Measuring Parton Densities with Ultra-Peripheral Collisions at the LHC

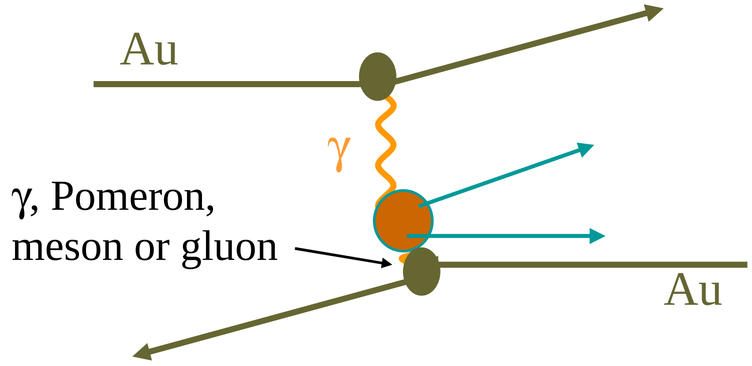
Spencer Klein, LBNL

- UPCs
- Photonuclear Interactions
- Measuring Structure Functions
  - Vector Mesons
  - Open Charm/Bottom
  - Other Channels
- Other UPC interactions

Berkeley Lab

Ultra-Peripheral Collisions

- Electromagnetic Interactions
- $b > 2R_{A;}$
  - no hadronic interactions
  - <b> ~ 20-300 fermi at the LHC
    - b up to few mm for e^+e^- pair production
- Ions produce strong EM fields
  - Treat as almost-real photons
    - Weizsacker-Williams method
    - Photon flux ~ Z^2
  - Maximum photon energy = γhc/RA
    - ~ 100 GeV (lab frame) for Pb at the LHC
    - ~ 600 TeV (target frame)
- Photonuclear and two-photon interactions occur

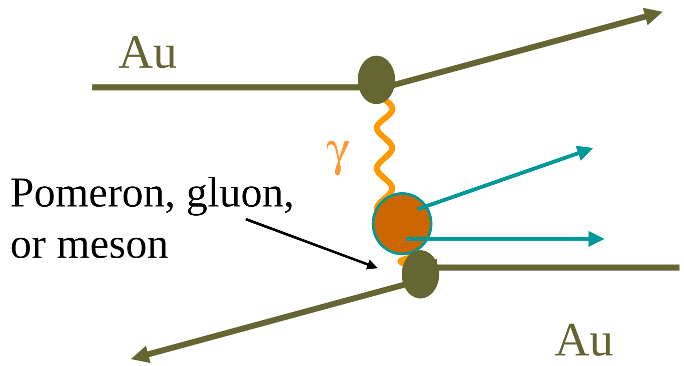


"Physics in the neighborhood of heavy ions"
– Urs. Wiedemann

Photonuclear Interactions

The photon fluctuates to a $q\bar{q}$ pair, which then interacts with the target

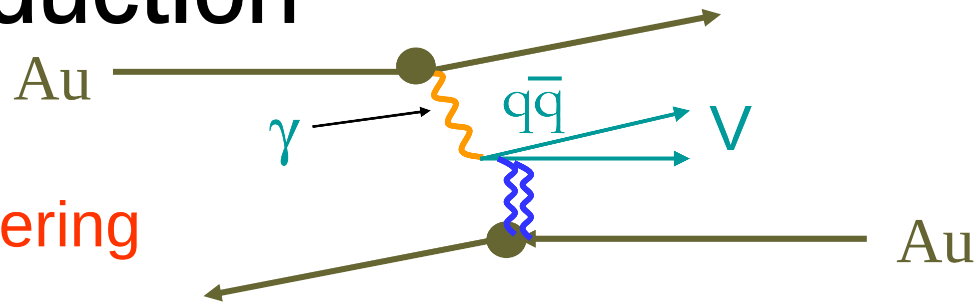
- Interactions can involve gluon, Pomeron (~2-gluons) or meson exchange
- Pomeron exchange ~ elastic scattering
  - Can be coherent over entire target
  - $\sigma \sim A^2$ (bulk) $A^{4/3}$ (surface)
    - $\sigma(Pb + Pb \to Pb + Pb + \rho^0) \sim 5.2$ barns!
  - $P_\perp < h/R_A$, ~ 30 MeV/c for heavy ions
  - $P_{||} < \gamma h/R_A \sim 100$ GeV/c at the LHC
- k_{max} in target frame is ~ 600 TeV!
- $E_{\gamma p}$ (max) = 705 GeV for PbPb
- Strong couplings --> large cross sections



