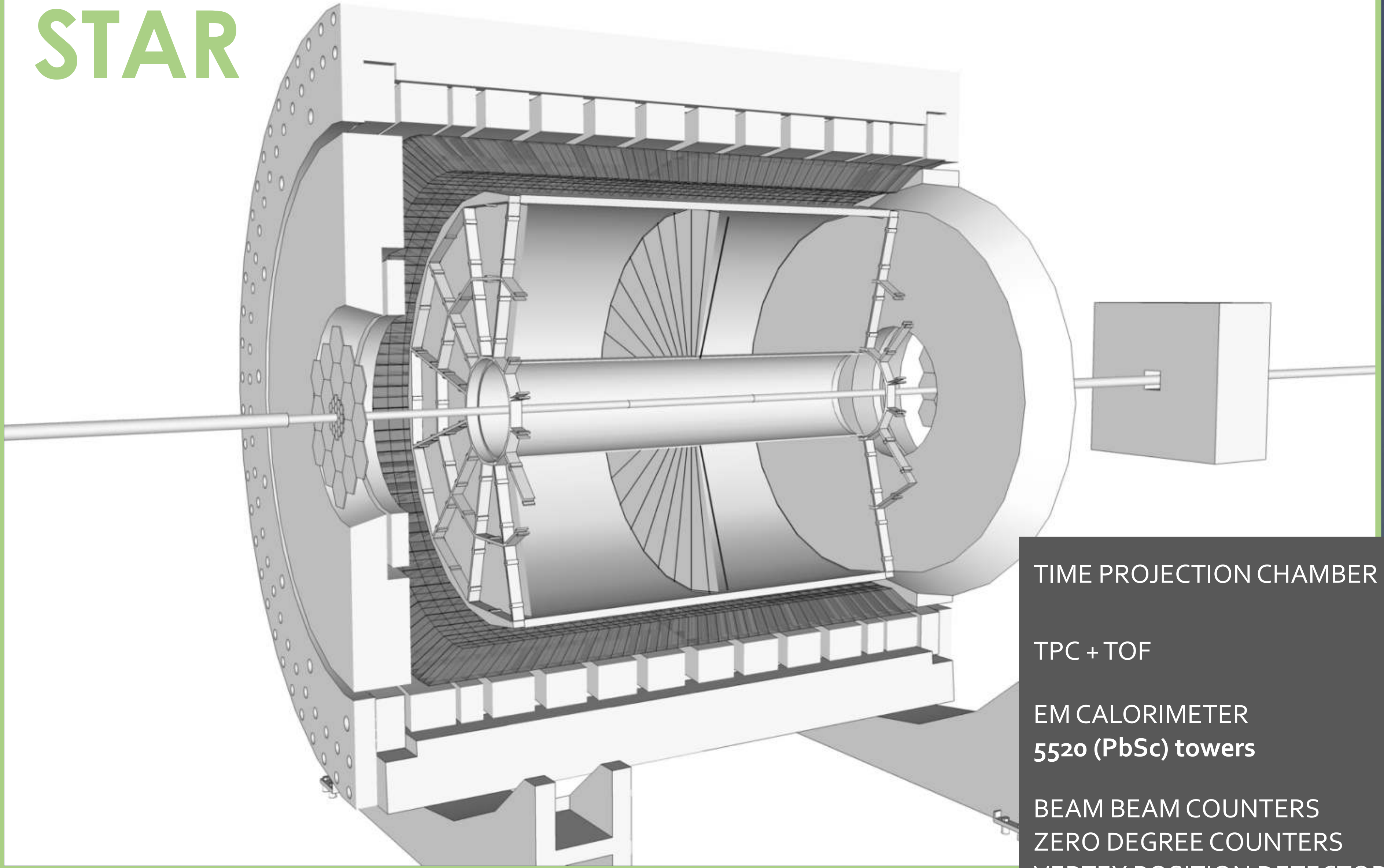
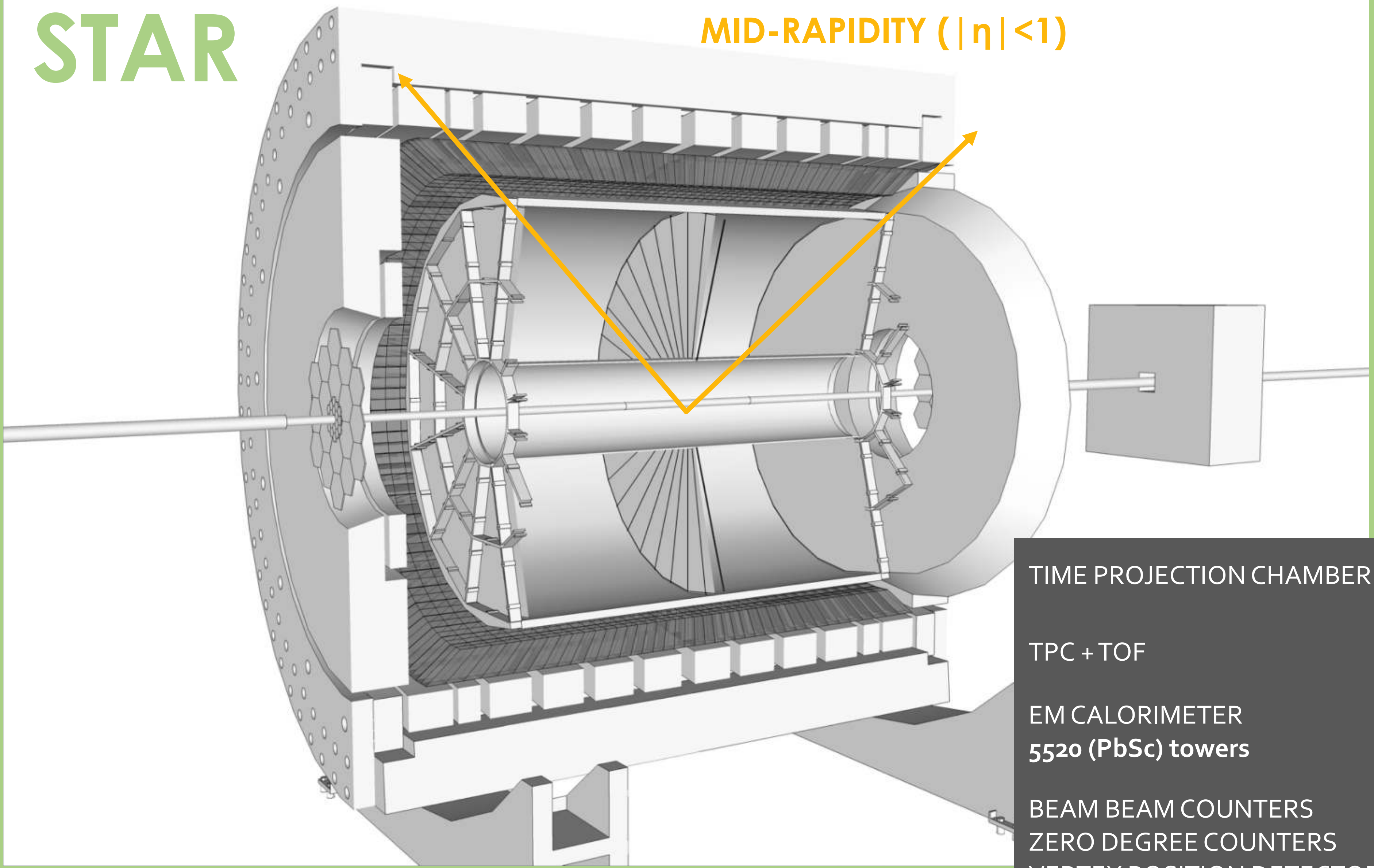


TIME PROJECTION CHAMBER	CHARGED PARTICLE TRACKING
TPC + TOF	CHARGED PARTICLE IDENTIFICATION
EM CALORIMETER **5520 (PbSc) towers**	EM PARTICLE DETECTION HIGH PT TRIGGERING
BEAM BEAM COUNTERS ZERO DEGREE COUNTERS VERTEX POSITION DETECTORS	RELATIVE LUMINOSITY MINIMUM BIAS TRIGGERING
FORWARD MESON DETECTOR	**Pb-Glass EM Calorimeter**

STAR



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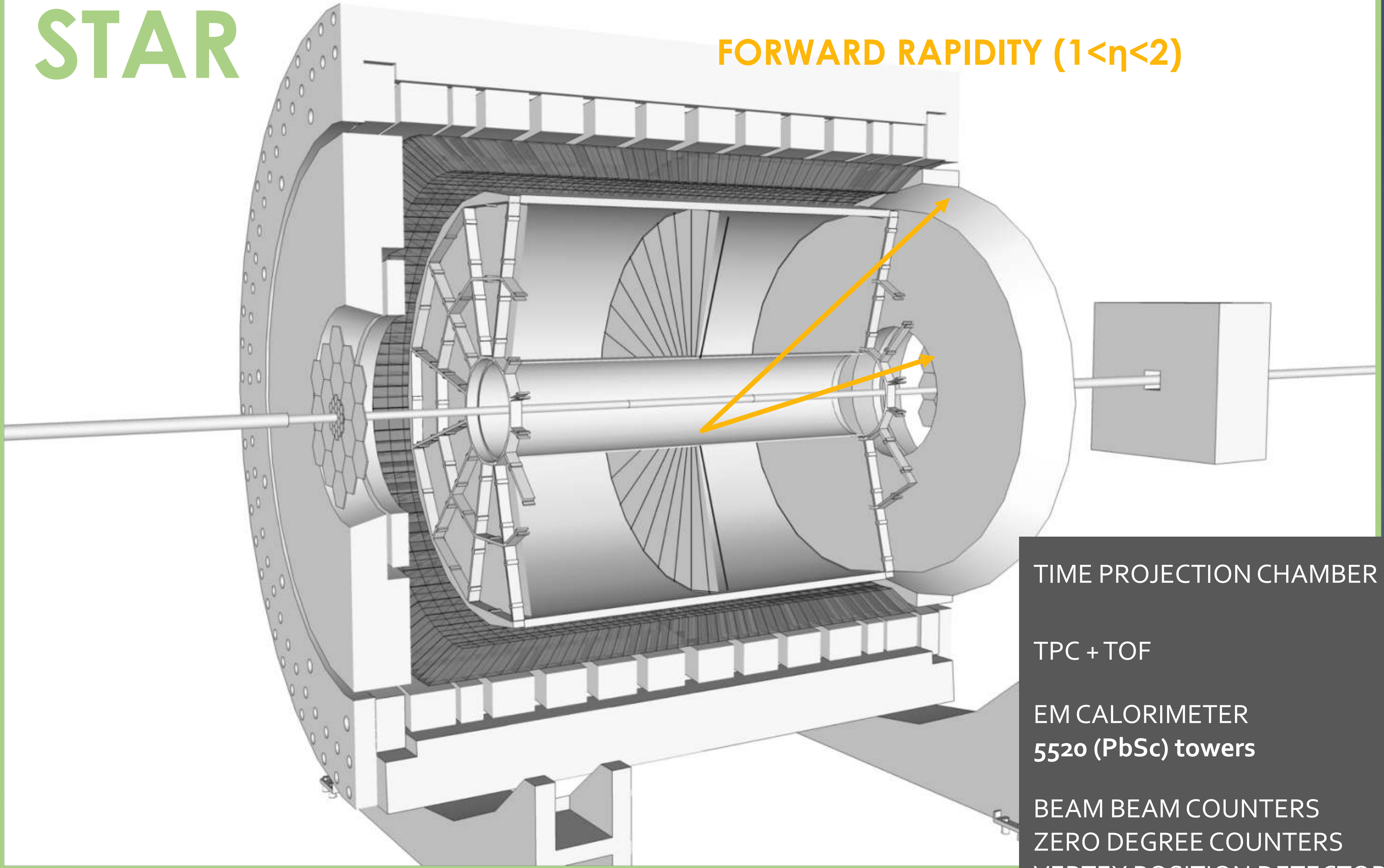

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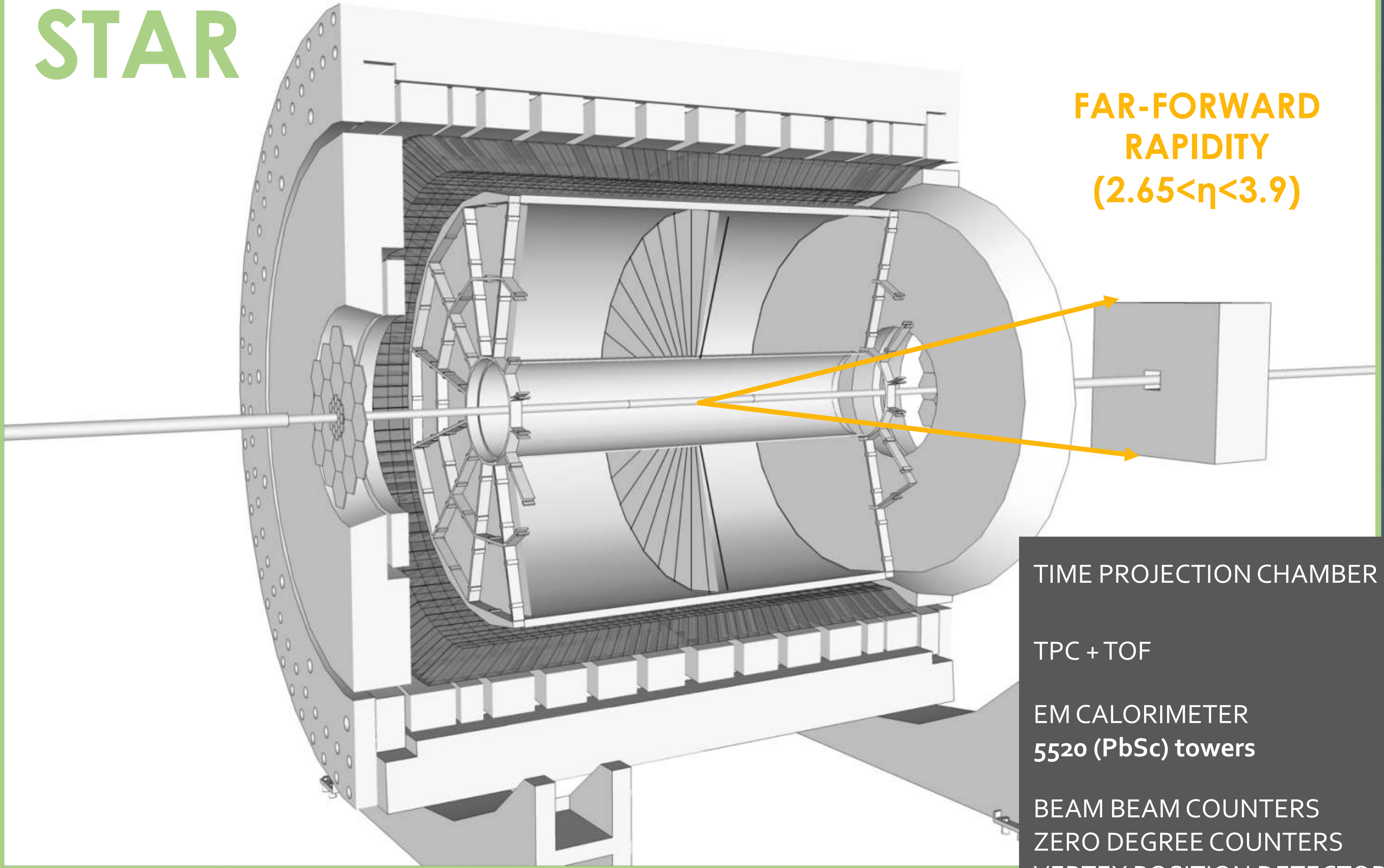

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FORWARD MESON DETECTOR	**Pb-Glass EM Calorimeter**

