Coherent Photonuclear Interactions at RHIC: Theory and Experiment

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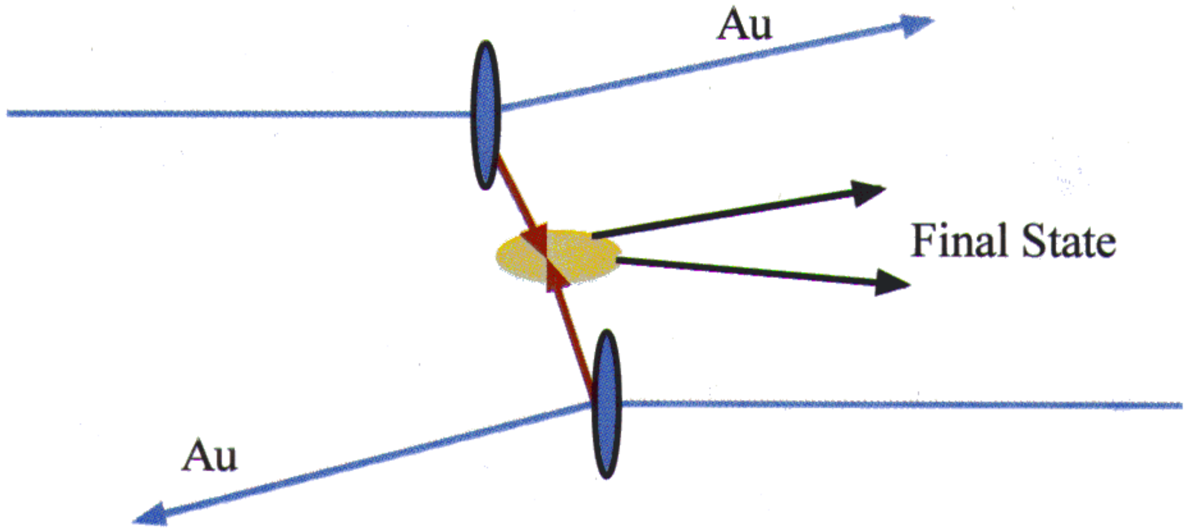
Coherent Interactions
Photonuclear Interactions preliminary
Vector Meson Lasers VERY preliminary
Peripheral Collisions with STAR
Signals & Backgrounds
Triggering
Conclusions

} STAR Collaboration is co-author

Colliding Fields from Heavy Ions



Ultra-relativistic nuclei act as sources of fields
- Electromagnetic fields - photons
- Strong force fields - pions/gluons
- Colorless strong force fields - 'Pomerons'

Nuclei act as coherent sources
- Strength ~ N^2
- Most intense electromagnetic collisions available

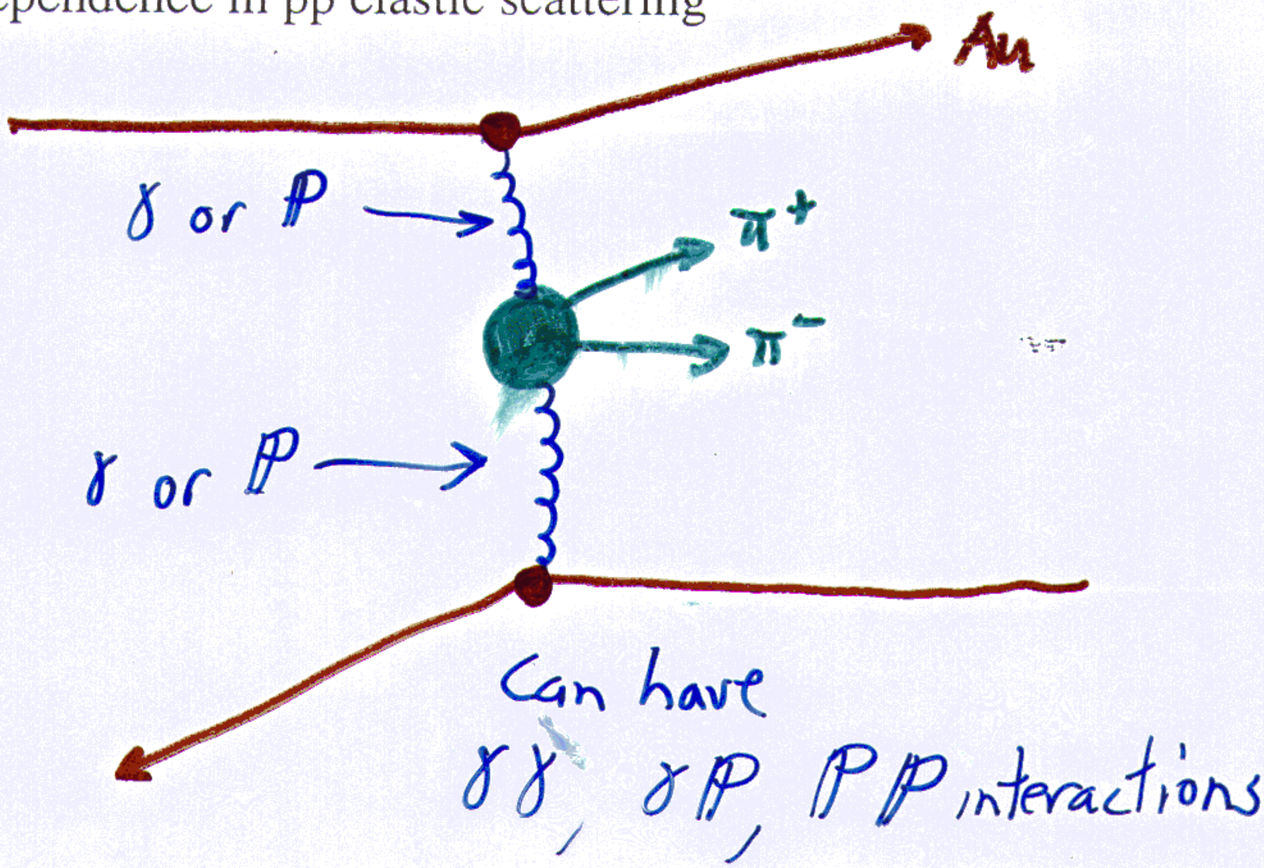
Coherent Couplings

The EM field of ultrarelativistic nuclei can be thought of as a virtual photon field (Weiszacker-Williams)

The Pomeron is a colorless object carrying the strong force, responsible for elastic scattering and diffractive hadron interactions.

