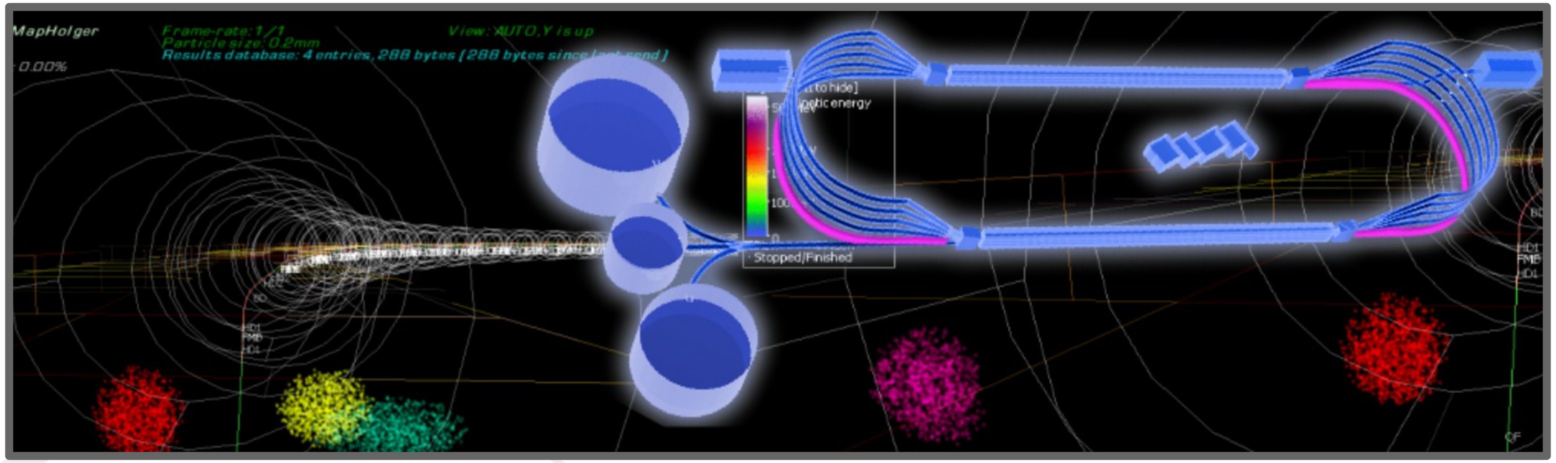
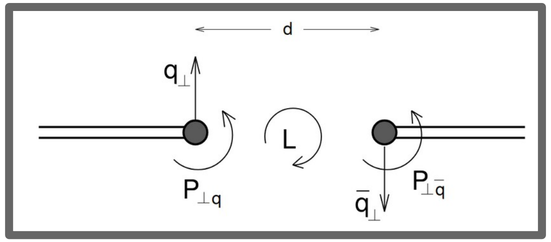
SIDIS Monte Carlo Including Polarization Effects





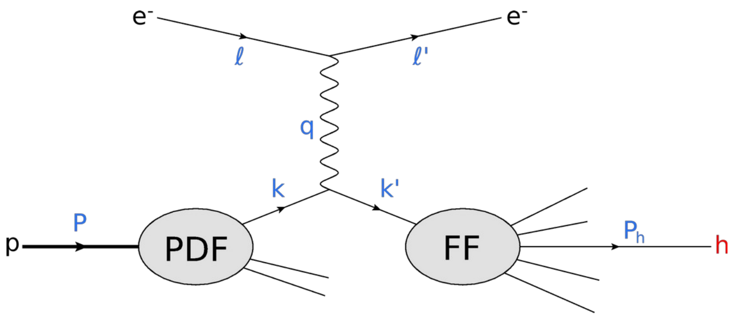
Christopher Dilks

Outline

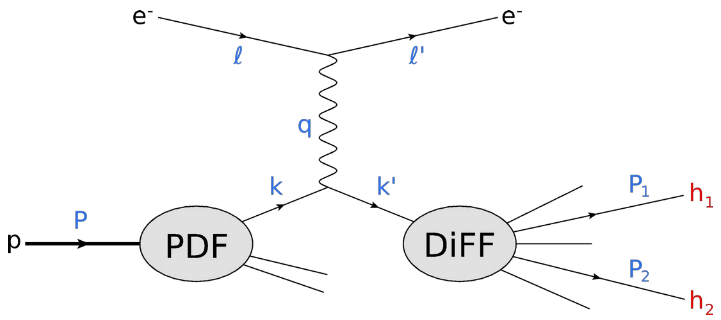
- Introduction: String + $^3P_0$ model for hadronization
- StringSpinner = Pythia + Spin in hadronization
- Comparisons with SIDIS dihadrons at CLAS in Hall B
- Outlook for 22 GeV

SIDIS and Spin

$$e + p \rightarrow e + h + X$$



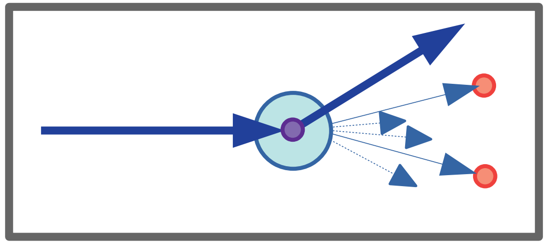
$$e + p \rightarrow e + h_1 + h_2 + X$$



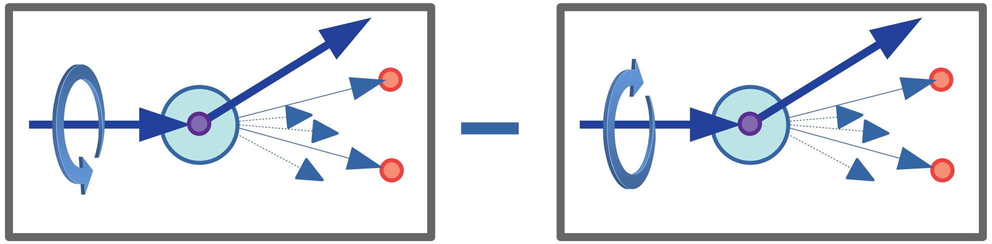
Cross Section

(Or Multiplicity)

$$d\sigma$$



Beam Spin Asymmetry A_{LU}



- Target Spin Asymmetry
- Double Spin Asymmetry
- For Transverse and Longitudinal polarizations

SIDIS and Spin

- Cross sections and spin asymmetries give access to structure functions
- Structure functions → distribution functions convolved with fragmentation functions

Structure Functions

$$d\sigma_{XY} \propto F_{XY} \propto \mathrm{PDF} \otimes \mathrm{FF}$$

$$A_{LU} = \frac{d\sigma_{LU}}{d\sigma_{UU}} = \frac{d\sigma_{+} - d\sigma_{-}}{d\sigma_{UU}}$$

Dihadron A_{LU} gives access to:

$$F_{LU}^{\mathrm{twist}\ 2} \propto f_1(x) \otimes G_1^{|\ell,m\rangle}(z, M_h, |\vec{p}_T|),$$

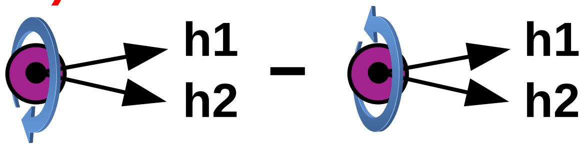
and higher twist structure functions

Unpolarized PDF

Helicity Dihadron FF (DiFF)

Partial waves |l,m>

Correlates to angular momentum of hadron pair



A. Bacchetta, M. Radici, Phys.Rev.D 67 (2003), 094002

Simulating Fragmentation: String + $^3P_0$ Model

- Fragmentation is handled by the Lund String Model
  - Spin effects in fragmentation are handled by the "$^3P_0$" model
  - Implemented in an event generator, "StringSpinner"