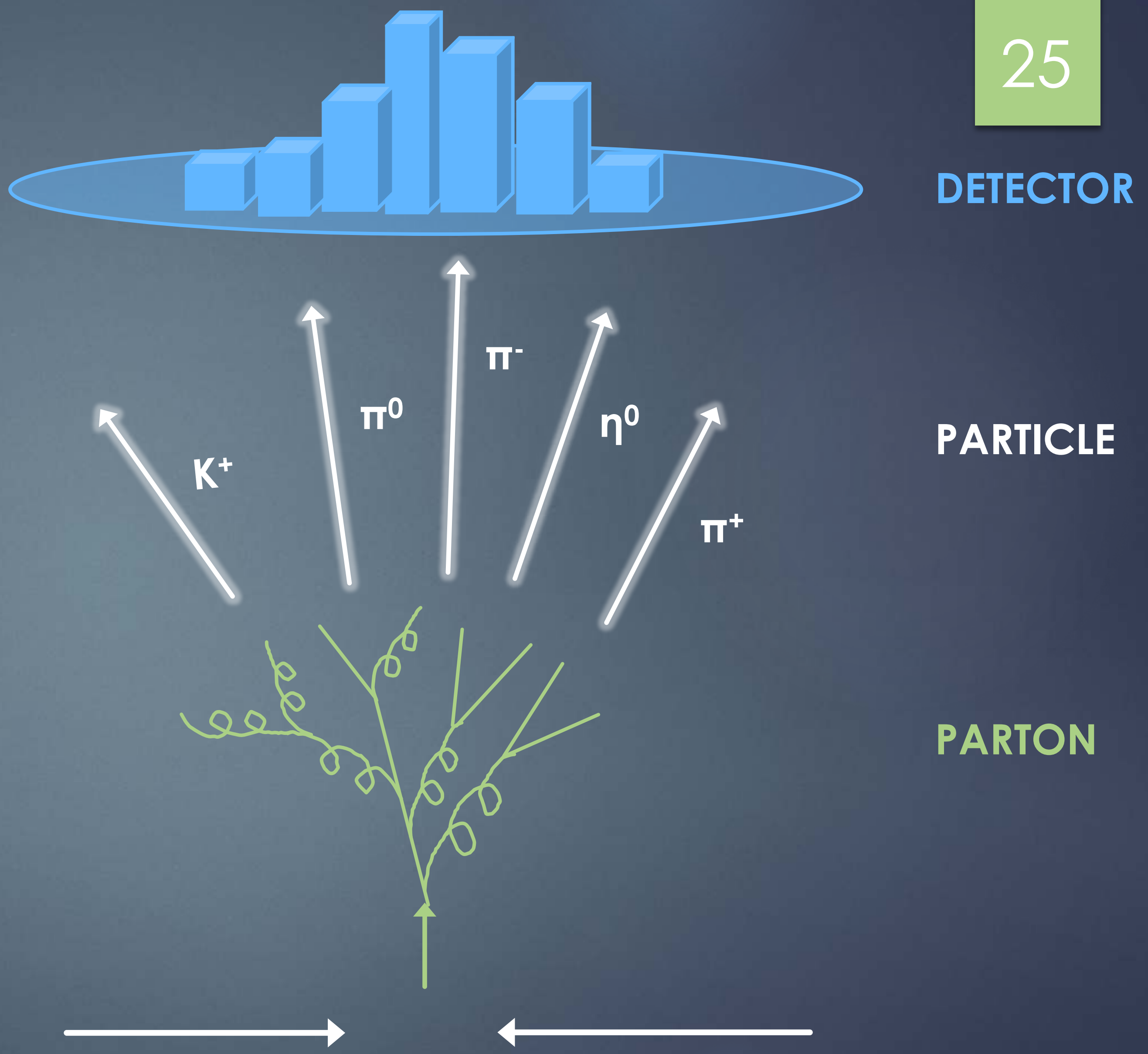
pp Jetfinder @ STAR

- Anti-kT algorithm via FastJet
  *Cacciari, Salam, Soyez, JHEP **04**, 063 (2008)*
  *Cacciari, Salam, Soyez, Eur. Phys. J. C **72**, 1896 (2012)*

- R = 0.6 200 GeV mid-rapidity
- R = 0.5 500 GeV mid-rapidity
- R = 0.7 500 GeV far-forward-rapidity

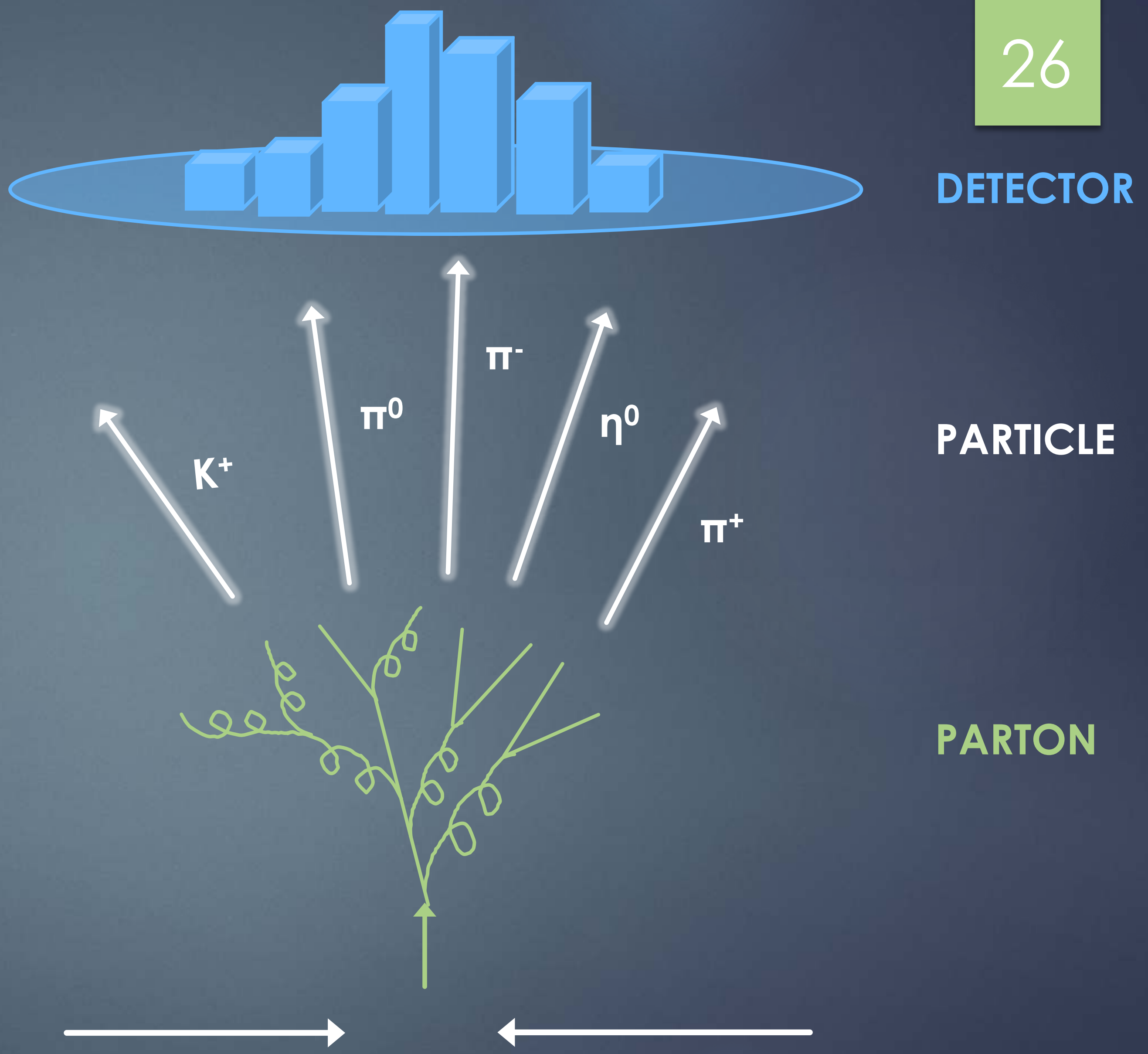
- Anti-kT is less susceptible to diffuse backgrounds from UE and pile-up contributions.

- In PYTHIA+GEANT simulation we remove UE contributions from PARTON level jets.

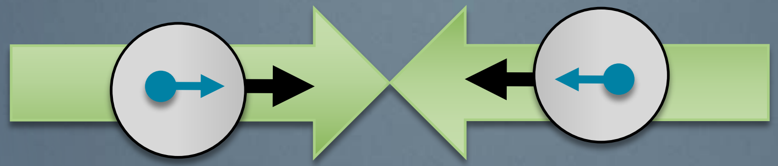


Questions we address along the way…

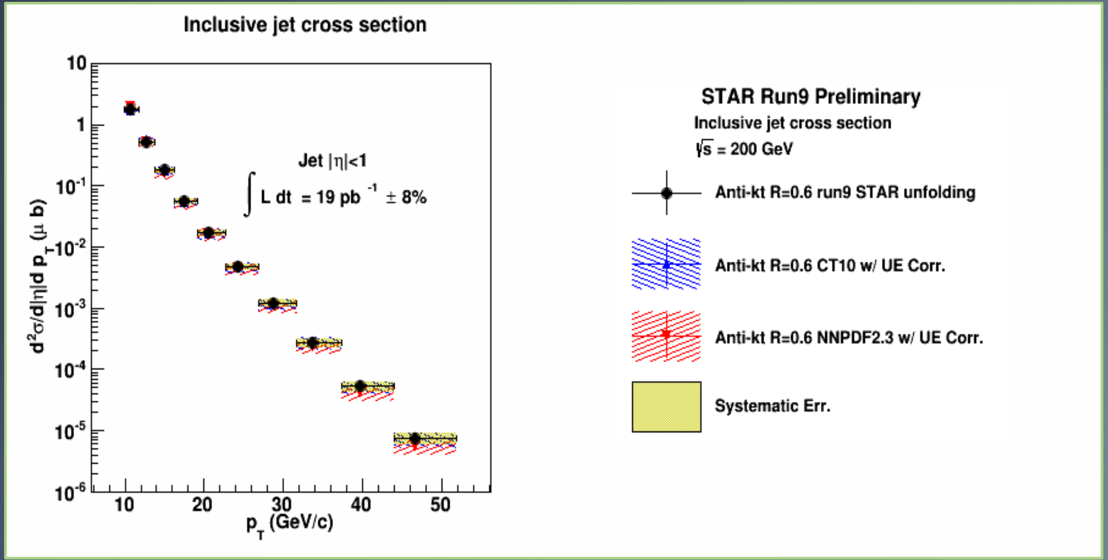
- Can we use pQCD to interpret our results at √s = 200 GeV?
- At what level should we report our results?
- Can we account for UE and hadronization effects in a data driven way?
- Do simulations that are tuned for LHC √s match our data? Is the underlying event well described?



Gluon Helicity

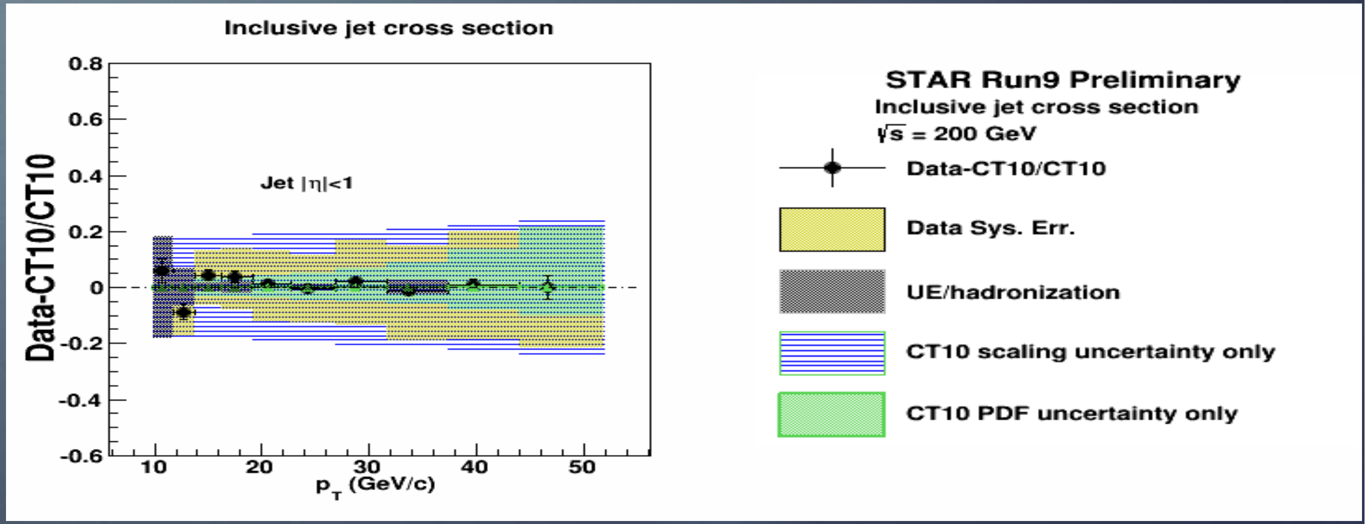


200 GeV Inclusive Jet Cross-section



Gluon helicity PDF is extracted in an NLO global analysis. We need to convince ourselves that NLO can describe jets we reconstruct at √s = 200 GeV

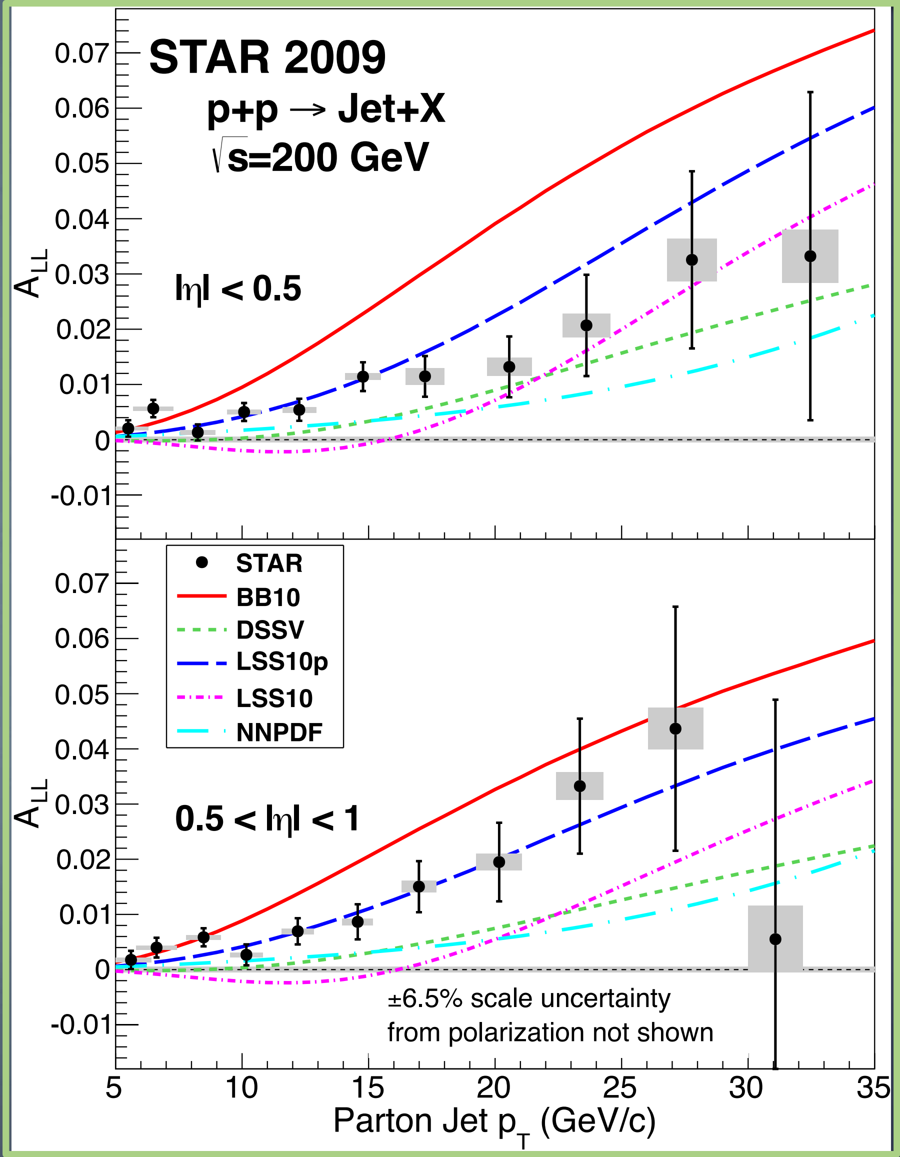
Theoretical and experimental systematic errors are large, but within those bands the data seems well described by NLO pQCD. Important check that we understand our trigger and detector corrections.



200 GeV Inclusive Jet A_{LL}

Phys. Rev. Lett. **115** (2015) 92002

- First RHIC result with sufficient precision to indicate a **non-zero** $\Delta g(x > 0.05)$
- First jet A_{LL} to **correct** for hadronization and underlying event effects.
- By correcting back to **parton level** the jet p_T is ``matched" to NLO calculations as closely as possible.
- The dominant systematic error on the jet scale comes from the effects of differences between PYTHIA and NLO pQCD cross-sections on this correction.
- Theoretical curves from jet code by Mukherjee & Vogelsang, Phys. Rev. **D 86**, 094009 (2012).

