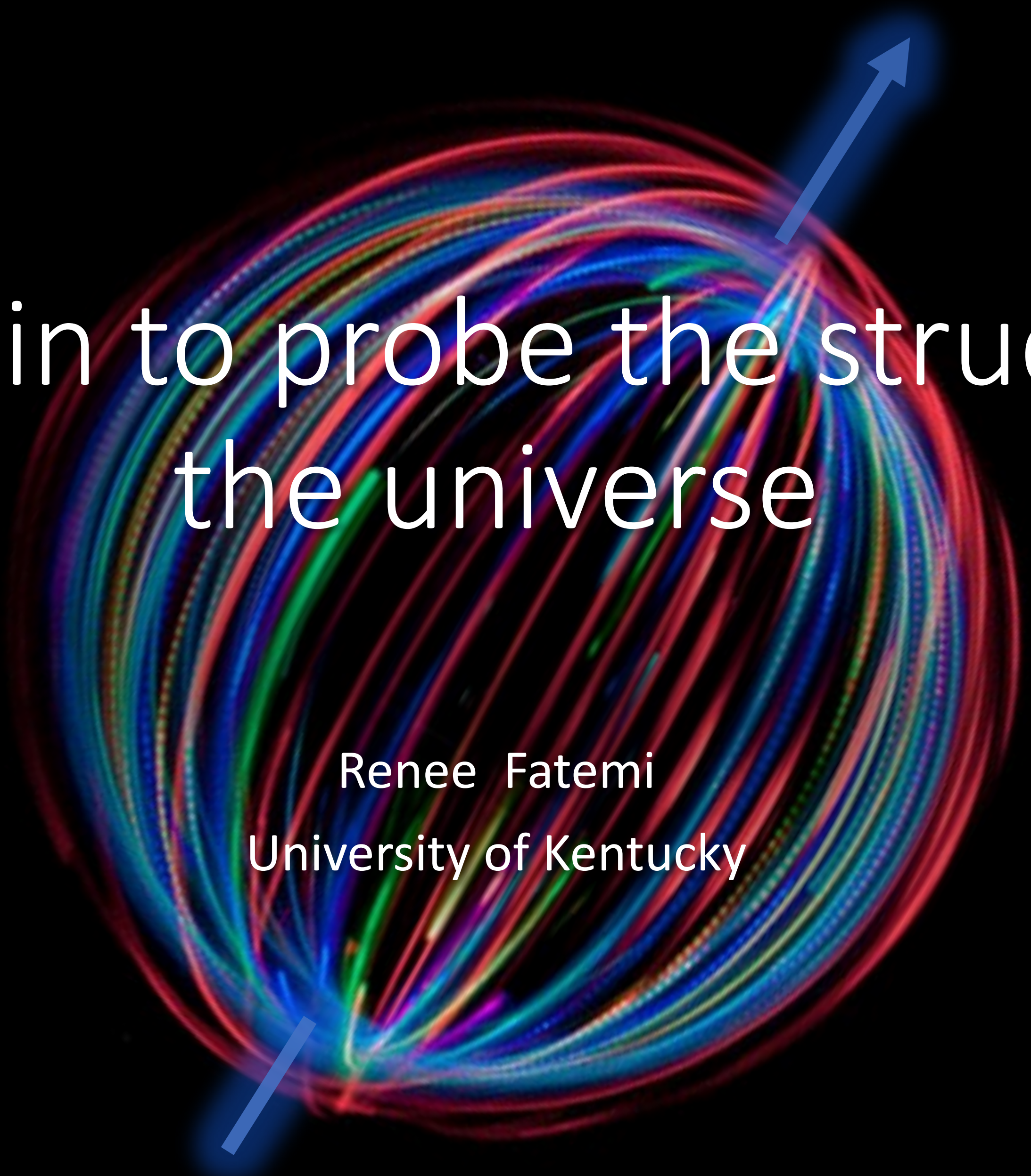
Using spin to probe the structure of the universe



Renee Fatemi

University of Kentucky

10th Workshop of the APS Topical Group on Hadronic Physics

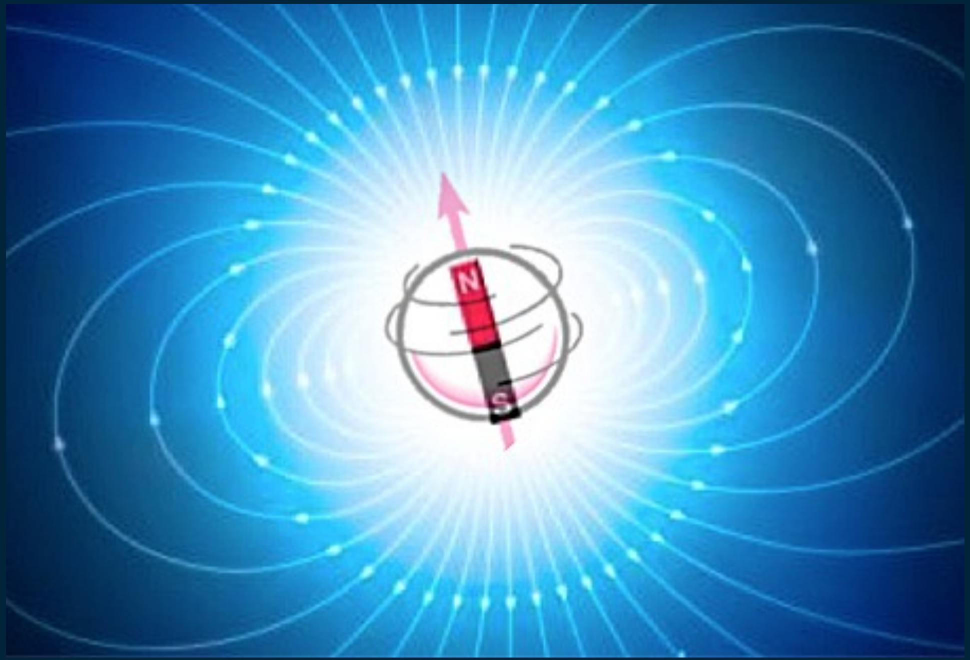
April 14, 2023

Spin

- Particles have intrinsic angular momentum called spin
- Fermion spin emerges naturally from relativistic quantum mechanics

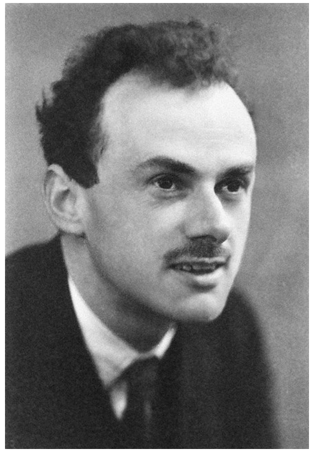
$$(i\gamma^\mu \partial_\mu - m)\,\psi = 0$$

- Implies a deep and fundamental connection between spin dynamics and the underlying forces that govern our universe.
- Classic example :
  the proton magnetic moment



$$\vec{\mu} = g\frac{Q}{2m}\vec{S}$$

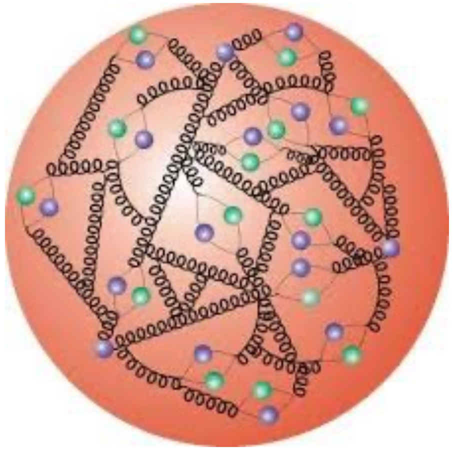
Magnetic Dipole Moments



Prediction of *g* = 2 for all point-like spin 1/2 fermions emerges from Dirac equation. *P.A.M. Dirac, Proc. R. Soc. A 118, 351 (1928)*

Stern & associates measured the proton magnetic moment in 1933 and find proton *g* = 5.59! *R. Frisch and O. Stern, Z. Phys. 85, 4,I. Estermann and O. Stern, Z. Phys 85, 17 (1933)*

"While we were measuring the magnetic moment of the proton we were strongly chided by the theoreticians since they thought they already knew the answer." [4] ETH-Bibliothek Zürich, Archive, http://www.sr.ethbib.ethz.ch/, Otto Stern tape-recording Folder »ST-Misc.«, 1961 at E.T.H. Zürich by Res Jost

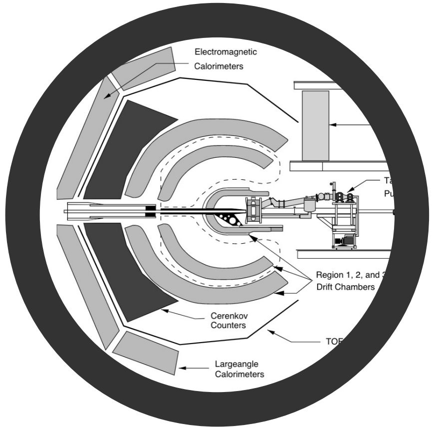


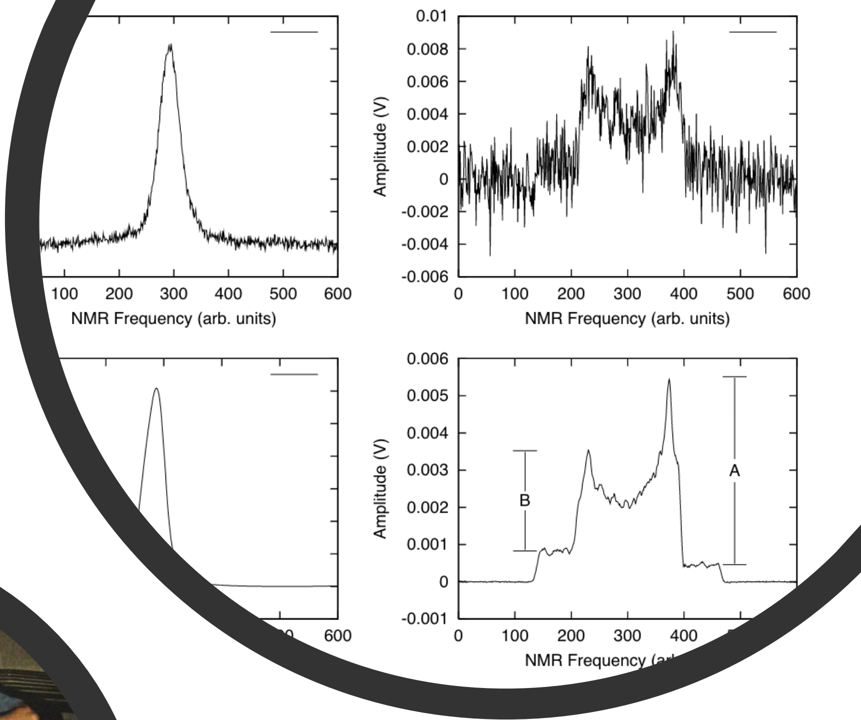
A measurement of the magnetic moment of a "point-like particle" leads to the discovery of substructure in the proton – decades before the discovery of quarks or gluons! Classic example of using spin to provide the structure of the universe!

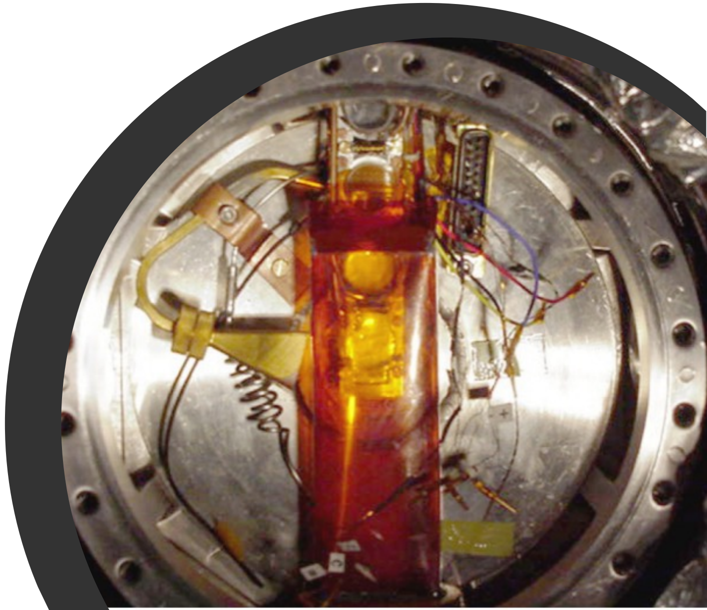
Early Adventures in Spin

- Thesis experiment in Hall-B @ Jefferson Lab
- Part of the team that built and operated the first polarized target in Hall B.
- My analysis was on spin structure of the proton g_1^P at low Q^2 =0.15- 1.64 GeV^2

$$g_1^p = \frac{\tau}{1+\tau}\left[\frac{A_{||}}{D} + (\gamma - \eta)A_2^p\right]F_1^p.$$

