Measurement of the Ratio $R=\sigma_L/\sigma_T$ in Exclusive and Semi-Inclusive π^0 Production

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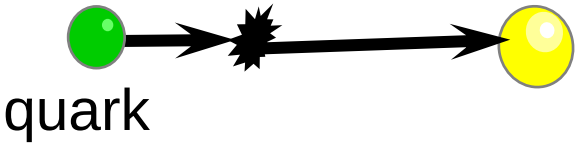
New collaborators in blue

JLab, CUA, HU, Alikhanyan NSL, ODU, IN2P3, NC A&T, Norfolk State, CEA-Saclay, Regina, CNU, Mississippi, JMU, U. South Carolina, FIU, Saint Mary's, Ohio, ANL, RPI, ITEP

Hadron production Reaction Dynamics

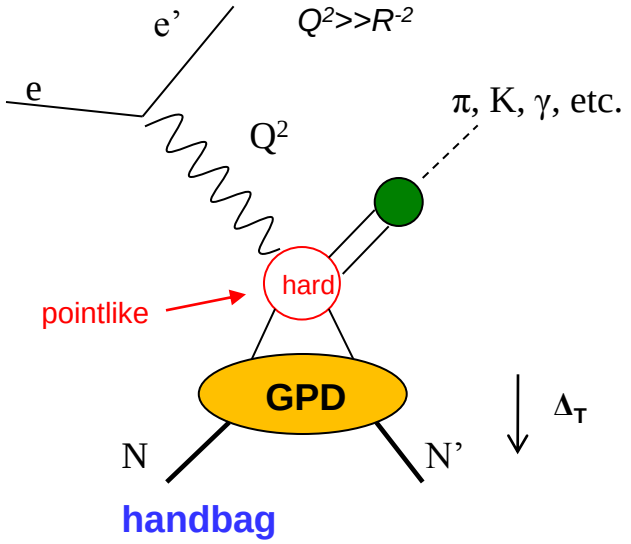
- In Semi-Inclusive DIS (SIDIS) one observes a single hadron carrying a fraction z of the photon energy in the target rest frame, in a final state of any multiplicity
  - At sufficiently high Q^2, cross section factorizes into target distribution and fragmentation functions (at LO, after integration over p_T and ϕ)
  - Flavor decomposition by tagging the active parton through its fragmentation properties
  - Distribution of spin and transverse momentum (TMD) carried by quarks in the nucleon



quark

$\Sigma e_q^2 q(x)\, D_q^{\pi}(z)$

- In the exclusive limit $(z \to 1)$ the final state recoiling baryon together with single meson carries the full photon energy
  - Hard-soft factorization theorem proven for longitudinal photons at sufficiently high Q^2
    - Non-perturbative (soft) physics represented by GPDs

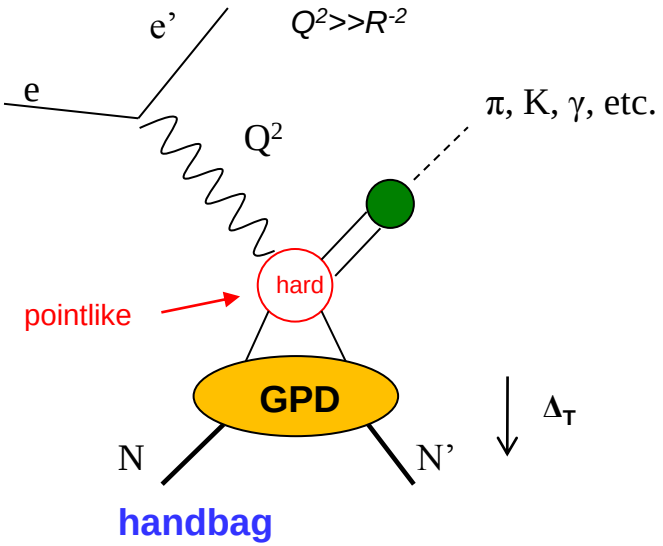


handbag

Ratio $R=\sigma_L/\sigma_T$ in the Exclusive limit

- Production of π^+ and K^+ feature a meson exchange contribution in the t-channel (pole term), whose impact on factorization has to be understood

- In π° production the pole term is suppressed
  - The t-dependence at small t can thus be associated with the structure of the nucleon rather than its pion cloud
    - A large $R=\sigma_L/\sigma_T$ would imply the realization of the factorization theorem
  - A large response in σ_L may indicate non-pole contributions in π^+ production



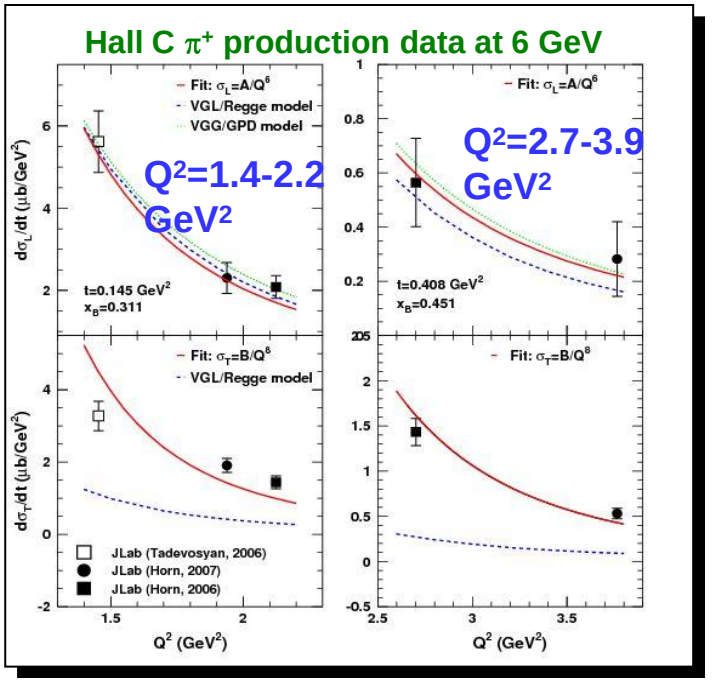
Comparison of R in π° and π^+ production important for understanding:
- Pole and non-pole contributions in nucleon (spin) structure studies
- Non-pole contributions in F_π extraction

Transverse Contributions

- Recent data suggest that transversely polarized photons play an important role in pion electroproduction
  - *Hall C π^+:* σ_L follows scaling prediction, σ_T does not follow the corresponding expectation
  - HERMES π^+: sin ϕ modulation is large [Airapetian et al, Phys. Lett. B 682, 345 (2010)]
  - CLAS: π^o data show substantial fraction of σ_{TT} in the *unseparated* cross section [Kubarovsky10+]

σ_L →

σ_T →



[Horn et al., Phys. Rev. C 78, 058201 (2008)]

- Recent theoretical developments suggest no strong suppression of σ_T at experimentally accessible values of Q^2 [Goloskokov, Kroll Eur. Phys. J. C 65, 137 (2010); Eur. Phys. J. A 45, 112 (2011)]
  - For π^o large σ_T may allow access to helicity flip GPDs

Measurement of the relative σ_L and σ_T contributions to the π° cross section important for reliable interpretation of data from 12 GeV JLab GPD program.

