Dihadron multiplicity studies with clas12

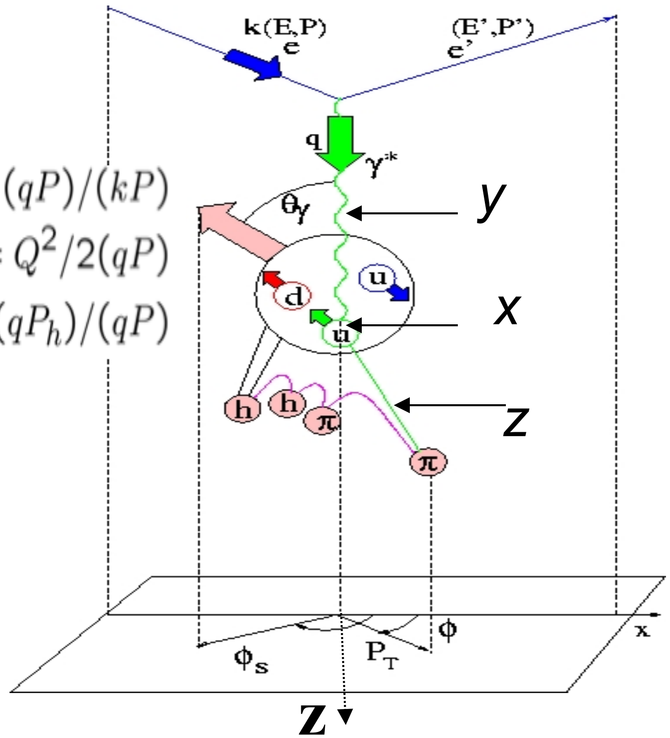
Harut Avakian (JLab)

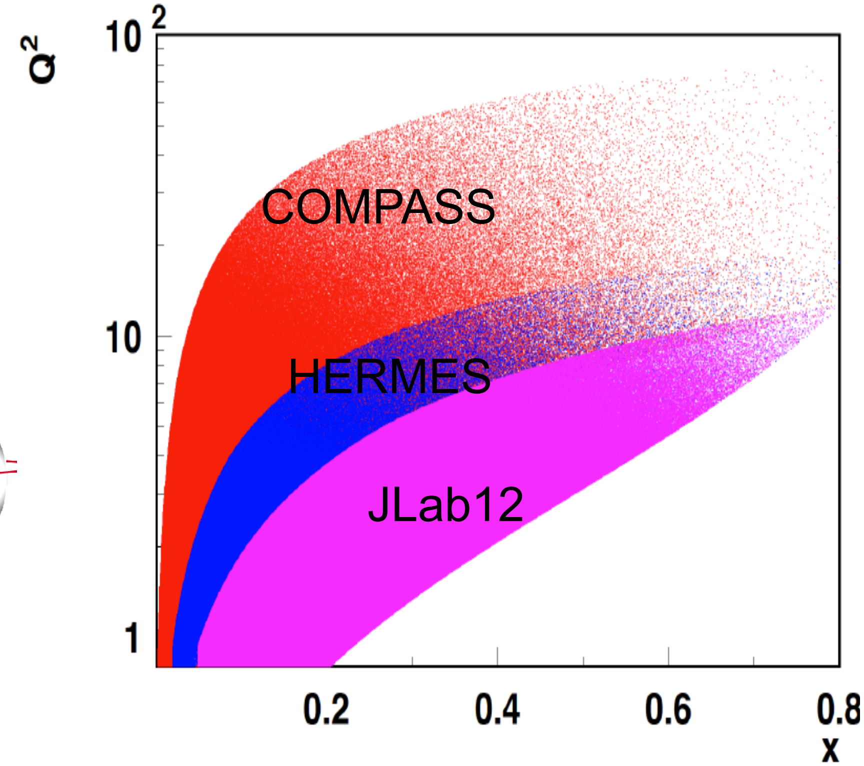
CLAS Collaboration Meeting June 20, 2019

- Studies of SIDIS at JLab
- Hadronization of quarks
- Dihadron production at CLAS12
- Separating resonance(VM) from uncorrelated 2 hadrons
- LUND MC vs Data
- Distributions of direct (string produced) pions vs VM decay pions
- Conclusions

SIDIS kinematical plane and observables

$y = (qP)/(kP)$
$x = Q^2/2(qP)$
$z = (qP_h)/(qP)$





$$\sigma = F_{UU} + P_t F_{UL}^{\sin\phi} \sin 2\phi + P_b F_{LU}^{\sin\phi} \sin\phi \ldots$$

$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

$$F_{XY}^h(x, z, P_T, Q^2) \propto \sum H^q \times f^q(x, k_T, ..) \otimes D^{q\to h}(z, p_T, ..) + Y(Q^2, P_T) + \mathcal{O}(M/Q)$$

beam polarization

target polarization

TMD distribution function

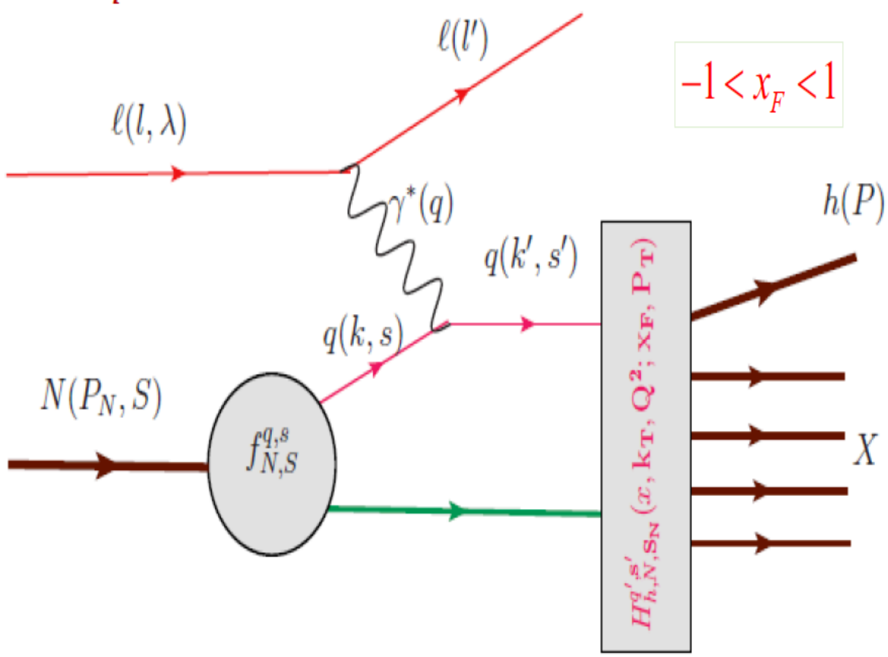
TMD fragmentation function

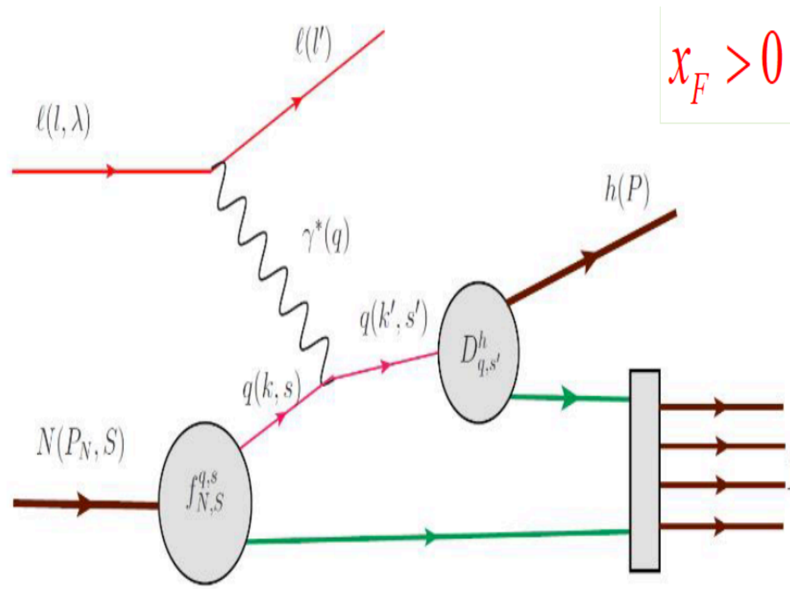
corrections for the region of large kT~Q

Hadronization

$Q^2 \gg M_p^2$

A.Kotzinian FF2019





Hadronization Function
→ conditional probability to produce hadron ***h***

$$H^{q'}_{h/N}\left(x,\mathbf{k}_T,Q^2;x_F,\mathbf{P}^h_T;\mathbf{s}'_q,\mathbf{S}_N\right)$$

Quark Fragmentation Functions
(*universal and independent*)

$$D^h_{q,s'}\left(z,\mathbf{p}_T,Q^2\right)$$

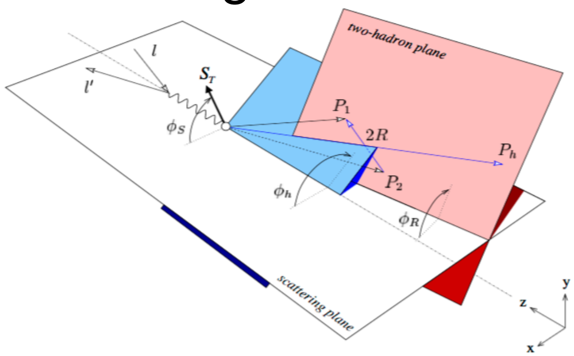
Where this works?

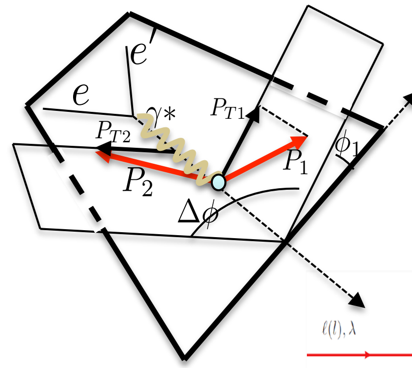
Correlated hadron production in hard scattering

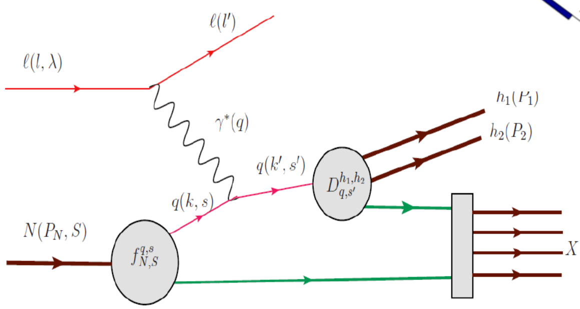
Dedicated CLAS12 proposals: E12-06-112B/E12-09-008B

2 hadrons in current fragmentation

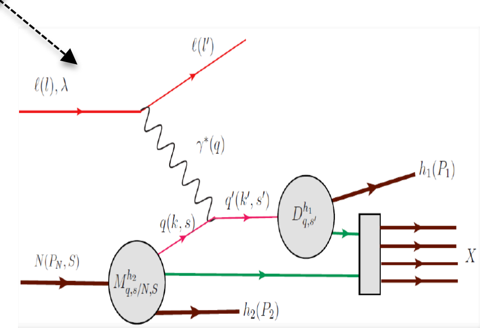
hadrons in current & target fragmentatior







$$P_h = P_1 + P_2,$$
$$R = \frac{1}{2}(P_1 - P_2).$$



With ϕ_S, ϕ_1, ϕ_2, ϕ_R, ϕ_h several observables have been identified to study correlations

$\phi_R - \phi_S$, ϕ_R -accessing transversity and quark-gluon correlations *Radici & Bacchetta*

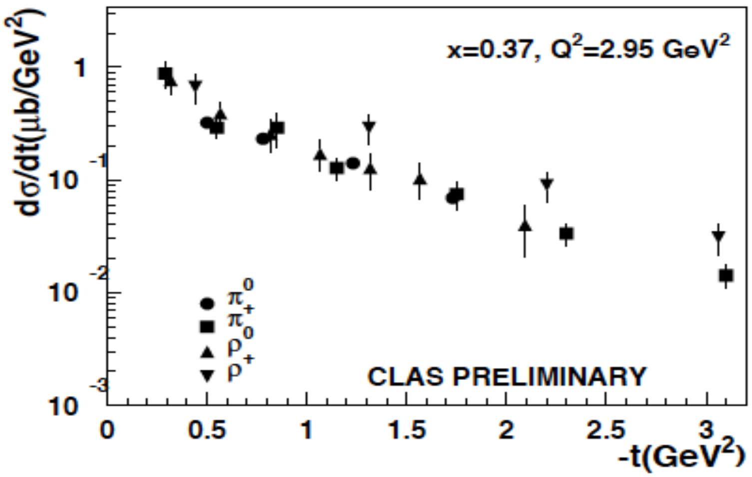
$\phi_R - \phi_h$ -accessing leading twist polarized fragmentation functions *Matevosyan,Kotzinian,Thomas*

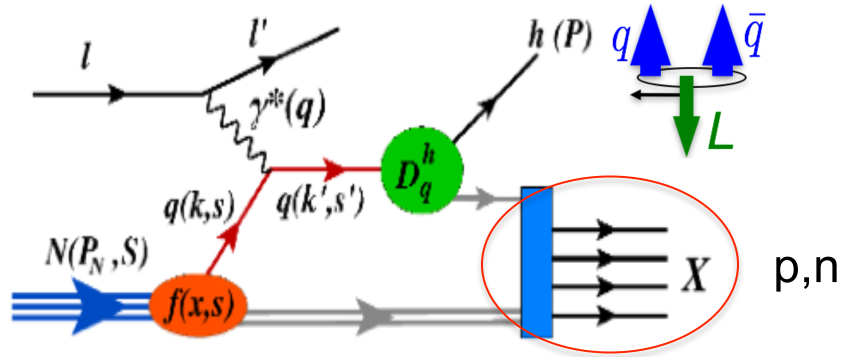
$\phi_1 - \phi_2$ -accessing correlations in current and target regions *Anselmino, Barone, Kotzinian*

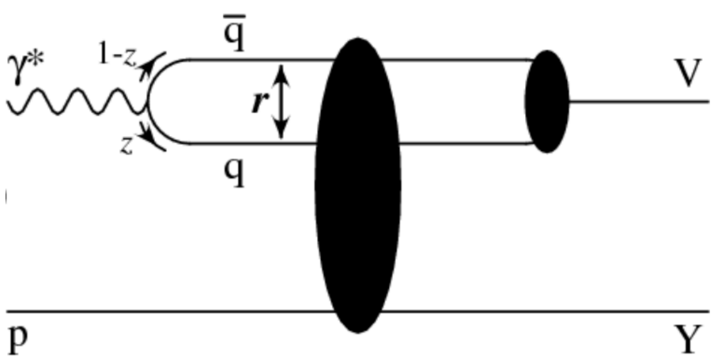
2h production in SIDIS provides access to correlations inaccessible in simple SIDIS

Exclusive π/ρ production at large t

Hard exclusive meson production from clas6







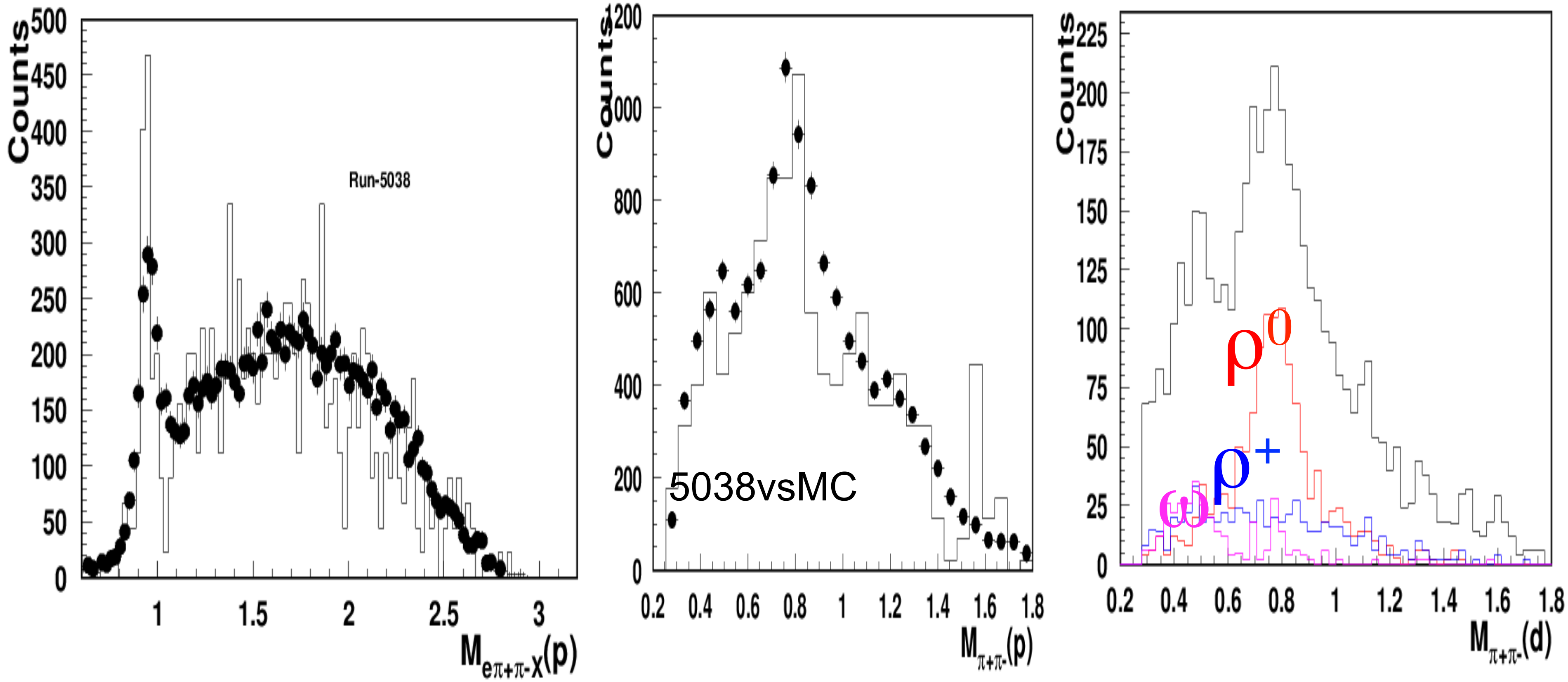
Implications

x-section of measured exclusive process at large t exhibit similar pattern

- $\rho+>\rho^0$ →Diffractive production suppressed
- at large t production mechanism most likely is similar to SIDIS (color transparency?)
- Slightly higher rho x-sections indicate the fraction of SIDIS pions from VM > 60%
- consistent with LUND-MC in fraction of pions from rho
- ………

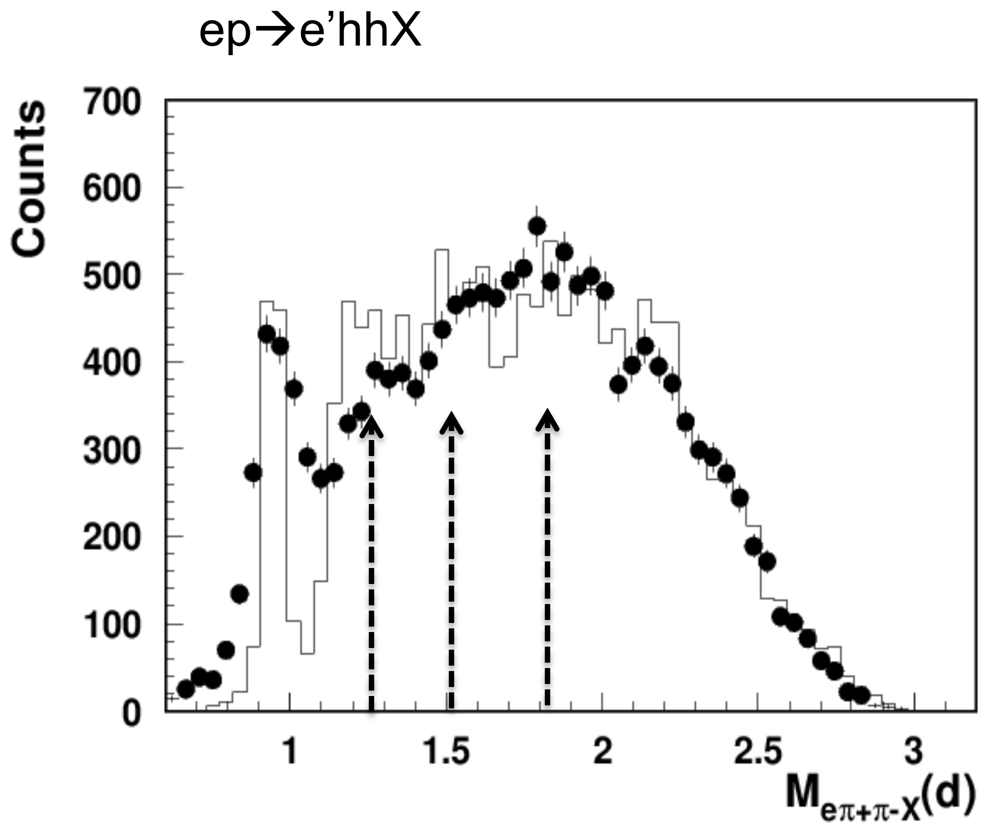
Correlated pairs: Data/MC(Run 5038,T-1,10.6GeV)

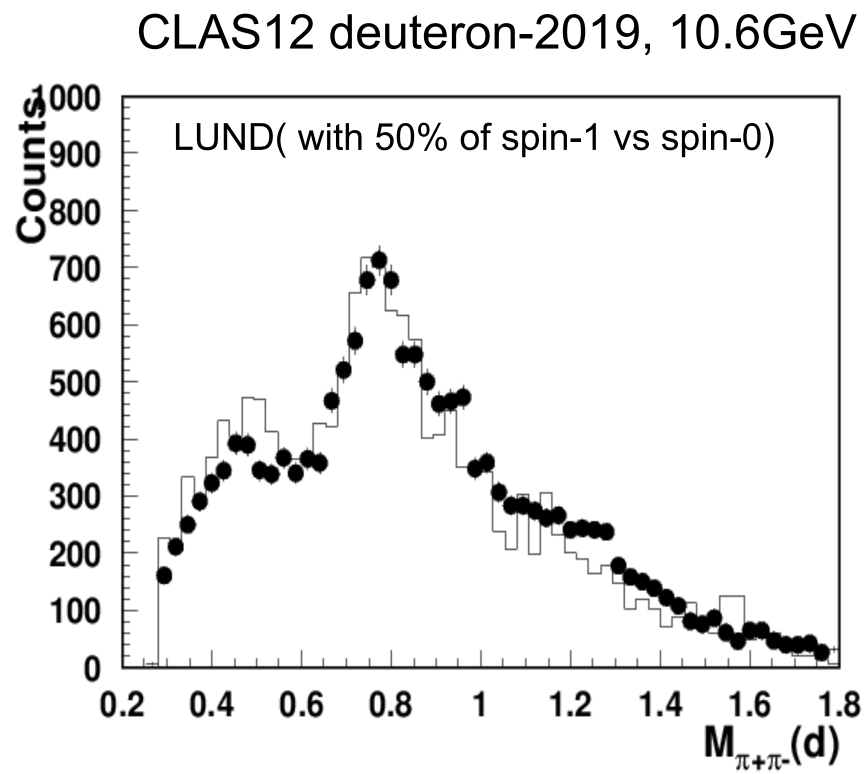
Data/MC normalization by number of reconstructed e'X events