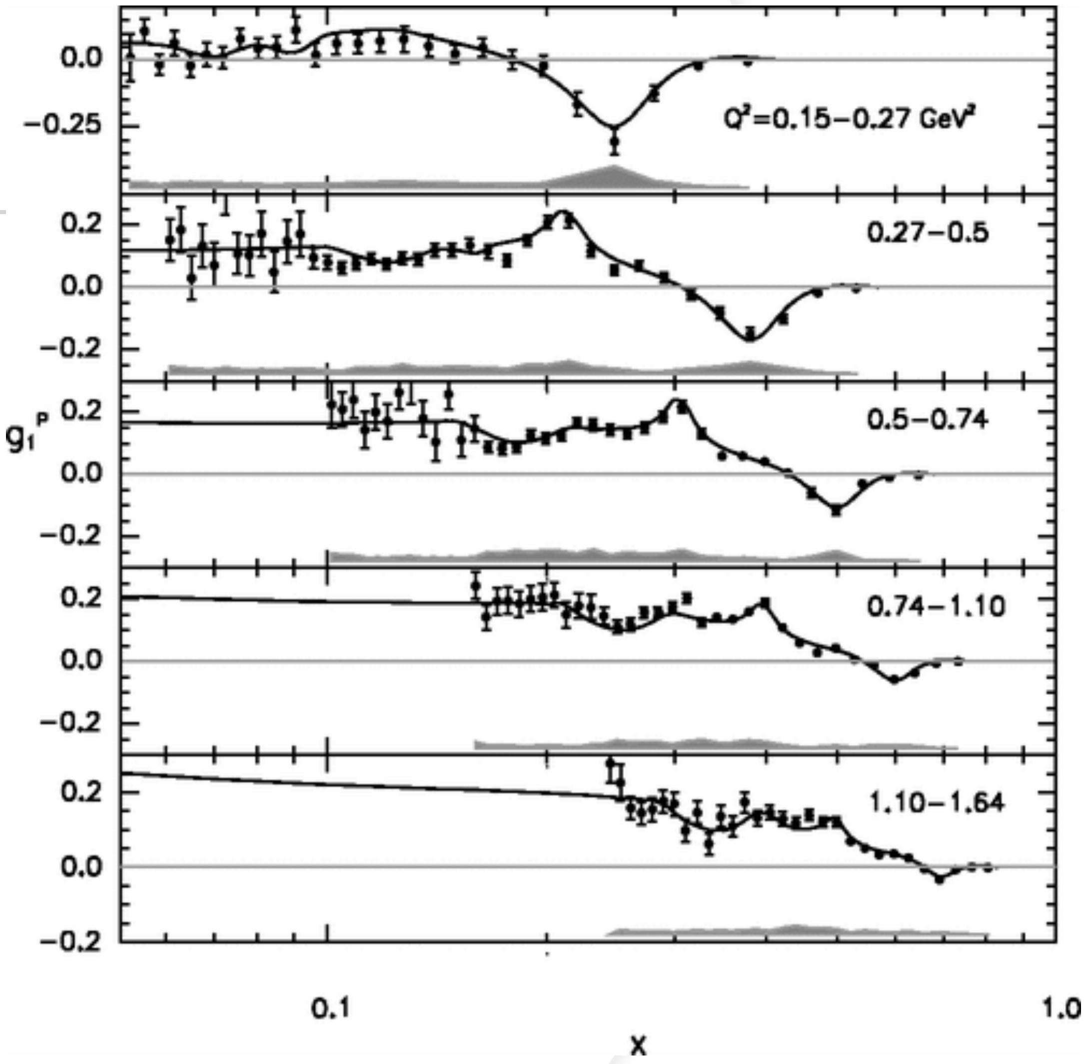


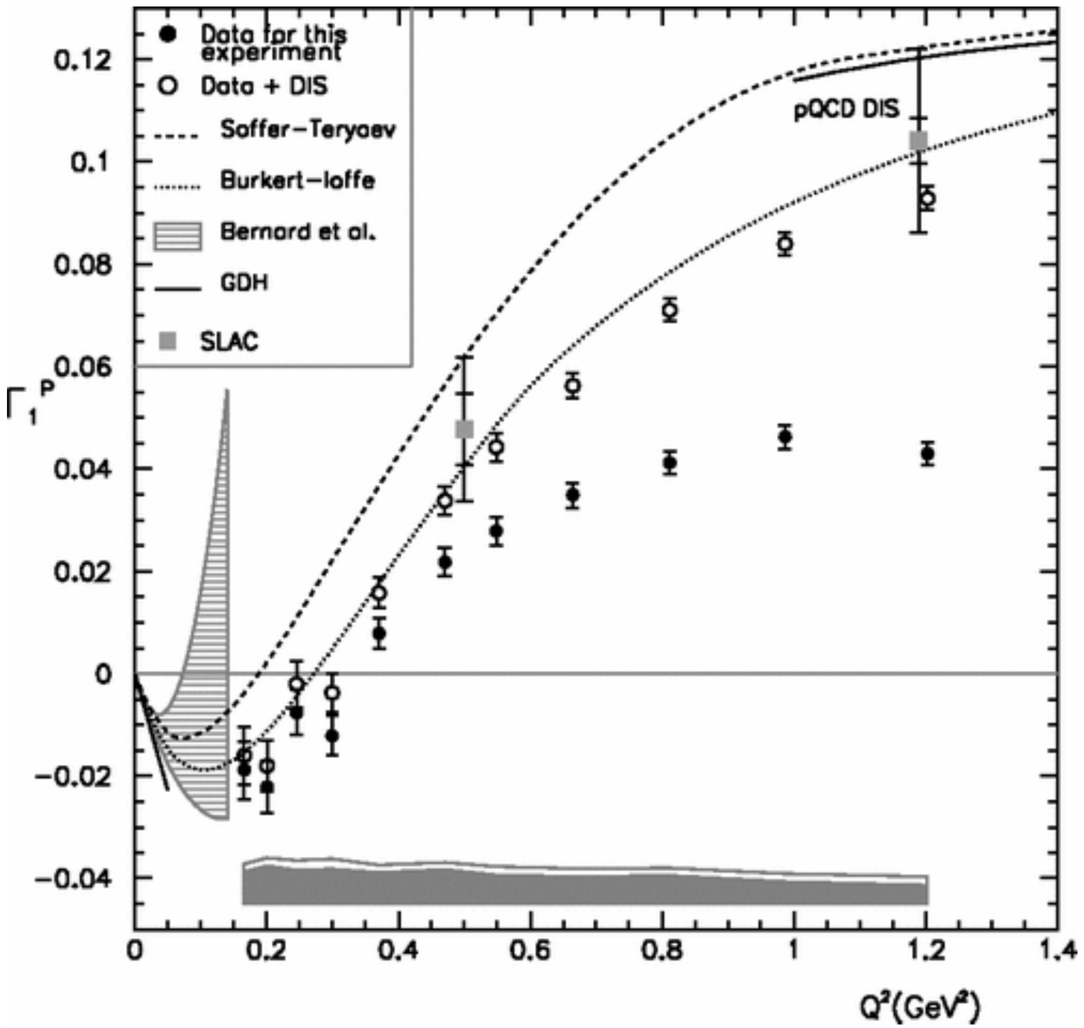




$$g_1^p = \frac{\tau}{1+\tau}\left[\frac{A_{||}}{D} + (\gamma - \eta)A_2^p\right]F_1^p.$$

Phys.Rev.Lett. 91, 222002

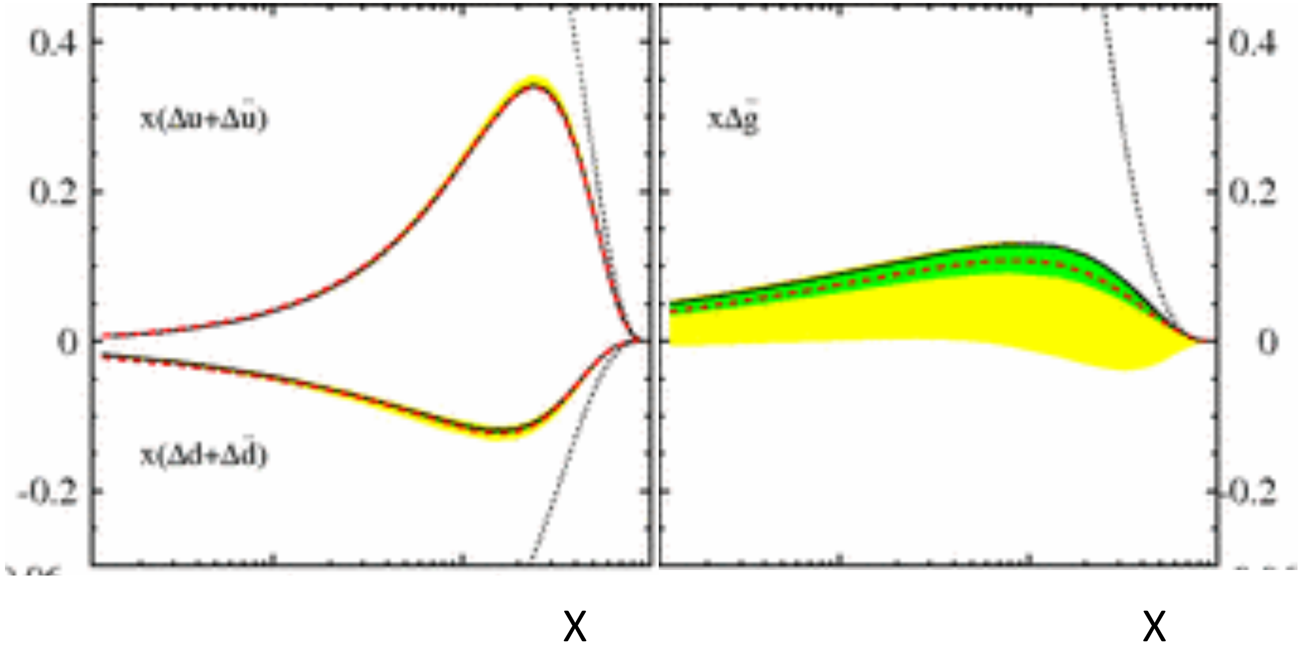




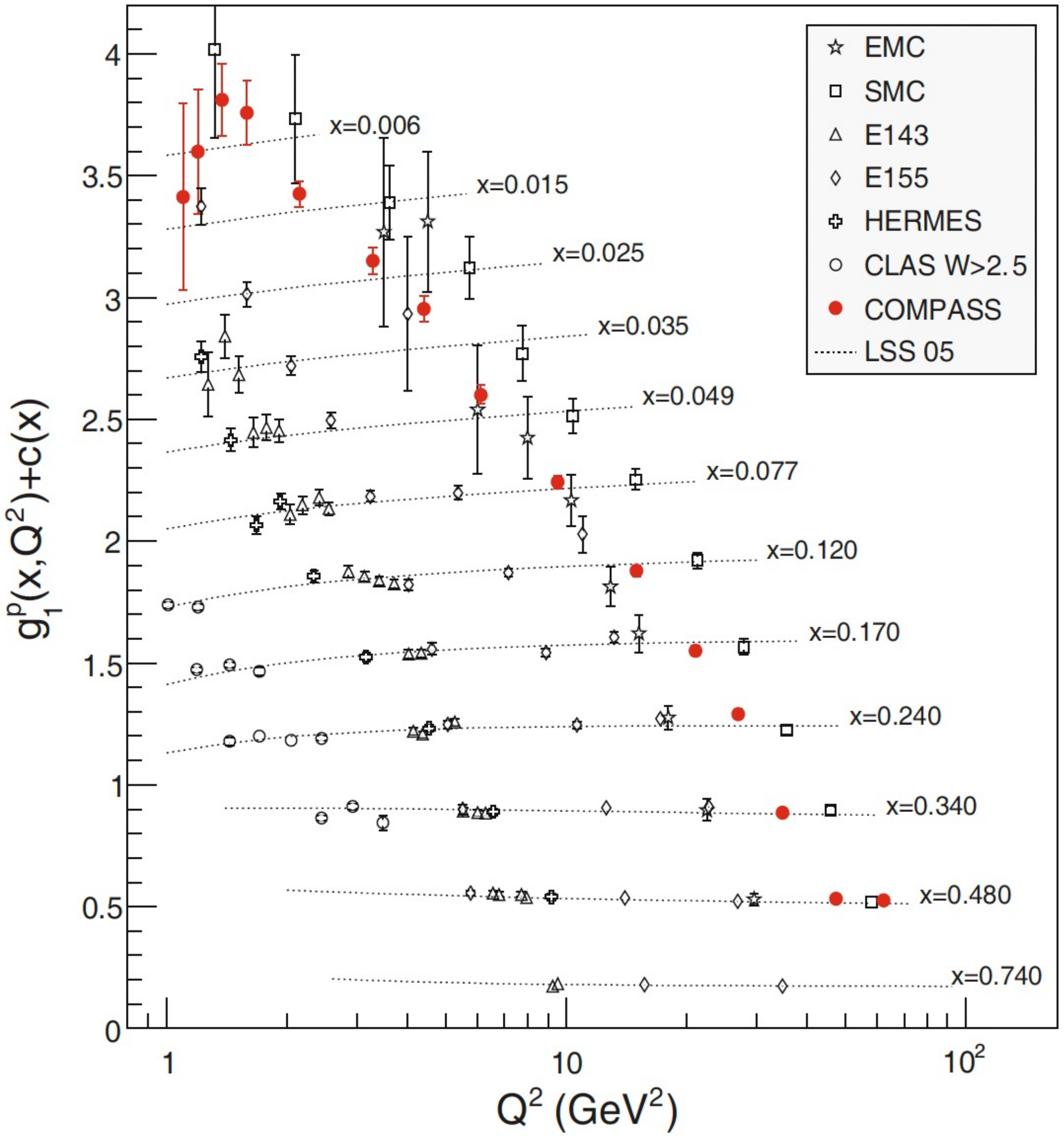
Next Spin Adventure

…the gluon!