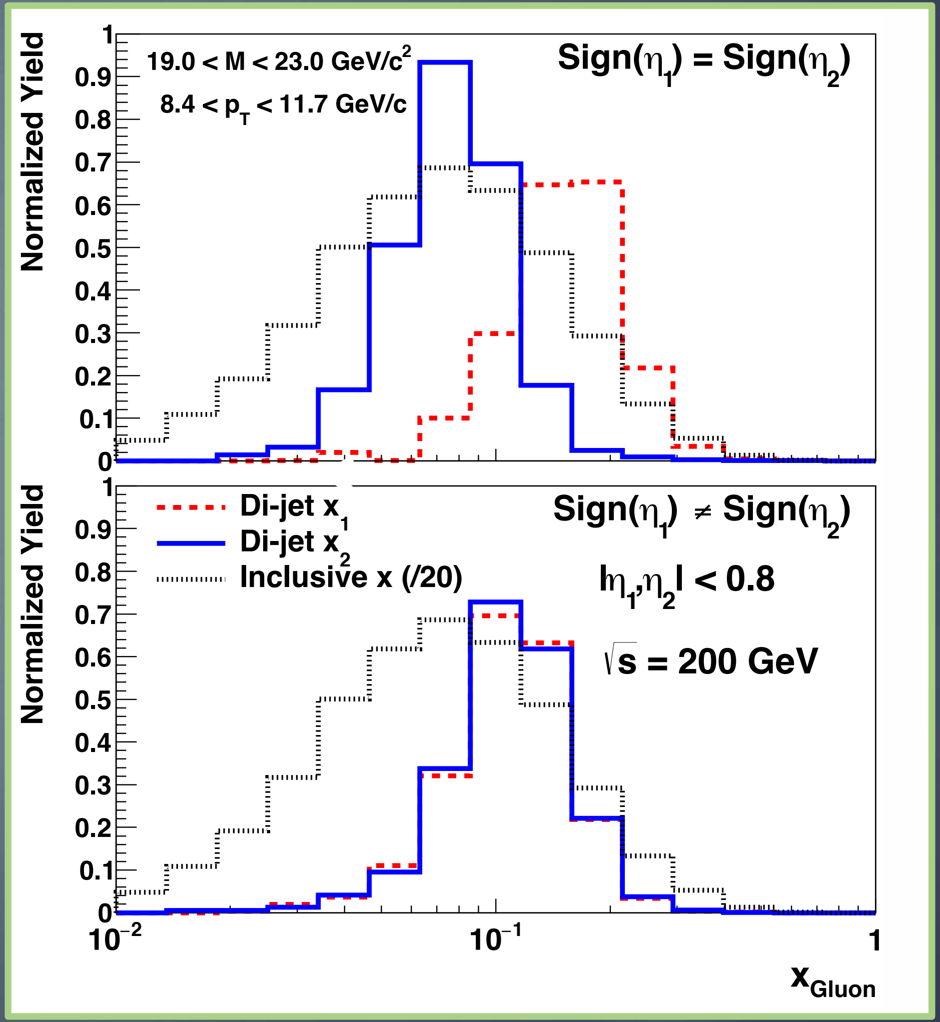


200 GeV Mid-Rapidity Dijets

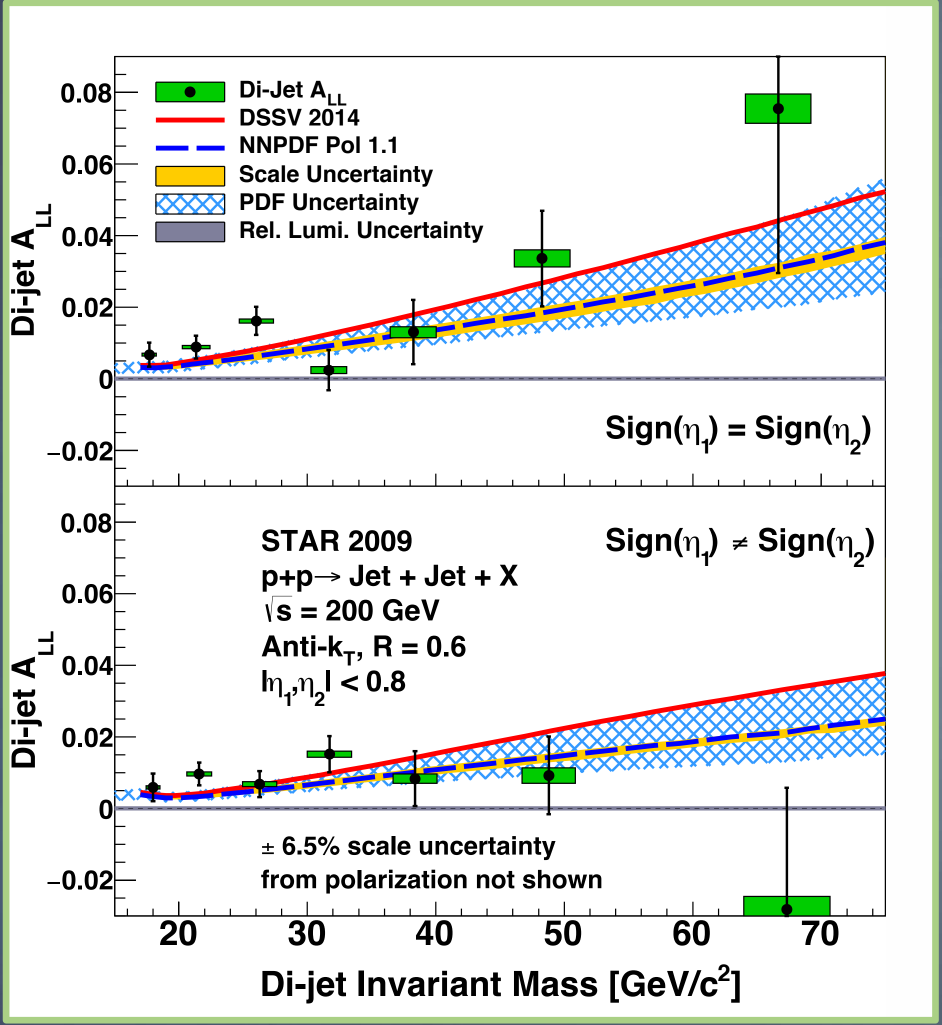
- Inclusive jets sample **broad range** of parton momentum fraction x.
- This limits constraints on the functional form of $\Delta g(x)$ and **increases uncertainty at lower x**.
- Dijets allow for reconstruction of the **initial parton x_1 and x_2** at leading order.

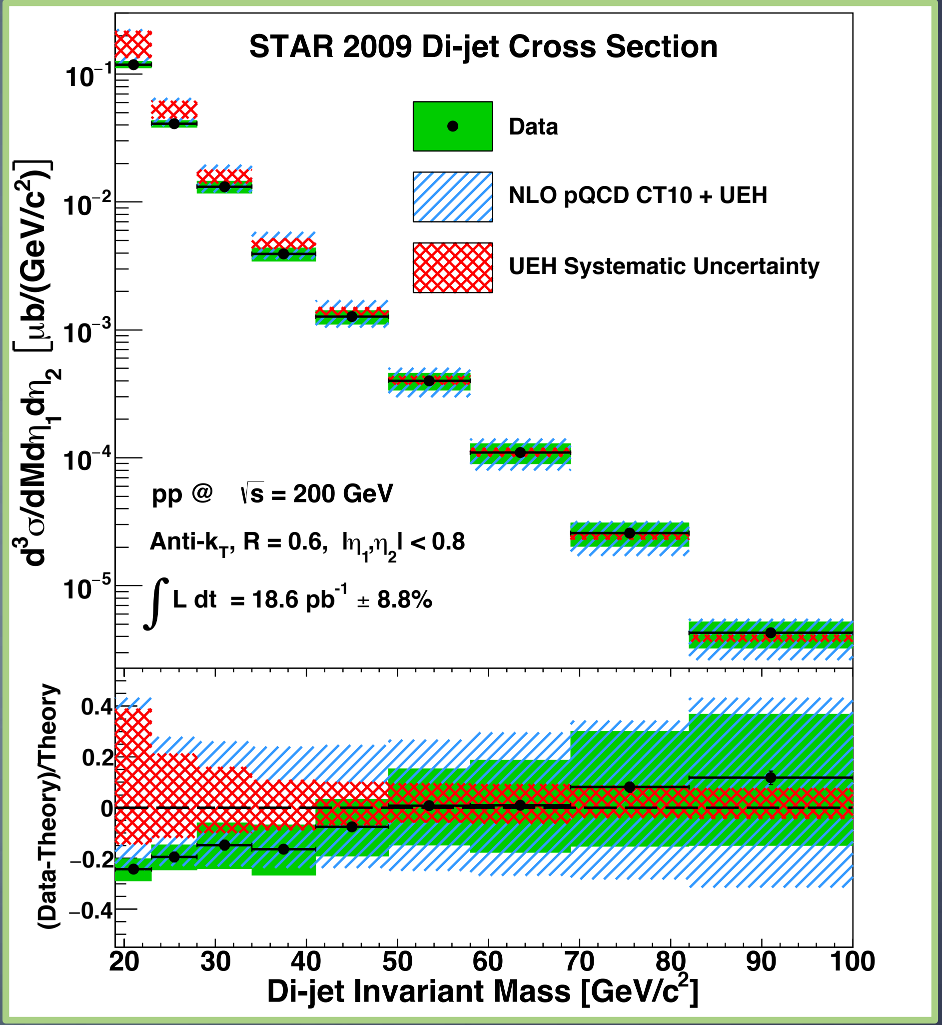
$$x_{1,2} = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\pm\eta_3} + p_{T4}e^{\pm\eta_4}\right)$$

$$|\cos\theta^*| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$



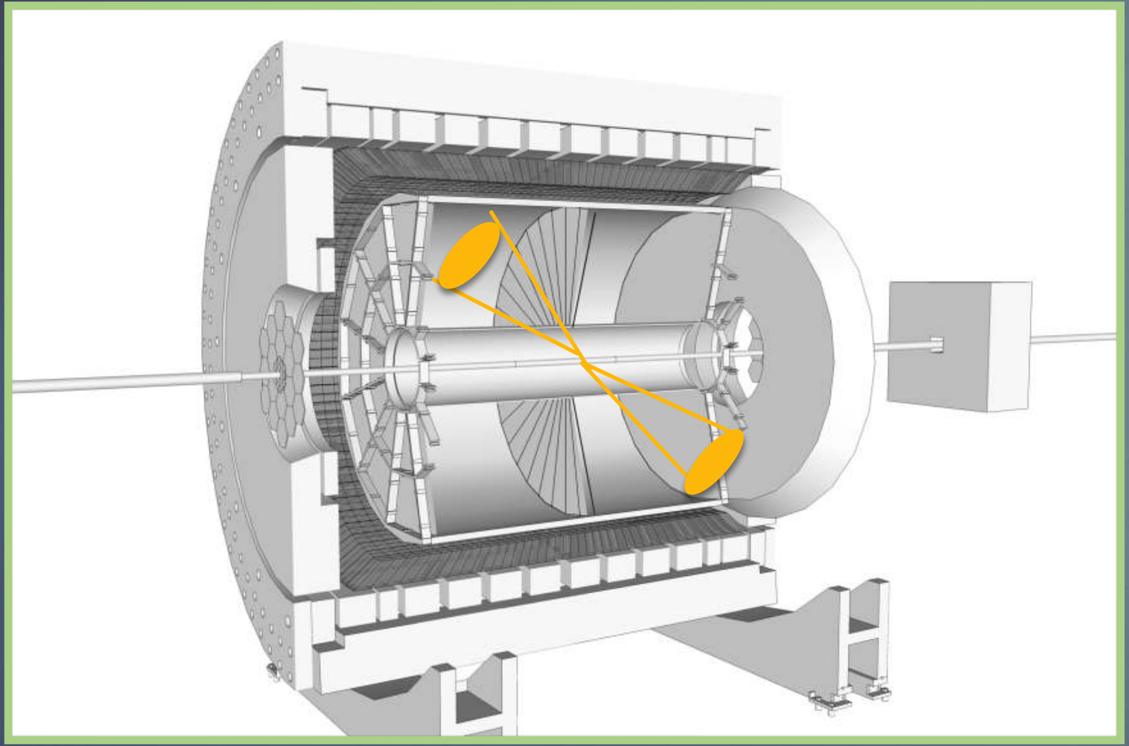
200 GeV Mid-Rapidity Dijet A_{LL} & Cross-section

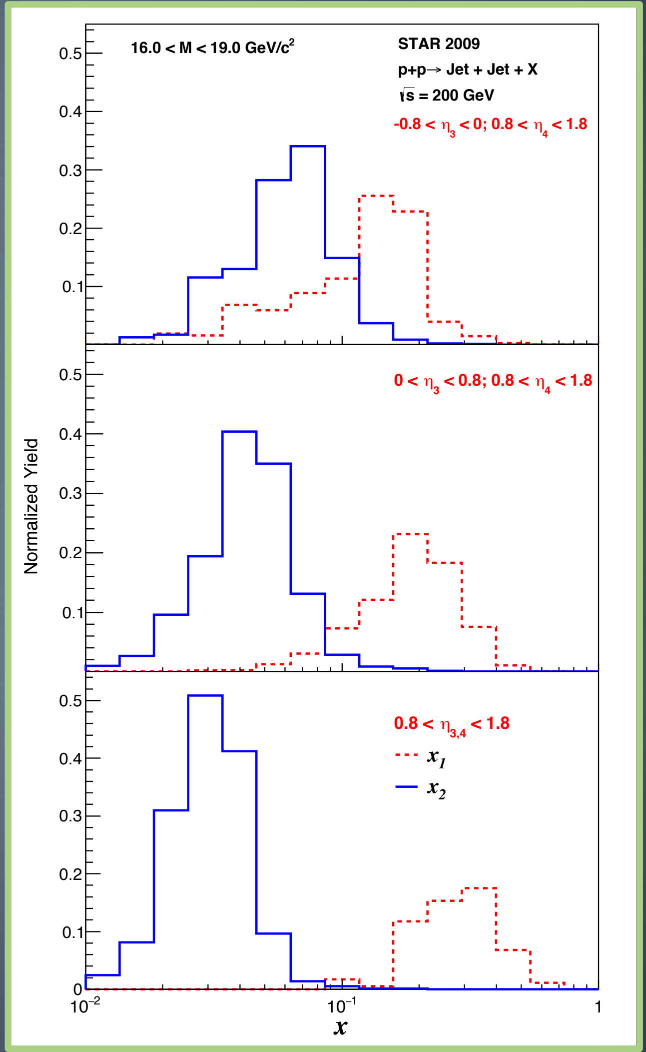




Phys.Rev.D95, 071103 (2017)

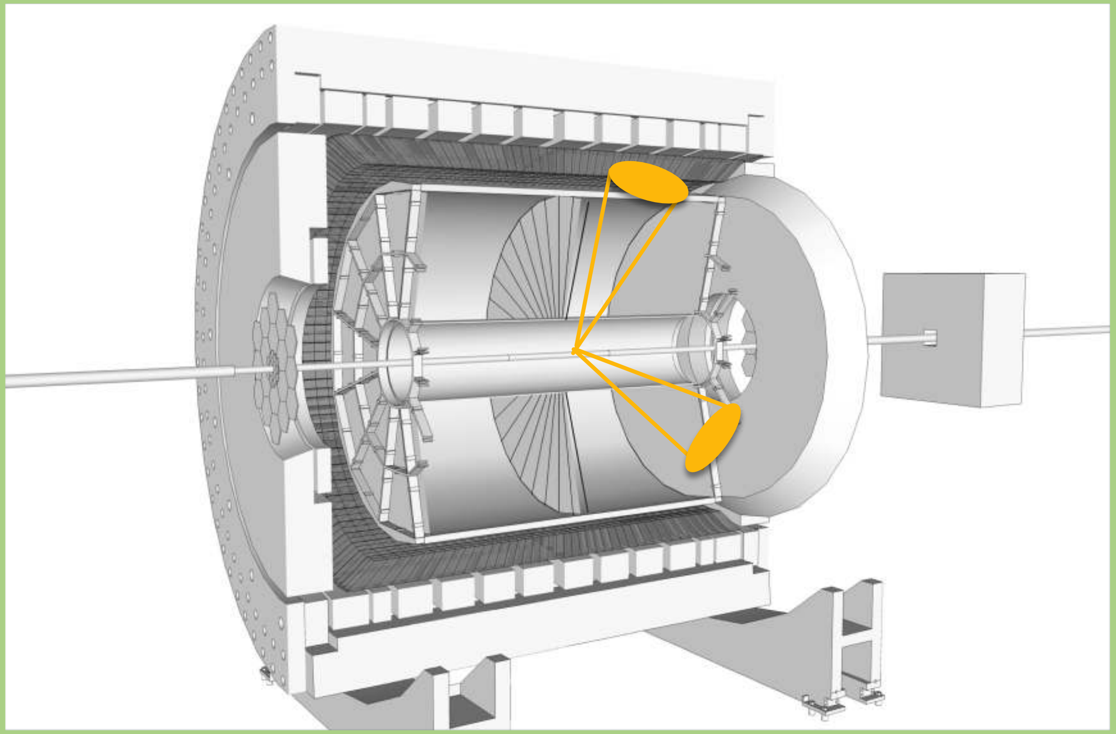
200 GeV Forward-Rapidity Dijet

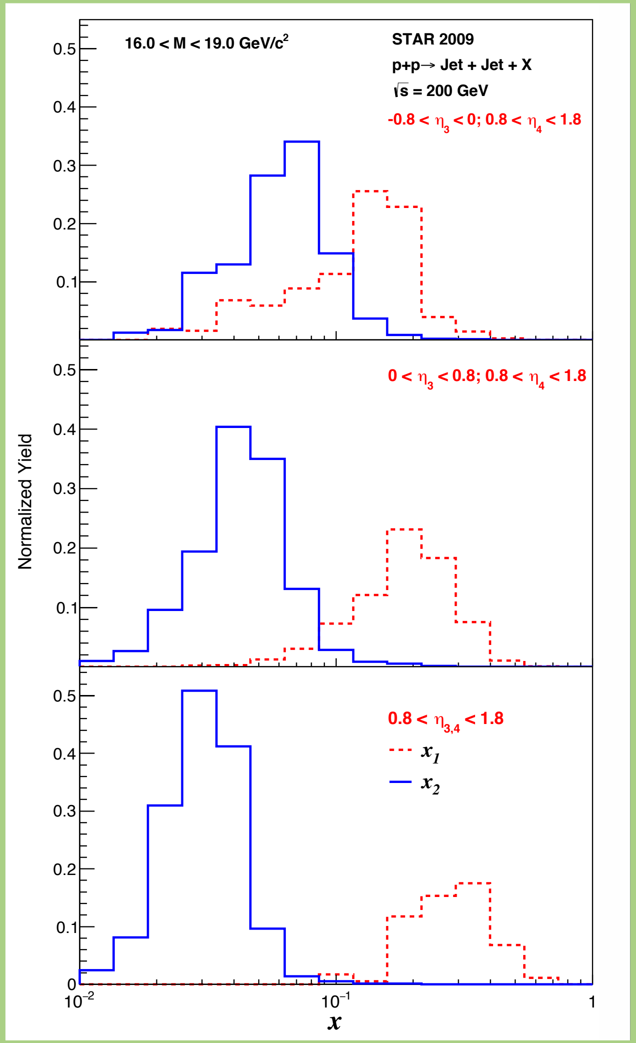




Can push to smaller x by using endcap calorimeter in forward region.