- Fraction of exclusive pairs could be separated
- Most of the pion pairs comes from SIDIS VM decays
  - those are mostly SIDIS VM

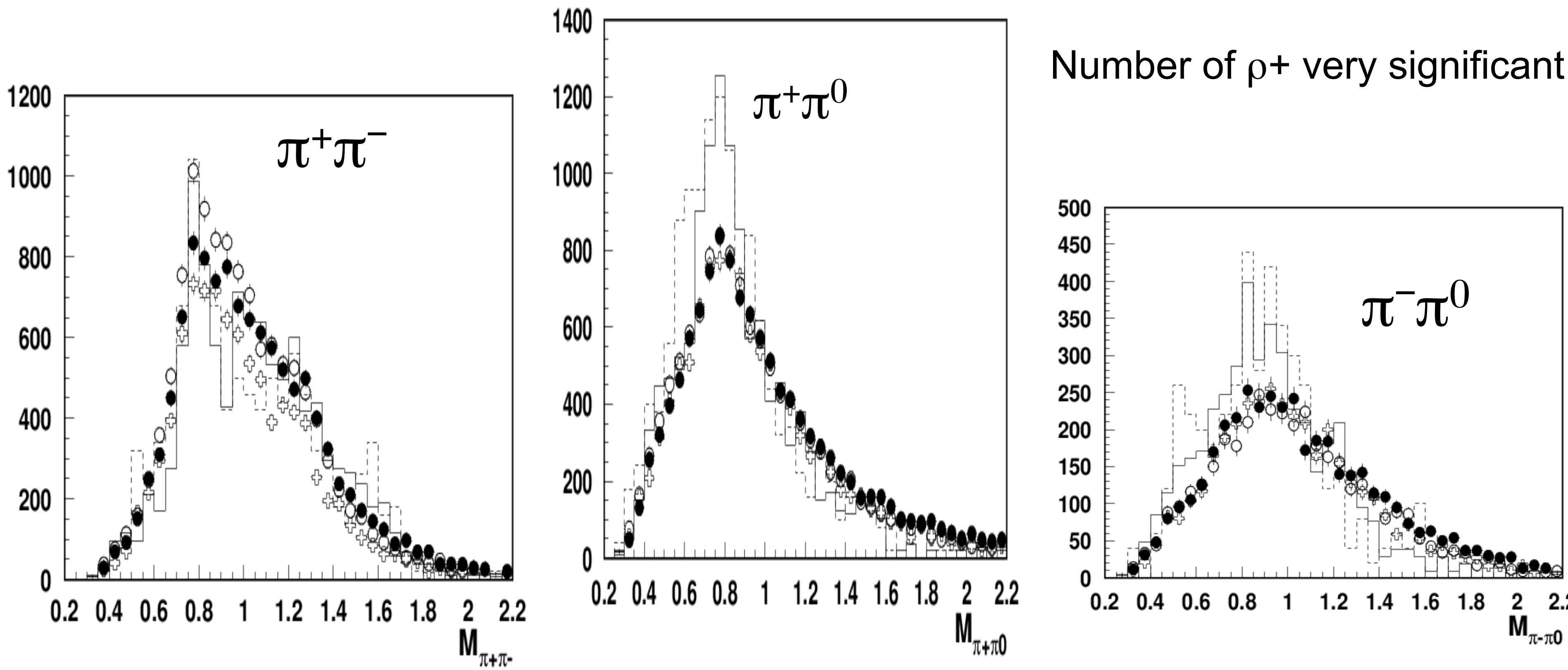
Correlated pairs: CLAS12 Data





- Normalized to number of electrons pion pair multiplicities uncorrected for acceptance are consistent with LUND-MC (no Fermi motion accounted)
- Fraction of exclusive states may be significant
- Background under $\rho 0$ in $M\pi\pi$ mainly from other VMs $\rho +$ and ω + some uncorrelated pions

Invariant mass of pion pairs Mππ



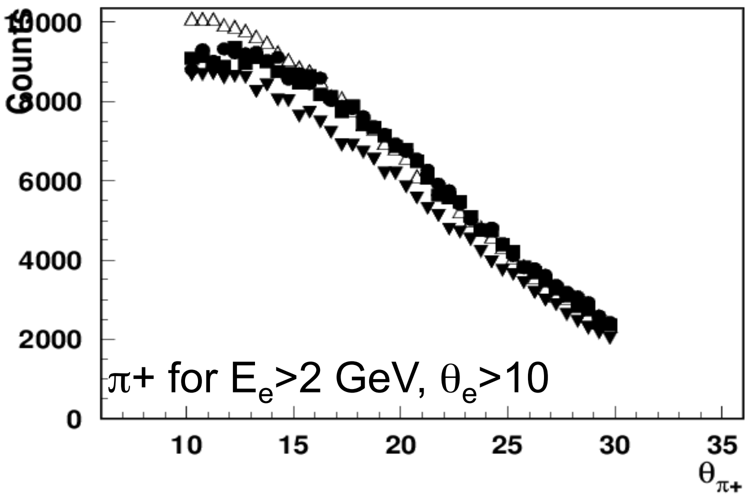
Curves 2 MC versions with 50 and 70% of spin-1
Circles 3 run sets RGA-Fall/Spring2019
5001(open), 5036 (full circles) 6715 (crosses)

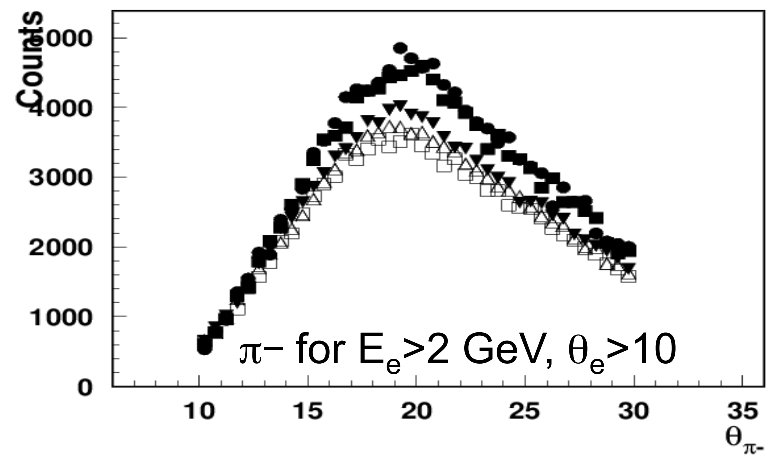
should be redone with new cook of low lumi runs

Multiplicities from data consistent with multiplicities coming from CLAS12 LUND MC

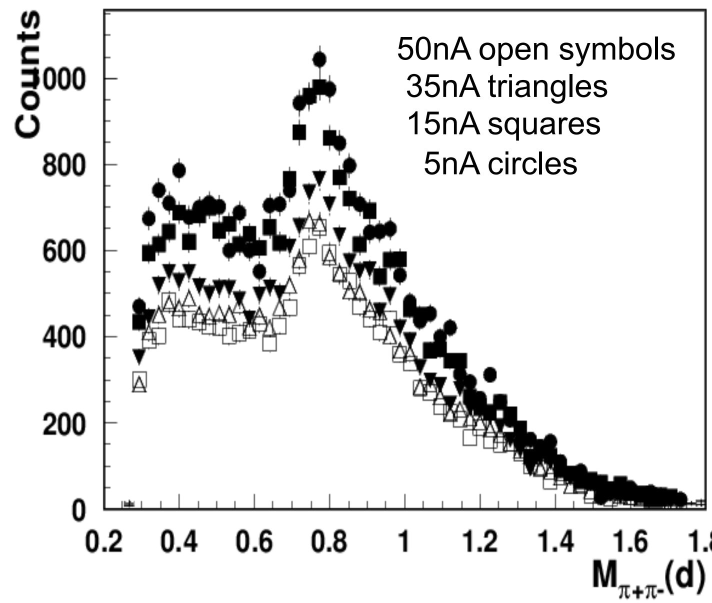
Lumi-dependence of couns from RGB

Runs 6226(5nA) 6227(15nA) 6240 (35nA), 6310,6328 (50nA)





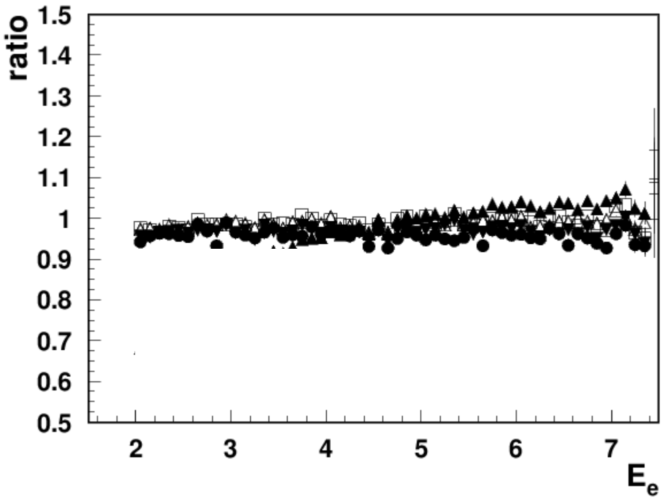
Runs normalized for Ee>2 GeV and θe>10 degrees

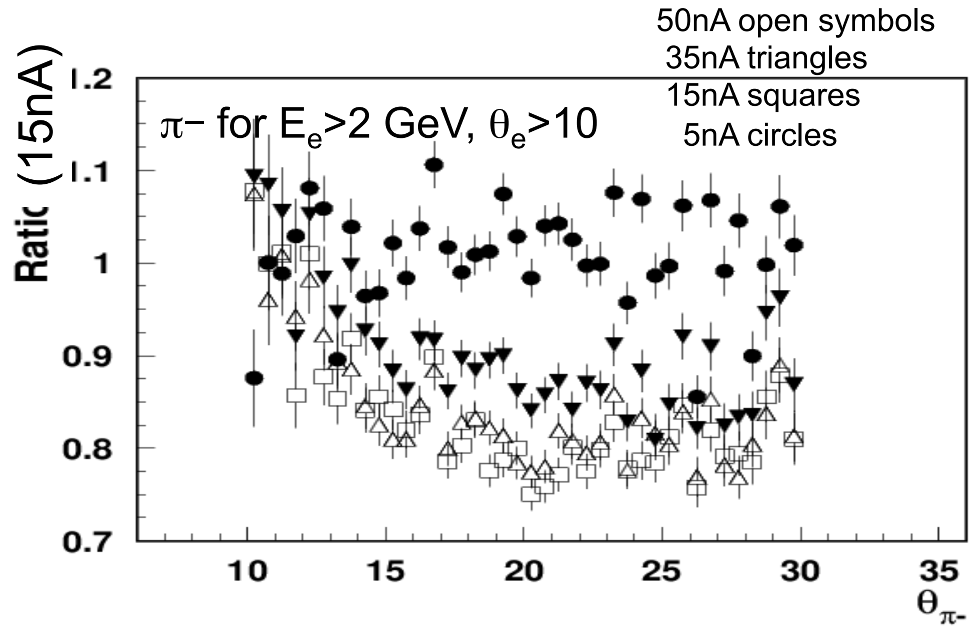


- Number of low momentum π+ is higher for higher lumi(junk?)
- π- follows the lumi
- May have some angular/energy dependence of eff.
- It is important to have low lumi data enough for detailed studies of efficiencies for all relevant processes.

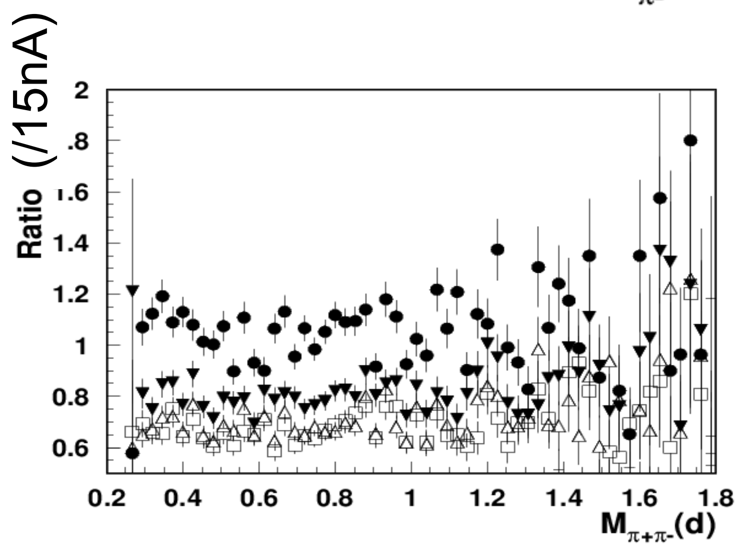
RGB lumi-dependence: ratios/15nA

Runs 6226(5nA) 6227(15nA) 6240 (35nA),
6310,6328 (50nA)





Runs normalized for Ee>2 GeV and θe>10 degrees



- Significant reduction of reconstruction eff. with lumi
- $\pi-$ may be used to estimate e- eff.
- overal reduction from 5nA to 50 nA for dihadron events is ~ factor of 2
- eff reduction may depend angle/energy
- With higher statistics can define the optimal lumi.

Correlated hadron production: Where it matters

- CLAS12 data supports predictions from different MCs a very significant fraction of inclusive pions coming from correlated dihadrons (large VM fraction supported by latest e+e- studies).

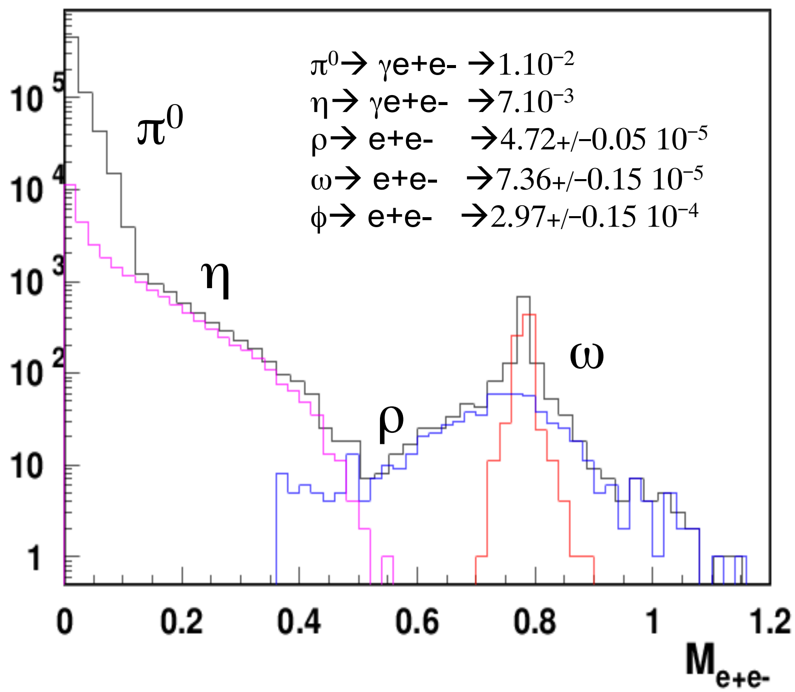
- Most pions coming from VM decays will change:
  - number of e+e-/μ+μ- pairs produced in hadronization process (may be relevant for DY)
  - account of radiative corrections will require a different set of SFs (exclusive VMs may contribute)
  - modeling of spin effects will be different (opposite sign for Collins predicted)
  - interpretation has to account lower P_T/z in case $z=E_h/\nu$ involves the energy of rho instead of pion

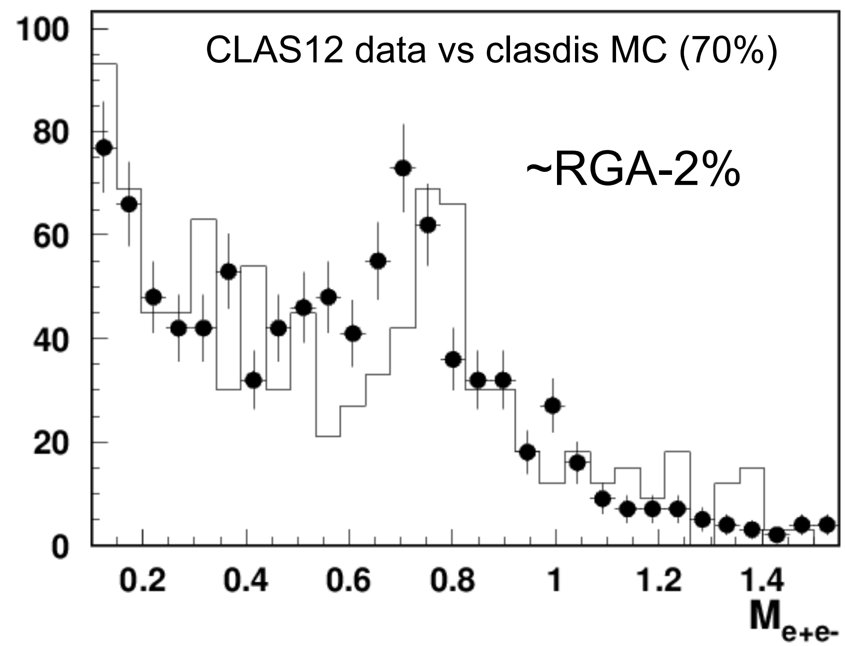
- Analysis of SIDIS involving direct pions may require higher P_T, where direct pions dominate the single pion sample.

Using e+e- to estimate vector mesons

<u>The invariant mass of dihadrons is contaminated by other vector mesons, with shape not changing significantly with hadronization fraction to spin-1 vs spin-0 mesons</u>

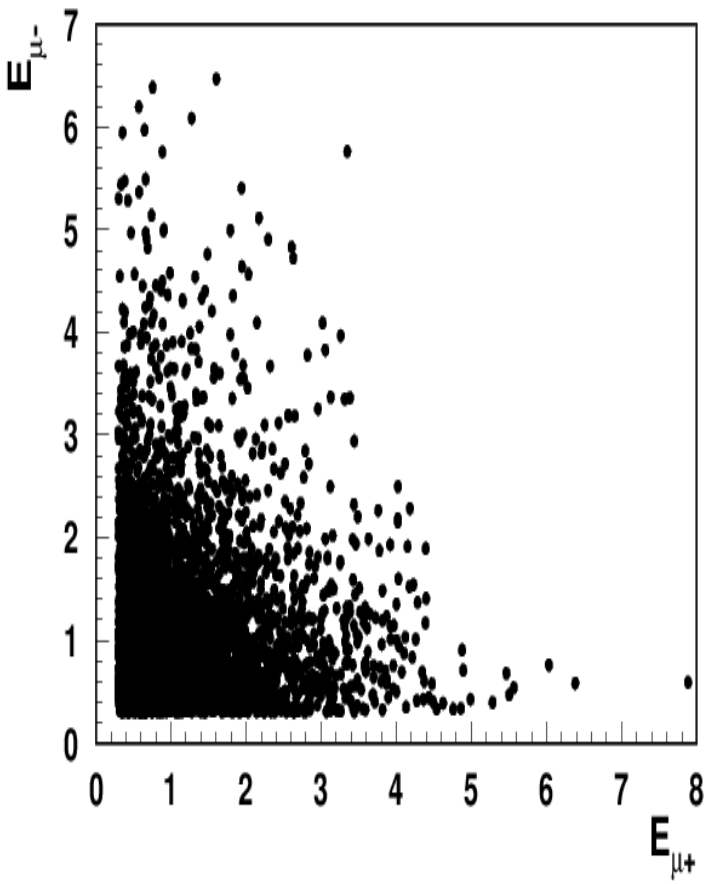
decays of π and η are kinematically separeated from ω and ρ^0

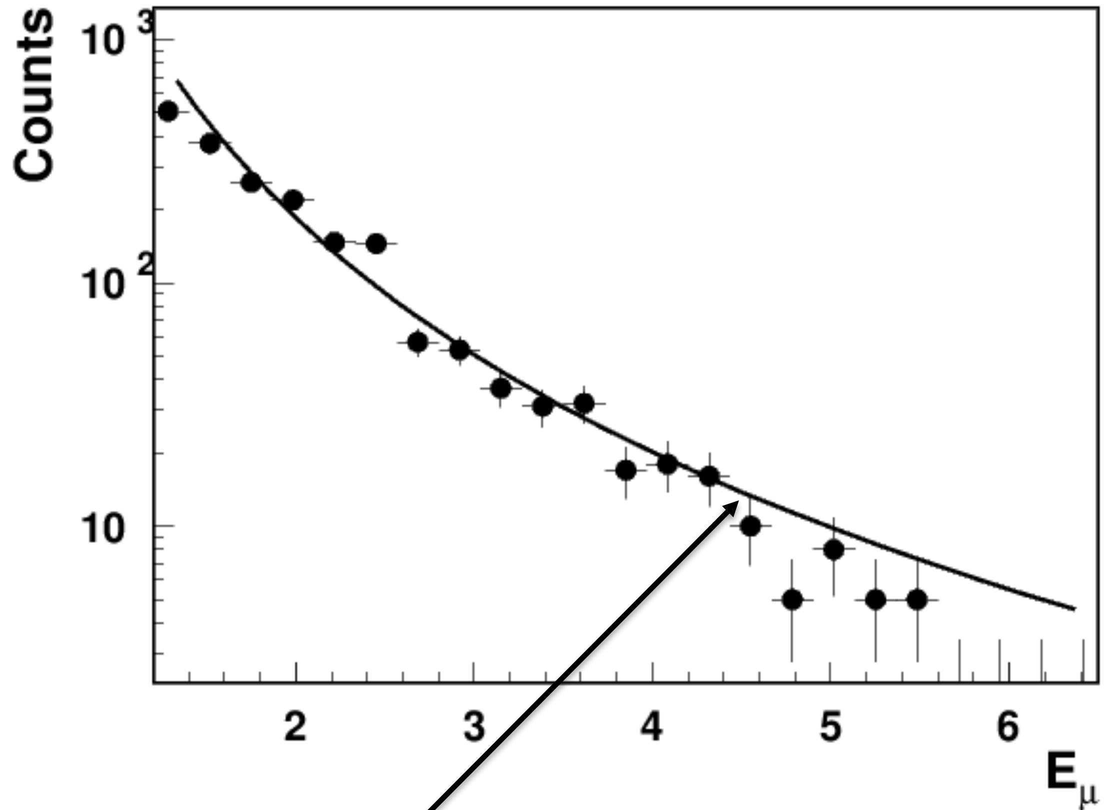




Vector meson per electron can be independently estimated from ep→e’e+e-X

Kinematical distributions of Muons at clas12





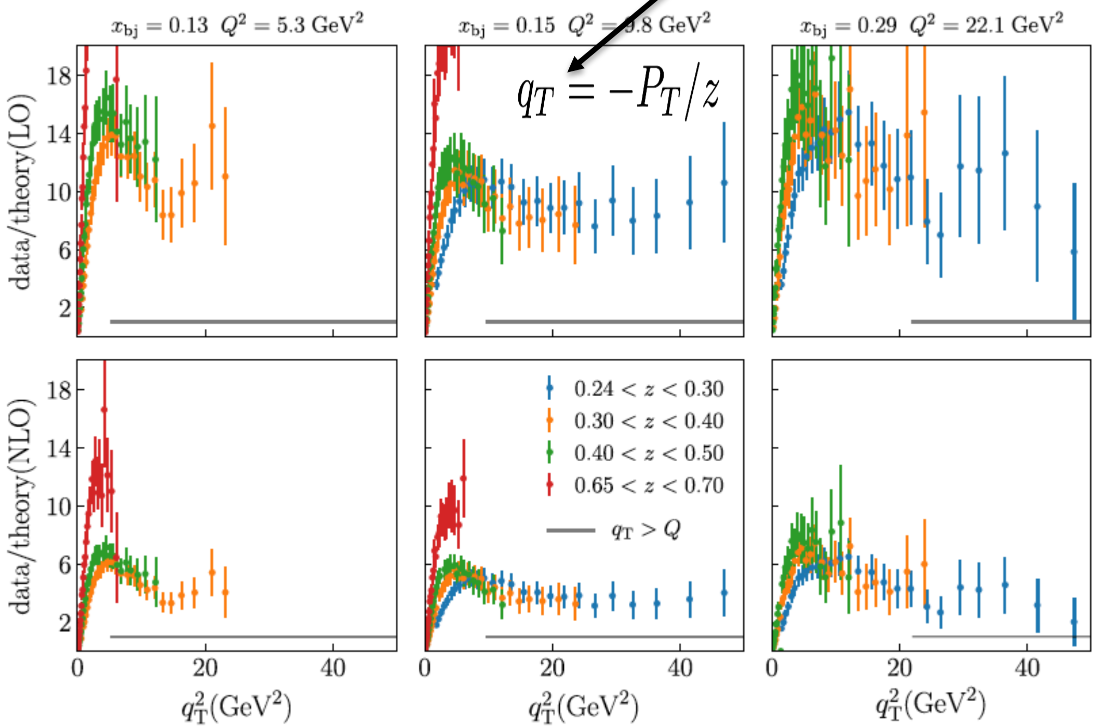
Muons from rho decays in clas12 follow $E^{-3.2}$
Similar behavior for cosmic e+e- PhysRevLett.
113.221102 (H.Dembinski and Co)
EPJ **52**, 02001 (2013) (Ostapchenko)

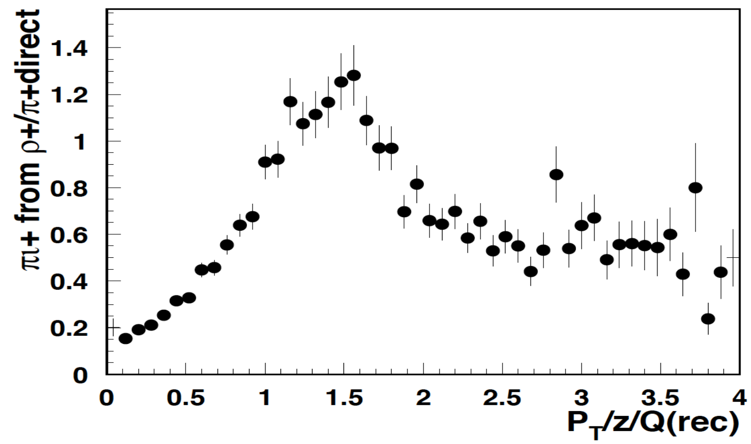
Does it matter if the pion comes from correlated pairs?