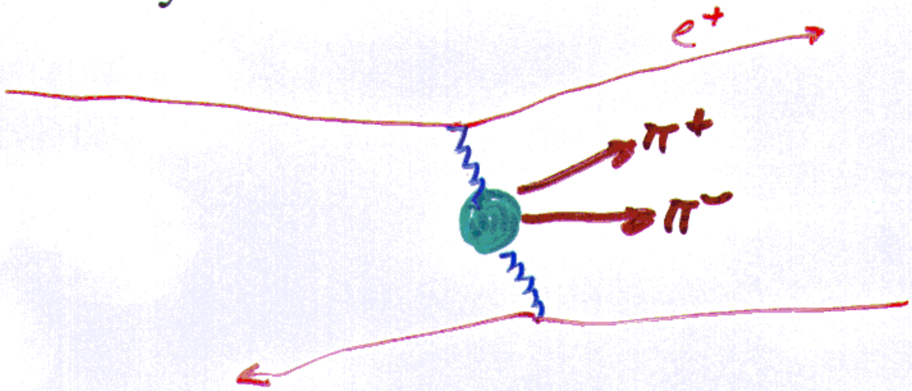
	γ	$\mathbb{P}$
Force	Electromag.	Strong
Couples to	protons	all nucleons
Coupling	Z^2	A^2 ($A^{4/3}$)
JPC	1^{--}	0^{++}
Range	infinite	short ~0.4 fermi ?

Pomeron range is measured by looking at momentum dependence in pp elastic scattering



Two Photon Interactions

Heavily studied at e+e- Colliders:



Couples to final states as (charge)^4
Spin 0 or 2 (for 2 massless photons)

- e^+e^- pairs - strong field QED $Z\alpha \sim 0.6$

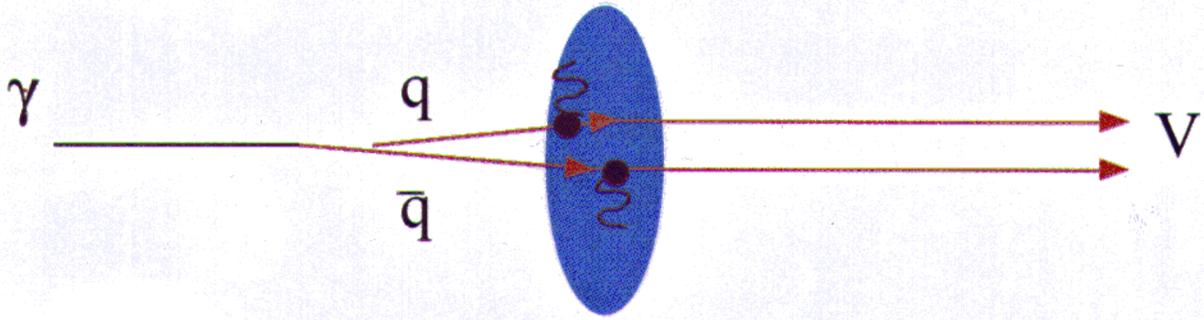
  e^+e^- pairs, with the e^- bound to the nucleus
- $\mu^+\mu^-$ pairs - luminosity monitor
- scalar/tensor mesons (exotica studies - glueballs)
- hadron pairs - quark structure of hadrons

  jet - photon fragmentation
- charmonium (for spectroscopy)
- $\tau^+\tau^-$ pairs

Pair production is diffractive

RHIC will have the highest $\gamma\gamma$ luminosity in the world for $W_{\gamma\gamma} \lesssim 1.5$ GeV

Photonuclear Interactions



A nucleus emits a photon

Weiszacker-Williams

The photon fluctuates to a $q\bar{q}$ pair (vector meson)

Prob ~ α; determined from $\Gamma(V \dashrightarrow e^+e^-)$

The meson elastically scatters off of the other nucleus

σ_{el} from $d\sigma/dt|_{t=0} = 16\pi\, \sigma_{tot}^2$ } from HERA & other $\gamma p \to Vp$ data

scaled from Vp to VA with Glauber calculation:

$\sigma \sim A^2$ (σ_{el} small; full coherence)

$\sigma \sim A^{4/3}$ (σ_{el} large; only sees surface)

Coherence limited by nuclear form factor

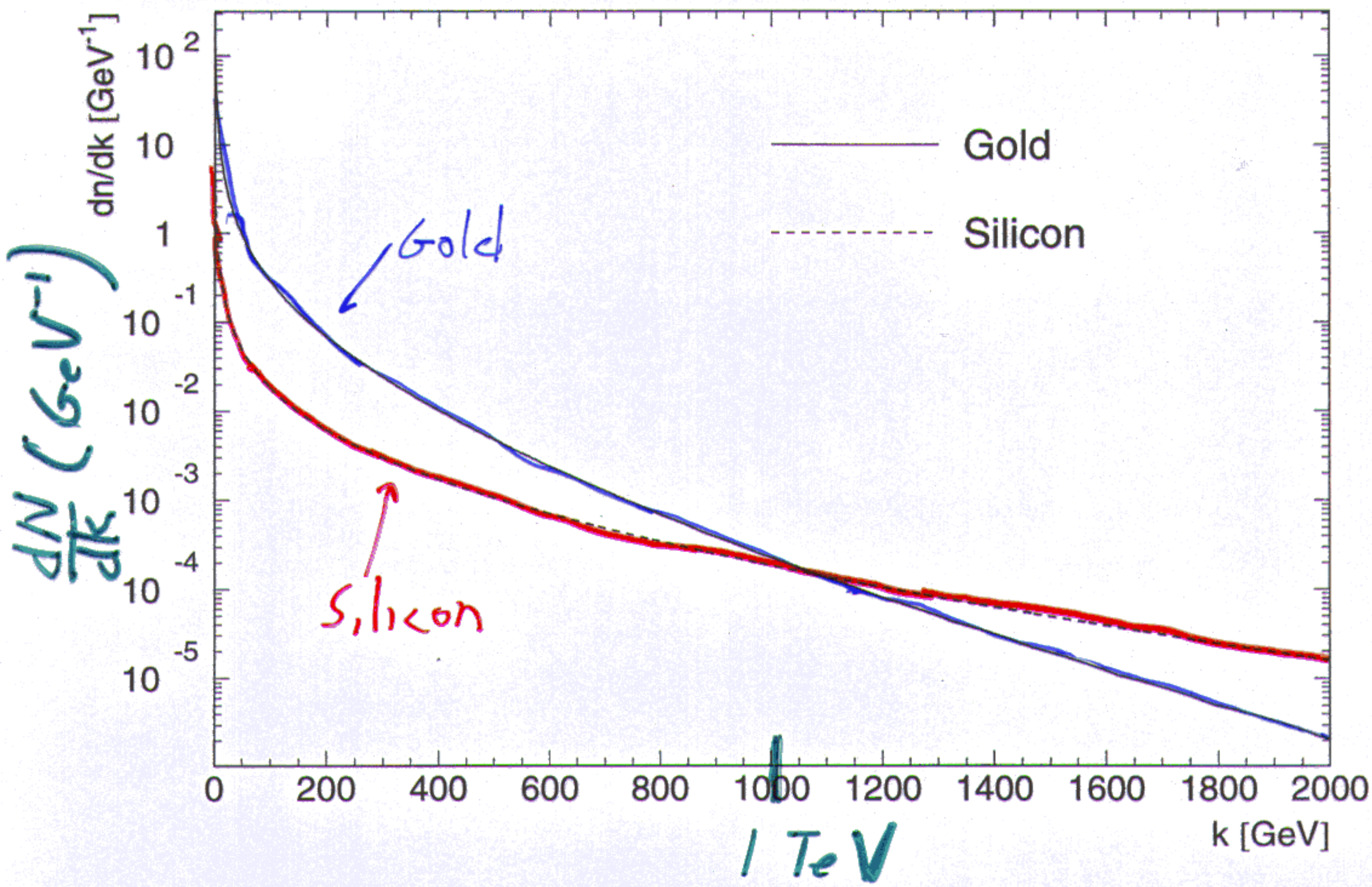
F(t) is convolution of hard sphere+Yukawa

