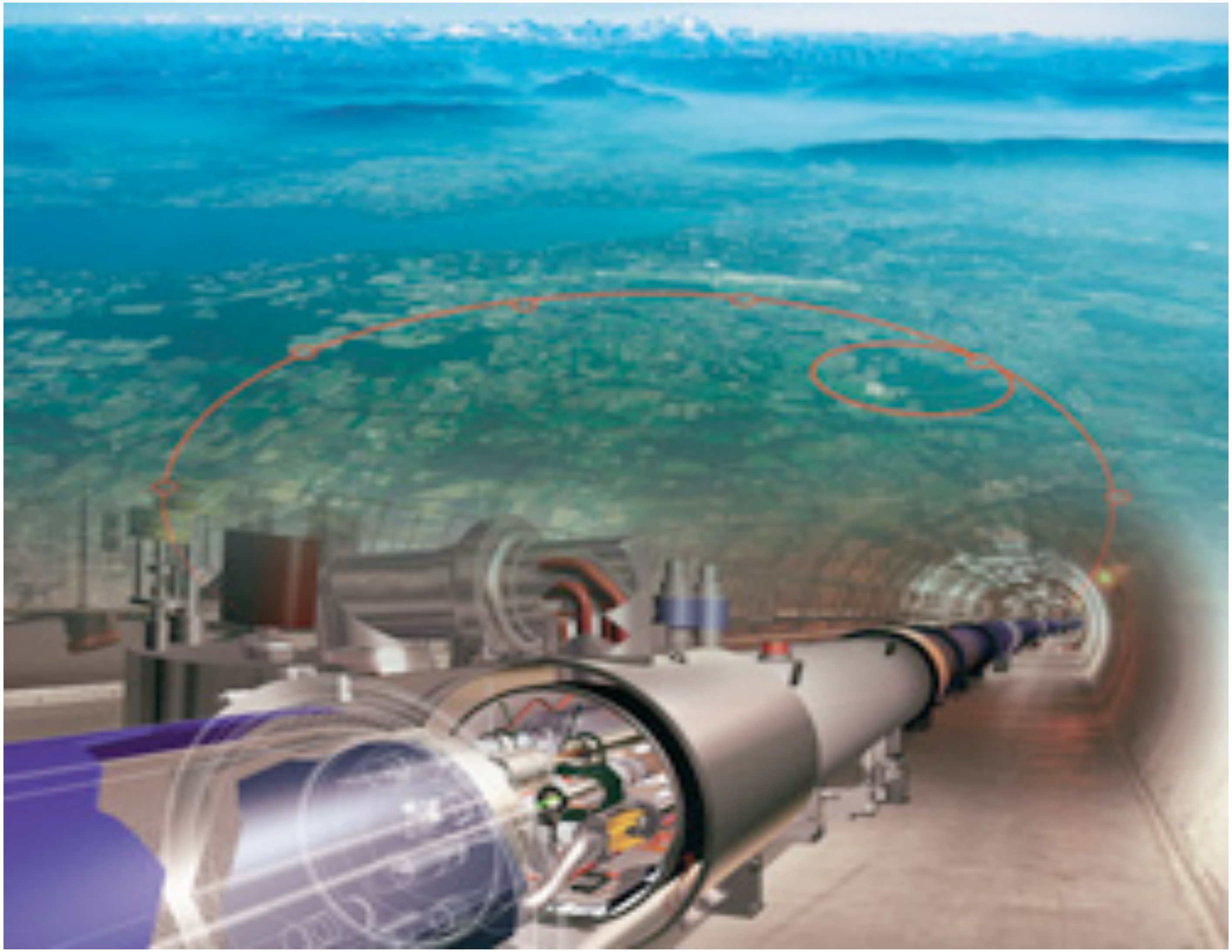
Topics in Forward Physics at RHIC and the LHC



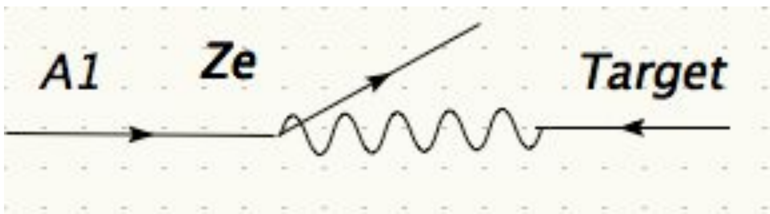
Sebastian White, Brookhaven XII Mexican Workshop Mazatlan Nov. 10 '09

Outline

- about 2009
- Hard Photoproduction
  - Method of equivalent quanta
  - applications in particle and nuclear physics
  - quarkonia at RHIC, LHC (and eIC)
- Coherence and diffraction
- Charge Exchange- forward neutron production and asymmetry at RHIC
- Potential for New Physics at the LHC

"Forward Physics"

- small momentum transfer to beam particle
- ie ATLAS-ALFA elastic scattering (nuclear +Coulomb): |t|=p_T^2~(10-20 MeV $)^2$
- coherence enhances diffractive σ's
- at LHC soft colorless exchange(γ,"g-g",$\pi^{\pm}$) can have very hard interaction with the target



- will discuss: Heavy Ion photoproduction, d-Au diffraction dissociation, forward n,CEP-Higgs
- not covered:fragmentation in RHIC/LHC HI

2009 startup of LHC at CERN

- Post WWII experiment in international collaboration
- US an observer state. Cooperative agreements with Mexico and Brazil
- 3 Nobels (Charpak, Rubbia, Van derMeer)
- Home of the world wide web-"Information Management" proposal 04/89
- Most complex scientific project ever

- First lab to accumulate antimatter

- Sited on Swiss-French border near Geneva

Sur le terrain du futur institut nucléaire

Sous la conduite de M. A. Picot, les membres du Conseil européen pour la recherche nucléaire se sont rendus hier à Meyrin pour reconnaître le terrain où s'élèvera le Centre nucléaire (voir en Dernière heure)

(Photo Freddy Bertrand, Genève)

***La Suisse* du 30 octobre 1953**

100 years of subatomic Structure

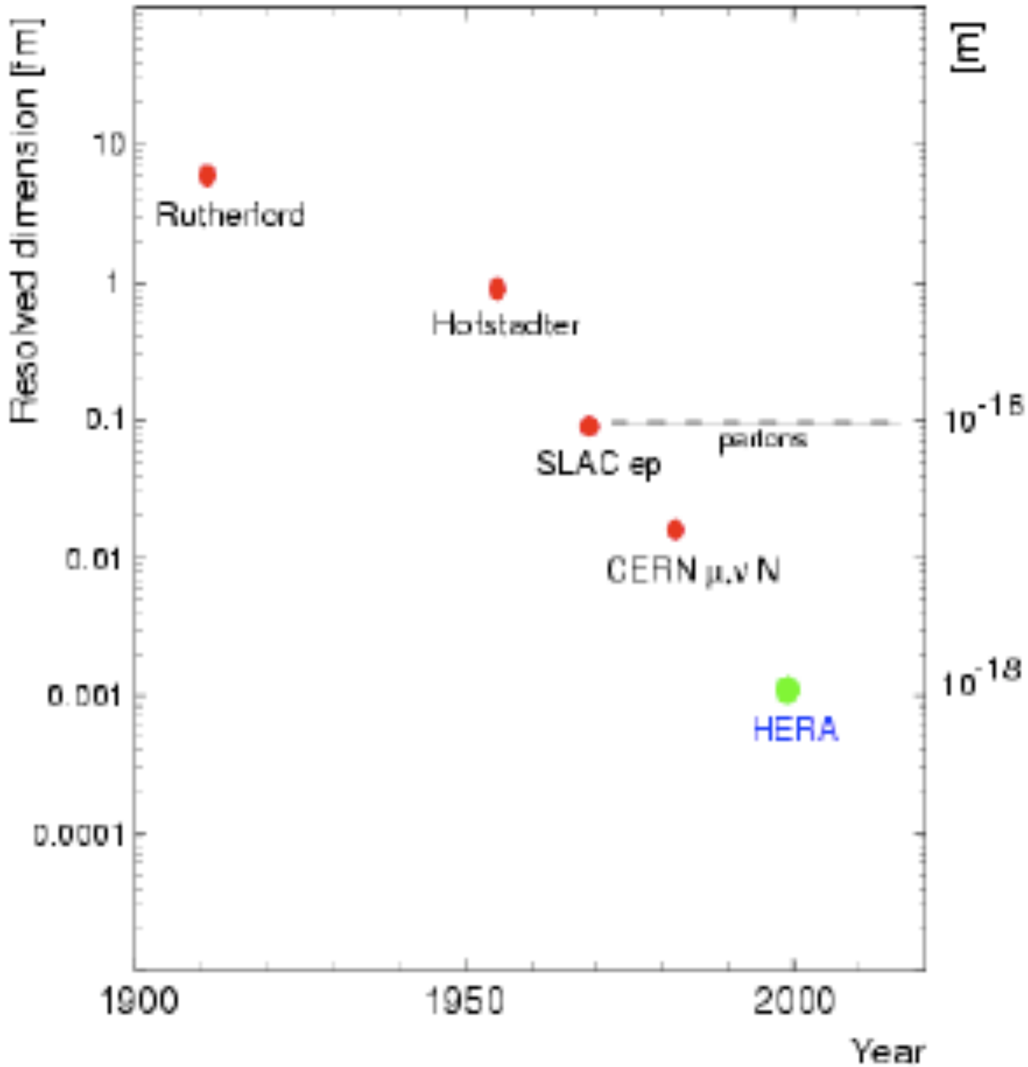
- Rutherford, Geiger, Marsden (1909)
  - Atom's 100th Birthday!
  - Rutherford's teacher, JJ Thomson, discovered electron 10 years earlier
- "counter experiment"
  - Beam of 5 MegaVolt α particles

  from Radium C decay
- R. showed that α= Helium Nucleus

JJ Thomson & Ernest Rutherford

Resolving Power: Radius (electron,quark)<10^{-8}* Radius (atom)

i.e. 1 centimeter/(New York-> Mazatlan)



- Stanford (Hofstadter) measured size and profile of nucleus and proton
- SLAC saw first evidence for quarks
- 2009-> quarks and electrons don't have substructure

Electrostatic Accelerators

- Cockroft-Walton

  (~1 Megavolt)

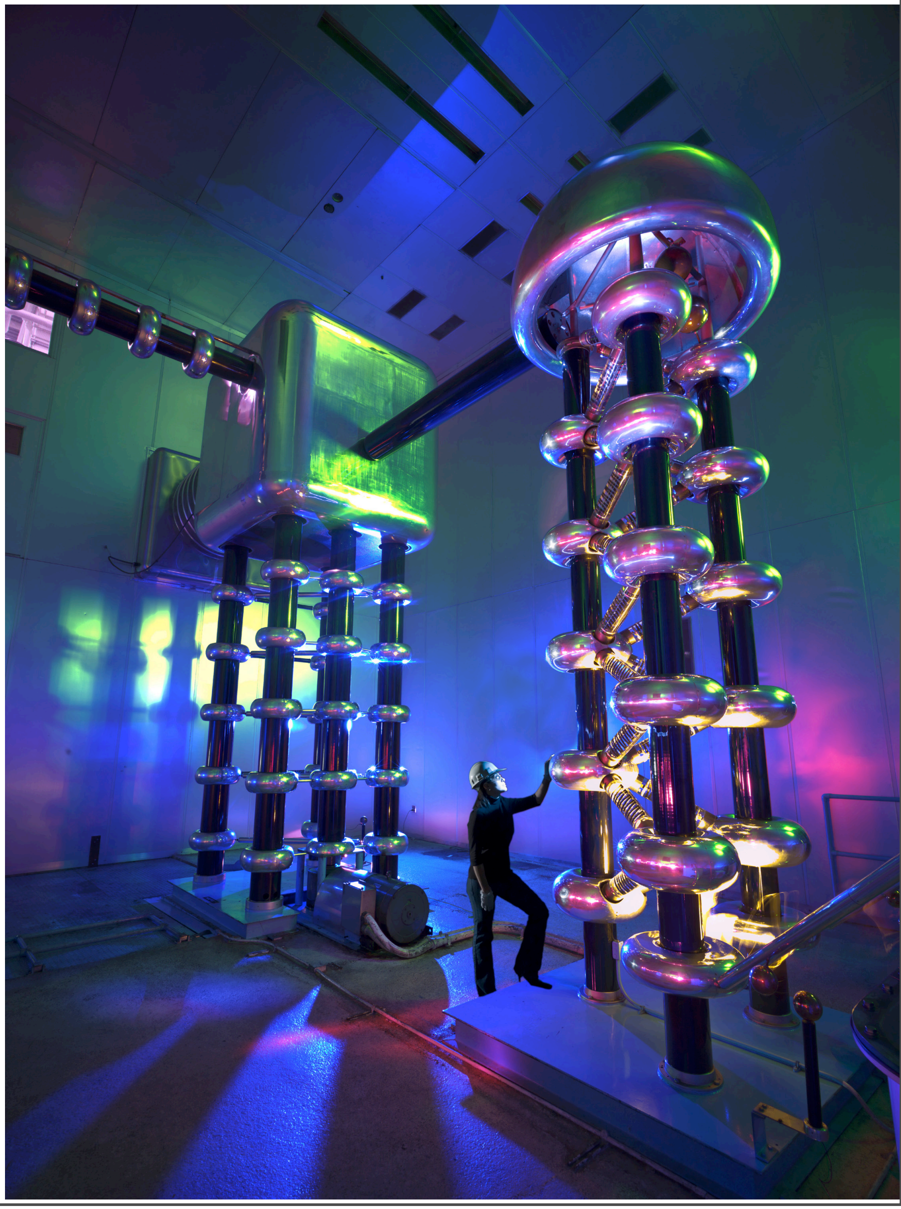
- Rutherford α's

  (~5 Megavolt)

- Van der Graaf

  (10 Megavolt)

- Above 10 MeV use high field RF (0.1-1 GigaHz) up to 10's MeV/meter



Colliders

Center of Mass Energy (E_{CM})

•Stationary Target:

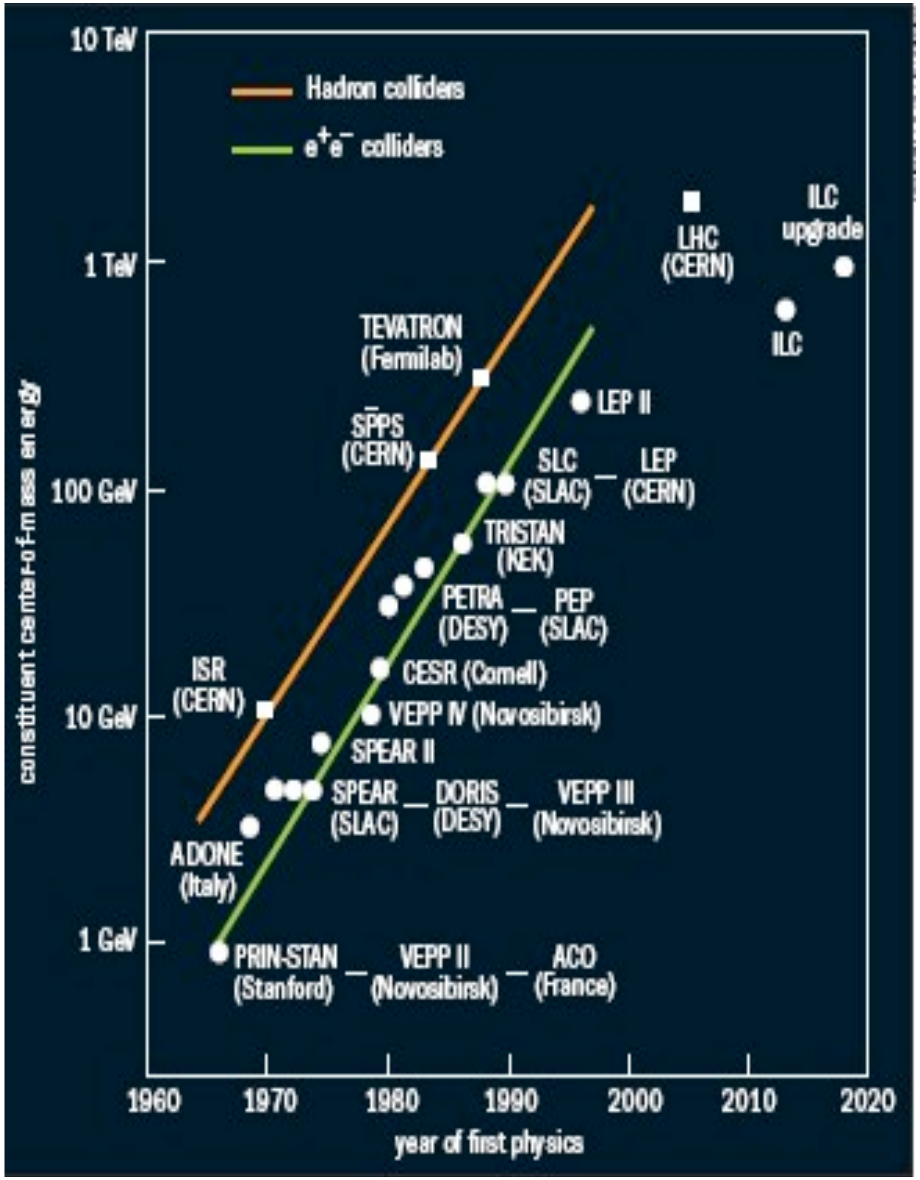
E_{CM}= $\sqrt{2 \times E_{Beam} \times M_{TARGET}}$
i.e. 7 TeraVolt beam->E_{CM}=0.12 TeV

•Collider:

$E_{CM}=2* E_{BEAM}$
i.e . E_{CM}->14 Teravolt

Constituent E_{CM}

If the proton is composite
E_{CM}->2*E_{BEAM}*f,
f= momentum fraction of the quarks

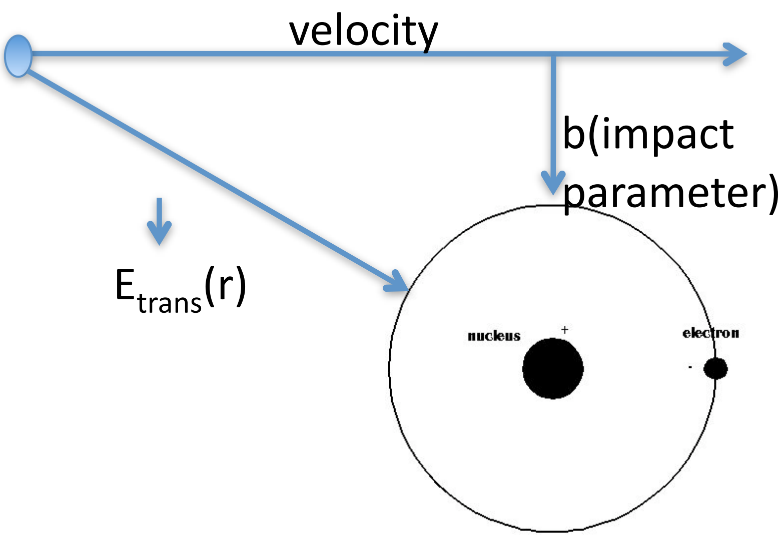


The Large Hadron Collider

- Total Beam energy:
  - **N_{proton}=27km*Frequency*(10^{11}proton/bunch) /c**
    ->E_{total}=N_{proton}*7*10^{12}eVolt=400 MegaJoule
    (=3 locomotives at top speed)
- Magnetic Field:
  - **E_{proton}(GeV)=15*B(kilogauss)*Rad_{LHC} (km)-> B=84 kgauss**
- Magnet Temperature: **2^{o} Kelvin**
- Interaction Rate: **1 GigaHertz**
- Radiation Dose/year:
  - **2*10^{14}neutrons/cm^2(Si), 5 Gigarad (Zero Degree Calorimeter)**

Inelastic Scattering: The Equivalent Photon Approximation

"On the theory of Collisions between Atoms and electrically Charged particles" E.Fermi translated by M.Gallinaro and SNW



$$E_{trans} = \frac{q \times b}{(b^2 + v^2 t^2)^{3/2}}$$

Expand in harmonics:

$$E_{trans} = \sum a_n^2 Cos(\frac{2\pi n \times t}{T})$$

$\Rightarrow$A "field of light" with intensity a_n^2 at frequency n/T

For resonant excitation all a_n ineffective except at resonant frequency.