Why use UPCs to study parton distributions?

- UPC reactions can directly probe gluon distributions
  - Study ‘new phases of matter’ like colored glass condensates.
  - Understand initial state ions for central collisions
- ~ 10X higher photon energies than HERA
  - Several times lower x values for protons
  - >1 order of magnitude lower x for nuclei
- Smaller (or at least different) systematics than from pA collisions
  - No Cronin Effect

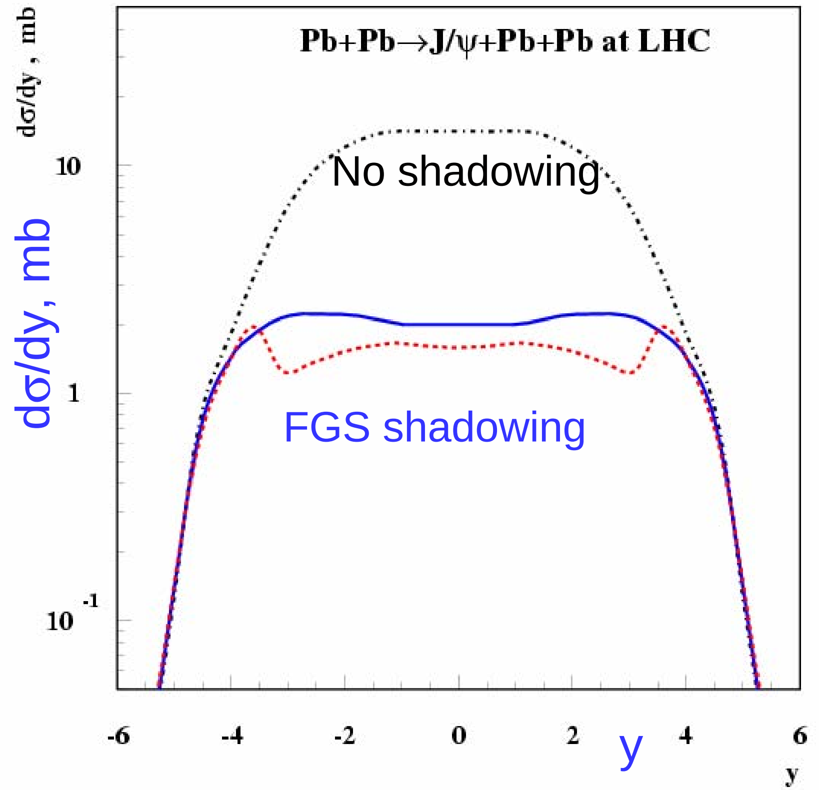
Vector Meson Production



- Quark-nucleus elastic scattering
  - Coherent enhancement to cross section
- Light vector mesons (ρ,ω,φ,ρ*…)
  - Soft (optical model) Pomeron
- Heavy vector mesons (J/ψ, ψ', Υ…)
  - Probe short distance scales
  - Scattering may be described via 2-gluon exchange
  - $\sigma(VM) \sim |g(x,Q^2)|^2$
    - $x = M_V/2\gamma m_p \exp(\pm y)$
    - $Q^2 \sim M_V^2$