very good fit to Woods-Saxon

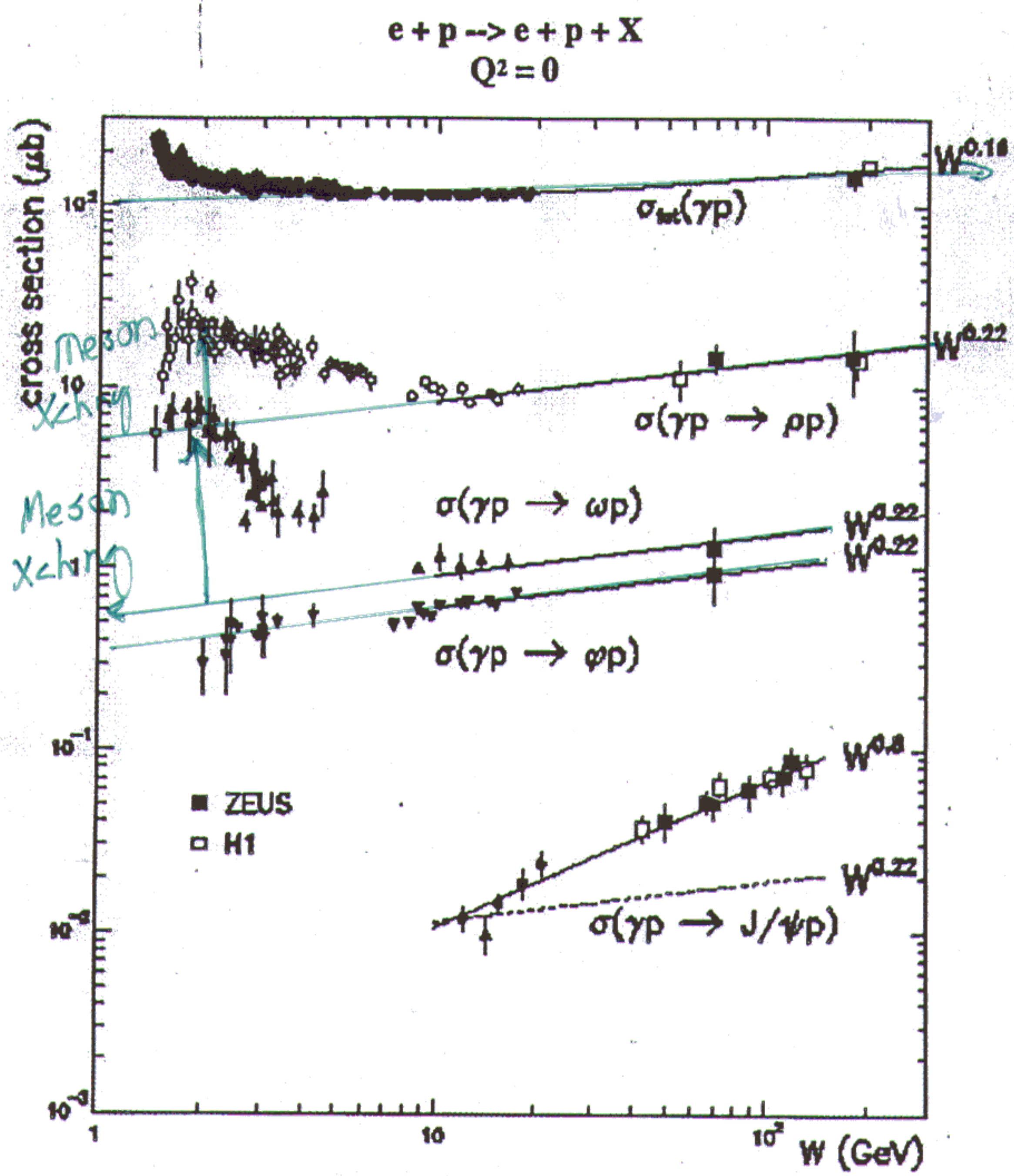
Exclusive Interaction --> No hadronic interactions

P(b) for no hadronic interactions; $\overline{N_{int}} \approx \sigma_{pp} T_{AA}(b)$

Photon Spectrum
(target frame)



