Vacuum and Particle Creation
-- from an experimental view

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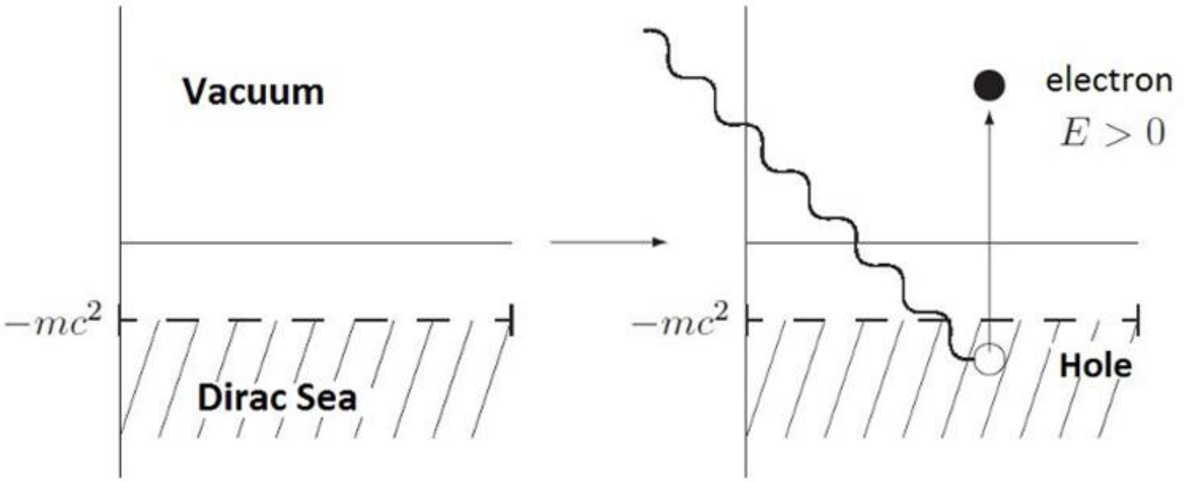
History:

Dirac: anti-matter, Dirac sea, negative energy & Vacuum (1928)
LUND & UK : studies of particle creation
T.D. Lee: Symmetry & Vacuum as new directions (~1985)

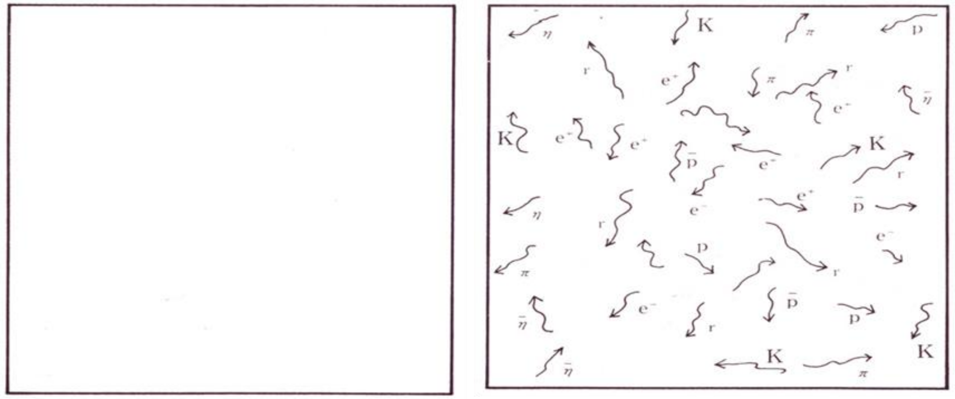
Wilczek: materiality of a vacuum (2017)
The lightness of being

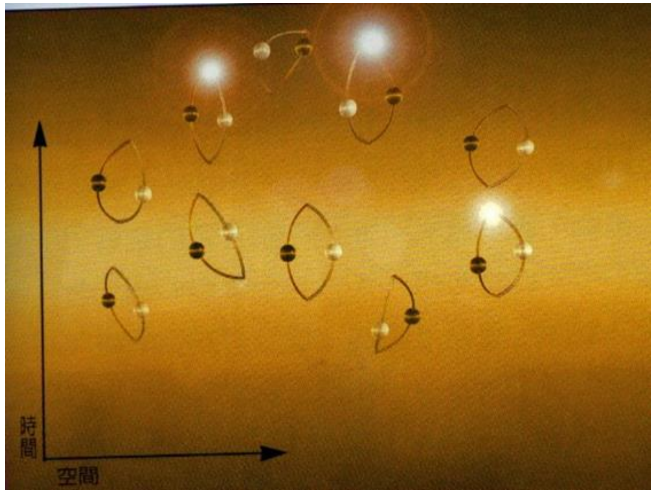
Bis & Wilczek: The structured vacuum theory
Lattice and superconductivity

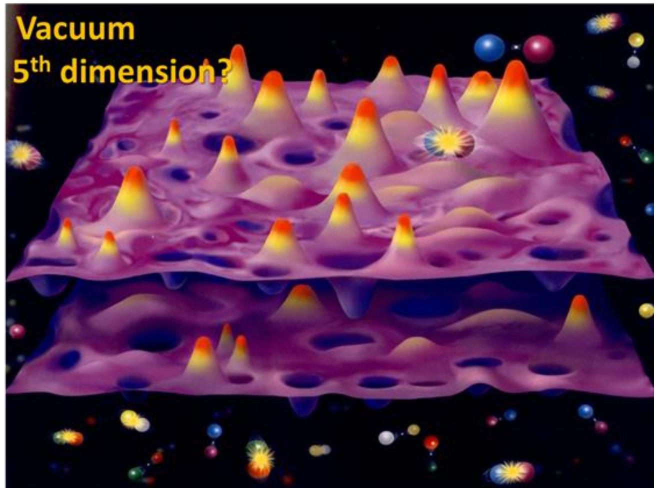
Description of Vacuum

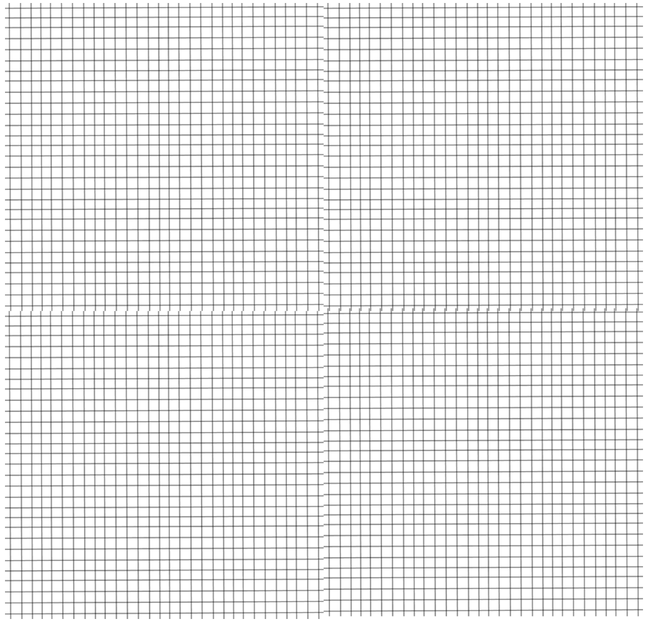


T.D. Lee: advocates RHIC experiments as an idea place to study Vacuum, and Symmetry and Vacuum are the two major physics topics in 21 century.









Experimental results related to Vacuum

DIS (Deep Inelastic Scattering)

BEC (Bose-Einstein correlation) – size of source

Charmed mesons production in e+e- experiment

e.g. $e^+e^- \rightarrow D^{*-}D^{0}\pi^{+}$

Groups from LUND U & UK have been working on particle creation

The Physical Vacuum: Where Particle Physics Meets Cosmology

Roman Pasechnik

LU, THEP Group

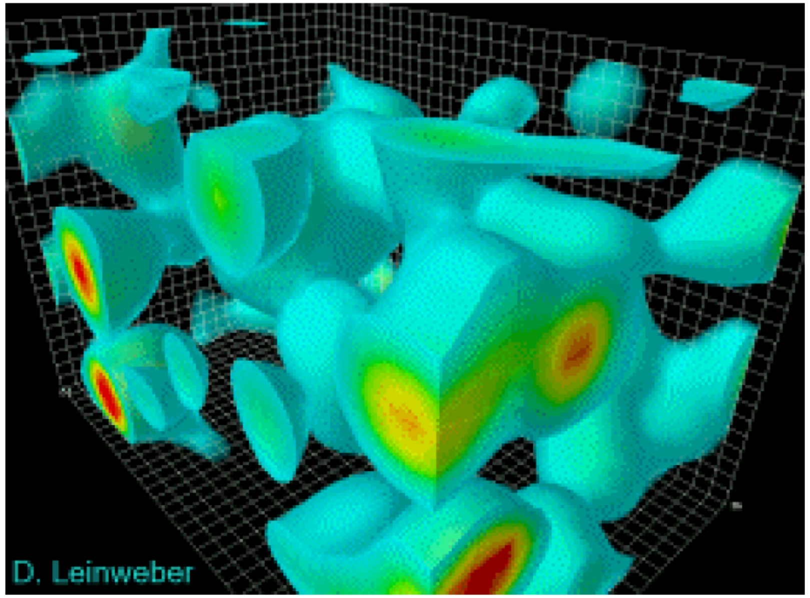
"We must be able to understand even those things which are impossible to imagine of…"

Lev Landau

Physical Vacuum: What is it?

Uncertainty principle

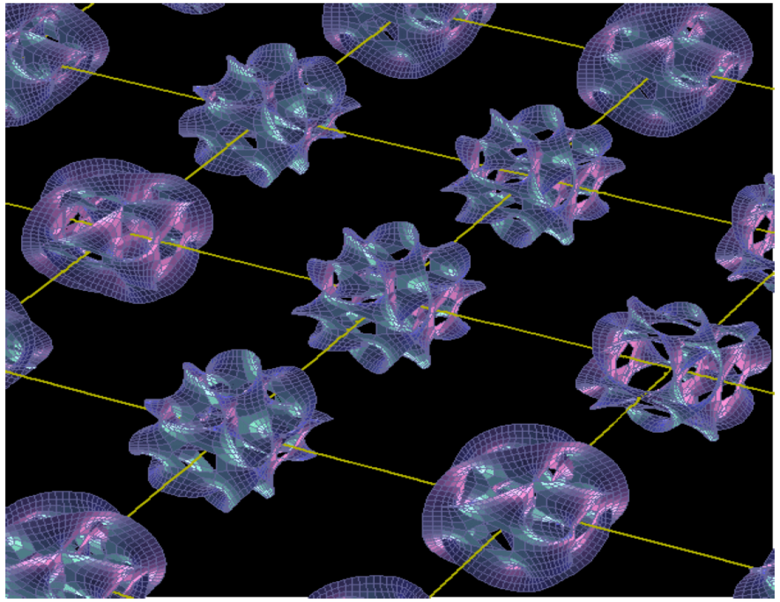
It is impossible to have zeroth value and change rate of a quantum field in a fixed point of space



QCD Vacuum energy fluctuations (lattice)

Geometry and topology of space time

Fields are internal characteristics of the space-time itself



Imagination of complicated space-time geometry

Zeroth fluctuations of non-deformed geometrical structures!

Geometry of non-perturbative vacuum

- *Electromagnetic vacuum*

✓ space-time "stratified" structure is charge-neutral;
✓ can be in a *non-deformed state*;
✓ delocalized zero-point fluctuations fill up the whole space-time

- *"Weak" vacuum* **(Higgs condensate)**

✓ space-time "stratified" structure is *spontaneously deformed*;
✓ layers are "weakly" charged;
✓ deformations (shifts) are regular and *continuous*;
✓ is *classically determined* and zero-point fluctuations is only slightly disturb it

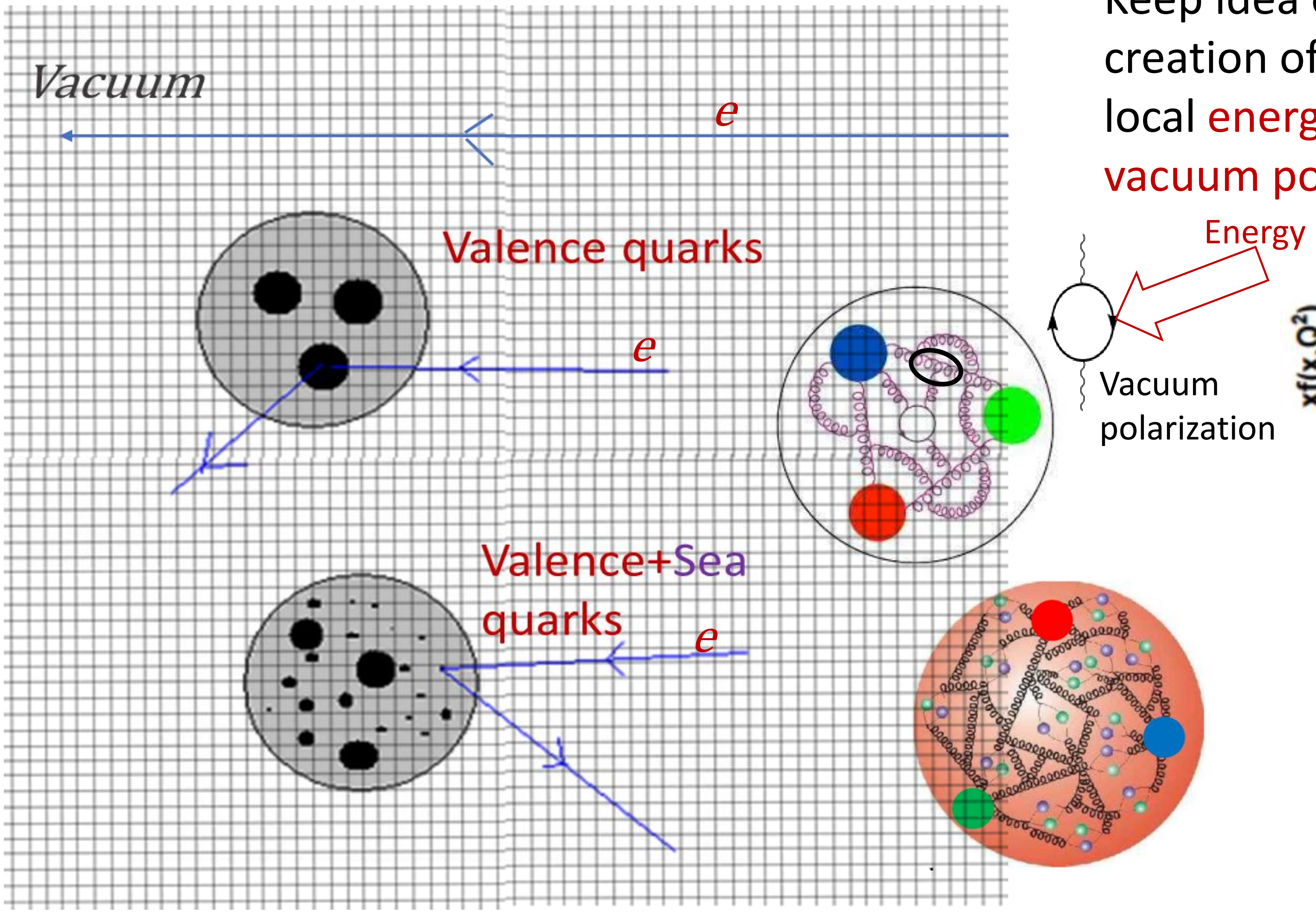
- *"Strong" or QCD vacuum* (**Quark-Gluon condensate**)

✓ space-time "stratified" structure is *spontaneously deformed;*
✓ layers carry different "color" charges;
✓ deformations are *localized* and determined totally by quantum effects;
✓ such a structure is *not classically determined*

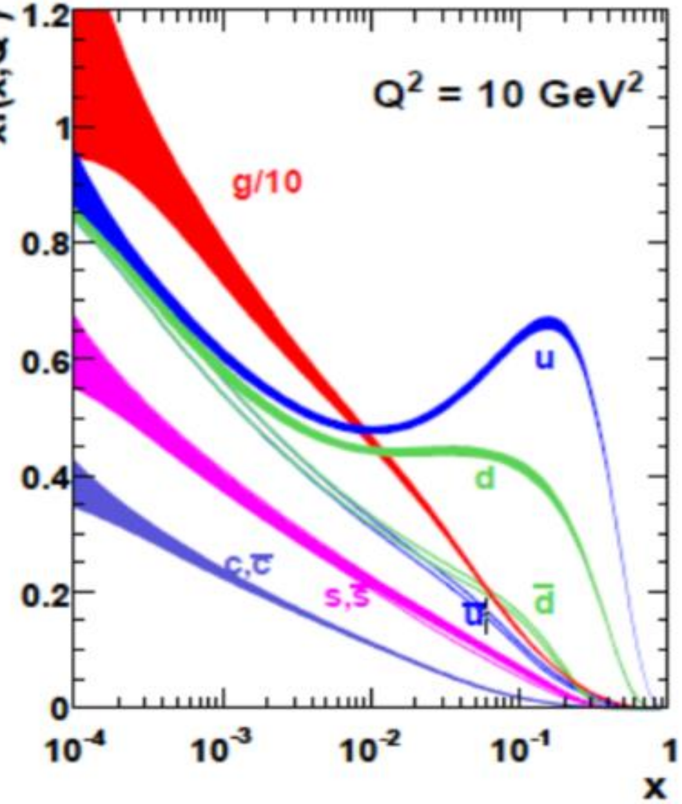
Physical Vacuum is the quantum superposition of substructures (vacuum condensates) constantly transforming one into another

Properties of matter are totally determined by properties of vacuum structures!