- Pythia handles PDFs
  - StringSpinner includes the quark transversity distribution
  - This presentation focuses on dihadron A_{LU} at leading twist:

$$A_{LU}^{P_{\ell,m}(\cos\theta)\sin(m\phi_h - m\phi_R)}$$

$$f_1 \otimes G_1^{|\ell,m\rangle}$$

The presented study only concerns spin effects in *fragmentation*

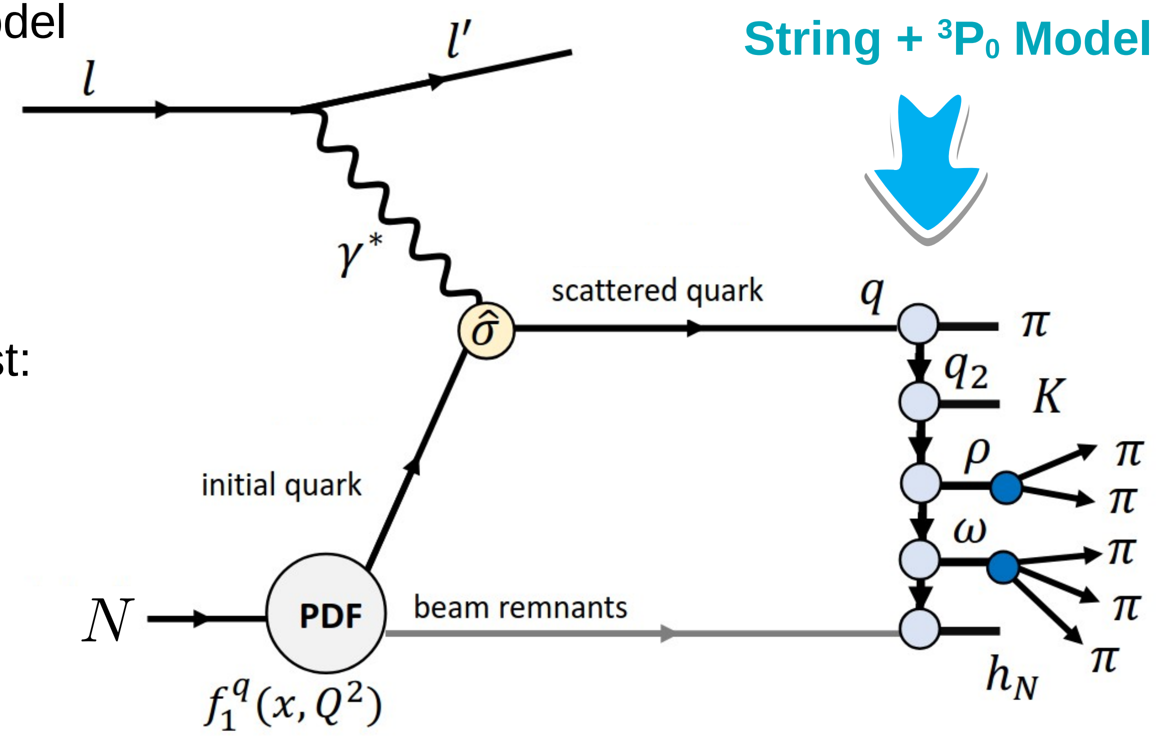
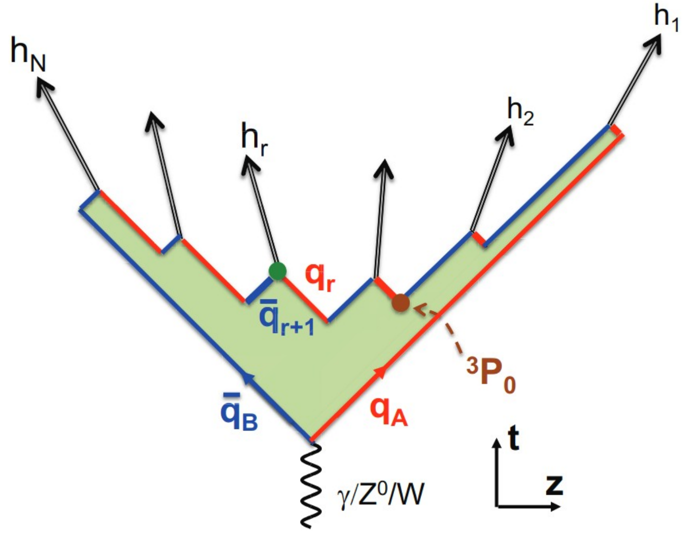


Figure adapted from A. Kerbizi, SPIN2023 presentation

String + $^3P_0$ Model

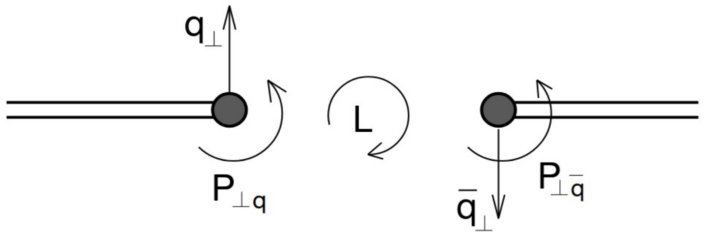
- Lund String Model for fragmentation
- Tunnelling of q-qbar pair in relative $^3P_0$ state



X. Artru, A. Kerbizi, JPS Conf.Proc. 37 (2022), 020101

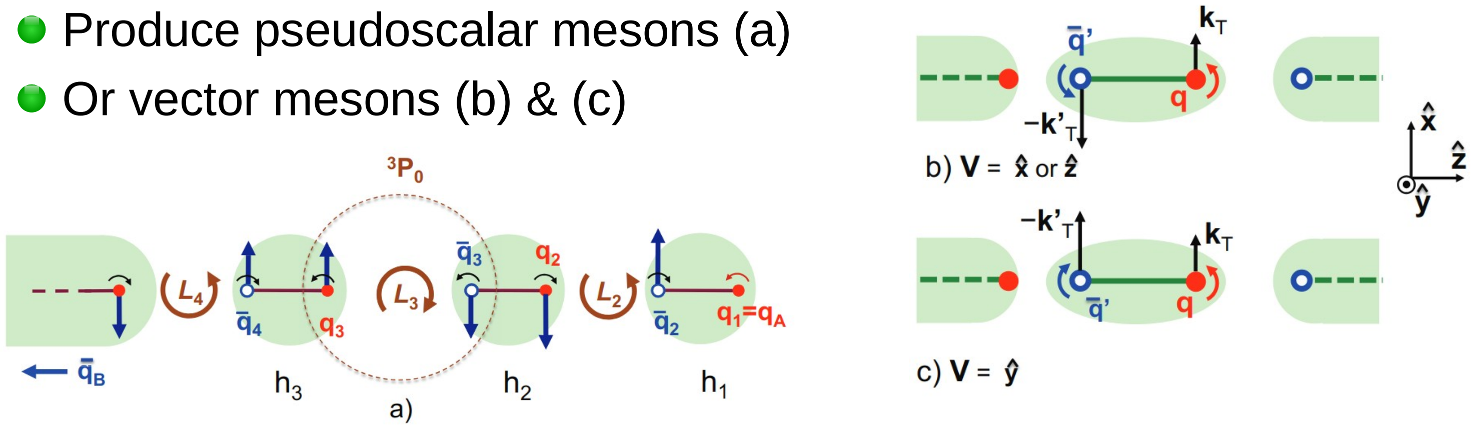
$^3P_0$ state

$^{2S+1}L_J \rightarrow S = 1 = -L \rightarrow J = 0$



X. Artru, J. Czyzewski, Acta Phys.Polon.B 29 (1998), 2115-2127

- Produce pseudoscalar mesons (a)
- Or vector mesons (b) & (c)



X. Artru, A. Kerbizi, JPS Conf.Proc. 37 (2022), 020101

String+$^3P_0$ Free Parameters

- **Complex mass for the $^3P_0$ wave function**

$$\mu \in \mathbb{C}$$

$\mathrm{Re}\mu$ Longitudinal spin effects

$\mathrm{Im}\mu$ Transverse spin effects

$$\mu = 0.42 + 0.76i \ \mathrm{GeV}$$

from e^+e^- Collins from data comparisons

A. Kerbizi, X. Artru, Z. Belghobsi, F. Bradamante, A. Martin, Phys.Rev.D 97 (2018) 7, 074010

- **Fraction of longitudinally polarized vector mesons (VMs)**

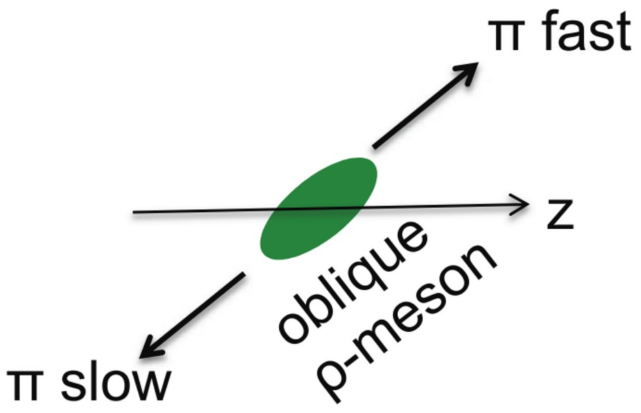
$$f_L := \frac{|G_L|^2}{2|G_T|^2 + |G_L|^2} \in [0,1]$$

$$G_L, G_T \in \mathbb{C}$$

couplings of quarks to VMs with Longitudinal (L) or Transverse (T) polarization (w.r.t. string axis)