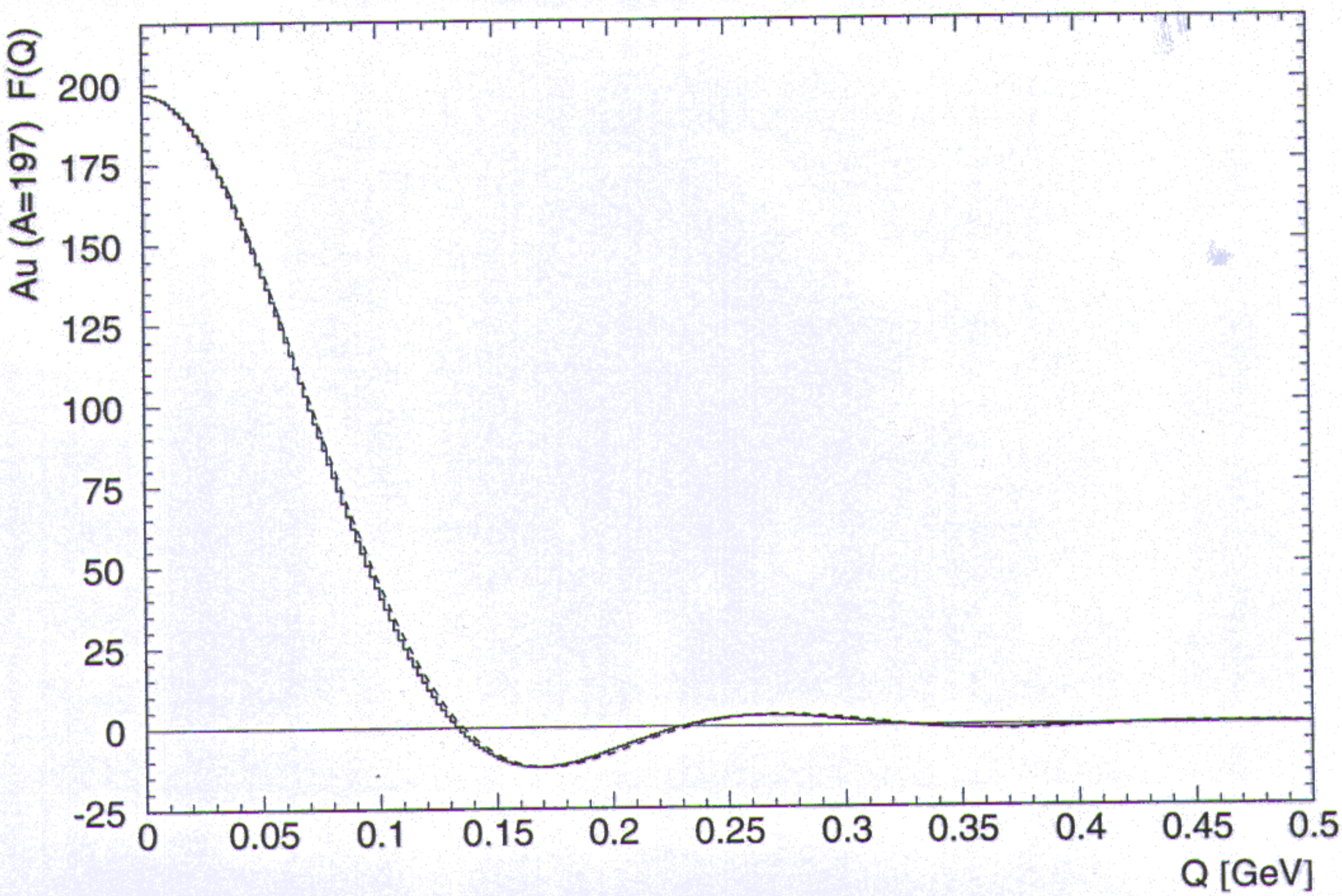
HERA data



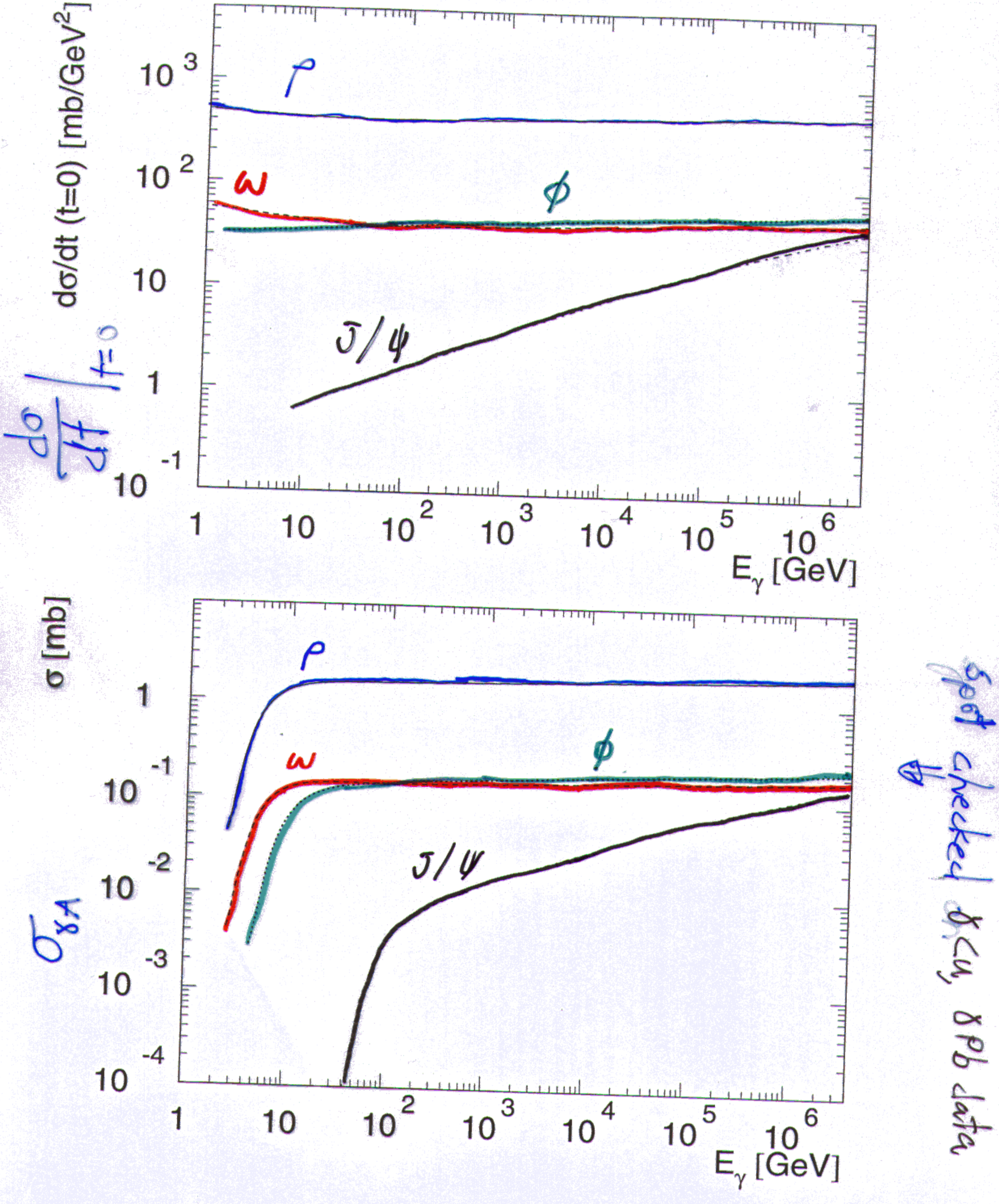
From A.T. Doyle, Talk presented at the Workshop on HERA Physics "Proton, Photon and Pomeron Structure" Durham, September 1995
http://ppewww.ph.gla.ac.uk/preprints/96/01/glasdiff/glasdiff.html

Meson Exchange will increase the rates. We do not yet include it.