PhysRevD.71 094018

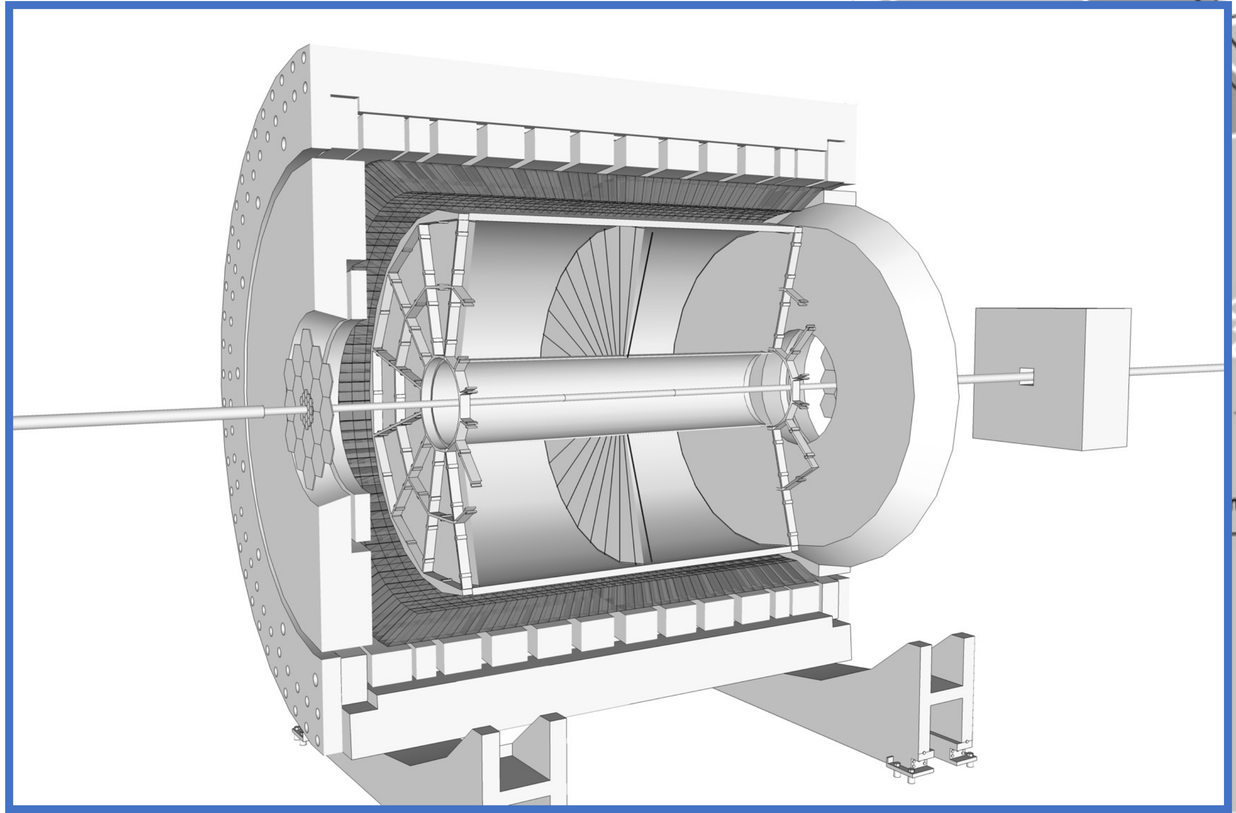


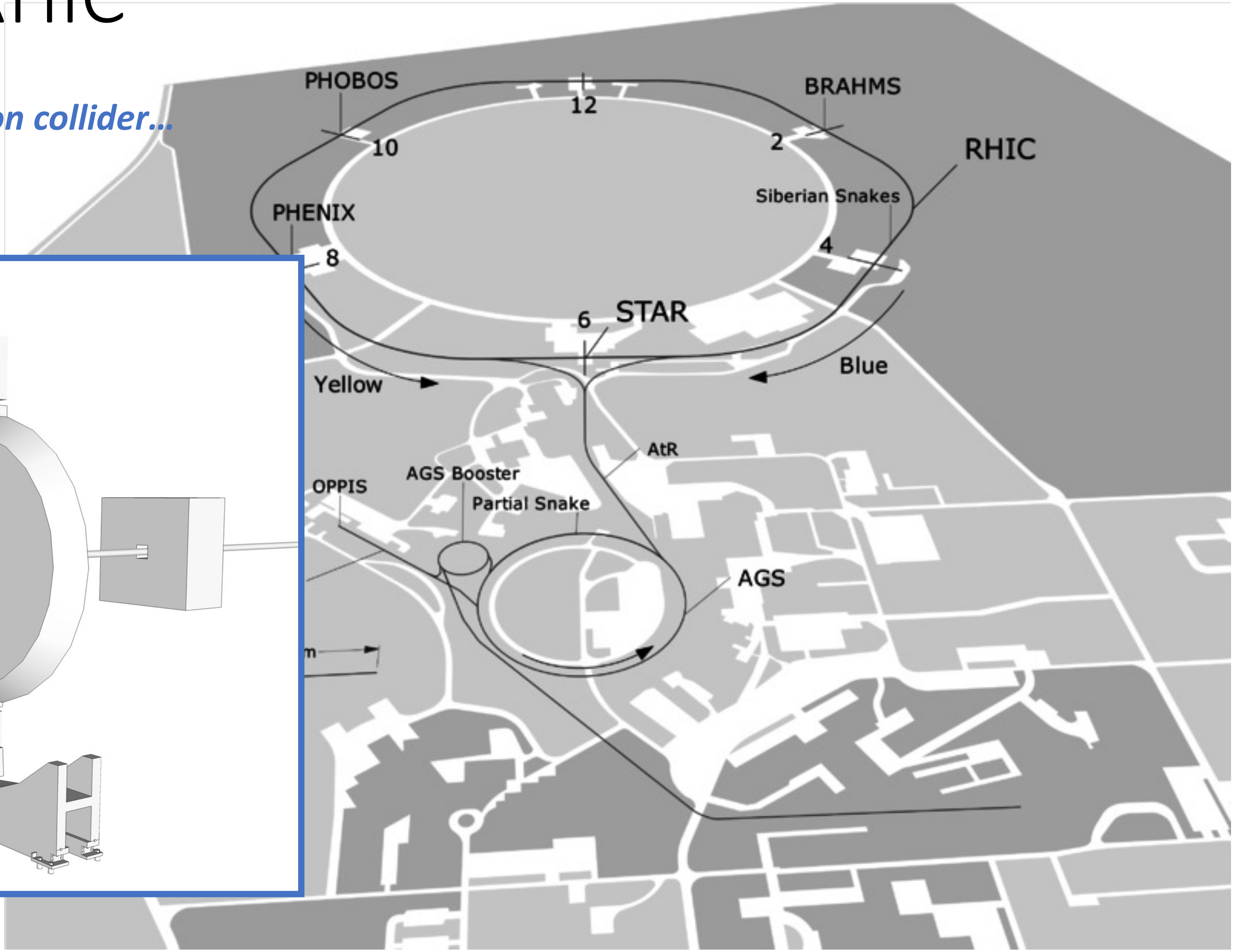
EIC White Paper arXiv 1212.1701



STAR Detector @ RHIC

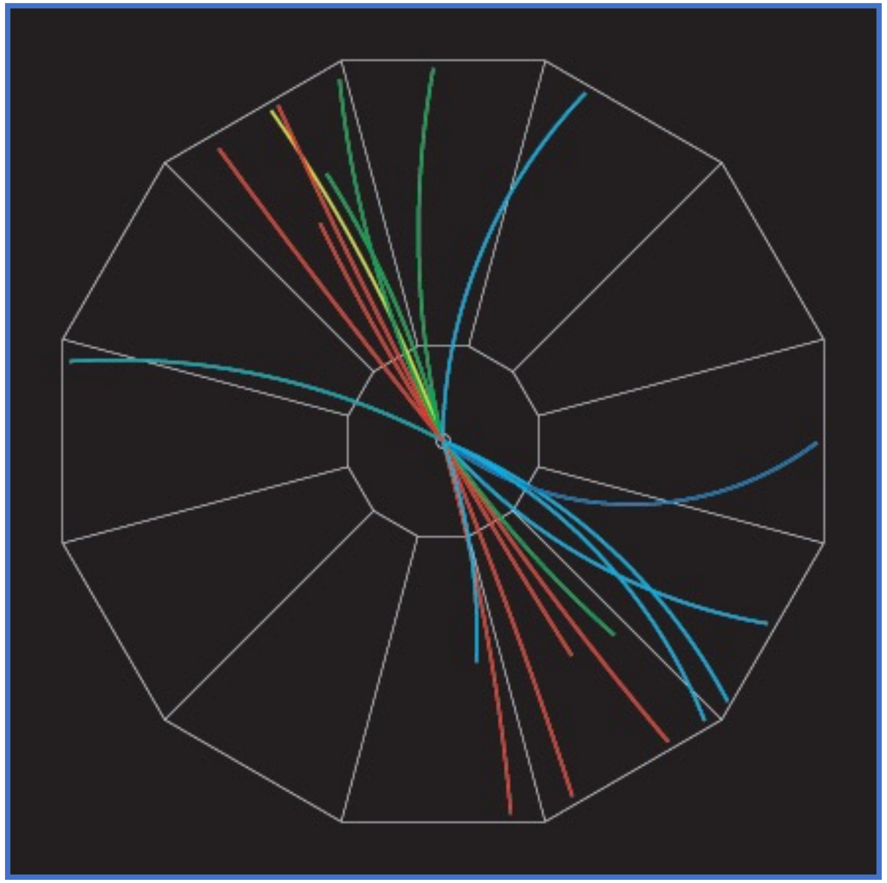
the world's first and only polarized proton collider…





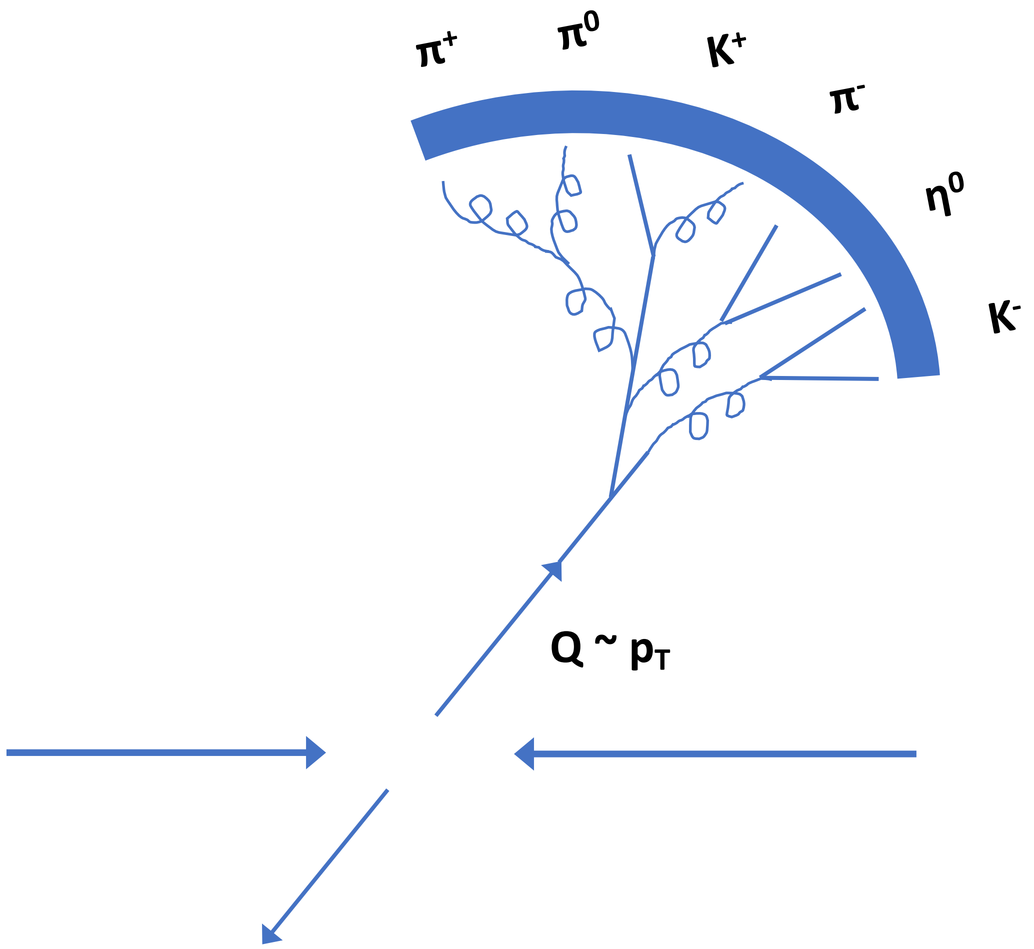
Jets as a tool for spin physics at STAR

- Jets are not well-defined objects
- Jets only become well defined objects when a clustering algorithm is specified.
- Need an algorithm that is not sensitive to soft gluon radiation and parton splitting.
- Anti-kT algorithm via FastJet
  Cacciari, Salam, Soyez, JHEP ***04****, 063 (2008)*
  Cacciari, Salam, Soyez, Eur. Phys. J. C ***72****, 1896 (2012)*