Cross sections

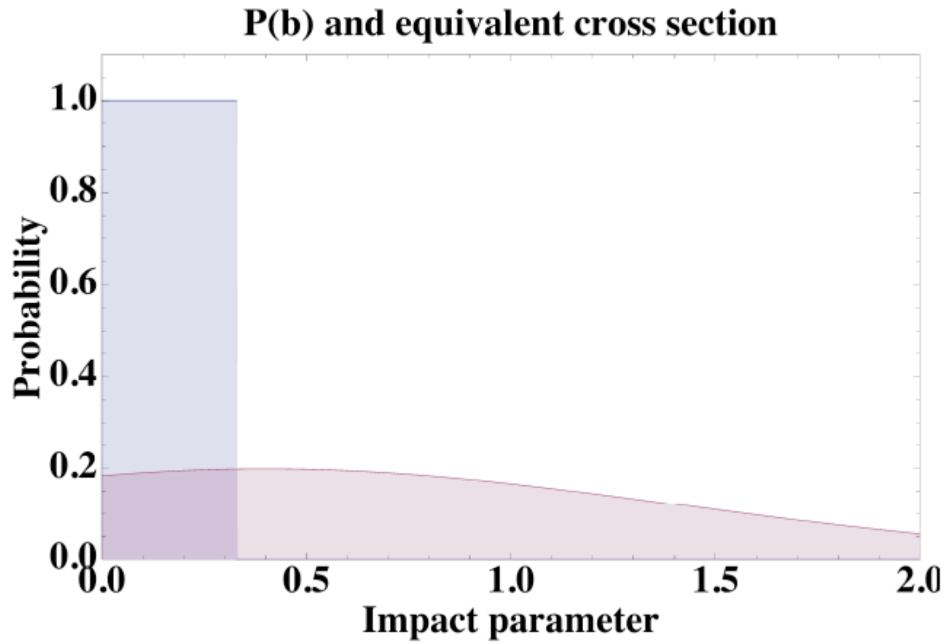
Equivalent field of light is calculated for each impact parameter.

But Impact parameter unmeasurable (i.e. ~10^{-10} meters)

->calculate an equivalent radius

$$\pi\rho^2 = 2\pi\int b\times P(b)\times db = \sigma$$

-> cross section (σ)



Units:

1 barn= 10^{-24} cm^2

1barn/atom->~1 interaction for typical target

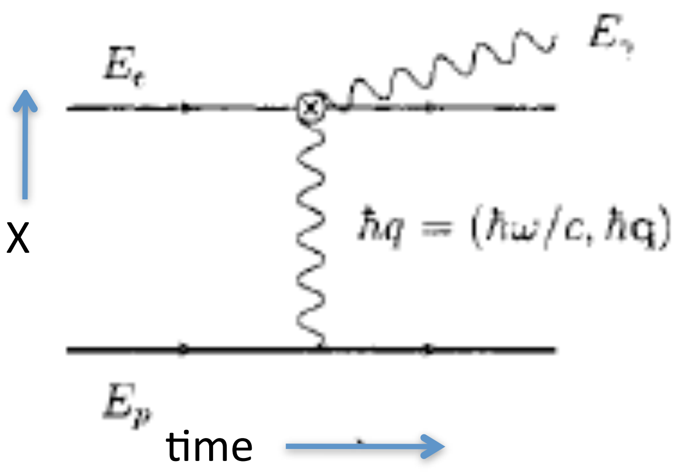
Examples:

Gold+Gold->e^+e^-+Gold+Gold	= 33,000 barns
Proton-proton Interaction	~0.1 barns
Diffractive Higgs@LHC	=10^{-14} barn

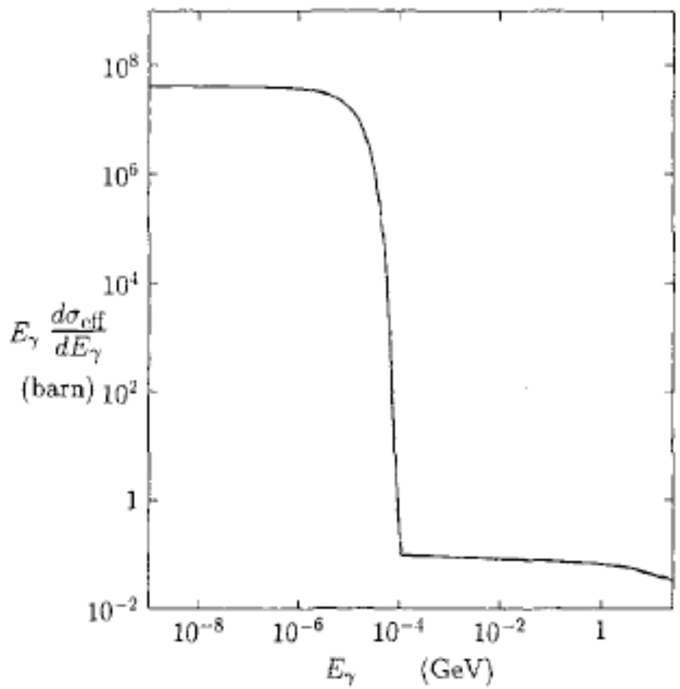
Other Applications of Equivalent Photon Approximation(1)

- N.Bohr (1914), C. von Weizsacker and E.Williams(1934, generalization to ultrarelativistic case)
- The power of coherence: beamstrahlung in electron-proton colliders(V.Serbo et al. 1996). Coherent radiation off ~10^9 proton bunch (l~ 1cm)

Coherence condition:



$$E_\gamma \leq 2\frac{\gamma^2{}_{Lorentz}hc}{l_{bunch}\pi}$$



EPA(2)

- The effect of coherence is significant in collisions with composite targets
  - **Single photon process** **$\to (Z_{nucleus} * q_e)^2$**
  - **Two photon** **$\to (Z_{nucleus} * q_e)^4$**
- The price of coherence is the limit on momentum transfer,

  $\Delta q < hc/(2\pi R_{nucleus})$ or $\lambda >$ target size
- In high energy (colliding) beams the maximum

  Δq is boosted by $2\gamma_{beam}^2$,where γ =Lorentz factor

  -> @LHC (2.75 TeraVolt/nucleon, Pb beam):

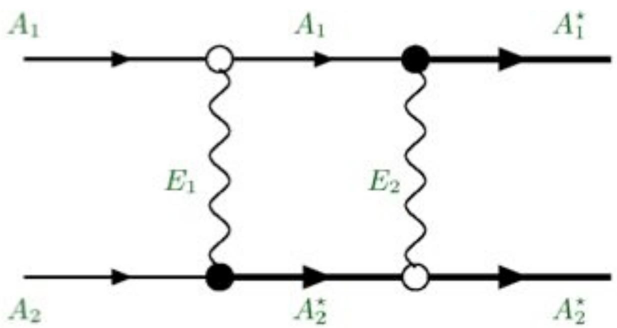
  28 MeV->400 TeV

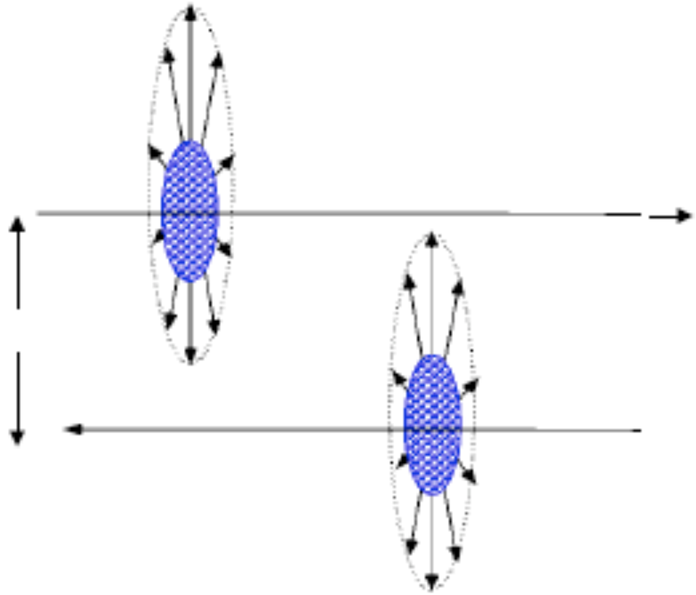
Heavy Ion Collider parameters

AB	L_{AB} ($mb^{-1}s^{-1}$)	$\sqrt{s_{NN}}$ (TeV)	E_{beam} (TeV)	γ_L	k_{max} (GeV)	E_{max} (TeV)	$\sqrt{s_{\gamma N}^{max}}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{max}}$ (GeV)
SPS								
In+In	-	0.017	0.16	168	0.30	5.71×10^{-3}	3.4	0.7
Pb+Pb	-	0.017	0.16	168	0.25	4.66×10^{-3}	2.96	0.5
RHIC								
Au+Au	0.4	0.2	0.1	106	3.0	0.64	34.7	6.0
pp	6000	0.5	0.25	266	87	46.6	296	196
LHC								
O+O	160	7	3.5	3730	243	1820	1850	486
Ar+Ar	43	6.3	3.15	3360	161	1080	1430	322
Pb+Pb	0.42	5.5	2.75	2930	81	480	950	162
pO	10000	9.9	4.95	5270	343	3620	2610	686
pAr	5800	9.39	4.7	5000	240	2400	2130	480
pPb	420	8.8	4.4	4690	130	1220	1500	260
pp	10^7	14	7	7455	2452	36500	8390	4504

EPA(3)-mechanisms of beam loss at the LHC

- **Mutual Coulomb Dissociation(A. Baltz, SNW)**
- **measured with first RHIC data. Calibrates RHIC and LHC luminosity**

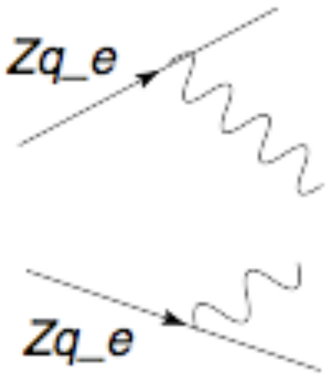




•**Coherent Pair Production (various)**

"inverse positron annihilation"
(Breit-Wheeler)

("photon flux")^2



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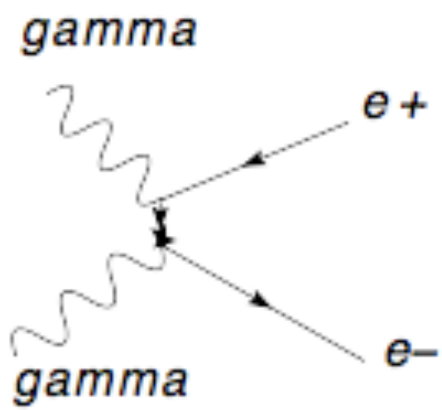
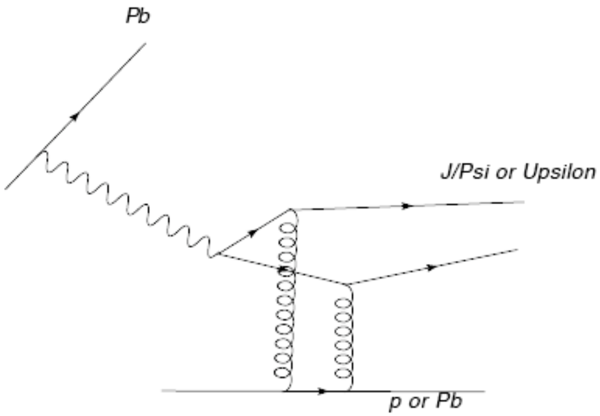


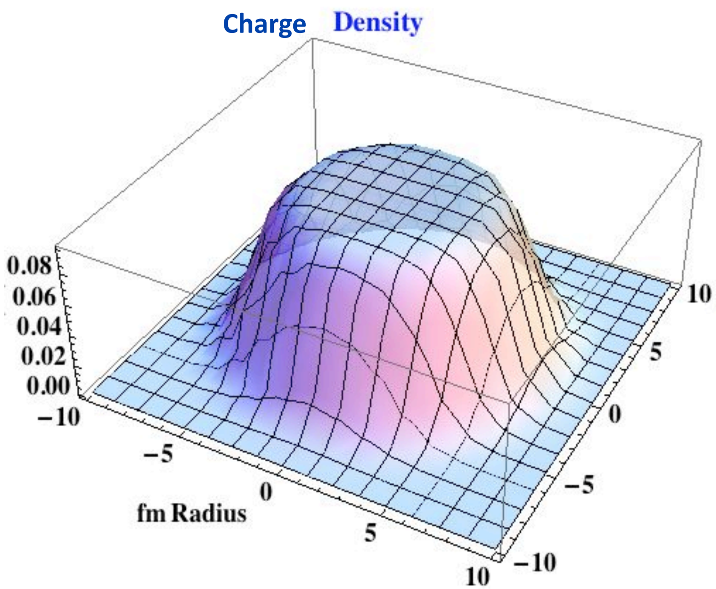
EPA(4):Vector meson photoproduction

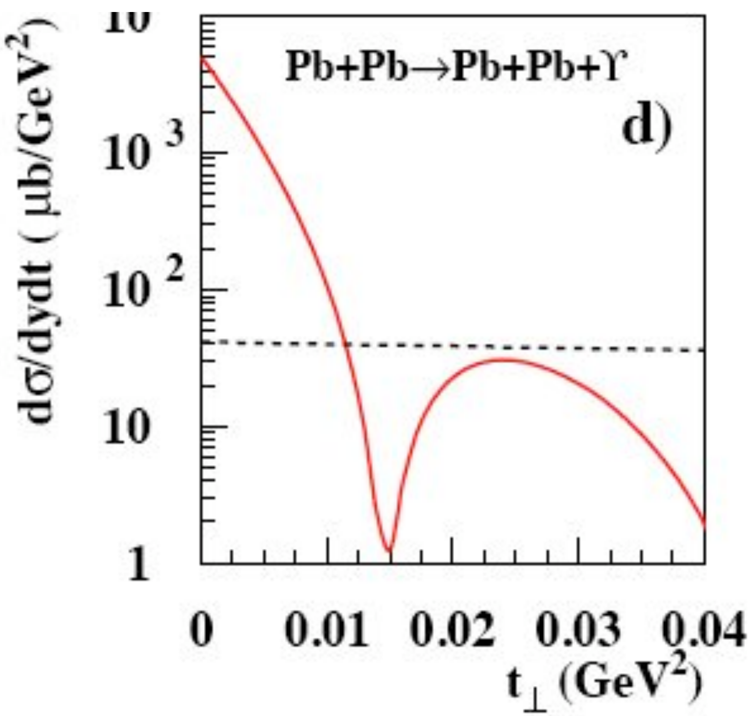
- gluon distribution in proton or nucleus



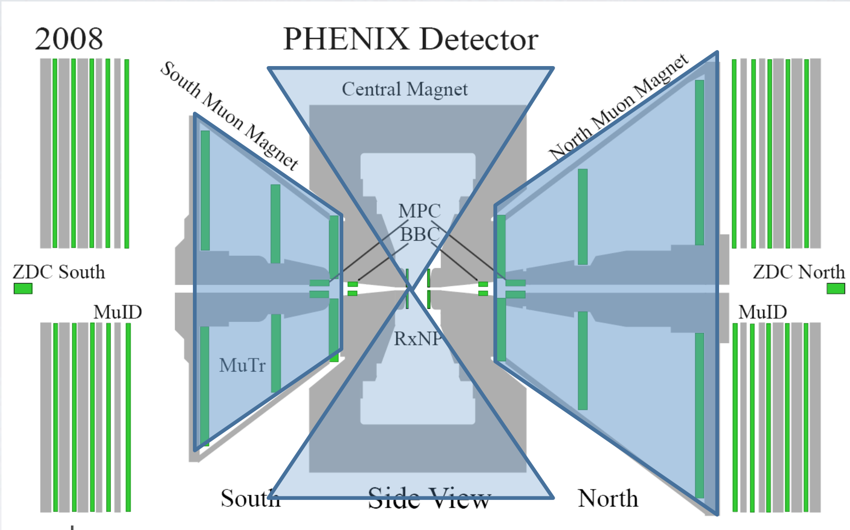
$$\frac{d\sigma}{dt}(J/Psi - Nucleus)$$

$\longrightarrow$ "QCD Rutherford scattering"