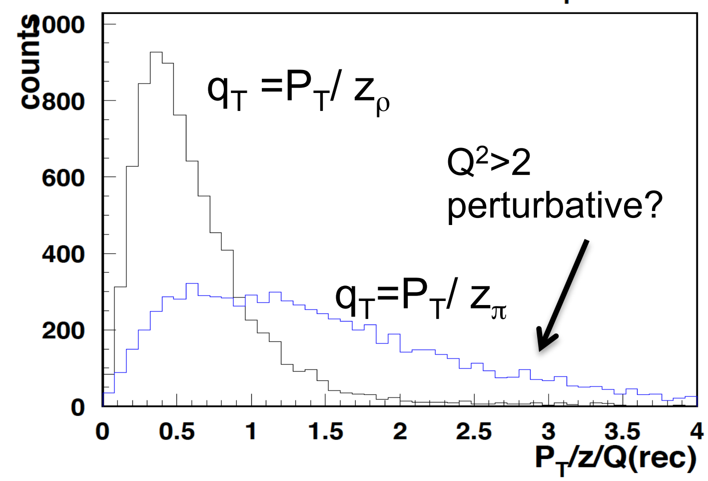
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

quark transverse momentum





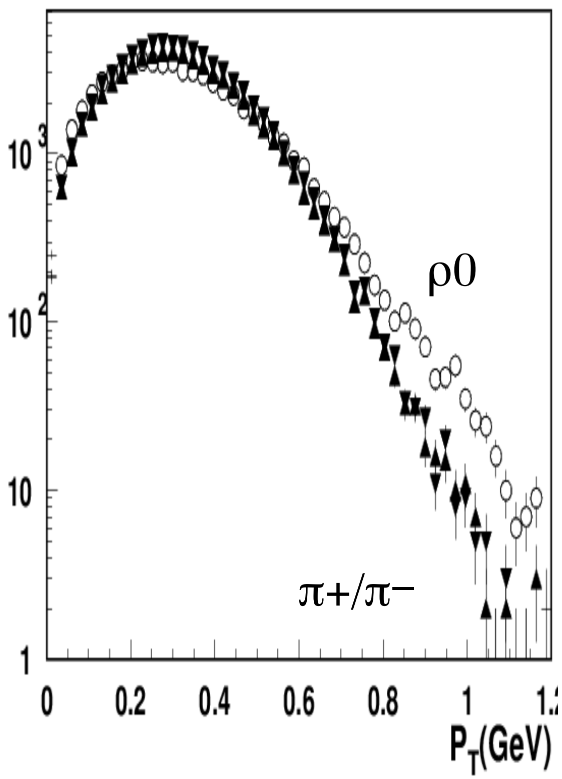


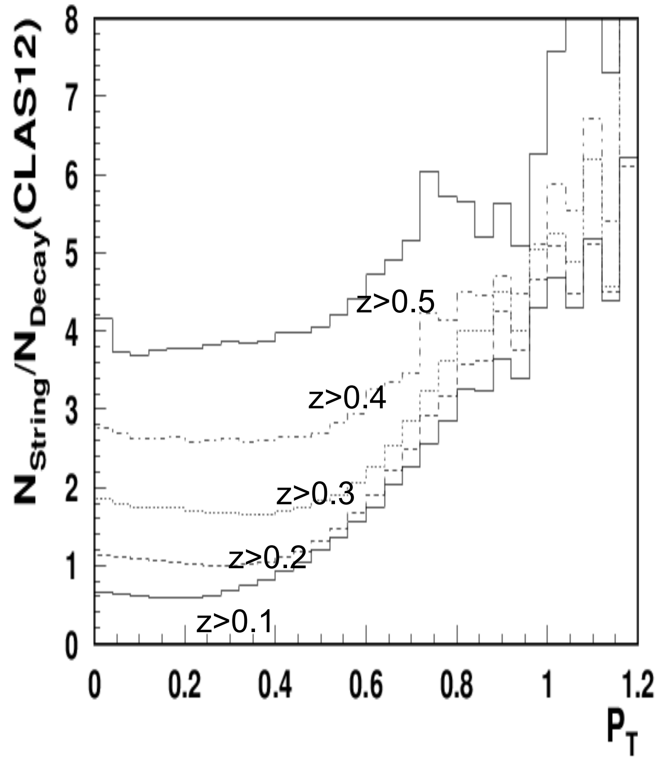
The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

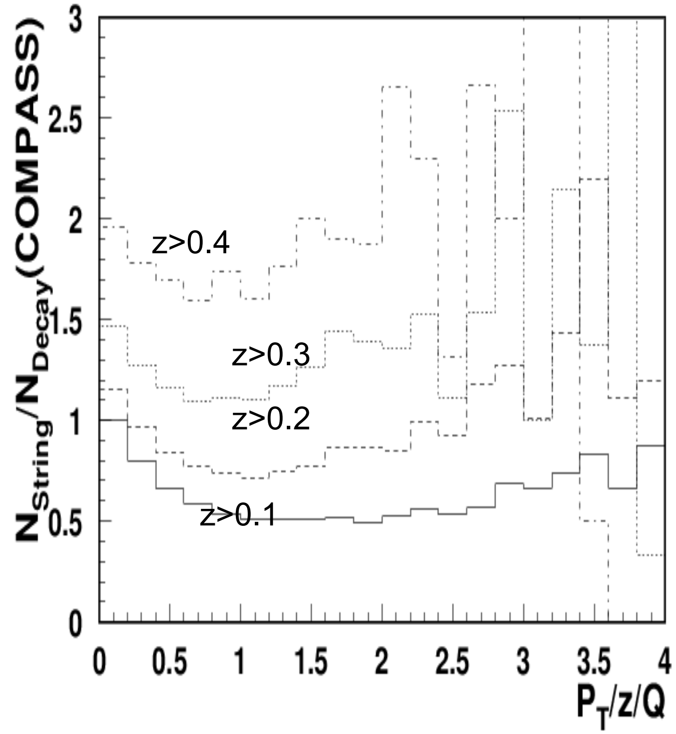
Gonzalez-Hernandez et al, PRD 98, 114005 (2018)

understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

P_T of pions from rho decays: LUND string fragmentation







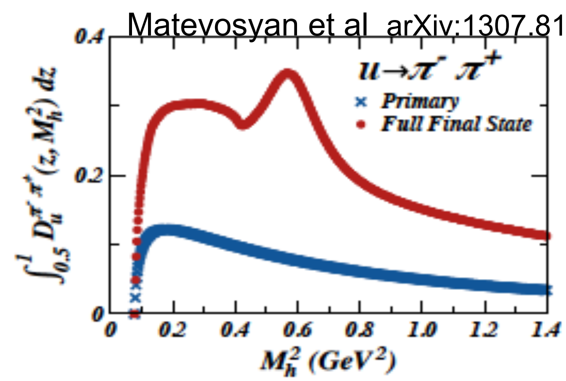
P_T-dependence of rho is similar to the one for decay pions at low P_T

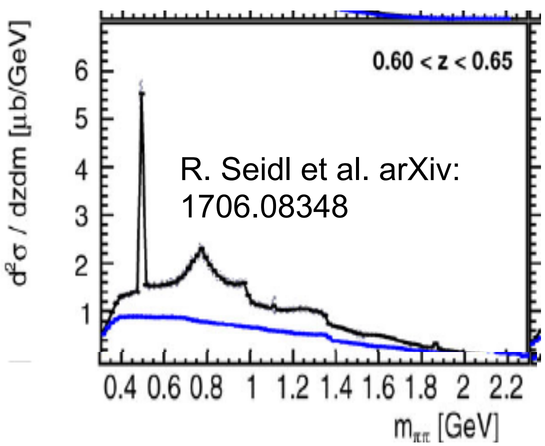
Fraction of direct π+ increases with P_T

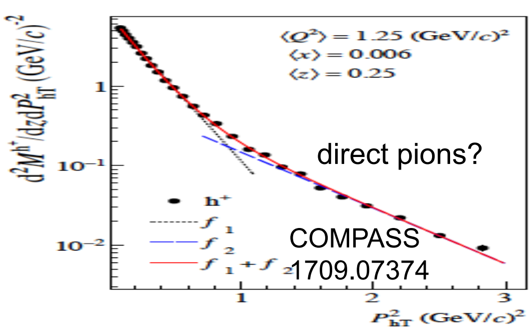
Fraction of direct π+ decreases with P_T/z/Q

Gaussian fits in low P_T-range are dominated by VM decay pions!

Dihadrons: key to hadronization?







How quarks hadronise?

1) the "real" multiplicity may be lower with most hadrons produced from struck quark with large z, and low z fraction filled by VM decay pions
   - intrinsic k_T may be higher
   - the z-dependence enhanced at large z (may be tuned better to describe single and di-hadron distributions)
   - contributions to pions from target fragmentation may be less relevant

2) Most hadrons at accessible in SIDIS P_Ts come from non-perturbative region, with direct pions dominating only the high P_T fraction
3) Fragmentation functions (production probability) of VMs, both unpolarized and polarized should be extracted from SIDIS and e+e- and compared to check the "independence" and "universality"

R.Seidl (preliminary) → at least 40% of dihadrons in e+e- are from rhos(good for universality)

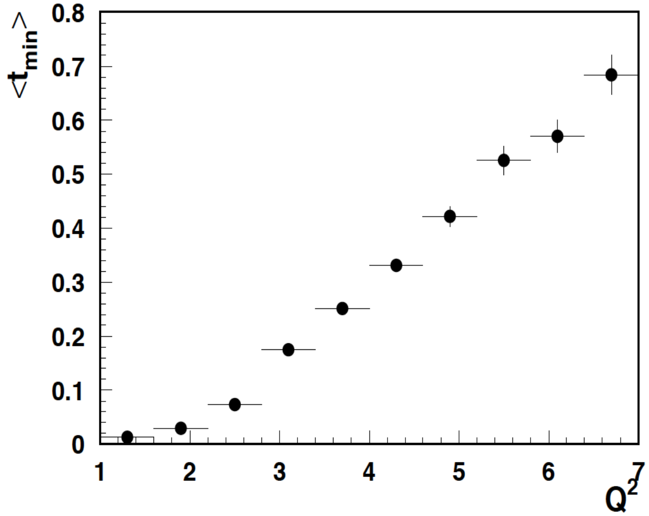
SUMMARY

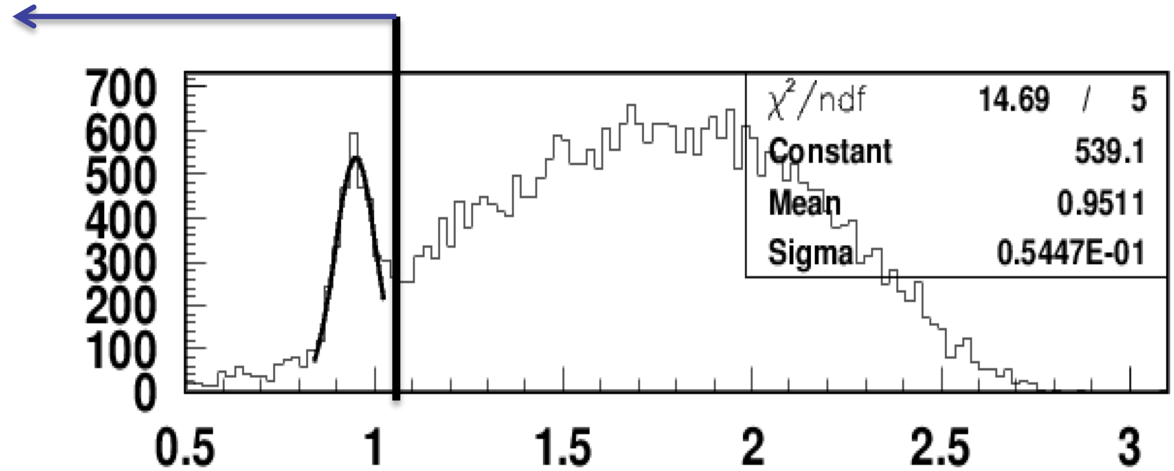
- The CLAS12 ata supports predictions from different MCs of very significant fraction of inclusive pions coming from correlated dihadrons (supporte by latest e+e- studies).
- Higher fraction of hadrons with spin-1 vs spin-0 in hadronization will have a number of implications
- The observables for pions from rhos have peculiar spin and momentum dependences and may require different RC, modeling, and interpretation
- Understanding of exclusive production of hadrons, in particular, at large t, where they show similar behavior, will be important for SIDIS
- Low lumi runs should have enough statistics (>10Mil reconstructed e-) to estimate the loss of event reconstruction efficiency (need for all pion combinations) for relevant distributions

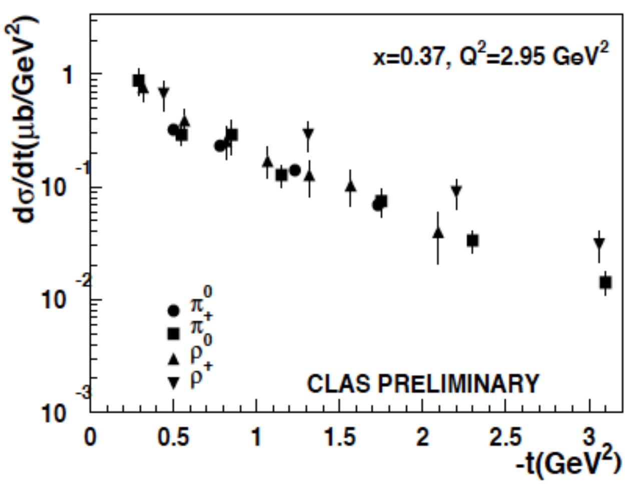
The interpretation of di-hadron production in SIDIS, as well as interpretation of single-hadron production, the independent fragmentation, in particular, are intimately related to contributions to those samples from correlated semi-inclusive and exclusive di-hadrons in general, and rho mesons, in particular.

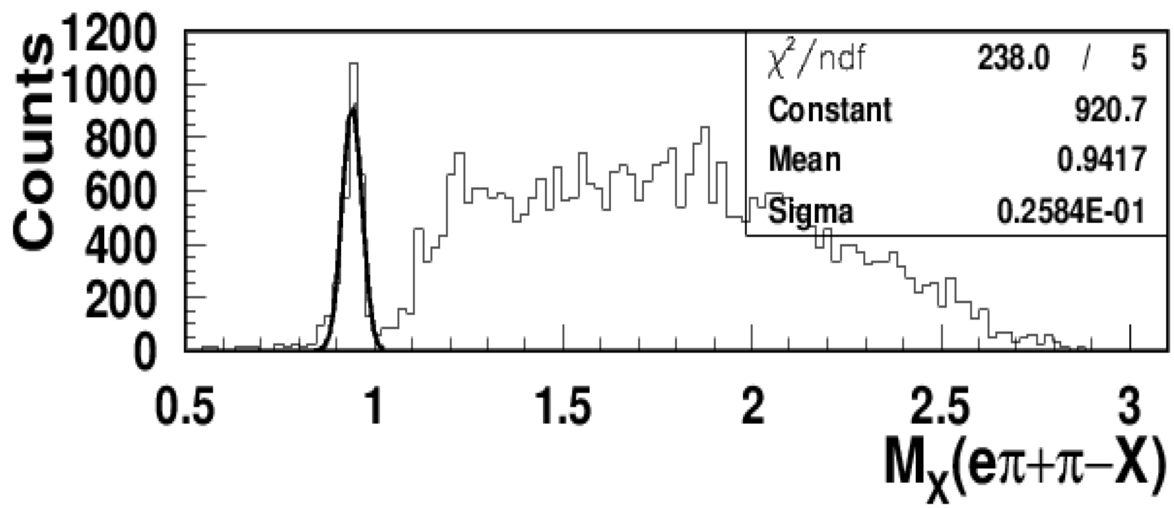
Support slides

Comparing MC and data (6715) v.6b2.0









Radiative DIS

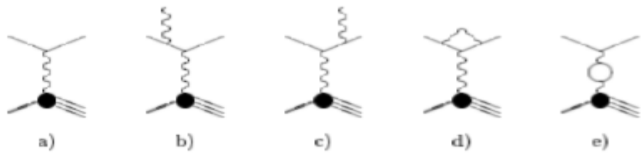


Figure 1: Feynman diagrams contributing to the Born and the radiative correction cross sections in lepton-nucleus scattering.

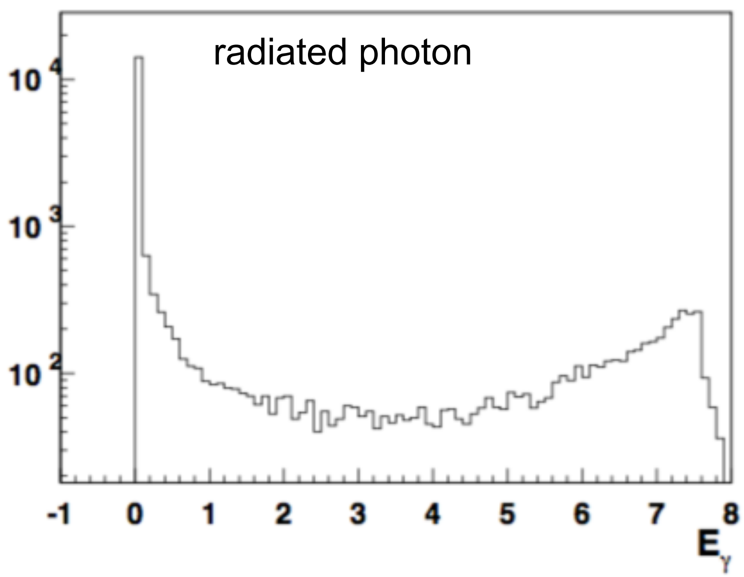
Akushevich et al. http://www.jlab.org/RC/radgen/

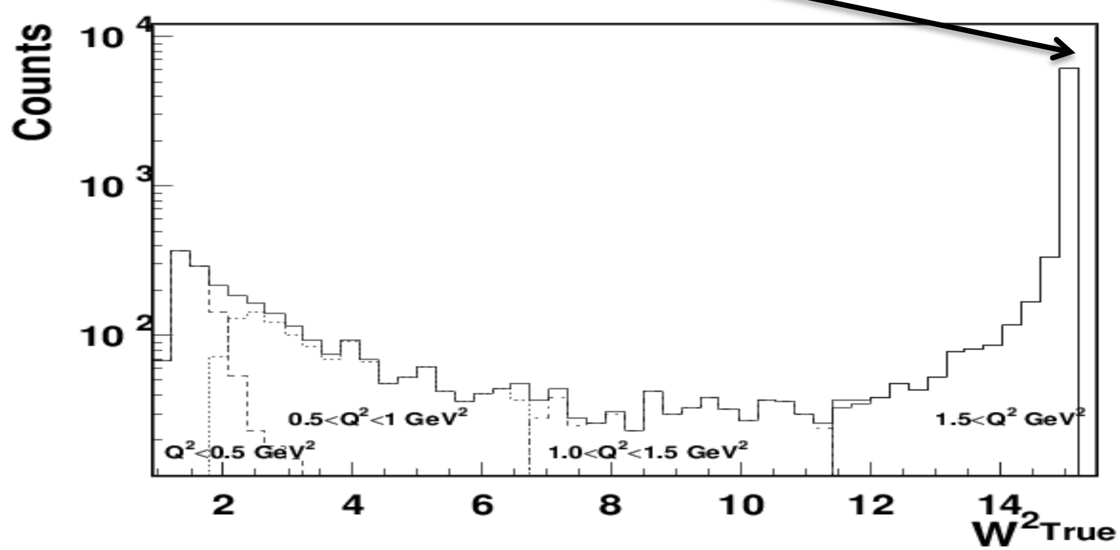
SIDIS version: JLAB-PHY-19-2938

For SIDIS may need "ρ" x-sections in the full W range, including exclusive part

generate a single kinematical point at E_b=10.6 GeV with e'=2.0 GeV, θ=0.3
→ **x,y,Q^2,W^2(0.12,0.8,1.9,15.1)**
Integrated over all **Eγ** **$\sigma_{Rad}/\sigma_{Born}$=1.24**