200 GeV Forward-Rapidity Dijet





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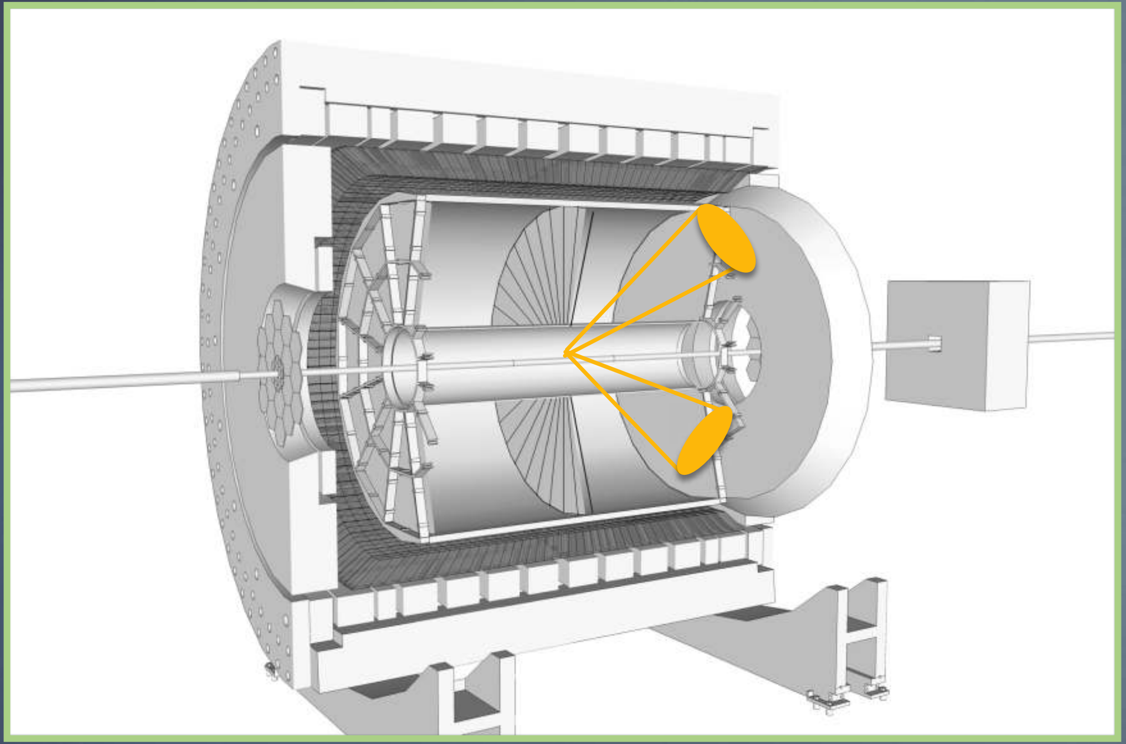

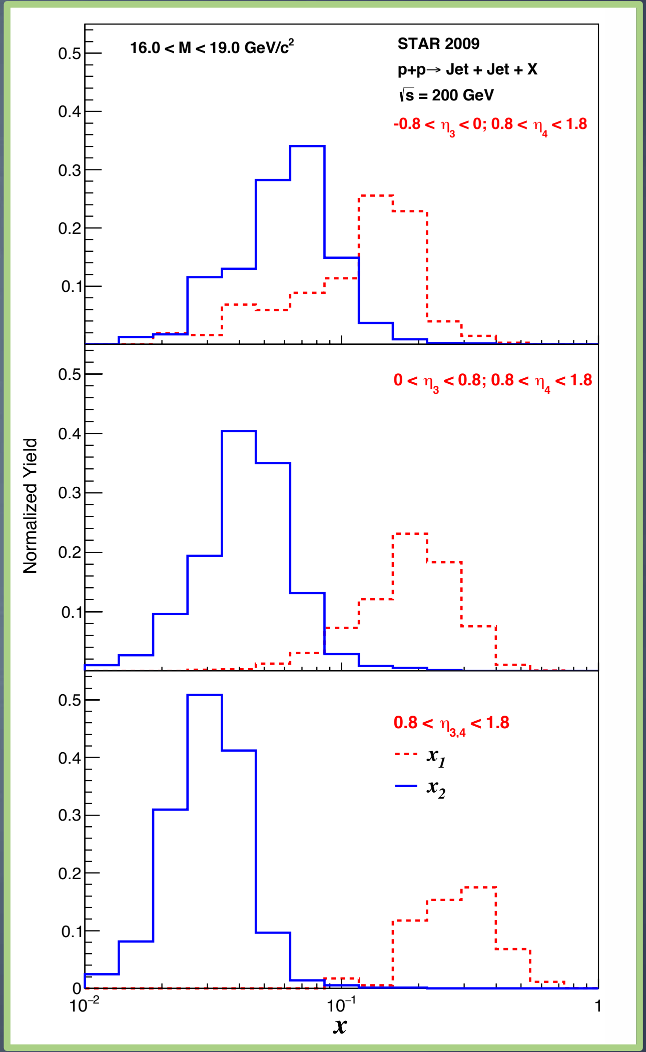

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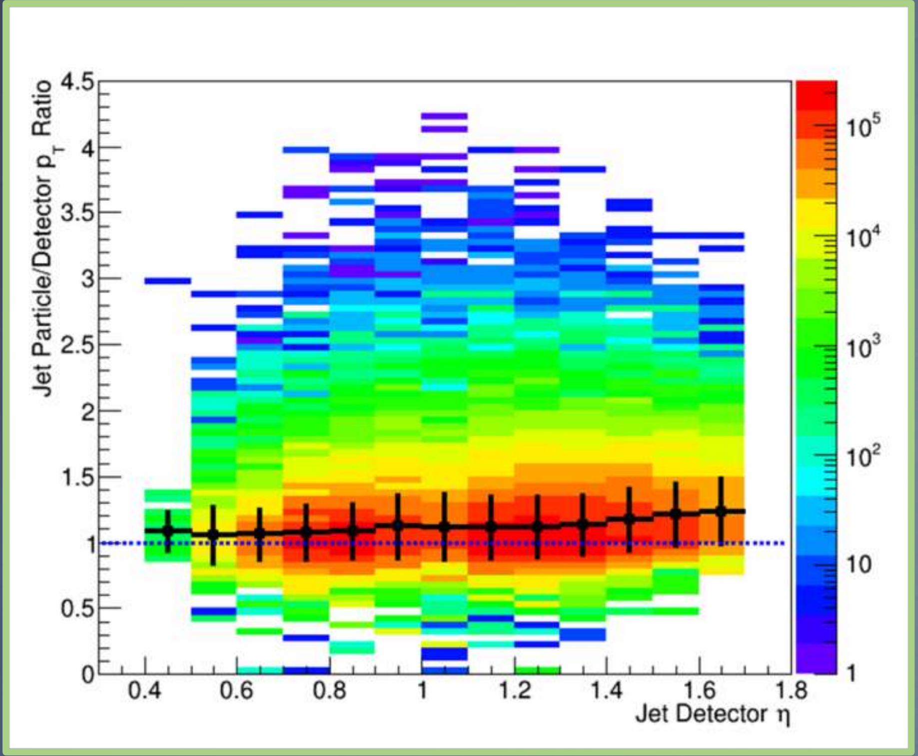
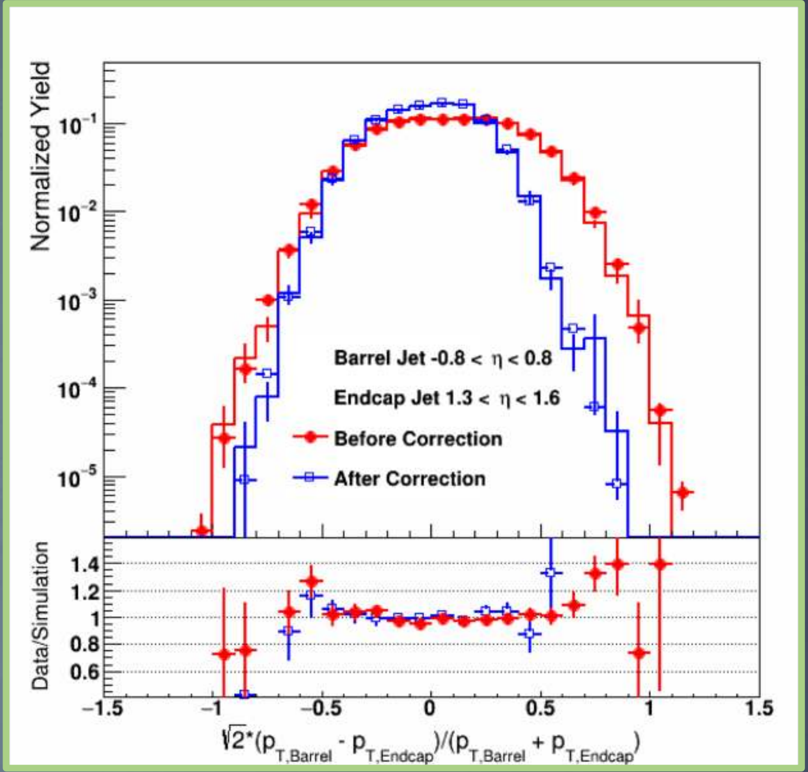
Machine Learning Techniques





TPC efficiency drops quickly for η > 1.2. Manifests as increasing ratio of particle to detector jet p_T.

Use Multi-layer Perceptron machine learning technique to correct p_T and mass of forward and mid-rapidity jets to the particle level.

Data Driven Underlying Event Correction

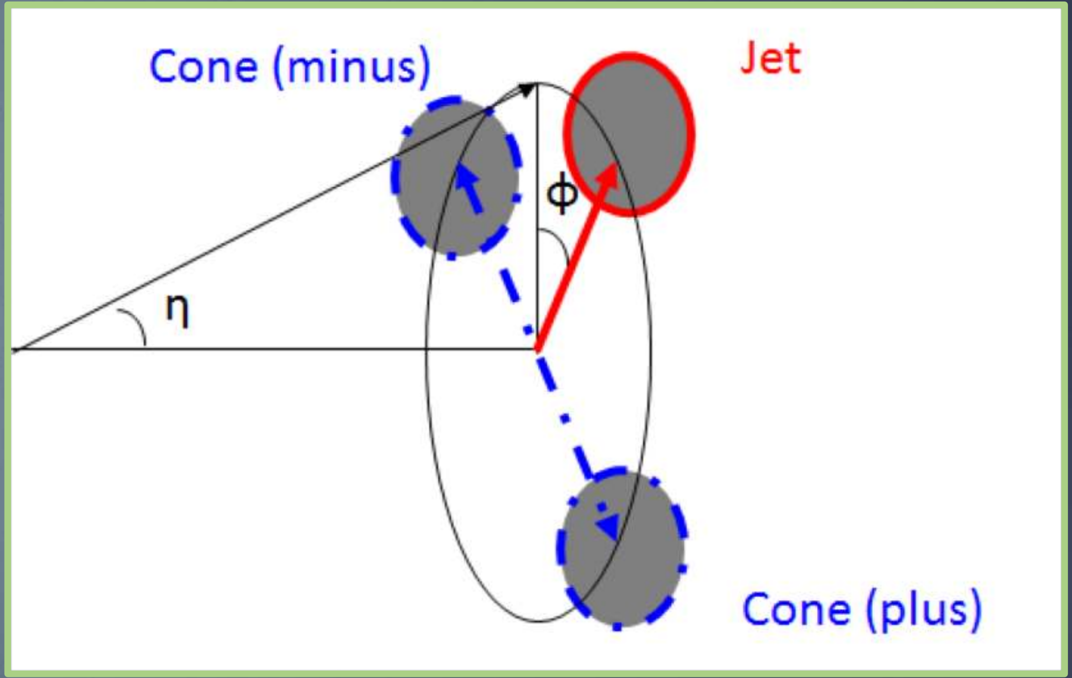
- UE and background contributions are subtracted using technique based on ALICE perpendicular cone method.
  Phys.Rev. ***D91****, no. 11, 112012 (2015)*

- For each jet two cones of radius R_{jet} are defined at $\phi = \phi_{jet} \pm 90$ and $\eta = \eta_{jet}$.

- Average transverse momentum **ρ** and mass density $\boldsymbol{\rho}_M$ are calculated from the cones.

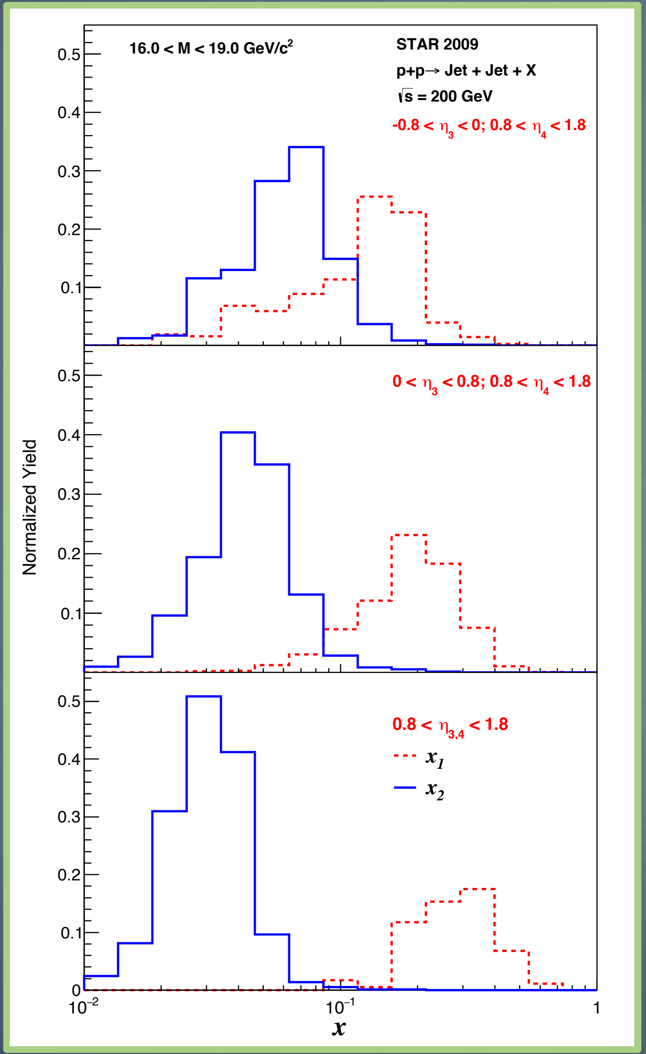
- Jet four momentum is corrected on an event-by-event basis.