PHENIX DI-LEPTONS



forward tags

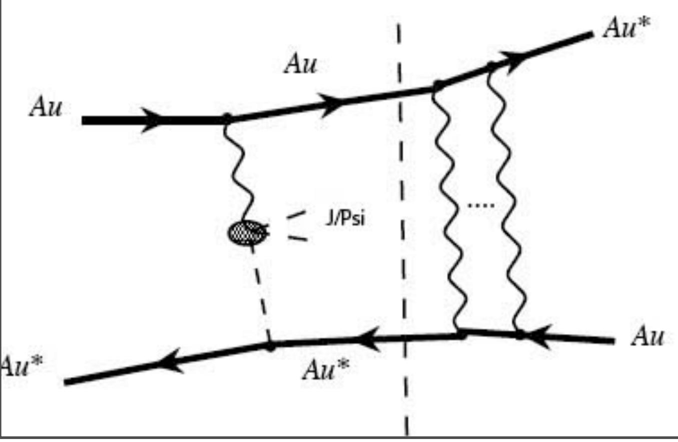
BBC (3.0 < |η| < 3.9)

(charged)

MPC,ZDC

(calorimeters, neutral)

additional photon exchange a la Baltz & SNW



Central arm : 0<|η|<0.35 e-pair(50%*2pi)

Muon arm : 1.2<|η|<2.4 μ-pair

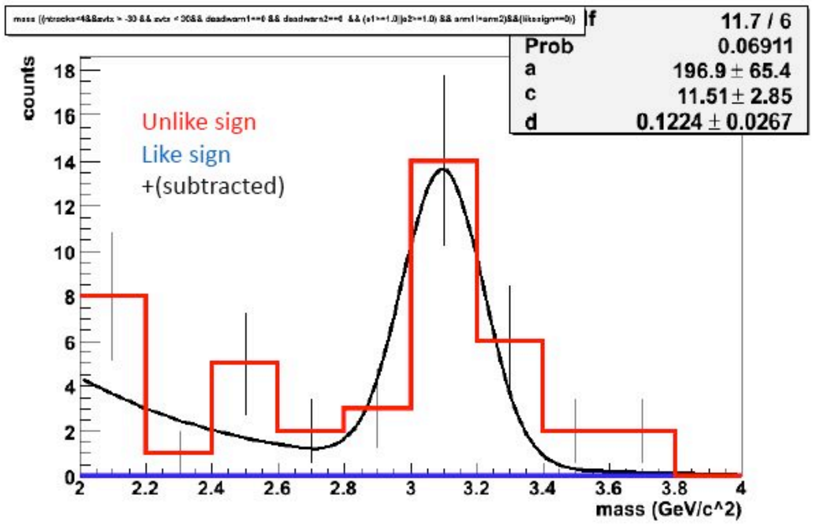
- 1 or 2 forward neutrons
- "rapidity gap"->veto BBC coincidence
- E(EMC)>0.8 GeV
  - **track cut to eliminate inelastic**
  - **overwhelming pion rejection**

“new” 2007 ee sample

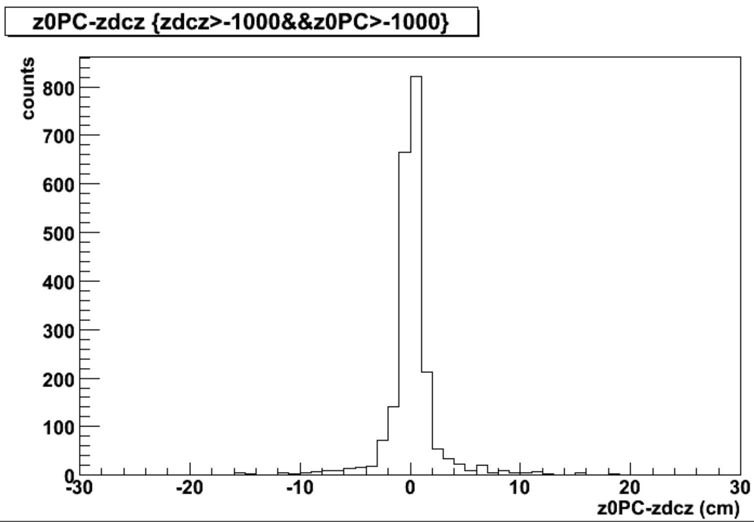
- results consistent with 2004 data publication
- PHENIX sees significant incoherent component

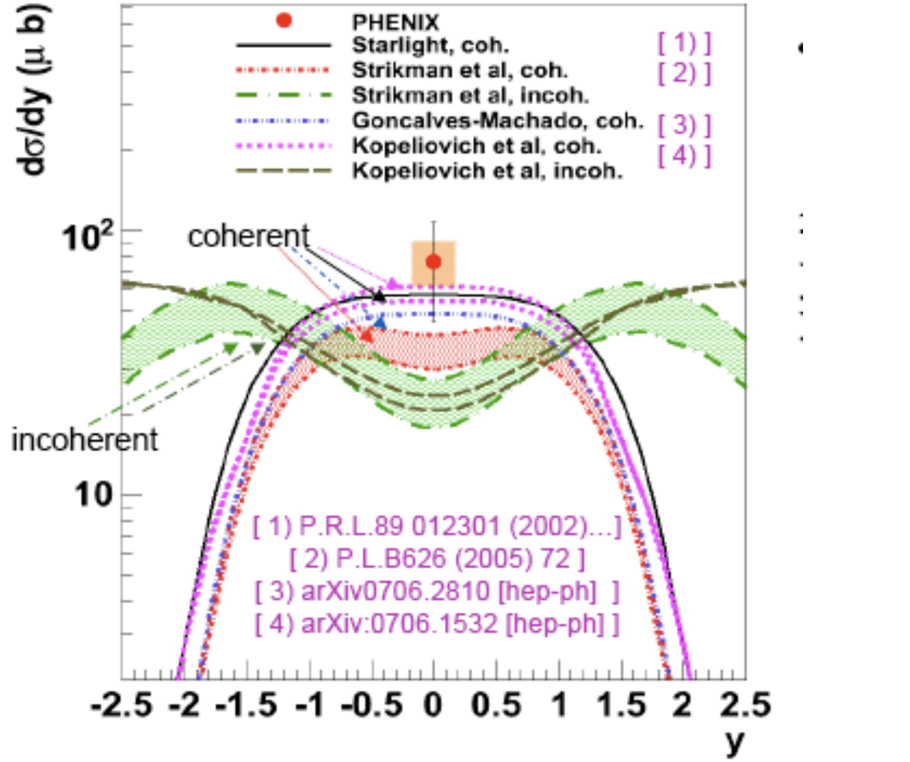
$$\sigma(\gamma + Au \rightarrow J/\psi) = A^{\alpha}\sigma(\gamma + p \rightarrow J/\psi), \alpha_{coh} = 1.01 \pm .07$$

Invariant mass distribution (Ntracks<4)



new algorithm for event vertex

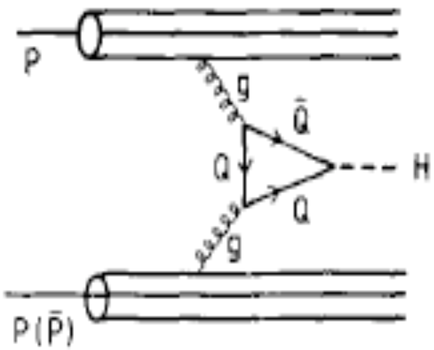




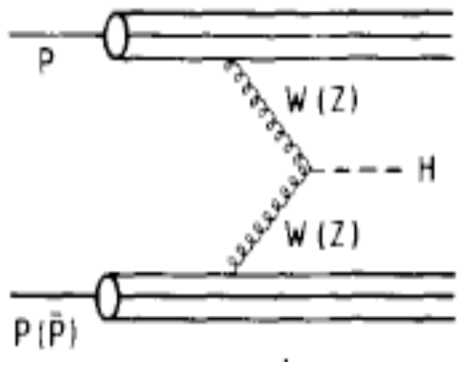
- ~1 J/ψ + n-tag per minute at RHIC
- -> 10 mbarn (10/second) in ATLAS@ LHC
- similar to planned eIC but higher $\sqrt{s}$
- PHENIX studying high acceptance $\mu\mu$ trigger
  - access to incoherent

EPA(5)-Equivalent W Approximation

- **Dominant Higgs production if $M_H \geq 300$ GeV (Dawson):**



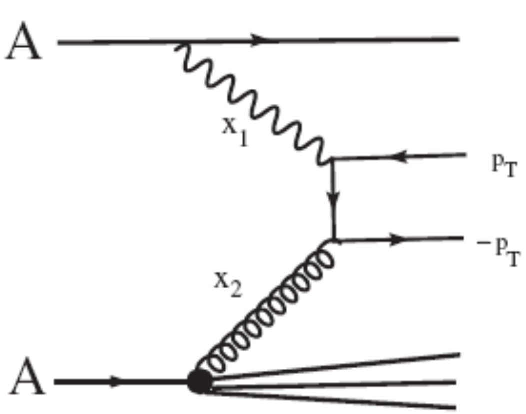
"gluon-gluon fusion"



"β-decay amplitude"

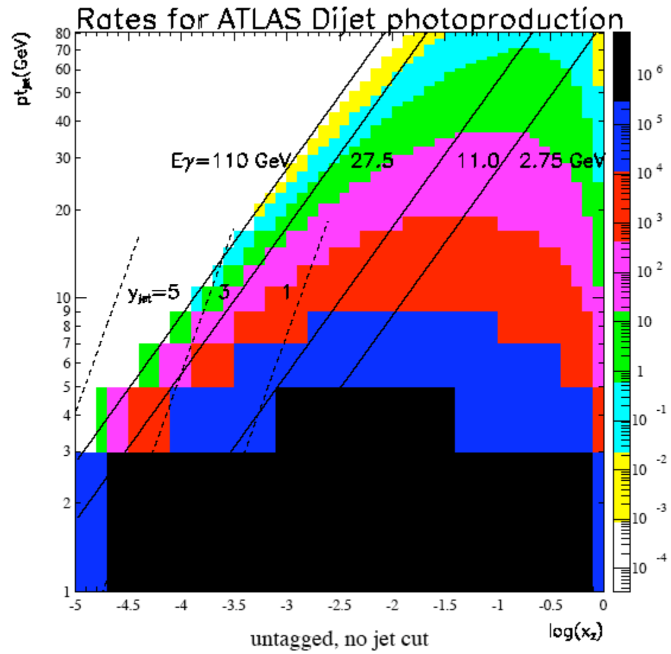
EPA(6): Measuring the structure of Protons and Nuclei

- **"Probing Small x parton densities in Ultraperipheral AA and pA collisions"(Strikman, Vogt, SNW)**



q,anti-q
"jets"

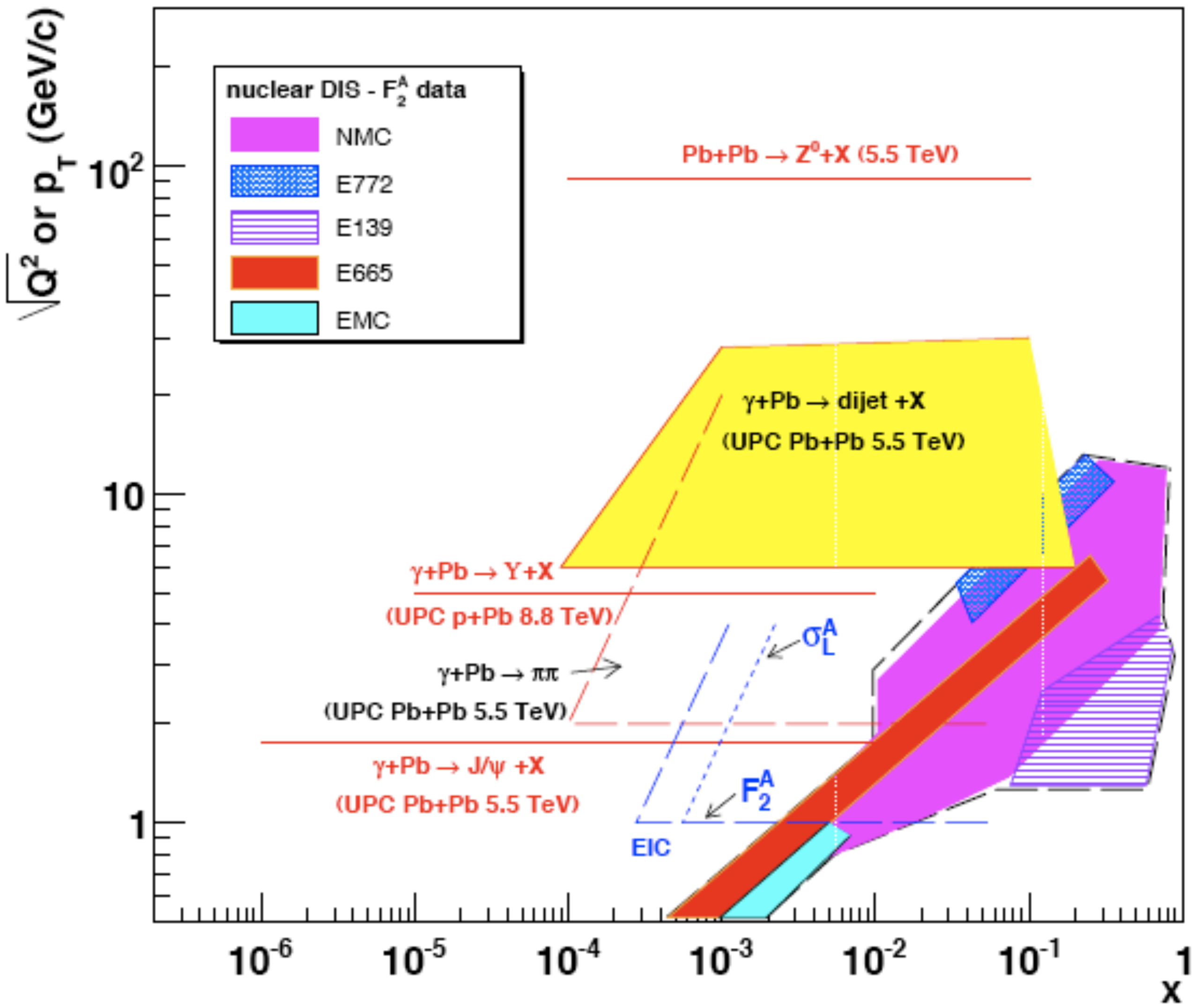
Resolving power



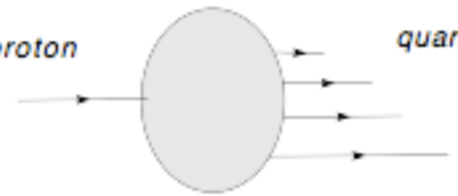
quark,gluon momentum fraction

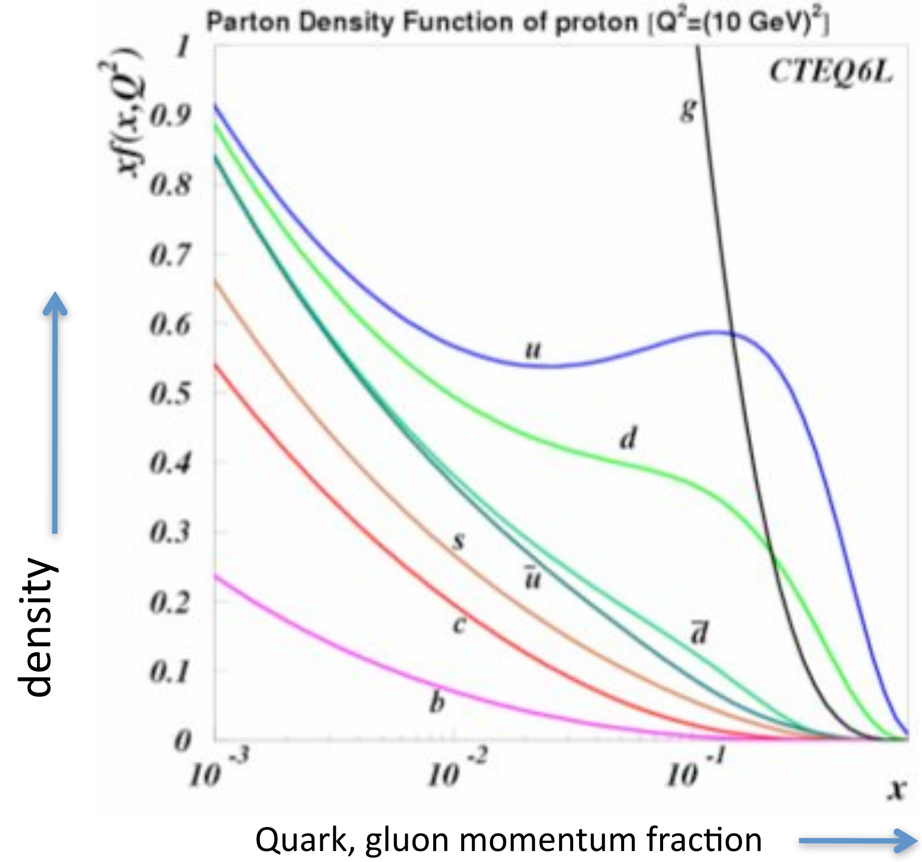
Structure ⇔ Distribution of partons(=quarks, gluons) inside proton- similar to EPA

Coverage by ATLAS hard photoproduction



- **Structure**



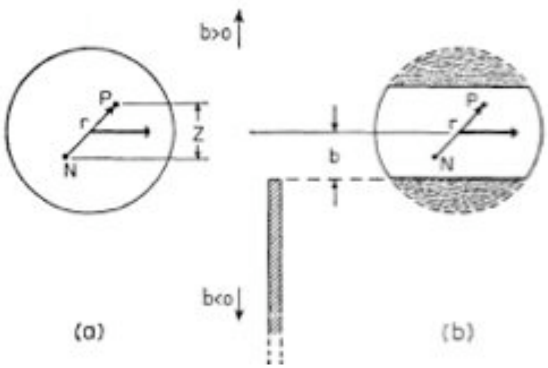


•Many other EPA analogies in QCD theory of strong interactions: e.g. Dokshitzer, Gribov, Lipatov, Altarelli and Parisi (DGLAP)

Inelastic Diffraction

- **Glauber (1955)- deuteron "free dissociation"**
- **Feinberg & Pomeranchuk('56)**