DIS (Deep Inelastic Scattering) – *e* P scattering



Keep idea of materiality of vacuum, creation of particle depends on local energy available and surround vacuum polarization



Mass in particle creation – from quark to particle
from massless to particle with mass

It is easy to write down $E = mc^2$, but it is hard to imagine both quark & antiquark having positive masses and reside in Vacuum. If we believe that quarks or antiquarks bares no mass in Vacuum, then WHEN will they gain their masses during particle creation?

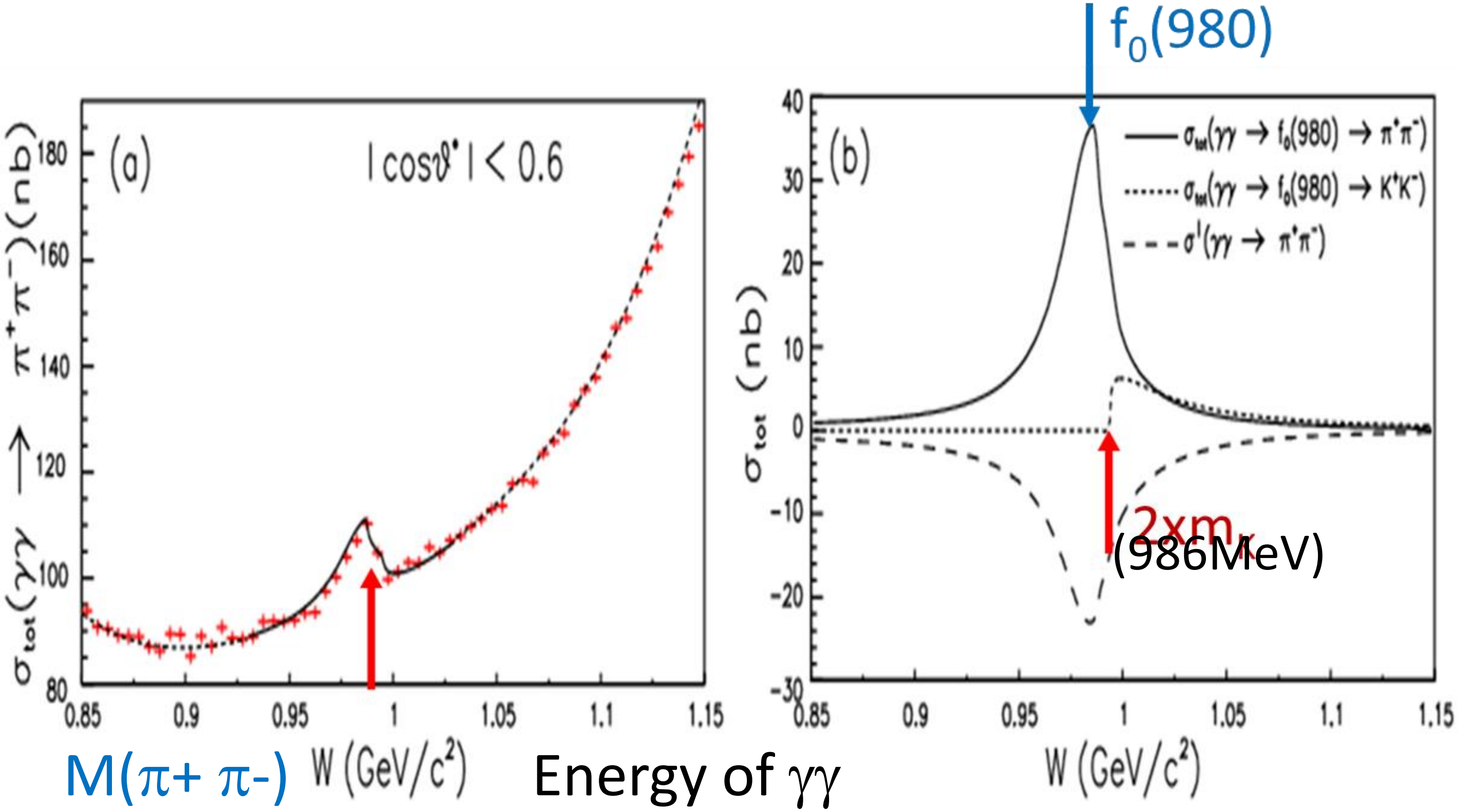
Two experimental examples:

-- $f_0(980)$ production in $\gamma\gamma$ collisions ($\gamma\gamma \rightarrow \pi+ \pi-$)

-- Exclusive e+e- → $D^{*-}D^0\pi^+$ events

Wave-Particle duality – $f_0(980)$ production in $\gamma\gamma$ collisions
as an example of particle creation from Vacuum

$\gamma\gamma$ (+Vacuum) → $f_0(980)$ → π+ π-



Contribution of KK wave function starts at $2xm_K$ (986MeV) as a pair of real particles – wave function and mass

Interference of $\pi\pi$ & KK in creation of $f_0(980)$, when both of them are created from Vacuum

PDG data

Mass $f_0(980)$: 990? ± 20 MeV

$f_0(980)$ decays into $\pi\pi$ & KK

Width: $\Gamma(\pi\pi)/\Gamma(\pi\pi$+KK)

= 0.52 ± 0.12

Similar situation for baryonium under PP threshold or search of D^{*0}→$D^+\pi^-$

(2006.8 → 1869.7+139.6 = 2009.3)

$\Gamma(D^{*0})$<2.1MeV

Size of source determined by BEC (Bose-Einstein correlation)

$(\pi^+\pi^+$ or $\pi^-\pi^-)/\pi^+\pi^-$ in e+e-. PP/P$\overline{\text{P}}$, Heavy ion

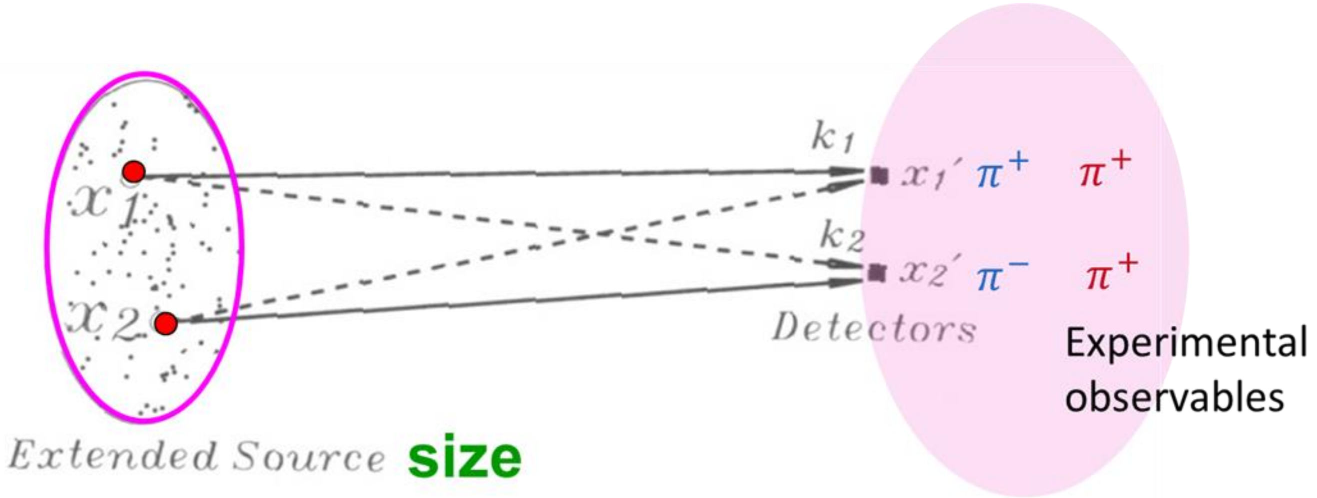


Fig. 17.2 A pion of momentum k_1 is detected at x_1' and another identical pion with momentum k_2 is detected at the space-time point x_2'. They are emitted from the source point x_1 and x_2 of an extended source. The solid lines joining x_1 to x_1' and x_2 to x_2', and the dashed lines joining x_1 to x_2' and x_2 to x_1' are possible trajectories for the pions.

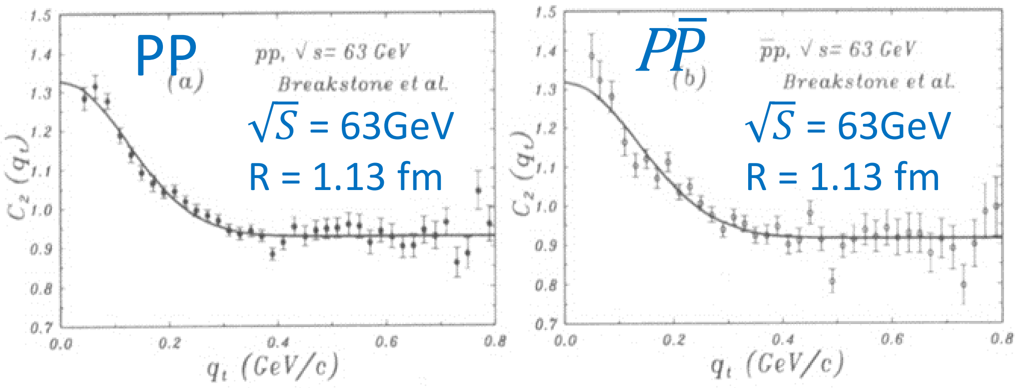
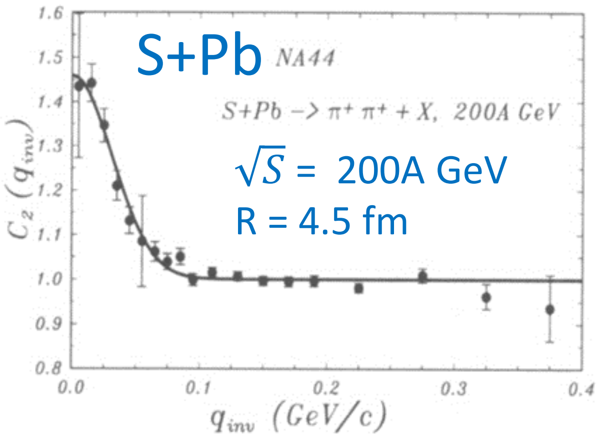
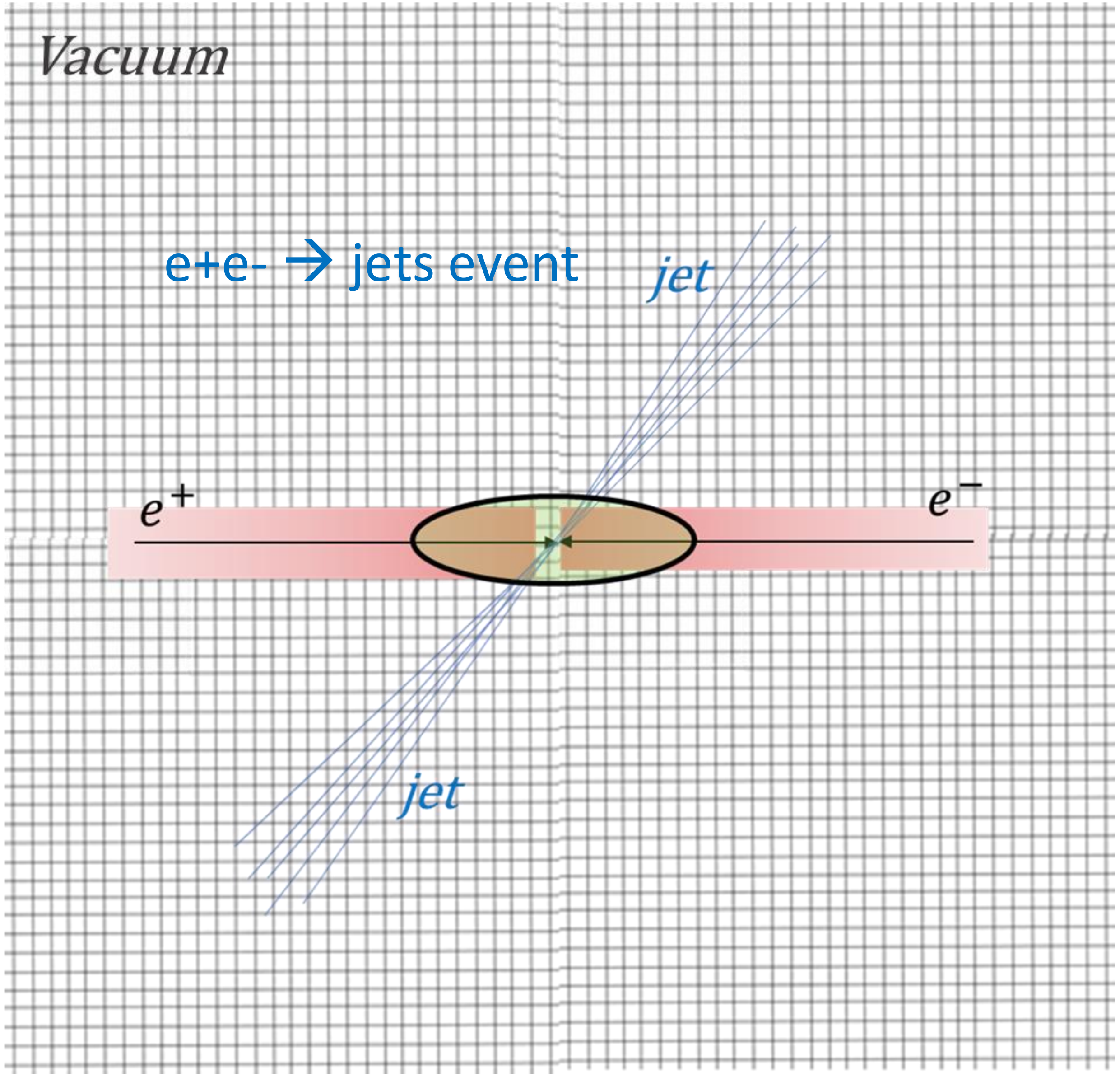


Fig. 17.6 The correlation functions for two identical pions observed for pp reactions at $\sqrt{s} = 63$ GeV are shown in Fig. 17.6a and for $\bar{p}p$ reactions are shown in Fig. 17.6b. The data points are from Refs. [32,33]. The solid curves are fits to the experimental data using equation (17.66).