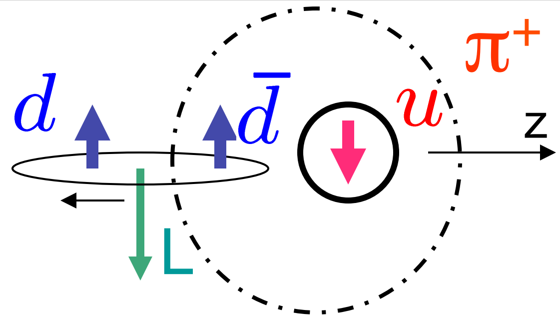
original Q^2,W^2(1.9,15.1)





SSA for pions from ρ (Collins effect,…)

Simple string fragmentation for pions (Artru model)



leading pion out of page

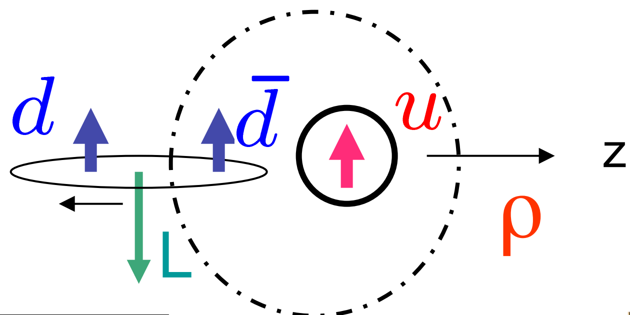
$$h_1 H_1^{\perp u \to \pi}$$

Leading ρ opposite to leading π(into page)

$$H_1^{\perp u \to \rho} \sim -\frac{1}{3} H_1^{\perp u \to \pi}$$

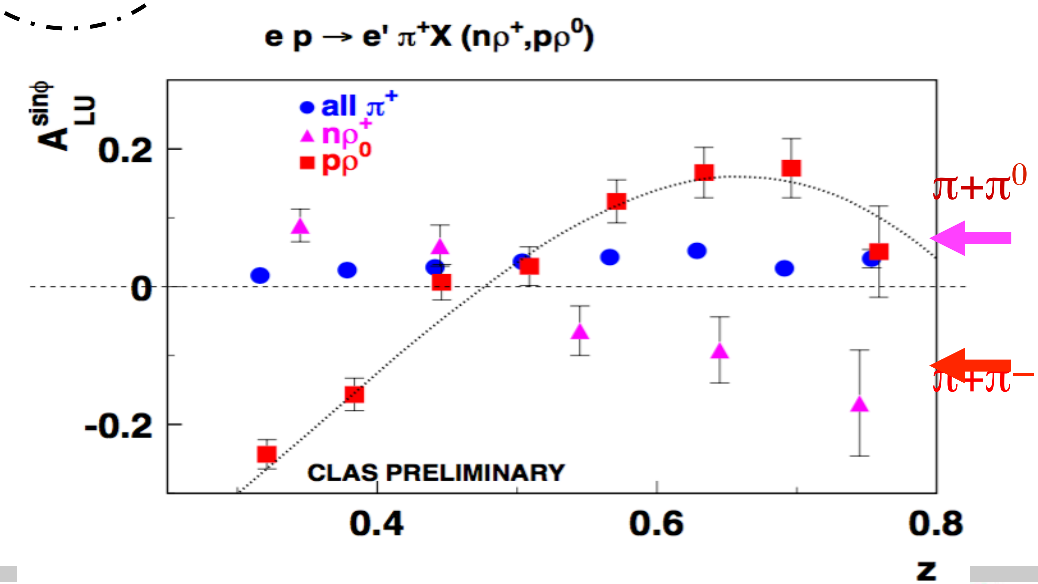
hep-ph/9606390

ρ production may produce an opposite sign A_{UT}

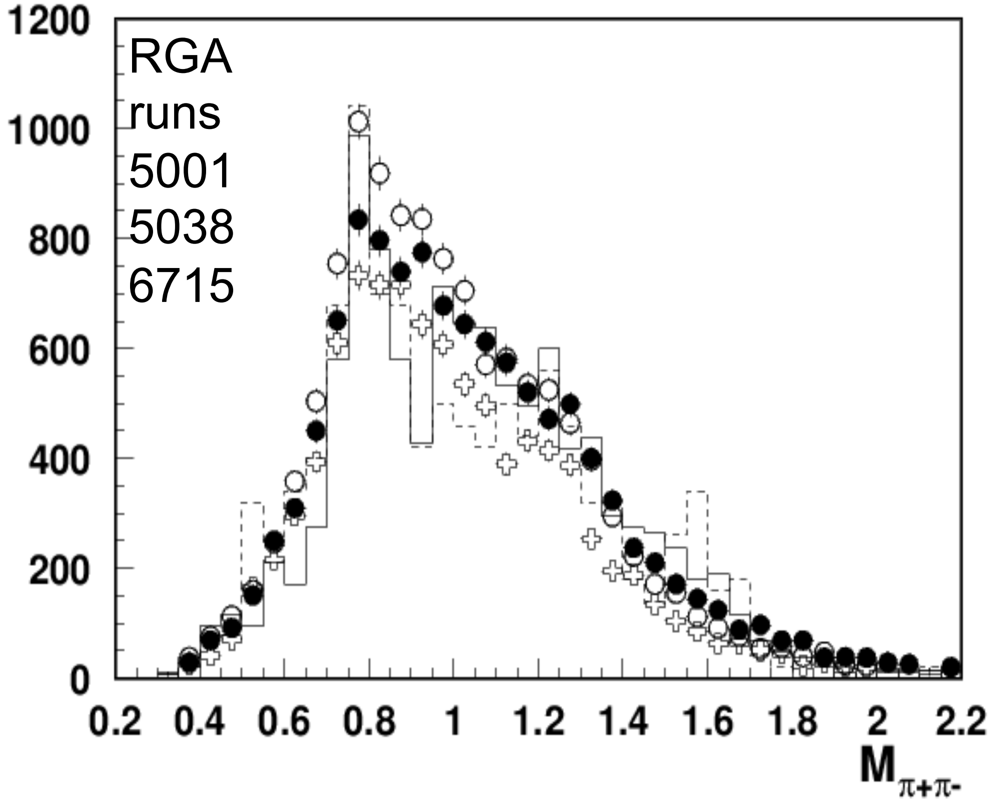


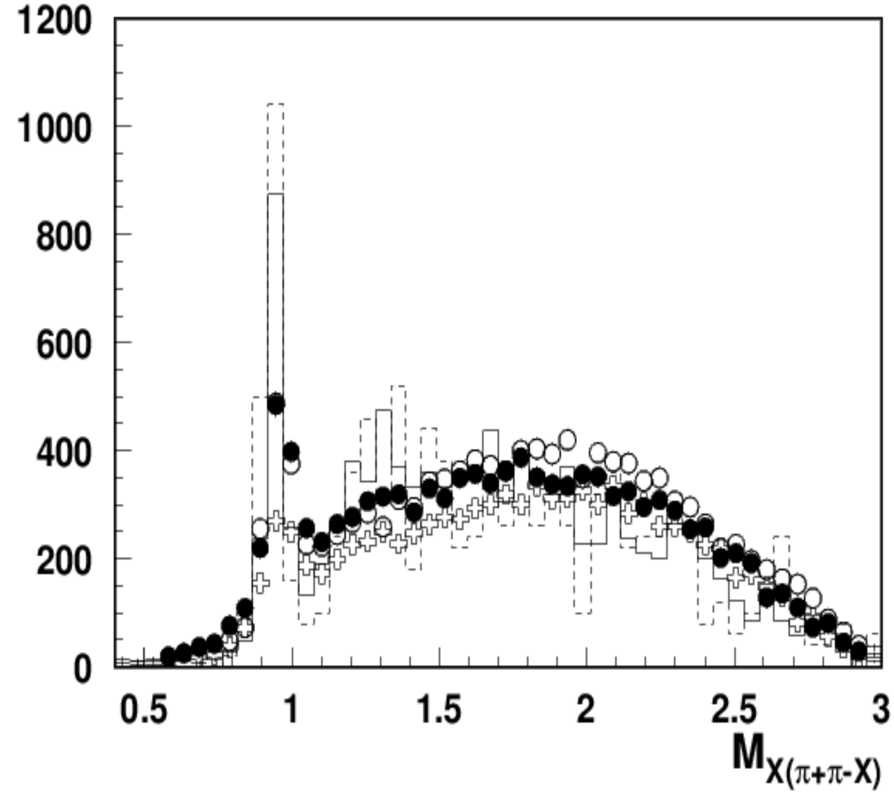
Fraction of ρ in eπX	% left from eπX asm
20%	~75%
40%	~50%

Pions from rho decays may require special treatment for understanding of certain observables



RGA-Invariant mass of pion pairs Mππ

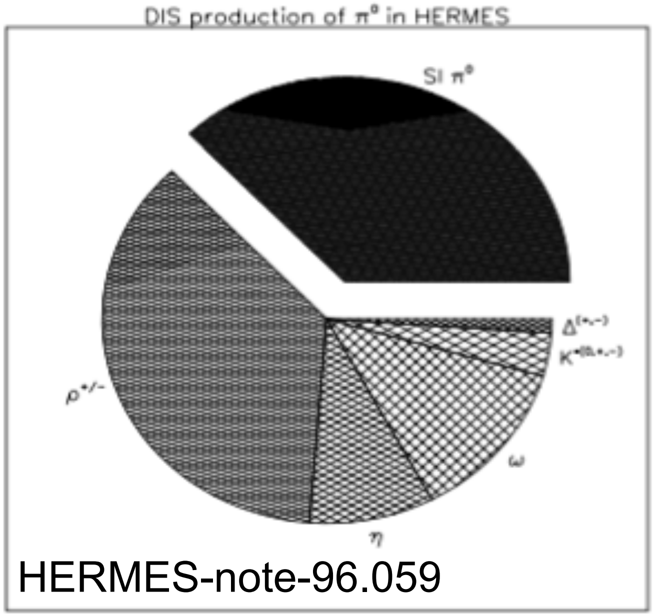




Curves 2 MC versions with 50 and 70% of spin-1
Circles 3 run sets RGA-Fall/Spring2019
5000(open), 5038 (full circles) 6715 (crosses)

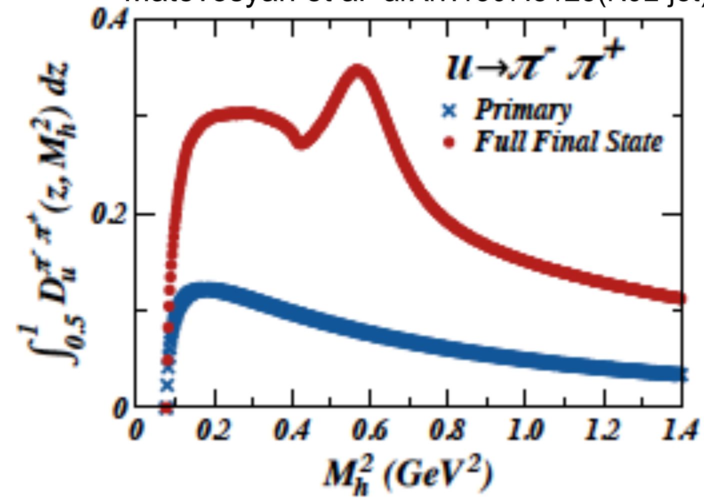
Multiplicities from data consistent with multiplicities coming from CLAS12 LUND MC

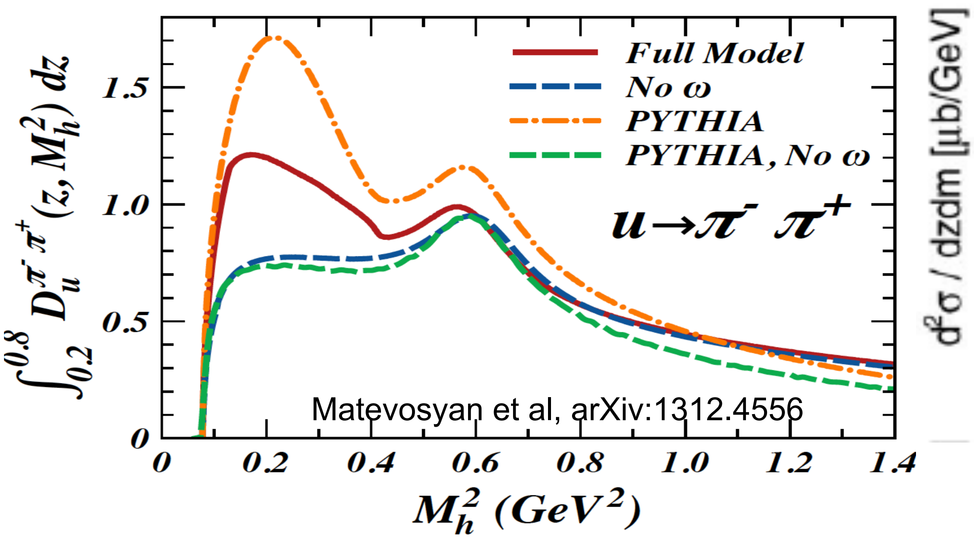
Dihadron production

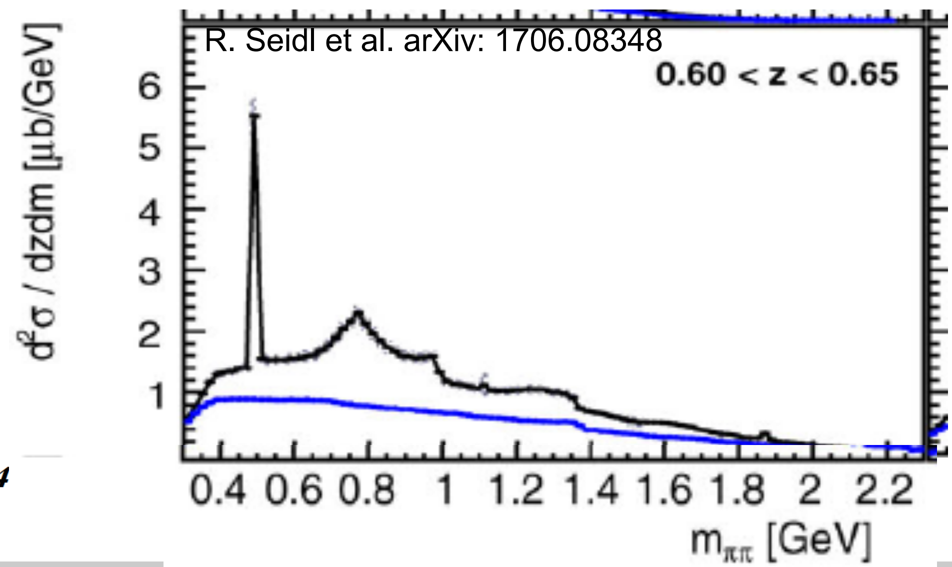


What is the origin o
dihadrons?
What is a single
hadron?

Matevosyan et al arXiv:1307.8125(NJL-jet)





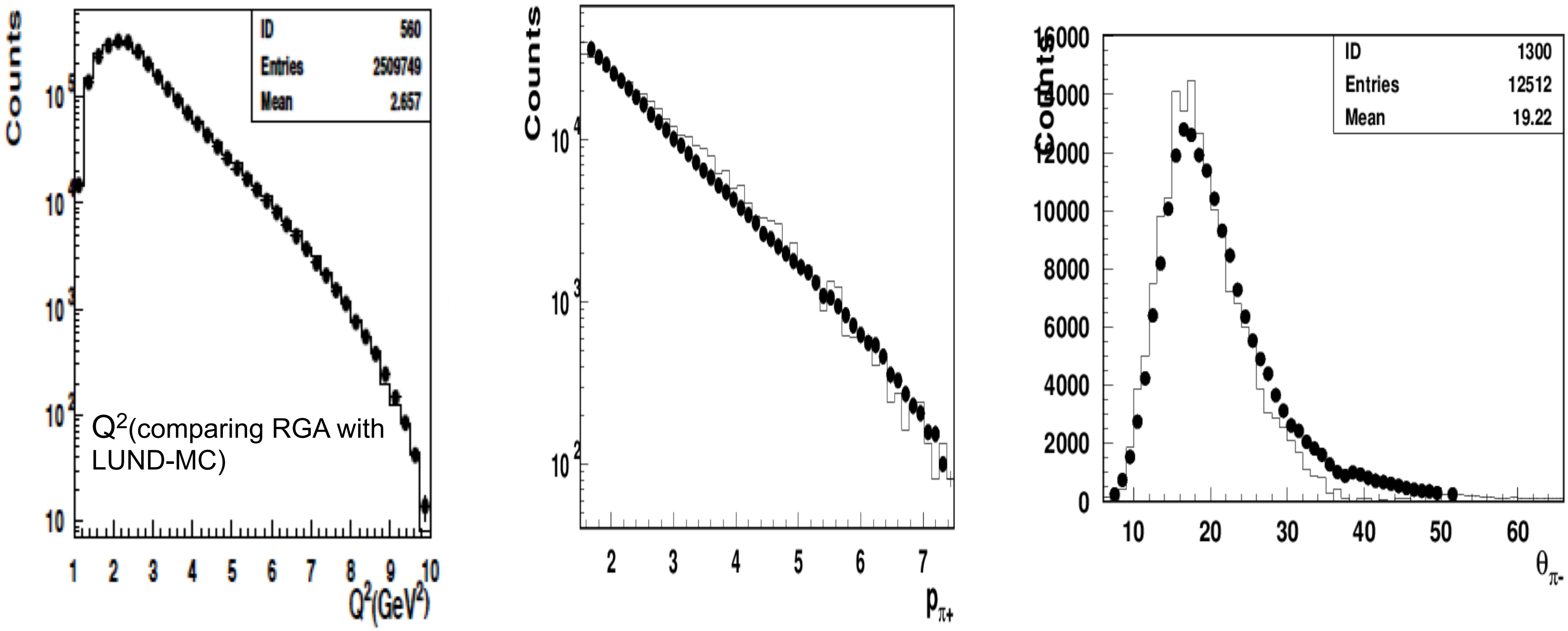


SIDIS ehX: CLAS12 data

ep→e'hX (Data/MC normalized to number of electrons)

(<1% of deuteron 2019 sample))

Full event generators (LUND-MC)

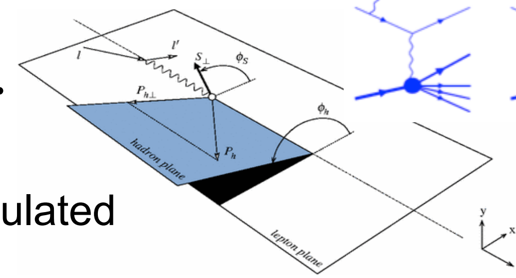


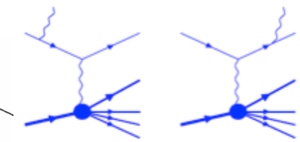
- Pion counts for normalized e'X events (uncorrected for acceptance) are consistent with clas12 LUND MC

Additional complications: Experiment can't measure just 1 SF

I. Akushevich et al

$$\sigma = \sigma_{UU} + \sigma_{UU}^{\cos\phi} cos\phi + S_T \sigma_{UT}^{\sin\phi_S} \sin\phi_S + \ldots$$





Due to radiative corrections, ϕ-dependence of x-section will get multiplicative R_M and additive R_A corrections, which could be calculated from the full Born (σ_0) cross section for the process of interest

$$\sigma_{Rad}^{ehX}(x,y,z,P_T,\phi,\phi_S) \rightarrow \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

Due to radiative corrections, ϕ-dependence of x-section will get more contributions
- Some moments will modify
- New moments may appear, which were suppressed before in the x-section

Simplest rad. correction

$$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$$

Correction to normalization

$$\sigma_0(1+\alpha\cos\phi_h)R_0(1+r\cos\phi_h) \rightarrow \sigma_0 R_0(1+\alpha r/2)$$

Correction to SSA

$$\sigma_0(1+sS_T\sin\phi_S)R_0(1+r\cos\phi_h) \rightarrow \sigma_0 R_0(1+sr/2S_T\sin(\phi_h-\phi_S)+sr/2S_T\sin(\phi_h+\phi_S))$$

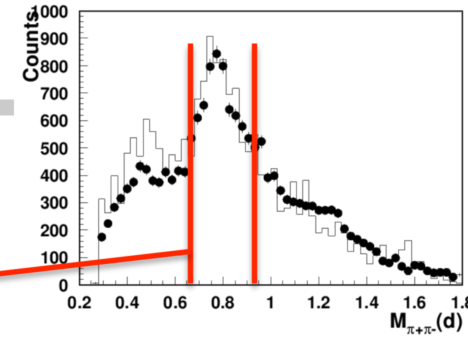
Correction to DSA

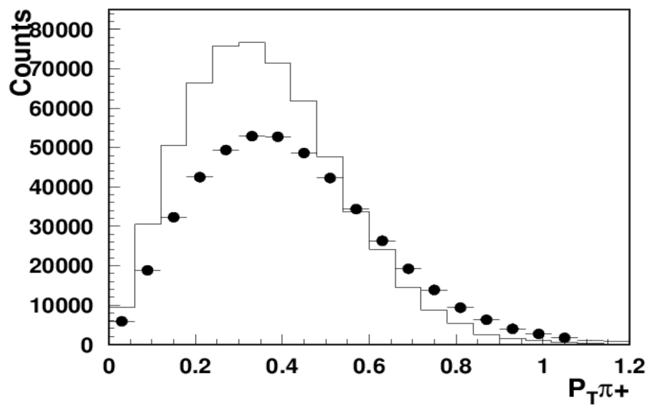
$$\sigma_0(1+g\lambda\Lambda+f\lambda\Lambda\cos\phi_h)R_0(1+r\cos\phi_h) \rightarrow \sigma_0 R_0(1+(g+fr/2)\lambda\Lambda)$$

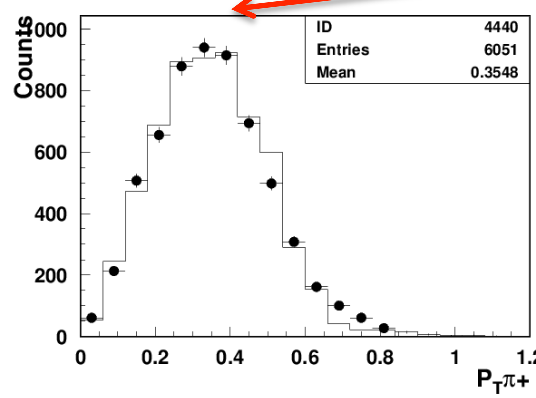
Simultaneous extraction of all moments is important also because of correlations!

