Exciting the Vacuum

aka Central Exclusive Production

***from the ISR** (Glueballs) …*

***to the Tevatron** (leptons, photons, hadrons, charmonium)…*

***to the LHC** (Higgs, WW, Z?, SUSY?)*

pp → p X p where X is *a simple system completely measured*

Mike Albrow

Fermilab

Outline

Part 1 :

The vacuum: an experimental viewpoint (hit it!)

Different hammers: electromagnetic, strong and weak
Different exposure times: shorter → Planck
longer → Age of Universe!

Experiments (observing) with **electromagnetic eyes**

Observing with **strong eyes** (looking for glueballs)

Combining the above (photoproduction)

Now at the LHC: (weak eyes) **exciting the Higgs** field

Part 2 : Central Exclusive $\pi^+\pi^-$ production in CDF (new)

GAP-X-GAP Physics or Central Exclusive Production

Mike Albrow, Fermilab

>> What is GXG and why is it interesting?

>> X = low mass hadrons (double pomeron exchange, D P E) at ISR (AFS), SPS (Ω), Tevatron (CDF), LHC

>> Other GXG channels: $\gamma+\gamma$, γ + P in CDF and CMS & P+P → χ_c

>> Future, high M(X) at LHC: X = H, JJ, W+W-

CMS: 2 candidates

Review:

Central Exclusive Particle Production at High Energy Hadron Colliders.
M.G. Albrow (Fermilab), T.D. Coughlin (University Coll. London), J.R. Forshaw (Manchester U.). Jun 2010. 64 pp.
Published in **Prog.Part.Nucl.Phys. 65 (2010) 149-184**

arXiv:1006.1289 [hep-ph]

What is GXG and why is it interesting?

G = GAP = Rapidity gap: $\Delta y >\sim 4$ with NO HADRONS

X = central particles, fully measured (exclusive, distinct from inclusive)

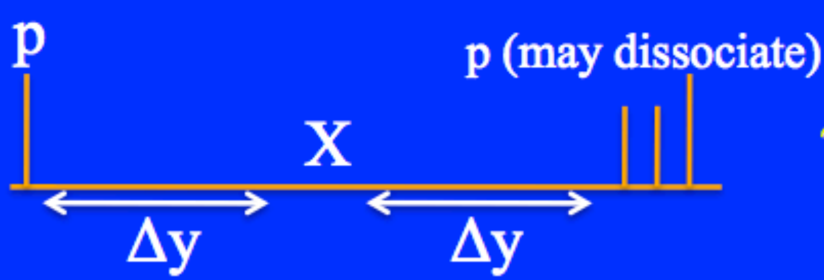
Examples of X, **all observed for 1st time in hadron+hadron by CDF:**

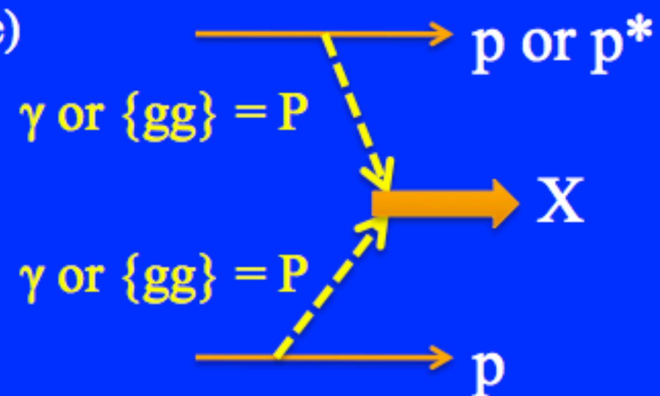
$X = e^+e^-, \mu^+\mu^-, \gamma + \gamma, J/\psi, \psi(2S), \chi_c$, Jet+Jet

New $X = 2 - 4$ hadrons ($\pi\pi$, & to come: KK, $\rho\rho$, $\varphi\varphi$, ΛpK(?) etc.)

Later in CDF: X = high n(ch), ΣE_T, gluon jets (leaders?), charm, etc.

Later at LHC: X = more Jet+Jet, W^+W^-, Higgs, ...





1960 & 900 & 300 GeV at CDF, 7 TeV at LHC

$\gamma + \gamma$ OR $\gamma + P$ OR $P + P$

Three classes of GXG:

2-photon (QED + small QCD corrections ... shadowing or P)
Studied in e+e- at LEP, a little in ep at HERA, now also in pp.
Photoproduction γ+P at HERA, now also in pp.
Double pomeron exchange, only in hadron-hadron (pp/ppbar)
Comparing M(X) spectra in different processes helps meson spectroscopy

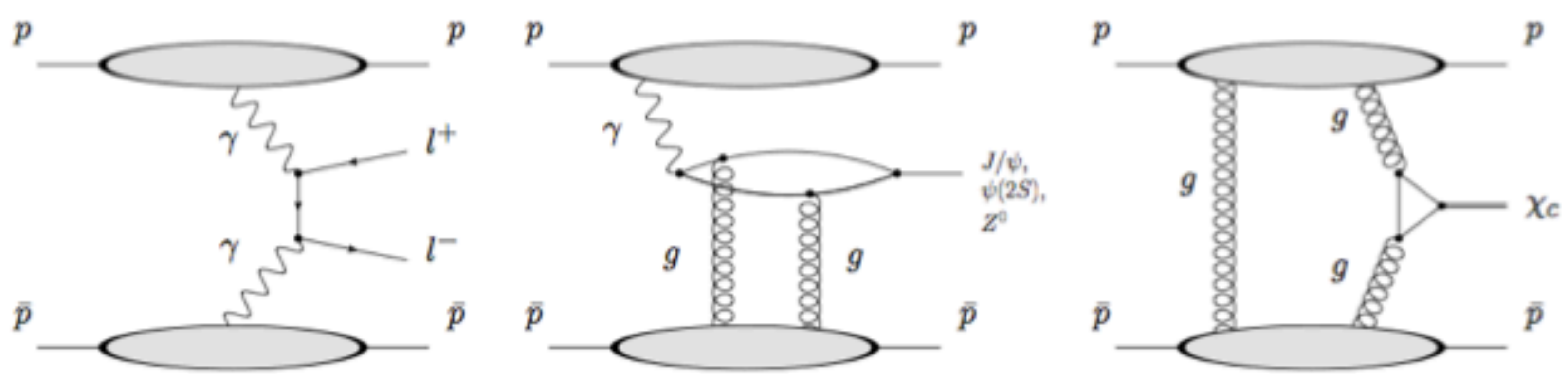


Figure 10: Feynman diagrams for processes contributing to the exclusive di-lepton signal. (a) $\gamma\gamma \to l^+l^-$, (b) $\gamma I\!P \to J/\psi, \psi(2S), Z^0$, and (c) $I\!P I\!P \to \chi_{c0}$.

At low masses, Double Pomeron region, non-perturbative and difficult to calculate. New efforts (Harland-Lang et al, Antoni Szczurek et al.)

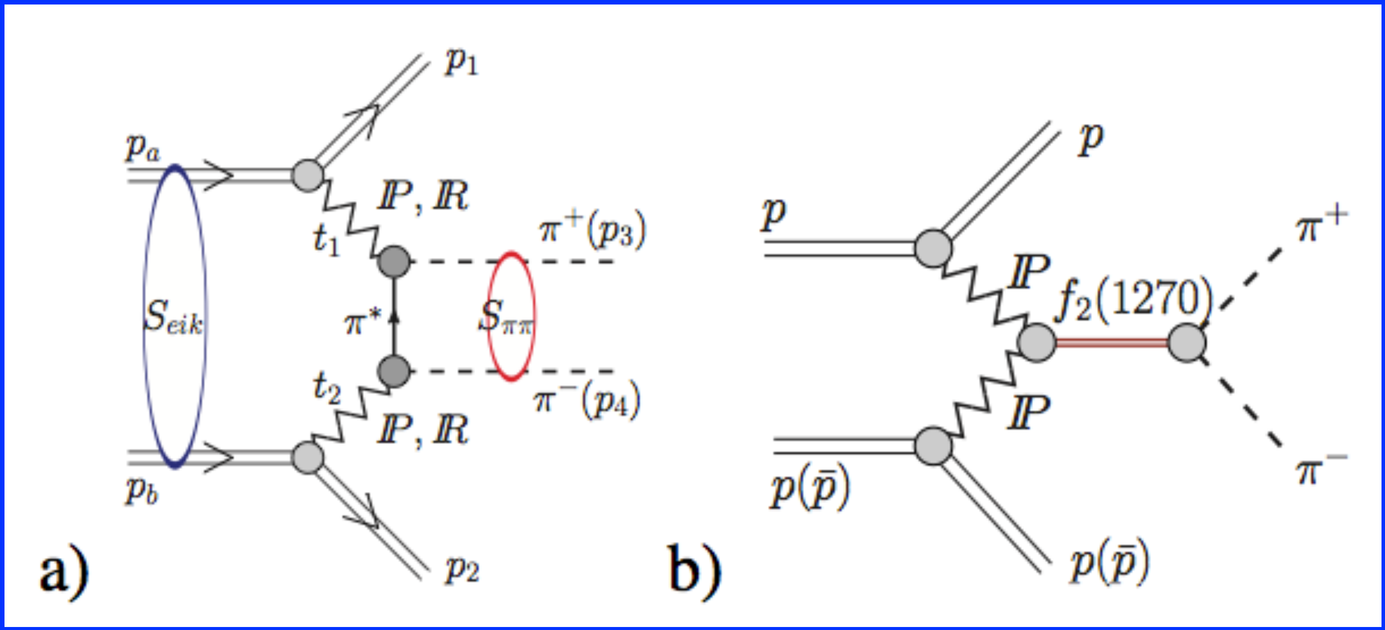


Diagram from P.Lebiedowicz & A.Szurek arXiv:12120166

or f0(600)/σ or f0(980) etc.

P + P

P = pomeron = strongly interacting color singlet t-channel exchange, in leading order {gg}, at higher Q^2 gluons and q-qbar pairs evolve in.
P + P → X has selection rules:
Q = S = C = B = 0 (of course), $I^G = 0^+$, $J^{PC} = 0^{++}$ or 2^{++} DOMINANT
Interesting for hadron spectroscopy, and for understanding pomeron (> 25% of p-pbar collisions have pomeron exchange!)
Higgs boson obeys all selection rules (vacuum) GHG expected at LHC (~ 2 - 5 fb)
We already did some, and they importantly tested the theory for p + H + p:

PHYSICAL REVIEW D **77**, 052004 (2008)

Observation of exclusive dijet production at the Fermilab Tevatron $\bar{p}p$ collider

X = JJ

PRL **108**, 081801 (2012) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2012

Observation of Exclusive $\gamma\gamma$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

$X = \gamma\gamma$

PRL **102**, 242001 (2009) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2009

Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

X = J/Ψ, Ψ(2S) & χ_c 0/1/2

ISR: 1st to allow $\Delta y = 3 + 2 + 3$

Low mass (<~ 2 GeV) DPE cross sections at ISR ($\sqrt{s}$ <= 63 GeV).

If central state (~ $\pi\pi$) restricted to fixed central y-bin, σ falls with $\sqrt{s}$. At lower $\sqrt{s}$ Regge exchanges, X includes ρ (I=1) etc., which die out at high $\sqrt{s}$ leaving P exchange.

If Gap widths Δy are fixed at 3, σ rises (more room for X, higher M(X) allowed.

At top ISR energy σ(DPE) ~ 15 μb

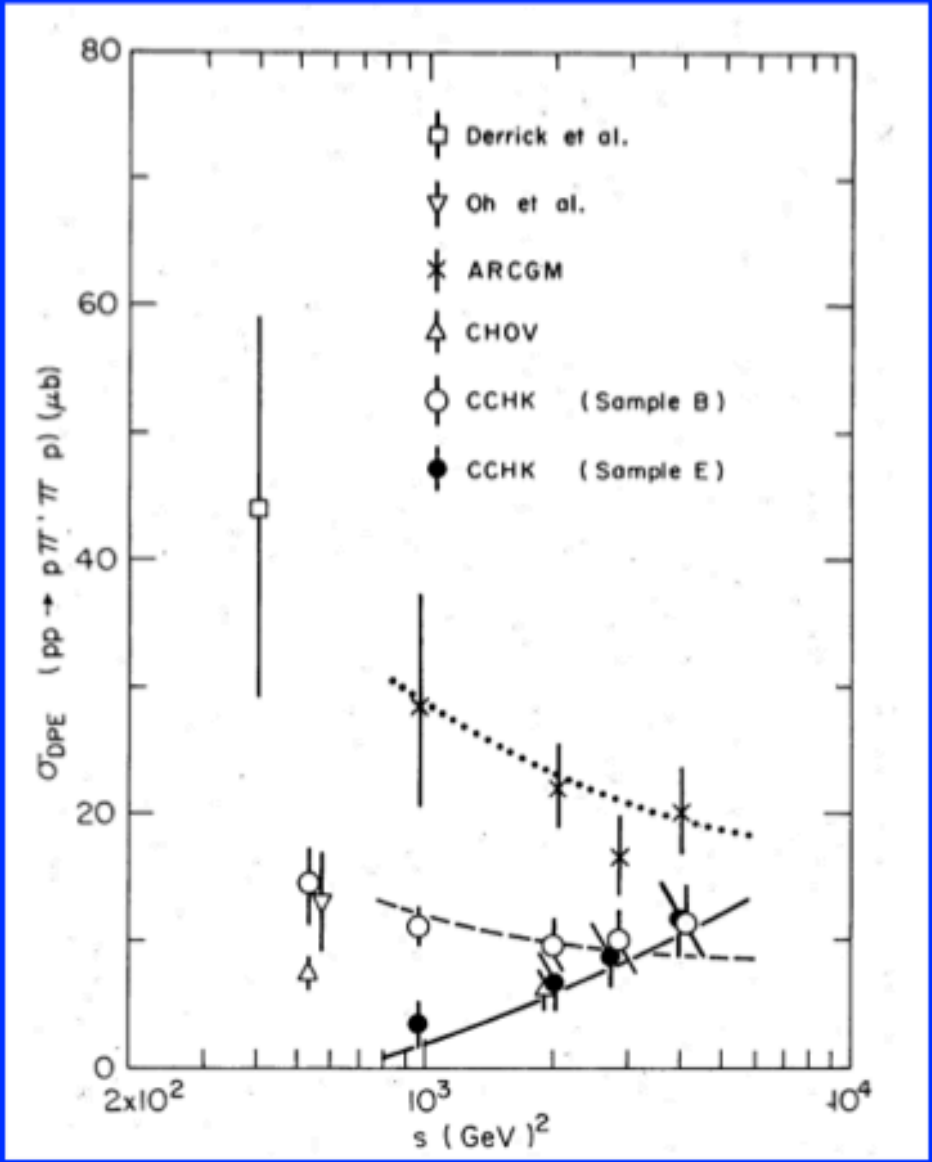
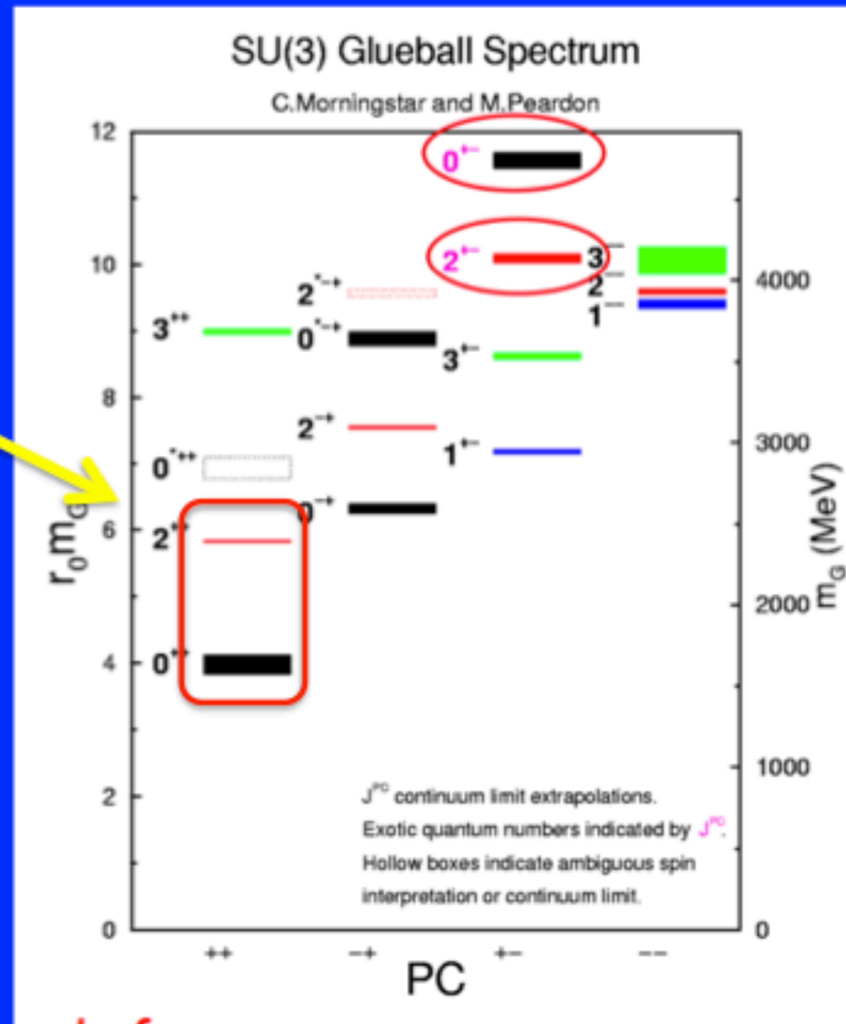


Figure 7: Experimental $DIPE$ cross sections (μb) versus s (GeV^2) at the ISR together with the Regge calculations of Ref [26]. The full circles and the rising solid line are for two gaps with $\Delta y > 3$. The dashed line is for $|y_\pi| < 1.0$ and the dotted line for $|y_\pi| < 1.5$. Figure from Ref. [26].

Double Pomeron Exchange favours Glueballs or Glue-rich hadrons

Scalars especially are poorly understood: big hole in understanding QCD.
Note: no narrow/light glueball: Γ_G > few 100's MeV, → not an isolated particle.
H(125) is ! $\Gamma_H \sim 5$ MeV << M(π)

Representative lattice QCD calculation:
Note especially lightest expected states
0++ (~1600) and 2++ (~2300)
These Q.Nos. could not be hybrids (?)

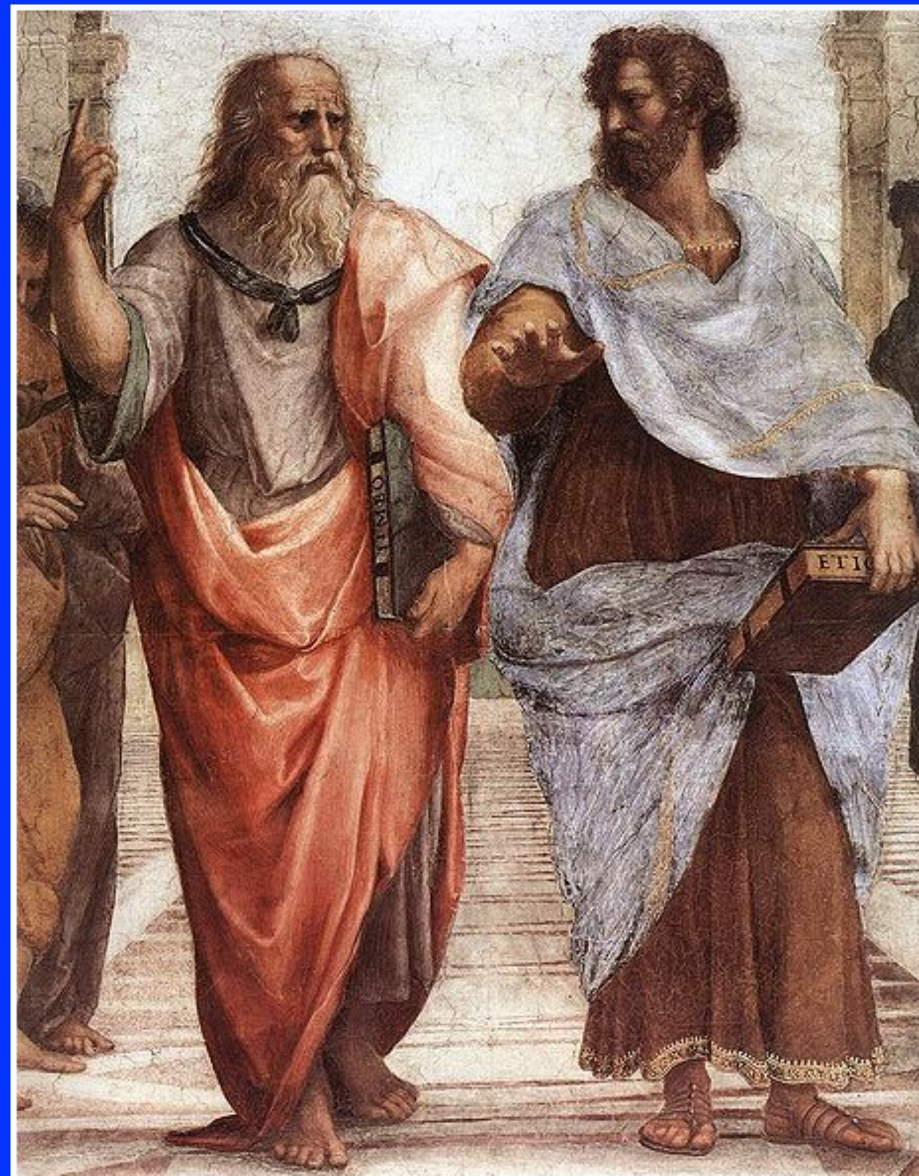


Need knowledge:
>> Different decay modes (B.R.'s)
>> Widths
>> Production mechanisms, e.g.
P+P favours g-g
while γ+γ favours q-qbar

"Nature abhors a vacuum"

Oh, really?