Principle of HBT interferometry
(Hanbury-Brown-Twiss)

BEC (size of source) in e+e- / PP/P$\overline{\text{P}}$ experiments



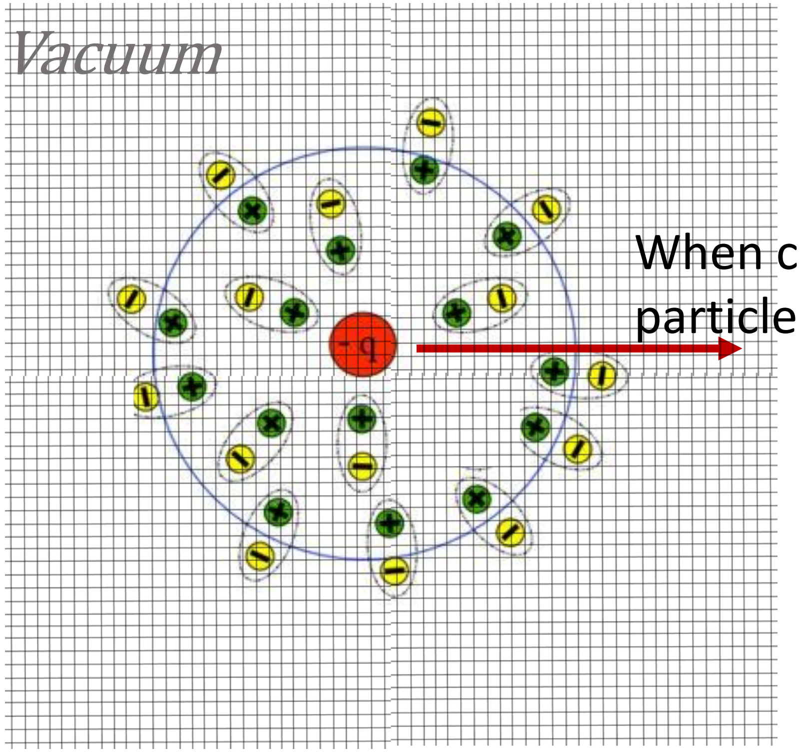
Published results show size of source increases as E_{CM} increases, with cigar shape. Size increases faster along beam direction, not jet direction.

Is this related to nature of Vacuum?
"medium" is excited (vacuum polarization) as e+ or e- passes through Vacuum and de-excites. The "excited medium" will be easier to be ionized/materialized and form matter. Consequently size increases along beam direction.

Analog: Geiger counter
Counter-Check: Is source size jet direction dependent

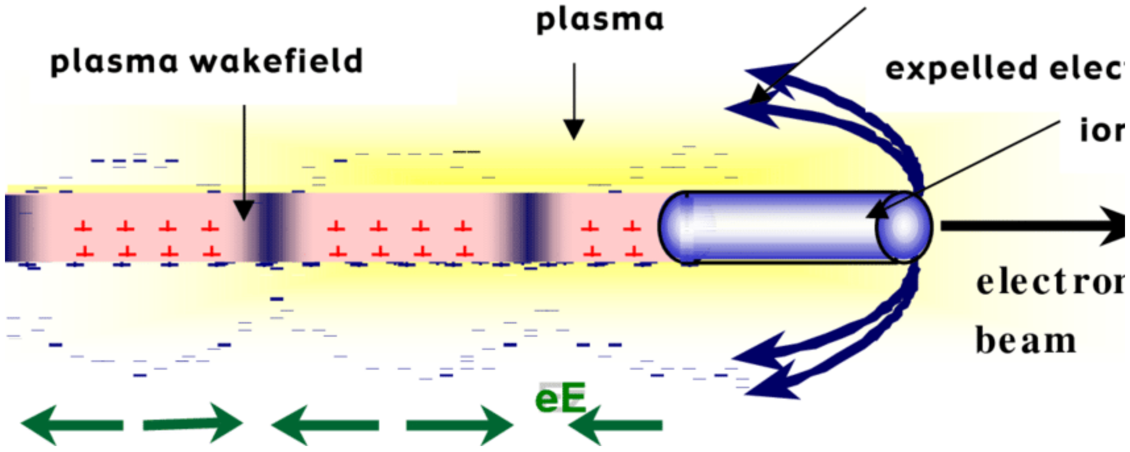
Vacuum polarization

Screening in QED

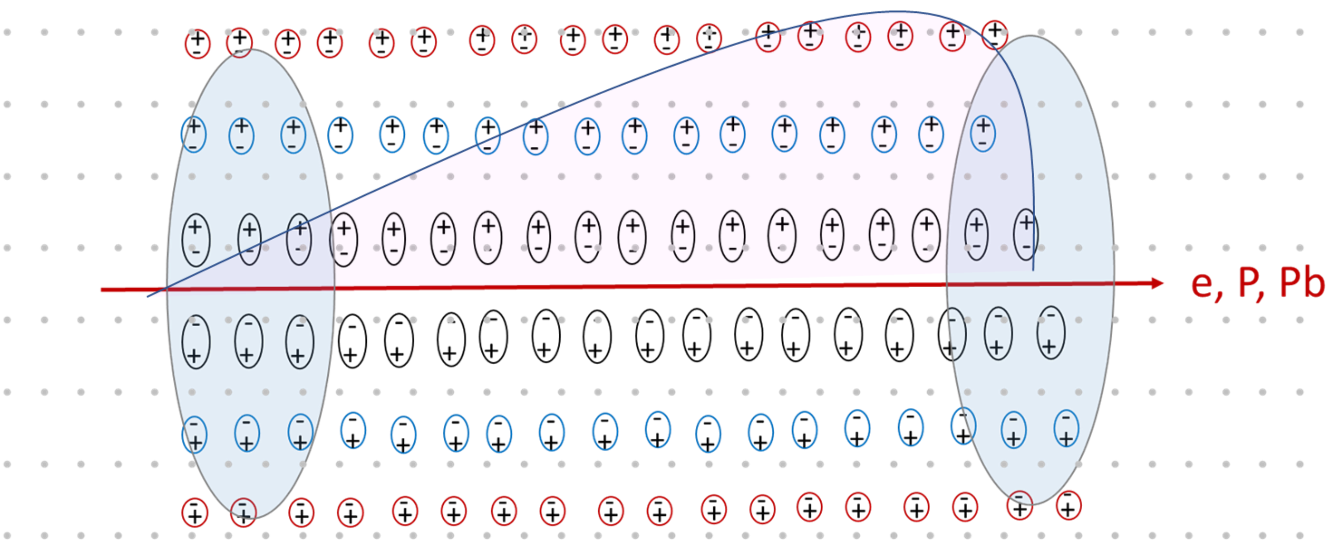


When charged particle is moving

Plasma wake field

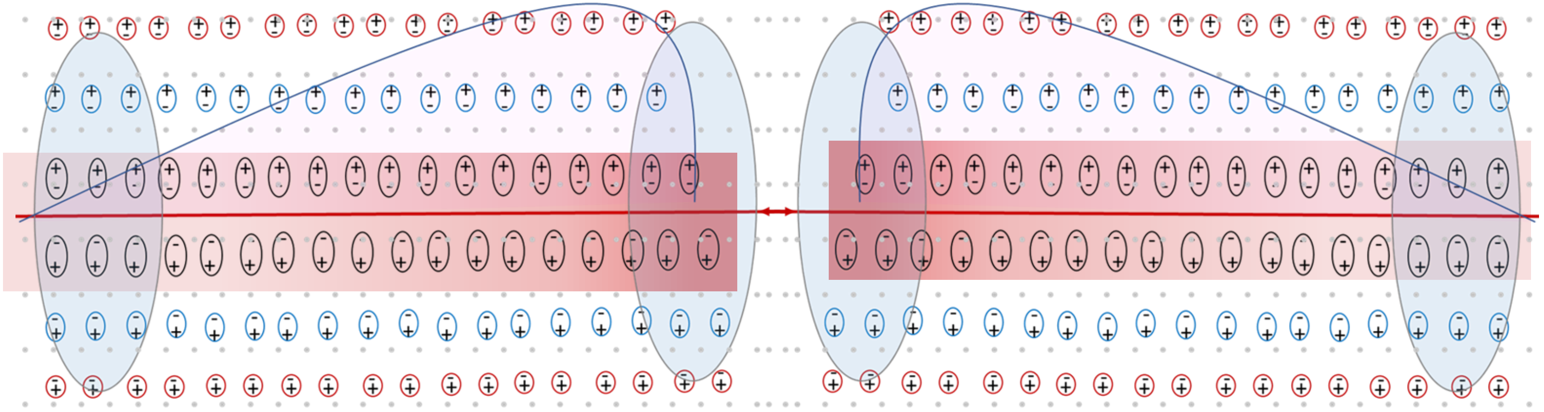


“Plasma wake field” in Vacuum

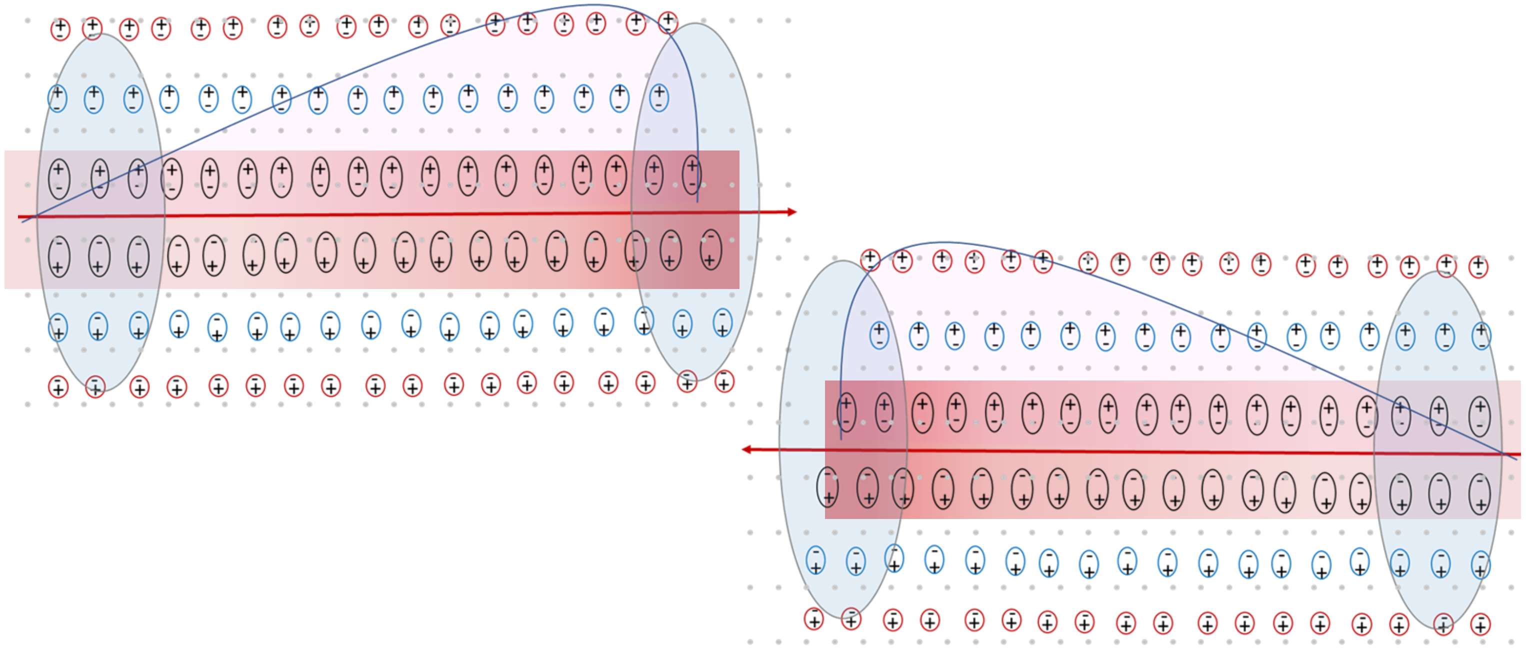


Vacuum polarization
disturbance caused by e+e- / PP / Heavy Ion

e+e- : Belle -2
PP : LHC
Heavy Ion: LHC, RHIC



Head-on collision



Peripheral collision
(Two-photon physics)
Ultra-peripheral collision

BEC (size of source) in heavy ion collision experiments

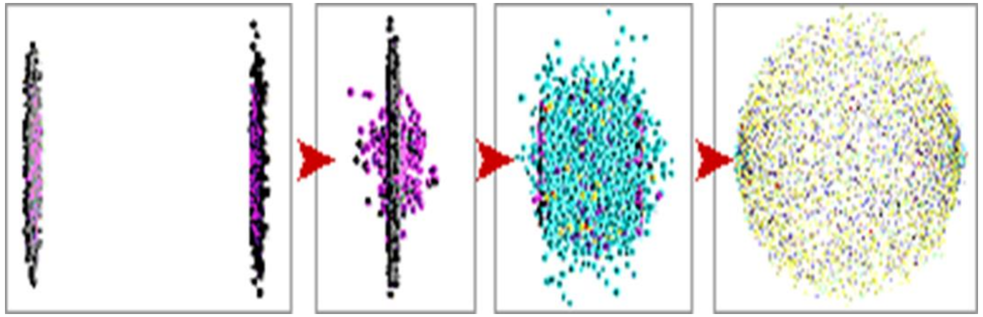
Will different conditions of center energy E_{CM} & impact parameter **b** affect BEC from the same heavy ion collision experiment.