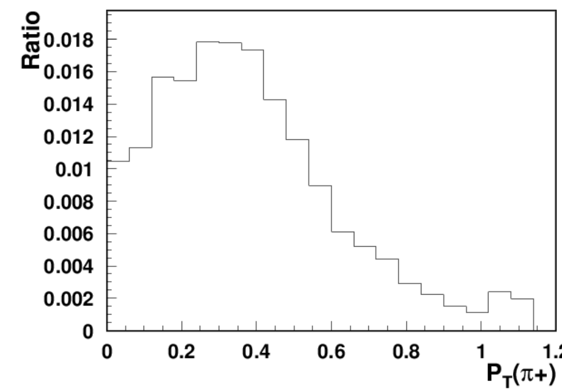
P_T distributions in the rho region

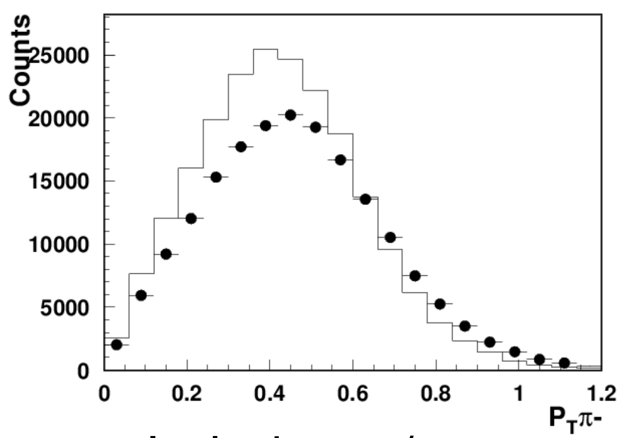
P_T- distributions of pions in the rho region look like Gaussian

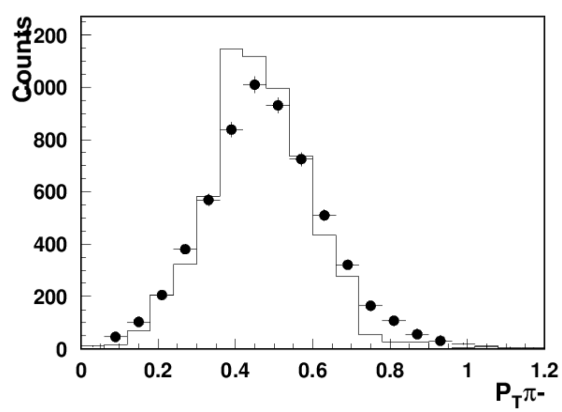


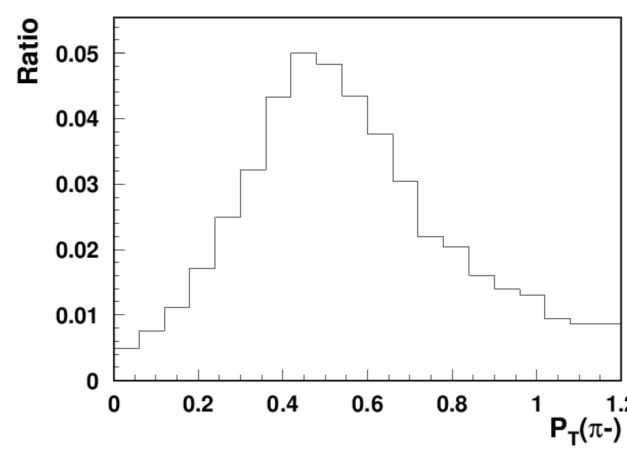










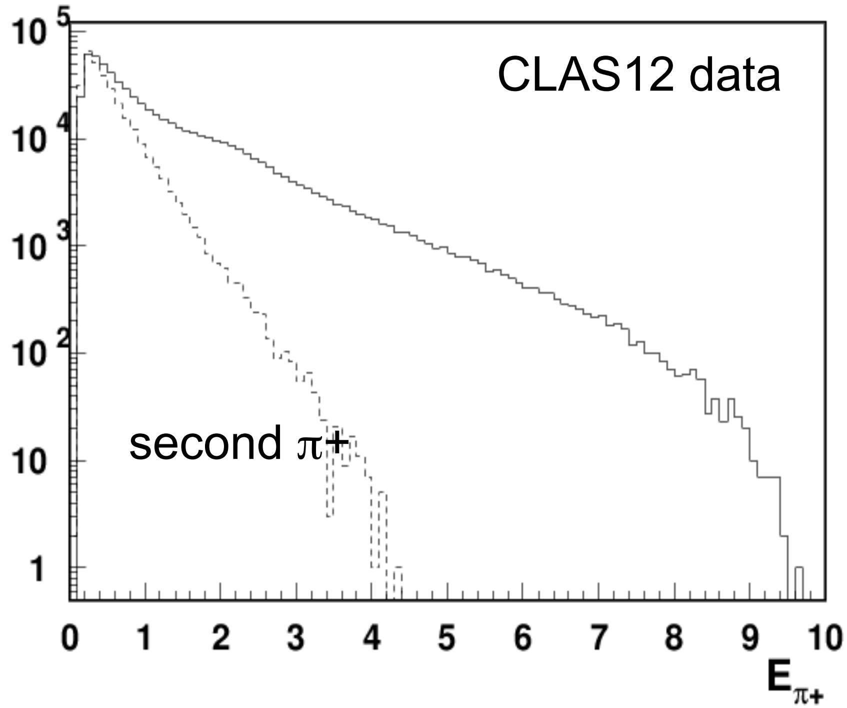


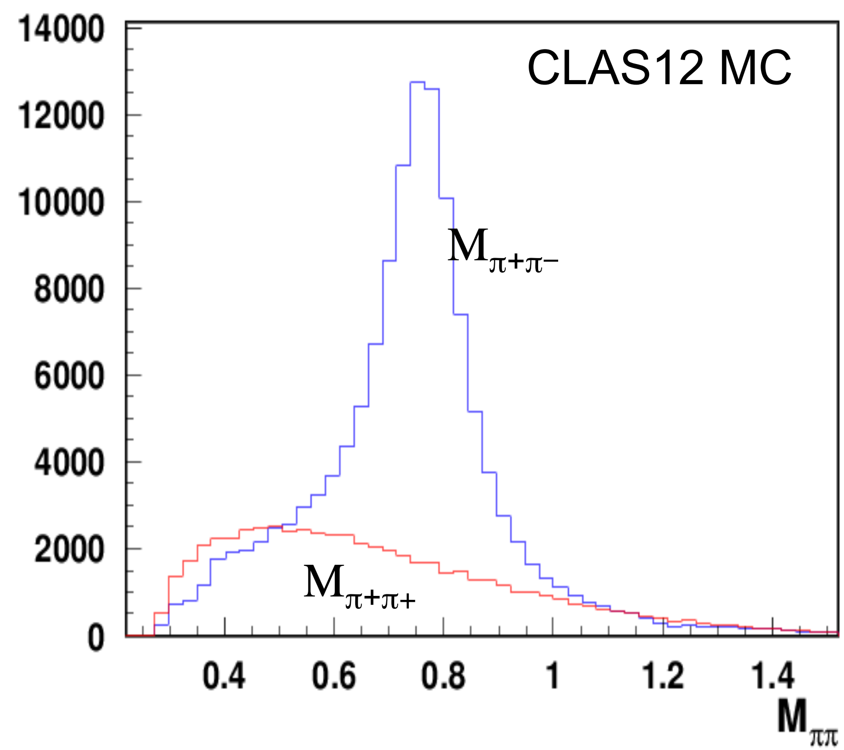
Inclusive $\pi+/\pi-$

$\pi+/\pi-$from ρ-region

Invariant mass distributions for 2π+

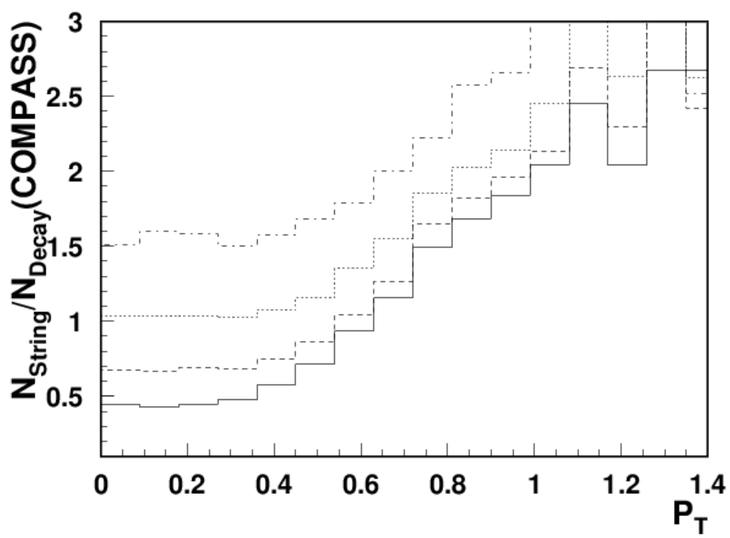
All events with parent of π+ is ρ0

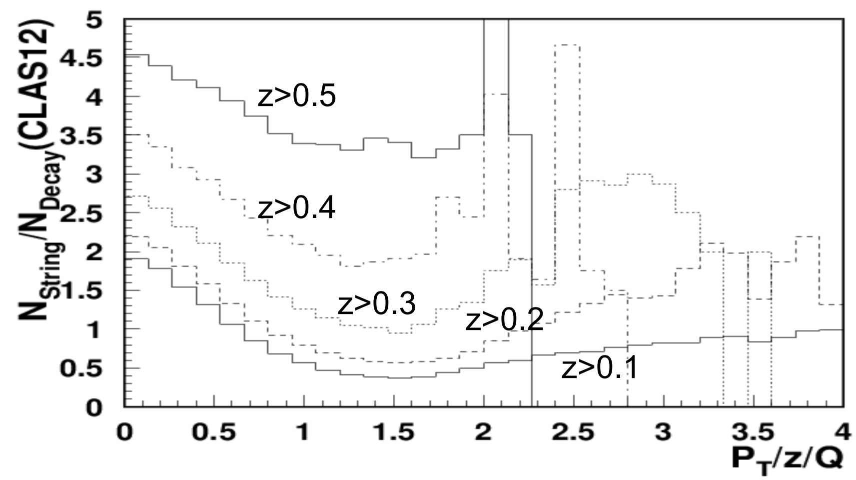




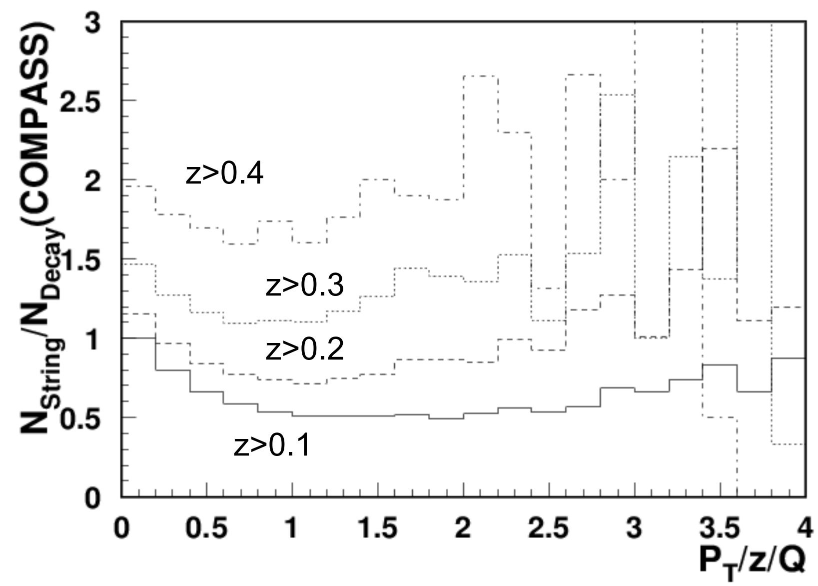
The π+/π− pairs out of ρ-region may still be generated by ρs

P_T of pions from rho decays: LUND string fragmentation



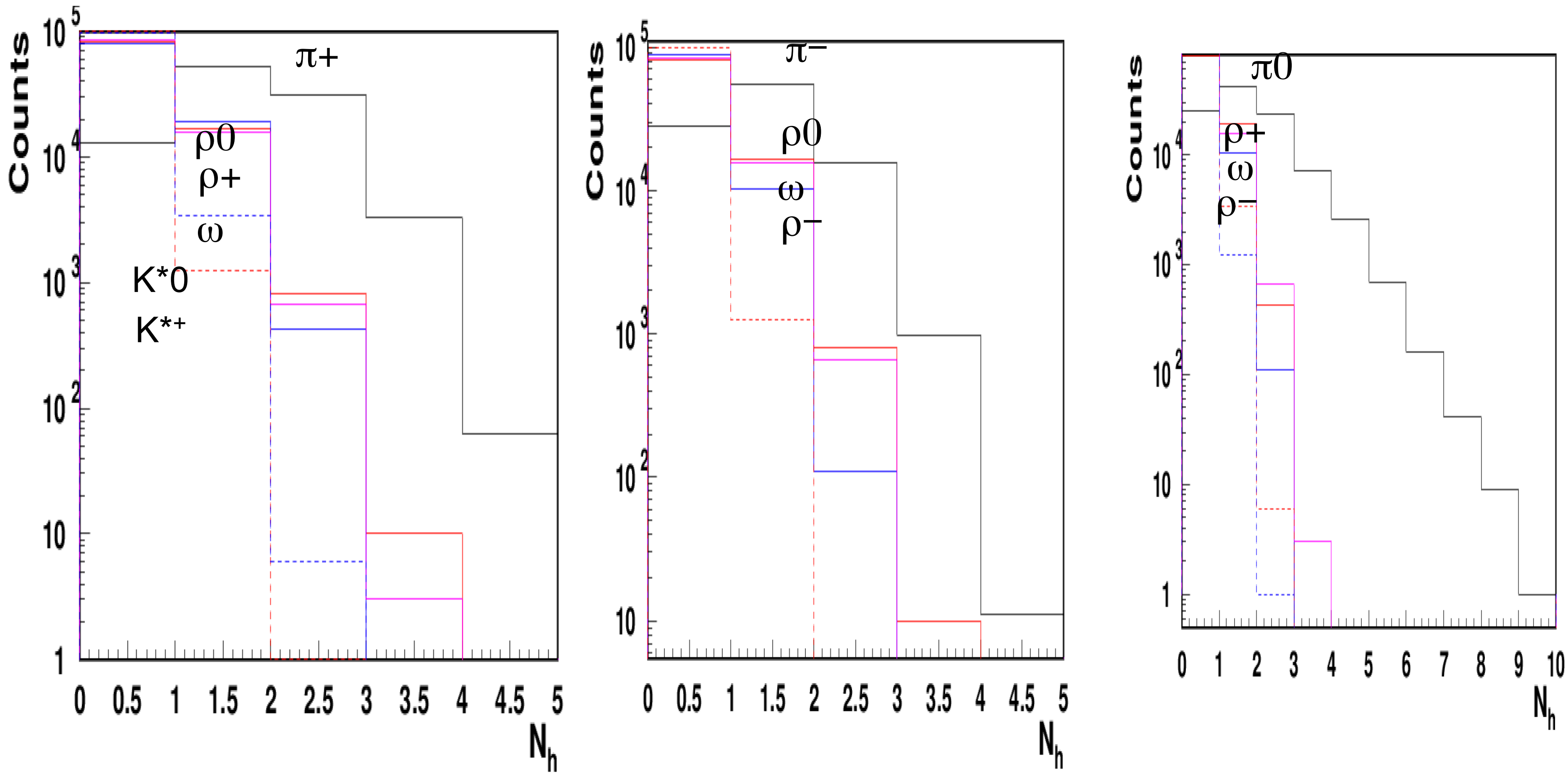


Fraction of direct π+ increases with P_T



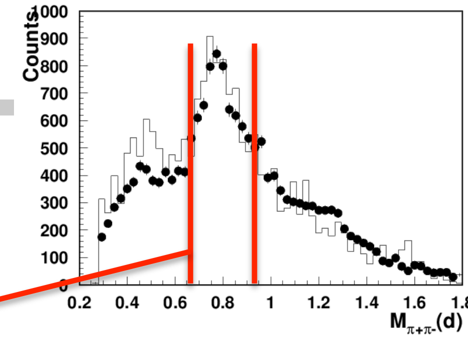
Fraction of direct π+ decreases with $P_T/z/Q$ at small z

Background events

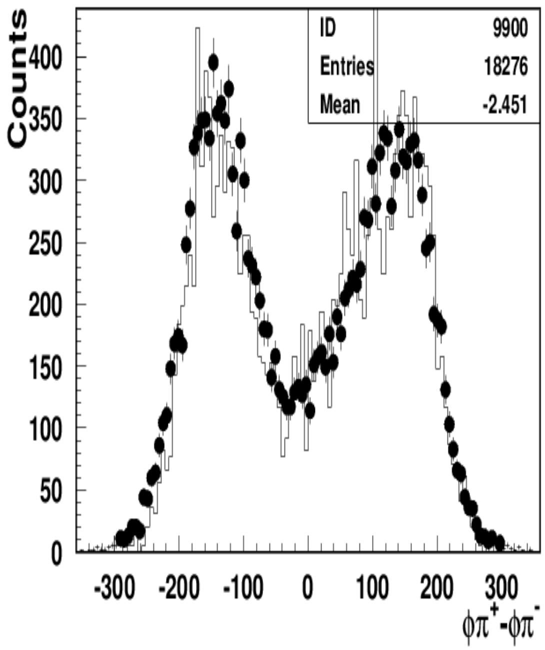


There are ~10% with 2 rho+/rho0/rho- (dashed show K*0 and K*+)

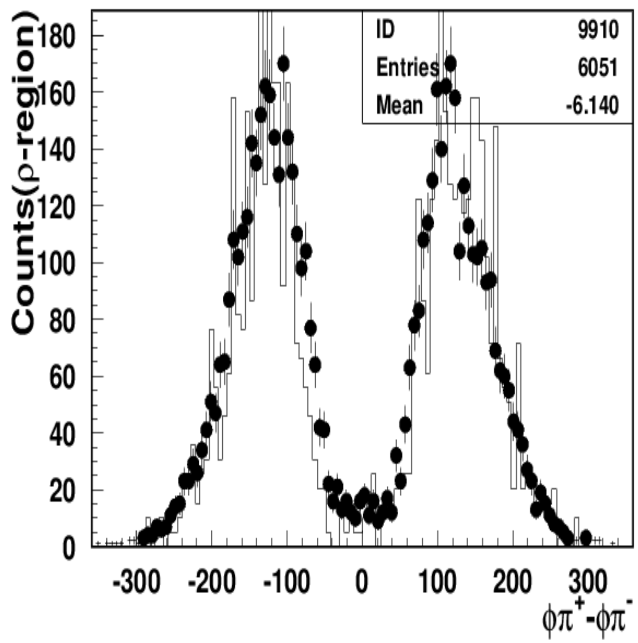
ϕ−distributions of hadrons in CM system



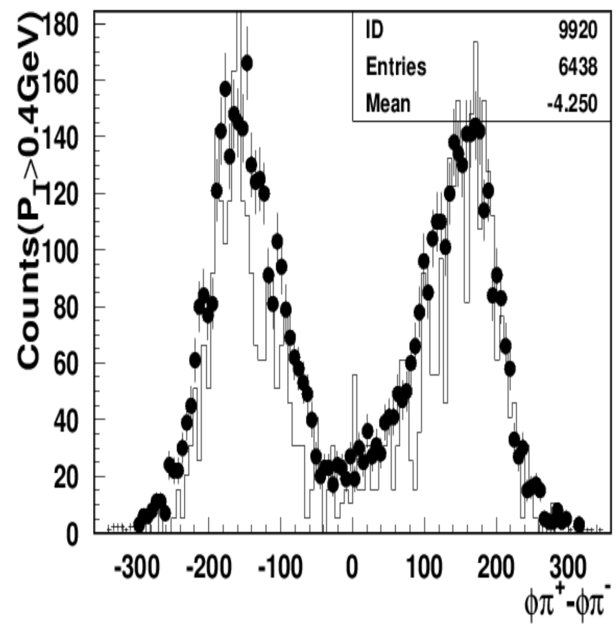
Most energetic π+ and π−appear back-to-back



Inclusive π+π−



π+π−from ρ-region



π+π−from P_T>0.4 GeV
"high P_T"-region

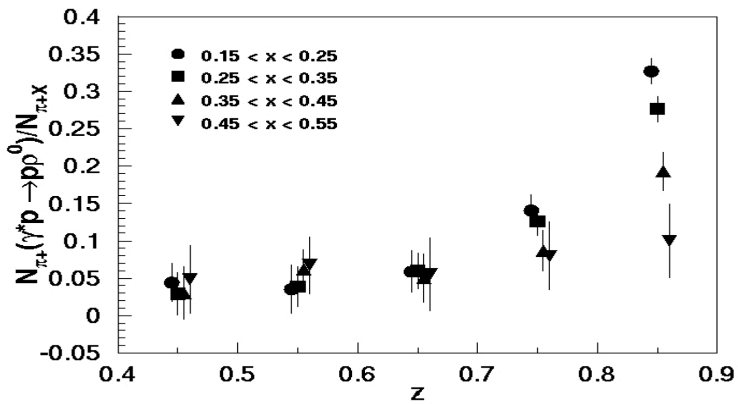
```
    cl_parj11=0.7          ! default PARJ(11) fraction of spin 1 light mesons (rho)
     cl_parj12=0.4         ! default PARJ(12) fraction of spin 1 strange mesons (affects K*s)
     cl_parj14=0.0         ! default PARJ(14) : (D = 0.) is the probability that a spin = 0 meson is produced
with an orbital angular momentum 1, for a total spin = 1.
     cl_parj15=0.0         ! defaultPARJ(15) : (D = 0.) is the probability that a spin = 1 meson is produced with
an orbital angular momentum 1, for a total spin = 0.
     cl_parj16=0.0         ! defaultPARJ(16) : (D = 0.) is the probability that a spin = 1 meson is produced with
an orbital angular momentum 1, for a total spin = 1.
     cl_parj17=0.0         ! defaultPARJ(17) : (D = 0.) is the probability that a spin = 1 meson is produced with
an orbital angular momentum 1, for a total spin = 2.
c
     cl_parj21=0.4         ! default PARJ(21) for the width of P_T distribution  default in JETSET 0.36

    cl_parj41=0.30         ! default parameter a in (1-z)^a large z-suppression in FF
    cl_parj42=0.58         ! default parameter b in exp(-bm_\perp^2/z) in FF
```

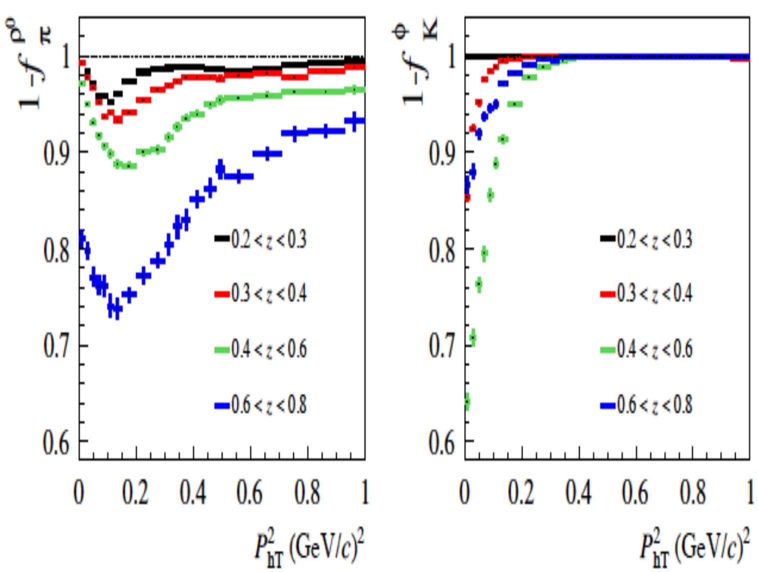
Parameter affecting single pion P_T(parj21), z(parj41)

Dihadrons and Vector meson contributions

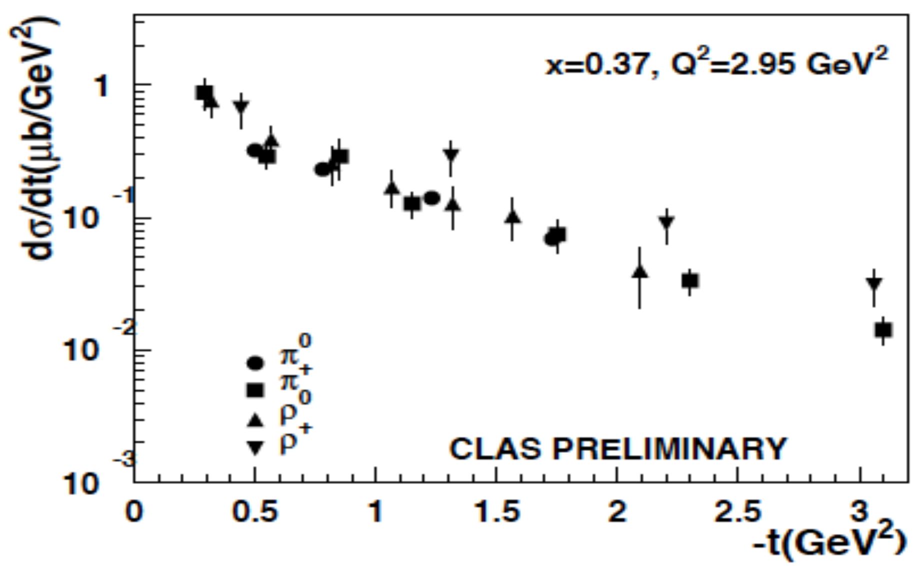
1) Should we worry about pions/kaons coming from vector meson decays?
2) What about ρ+ and ρ-
3) What do we know about relevant observables for pions specifically coming from vector meson decays
4) What about SIDIS rhos (can we measure?)
5) What is radiative correction due to rho?
6) Vector meson as resonance in dihadron production?