The vacuum $\supset$ all of physics



Plato & Aristotle

An early experiment on the vacuum: (Otto von Guericke, 1650)

"The vacuum sucks!"

Common wisdom, but it's those tiny atoms pushing in from the outside, and even teams of horses could not beat those tiny atoms! 16 horses against lots of atoms! There's strength in numbers.

Atoms are much emptier than most people imagine

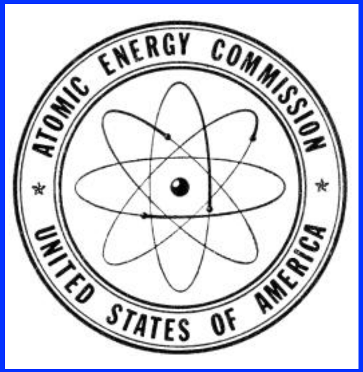
Typical:

Really more like a pinhead in a Welsh house

Even:

Cold fusion anyone?

Better:



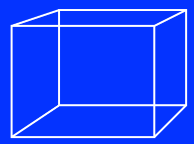
Sorry, • should be much smaller

10^{-13} cm / 10^{-8} cm
~ 0.2mm / 20m

How can an experimenter study the vacuum?

HIT IT! (How else?)

Box of vacuum:

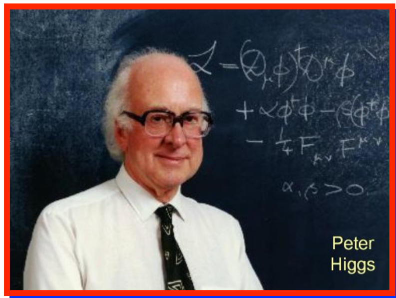


In copper: 5.10^{-15} …of course its ***full*** of EM fields.

Matter (nucleons) take
10^{-18} of volume! (in air)

In pursuit of the perfect vacuum (recipe) :

1) Remove all the nucleons and electrons
2) Cool down to so close to T = 0 that thermal μ waves don't fit.
3) Thick shield (no radioactivity) to kill X-rays and γ-rays.
4) Choose a time window when no high energy cosmic rays traverse.
5) Damn the neutrinos! Bright to weak eyes, but invisible to EM eyes.
6) Pionic and gluonic fields on the walls, but they don't come in far.
7) Let the box fall freely in outer space : no gravitational fields.



Are we there yet?

Nice try, but no, for at least 2 reasons

1) Professor Higgs said that a "potential" (usually called a "vacuum expectation value") or scalar field is everywhere. So ***that's*** why an electron (or μ) here and in Andromeda have the same mass, and they know what mass to have even in $\gamma\gamma \rightarrow \mu^+\mu^-$. If there's really "nothing", how could they possibly know?

How do we define the vacuum anyway, if not the absence of any stuff?
Let's say: the lowest possible energy state

$\Delta E . \Delta t >\sim \hbar$

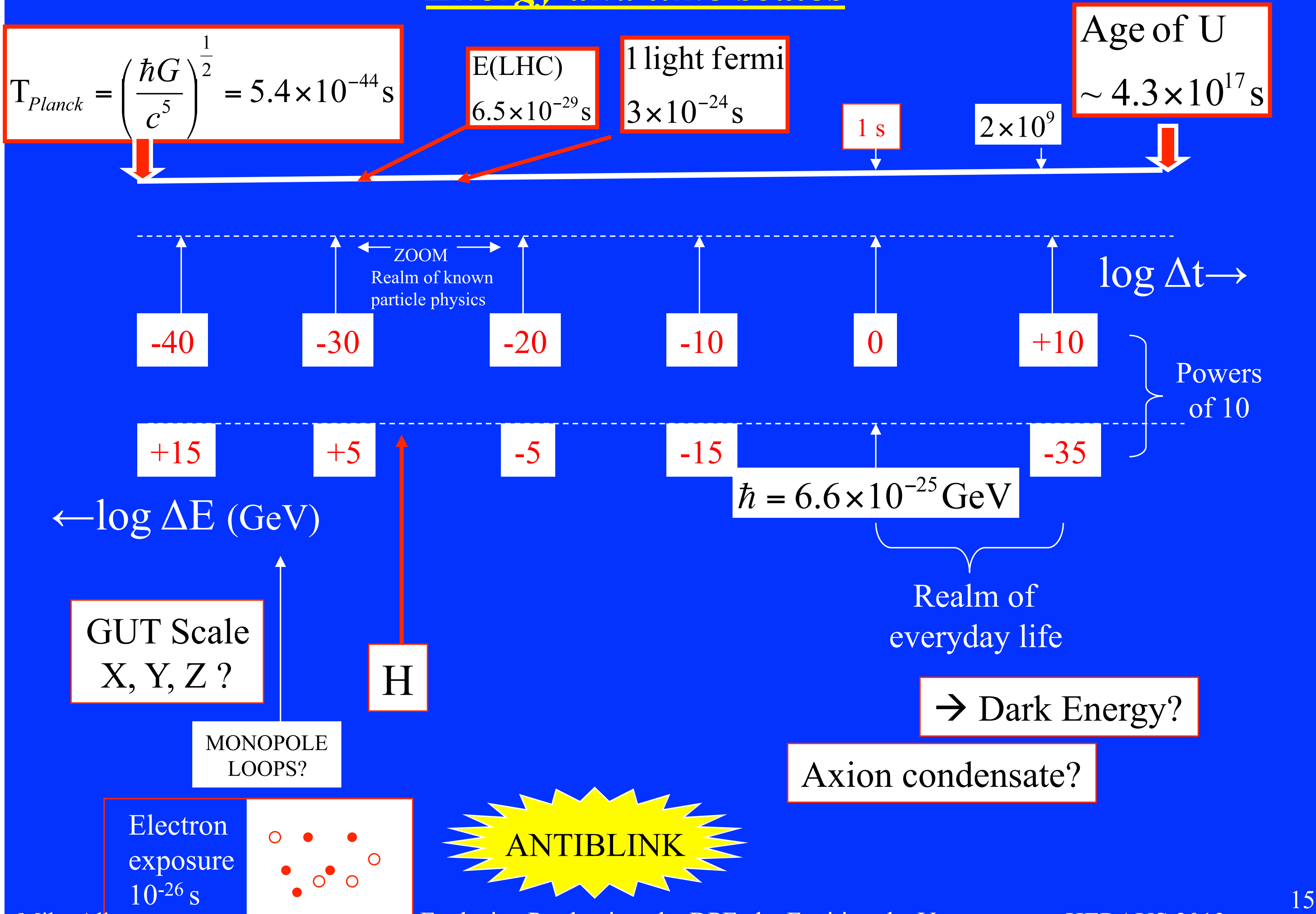
But Professor Heisenberg said that E = 0 does not make sense unless you have an ∞ exposure time.

BLINK

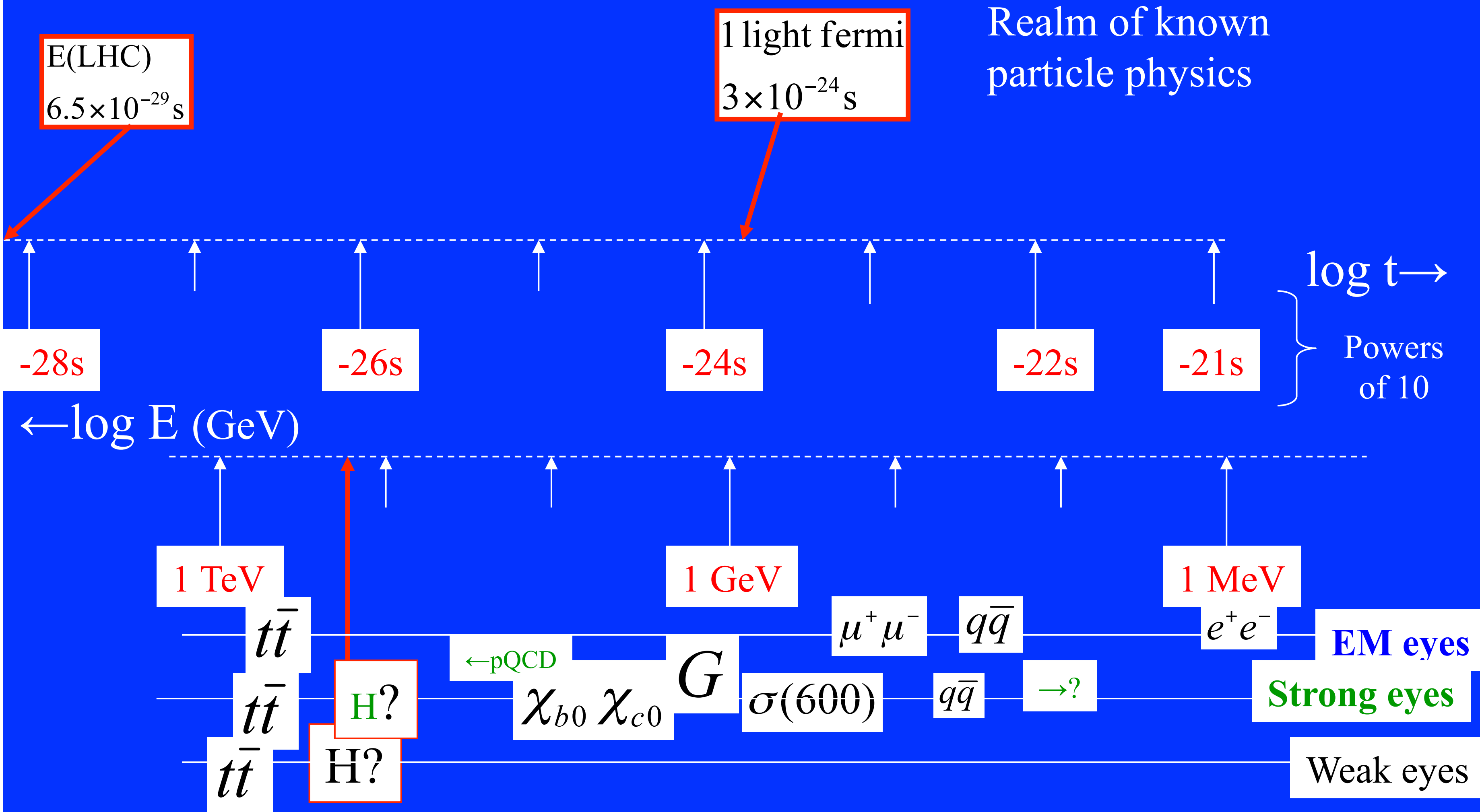
ANTIBLINK

If you antiblink,
short exposure, high energy fluctuations.

Energy and time scales



Energy and time scales : ZOOM IN

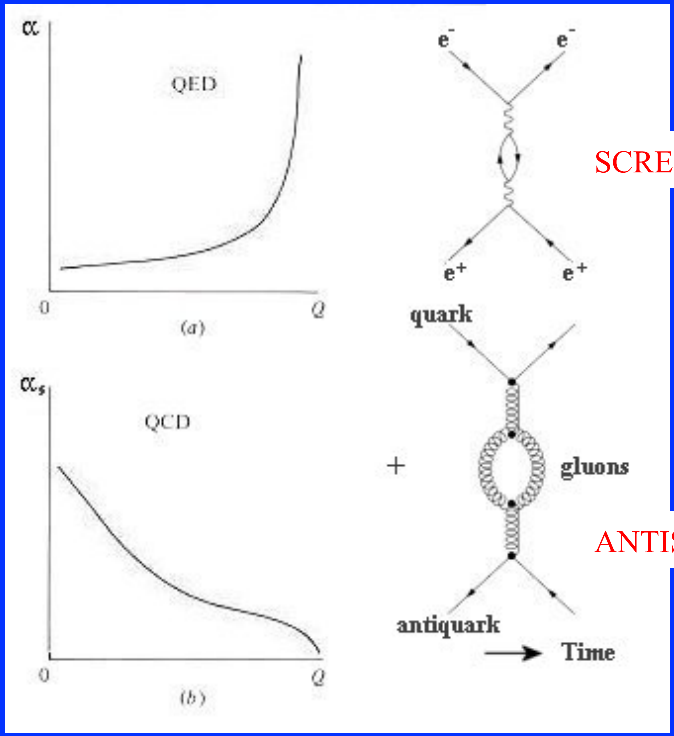


Particles shown have vacuum quantum numbers

hadrons → $I^G J^{PC} = 0^+0^{++}$ and can fluctuate up in time Δt

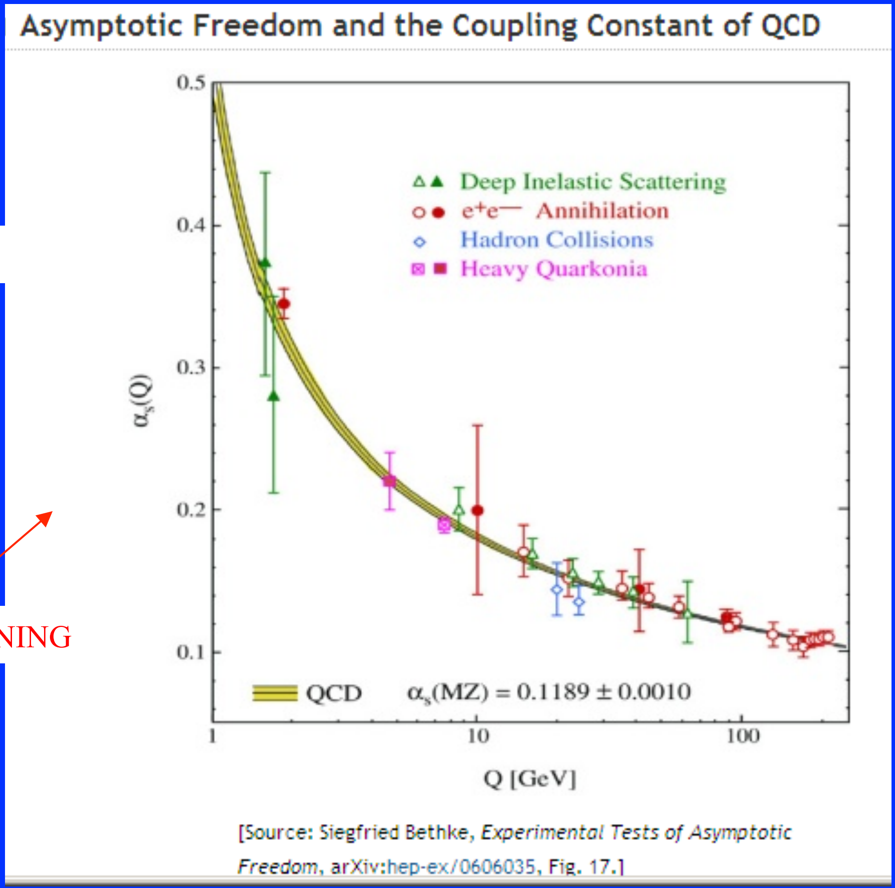
($I^G = 0+$ if appropriate ... hadrons)

Vacuum polarization:
opposite effect in QED
and QCD (g-self interactions)



SCREENING

ANTISCREENING

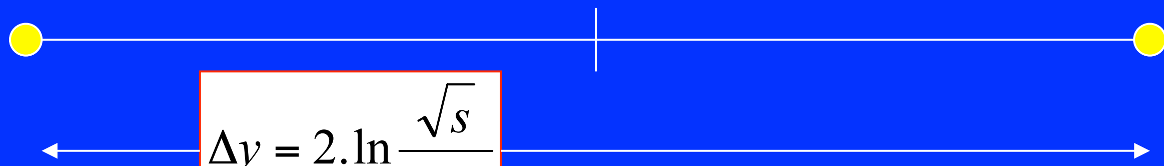


Also interesting!
This we will study

Typical collider
tests of QCD
SMALL DISTANCES

Rapidity gaps, with (almost) no Regge theory

The mother of all rapidity gaps Δy …. Elastic scattering:



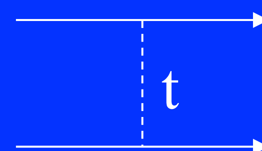
$$\Delta y = 2.\ln \frac{\sqrt{s}}{m_{p/e}}$$

$$y_{beam} = \ln \frac{\sqrt{s}}{m_{p/e}}$$

Gap = no particles:

= 24.4 LEP e+e-
= 8.4 ISR pp
= 15.3 TeV pp
= 18.0 LHC13 pp

4-momentum is exchanged across the gap: t-channel
4-mom^2 is –ve; virtual exchange.
Exchange carries spin J, but strictly α(t)
where α(t) is complex.



Rap-gap cross sections go like: $\sigma(\Delta y) \sim e^{(\alpha(0)-1).\Delta y} \sim e^{(J-1).\Delta y}$

Thus: over large gaps exchange has J >= 1, Q = 0, color singlet.
Only 2 possibilities:
Photon γ (in ee and pp and ep)

Gluon (ep and pp) … ?color!!? Cancel it with >= 1 other gluon. Call it pomeron (gg) α(0)=1+ε
Pomeron has C = +1 (2 gluons OK). C = -1 OK with (ggg) : odderon ... @ large |t| ?
Z obeys the above rules, OK in e+e- but p inevitably break up.

Large (>~4) rapidity gaps only possible by (t) exchange of 4-momentum with:
No color or charge, and effective spin at t ~ 0 >= 1. **J = 1, α(0) >=1.**
But (a) we have such large gaps in strong interactions
(b) QCD is THE theory of strong interactions. Unlike QED, there is no elementary (q,g) object with these properties.
(c) In QCD, with Regge theory to describe exchanges of states in the t-channel, only >= 2 g exchange can work.

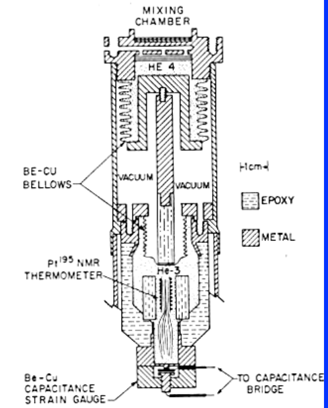
Scattering amplitudes must obey analyticity, crossing symmetry & unitarity.
Allow complex angular momenta → Regge theory

gg (C = +1) → Pomeranchukon → Pomeron IP
ggg (C = -1) → Odderon O
(not yet (?) detected. α < 1 ?)

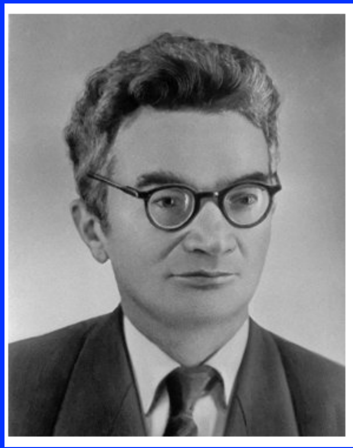

Tullio Regge

Pomeranchuk cooling cell (1950)
→ 1 mK

Are you a theorist?