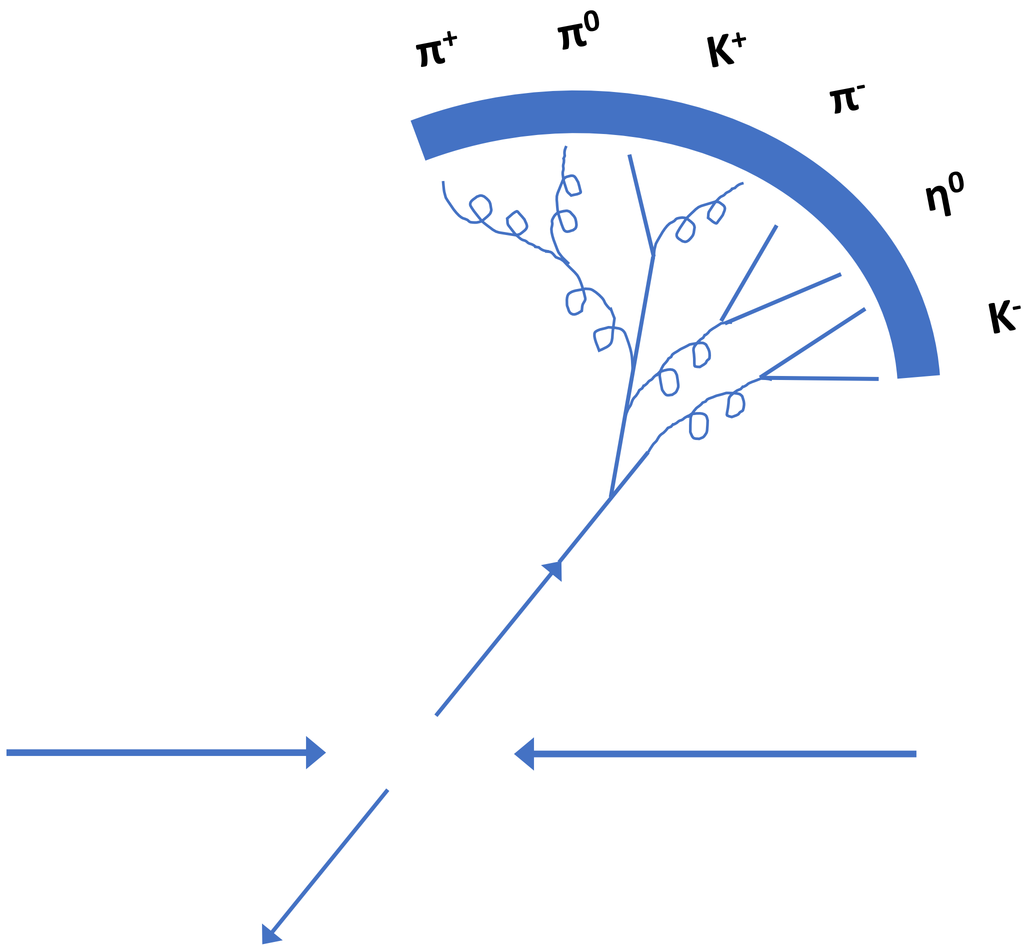
Jets : Microcosm of QCD

- Hard Scattering



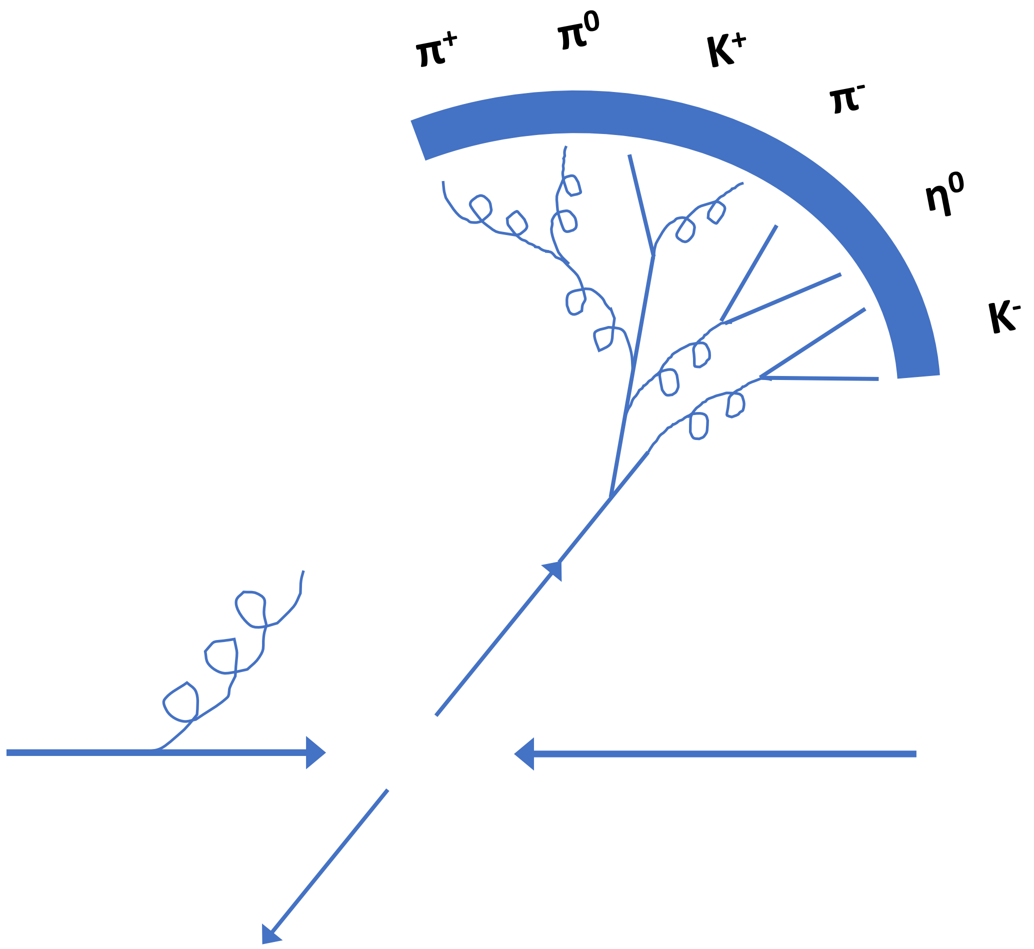
Jets : Microcosm of QCD

- Hard Scattering
- Fragmentation and Hadronization



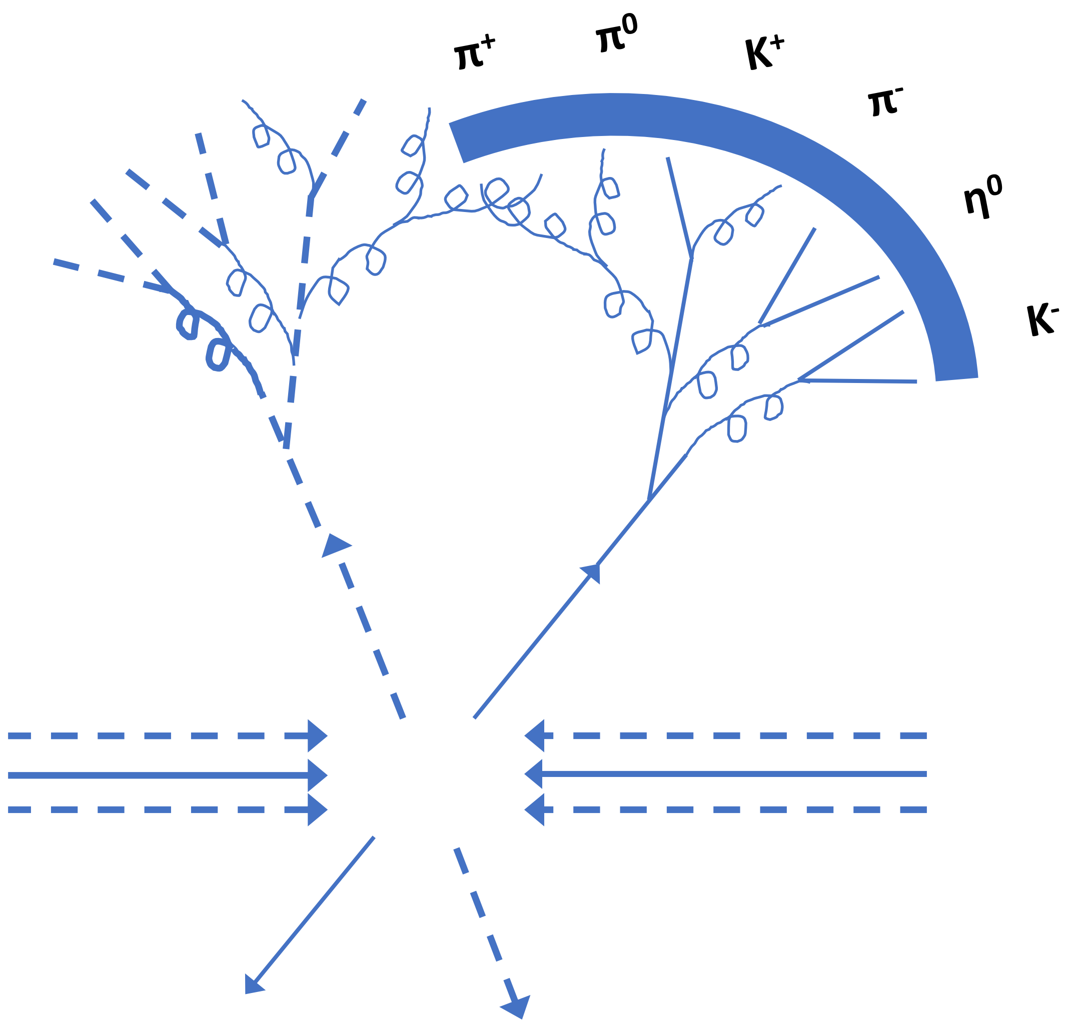
Jets : Microcosm of QCD

- Hard Scattering
- Fragmentation and Hadronization
- Radiation



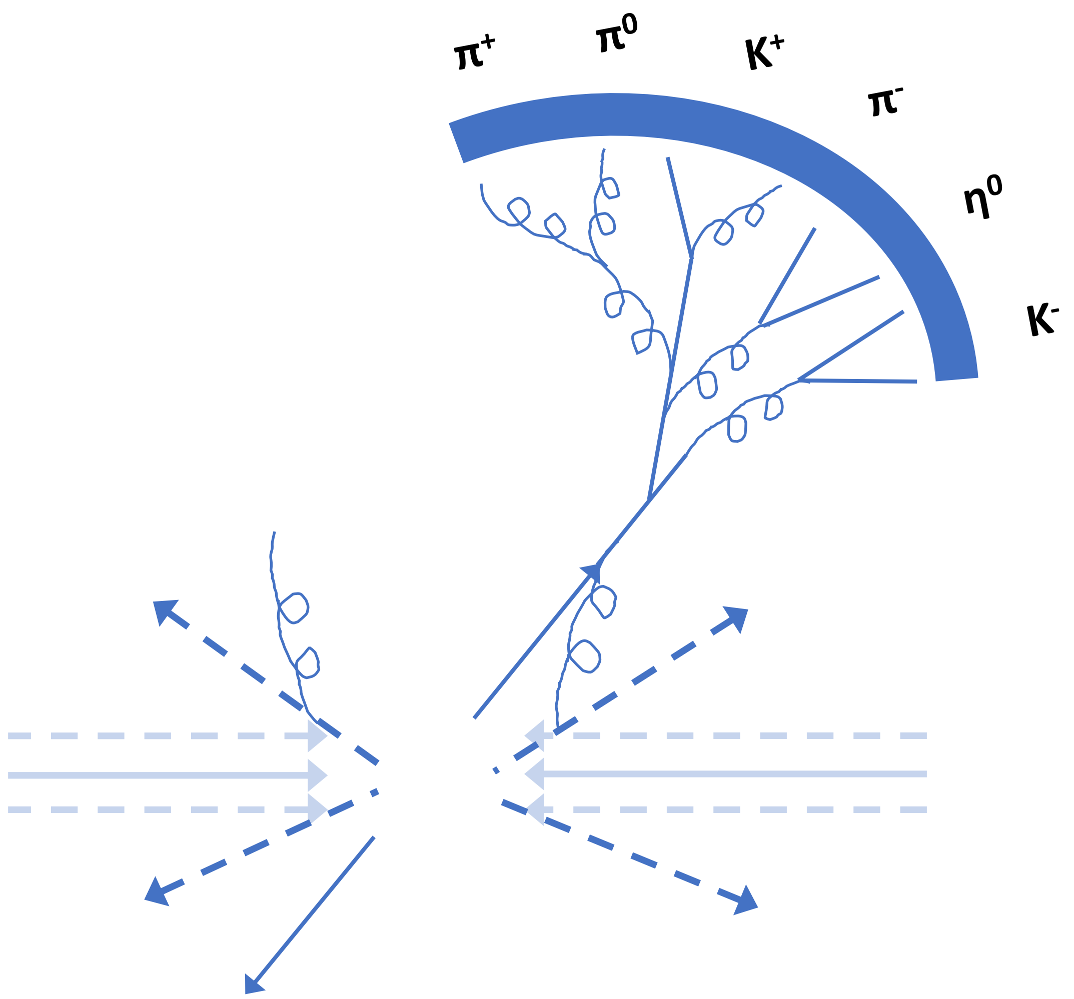
Jets : Microcosm of QCD

- 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



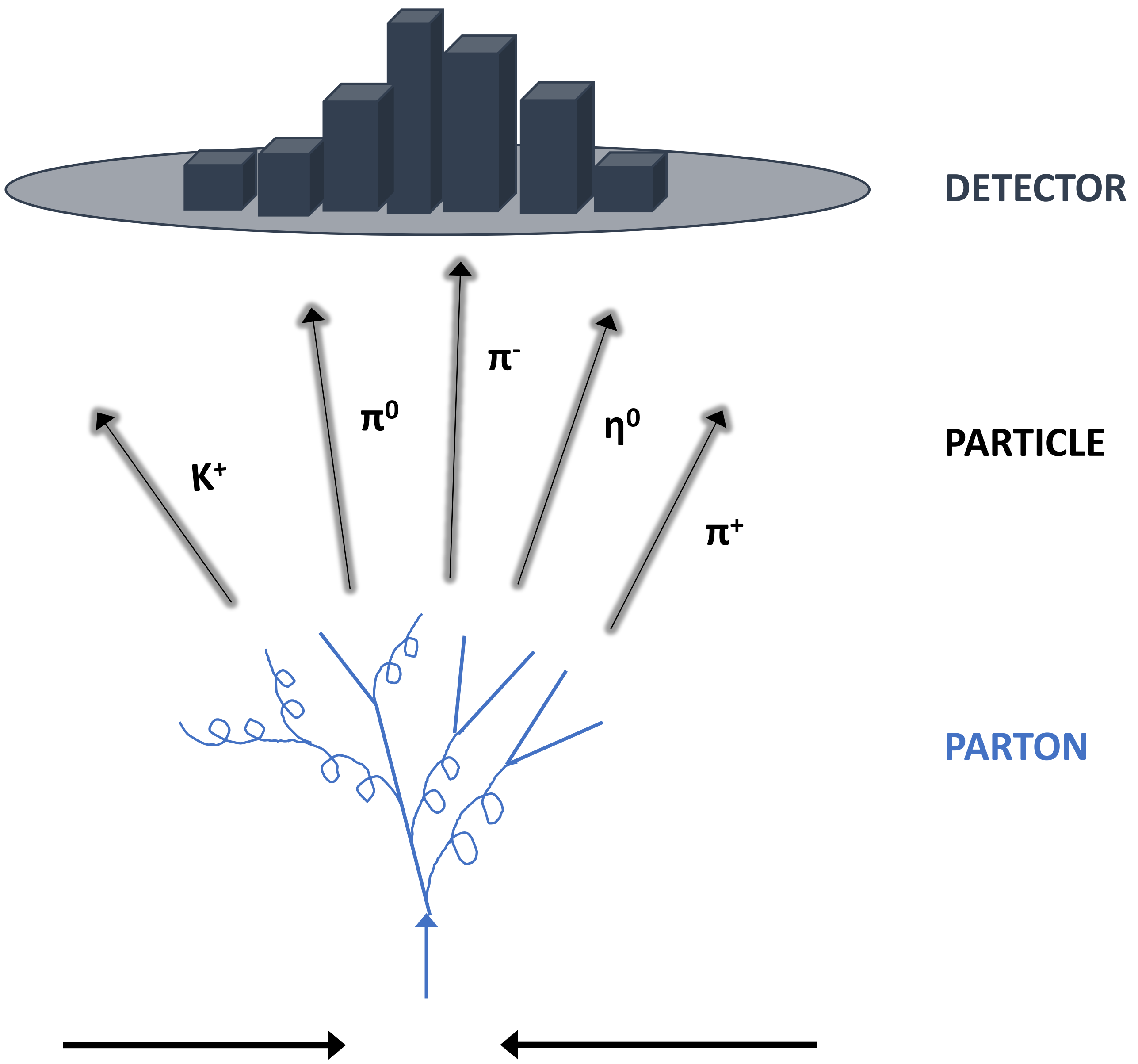
pp Jetfinder @ STAR

- R = 0.6 200 GeV mid-rapidity
- R = 0.5 500 GeV mid-rapidity

- Jet p_T > 5 GeV

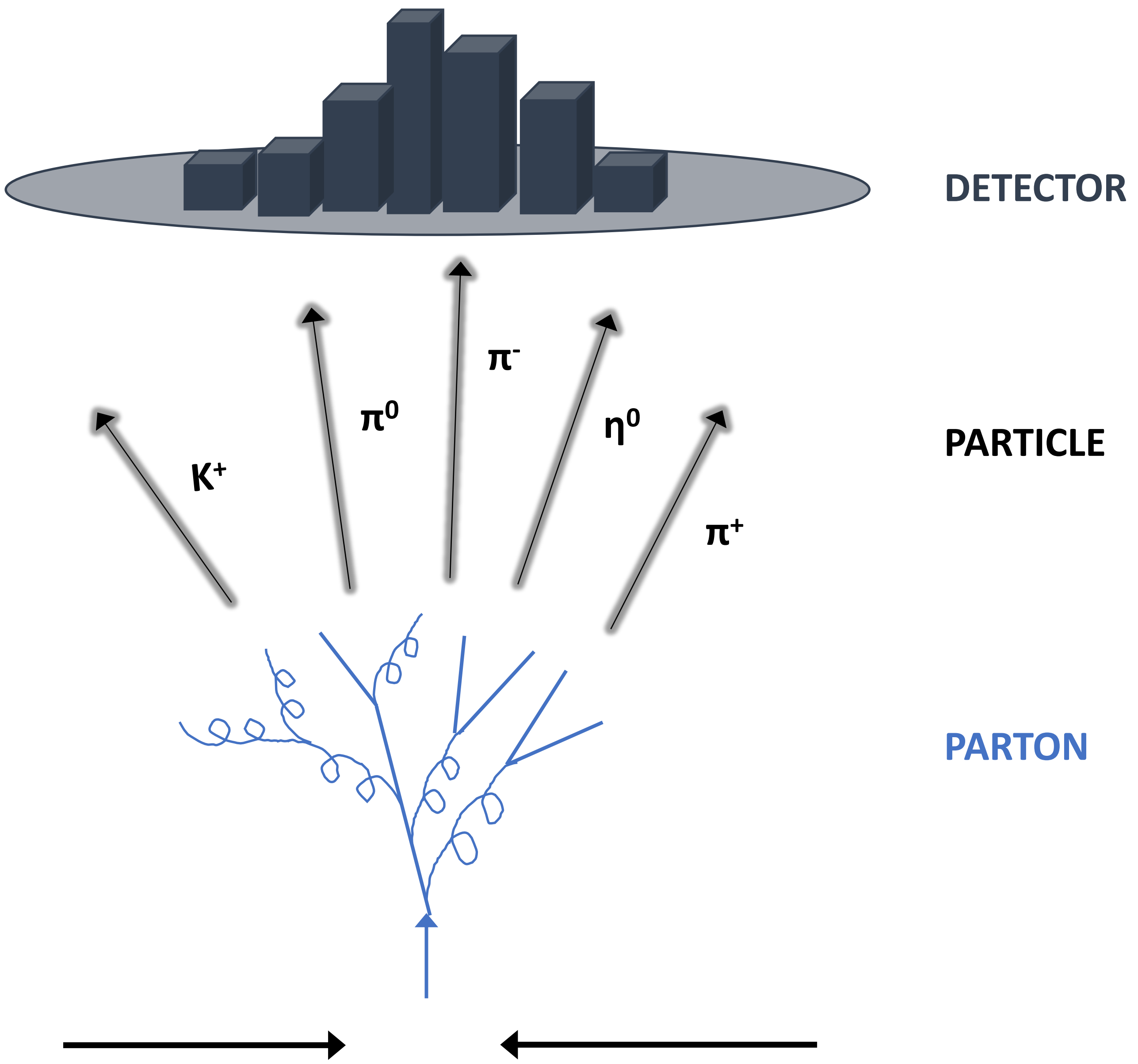
- In PYTHIA+GEANT simulation we apply anti-kT algorithm at **PARTON**, **PARTICLE** and **DETECTOR** level.

- Underlying event contributions are removed from PARTON level jets.

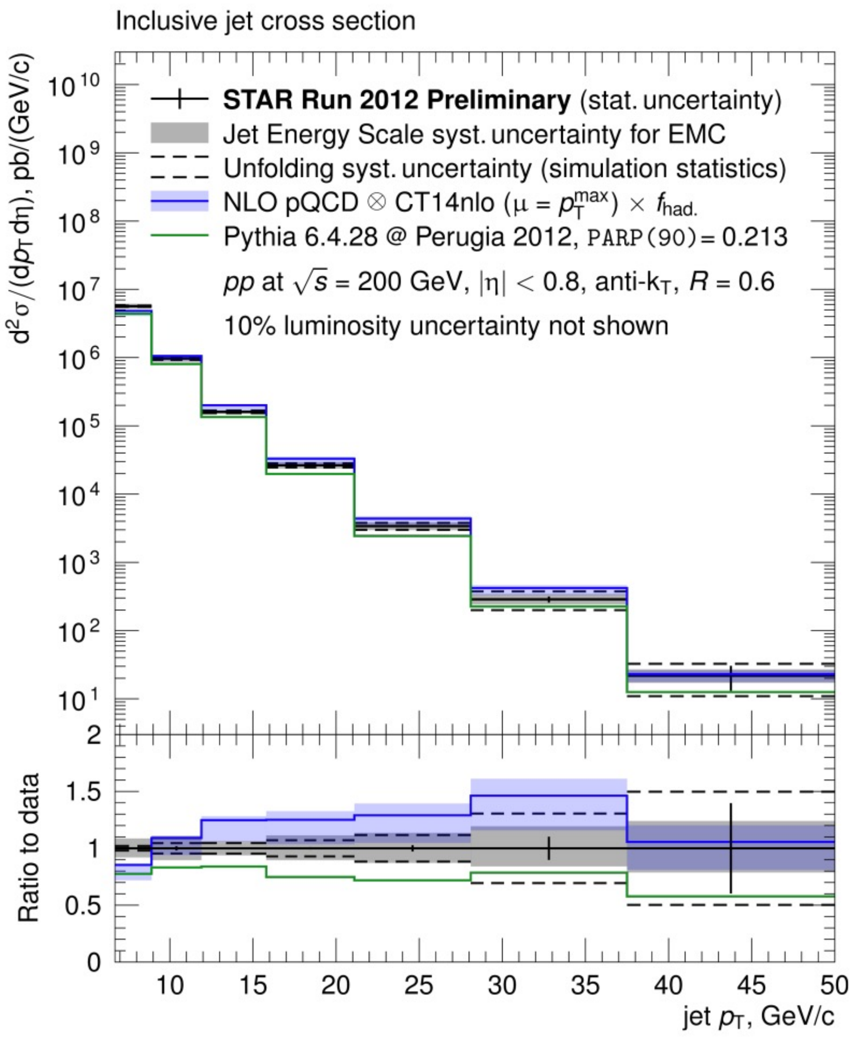


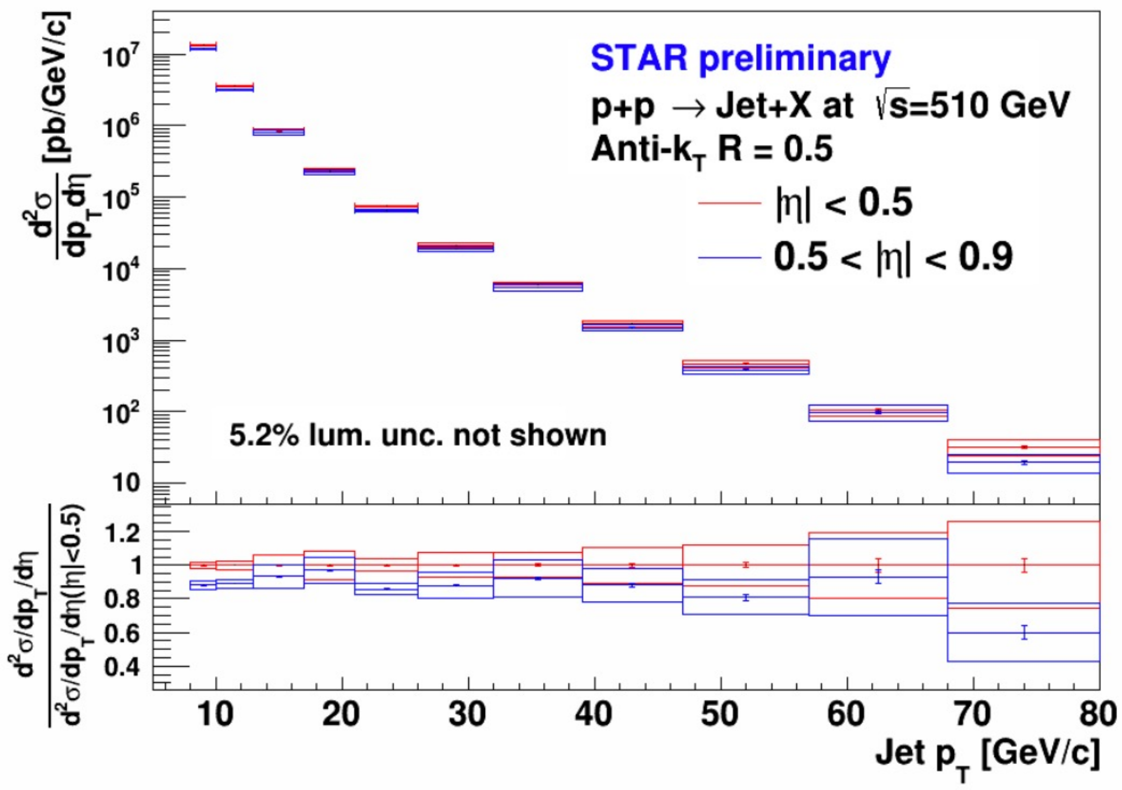
Questions we had to address along the way...