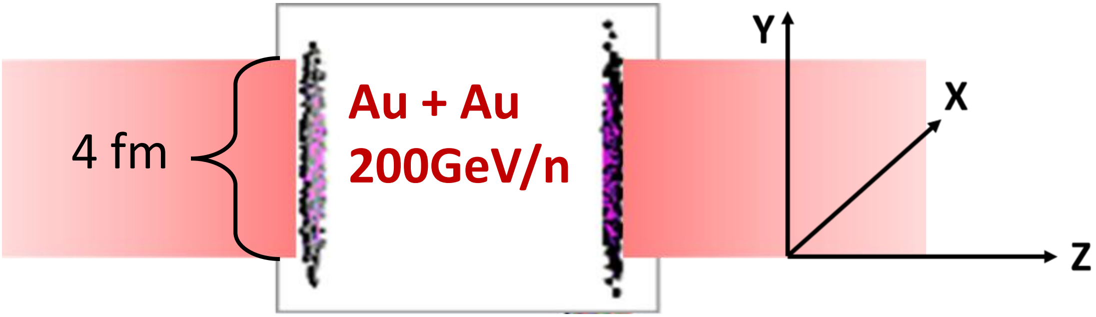
Head-on collision

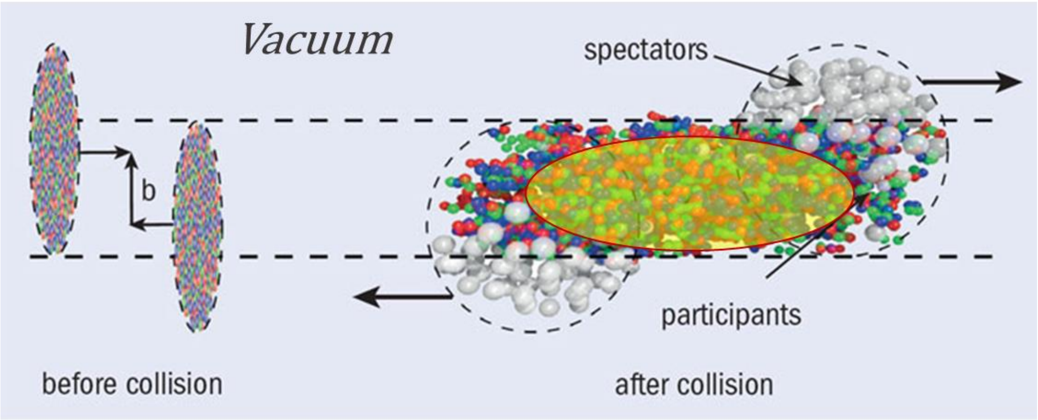
Peripheral collision

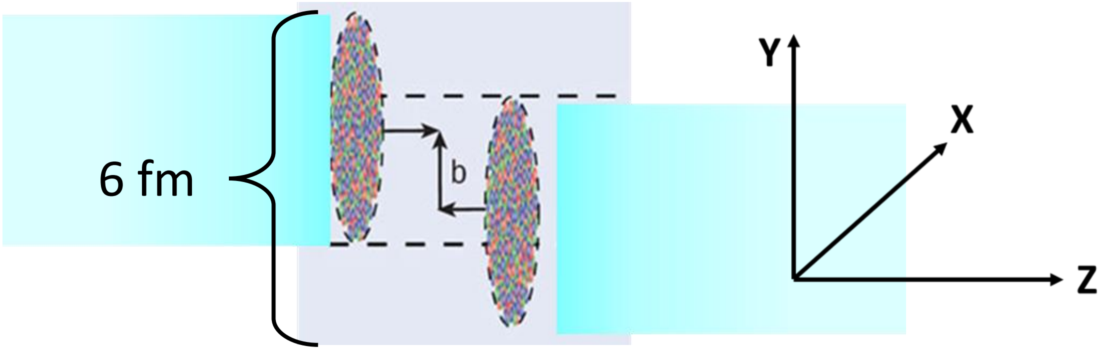
Ultra-peripheral collision

Multiplicity of heavy ion collision could be > 10,000, most of them come from Vacuum. Expect size of source in X&Y increases in peripheral events when E_{CM} decreases.



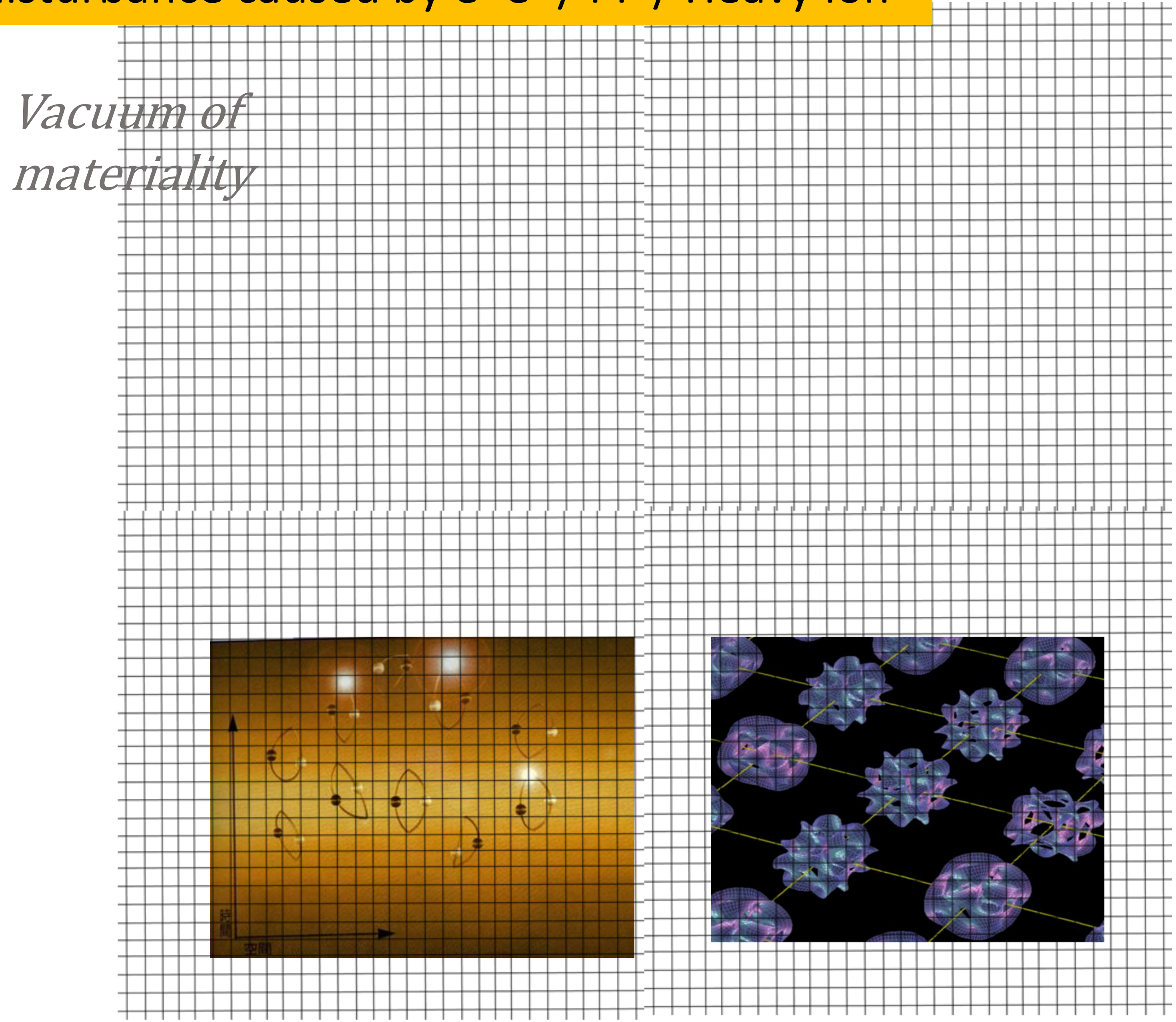






8 fm Ultr-peripheral collision

Vacuum polarization
disturbance caused by e+e- / PP / Heavy Ion



vacuum polarization can be studied by source size in e+e- / PP / Heavy Ion experiments under different conditions.

Comparison of e+e- / PP / Heavy Ion and Central/Peripheral/ Ultra-peripheral events renders an inner look how polarization occurs at extremely small scale of space & time.

Energy available @RHIC~200A GeV, & ~2000A GeV@LHC, but source size x10?

When and where mass comes

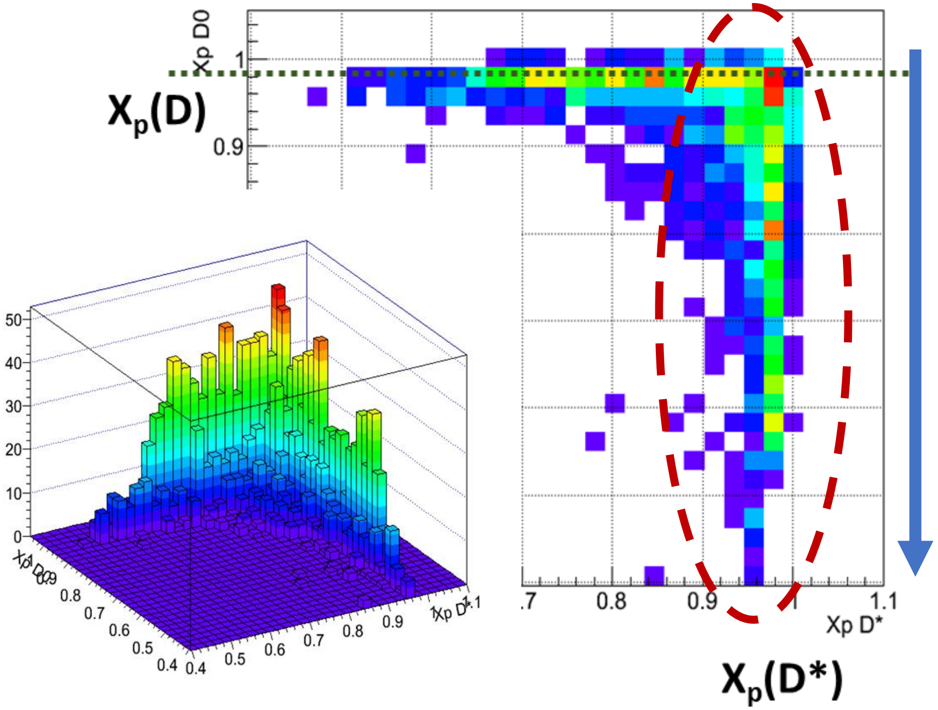
Exclusive:
$\Sigma E_i = \sqrt{S}$; $\Sigma \vec{P}_i = 0$

Exclusive e+e- → $D^{*-}\mathcal{M}$ → $D^{*-} D^0 \pi^+$ events (3-body)

Experimental data shows D^{*-} recoils against a quasi-particle $\mathcal{M}$, where $\mathcal{M}$ is invariant mass of $D^0 \pi^+$

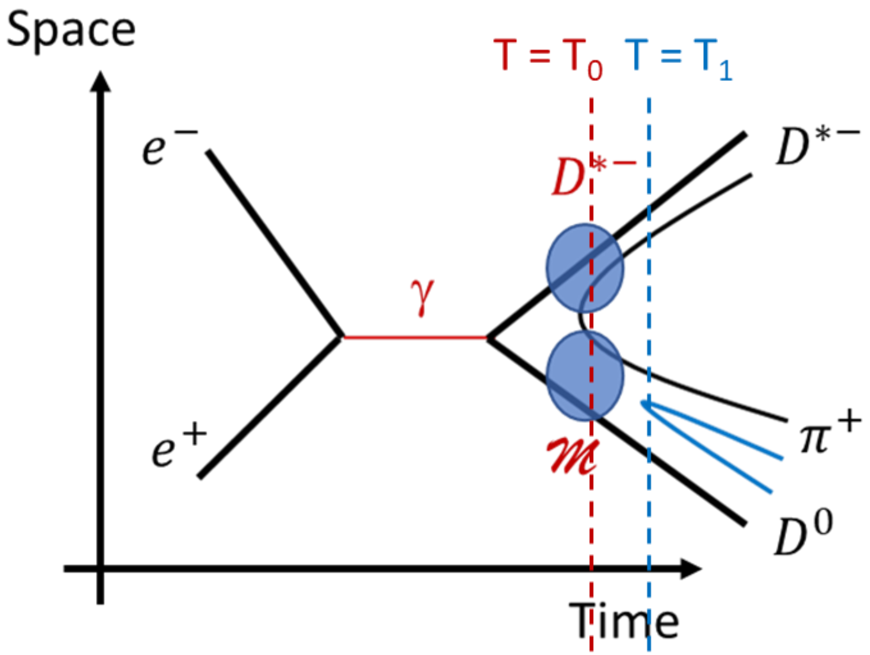
Exclusive e+e- → $D^{*-} D^+ \pi^+ \pi^-$

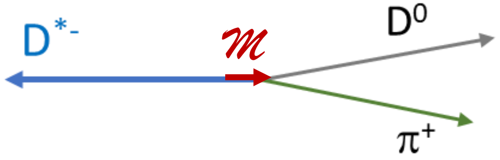
Exclusive e+e- → $D^{*-} D^0 \pi^+ \pi^+ \pi^-$



Increasing mass of $\mathcal{M}$ ($D^0 \pi^+$)