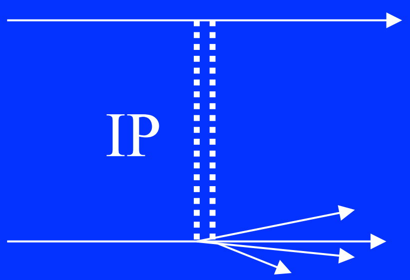
The Pomeranchuk cell used for cooling and measuring


Isaak Pomeranchuk
1913 - 1966

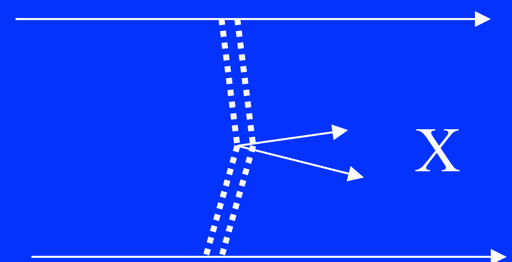
Pre 1970: Strong interactions described by Regge Theory.
Reggeons, pomerons, …

Post ~1974: **QCD rules!** But hadrons @ low Q^2 on the outside looking in.
Make spacetime a lattice (Wilson) : Lattice Gauge Theory
"Pomeron" not invited to the party. … "the P-word"
Double Pomeron Exchange (DPE) double yuk!

Yet: **it's fundamental strong interaction physics, at large distances. New phenomena invited.**



Diffractive excitation
of a hadron
IP = vacuum exchange



Very restrictive
X properties

Diffractive excitation
of the vacuum

* Masses of unstable particles also complex:
$M + i\Gamma$

Low & Nussinov: IP = gg

Not a real particle, ~ {gg} color singlet in/around p

The **QCD vacuum** is a very complicated matter, made of strongly interacting quark and gluon fields, and one can hardly understand the hadrons without understanding the vacuum first. (Ed Shuryak)

The **vacuum has phases** revealed under extreme conditions:

Quark gluon plasma (or perfect liquid?) at high temperature
Color superconductor at high density

→numerical simulations : **Lattice Gauge Theory LGT**

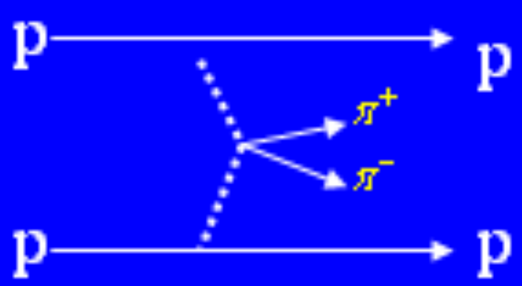
→**Semiclassical methods** : Fundamental topological solutions of Yang-Mills equations called instantons (these are not particles)

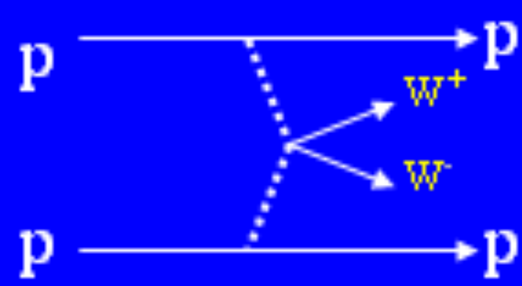
The playing fields (personal bias; LEP and HERA too)

ISR – Tevatron -- LHC

$\sqrt{s}$ = 63 1960 7-13,000 GeV

G?





H?

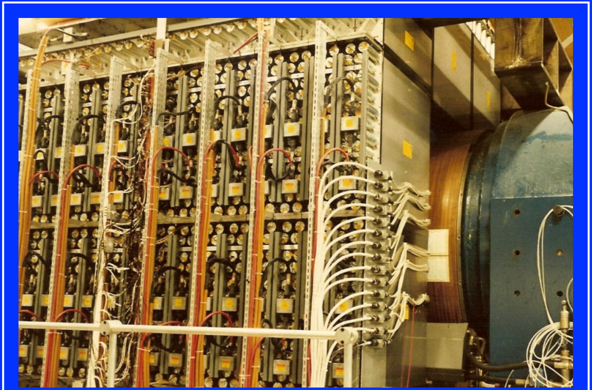
$(\pi^+\pi^-, K^+K^-, p\bar{p})$

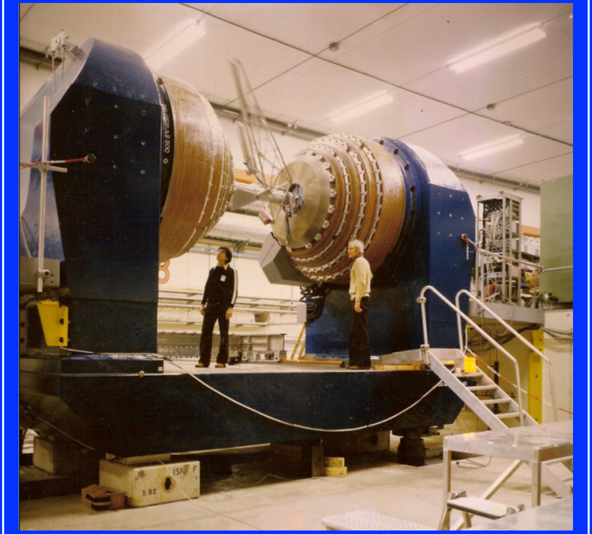
Tevatron (CDF)

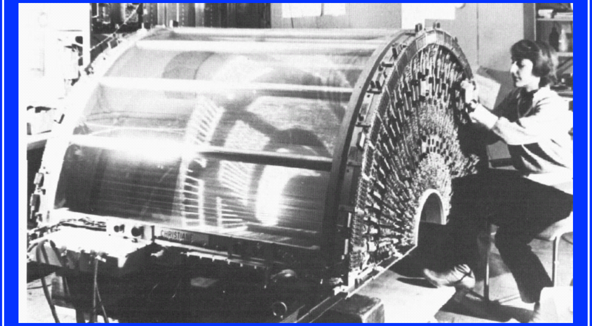
$e^+e^-, \mu^+\mu^-, J/\psi, \psi(2S), \chi_c, JJ \ldots \pi^+\pi^-, f_0, \phi\phi, \ldots$

$\sqrt{s}$ =	63	1960	14000	GeV
$\Delta y = 2\ln\frac{\sqrt{s}}{m_p} =$	8.4	15.3	19.2	(- 6 for gaps)
	3	100	700	GeV M(cen)

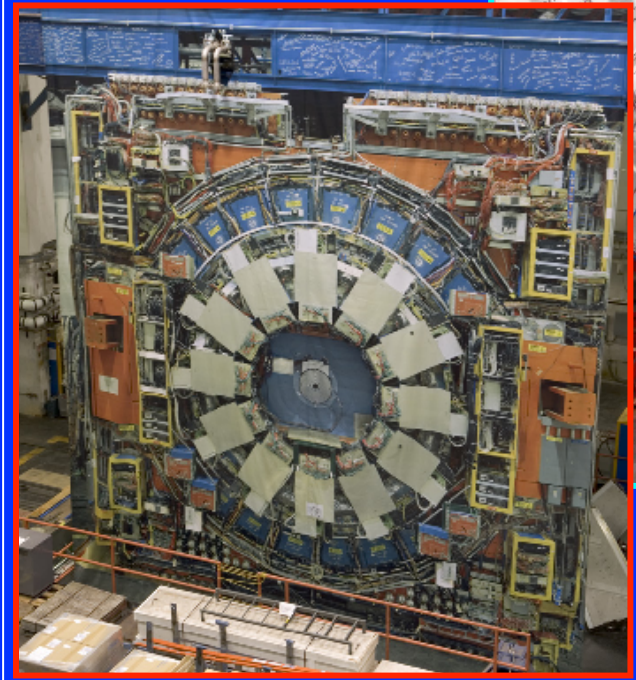
Axial Field Spectrometer (ISR)







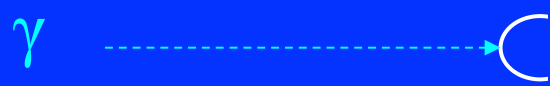
CDF (Tevatron)



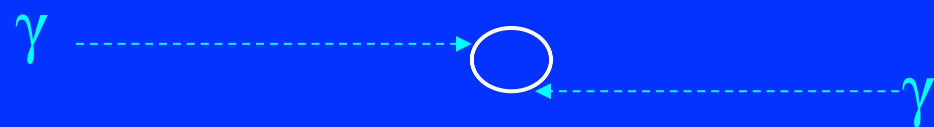
CMS (LHC)

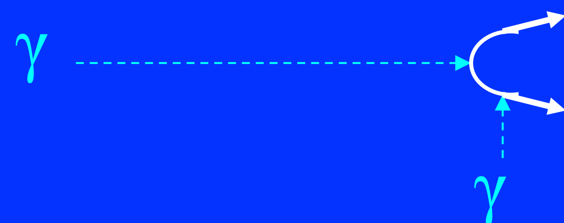
& ALICE, LHCb,
TOTEM, ATLAS? &

Exciting the vacuum with photons



Doesn't work!
E-p conservation forbids it;
except for v. short times
(evanescent)





Does work!
E-p conservation allows it;
Energy injection promotes loop to reality.

Heirarchy: $e^+e^-, q\bar{q}$ (& π^0etc.), $\mu^+\mu^-$,...$W^+W^-, t\bar{t}$,...?

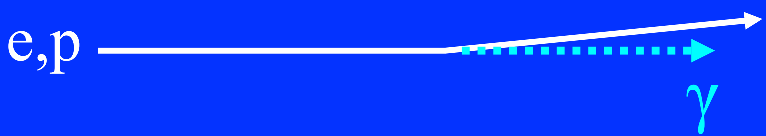
Smaller space-time intervals; higher energies

How do e,μ,τ,q…
know what mass to have?

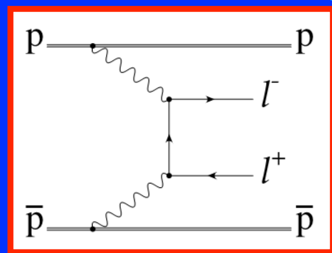
Example from Cosmos:

$$10^{17}\,\text{eV}\ \gamma-\text{rays} + \text{CMB 2K photons} \rightarrow e^+e^-\,(\text{GZK})$$

Photon “beams” radiated from electrons and protons

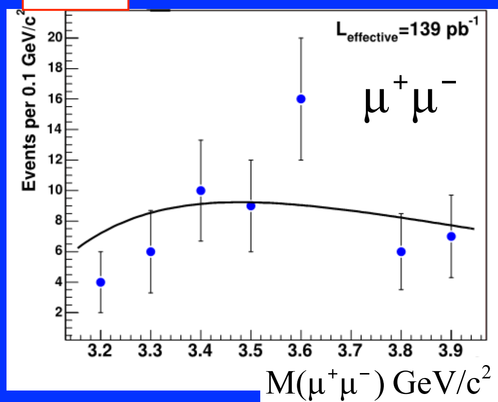


LEP etc: e+e- (~ background free)
HERA: e p (more background, little done)
pp/ ppbar: Very high b/g … Seen in CDF

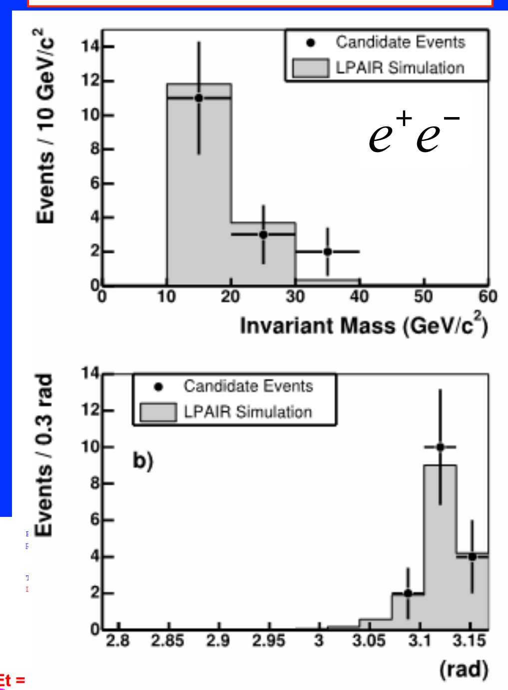


Tevatron, LHC as γγ colliders!

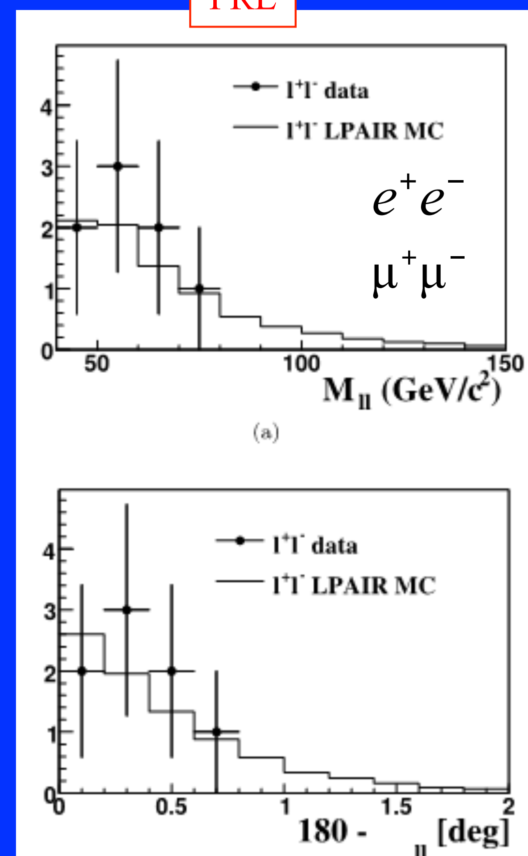
PRL

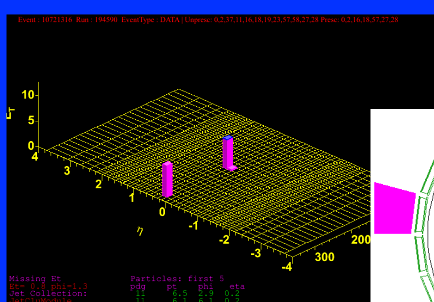


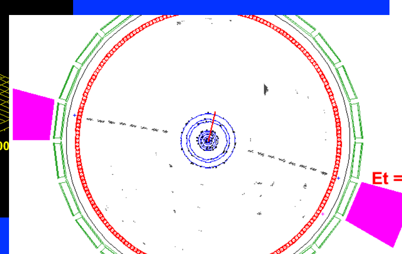
Phys.Rev.Lett 98,112001(2007)



PRL

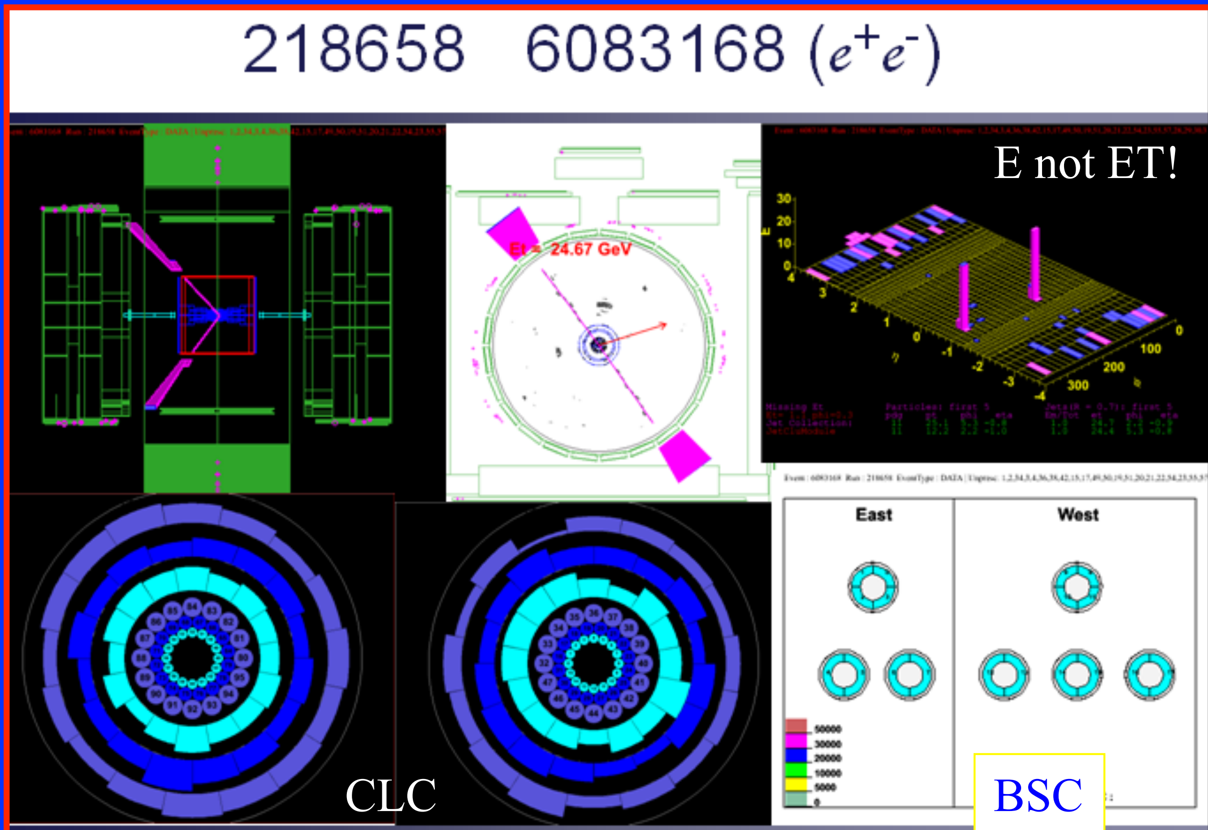






$\sigma \sim 0.24$ pb $\sim 3\times10^{-12}\sigma_{inel}$

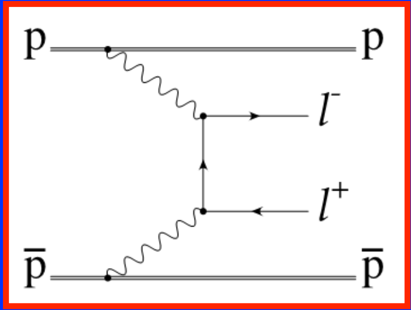
M(ee) = 49.3 GeV/c^2 |Δφ-π| = 6 mrad = 0.34 deg, p_T(ee) = 210 MeV



$$\sigma(p+\bar{p}\rightarrow p+e^+e^-+\bar{p})\ \text{or}\ \mu\mu$$
$$M > 40\ \text{GeV/c}^2, |\eta| < 4$$
$$= 0.24^{+0.13}_{-0.10}\ \text{pb}$$
$$\text{cf QED}_{(\text{LPAIR})} = 0.256\ \text{pb}$$

M reach Tevatron >~ HERA, LEP !
M reach LHC >> 2 M(W)

All CDF measurements agree with QED: So what?