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



200 & 500 GeV Inclusive Jet Cross-section

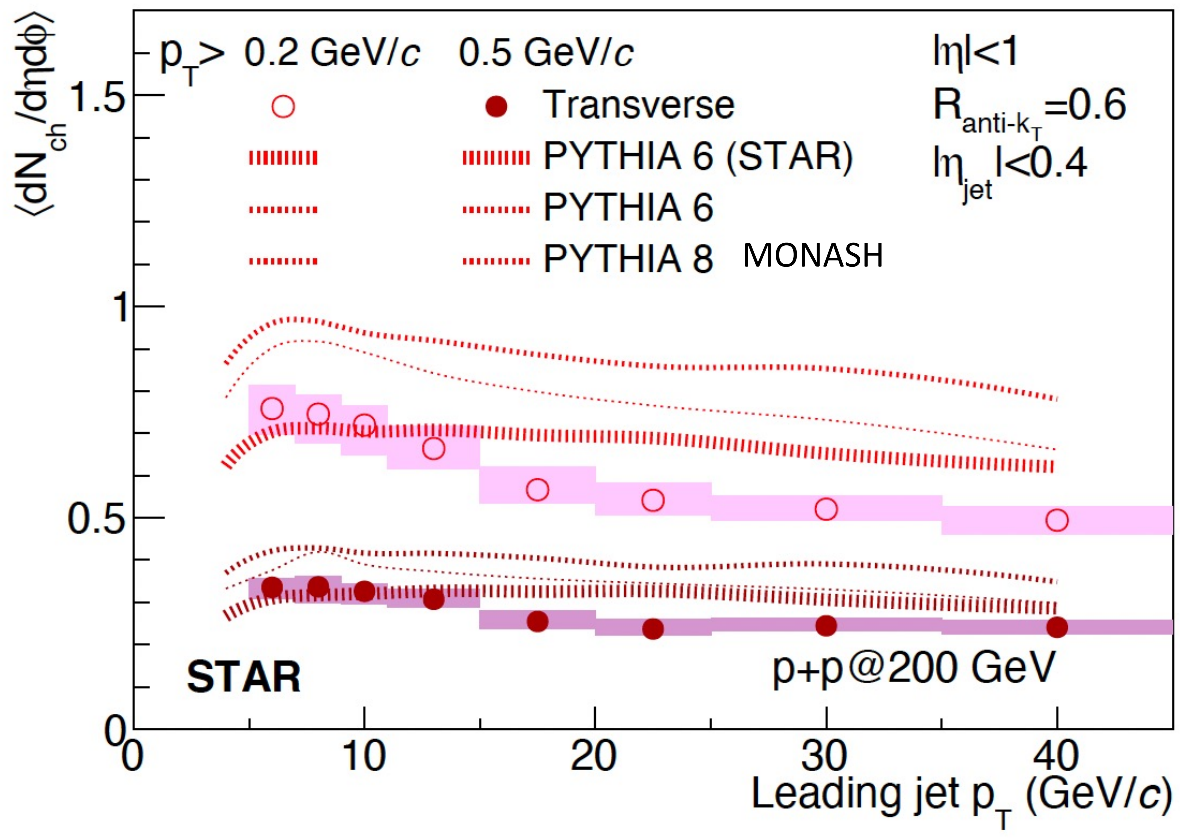




Tuning the underlying event

- Unfolding and corrections for hadronization and underlying event require simulations that reflect the data
- Before RHIC, PYTHIA tunes were dominated by Tevatron data, and then LHC data.
- Requires tune UE in simulation to reflect our √s = 200 and 500 GeV.
- Optimize the PYTHIA parameter that controls the multiple parton interactions to reflect fully corrected STAR inclusive pion samples.

Phys.Rev.D 101 (2020)



PERUGIA 2012, CTEQ6L1, PARP(90)=0.213

Tuning the underlying event

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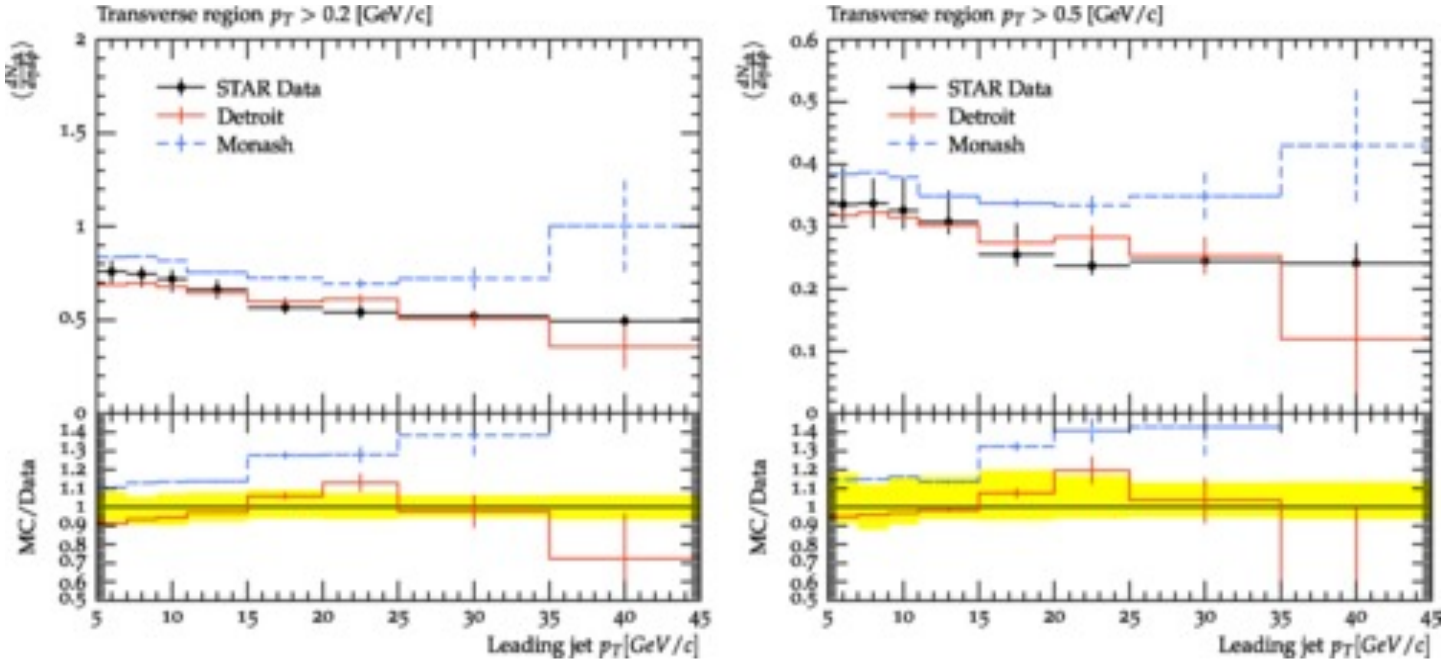
PYTHIA8 "Detroit Tune"
Phys. Rev. D 105, 015011



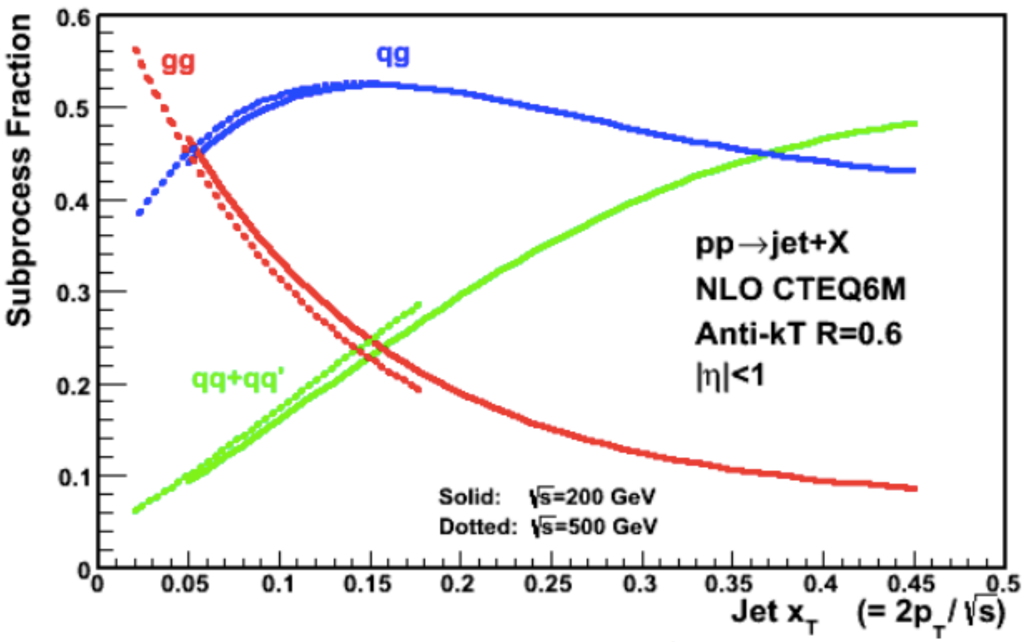
GLUON Spin

Gluons!

- Lower jet p_T → more gluons
- Measurements at higher √s access lower partonic x

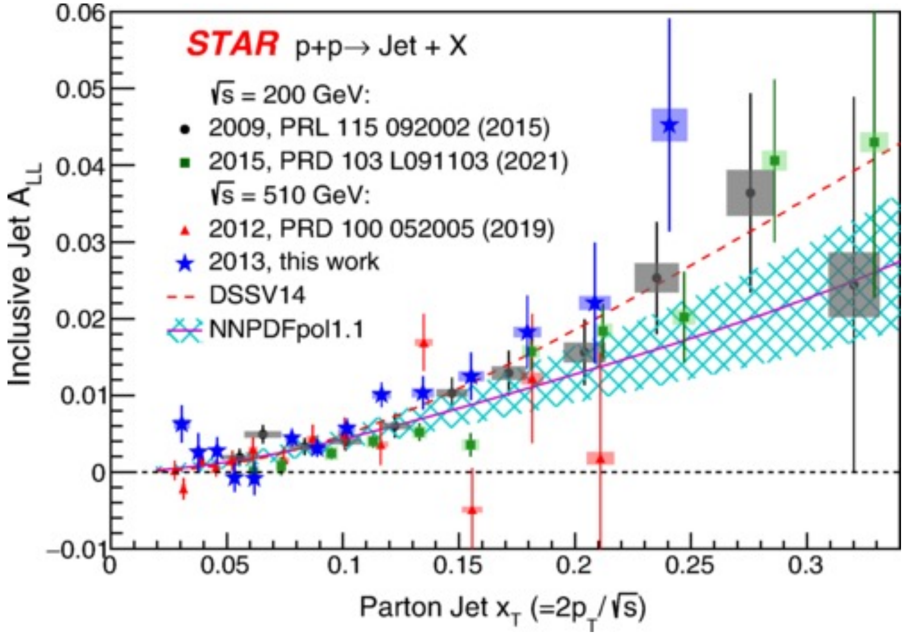
$$x \sim x_T e^{\pm\eta} = \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$$

- Look at all the jets in an event – Inclusive. Gives highest statistical power.
- Look at two highest pT jets in the the event – Dijets. Allows for 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.



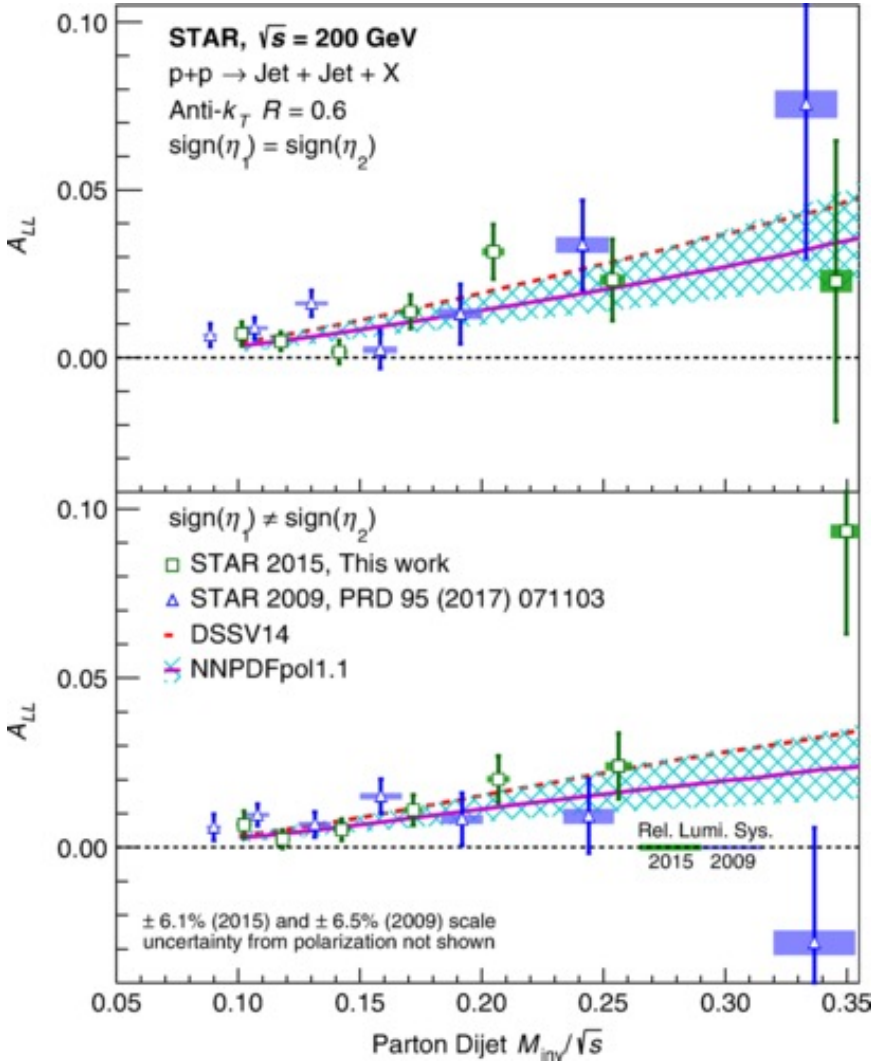
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\sum_{AB} \Delta f_A \Delta f_B \times \Delta\sigma_{AB\to jet+X}}{\sum_{AB} f_A f_B \times \sigma_{AB\to jet+X}}$$