- **VM oblique polarization: interference between L and T polarization**

$$\theta_{LT} := \arg\left(\frac{G_L}{G_T}\right) \in [-\pi, \pi]$$



A. Kerbizi, X. Artru, A. Martin, Phys.Rev.D 104 (2021) 11, 114038
X. Artru, A. Kerbizi, JPS Conf.Proc. 37 (2022), 020101

StringSpinner

- **StringSpinner = Pythia 8 + String+$^3P_0$ model**
  - Uses Pythia's UserHooks to reweight unpolarized hadronization procedure according to the String+$^3P_0$ model
  - Angular momentum correlations with vector meson decay handled by Collins-Knowles recipe via Pythia's DecayHandler
  - Compatible with Pythia 8.3
- **Available on GitLab at https://gitlab.com/albikerbizi/stringspinner/-/tree/master**
  - Maintained by Albi Kerbizi, et al.
  - Allows anyone to use the String+$^3P_0$ model
- **For usage at CLAS, we have "clas-stringspinner"**
  - Available at https://github.com/JeffersonLab/clas-stringspinner
  - This is StringSpinner + Pythia8 tune for CLAS(12) + Front end interface for OSG
    - Simulations + reconstruction runs on Open Science Grid (OSG) (distributed high throughput computing)
  - May be used as a standalone event generator (currently only outputs "Lund" files)
  - Applicable for studies at 22 GeV (if we trust the tune, etc.)

StringSpinner References:

- A. Kerbizi and L. Lönnblad, Comput.Phys.Commun. 272 (2022), 108234
- A. Kerbizi and L. Lönnblad, Comput.Phys.Commun. 292 (2023), 108886

Pythia 8.3:

- C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, et al., SciPost Phys.Codeb. 2022 (2022), 8

Event Generators for CLAS

- Several generators are available on OSG
- SIDIS MC studies have been focused on using:
  - CLASDIS (PEPSI based)
  - Pythia 6
- StringSpinner is our first attempt at using **Pythia 8** for our SIDIS MC studies
  - Pythia 6 → 8 tuning parameters aren't exactly one-to-one
  - Pythia 8 defaults are different
  - Pythia 8 tuning guided by CLASDIS tune, which reproduces CLAS12 SIDIS data rather well

List of Generators from clas12-mcgen

name	description	maintainer
clasdis	SIDIS MC based on PEPSI LUND MC	Harut Avakian
claspyth	SIDIS full event generator based on PYTHIA	Harut Avakian
clas-stringspinner	SIDIS PYTHIA with hadronization spin effects	Christopher Dilks
dvcsgen	DVCS/pi0/eta generator based on GPD and PDF parameterizations	Harut Avakian
genKYandOnePion	KY, pi0P and pi+N	Valerii Klimenko
inclusive-dis-rad	Inclusive electron and optionally radiative photon using PDFs	Harut Avakian
tcsgen	Timelike Compton Scattering	Rafayel Paremuzyan
jpsigen	J/Psi photoproduction	Rafayel Paremuzyan
twopeg	pi+pi- electroproduction off protons	Iuliia Skorodumina
clas12-elspectro	General electroproduction final states	Derek Glazier
MCEGENpiN_radcorr	Exclusive single pion electroproduction based on MAID	Maksim Davydov
deep-pipi-gen	Deep double pion production	Dilini Bulumulla
genepi	Photon and meson electroproduction	Noémie Pilleuxi
onepigen	Single charged pion production based on AO/Daresbury/MAID	Nick Tyler
GiBUU	Quark and hadron propagation in nuclear media	Ahmed El Alaoui

Pythia 8 Tune for CLAS at 10.6 GeV

- NNPDF 2.3 PDFs (Pythia 8.3 default)
- SpaceShower:dipoleRecoil = off, since StringSpinner not handling multiple partons in showering process
- ISR, FSR, MPI = off
- Fragmentation Parameters
  - a = 1.2
  - b = 0.58 GeV^{-2}

$$\frac{1}{z}(1-z)^a e^{-bm_T^2/z}$$

- Ratio of Vector Meson to Pseudoscalar meson
  - 0.7 for light quarks (ρ/π)
  - 0.75 for strange quarks (K^*/K)
- Quark transverse momenta
  - p_T width: StringPT:sigma = 0.5 GeV
  - k_T width: 0.64 GeV → understood in CLASDIS, needs <u>more study</u> in Pythia 8
- StringSpinner Parameters: needs more precise comparison to data
  - $|G_L/G_T|$ = 1.4 → f_L = 50%
  - θ_{LT} = arg(G_L/G_T) = 0

see backup slides for all tune parameters

Dihadron Kinematic Comparisons

- The following slides show some Data and MC comparisons
  - CLAS12 data from 10.6 GeV electrons on proton target, (inbending torus field, Run Group A, Fall 2018)
  - Full simulations and reconstruction from:
    - StringSpinner
    - CLASDIS
- Distributions are
  - SIDIS $\pi^+\pi^-$ dihadrons
  - Standard cuts used for dihadron spin asymmetry analysis →
  - Normalized by electron yield

clas vs. PYTHIA 8.3

General Cuts
- $Q^2 > 1$ GeV^2
- $W > 2$ GeV
- $y < 0.8$
- $5° < \theta < 35°$ (applied to $e^-,\pi^\pm$)

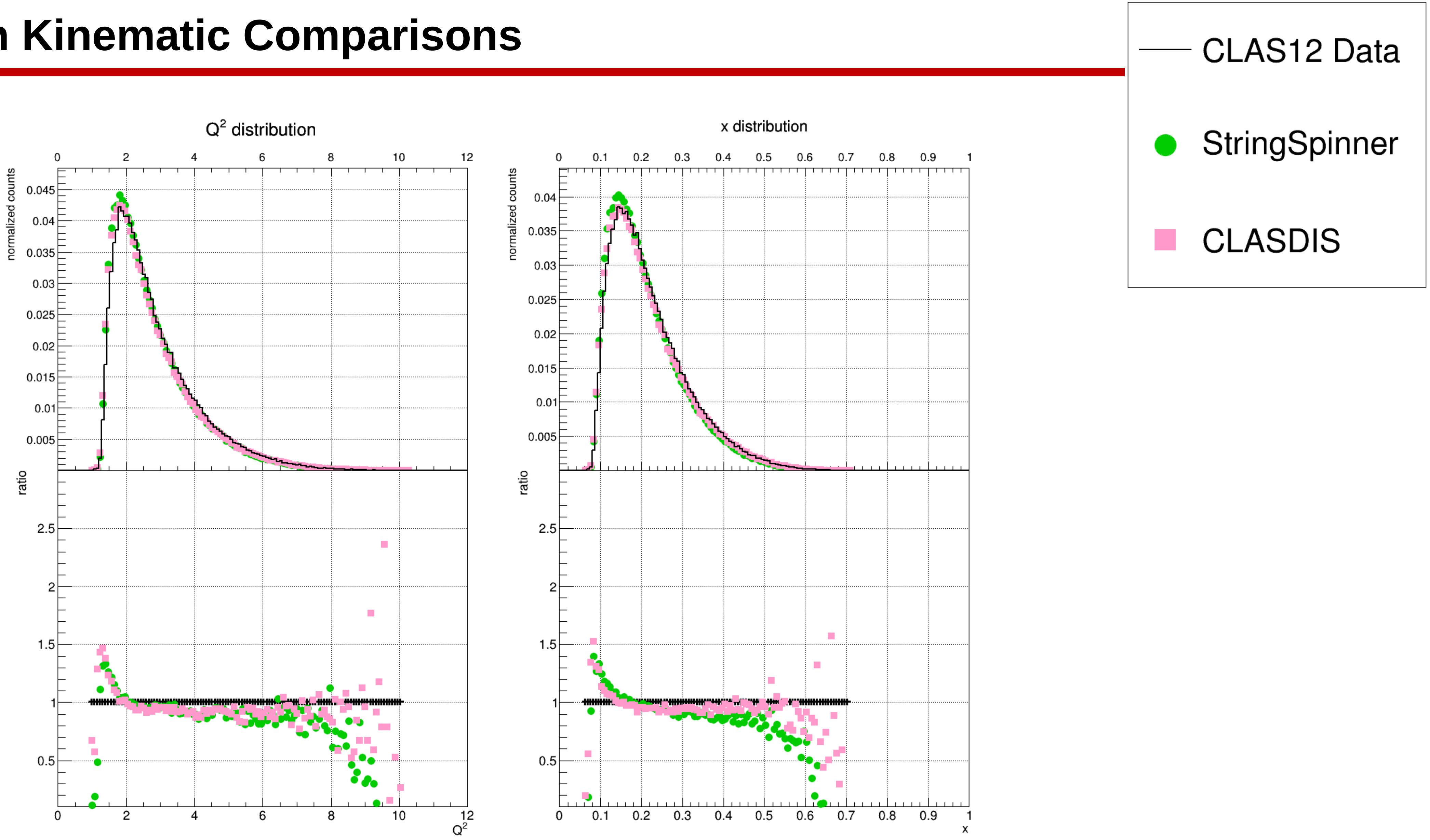
Pion and Dihadron Cuts
- $x_F(\pi^\pm) > 0$
- $p(\pi^\pm) > 1.25$ GeV
- $z_{pair} < 0.95$
- $M_{miss} > 1.5$ GeV