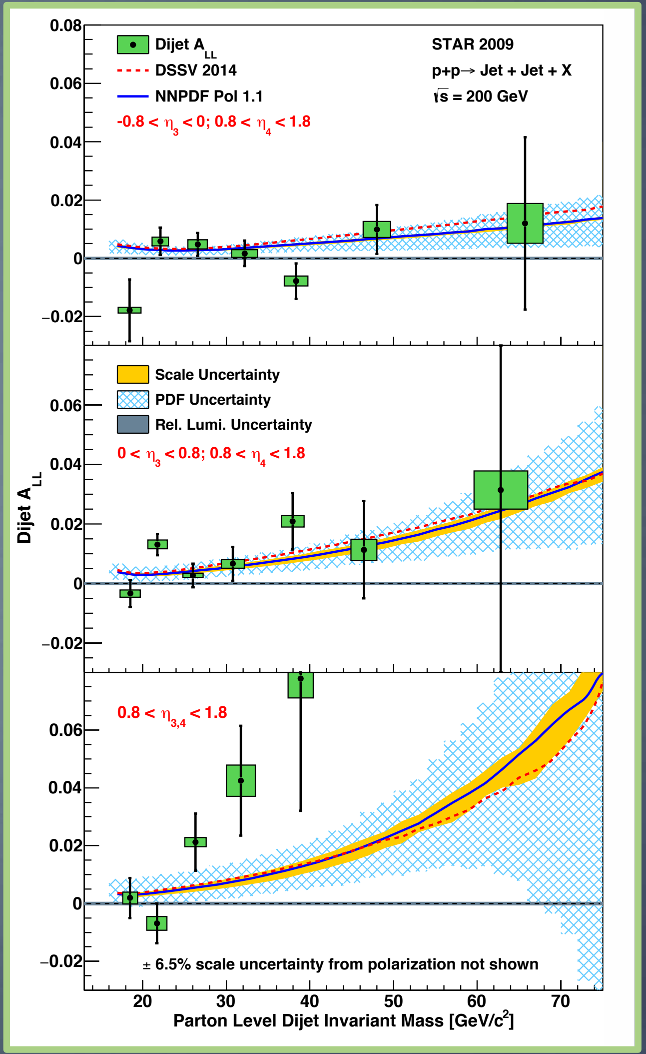
$$P'^{\mu}_{jet} = P^{\mu}_{jet} - \rho A^{\mu}_{jet}$$



200 GeV Forward-Rapidity Dijet

These asymmetries sample both low x gluons and high x quarks!





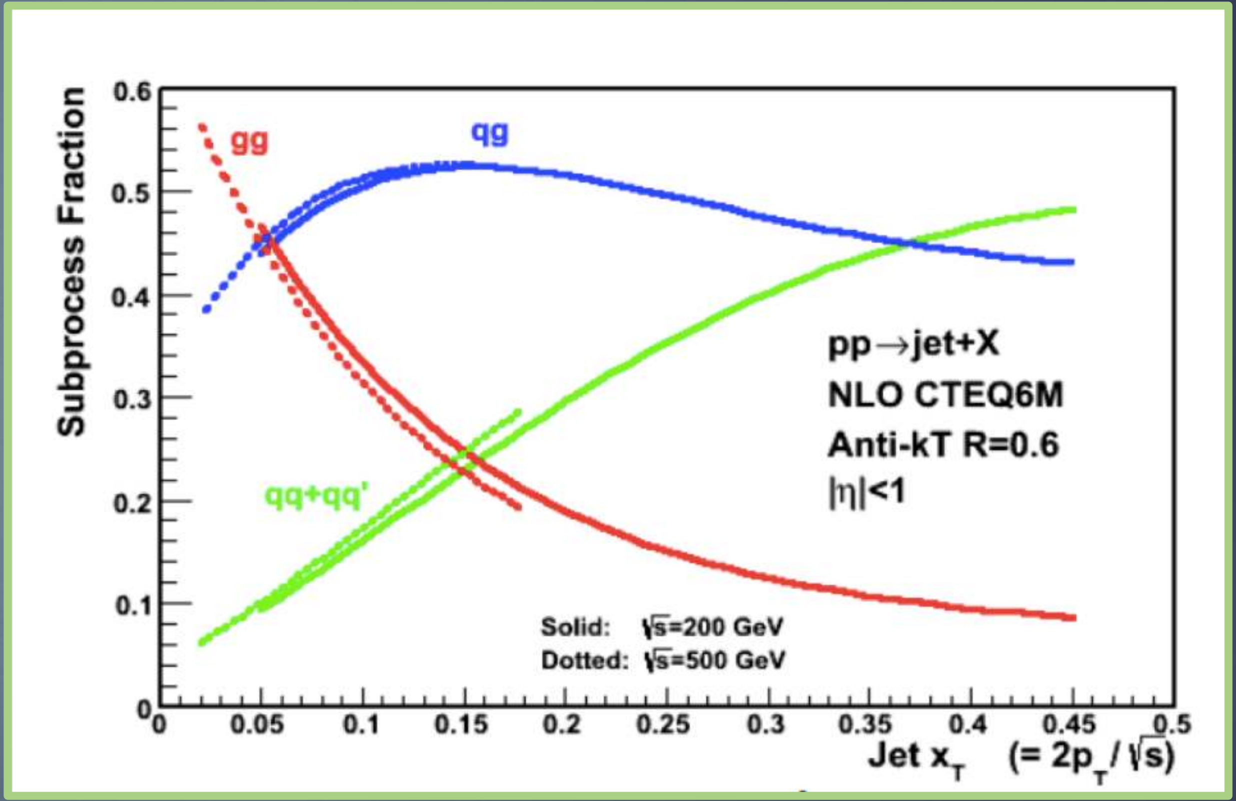
Phys. Rev. D **98** (2018) 32011

500 GeV Mid-rapidity Inclusive and Dijet A_{LL}

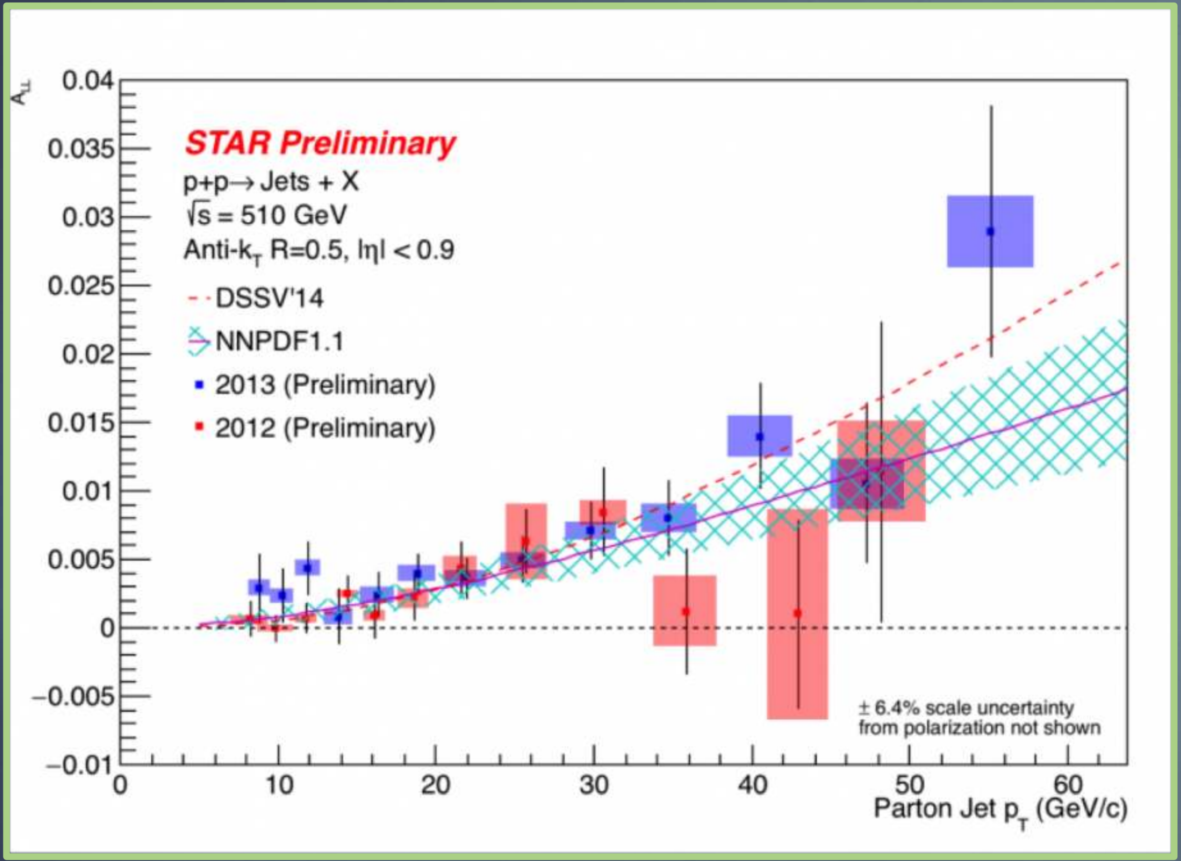
- Measurements at higher √s access lower partonic x

$$x \approx x_T e^{\pm\eta} = \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$$

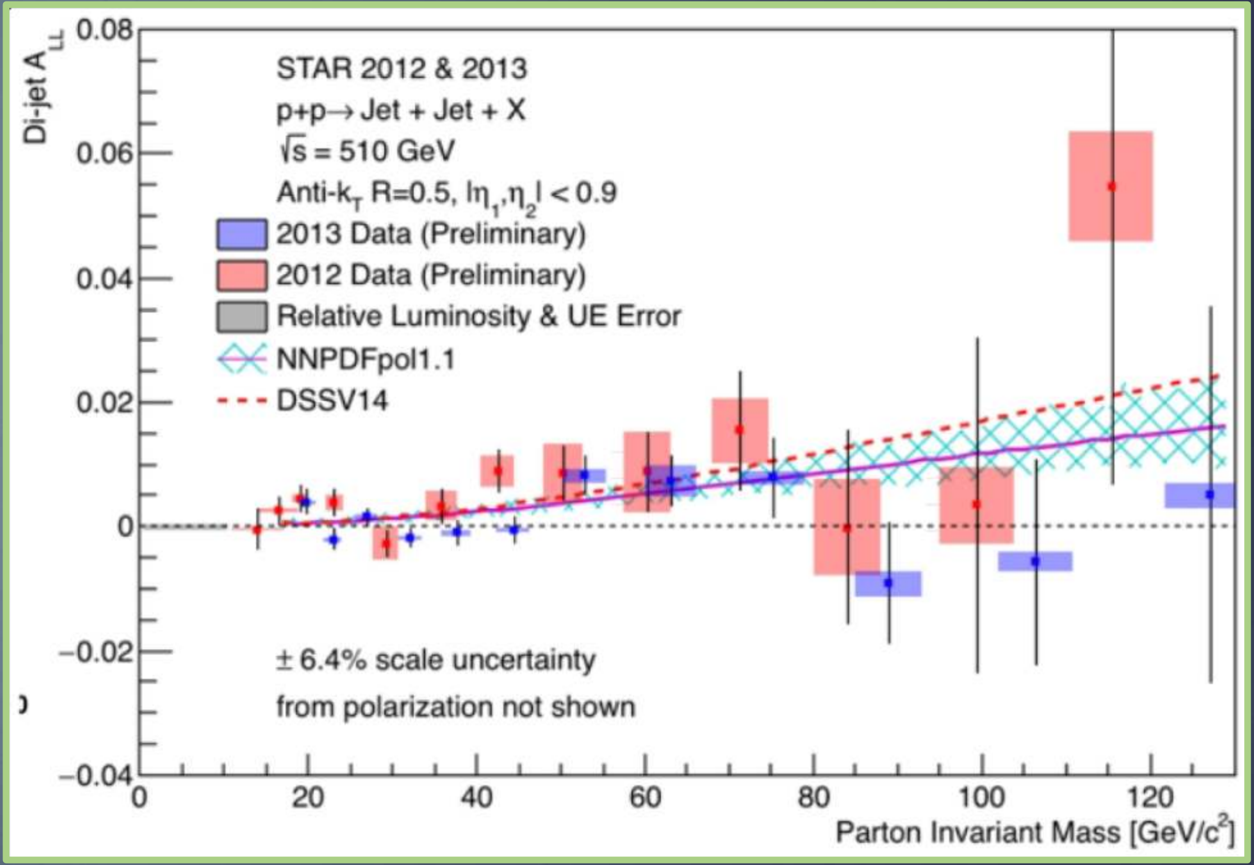
- Optimize R_{jet} = 0.5 to accommodate increased UE and pileup at higher center of mass energies



500 GeV Mid-Rapidity Inclusive and Dijet A_{LL}



INCLUSIVE JET



DIJET

RHIC's impact on

**jets and pions*

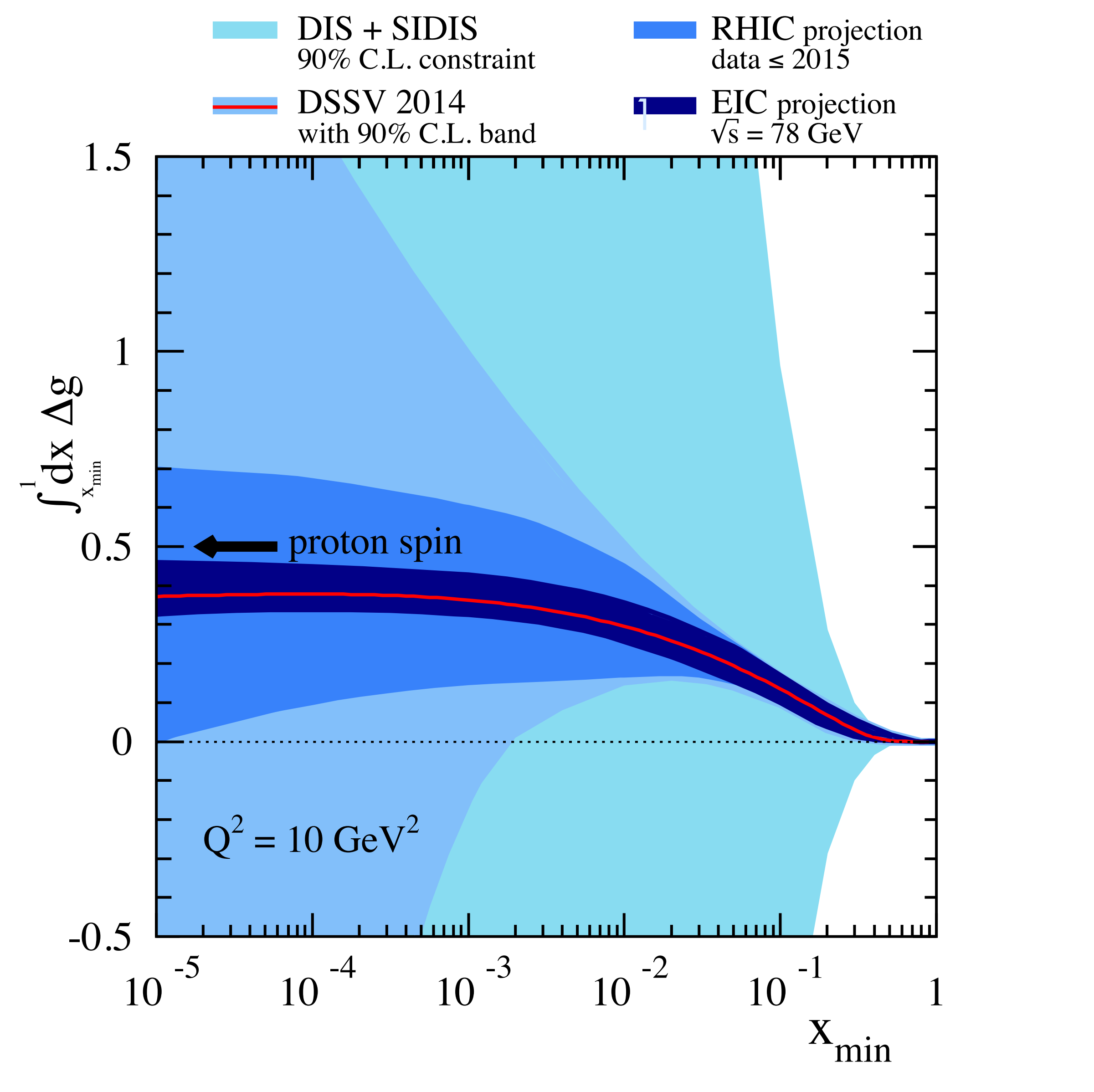
$$\Delta G = \int_{x_{min}}^{1} \Delta g(x)dx$$

DSSV
Phys.Rev.Lett. 113 1, 012001 (2014)

ΔG ($x > 0.05$) @ Q^2=10 GeV^2
= 0.2 (+0.06/-0.07)

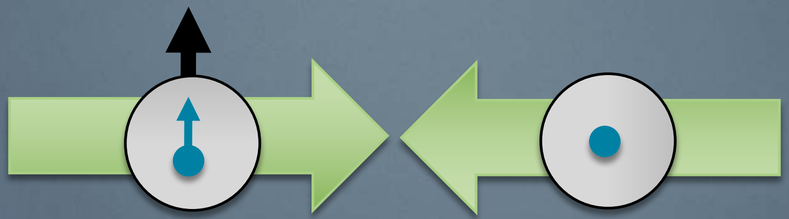
NNPDF
Nucl.Phys.B887, 276-308 (2014)

ΔG ($0.2 > x > 0.05$) @ Q^2=10 GeV^2
= 0.17 (+/- 0.06)