Gold Form Factor



Woods-Saxon ⟺
Hard Sphere + Yukawa



dσ/dt (t=0) [mb/GeV²]
ρ
ω
φ
J/ψ
E_γ [GeV]
σ [mb]
ρ
ω
φ
J/ψ
E_γ [GeV]

Rates for γP --> Vector Meson

γ --> $q\bar{q}$ is from $\Gamma(V \to e^+e^-)$
$\sigma_{tot}(VA)$ is determined from data
σ(elastic) is found by an eikonal calculation
F(t) is based on a Woods-Saxon fit to the data
P(b) is based on $\sigma_{had}T_{AA}(b)$

$$\sigma(AA \to AAV) = \int dk\, N_\gamma(k)\, \sigma(\gamma A \to VA)$$

Rates at RHIC (Design Luminosity)

	Gold		Iodine	
	σ(mb)	Rate (Hz)	σ(mb)	Rate (Hz)
ρ	700	141	260	690
ω	62	12	25	66
ϕ	42	8	15	41
J/ψ	0.33	0.07	0.13	0.35

RHIC will be a vector meson factory!
LHC rates are 10-100 times higher!

Physics with Vector Mesons

Breakdown of soft Pomeron (J/Ψ & large p_t mesons.

$\gamma\gamma/\gamma N$ interference, through
$\gamma\gamma \dashrightarrow e^+e^-$ & $\gamma N \dashrightarrow V \dashrightarrow e^+e^-$

Higher Resonances: ρ^{*0}, ω^{*0}, etc.