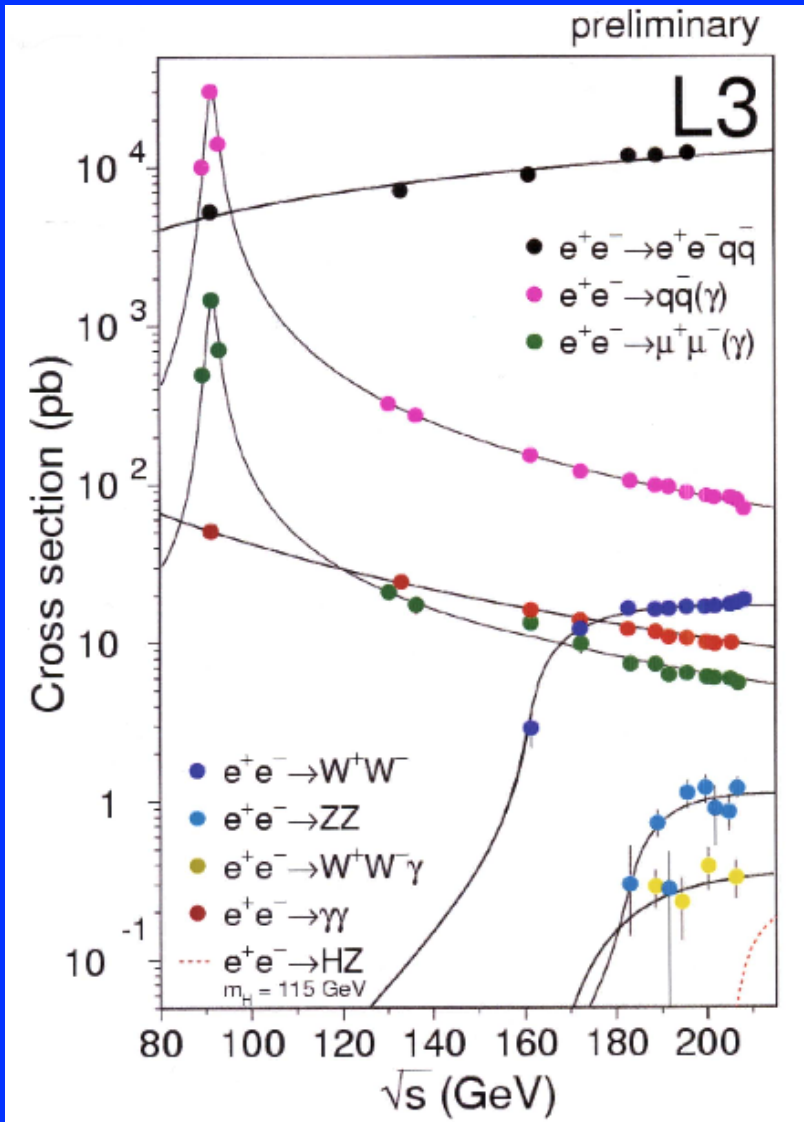


1) It shows we know how to select rare exclusive events in hadron-hadron environment
2) No other h-h cross section is so well known theoretically except Coulomb elastic.
   Possible Luminosity calibration at LHC (but Van der Meer v.good)
3) Outgoing p-momenta extremely well-known (limited by beam spread). Calibrate forward proton spectrometers.
4) Practice for other γγ collisions at LHC: $\gamma\gamma \rightarrow W^+W^-, \tilde{l}^+\tilde{l}^-, \ldots$

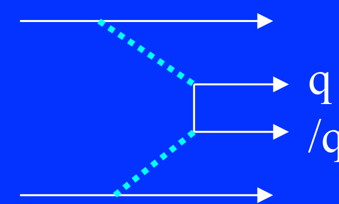
Note: These are present in the vacuum if you look quickly enough, and charged so they are visible to "light", rather EM, probes.

4400 events in 500 pb^{-1} with $M(\mu^+\mu^-) > 10$ GeV and $|\eta| < 2$

Exciting the vacuum with electromagnetic eyes

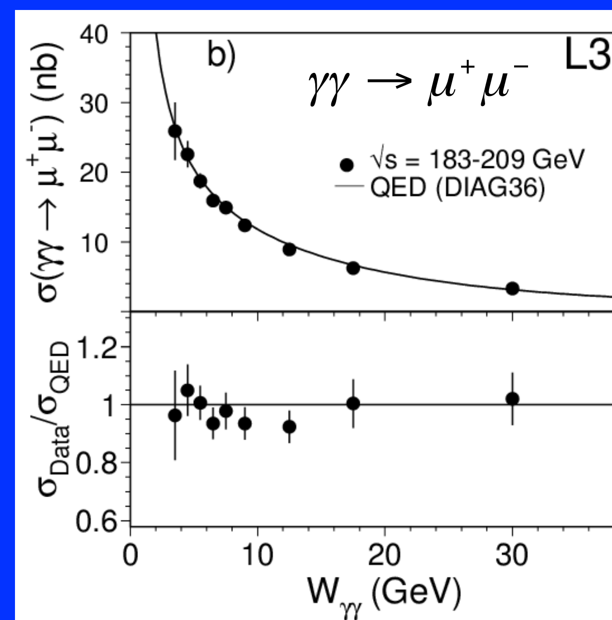


← These are:



Note dominance (> 100x) over annihilation.

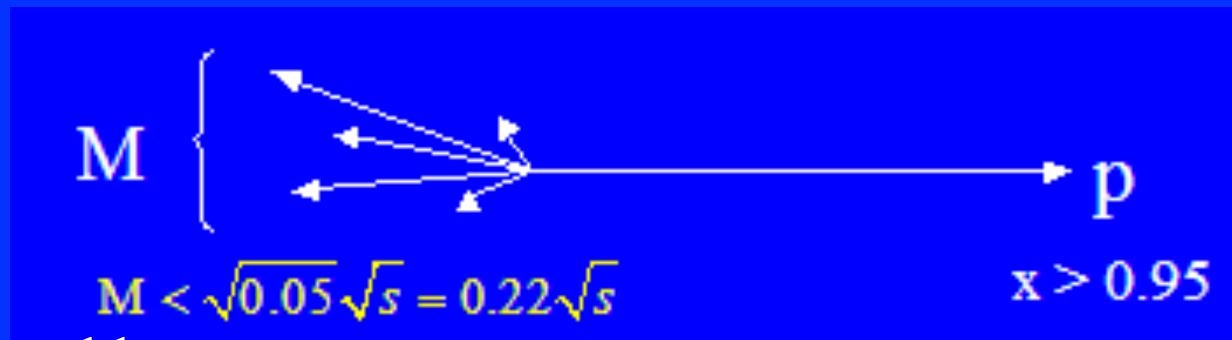
At **CLICILC** 999/1000 inelastic events are γ γ



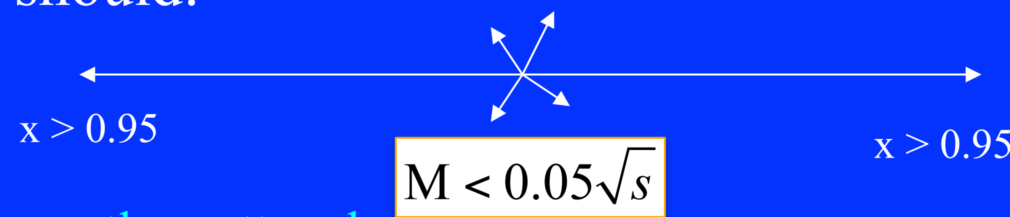
At Tevatron we have events to 75 GeV!

Central Diffractive Excitation

Theoretically
(Regge theory)
if:



happens, so should:



… both protons coherently scattered

H,WW →

M up to about 3 GeV at ISR – √s = 63 GeV
100 GeV at Tevatron – 1960 GeV
700 GeV at LHC – 14,000 GeV

Optical theorem: total cross section = *Im*(forward scattering amplitude)

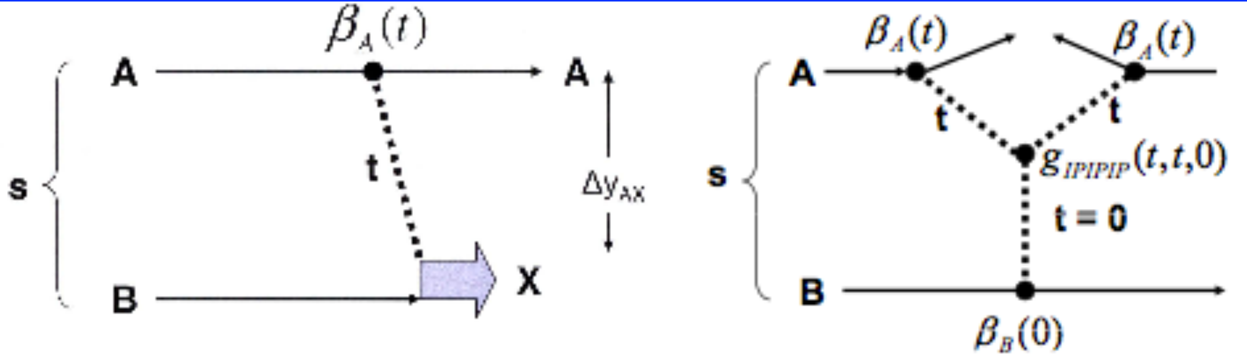


Figure 2: (a) Diffractive excitation of particle B to a state of mass M_X by pomeron exchange. (b) The corresponding cut diagram in the limit of large M_X.

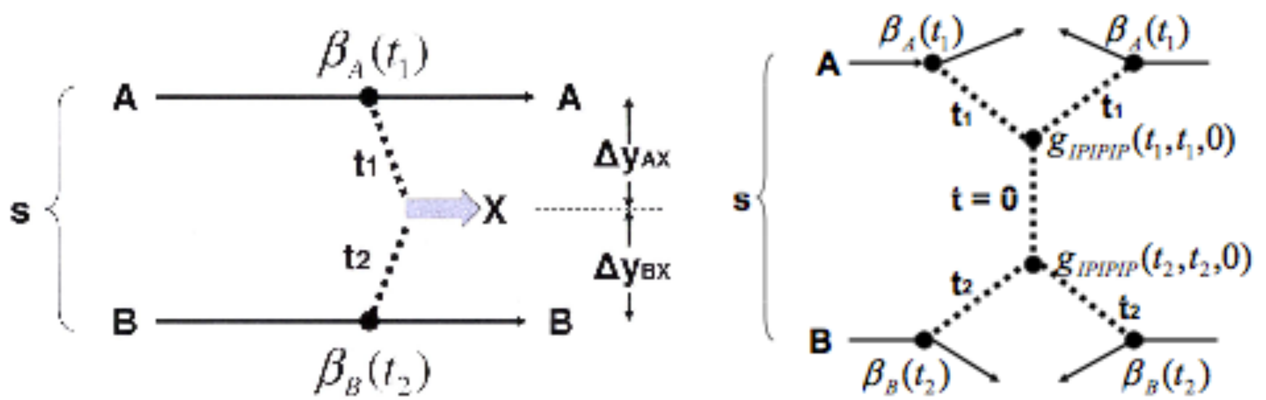
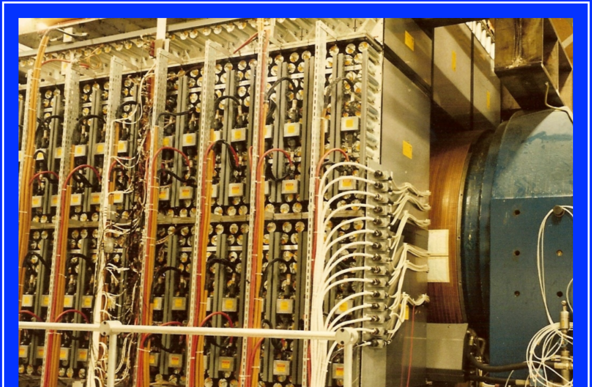
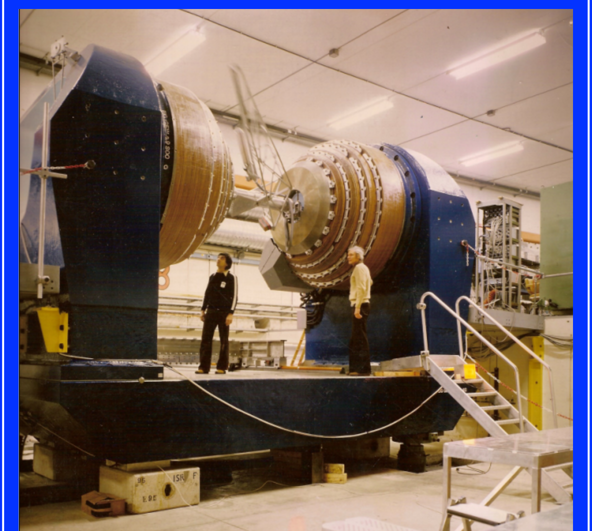


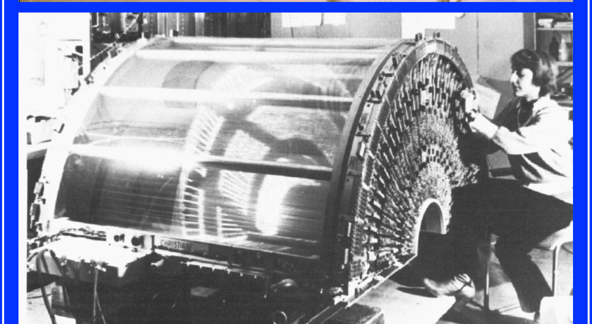
Figure 3: (a) Diagram for double pomeron exchange. (b) The corresponding cut diagram in the limit of large M_X.

ACF

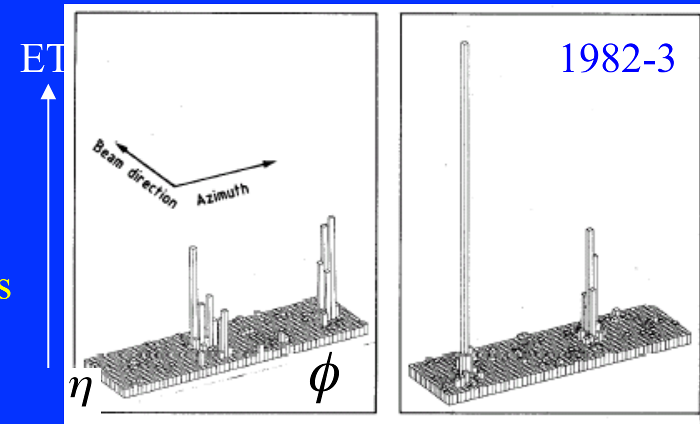
Axial Field Spectrometer (ISR)







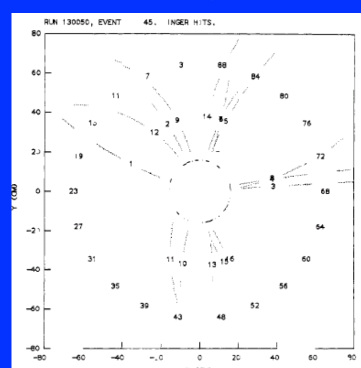
Uranium-scintillator
full-azimuth calorimeter
37%/sqrt(E) hadron showers

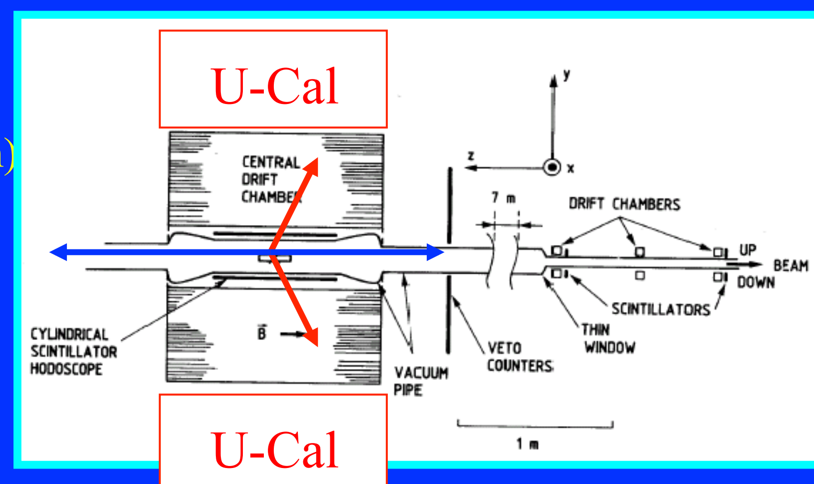


Jets! When E_T = 35-40/63 GeV

Search for glueballs : p + ππ + p
Added small drift chambers

Full-azimuth
drift chamber
dE/dx & z (Q-division)

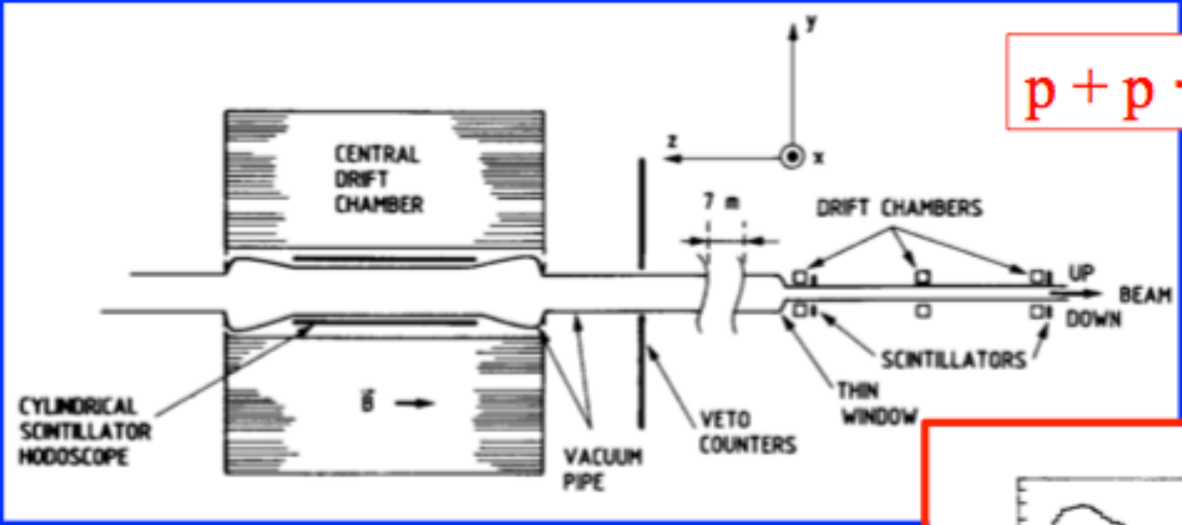




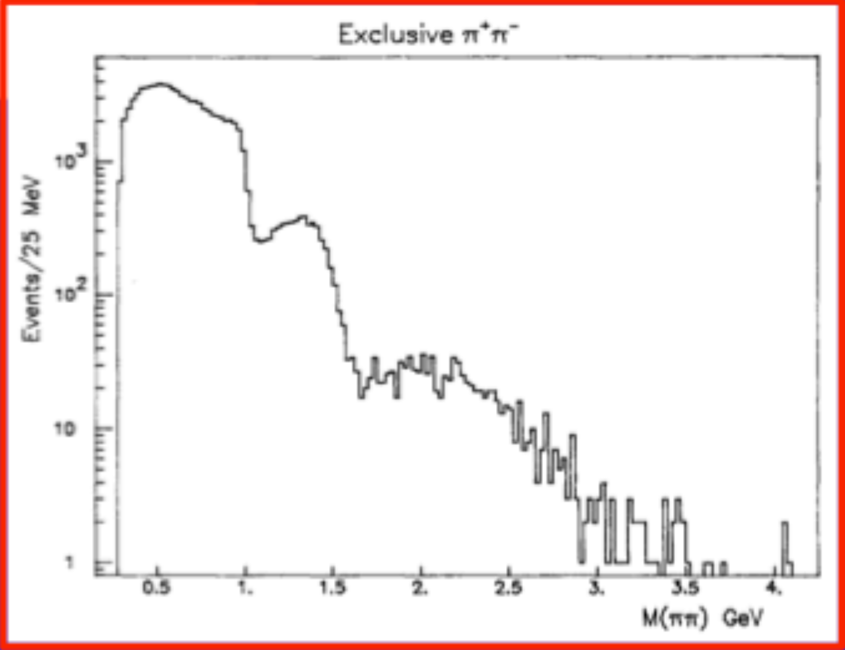
Axial Field Spectrometer at CERN ISR (pp @ 63 GeV)

A SEARCH FOR GLUEBALLS AND A STUDY OF DOUBLE POMERON EXCHANGE AT THE CERN INTERSECTING STORAGE RINGS

Nucl.Phys. B 264 (1986) 154



$p + p \rightarrow p + \pi^+\pi^- + p$ (DPE)

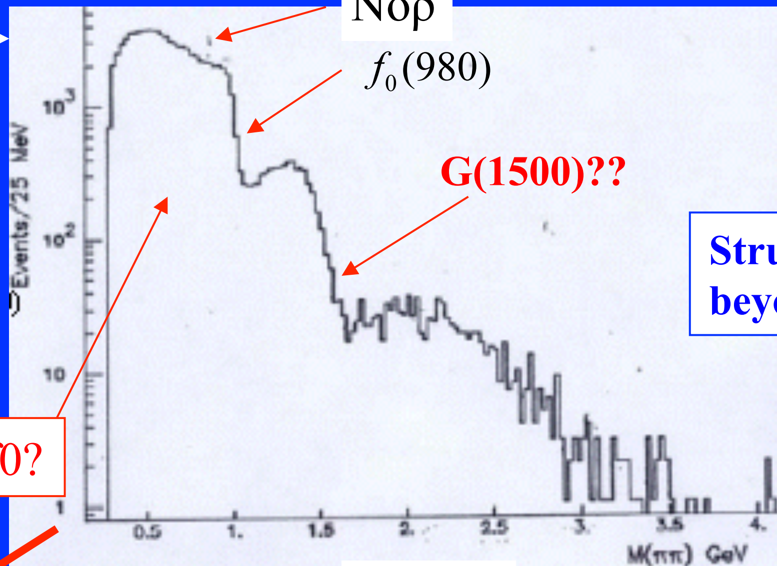


Pions assumed (but dominant) central
Cliff at 1 GeV (f0(980), KK threshold)
Broad bump 1.0 – 1.5 GeV (f2,f0(1370)?)
Dip around 1.5 GeV.