Additional Cuts
- PID Refinement
- Vertex
- Fiducial volume

Dihadron Kinematic Comparisons

Comparisons

$$\frac{N^{\mathrm{MC}}_{\pi^+\pi^-}/N^{\mathrm{MC}}_{e^-}}{N^{\mathrm{data}}_{\pi^+\pi^-}/N^{\mathrm{data}}_{e^-}}$$



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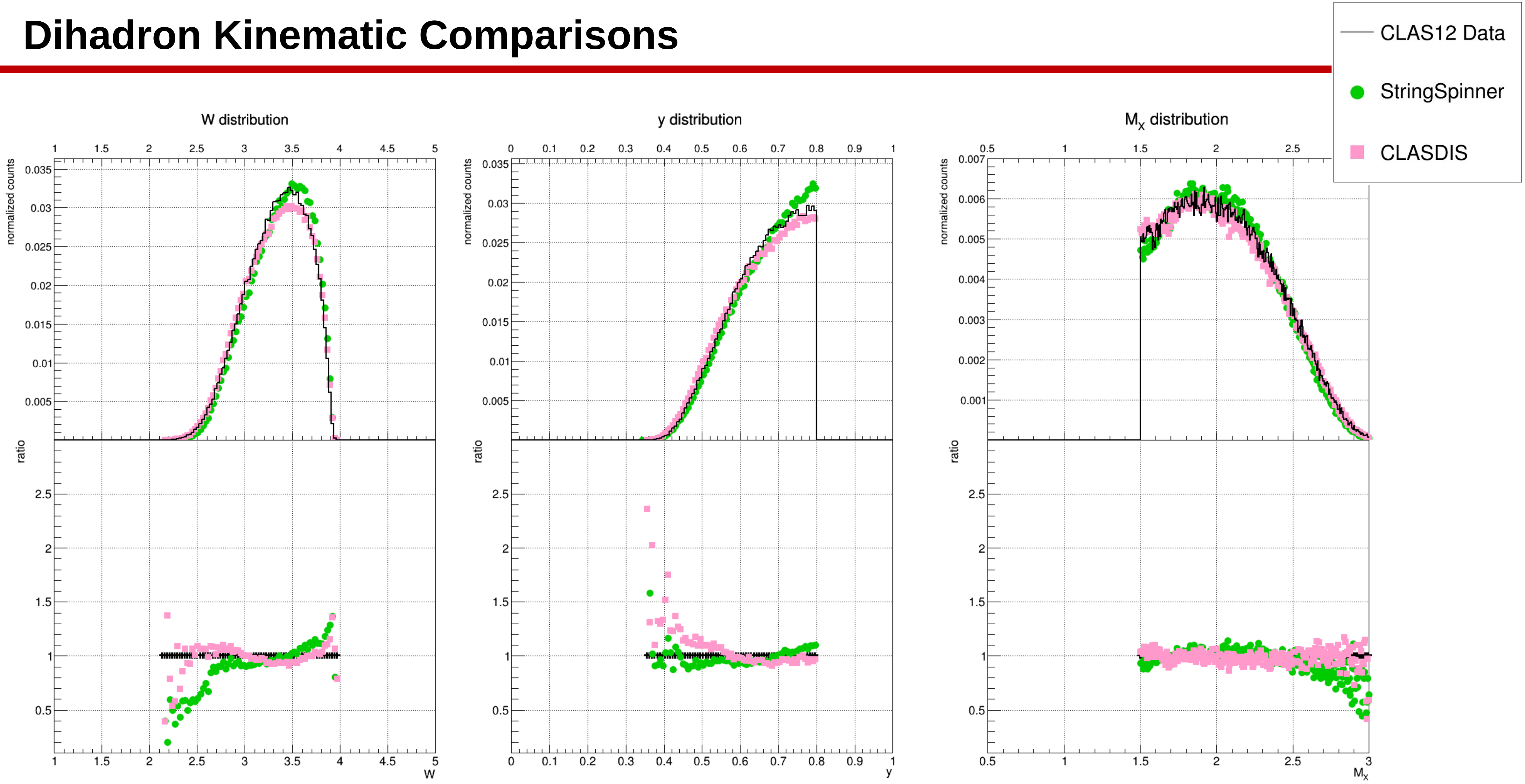
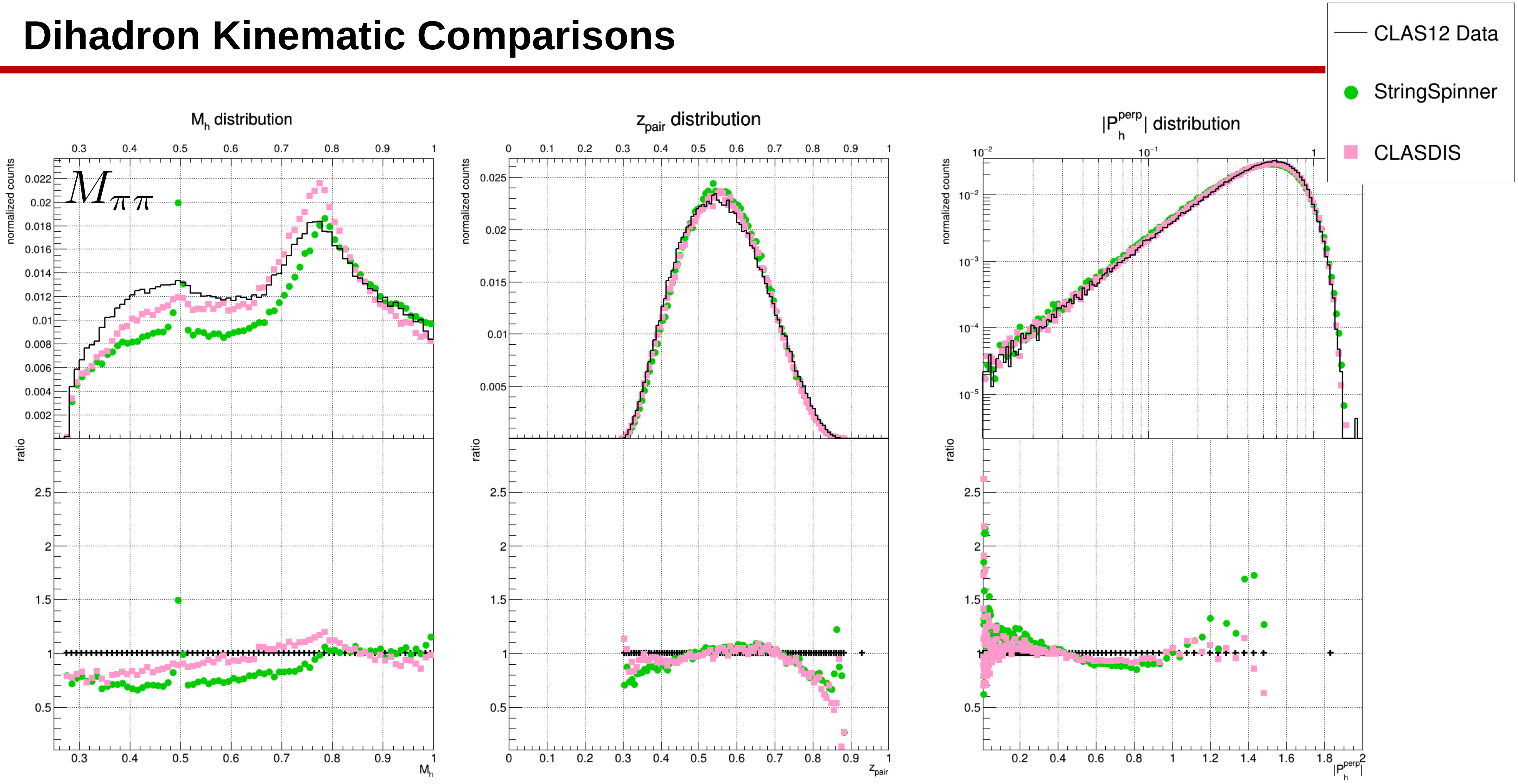
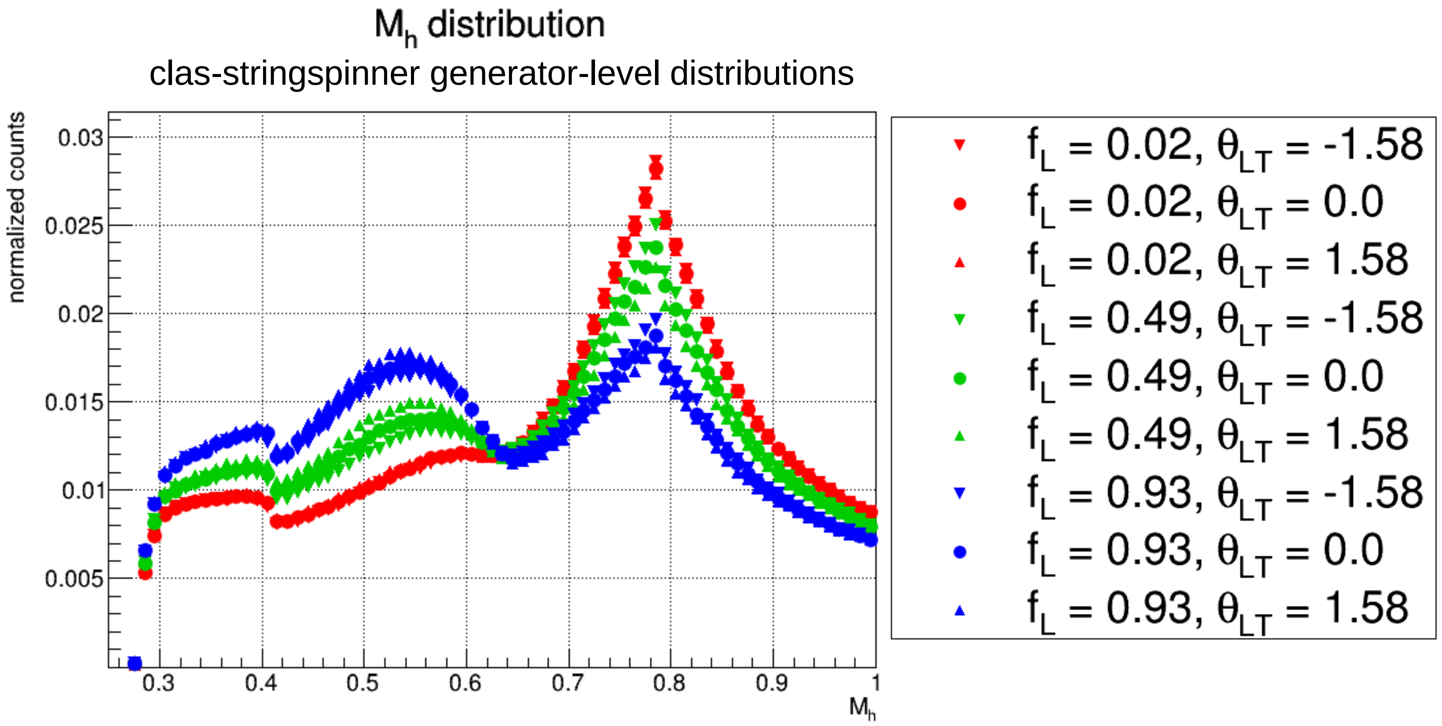
Dihadron Kinematic Comparisons