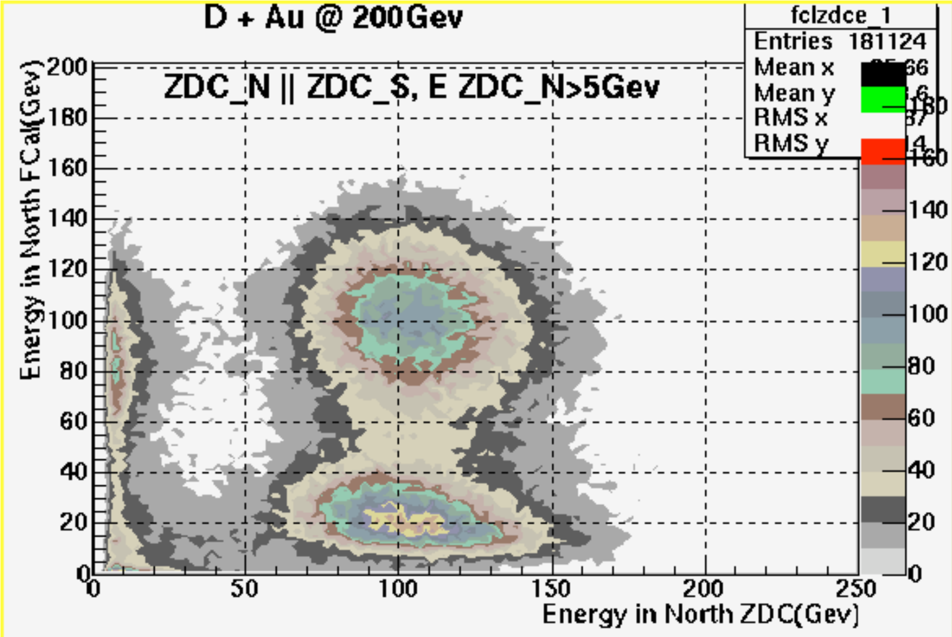
- **"Diffraction Dissociation-50 Years Later"-SNW**

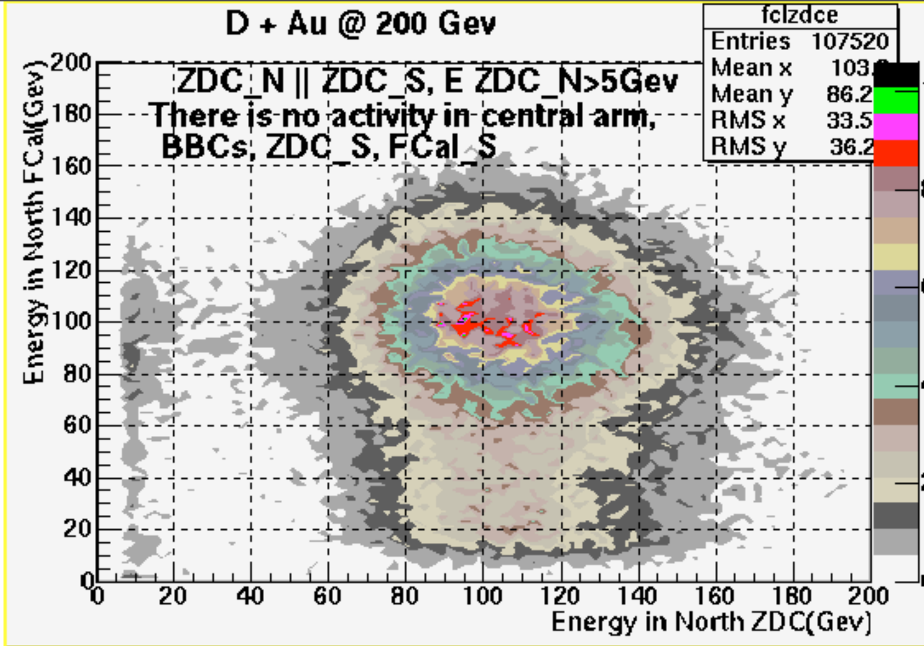


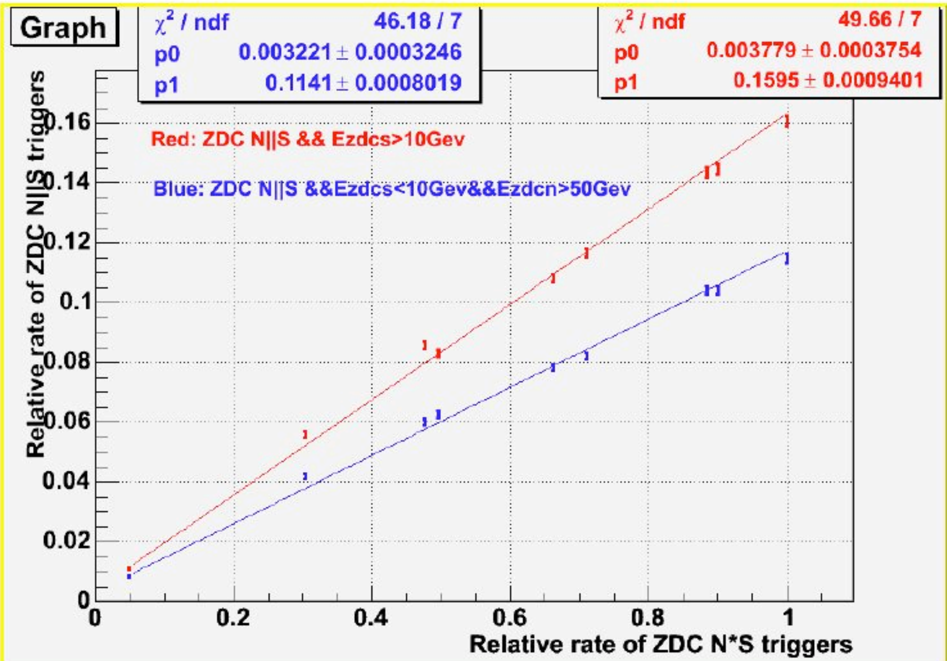
Collisionless interaction->excitation to unbound n,p

$d = \sum c_n \Psi_n , \Psi_n =$ Scattering basis states

•Measured in PHENIX: σ =138 mbarn







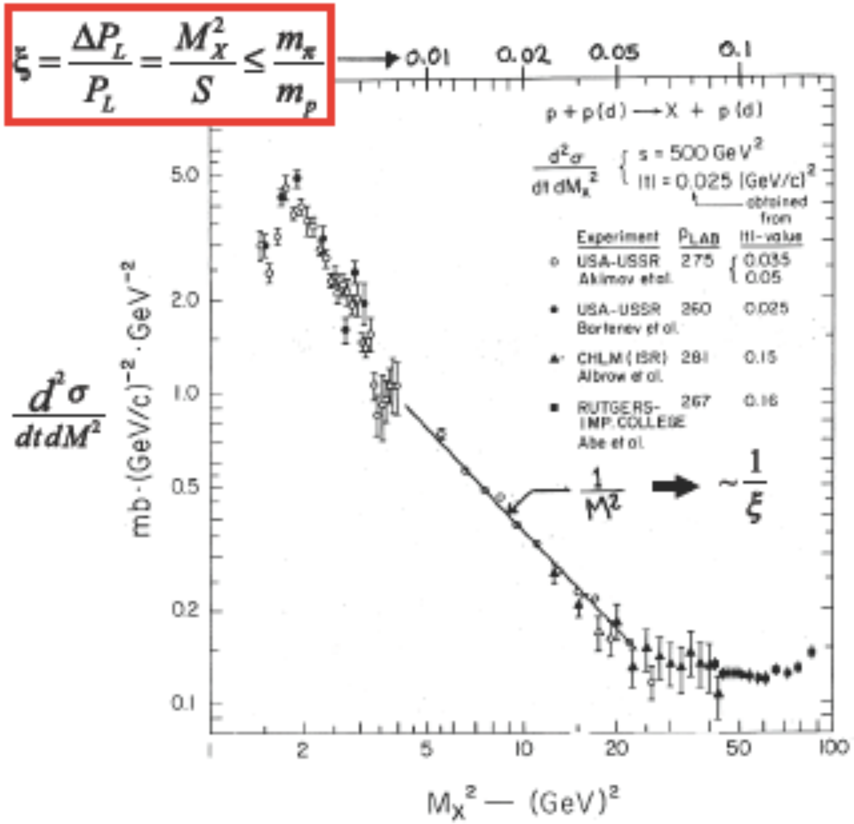
- R(d-AU dissociation)= Luminosity×
- d breakup background ie on accelerator residual gas ->beam current

- -> special data runs changing beam separation

- This result became basis for PHENIX luminosity calibration

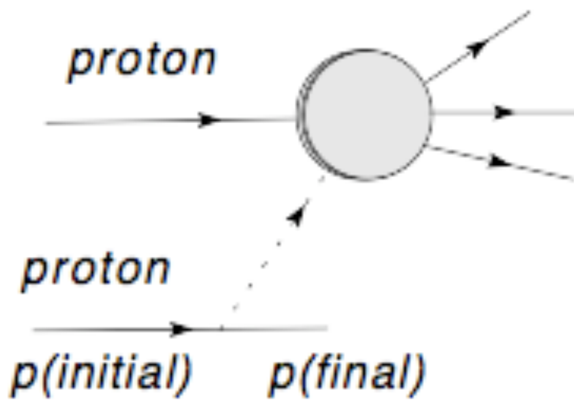
Proton diffraction dissociation

- Large coherence peak for $\lambda > R_{proton}$

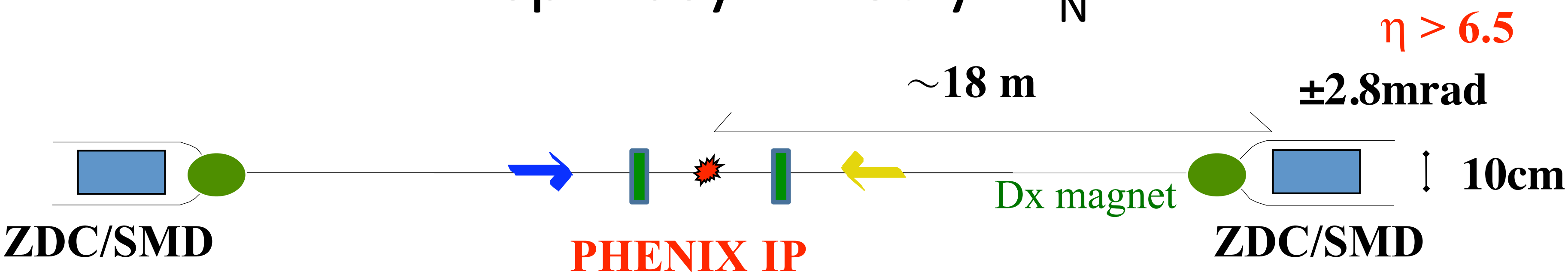


K.Goulianos('83)

- Observed for p,π,K, high energy γ's and nuclei
- $\sigma \sim A^{1/3}$-> peripheral interaction
- Responsible for K_L regeneration in particle physics



forward neutron production and single transverse spin asymmetry- A_N



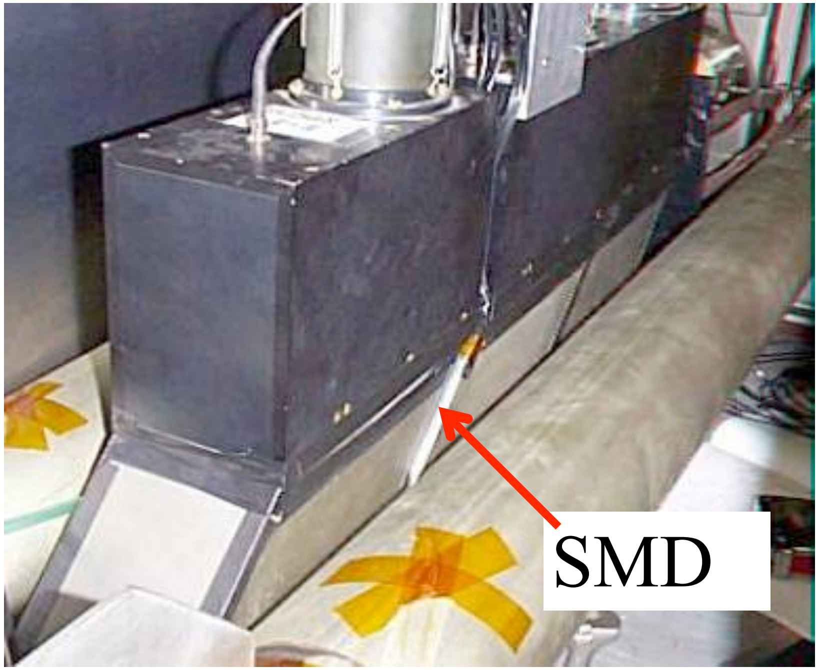
- ZDC (Zero Degree Calorimeter)
  - 3 modules : 5.1 λ_I

    (1.7 λ_I 50 X_0 for each module)

  → Measure neutron energy
- SMD (Shower Max Detector)
  - Sintillator hodoscope in x and y

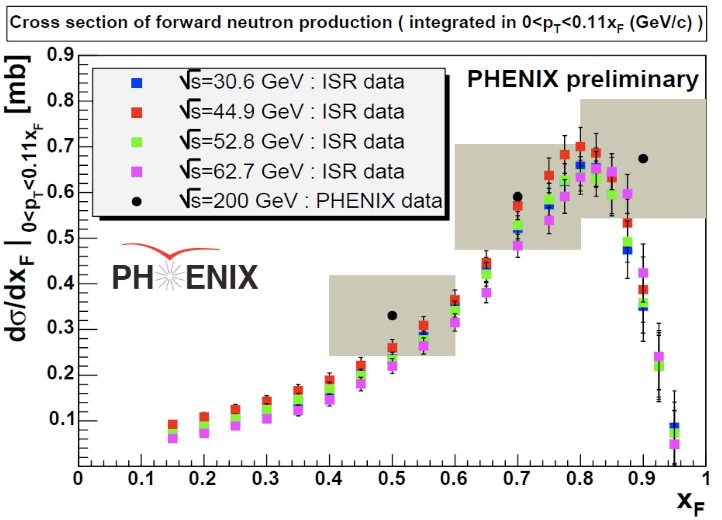
  → Measure neutron position :

  Enables us to measure A_N
- Placed at a very forward angle

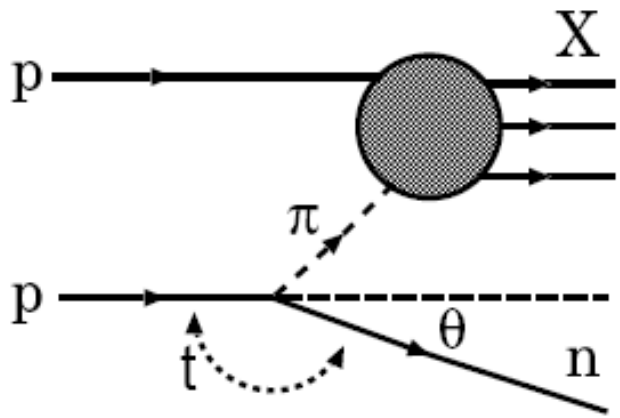


Physics : origin of neutron A_N

- Cross section measurements of very forward neutron production were performed at ISR.
  - Large cross section at high x_F region (x_F ~ 0.8)
  - No √ s dependence, scaled by x_F (31-63 GeV)
- Consistent with one pion exchange model.
  - In this picture A_N needs interference between spin flip and non-spin flip amplitudes. Pion exchange → spin flip



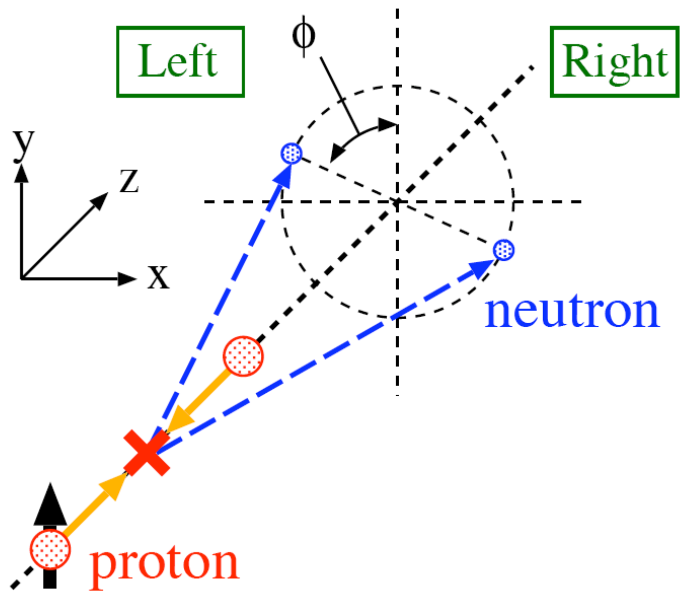
Nucl. Phys. B109 (1976) 347-356

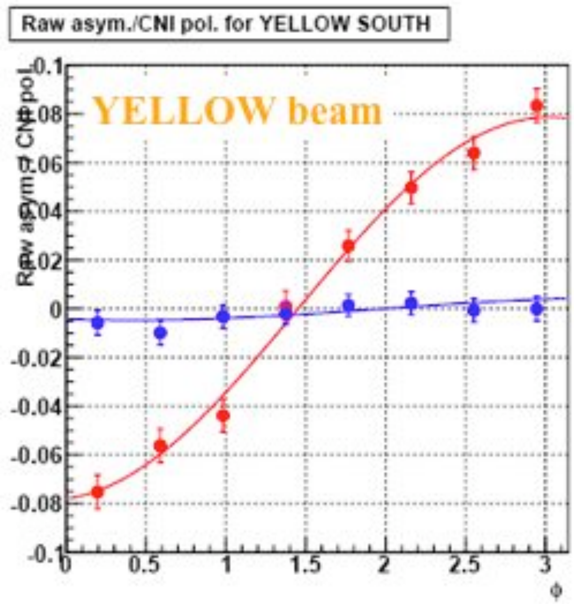


One pion exchange model

Polarized pp collision at √ s = 500 GeV

- In 2009 Pol. beams were colliding at √ s = 500 GeV for the first time.
  - Average polarization ~ 35% (online value)
- Neutron asymmetry persists at this high energy !
  - **Local polarimetry performed with neutrons at all energies.**