COMPASS:1709.07374



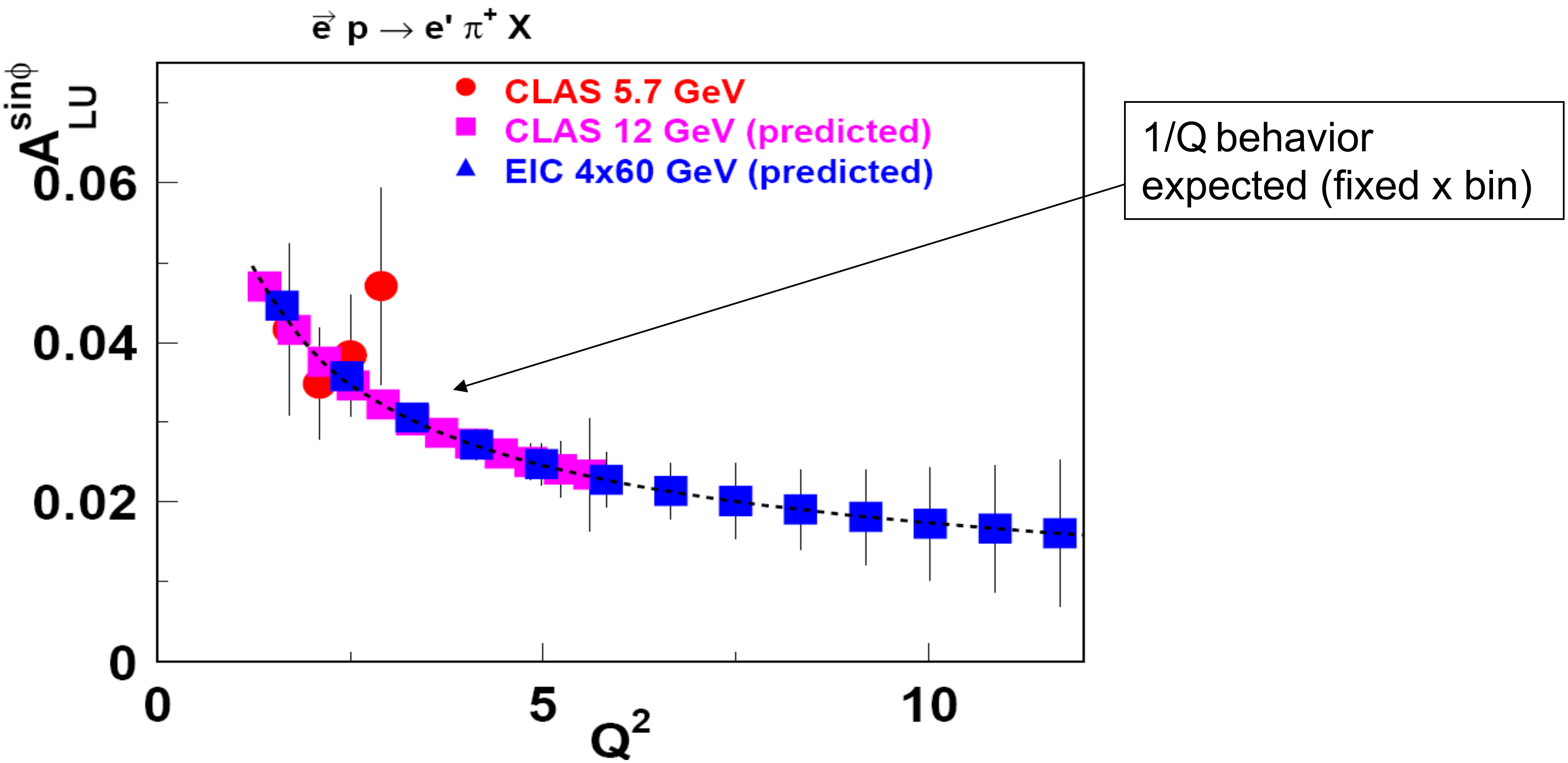
Hard exclusive meson production from clas6



Q^2-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)}$ ~$F_{LU(UL)}$~ 1/Q (Twist-3)

$A_{LU} \propto g^{\perp}(x) D_1(z)$

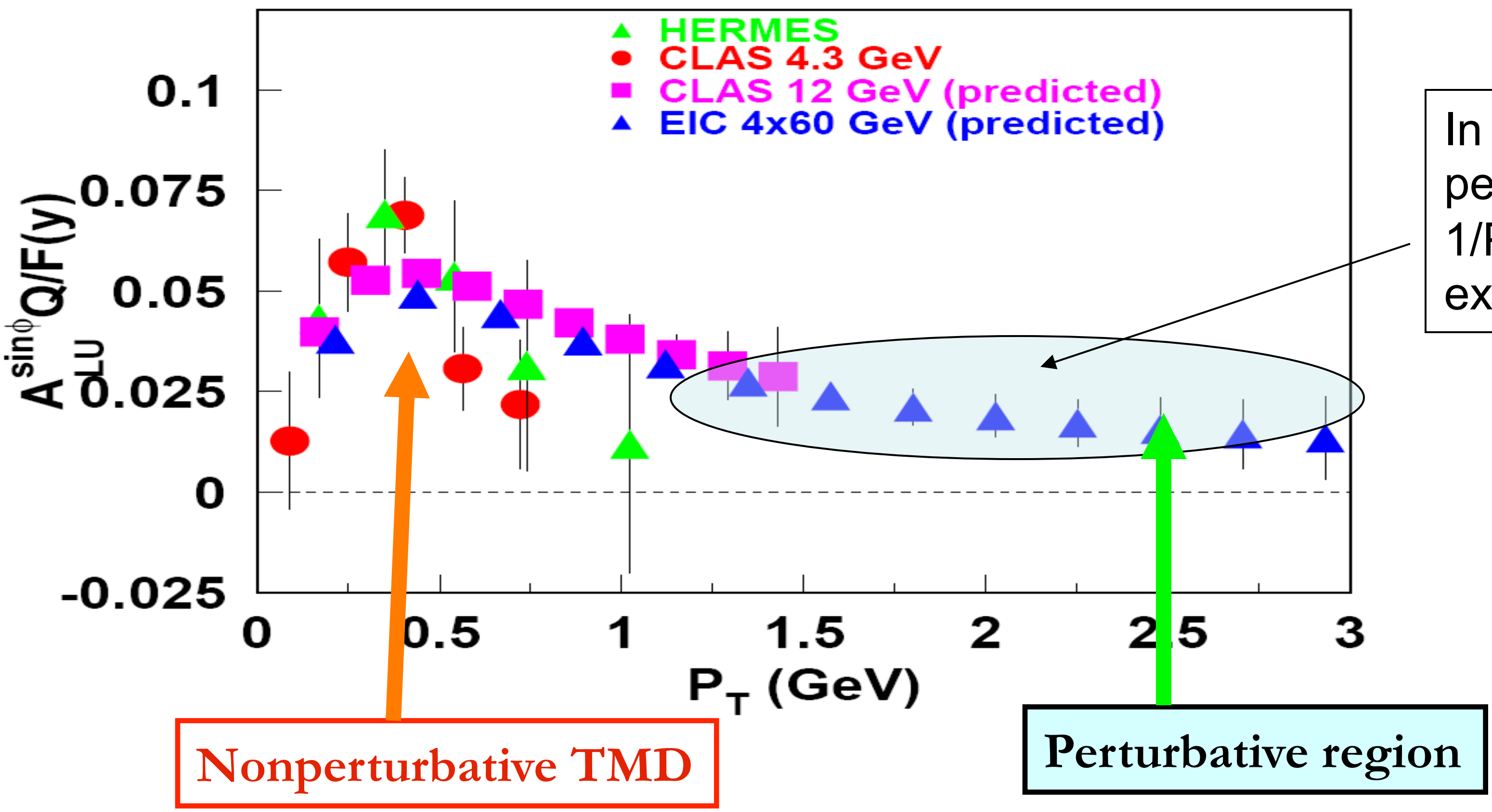


Study for Q^2 dependence of beam SSA allows to check the higher twist nature and access quark-gluon correlations.

P_T-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

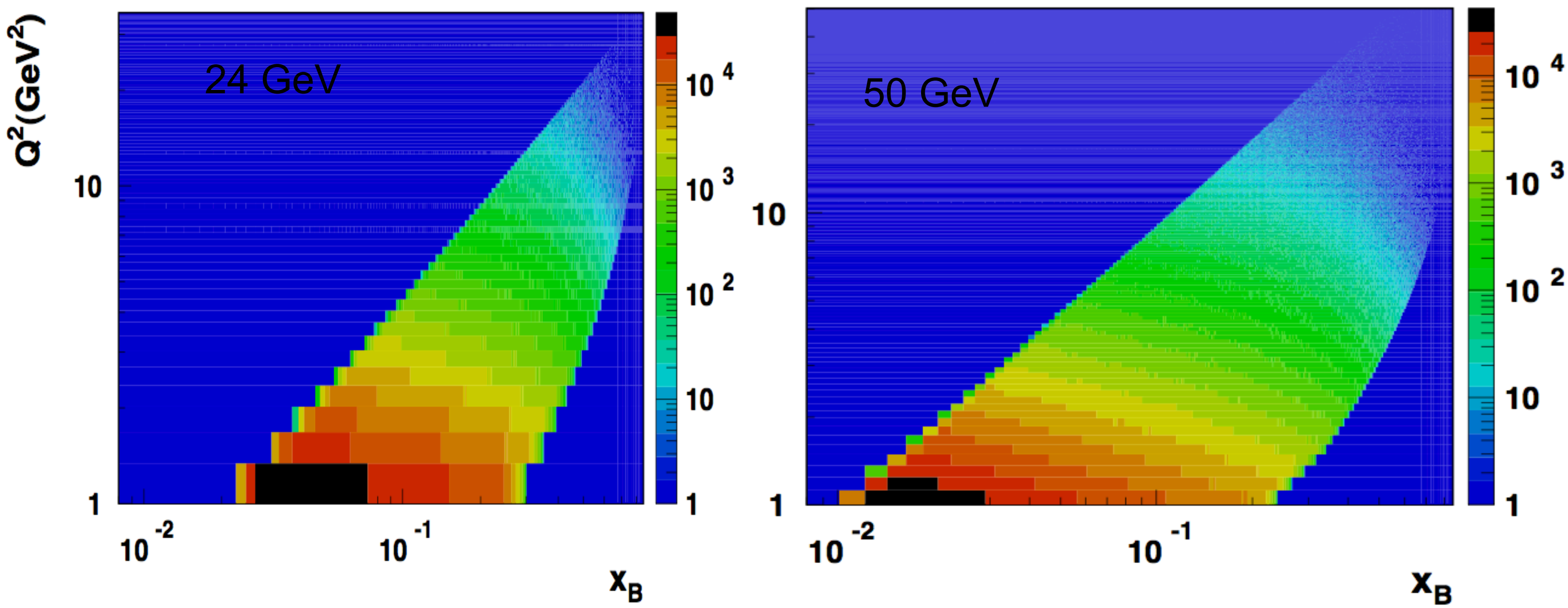
$$A_{LU} \propto g^{\perp}(x) D_1(z)$$



In the perturbative limit $1/P_T$ behavior expected

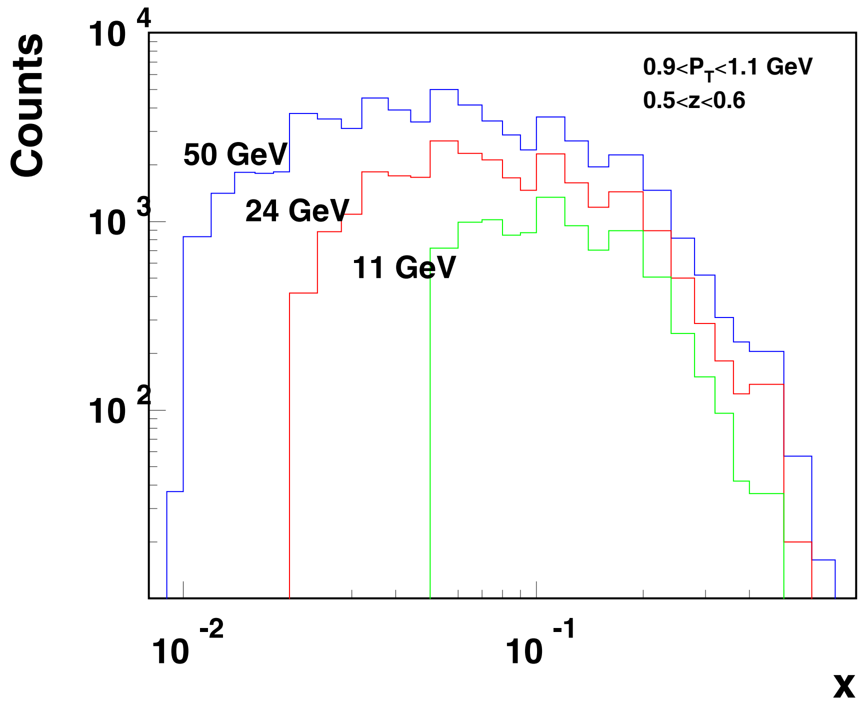
Study for SSA transition from non-perturbative to perturbative regime.
EIC will significantly increase the P_T range.

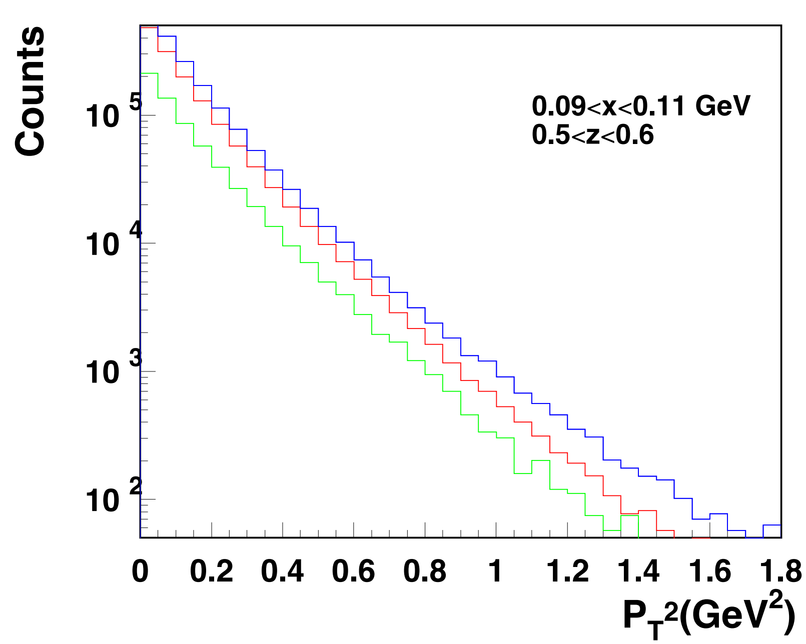
$ep \rightarrow e' \pi^+ X$ Kinematic coverage



For a given lumi (30min of runtime with $L=10^{35} cm^{-2}s^{-1}$) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in x and Q^2

$ep \rightarrow e' \pi^+ X$ Kinematic coverage



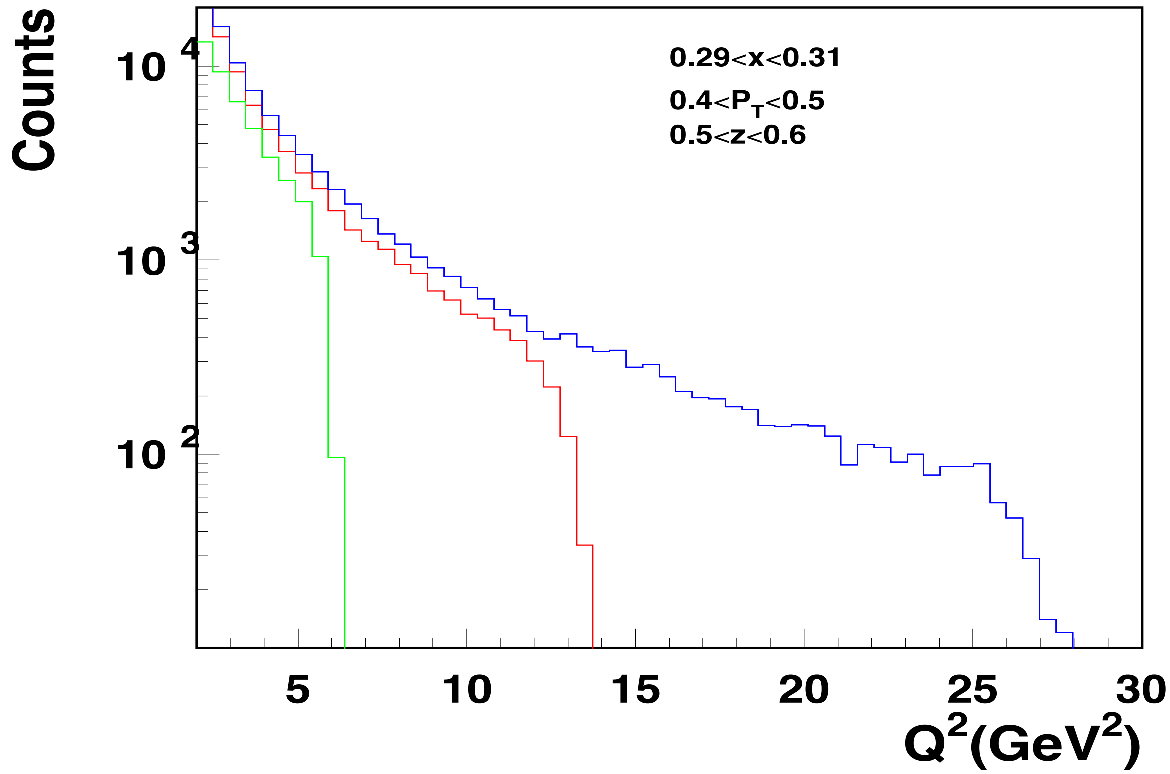


Wider x range allow studies of transverse distributions of sea quarks and gluons

Wider P_T range will be important in extraction of k_T-dependences of PDFs

For a given lumi (30min of runtime with 10^{35}) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in x and P_T to allow studies of correlations between longitudinal and transverse degrees of freedom

ep→e' π^+X Kinematic coverage



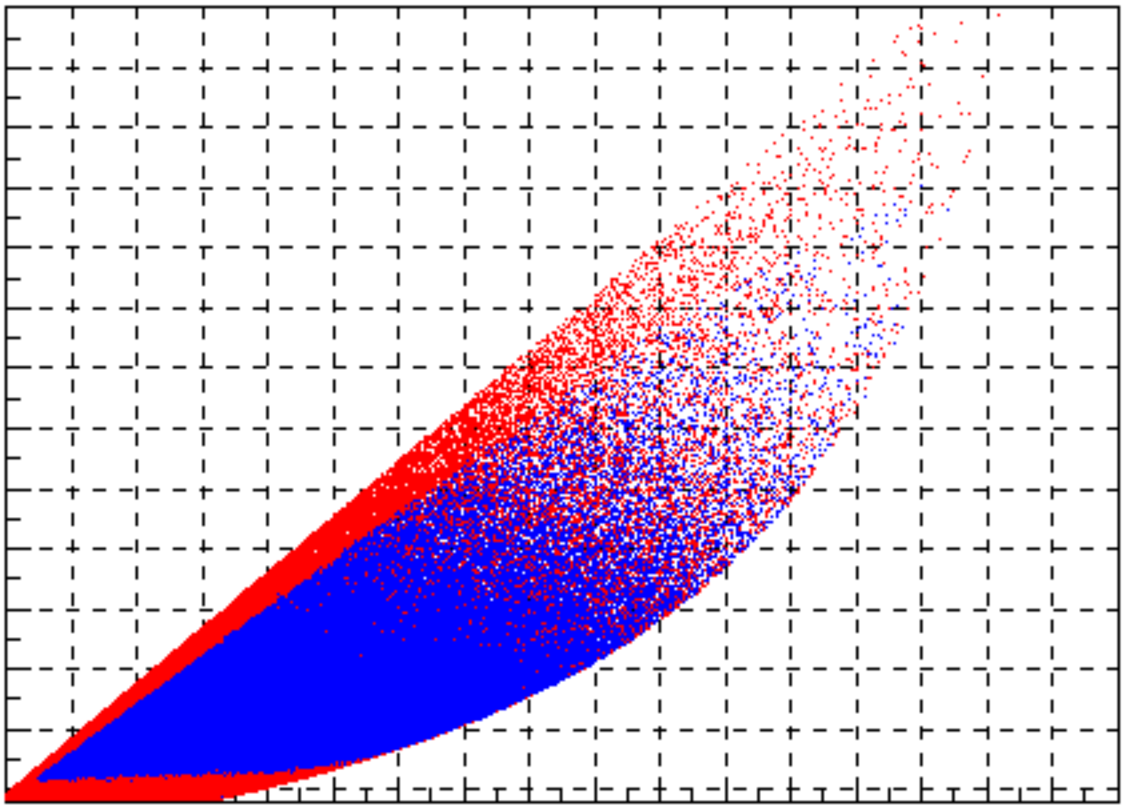
For a given lumi (30min of runtime) and given bin in hadron z and P_T, higher energy provides higher counts and wider coverage in Q^2, allowing studies of Q^2 evolution of 3D partonic distributions in a wide Q^2 range.