Inclusive Jet



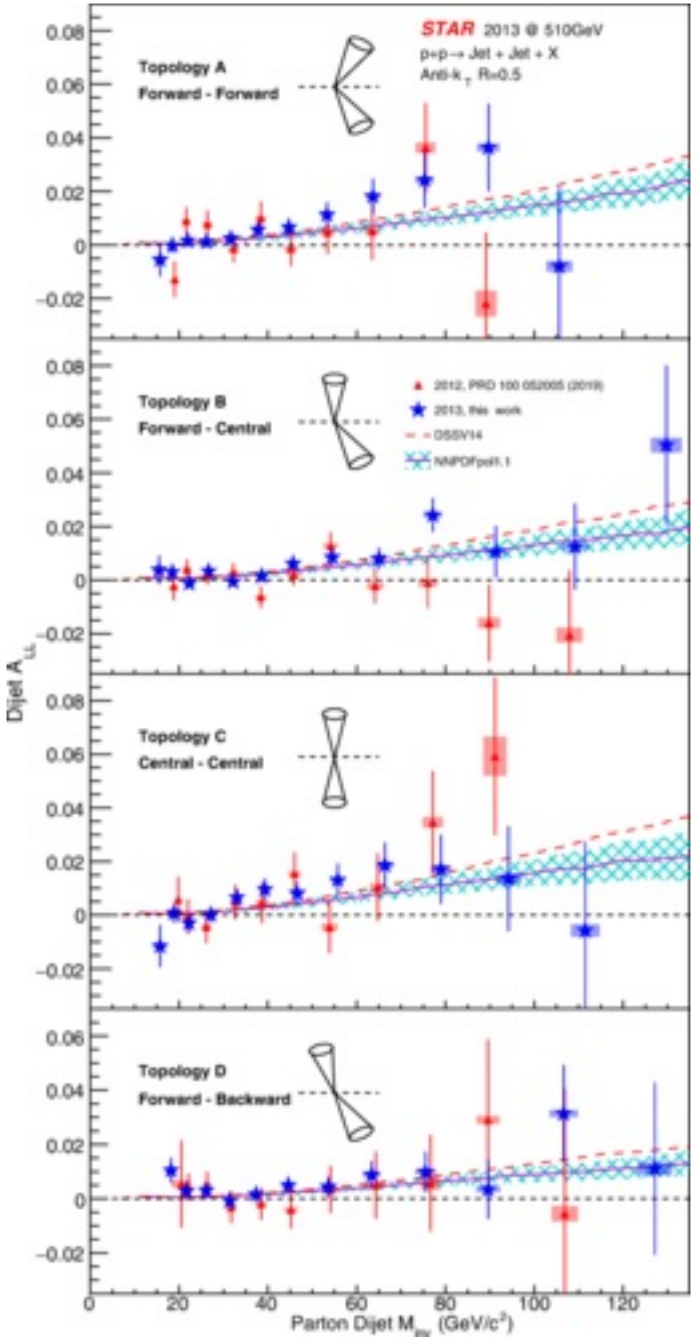
Phys.Rev.D 105, 092011

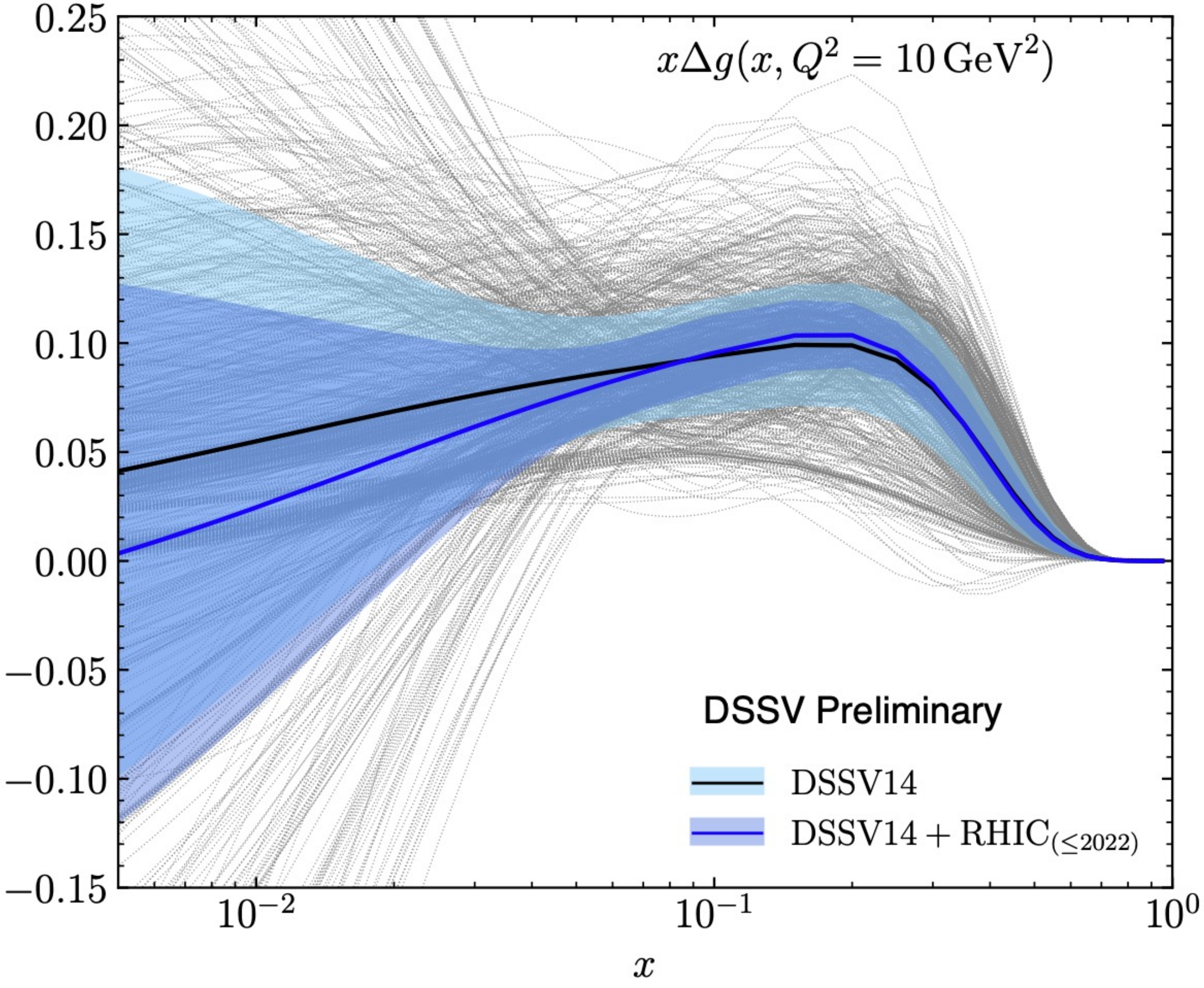
200 GeV Dijet

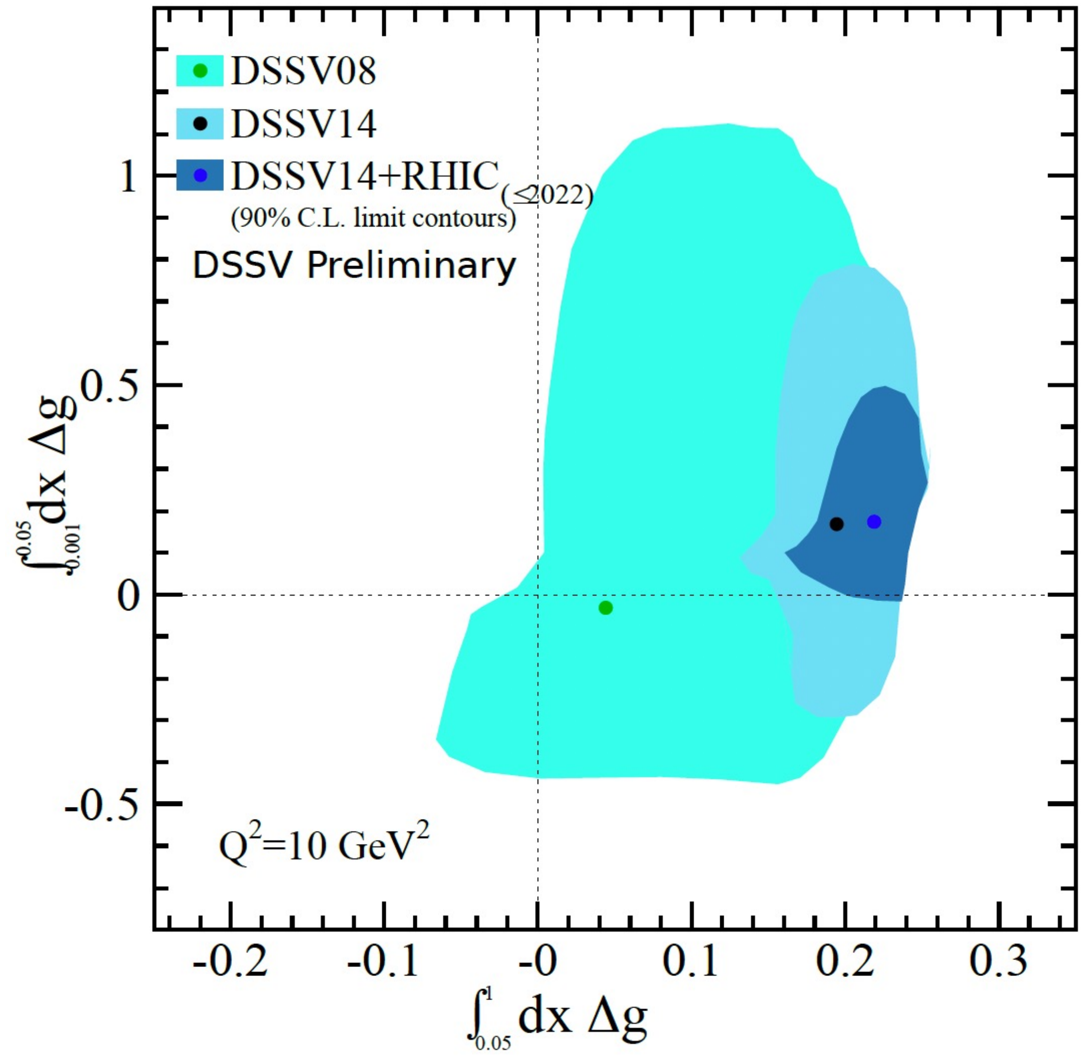


Phys.Rev.D 103, L091103

500 GeV Dijet





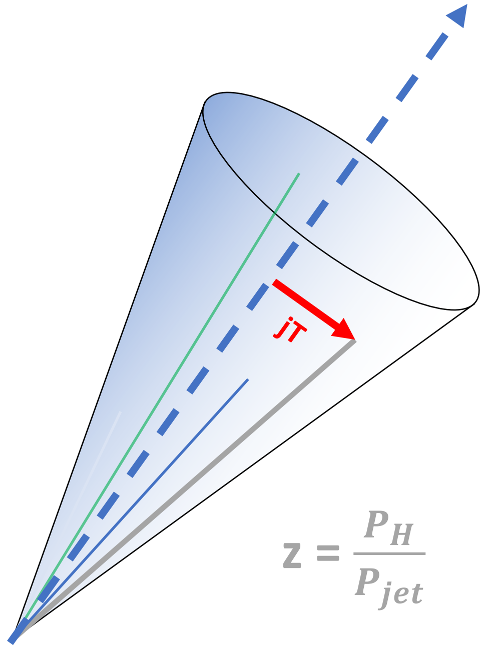


[RHIC Cold QCD Whitepaper 2302.00605]

SPIN Dependent Fragmentation

Transverse Momentum Distributions

- Typically jets are made up of several hadrons.
- Reconstruction of hadrons inside a jet provides access to
  - Z - Fraction of the jet momentum (z) carried by the hadron
  - j_T - Component of hadron momentum transverse to the jet axis
- Study of correlations between the spin of the parent quark and the azimuthal distribution of the hadrons inside the jet.
- Use single spin asymmetries A_{UT} in **transversely polarized** proton collisions to gain sensitivity to both gluon and quark TMDs

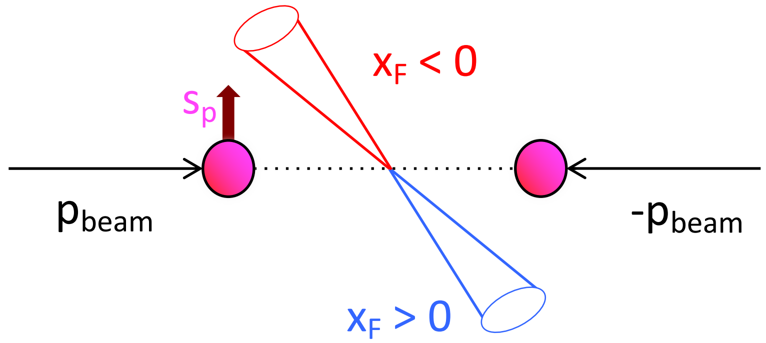


$$z = \frac{P_H}{P_{jet}}$$

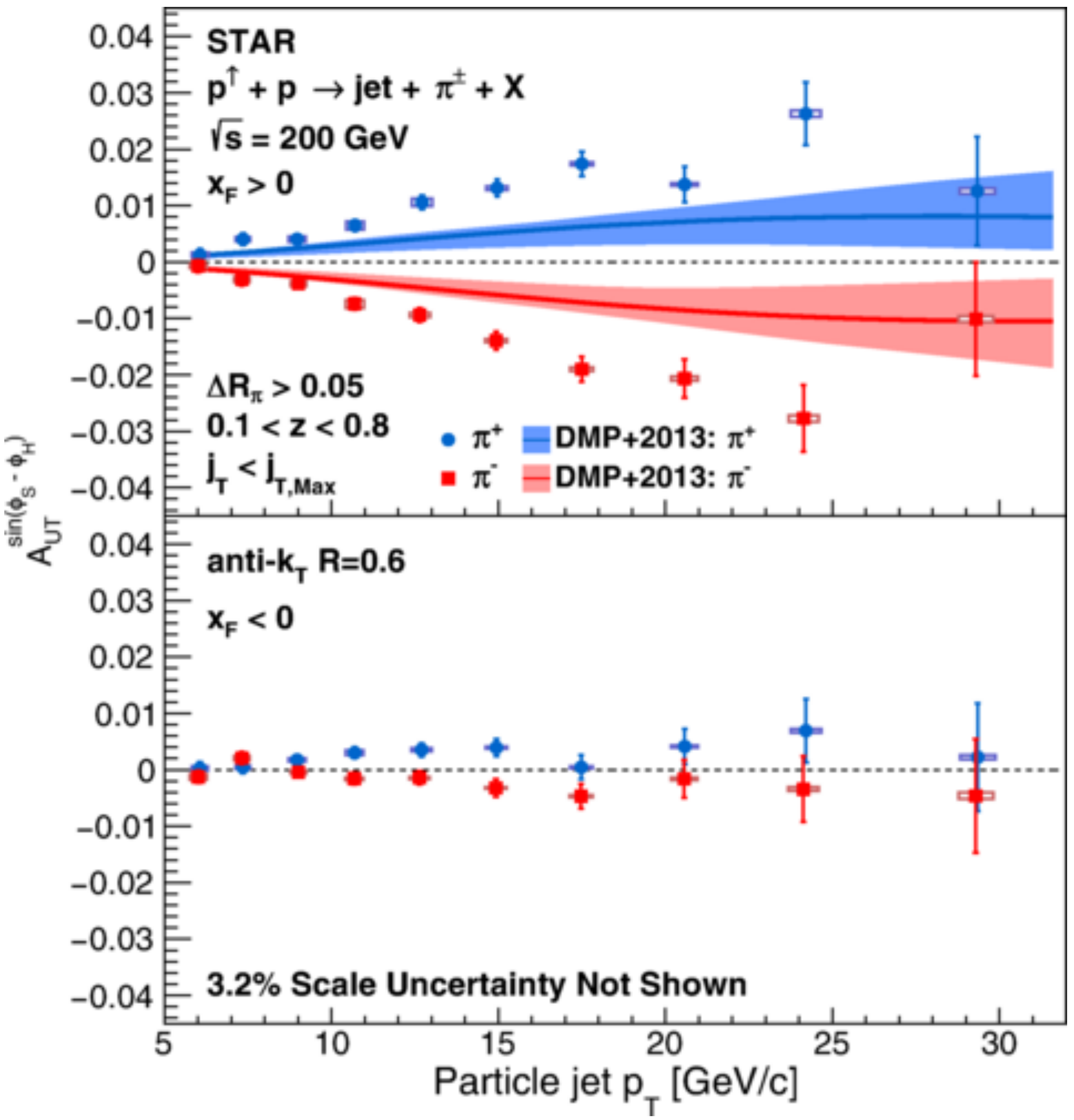
$$A_{UT}^{\sin\phi}\sin(\phi) = \frac{\sigma^{\uparrow}(\phi)-\sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi)+\sigma^{\downarrow}(\phi)} \propto \frac{\sum_{AB}\Delta_T q_A f_B \times \Delta\sigma_{AB\to jet+\pi}\times H_1^{\perp}}{\sum_{AB} q_A f_B \times \sigma_{AB\to jet+\pi}\times D}$$

$A_{UT}^{\sin(\phi_S-\phi_H)}$ p_T @ 200 GeV

- Observe large spin asymmetries for charged pions in jets
- Sign flips with charge
- Clear dependence on jet p_T
- Signal reduced for backward $x_F < 0$ jets