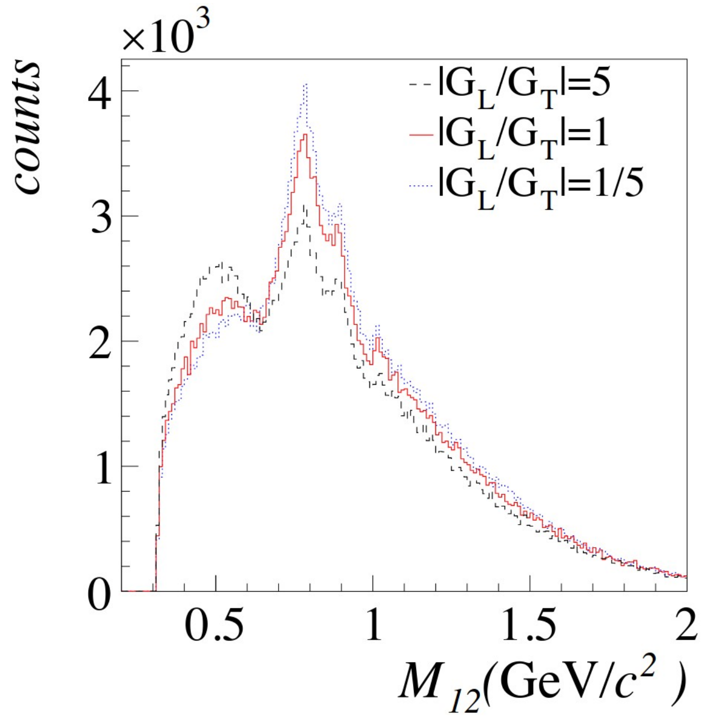


Dihadron Kinematic Comparisons



About the Dihadron Invariant Mass

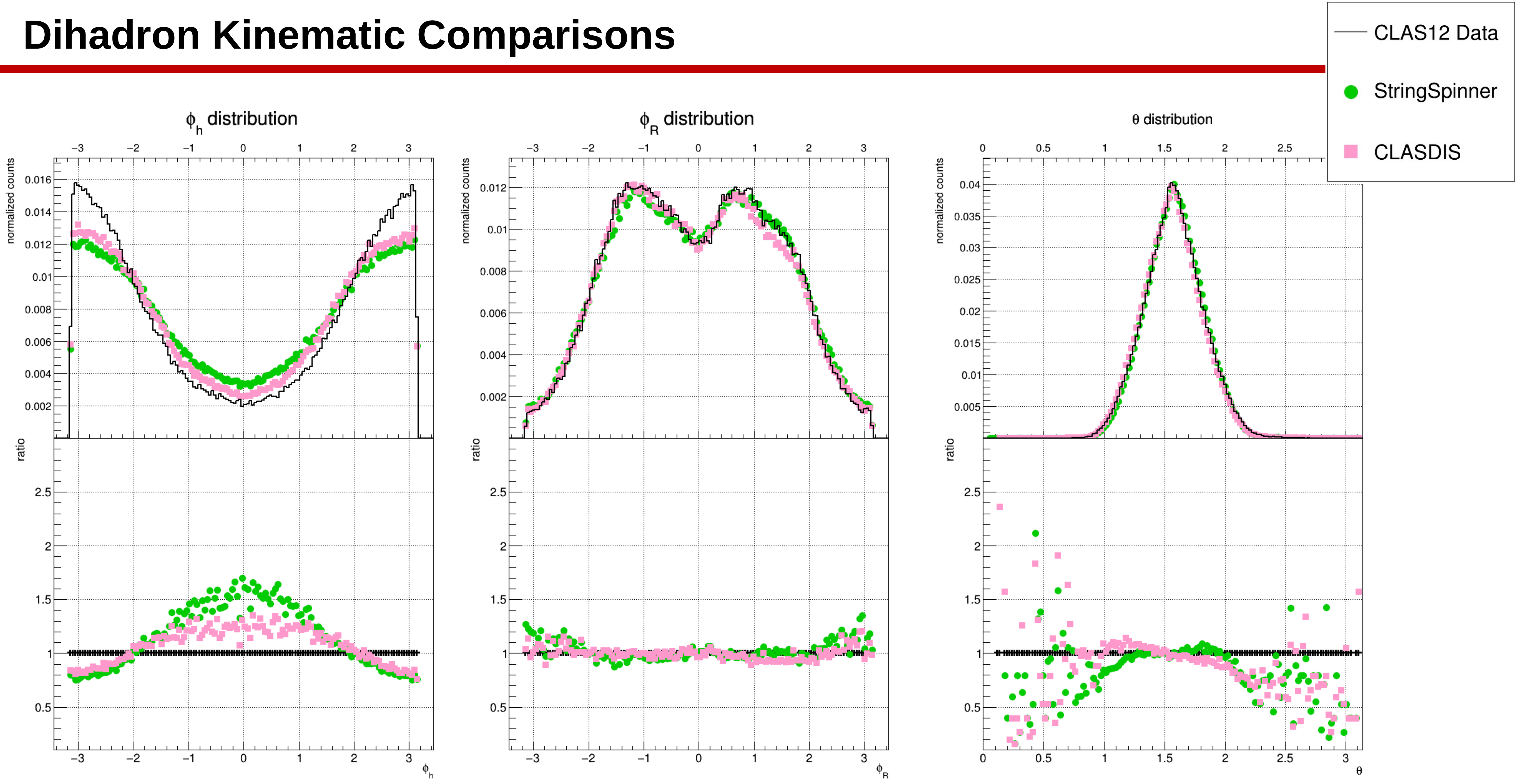




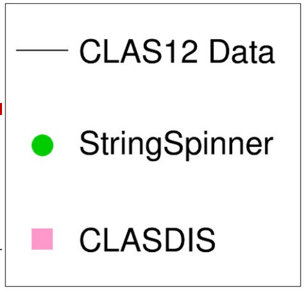
Consistent with results from
A. Kerbizi, X. Artru, A. Martin, Phys.Rev.D 104 (2021) 11, 114038

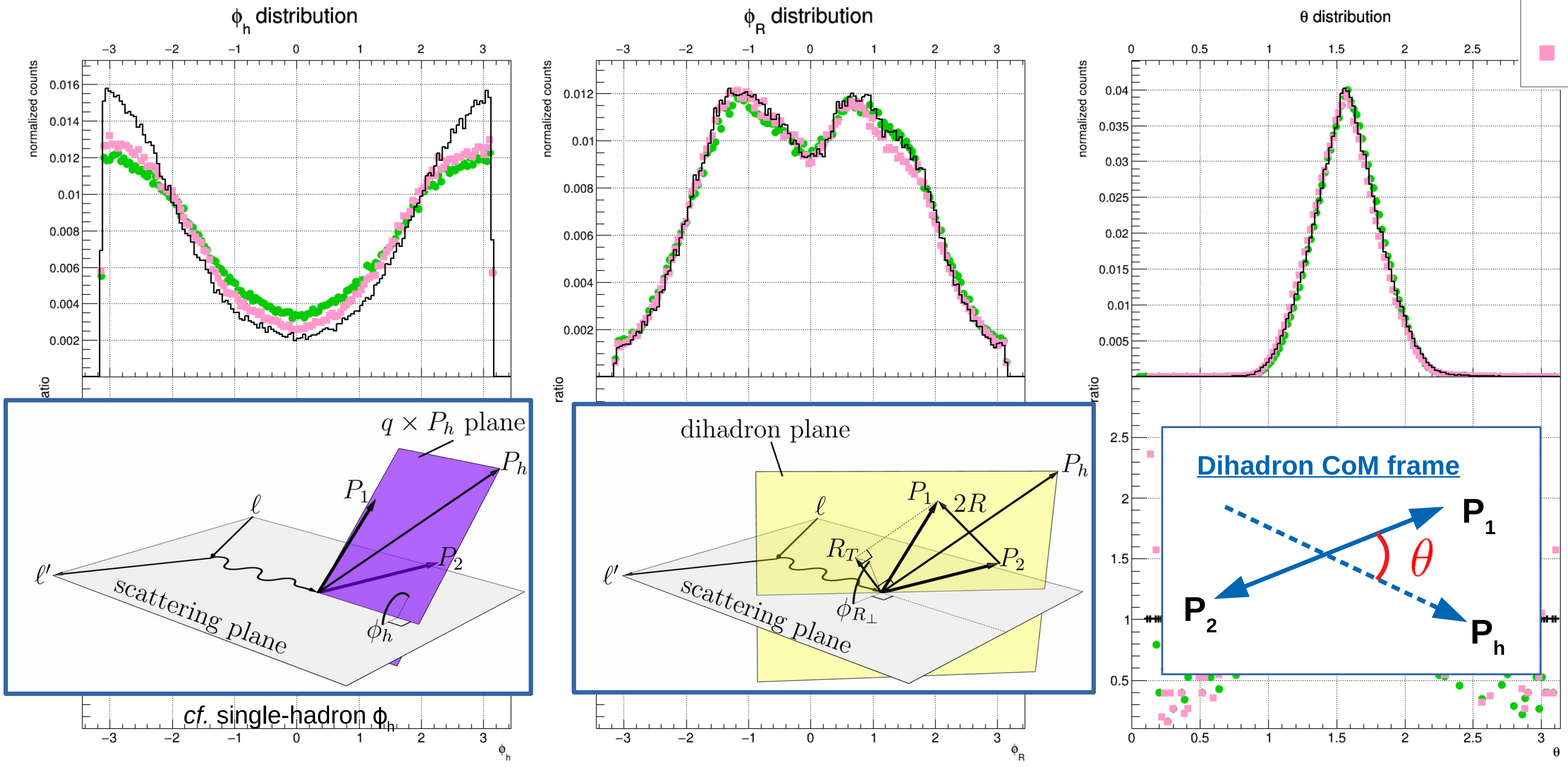
- Strong dependence on the free parameters
  - f_L – fraction of long. pol. vector mesons → high sensitivity of relative ratios of ρ and ω production
  - θ_{LT} – oblique polarization → mild sensitivity
- Needs more study and tuning!