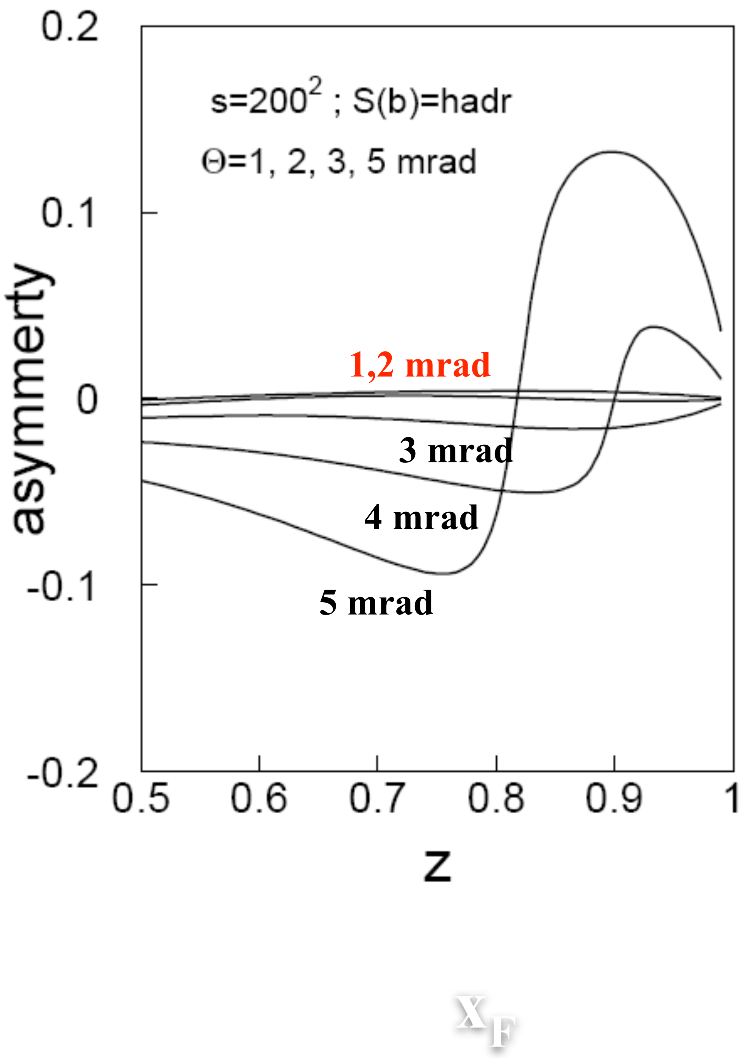




Red : Transverse run (Fill#10340)
Blue : Longitudinal run (Fill#10382)

Forward neutron issues at high energy

B.Z. Kopeliovich, I.K. Potashnikov, I. Schmidt and J.Soffer,arXiv:0807.1449



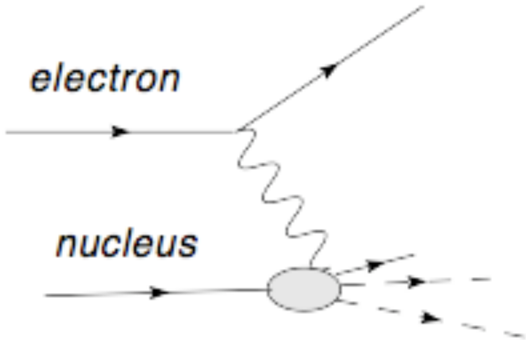
- Asymmetry calculated with one pion exchange model disagrees badly with PHENIX data(x_F=0.6-0.8, and $\theta < 2$ mrad.
  - possibly due to other reggeon exchanges. (*e.g.* a_1 exchange)
  - testable with neutron p_t dist.

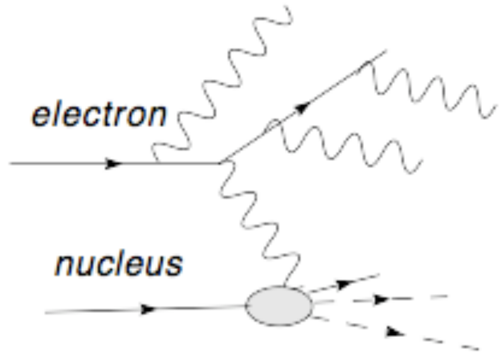
$$\frac{d\sigma}{dp_t^2} \vec{?} \rightarrow \frac{1}{(p_t^2 + m_\pi^2)^2}$$

- Much interest in ATLAS inclusive n
  - >measures gap survival probability at LHC energy. determines CEP (below)

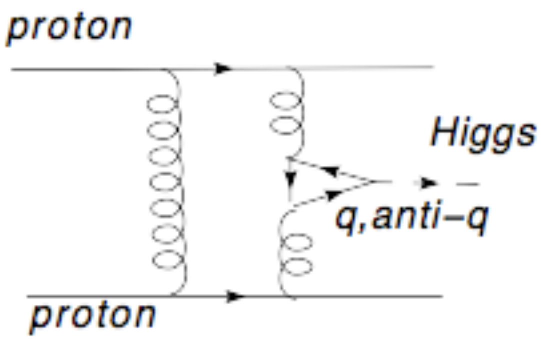
Diffraction(e-nucleus analogy)

- **Diffractive electroproduction** **non-diffractive**

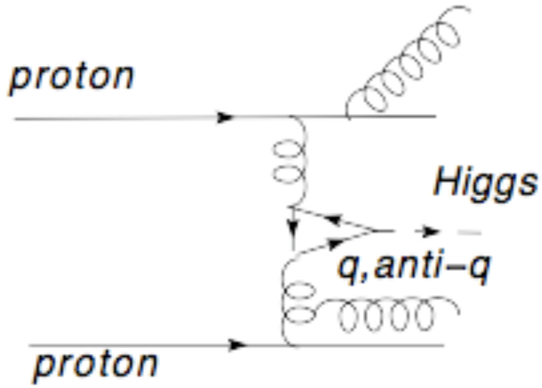




Diffractive Higgs production **non-diffractive**

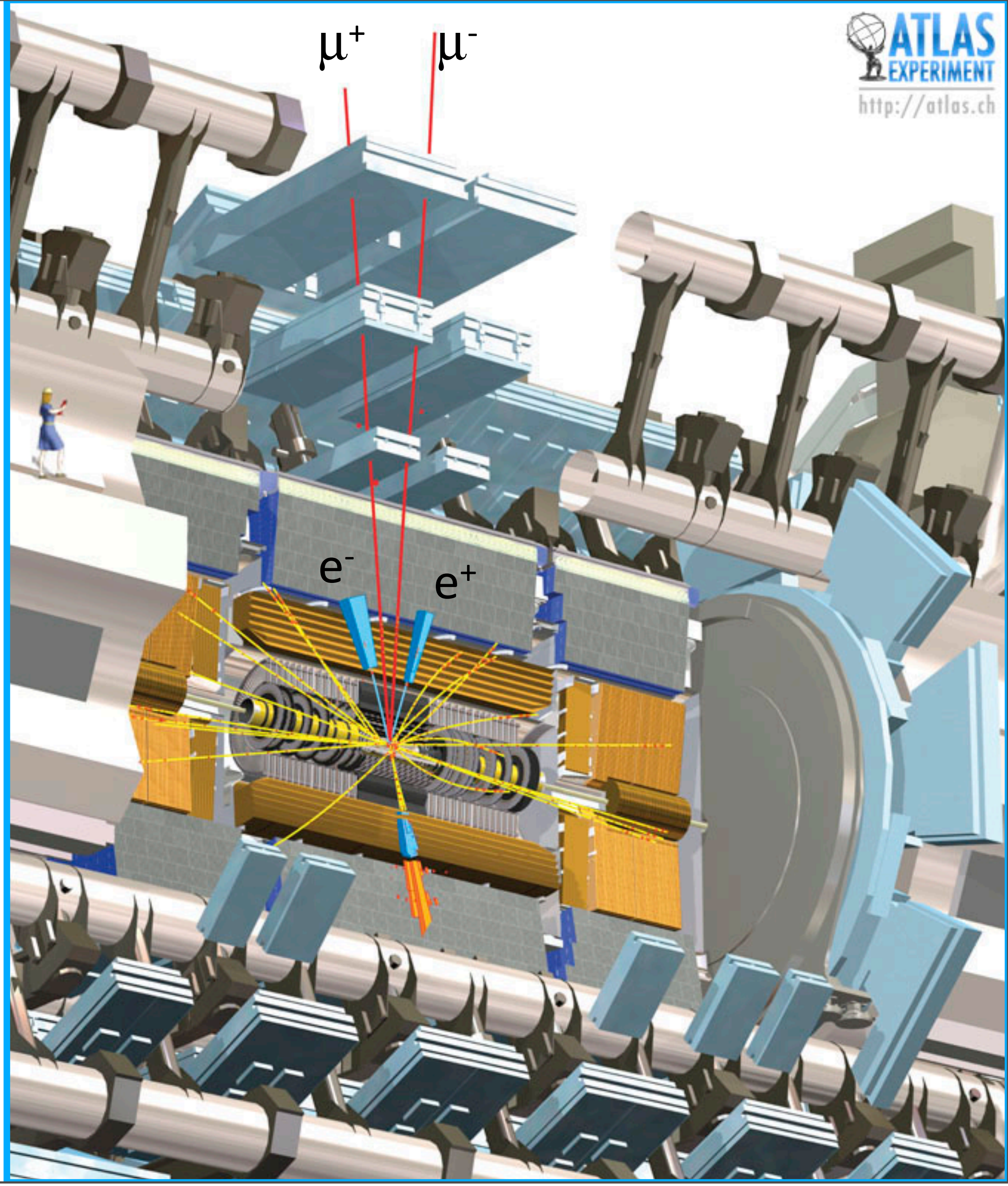


“color screening”



Higgs-> Z^0Z^0+...

Z^0->e^+e^-, $\mu^+\mu^-$



The ATLAS detector

- dimensions ~1/2 Notre Dame de Paris
- weight ~ Eiffel tower
- A 100 MegaPixel detector with 40MHz frame rate
  – (~ 1 million CD’s/10sec)
- 80% of pixels in first~ 30 cm.
- Trigger filters data in real time(1GHz->200Hz)
  – Data reduced to ~7km high stack of CD’s/year

more forward: Central Exclusive Production as a tool for new physics

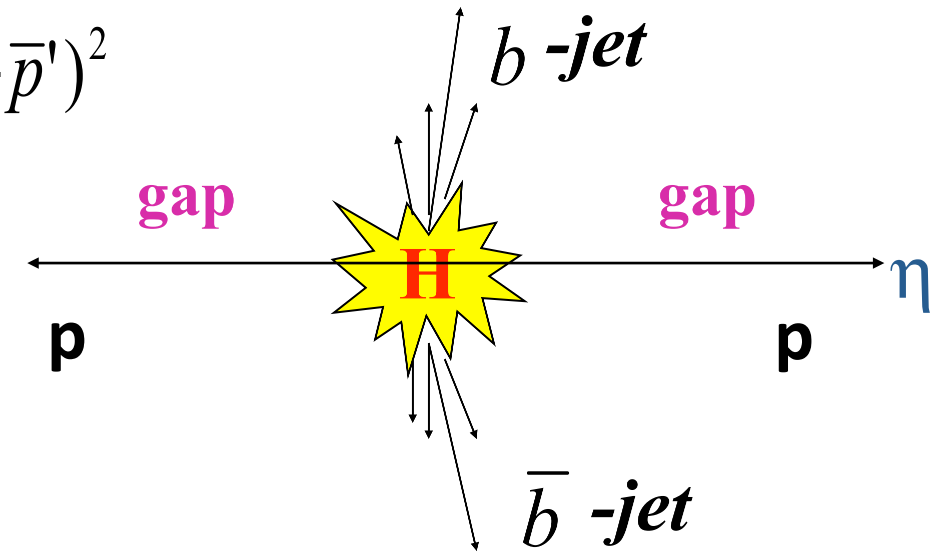
Central Exclusive Higgs Production

Central Exclusive Higgs production pp→p H p : >3 fb (SM)
~10-100 fb (MSSM)

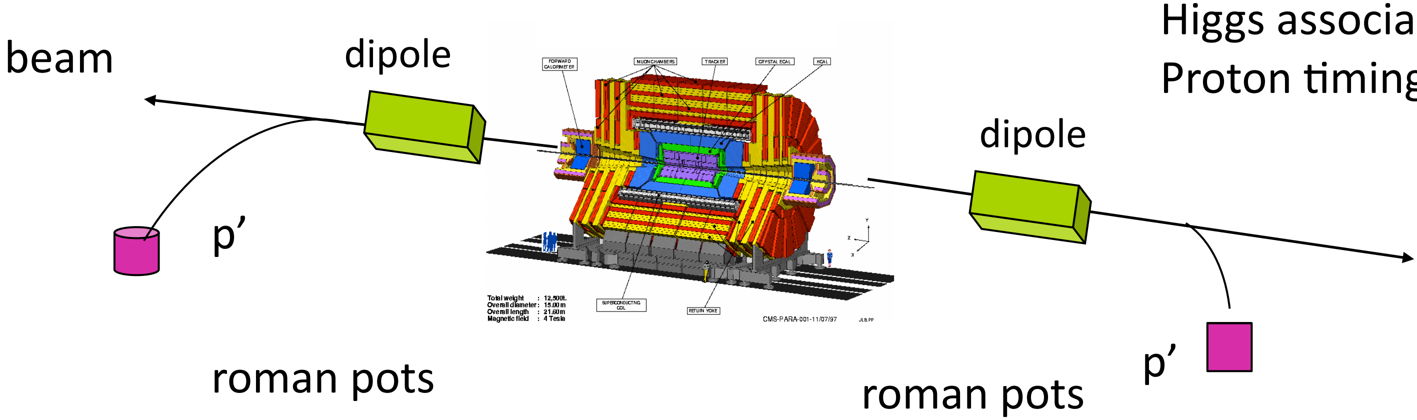
$$M_H^2 = (p + \overline{p} - p' - \overline{p}')^2$$

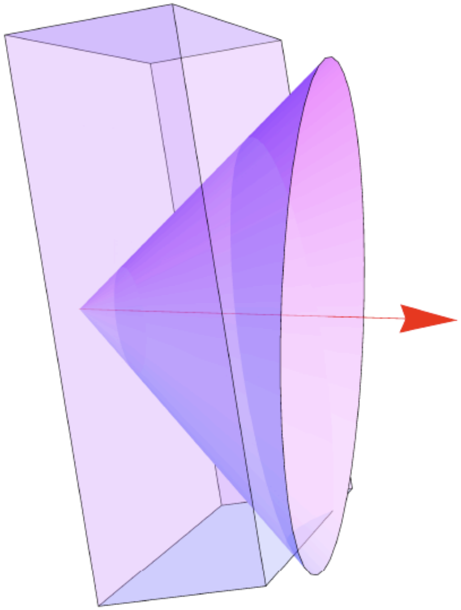
ΔM = O(1.0 - 2.0) GeV

Background suppressed
By 0^+ selection rule



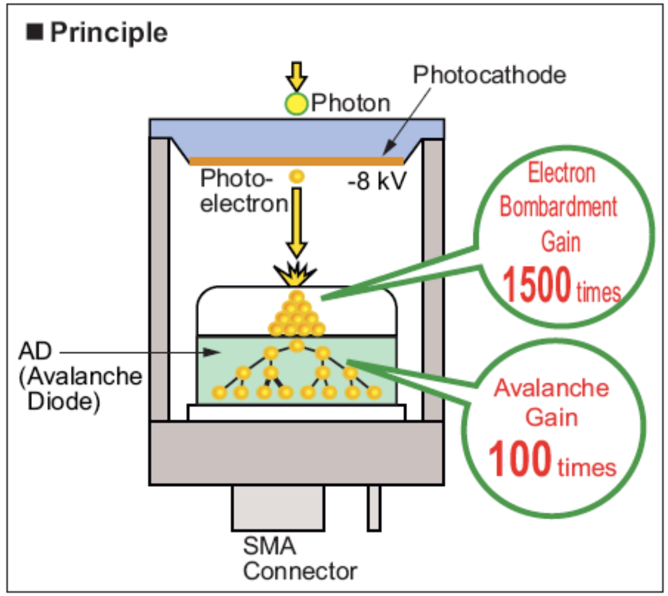
Higgs association from
Proton timing (~ 10 picosecond)





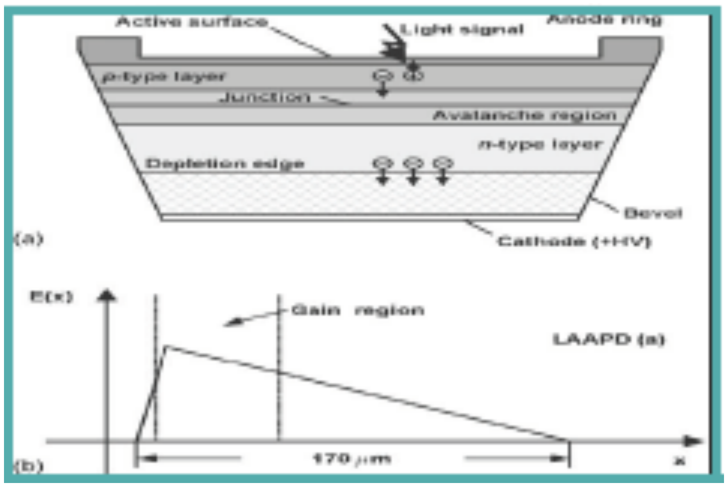
Cerenkov Radiation cone

Cerenkov
or
APD
option

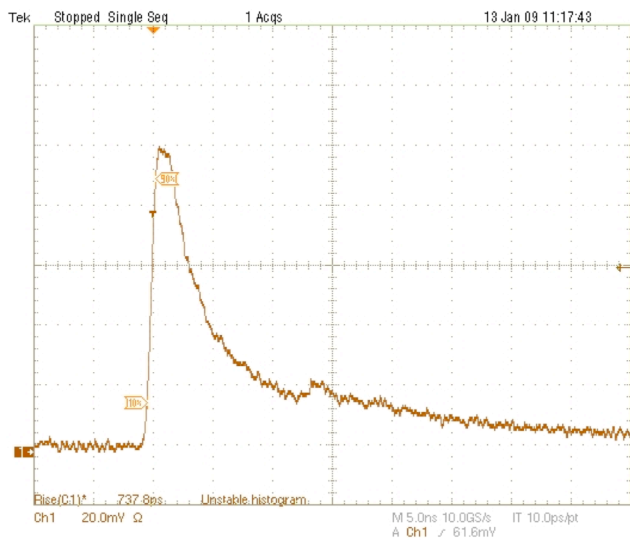


Pre-production Hybrid photodetector

"A 10 picosecond time of flight detector using APD's", SNW et al.