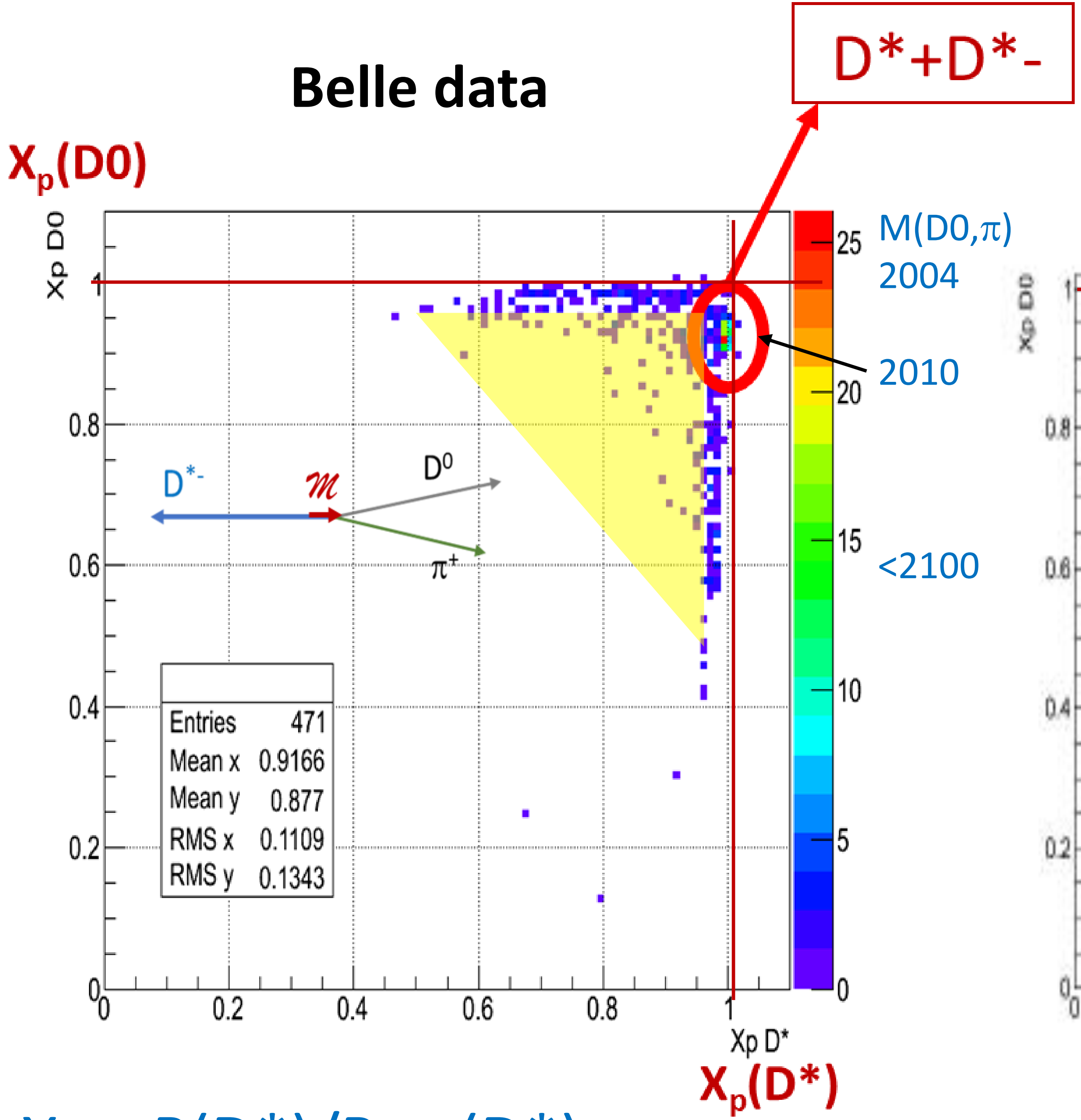
$X_P(D) = P(D)/P_{max}$



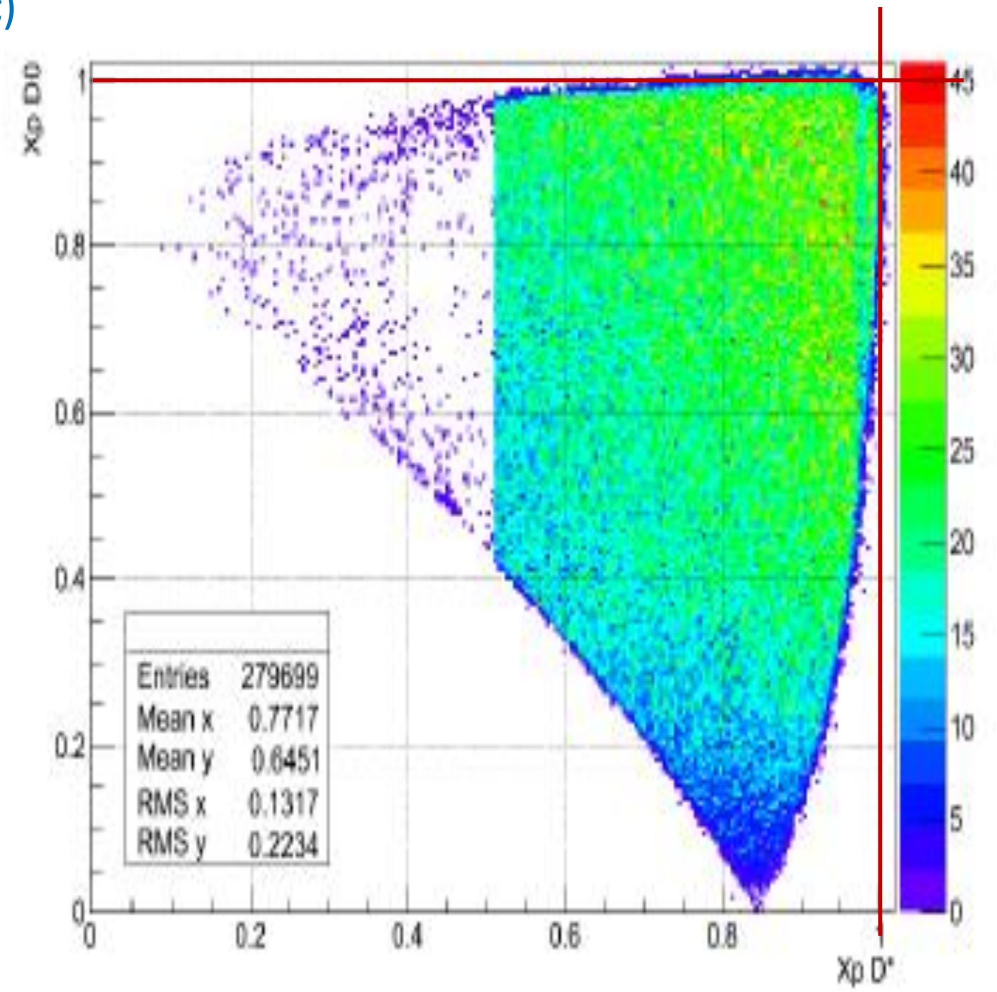


As if "two-particles" are created from Vacuum @T = T_0, and $\mathcal{M}$ decays into $D^0 \pi^+$ @T = T_1.

Belle data



MC
Phase space



$X_p = P(D^*)/P_{max}(D^*)$

When and where mass comes

Exclusive:
$\Sigma E_i = \sqrt{S}; \Sigma \vec{P}_i = 0$

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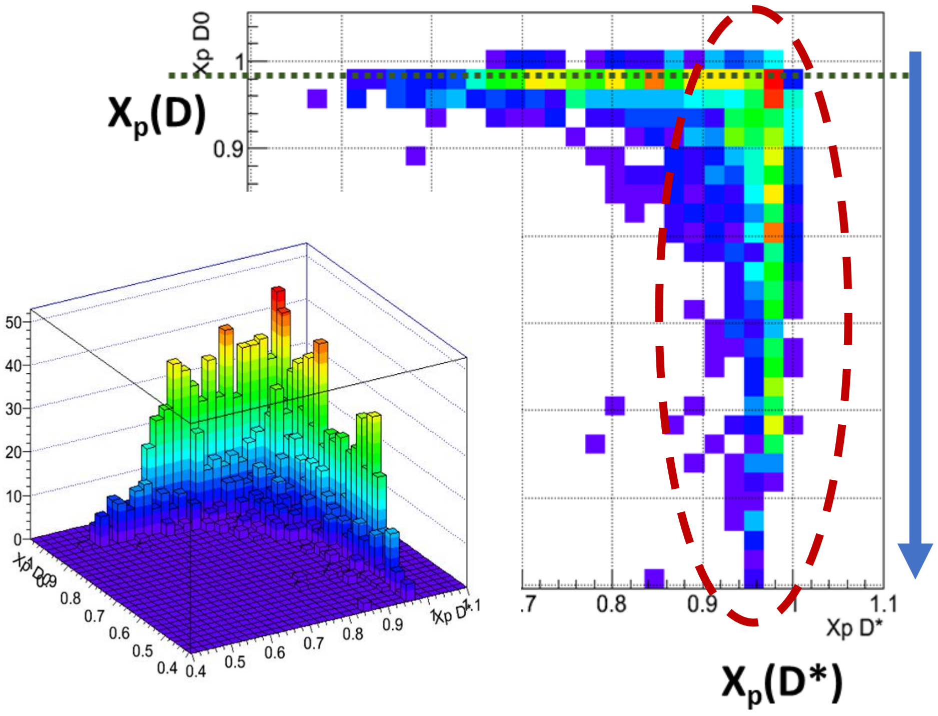
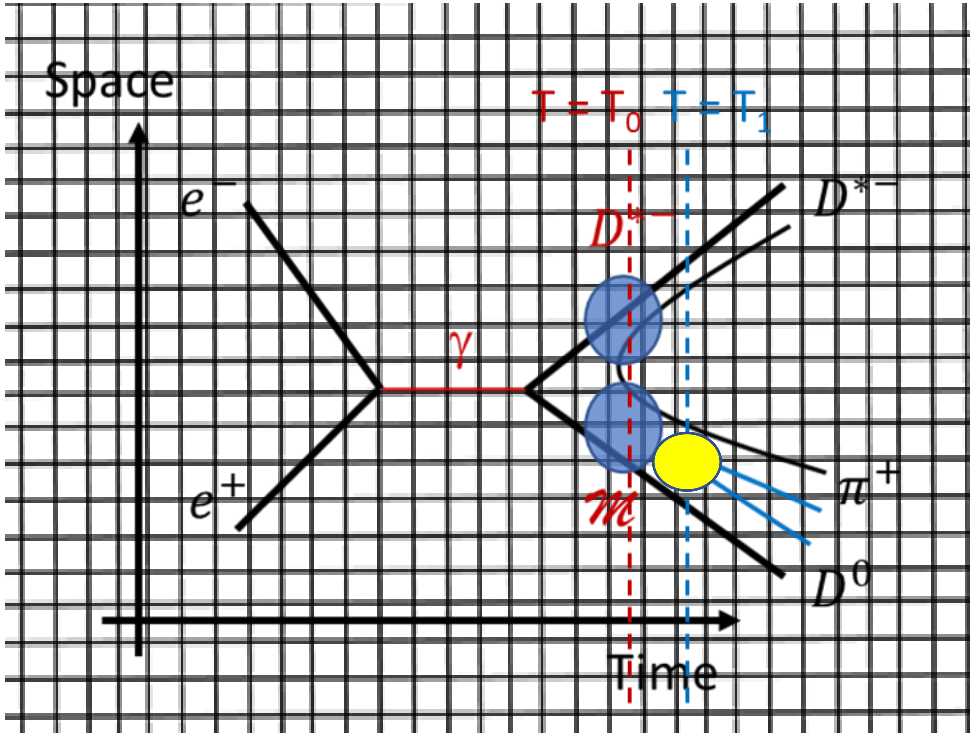
Exclusive e+e- → $D^{*-}D^+\,\pi^+\,\pi^-$

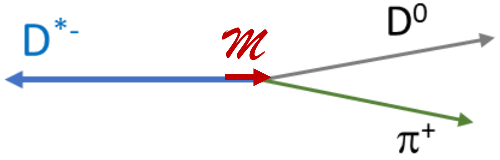
Exclusive e+e- → $D^{*-}D^0\,\pi^+\,\pi^+\,\pi^-$



Increasing mass of $\mathcal{M}$ ($D^0\,\pi^+$)

$X_P(D) = P(D)/P_{max}$





As if "two-particles" are created from Vacuum @T = T_0, and $\mathcal{M}$ decays into $D^0\,\pi^+$ @T = T_1.

Quark contents in Vacuum: Exclusive e+e- → $D^{*-}D^0\pi^+$/ Inclusive e+e- → $(D^{*-}D^+X)/(D^{*-}D_s^+X)$ / π & k mesons created from Vacuum

A series studies on

Exclusive e+e- → $D^{*-}D^0\pi^+$ / $D^{*-}D^+\pi^0$ / $D^{*-}D_s^+k^0$ events

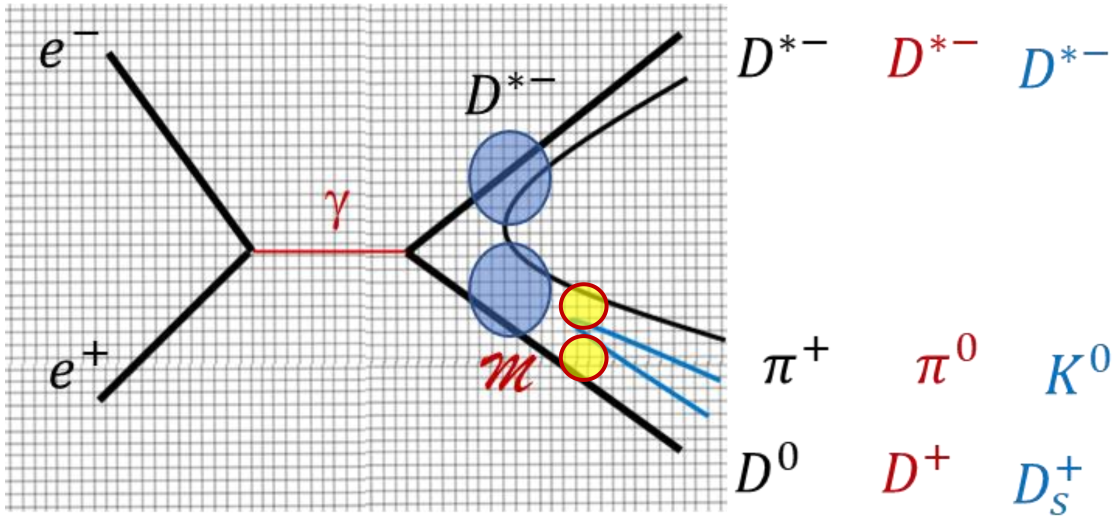
Quark $\bar{c}u$ $c\bar{u}$ $u\bar{d}$ / $\bar{c}u$ $c\bar{d}$ $d\bar{u}$ / $\bar{c}u$ $c\bar{s}$ $s\bar{d}$

$u\bar{u}$: $d\bar{d}$: $s\bar{s}$

1 : ~1 : ~0.4

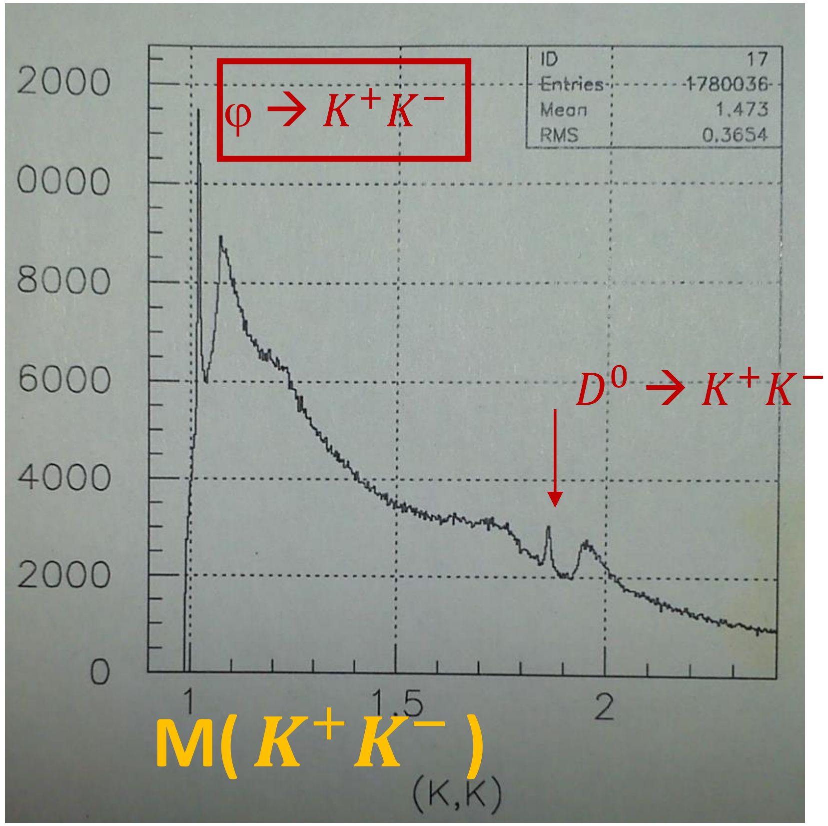
π & K are not created equally by Vacuum

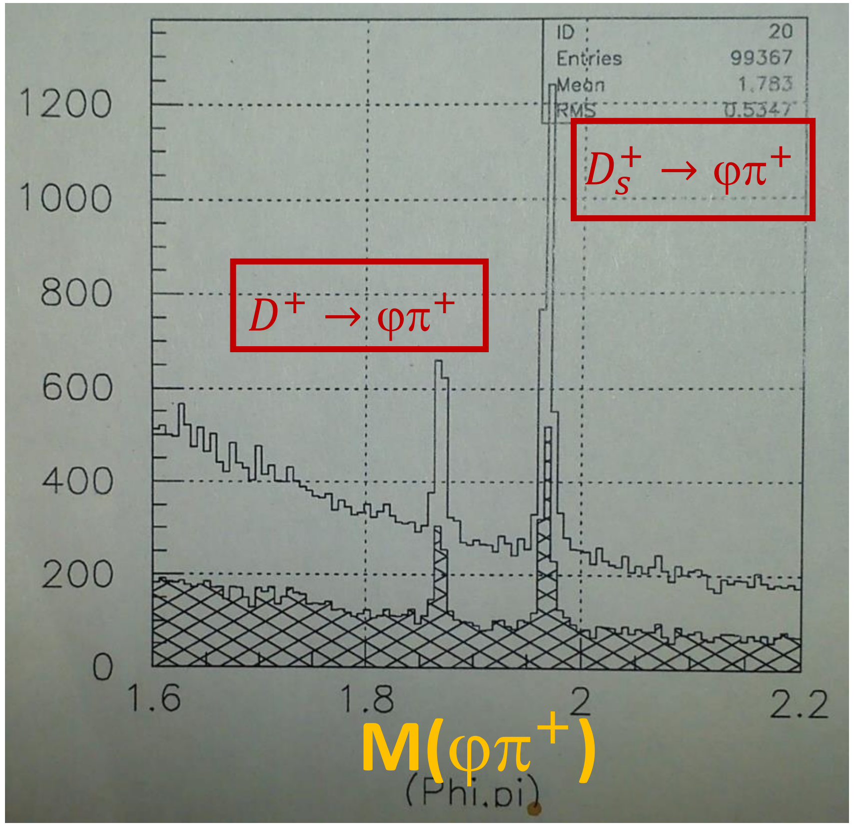
Maybe we can monitor near threshold behavior of π^+ or K_s^0 in e+e-→$D^{*-}D^0\pi^+$ or $D^{*-}D_s^+K_s^0$ events closely, because π^+ or K_s^0 mass are different from u or s-quark mass or both of them are massless? Just like how BES collaboration determines τ mass precisely.