Dihadron Kinematic Comparisons



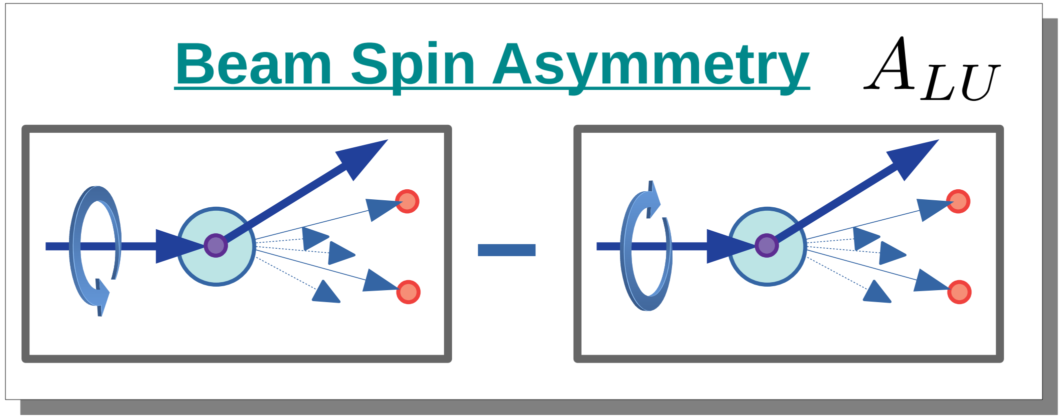
Dihadron Kinematic Comparisons



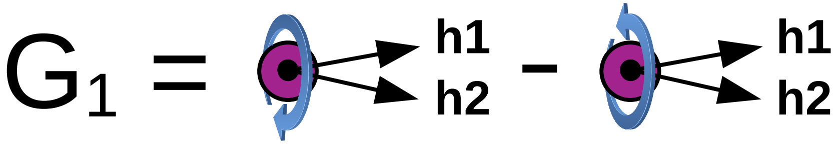


Dihadron Spin Asymmetries

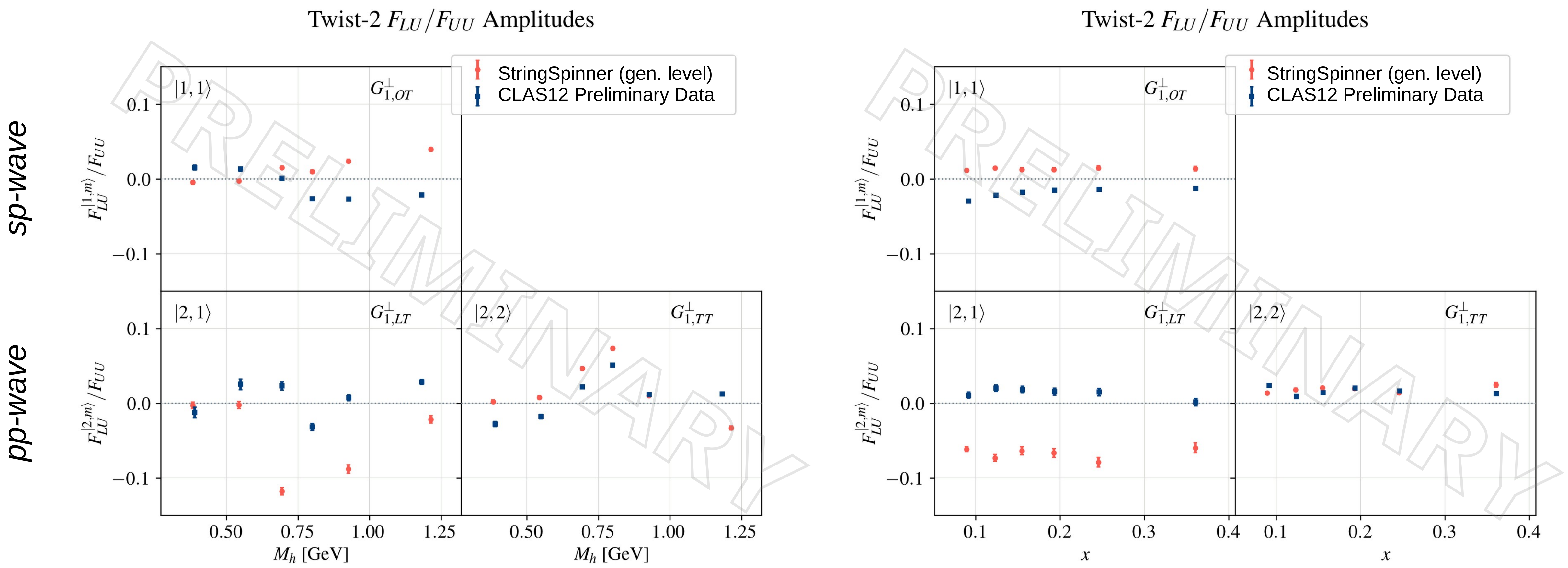
- Running full simulations with enough statistics for an asymmetry requires:
  - Large CPU usage → Open Science Grid
  - Large disk space
- Could try generator level “pre-selection” cuts to save time and space, but may introduce bias
- For now, presenting comparisons of generator-level asymmetries, with all the same cuts applied
- Comparisons to Preliminary Results: CD, Transversity 2022
- Technical note: the sign of StringSpinner asymmetries had to be flipped



leading twist → f_1 G_1



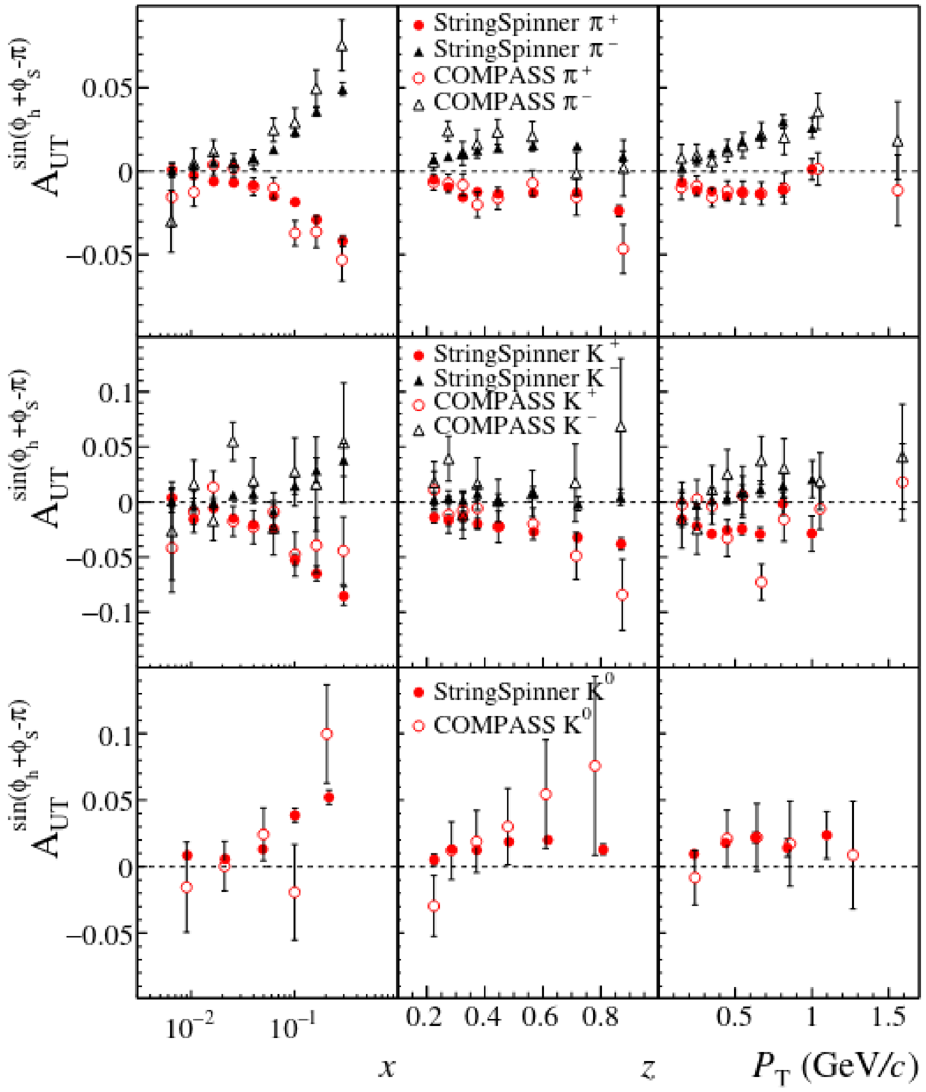
Dihadron Spin Asymmetries



- StringSpinner reproduces ρ enhancement in |2,2>, but overestimates that in |2,1>
- Sign change at ρ mass in |1,1> not *quite* reproduced; may also be a relative sign issue