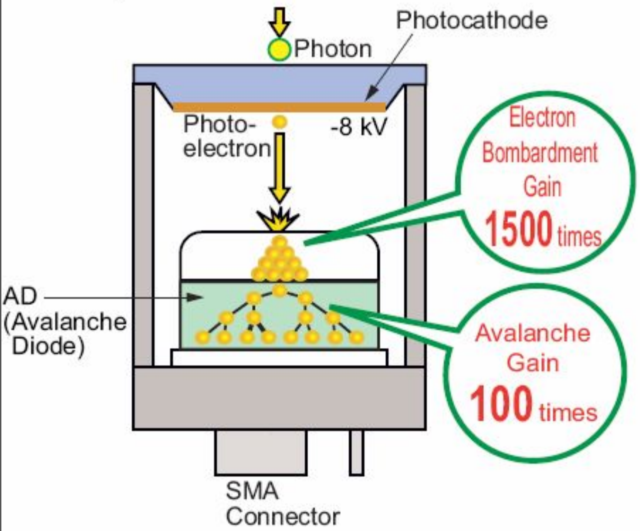
Deep diffused avalanche photodiode

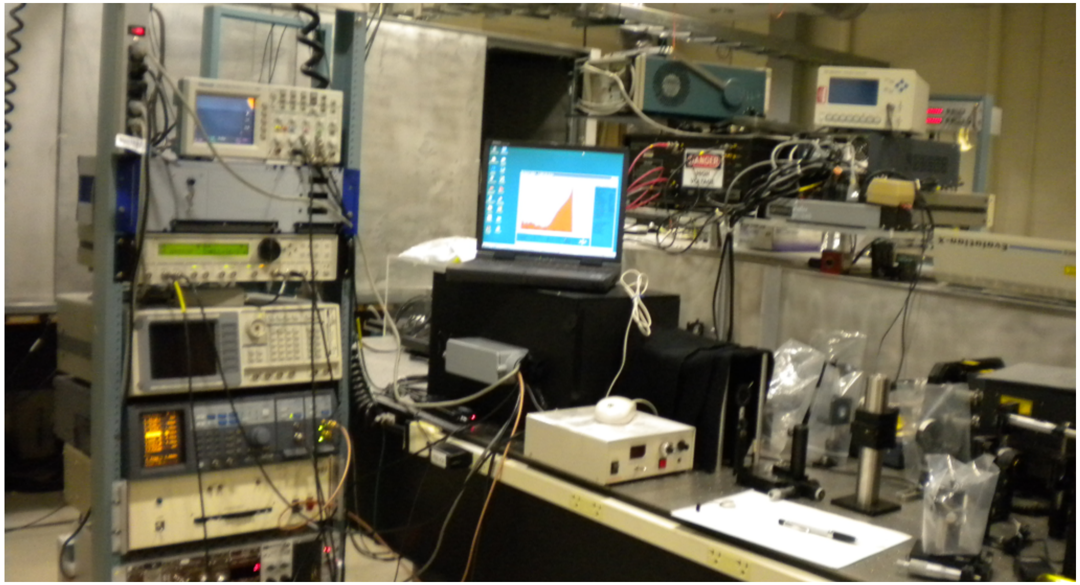


650 picosecond risetime (β's)

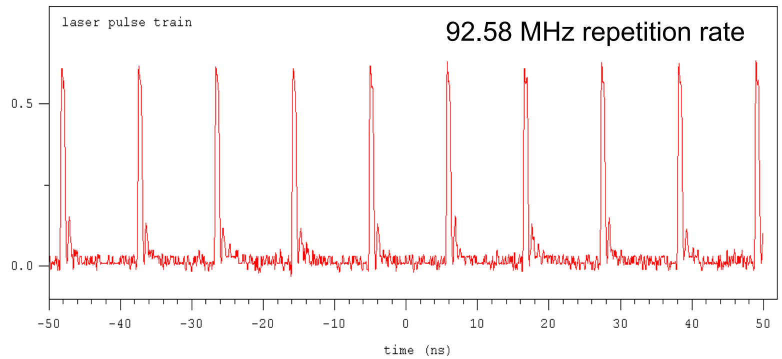
Evaluation of Hamamatsu HPD R10467-06, transit time spread & temporal shape

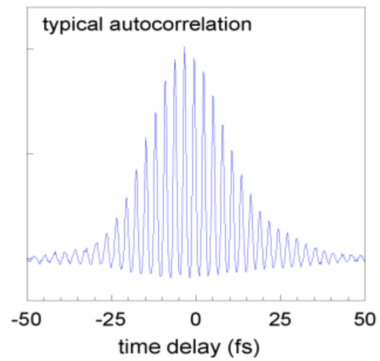
(Precise detection of time of arrival of (single) photons from large distances)

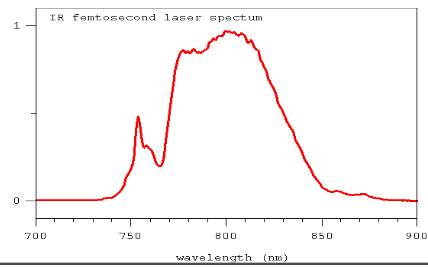


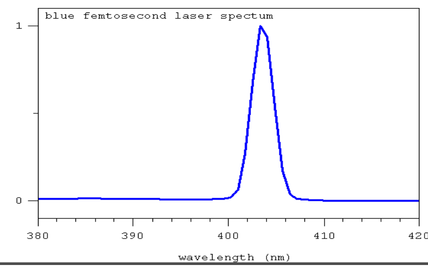


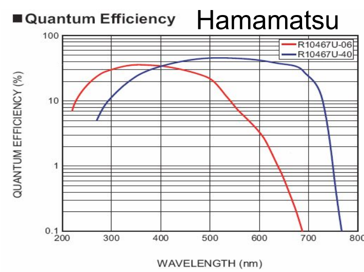
Mode-locked femtosecond Ti:sapphire laser: frequency doubled from 800 nm to 400 nm









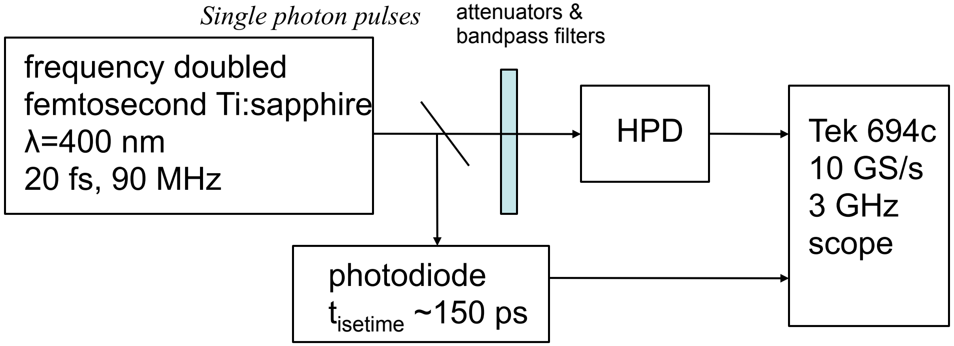


Wavelength of single photon source is chosen to match the peak of the quantum efficiency of the HPD

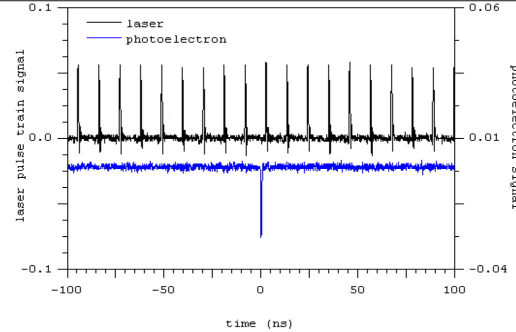
Tuesday, November 10, 2009

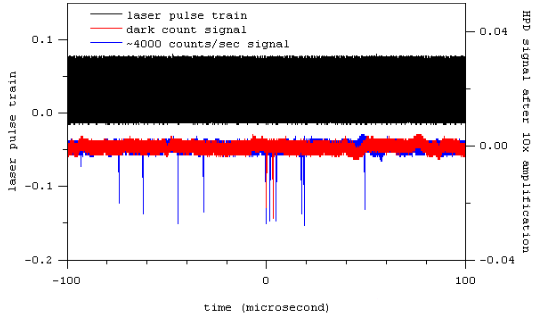
Temporal response of Hamamatsu HPD R10467-06

A. Experiment

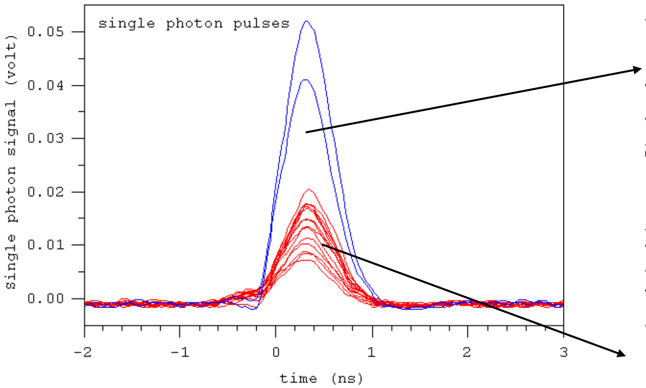


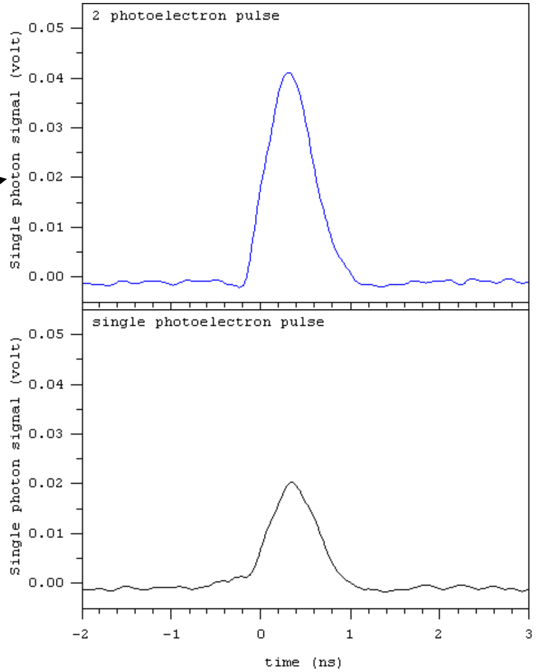
Ti:sapphire oscillator:
attenuate to
95 femtoWatt
~2×10^5 photons/sec
(<0.002 photon/pulse)

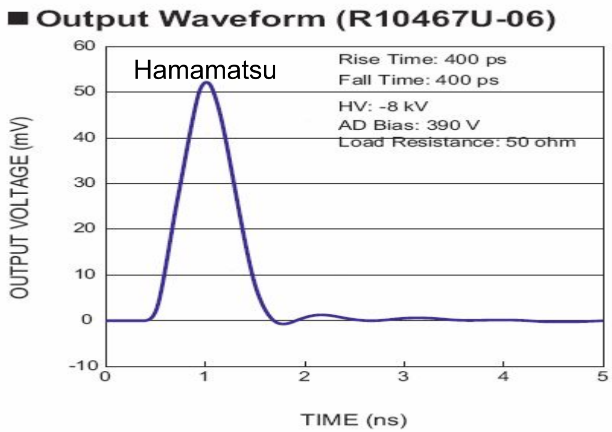




B. Temporal results



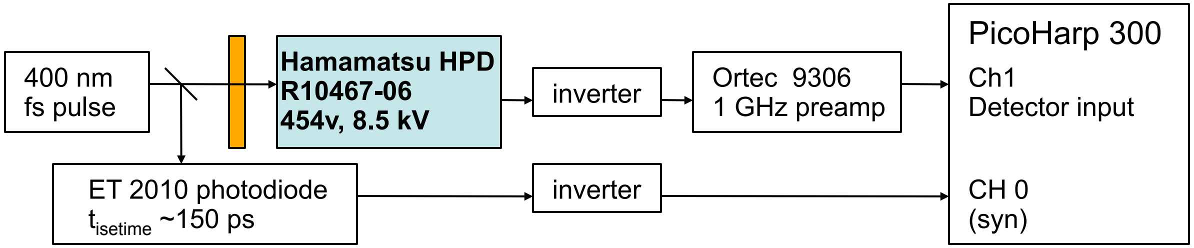


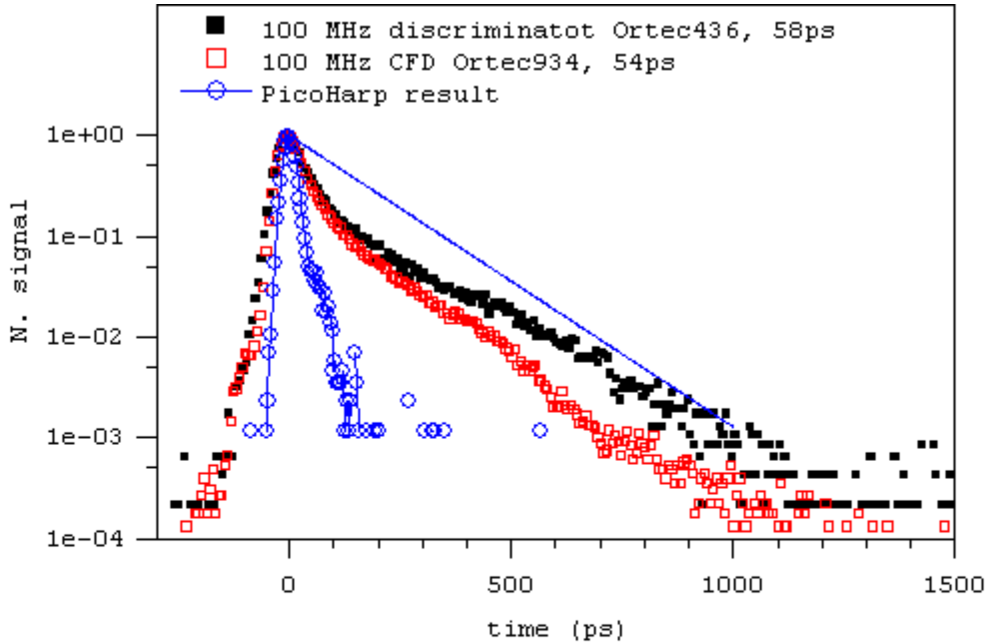


C. Summary

1. HPD has good temporal response with a rise/fall time of ~0.3/0.4 ns (both are not instrument limited).
2. One and two photoelectron pulses were observed.

Transit time spread & time jitter, using 100 MHz leading-edge vs CFD vs PicoHarp



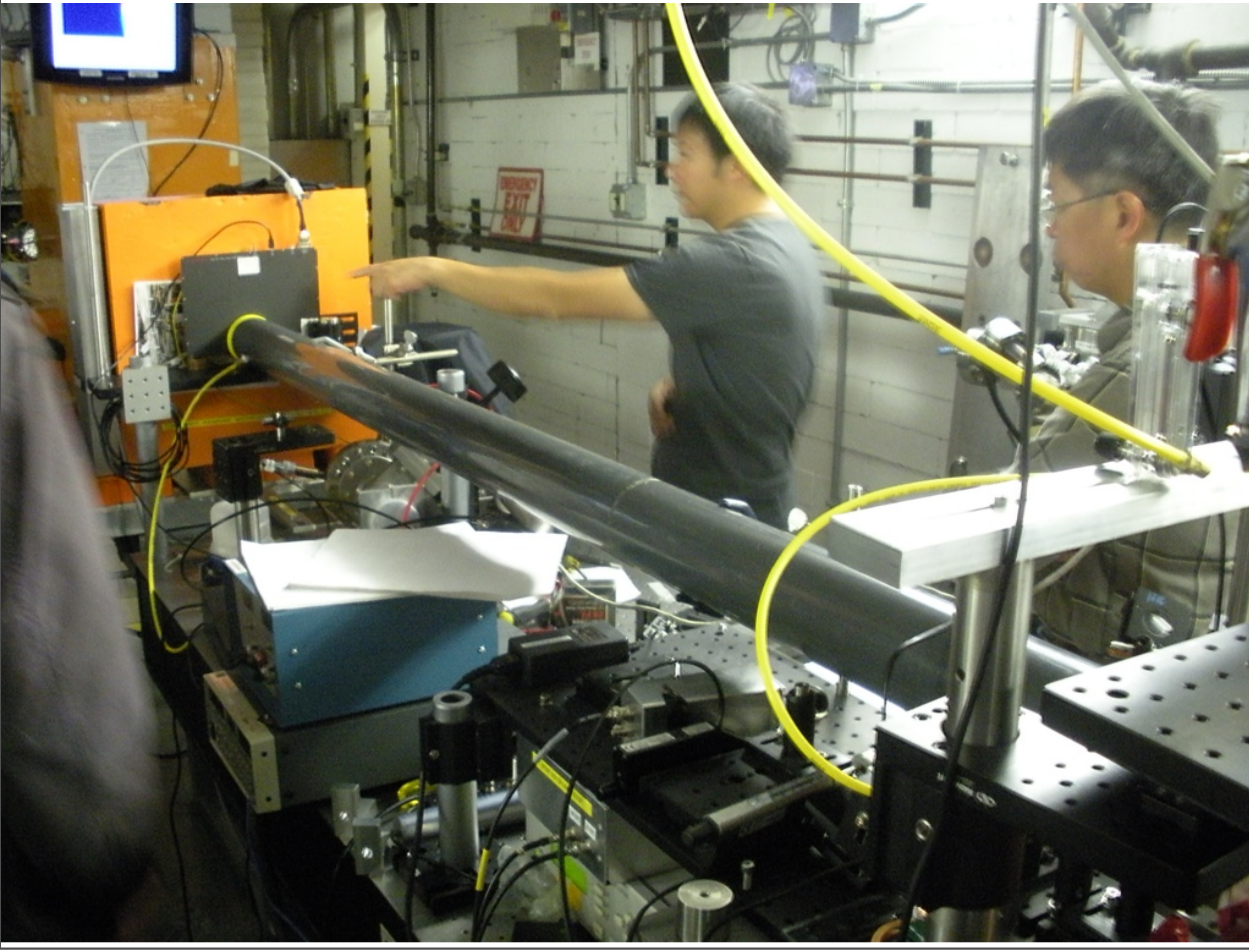


PicoHarp TTS measurement = square root((32 ps)^2 –(18 ps^2)) = **~26.4 ps (FWHM)**
A short exponential tail remains.