The effect of shadowing

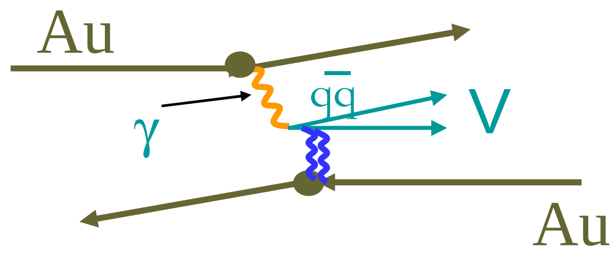
- $\sigma(VM) \sim |g(x,Q^2)|^2$
- Shadowing reduces cross section
  - Factor of 5 for one standard shadowing model
- Rapidity maps into x
  - $y = \pm\ln(2x\gamma m_p/m_V)$
    - $x = m_V/2\gamma m_p \exp(\pm y)$
- A colored glass condensate could have a larger effect



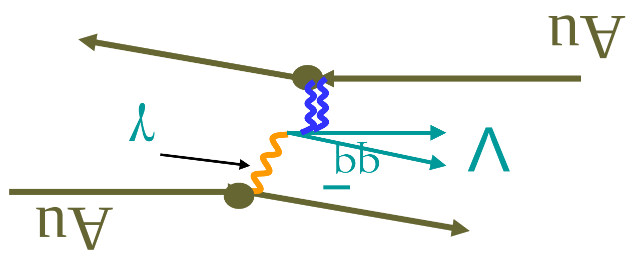
Frankfurt, Strikman & Zhalov, 2001

The 2-fold ambiguity

- Which nucleus emitted the photon?
  - x or k ~ $m_V/2\gamma m_p \exp(\pm y)$
  - Photon fluxes, cross sections for different photon energies (directions) are different
- 2 Solutions
  - Stick to mid-rapidity
    - For J/ψ at y=0, x= $6*10^{-4}$
  - Compare two reactions
    - Pb + Pb --> Pb + Pb + J/Ψ
    - Pb + Pb --> Pb* + Pb* + J/Ψ
    - Nuclear Excitation via additional photon exchange
    - 2 reactions have different impact parameter distributions
      - Different photon spectra
      - Solve system of 2 linear equations
    - Probe down to x ~ few 10^{-5}



Or…



Rates (w/o shadowing)

Table 8: Cross sections and median impact parameters b_m, for production of vector mesons with lead beams at LHC ($\gamma_{cm} = 2940$).

Meson	overall		XnXn		1n1n	
	σ [mb]	b_m [fm]	σ [mb]	b_m [fm]	σ [mb]	b_m [fm]
ρ^0	5200	280	210	19	12	22
ω	490	290	19	19	1.1	22
ϕ	460	220	20	19	1.1	22
J/ψ	32	68	2.5	19	0.14	21
$\Upsilon(1S)$	0.17	[]	0.025	[]	0.0013	[]

- J/ψ --> 32 Hz --> 30M/year
- ~ 3M Ψ' and 170,000 Υ(1S)
- 360,000 J/ψ --> e^+e^- with |y|<1 /year
  - ~3,600 Ψ' and ~1,000 Υ(1s)
  - Rate scales with rapidity coverage
- Rates are higher with lighter ions (higher L_{AA}) and pA