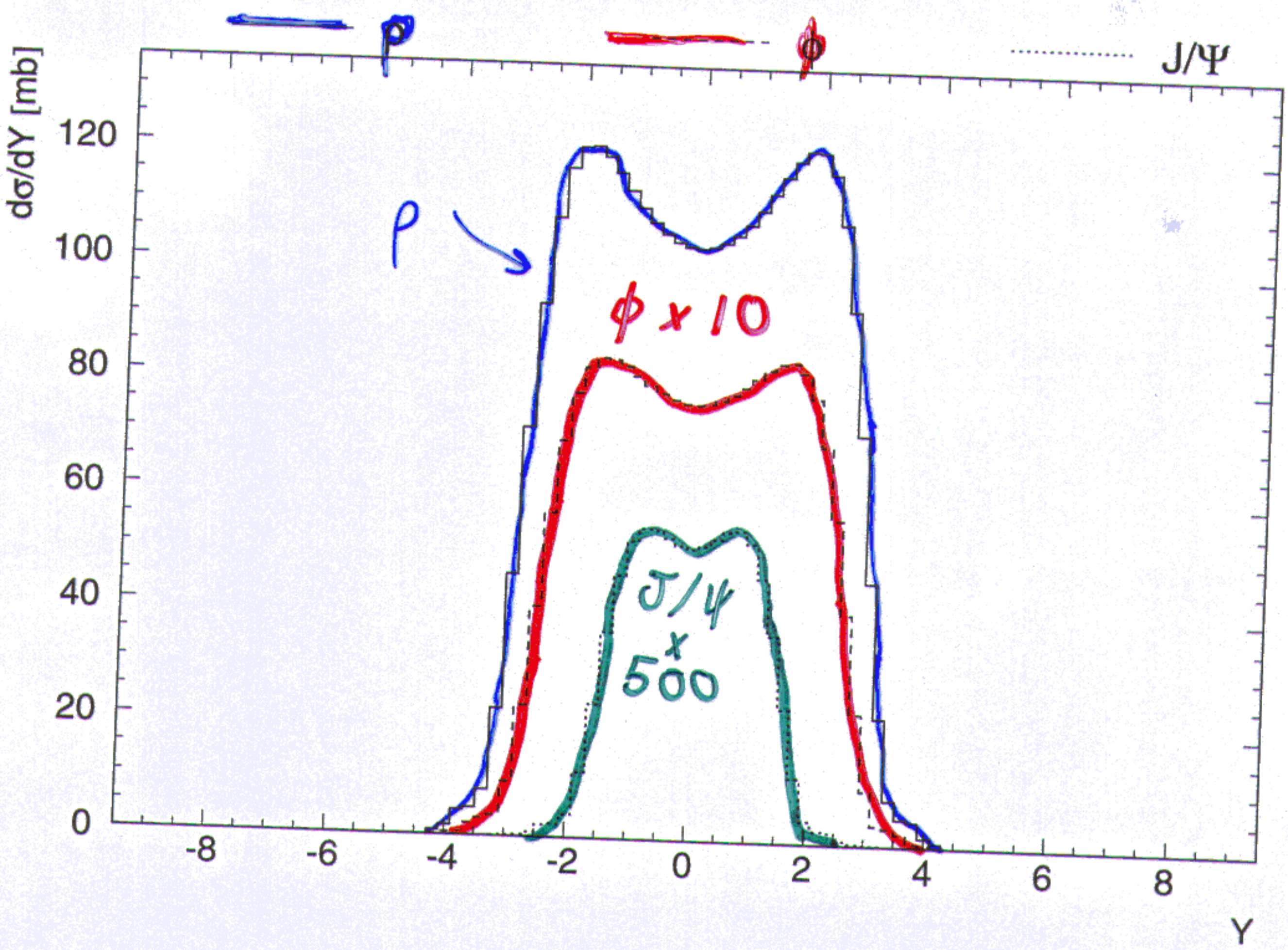
Rare Decays

Nuclear Excitation in Pomeron exchange

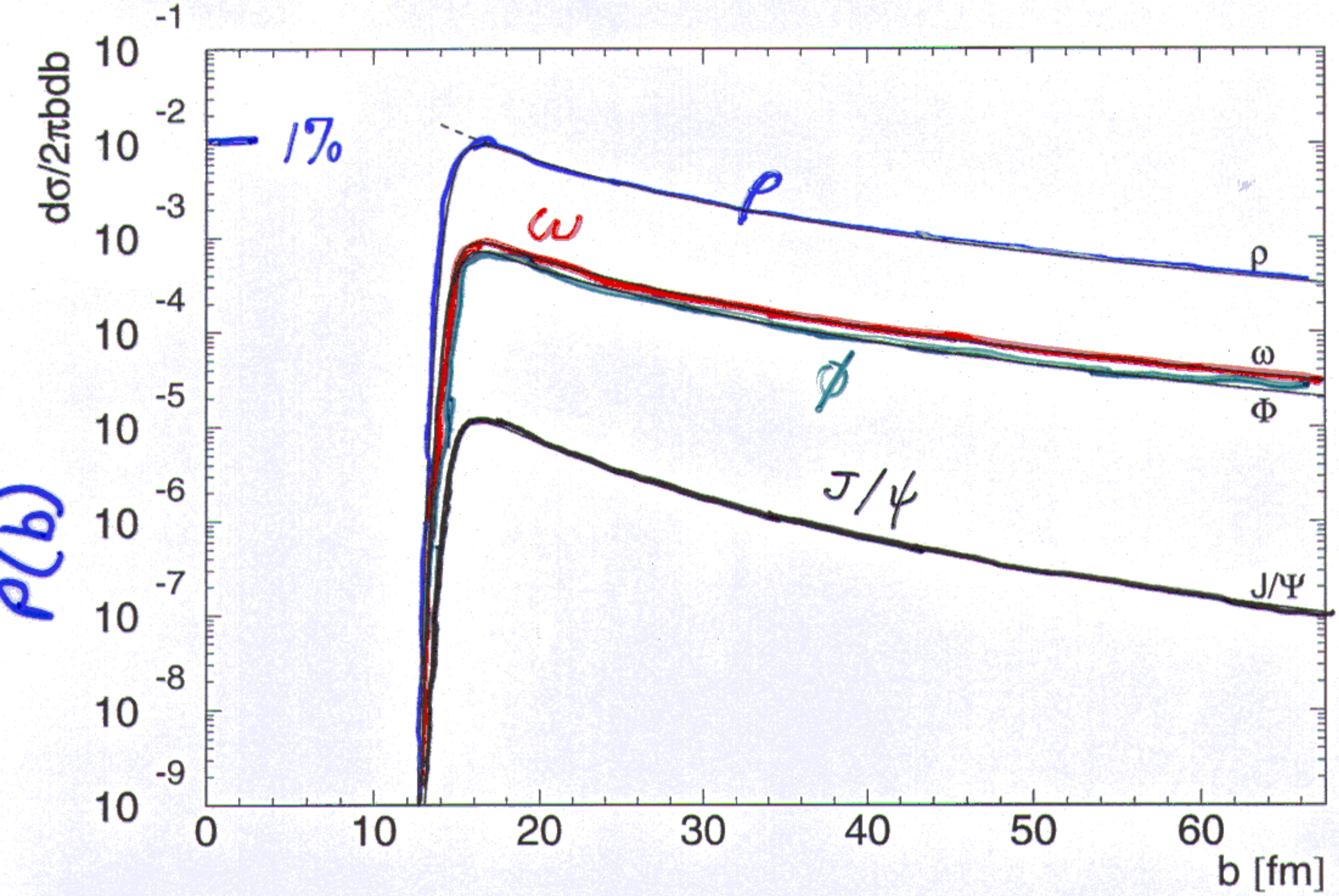
Precision Measurements of Nuclear Form Factors

Rapidity Distribution

$$y = \ln \frac{k}{2M_V}$$



Impact Parameter·



Vector meson pairs

Probability(b=2R) ~ 1%

IF (let us pretend for a moment)

there are no correlations, then

P(2 interactions at b=2R) ~ 1/2 $(0.01)^2$

P(3 interactions at b=2R) ~ 1/6 $(0.01)^3$

Total rate:

$$N_{pair\,(2\rho)} = \int 2\pi b\,db \left(\int dk \frac{dN(b)}{dk}\right)^2 \frac{1}{P(b)}$$

(correlations between b and k are ignored)

Pair rates at RHIC for gold beams

	σ(μb)	Rate/year
ρρ	720	1,400,000
ωω	6.3	12,500
φφ	3.8	7,600
ρφ	52	105,000

Multiple Photons

Weiszacker-Williams is accurate for single photon production.

What about multiple photons?
From different nuclei --> independent
From same nucleus --> ???

Weiszacker- Williams gives
$\langle N\gamma \rangle \sim |I(\omega,b)|^2 \Delta\omega$

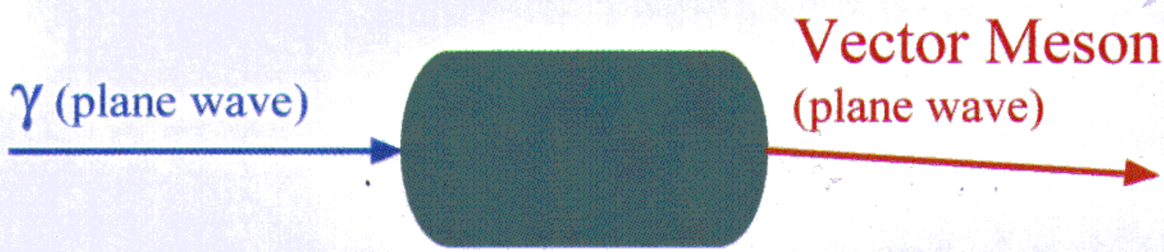
Virtual photon lifetime >> other time scales in problem

Actual number of photons follows a Poisson distribution.

Stimulated Emission

γ --> qq fluctuations, elastic scattering should be independent, except for stimulated emission

The amplitude for emitting a boson $\sqrt{N+1}$ where N is the number of bosons in that state



Formation Zone

Radius ~ nuclear radius
length - formation length $l_f = h/\Delta p_Z$ - distance over which the γ and VM waves maintain coherence

The two photon/vector meson waves must maintain coherence over this volume.

$\Delta p_X < h/R_A$ $\Delta p_Y < h/R_A$ $\Delta p_Z < h/l_f$

Must also have same spin

P_Z & Coherence

The length of the elastic scattering is l_c, determined by the kinematics

$$l_c = \frac{2\hbar k}{M_V^2} \gg R_A \text{ in target frame}$$

2 mesons are in 'the same state' if

$$\frac{\Delta k}{k} < \frac{\hbar}{k l_c} = \frac{M_V^2}{2k^2}$$

In the target frame.

This does not appear Lorentz Invariant. But, in other frames, the momentum transfer has additional components.