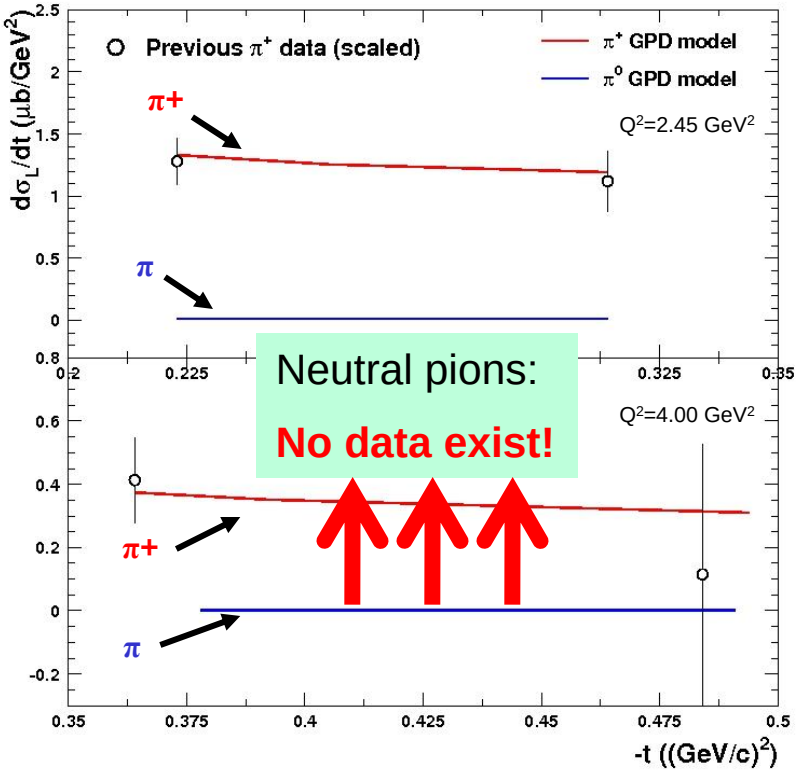
Relative σ_L and σ_T unknown for neutral pions

- GPD studies with pions require understanding relative contributions of σ_L and σ_T

- Is the relative contribution of σ_L in π production significant?
  - Understand the size of non-pole contributions in π^+ production
  - 12 GeV: Opportunity to compare to separated σ_L and σ_T in π^+ production (E12-07-105)

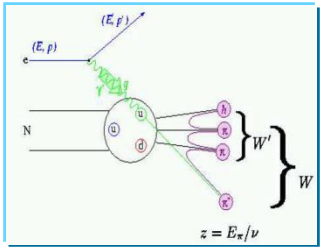
- Unseparated π data from Hall A suggest that σ_L may be larger than predicted by models and shows no t-dependence

Separated σ_L data and predictions



σ_L/σ_T important for studies of scaling in neutral systems and understanding of pole and non-pole contributions

Ratio $R=\sigma_L/\sigma_T$ in SIDIS



- Experimental studies of R_{SIDIS} are needed for proper analysis and interpretation of SIDIS measurements and angular asymmetries
  - In the asymptotic limit, the ratio disappears like Q^{-2} and $R_{SIDIS}=R_{DIS}$
  - For intermediate energies, expect differences as function of z and Q^2
  - Fractional uncertainties to asymmetries ~ $\varepsilon\delta R$

Exclusive limit of SIDIS

	π^+	π^-	π^o
p	pole	X	-
n	X	pole	-

- A comparison of charged (E12-06-104) and neutral pions in the transition from SIDIS to exclusive scattering may shed further light on the reaction mechanism
  - Behavior of charged and neutral pions in transition to the exclusive limit expected to be different
  - Verify naïve assumption $\pi^0 = (\pi^+ + \pi^-)/2$
    - In kaon case, for example, huge differences between D_u^{K+} and D_s^{K+}
  - Sensitivity to target-mass and higher-twist contributions at JLab energies
  - $\rho \rightarrow \pi^+\pi^-$ contributions non-existing for π^0

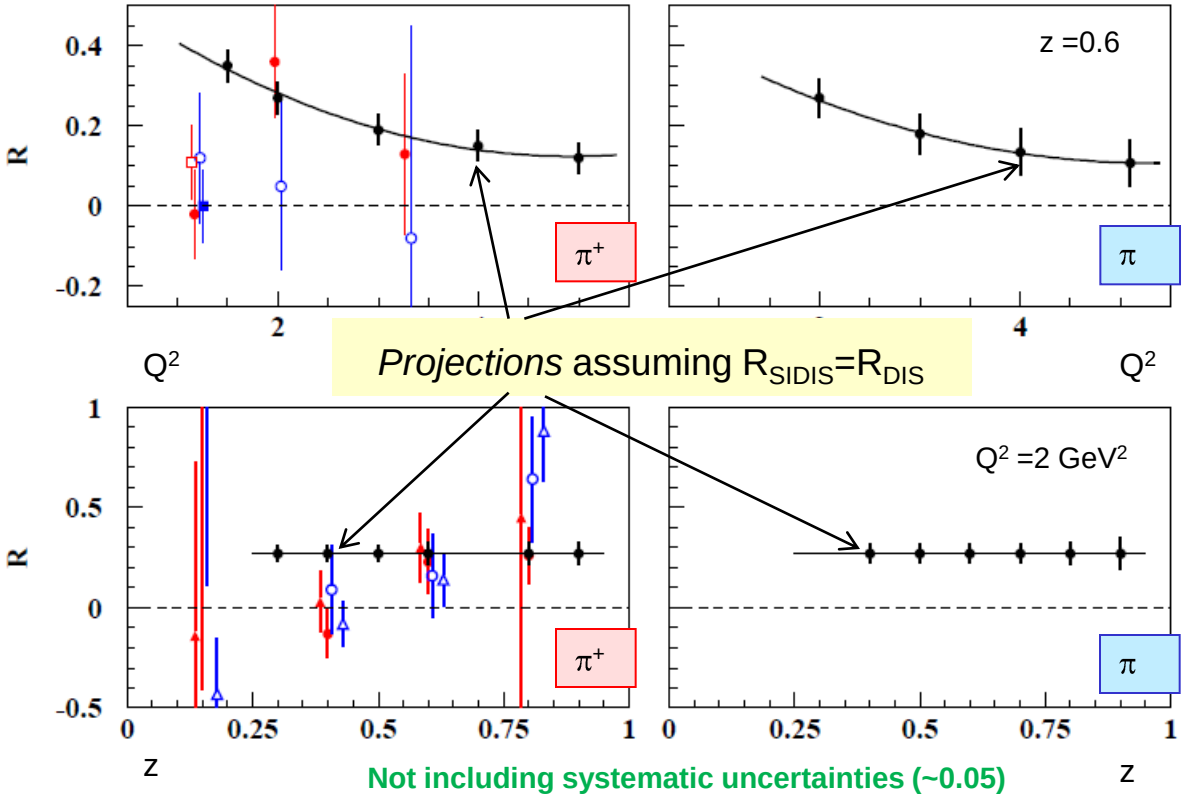
No R = σ_L/σ_T data exist for neutral pions

"Semi-inclusive DIS": $\Sigma e_q^2 q(x)\, D_q^{\pi}(z)$

$R_{SIDIS} \rightarrow R_{DIS}$ disappears with Q^2! (?)