Densities of $u\bar{u}$ and $s\bar{s}$ in Vacuum is different as an intrinsic property of Vacuum. or, strong coupling constant (α_s) is different for g → $u\bar{u}$ and g → $s\bar{s}$

Another check on Inclusive e+e- → $(D^{*-}D^{+}X)/(D^{*-}D_s^{+}X)$





e+e- → $D^{*-}(K^+K^-)$

e+e- → $D^{*-}(\varphi\pi^+)X$ → $D^{*-}D^{+}X$ / $D^{*-}D_s^{+}X$

$D_s^+ \to \varphi\pi^+$

$D^+ \to \varphi\pi^+$

$$\frac{\sigma(D^{*-}D_s^{+}X)}{\sigma(D^{*-}D^{+}X)} = \frac{\frac{2160}{4.5\%\text{x}49.2\%}}{\frac{660}{0.00276}} = \frac{97{,}560}{239{,}130} = 0.41$$

s/d = 0.41

s/d =0.41 consists with s/(u+d+s) = 0.1

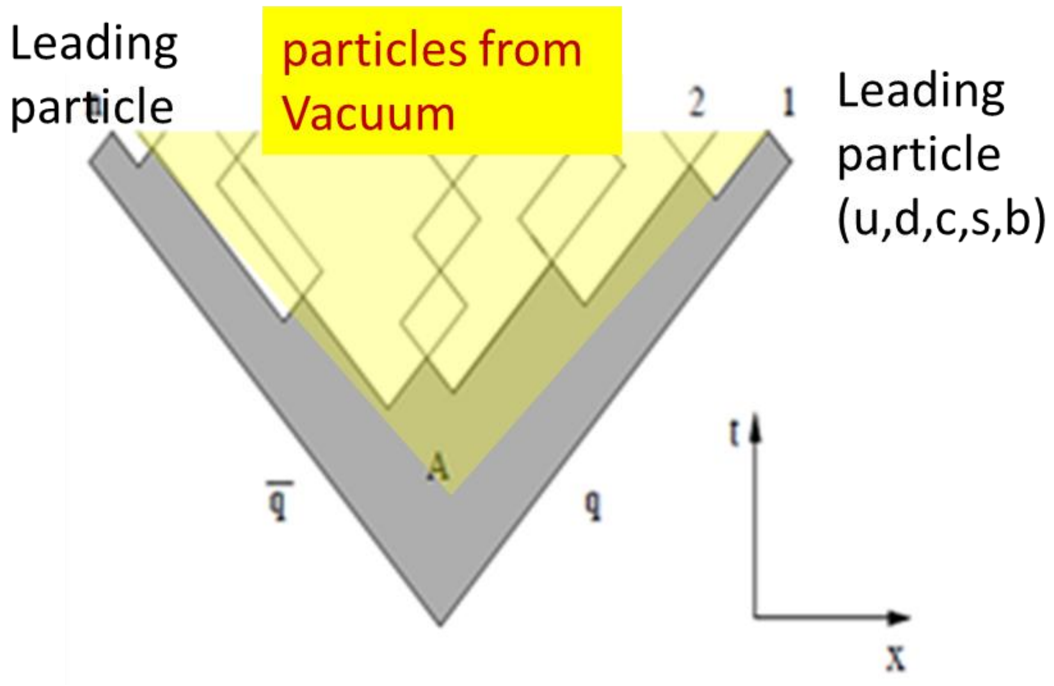
Branching fractions: (PDG 2023)

$D^+ \rightarrow \phi\pi^+, \phi \rightarrow K^+K^-$ (2.69 + 0.07 − 0.08) × 10−3

$D_s \rightarrow \phi\pi^+, \phi \rightarrow K^+K^-$ (2.21 ±0.06) %

Numbers of π & k mesons created from Vacuum (via gluon) In e+e- annihilation events

From number of hadrons in e+e- annihilation at different E_{CM}, one can extract number of π & k mesons created from Vacuum. There are two components of hadron creations in e+e- annihilations: hadrons from (1) leading quarks & the rest from (2) Vacuum. Leading quark forms leading particles as fragmentation process, then π & k from leading particle decay are the same at different E_{CM}.
Subtraction of numbers of π & k at different E_{CM} cancels contribution from leading particle and leaves contribution of Vacuum.



Leading c-quark → D / b-quark → B meson. Numbers of π & k-meson from D or B meson decay are the same no matter what e+e- annihilation energy E_{CM}, is.

A quick check on Numbers of π & k mesons created from Vacuum (via gluon)

e+e- → u,d,c,s,b + (gluon)
→(mesons)+(mesons)

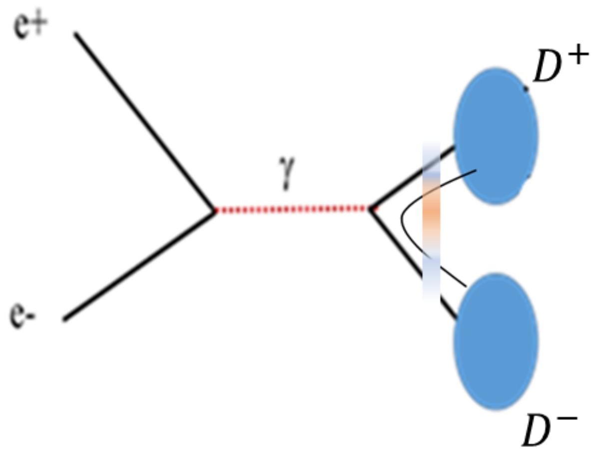
(u,d,c,s,b) (u,d,c,s,b)

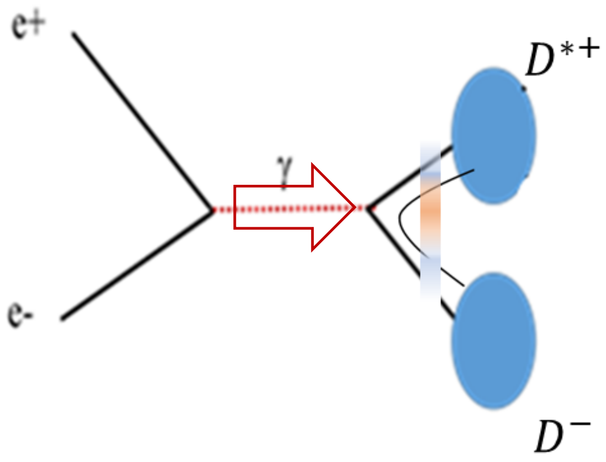
Particle	$\sqrt{s} \approx 10$ GeV	$\sqrt{s} = 29$–35 GeV	$\sqrt{s} = 91$ GeV	$\sqrt{s} = 130$–200 GeV
Pseudoscalar mesons:				
π^+	6.52 ± 0.1	10.3 ± 0.4	17.02 ± 0.19	21.24 ± 0.39
π^0	3.2 ± 0.3	5.83 ± 0.28	9.42 ± 0.32	
K^+	0.953 ± 0.018	1.48 ± 0.09	2.228 ± 0.059	2.82 ± 0.19
K^0	0.91 ± 0.05	1.48 ± 0.07	2.049 ± 0.026	2.10 ± 0.12
	from s,c,b quarks + from gluons		from s,c,b quarks + from gluons	from s,c,b quarks + from gluons

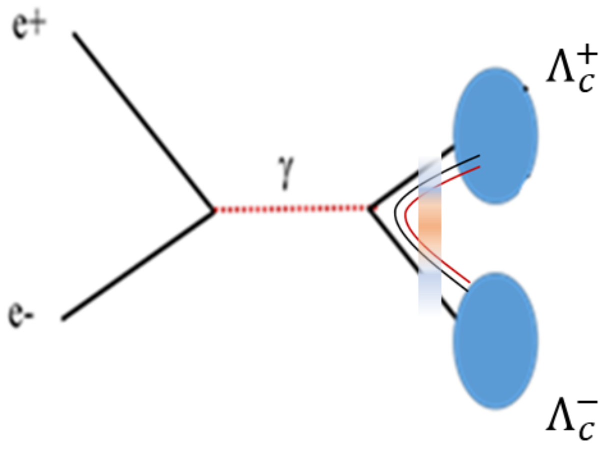
	91 – 10 GeV	160-10 GeV	160-91 GV
π's	17.0 - 6.5 = 10.5;	21.2 – 6.5 = 14.7;	21.2 – 17.0 = 4.2
k's	2.2 – 0.9 = 1.3;	2.8 – 0.9 = 1.9;	2.8 – 2.2 = 0.6
Ratio k/π	12.4%	12.0%	14.3%

(multiplicity of charm & bottom particles are even lower)

More from Exclusive charmed meson events
flavor, **spin** and **diquark** from Vacuum (mass issue)







e+e- → $D^+ \, D^-$
e+e- → $D^0 \, \overline{D}^0$
e+e- → $D_s^+ \, D_s^-$

$u\bar{u}$ / $d\bar{d}$ / $s\bar{s}$

e+e- → $D^{*+} \, D^-$

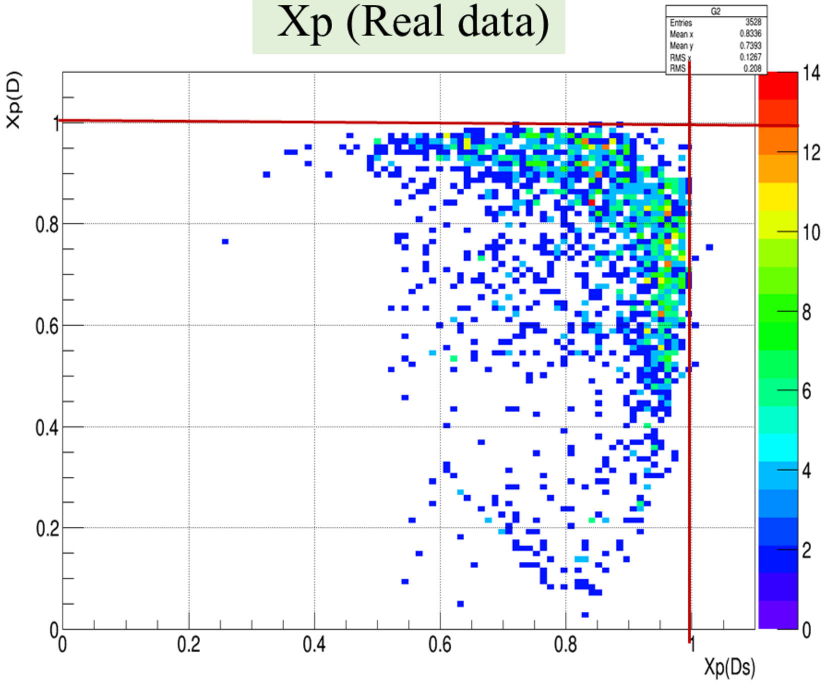
spin

e+e- → $\Lambda_c^+ \, \Lambda_c^-$

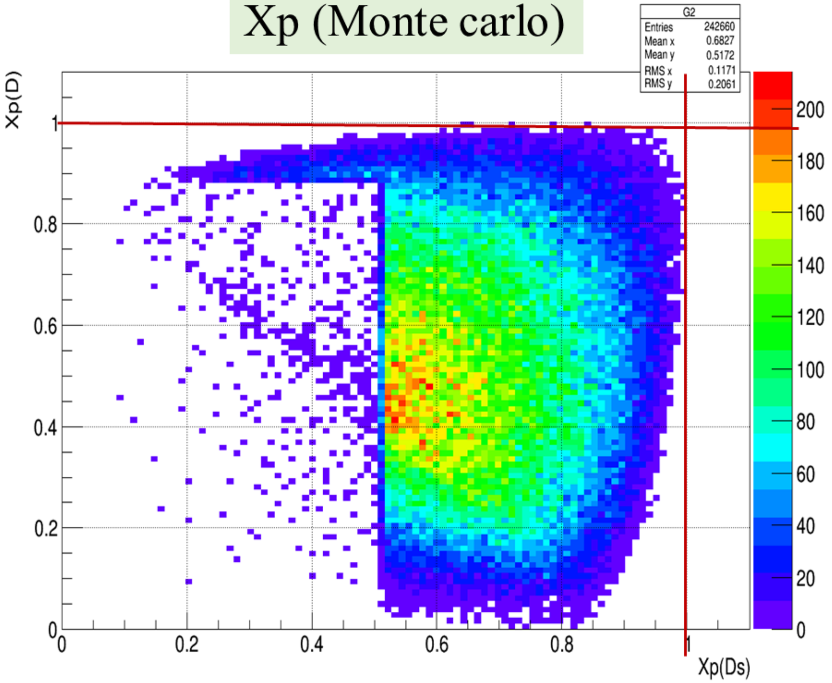
di-quark

X_p distribution of exclusive $D^*D\ \pi\ \pi$ (4-body) / $D^*D\ \rho$ events

Xp (Real data)

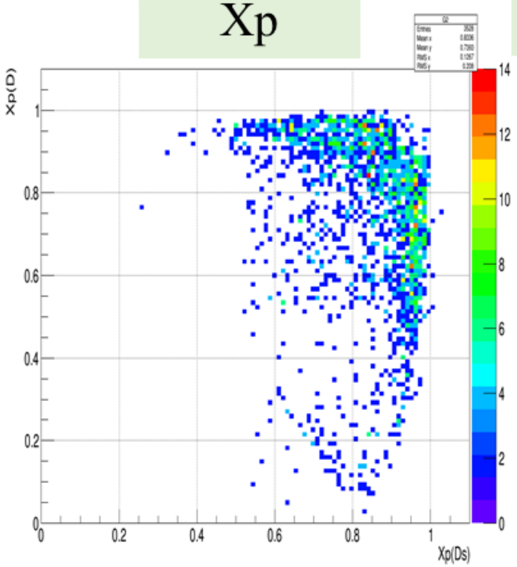


Xp (Monte carlo)