Central Exclusive π+π- Production (AFS)

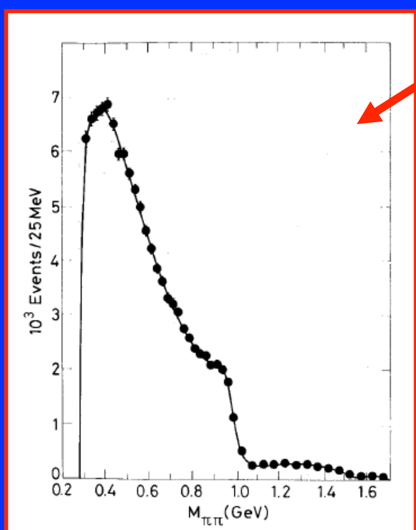
3500 events/25 MeV

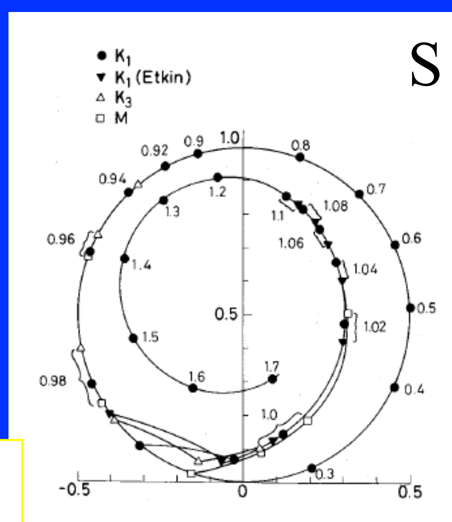
(Also K+K-, p-pbar)



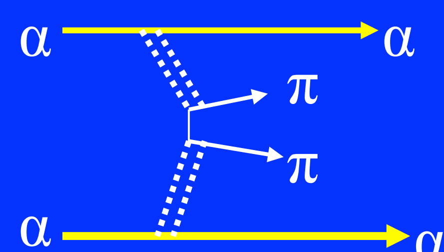
√s = 63 GeV, Δy > 3
Much data at SPS FT Ω
but shorter gaps

Structures not well understood beyond f(980).

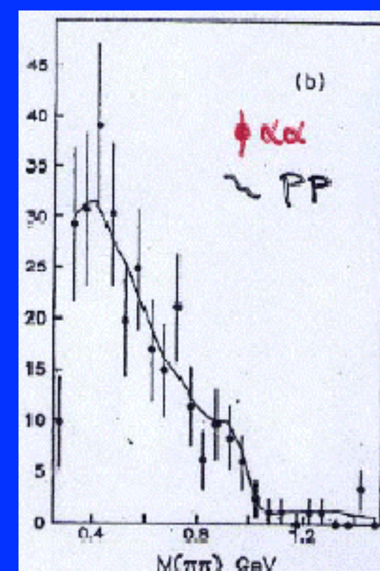




It's absolutely coherent!

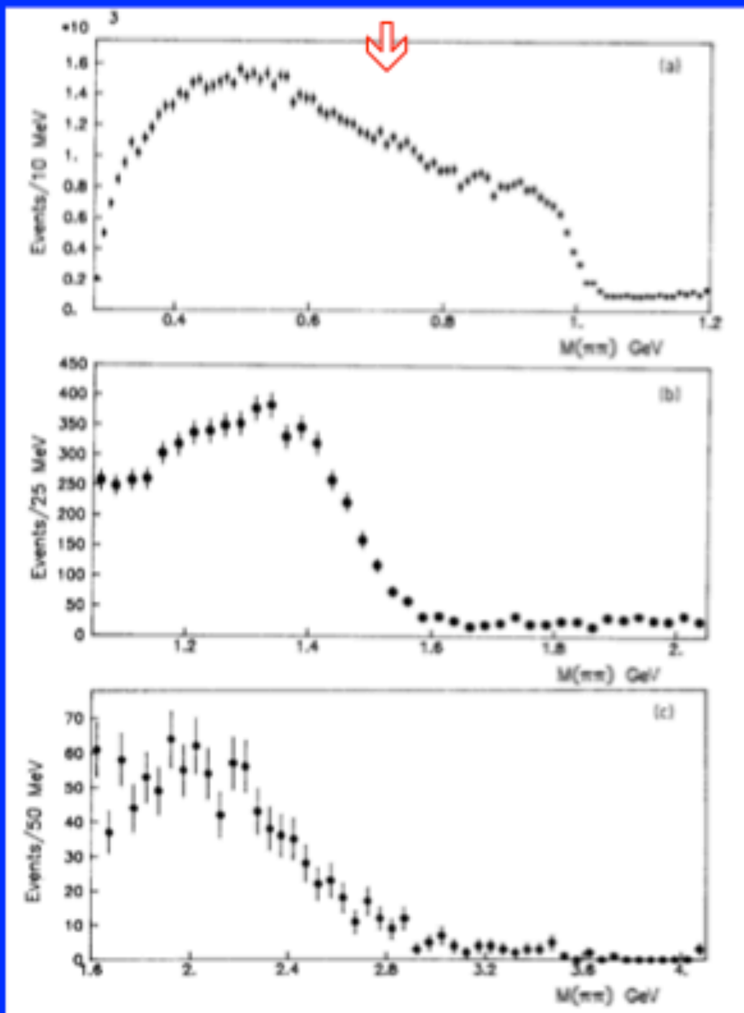


Versatile ISR !



Au,Morgan,Pennington
Coupled channel analysis
Extra state ~ 1 GeV?

Same AFS data, linear scale
No ρ(770) (I = 1)



Partial wave analysis by bin above 1 GeV. Mostly S-wave (as < 1 GeV). Small D-wave structures ...
$f_2(1270)$, $f_2'(1525)$?, $f_2(2130)$?

w/SUC

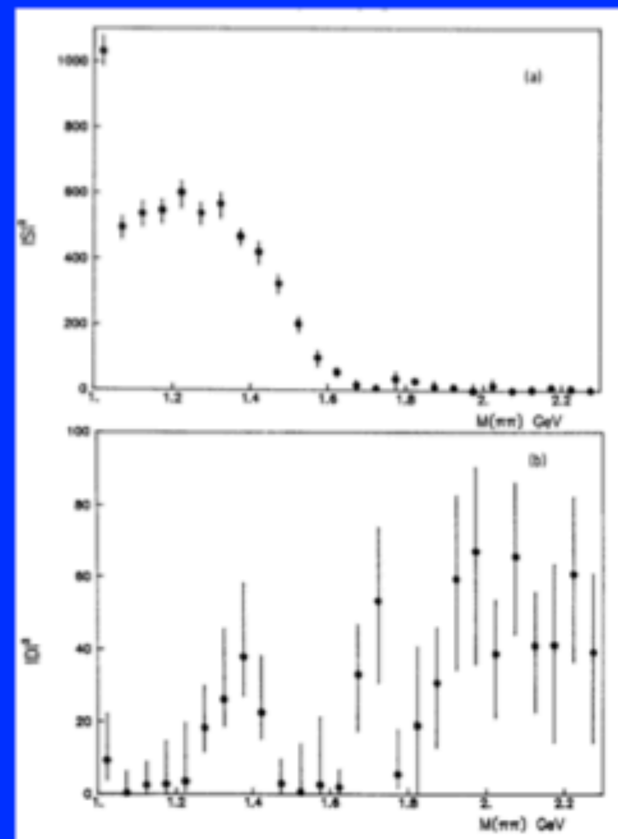


Fig. 11. The relative S- and D-wave cross-sections. (a) $|S|^2$. (b) $|D|^2$.

Note: GXG includes t = 0.
Here p-seen, |t| > min value, different.

Hadron spectrum in DPE:

Neutral, I = 0, G = P = C = 0, J = 0, 2, … even

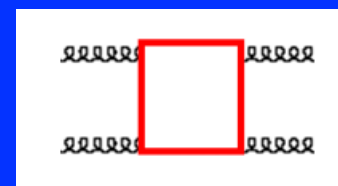
IP has no valence quarks: glue dominated.

Glueballs (gluerings?) enhanced relative to q-qbar states

But nearby states with same Q.N.s will mix. No "pure" state (QCD)

After 30 years, still uncertainties.

NB Pomeron is **not** a particle
Sum(virtual) t-exchanges
{gg} sub-cluster in hadron?



Distinguishing data:

$J/\psi \rightarrow \gamma + G$

p-pbar → X + G

IP + IP → G or G+G

Also: no place in q-qbar nonets
Decay B.F.s not right for SU(N)

Lattice calculations:

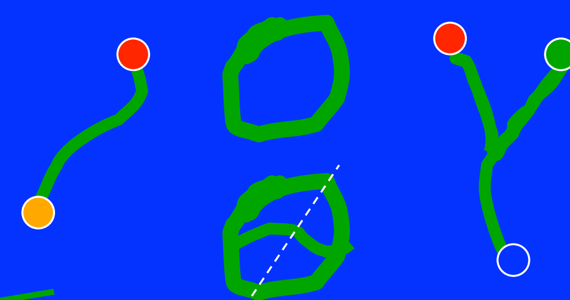
Lightest have $J^{PC} = 0^{++}$ and 2^{++}

Could not be on pomeron trajectory — M ~ 1650 MeV?

Probably on pomeron trajectory — M ~ 2300 MeV?

$\rightarrow \Lambda\bar{\Lambda}$ etc?

Stringy hadrons:



Meson Glue(ring) Baryon

Double Pomeron Exchange opens a special window on hadron spectroscopy!
All isoscalars:

Allowed central exclusive states (PDG2008)

States (0+0++)	(2++)	M(MeV)	Γ(MeV)
σ(600) = f0(600)		400-1200	600-1000
f0(980)		980	40-100
	f2(1270)	1275	185
f0(1370)		1200-1500	200-500
fo(1500)		1505	109
	f2(1525)	1525	73
f0(1710)		1724	137
	f2(1950)	1944	472
	f2(2010)	2010	202
	f2(2300)	2297	149
	f2(2340)	2339	319
χc0		3415	10
	χc2	3556	2
X(3872)?		3872	3
χb0		9859	
	χb2	9912	
χb0		10232	
	χb2	10269	

$qq\bar{q}\bar{q}$ or $M\bar{M}$?

ππ

Not seen in γγ
G favored.

Seen in γγ K$^+$K$^-$

Seen by CDF

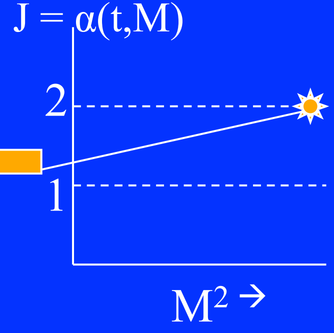
$I^G J^{PC} = 0^? ?^{?+}$

If X(3872) seen in DPE
G,P ++ and J even

H

Strong in γγ,
not there in DPE

$\alpha(t)[J] \approx 1.08 + 0.2M^2$



J needs
confirmation.
Decays ???

Name	$M(MeV/c^2)$	$\Gamma(MeV)$	$I^G J^{PC}$	$\pi\pi$	$K\bar{K}$	Other modes
$f_0(600)/\sigma$	400-1200	600-1000	0^+0^{++}	$\sim$100	-	-
$f_0(980)$	980±10	40-100	0^+0^{++}	dominant	seen	-
$f_2(1270)$	1275.1±1.2	185±3	0^+2^{++}	$84.8^{+2.4}_{-1.2}$	4.6 ± 0.4	$2\pi^+2\pi^-$ 2.8%
$f_0(1370)$	1200-1500	150-250	0^+0^{++}	seen	seen	$\rho\rho$ dominant
$f_0(1500)$	1505±6	109±7	0^+0^{++}	34.9±2.3	8.6±1.0	4π 49.5±3.3
$f_2'(1525)$	1525±5	76±10	0^+2^{++}	0.8±0.2	88.7±2.2	$\eta\eta$ 10.4±2.2
$f_0(1710)$	1720±6	135±8	0^+0^{++}	seen	seen	$\eta\eta$ seen
$f_2(1950)$	1944±12	472±18	0^+2^{++}	seen	seen	$\eta\eta$ seen
$f_2(2010)$	2011$\pm\sim$ 70	202$\pm\sim$ 70	0^+2^{++}	-	seen	$\phi\phi$ seen
$f_2(2300)$	2297±28	149±41	0^+2^{++}	-	seen	$\phi\phi$ seen
$f_2(2340)$	2339±55	319^{+81}_{-69}	0^+2^{++}	-	-	$\phi\phi$ seen
$f_6(2510)$	2465±50	255± 40	0^+6^{++}	6.0±1.0	-	

Table 5: Light quark meson states allowed in DIPE. Branching fractions are in %. (PDG 2010)

With large samples of DPE data and multi-channels identified we could clean this up!
CDF now: 350,000 π+π-, to come: 4π, K+K-. K*K*, ηη, n'n', ρρ, ΦΦ, etc.
One week of low P-U running (μ~1) at LHC with special triggers – **fantastic!!** 2015?

Central Exclusive Production (DPE) of hadrons

GTeV!

Higher energy is better, larger Δy (>5 at Tevatron)
Tevatron and LHC both good for this physics (but R.I.P. Tevatron)
(LHC is overkill in terms of energy, but need low pile-up runs & triggers)
CDF is an excellent detector: **especially tracking, vertexing and particle ID**

Establishing the spectroscopy of scalar and tensor states is one program.
But there's much more!

$$K_S^0 K_S^0,\ D^0\overline{D}^0,\ D_S\overline{D}_S, \ldots \Lambda\overline{\Lambda},\ \Sigma\overline{\Sigma},\ \Omega\overline{\Omega}, \ldots !$$

Produced in pure CP-even state.
In e+e- (and φ-decay) pure CP-odd

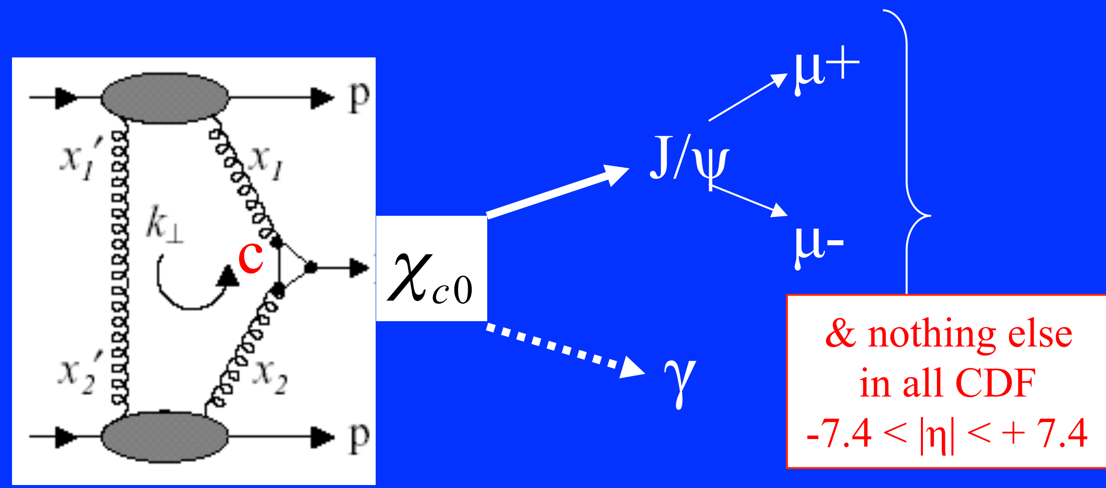
IP is flavor-blind:

$p\bar{p}$ seen, $\Lambda\overline{\Lambda} \ldots \Omega^-\overline{\Omega}^+$

Down by masses^4

{q} – {qq}
or {q} {q} {q} ?

CDF measurement exclusive $\chi_c \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^- \gamma$

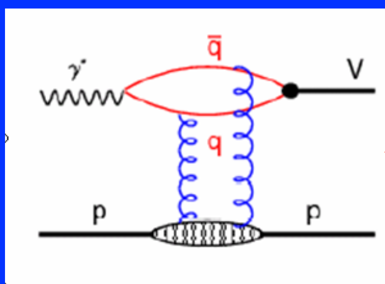


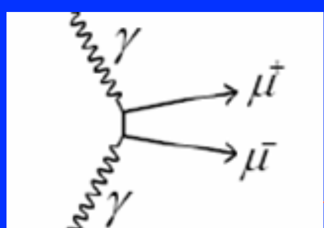
Added to CDF: Beam Shower Counters BSC: 5.2 < |η| < 7.4 (5.9)
Scintillator paddles tightly wrapped around beam pipes.
Detect showers produced in beam pipes if p or p dissociate.
e.g. p → p π π 8 + 10 counters (4 + 4)

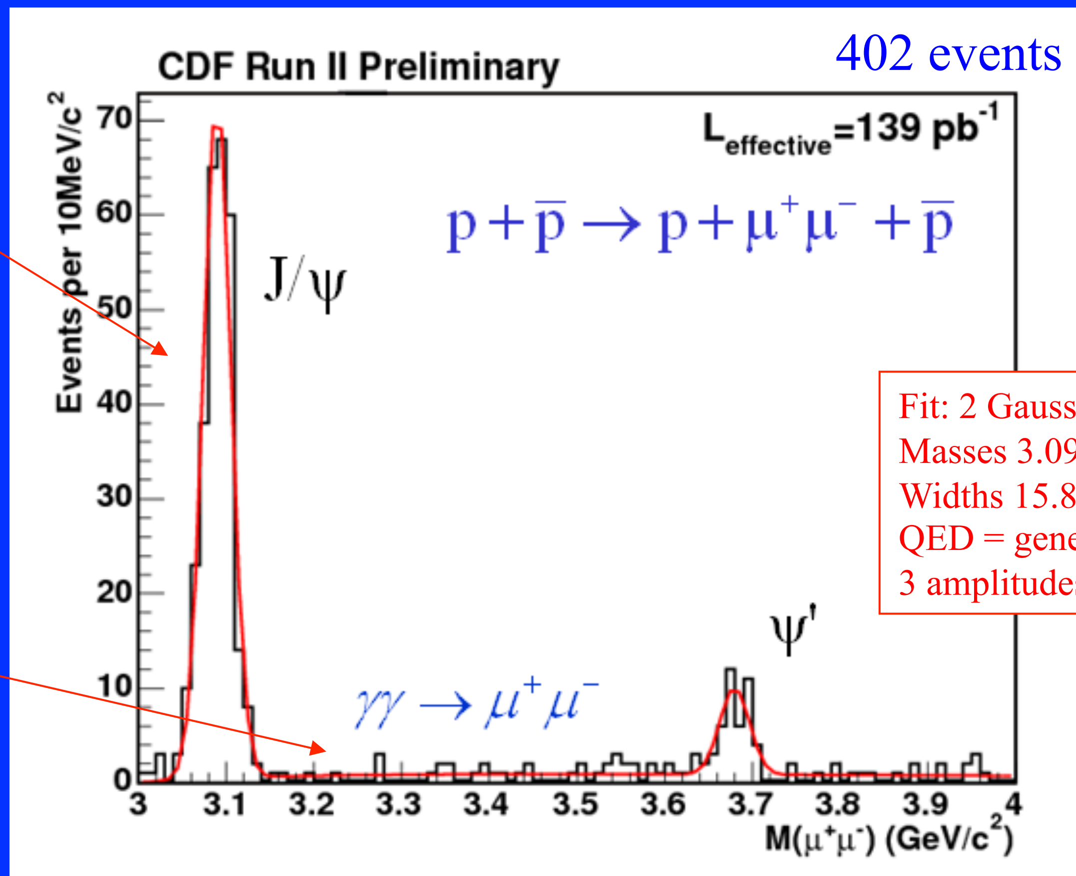
If these are all empty, p and p did not dissociate
(or BSC inefficient, could estimate from data)
but went down beam pipe **with small (<~ 1 GeV/c) transverse momentum.**

Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV.

$$p + \bar{p} \to p + \mu^+\mu^- + \bar{p}$$

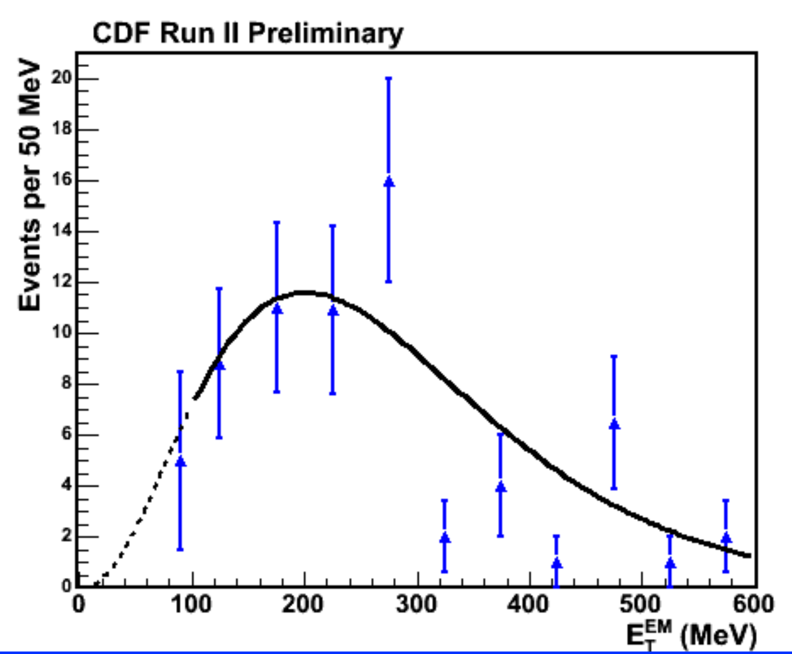






Fit: 2 Gaussians + QED continuum.
Masses 3.09, 3.68 GeV == PDG
Widths 15.8,16.7 MeV=resolution.
QED = generator x acceptance
3 amplitudes floating

Now allow photons: EmEt spectrum with J/ψ mass cut:



J/ψ have photons : 286 → 352
ψ(2S) do not :

χ_c → J/ψ + γ

Empirical functional form

65 events above 80 MeV cut.
3 events below (estimated from fit)
→4% background under J/psi
→# χ_c = 65 +/- 8

MC also estimates only few % of χ_c → J/ψ + γ under the cut
But CDFSIMulation not reliable for such low E_T

Cannot resolve three χ_c states ... really measured $\Sigma B_i \sigma_i$ hadronic decays can resolve.