"Deep exclusive scattering" is the $z \rightarrow 1$ limit of this "semi-inclusive DIS" process

Here, $R = \sigma_L/\sigma_T \sim Q^2$ (at fixed x)



Charged pions:

Pole @ z = 1

Neutral pions:

No pole @ z = 1

No data exist!

There **should** be differences between $R(\pi^+)$ (and $R(\pi^-)$) & $R(\pi^0)$ at intermediate energies → *must* know these for a *proper analysis and interpretation* of TMD measurements and corresponding angular asymmetries

Motivation Summary

- Measuring R in the exclusive limit is important for the interpretation of data from the GPD and form factor program at JLab 12 GeV
  - Relative σ_L and σ_T contributions are essential for GPD studies
  - Comparison of π and π^+ to understand size of pole and non-pole contributions

- Understanding the nature of the SIDIS process is important for the TMD program at 12 GeV JLab
  - SIDIS analyses require knowledge of R and information on target-mass and higher-twist contributions
  - Comparative studies of SIDIS and exclusive limit can further elucidate reaction mechanism

Knowledge on $R = \sigma_L/\sigma_T$ in π^0 production is non-existing!

Theory Report Summary

- ***THYTAC38:*** "…several intriguing differences between the properties of L/T separated charged and neutral pion production cross sections … can be studied in tandem with E12-06-104 [and] E12-07-105…" and "…can also test the extent to which $R_{SIDIS} \sim R_{DIS}$"

- ***THYTAC39:*** "…the motivation for this experiment remains as strong as it was at PAC38…"

Goals of the Experiment

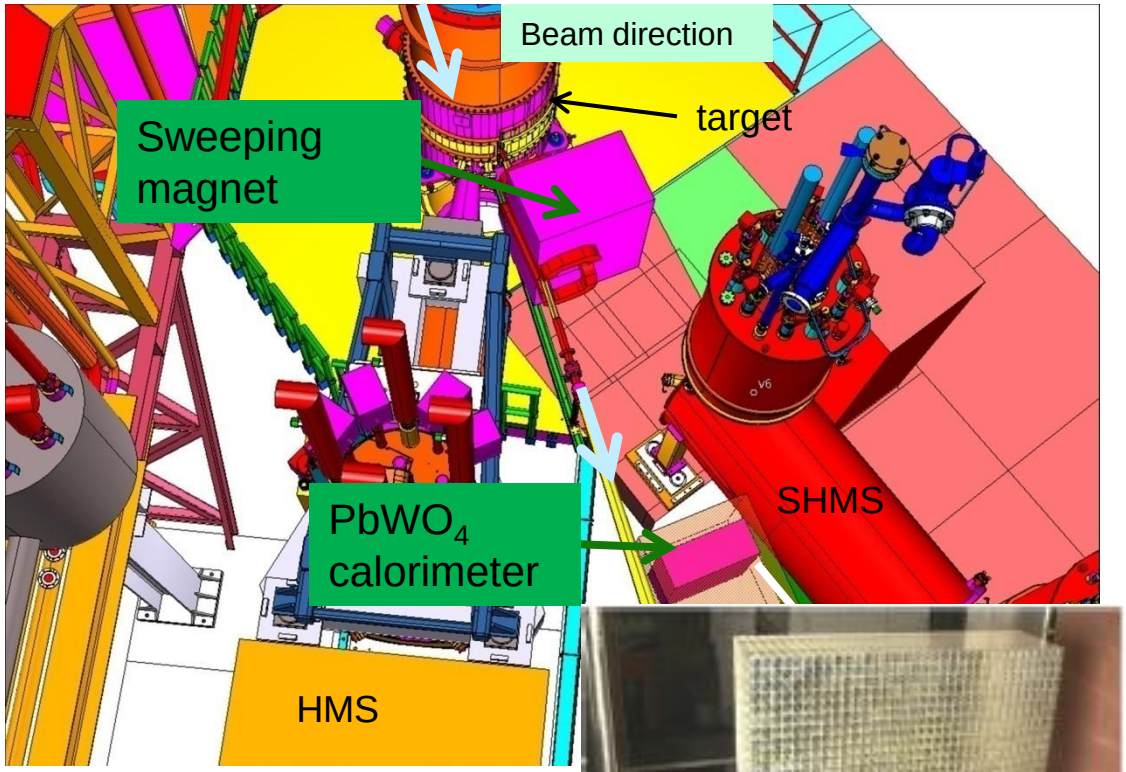
- **Measure the separated π cross section as a function of z at fixed (x_B,Q^2)**
  - Simultaneous separation of the cross section components for both deep exclusive and semi-inclusive reactions
  - First L/T measurement above the resonance region in π^0 production over a wide range of Q^2 and z, up to the exclusive limit
  - Test the appropriateness of the equality $\pi = (\pi^+ + \pi^-)/2$

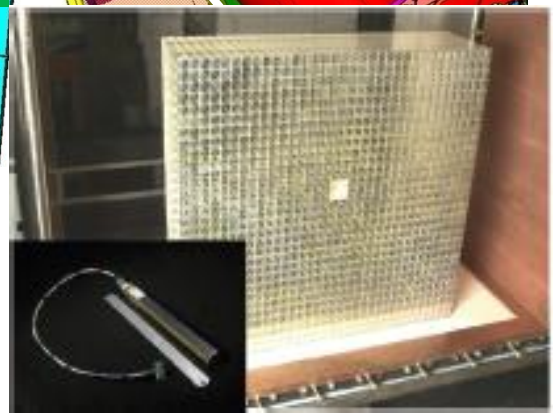
- **Measure the Q^2-dependence at fixed x_B=0.5 and t=0.4 to investigate scaling behavior of neutral-pion systems**
  - Simultaneous separation of the cross section components for both deep exclusive and semi-inclusive reactions
  - Highest Q^2 and largest Q^2 lever arm in L/T separated π production

- **Measure relative σ_L and σ_T contributions at fixed values of t'=t-t_{min} and W**
  - Simultaneous separation of the cross section components: L, T, LT, TT for DES
  - Study importance of pole and non-pole contributions

π^o L/T facility in Hall C

- New $PbWO_4$ calorimeter provides π^o detection facility in Hall C
  - Initially for C12-11-102
- C12-11-102 data will provide opportunities to extend separations program for DVCS
  - initial DVCS separation
  - extensions to a broader kinematic range anticipated