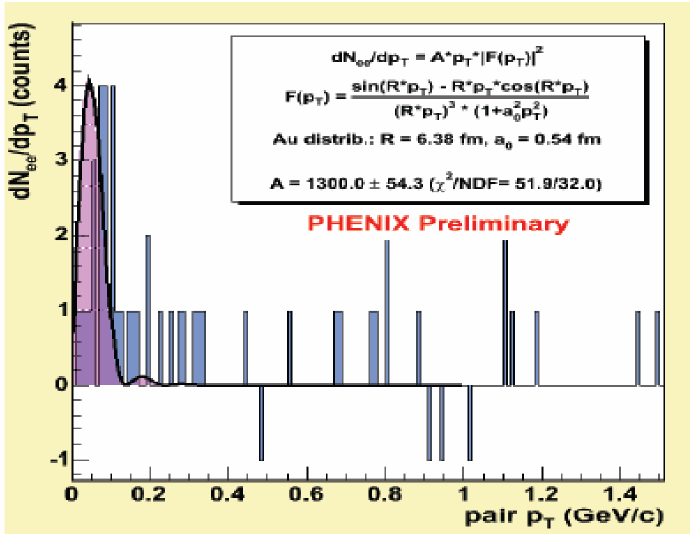
10^6 s run at $L=10^{27}/cm^2/s$

AA vs. pA vs. pp

- Exclusive J/ψ production can be studied in AA, p/dA and pp collisions
  - Rates are high with all species
  - With it's distinctive signature, signal to noise ratio should be high for all species
  - In p/dA collisions the photon usually comes from the nucleus, and strikes the proton/deuteron.
    - Avoids two-fold ambiguity for proton targets
- Measure parton distributions in protons and nuclei
- σ(AA)/σ(pA) gives a quite direct, low systematics measurement of shadowing

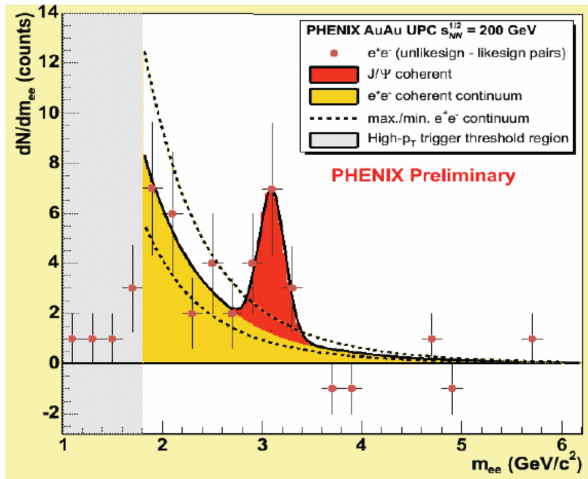
Reconstruction

- Exactly 2 tracks in event
- $p_T < 150$ MeV/c
  - leptons are nearly back-to-back
- PID as leptons with calorimeter or μ system
  - Some background from $\gamma\gamma \to e^+e^-$



PHENIX, QM2004

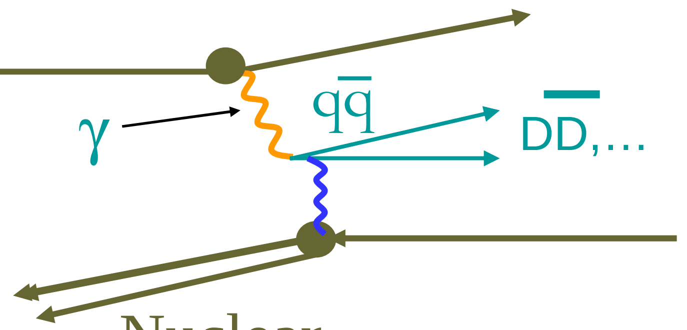
dN/dm_{ee} (background subtracted) w/ fit to (MC) expected dielectron continuum and J/Ψ signals:



Triggering

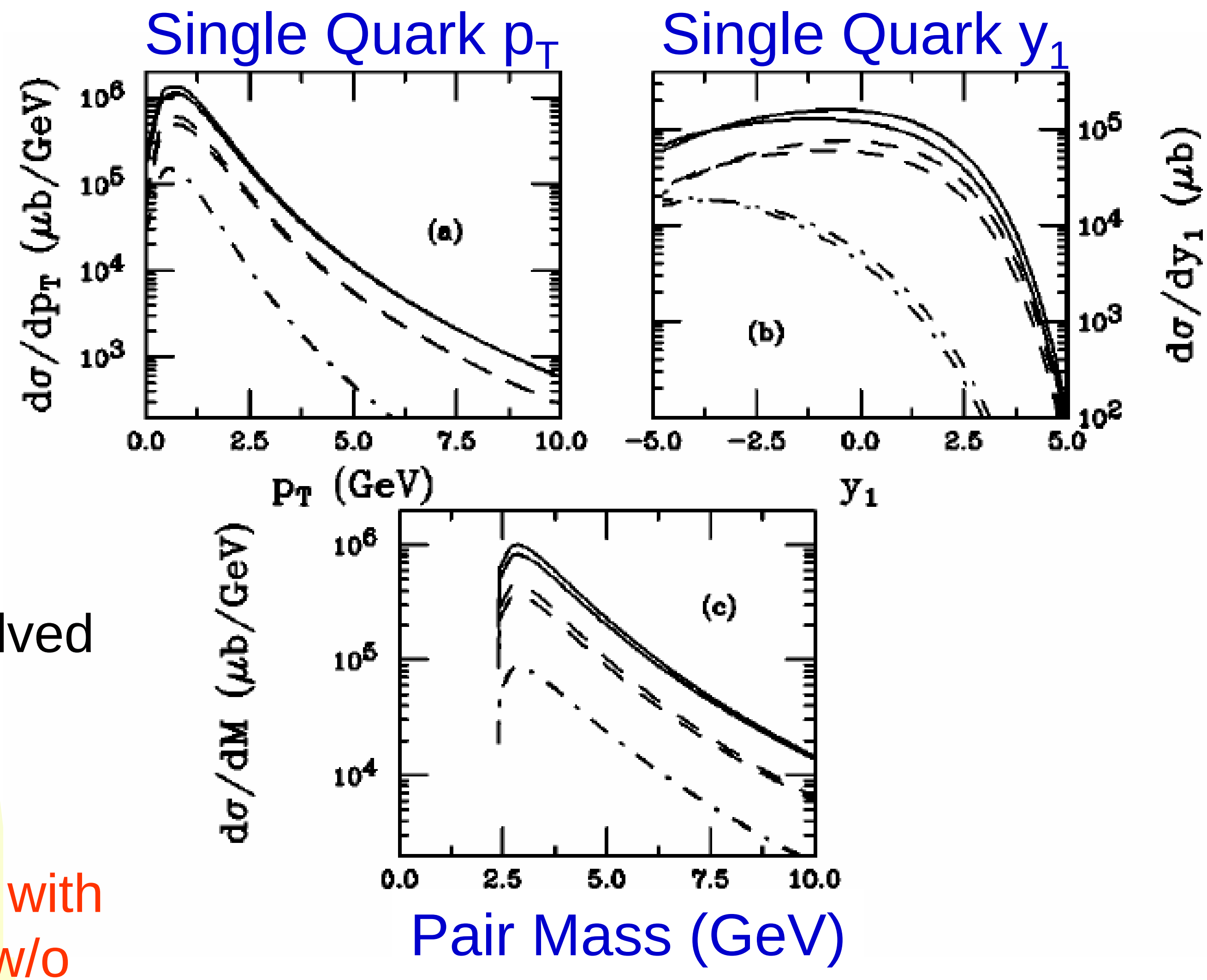
- Trigger on a vector meson + nothing else
  - 2 leptons, roughly back-to-back
    - For J/ψ, $p_T \sim 1.5$ GeV
  - Inital trigger based on leptons (+ low multiplicity?)
  - Dileptons, mass, p_T, angle cuts possible at higher levels
- No ZDCs in trigger
  - To study VM production both with and without nuclear excitation
  - ZDCs can't be used in Level-0, due to timing constraints, so aren't very useful.
- Biggest challenge for UPCs

Open Charm/Bottom



- Occurs via gluon exchange
  - Well described in QCD (& tested @ HERA)
  - Sensitive to gluon distribution
    - x and Q^2 depend on final state configuration ($M(Q\bar{Q})$…)
      - Wider range of Q^2 than vector meson production
- High rates
  - σ(charm) ~ 1.8 barns ~ 25% of $\sigma_{hadronic}$
  - σ(bottom) ~ 700 μb ~ 1/10,000 of $\sigma_{hadronic}$
  - (without shadowing)
- One nucleus breaks up
- $t\bar{t}$ possible in pA collisions
  - Measure charge of top quark