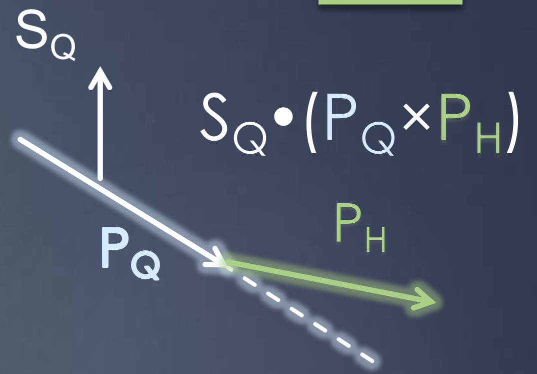


Phys.Rev. D92, 094030 (2015)

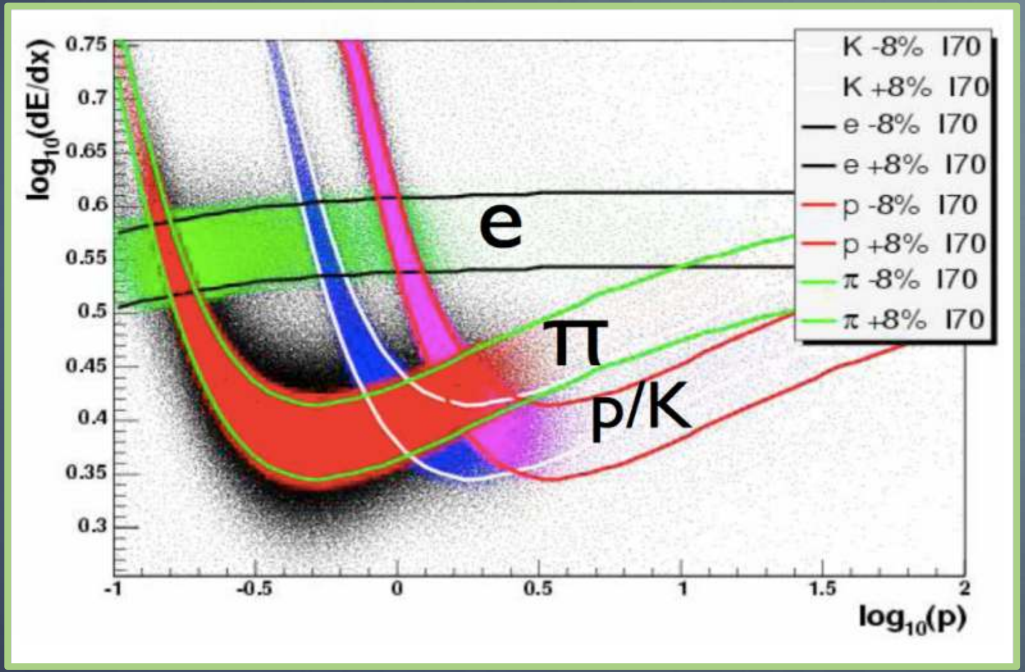
Transverse Momentum Distributions

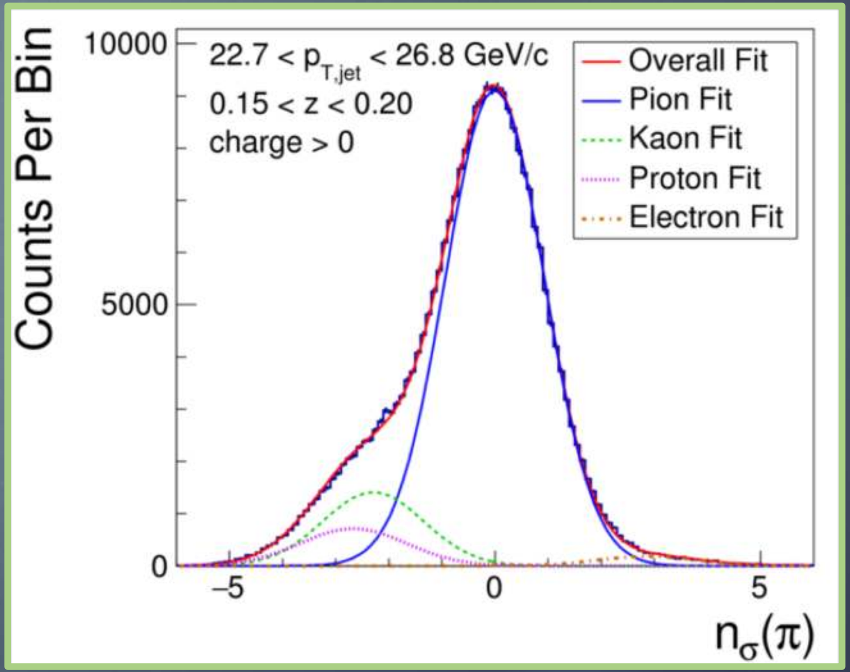


Collins TMD Fragmentation Function



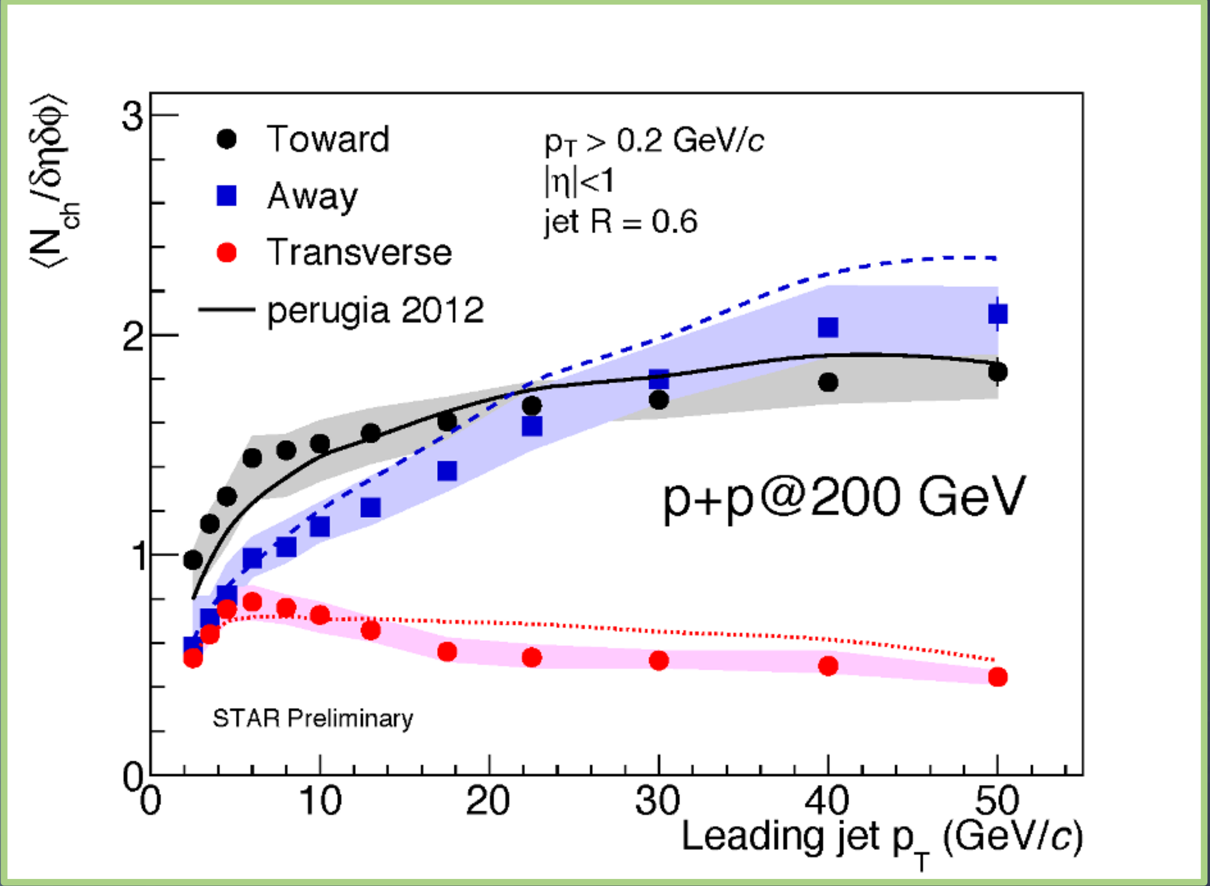
Correlation between spin of transversely polarized quark and transverse momentum kick given to fragmentation hadron.
Use the STAR TPC and TOF to identify charged pions inside jets!





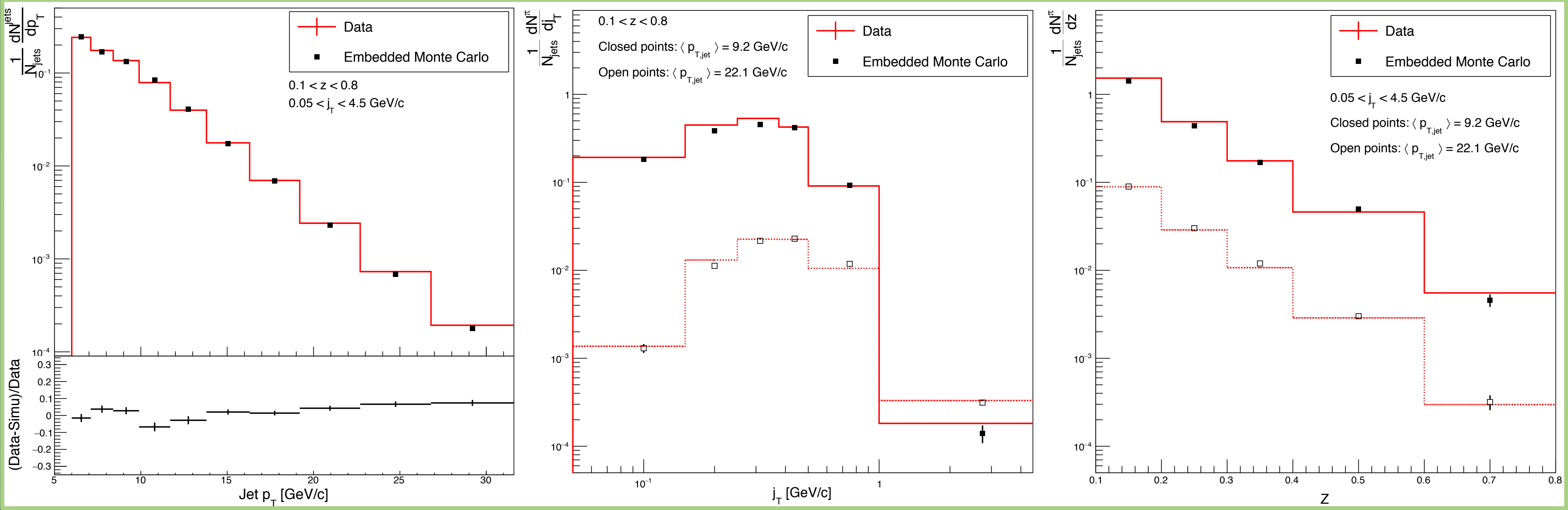
Tuning the underlying event

- UE subtraction is tricky – is π^+ from the UE or the hard scattering?
- For this reason $A_{UT}^{\sin\phi}$ is corrected back to **PARTICLE** level only.
- Must tune UE in simulation to reflect our $\sqrt{s}$ = 200 and 500 GeV.
- Optimize the PYTHIA parameter that controls the multiple parton interactions to reflect fully corrected STAR inclusive pion samples.



PERUGIA 2012, CTEQ6L1, PARP(90)=0.213

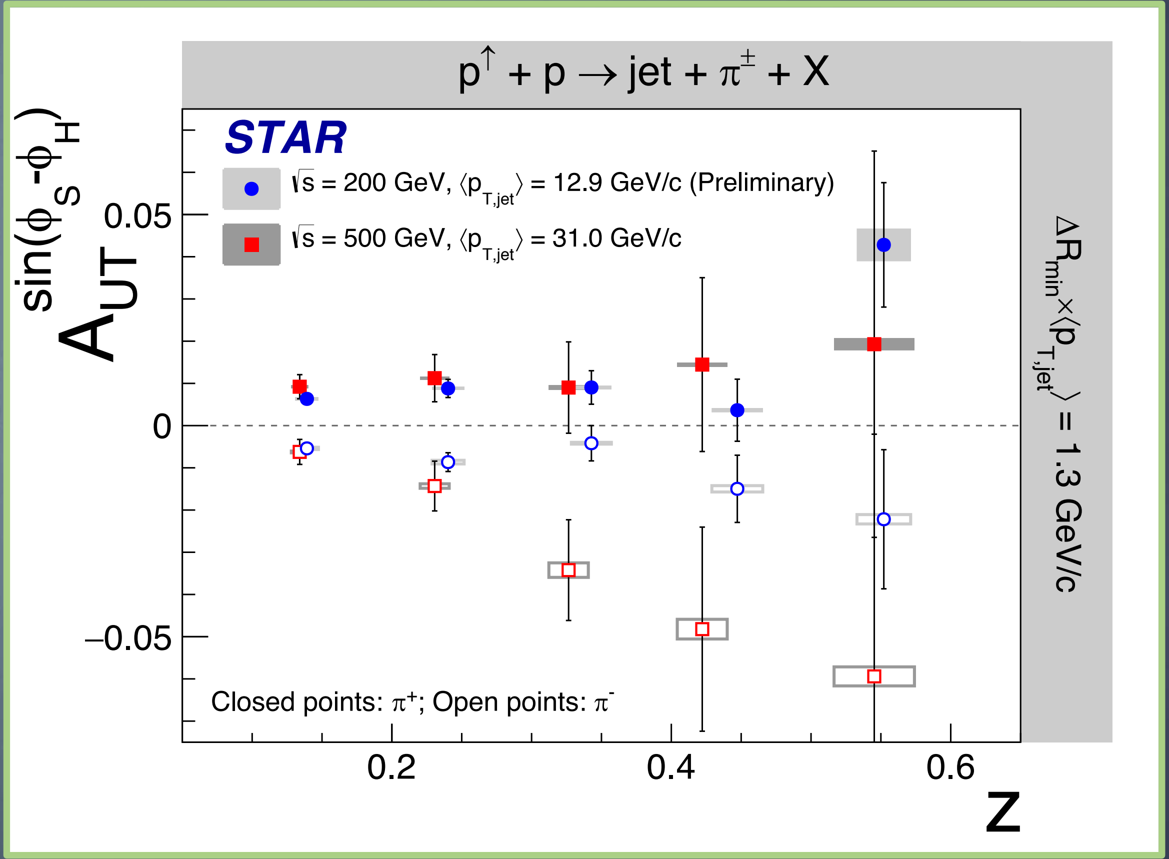
Excellent Data-Simulation matching!



JET pT **PION jT** **PION z**

$A_{UT}^{\sin(\phi_S-\phi_H)}$ vs Z

- Apply cuts to ensure same average quark x and hadron J_T ranges.
- Excellent agreement between 200 and 500 GeV for π+ … π- not as strong.
- Need more statistics in 500 GeV to match precision of 200 GeV.