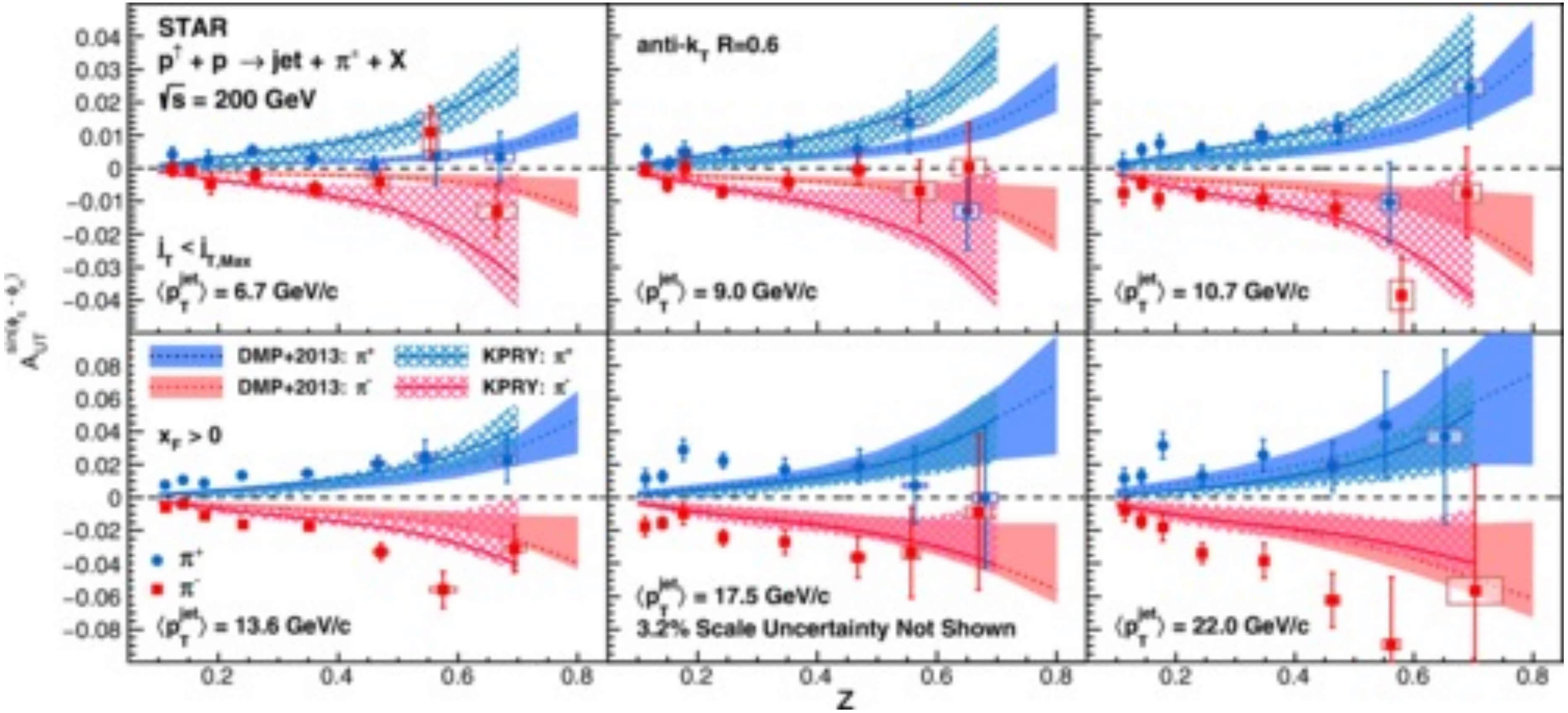
Phys.Rev.D 106, 072010



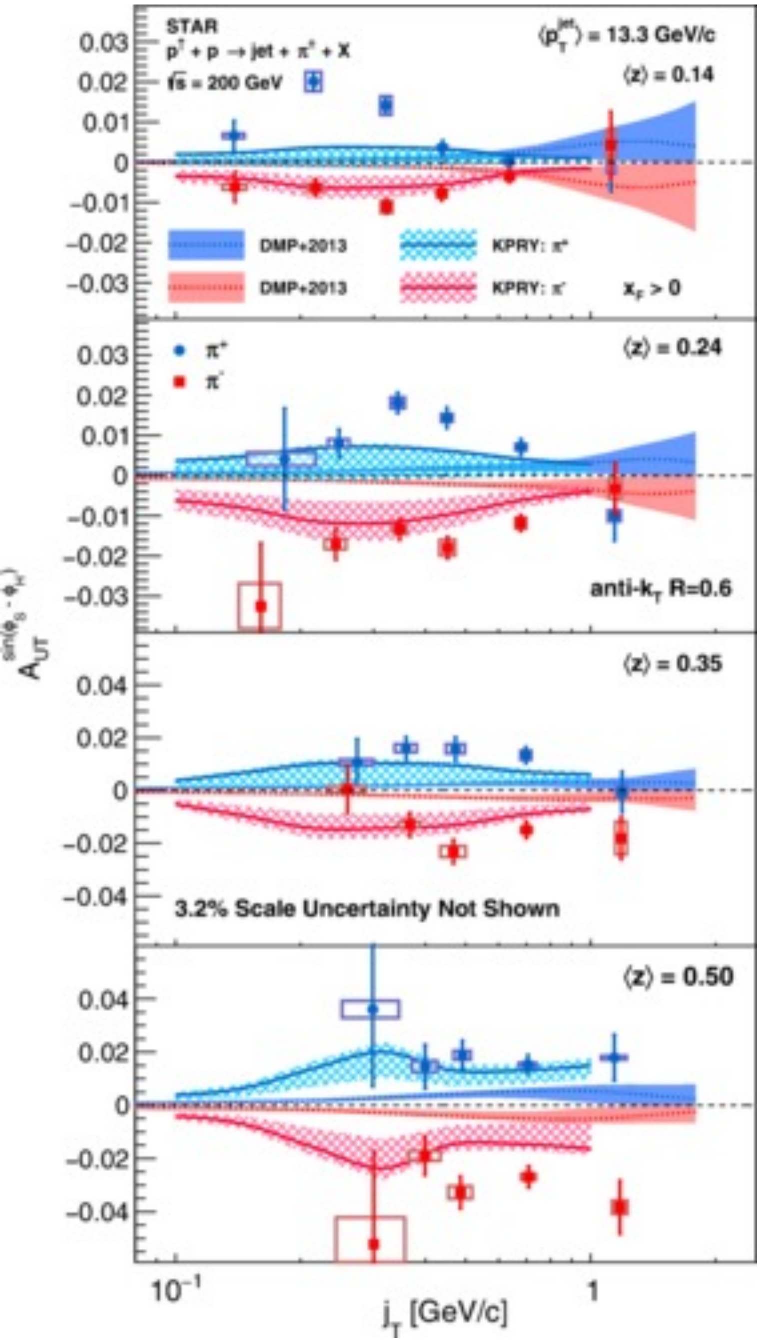
$A_{UT}^{\sin(\phi_S-\phi_H)}$ vs Z in bins of p_T @ 200 GeV

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.

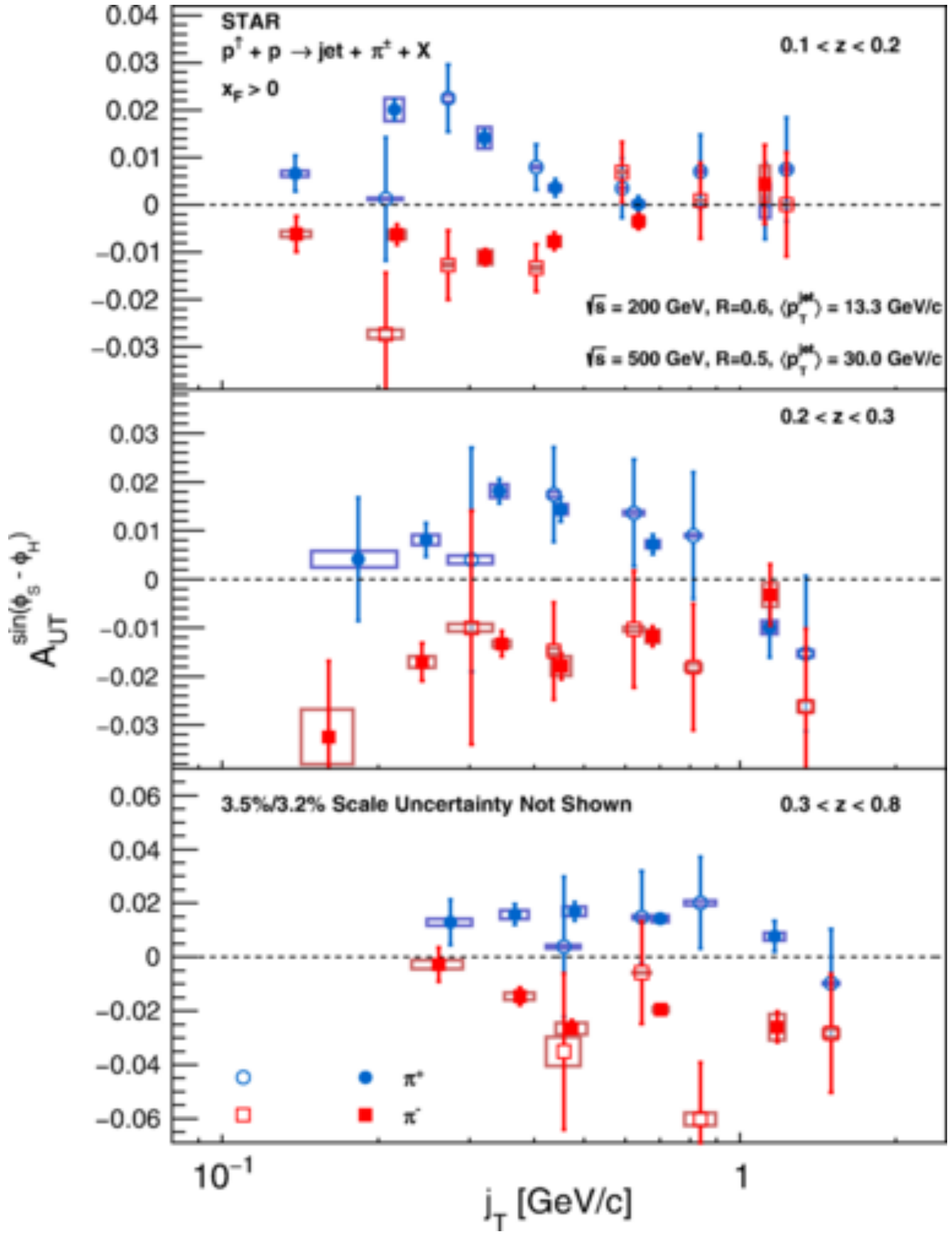


Phys.Rev.D 106, 072010



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

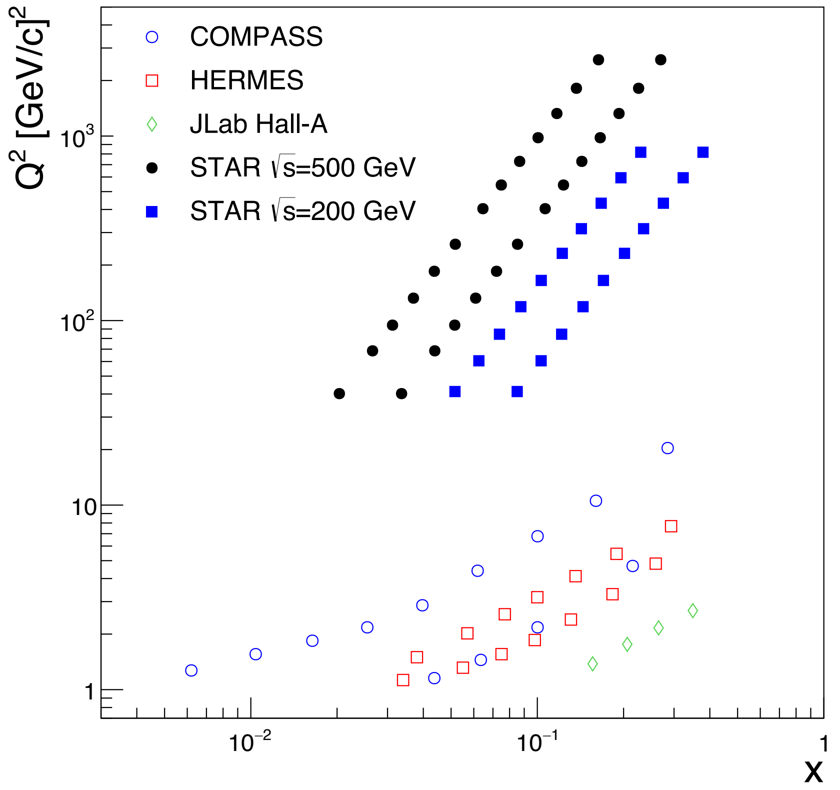
- Shape of j_T changes with z
- Peak of distribution moves higher as z increases.
- In contrast to SIDIS measurements hadron j_T is independent of initial state transverse momentum.
- 200 and 500 GeV tell the same story.



Phys.Rev.D 106, 072010

Transverse Momentum Distributions

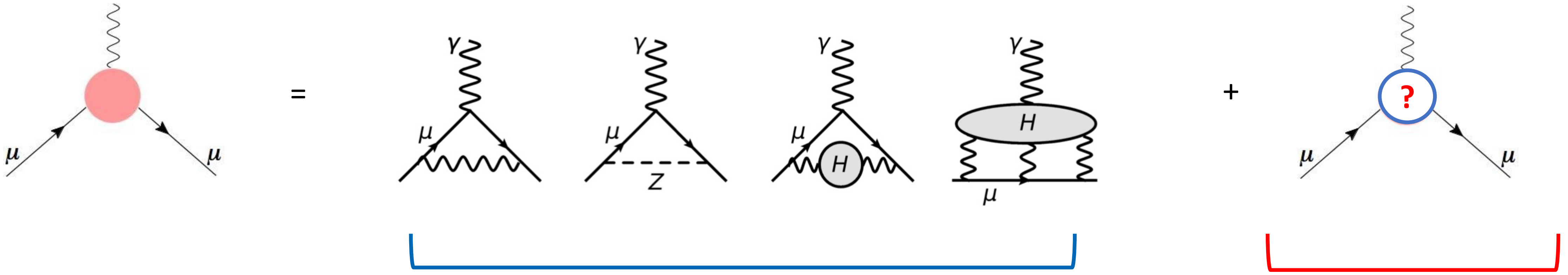
- **Evolution**
  - non-perturbative factors that must be measured
  - pp colliders access higher Q^2 than fixed target experiments
  - Provides insights into the size of observables we want to measure at an EIC.
- **Universality**
  - Comparisons to SIDIS allow separation of intrinsic properties of hadrons from interaction dependent dynamics
  - Work by Kang, Liu, Ringer and Xing JHEP 1711 (2017) 068 indicate universality holds in pp collisions!



Taking the muon out for a spin…

Anomalous Magnetic Dipole Moment

$$a_\mu = \frac{g-2}{2}$$



$$a_\mu = \frac{g-2}{2}$$

Standard model contributions:
QED, electroweak, QCD

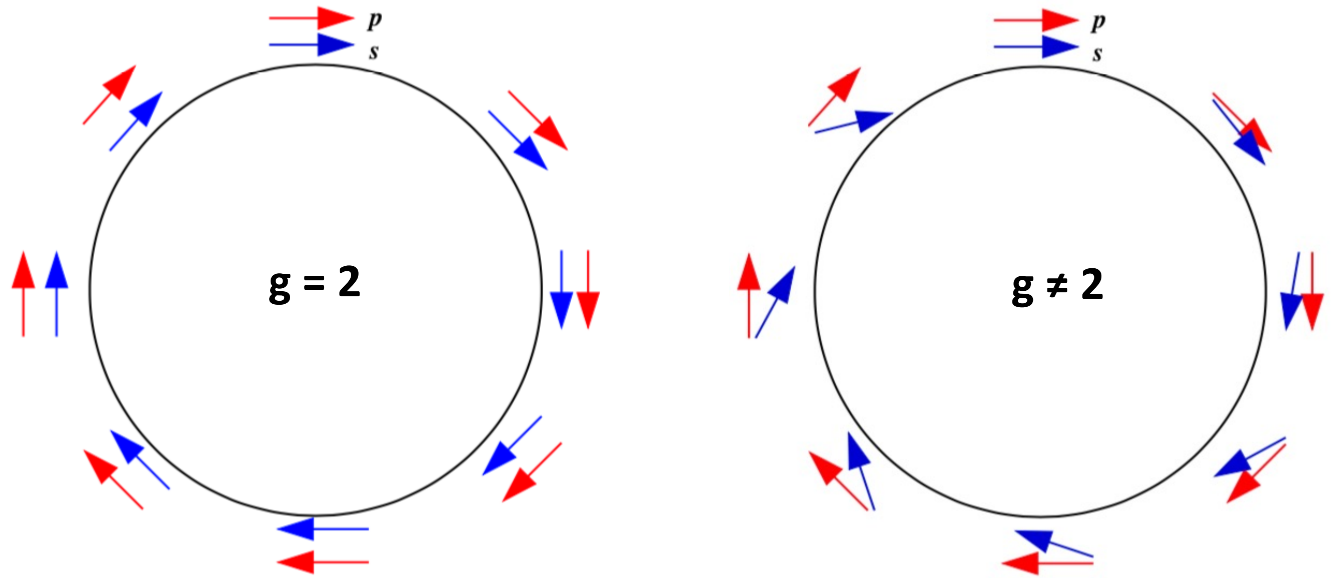
Beyond the standard model contributions

Experimental measurement of a_μ

1. Store highly polarized relativistic muons in a uniform magnetic field
2. Measure ω_a the rate at which the spin of the muon turns with respect to the momentum of the muon.
3. Measure the magnetic field **B**