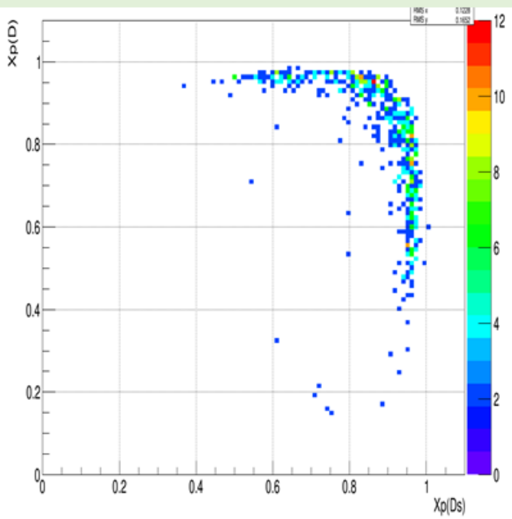


Real data

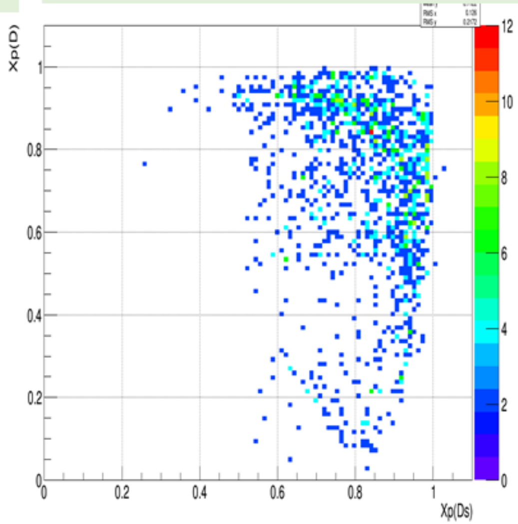
Xp



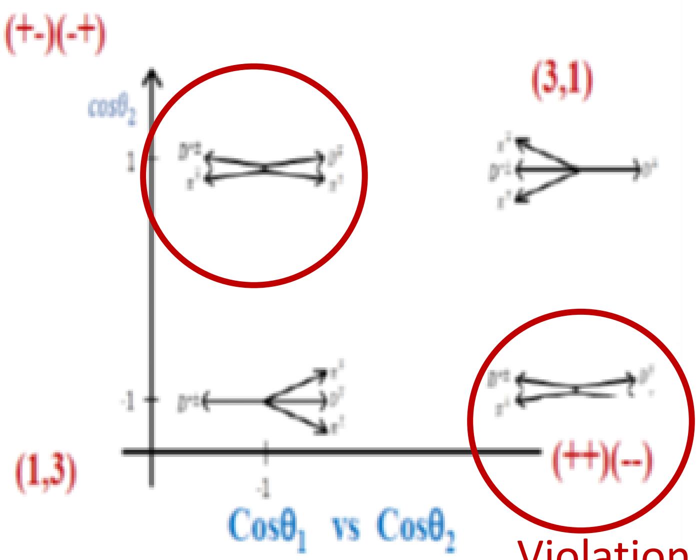
$|M(\pi\pi) - 0.7525| < 0.1411$



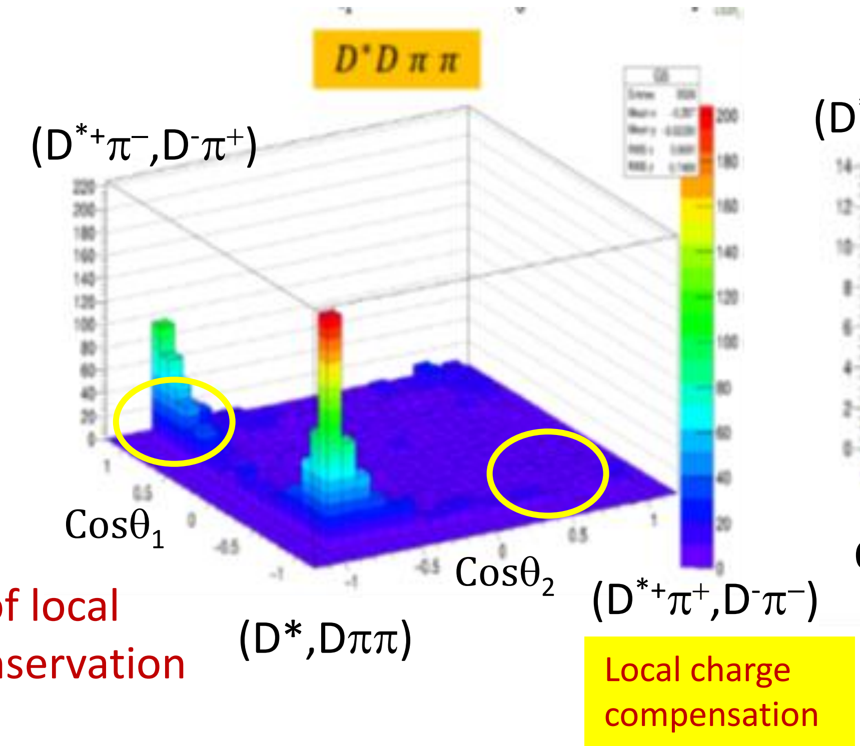
$|M(\pi\pi) - 0.7525| > 0.1411$



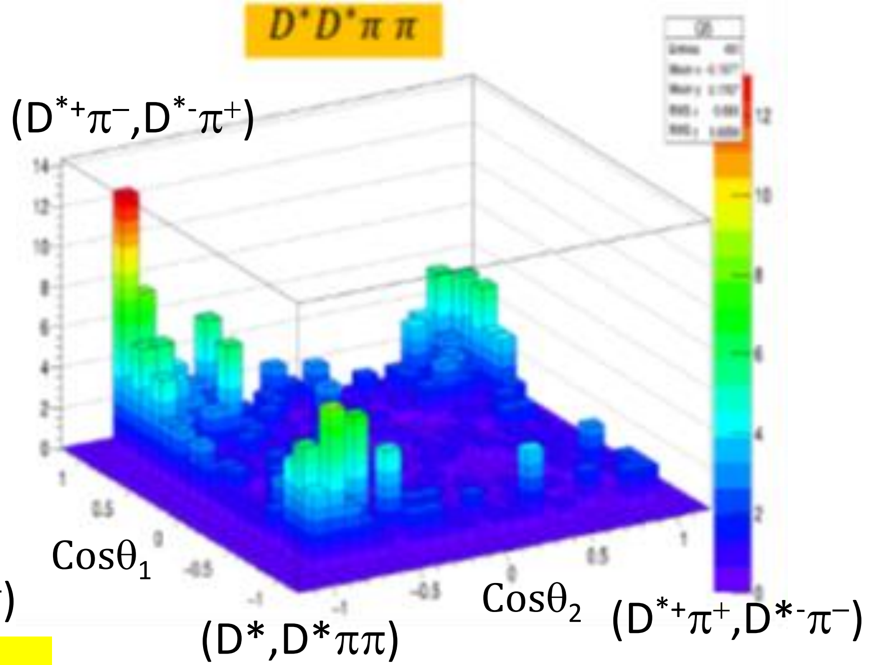
X_p distribution of exclusive $D^*D\,\pi\,\pi\,/D^*D^*\pi\,\pi$ (4-body) events



Opening angles between D* and π_1, π_2 in 4-body events



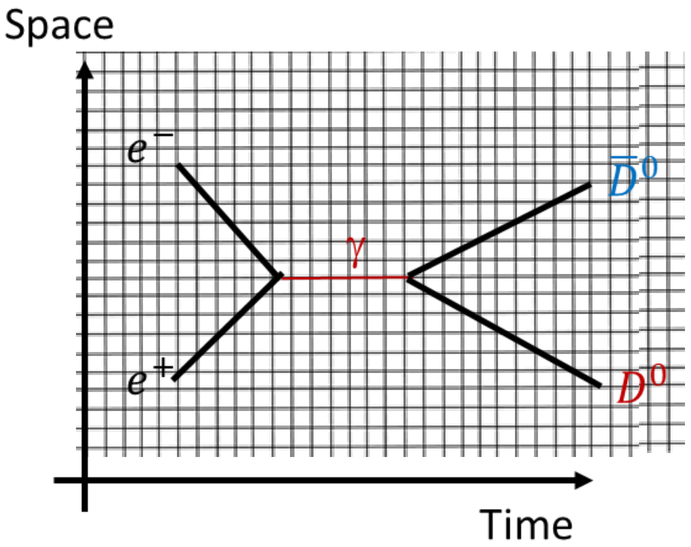
b. D*D ππ events



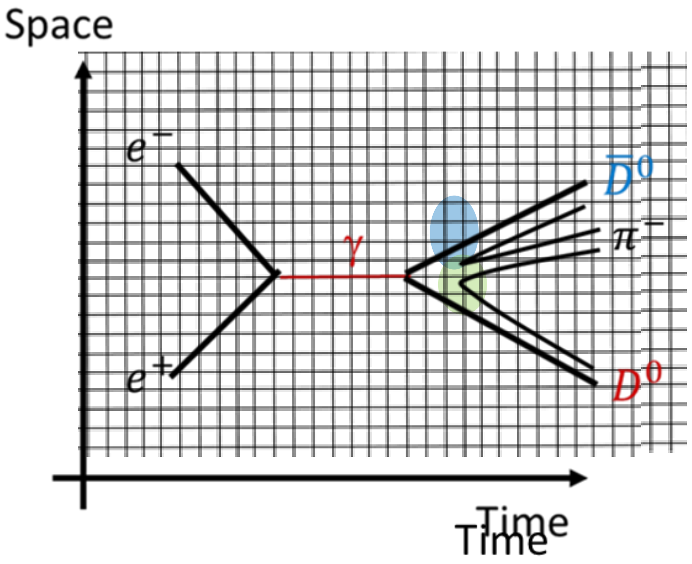
c. D*D*ππ events

As if “two-particles” are created from Vacuum,
Then Quasi particle decays (like cluster model)

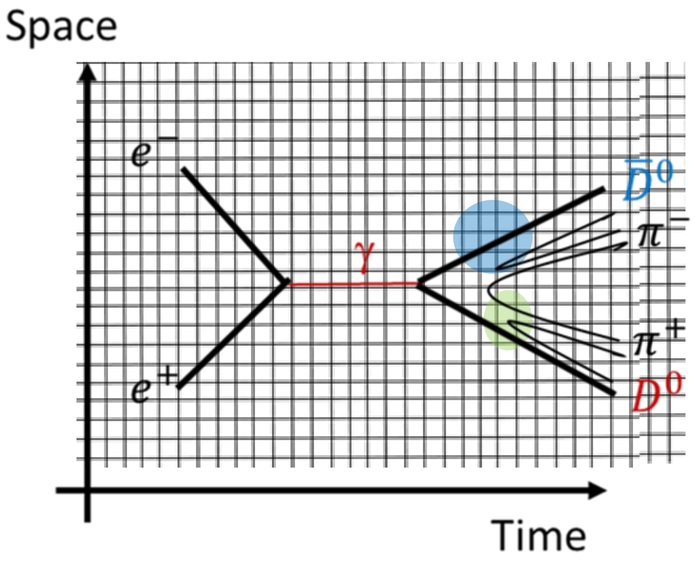
Quantum correlation -- $\bar{D}^0 D^0$ / $\boldsymbol{D_1 D_2}$ in exclusive 2-, 3- & 4-body events in e+e- → $\bar{D}^0 D^0$ / $\bar{D}^{*0} D^0$ → $\bar{D}^0 \pi^- D^0$ / $D^{*-} D^0 \pi^+$ → $\bar{D}^0 \pi^- D^0 \pi^+$ processes



e+e- → $\bar{D}^0 D^0$ → $\boldsymbol{D_1 D_2}$



→ $\bar{D}^{*0} D^0$ → $\bar{D}^0 \pi^- D^0$
or → $\bar{D}^0 \pi^- D^0$
→ X $\boldsymbol{D_1 D_2}$

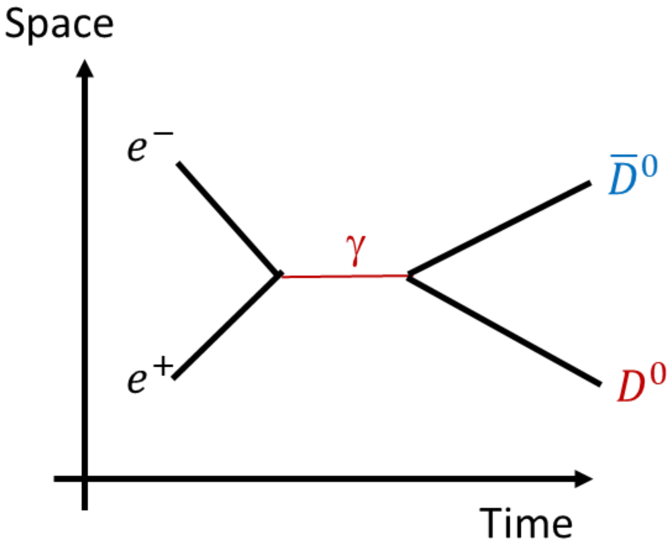


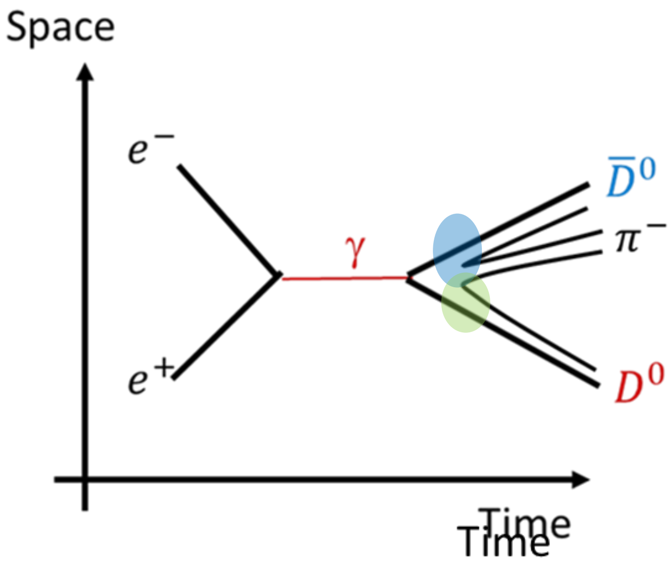
→ $D^{*-} D^0 \pi^+$ → $\bar{D}^0 \pi^- D^0 \pi^+$
or → $\bar{D}^0 \pi^- D^0 \pi^+$
→ XX $\boldsymbol{D_1 D_2}$

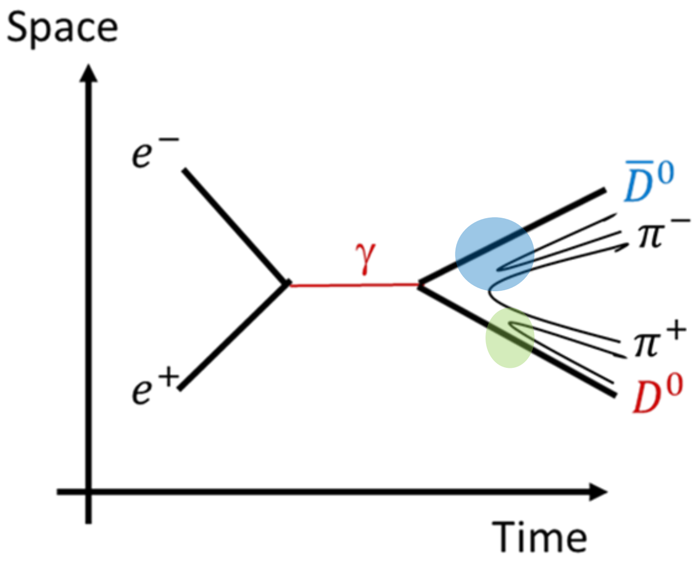
When and where Wave function collapses?
When and where mass comes

If it is materiality Vacuum, then Vacuum can “store” information, like correlation.