Charm kinematic distributions



Solid – Total
Dashed – Direct/2
Dot-Dashed – Resolved Photon Contribution

2 sets of curves are with EKS98 (small) and w/o shadowing

SK, Joakim Nystrand & Ramona Vogt, 2002

Charm Reconstruction

- $c\bar{c}$ reconstruction
- Well-understood techniques
  - Direct Reconstruction of charm
    - Should be feasible in all 3 large LHC detectors
    - Low efficiency to reconstruct both c and cbar
  - Semi-leptonic decay
    - Should be able to detect leptons from dual semi-leptonic decay

Separating Photoproduction and Hadroproduction

- Photoproduction of charm is very favorable
  - $P(\gamma \to c\bar{c}) \sim 4/10$
- Cross Sections are large
  - σ(charm photoproduction) ~ 1.8 barns
    - For lead at the LHC
    - No shadowing
  - σ(charm hadroproduction) ~ 240 barns

SK, Joakim Nystrand & Ramona Vogt, 2002

Rejecting Hadroproduction

- Single nucleon-single hadronic interactions
  - Eliminate more central reactions with multiplicity cut
    - σ_{1n1n} ~ 700 mb
    - σ_{1n1n}, with charm ~ 5.5 mb
    - $\sigma_{b>2R}$ with charm ~ 1100 mb
- One nucleus remains intact
  - Assume <10% chance
- Particle-free rapidity gap around photon emitter
  - P~ exp(-Δy dN/dy)
    - dN_{ch}/dy ~ 4.4 at midrapidity for pp the LHC
      - 40% lower at large |y|
    - For Δy= 2 units, P ~ 0.005
  - $\sigma_{remaining}$, with charm ~ 3 μb

SK, Joakim Nystrand & Ramona Vogt, 2002

Triggering

- Direct Charm decays
  - Trigger may be tough
- Semileptonic decays
  - Use leptons, as with vector mesons
  - May get some usage out of multiplicity detectors

Other channels

- Dijets
  - Large rates
    - $\sigma(E_T > 20$ GeV$) \sim 1$/minute
  - Separating photoproduction and hadroproduction may be difficult
- Photon + jet (Compton scattering)
  - Distinctive signature
  - σ (1% of dijet rate)

Ramona Vogt, 2004

‘New Physics’

- $\gamma\gamma$ --> Higgs --> $b\bar{b}$
  - Rate is very low
    - Probably not the ‘discovery’ channel
    - Most attractive with lighter ions, or pA (or pp)
  - Important in establishing the nature of the Higgs
    - Is it the standard model Higgs?
- Photoproduction of W^+W^-
  - Study γWW vertex
  - Can be sensitive to new physics
- $\gamma\gamma$ production of magnetic monopoles
  - $\gamma\gamma$ is the preferred channel

Other UPC@LHC studies

- Vector Meson Spectroscopy
  - Rates are very high
    - $\sigma(\rho)$ ~ 5.2 barns
    - $\sigma(\rho^*(1450/170)$ down by factor of 10
    - $\sigma(\omega,\phi)$ ~ 460-490 mb
- e^+e^- pair production
  - Tests QED in very strong fields
    - In grazing b=2R collisions ~ 5 e^+e^- pairs are produced
  - Enormous rates
    - Studied in ALICE; σ~13,000 barns in inner silicon
    - A trigger is probably not needed
- Quantum correlations in multiple Vector Meson Production

Conclusions

- UPC photoproduction is sensitive to parton distributions in ions and protons, and can test models of low-x behavior.
- Vector mesons and open charm can be studied at the LHC
  - The analyses seem relatively straightforward.
  - Attention to the trigger is required to collect the data required for these analyses.
- Many other UPC studies are possible
  - 'new physics'