MRI Consortium proposal submitted Jan 2012:
CUA, ODU, FIU, JLab, Yerevan

C12-11-102: Summary of PAC38 Report Conditions

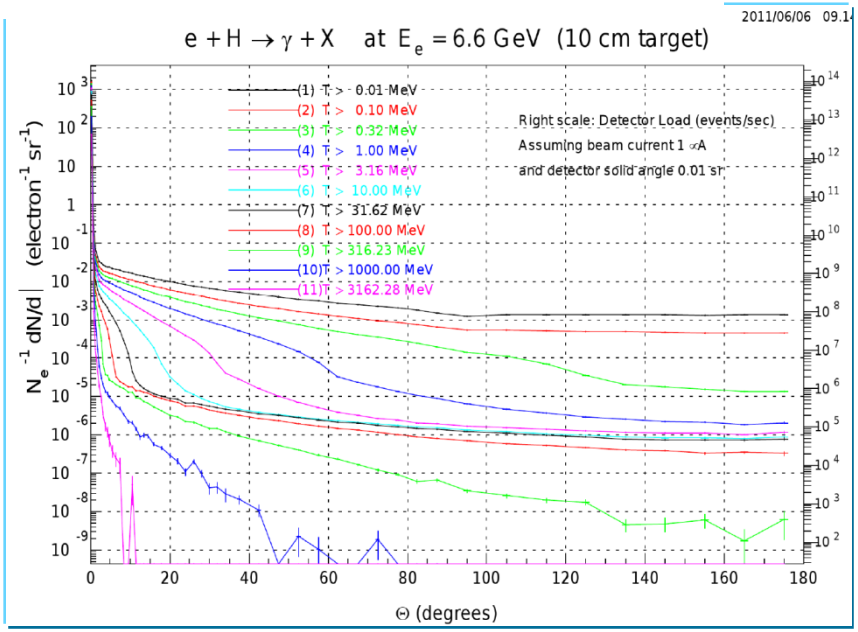
- ✓ **Placed emphasis in the choice of kinematics on DES**
  - Note that with the proposed setup exclusive and semi-inclusive data are accumulated simultaneously
- ✓ **Clarified discussion of predictions for $R=\sigma_L/\sigma_T$ in the context of count rates and included a new calculation by GK**
  - Theoretical predictions for R in the exclusive limit give similar values for realistic experimental bins. The average of VGG and VGL is generally compatible with calculations from GK
- ✓ **Performed detailed simulations of the π^o detector including charged and neutral backgrounds to study the π^o detection efficiency**
  - Already had realistic particle fluxes at PAC38 as provided by RadCon calculation
  - Using a GEANT4 simulation with realistic event generator verified that combinatorial background is indeed small as already shown with analytic estimates at PAC38
  - Improved the PMT base to have linearity up to the largest expected rates
  - Provided more detail on the detection efficiency, which is stable to better than 0.5%

All conditions from the PAC 38 report have been addressed

Background Simulations

Background calculations performed by RadCon group (P. Degtiarenko)

- Provide realistic fluxes of particles
- Checked against 15+ years of radiation background measurements
- Used for scheduling purposes to remain under DOE limits outside the Hall domes
- Used to quantitatively estimate backgrounds and required shielding configurations for, e.g., G0 and Qweak



GEANT4 Detector Simulations

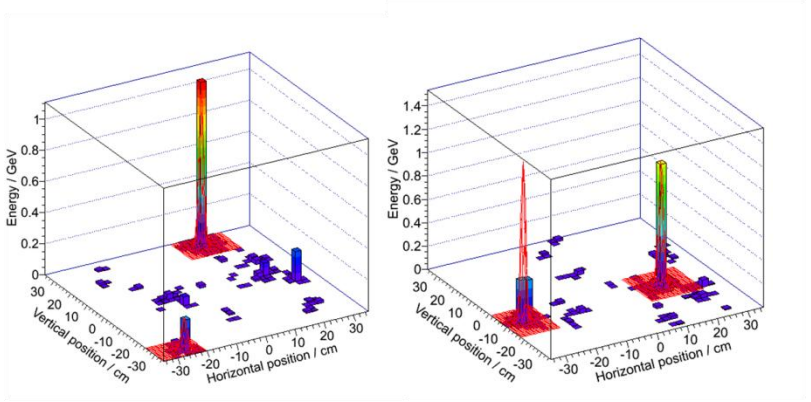
- Includes photons from π decay
  - Simulate π signal normalized to rate.
  - For each event decay π into 2 γ

- Simulated background consists of realistic fluxes of neutral and charged particles, the latter suppressed by sweeper magnet

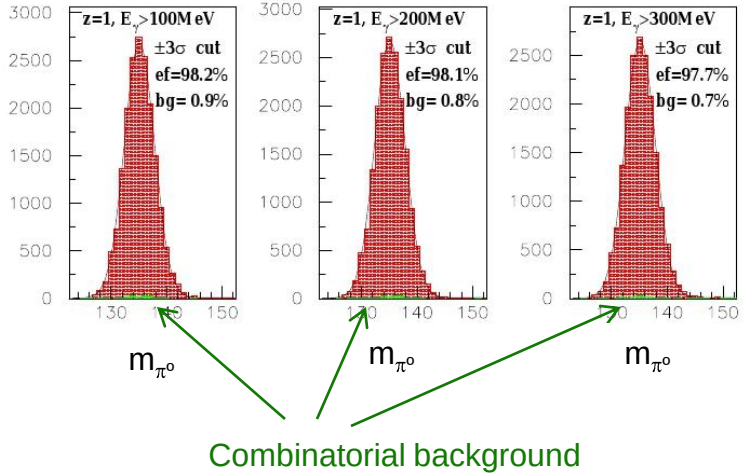
- Photon pair is selected from other processes in the calorimeter using a cluster finding algorithm

- π invariant mass reconstructed for each hit in the calorimeter

Combinatorial background is small (<1%)

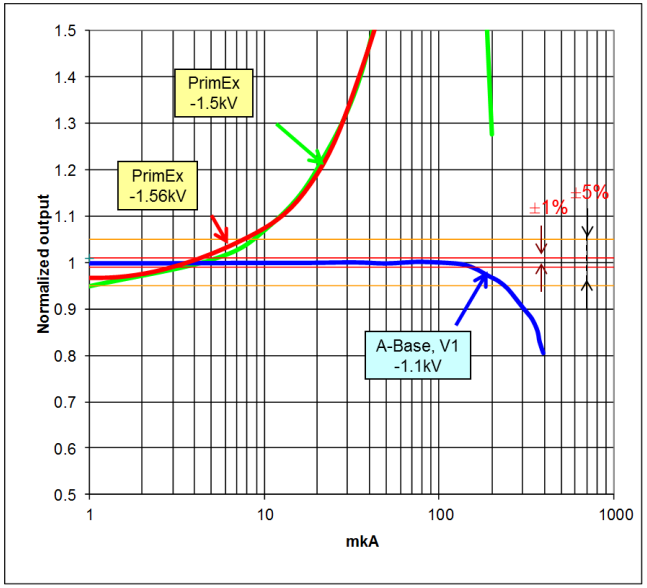


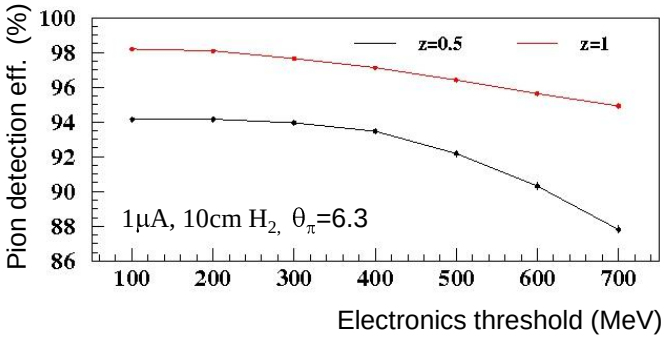
100 ns $\gamma\gamma$ coincidence time window