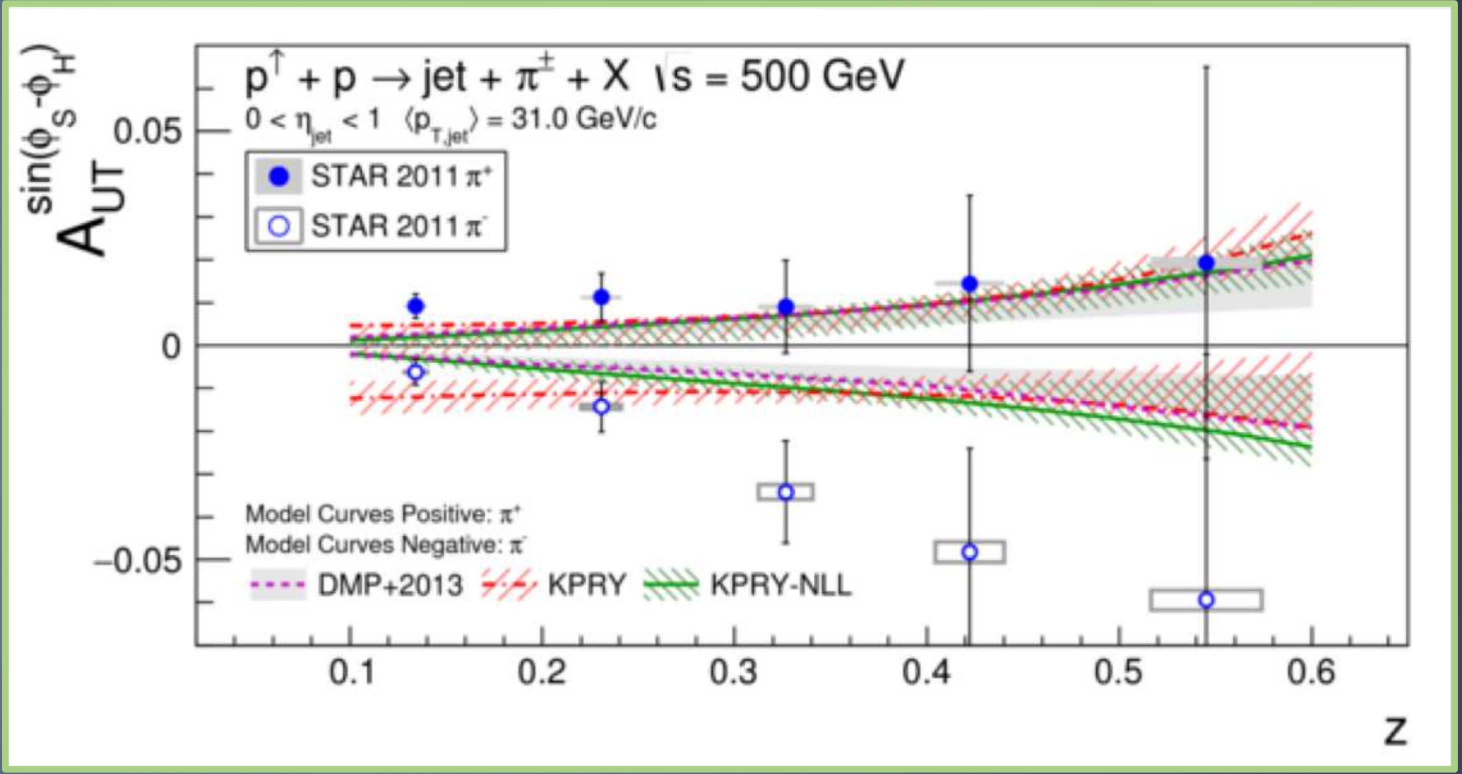


500 GeV $A_{UT}^{\sin(\phi_S - \phi_H)}$ vs Z

STAR data compared to calculations by

1. D'Alesio, Murgia & Pisano, Phys. Lett. **B773**, 300 (2017)

2. Kang, Prokudin, Ringer, & Yuan, Phys.Lett. **B774** 635-642 (2017) without and with evolution.



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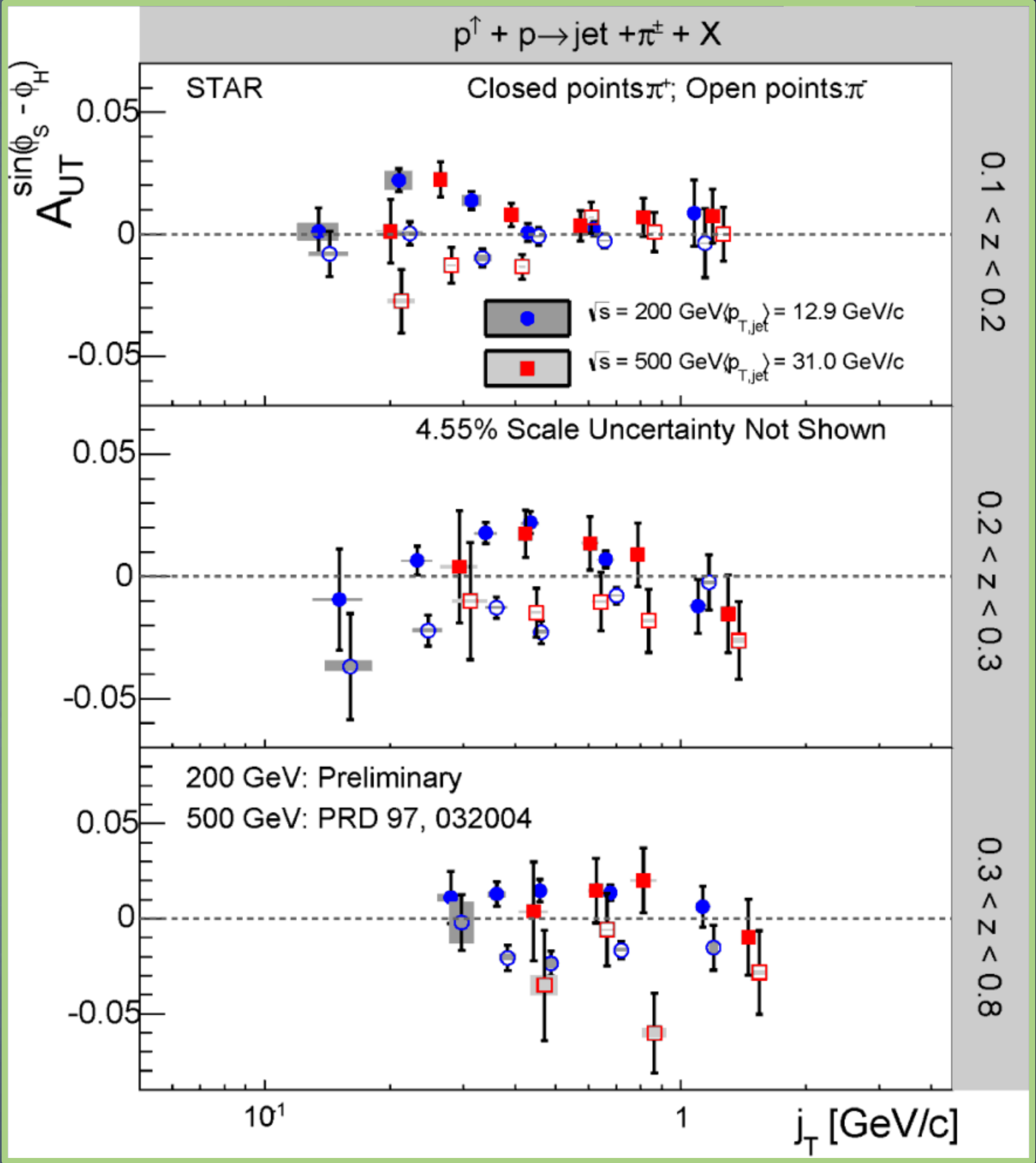
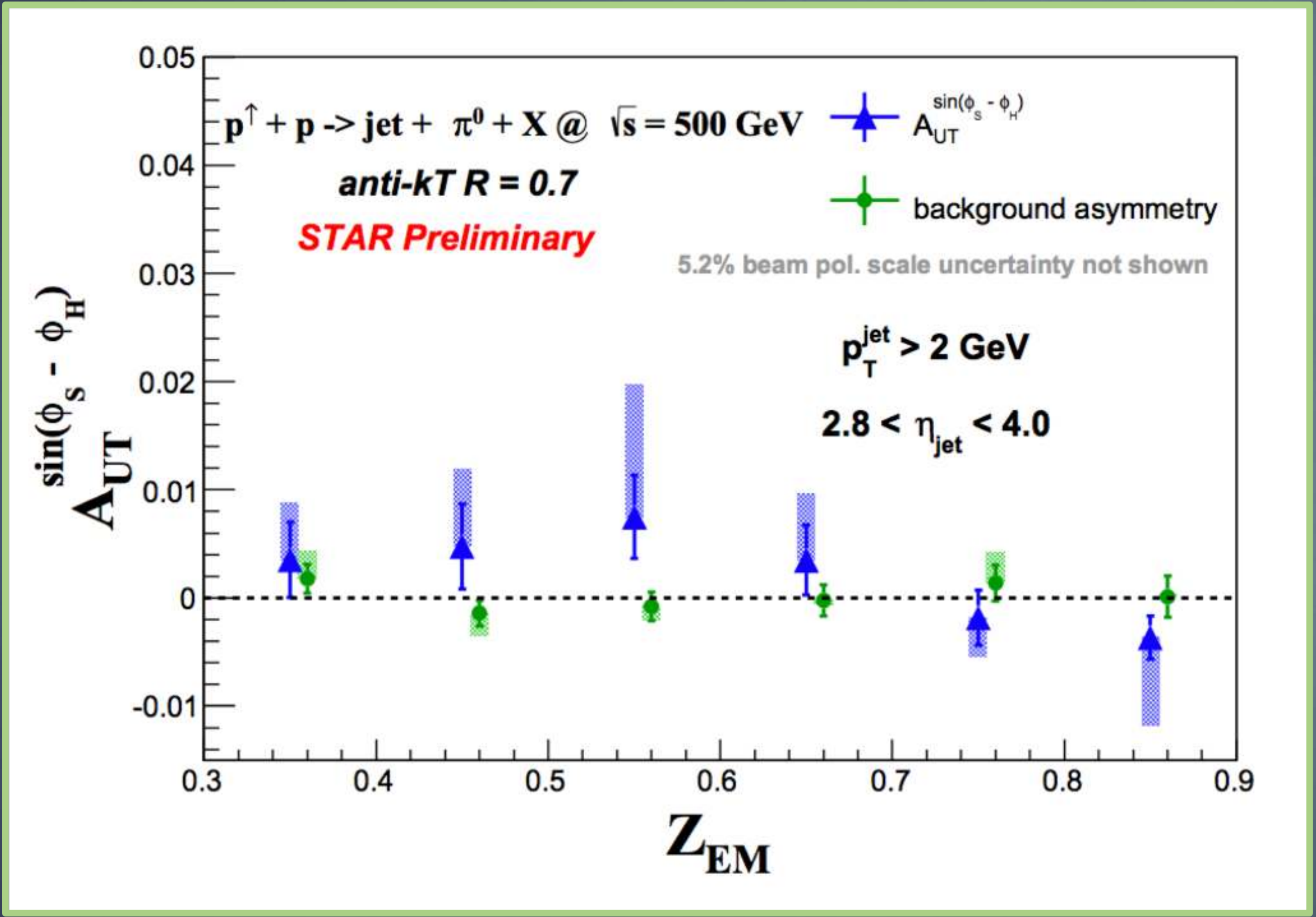
Data and theory agree - **TMD Evolution effects appear to be small.** At the current level of precision the data supports theoretical work by by Kang, Liu, Ringer and Xing JHEP 1711 (2017) 068 , ie **universality holds for Collins TMDs in p+p collisions.** Need more data!

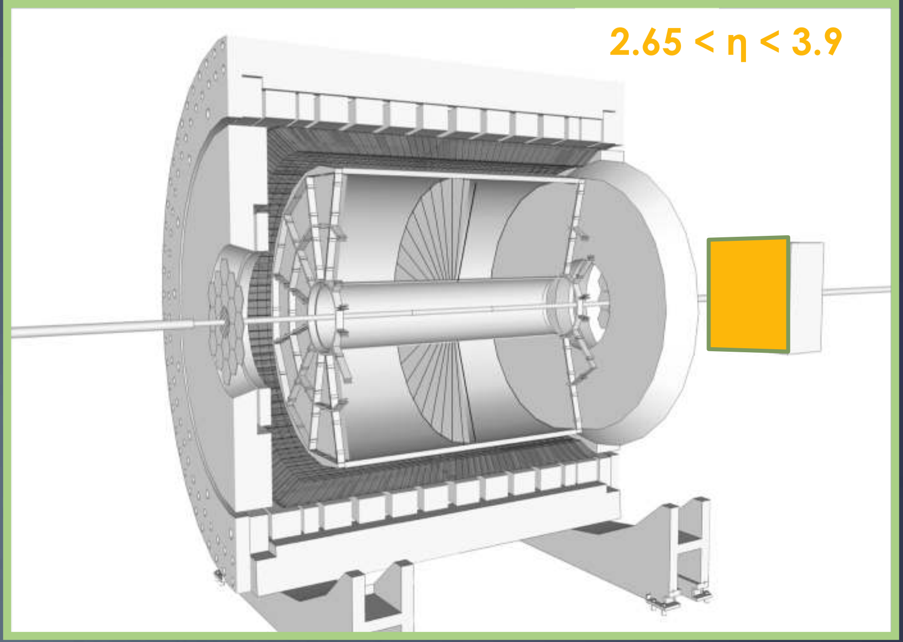
$A_{UT}^{\sin(\phi_S-\phi_H)}$ vs j_T in bins of z

- 200 and 500 GeV tell the same story
- Shape of j_T changes with z
- Peak of distribution moves higher as z increases.
- Hadron j_T is independent of initial state transverse momentum.



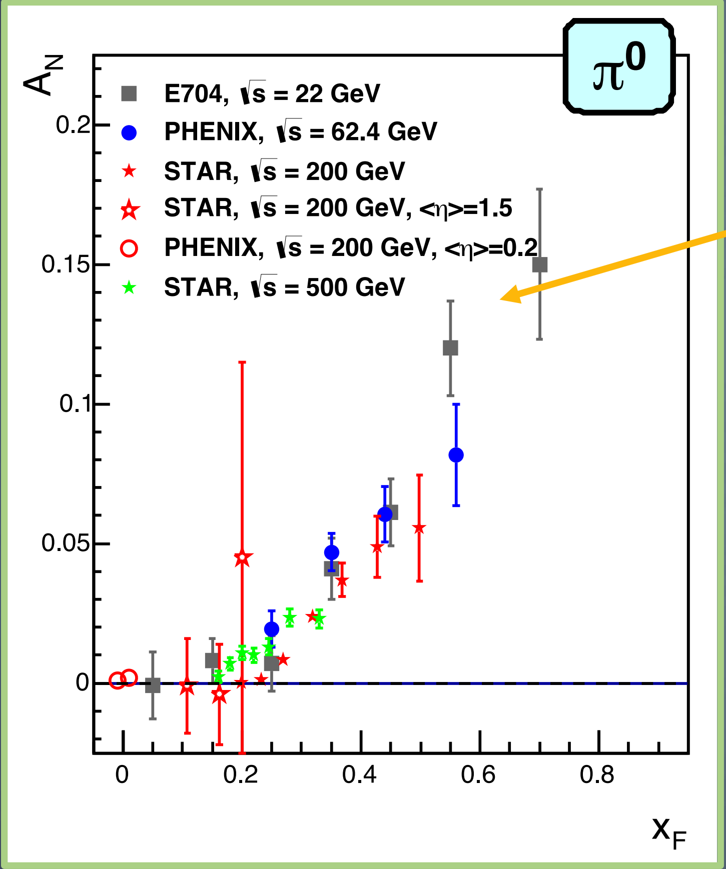
Far-Forward Collins TMDFF

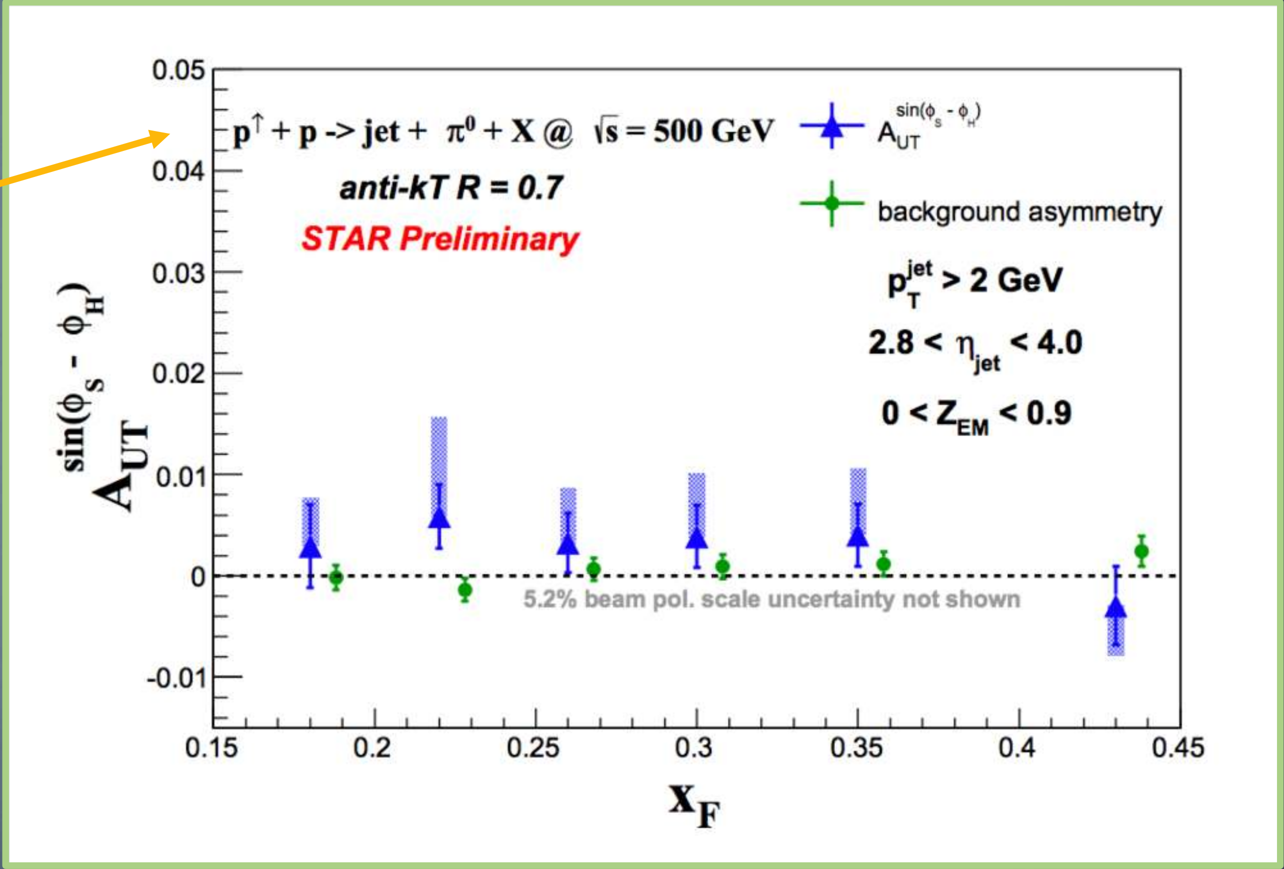




- No charged tracks – EM jets only. Leads to large systematic error on reconstruction of the Collins angle.
- π^0 reconstruction
- Size and shape of asymmetries very similar to mid-rapidity.