Choosing binning (x vs Q^2)

SFs defined for practically a full grid

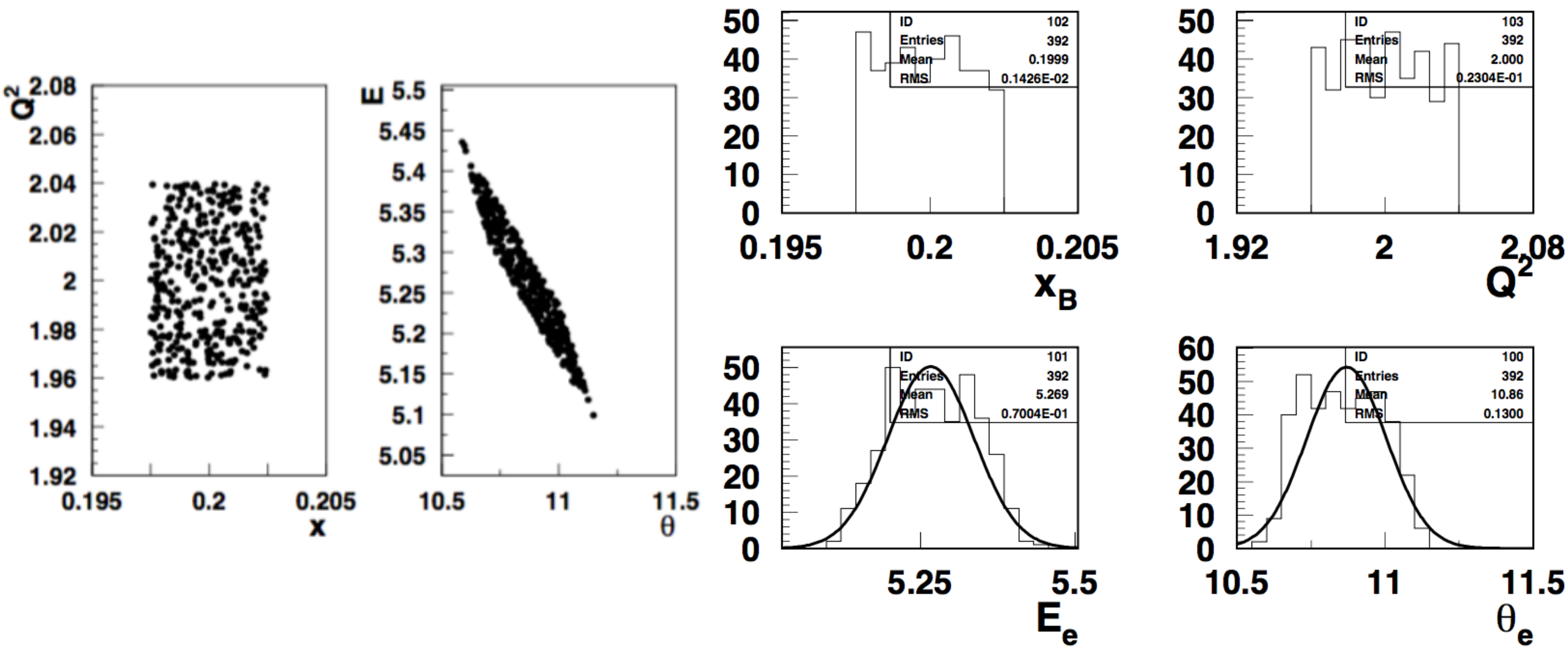
Fixed beam energy limits the coverage

Detector acceptance limits further the coverage



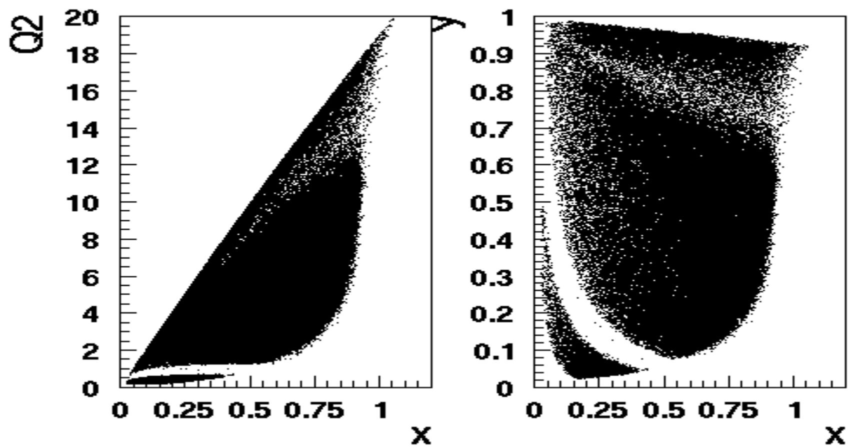
Need theory guidance to put effort on small x,Q^2 region

Binning in DIS



For small bins in x-Q^2 or x-y, spread in other kinematical variables is becoming small (x2-3 resolution in θ and E'), reducing the role of bin-centering corrections and variations of structure functions in the bin

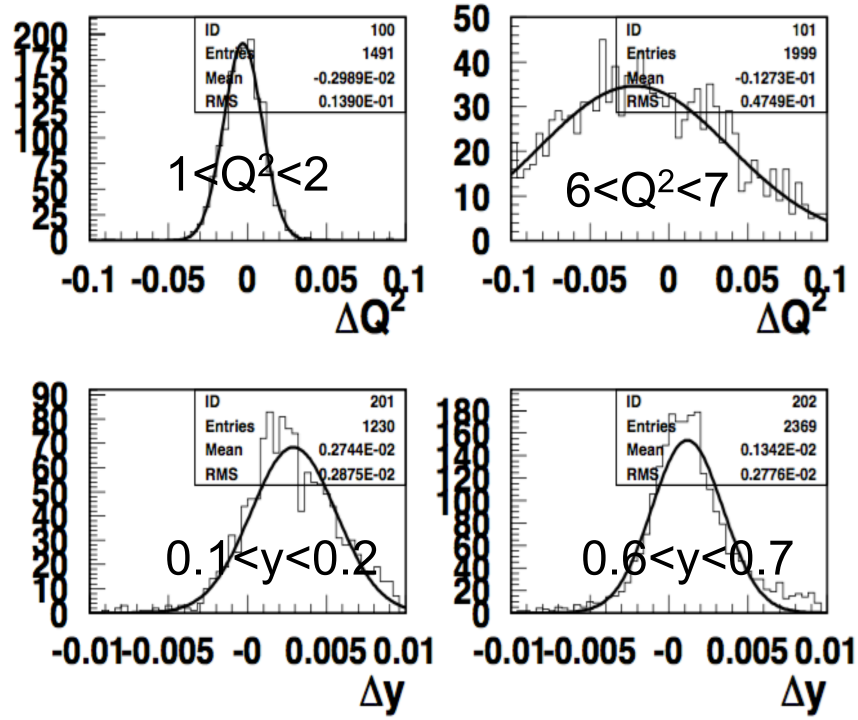
Binning in DIS



With small bins x,y-binning will be much better for extraction of SFs

1) scale variable
2) fixed range
3) smaller change in resolution

x=0.4



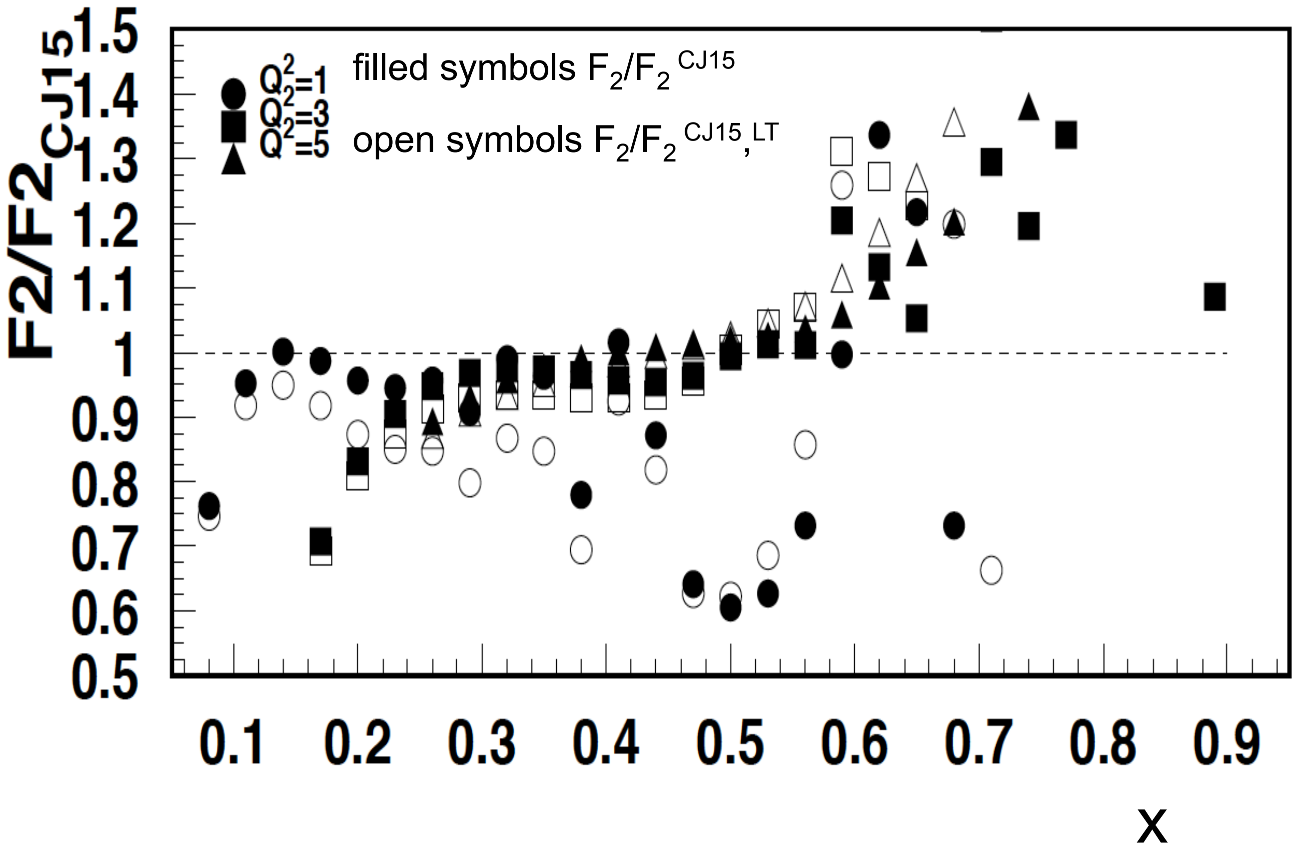
More traditional binning in x Q^2 used so far

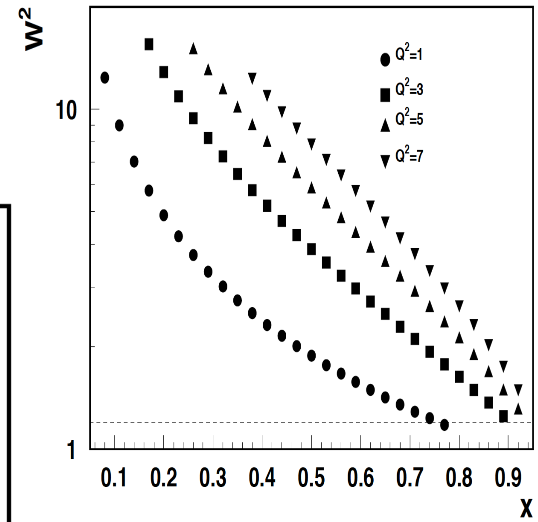

```
{
    "model": "Nobuo_F2,FL"
    "reference": "N. Sato et al"
    "multiplicity":"Counts"
    "Beam Energy": 10.600
    "lepton-polarization": "0"
    "nucleon-polarization": "0"
    "particle": "pi+"
    "variables":["Counts","Err.Counts","acc","xav","yav","q2av"
    "axis":[
        {"name":"a","bins": 99,"min": 0.05, "max": 0.95, "scale":"lin","description":"x_bj"}
        {"name":"b","bins": 99,"min": 0.95, "max": 13.1, "scale":"lin","description":"Q^2"}
  ],
    "parameters":[
  ]
}
```


0	0	0.26510E+01	0.65582E-01	0.2844	0.0567	0.9068	1.0230
0	1	0.45973E+00	0.26153E-01	0.1292	0.0583	0.9387	1.0889
1	0	0.50249E+01	0.93813E-01	0.4135	0.0633	0.8204	1.0316
1	1	0.74271E+01	0.10466E+00	0.4572	0.0640	0.8863	1.1270
1	2	0.16775E+01	0.45997E-01	0.2508	0.0664	0.9288	1.2271
2	0	0.42042E+01	0.90587E-01	0.3478	0.0726	0.7160	1.0321
2	1	0.68917E+01	0.10499E+00	0.4300	0.0725	0.7861	1.1326
2	2	0.67994E+01	0.93186E-01	0.5257	0.0726	0.8699	1.2546
2	3	0.32602E+01	0.59573E-01	0.3875	0.0745	0.9191	1.3624
2	4	0.10215E+00	0.99691E-02	0.0751	0.0768	0.9474	1.4476
3	0	0.34061E+01	0.85340E-01	0.2959	0.0818	0.6358	1.0339
3	1	0.56184E+01	0.99012E-01	0.3585	0.0817	0.6982	1.1334
3	2	0.54527E+01	0.86880E-01	0.4473	0.0817	0.7737	1.2556
3	3	0.55007E+01	0.78669E-01	0.5458	0.0816	0.8494	1.3780
3	4	0.42467E+01	0.63689E-01	0.5134	0.0825	0.9090	1.4907
3	5	0.67098E+00	0.23812E-01	0.2186	0.0851	0.9380	1.5869

Comparing different DIS models

$$F_2(x,Q^2) = F_2^{\rm LT}(x,Q^2)\left(1+\frac{C_{\rm HT}(x)}{Q^2}\right)$$

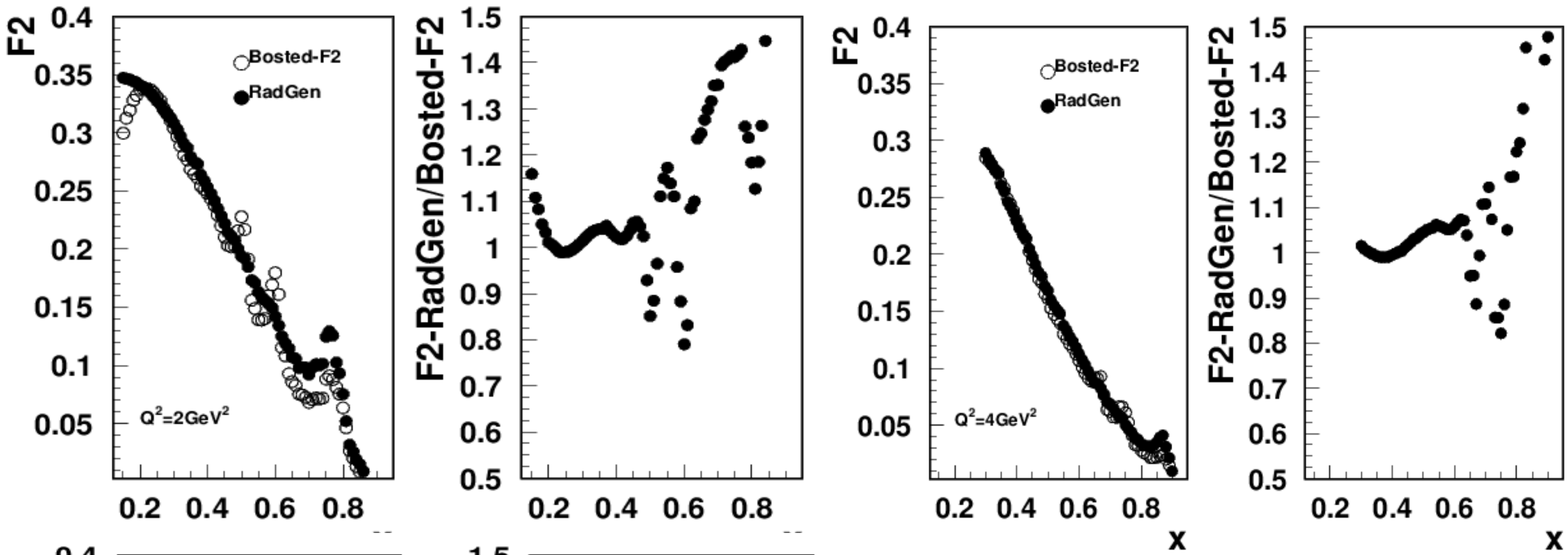


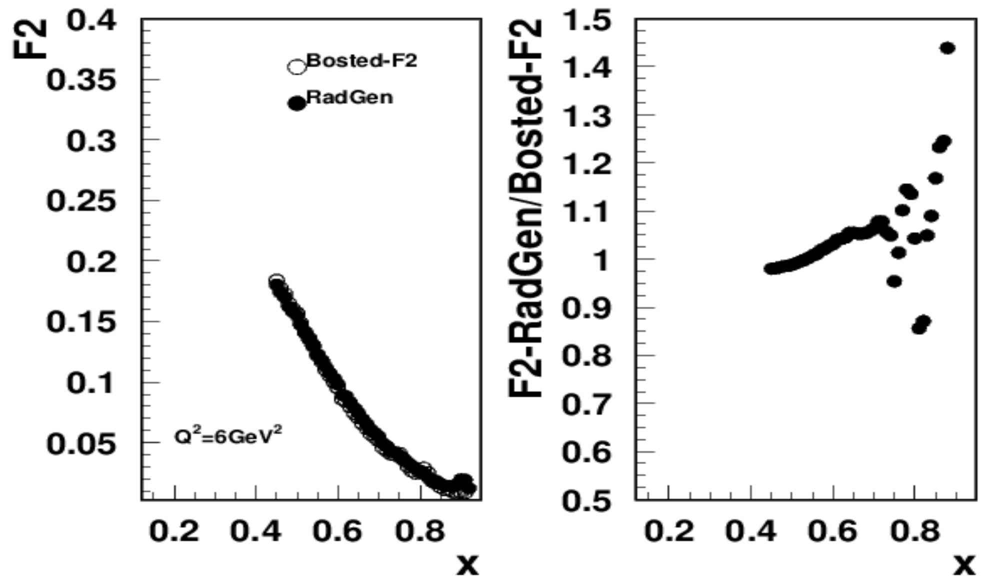


reasonable agreement in most of the relevant kinematics

How critical are 10-20% differences in extraction of underlying PDFs?

Comparing DIS MCs (Bosted vs RadGen)

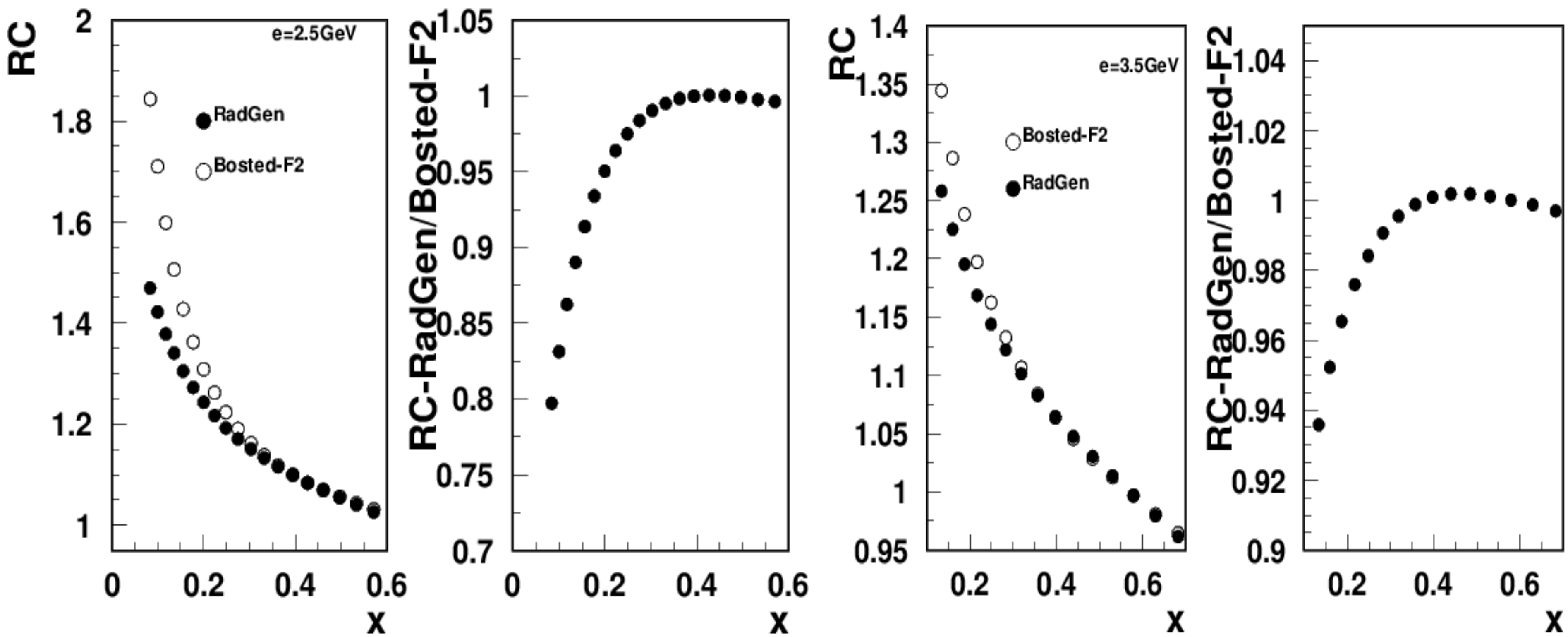




reasonable agreement in F2s with ~20-30% differences in resonance region

How critical are 10-20% differences in extraction of underlying PDFs?