Quantum correlation -- $\bar{D}^0 D^0$ / $\boldsymbol{D_1 D_2}$
in e+e- → $\bar{D}^0 D^0$ / $\bar{D}^{*0} D^0 \rightarrow \bar{D}^0 \pi^0 D^0$ / $D^{*-} D^0 \pi^+ \rightarrow \bar{D}^0 \pi^- D^0\ \pi^+$ processes







e+e- → $\bar{D}^0 D^0 \rightarrow \boldsymbol{D_1 D_2}$

→ $\bar{D}^{*0} D^0 \rightarrow \bar{D}^0 \pi^- D^0$

→ $D^{*-} D^0 \pi^+ \rightarrow \bar{D}^0 \pi^- D^0\ \pi^+$

When and where Wave function collapses?

When and where mass comes

Conclusion:

The interplay between Vacuum and particle creation helps us to understand **intrinsic properties** of Vacuum, if Vacuum is treated as a materiality one.

--- Particles are created from Vacuum via two-particle process (e+e- annihilation)

--- densities of **flavor** $u\bar{u}$: $d\bar{d}$: $s\bar{s}$ = 1 : 1 : 04;

--- possible studies on roles of **spin**, **di-quark** in Vacuum

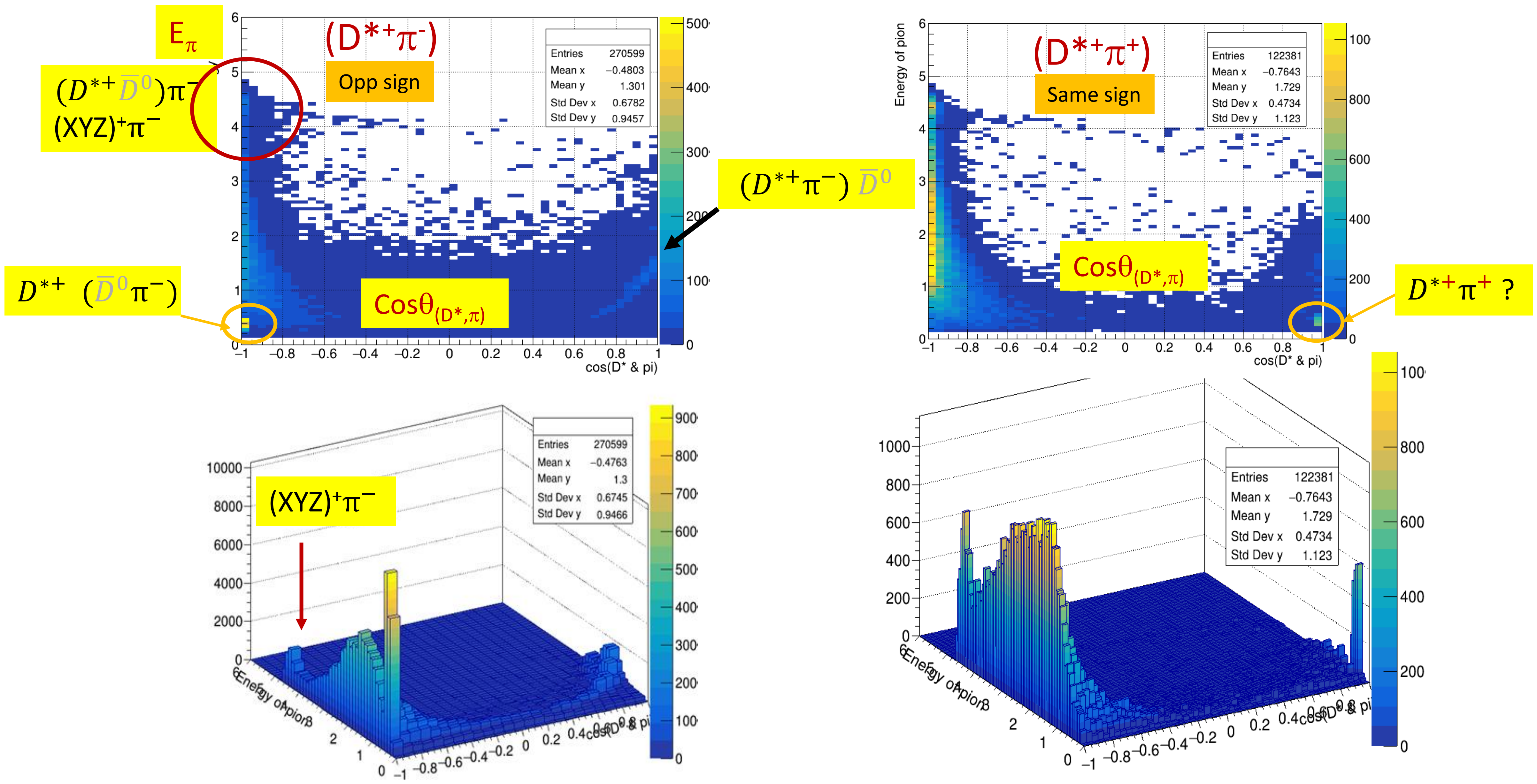
--- **mass** in Vacuum: when & where

--- **Quantum correlation** in Vacuum : when & where wave function collapses

On-going experiments, Belle-2, LHCb, heavy ion, will continue to provide data to support studies of Vacuum and particle creation.

Search for e+e- → (XYZ) π; $(XYZ)^{\pm}$→ D*D from inclusive ($D^{*-}\pi^{+}\ x$) events

signature: High momentum π (~ 4 GeV) against D^{*+}



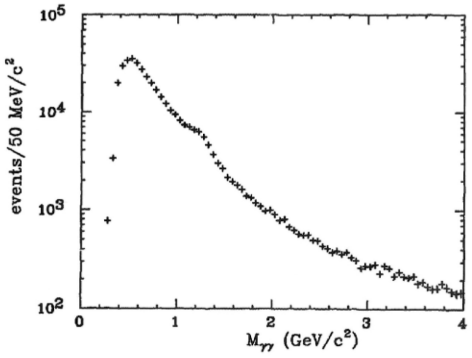
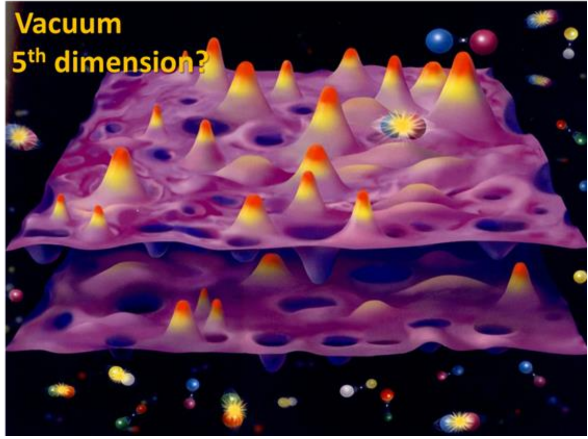
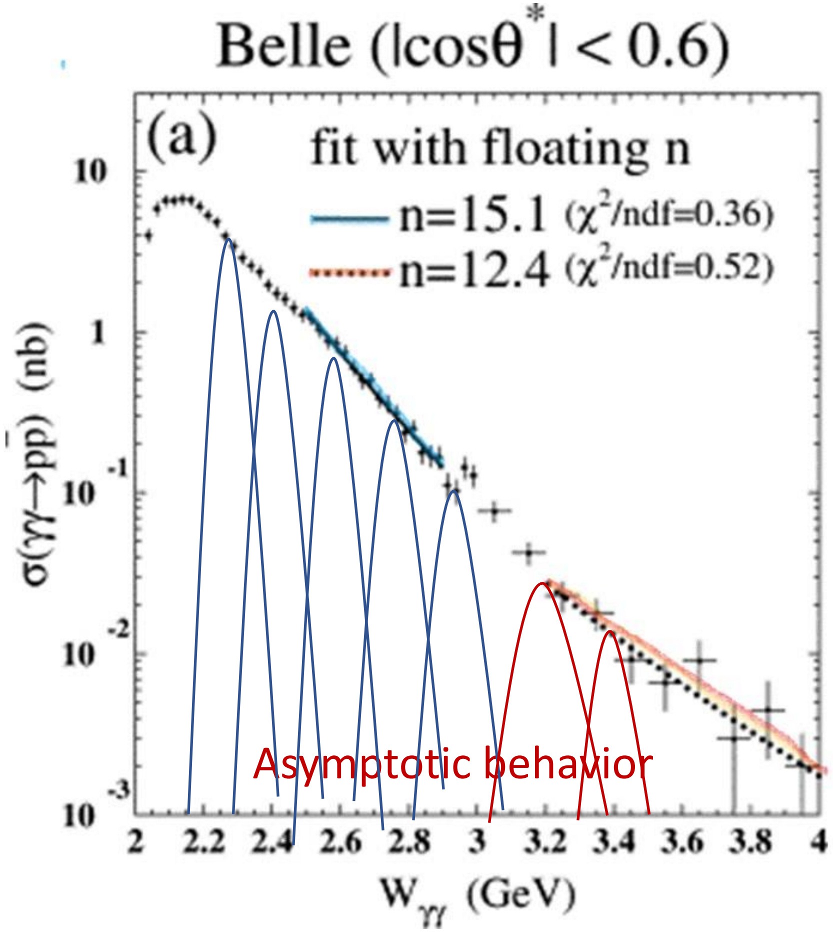


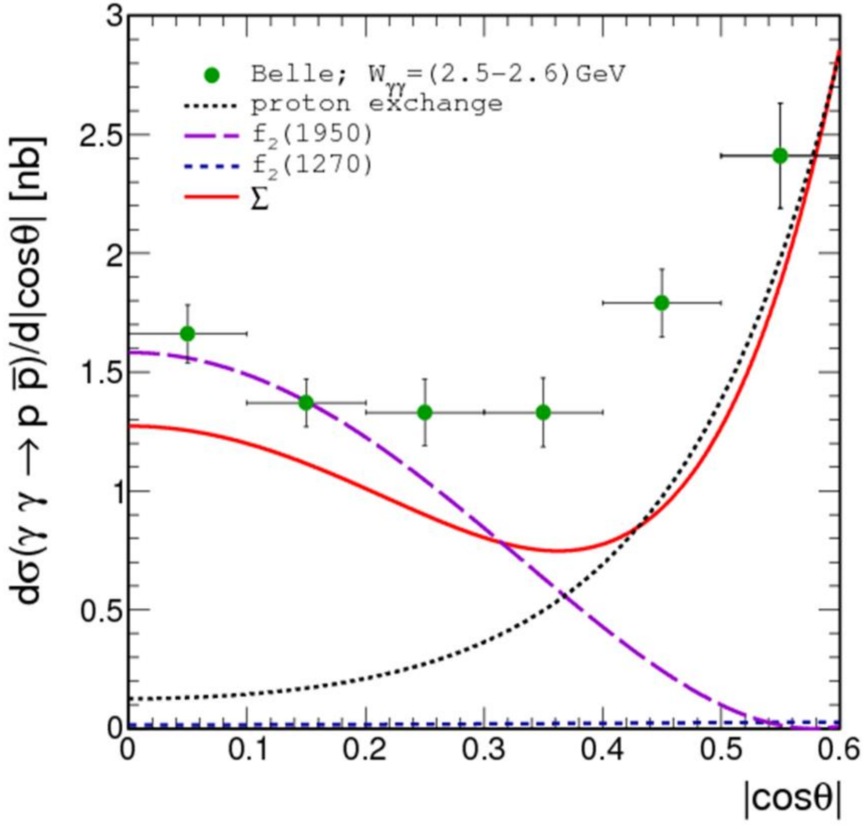
Fig. 4.1 *Effective mass of two-prong events. All tracks have been given the pion mass. The crosses do not everywhere represent statistical errors.*

$\sigma(\gamma\gamma \rightarrow P\bar{P})$

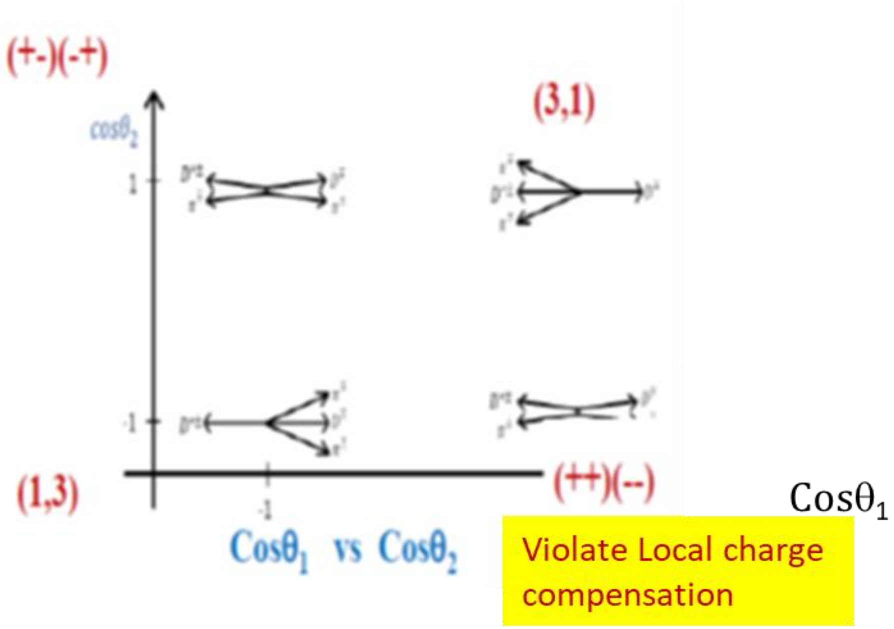


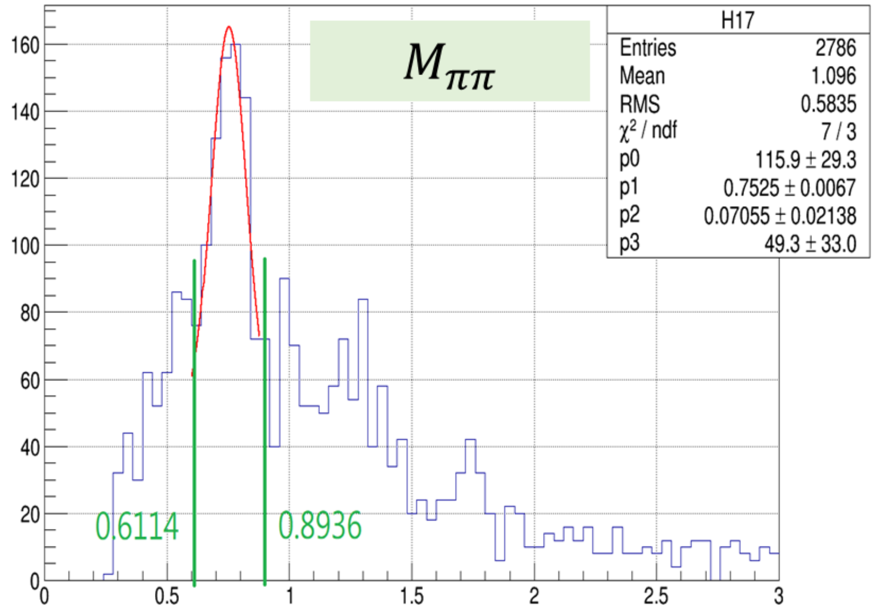


Poles & Angular analysis



Resonance in Exclusive $D^{*+}D^{-}\pi^{+}\pi^{-}$ events





There are about 1/5 of $\pi^+\pi^-$ events comes from ρ^0 decay and topology of those events are either (1, 3) or (3, 1). So, events with (2, 2) topology are "pure" 4-body events and (1, 3) events with ρ^0 should be treated as 3-body events ($D^{*+}D^-\rho$).