-> going into beam test rms jitter from electronics&TTS< 10^{-11} sec

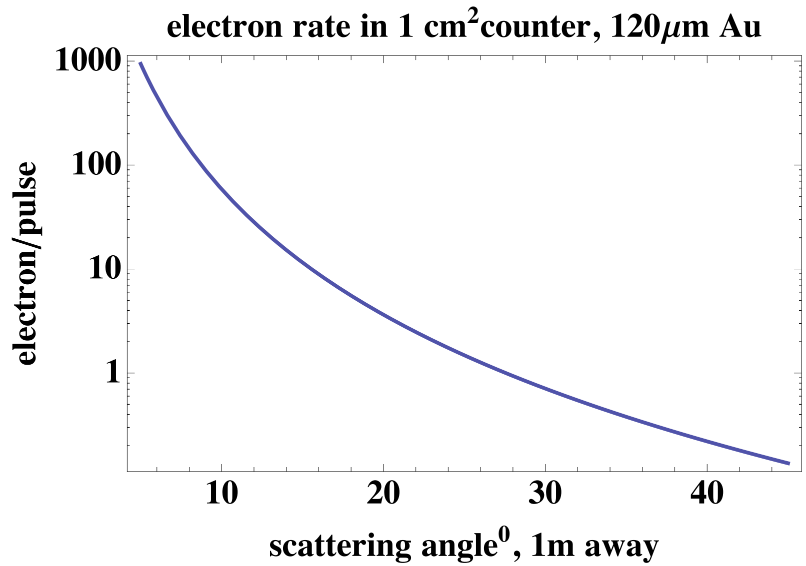
T. Tsang, M.Chiu, M. Diwan, S. White,G. Atoian, K. McDonald, K. Goulianos, D. Acker

Applications: RHIC upgrades, electron-Ion Collider, SuperBelle, ATLAS- AFP



Convert $10^7 - 10^9/pulse \rightarrow 10^0$

$$\left.\frac{d\sigma}{d\Omega}\right|_{\rm point} = \frac{Z^2\alpha^2}{4p_e^2\sin^4\frac{\theta}{2}}\left(\cos^2\frac{\theta}{2} - \frac{q^2}{2m_p^2}\sin^2\frac{\theta}{2}\right)$$



a thin foil (~50 micron Lexan) sufficient for 1e/cm^2 @ 1 meter and 90 deg.

Some Picks for LHC

Hard photoproduction(dijet,etc)	**inclusive and diffractive PDFs (p and Pb)**
Quarkonium photoproduction	$g^2(x)$
inclusive neutron at large xF	gap survival probability at LHC
$\pi^0, \eta^0, n, x_F > .8(ATLAS - ZDC)$	critical for CR physics at E>10^16 eV
very forward upgrade to ATLAS	new physics through central exclusive

Summary

- a century of progress on the structure of nuclei and the proton
- enabled calculation of new physics at level of

$$10^{-12} \times \sigma_{tot}$$

- Forward physics covers a wide range of topics
- very significant among them is EM interactions of nuclei which will be the frontier for nuclear and proton structure in the next decade.

Extra Slides

Summary

- Significant advances in understanding of structure
- These enable searches to level of $\sim 10^{-12}$ of interaction rate
- Coherence is potentially a powerful tool for measurement and discovery of the Higgs

Time of Flight at 10 MHz with 10 picosecond resolution

BNL Instrumentation: T. Tsang

BNL Physics: M.Chiu, M. Diwan, S. White

BNL CAD: G. Atoian

(BNL ATF: V. Yakimenko)

Princeton: K. McDonald

Rockefeller: K. Goulianos

D. Acker, co-Chair SUSB Trustees

Applications:

- RHIC upgrades
- electron Ion Collider
- SuperBelle: Top counter, etc.
- ATLAS- AFP system

Time of Flight at 10 MHz with 10 picosecond resolution

T. Tsang, M.Chiu, M. Diwan, S. White,G. Atoian, K. McDonald, K. Goulianos, D. Acker

(BNL ATF: V. Yakimenko)

Princeton: K. McDonald

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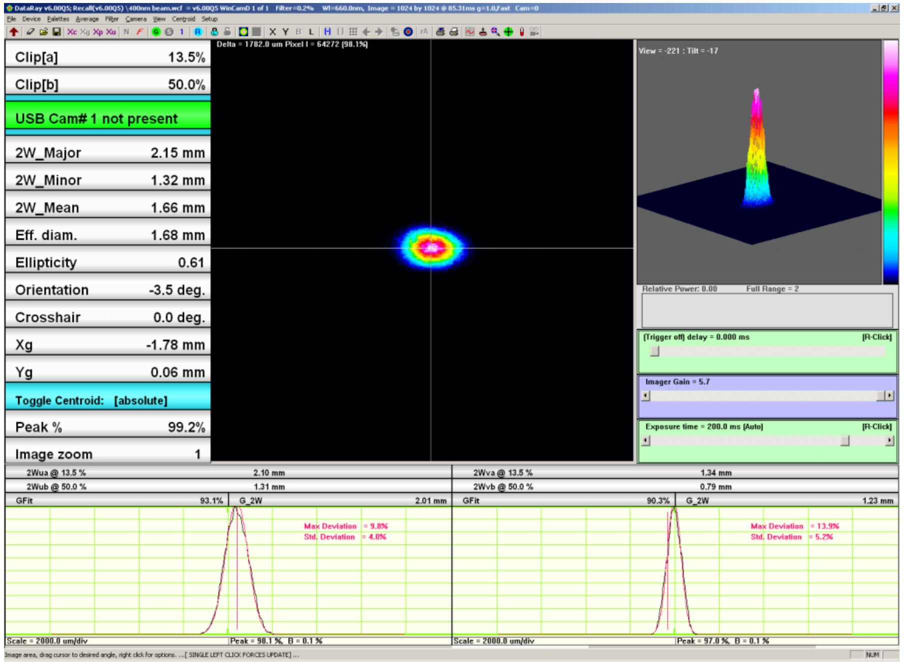
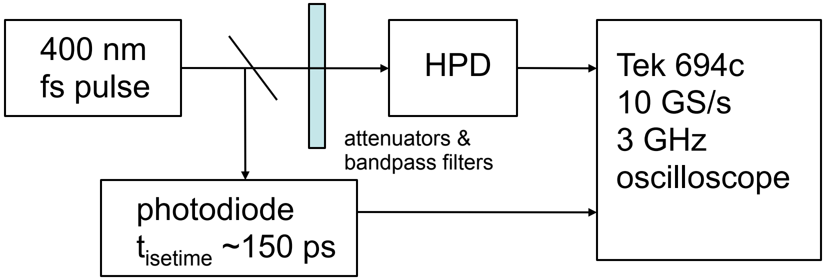
D. Acker, co-Chair SUSB Trustees

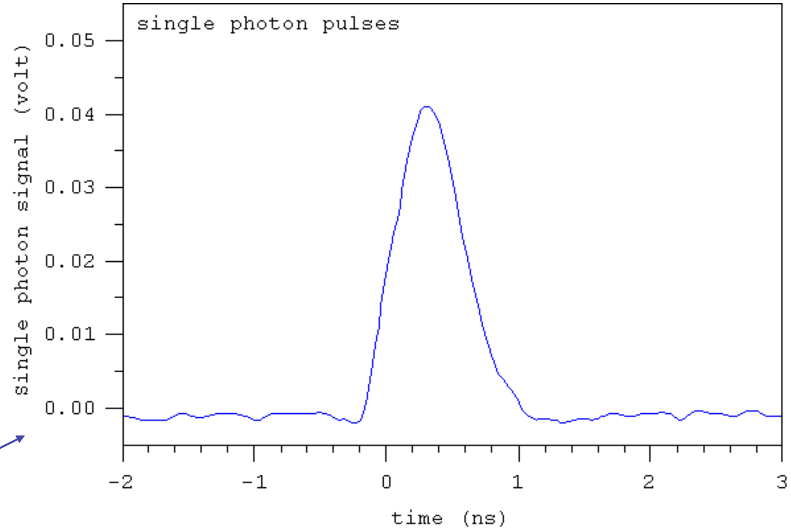
Applications: RHIC upgrades, electron-Ion Collider, SuperBelle, ATLAS- AFP

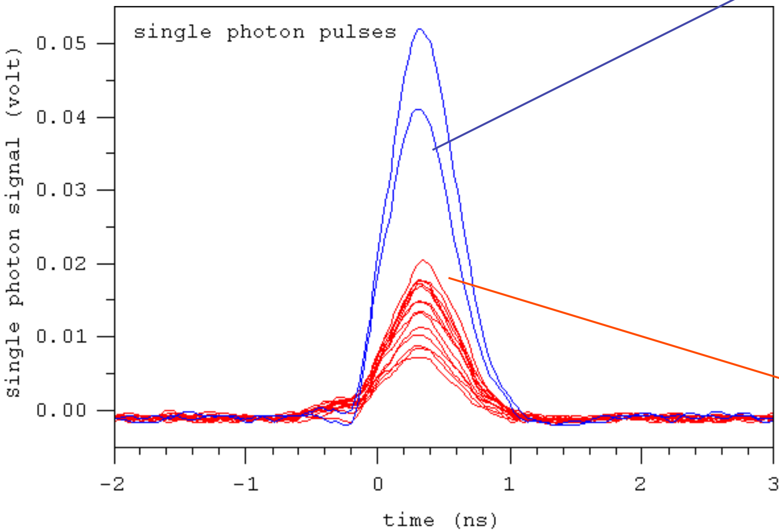
- RHIC upgrades
- electron Ion Collider
- SuperBelle: Top counter, etc.
- ATLAS- AFP system

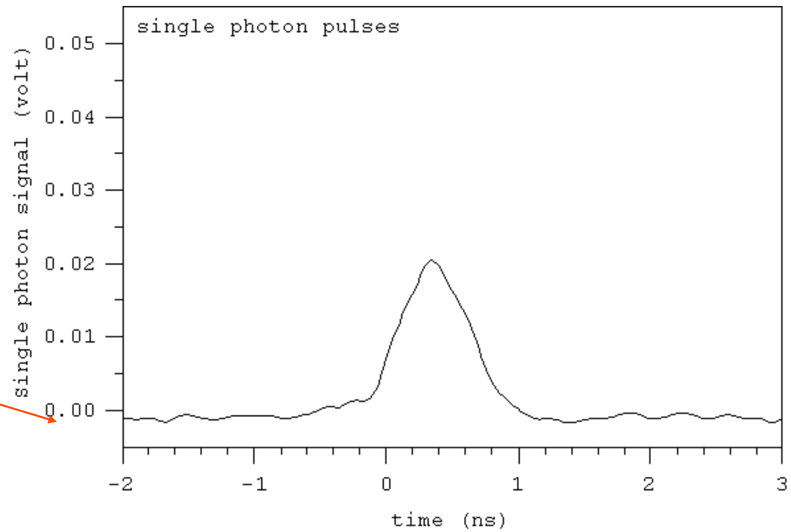
Single photon response











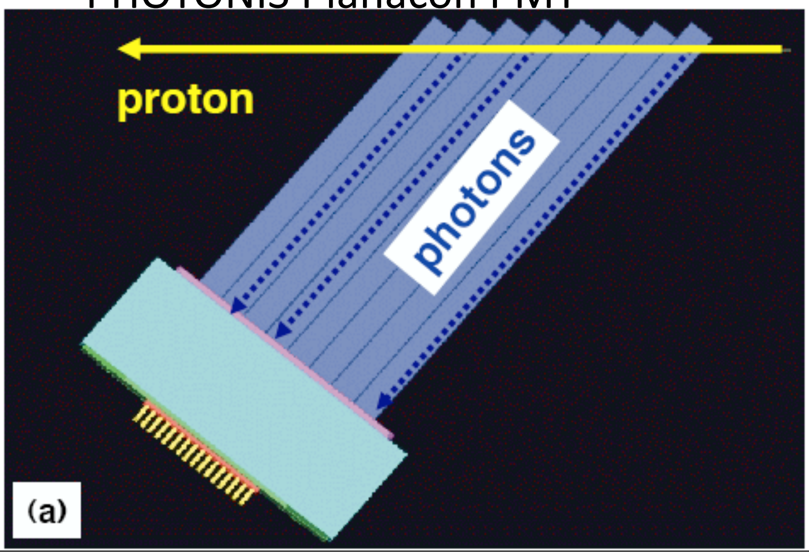
Fast Timing Principle for ATLAS FP

- Particles pass through Cerenkov radiator-> prompt light pulse(unlike scintillator)
- Photons are nearly along particle path for gas radiator: $\tan\theta_C \sim \sqrt{(n^2-1)}$ so very small transit spread
- Light peaked in UV- $N(\lambda) \sim (1-1/(n^2(\lambda)))/\lambda^2$
- For simple thin quartz radiator $\sigma_t^2 = \sigma_{RADIATOR}^2 + \sigma_{PMT}^2 \sim 1.7 * \ell(\text{cms.}) + 25/\ell$ picosec so optimum at length ~ 1-2 cms

Quartz Radiator

Better suited for pixels

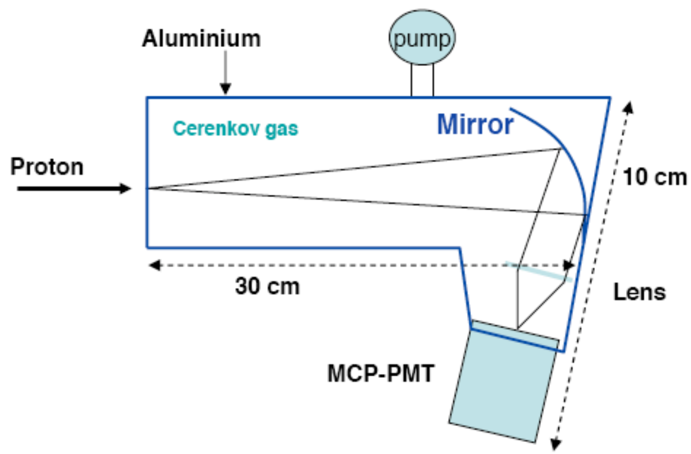
Achieved σ_t=40 psec/bar with PHOTONIS Planacon PMT



Gas Radiator

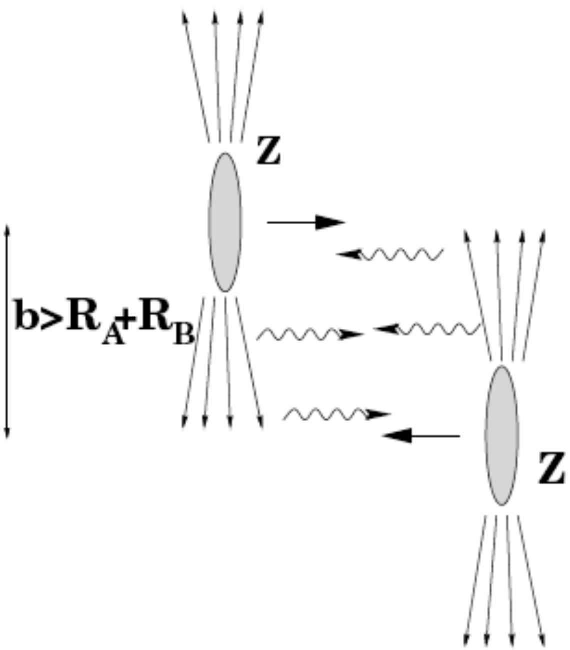
Better for light spread and collection bad for segmentation

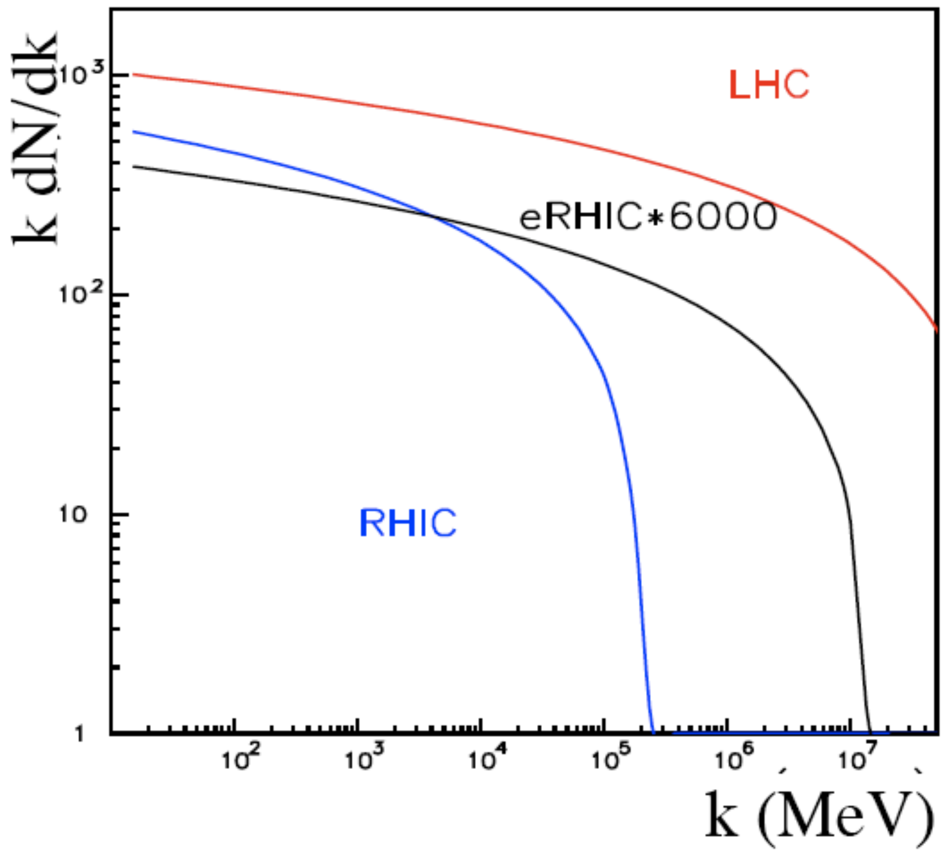
Achieved σ_t=13 psec with Hamamatsu R3809U MCP-PMT



Handling antimatter(Sony Pictures)