- Remember the invariant mass distribution is not consistent with data → needs free-parameter tuning!

StringSpinner Asymmetries from other Experiments

- Collins asymmetries from COMPASS are well reproduced by StringSpinner →
  - Similarly for HERMES
    - A. Kerbizi and L. Lönnblad, Comput.Phys.Commun. 292 (2023), 108886
  - And satisfactorily Belle and BaBar (e^+e^-)
    - A. Kerbizi, L. Lönnblad, A. Martin, Phys.Rev.D 110 (2024) 7, 074029
- Optimism for StringSpinner at CLAS
  - Need more tuning…



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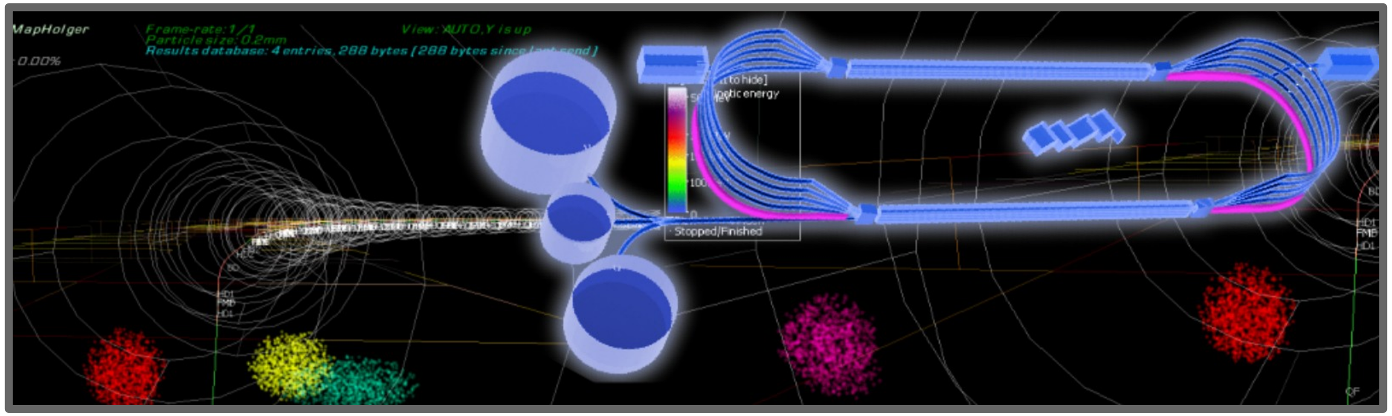
Outlook for 22 GeV

- In StringSpinner, should be straightforward
  - Increase electron beam energy
  - Will we need to adjust the tune?
  - Run existing (or updated) simulation and reconstruction
- May be useful for impact studies of asymmetries and cross sections
  - Need to improve the tune, among other issues…