Detector Linearity and Efficiency

- Realistic background simulations show that main contribution is low-energy photons
- With improved PMT base design gain stable to 0.2% for all kinematics and background conditions
  - factor ~25 improvement compared to PRIMEX!
- Low-energy background can give (small) baseline shift
  - Event-by-event subtraction using signal sampling fADCs
- Verified that combinatorial background is small (<1%), assumed to be known to 0.2-0.5%
- Geometric acceptance known to better than 0.1%
  - Depends on survey and actual beam position





π detection efficiency is stable to better than 0.5%

Experiment Overview

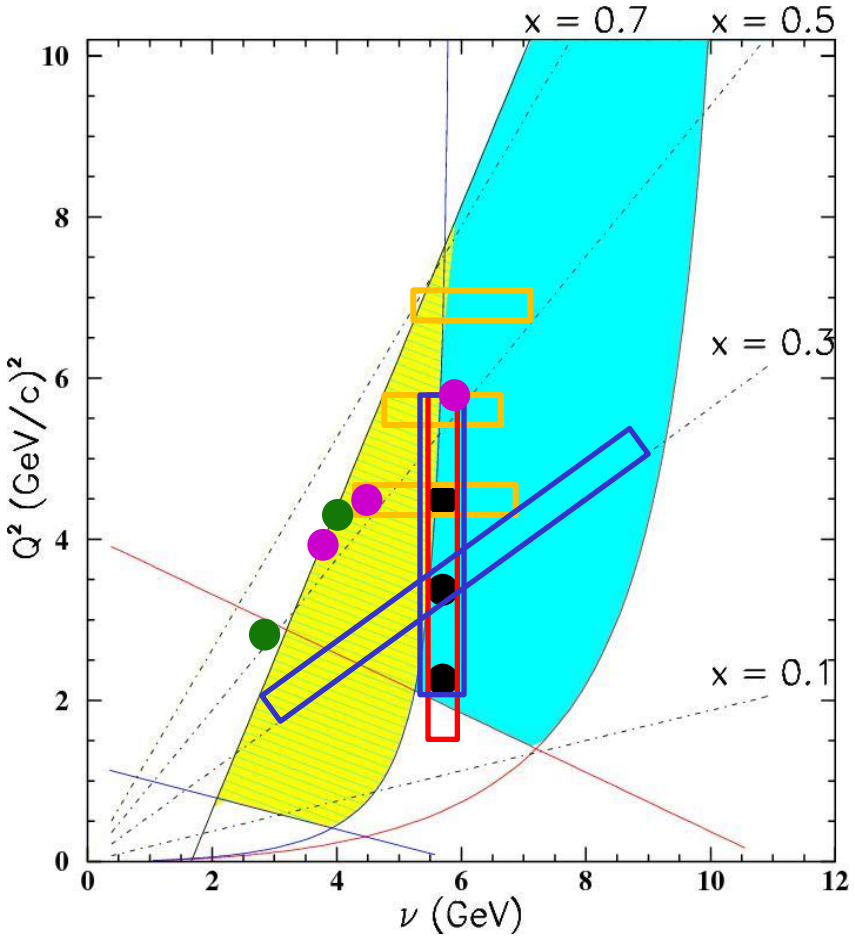
HMS + SHMS/π° Accessible Phase Space for *Deep Exclusive Scattering*

Neutral pions:

C12-11-102

- Scan in x and z
- + scan in Q^2 at fixed x
- + scan in t for DES (at fixed W, x ~ 0.5)

Optimized for both $z < 1$ & $z = 1$ studies



Charged pions:

E12-06-104 (L/T)

Scan in (z,p_T)

No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017

Scan in (x,z,p_T)

+ scan in Q^2 at fixed x

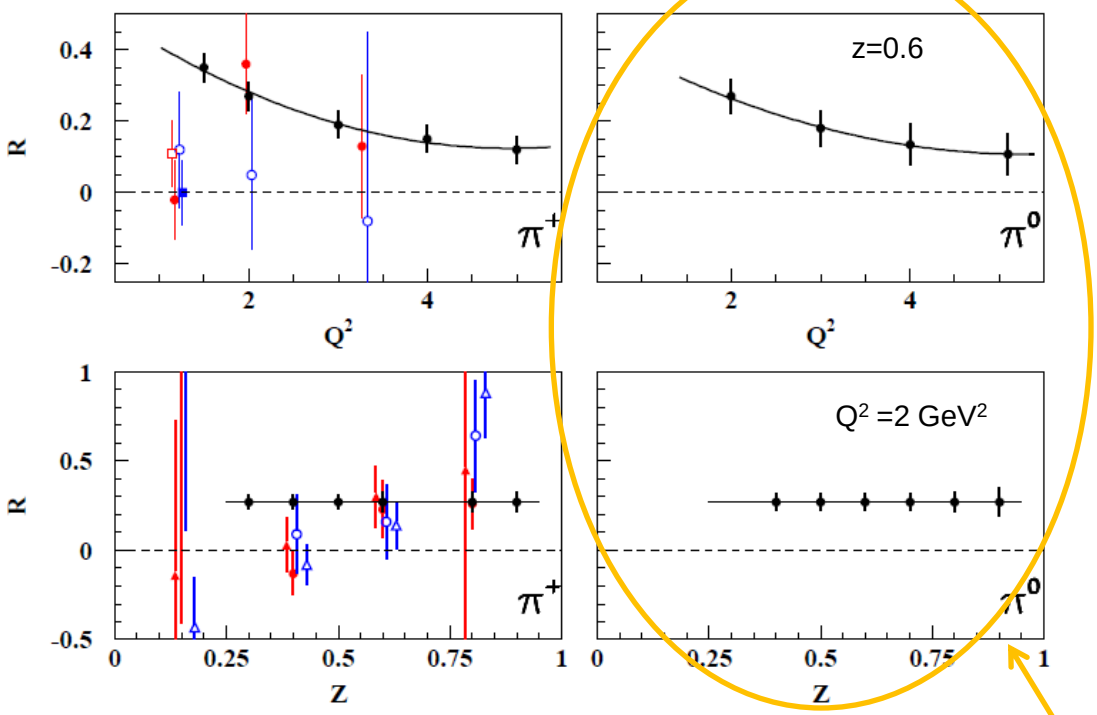
E12-09-002

+ scans in z

π calorimeter in a natural way allows accumulation of exclusive and semi-inclusive data in parallel