Momentum bite

For the ρ, at mid-rapidity k=70 GeV

so $\Delta k/k \sim 10^{-4}$

In CM frame

$4k_\gamma k_p = M_V^2$

$y = 1/2 \ln (k_\gamma/k_p)$

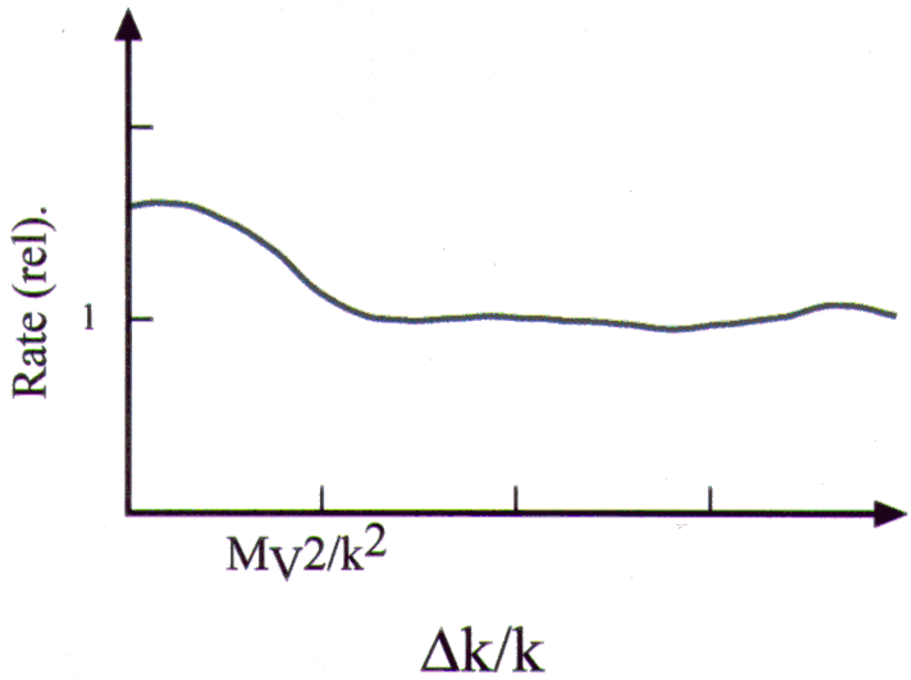
In target frame

$$\frac{\Delta k}{k} = \frac{e^y}{\gamma^2}$$

Averaging over y (cross section weighted)

Average probability $\sim 4*10^{-4}$

Detection & Rates



Preliminary!!

Number with $\Delta k/k < Mv^2/k^2$

~ 5600/year with gold

w/o enhancement

Can't tell where photon came from. Assume it is lower momentum; uncertain around y=0

Height of enhancement ~ 1.7 w/o spin

1.3 w/spin

Net excess ~ 1700 events

What's missing?

Final State Interactions

$\rho^0\rho^0$ --> $\rho^+\rho^-$

Probably not too large(?)

Correlated decays because of spin

May enhance same-spin pairs

Other correlations in decays

$\tau_\rho > t_c$, so it's not too likely

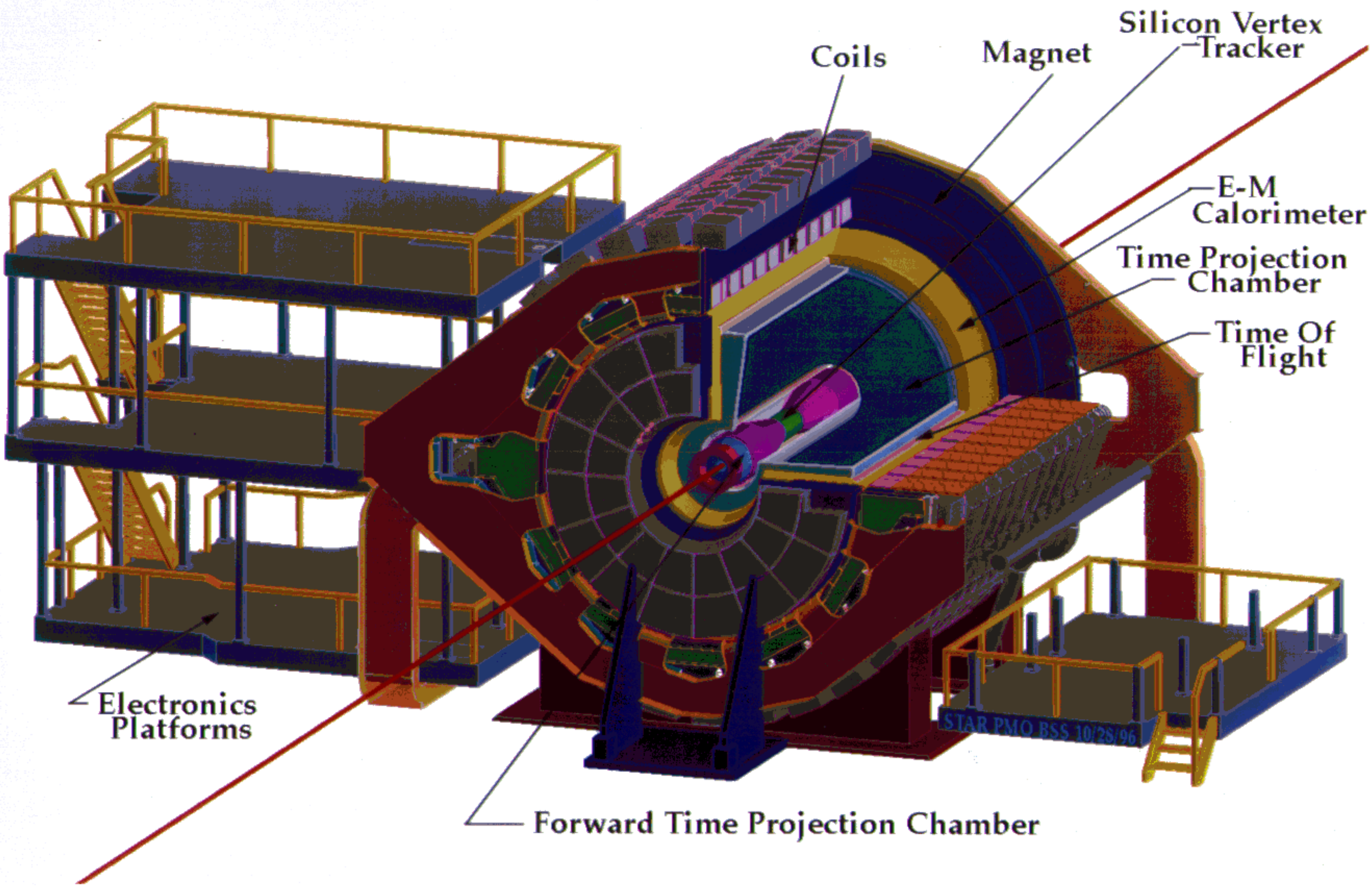
ρ^0 width

There may be two acceptable pairings from the 4 charged particles. Can reduce with $p_t < 50$ MeV/c cut on each