Issues

- k_T tuning
  - Evident in *single*-pion p_T distributions: CLASDIS agrees much better with data than StringSpinner
- Lorentz frame issue
  - Event record is in some event-dependent frame, not the lab frame
  - Missing Mass and Missing Energy peaks are shifted → impacts exclusive region
  - Boosting back does not work consistently; Pythia developers are investigating
  - Details: https://gitlab.com/Pythia8/releases/-/issues/529
- StringSpinner parameter tuning → M_h distribution dependence
- Asymmetry sign
- Pythia's CoM energy lower limit for validity is around 10 GeV, but CLAS12 is around 4.5 GeV

C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, et al., SciPost Phys.Codeb. 2022 (2022), 8

Summary

- StringSpinner is an extension to Pythia modeling spin effects in hadronization
- Tuning Pythia 8 parameters for CLAS is in progress
- StringSpinner generates significant asymmetries, which may be useful to assist impact studies for 22 GeV
  - Consistency with data seen in several measurements (COMPASS, et al.)
- Future Improvements
  - Include polarized PDFs, e.g., Sivers and twist-3 e(x)
  - Use other channels (e.g., single-pion) to help tune free parameters

backup

Pythia Tune (slide 1/3)

Parameter	Value	Description / Notes
`Beams:frameType`	2	the beams are back-to-back, but with different energies
`Beams:idA`	11	electron beam
`Beams:idB`	2212	proton target
`Beams:eA`	E_e	electron beam energy
`Beams:eB`	0	fixed proton
`Random:setSeed`	on	use custom RNG seed
`Random:seed`	set by OSG	RNG seed, controlled by caller (OSG)

Parameter	Value	Description / Notes
`StringSpinner:GLGT`	1.4	free parameter $\lvert G_L/G_T \rvert$
`StringSpinner:thetaLT`	0	free parameter $\theta_{LT} = \arg(G_L/G_T)$
`StringSpinner:`**`q`**`Polarisation`	$(0, 0, -\lambda_e)$	quark polarizations, where λ_e is the beam-electron helicity; defined with **q** for each of `u`, `d`, `s`, `ubar`, `dbar`, `sbar`
`StringSpinner:targetPolarisation`	$(0, 0, 0)$	unpolarized target

Pythia Tune (slide 2/3)

Parameter	Value	Description / Notes
WeakBosonExchange:ff2ff(t:gmZ)	on	Scattering $ff' \to ff'$ via γ^*/Z^0 t-channel exchange, with full interference between the γ^* and Z^0
PDF:pSet	13	NNPDF2.3 QCD+QED LO $\alpha_s(M_Z) = 0.130$ (the current Pythia 8 default)
PhaseSpace:Q2Min	1.0	minimum Q^2
PhaseSpace:pTHatMinDiverge	0.5	extra p_T cut to avoid divergences of some processes in the $p_T \to 0$ limit (for low-x)
PhaseSpace:mHatMin	0.0	minimum invariant mass (for low-x)
PDF:lepton	off	do not use parton densities for lepton beams
SpaceShower:dipoleRecoil	off	string+${}^3P_0$ model does not handle the more general string configurations involving multiple partons that would be produced in the showering process
TimeShower:QEDshowerByL	off	disallow leptons to radiate photons
PartonLevel:FSR	off	
PartonLevel:ISR	off	
PartonLevel:MPI	off	
ProcessLevel:resonanceDecays	off	
PartonLevel:FSRinResonances	off	
HadronLevel:BoseEinstein	off	
ParticleData:modeBreitWigner	3	particles registered as having a mass width are given a mass in the range $m_{\text{min}} < m < m_{\text{max}}$, according to a truncated relativistic Breit-Wigner, i.e., quadratic in m

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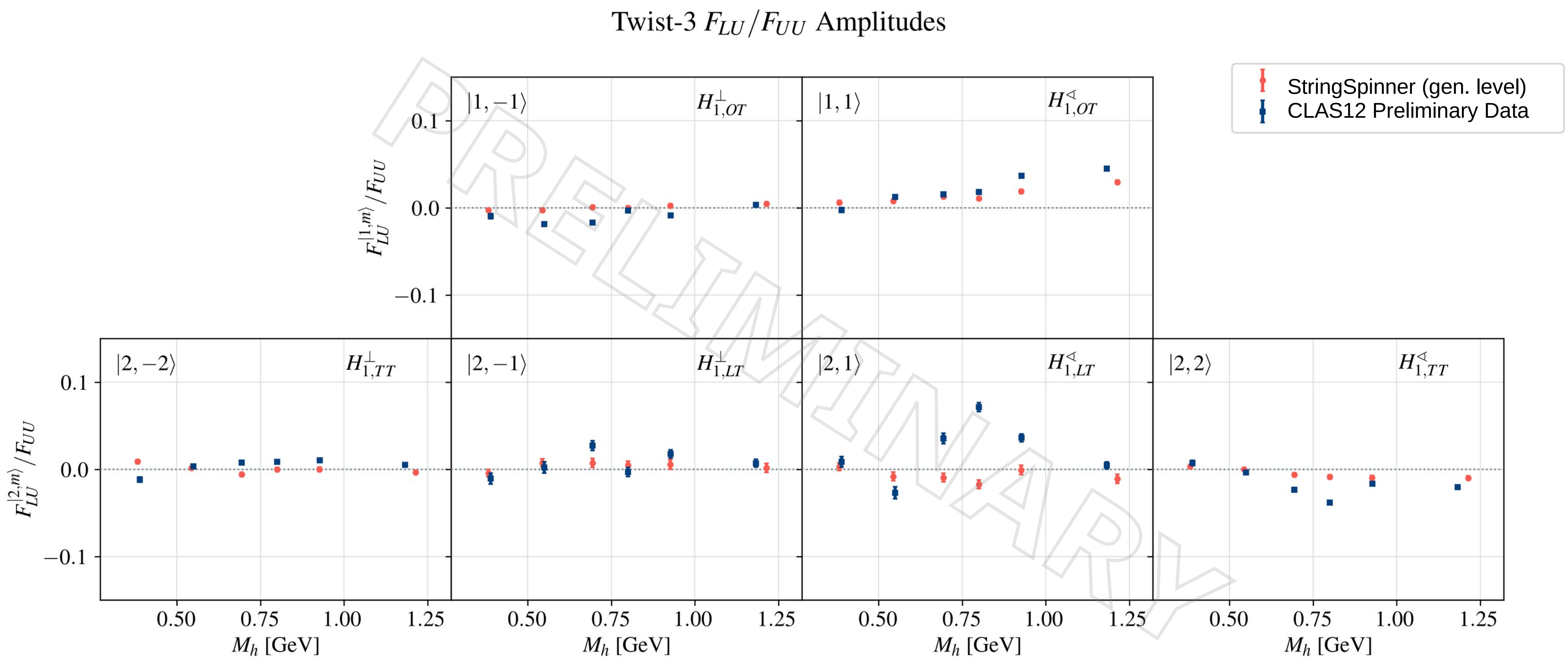
Pythia Tune (slide 3/3)

Parameter	Value	Description / Notes
StringPT:enhancedFraction	0.0	the fraction of string breaks with enhanced width
StringPT:enhancedWidth	1.0	the enhancement of the width in this fraction
StringZ:aLund	1.2	fragmentation parameter a of $\frac{1}{z}(1-z)^a e^{-bm_T^2/z}$
StringZ:bLund	0.58	fragmentation parameter b of the above
StringFragmentation:stopMass	0.0	used to define a $W_{\mathrm{min}} = m_{q1} + m_{q2} + \mathrm{stopMass}$, where m_{q1} and m_{q2} are the masses of the two current endpoint quarks or diquarks; analogous to PARJ(33)
StringFlav:mesonUDvector	0.7	ratio of vector meson to pseudoscalar mesons, for light quarks (ρ/π); analogous to PARJ(11)
StringFlav:mesonSvector	0.75	ratio for strange quarks (K^*/K); analogous to PARJ(12)
StringPT:sigma	0.5	p_T width of the fragmentation process (analogous to PARJ(21))
BeamRemnants:primordialKT	on	allow selection of primordial k_T according to the parameter values
BeamRemnants:primordialKThard	0.64	initial k_T width, analogous to PARL(3) (**FIXME**: is this right?)
BeamRemnants:halfScaleForKT	0.0	set these parameters to zero, to try to make k_T width relatively constant
BeamRemnants:halfMassForKT	0.0	
BeamRemnants:primordialKTremnant	0.0	

Twist-3 Asymmetries



- Sensitive to transverse-spin dependent DiFF H_1 coupled with twist-3 PDF
- Important: the twist-3 PDF *e(x)* is *not* in Pythia

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