Projections for $R=\sigma_L/\sigma_T$

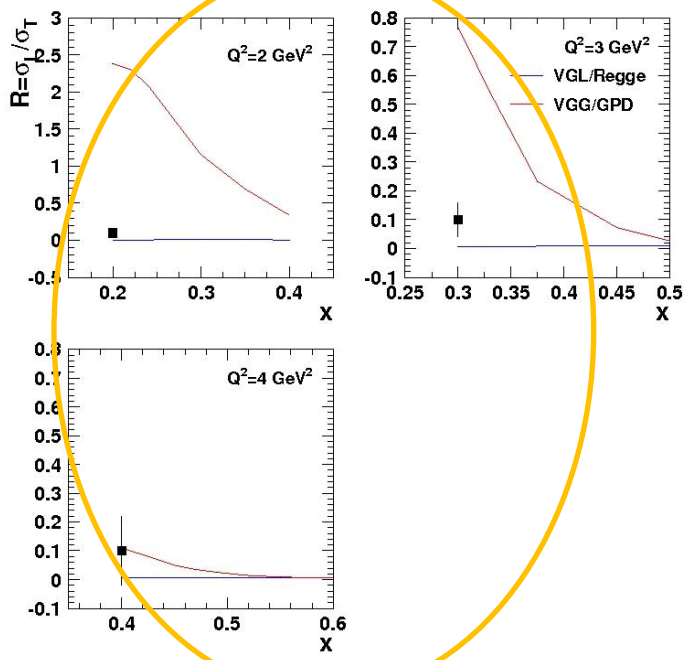
"Semi-inclusive DIS": $\Sigma e_q^2 q(x)\, D_q^{\pi}(z)$



Not including systematic uncertainties (~0.05)

- Well known parameterizations were used for PDFs and fragmentation functions in the rate estimates
  - Assumes $R_{SIDIS}=R_{DIS}$

"Deep exclusive scattering" is the z → 1 limit of this "semi-inclusive DIS" process



Projected Δ(L/T)=5-10%

- Average of VGL/VGG models used for rate estimates

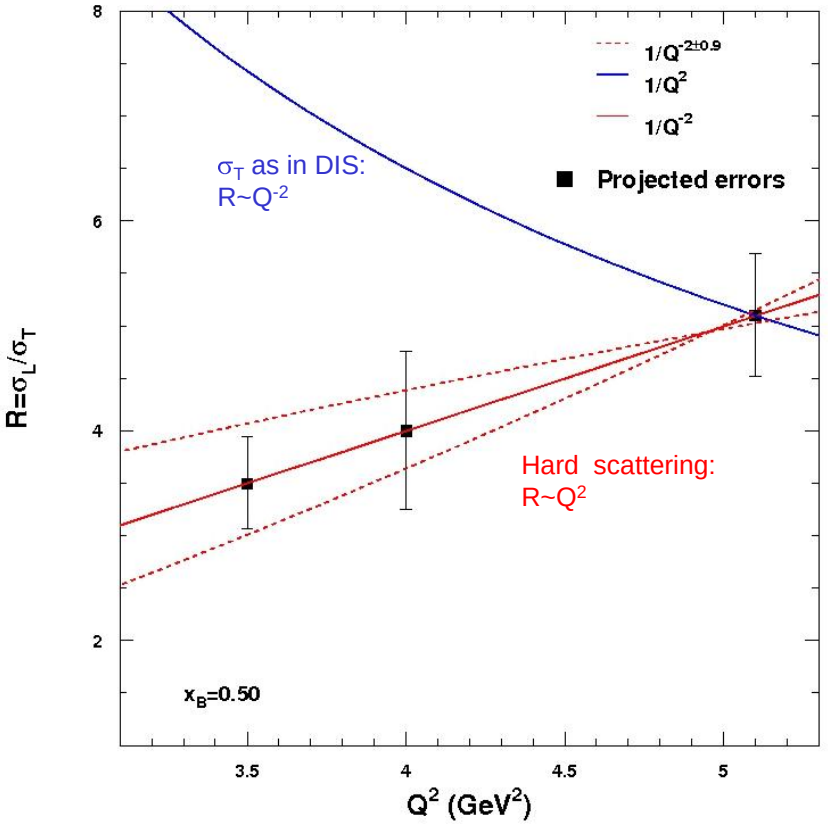
C12-11-102:

Precision L/T π data

Relative contribution of σ_L and σ_T in the exclusive limit

- GPD studies with pions require understanding relative contributions of σ_L and σ_T
  - A large $R=\sigma_L/\sigma_T$ would imply the realization of the factorization theorem

- Understand the relative contribution of σ_L in π production
  - 12 GeV: Opportunity to compare to π^+ cross sections (E12-07-105)
  - Significant response in σ_L in π^o could indicate non-pole contributions in π^+ production
    - If non-pole contributions smaller than anticipated may extract F_π to higher Q^2



Projected uncertainties for R are absolute

C12-11-102: Relative σ_L and σ_T for for reliable interpretation of data from 12 GeV JLab GPD program and form factor studies

Beam Time Estimate

SIDIS+DES
DES
SIDIS

Q^2 (GeV^2)	x_B	LH_2 (hrs)	Dummy	Overhead (hrs)	Total (hrs)
2.00	0.20	50	7	4	61
3.00	0.30	217	33	4	254
4.00	0.40	141	21	4	166
Subtotal R mapping					**481 (20 days)**
3.50	0.50	63	9	4	76
4.00	0.50	96	15	4	115
5.10	0.50	300	46	4	350
Subtotal Q^2 scan					**541 (22.5 days)**
2.45	0.50	222	34	4	260
3.80	0.50	31	5	4	40
Subtotal t scan					**300 (13.0 days)**
LD2		51		2	**53 (2 days)**
SIDIS enhanced $\Delta\varepsilon$		103	16	4	**123 (5 days)**
Subtotals/π		1274	186	38	1498.0
Calibrations					48.0
Calorimeter curing					72.0
Beam energy					32.0
Total					**1650 (69 days)**

C12-11-102 Summary

- Relative σ_L and σ_T contributions are essential for GPD studies through π^o electroproduction
- Comparison of the π^- and π^+ L/T ratio in the exclusive limit is of significant interest for pole/non-pole contribution and form factor studies at 12 GeV
- L/T separated π^- production data are important for understanding the SIDIS process
- Our theoretical understanding of hard (partonic?) reactions will benefit from π° data on relative σ_L and σ_T contributions
  - TMD, GPD, and studies of SIDIS and exclusive limit
  - Compare trends in neutral and charged pion production, $\pi^\circ=(\pi^+ + \pi^-)/2$

Conditions of PAC38 have been addressed.