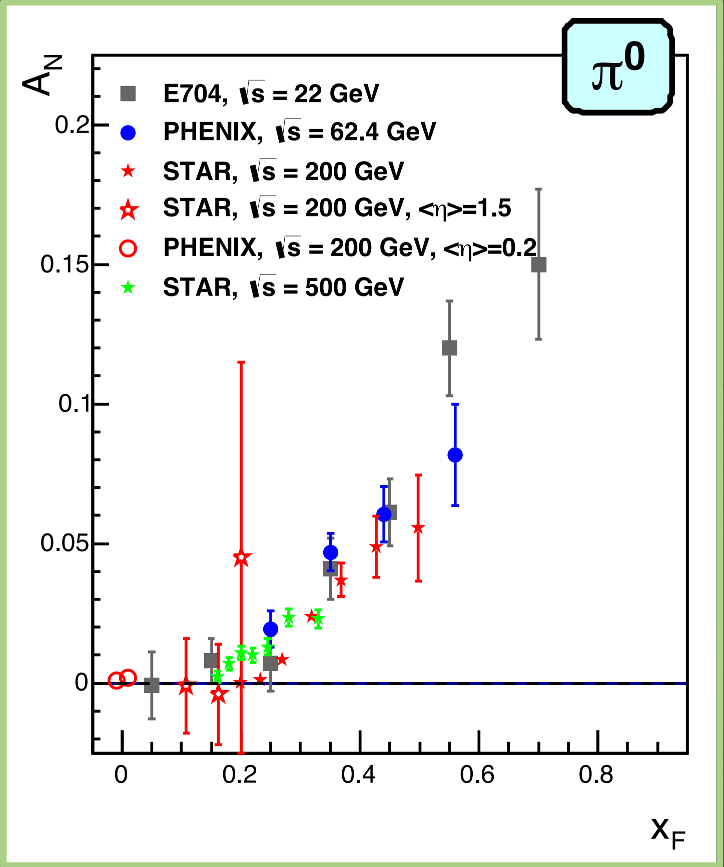
Doesn't explain Large Forward SSA

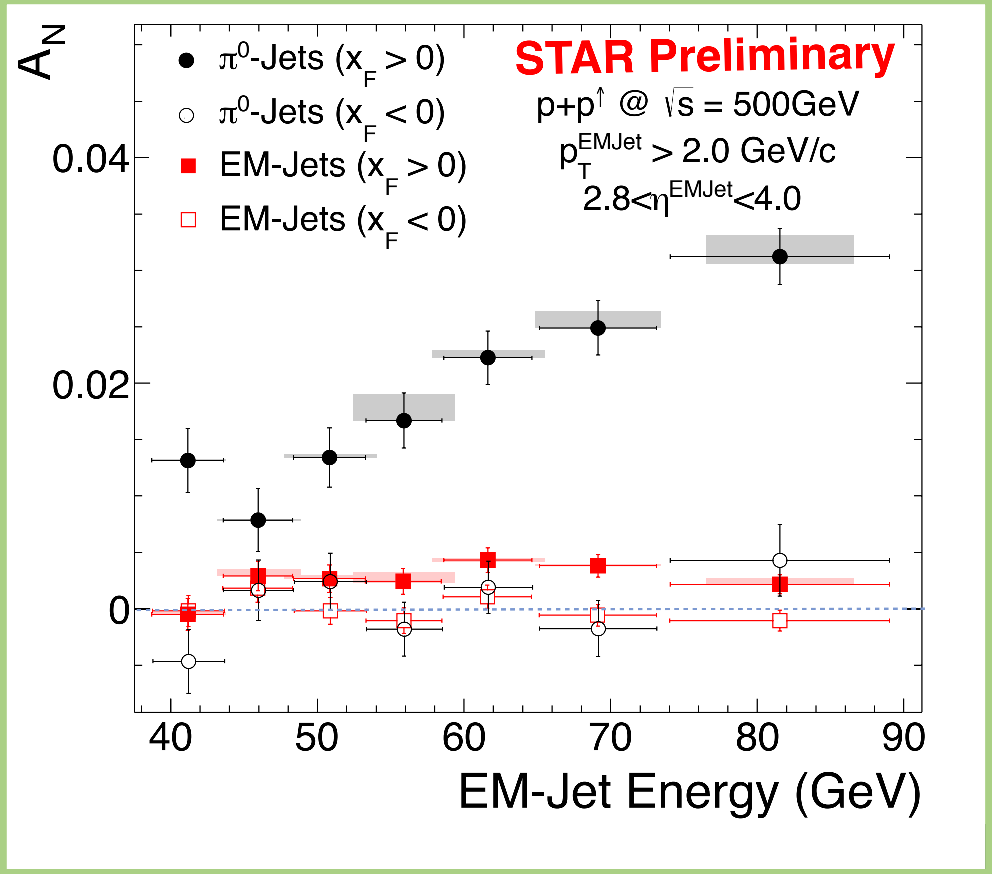




Jet asymmetries don't represent size or shape of inclusive π^0 SSA!

Doesn't explain Large Forward SSA





"Recover" asymmetries if "jet" is composed largely of a single pion.

Gluon TMDs @ 200 and 500 GeV

- **$\sin(\phi_s\text{-}2\phi_H)$ moment** Gluon Linear Polarization ⊗ Collins-Like FF
- First limit on linearly polarized gluons in a polarized proton!

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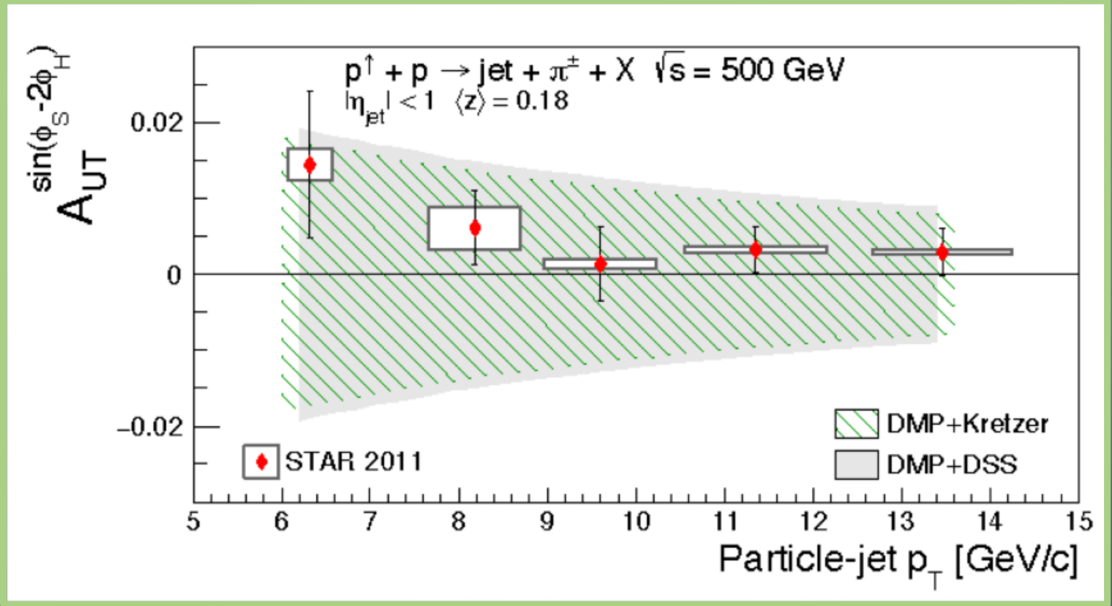
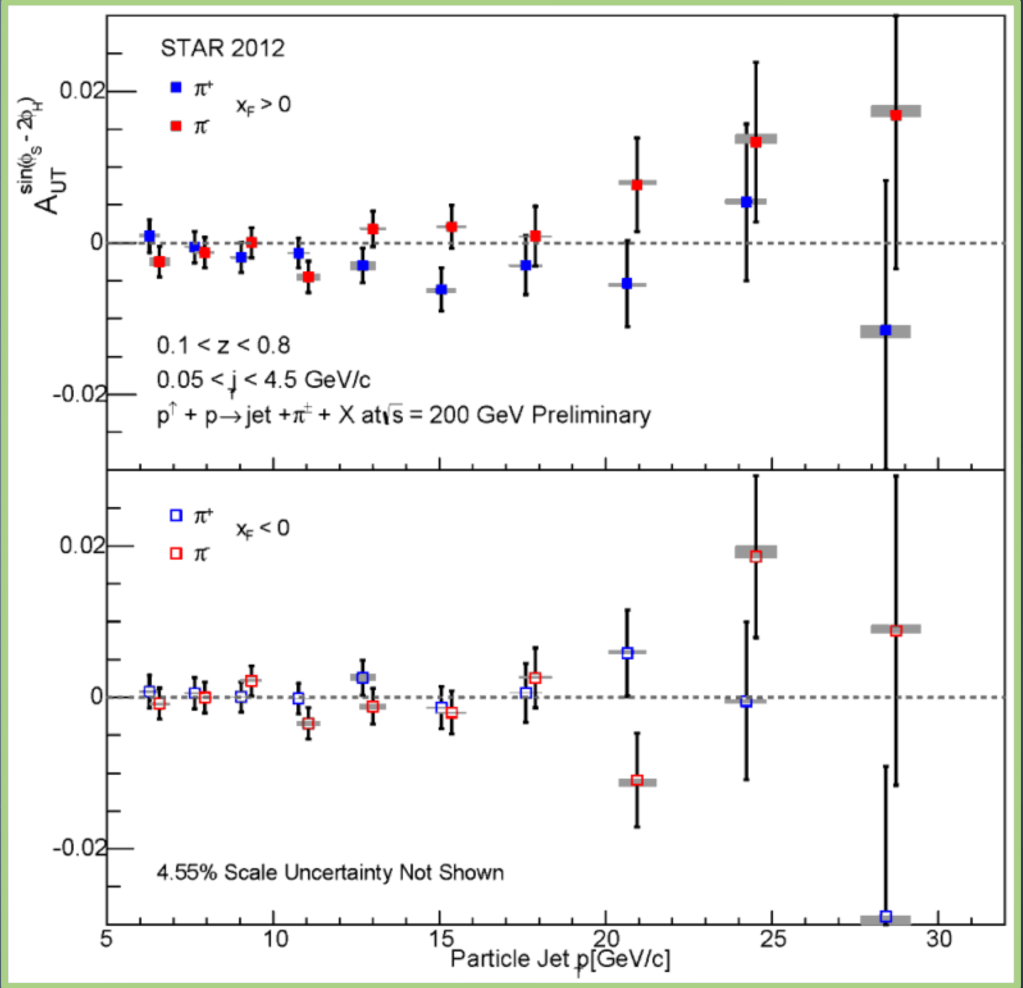




This is the end of the Jets in Spin Ride

…in case you fell off somewhere this is the one page summary

- The commencement of high energy polarized proton-proton collisions at RHIC has opened a new sub-field of **spin phenomena with jets**.
- RHIC's ability to provide both transversely and longitudinally polarized beams at a variety of energies has facilitated a robust **gluon helicity** and **transverse spin** program based entirely on jet observables.
- The inclusive jet A_{LL} was the first measurement to indicate that ΔG is non-zero. These data, combined in a global analysis with inclusive pion results give **ΔG ~ 40% of the proton spin for x > 0.05** !
- Large azimuthal asymmetries of charged pions in jets have been measured for the first time in hadronic collisions. These observables are sensitive to the same **Collins fragmentation functions** as measured in SIDIS and e+e- collisions.
- Measurements of **jet substructure** have shed light on source of the large forward inclusive pion single spin asymmetry.
- RHIC pp collisions provide unique access to **gluon TMDs** as well.

Thank you!

Backup

Anti-kT algo

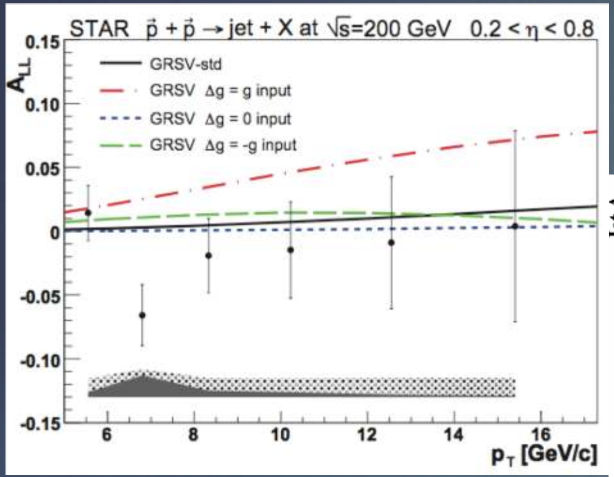
1. Create list of a tracks and towers
2. Find smallest of dij and diB
3. If ij is the smallest combine I and j
4. If iB is the smallest call i a jet and remove from list
5. Repeat until there are no towers/tracks left in list
6. Apply minimum jet p_T cut for final sample.

$$d_{ij} = \frac{1}{\max\left(p_{Ti}^2, p_{Tj}^2\right)} \frac{\Delta R_{ij}^2}{R^2}$$

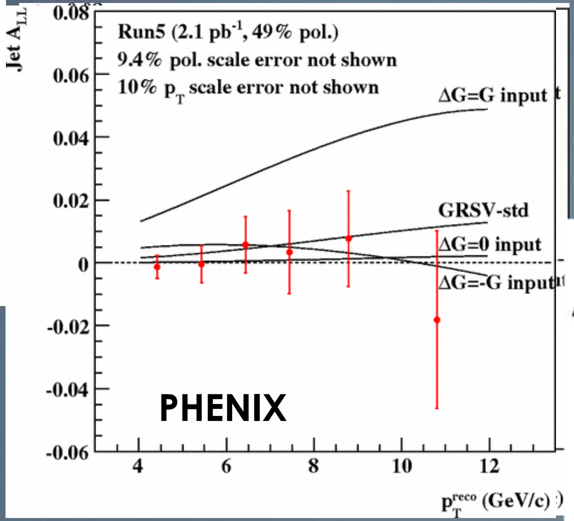
$$d_{iB} = \frac{1}{p_{Ti}^2}$$

Disfavors clustering between pairs of soft particles. Most pairwise clusterings involve at least one hard particle.

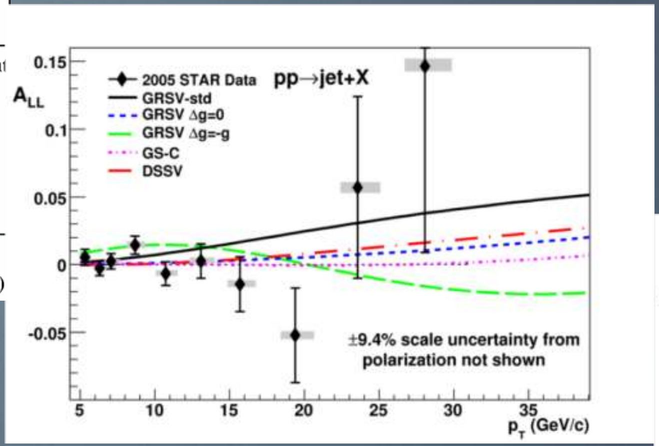
Pre-run 9 RHIC Jet A_{LL} Results



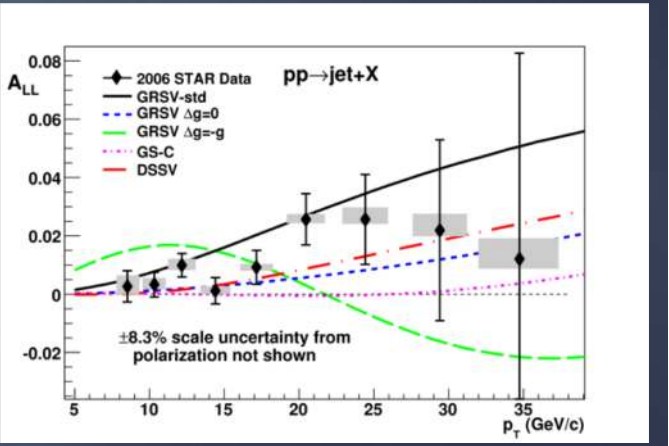
2003+2004



2005



2005



2006

All jets reconstructed using seed-cone algorithm.

Data Driven Underlying Event Correction

- In general data and simulation comparisons are quite good after UE subtraction.
- There is a systematic difference in the size of the UE correction, This is incorporated into systematic errors.