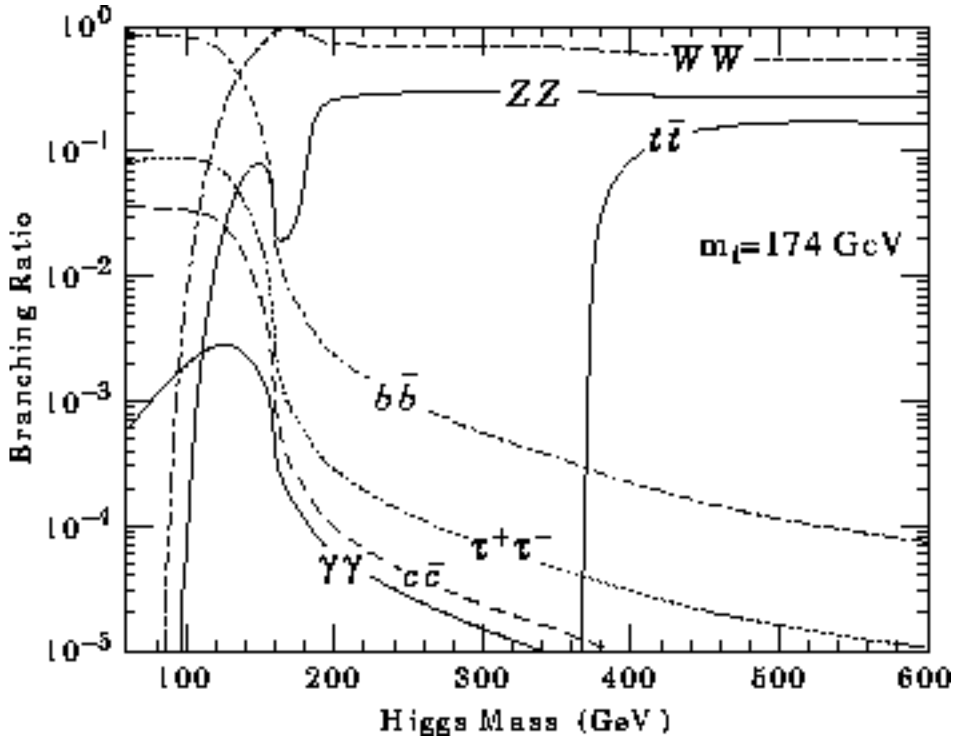
extra





Movie Star visits ATLAS

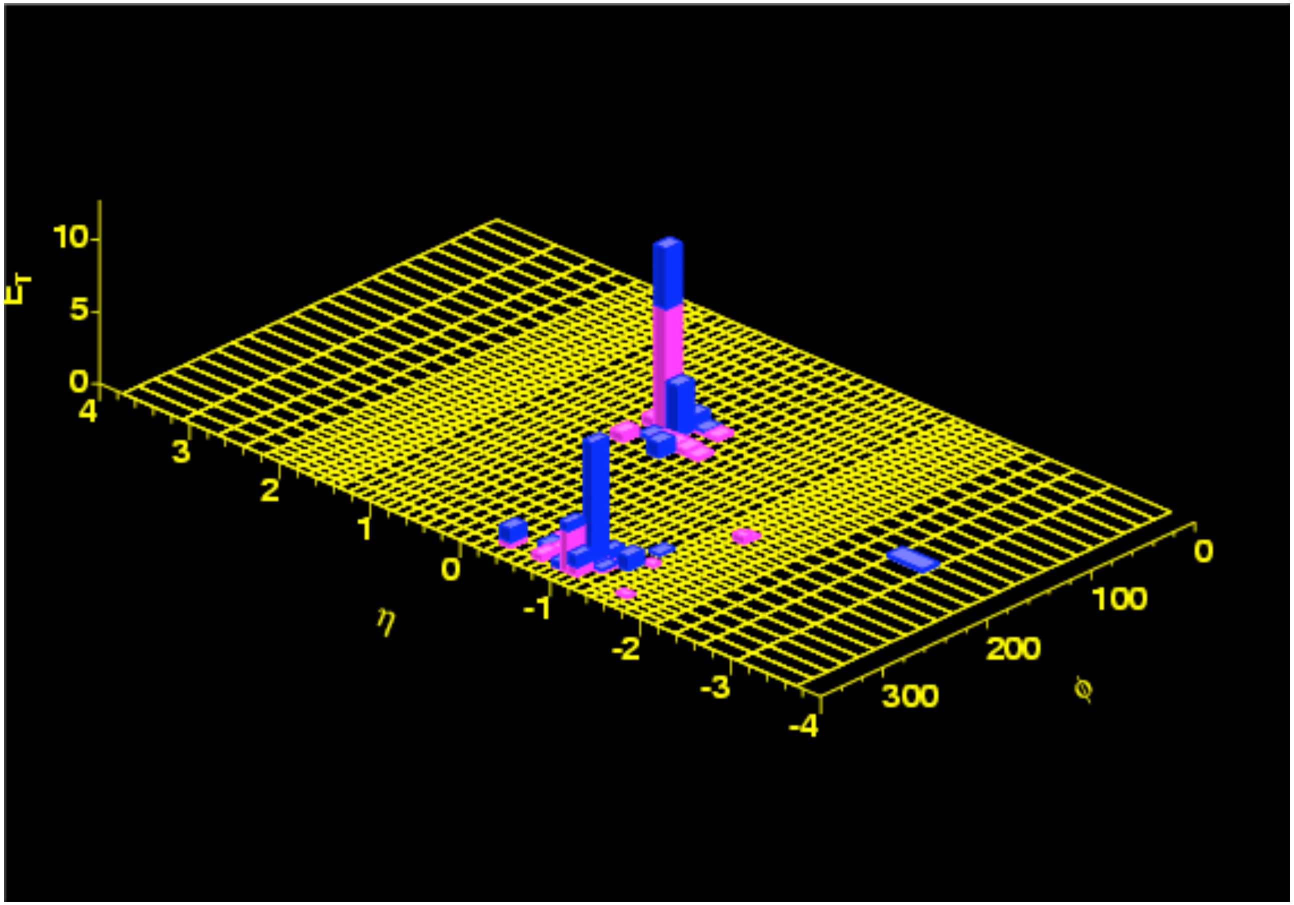
Decay modes of the Higgs



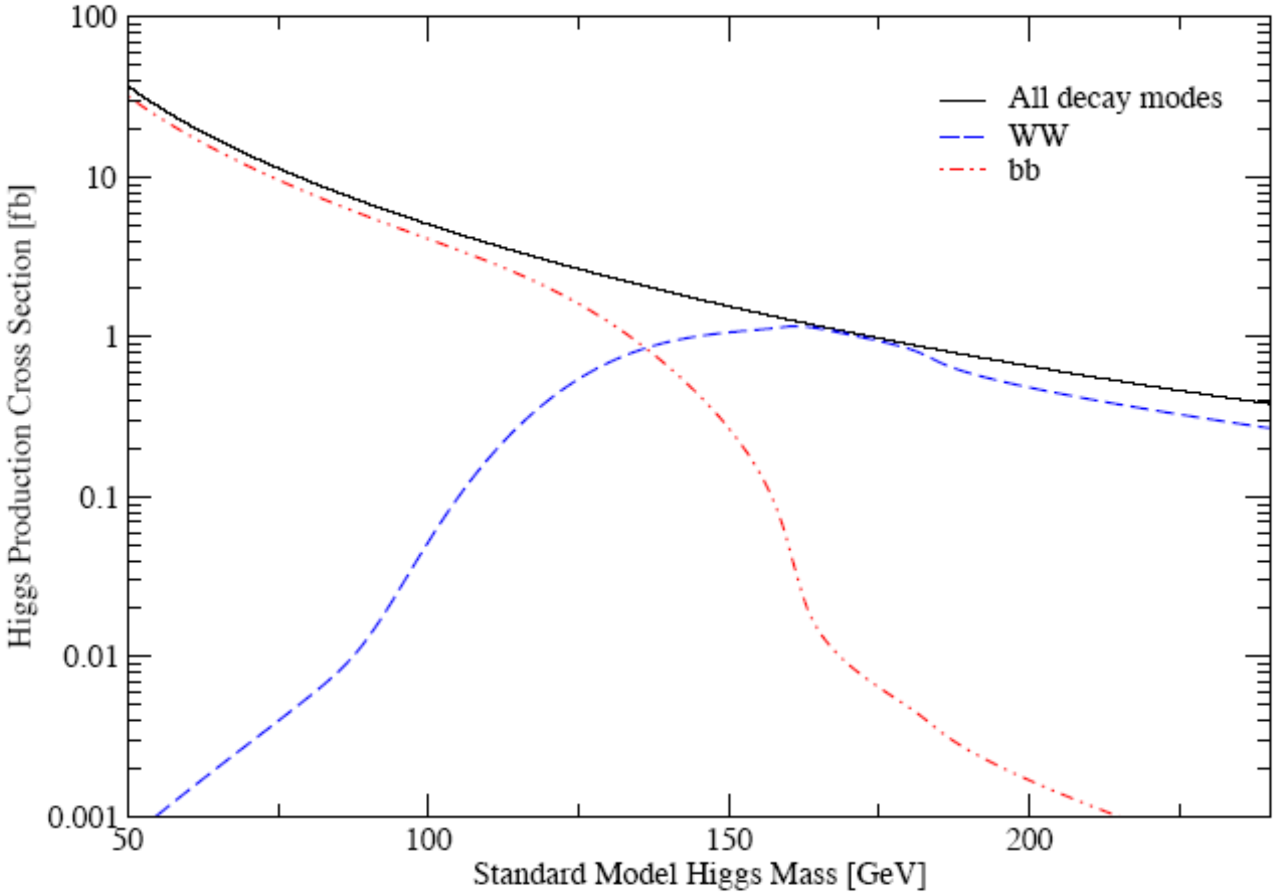
Central Exclusive Dijet @Tevatron

pp->p+JetJet(=q antiquark)+p

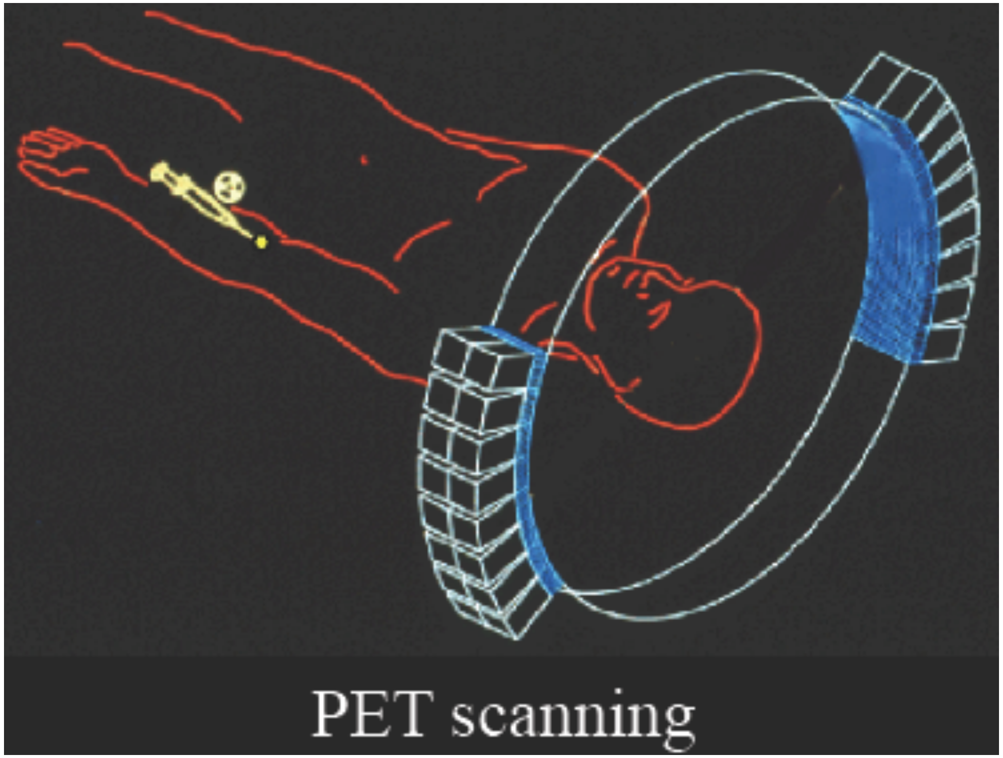
Supports exclusive H^0 prediction of Khoze, Martin & Ryskin



Higgs Production and Decay



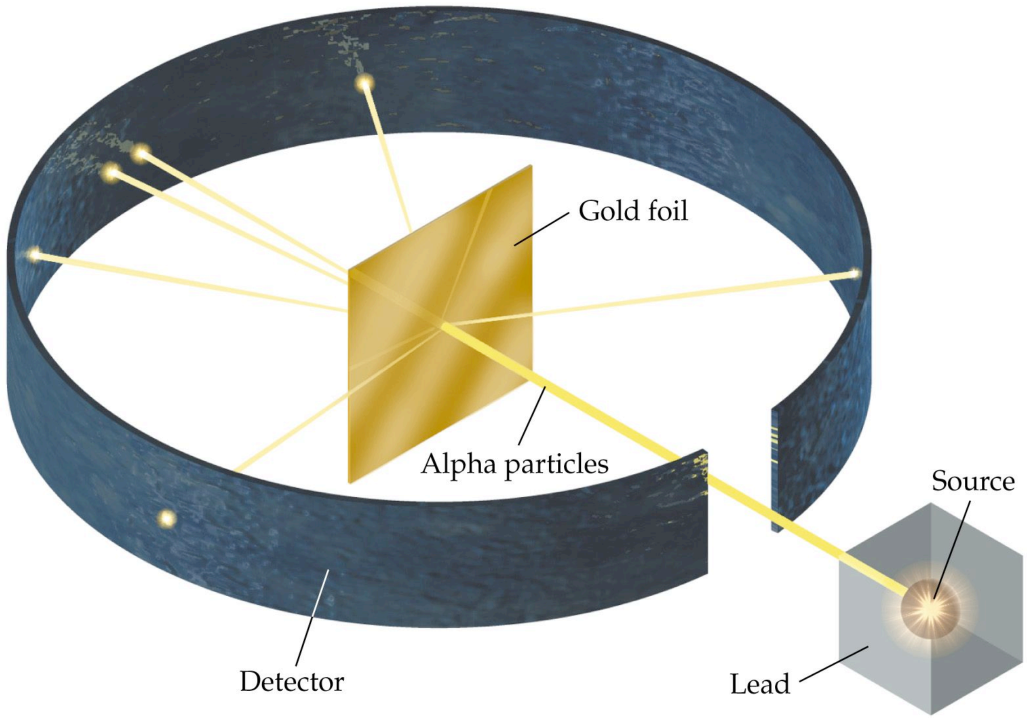
spinoff

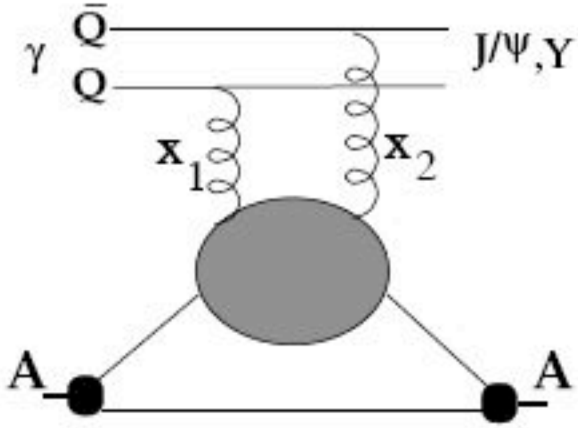


High resolution timing could significantly improve image resolution and speed

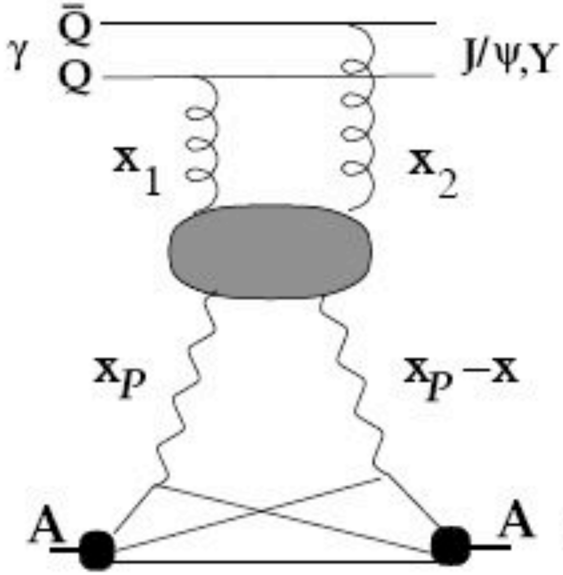
Rutherford Experiment

- Measured Angular dependence of rate using scintillation flashes in ZnS
- R. Calculated an angular dependence of ~ $\frac{1}{\vartheta^4}$ for a point nucleus and a distance of closest approach (potential energy= 5 MegaVolt) of ~30* 10^{-13} centimeters (a bit bigger than the gold nucleus)

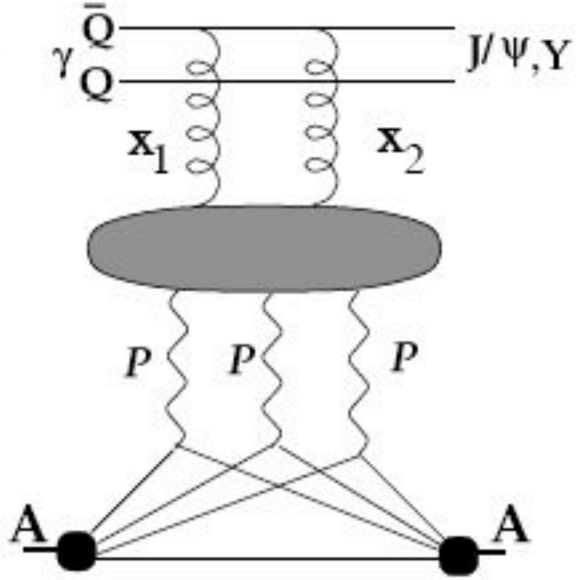



$\bar{Q}$
γ
Q
J/ψ,Y
x_1
x_2
A
A

(a)


$\bar{Q}$
γ
Q
J/ψ,Y
x_1
x_2
x_P
$x_P - x$
A
A

(b)


$\bar{Q}$
γ
Q
J/ψ,Y
x_1
x_2
P
P
P
A
A

(c)

the ATLAS detector