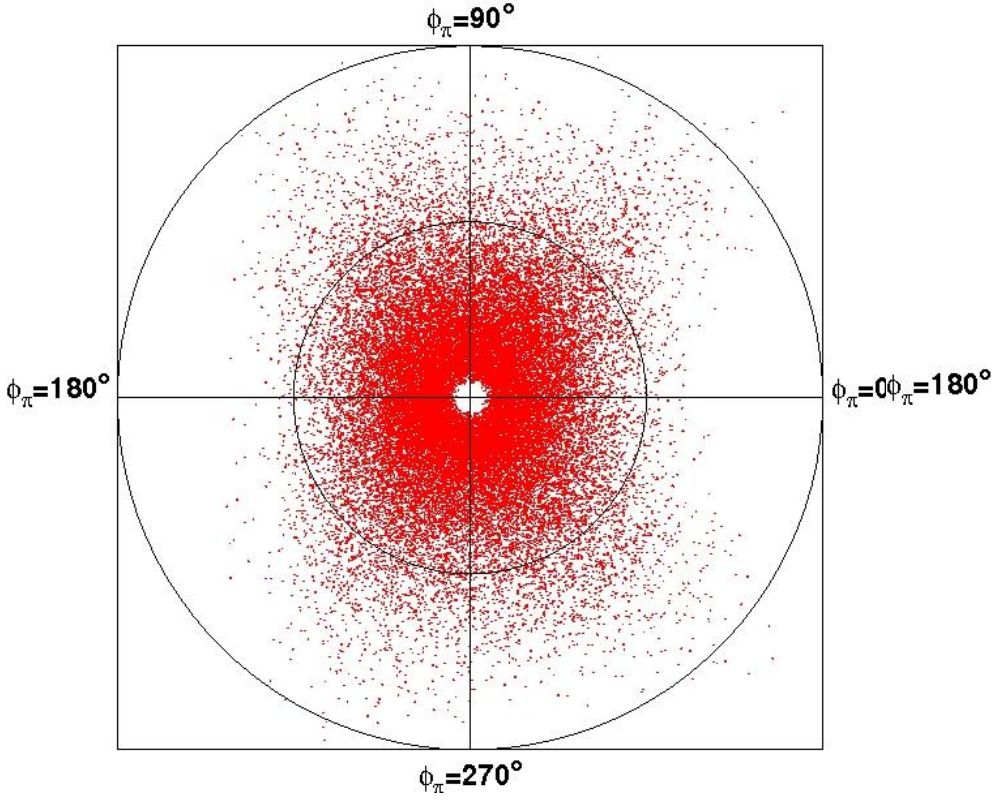
Request full approval of C12-11-102.

- Experiment provides a neutral-pion spectrometer facility in Hall C

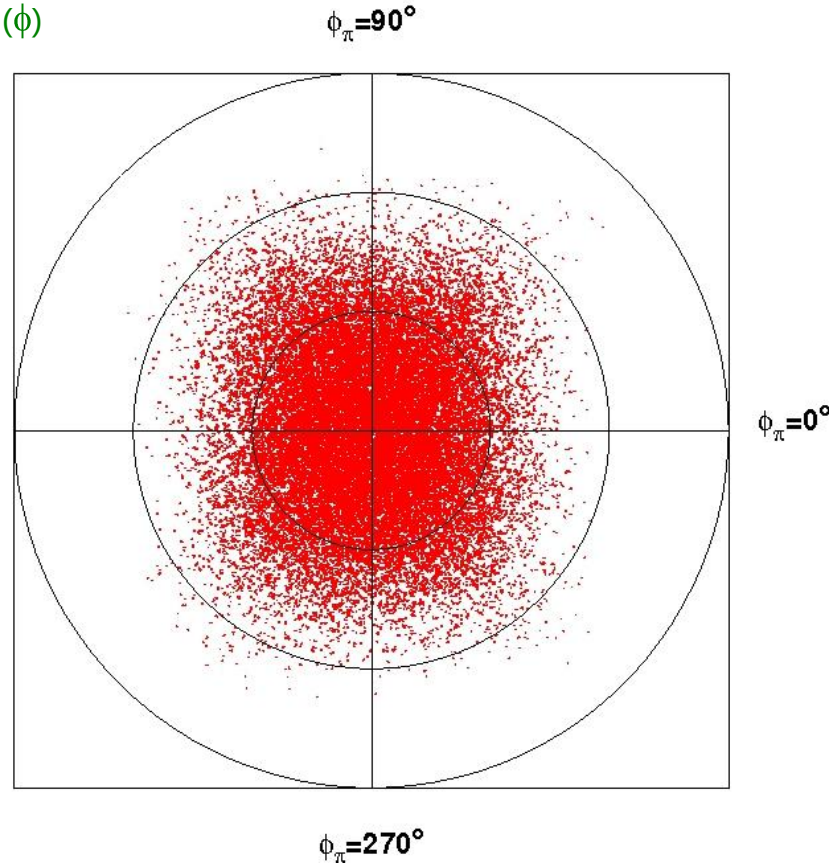
Azimuthal coverage

Radial coordinate (t or p_T),

Azimuthal coordinate (ϕ)



z = 1.0



0.4 < z < 0.6

The 25 msr solid angle provides good ϕ coverage over a range of p_T/t

Systematic Uncertainties

Source	pt-to-pt (%)	Scale (%)
Acceptance	0.4	1.0
Electron PID	<0.1	<0.1
π^o detection efficiency	0.5	1.0
ElectronTracking Efficiency	0.1	0.5
Charge	0.5	2.0
Target Thickness	0.2	0.5
Kinematics	0.4	<0.1
Total (incl. rad, mod)	1.6	3.4
Total	**0.9**	**2.5**

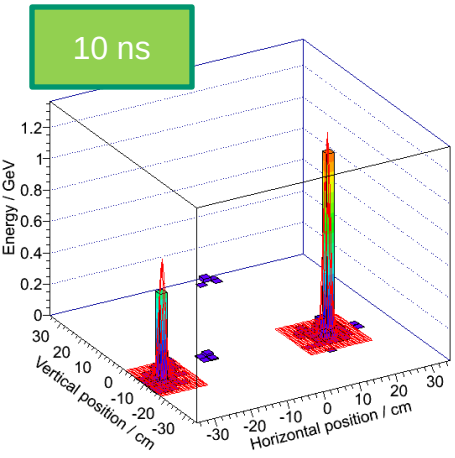
π^o detection efficiency stable to 0.5%

- Gain stable to 0.2% for all kinematics and background conditions
- Temperature stability better than 0.2%
- Background (e.g., combinatorial) known to 0.2-0.5%
- Geometric acceptance known to better than 0.1%