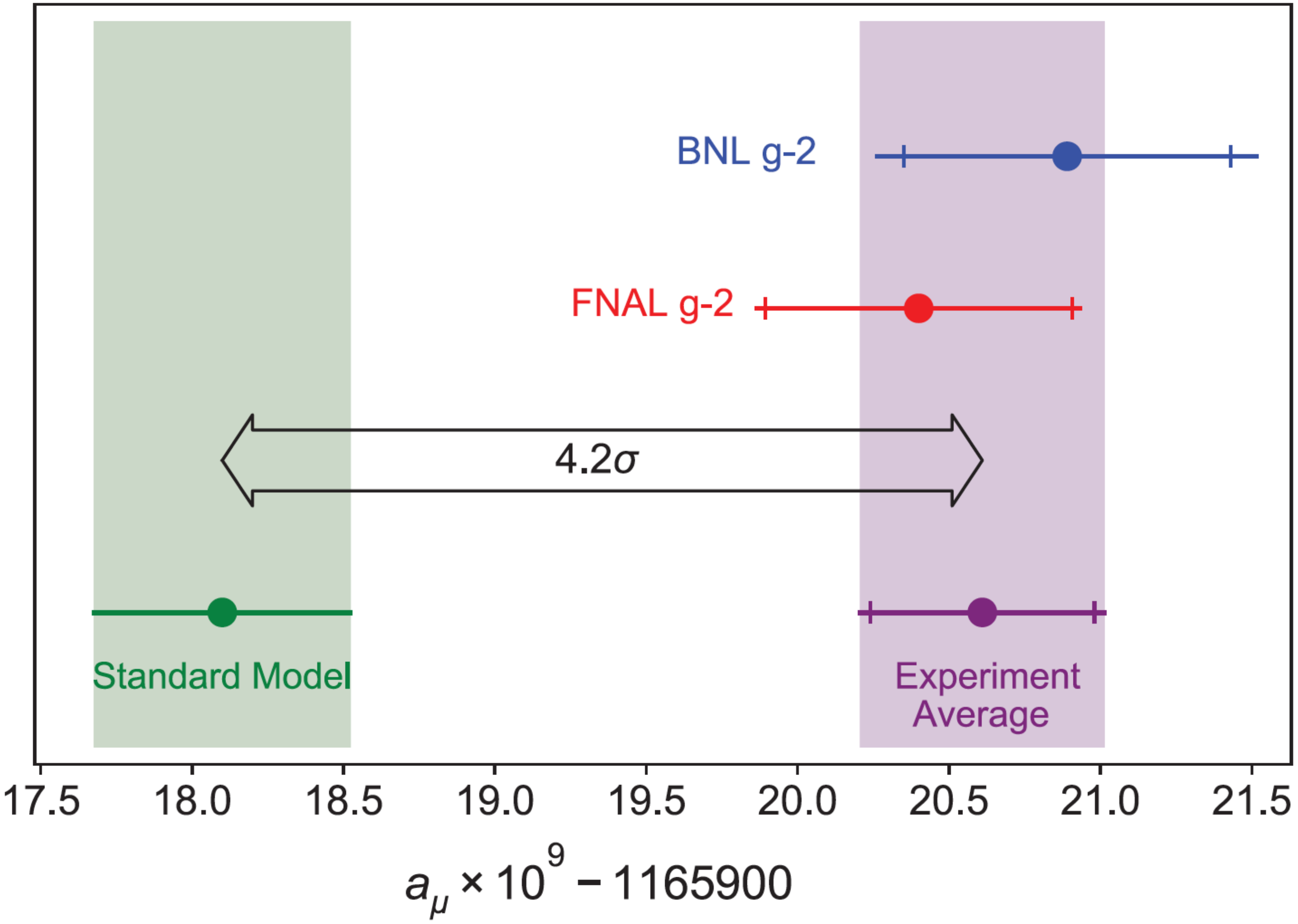
$$a_\mu = \frac{\omega_a m}{eB}$$

$$\omega_a = \omega_S - \omega_C$$



FNAL Run 1 Result

muon g-2 theory initiative arxiv.org/abs/2006.04822



FNAL Run 1

$a_\mu = 116\,592\,040(54)\times 10^{-11}$

(462 ppb)

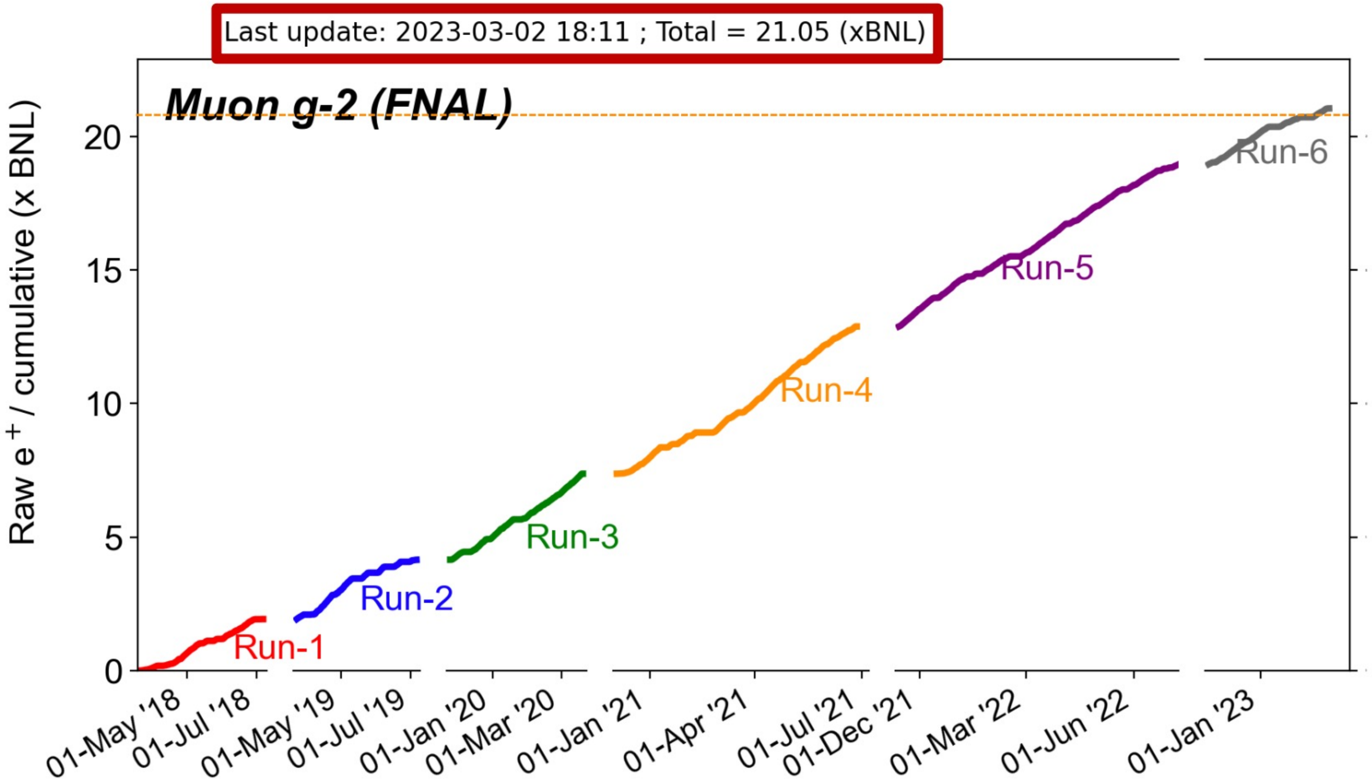
Statistical: 434 ppb

Systematic: 157 ppb

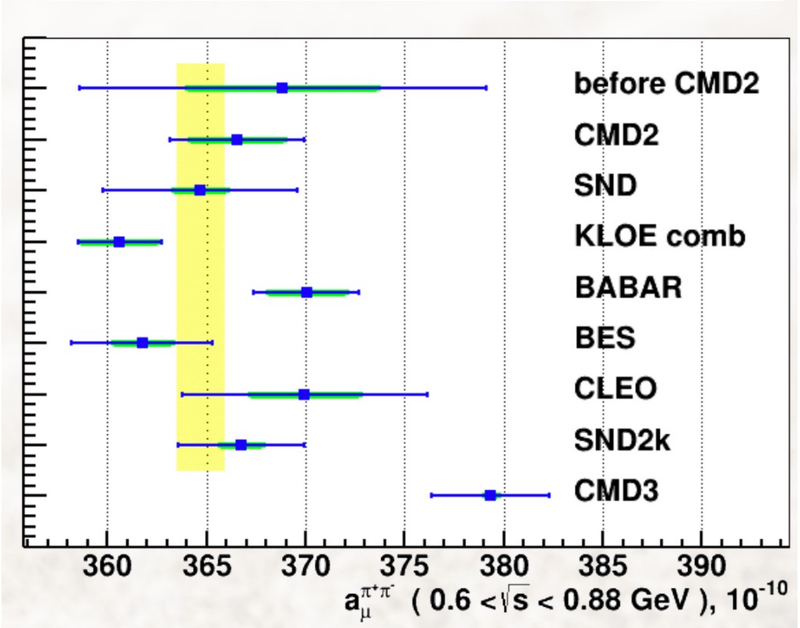
Phys.Rev.Lett. 126 14, 141801

Since Run 1 Release

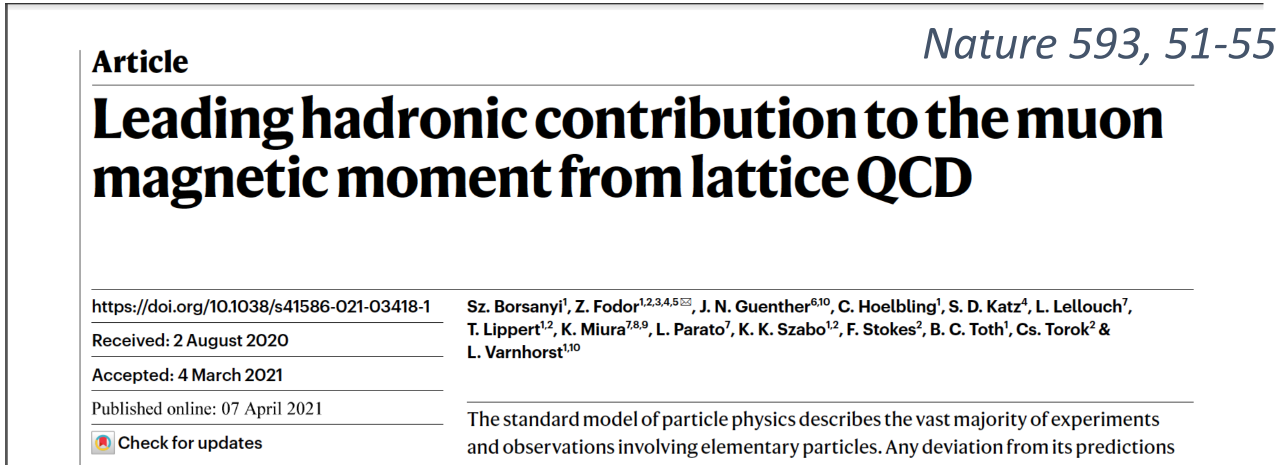
- Achieved goal of collecting 20 BNL worth of data in early March of 2023
- Experiment will turn off after Run 6
- Planning for release of Run 2+3 mid to late summer.
- Run 2+3 results in x2 reduction in errors
- Two big developments on theory side – both in HVP calculation - that point to a reduced tension!



arxiv 2302.08834



Nature 593, 51-55



Article

Leading hadronic contribution to the muon magnetic moment from lattice QCD

https://doi.org/10.1038/s41586-021-03418-1

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Accepted: 4 March 2021

Published online: 07 April 2021

Check for updates

Sz. Borsanyi[1], Z. Fodor[1,2,3,4,5], J. N. Guenther[6,10], C. Hoelbling[1], S. D. Katz[4], L. Lellouch[7], T. Lippert[1,2], K. Miura[7,8,9], L. Parato[7], K. K. Szabo[1,2], F. Stokes[2], B. C. Toth[1], Cs. Torok[2] & L. Varnhorst[1,10]

The standard model of particle physics describes the vast majority of experiments and observations involving elementary particles. Any deviation from its predictions

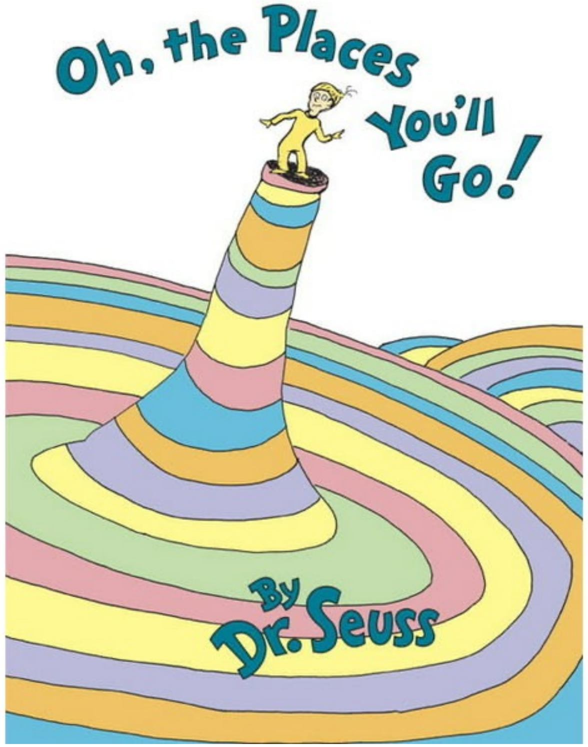
Adventures in spin

- Spin is a powerful tool for studying the structure of the universe and often leads to unexpected and intriguing results.

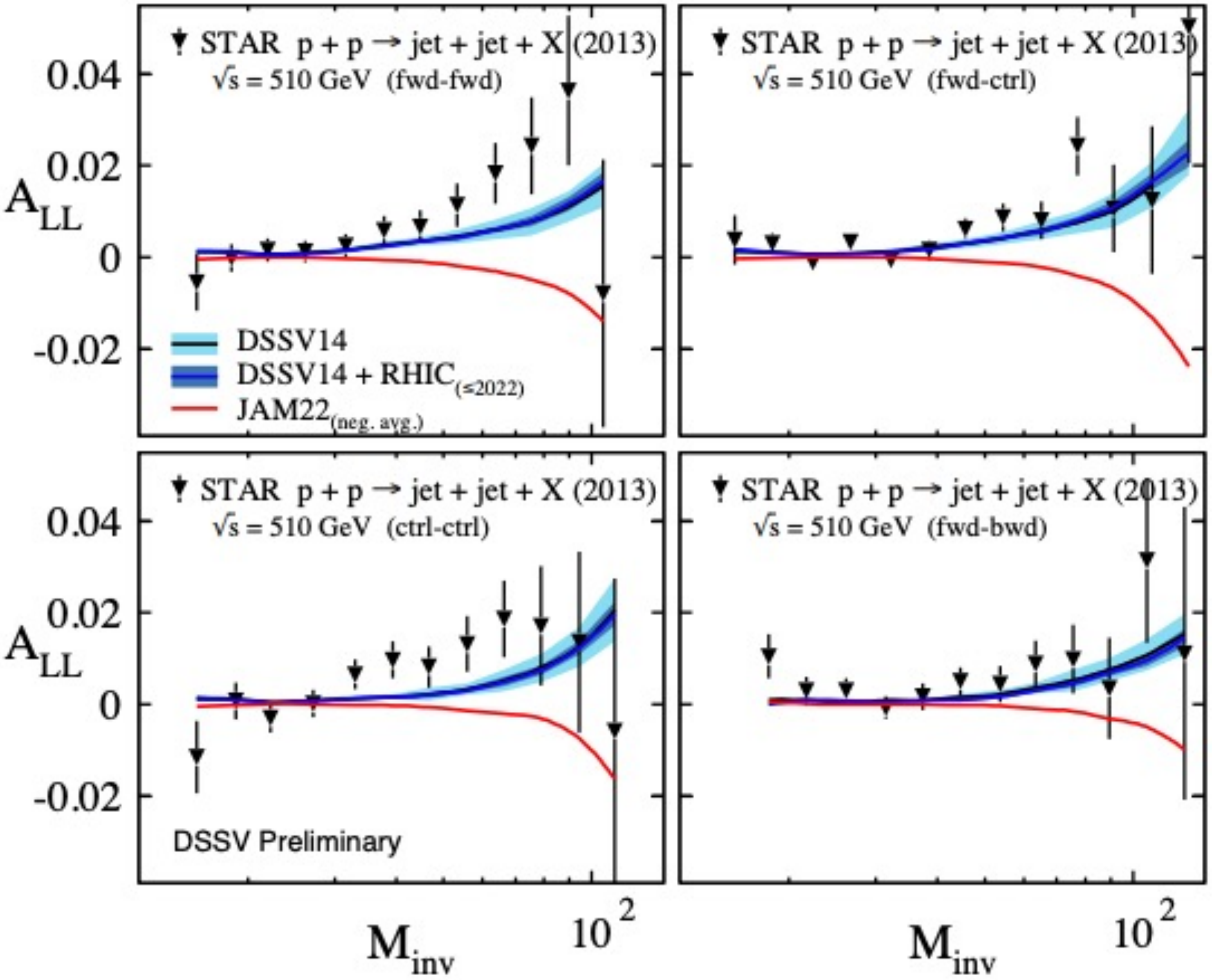
- The results presented here reflect my personal journey studying spin dynamics – not meant to represent the broad range of activities in the CLAS, STAR and g-2 collaborations.

- That said, these measurements are the product of vibrant collaborations, both experimental and theoretical, that have made the results better and taught me a lot.

- Thank you for joining me on these adventures!



Thank You


STAR p + p → jet + jet + X (2013)
√s = 510 GeV (fwd-fwd)
√s = 510 GeV (fwd-ctrl)
√s = 510 GeV (ctrl-ctrl)
√s = 510 GeV (fwd-bwd)
DSSV14
DSSV14 + RHIC(≤2022)
JAM22(neg. avg.)
DSSV Preliminary
A_LL
0.04
0.02
0
-0.02
M_inv
10^2