Table 9: Branching fractions (BF in %) of χ_c states, for decays to all charged particles with BF > 0.1%.

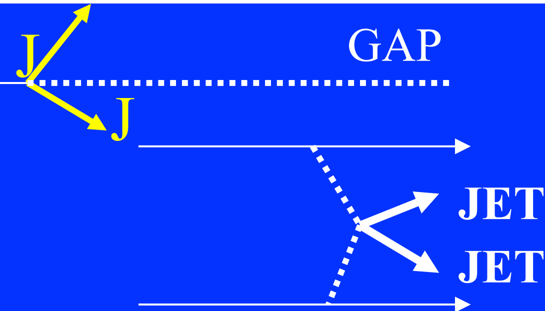
State $I^G J^{PC}$	$\chi_{c0}(3415)$ 0^+0^{++}	$\chi_{c1}(3511)$ 0^+1^{++}	$\chi_{c2}(3556)$ 0^+2^{++}
Mass(MeV):	3414.76±0.35	3510.66±0.07	3556.20±0.09
Width (MeV):	10.4±0.7	0.89±0.05	2.06±0.12
BF(Channel)			
$J/\psi + \gamma$	1.16±0.08	35.6±1.9	20.2±1.0
Above with $J/\psi \to \mu^+\mu^-$	0.077	0.021	0.012
$\pi^+\pi^-\pi^+\pi^-$	2.27±0.19	0.76±0.26	1.11±0.11
$\pi^+\pi^-K^+K^-$	1.80±0.15	0.45±0.10	0.92±0.11
$3(\pi^+\pi^-)$	1.20±0.18	0.58±0.14	0.86±0.18
$\pi^+\pi^-$	0.56±0.03	<0.1	0.159±0.009
K^+K^-	0.60±0.03	<0.1	0.11±0.008
$\pi^+\pi^-K_s^0K_s^0$	0.58±0.11	<0.1	0.92±0.11
Above with $K_S^0 \to \pi^+\pi^-$	0.27±0.05	<0.1	0.43±0.05
$K^+K^-K^+K^-$	0.28±0.03	0.06±0.01	0.18±0.02
$\pi^+\pi^-p\bar{p}$	0.21±0.07	<0.1	0.13±0.03
Total %	7.2	1.9	4.7

Table 8: Upper limits on χ_{c0} cross sections.

State:	$\chi_{c0} \to \pi^+\pi^-$	$\chi_{c0} \to K^+K^-$
Background (est.)	722.9	940.0
Events in window	754	951
90% CL upperlimit (events)	69.6	59.2
Acceptance	24.2%	21.8%
$d\sigma/dy\|_{y=0}$, 90% CL UL	21.4±4.2 (syst.) nb	18.9±3.8 (syst.) nb

Exclusive Di-Jets

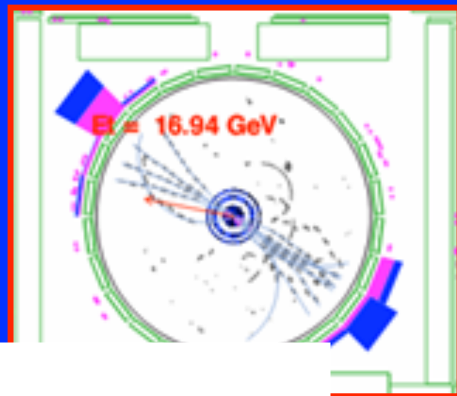
$\bar{p}$



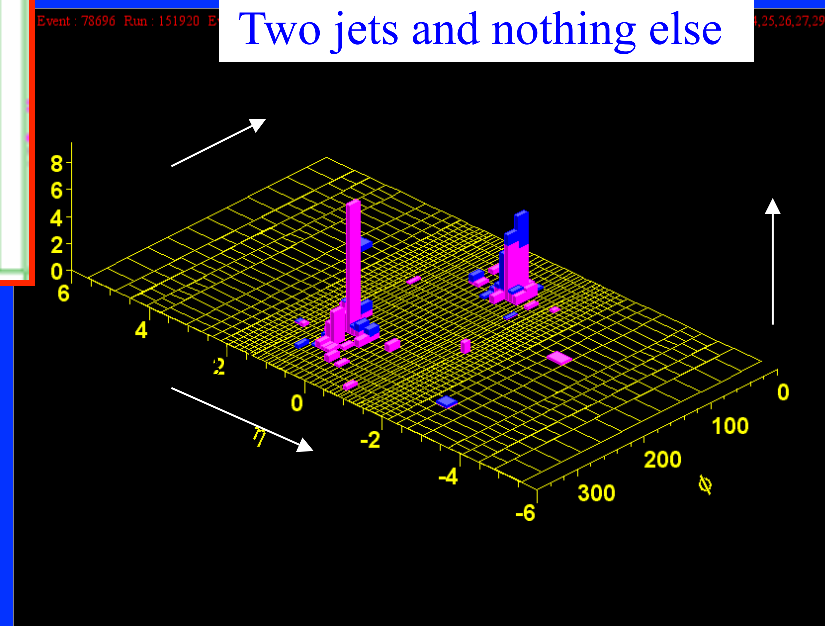
$$p + \bar{p} \rightarrow p + JJ + \bar{p} + \sim \text{nothing else}$$

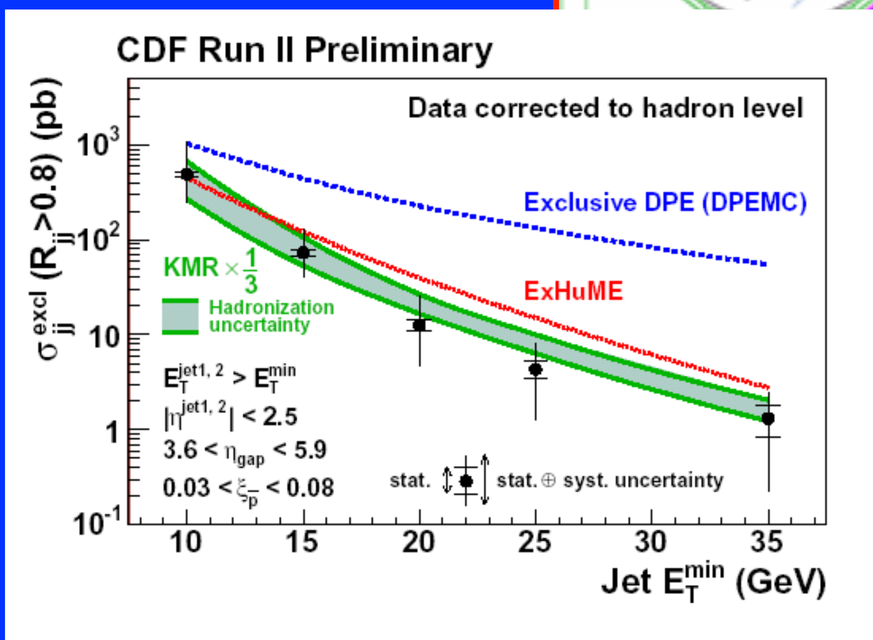
Observed in CDF, QCD tests
& related to p+H+p

$$R_{JJ} = \frac{M_{JJ}}{M_X} \approx 1.0$$



"Almost" exclusive di-jet,
Two jets and nothing else





Interesting QCD: gap survival, Sudakov factor
Nearly all jets should be gg …. qq suppressed
by M(q)/M(JJ) (Jz=0 rule)

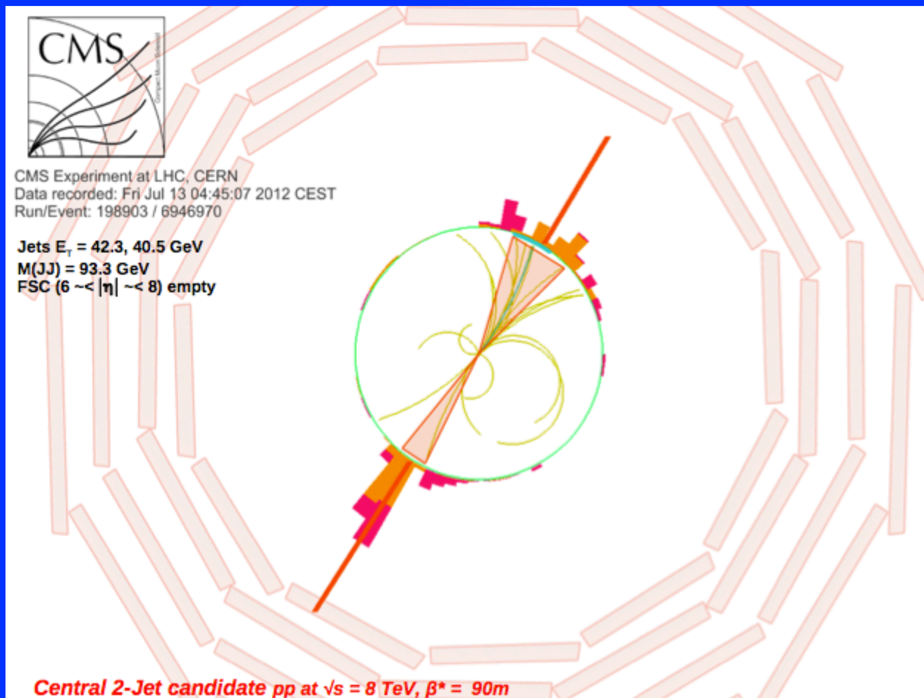
Gluon jet physics.

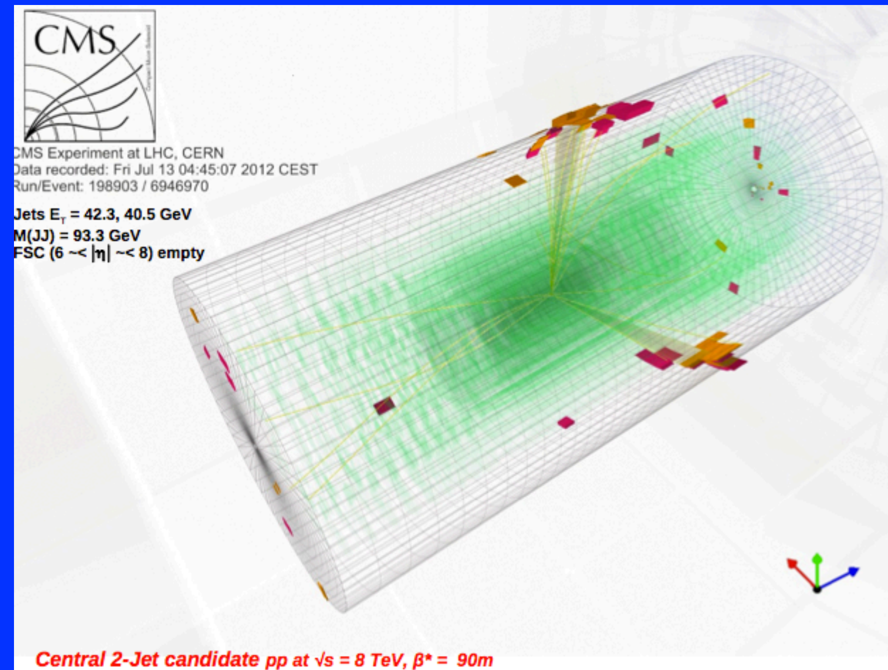
Forward Shower Counters, FSC, installed on both sides of CMS
$|\eta| \sim 6 - 8$ (simple counters, otherwise blind region)
Mainly useful as rapidity gap detectors in low – pile-up runs

3rd station at 114 m after warm dipoles

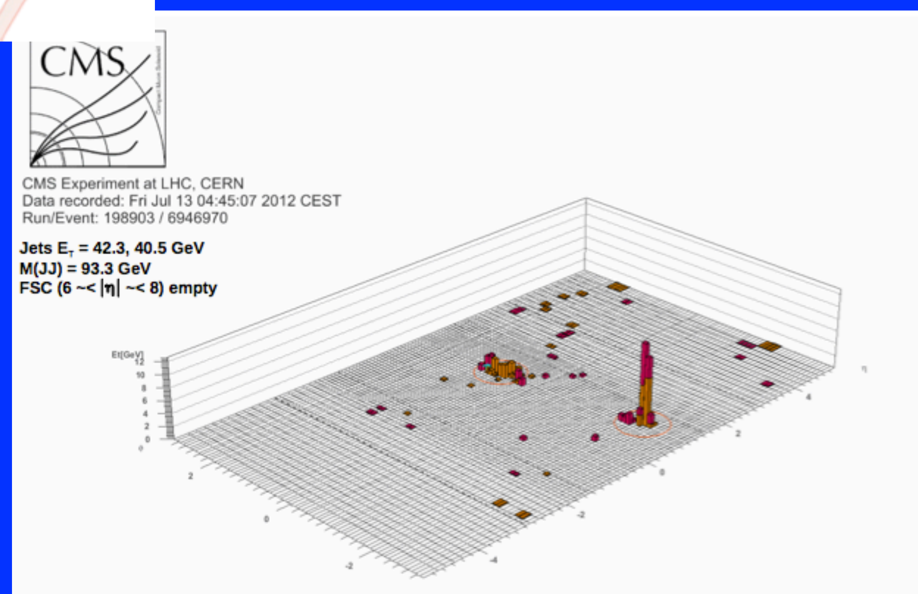
2nd station at 85 m

Following from BSC counters in CDF

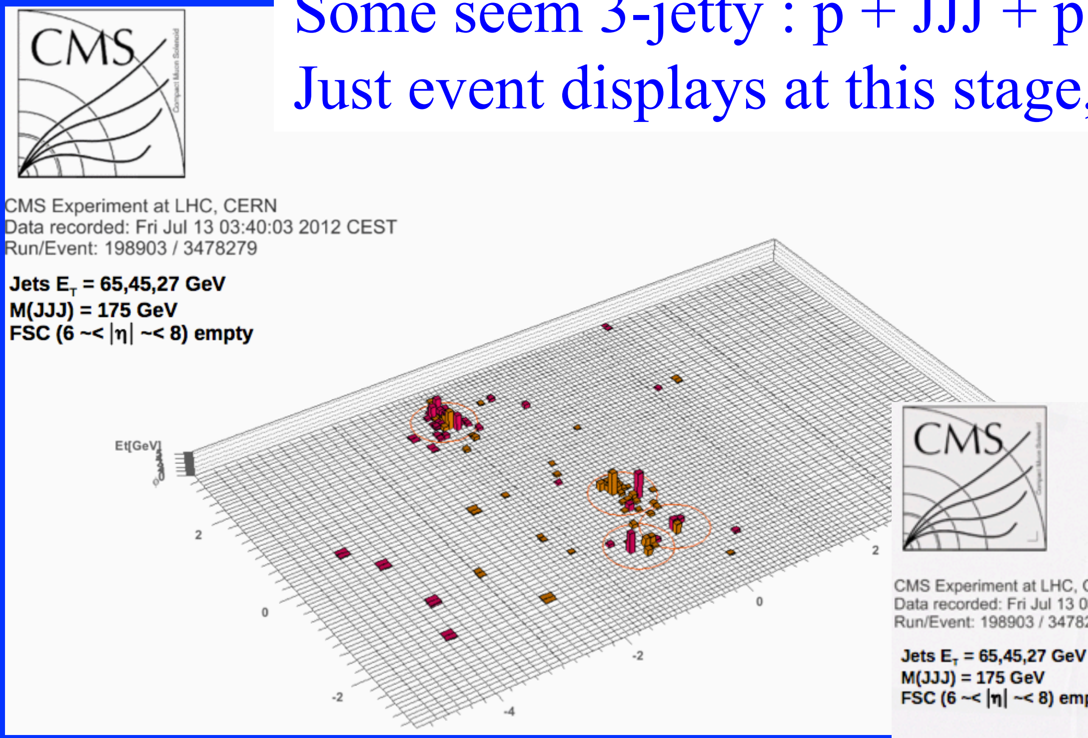


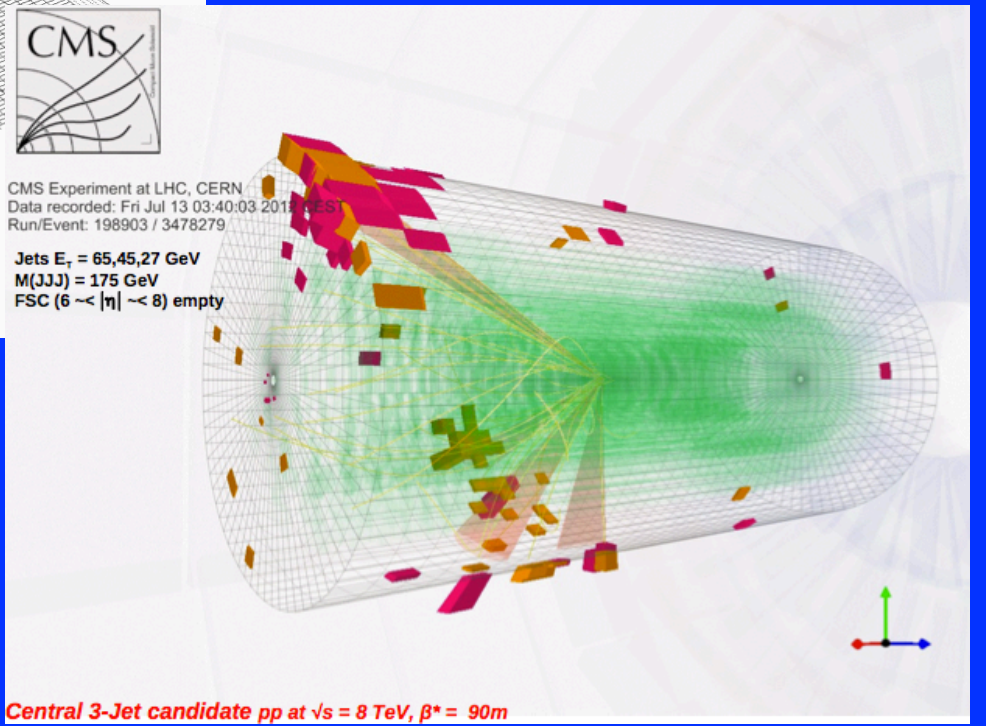


Event from 90m β* run, low PU, with TOTEM:
p + JetJet + p
with FSC empty both sides