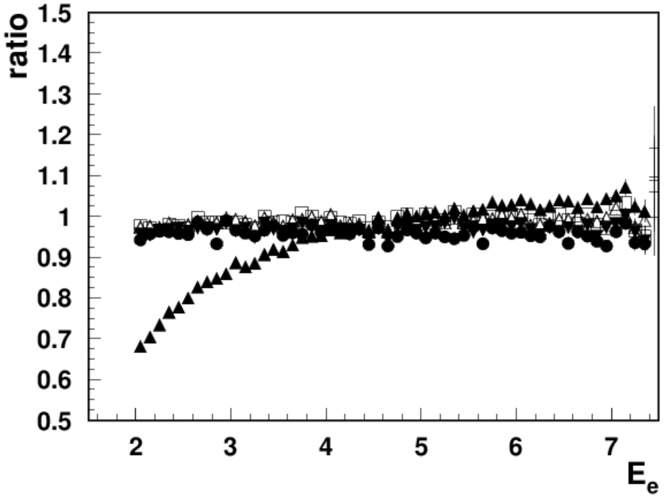
Sensitivity of RC to SFs

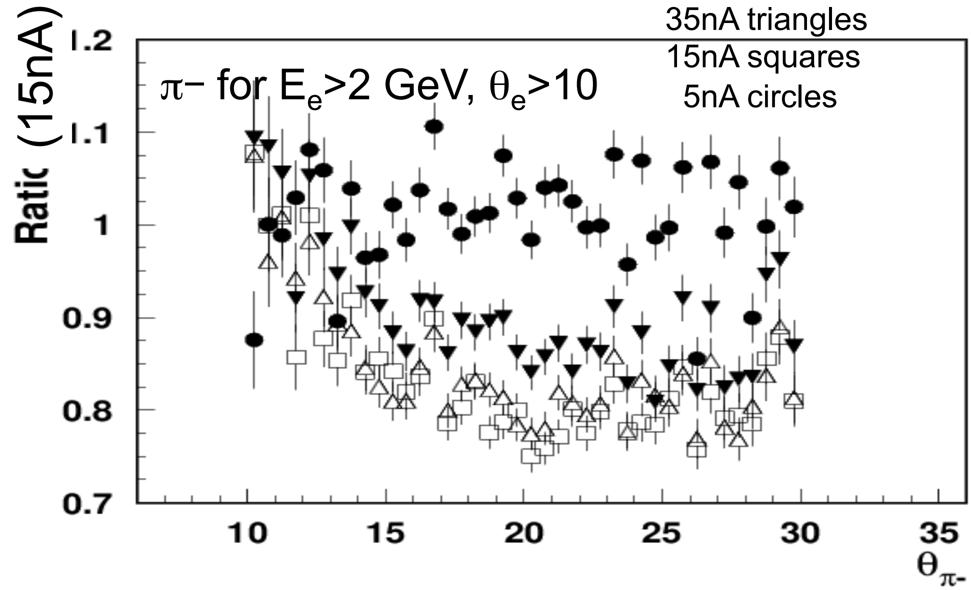


RC change few % with input SFs, and can affect precision measurements
Bins with large RC could be eliminated from first stage of data analysis

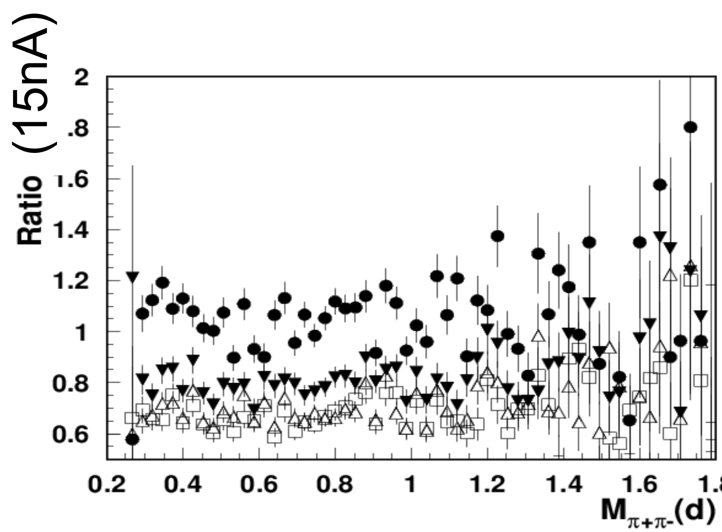
RGB lumi-dependence: ratios/15nA

Runs 6226(5nA) 6227(15nA) 6240 (35nA),
6310,6328 (50nA)





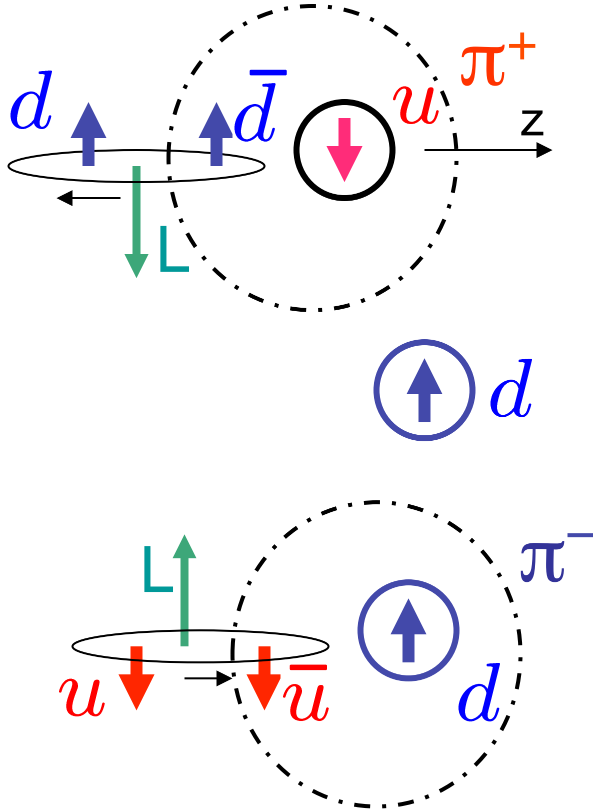
Runs normalized for Ee>2 GeV and θe>10 degrees



- Significant reduction of reconstruction eff. with lumi
- $\pi-$ may be used as an upper limit for e-
- overal reduction from 15nA to 50 nA for dihadron
- events is ~ factor of 2
- eff reduction depends on angle/energy
- With higher statistics can define the optimal lumi.

Collins effect

Simple string fragmentation (Artru model)



Leading pion out of page ($\bar{d}$ - direction)

$$h_1 H_1^{\perp u\to\pi^+}$$

d kicked in the opposite to the leading pion(into the page)

Sub-leading pion opposite to leading (double kick into the page)

$$H_1^{\perp u\to\pi^-} > H_1^{\perp u\to\pi^+}$$

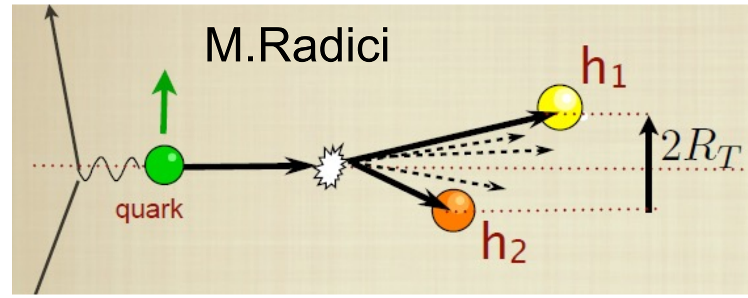
If unfavored Collins fragmentation dominates measured π- vs π+, why K- vs K+ is different?

HT-distributions and dihadron SIDIS

Compare single hadron and dihadron SSAs

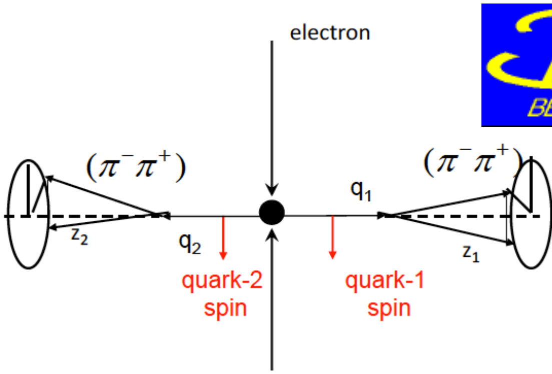
$$\frac{M}{M_h}\, x\, e(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$

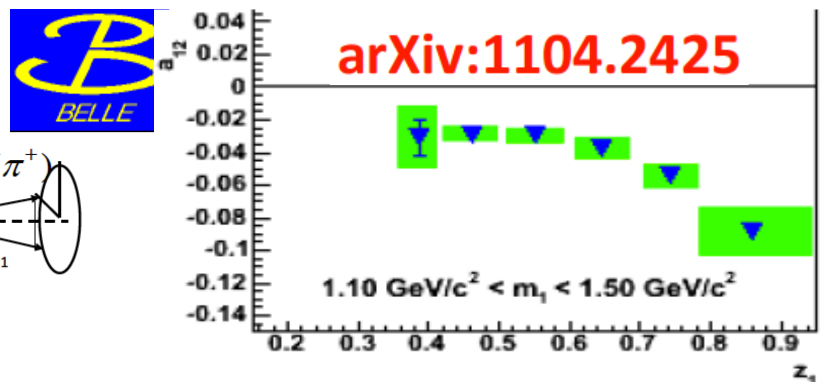
$$\frac{M}{M_h}\, x\, h_L(x)\, H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} g_1(x)\, \widetilde{G}^{\sphericalangle}(z,\zeta,M_h^2)$$



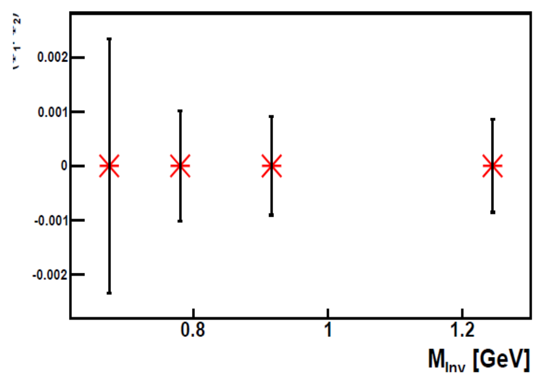
Only 2 terms with common unknown HT G~ term!

Aurore Courtoy/Anselm Voosen - Spin session



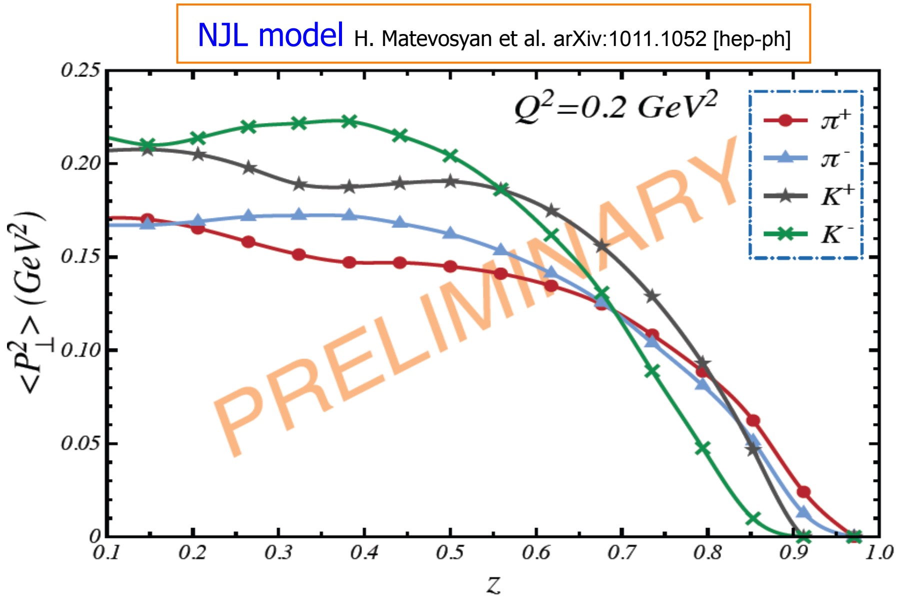


Projections for
(π^+K^-) $(K^+\pi^-)$ for 580 fb^{-1}



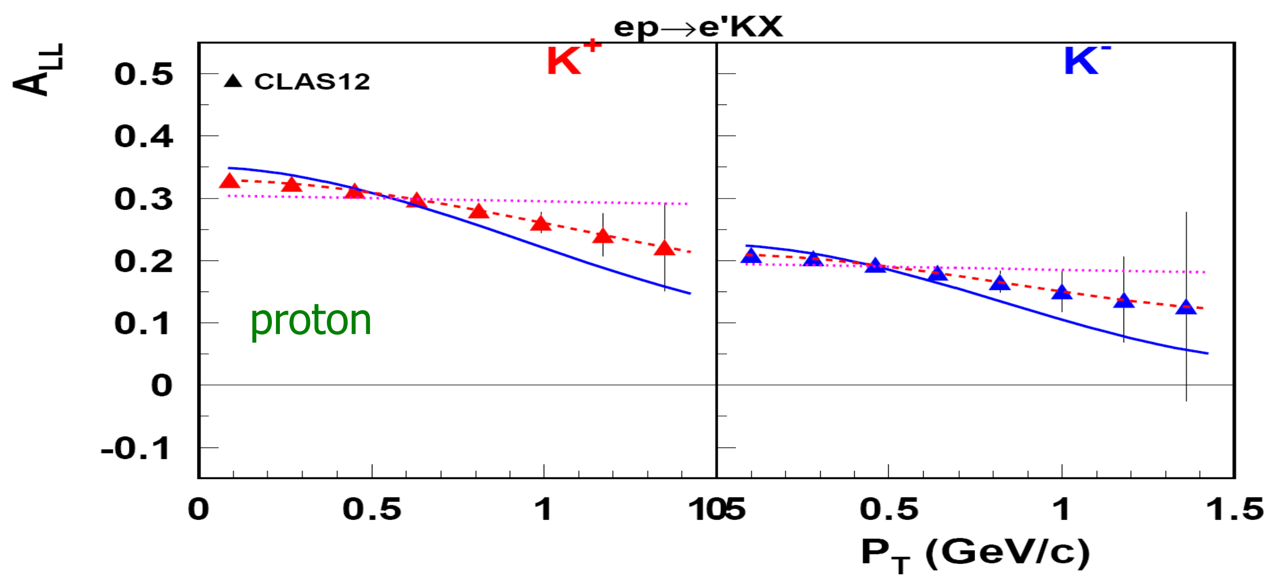
- Higher twists in dihadron SIDIS collinear (no problem with factorization)
- Bell can measure K+π- dihadron fragmentation functions

Transverse momentum distributions of partons



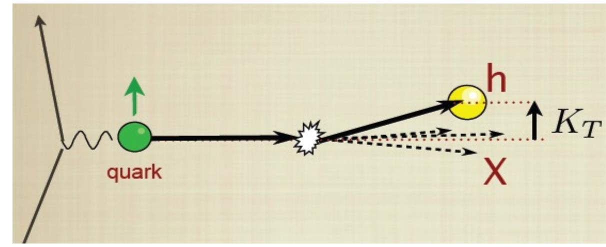
$$\langle P_T^2 \rangle \approx z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$$

Transverse momentum distributions in hadronization may be flavor dependent
=> measurements of different final state hadrons required

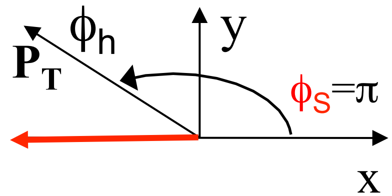


Chiral odd HT-distribution

How can we separate the HT contributions?



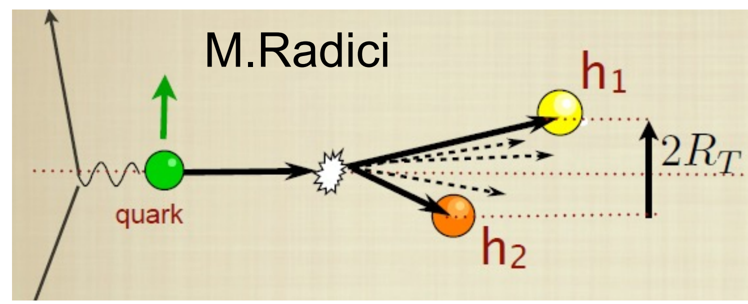
$F_{LU}^{\sin\phi}$ $F_{UL}^{\sin\phi}$



$eH_1^{\perp}$, $h_L H_1^{\perp}$ $\sin\phi_h$

HT function related to force on the quark. M.Burkardt (2008)

Compare single hadron and dihadron SSAs



$$\frac{M}{M_h} x\, e(x)\, H_1^{\triangleleft}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x)\, \widetilde{G}^{\triangleleft}(z,\zeta,M_h^2)$$

$$\frac{M}{M_h} x\, h_L(x)\, H_1^{\triangleleft}(z,\zeta,M_h^2) + \frac{1}{z} g_1(x)\, \widetilde{G}^{\triangleleft}(z,\zeta,M_h^2)$$

Only 2 terms with common unknown HT G~ term!

Azimuthal moments with unpolarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{UU}^{\cos\phi} \propto \frac{M_h}{M}\mathbf{f_1}\frac{D^\perp}{z} - \frac{M}{M_h} x f^\perp D_1$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

Azimuthal moments with unpolarized target

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N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{UU}^{\cos\phi} \sim -h_1^\perp \frac{H}{z} + x h H_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	H, E	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{LU}^{\sin\phi} \propto \frac{M_h}{M}\mathbf{f_1}\frac{G^\perp}{z} - \frac{M}{M_h} x g^\perp D_1$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, $\mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{LU}^{\sin\phi} \sim h_1^\perp \frac{E}{z} + xeH_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	H, $\mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with long. polarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathsf{UL}}^{\sin\phi} \propto \frac{M_h}{M}\mathbf{g_1}\frac{G^\perp}{z} + \frac{M}{M_h} x f_L^\perp D_1$$

q/h	U	L	T
U	$D_1^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with long. polarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{UL}^{\sin\phi} \sim h_{1L}^\perp \frac{H}{z} + x h_L H_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{LL}^{\cos\phi} \sim \frac{M_h}{M} g_{1L} \frac{D^\perp}{z} + x e_L H_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{LL}^{\cos\phi} \sim \frac{M_h}{M} h_{1L}^\perp \frac{E}{z} + x g_L^\perp D_1$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

Twist-3 PDFs : "new testament"

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h ,e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L ,e_L
T	f_T , $f_T^{\perp}$	g_T , $g_T^{\perp}$	h_T ,e_T ,$h_T^{\perp}$, $e_T^{\perp}$

$$\frac{1}{2Mx}\,\mathrm{Tr}\left[\tilde{\Phi}_{A\alpha}\,\sigma^{\alpha+}\right] = \tilde{h} + i\,\tilde{e} + \frac{\epsilon_T^{\rho\sigma}\,p_{T\rho}S_{T\sigma}}{M}\left(\tilde{h}_T^{\perp} - i\,\tilde{e}_T^{\perp}\right),$$

$$\frac{1}{2Mx}\,\mathrm{Tr}\left[\tilde{\Phi}_{A\alpha}\,i\sigma^{\alpha+}\gamma_5\right] = S_L\left(\tilde{h}_L + i\,\tilde{e}_L\right) - \frac{p_T\cdot S_T}{M}\left(\tilde{h}_T + i\,\tilde{e}_T\right),$$

$$\frac{1}{2Mx}\,\mathrm{Tr}\left[\tilde{\Phi}_{A\rho}(g_T^{\alpha\rho} + i\epsilon_T^{\alpha\rho}\gamma_5)\gamma^+\right] = \frac{p_T^{\alpha}}{M}(\tilde{f}^{\perp} - i\tilde{g}^{\perp}) - \epsilon_T^{\alpha\rho}\,S_{T\rho}\left(\tilde{f}_T + i\tilde{g}_T\right)$$

$$- S_L\,\frac{\epsilon_T^{\alpha\rho}\,p_{T\rho}}{M}\left(\tilde{f}_L^{\perp} + i\,\tilde{g}_L^{\perp}\right) - \frac{p_T^{\alpha}\,p_T^{\rho} - \frac{1}{2}\,p_T^2\,g_T^{\alpha\rho}}{M^2}\,\epsilon_{T\rho\sigma}\,S_T^{\sigma}\left(\tilde{f}_T^{\perp} + i\tilde{g}_T^{\perp}\right),$$

$\rho(770)$ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$		$\sim$ 100 %	
	$\rho(770)^{\pm}$ decays			
Γ_2	$\pi^{\pm}\pi^0$		$\sim$ 100 %	
Γ_3	$\pi^{\pm}\gamma$		$(4.5 \pm 0.5) \times 10^{-4}$	S=2.2
Γ_4	$\pi^{\pm}\eta$		$< 6 \times 10^{-3}$	CL=84%
Γ_5	$\pi^{\pm}\pi^+\pi^-\pi^0$		$< 2.0 \times 10^{-3}$	CL=84%
	$\rho(770)^0$ decays			
Γ_6	$\pi^+\pi^-$		$\sim$ 100 %	
Γ_7	$\pi^+\pi^-\gamma$		$(9.9 \pm 1.6) \times 10^{-3}$	
Γ_8	$\pi^0\gamma$		$(4.7 \pm 0.6) \times 10^{-4}$	S=1.4
Γ_9	$\eta\gamma$		$(3.00 \pm 0.21) \times 10^{-4}$	
Γ_{10}	$\pi^0\pi^0\gamma$		$(4.5 \pm 0.8) \times 10^{-5}$	
Γ_{11}	$\mu^+\mu^-$	[a]	$(4.55 \pm 0.28) \times 10^{-5}$	
Γ_{12}	e^+e^-	[a]	$(4.72 \pm 0.05) \times 10^{-5}$	
Γ_{13}	$\pi^+\pi^-\pi^0$		$(1.01^{+0.54}_{-0.36} \pm 0.34) \times 10^{-4}$	
Γ_{14}	$\pi^+\pi^-\pi^+\pi^-$		$(1.8 \pm 0.9) \times 10^{-5}$	
Γ_{15}	$\pi^+\pi^-\pi^0\pi^0$		$(1.6 \pm 0.8) \times 10^{-5}$	
Γ_{16}	$\pi^0 e^+e^-$		$< 1.2 \times 10^{-5}$	CL=90%
Γ_{17}	ηe^+e^-			

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

[a] The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \to \mu^+\mu^-) = \Gamma(\rho^0 \to e^+e^-) \times 0.99785$.

$\omega(782)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\pi^0$	(89.3 ± 0.6) %	
Γ_2	$\pi^0\gamma$	(8.40 ± 0.22) %	S=1.8
Γ_3	$\pi^+\pi^-$	(1.53 ± 0.06) %	
Γ_4	neutrals (excluding $\pi^0\gamma$)	$(7\ ^{+7}_{-4}) \times 10^{-3}$	S=1.1
Γ_5	$\eta\gamma$	$(4.5 \pm 0.4) \times 10^{-4}$	S=1.1
Γ_6	$\pi^0 e^+e^-$	$(7.7 \pm 0.6) \times 10^{-4}$	
Γ_7	$\pi^0\mu^+\mu^-$	$(1.34 \pm 0.18) \times 10^{-4}$	S=1.5
Γ_8	ηe^+e^-		
Γ_9	e^+e^-	$(7.36 \pm 0.15) \times 10^{-5}$	S=1.5
Γ_{10}	$\pi^+\pi^-\pi^0\pi^0$	$< 2 \times 10^{-4}$	CL=90%
Γ_{11}			5%
Γ_{12}			0%
Γ_{13}			
Γ_{14}			0%
Γ_{15}			
Γ_{16}			5%
Γ_{17}			0%
Γ_{18}			0%
Γ_{19}			0%
Γ_{20}			0%

$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.2 ± 0.5) %	S=1.3
Γ_2	$K^0_L K^0_S$	(34.0 ± 0.4) %	S=1.3
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	(15.24 ± 0.33) %	S=1.2
Γ_4	$\rho\pi$		
Γ_5	$\pi^+\pi^-\pi^0$		
Γ_6	$\eta\gamma$	(1.303 ± 0.025) %	S=1.2
Γ_7	$\pi^0\gamma$	$(1.30 \pm 0.05) \times 10^{-3}$	
Γ_8	$\ell^+\ell^-$	—	
Γ_9	e^+e^-	$(2.973 \pm 0.034) \times 10^{-4}$	S=1.3
Γ_{10}	$\mu^+\mu^-$	$(2.86 \pm 0.19) \times 10^{-4}$	

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update