$\gamma\gamma$ --> $\rho^0\rho^0$ background

small

STAR Detector



Separating Signals from Backgrounds

Nothing Else in the Event

(Rapidity Gaps)

P_t balance

Coherent Coupling--> Final state p_t < 45 MeV/c

Backgrounds p_t ~ 300 MeV/c

Outgoing Nuclei ~ mostly undisturbed

'Signal' event nuclei may break up by
giant dipole resonance excitation.

Complete Reconstruction

Charge, strangeness, etc. conservation

Backgrounds

Grazing Nuclear Collisions (FRITIOF & VENUS)

γN Interactions (DTUNUC)
w/ 1 rapidity gap.

Beam Gas (FRITIOF & VENUS)

- 10^{-9} Torr in IP, 10^{-10} at ends
  Mostly a problem for triggering

Cosmic Ray Muons (HEMICOSM)
A problem for triggering only

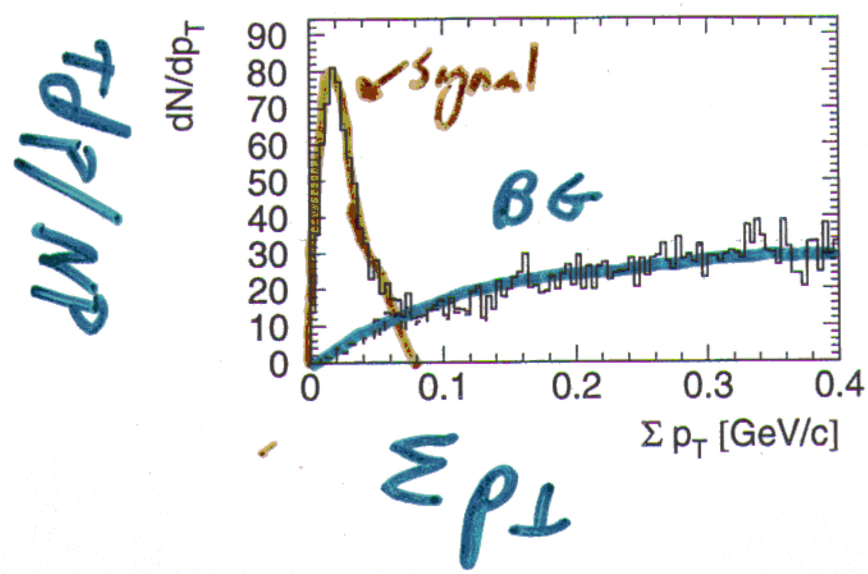
Upstream Beam Interactions (Alan Stevens)
Not a problem

For analysis, γN interactions are the largest background.

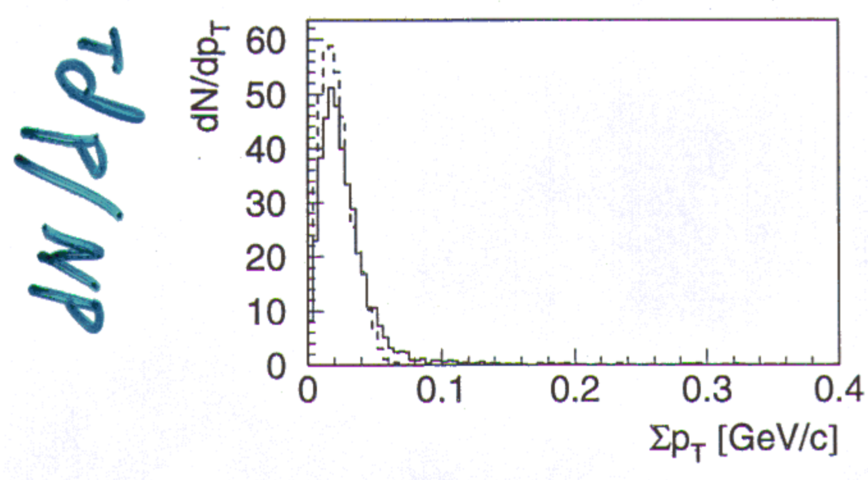
For early triggering, beam gas is probably the biggest background.

Final State $p_\perp$

$\gamma\gamma \to \rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$



Before / after Simulation + Reconst.



work in progress!

SNR's: 2 Case Studies

$\gamma\gamma \rightarrow f_2(1270) \rightarrow \pi^+\pi^-$

$q\bar{q}$ meson; decays to 2 prongs

Detected Signal: 660,000 events/year

Backgrounds	FRITIOF	VENUS
Grazing Nuclear	1,000	5,000
Beam Gas	1,000	1,000
Photonuclear	24,000	24,000
	26,000	30,000

$\gamma\gamma \rightarrow \rho^0\rho^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$

observed bump at threshold (1.5-1.6 GeV)

Detected Signal: 12,000 events/year

(γAu + γAu + 100 x bigger)

Backgrounds	FRITIOF	VENUS
Grazing Nuclear	200	800
Beam Gas	100	100
Photonuclear	1,200	1,200
	1,500	2,100

Triggering

Low multiplicity in large solid angle

Multi level trigger

Level 0: 2-5 tracks with $|\eta|<2$
timing to reject cosmics
some topological cuts

Level 1/2: 2 or 4 tracks with $|\eta|<2$
more topological cuts

Level 3: tracking info
vertex in diamond
Σ charge=0
$\Sigma p_t < 100$ MeV/c
nothing in FTPC

Rates close to acceptable at all levels

Conclusions

Coherent Interactions at RHIC access a large range of physics:

- $\gamma\gamma$ stronge field QED, meson spectroscopy
- Photonuclear- Pomerons, meson decays
- $\gamma\gamma$ /Photonuclear interference

Vector Meson stimulated emission (lasing) should be observable at RHIC

The STAR detector is preparing to do this physics. The large solid angle and flexible trigger are important elements in it's success.

By selecting specific final states with low pt, good signal to noise ratios may be obtained in variety of analyses.