Some seem 3-jetty : p + JJJ + p. Not claiming “exclusive”
Just event displays at this stage, analysis underway

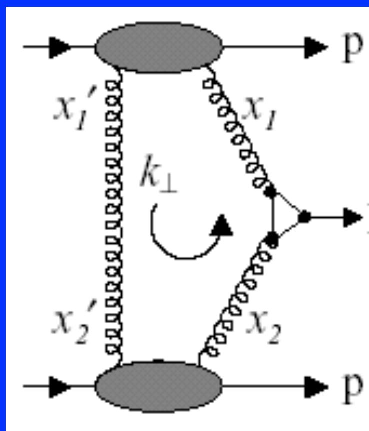




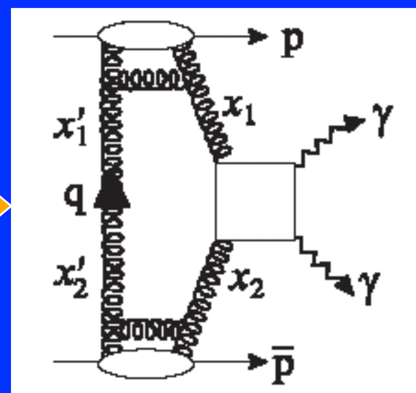
Exclusive 2-Photon Production in CDF

Khoze, Martin and Ryskin, hep-ph/0111078,
Eur.Phys.J. C23: 311 (2002)
KMR+Stirling hep-ph/0409037

Claim factor ~ 3 uncertainty ; Correlated to p+H+p



H



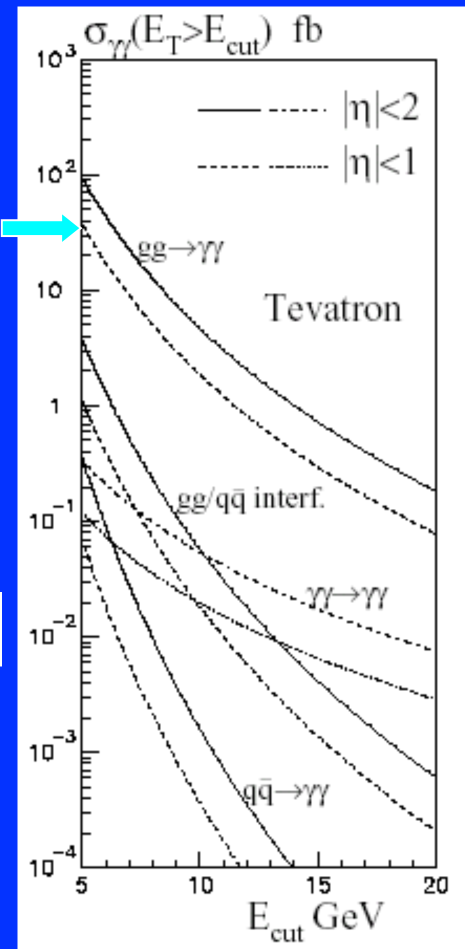
$\gamma\gamma \to \gamma\gamma$ & $q\bar{q} \to \gamma\gamma$ much smaller

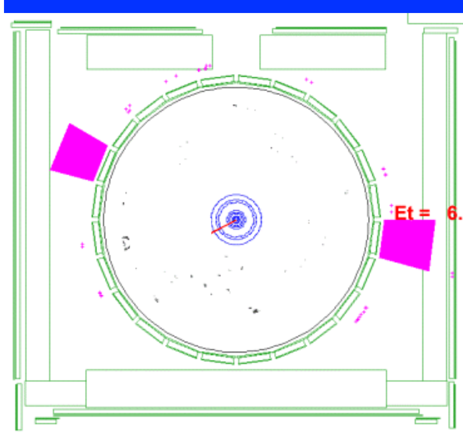
Phys.Rev.Lett. 99,242002 (2007)

$E_T(\gamma) > 5\ \text{GeV}; |\eta(\gamma)| < 1.0$

Tevatron

36 fb





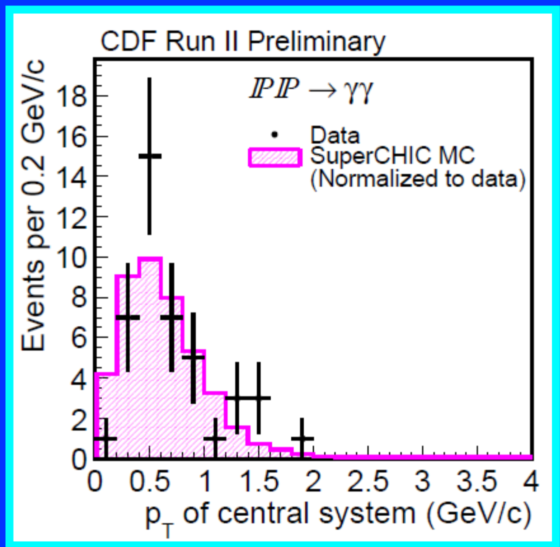
3 candidates, 2 golden

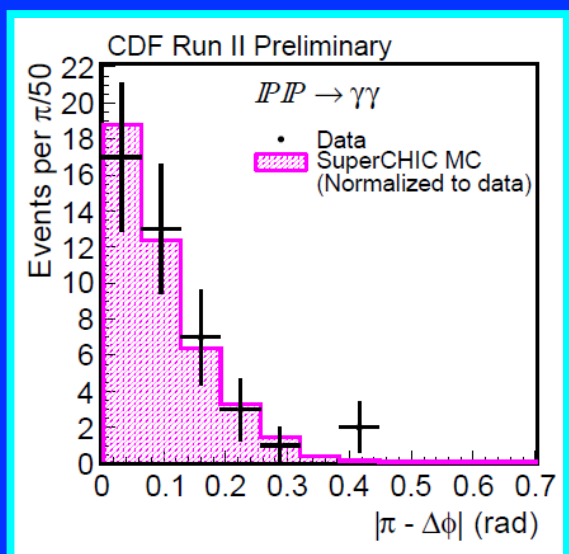
$\text{Note}: \sigma_{MEAS} \approx 2\times10^{-12}\sigma_{INEL}!$

NEW SEARCH:
$E_T(\gamma) > 2.5$ GeV

NEW SEARCH:
$E_T(\gamma) > 2.5$ GeV

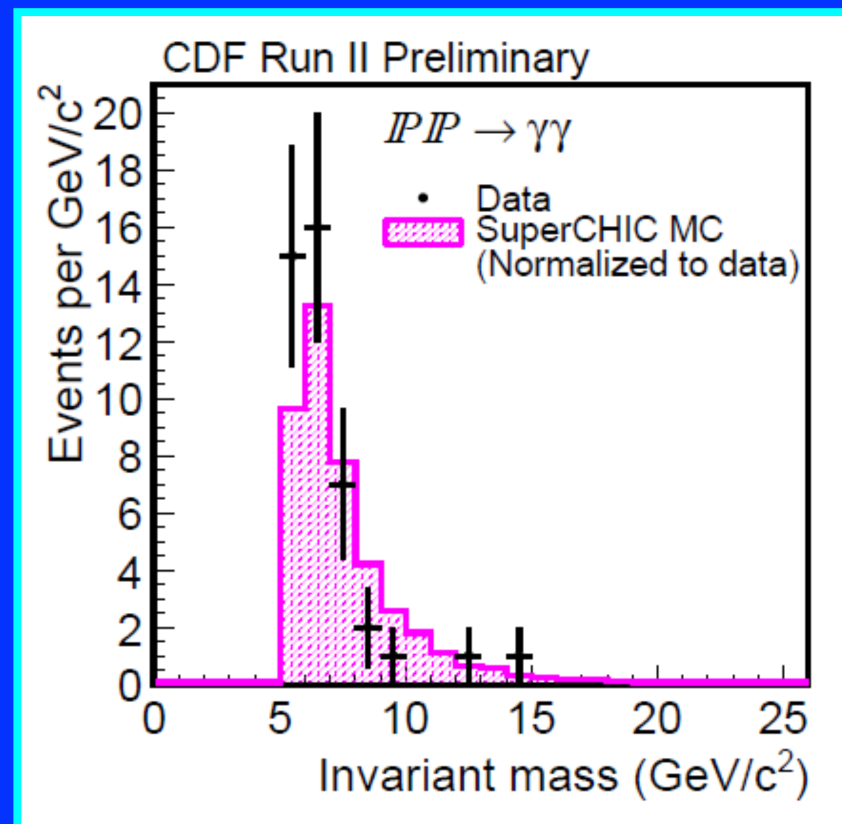
43 candidate events.
$\pi^0\pi^0$ background fit = 0, < 30% at 95% cl



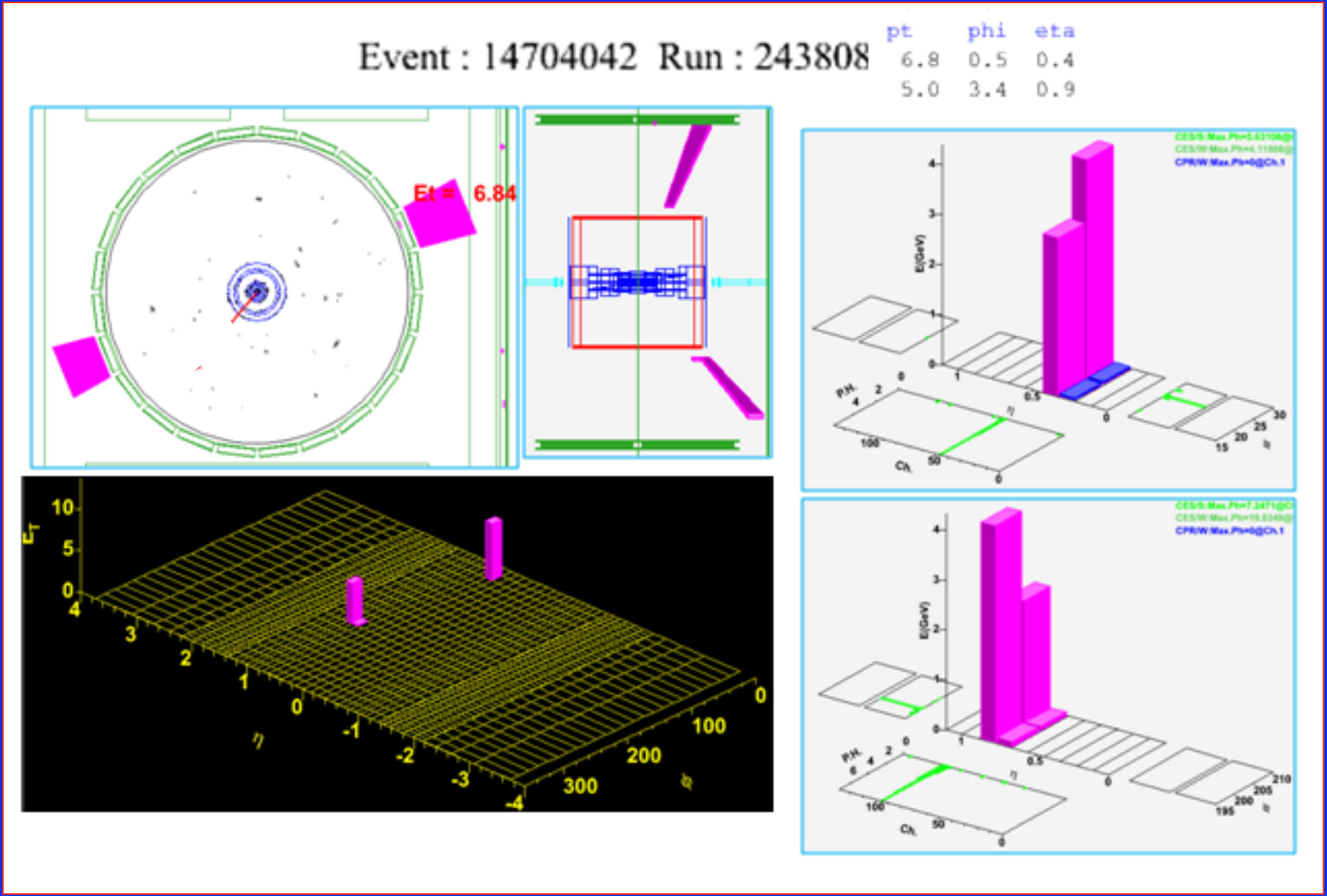


<u>Distributions of photon pairs</u>

Normalization to equal area
(shape comparison)



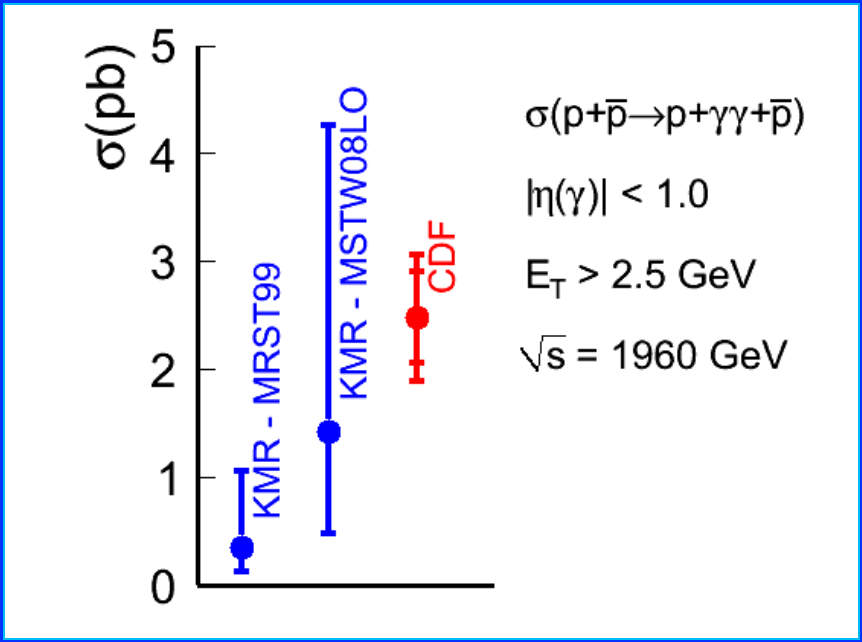
Example of γγ event



$p+\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$ via $IP+IP$ (QCD)

43 candidate events.
$\pi^0\pi^0$ background fit = 0, < 30% at 95% cl

$$\sigma_{\gamma\gamma excl.}^{|\eta|<1,E_T>2.5GeV} = 2.48 \pm 0.42(stat) \pm 0.41(sys)\ pb$$
$$\sigma_{SuperCHIC\ (MSTW08LO)}^{|\eta|<1,E_T>2.5GeV} = 1.42^{\times 3}_{\div 3}\ pb$$
$$\sigma_{SuperCHIC\ (MRST99)}^{|\eta|<1,E_T>2.5GeV} = 0.35^{\times 3}_{\div 3}\ pb$$



Implies that p + H + p happens at LHC (if H) with σ(SMH120) ~ 3-10 fb

Exclusive χ_c and JJ agree too

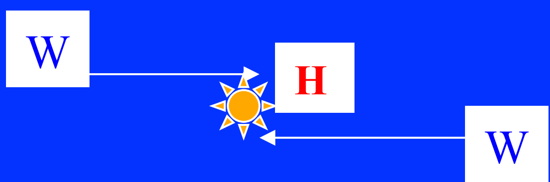
The Ultimate Vacuum Excitation

Above the χb, the only "known" heavier particle with vacuum Q.Nos. is the Higgs.

Vacuum is everywhere Higgs field. ANTIBLINK quickly enough and with weak eyes you can "see" them.

Hit the vacuum hard with a pair of weak probes, and you can promote them

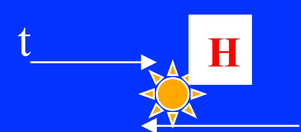
Virtual → Real

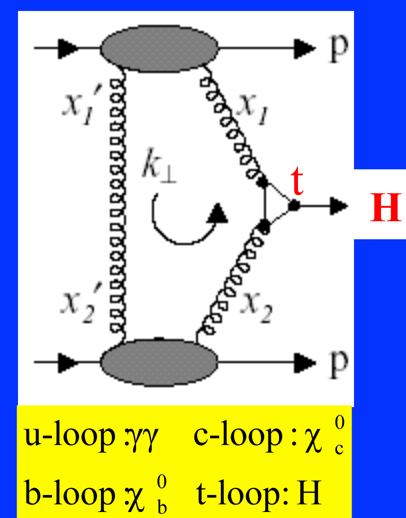


Weak "light" = W,Z

Top quarks work too

(they have weak charges)





gg→H is the main production process at LHC

Sometimes : Another gluon cancels the color

No other parton-parton collisions occur

All gluon radiation is suppressed (Sudakov)

Price ~ 1/2000 – 1/10000

σ (excl) ~ 1 – 10 fb cf ~ 20 pb

But if you see them, and measure both p, powerful benefits

$$M_{CEN} = \sqrt{(p_1 + p_2 - p_3 - p_4)^2} \Rightarrow \sigma(M_H) \approx 2 \text{ GeV per event}$$

J,C,P,Γ?