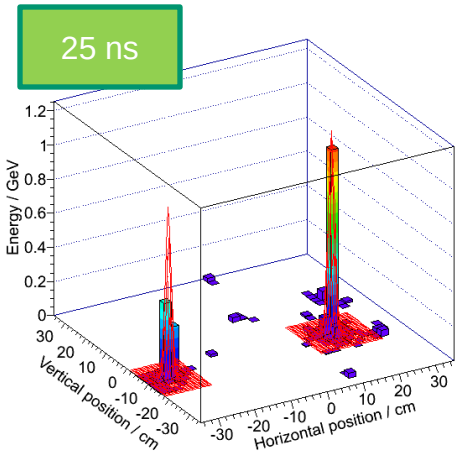
γγ coincidence time window

Representative event

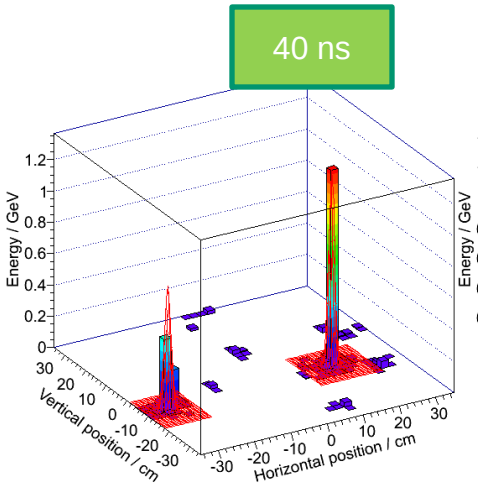
10 ns



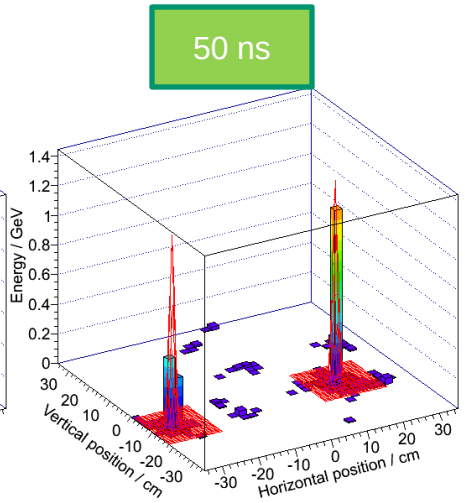
25 ns



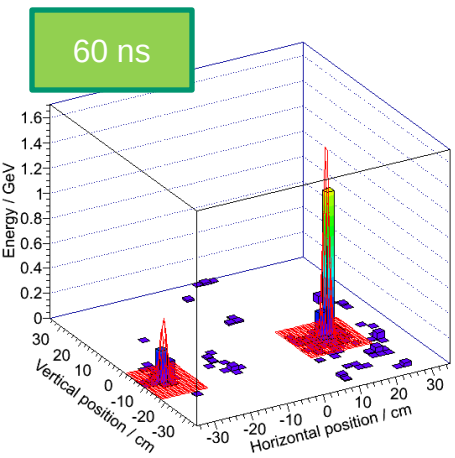
40 ns



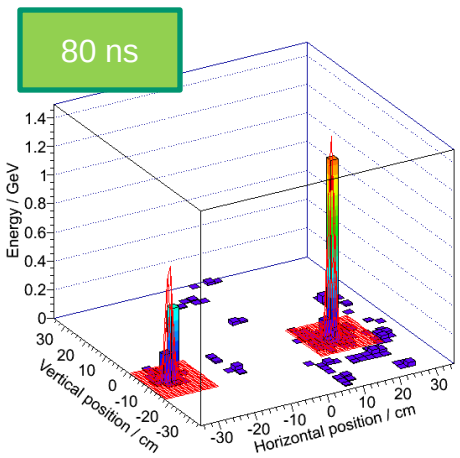
50 ns



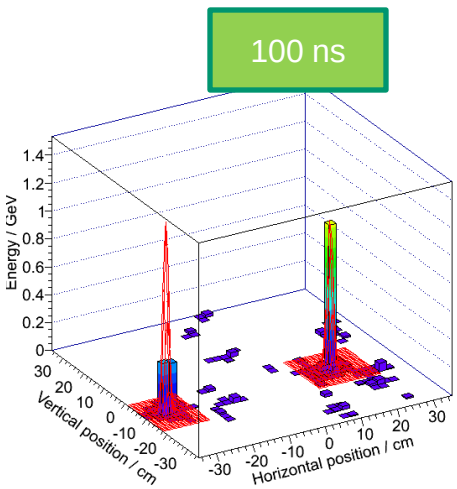
60 ns



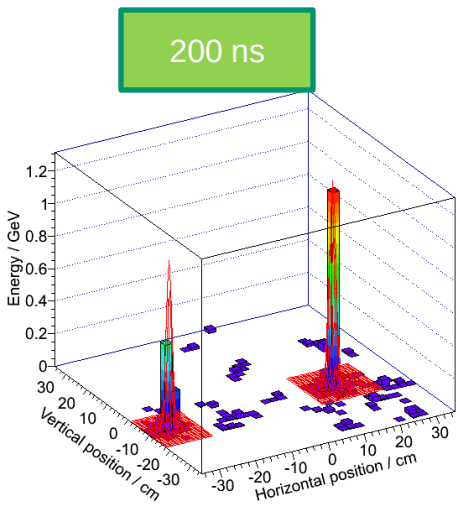
80 ns



100 ns



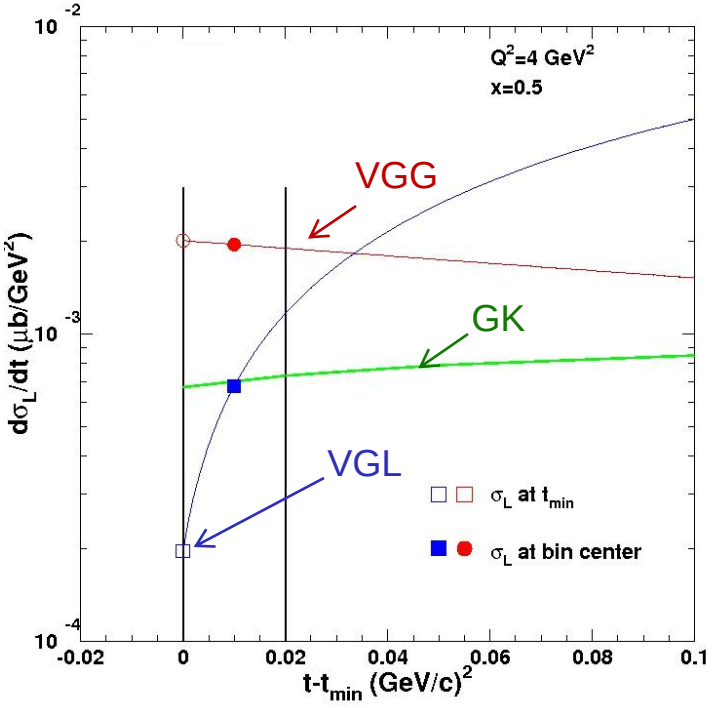
200 ns



Model Comparison for Rate Estimates

- R not well known above resonance region
  - Theoretical predictions for σ_L disagree at $t=t_{min}$
  - In a realistic bin, the differences are quite modest and average value provides very reasonable estimate of count rate

- Average of VGG/VGL generally compatible with calculations from Goloskokov/Kroll (GK)



- Relative σ_L and σ_T data would be of great interest for understanding transverse contribution in pion data