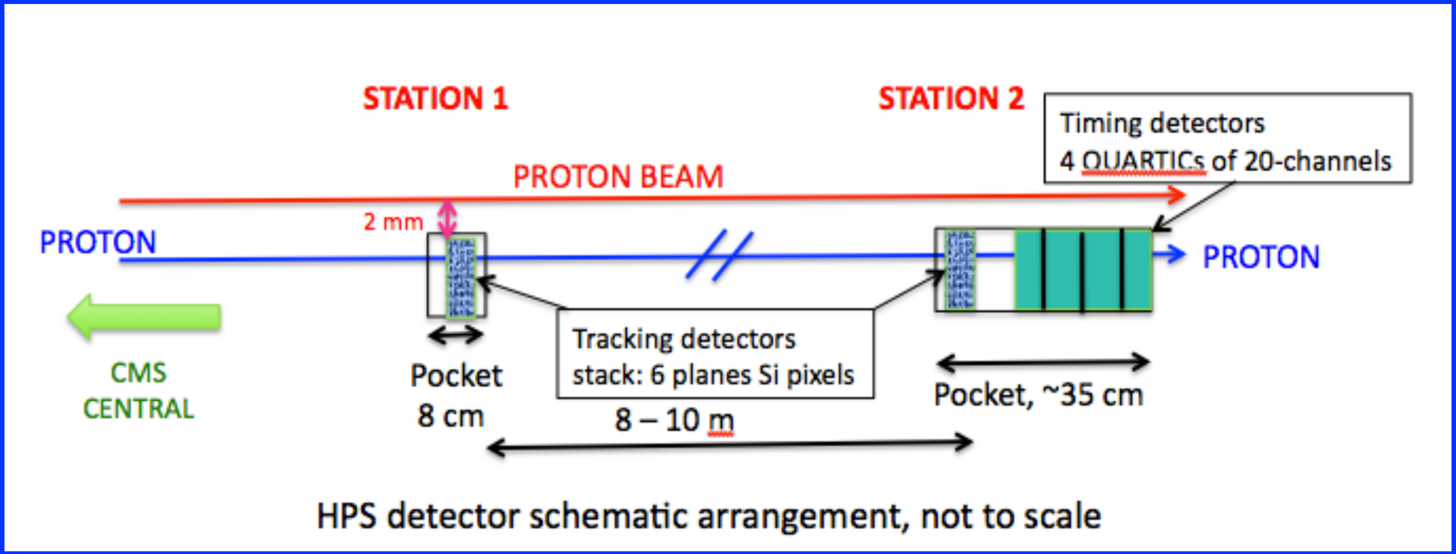
FP420 : Forward Protons 420m & 220m downstream of CMS & ATLAS

CMS: Inner Vacuum Tank insertion

$$\gamma\gamma \rightarrow WW; H \rightarrow WW, H \rightarrow ZZ$$
$$H \rightarrow b\bar{b}; BSM \rightarrow WW, SUSY\ etc$$

420 & 220m **CMS: PPS** **ATLAS: AFP** **220 & 420m**

At 240 m (& 220 m) the beam pipe is exposed, so it's relatively easy to install the detectors:



At 420 m missing magnet,
pipe straight but cold.
It requires a cryogenic by-pass
Needed for p + H(126) + p

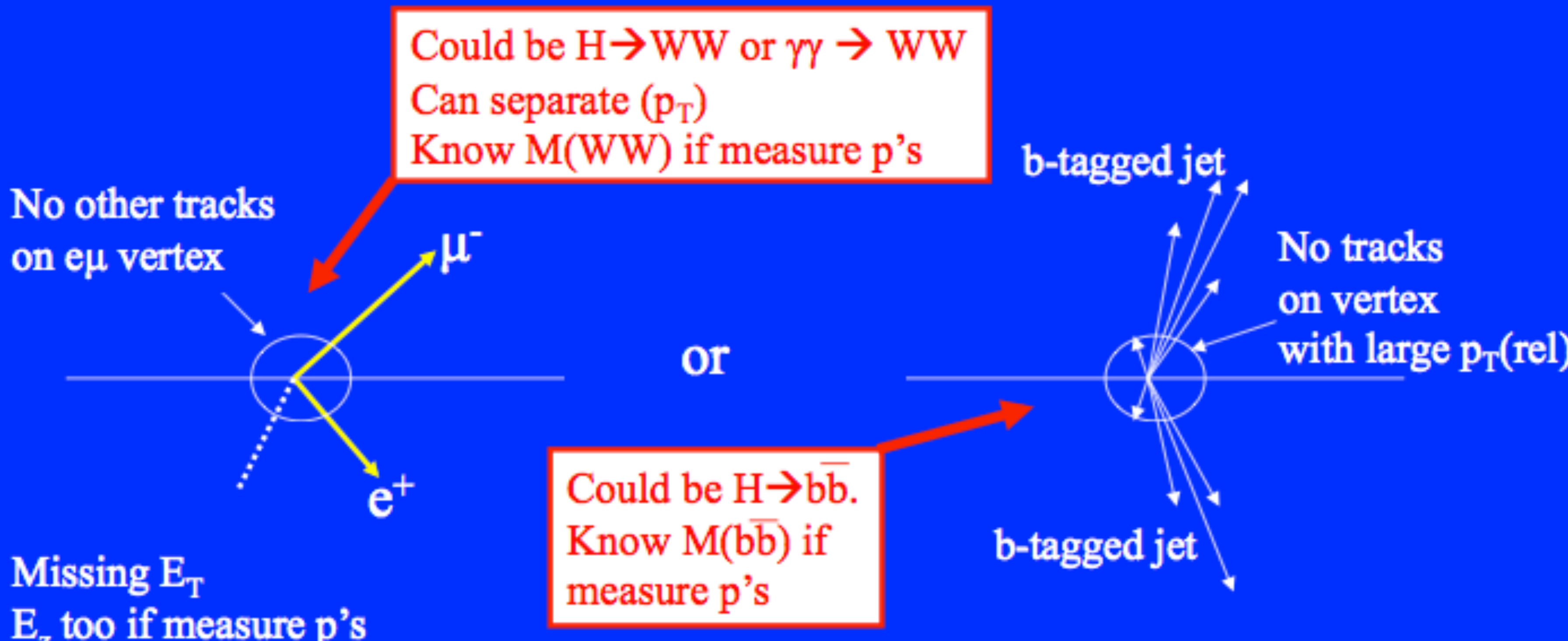
Looking
downstream
(CMS behind you)

The cleanest, simplest inelastic pp collisions.

Class 3 Interactions at the LHC:
"Inelastic, with no hadrons produced"

Consider WW + nothing (p's go down pipe, small p_T)

$\sigma(\gamma\gamma \rightarrow W^+W^-) \sim 50$ fb ... or H + nothing



What is Signal:Background? H(135-200)→ WW(*)

$$WW \to l\nu JJ,\ l = e, \mu, \tau$$

Durham Gp: Khoze, Martin, Ryskin, Stirling hep-ph/0505240

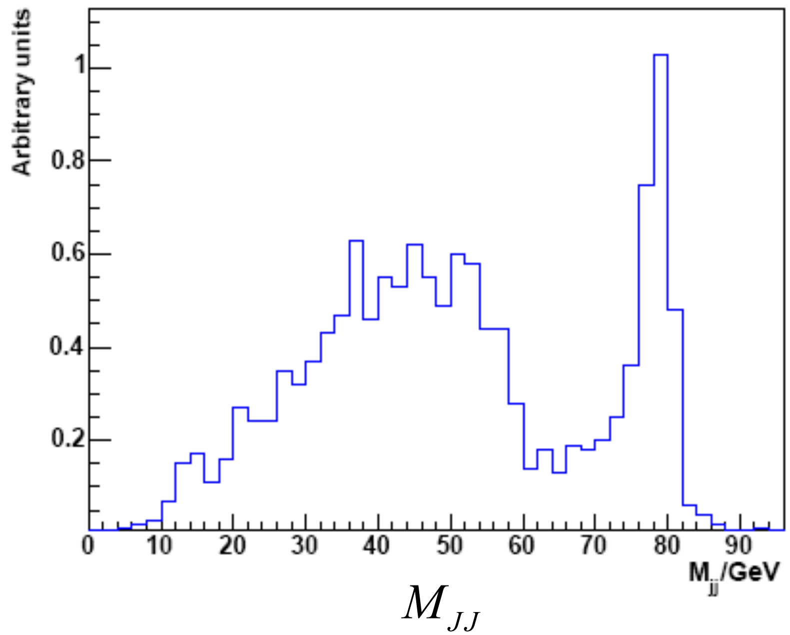
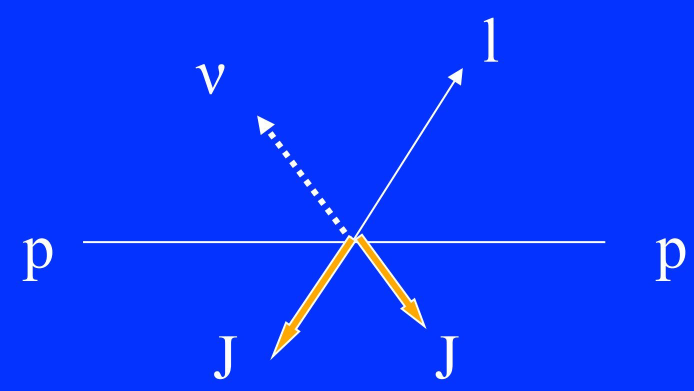


Fig. 6: The di-jet invariant mass distribution dN/dM_{jj} in the semi-leptonic decay channel $H \to WW^* \to l\nu jj$ for M_H = 140 GeV.



$$MM(12-34\mathrm{JJ}l) \approx 0(M_\nu)$$

$$MM(12-34\mathrm{JJ}) = M_W^{(*)}\ (\text{even for } \tau\nu)$$

$$M(JJ) = M_W^{(*)}$$

Can use ~ 50% of WW (all but JJJJ)

$$\mathrm{H}(180) \to \mathrm{ZZ} \to l^+l^-\nu\bar{\nu}\ (\mathrm{BR} \sim 10 \times l^+l^-l^+l^-)$$

$$MM(12-34\,l^+l^-) = M(Z_{\nu\bar{\nu}}),\ \sigma_M \sim 2\ \mathrm{GeV!}$$

Also (50fb) $\gamma\gamma \to \mathrm{W^+W^-} \Rightarrow \mu(\mathrm{W})$

!! **Unfortunately very few events (SM)**

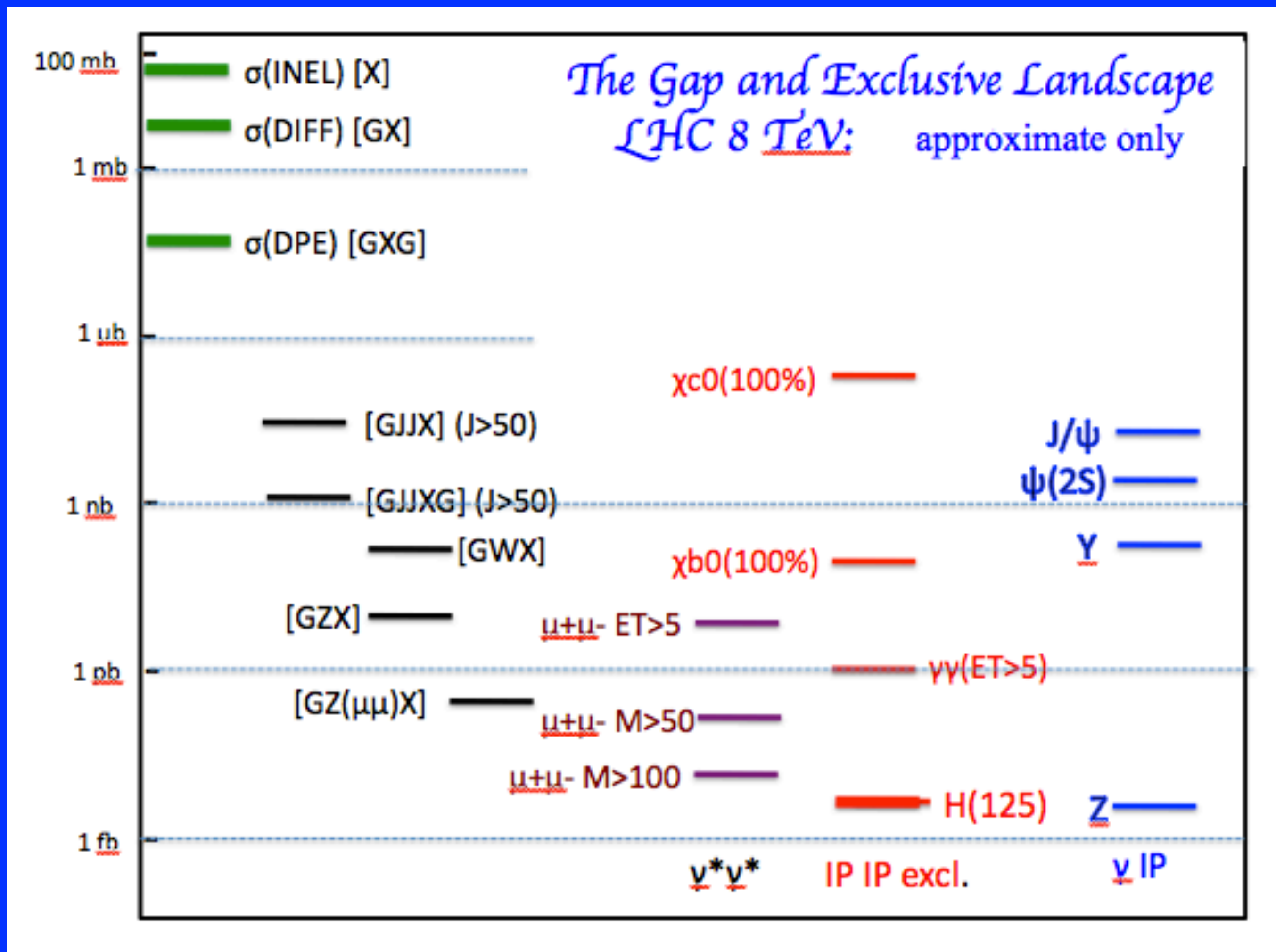
What could one do in a low pile-up (<n/x> = 1) week?

1 week of <n/x> = 1 running:

120 hours x 3600 secs x 2800 bunches x 11,625 O/s = 1.4 10^{13} X/week

1X == 80 mb → 1.8 10^{11} mb^{-1}/week = 180 pb^{-1} / week → 66 pb^{-1} of no-PU events

If for γγ(sa) PU ~ 5 can be used, ~ 0.8 fb^{-1} gets ~ 1000 γγ events



For 8 TeV need 13 TeV

1 event in 66 pb^{-1}

Summary

The vacuum (QCD, Electroweak, ..) is teeming with states,
from e+e- loops (even ν-loops if you have weak eyes) to H (maybe).

If you truly understand the vacuum you'll understand all of physics.

Theoretically amazing; experimentally we can excite it with a pair of hammers

Electromagnetic probes: γγ → charged pairs $e^+e^-, \mu^+\mu^-, \tau^+\tau^-, ... W^+W^-, \tilde{l}\tilde{l}$?

Strong probes: IP IP → Neutral states (G?) & Pairs $\sigma, f_0, G, \chi_c, \chi_b, D\overline{D}, \Omega\overline{\Omega}...$

Weak probes: WW → H, etc… $e^+e^- \rightarrow \nu + W^+W^- + \nu \rightarrow \nu + H + \nu$

There is much more to be done: Tevatron data and especially LHC (low & high PU)

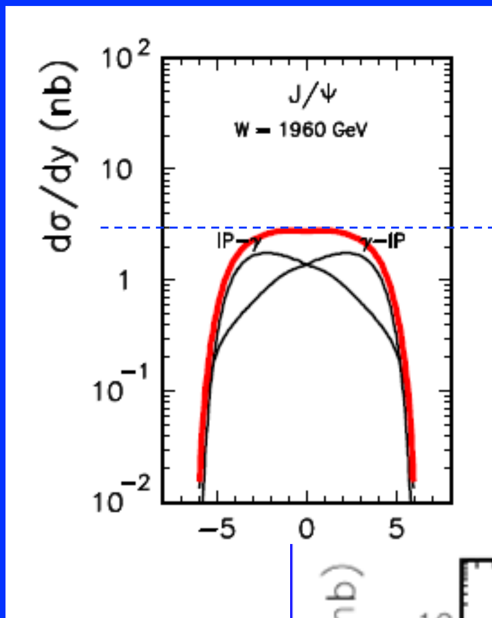
Use the LHC as a γγ and gg collider with tiny but high precision detectors
(present and future)

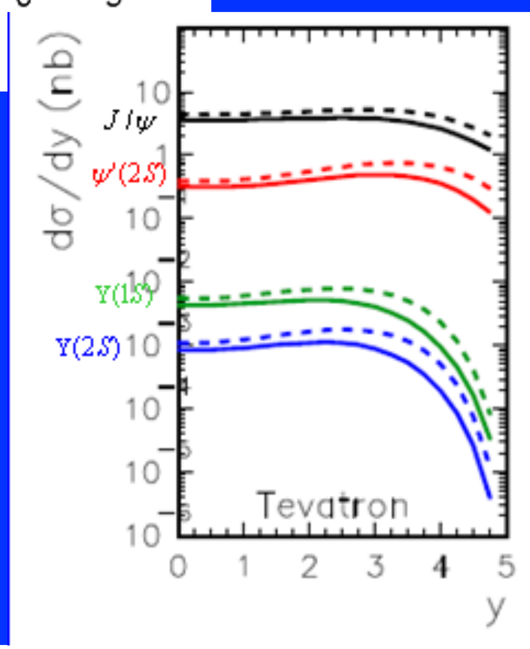
Thank you

Overflow slides :

Some predictions for J/psi photoproduction:

e.g. Schafer and Szczurek:
arXiv:0705.2887 [hep-ph]





Take 3.0 +- 0.3

Machado,Goncalves 3.0 nb
Motyka and Watt: 3.4 +- 0.4 nb
Schafer & Szczurek ~ 2.8 nb
Nystrand 2.7+0.6-0.2 nb

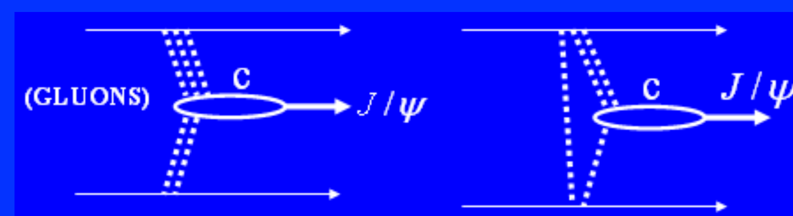
Our result: 3.92 +- 0.62 nb

$$\frac{d\sigma}{dy}|\, y=0\,(J/\psi) = 3.0 \pm 0.3\ \text{nb (theory,average)}$$

$$\frac{d\sigma}{dy}|\, y=0\,(J/\psi) = 3.92 \pm 0.62\ \text{nb (CDF)}$$

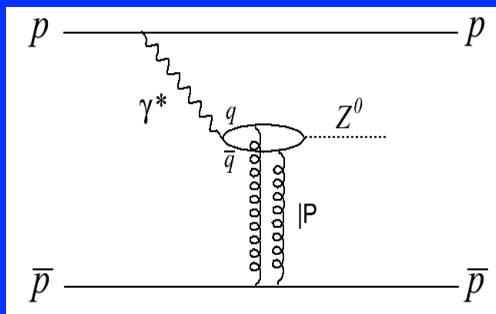
$$\frac{d\sigma}{dy}|\, y=0\,(J/\psi) < 2.3\ \text{nb for OIP} \rightarrow J/\psi\ (95\%)$$

Our limits on O-exchange are close to, and constrain, theoretical predictions

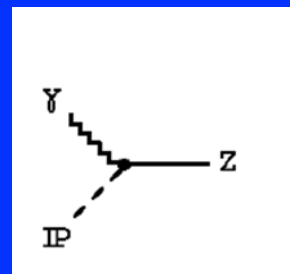


Exclusive Z production : CDF Search

Allowed in SM (like V)
but σ ~ 0.3 fb (Motyka+Watt)

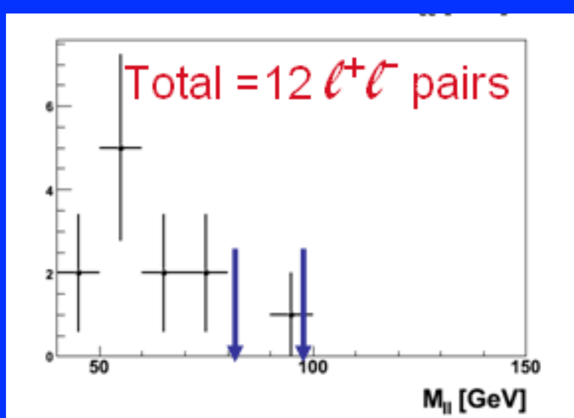


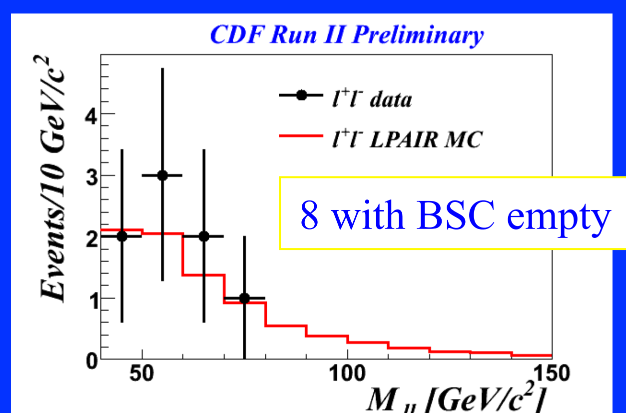
Could be enhanced by BSM loops?

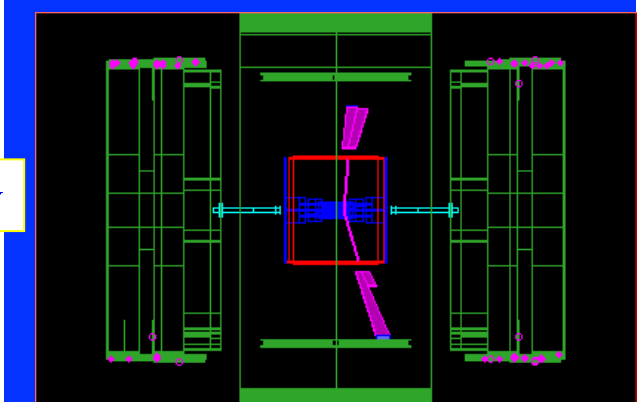


Interesting?!
γ-IP-Z eff.coupling.
ZOOM IN to see how!

2.2/fb : 318K e+e- & μ+μ- M > 40 GeV; 183K in Z window 82-98 GeV
Require no other interaction, no additional tracks, all calorimeters in noise (E)







$\sigma(Z_{excl}) < 0.96$ pb (95% C.L.)
$\sigma(Z_{excl})$ Theory = 0.3fb
(13fb@ LHC)

was record E(γγ)
..no longer